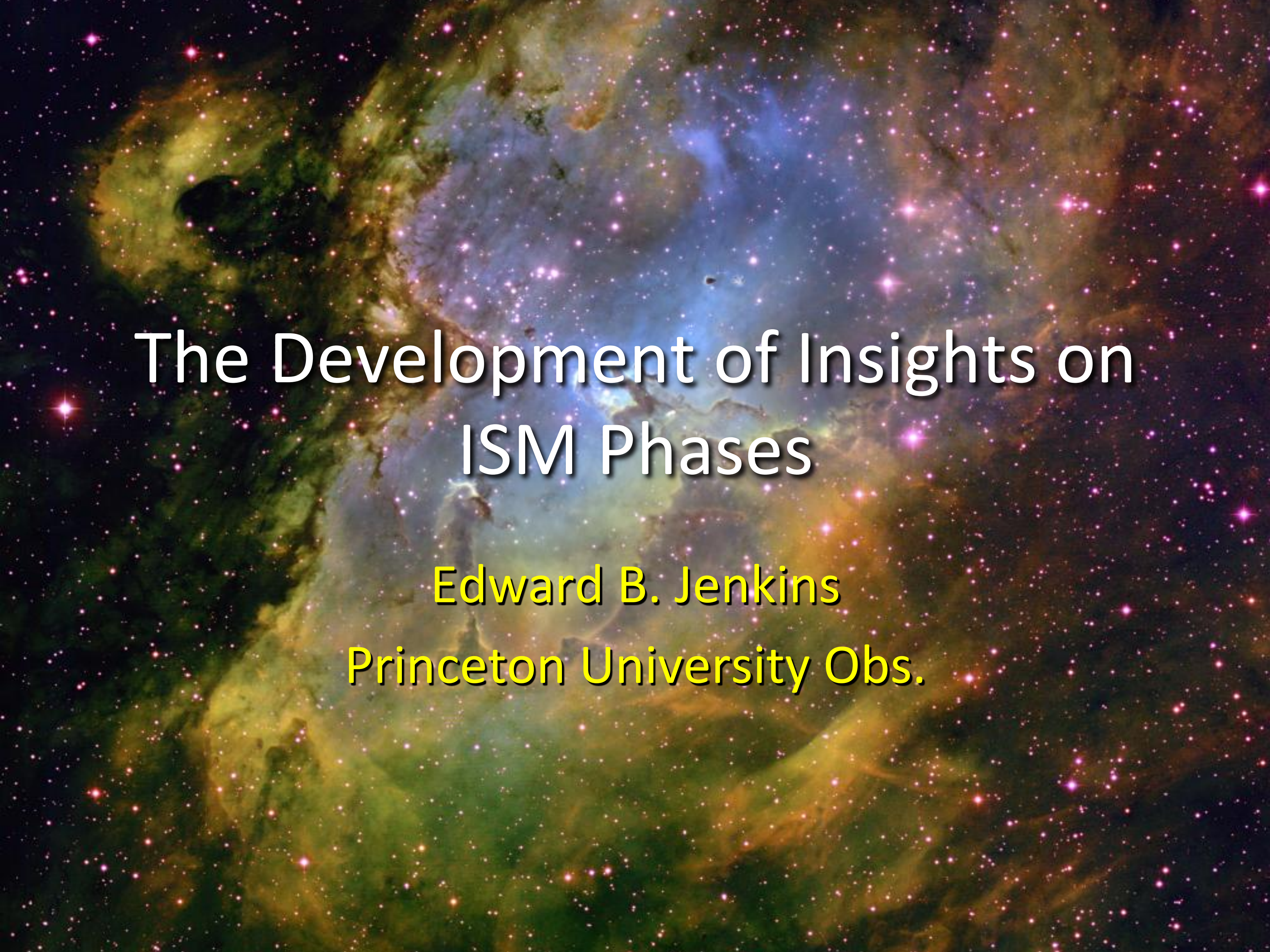
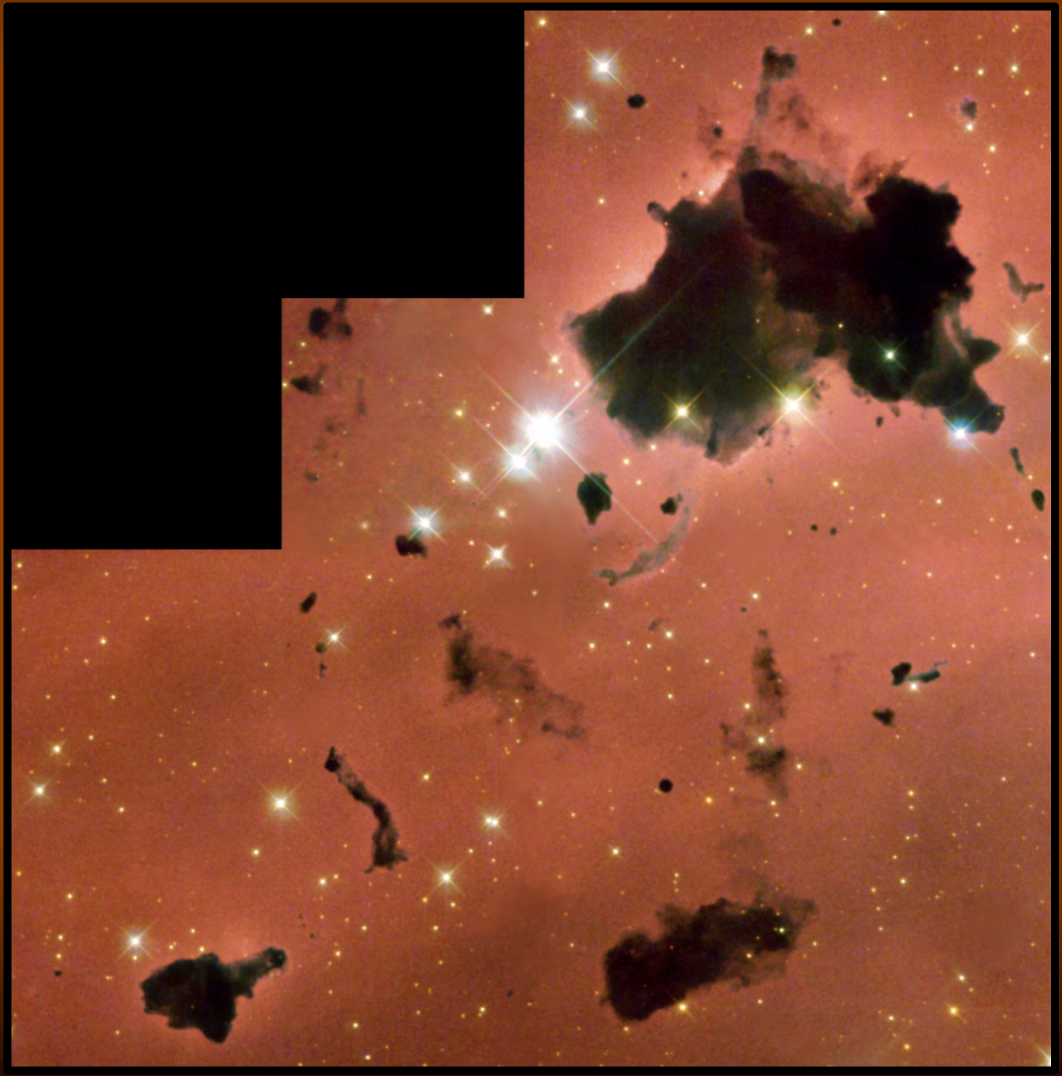


The Development of Insights on ISM Phases

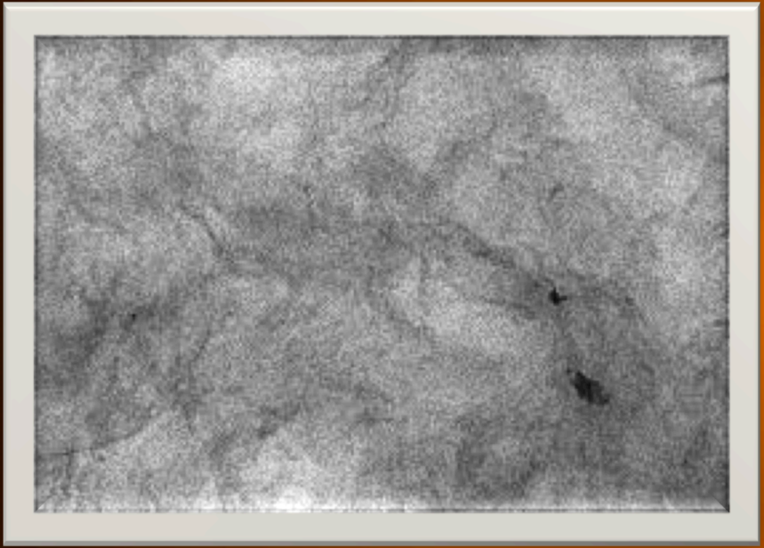
Edward B. Jenkins
Princeton University Obs.

Morphology of the ISM



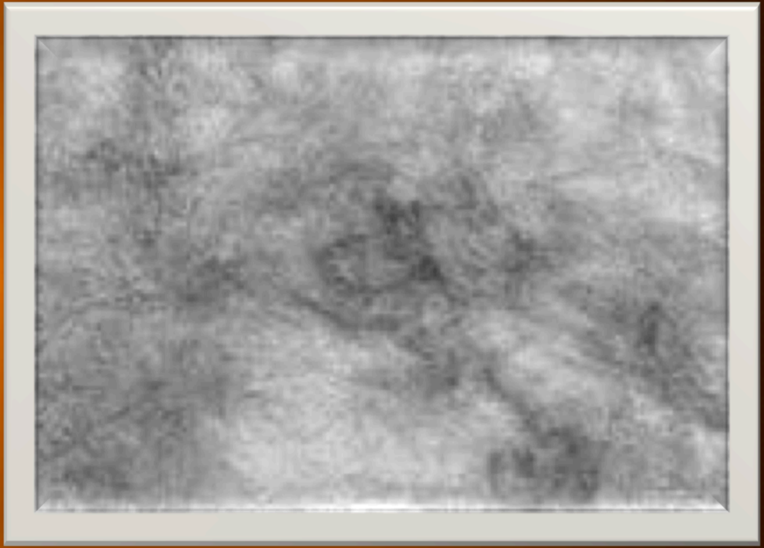
Morphology of the ISM

Federrath et al (2010: A&A, 512, A81



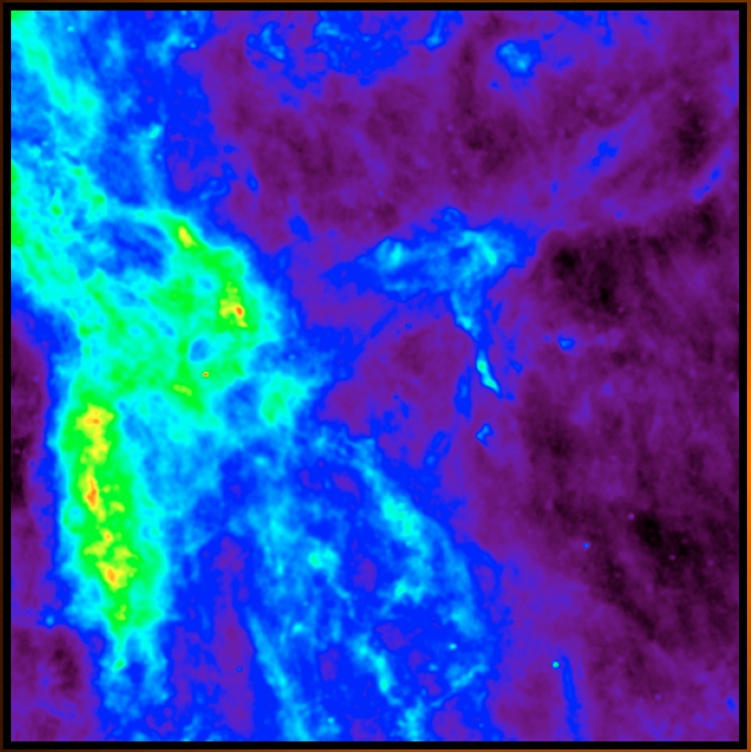
Simulation of a Turbulent Medium

Canadian Galactic Plane Survey of 21-cm emission from H I (Taylor et al. 2003: AJ, 125, 3145)

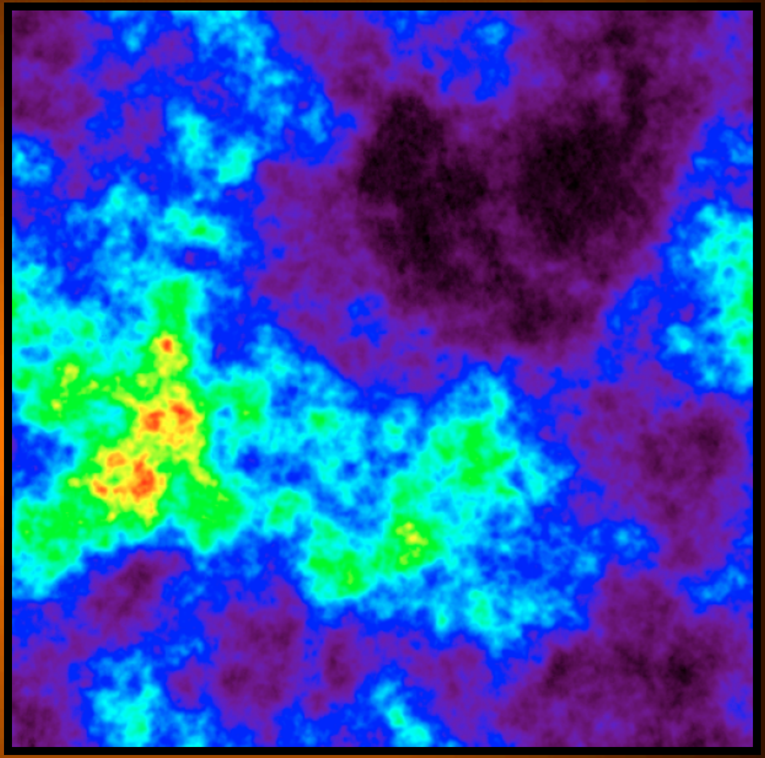


Real Data

Morphology of the ISM



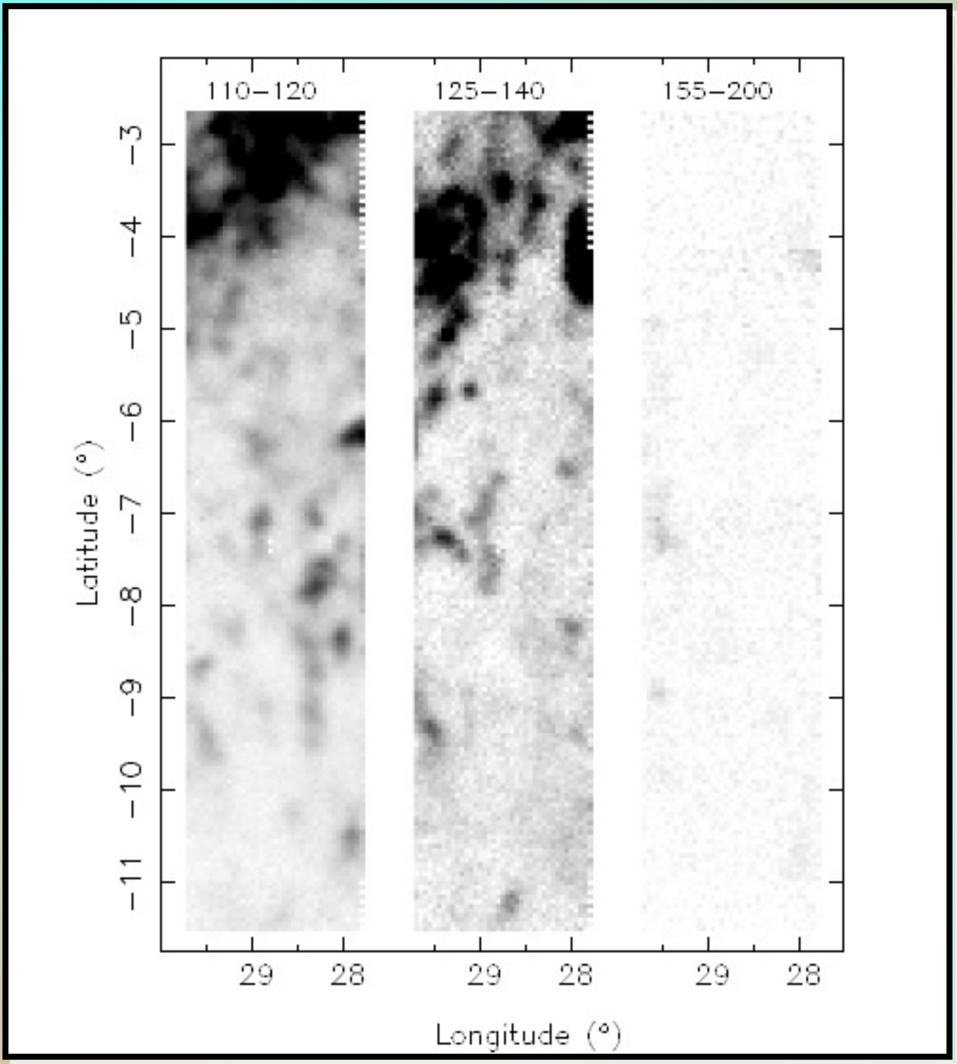
IRAS 100μm image



A construction of a field containing random Gaussian amplitudes in *k*-space

Images from Miville-Deschênes, Lagache, Boulanger & Puget 2007, A&A, 469, 595

High Latitude Clouds Visible in 21-cm Emission



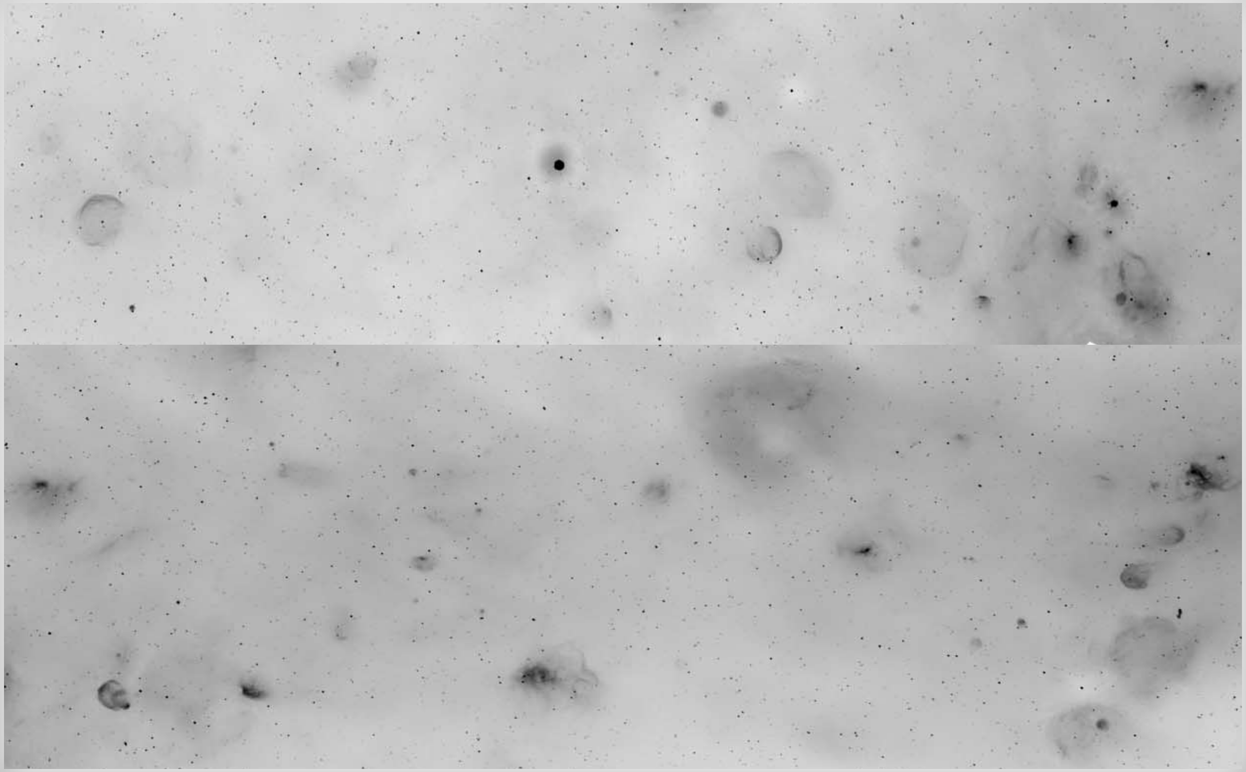
Observations from the Green Bank Telescope (GBT)

Lockman (2002: ApJ, 580, L47)

EARLY INSIGHTS ON FULLY IONIZED GAS

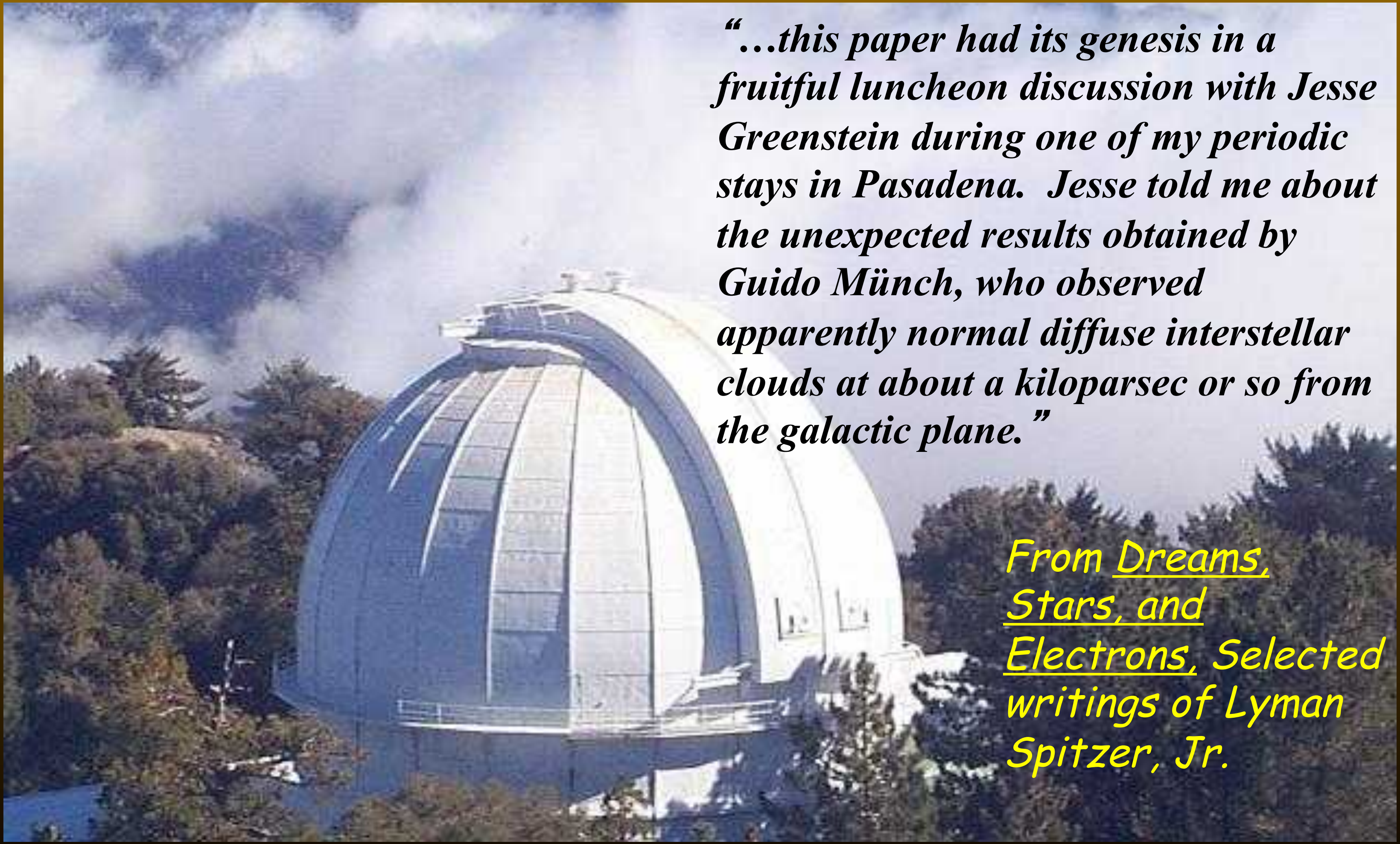
Strömgren Spheres

"It is found that the Balmer-line emission should be limited to certain rather sharply bounded regions in space surrounding O-type stars or clusters of O-type stars." (Strömgren 1939: ApJ, 89, 526)



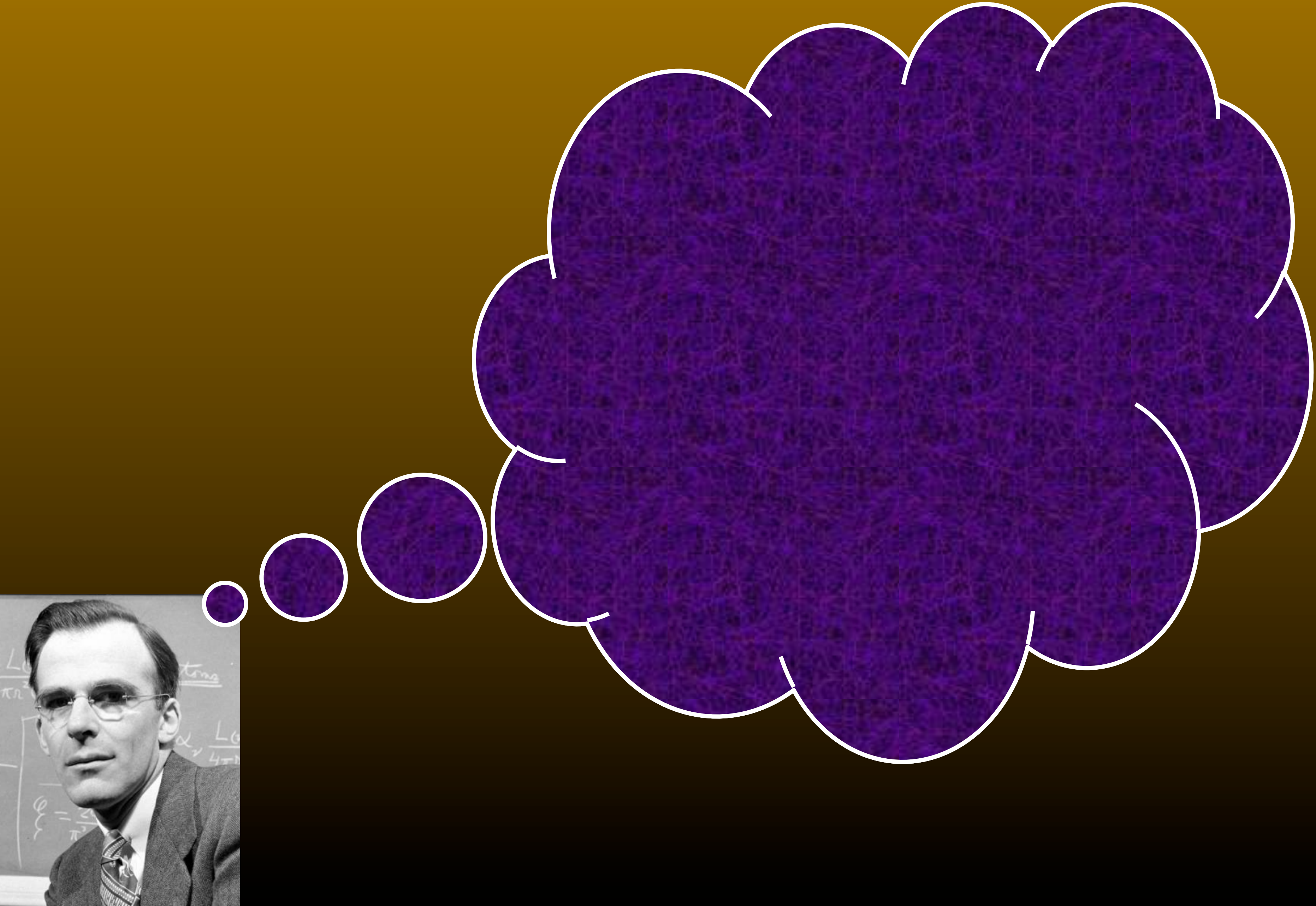
21-cm continuum emission observed in the Canadian Galactic Plane Survey (Taylor et al 2003: AJ, 125, 3145)

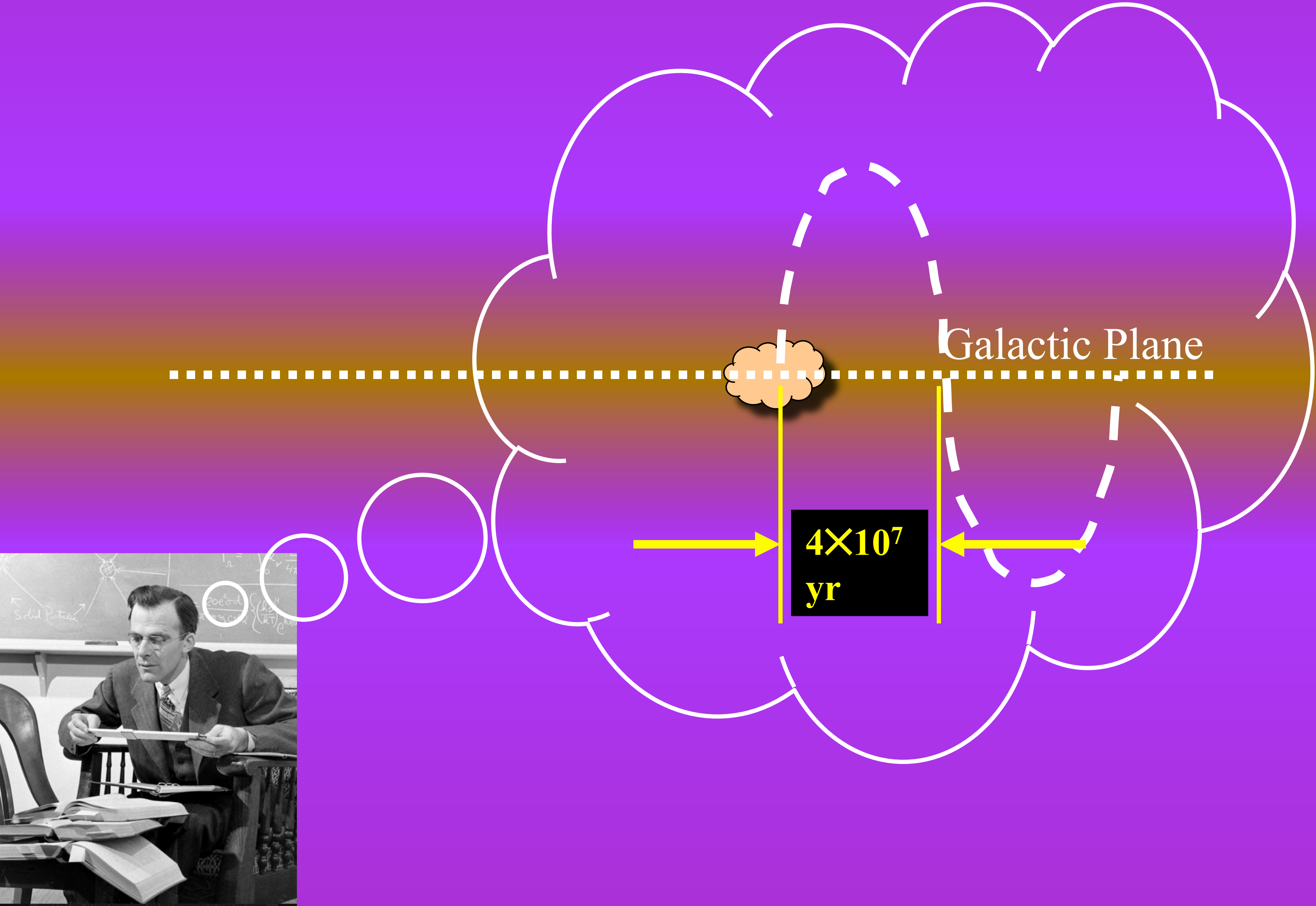
Beginnings …..



