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-They transform hydrogen, the primary product of the big bang, into the heavy elements of the periodic table.

-Through stellar evolution they control evolution of all stellar systems including clusters and galaxies.

-They provide the sites for planetary systems and the energy necessary for development of life.

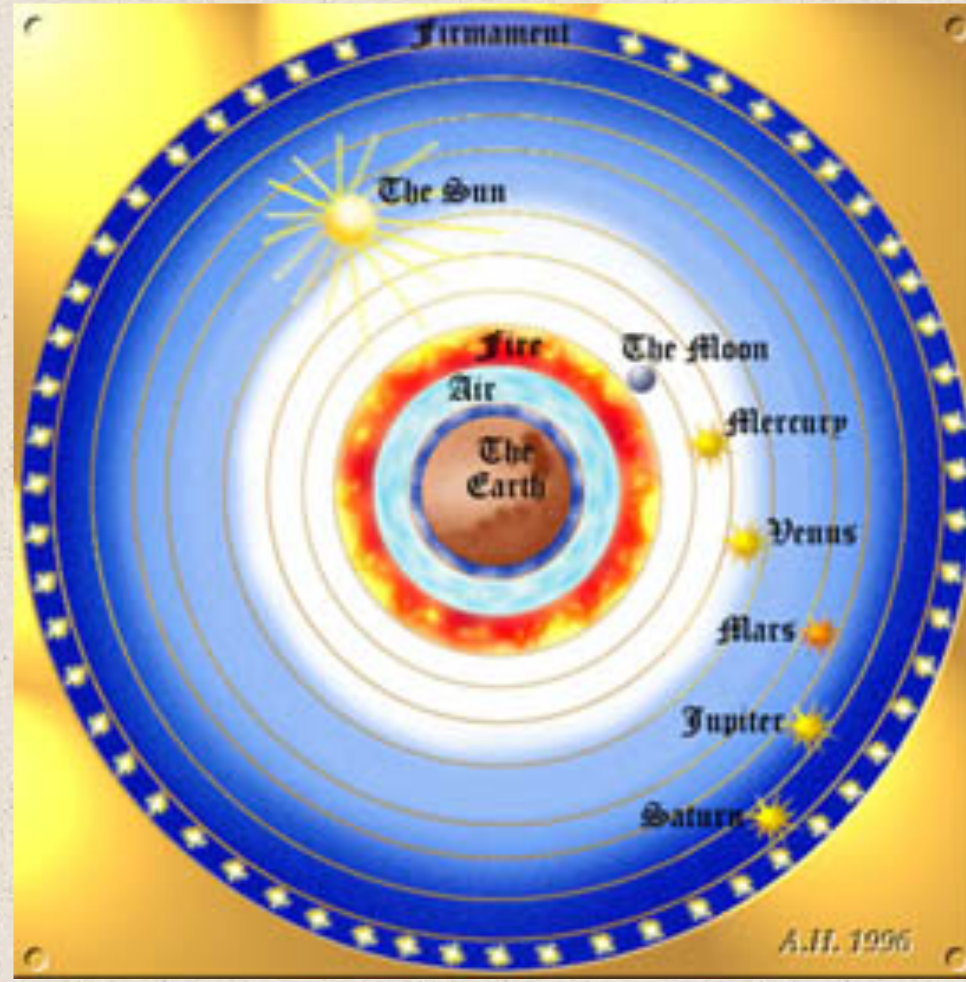
A Little History.....

Genesis 1-16,17

And God made two great lights; the greater light to rule the day and the lesser light to rule the night: he made the stars also.

And God set them in the firmament of the heaven to give light upon the earth.

Aristotle's Universe (384 BC – 165 AD)
Greeks Invent The Scientific Cosmos



There are two realms of the Universe:

the perfect heavens
and
the imperfect earth.

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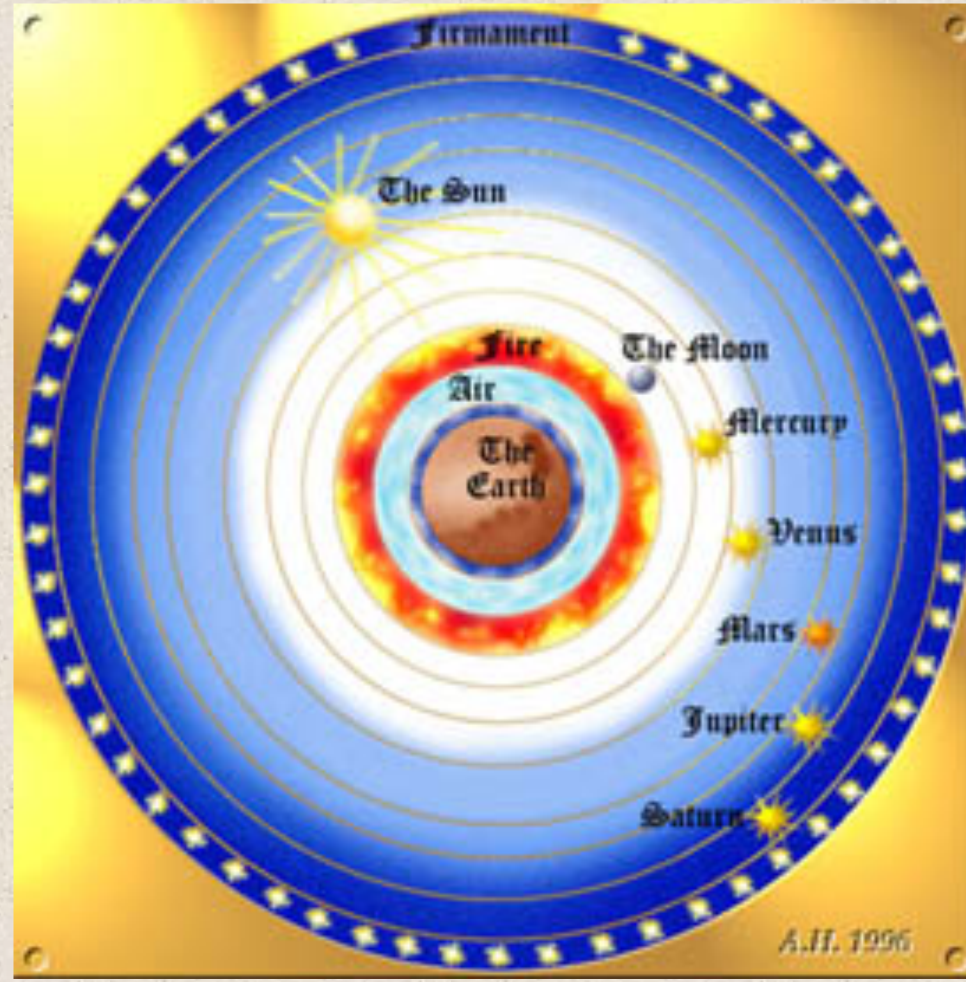
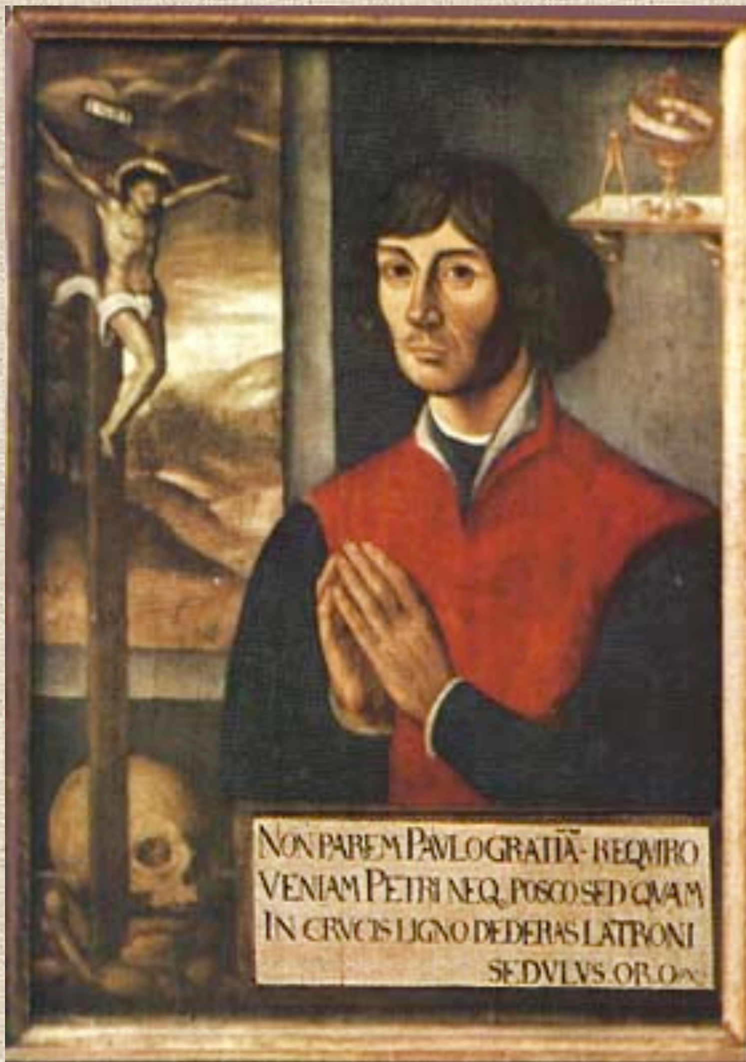


There are two realms of the Universe:

the perfect heavens
and
the imperfect earth.

Stars consist of *aether*, a perfect, unchanging substance.

Copernicus 1473-1543



NICOLAI COPERNICI

net, in quo terram cum orbe lunari tanquam epicyclo contineri diximus. Quinto loco Venus nono mense reducitur. Sextum deniq; locum Mercurius tenet, octuaginta dierum spacio circu currens. In medio uero omnium residet Sol. Quis enim in hoc

pulcherimo templo lampadem hanc in alio uel meliori loco poneret, quàm unde totum simul possit illuminare? Siquidem non inepte quidam lucernam mundi, alij mentem, alij rectorem uocant. Trimegistus uisibilem Deum, Sophoclis Electra intuentē omnia. Ita profecto tanquam in solio regali Sol residens circum agentem gubernat Astrorum familiam. Tellus quoq; minime fraudatur lunari ministerio, sed ut Aristoteles de animalibus ait, maximā Luna cū terra cognationē habet. Concipit interea à Sole terra, & impregnatur annuo partu. Inuenimus igitur sub hac

Tycho Brahe 1546 - 1601

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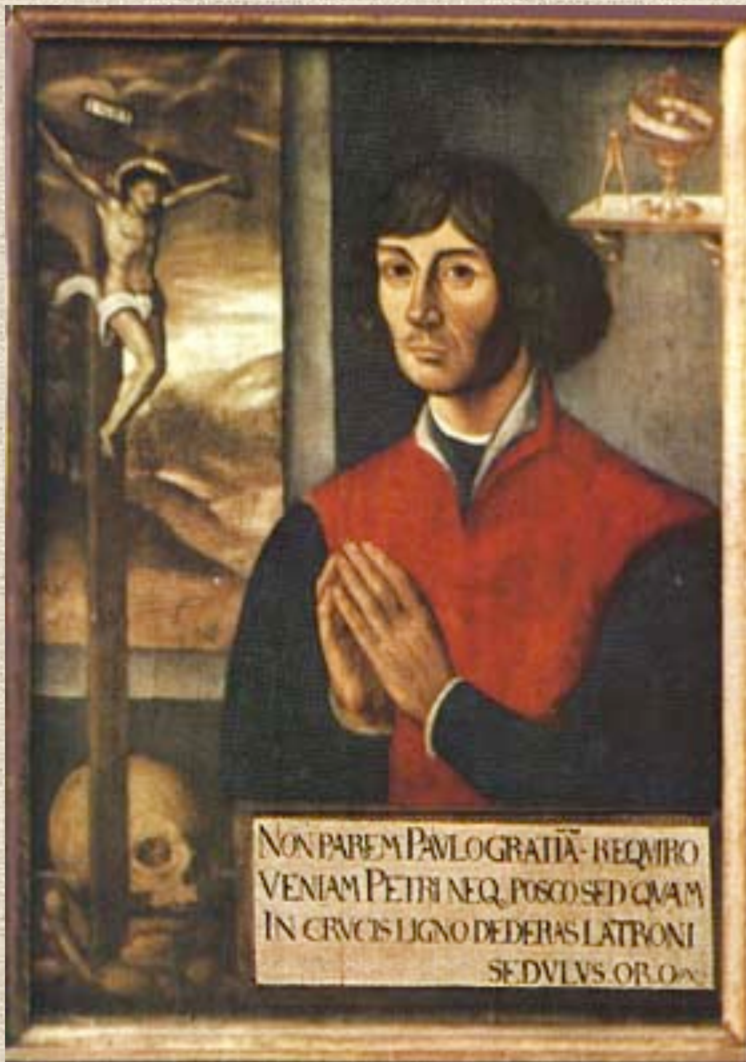
Problem: no stellar parallax!

Copernicus 1473-1543



Solution: stars are very distant (and *very luminous)*!


NICOLAI COPERNICI

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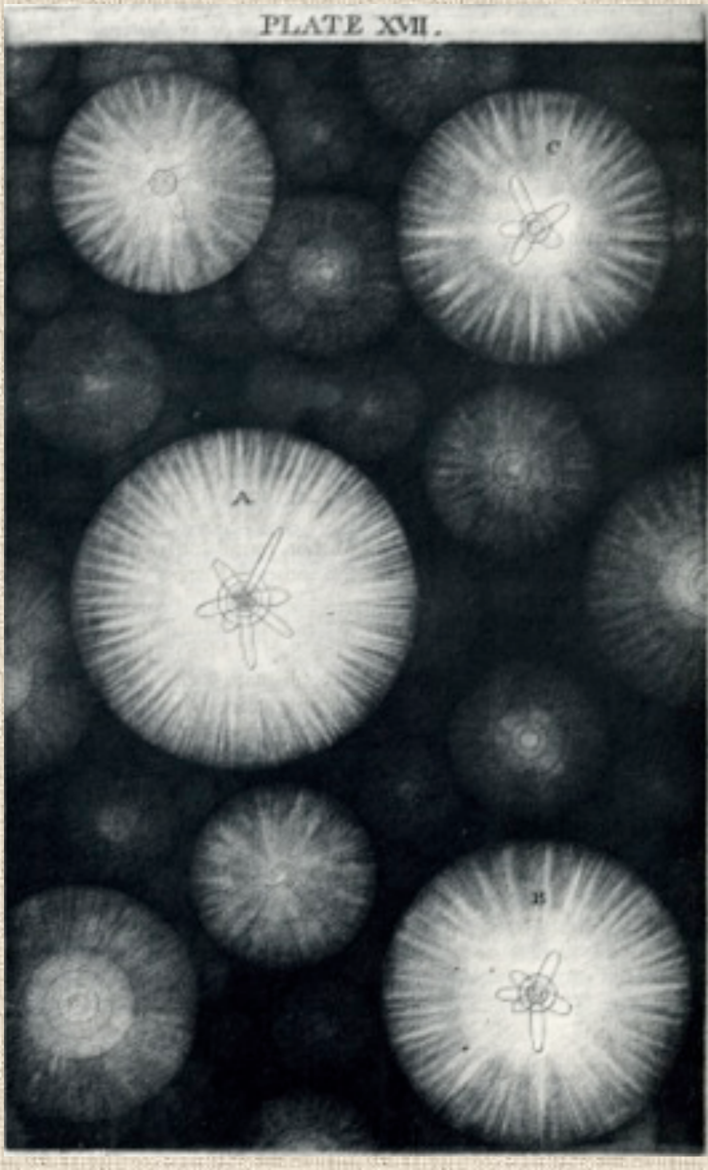
Equivalence of the Sun and Stars



"First it is allowed, as I have endeavoured to shew, by all modern Philosophers, that the Sun and the Stars are all of the same or like Nature; consequently, that the Stars are all Suns, and that the Sun himself is a Star"

Thomas Wright in "An Original Theory of The Universe", 1750

But what ‘s the Sun?

Universal Gravitation and Star Formation

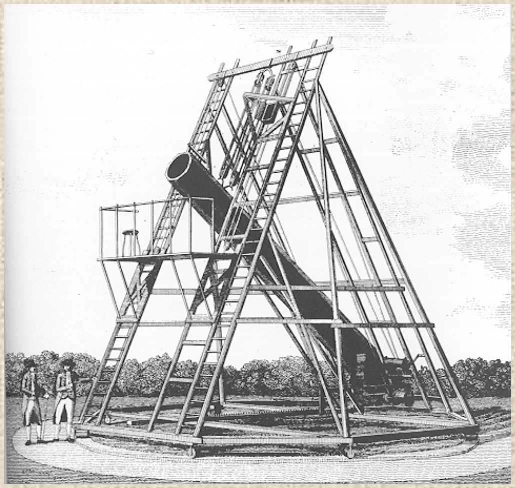
Isaac Newton 1642 - 1727

"But if the matter was evenly diffused through an infinite space, it would never convene into one mass but some of it convene into one mass & some into another so as to make an infinite number of great masses scattered at great distances from one another throughout all the infinite space. And thus might the Sun and Fixt stars be formed supposing the m

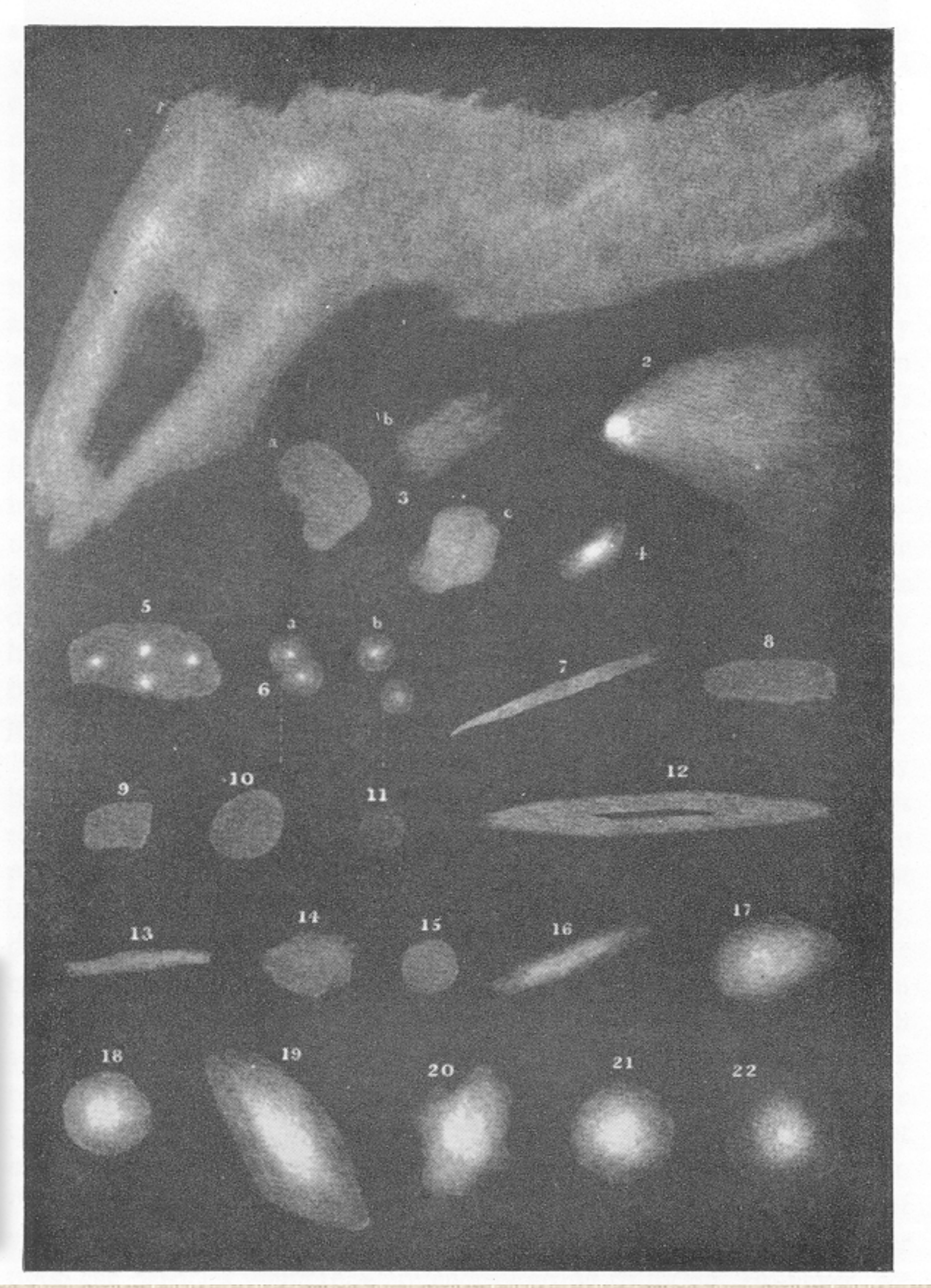
Newton to Rev. Richard Bentley, 10 December 1692

William Herschel and The Concept of Cosmic Evolution

William Herschel
1738-1822



"In my paper of observations of the nebulous part of the heavens, I have endeavored to shew the probability of a very gradual conversion of the nebulous matter into the sidereal appearance."



Observations relating to the Construction of the Heavens, 1811, *Phil. Trans., CI*, 269-336.

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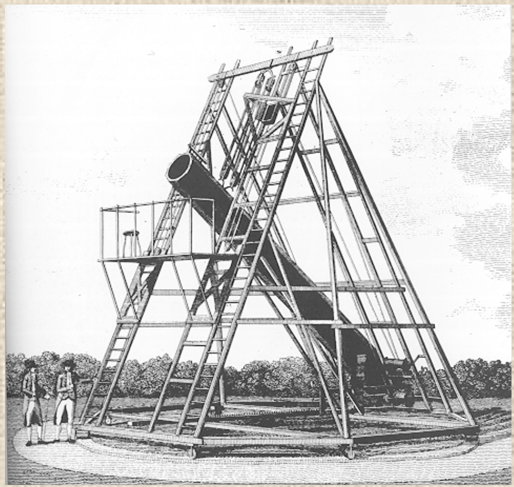
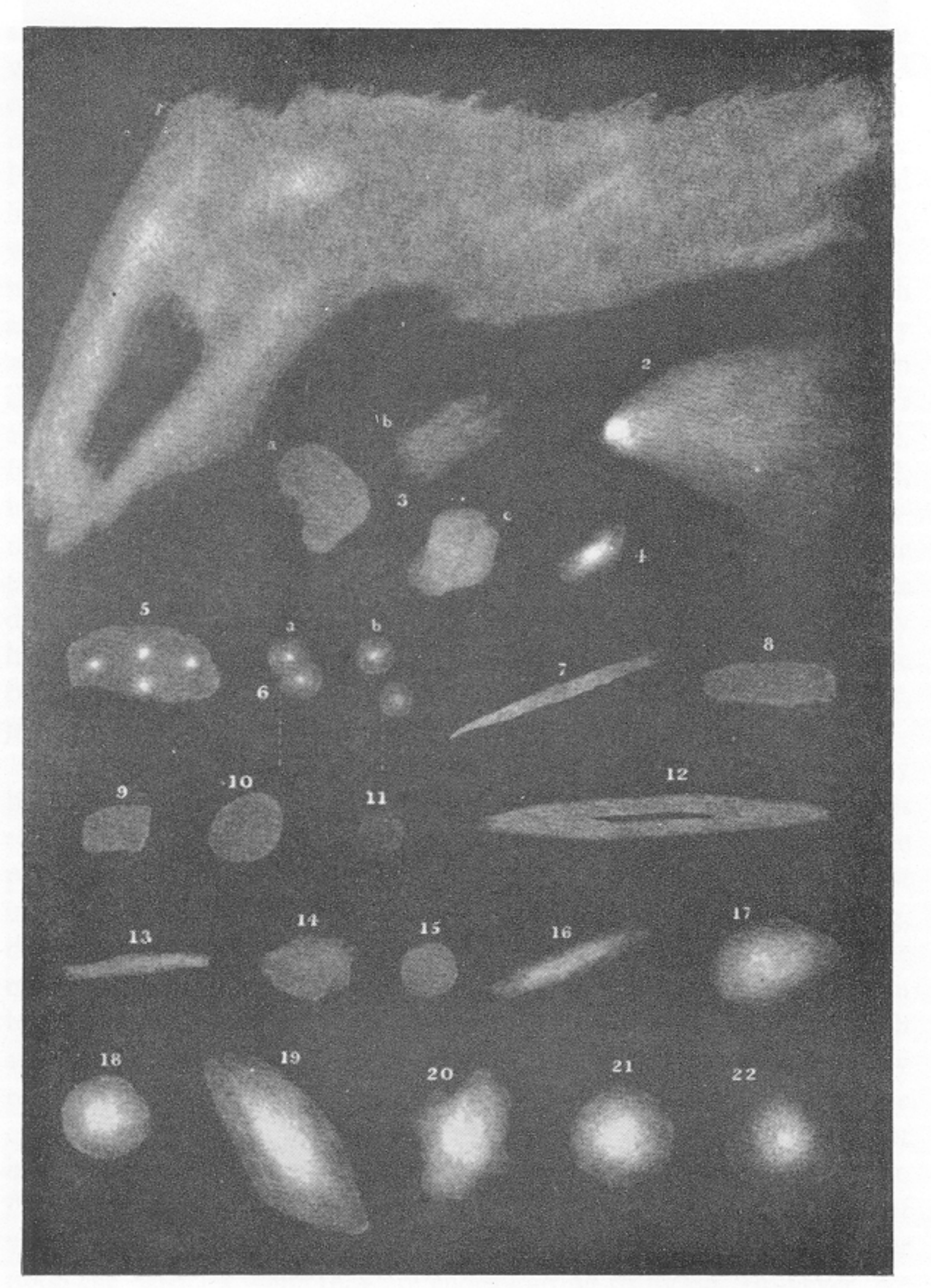


"but… why should we not look up to the universal gravitation of matter as the cause of every condensation, accumulation , compression and concentration of the nebulous matter?



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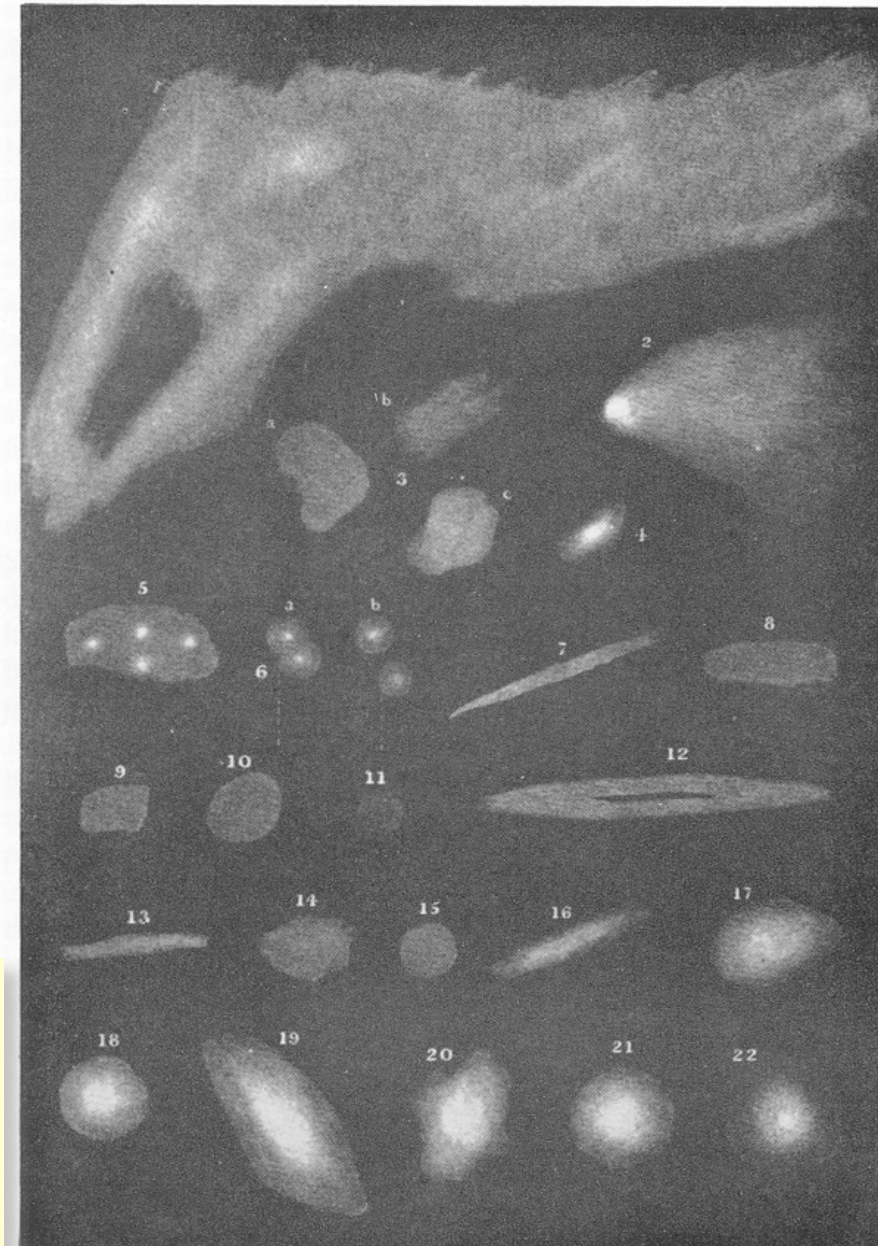


Star Formation is an ongoing process!

As such it is subject to direct empirical study.

Observations relating to the Construction of the Heavens, 1811, *Phil. Trans., CI*, 269-336.

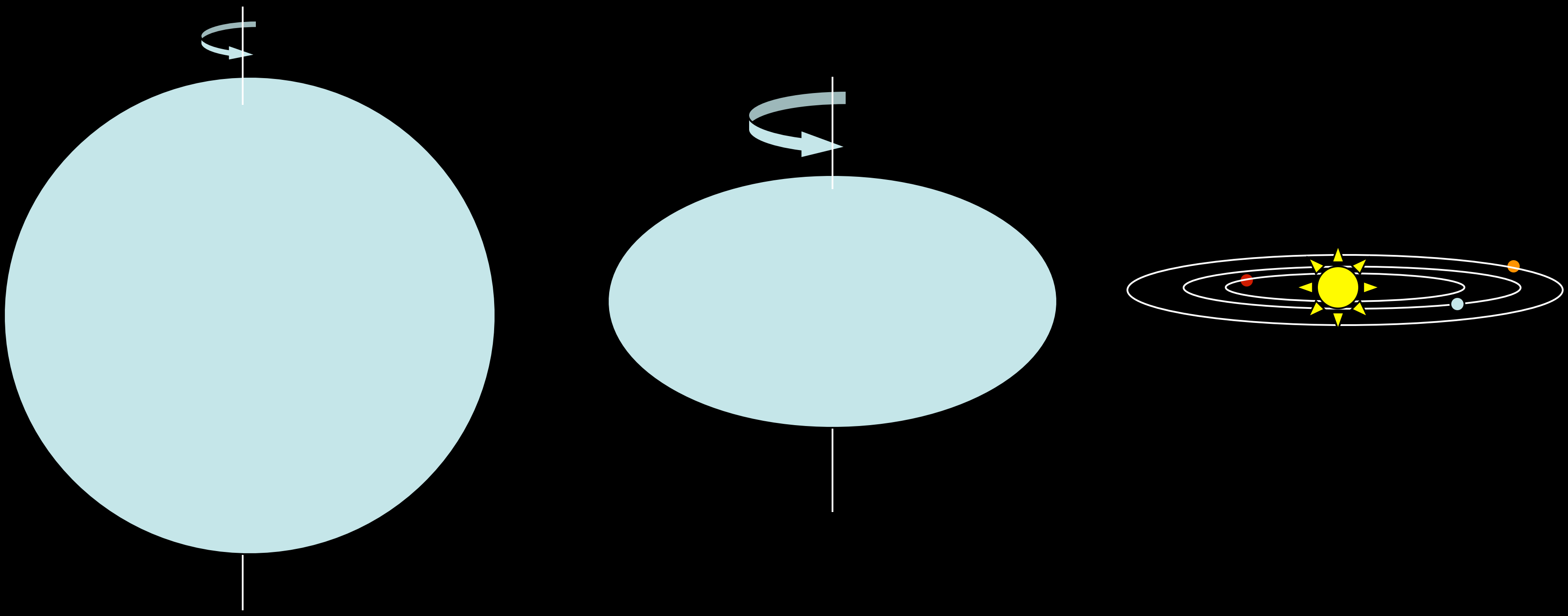
Protoplanetary Disks: A slight digression

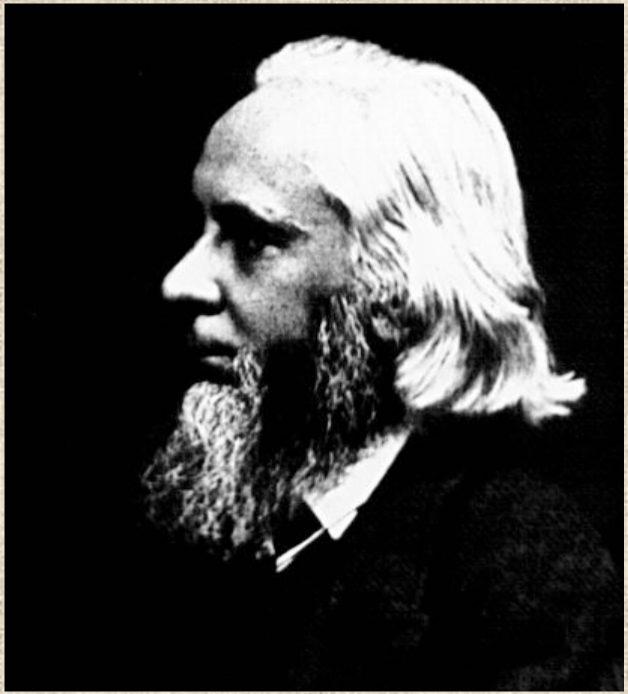
E. Kant 1724-1804

P.S. Laplace 1749-1827

Kant-Laplace Nebular Hypothesis

A nebula in slow rotation, gradually pulled together by its own gravitational force and flattened into a spinning disk, gave birth to the Sun and planets.

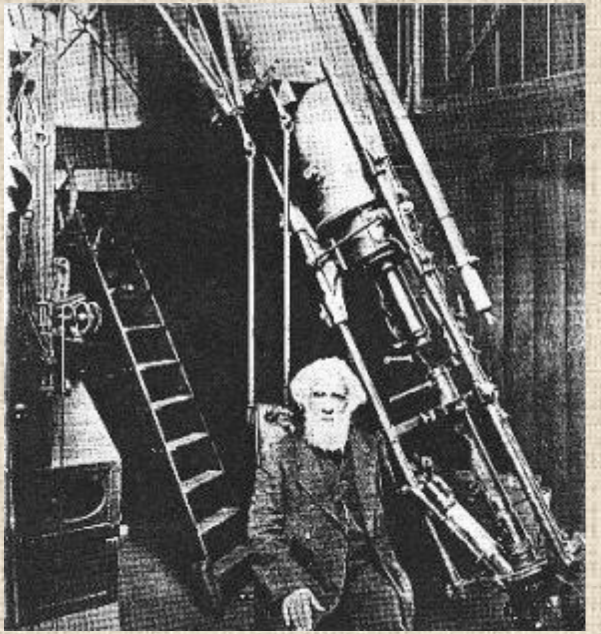


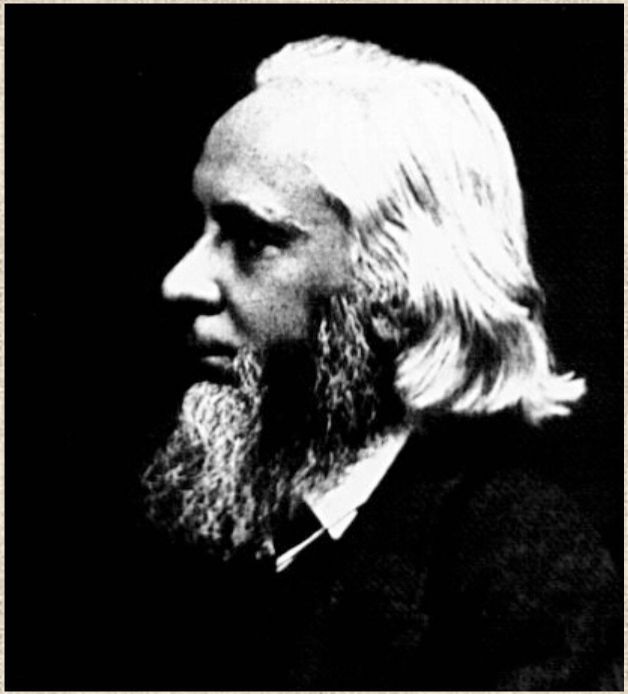


William Huggins
1824 - 1910

"The riddle of nebulae was solved. The answer which had come to us in the light itself read: Not an aggregation of stars, but luminous gas…the light of this nebula had been emitted by a luminous gas."

The New Astronomy of the Nineteenth Century, June, 1897





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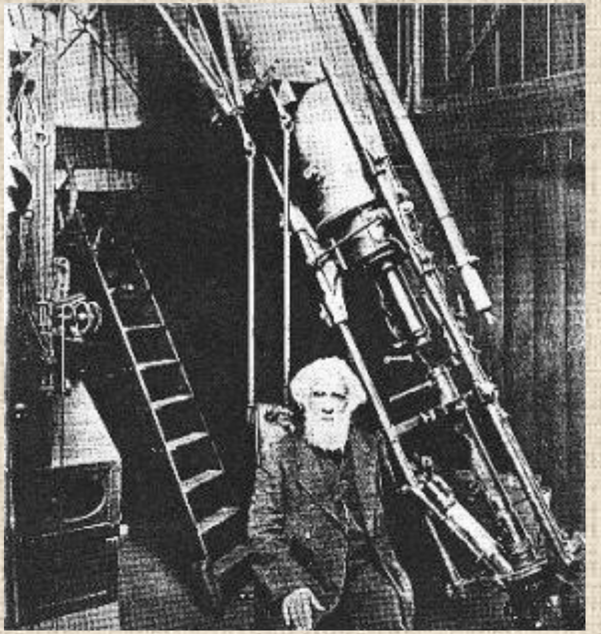
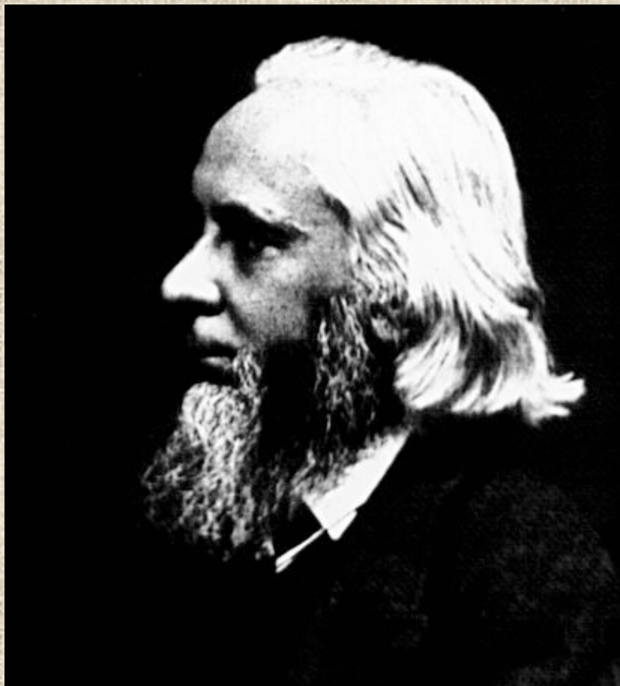
But the composition of these luminous fluids, being composed of <u>hydrogen</u> and <u>nitrogen</u>, differed from stars and planets and could not be the material from which stars formed as Herschel had suggested!





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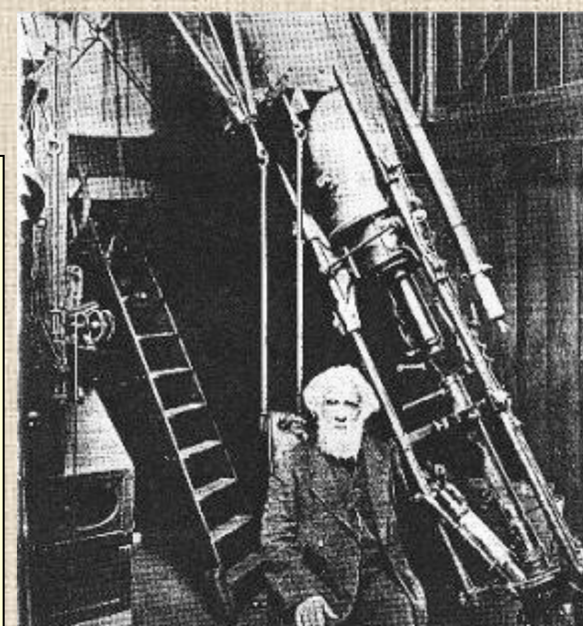
"The conclusion is strongly indicated that the order of the abundance of the elements in the solar atmosphere is much the same as in the earth's crust."

Russell, Dugan & Stewart 1927 in Astronomy, Ginn & Co., 502



Setting the Stage: Discovery of The Composition of Stars

C. Payne-Gaposchkin
1900-1980

***Stellar Atmospheres*: PhD Thesis Harvard 1925**

Two fundamental results:

1- Stars have uniform composition and

2- Stars are primarily made up of hydrogen

“It is the best doctoral thesis I have ever read” H.R. Russell

“undoubtedly the most brilliant PhD thesis ever written in astronomy” O. Struve

The Physical Nature of Stars

Bengt Stromgren
1908-1987

Hans Bethe
1906 - 2005

In 1938 Stromgren showed that stellar interiors composed of primarily hydrogen would have central temperatures ~ 10^7 K much lower than if they were made of iron.

In 1938 Bethe showed that with such central temperatures fusion reactions (CNO and p-p cycles) could power stars and thus demonstrated that:

Stars are thermo-nuclear reactors which fuse the primary product of the big bang into heavier elements of the periodic table releasing enormous amounts of energy in the process.

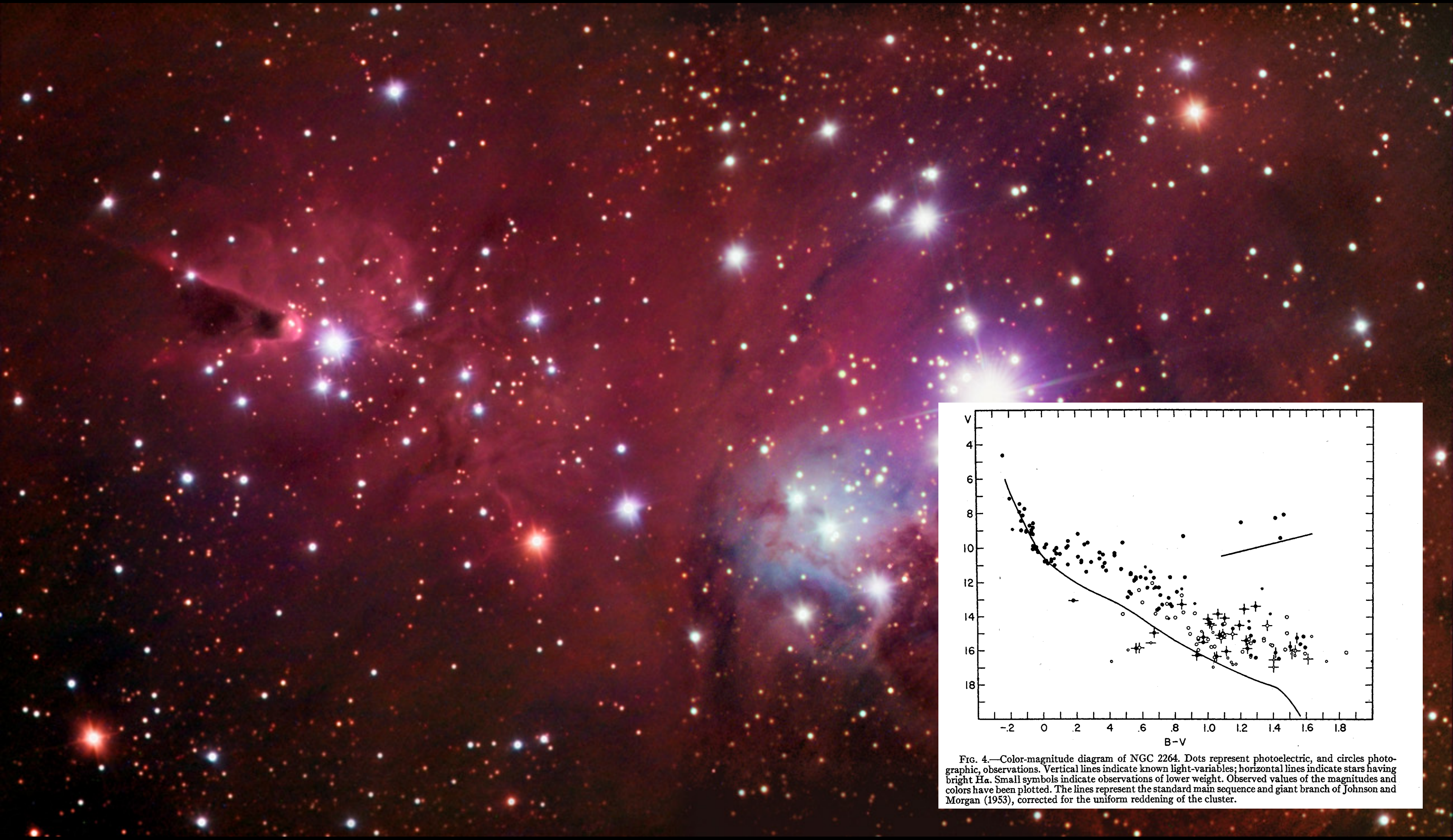


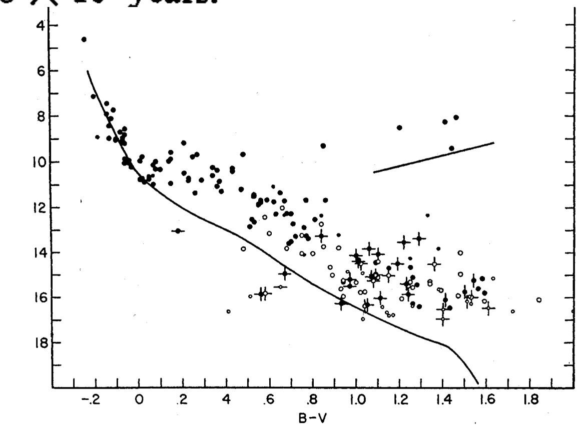
FIG. 4.—Color-magnitude diagram of NGC 2264. Dots represent photoelectric, and circles photographic, observations. Vertical lines indicate known light-variables; horizontal lines indicate stars having bright Hα. Small symbols indicate observations of lower weight. Observed values of the magnitudes and colors have been plotted. The lines represent the standard main sequence and giant branch of Johnson and Morgan (1953), corrected for the uniform reddening of the cluster.

STUDIES OF EXTREMELY YOUNG CLUSTERS. I. NGC 2264

MERLE F. WALKER*
Mount Wilson and Palomar Observatories
Carnegie Institution of Washington, California Institute of Technology
Received May 21, 1956

ABSTRACT

Three-color photoelectric and photographic observations of NGC 2264 have been obtained to $V = 17$, in order to investigate the color-magnitude diagram of an extremely young cluster of stars. The diagram indicates that the cluster possesses a normal main sequence extending from O7 to A0, below which the stars fall above the main sequence. The reality of this effect has been confirmed by spectroscopic observations. The shape of the color-magnitude diagram agrees approximately with that predicted theoretically for clusters which are so young that the fainter stars are still in the process of contracting gravitationally from the prestellar medium and have not yet reached the main sequence. The age of the cluster given by the point where the cluster stars depart from the main sequence is about 3×10^6 years.



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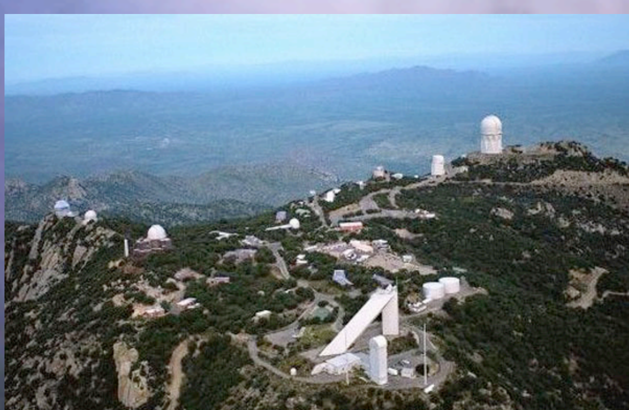
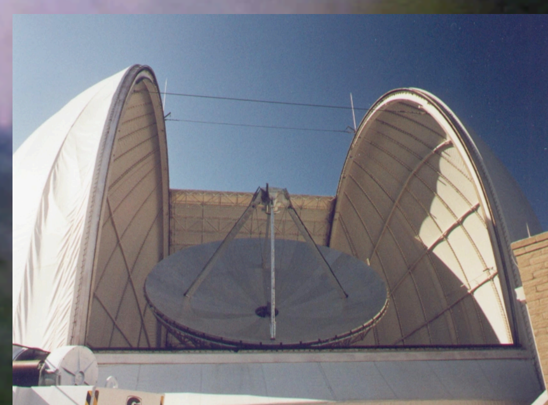
Herschel was Right!

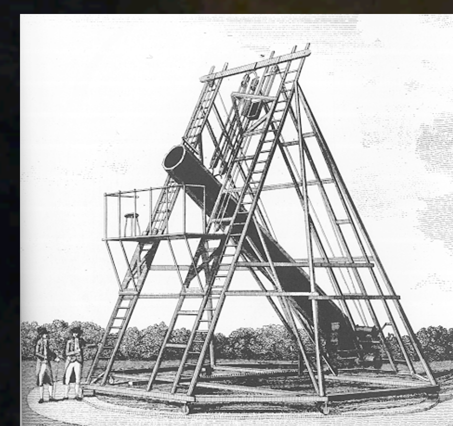
William Herschel
1738-1822

Star Formation is an ongoing process!

And is subject to direct empirical study.







The Unsolved Problem of Star Formation:

Setting the Boundary and Initial Conditions

BOUNDARY CONDITIONS

BOUNDARY CONDITIONS

Compositions, Luminosities, Temperatures, Sizes, & Masses

BOUNDARY CONDITIONS

Luminosities, Temperatures, Sizes, & Masses

BOUNDARY CONDITIONS

Masses

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Mass

BOUNDARY CONDITIONS

- **Once formed, the entire life history of a star is essentially predetermined by a single parameter*: <u>the star's initial mass</u>*.**

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- The IMF (the frequency distribution of stellar masses at birth) plays a pivotal role in the evolution of all stellar systems from clusters to galaxies.

BOUNDARY CONDITIONS

The Initial Mass Function (IMF) = first fundamental boundary condition

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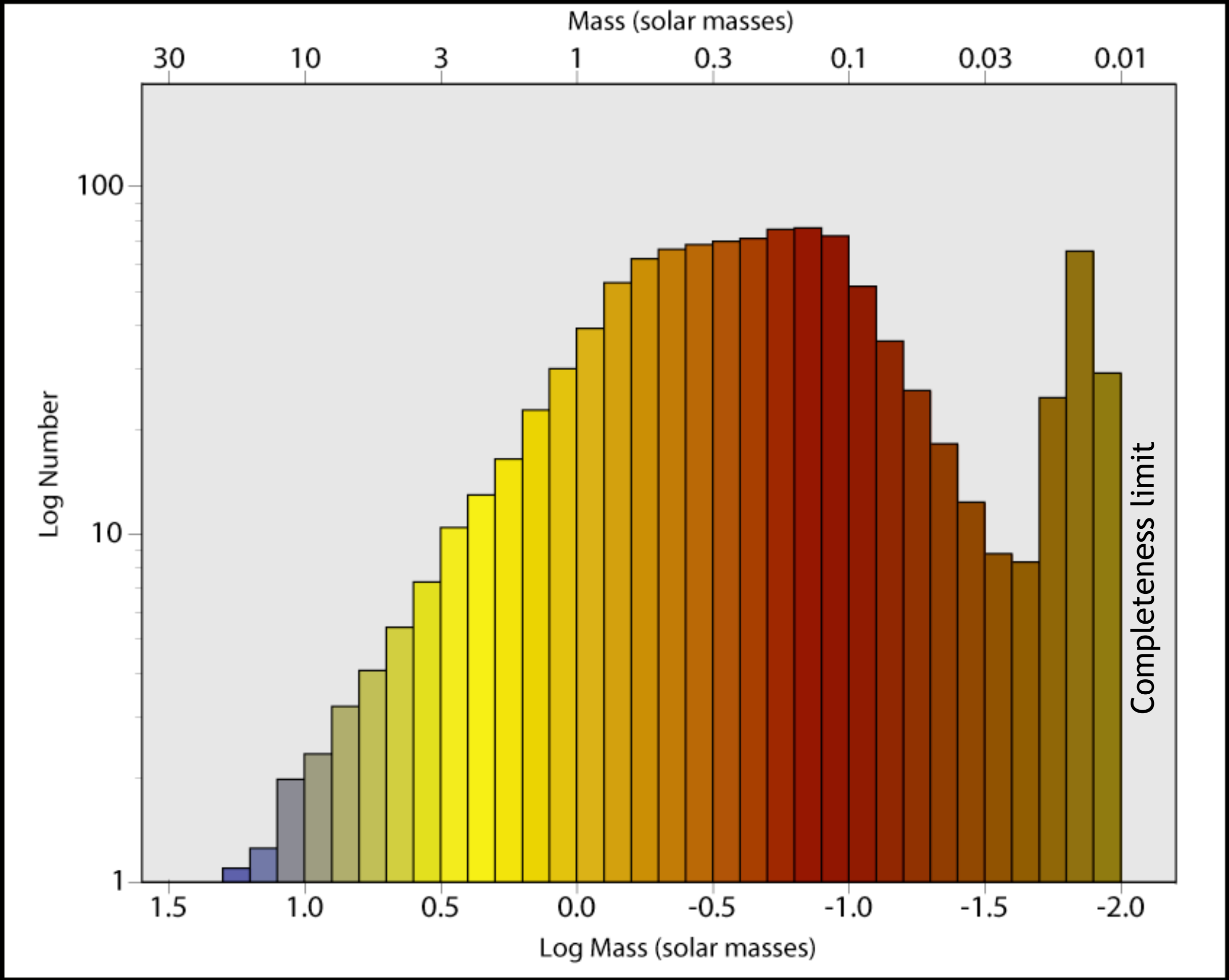
- **The IMF (the frequency distribution of stellar masses at birth) plays a pivotal role in the evolution of all stellar systems from clusters to galaxies.**

Fundamental Boundary Conditions

1- The Initial Mass Function (**IMF**)

Muench et al. 2002



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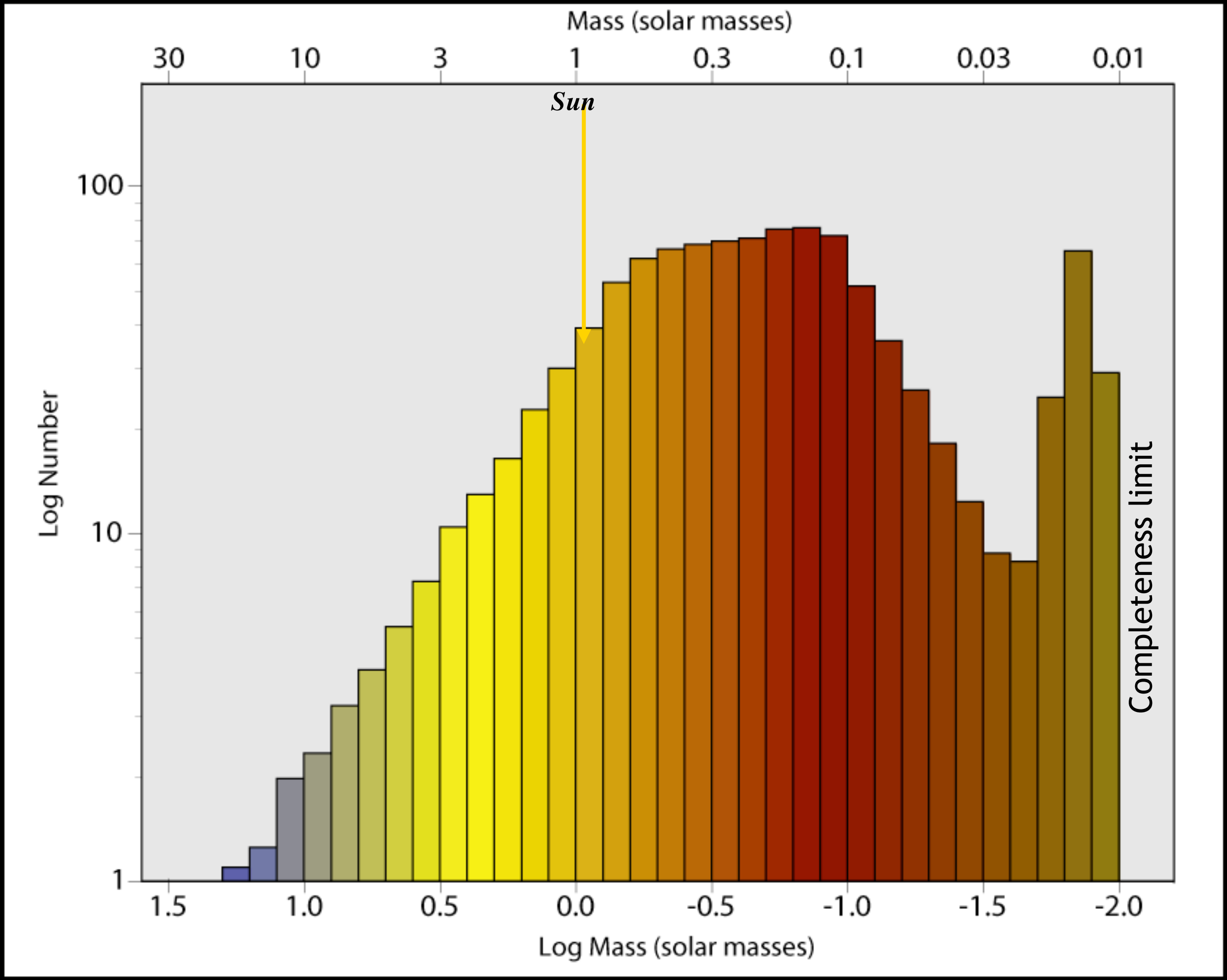