"…this paper had its genesis in a fruitful luncheon discussion with Jesse Greenstein during one of my periodic stays in Pasadena. Jesse told me about the unexpected results obtained by Guido Münch, who observed apparently normal diffuse interstellar clouds at about a kiloparsec or so from the galactic plane."

From Dreams, Stars, and Electrons, Selected writings of Lyman Spitzer, Jr.





Galactic Plane

4×10^7 yr

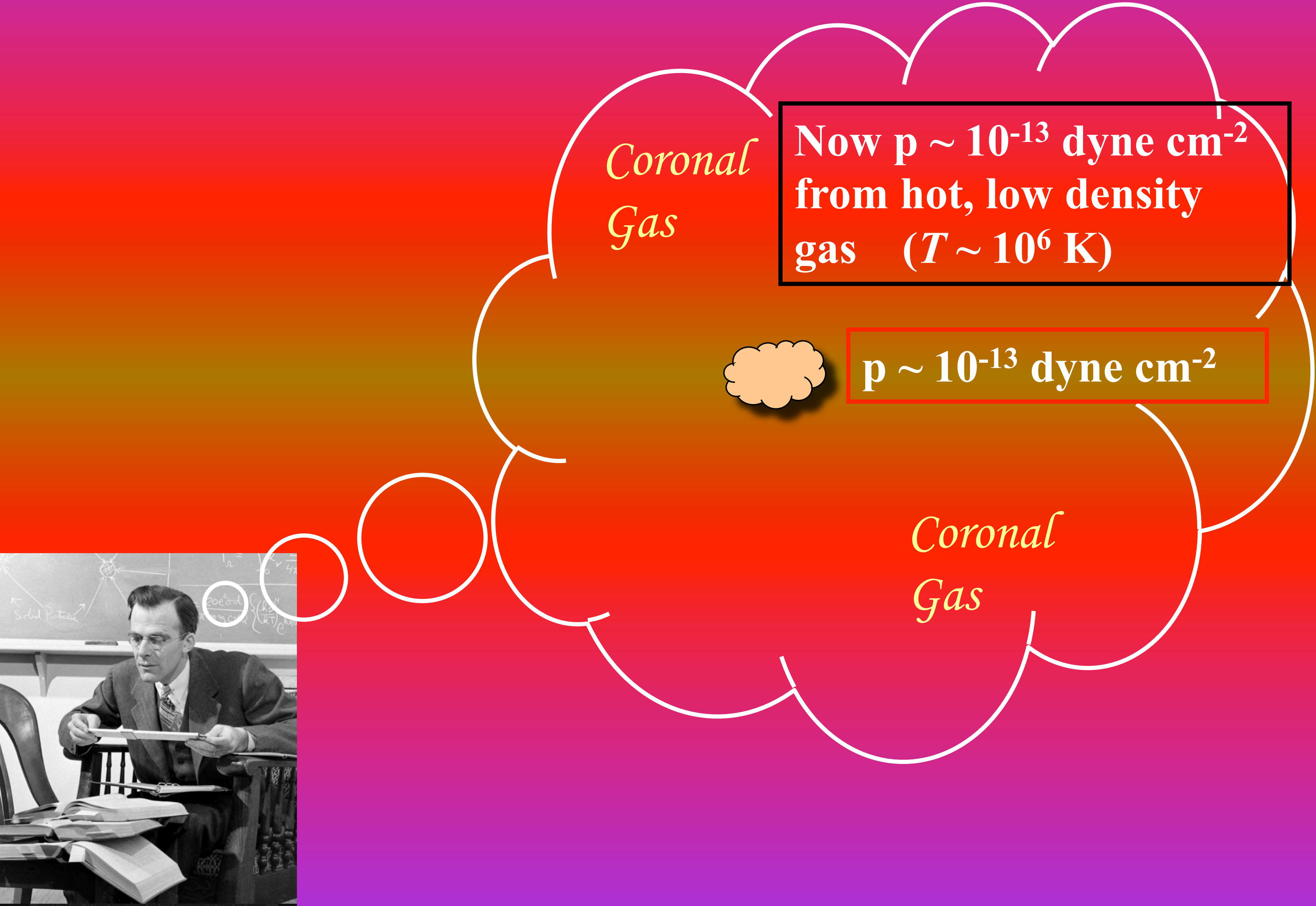
Cloud of radius of 5 pc would double in size in 5×10^{6} yr as it expands at a sound speed of 1 km s^{-1}

p ~ 0 dyne cm^{-2} ?

Ca II no longer visible as ionization equilibrium shifts to Ca III and cloud dissipates

p ~ 10^{-13} dyne cm^{-2}

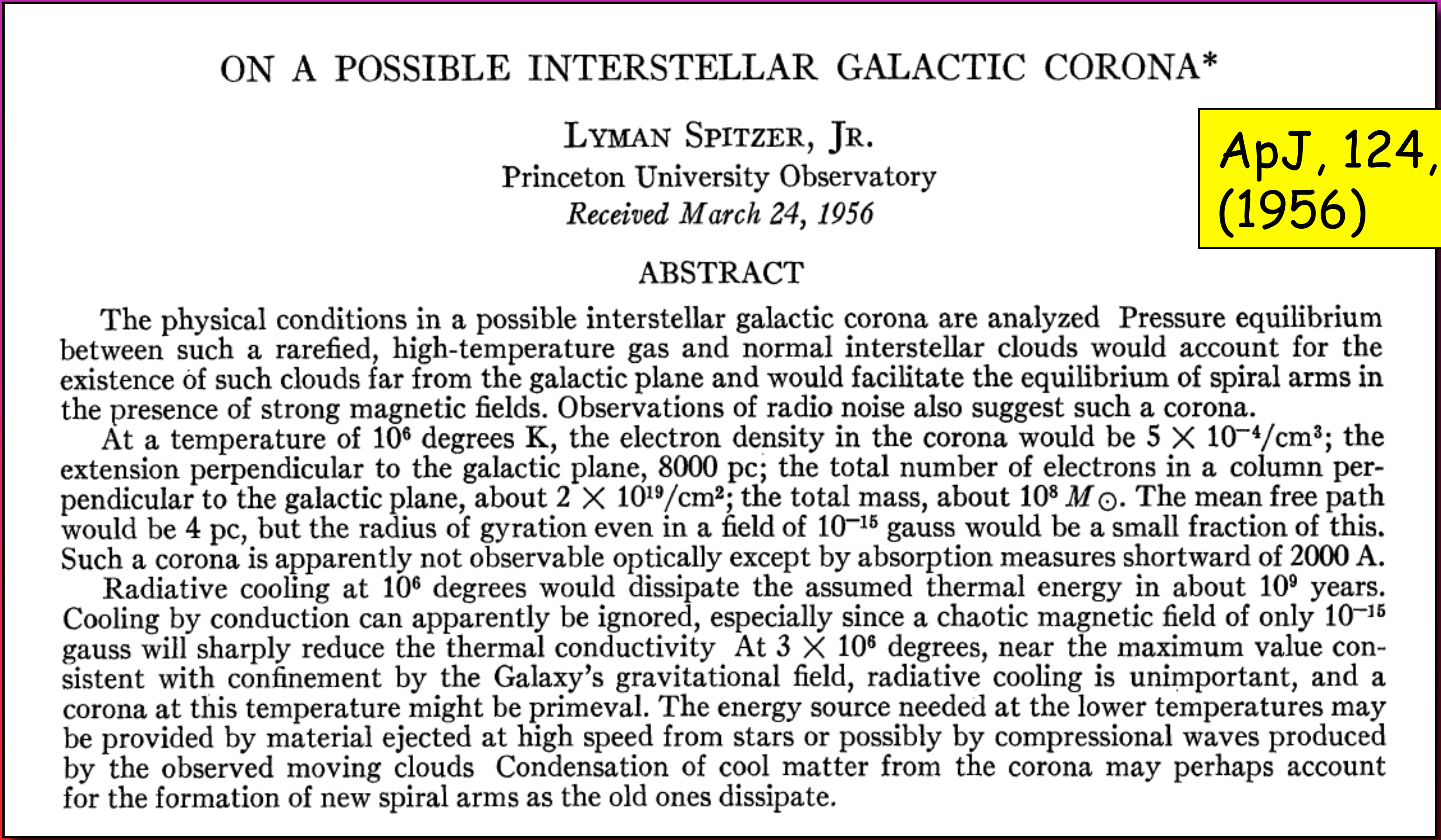
Cloud confinement



Now p ~ 10^{-13} dyne cm^{-2} from hot, low density gas (*T* ~ 10^{6} K)

p ~ 10^{-13} dyne cm^{-2}

Spitzer's 1956 Paper



ON A POSSIBLE INTERSTELLAR GALACTIC CORONA*

LYMAN SPITZER, JR.
Princeton University Observatory

Received March 24, 1956

ABSTRACT

The physical conditions in a possible interstellar galactic corona are analyzed Pressure equilibrium between such a rarefied, high-temperature gas and normal interstellar clouds would account for the existence of such clouds far from the galactic plane and would facilitate the equilibrium of spiral arms in the presence of strong magnetic fields. Observations of radio noise also suggest such a corona.

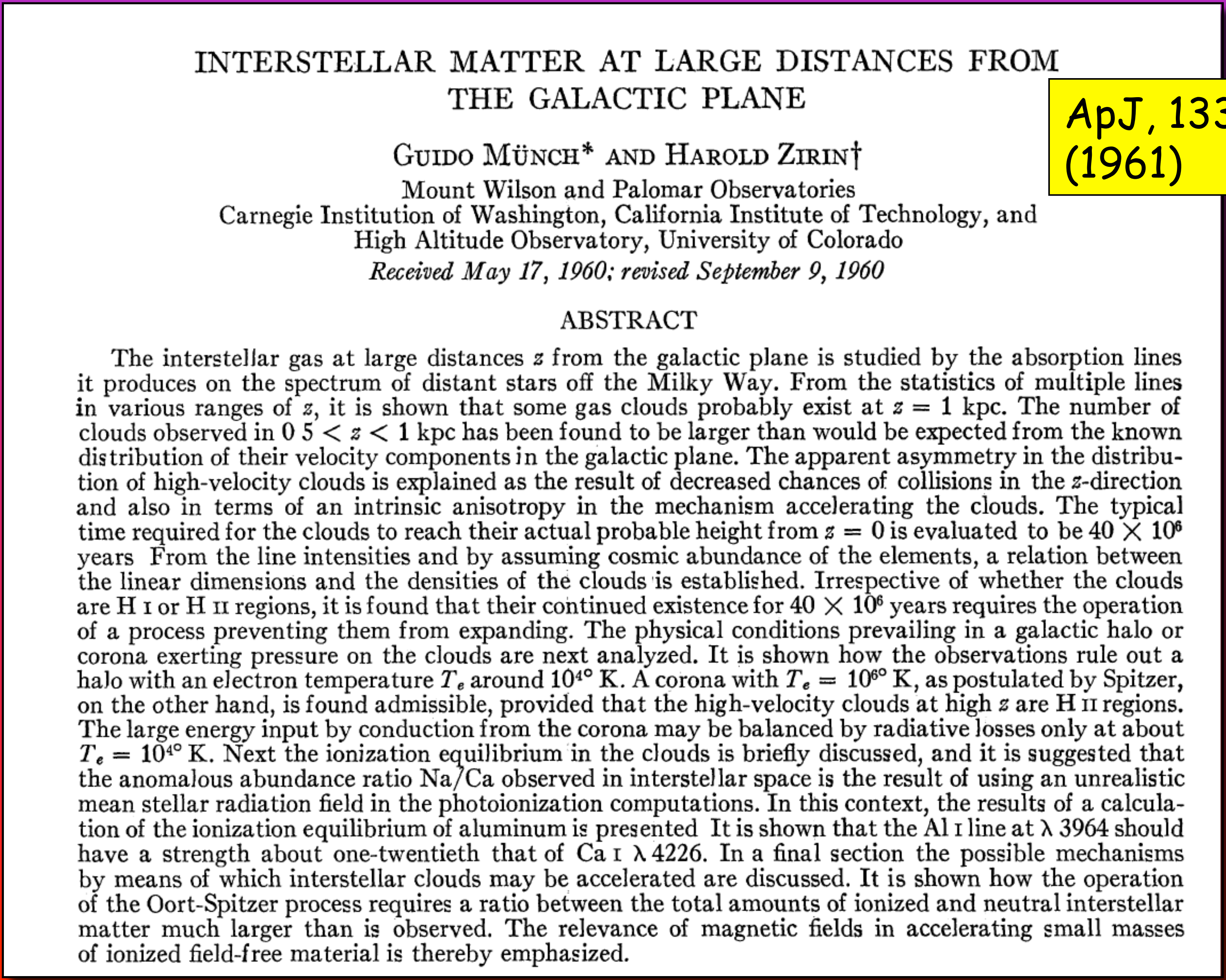
At a temperature of 10^6 degrees K, the electron density in the corona would be $5 \times 10^{-4}/\mathrm{cm}^3$; the extension perpendicular to the galactic plane, 8000 pc; the total number of electrons in a column perpendicular to the galactic plane, about $2 \times 10^{19}/\mathrm{cm}^2$; the total mass, about $10^8\ M_\odot$. The mean free path would be 4 pc, but the radius of gyration even in a field of 10^{-15} gauss would be a small fraction of this. Such a corona is apparently not observable optically except by absorption measures shortward of 2000 A.

Radiative cooling at 10^6 degrees would dissipate the assumed thermal energy in about 10^9 years. Cooling by conduction can apparently be ignored, especially since a chaotic magnetic field of only 10^{-15} gauss will sharply reduce the thermal conductivity At 3×10^6 degrees, near the maximum value consistent with confinement by the Galaxy's gravitational field, radiative cooling is unimportant, and a corona at this temperature might be primeval. The energy source needed at the lower temperatures may be provided by material ejected at high speed from stars or possibly by compressional waves produced by the observed moving clouds Condensation of cool matter from the corona may perhaps account for the formation of new spiral arms as the old ones dissipate.

ApJ, 124, 20 (1956)

Five years later …

ApJ, 133, 11
(1961)



INTERSTELLAR MATTER AT LARGE DISTANCES FROM THE GALACTIC PLANE

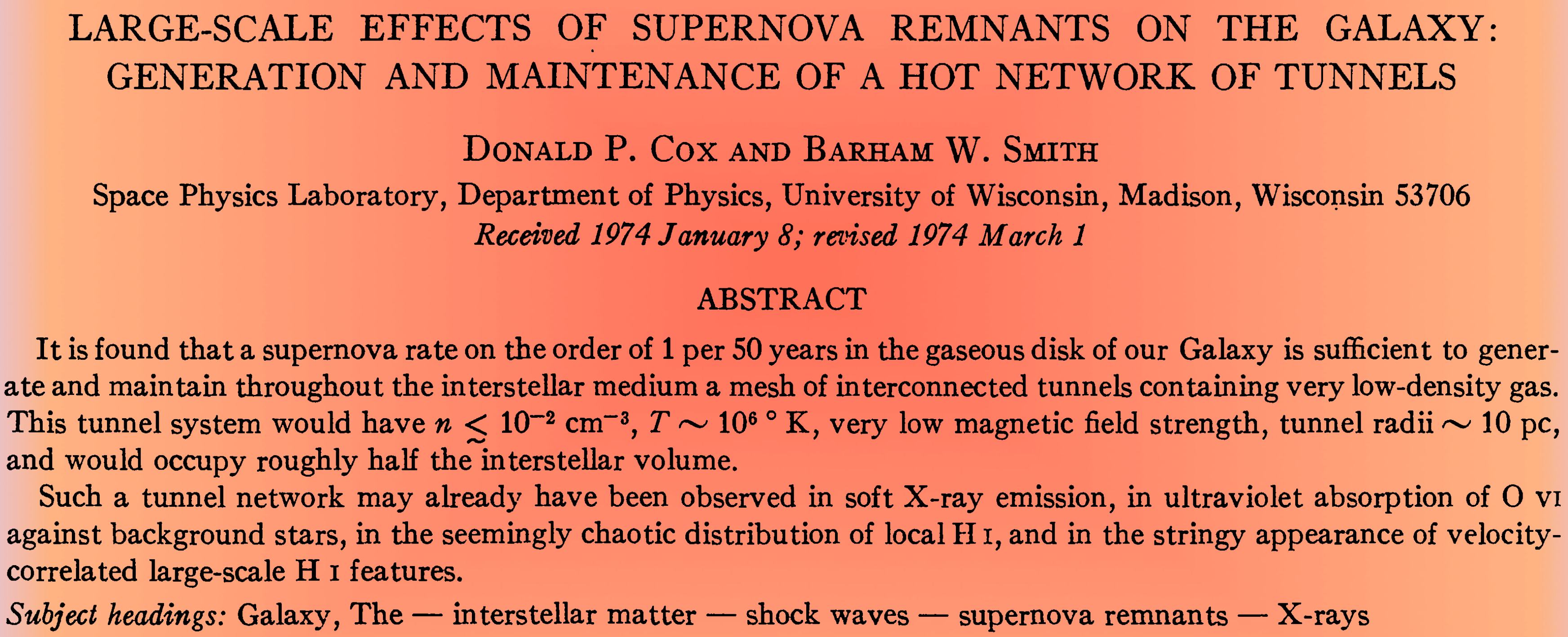
GUIDO MÜNCH* AND HAROLD ZIRIN†
Mount Wilson and Palomar Observatories
Carnegie Institution of Washington, California Institute of Technology, and
High Altitude Observatory, University of Colorado

Received May 17, 1960; revised September 9, 1960

ABSTRACT

The interstellar gas at large distances z from the galactic plane is studied by the absorption lines it produces on the spectrum of distant stars off the Milky Way. From the statistics of multiple lines in various ranges of z, it is shown that some gas clouds probably exist at $z = 1$ kpc. The number of clouds observed in $0\ 5 < z < 1$ kpc has been found to be larger than would be expected from the known distribution of their velocity components in the galactic plane. The apparent asymmetry in the distribution of high-velocity clouds is explained as the result of decreased chances of collisions in the z-direction and also in terms of an intrinsic anisotropy in the mechanism accelerating the clouds. The typical time required for the clouds to reach their actual probable height from $z = 0$ is evaluated to be 40×10^6 years From the line intensities and by assuming cosmic abundance of the elements, a relation between the linear dimensions and the densities of the clouds is established. Irrespective of whether the clouds are H I or H II regions, it is found that their continued existence for 40×10^6 years requires the operation of a process preventing them from expanding. The physical conditions prevailing in a galactic halo or corona exerting pressure on the clouds are next analyzed. It is shown how the observations rule out a halo with an electron temperature T_e around $10^{4\circ}$ K. A corona with $T_e = 10^{6\circ}$ K, as postulated by Spitzer, on the other hand, is found admissible, provided that the high-velocity clouds at high z are H II regions. The large energy input by conduction from the corona may be balanced by radiative losses only at about $T_e = 10^{4\circ}$ K. Next the ionization equilibrium in the clouds is briefly discussed, and it is suggested that the anomalous abundance ratio Na/Ca observed in interstellar space is the result of using an unrealistic mean stellar radiation field in the photoionization computations. In this context, the results of a calculation of the ionization equilibrium of aluminum is presented It is shown that the Al I line at λ 3964 should have a strength about one-twentieth that of Ca I λ 4226. In a final section the possible mechanisms by means of which interstellar clouds may be accelerated are discussed. It is shown how the operation of the Oort-Spitzer process requires a ratio between the total amounts of ionized and neutral interstellar matter much larger than is observed. The relevance of magnetic fields in accelerating small masses of ionized field-free material is thereby emphasized.

1974: ApJ, 189, L105



LARGE-SCALE EFFECTS OF SUPERNOVA REMNANTS ON THE GALAXY: GENERATION AND MAINTENANCE OF A HOT NETWORK OF TUNNELS

DONALD P. COX AND BARHAM W. SMITH
Space Physics Laboratory, Department of Physics, University of Wisconsin, Madison, Wisconsin 53706

Received 1974 January 8; revised 1974 March 1

ABSTRACT

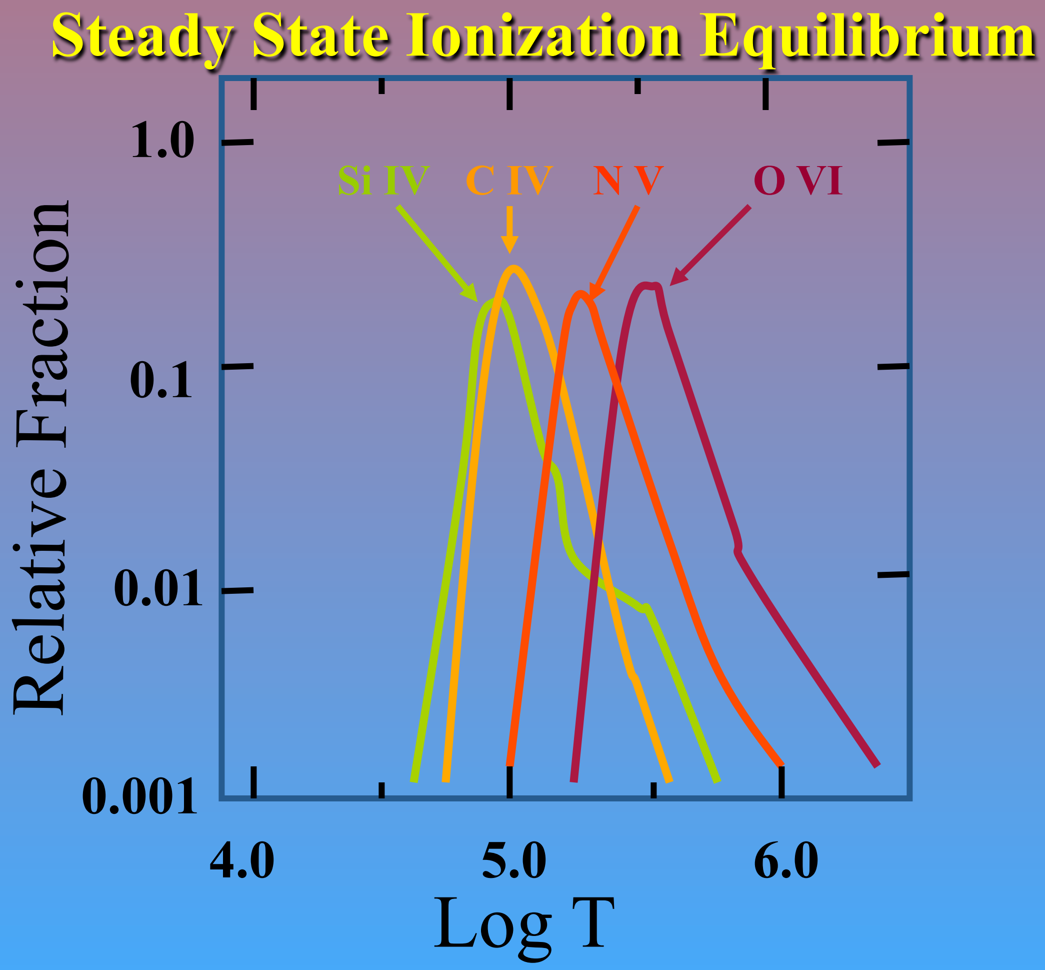
It is found that a supernova rate on the order of 1 per 50 years in the gaseous disk of our Galaxy is sufficient to generate and maintain throughout the interstellar medium a mesh of interconnected tunnels containing very low-density gas. This tunnel system would have $n \lesssim 10^{-2}$ cm^{-3}, $T \sim 10^6$ ° K, very low magnetic field strength, tunnel radii $\sim$ 10 pc, and would occupy roughly half the interstellar volume.

Such a tunnel network may already have been observed in soft X-ray emission, in ultraviolet absorption of O VI against background stars, in the seemingly chaotic distribution of local H I, and in the stringy appearance of velocity-correlated large-scale H I features.