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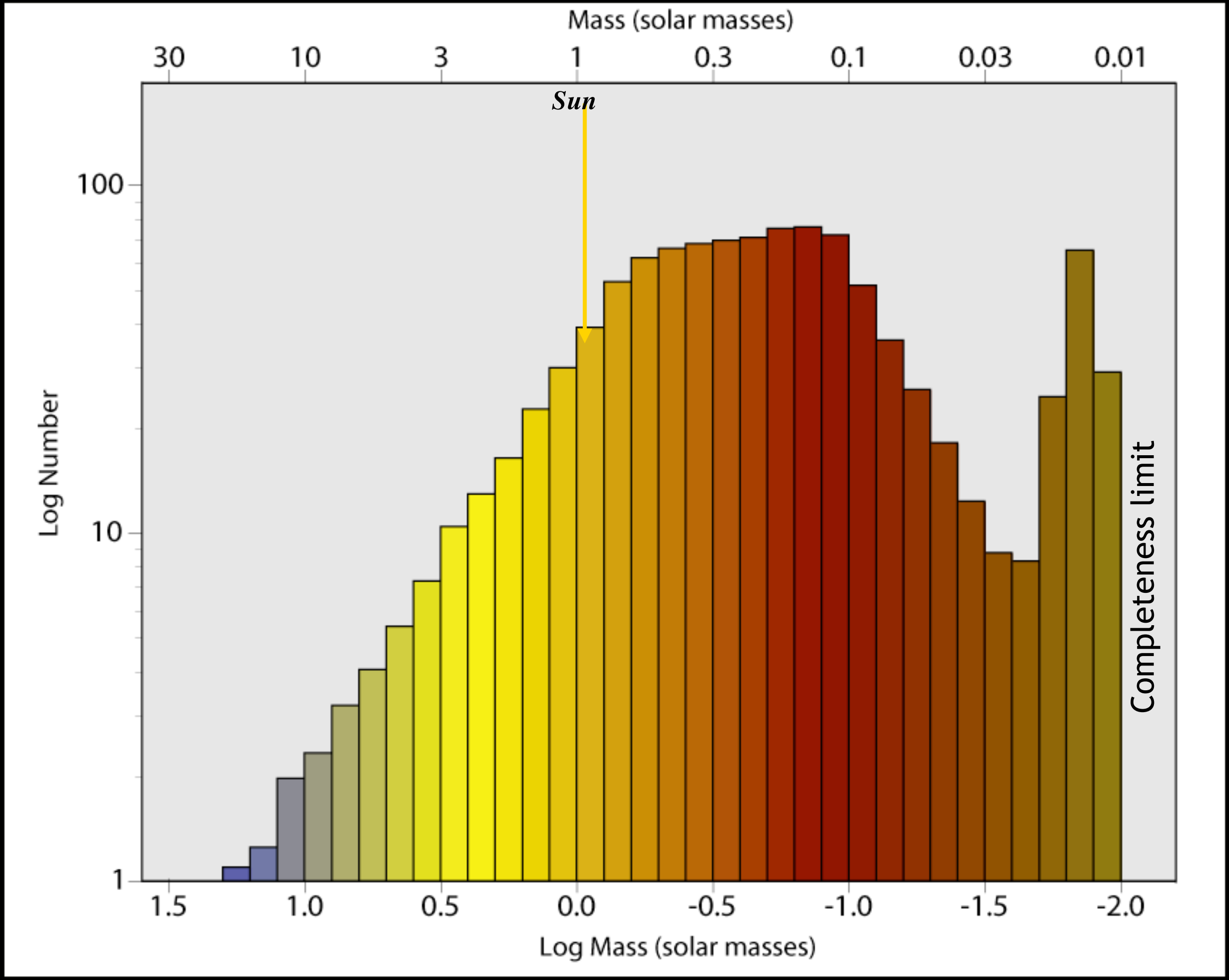


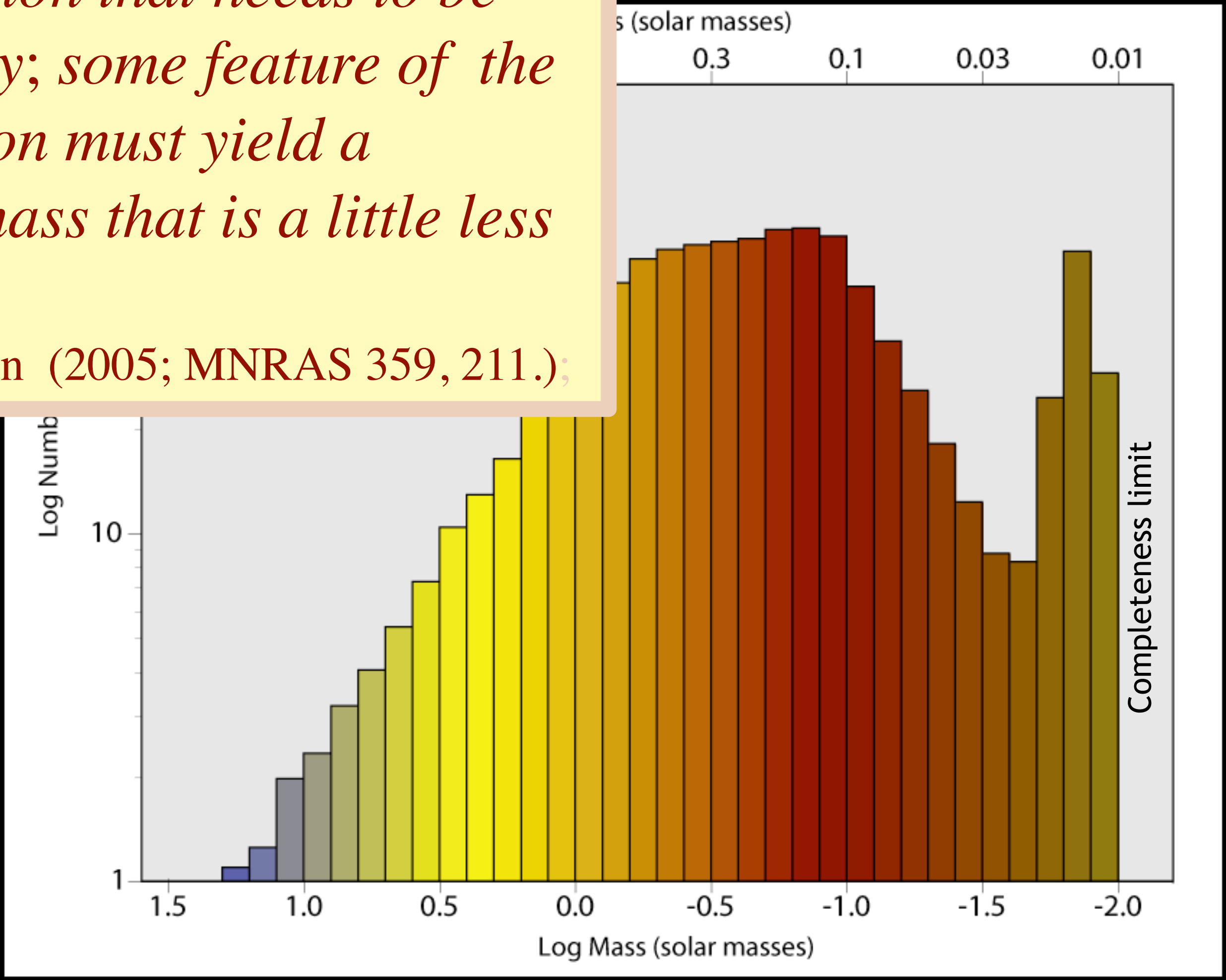
The IMF exhibits a broad peak between 0.6 and 0.1 $M_\odot$ suggesting a characteristic mass associated with the star formation process.

Fundamental Boundary Conditions

This is perhaps the most fundamental fact concerning star formation that needs to be explained by any theory; some feature of the physics of star formation must yield a characteristic stellar mass that is a little less than one solar mass.

Larson (2005; MNRAS 359, 211.);

Muench et al. 2002



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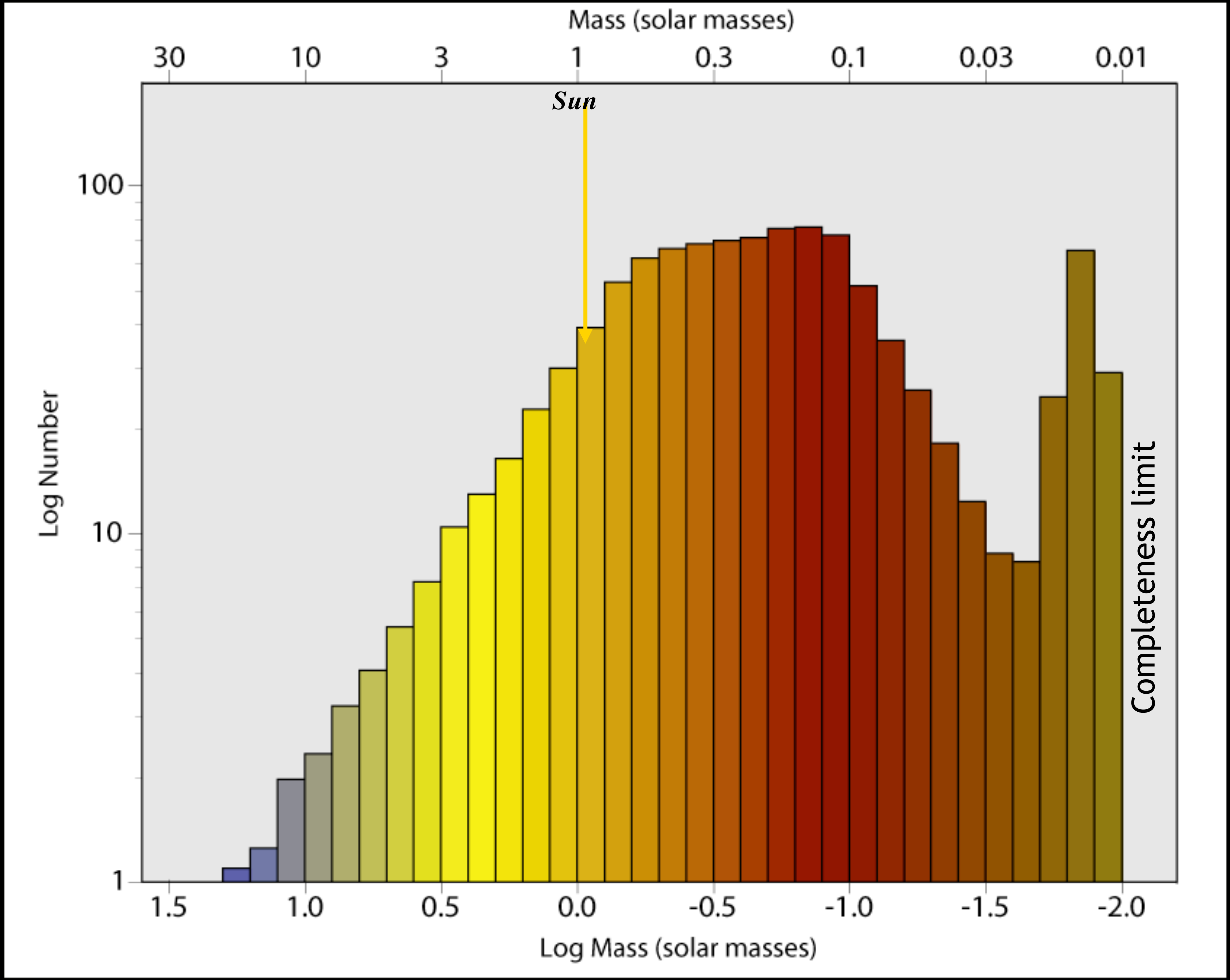

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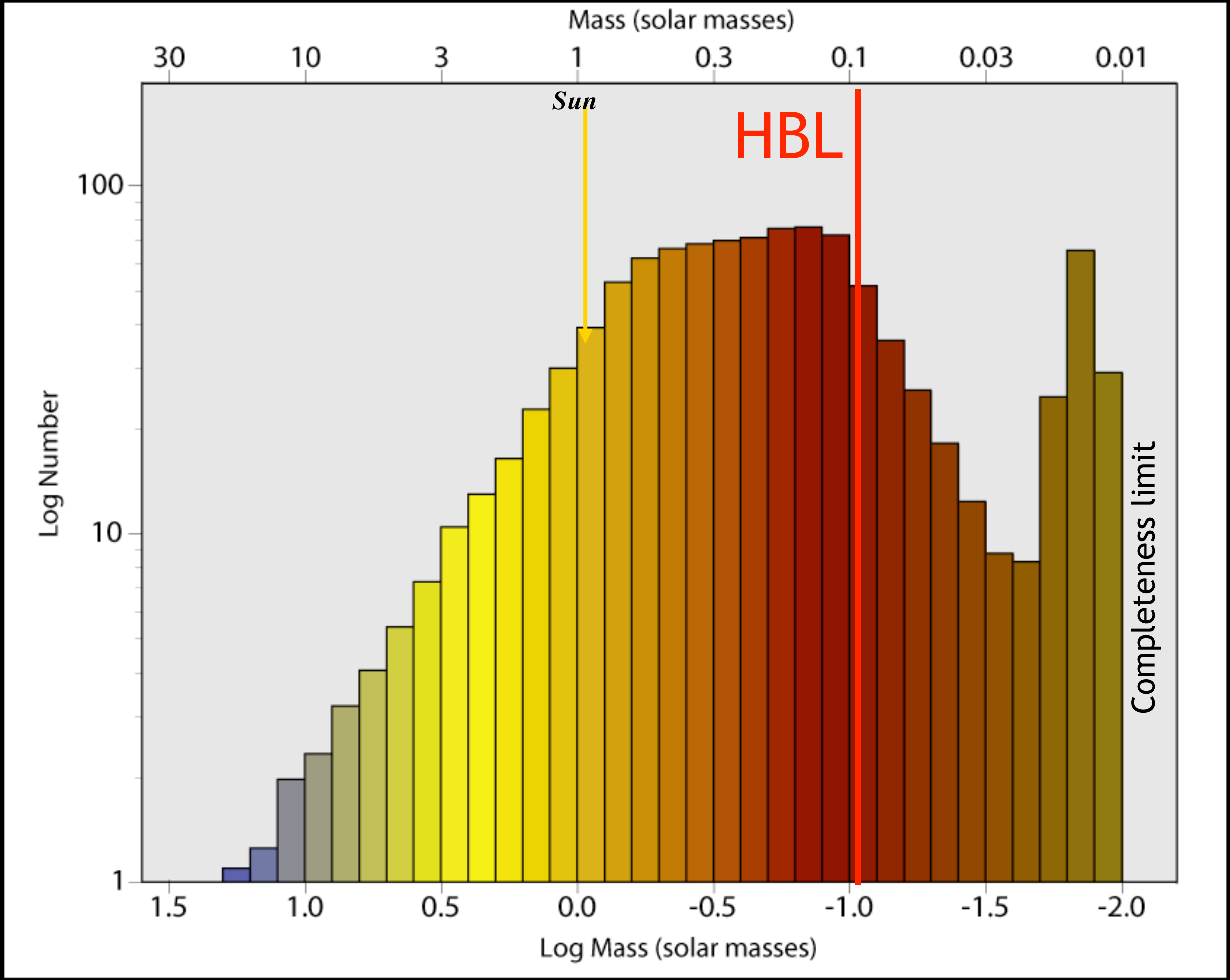

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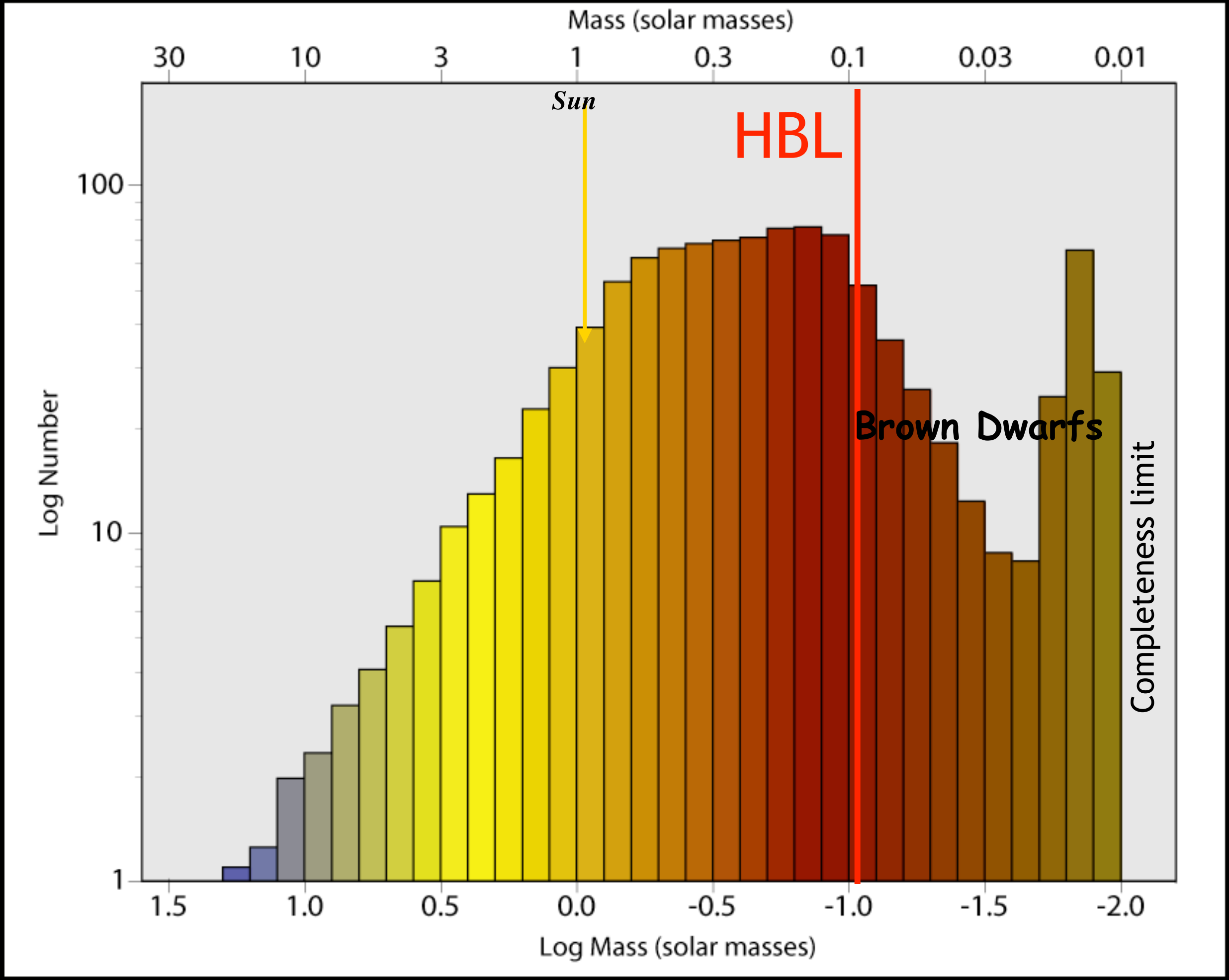

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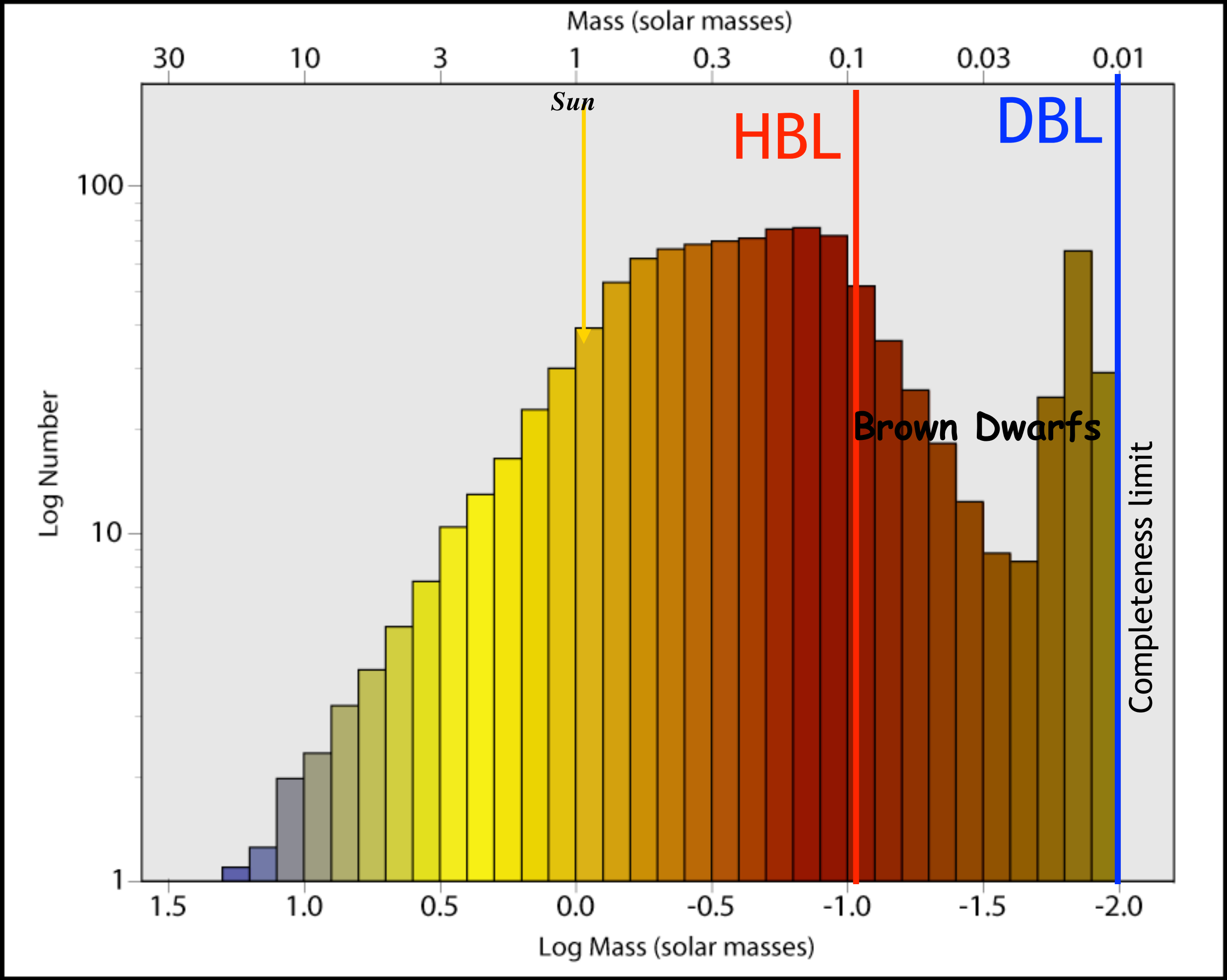

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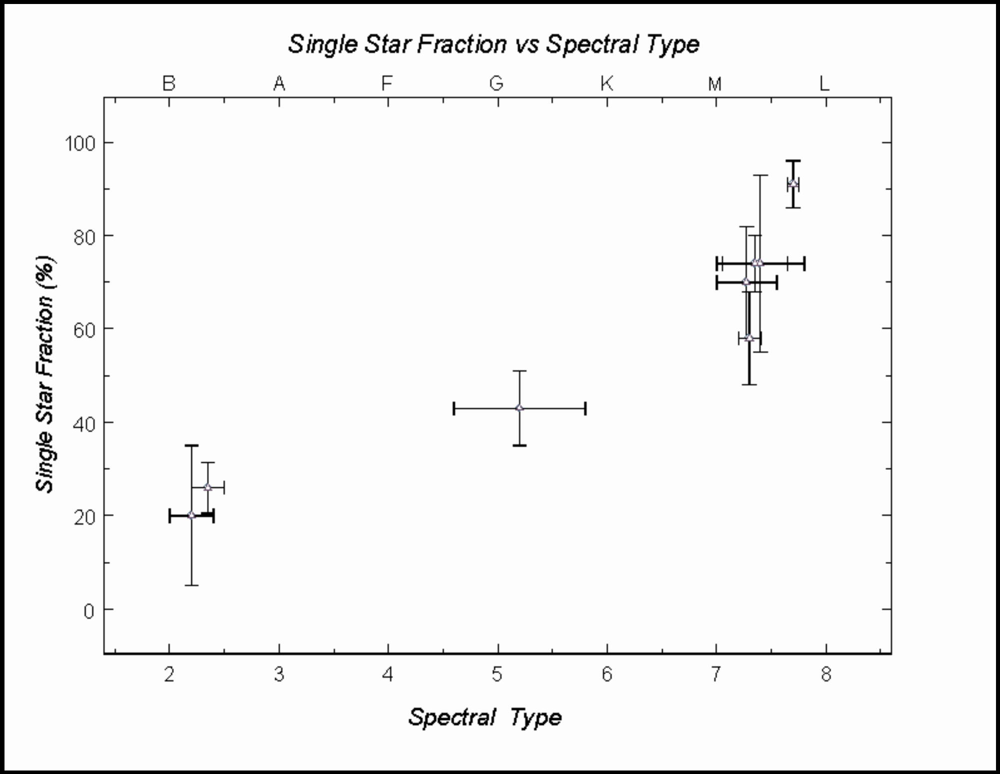
Fundamental Boundary Conditions

2- Stellar Multiplicity



Lada 2006

Beichman & Tanner

Fundamental Boundary Conditions

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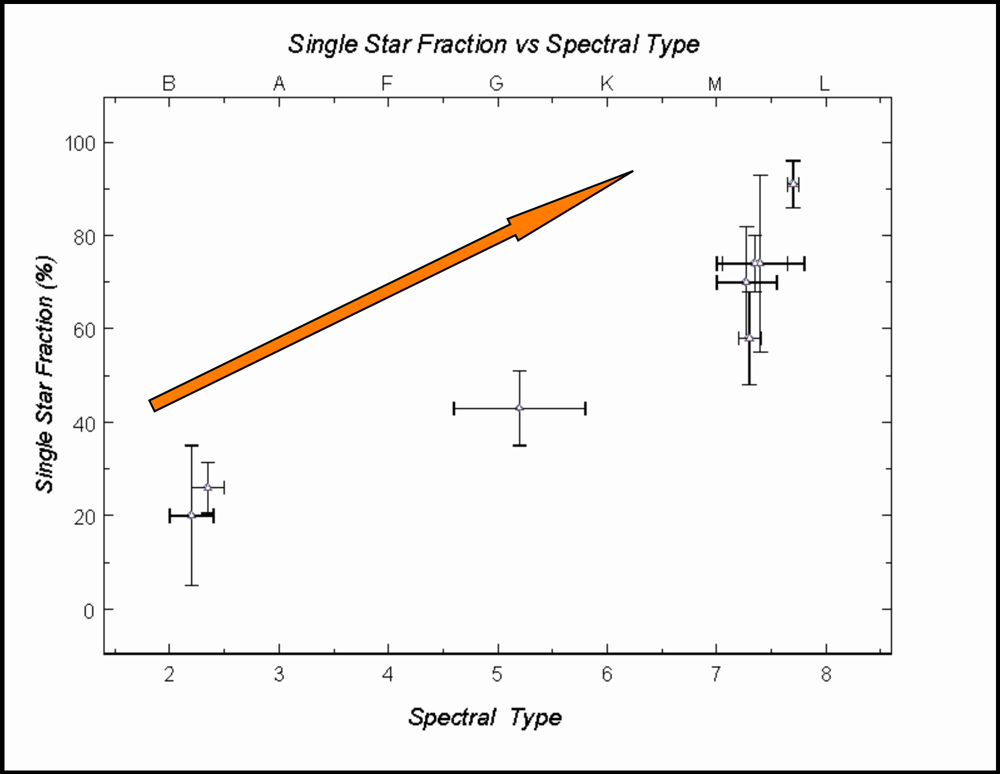

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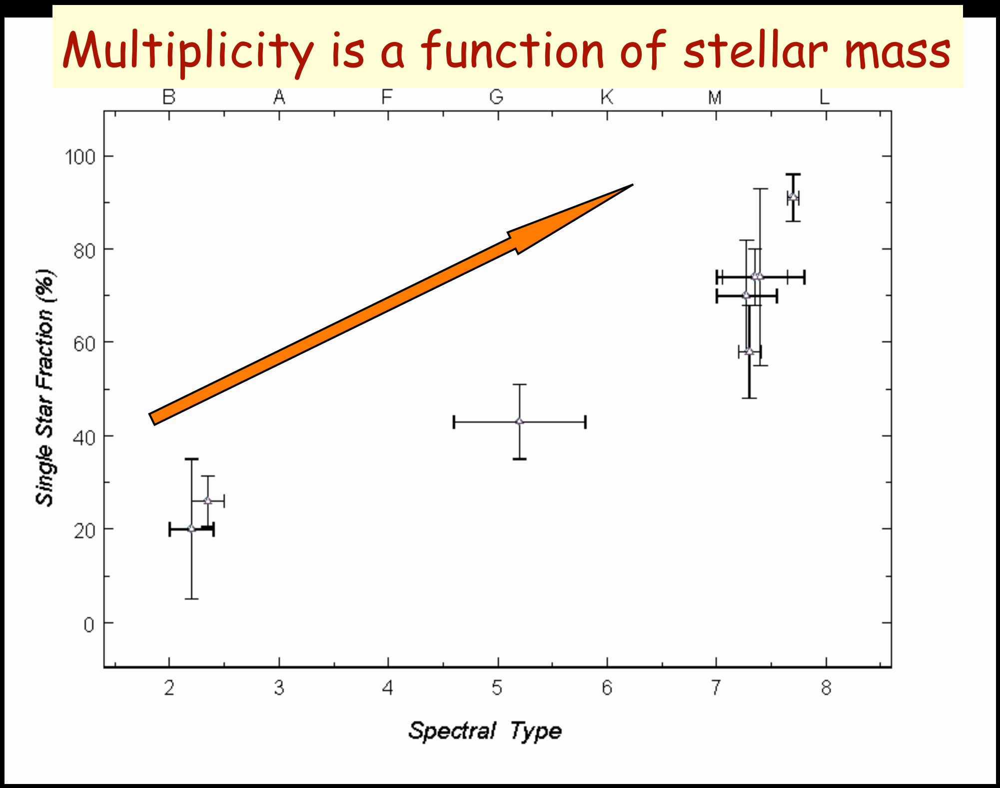

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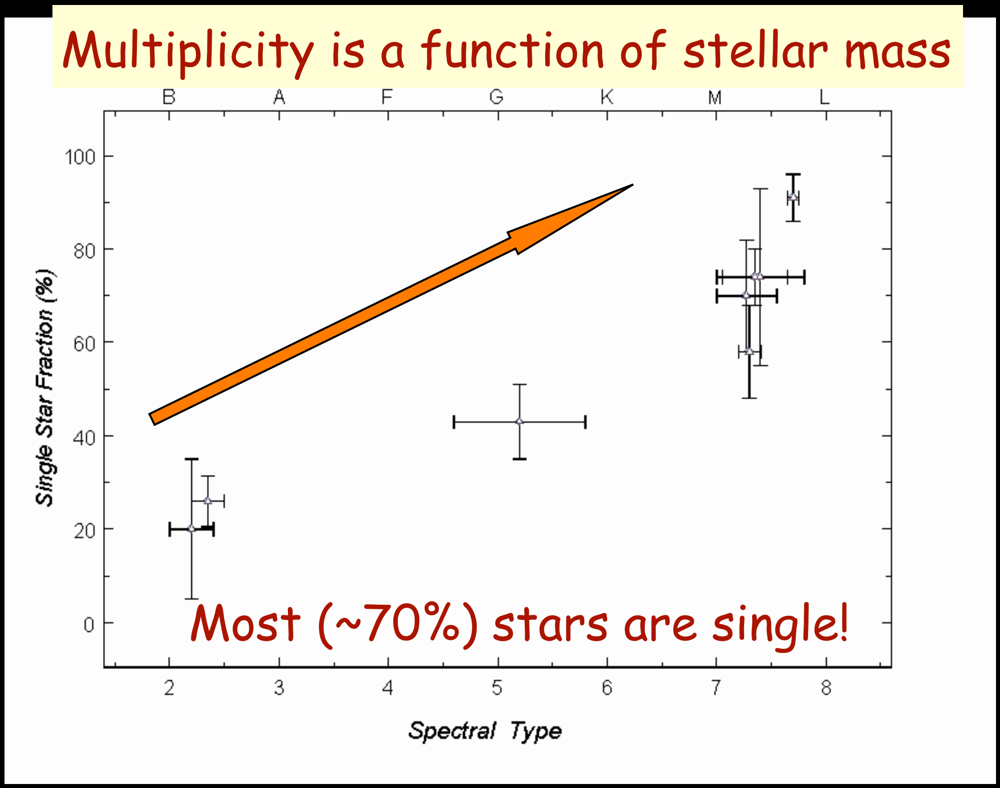


Lada 2006

Beichman & Tanner

Fundamental Boundary Conditions

2b- Primordial Stellar Clustering

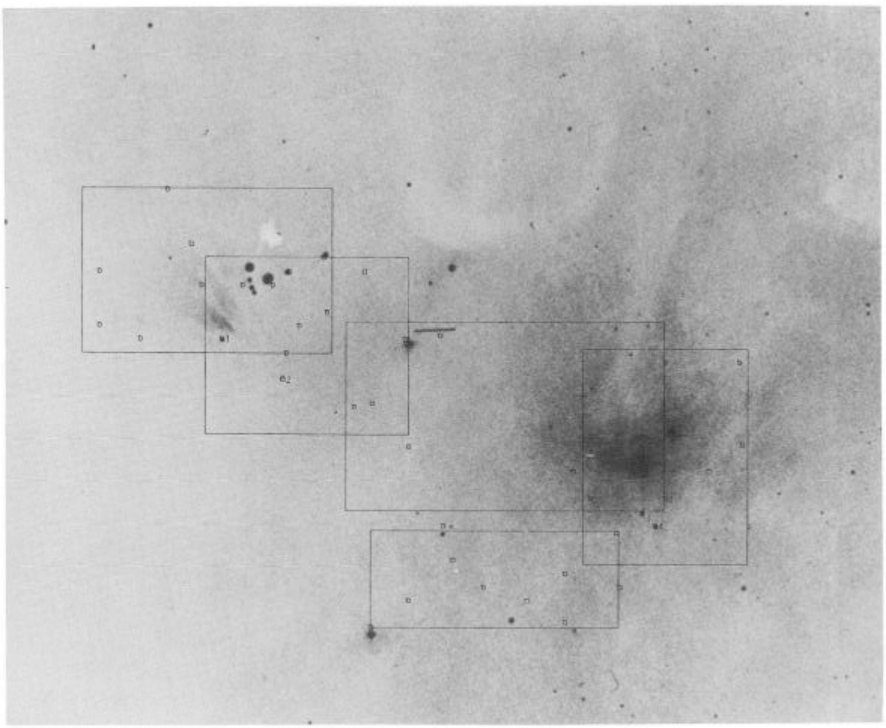


PLATE L1

FIG. 1.—The *Palomar Sky Survey* red plate of the region mapped at 2 μ with the positions of the infrared sources indicated. The scale is 13″ mm^{-1}. The size of the boxes indicating source positions is 9″. The beam size is 35″. The five larger boxes show the regions mapped on individual nights. North is to the top; east is to the left.

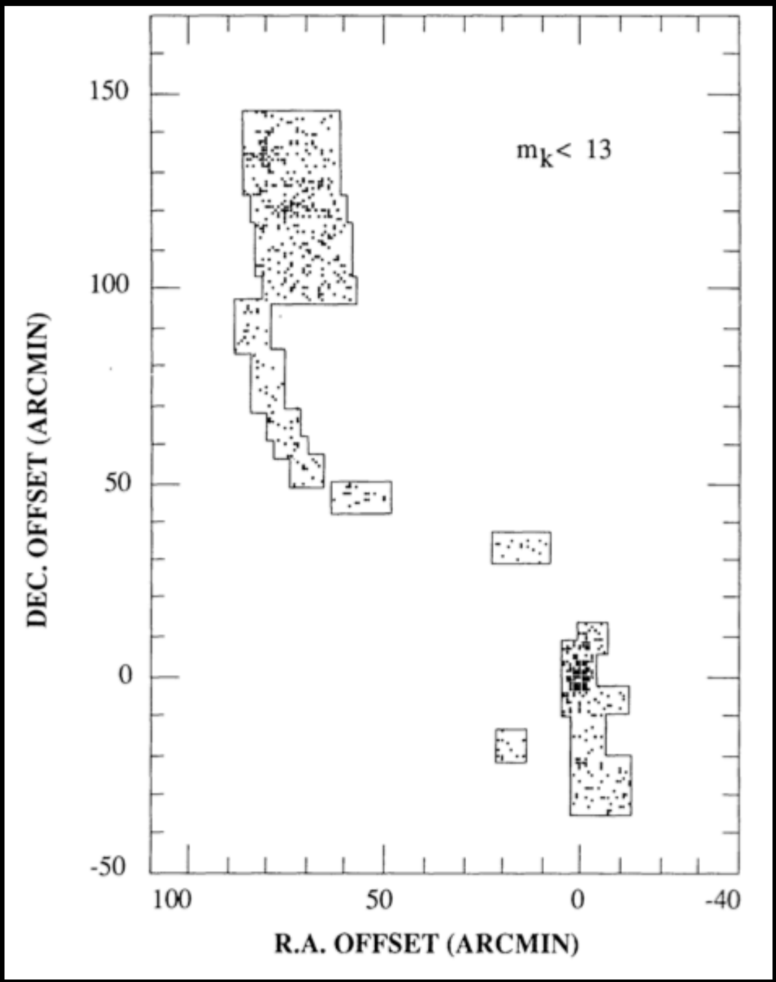
GRASDALEN *et al.* (*see* p. L53)

Grasdalen, Strom and Strom 1974

KPNO 50 inch

Fundamental Boundary Conditions

2b- Primordial Stellar Clustering



E. Lada, Depoy, Evans & Gatley 1991

KPNO 50 inch

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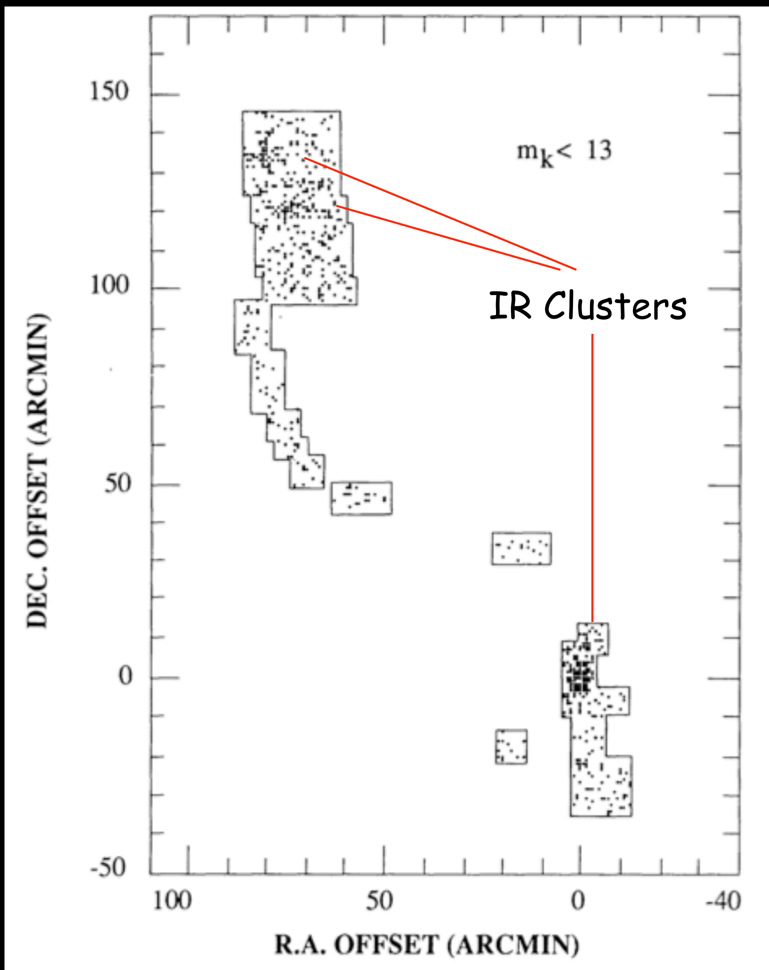

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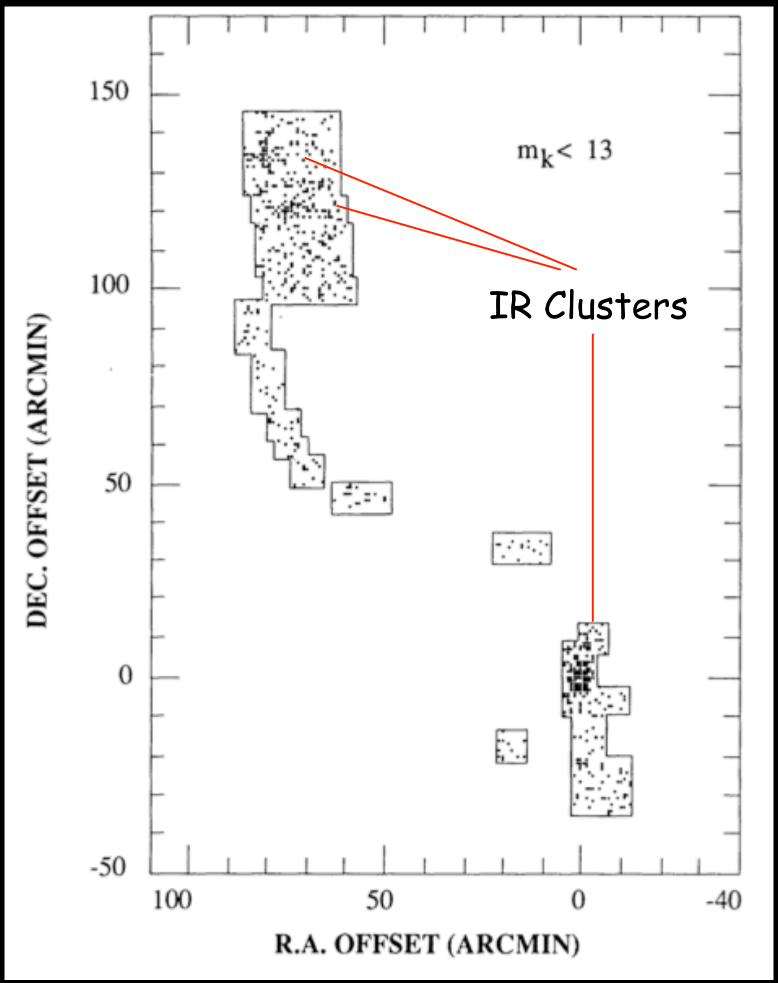

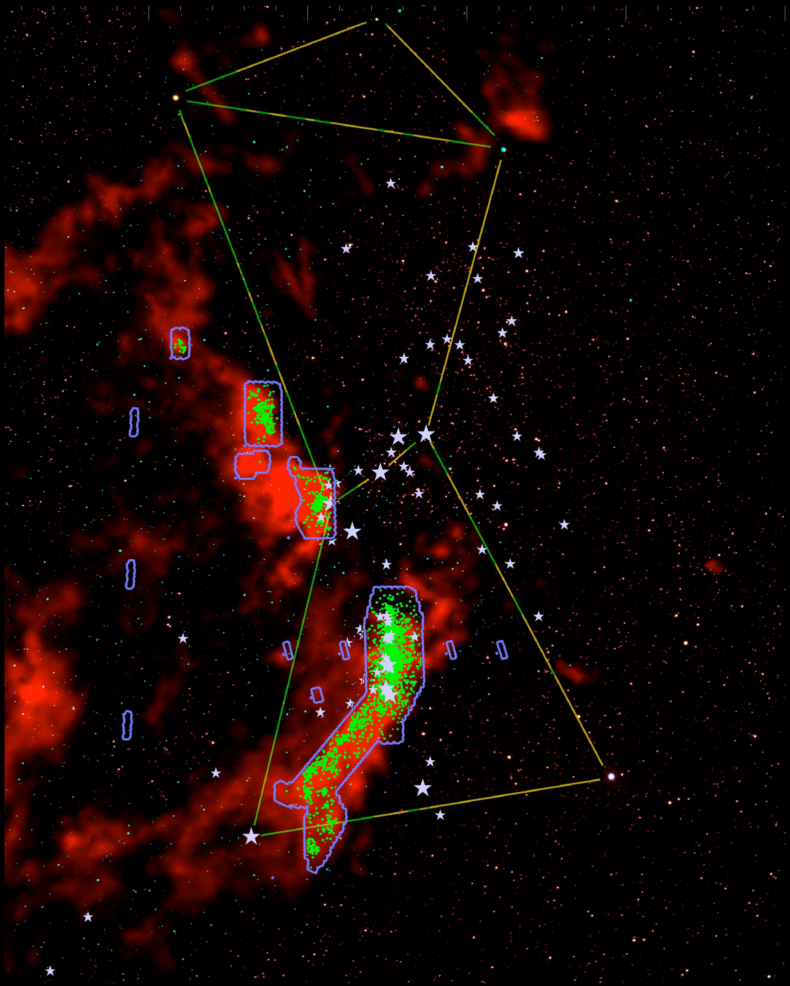

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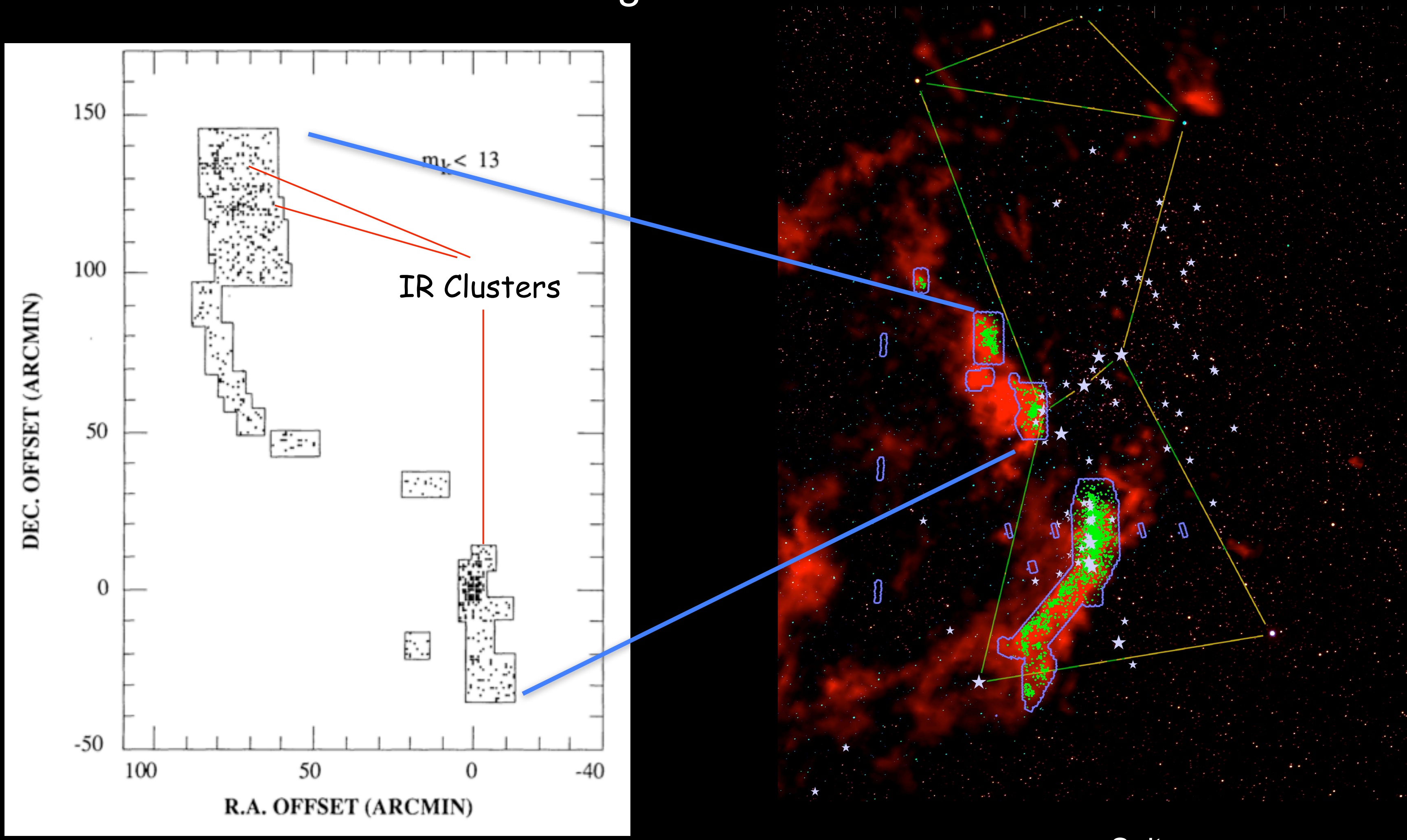
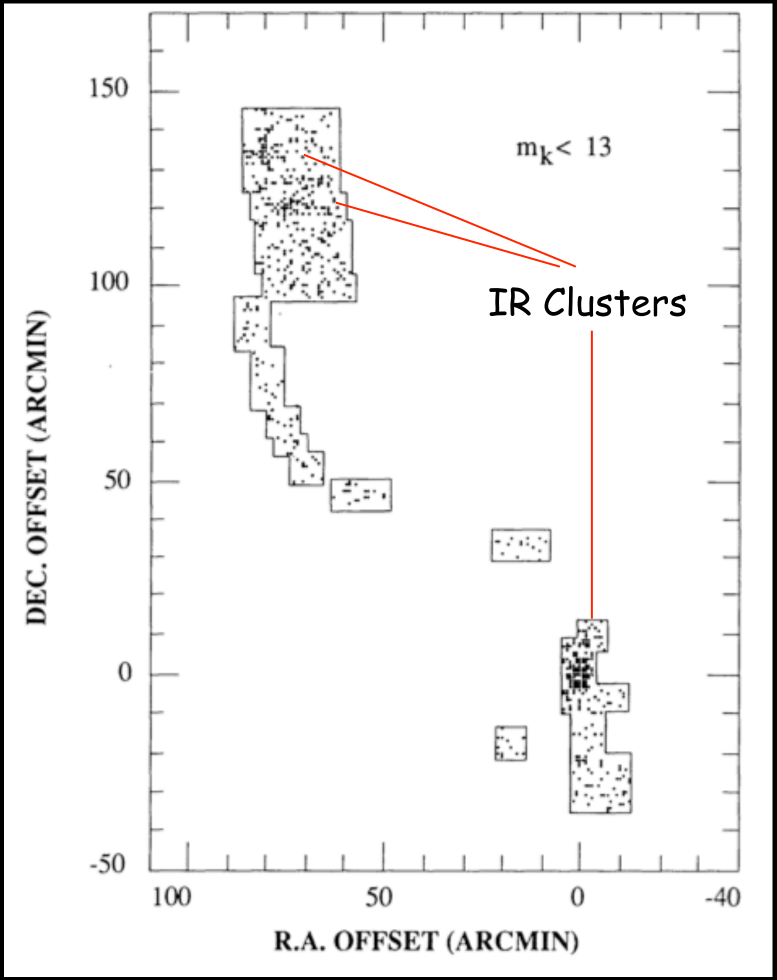