Subject headings: Galaxy, The — interstellar matter — shock waves — supernova remnants — X-rays

Ionization Fractions for Li-like ions that have Strong UV Features

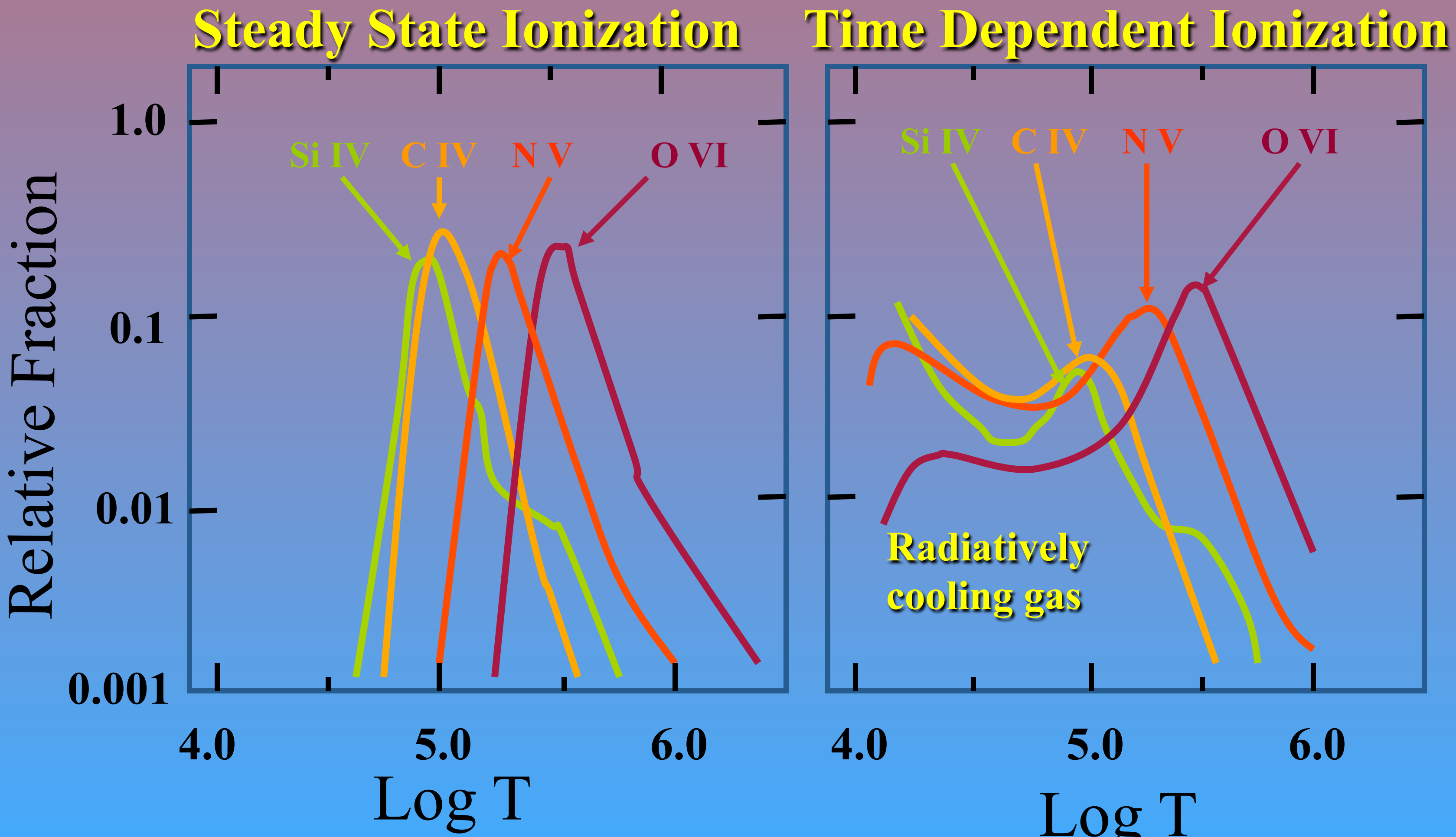
[from Shapiro & Moore (1976: ApJ, **207**, 460)]



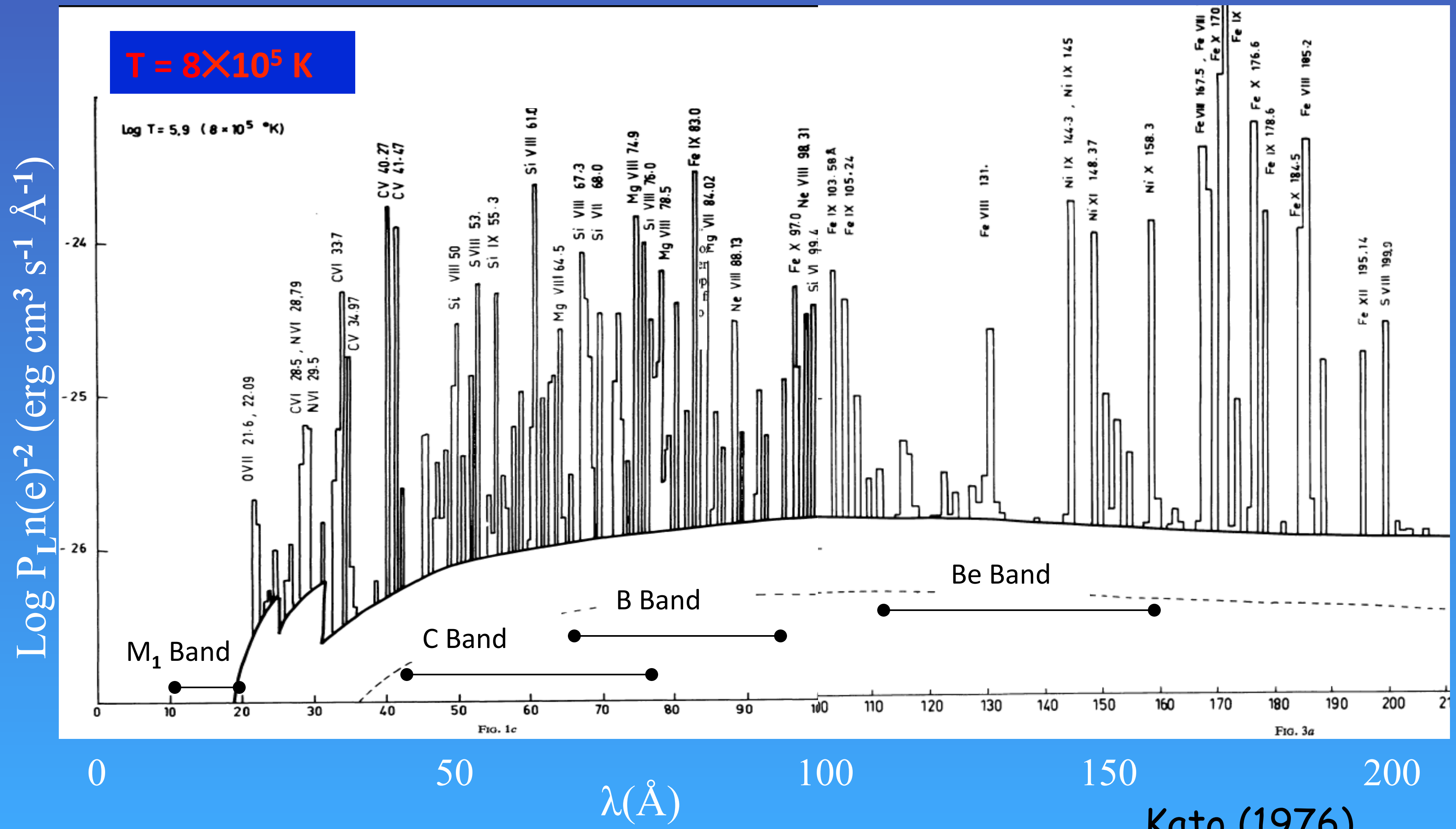
Note that Si IV, C IV and N V can also be created by photoionization of the atoms by starlight from the hottest stars. However, the C IV emission at high Galactic latitudes reported by *Martin & Bowyer (1990)* indicate that collisional ionization is important in the halo of our Galaxy.

Ionization Fractions for Li-like ions that have Strong UV Features

[from Shapiro & Moore (1976: ApJ, **207**, 460)]



X-Ray Emission from an Optically Thin Plasma with a Cosmic Abundance of Heavy Elements

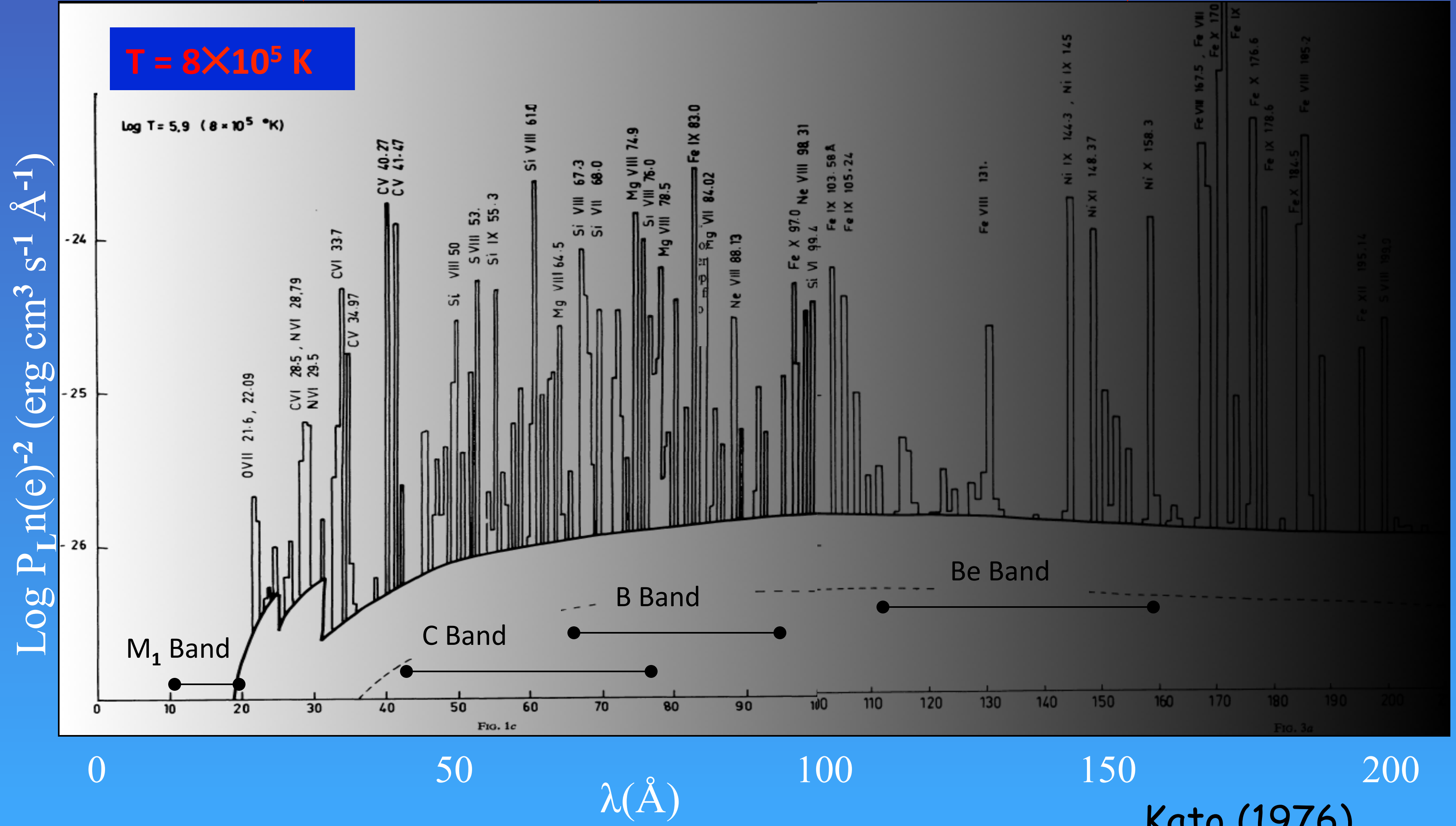


Kato (1976)

τ = 1 at N(H) = 1×10^{19}cm^{-2}

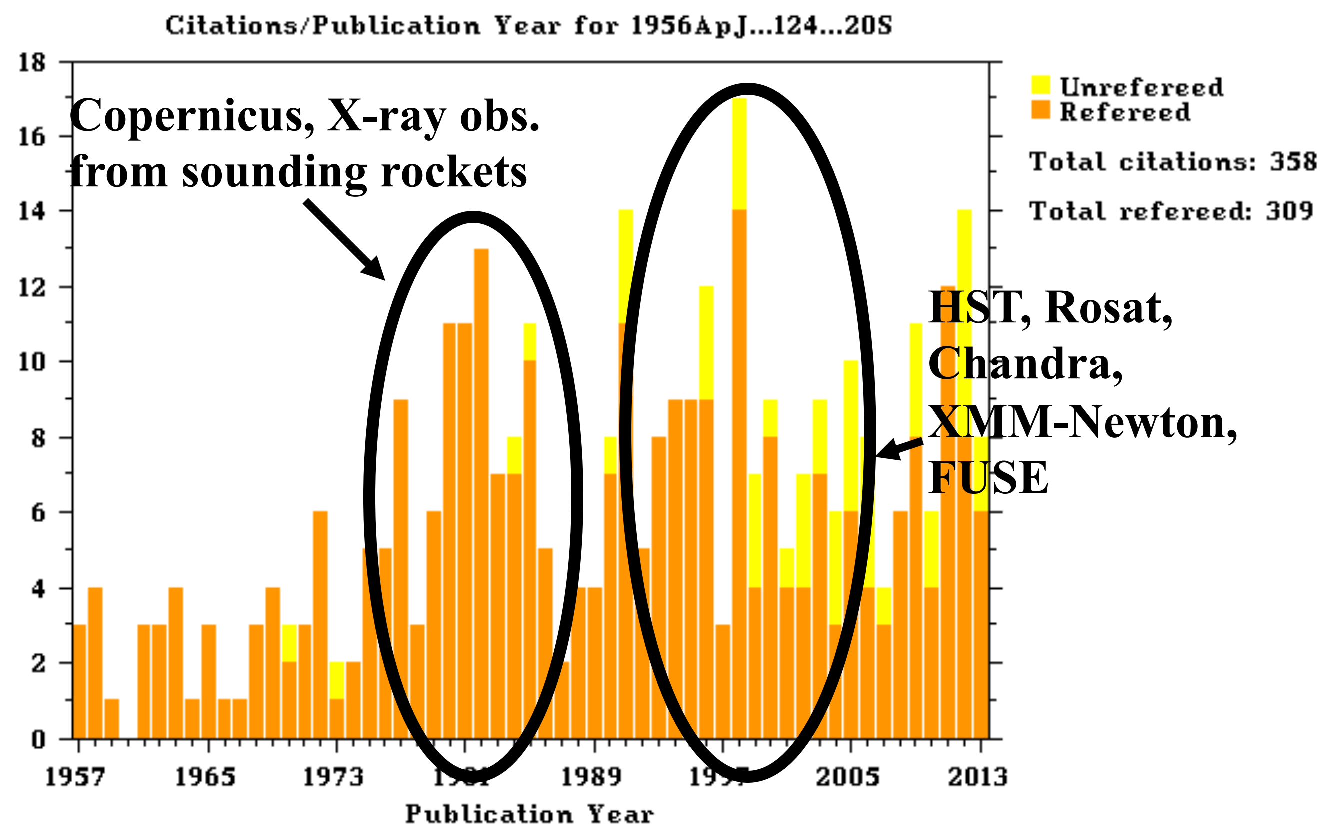
τ = 1 at N(H) = 1×10^{20}cm^{-2}

τ = 1 at N(H) = 1×10^{21}cm^{-2}



Kato (1976)

Activity in Research on Hot Gas, as Revealed by Citations to Spitzer's 1956 Article



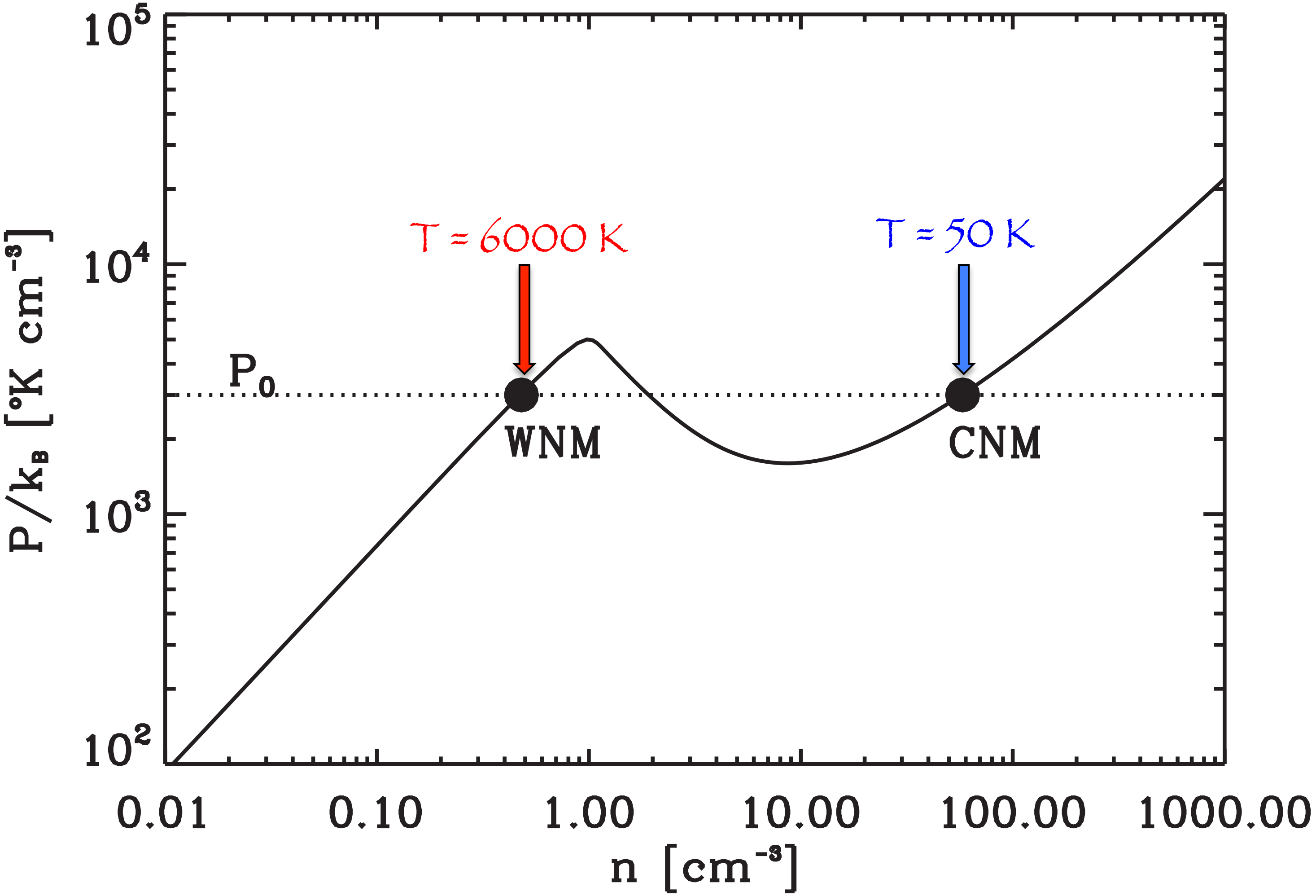
Copernicus, X-ray obs. from sounding rockets

HST, Rosat, Chandra, XMM-Newton, FUSE

Citations compiled by ADS

Neutral Gas

Phase Diagram

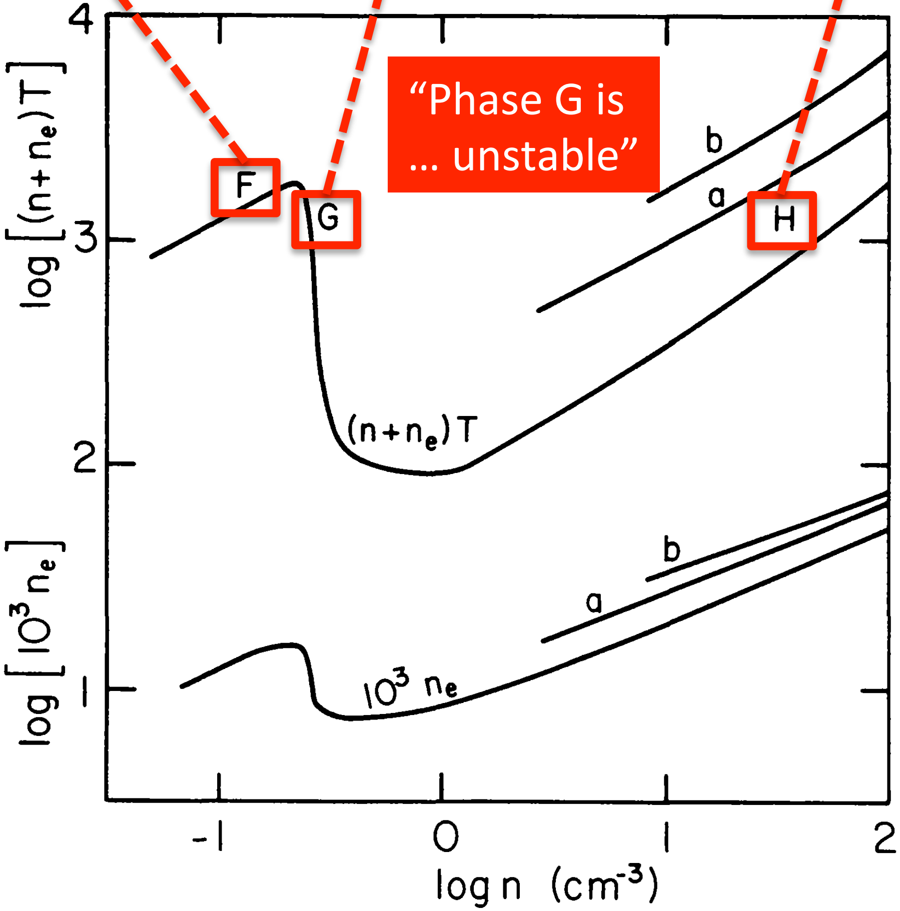


A diagram taken from Vázquez-Semadeni (2012 in *The Role of the Disk-Halo Interaction in Galaxy Evolution: Outflow vs. Infall?* M. A. de Avillez (ed) p. 39)

Story of 2 Phases

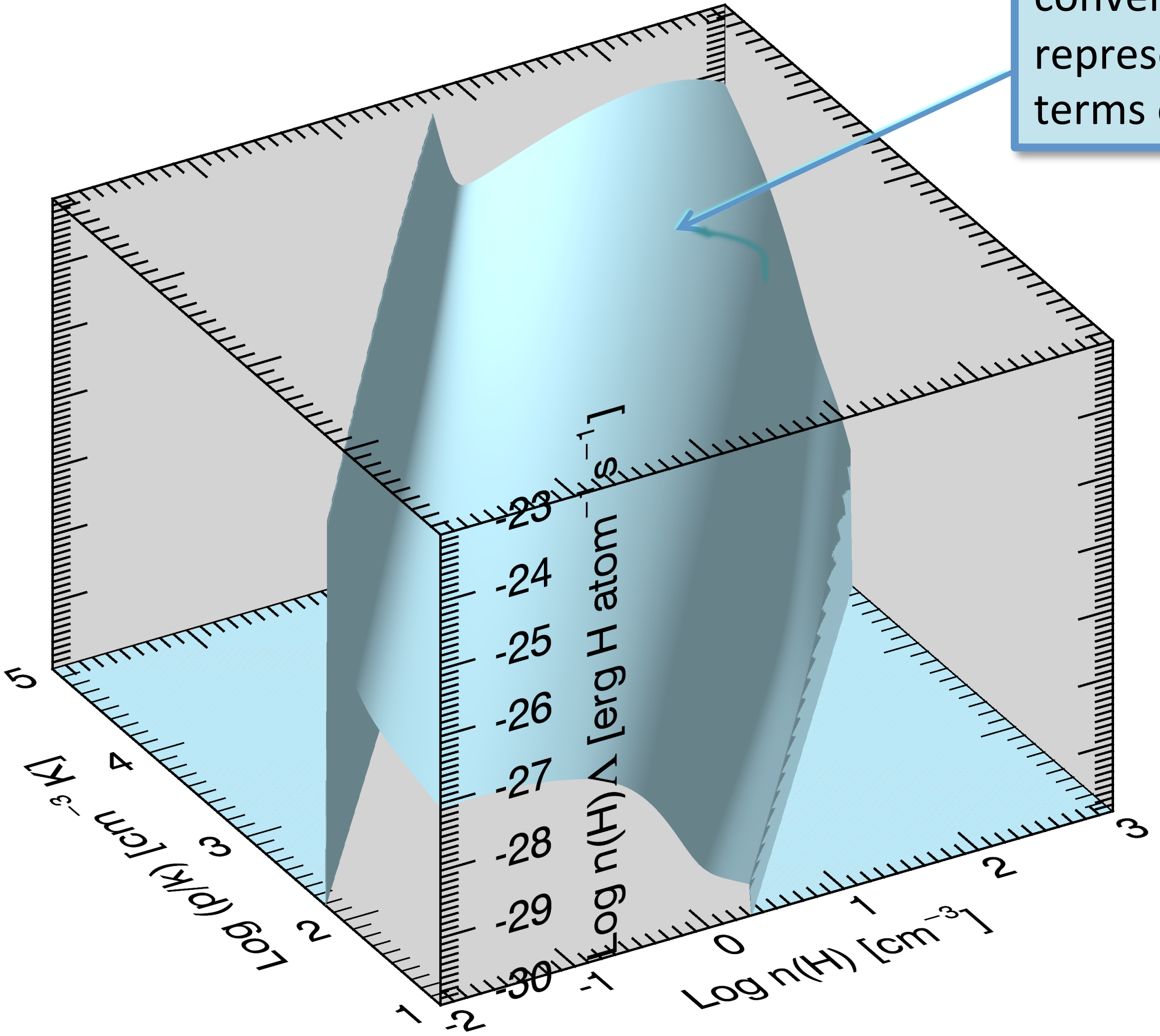
COSMIC-RAY HEATING OF THE INTERSTELLAR GAS

G. B. FIELD, D. W. GOLDSMITH, AND H. J. HABING* ApJ, 155, 149 (1969)



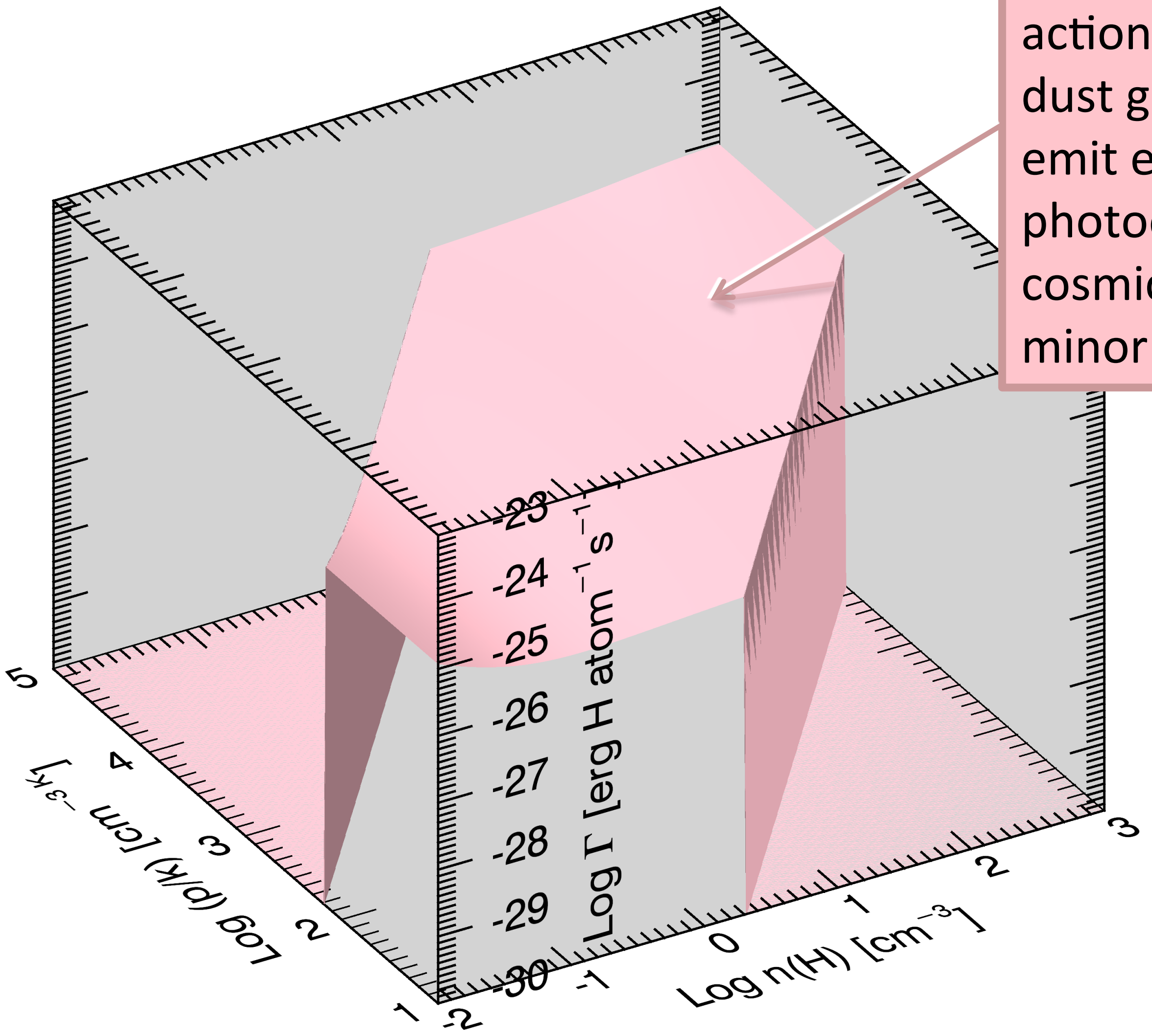
"Phase G is … unstable"

Cooling Function



Note: This is not the conventional representation in terms of erg cm^{3} s^{-1}

Heating Function



Primary source of heat is from the action of starlight on dust grains, which emit energetic photoelectrons – cosmic ray heating is minor by comparison.

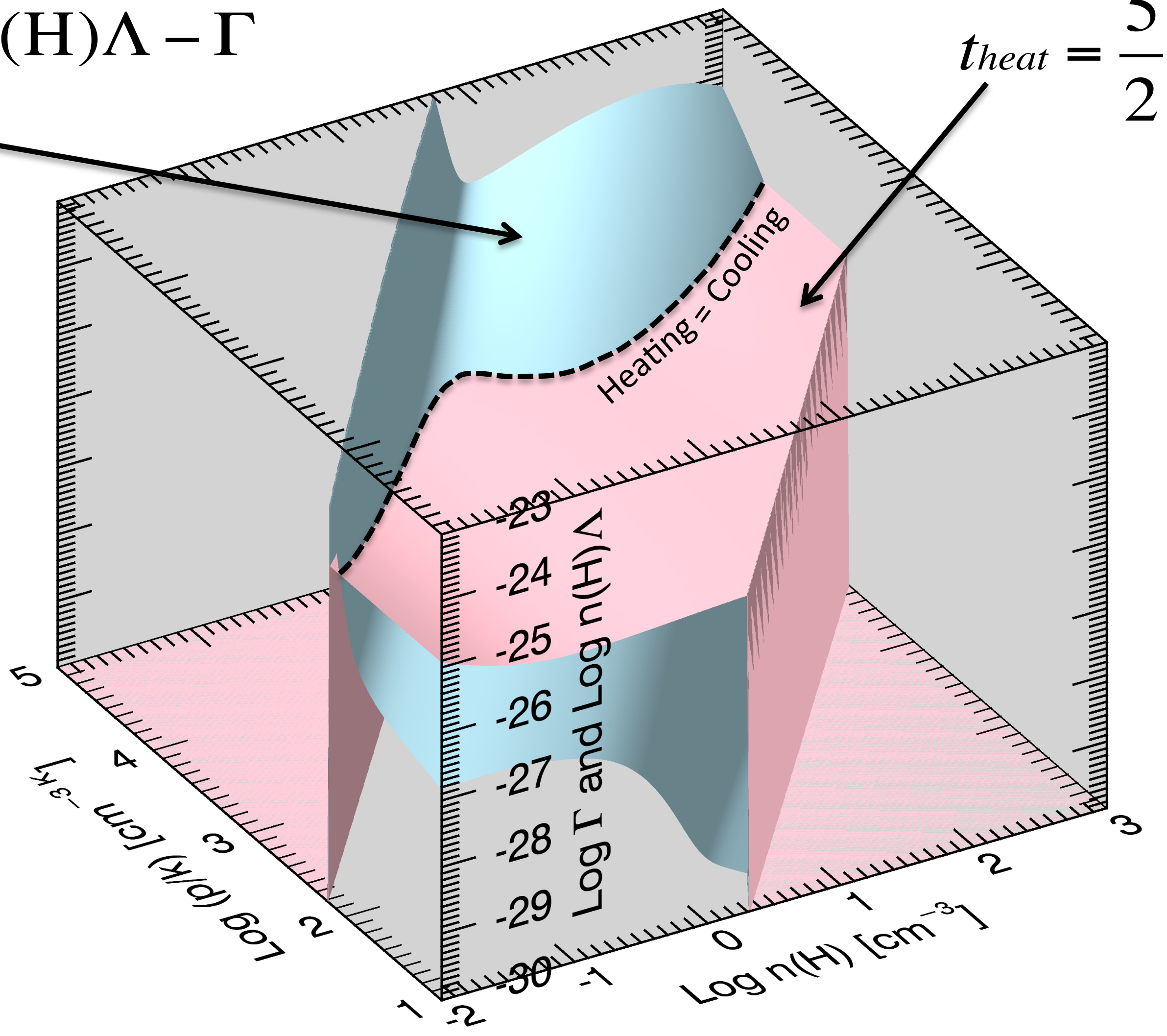
Both Functions

Isobaric e-folding time

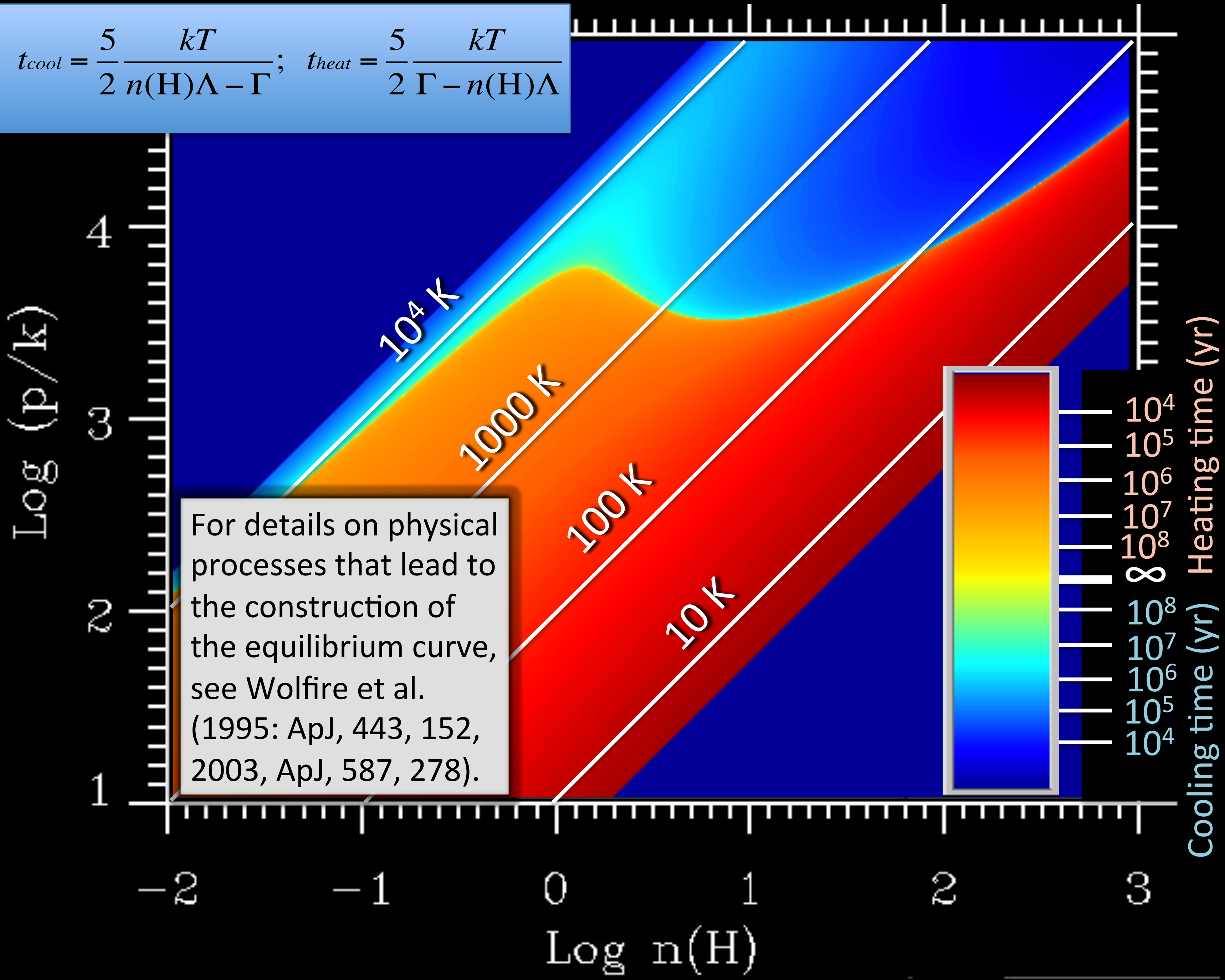
$$t_{cool} = \frac{5}{2}\frac{kT}{n(\mathrm{H})\Lambda - \Gamma}$$

Isobaric e-folding time

$$t_{heat} = \frac{5}{2}\frac{kT}{\Gamma - n(\mathrm{H})\Lambda}$$

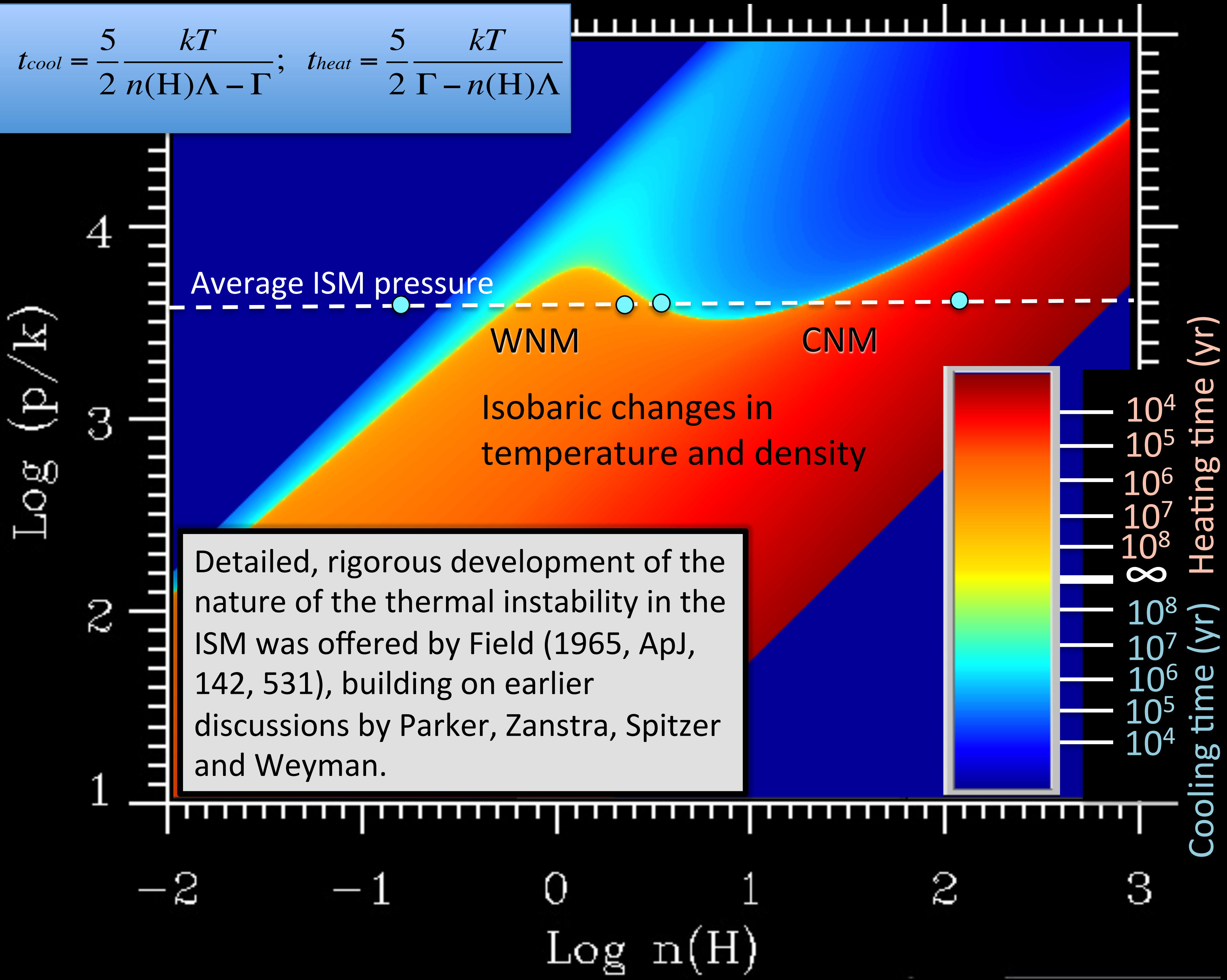


$$t_{cool} = \frac{5}{2}\frac{kT}{n(\mathrm{H})\Lambda - \Gamma}; \quad t_{heat} = \frac{5}{2}\frac{kT}{\Gamma - n(\mathrm{H})\Lambda}$$



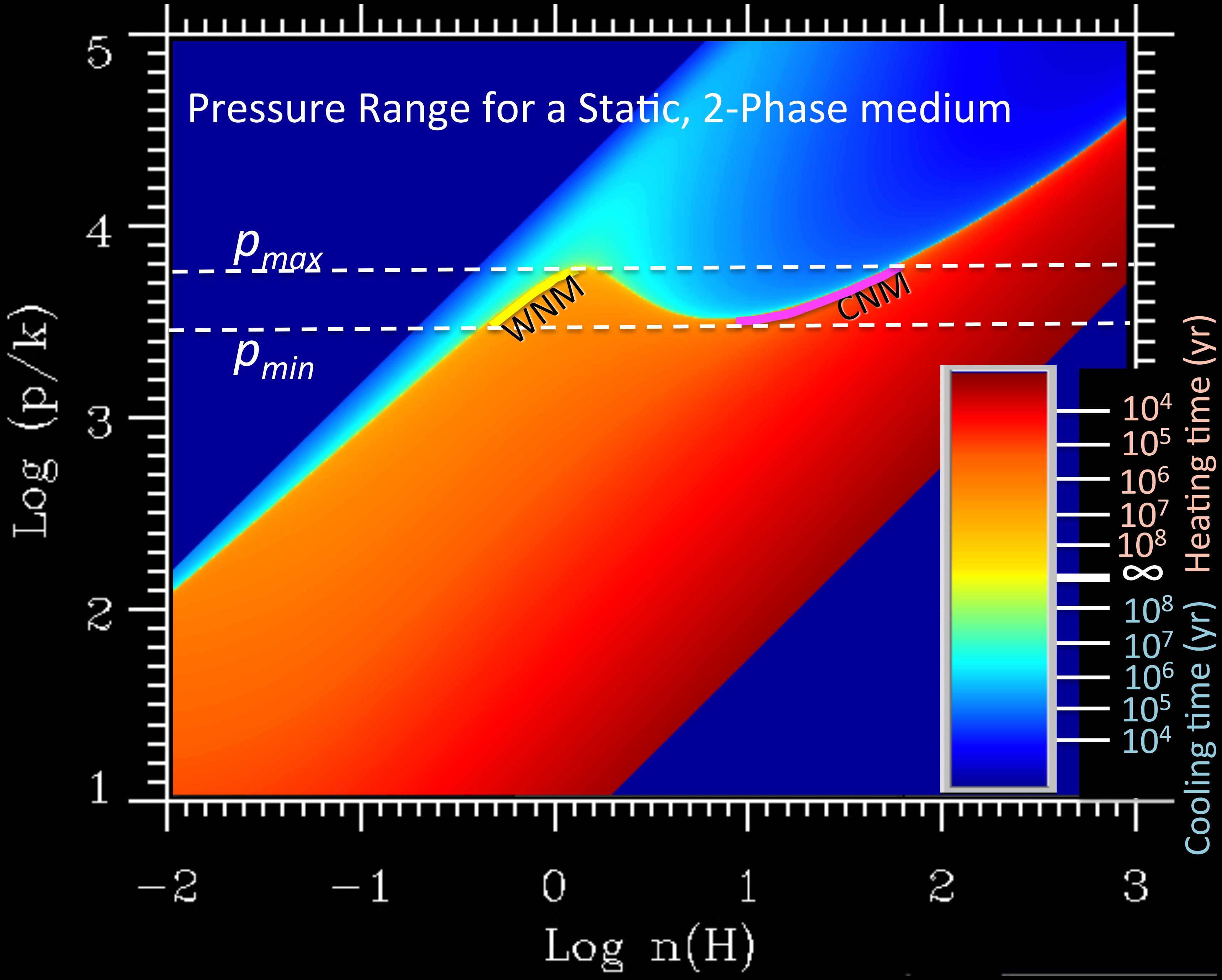
For details on physical processes that lead to the construction of the equilibrium curve, see Wolfire et al. (1995: ApJ, 443, 152, 2003, ApJ, 587, 278).

$$t_{cool} = \frac{5}{2}\frac{kT}{n(\mathrm{H})\Lambda - \Gamma}; \quad t_{heat} = \frac{5}{2}\frac{kT}{\Gamma - n(\mathrm{H})\Lambda}$$



Detailed, rigorous development of the nature of the thermal instability in the ISM was offered by Field (1965, ApJ, 142, 531), building on earlier discussions by Parker, Zanstra, Spitzer and Weyman.

Pressure Range for a Static, 2-Phase medium



The Effects of X-ray Bursts from Random SN Explosions

The Effects of X-ray Bursts from Random SN Explosions

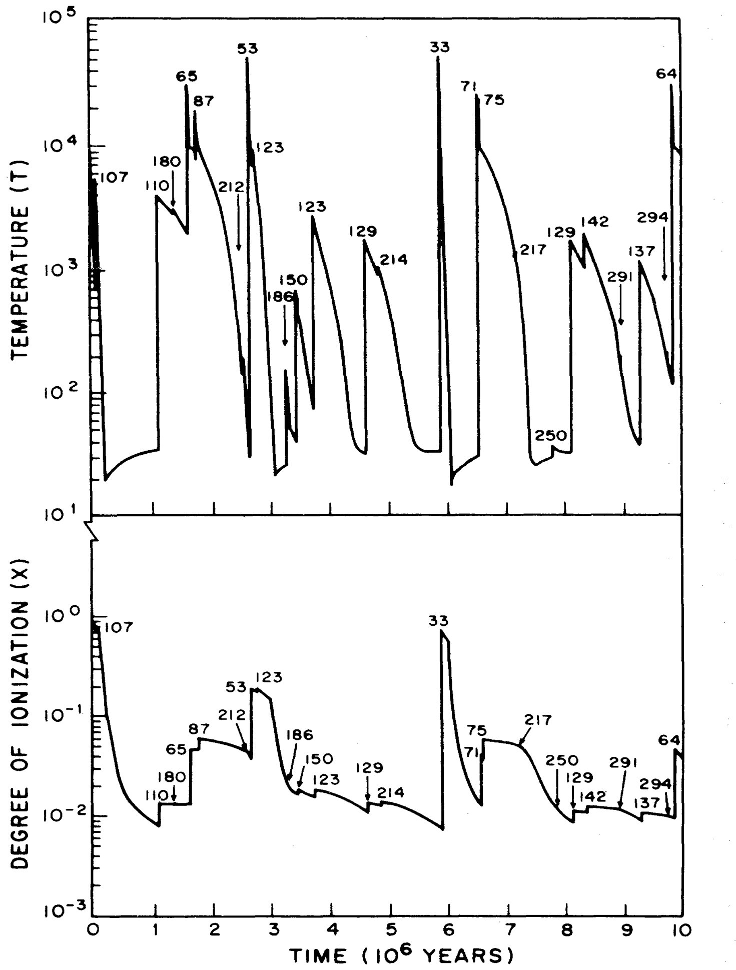
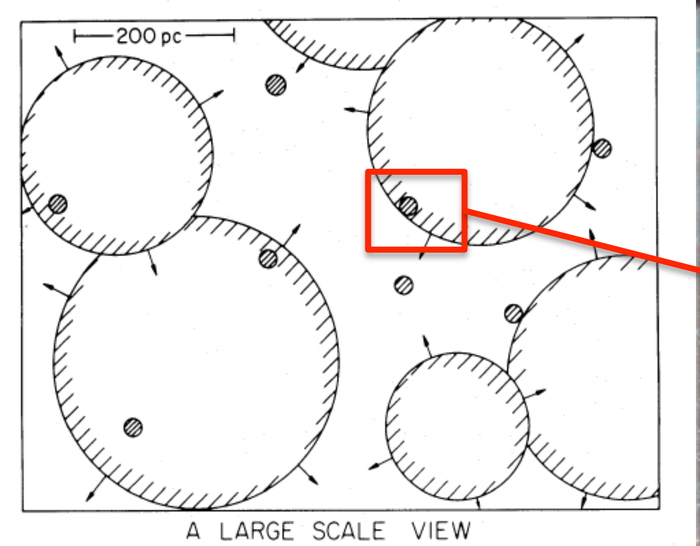


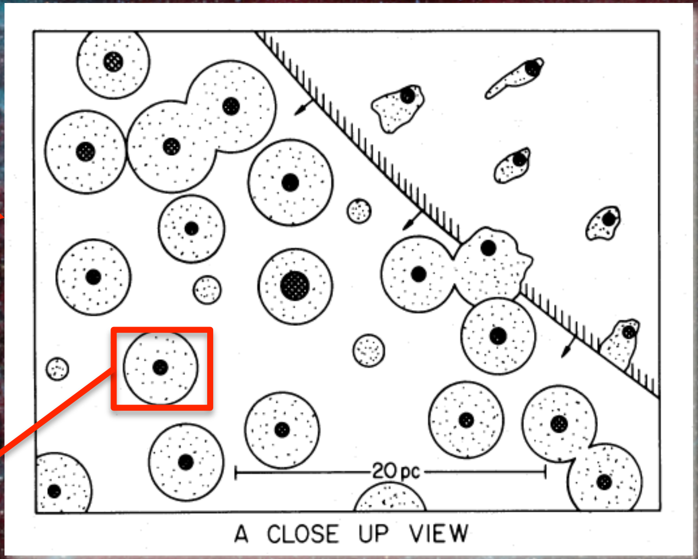
FIG. 2*a* (*top*).—Time evolution of temperature at a given point *P* in the galactic disk as a function of time. The numbers on the curve indicate the distance (in parsecs) from *P* at which each supernova occurs $\tau_{SN} = 30$ years; $n = 0.3$ cm^{-3}.

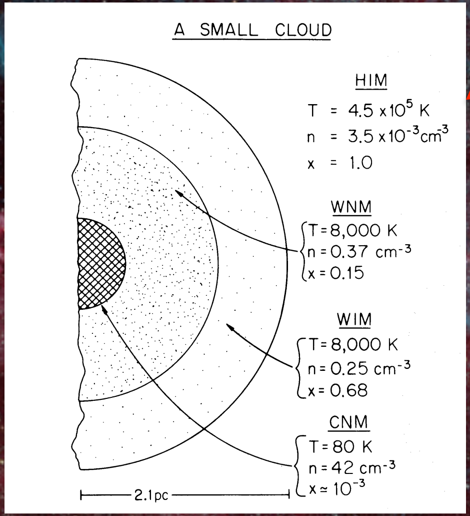
FIG. 2*b* (*bottom*).—Time evolution of the ionization fraction x.

Gerola, Kafatos & McCray (1974, ApJ, 189, 55)

The Effects of SN Blast Waves on the ISM

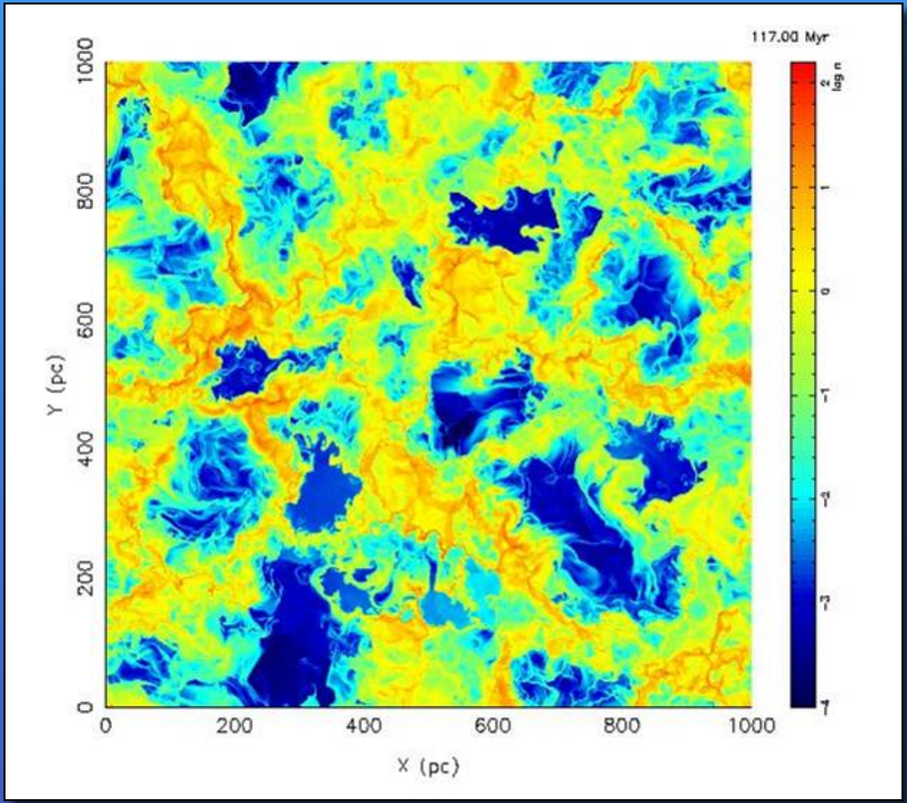




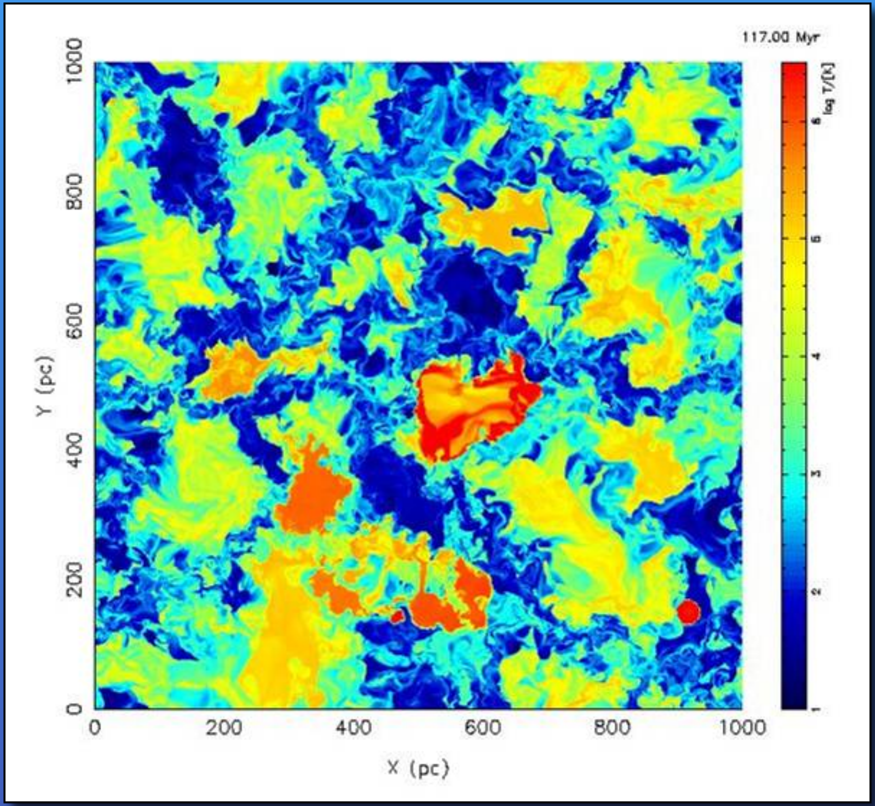


From McKee & Ostriker (1977, ApJ, 218, 148)

Hydrodynamic Simulations Showing the Consequences of Supernova Activity in the Galactic Plane

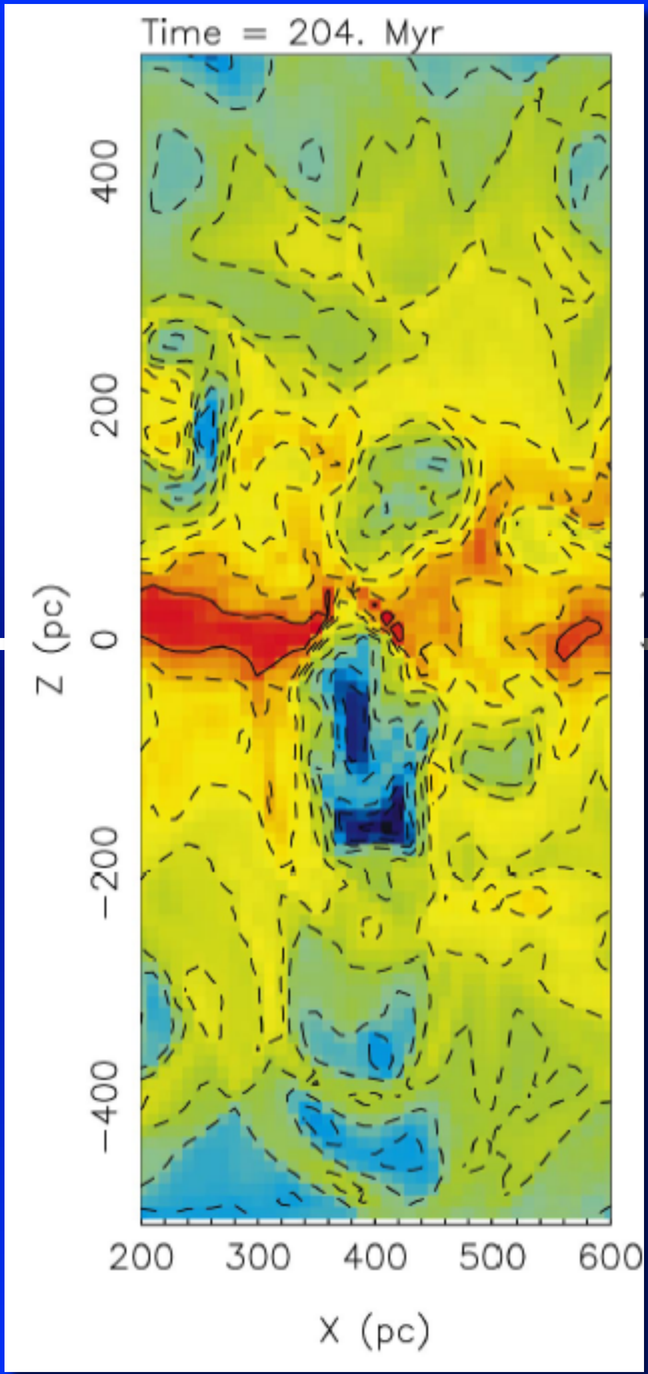


Log (density)