E. Lada, Depoy, Evans & Gatley 1991

Spitzer survey
Megeath et al. 2010

Fundamental Boundary Conditions

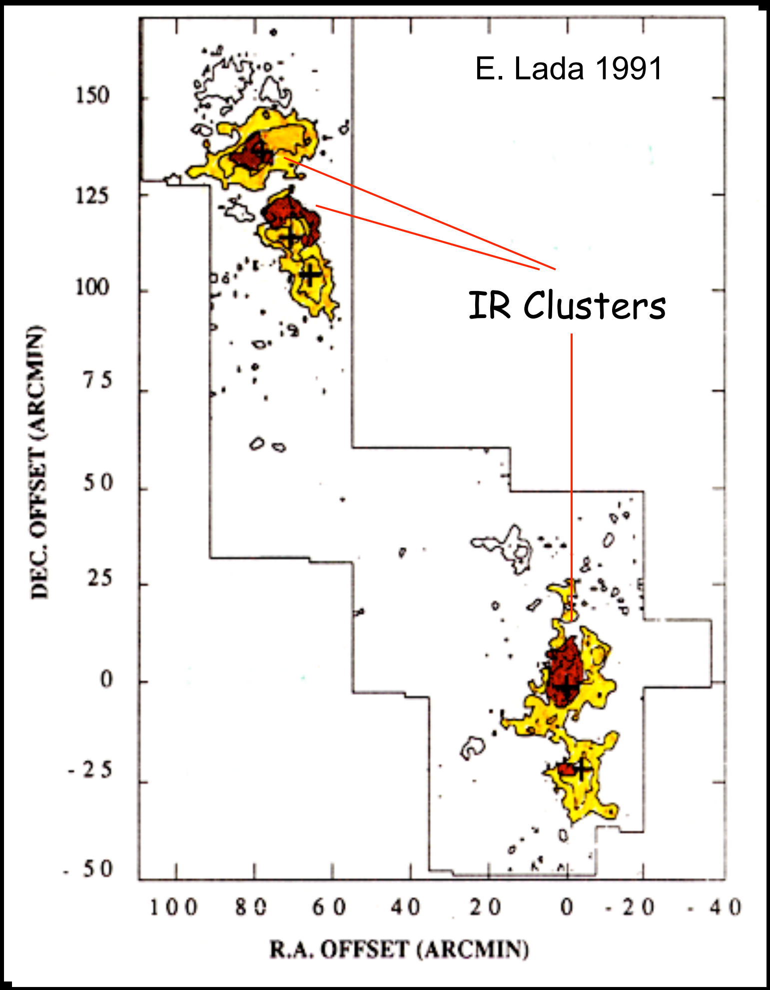
2b- Primordial Stellar Clustering



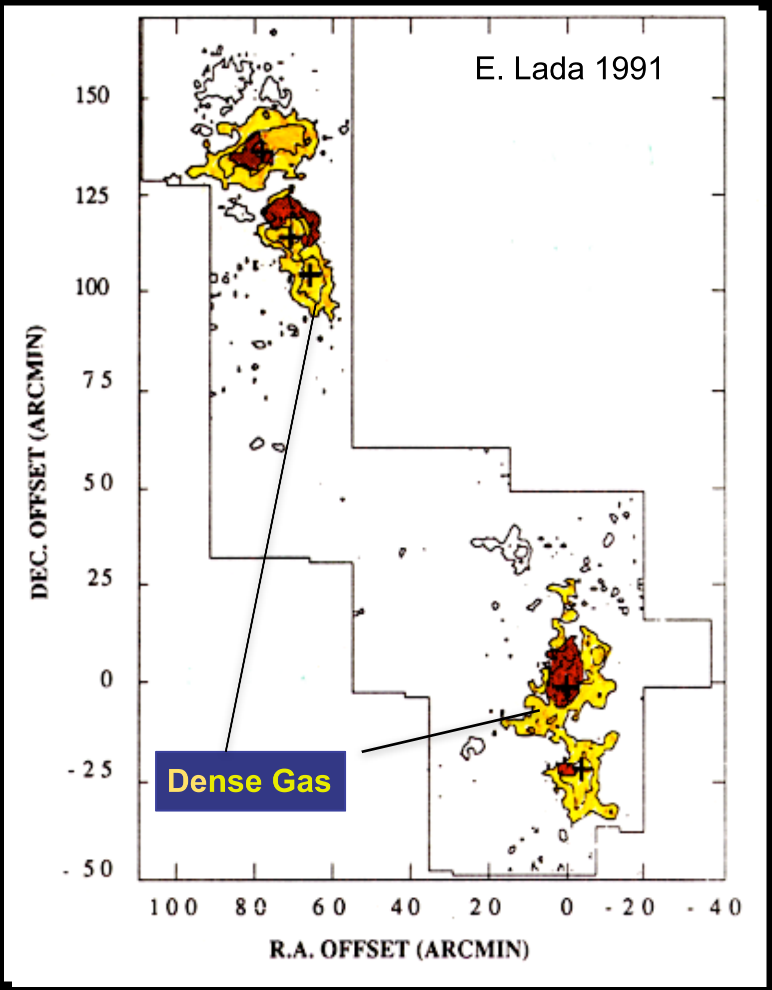
E. Lada, Depoy, Evans & Gatley 1991

INITIAL CONDITIONS

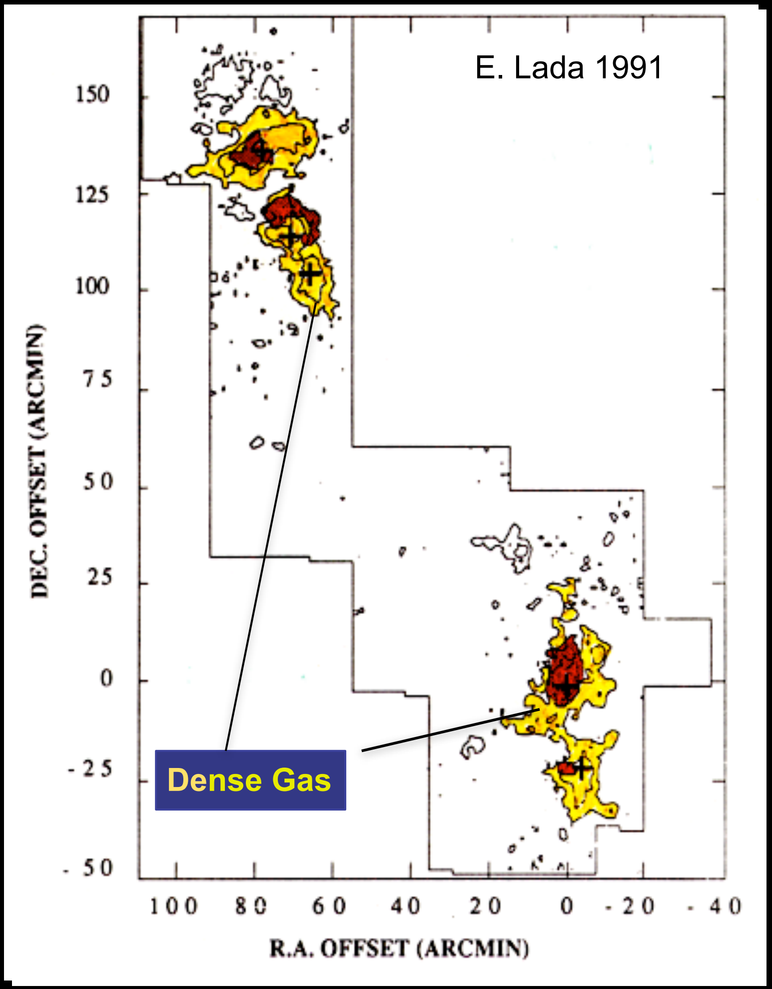
Initial Conditions



Initial Conditions



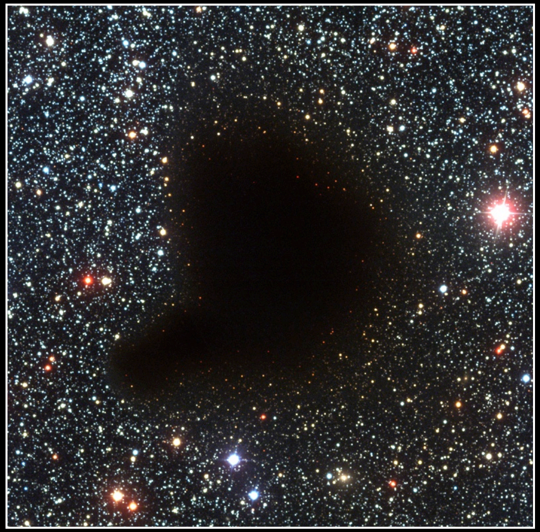
Initial Conditions

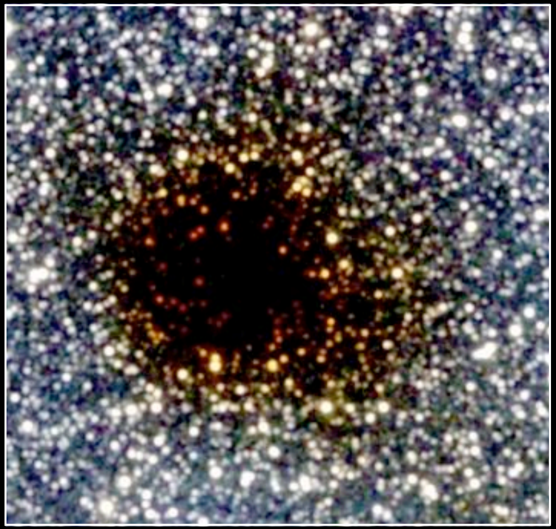


Star formation confined to relatively dense (>10^4 cm^{-3}) gas (A_V > 10 mag).

Initial Conditions

Stars form in Dense, Dark Cloud Cores

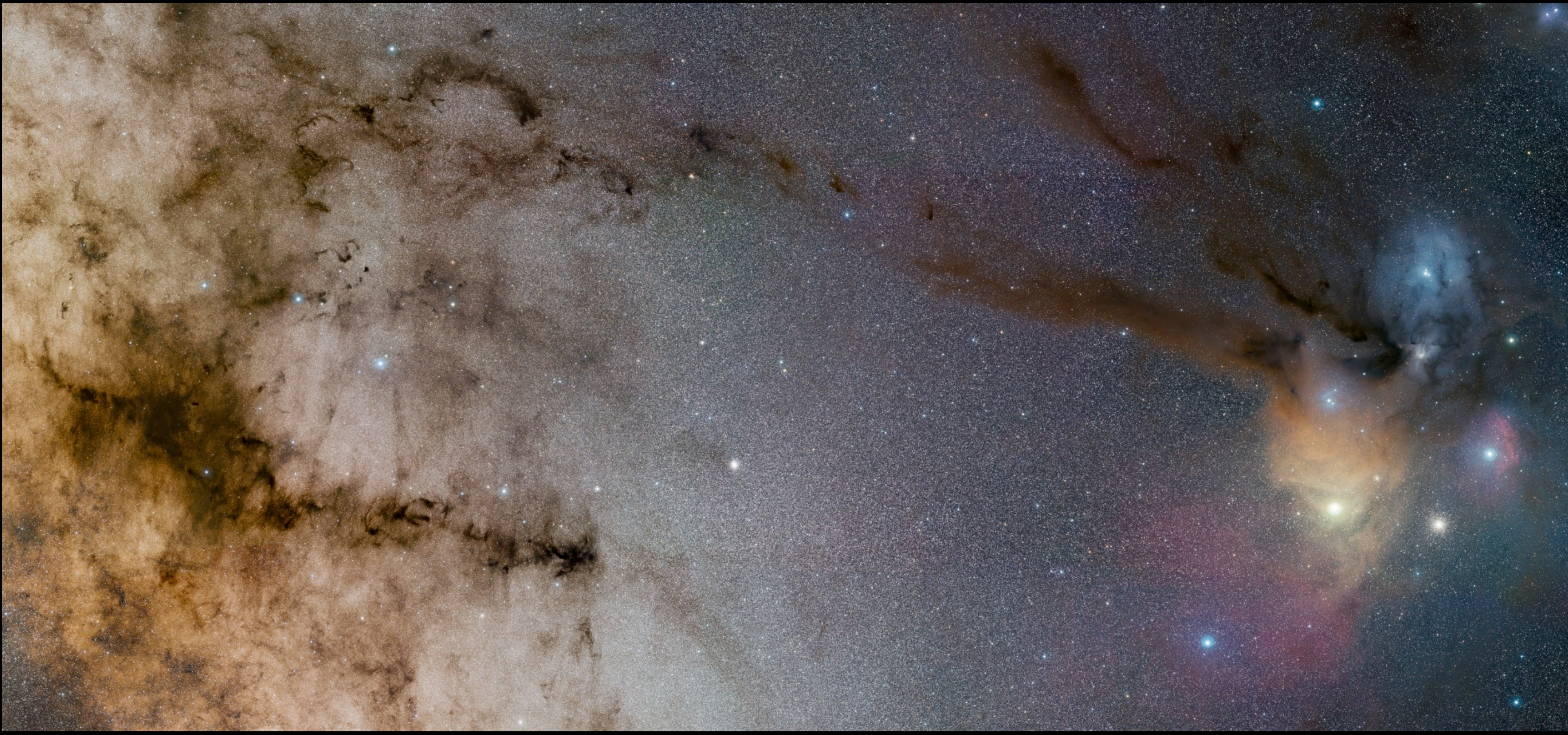


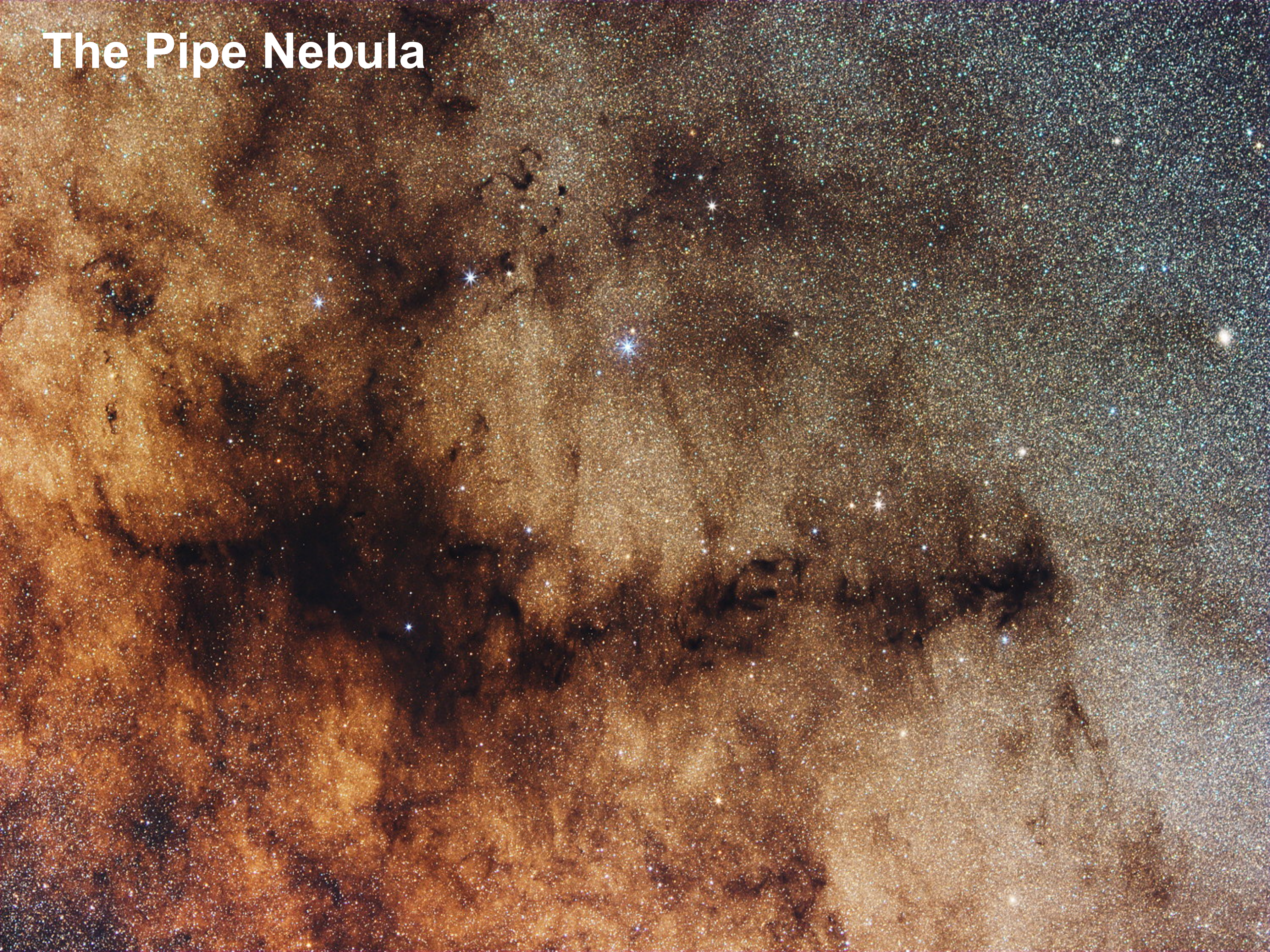


Initial Conditions = Basic physical properties of <u>starless</u> cores:

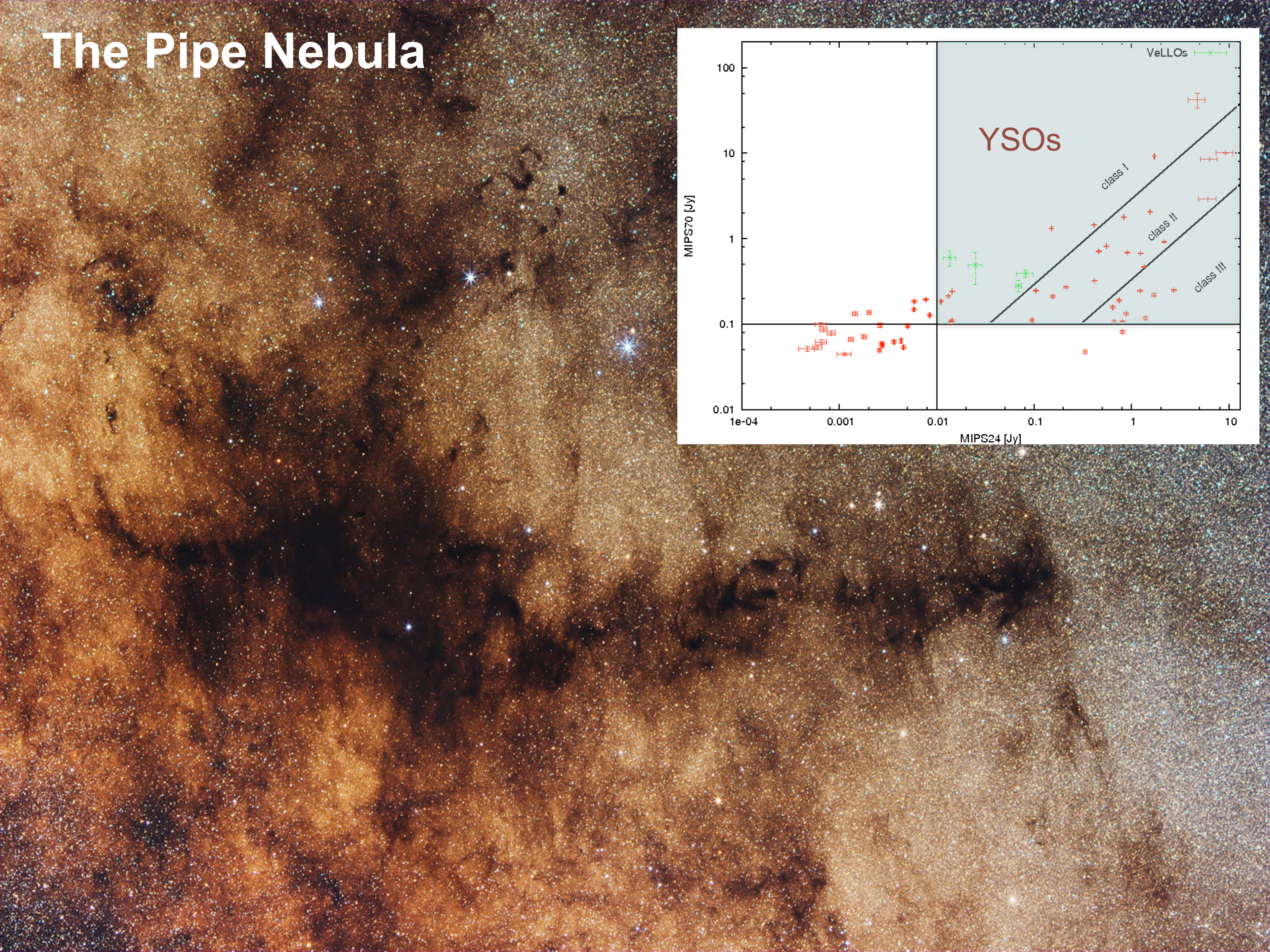
mass, size, temperature density, pressure, kinematics

Initial Conditions

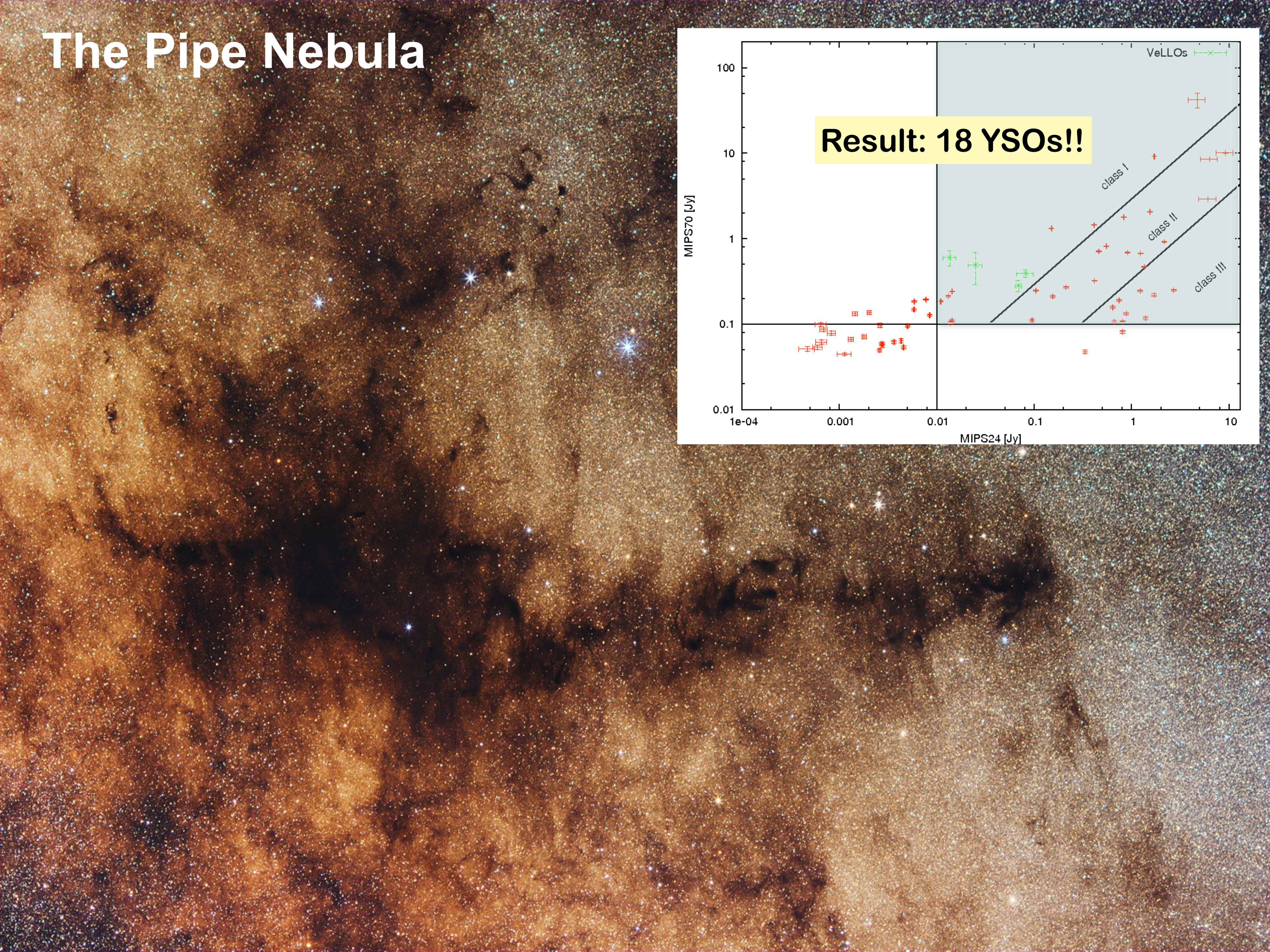



The Pipe Nebula

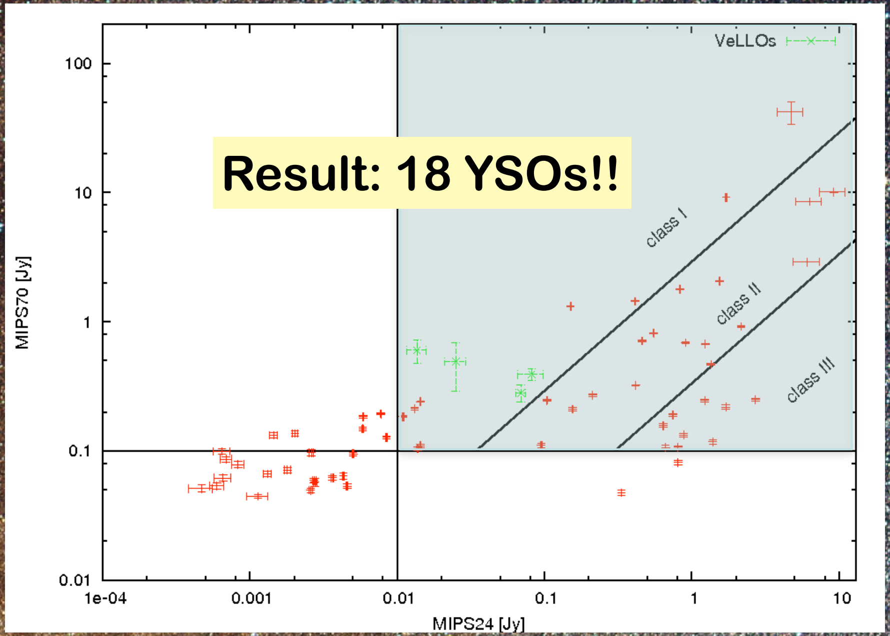
The Pipe Nebula

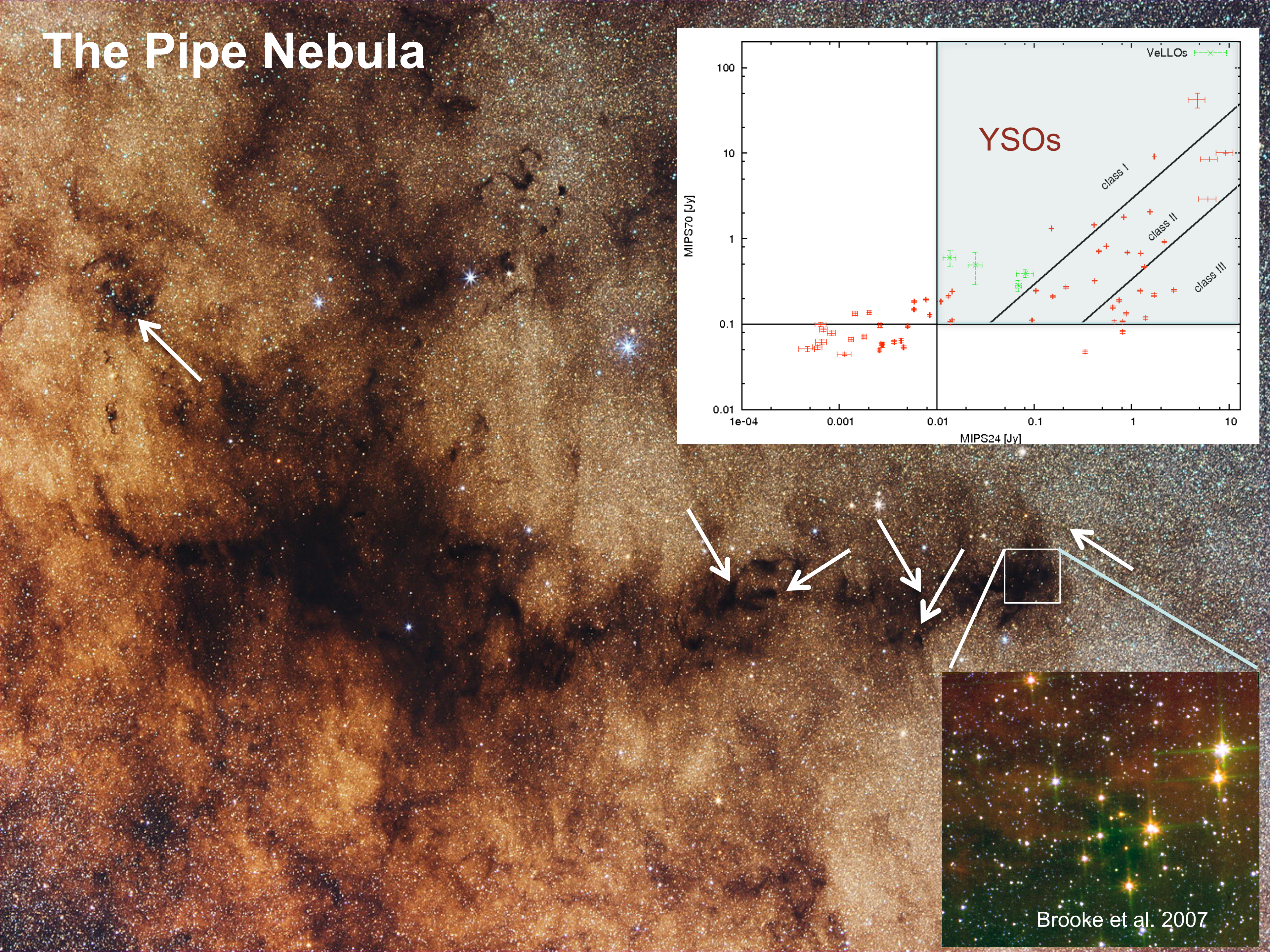


The Pipe Nebula



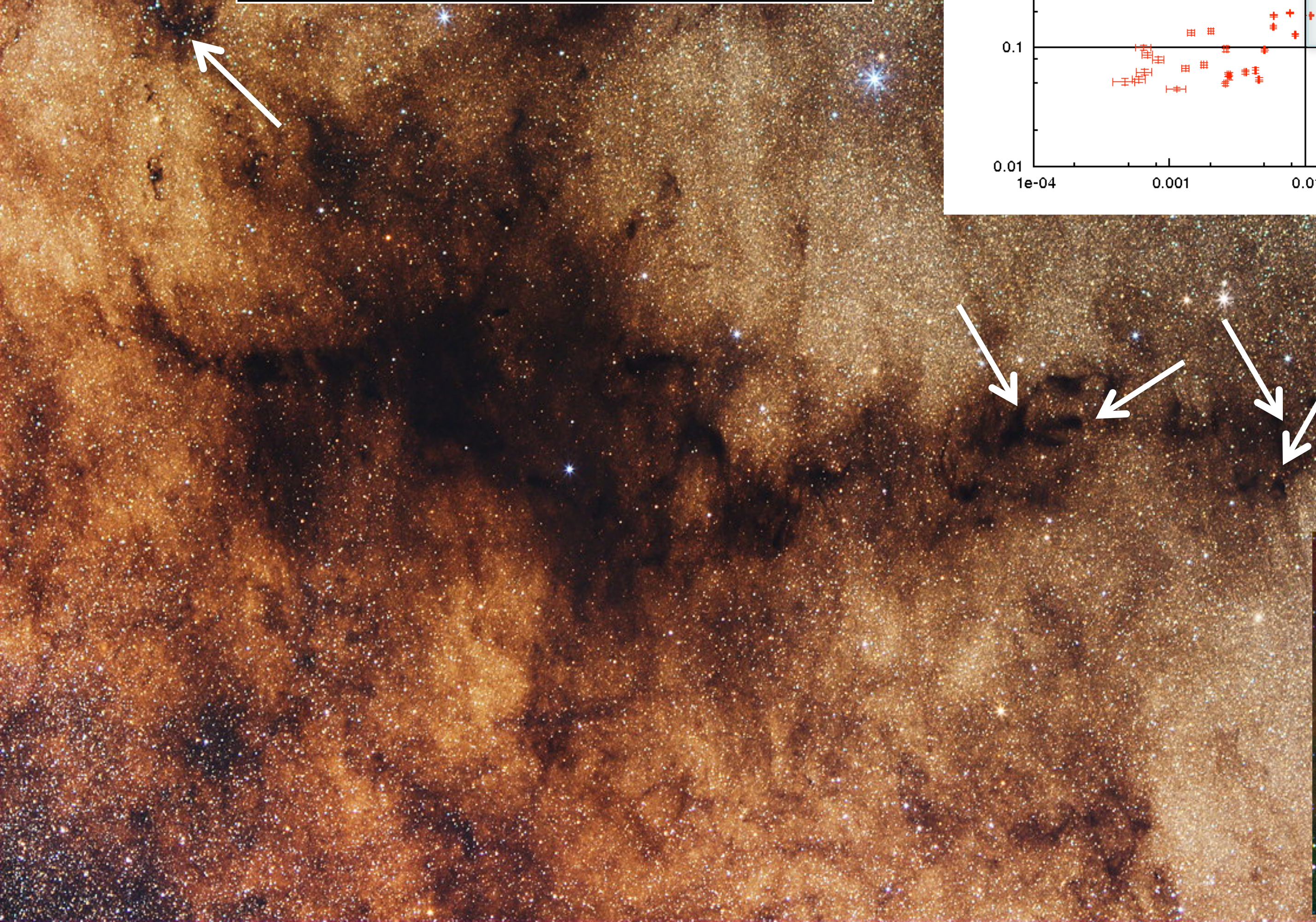
The Pipe Nebula

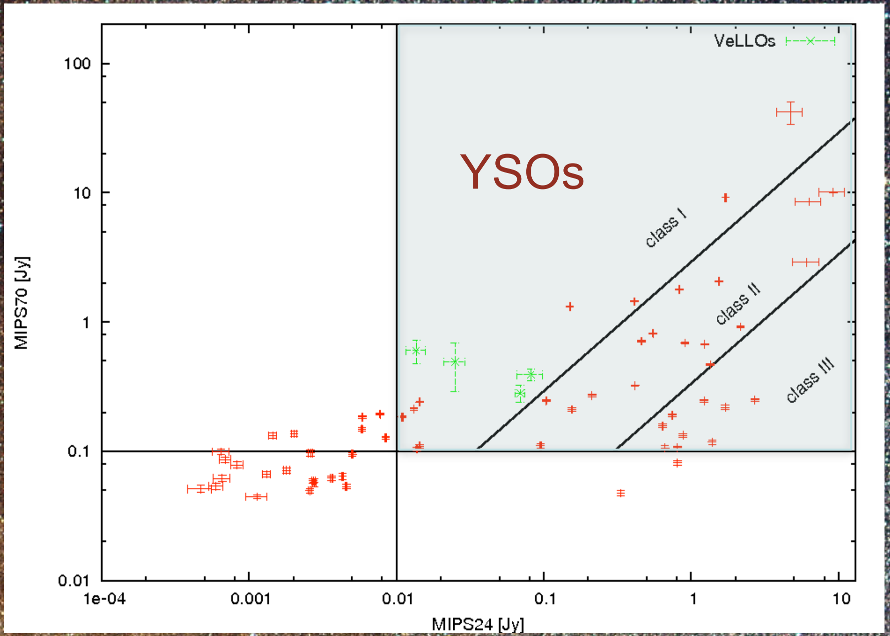



The Pipe Nebula
VeLLOs
100
10
1
0.1
0.01
1e-04
0.001
0.01
0.1
1
10
MIPS70 [Jy]
MIPS24 [Jy]
YSOs
class I
class II
class III
Brooke et al. 2007