Log (temperature)

From de Avillez & Breitschwerdt (2003) astro-ph/0303322

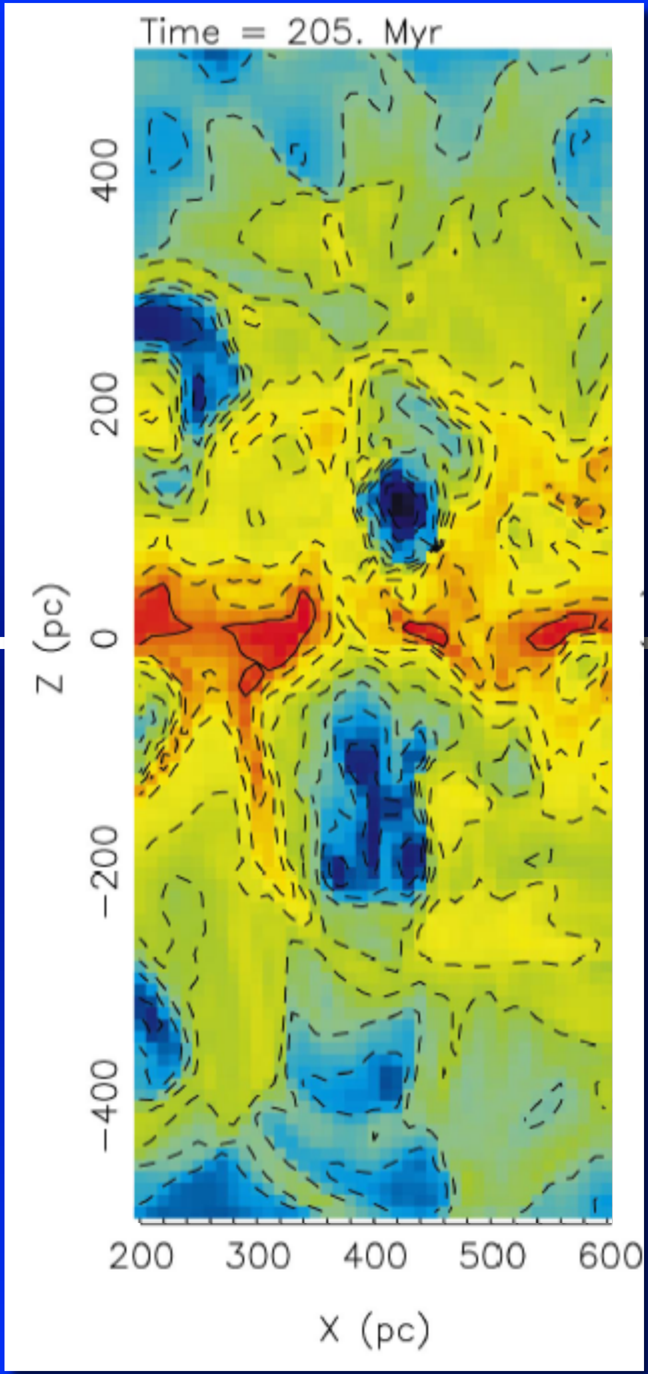


Galactic Plane

From hydrodynamical simulations by *de Avillez & Berry (2001: MNRAS, 328, 708)*

Log (density)

The bubble interiors contain hot, low density gas

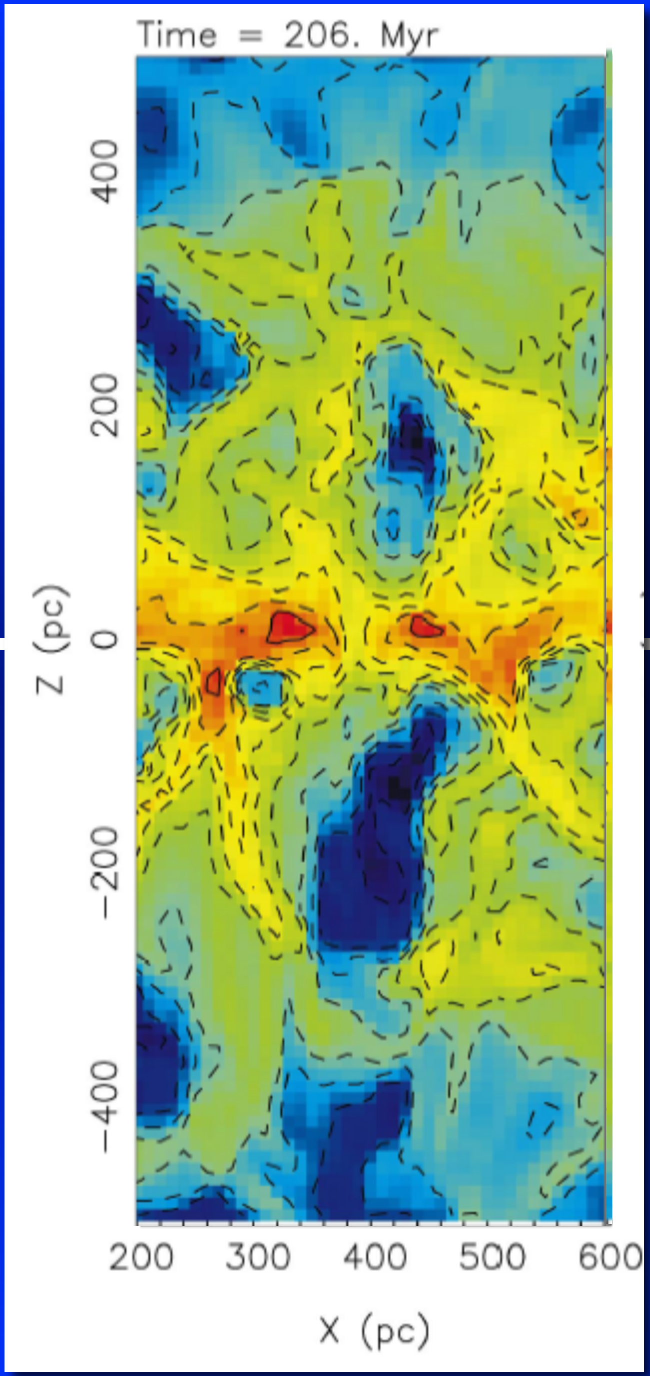


Galactic Plane

Log (density)

The bubble interiors contain hot, low density gas

From hydrodynamical simulations by *de Avillez & Berry (2001: MNRAS, 328, 708)*



Galactic Plane

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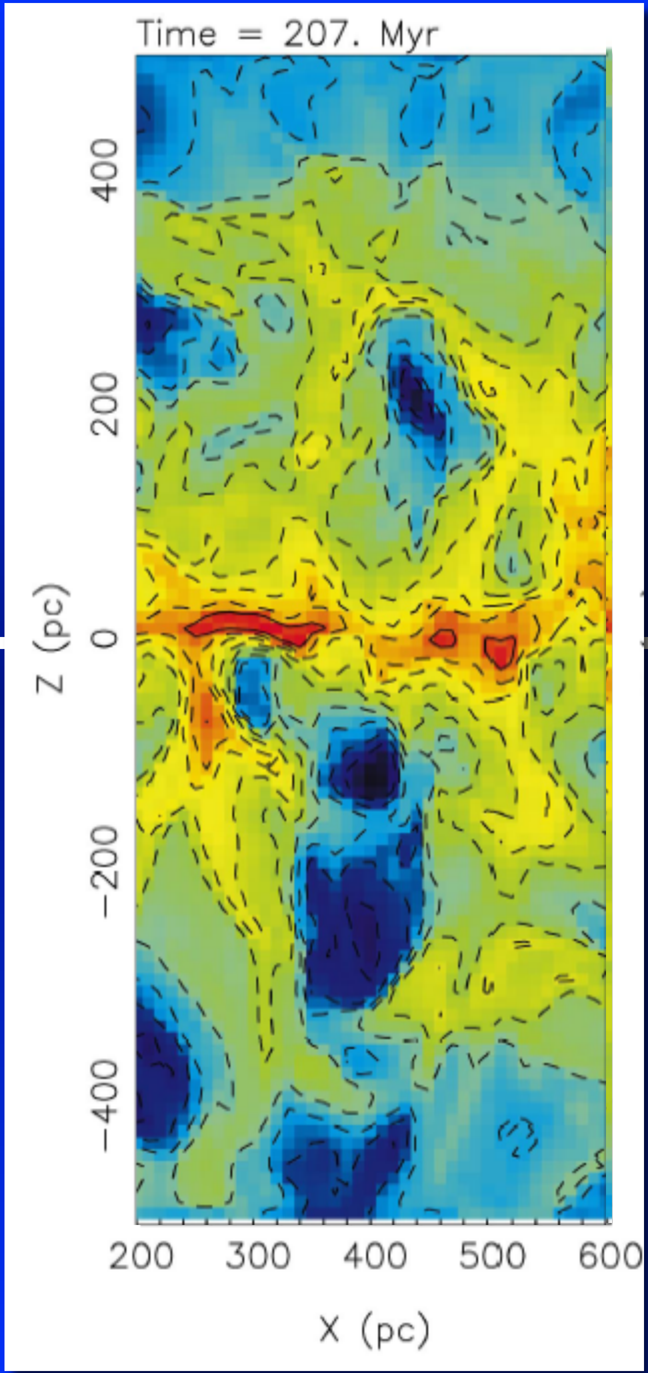

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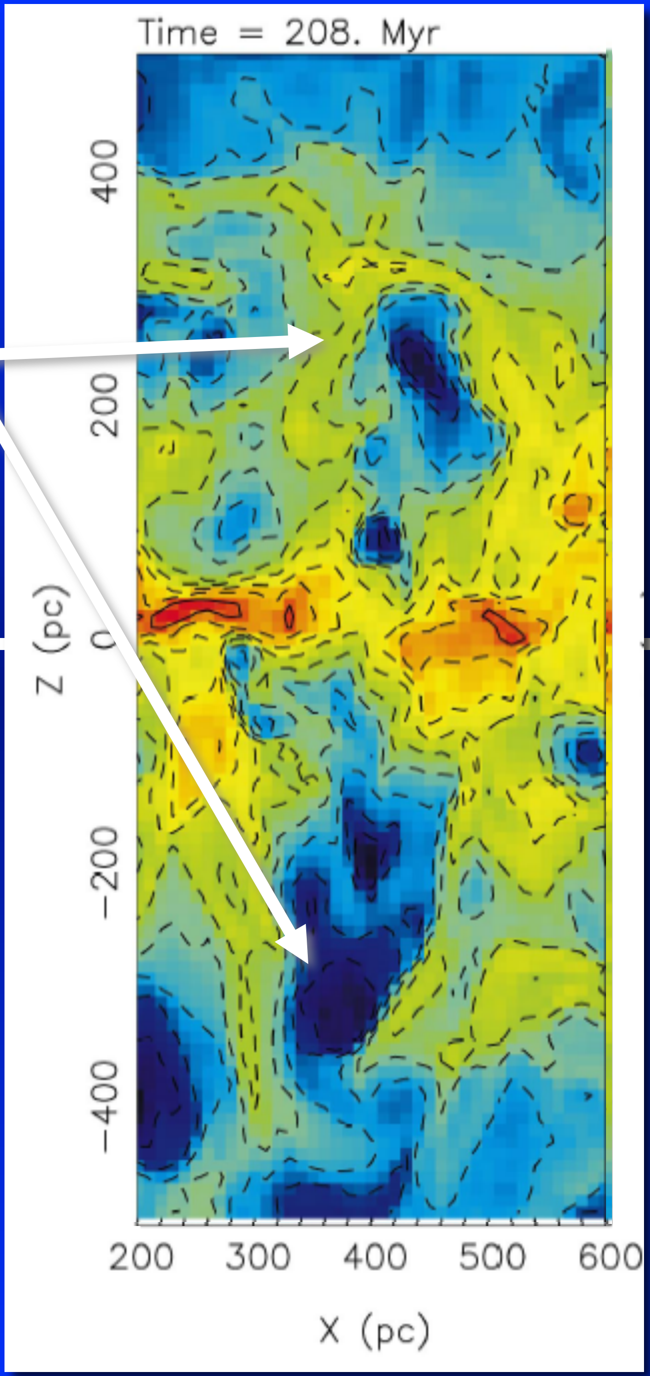
These structures of denser gas away from the plane resemble the superbubbles seen in H I.



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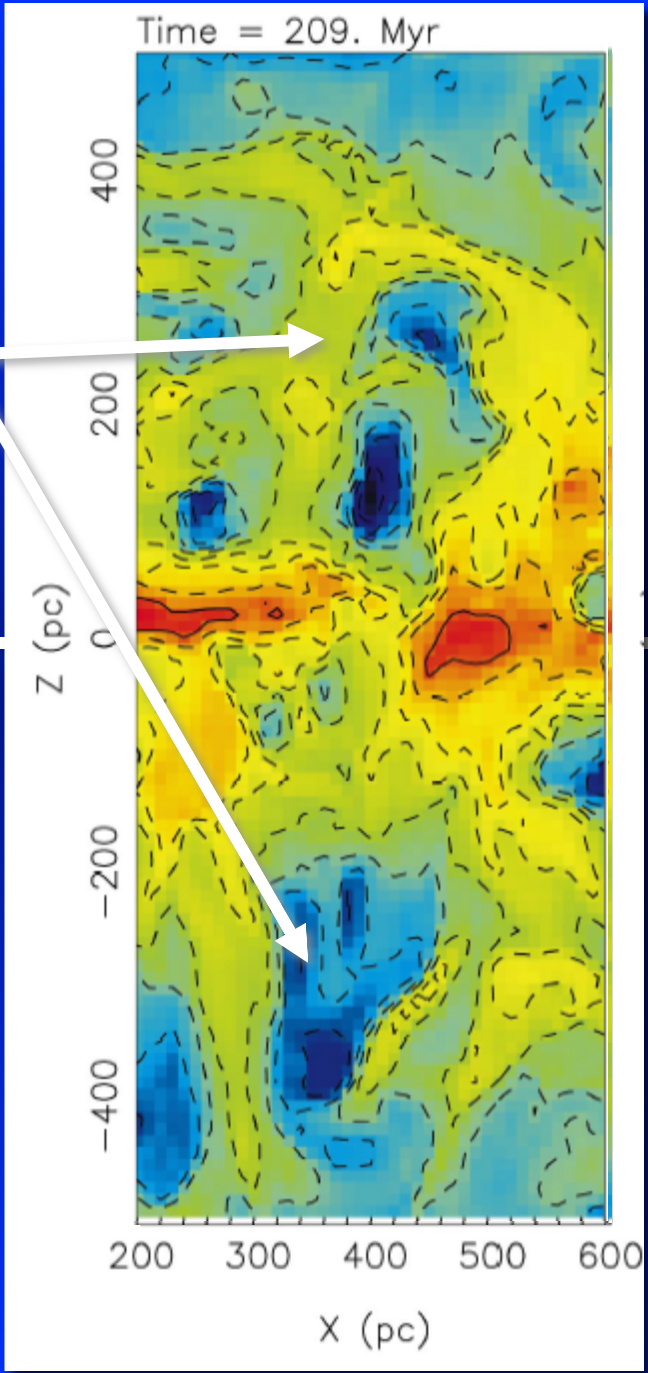


Galactic Plane

Log (density)

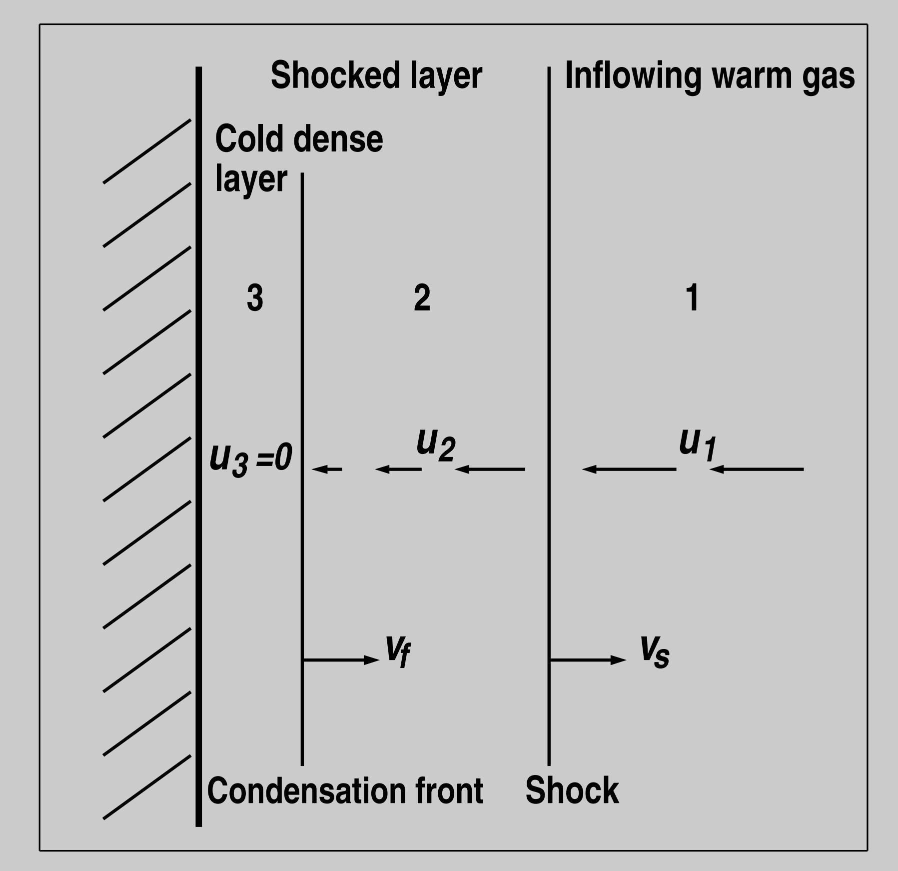
The bubble interiors contain hot, low density gas

From hydrodynamical simulations by *de Avillez & Berry (2001: MNRAS, 328, 708)*

The Influence of Dynamical Effects on the Creation and Maintenance of a 2-Phase Medium

1. Colliding Warm Neutral Media
2. Turbulent Warm Neutral Medium

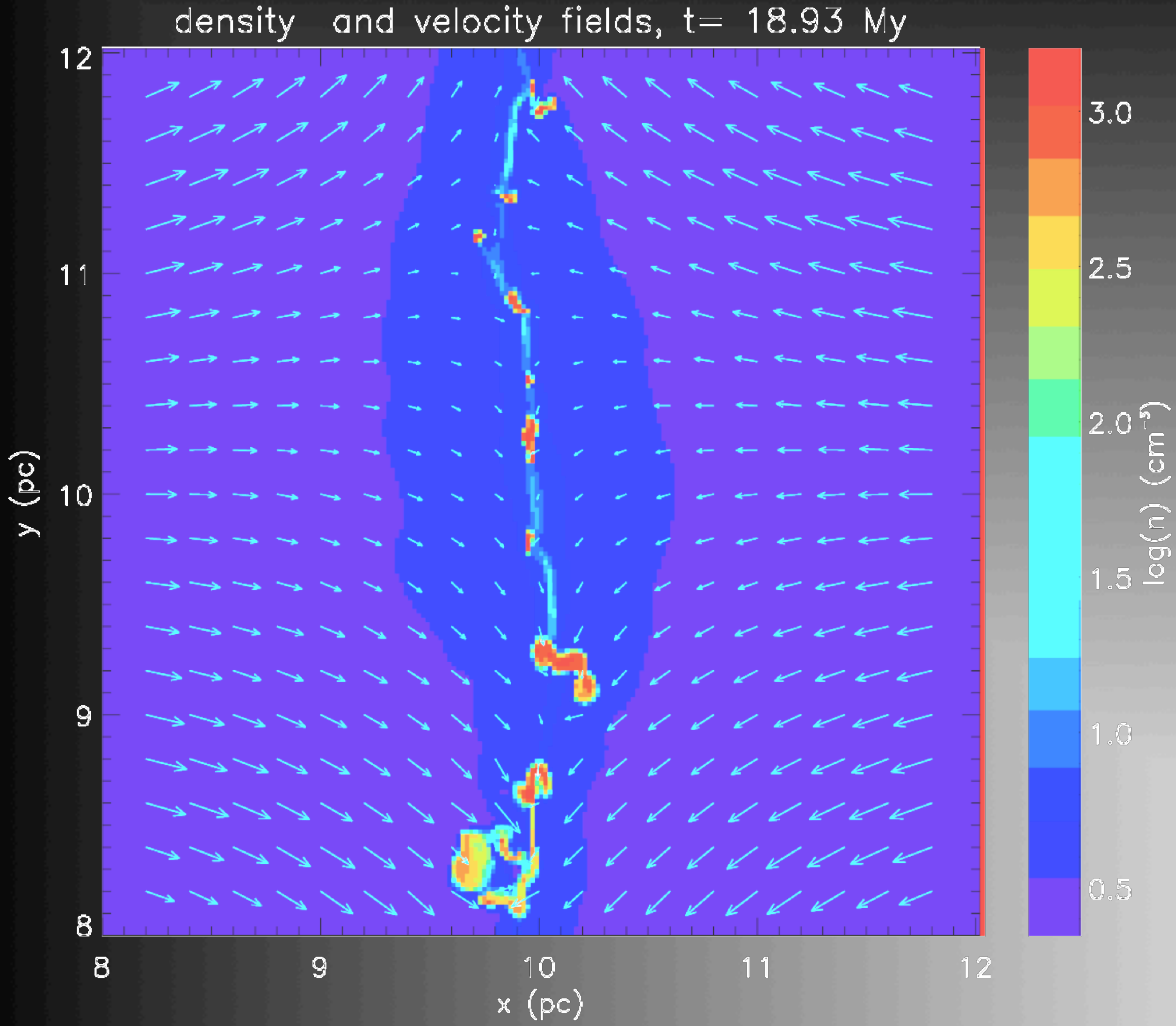
Simulations of Colliding WNM Flows



A diagram taken from Vázquez-Semadeni et al. (2006: ApJ, 643, 275)

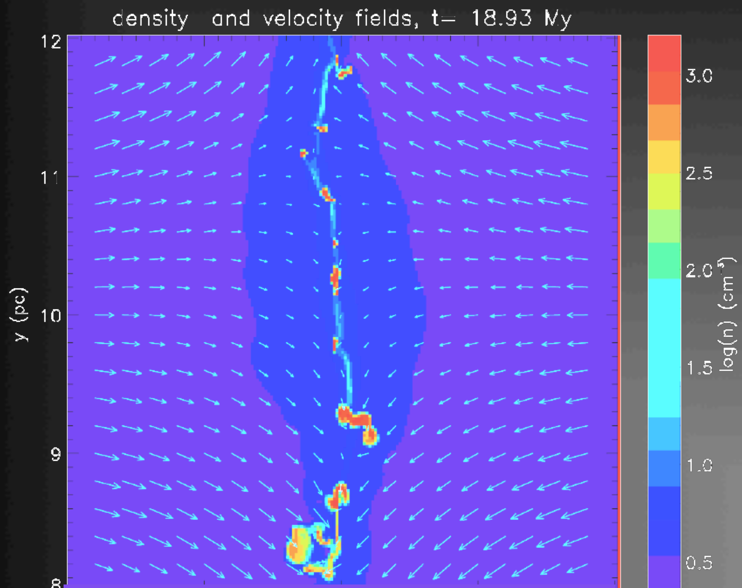
Simulations of Colliding WNM Flows

Audit & Hennebelle (2005: A&A, 473, 1)

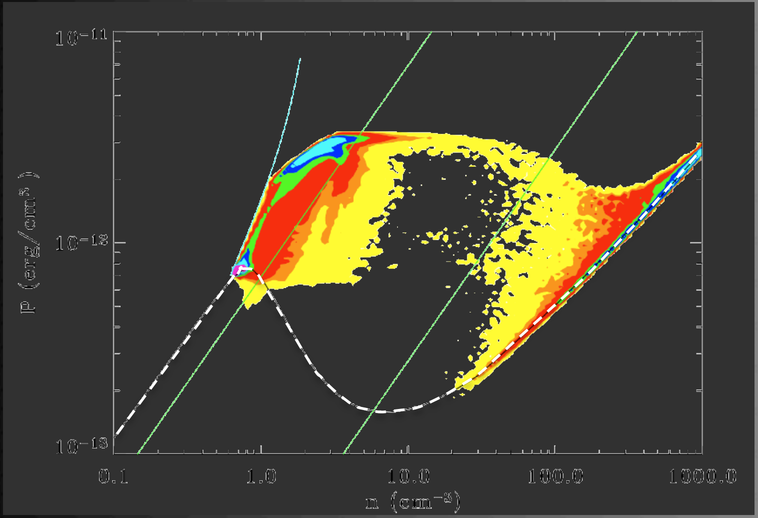


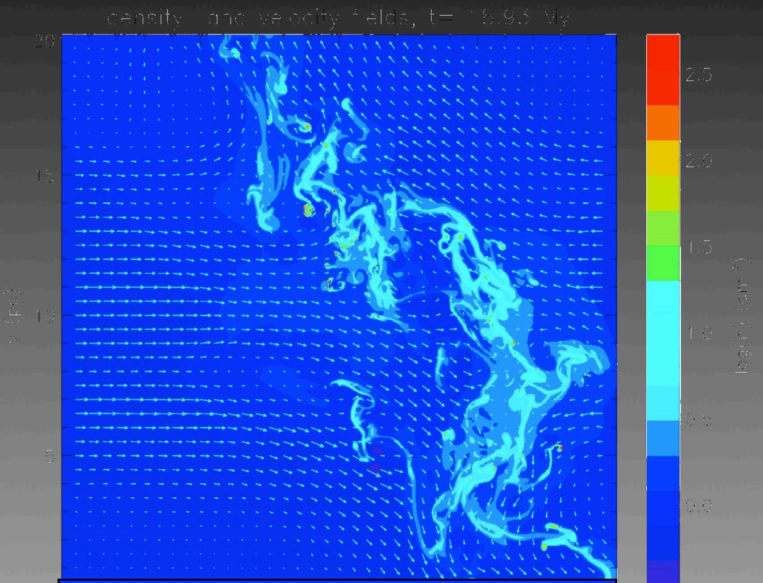
Simulations of Colliding WNM Flows

Audit & Hennebelle
(2005: *A&A*, 473, 1)

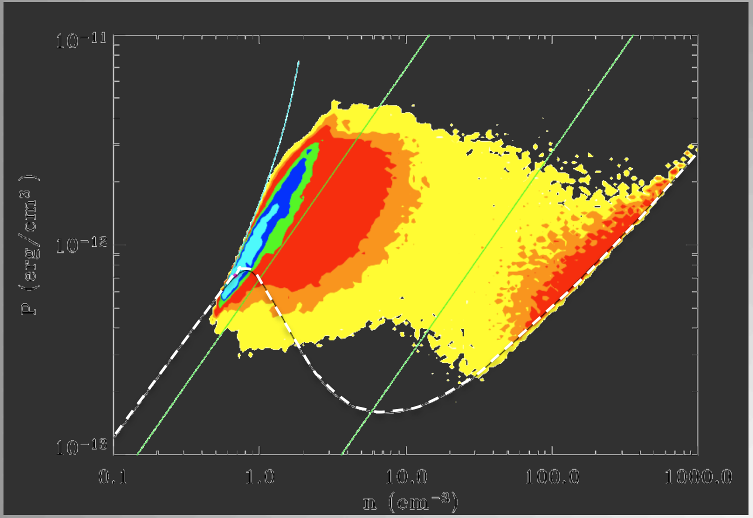


Weak initial turbulence





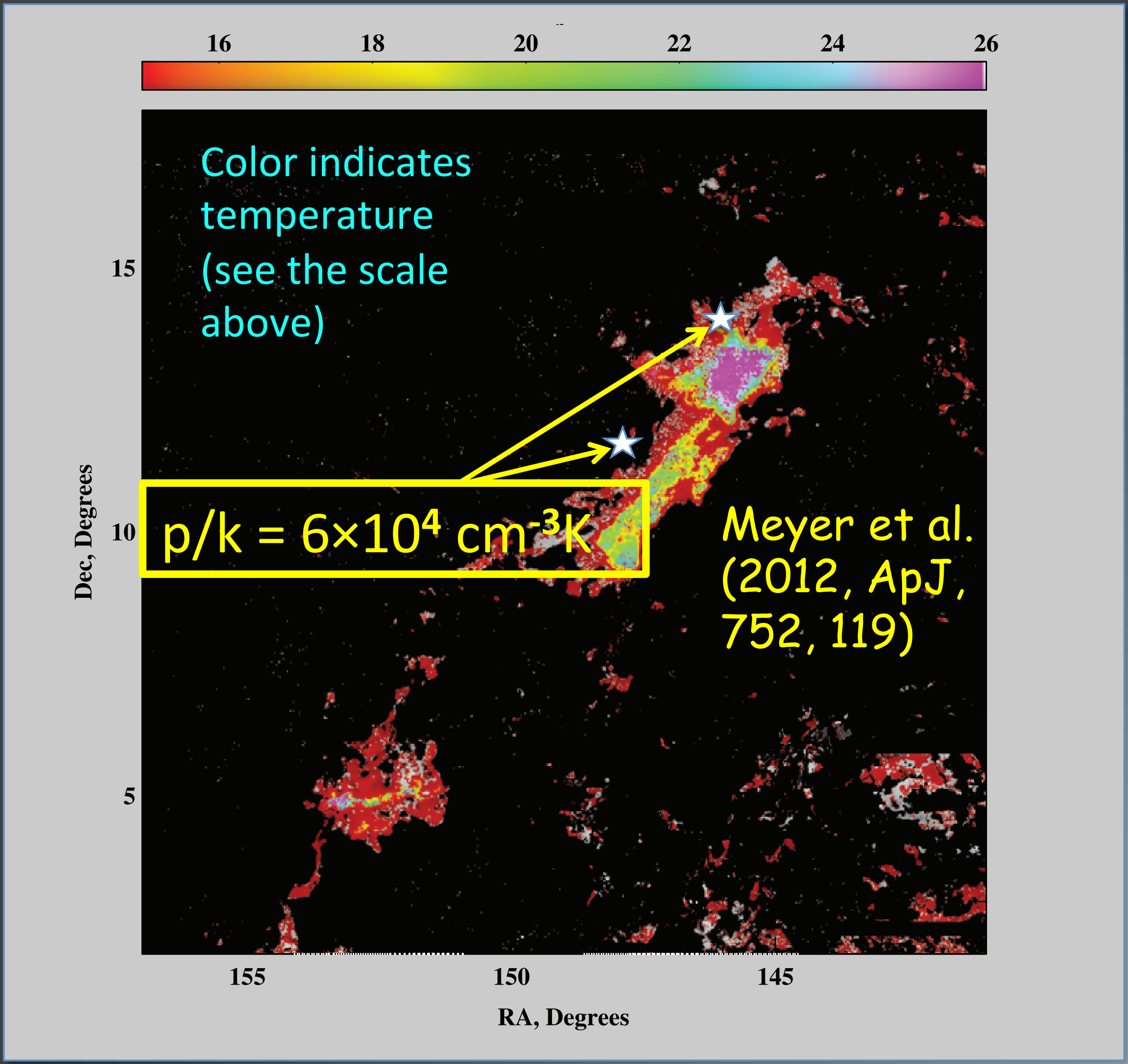
Strong initial turbulence



Well, that's Theory … What about Observations?

Leo Cloud, situated well inside the Local Bubble that contains mostly very low density gas

Peek et al. (2011, ApJ, 735, 129)



Color indicates temperature (see the scale above)

$p/k = 6\times10^{4}\ \mathrm{cm^{-3}K}$

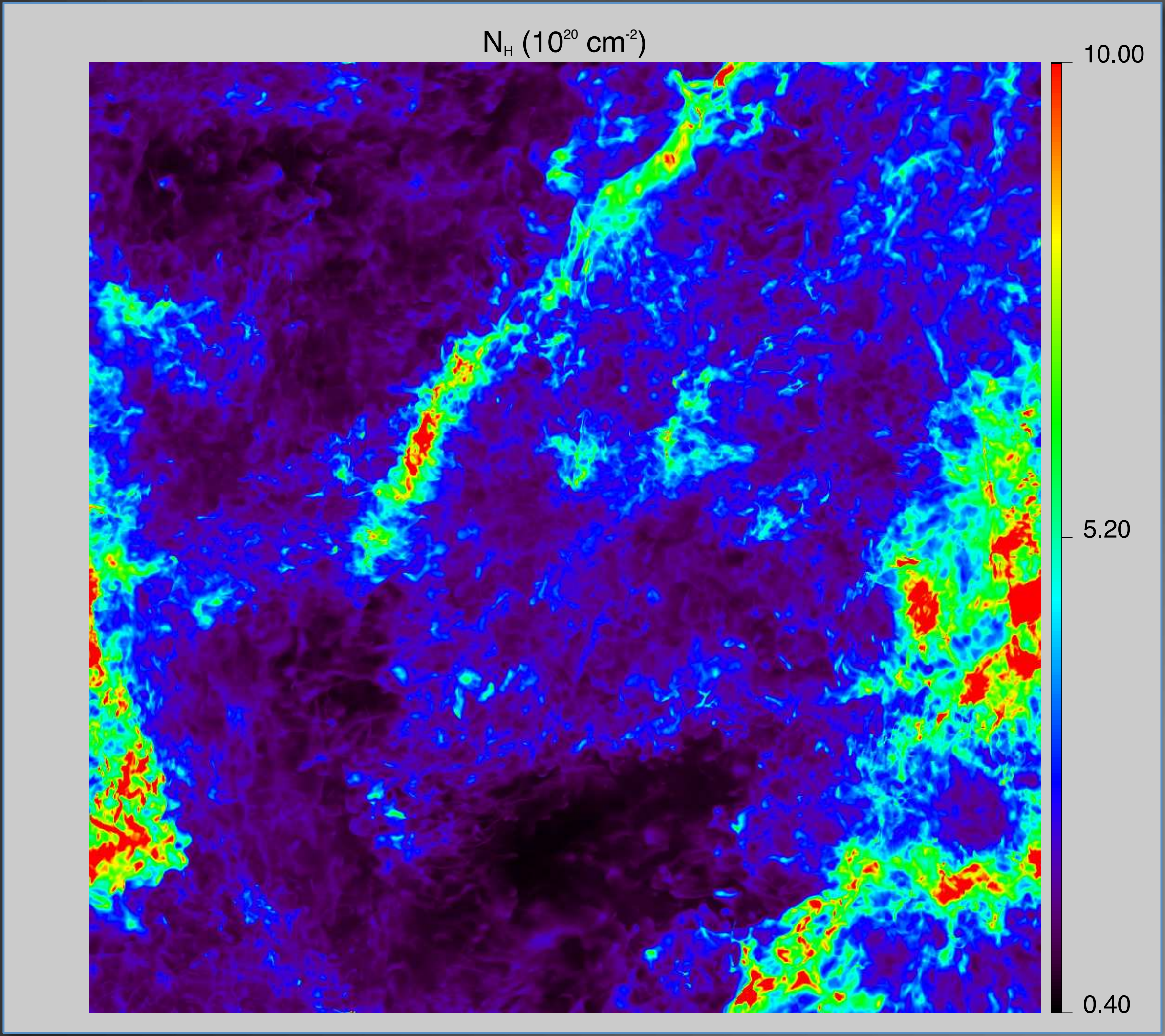
Meyer et al. (2012, ApJ, 752, 119)

The Influence of Dynamical Effects on the Creation and Maintenance of a 2-Phase Medium

1. Colliding Warm Neutral Media
2. Turbulent Warm Neutral Medium

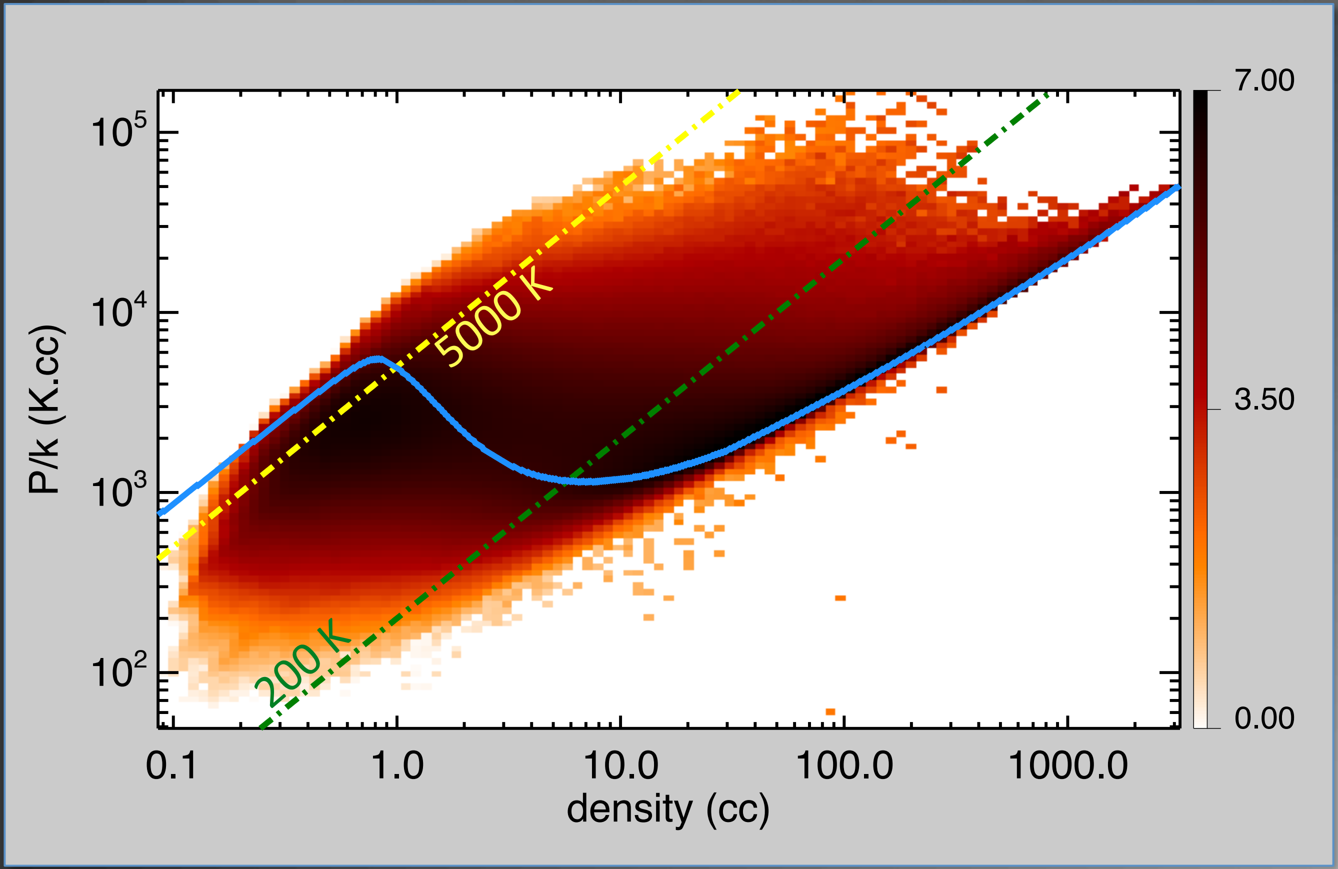
Distribution of Pressures and Densities in Mildly Supersonic Turbulence

Saury, et al. (2013: arXiv 1301.3446

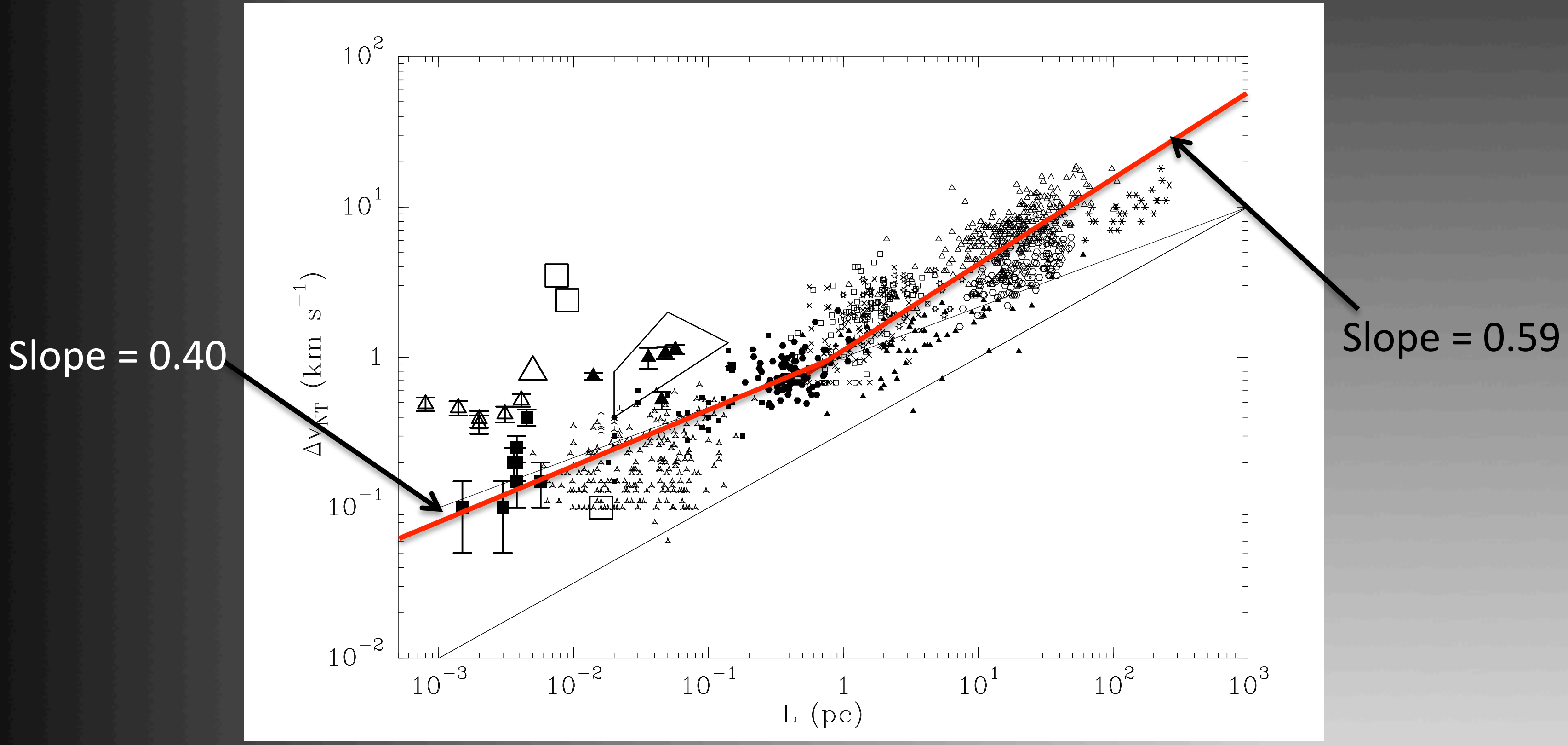


Distribution of Pressures and Densities in Mildly Supersonic Turbulence

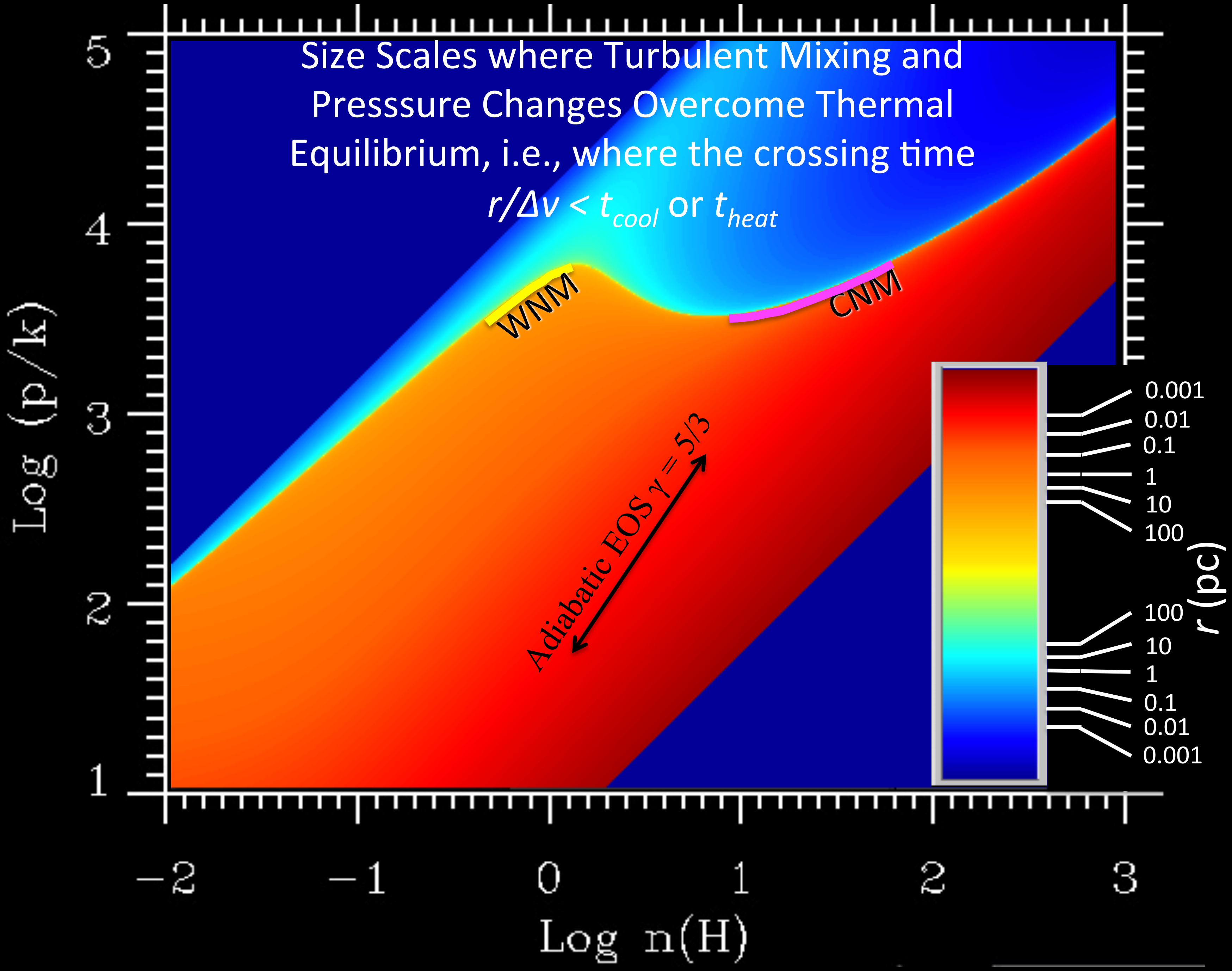
Saury, et al. (2013: arXiv 1301.3446



Velocity Shear as a Function of Linear Separations within Molecular Clouds



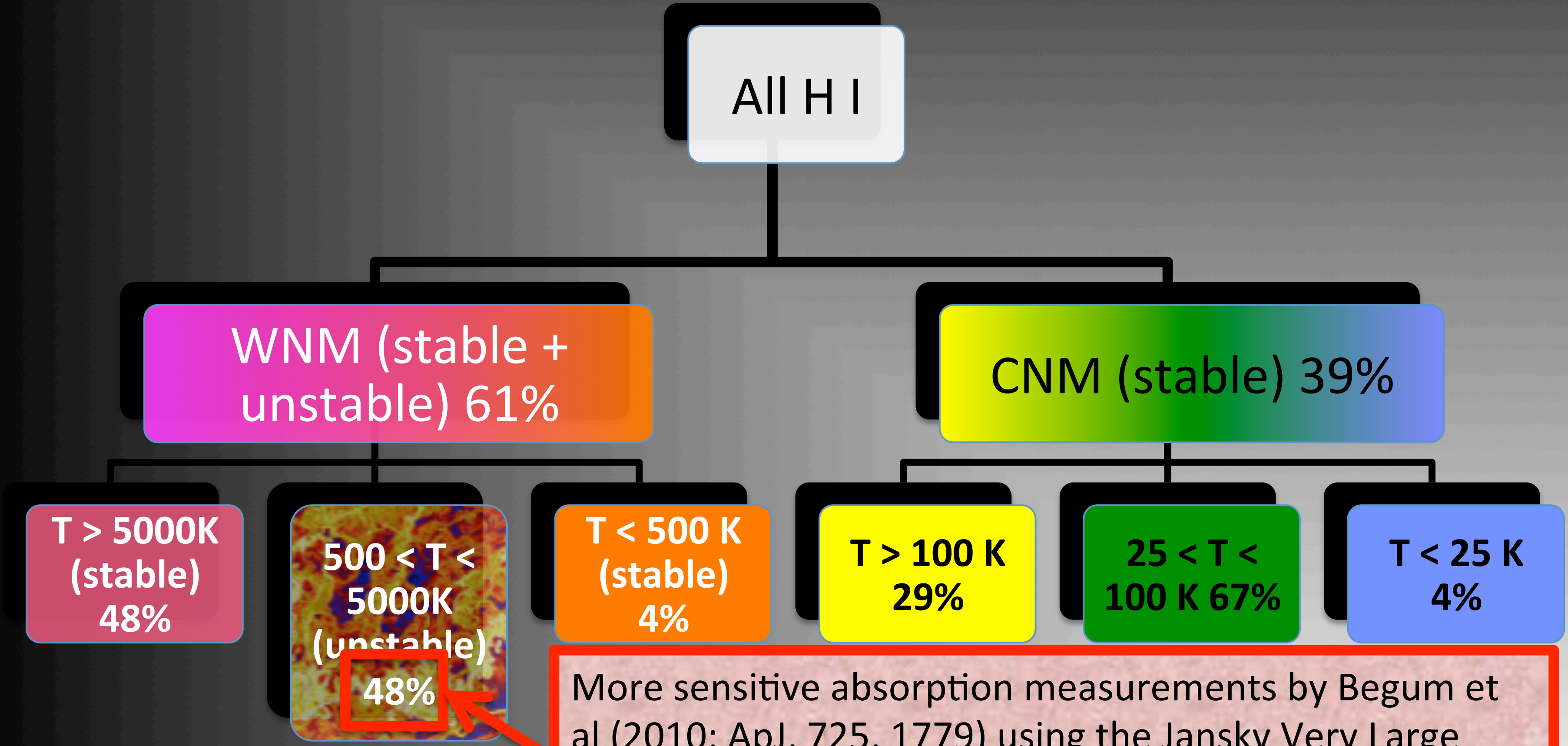
Plot shows CO (1-0) line velocity separations compiled by Falgarone, Pety & Hily-Blant (2009: A&A, 507, 355) -- Trend at large *L* defined by Heyer & Brunt (2004: ApJ, 615, L45)



Size Scales where Turbulent Mixing and Presssure Changes Overcome Thermal Equilibrium, i.e., where the crossing time $r/\Delta v < t_{cool}$ or t_{heat}

Well, that's Theory … What about Observations?

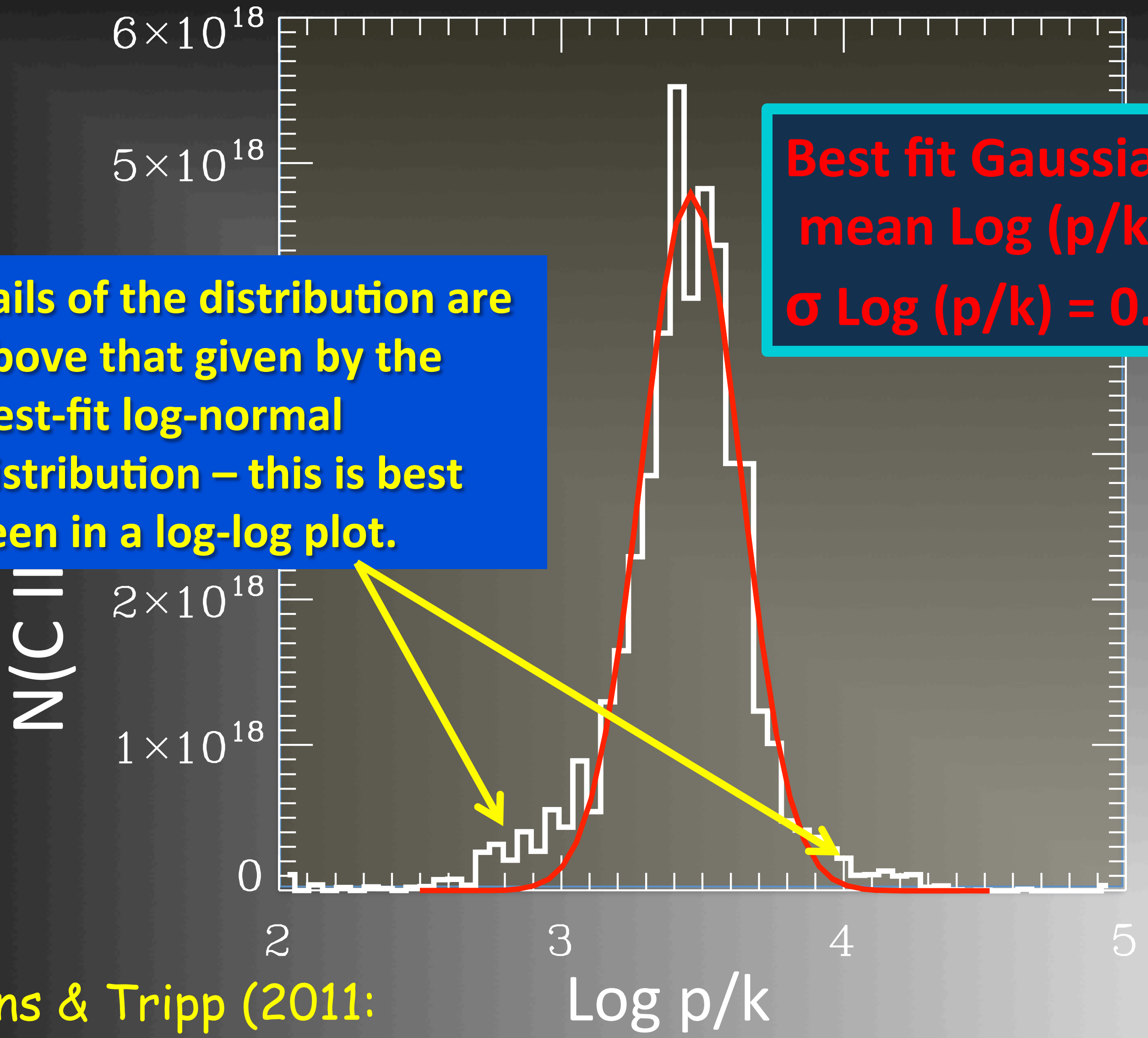
Results from the Millennium Arecibo 21-cm Absorption-Line Survey (Heiles & Troland (2003: ApJ, 586, 1067)



- All H I
  - WNM (stable + unstable) 61%
    - T > 5000K (stable) 48%
    - 500 < T < 5000K (unstable) 48%
    - T < 500 K (stable) 4%
  - CNM (stable) 39%
    - T > 100 K 29%
    - 25 < T < 100 K 67%
    - T < 25 K 4%

More sensitive absorption measurements by Begum et al (2010: ApJ, 725, 1779) using the Jansky Very Large Array (aka EVLA) indicate a somewhat lower fraction, but this conclusion is based on fewer sightlines.

Well, that's Theory … What about Observations?