The Pipe Nebula

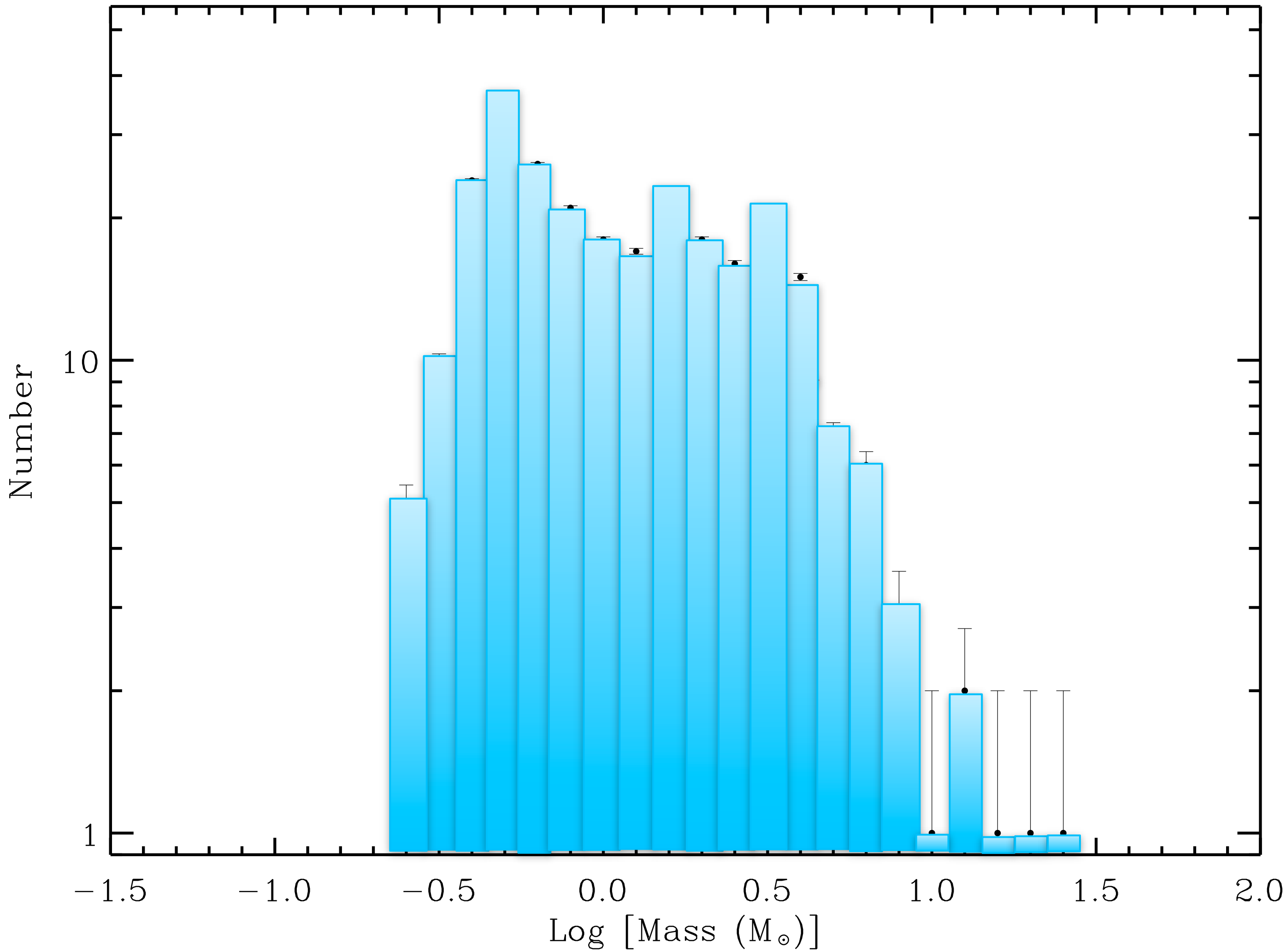
Overall star formation activity is insignificant, confined to 0.1 % of the total gaseous mass.





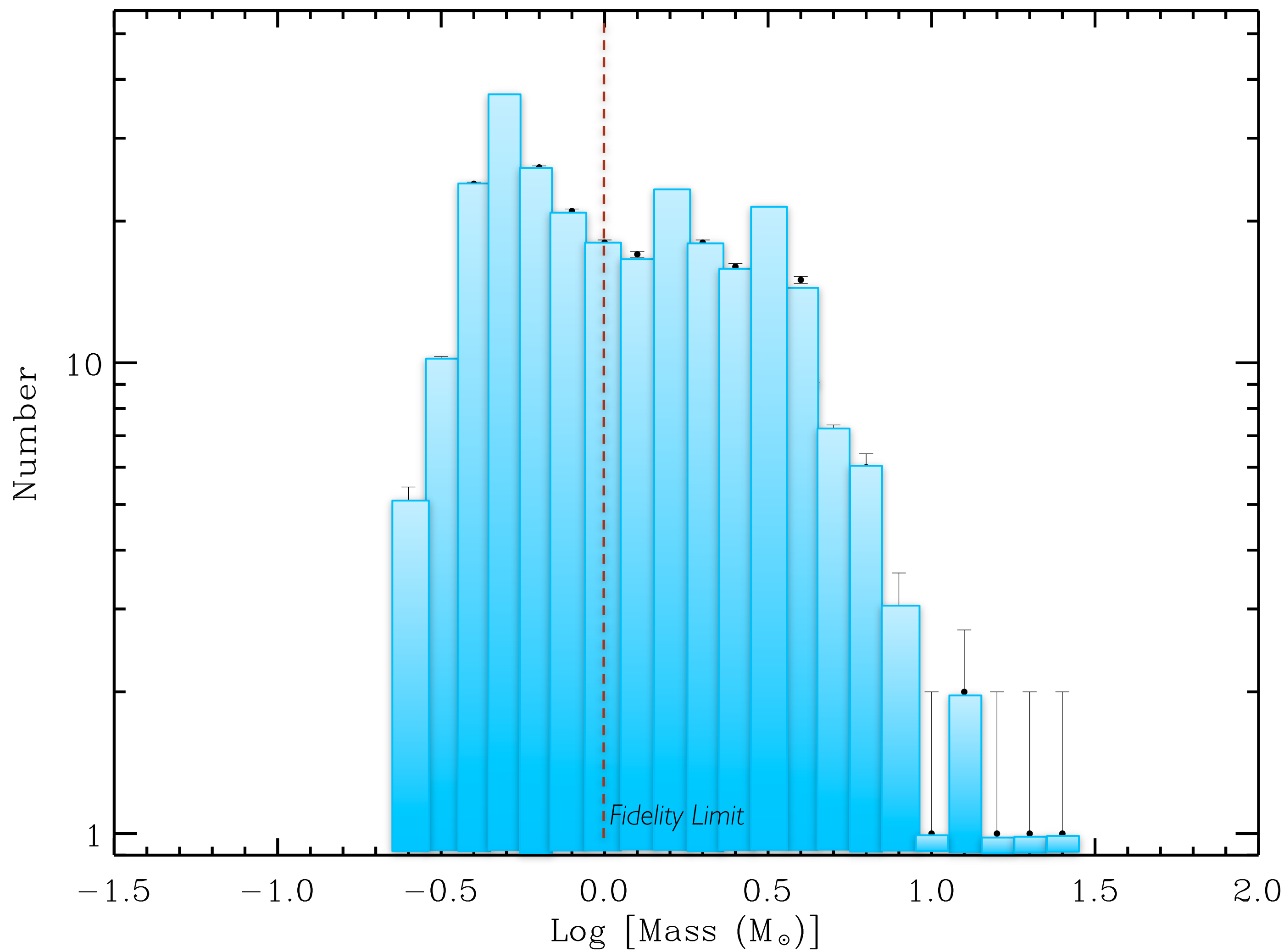
Brooke et al. 2007

Distribution of core masses (139 cores)



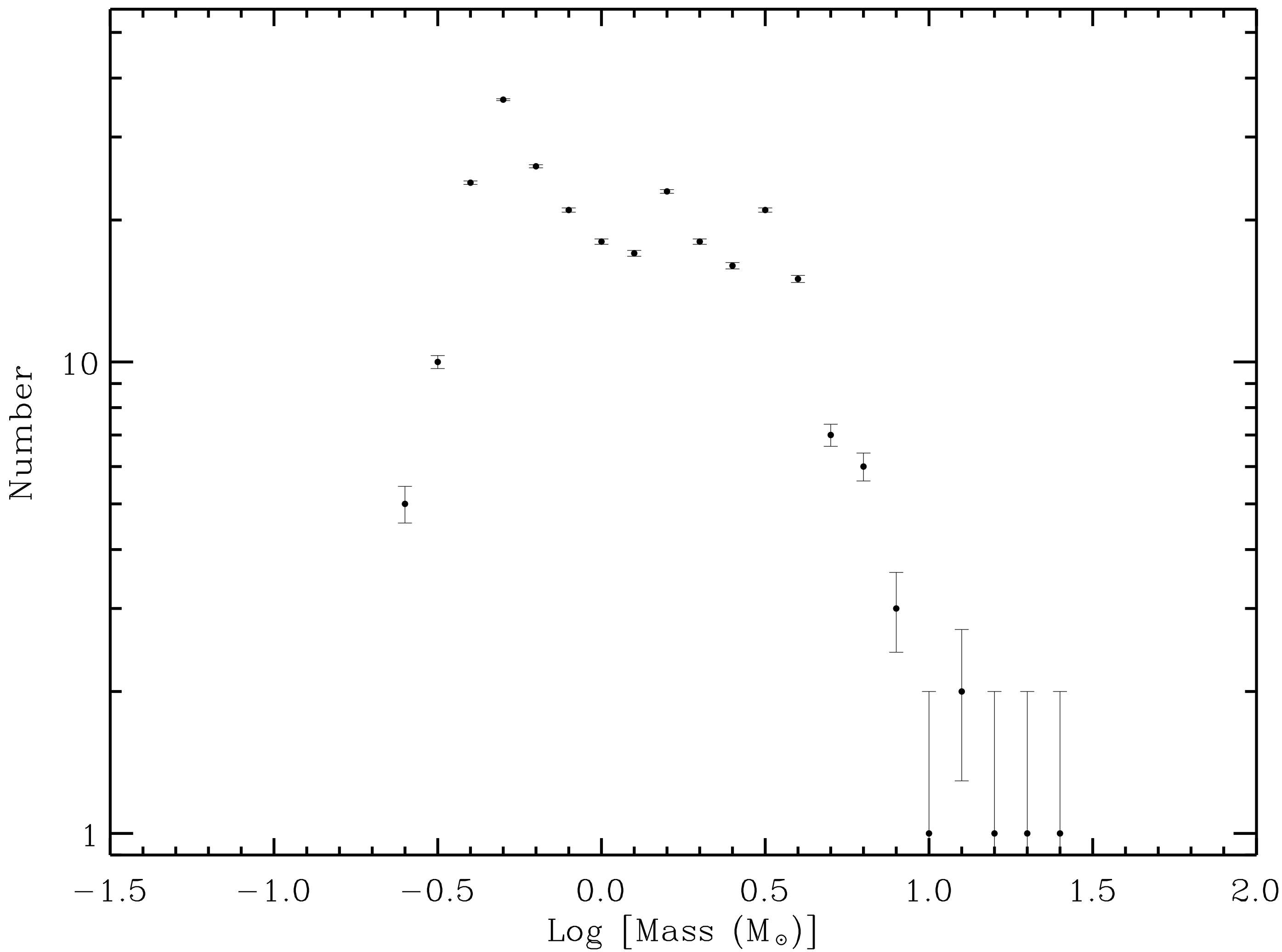
Alves, Lombardi, Lada 2007; Rathborne et al. 2008

Distribution of core masses (139 cores)



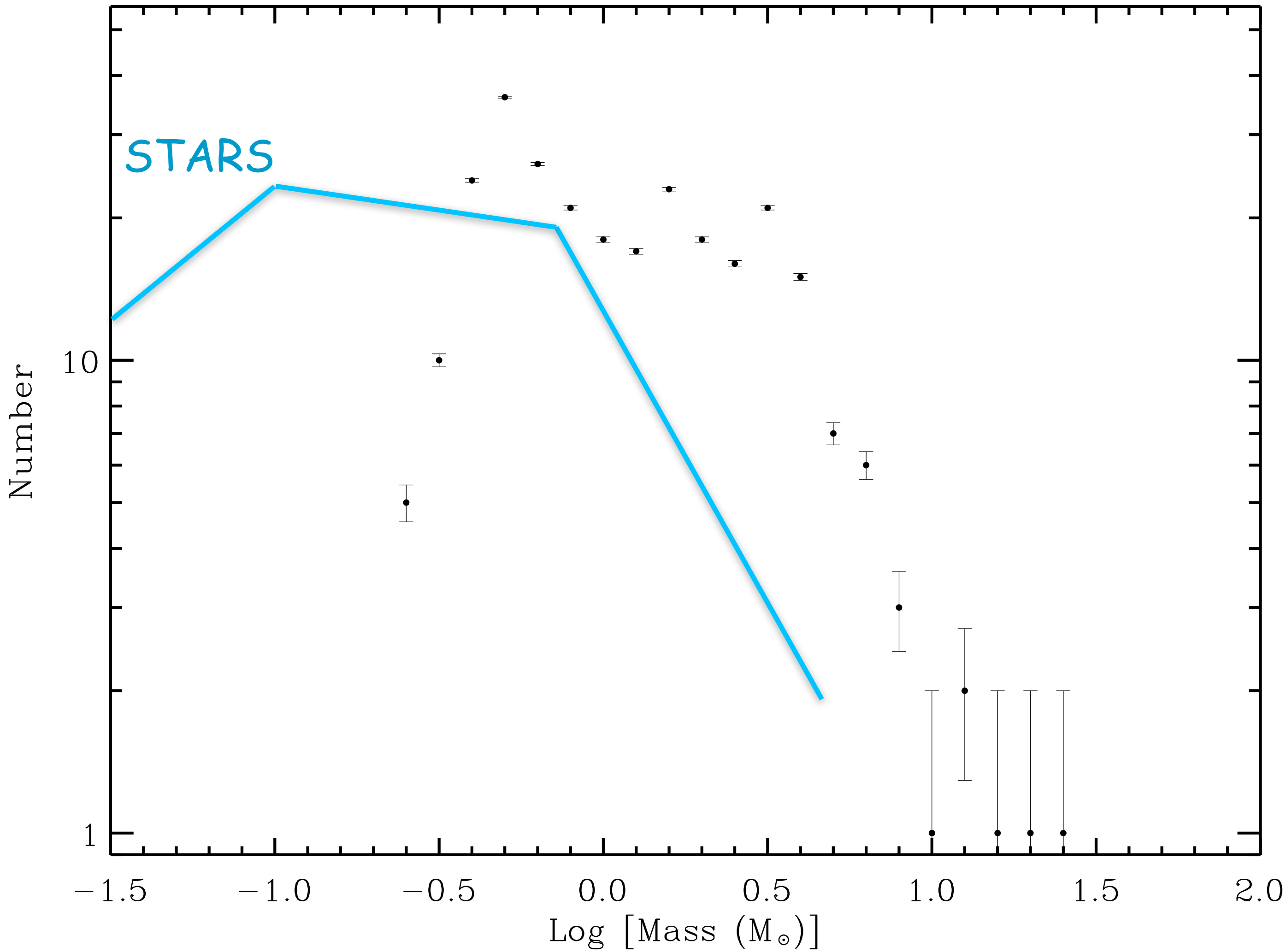
Alves, Lombardi, Lada 2007; Rathborne et al. 2008

Distribution of core masses (139 cores)



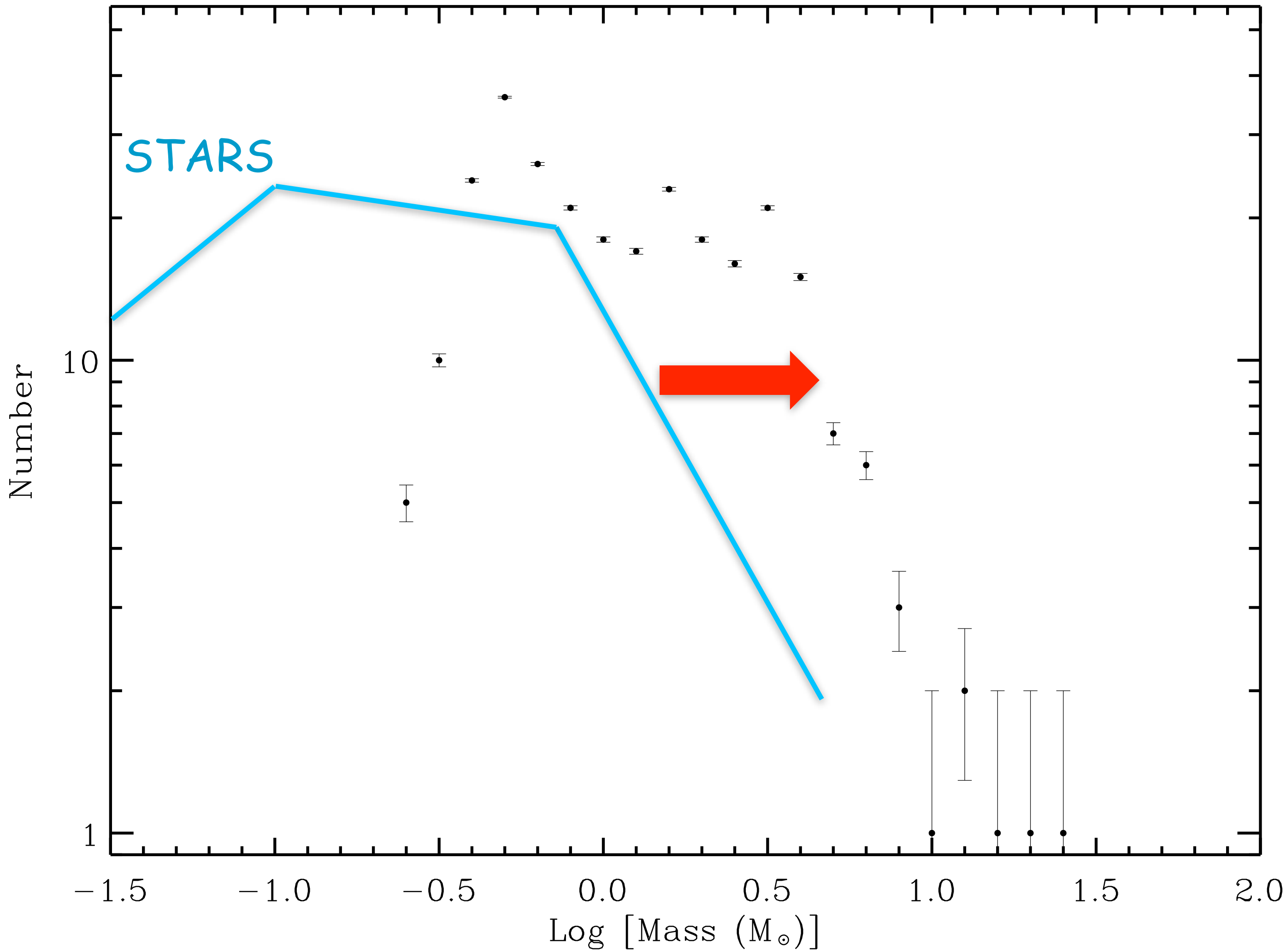
Alves, Lombardi, Lada 2007; Rathborne et al. 2008

Distribution of core masses (139 cores)



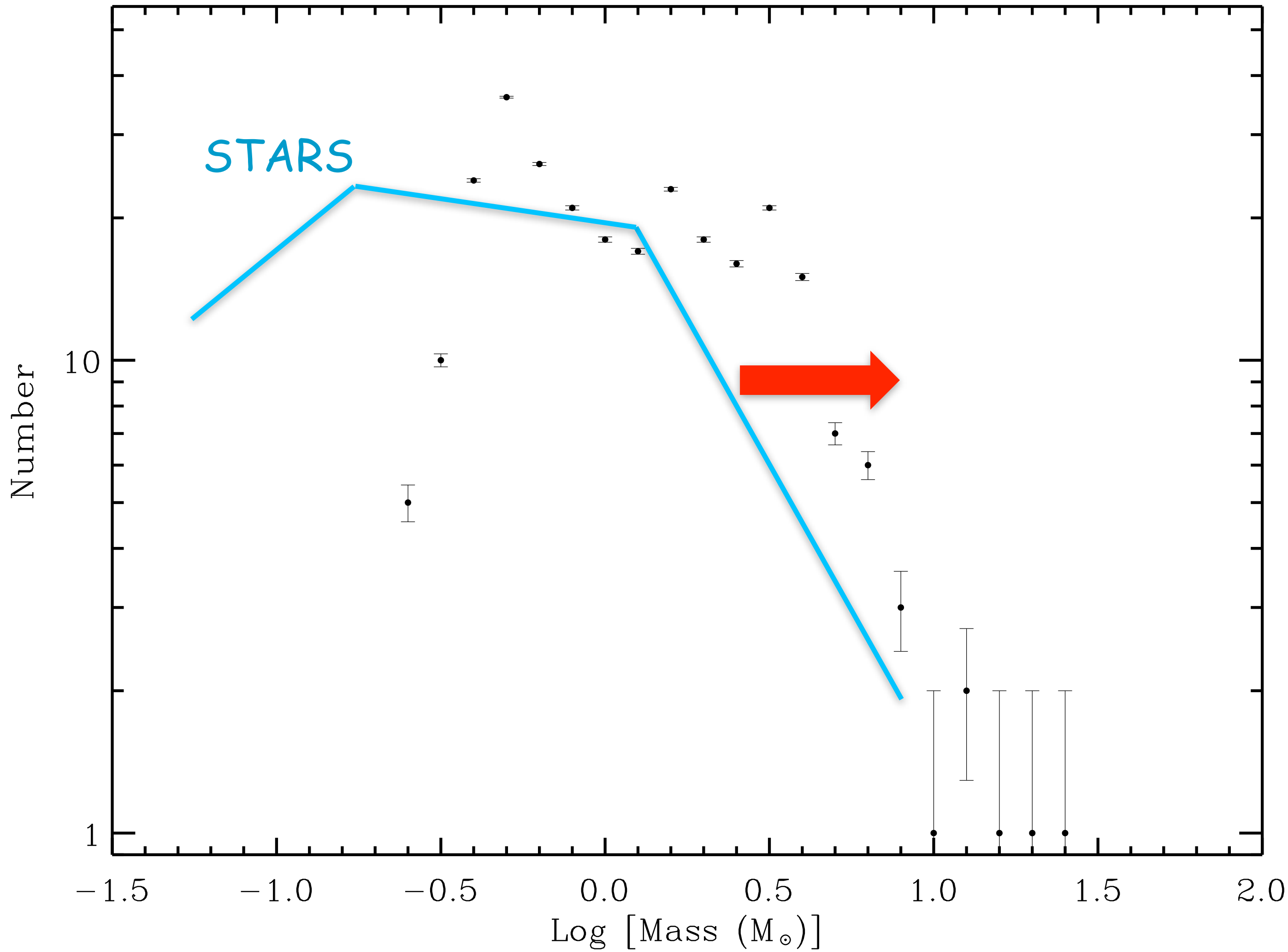
Alves, Lombardi, Lada 2007; Rathborne et al. 2008

Distribution of core masses (139 cores)



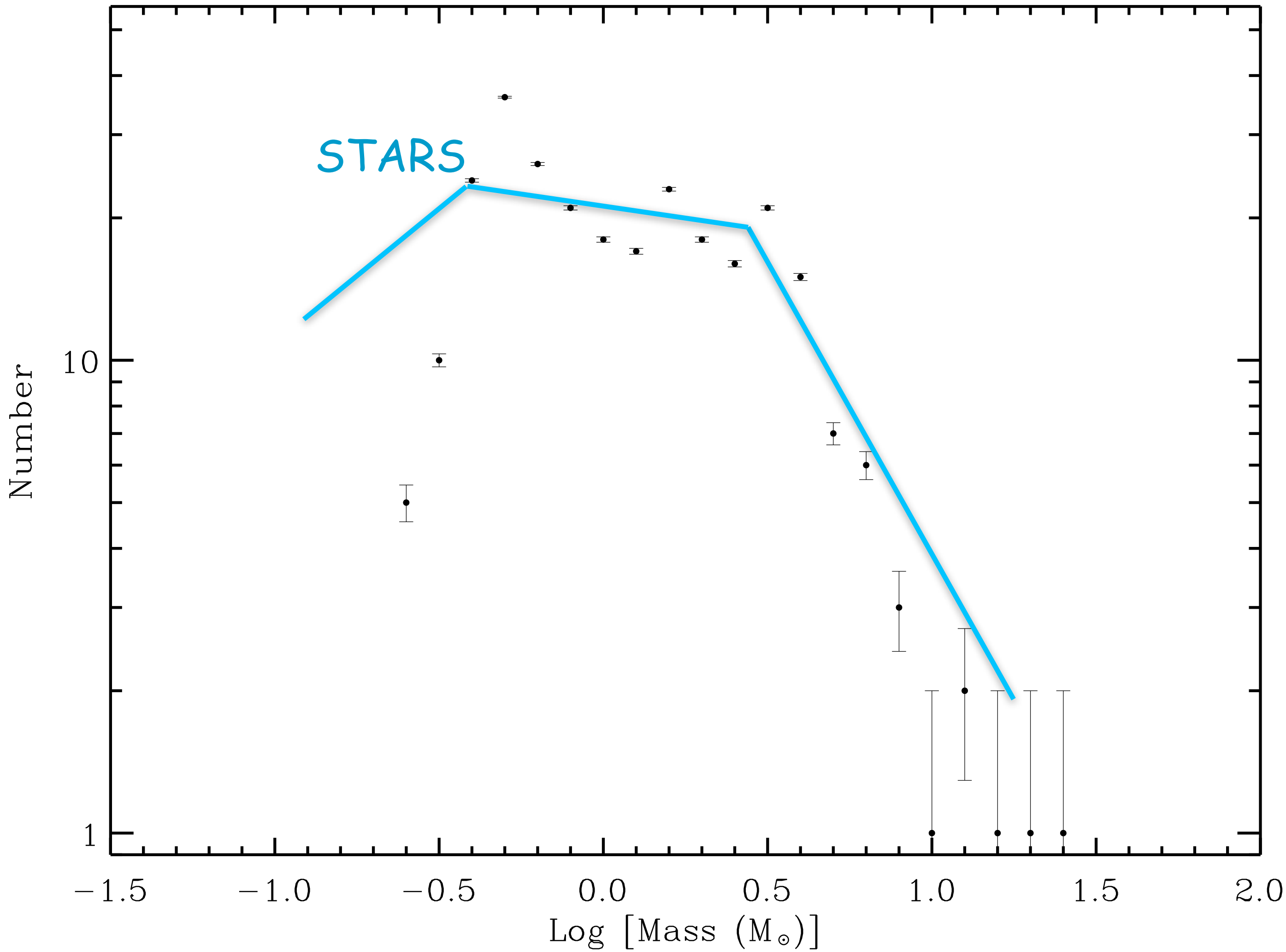
Alves, Lombardi, Lada 2007; Rathborne et al. 2008