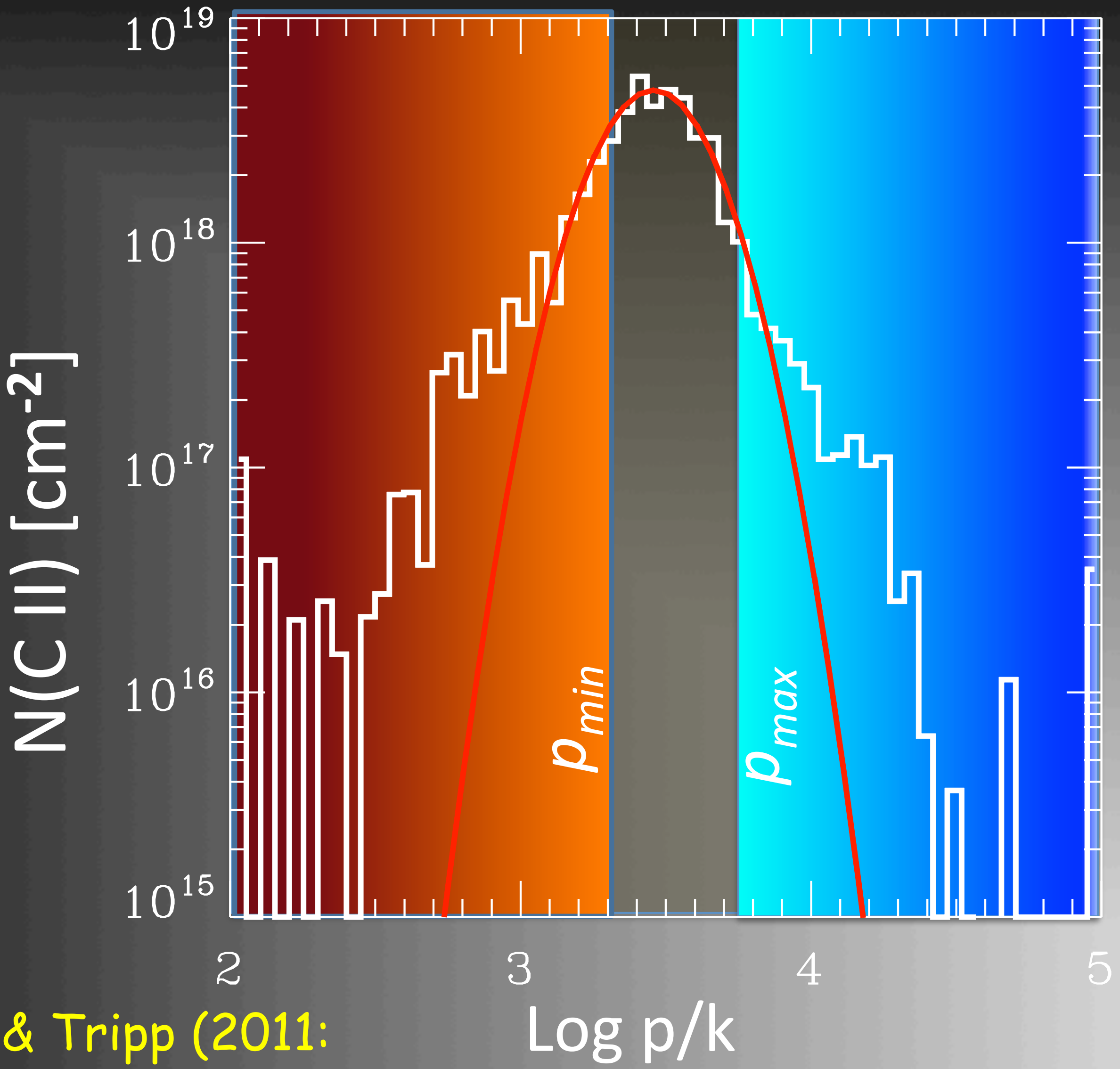


Best fit Gaussian profile:
mean Log (p/k) = 3.58,
σ Log (p/k) = 0.175

Tails of the distribution are above that given by the best-fit log-normal distribution – this is best seen in a log-log plot.

Jenkins & Tripp (2011: ApJ, 734, 65)

Well, that's Theory … What about Observations?

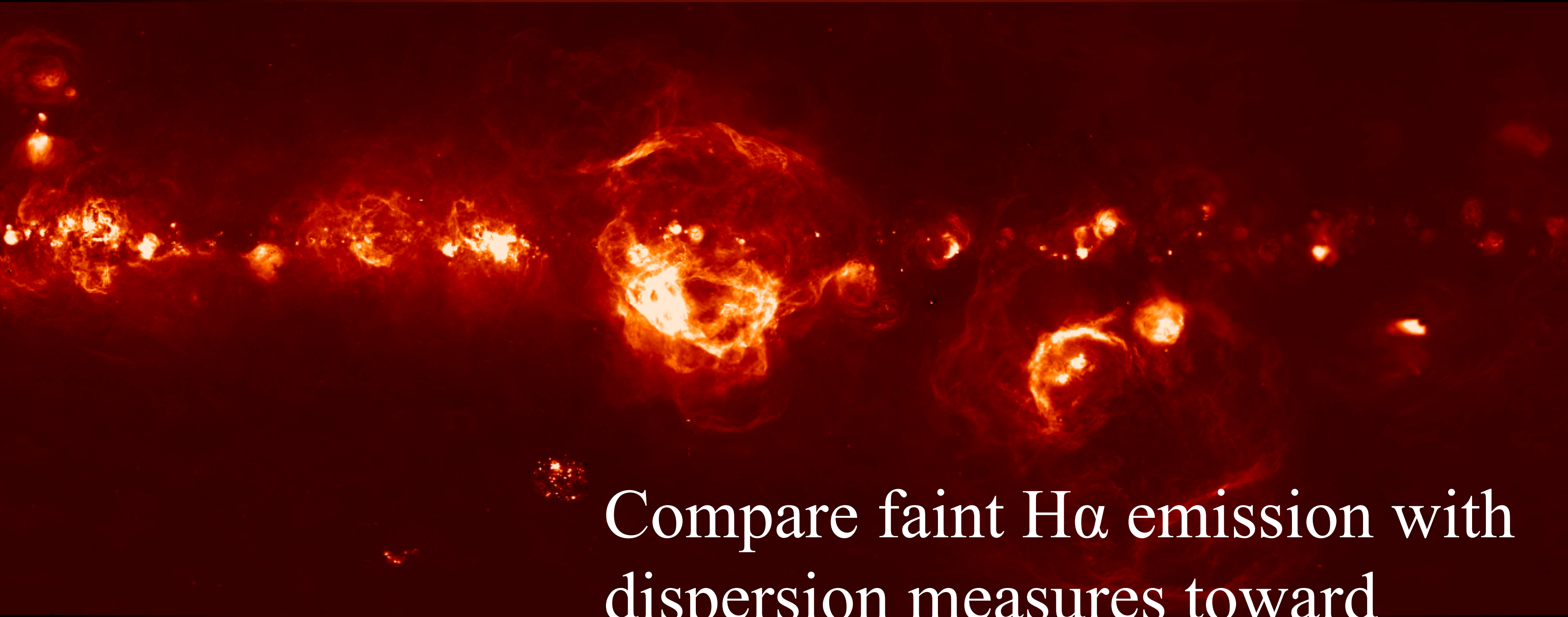


Jenkins & Tripp (2011: ApJ, 734, 65)

Ionization

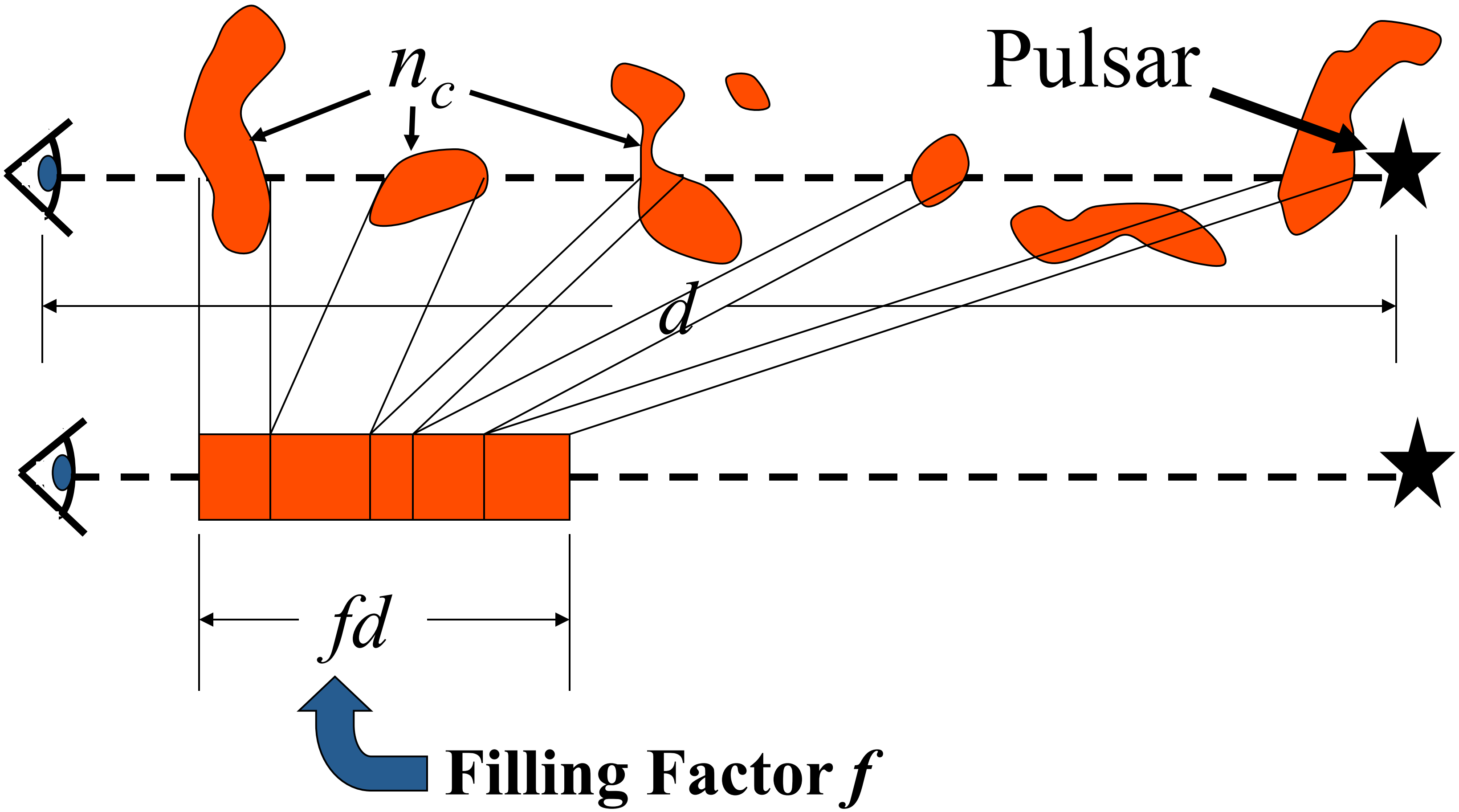
Varying States for Gas Containing Free Electrons

Hα Emission

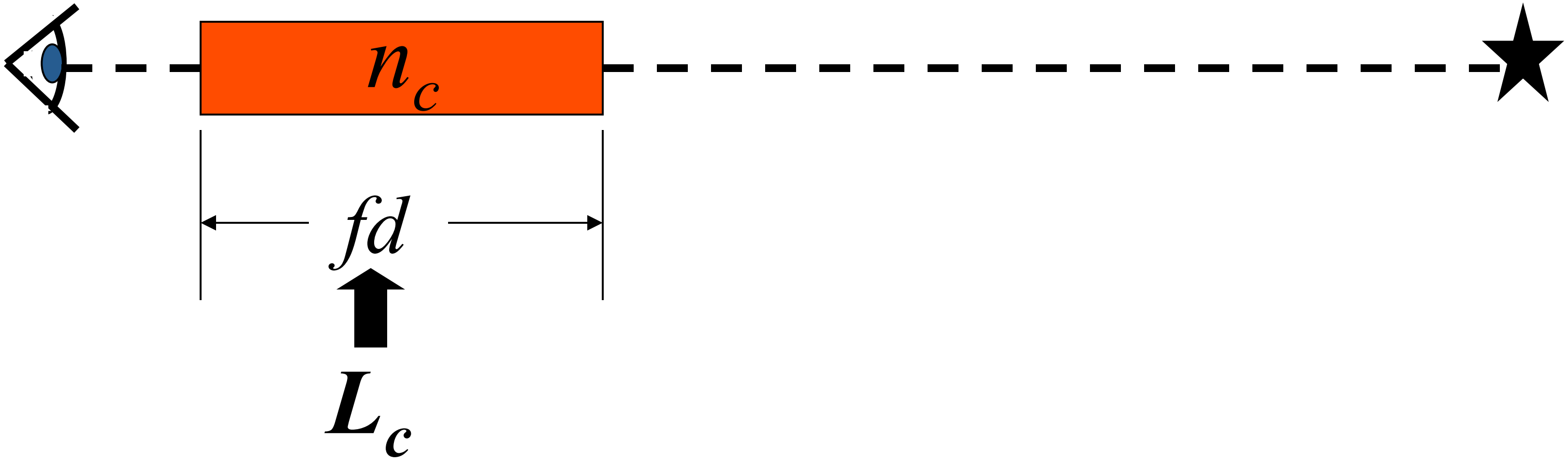


Compare faint Hα emission with dispersion measures toward pulsars in the same direction

Filling Factors and Thermal Pressures



Filling Factors and Thermal Pressures



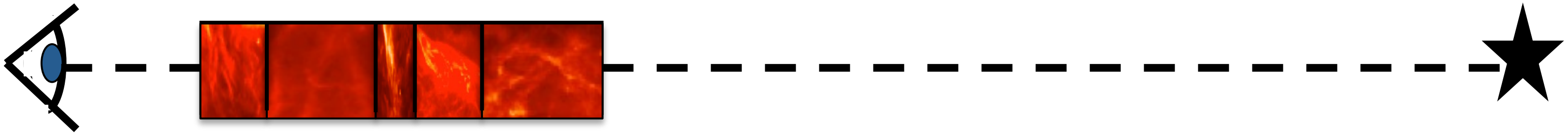
Hα Emission Measure (EM) = $\int n_e^2 dl = n_c^2 L_c$

Dispersion Measure (DM) = $\int n_e dl = n_c L_c$

Hence n_c = EM / DM

$L_c = (\mathrm{DM})^2/\mathrm{EM}$

Filling Factors and Thermal Pressures



Regions are now inhomogeneous

$$\text{Average electron density } \langle n_e \rangle = \frac{\int n_e dl}{L} = n_c \left(1 + \frac{\sigma^2}{\langle n_e \rangle^2}\right)^{-1}$$

$$\text{Real length } L = L_c \left(1 + \frac{\sigma^2}{\langle n_e \rangle^2}\right)$$

Where $\frac{\sigma^2}{\langle n_e \rangle^2}$ represents the mean squared relative fluctuations in electron density from one region to the next and within each region.

These equations were developed by Reynolds (1977: ApJ, 216, 433)

Results

- A comparison of EM and DM toward 194 pulsars with b > 10° and that avoid obvious H II regions

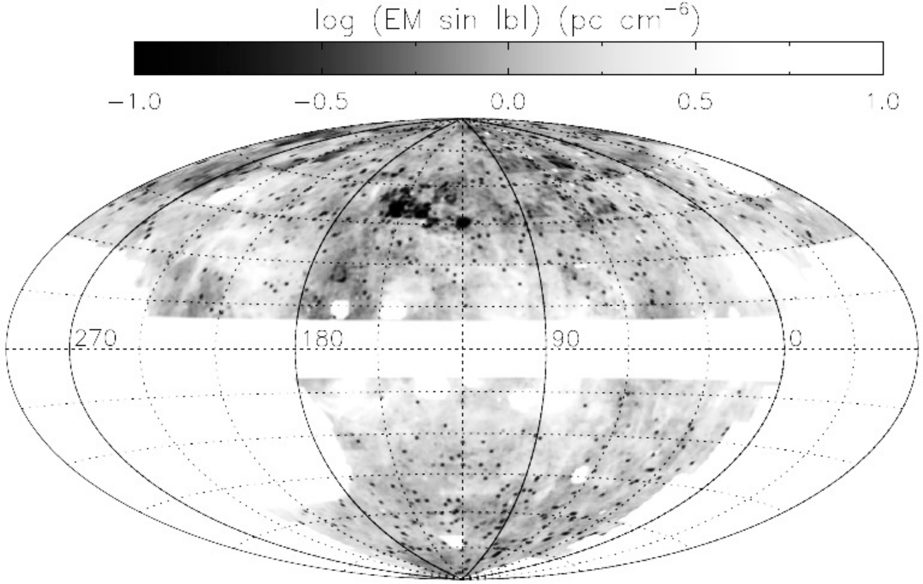
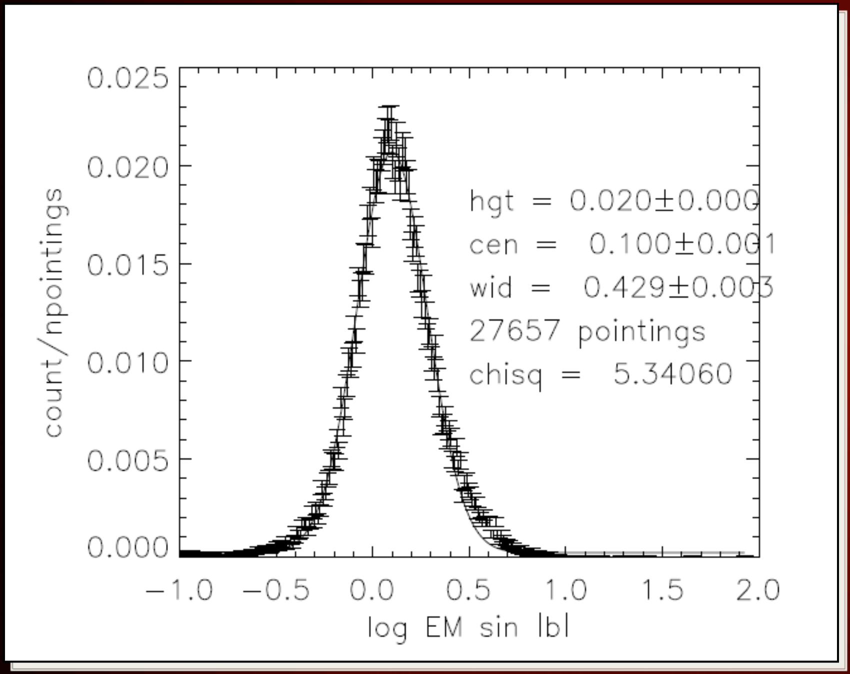


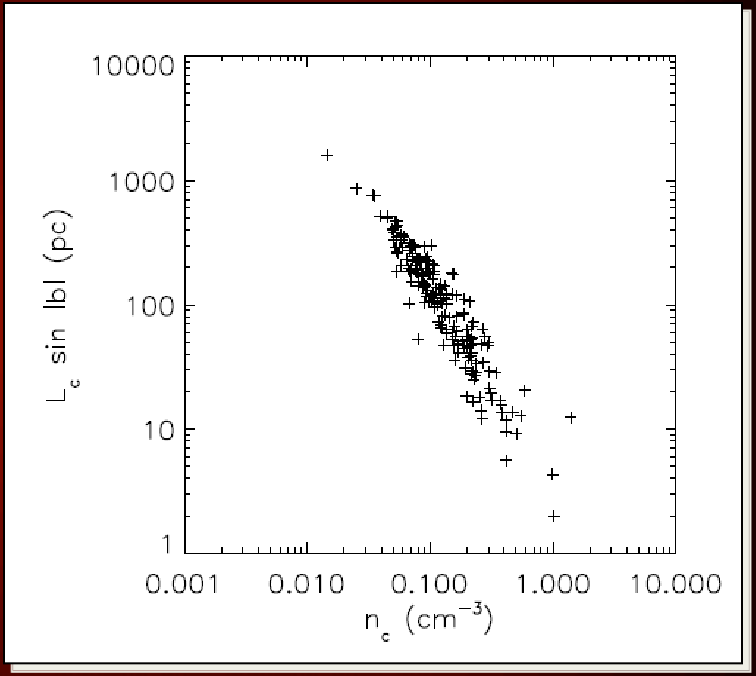
Figure 1. Map of EM sin $|b|$ from the WHAM Northern Sky Survey for Galactic latitude $|b| > 10°$ with sightlines that intersect known classical H II regions eliminated. Dashed lines represent 30° increments in longitude and 15° increments in latitude.

Hill, Reynolds, Benjamin & Haffner (2007: *SINS Conf. Proc.*, p. 250)

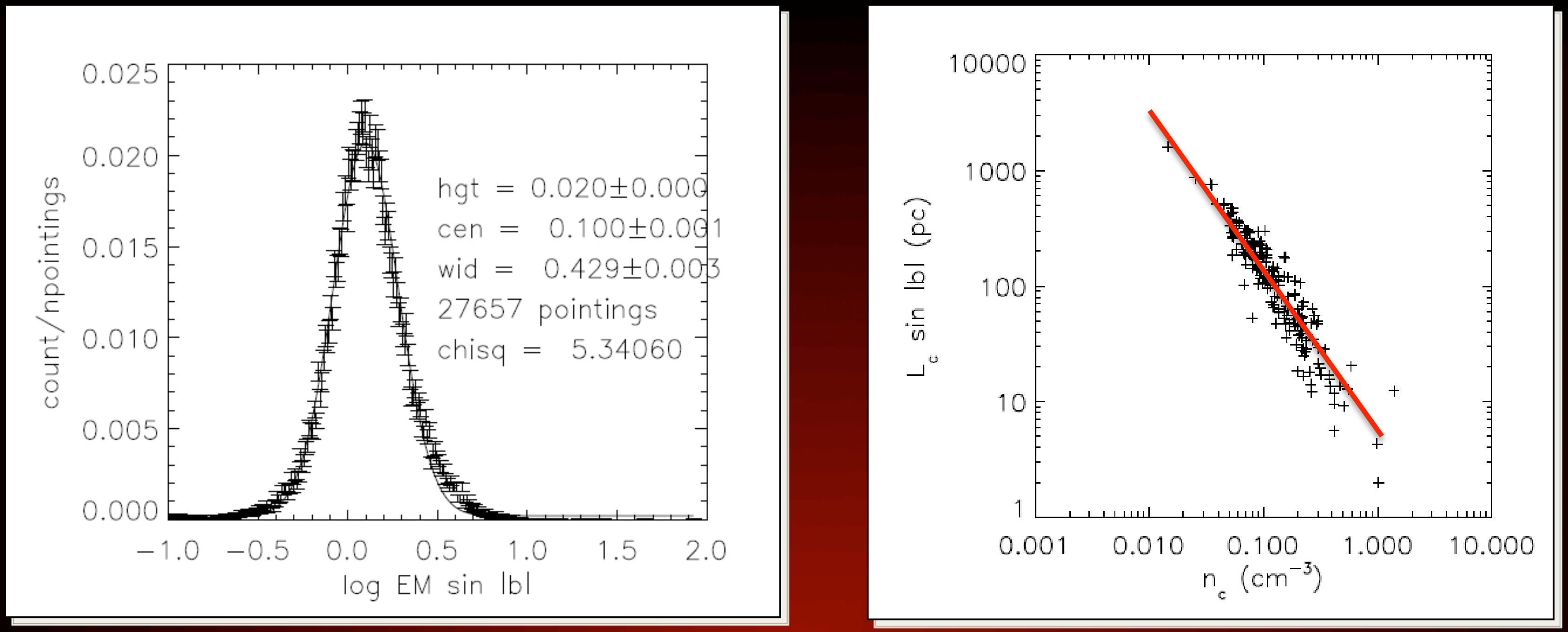
Hill, Reynolds, Benjamin & Haffner (2007: *SINS* Conf. Proc., p. 250)

Results





Conclusion: peak in Log n_c centered at -1.0, dispersion σ (Log n_c) = 0.43



1. **Slope of the trend of log (L_c |sin *b*|) *vs.* Log n_c is -1, hence EM varies over 2 orders of magnitude while DM |sin *b*| is relatively constant.**

2. **$\sigma/\langle n_e\rangle \approx 1.5$, which means that $\langle n_e\rangle = n_c/3.3 = 0.03\ \mathrm{cm}^{-3}$**

3. **If $T = 8000$ K, we find that $p/k = 2\langle n_e\rangle T = 480$!**

This pressure is a factor of 8 below the representative pressure of the CNM, which is 3800 cm^{-3} K -- a problem identified by Heiles in 2001 (conf. proc. paper).

Solution suggested by Heiles: Hα emission comes exclusively from high density, fully ionized regions, whereas pulsar dispersion measures arise almost entirely from a partly ionized neutral medium, which is almost invisible in Hα.

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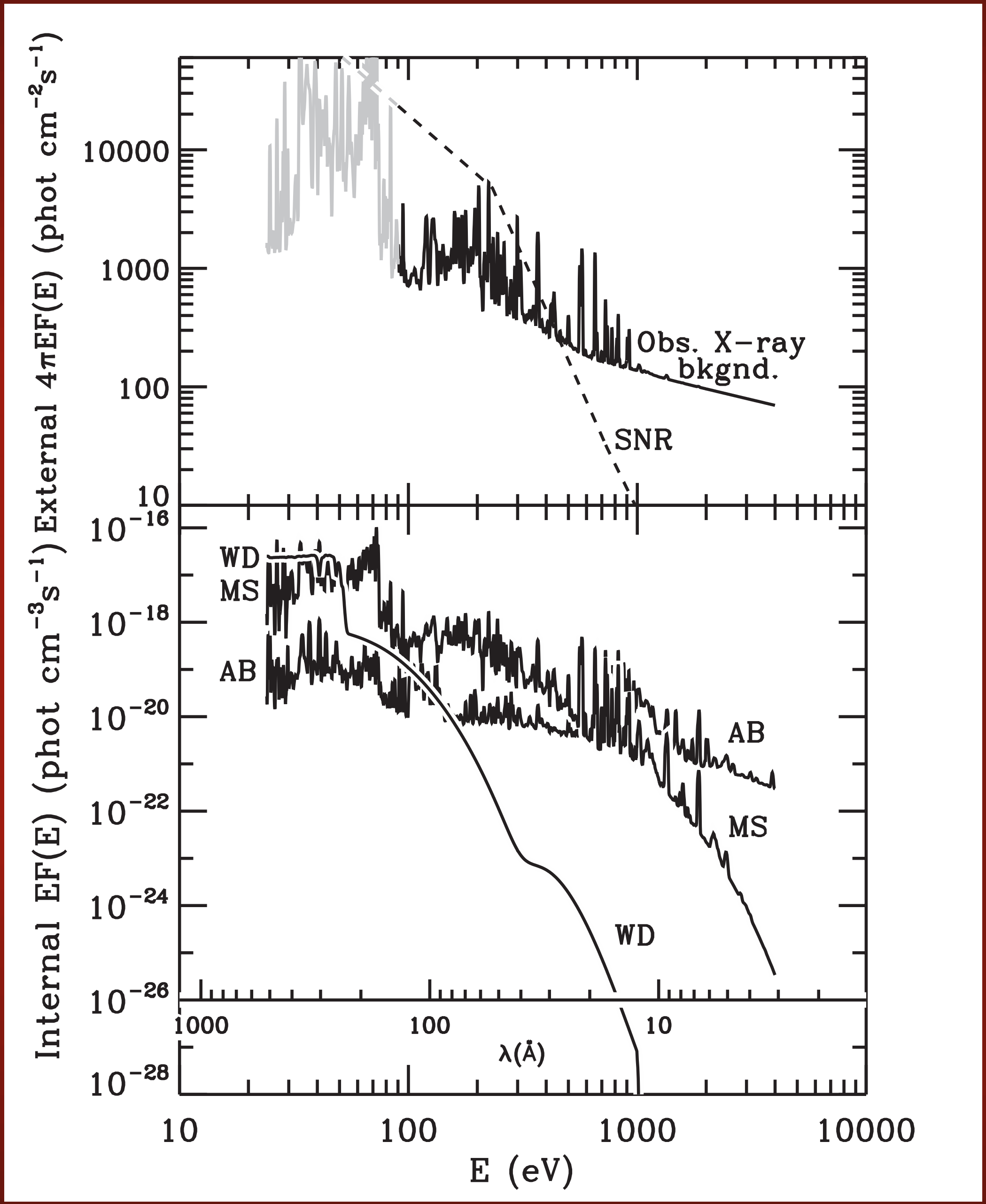
Supporting Evidence:

1. **Fractional ionization of the WNM within several hundred pc is about 8%, much higher than conventional calculations based on ionization by external x-rays and cosmic rays.** Jenkins (2013: ApJ, 764, 25)
2. **Rotation measures of extragalactic radio sources strongly correlated with H I 21-cm emission.** Foster, Kothes & Brown, arXiv 1307.4358

Radiation from the hot gas surrounding the WNM

Radiation from sources embedded in the WNM

Jenkins (2013: ApJ, 764, 25)



Temperature of the Ionized Gas

For the free-free emission at 41 GHz observed by WMAP that is correlated with Hα emission, the ratio

$$j_\nu(\mathrm{ff}) \propto T^{-0.5} n_e^2$$

$$j_\nu(\mathrm{H}\alpha) \propto T^{-0.94} n_e n(\mathrm{H}^+)$$

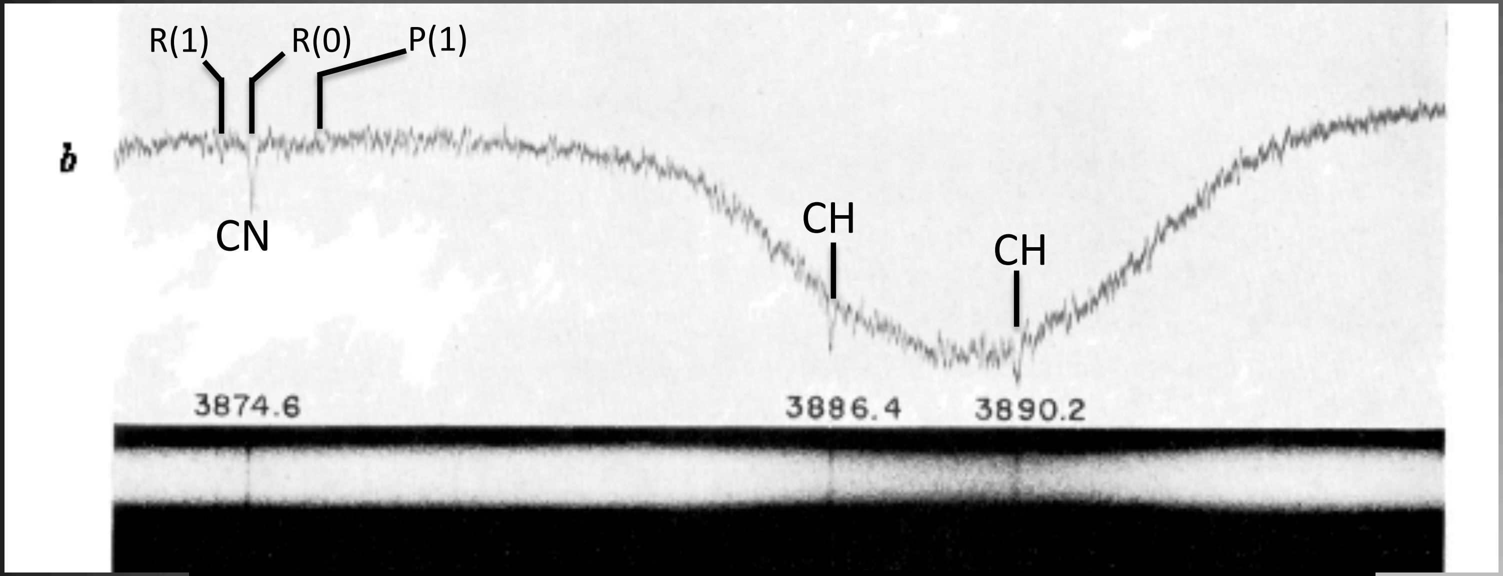
indicates that $T = 3000$K, which is much lower than standard, steady-state H II region temperatures (Dobler, Draine & Finkbeiner 2009: ApJ, 699, 1374).