Distribution of core masses (139 cores)



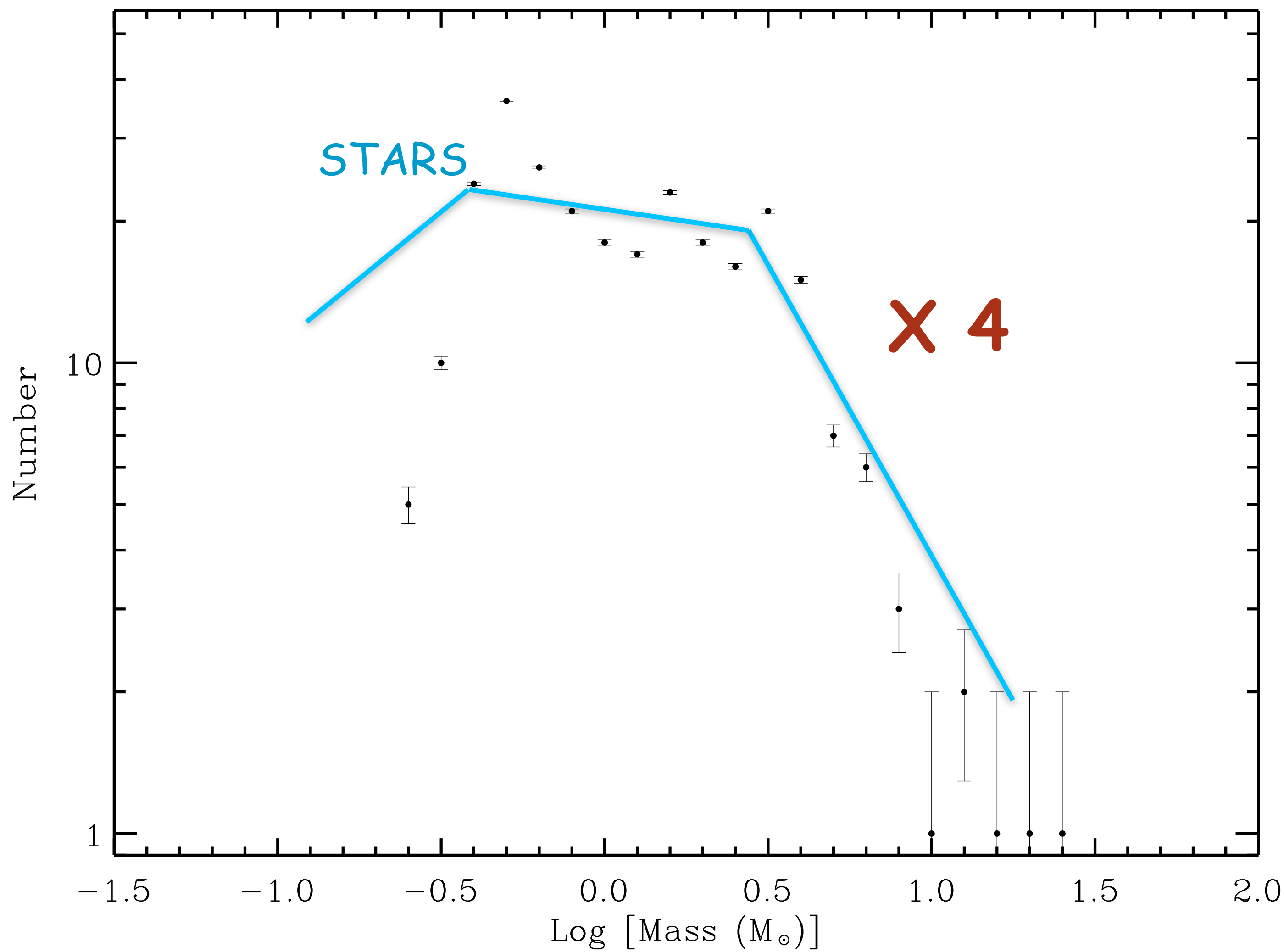
Alves, Lombardi, Lada 2007; Rathborne et al. 2008

Distribution of core masses (139 cores)



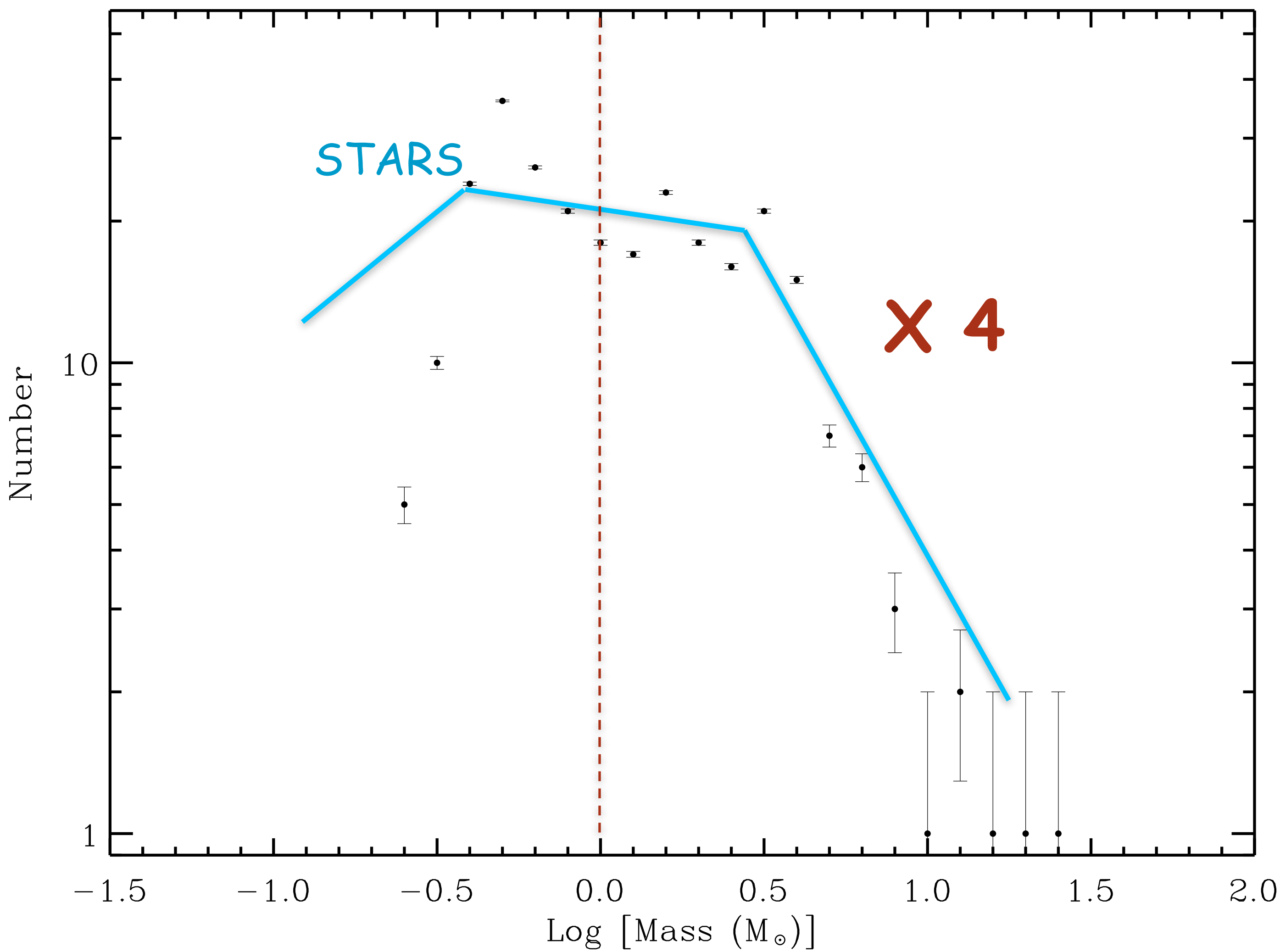
Alves, Lombardi, Lada 2007; Rathborne et al. 2008

Distribution of core masses (139 cores)



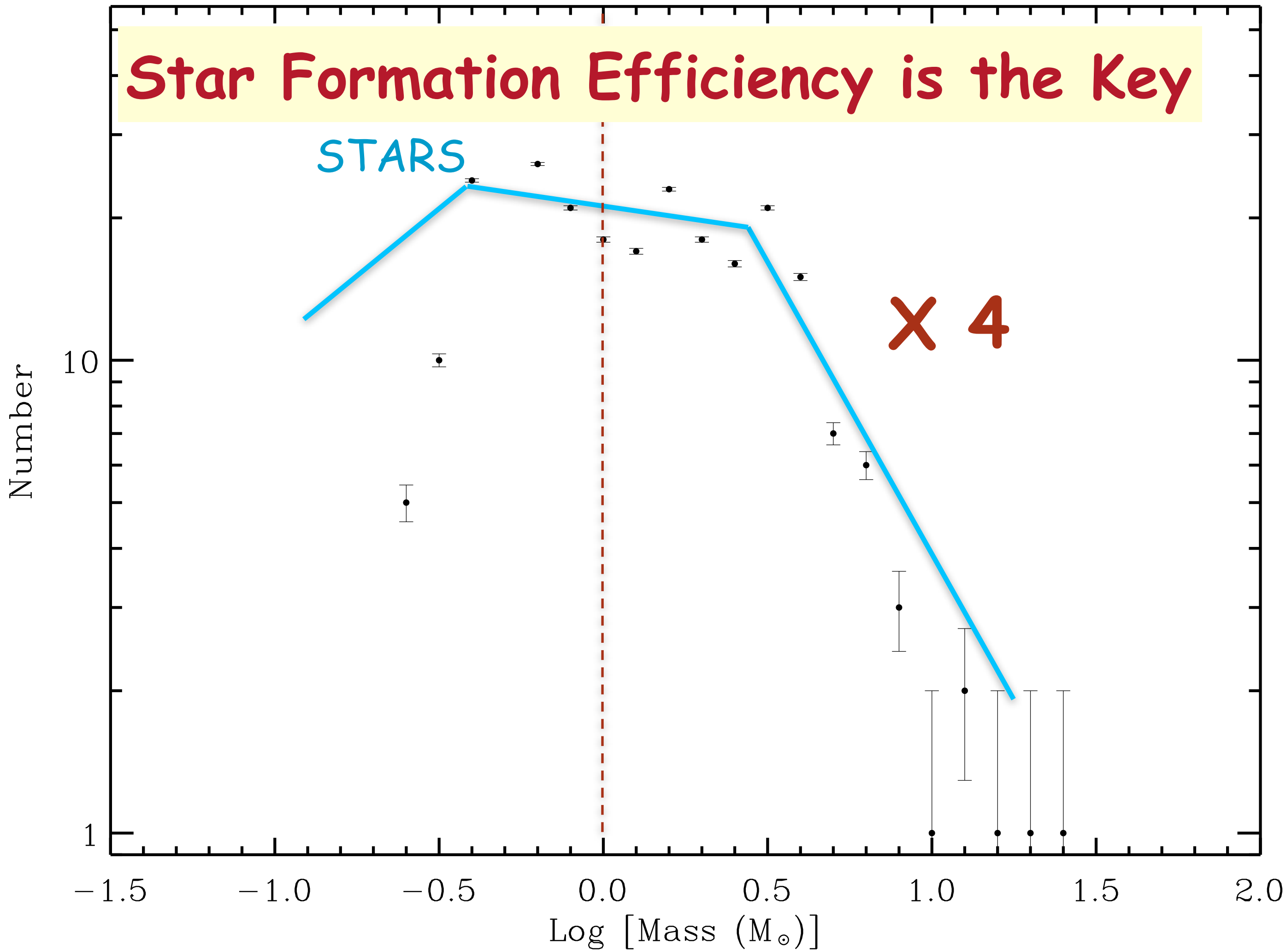
Alves, Lombardi, Lada 2007; Rathborne et al. 2008

Distribution of core masses (139 cores)



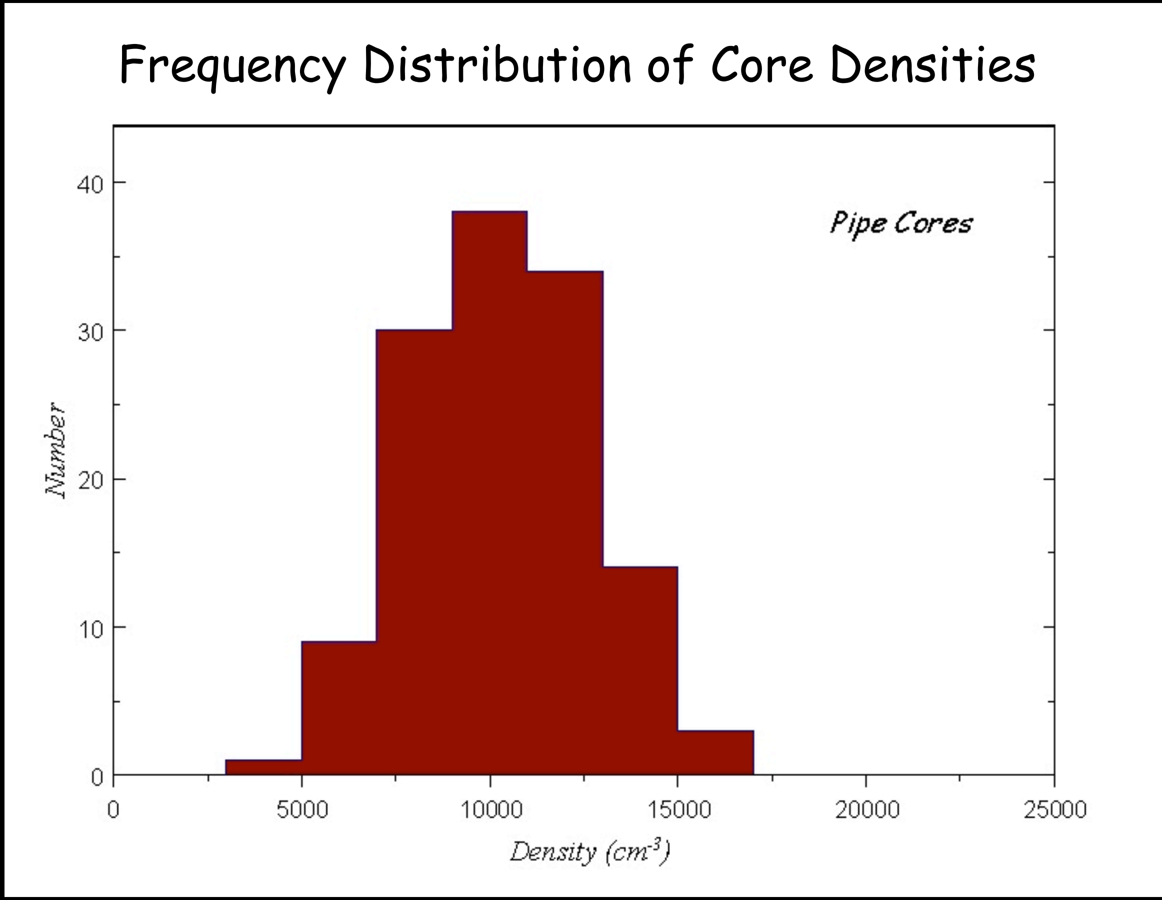
Alves, Lombardi, Lada 2007; Rathborne et al. 2008

Distribution of core masses (139 cores)