This indicates a strong presence of gas that was once ionized by starlight, but then cooled more rapidly than it recombined when the ionizing photon flux was removed [either by the hot stars evolving off the main sequence or the gas became shielded from the radiation] (Dong & Draine, 2011, ApJ, 727, 35).

Molecular Gas

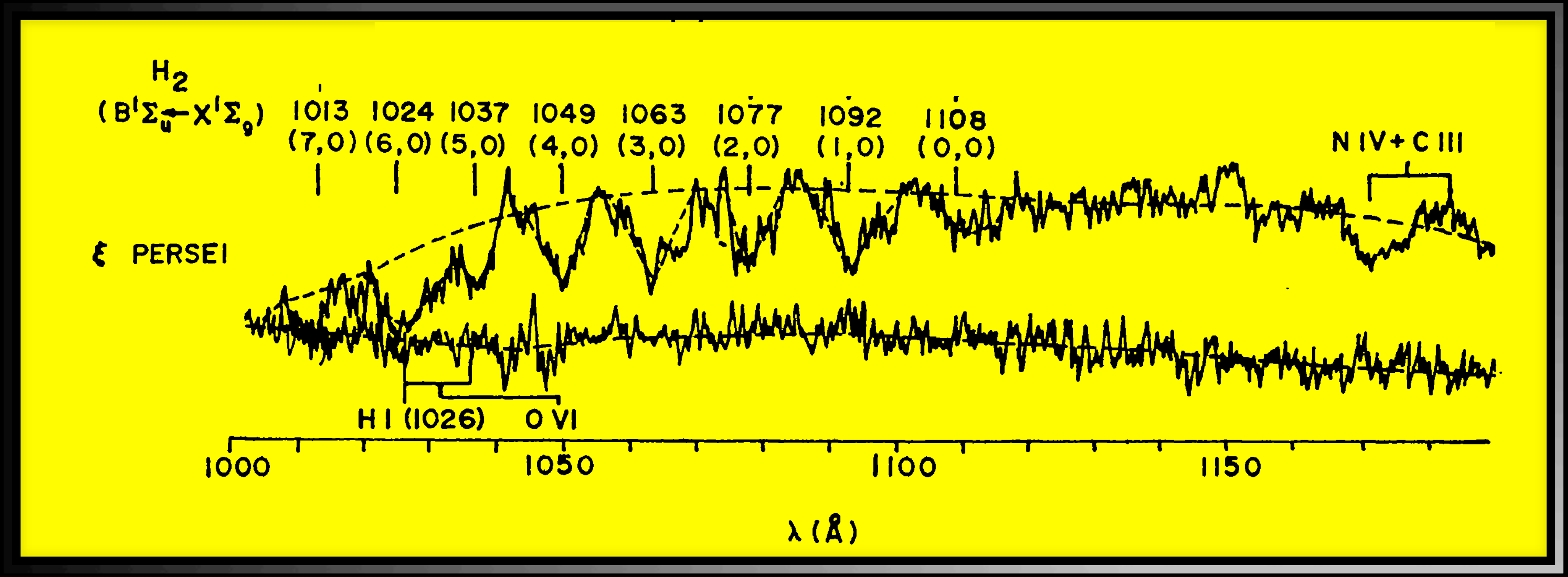
Early Evidence for Interstellar Molecules

Definitive identifications were carried out by McKellar (1941)



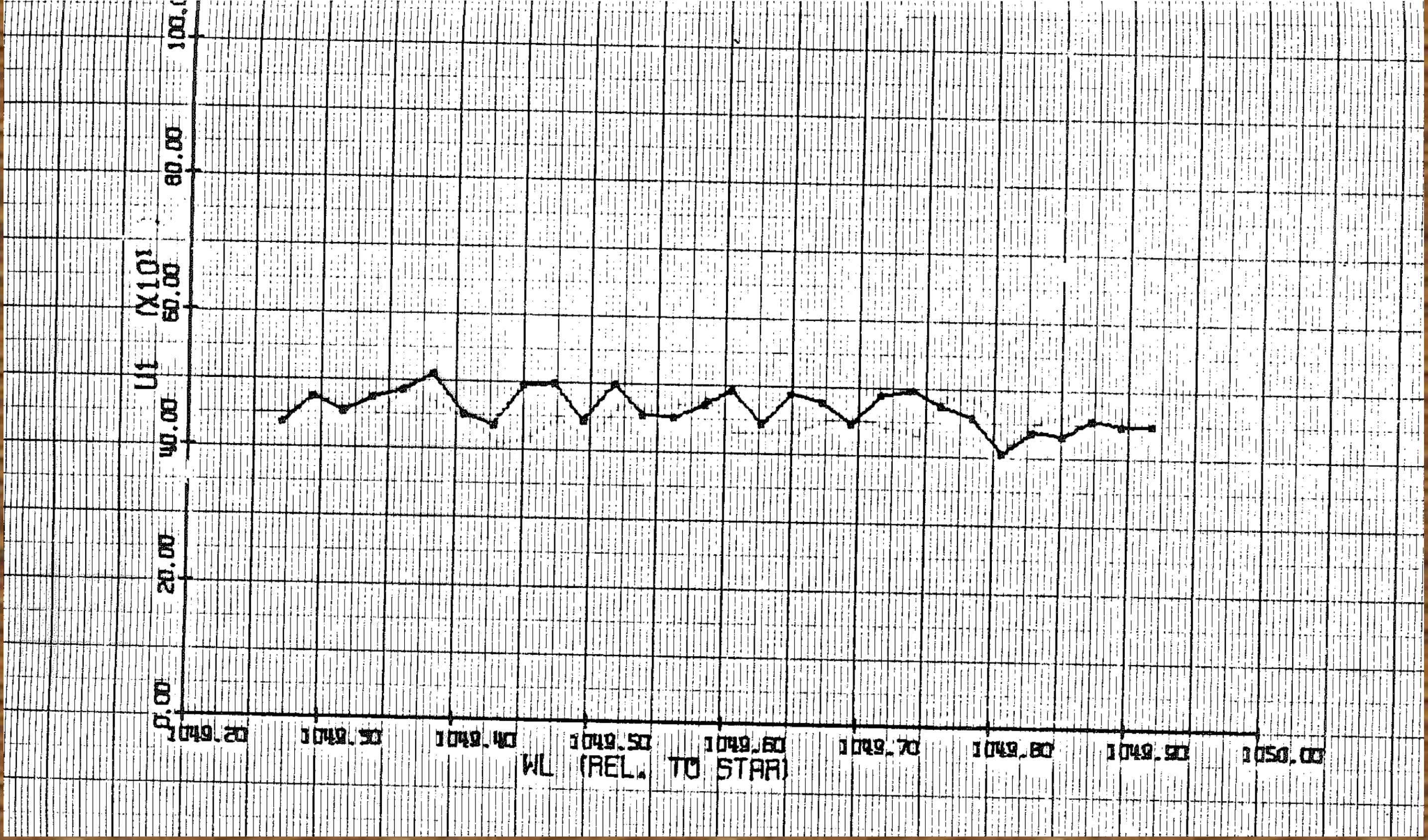
Spectrum of ζ Oph recorded at the Mt. Wilson 100-inch Coudé Spectrograph by Adams (1941: ApJ, 93,11)

First Detection of H_2 in the ISM



Carruthers (1970: ApJ, 161, L81)

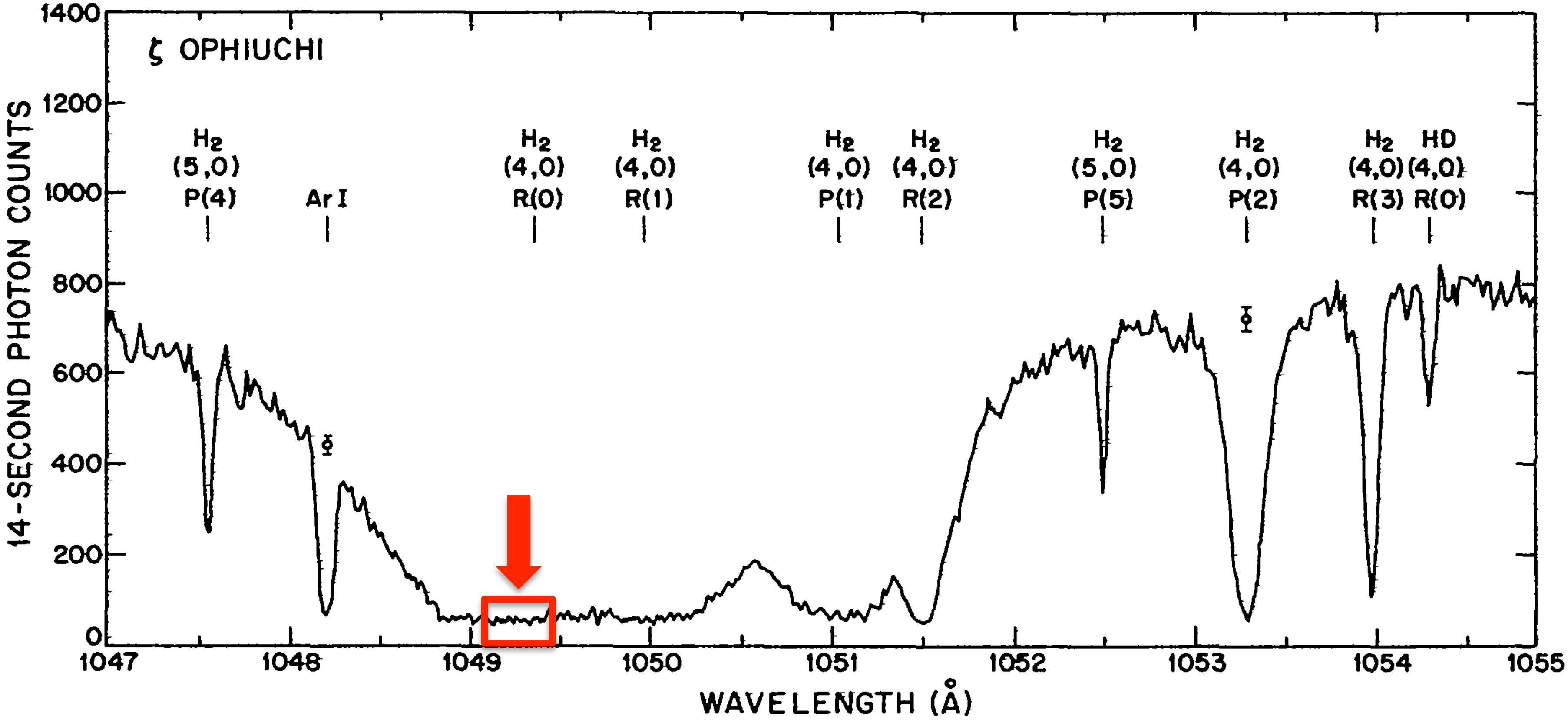
Initial Observation of H_2 toward ζ Oph with the Scanning Spectrometer on the *Copernicus* Satellite



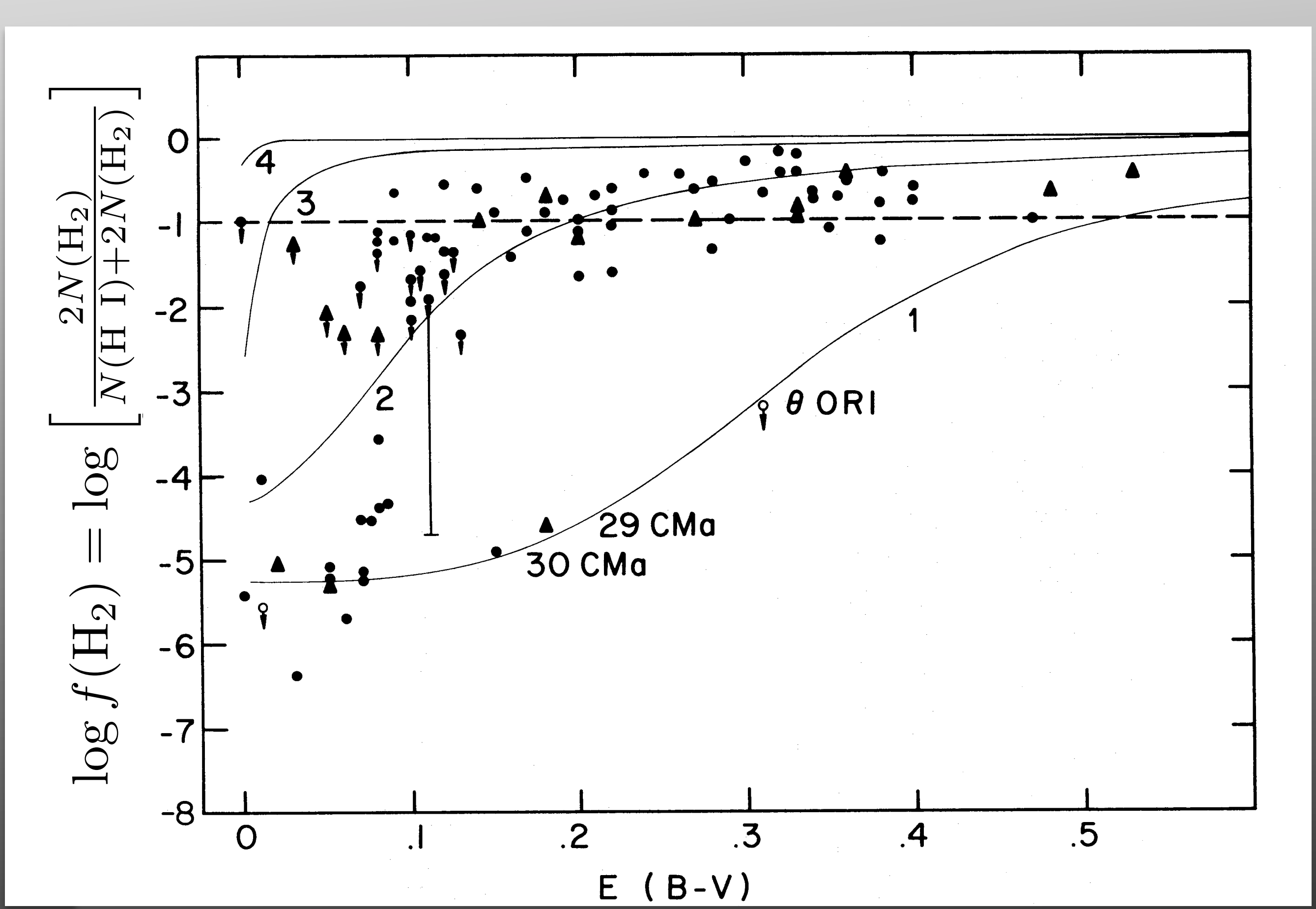
Scan centered on the 4,0 R(0) transition of H2

Obtained soon after launch in August 1972

Initial Observation of H_2 toward ζ Oph with *Copernicus*

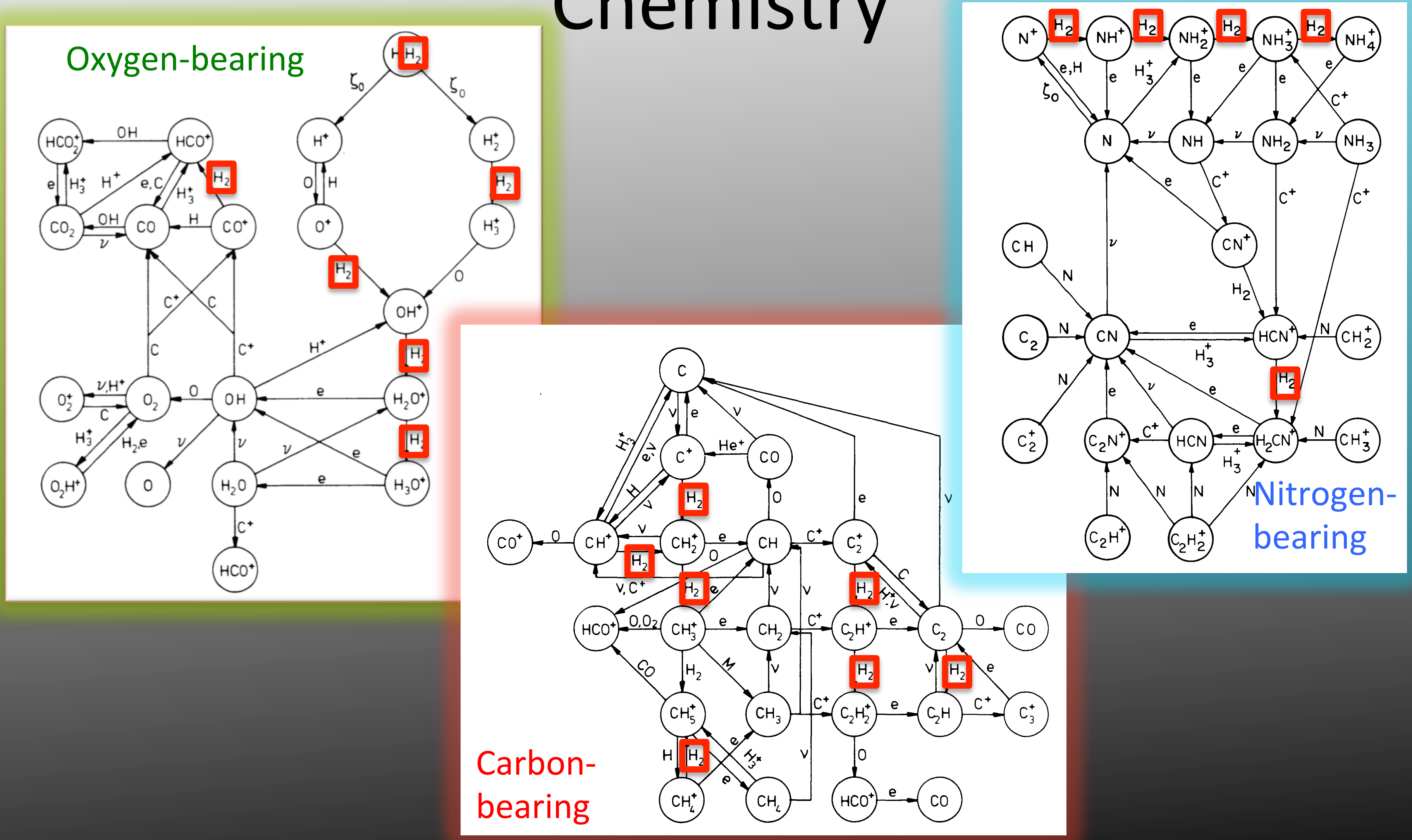

ζ OPHIUCHI
14-SECOND PHOTON COUNTS
1400
1200
1000
800
600
400
200
0
H_2 (5,0) P(4)
Ar I
H_2 (4,0) R(0)
H_2 (4,0) R(1)
H_2 (4,0) P(1)
H_2 (4,0) R(2)
H_2 (5,0) P(5)
H_2 (4,0) P(2)
H_2 (4,0) R(3)
HD (4,0) R(0)
1047
1048
1049
1050
1051
1052
1053
1054
1055
WAVELENGTH (Å)

Hydrogen in Molecular and Atomic Forms



Copernicus survey of H_2 reported by Savage et al. 1977: ApJ, 216, 291

H_2 is a Key Ingredient for Molecular Chemistry



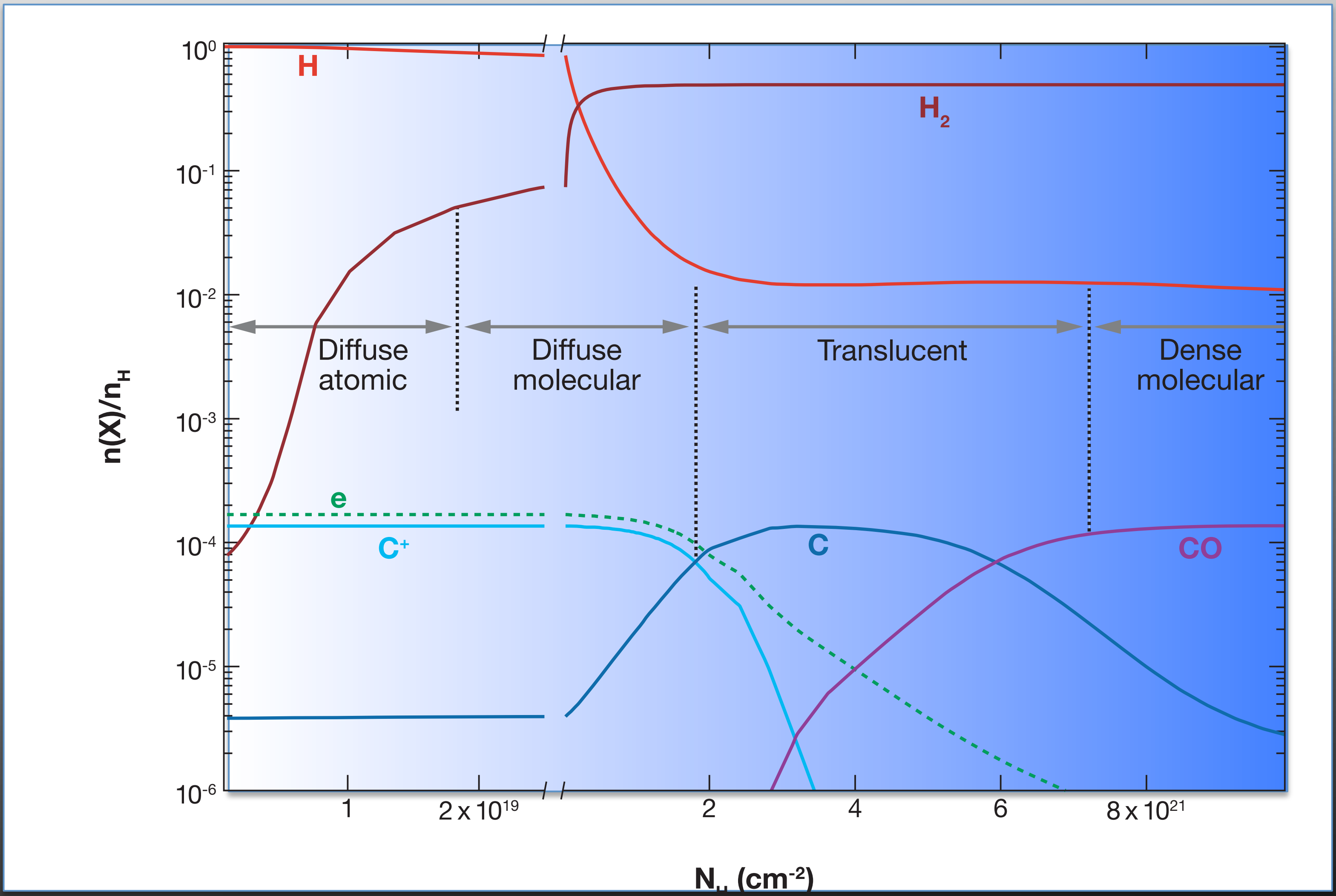
Oxygen-bearing

Carbon-bearing

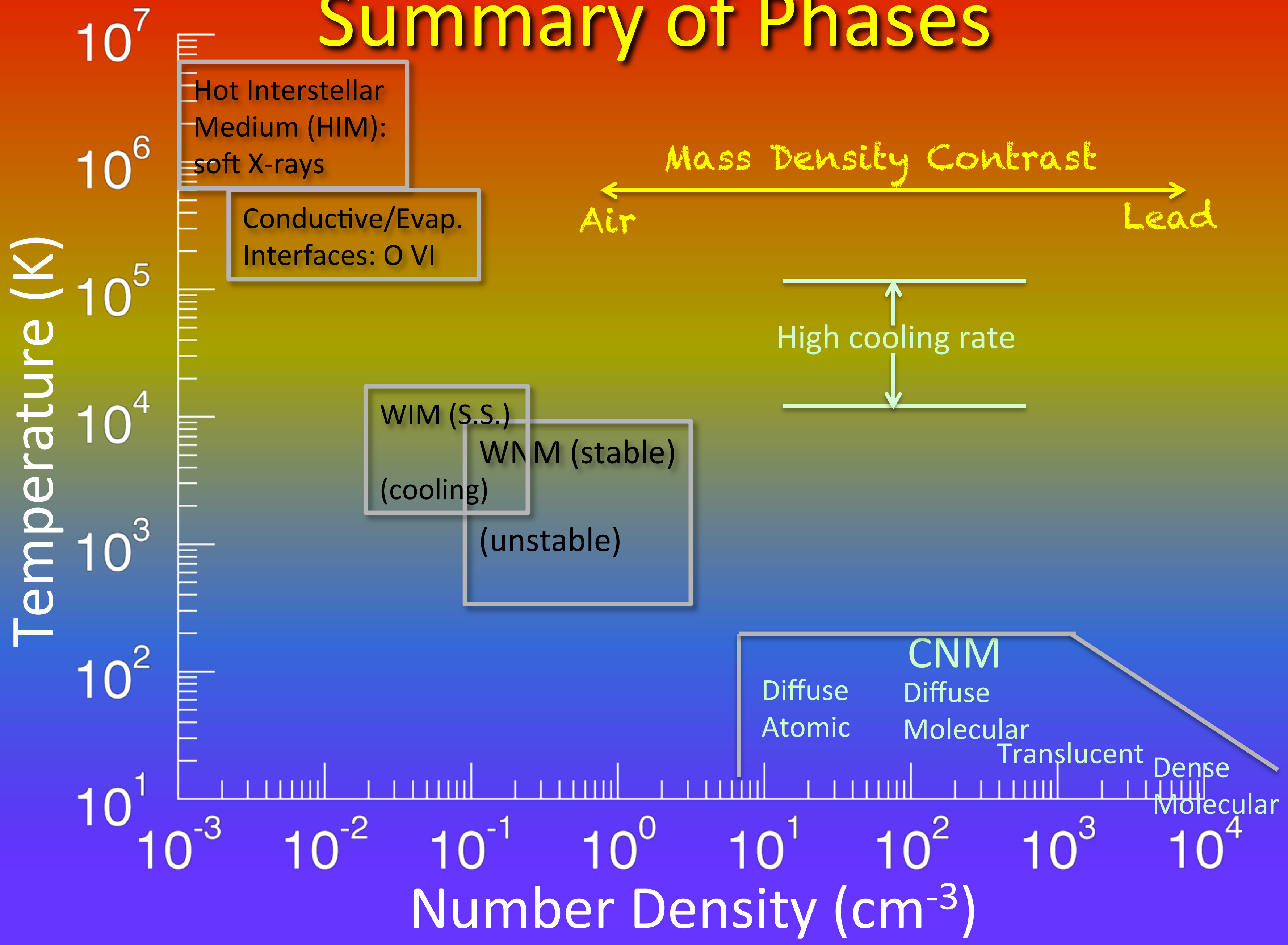
Nitrogen-bearing

CNM Molecular Phases

Definitions from Snow & McCall (2006: ARAA, 44,367)



Summary of Phases



Hot Interstellar Medium (HIM): soft X-rays

Conductive/Evap. Interfaces: O VI

Mass Density Contrast

Air

Lead

High cooling rate

WIM (S.S.)

(cooling)

WNM (stable)

(unstable)

CNM

Diffuse Atomic

Diffuse Molecular

Translucent

Dense Molecular