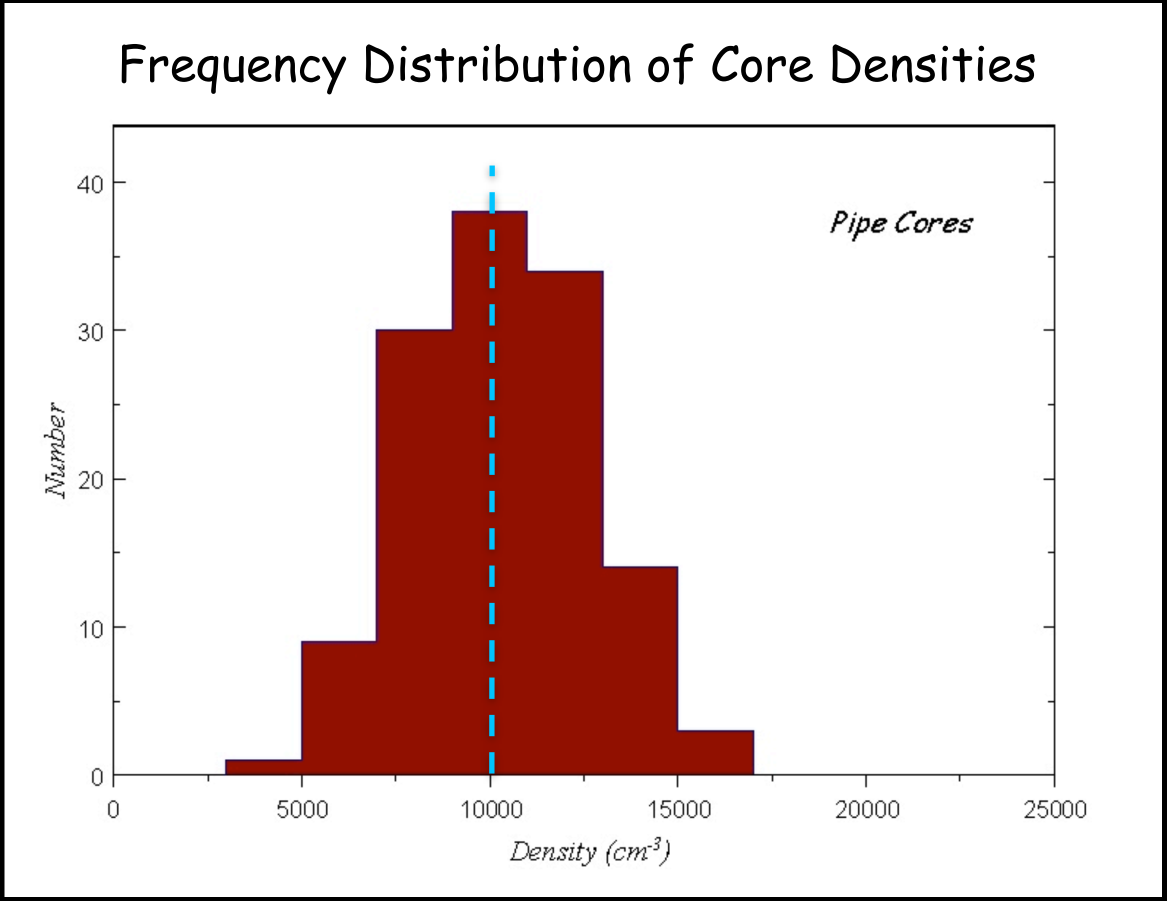


Alves, Lombardi, Lada 2007; Rathborne et al. 2008

Mean Core Densities

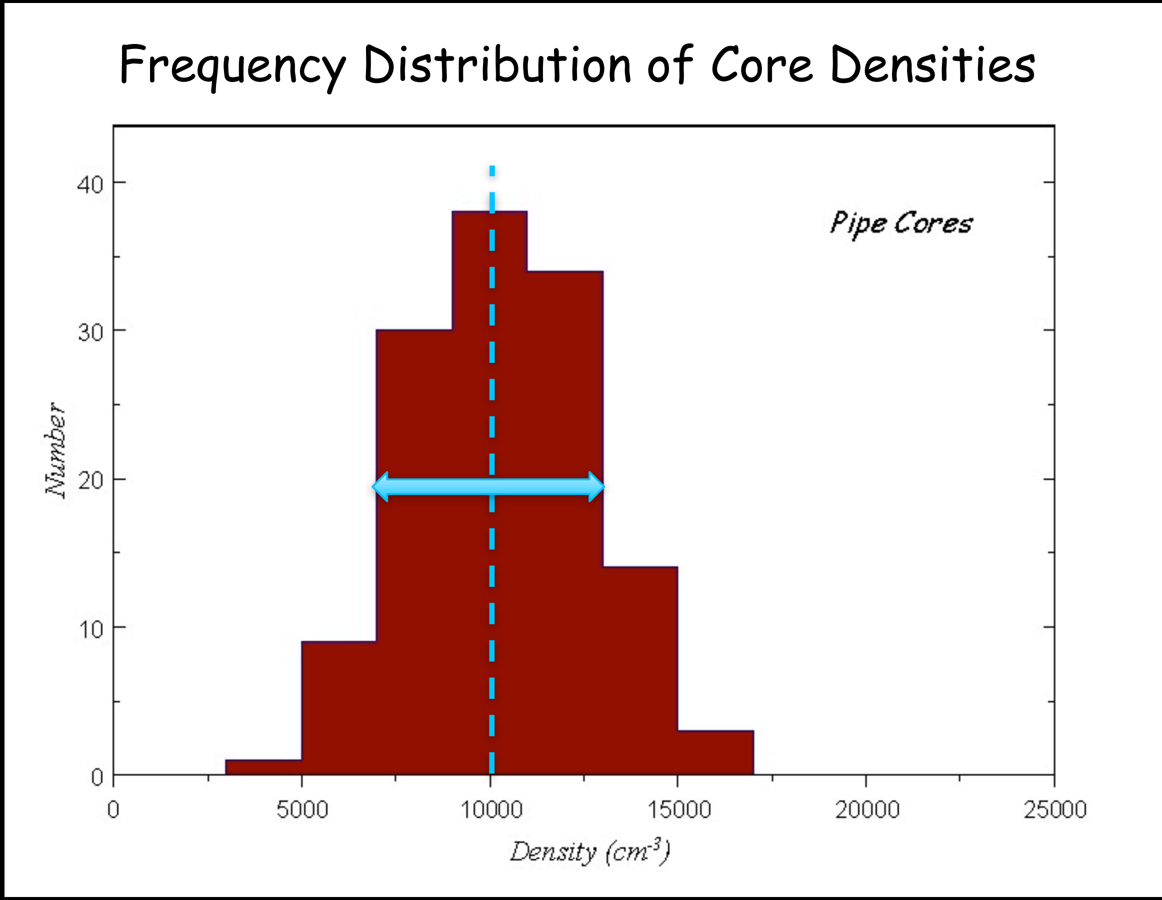


Mean Core Densities



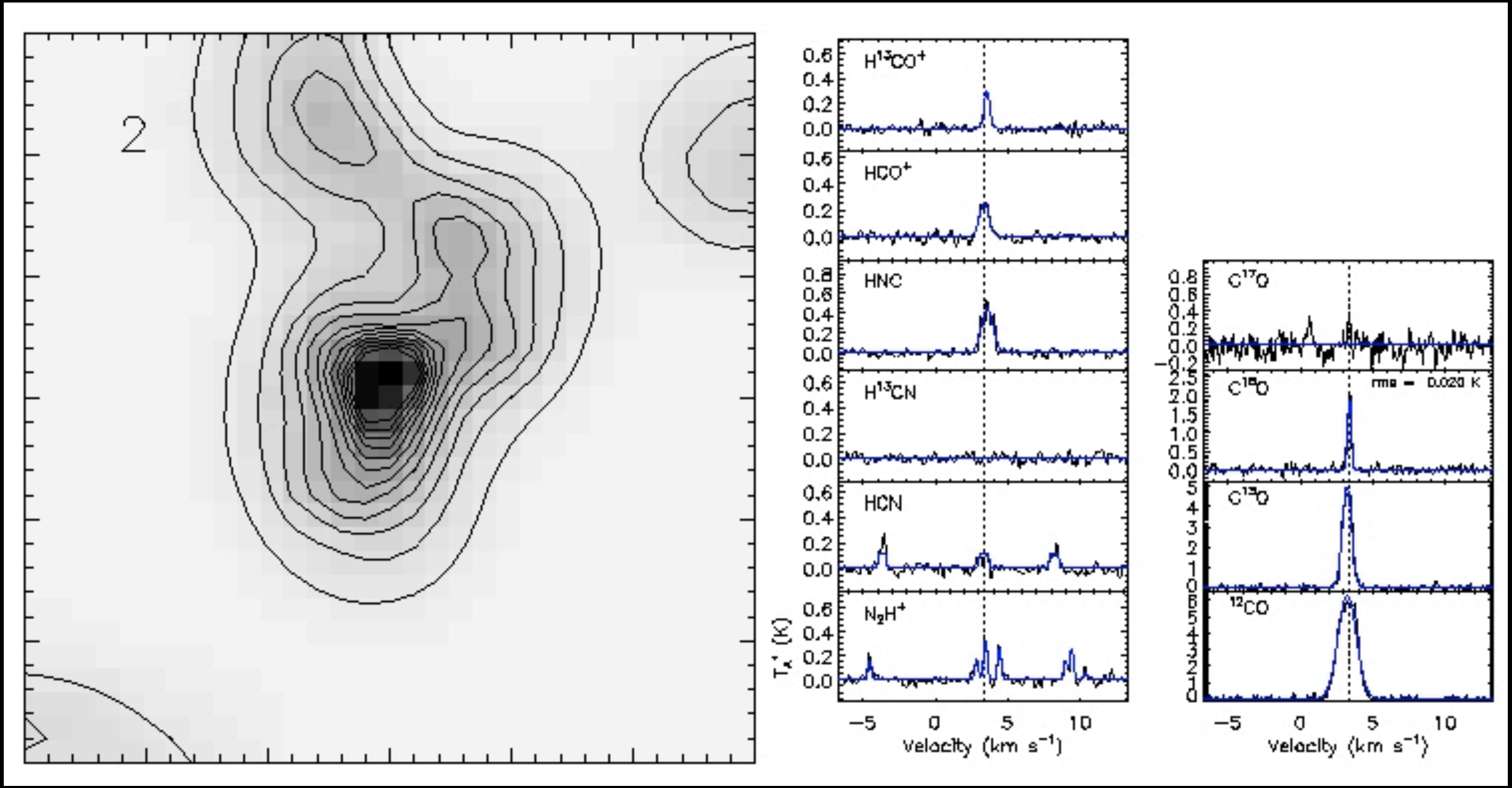
Median Core Density = 10,000 cm^{-3}

Mean Core Densities

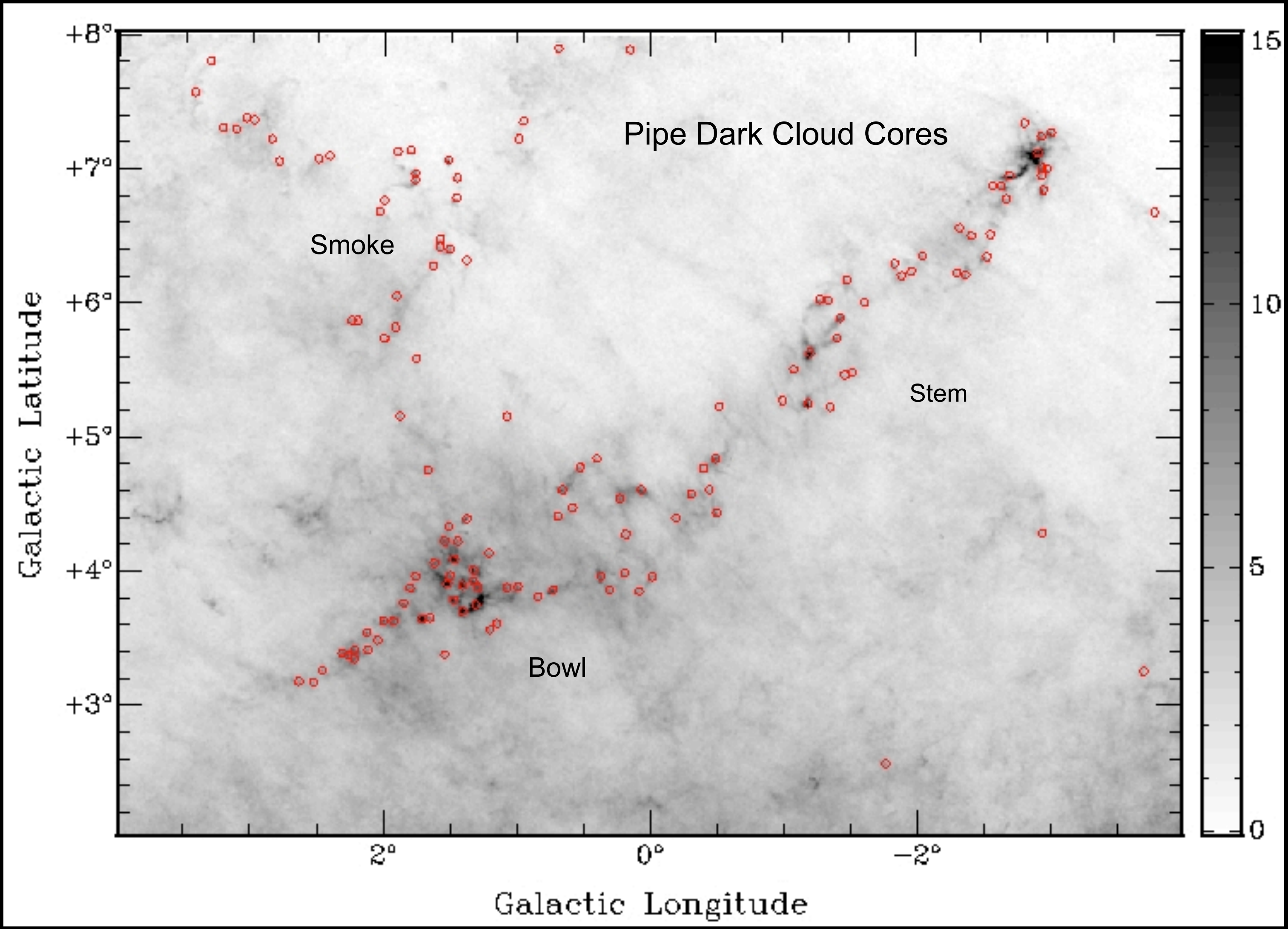


Median Core Density = 10,000 cm^{-3}

Molecular Line Survey

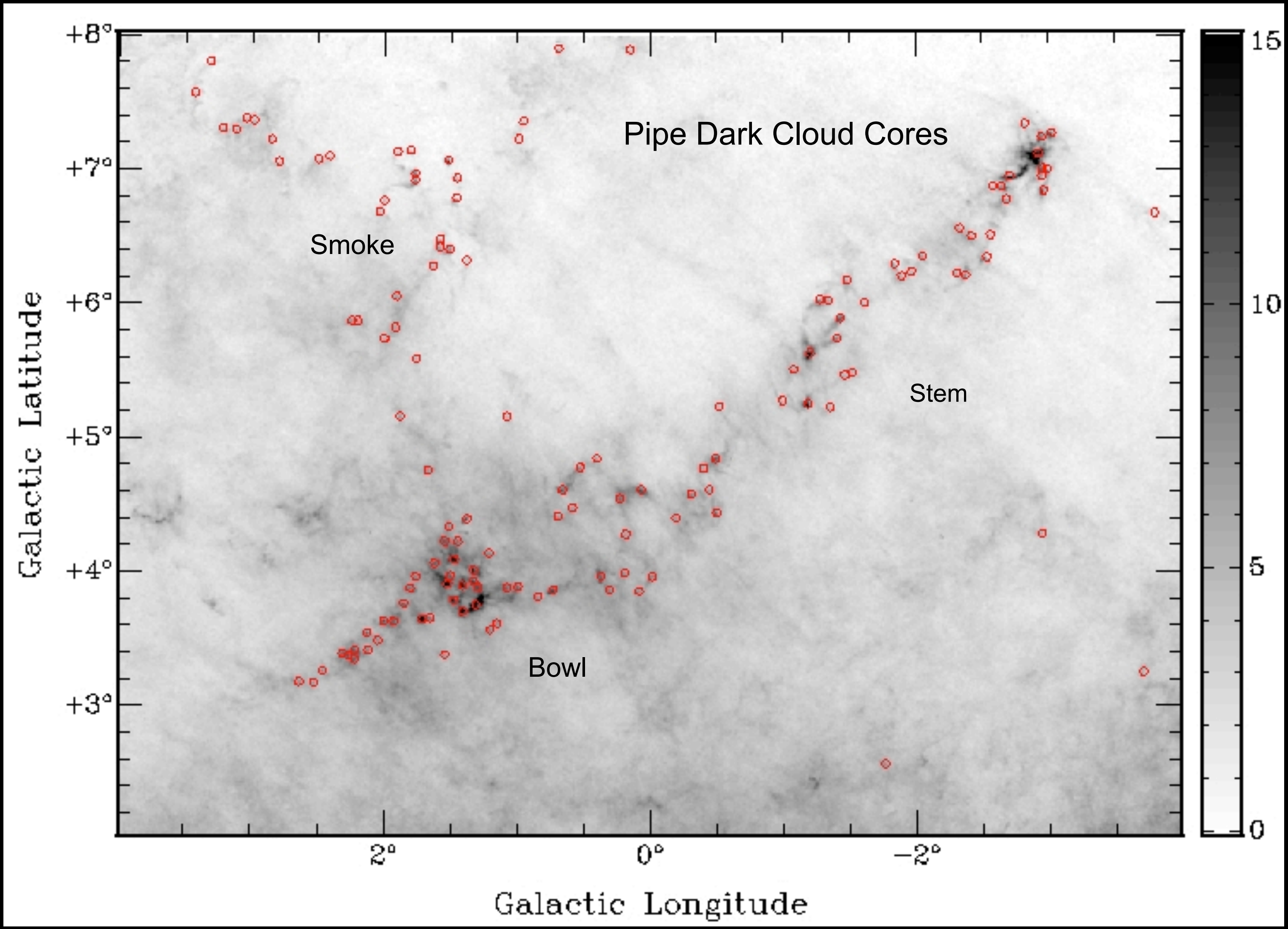


Rathborne et al. 2008



Core to Core Velocity Dispersion ($C^{18}O$):

Muench et al. 2007

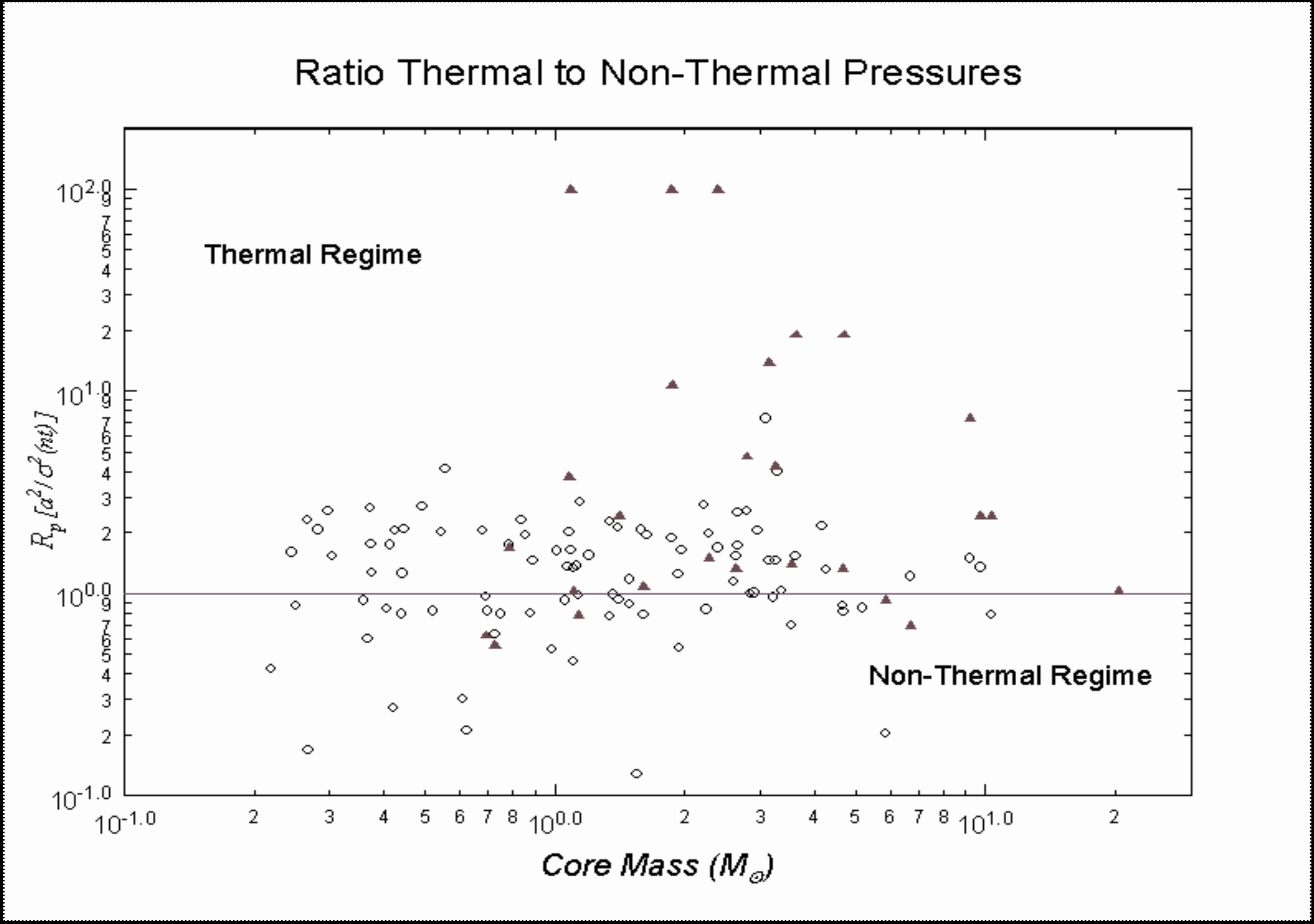


Core to Core Velocity Dispersion ($C^{18}O$):

σ_{pipe} **= *0.26 - 0.28 km/s***

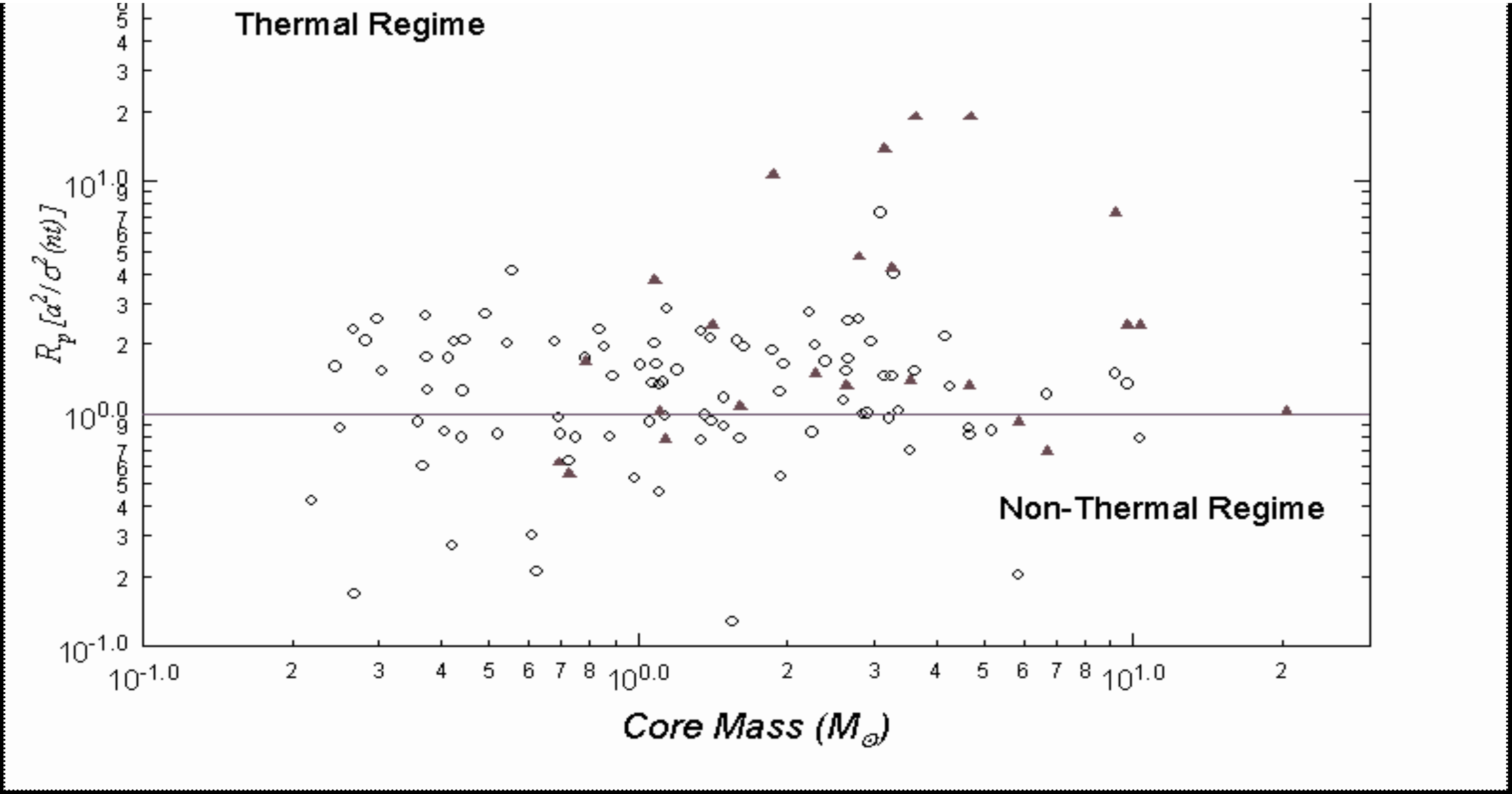
Muench et al. 2007

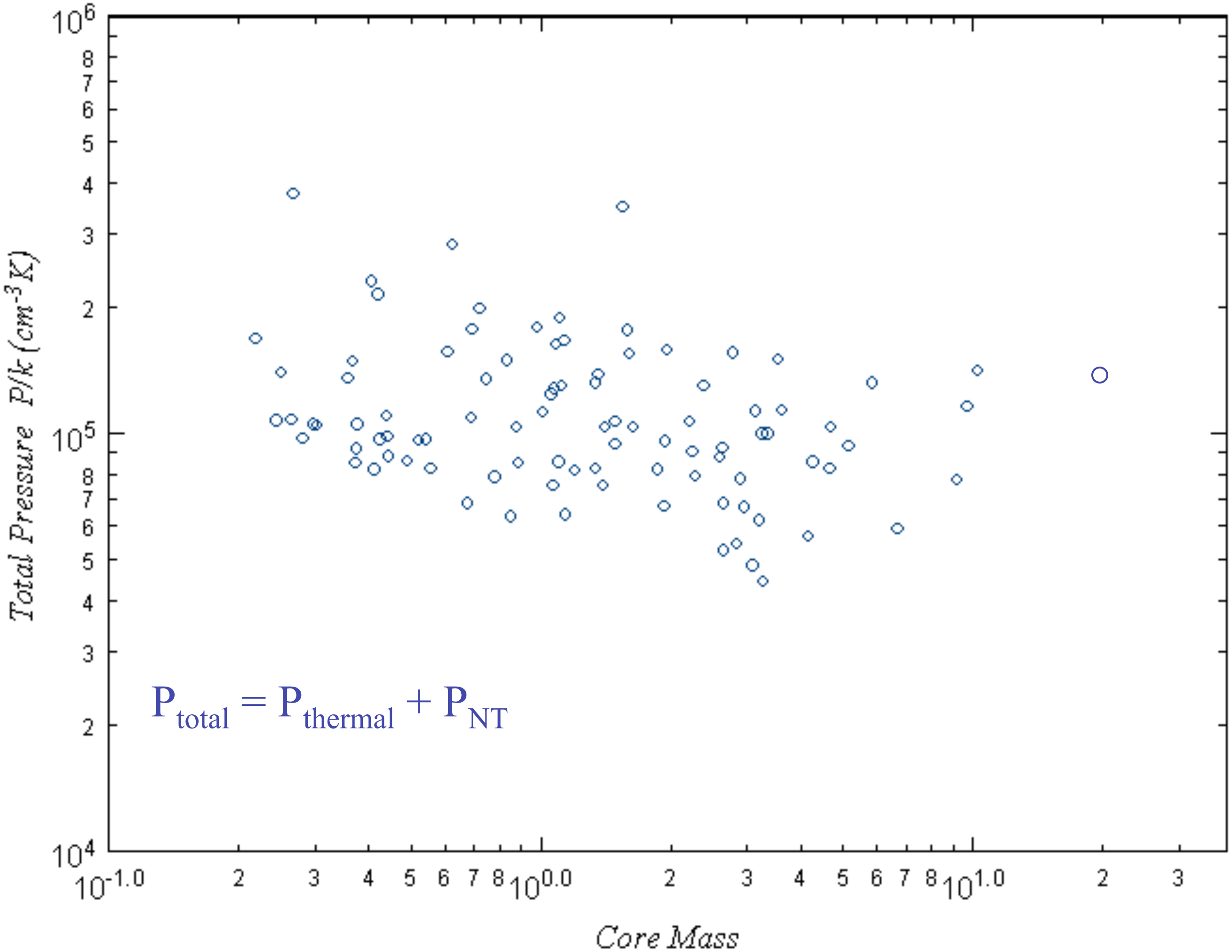
Dense cores are thermally supported!

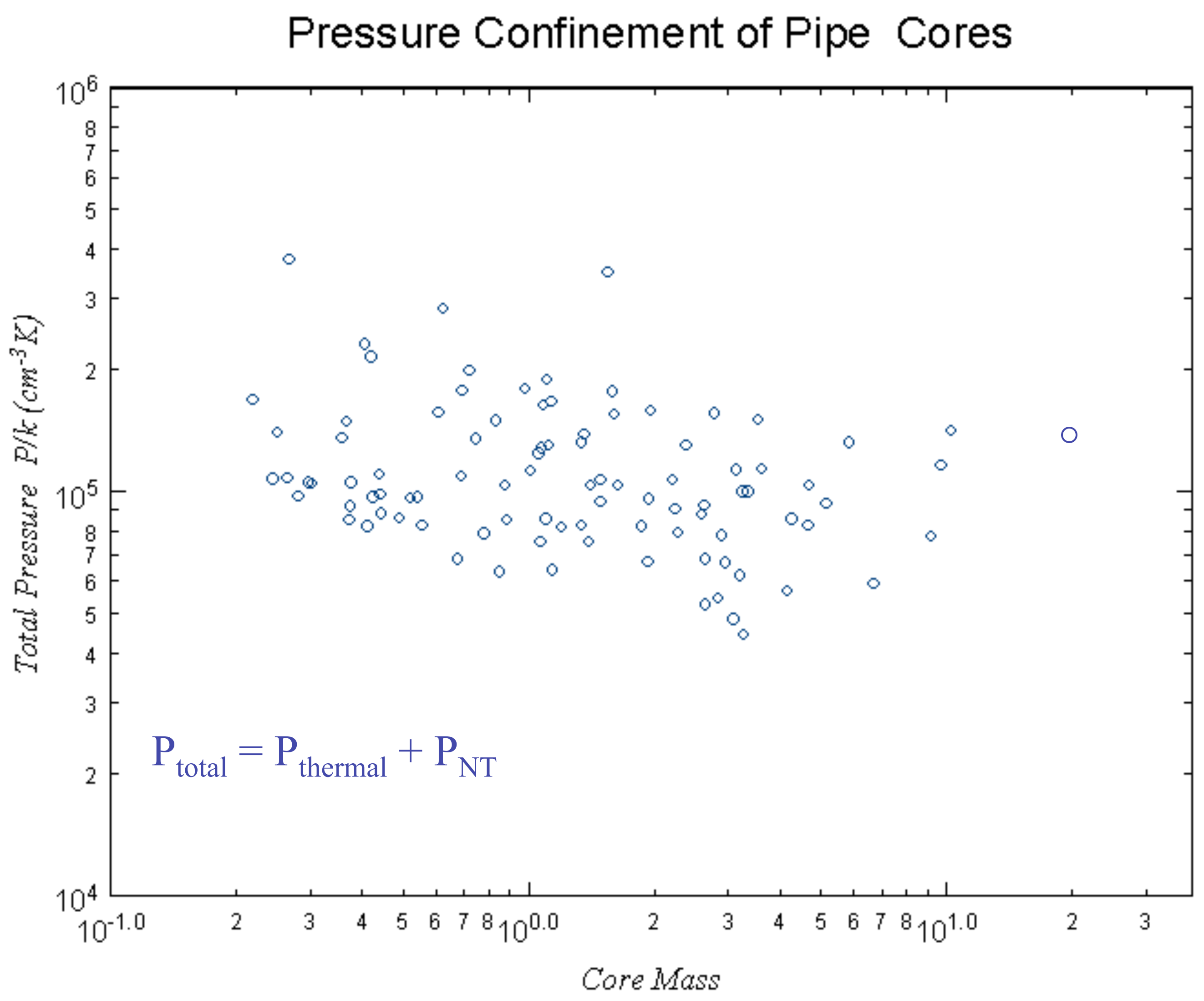


Dense cores are thermally supported!

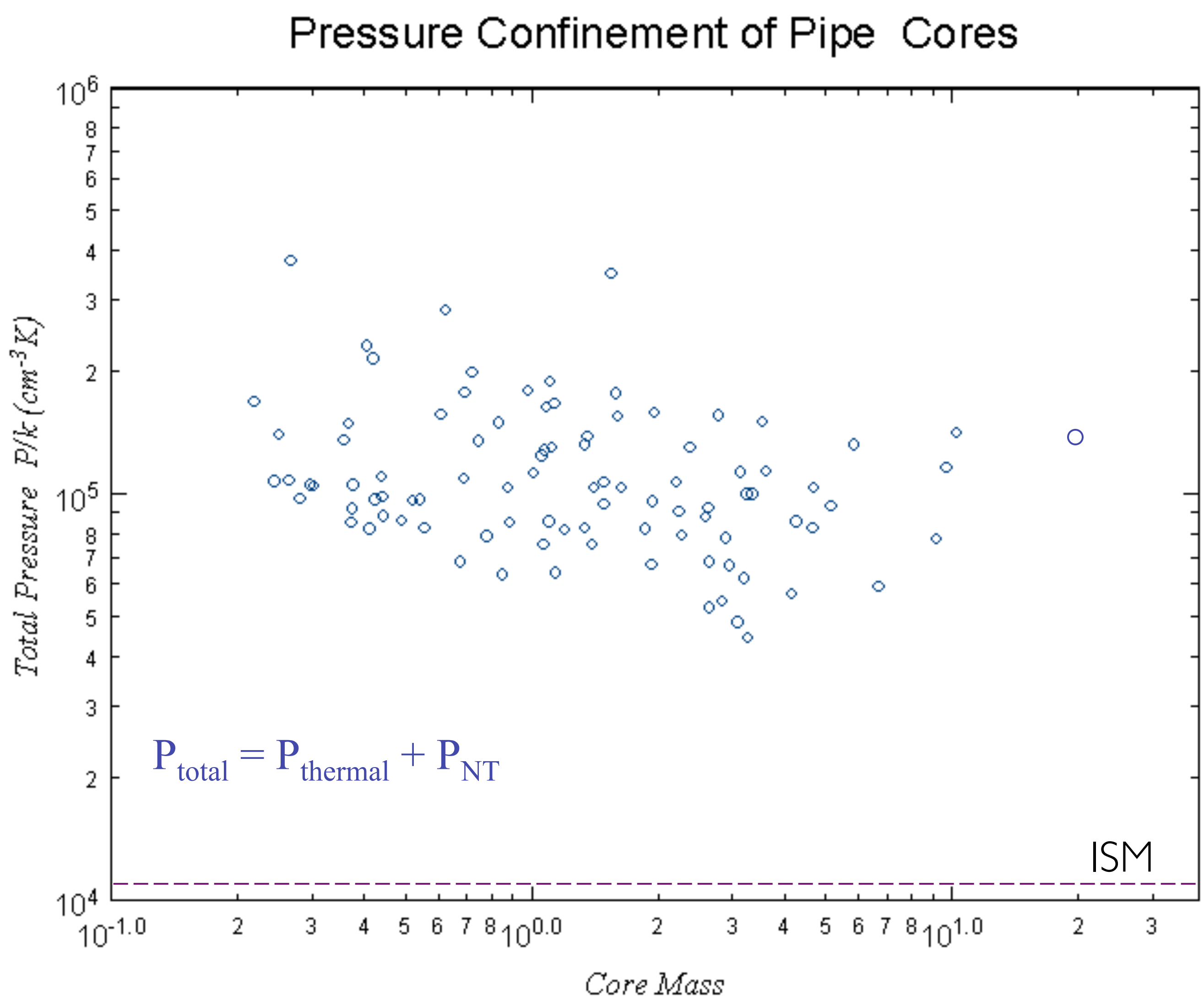
"Thermal pressure is thus a final irreducible barrier to star formation that remains even after turbulence and magnetic fields have been dissipated." Larson (2005)



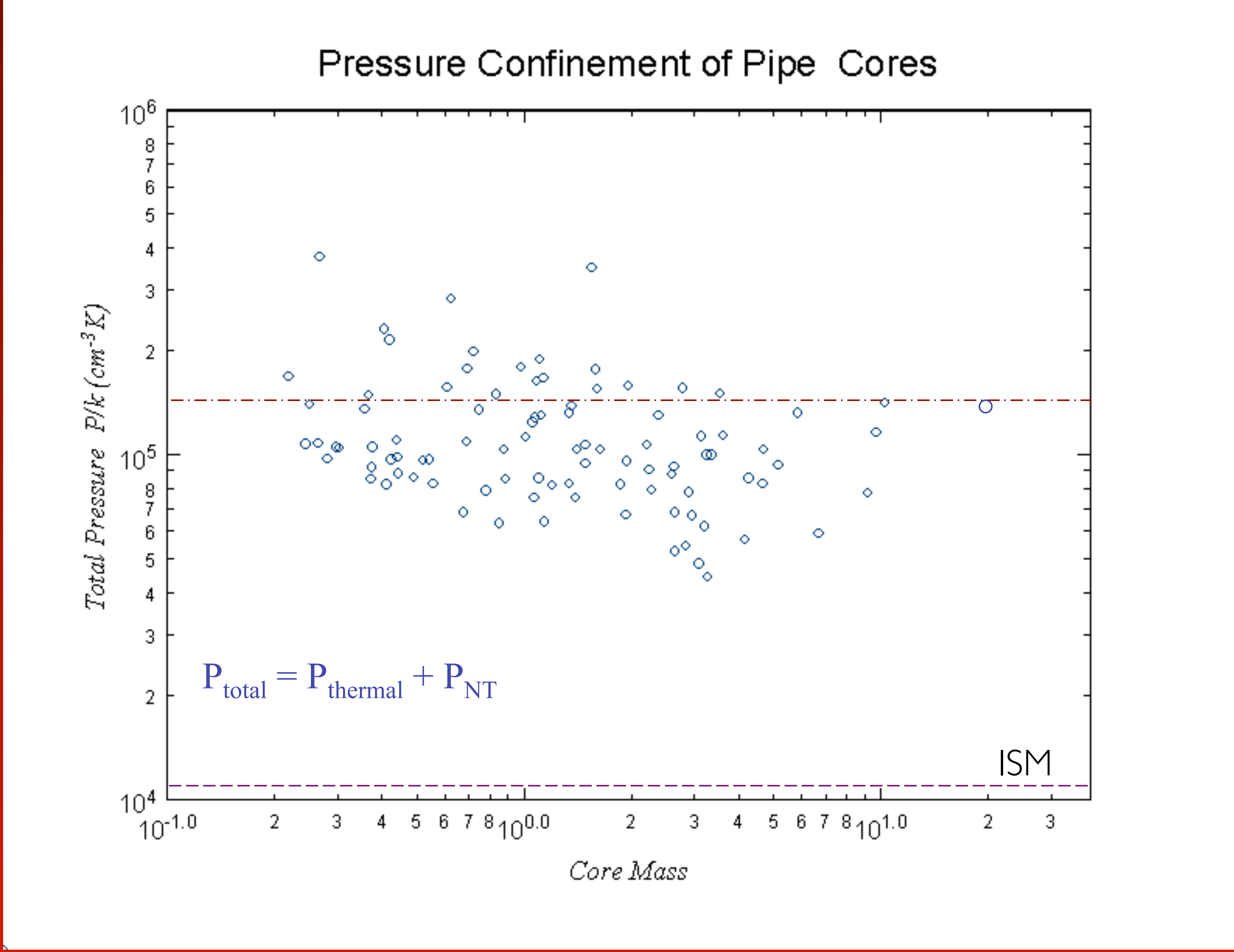

10^6
8
7
6
5
4
3
2
10^5
8
7
6
5
4
3
2
10^4
Total Pressure P/k (cm^{-3} K)
$P_{total} = P_{thermal} + P_{NT}$
$10^{-1.0}$
2
3
4
5
6
7
8
$10^{0.0}$
2
3
4
5
6
7
8
$10^{1.0}$
2
3
Core Mass

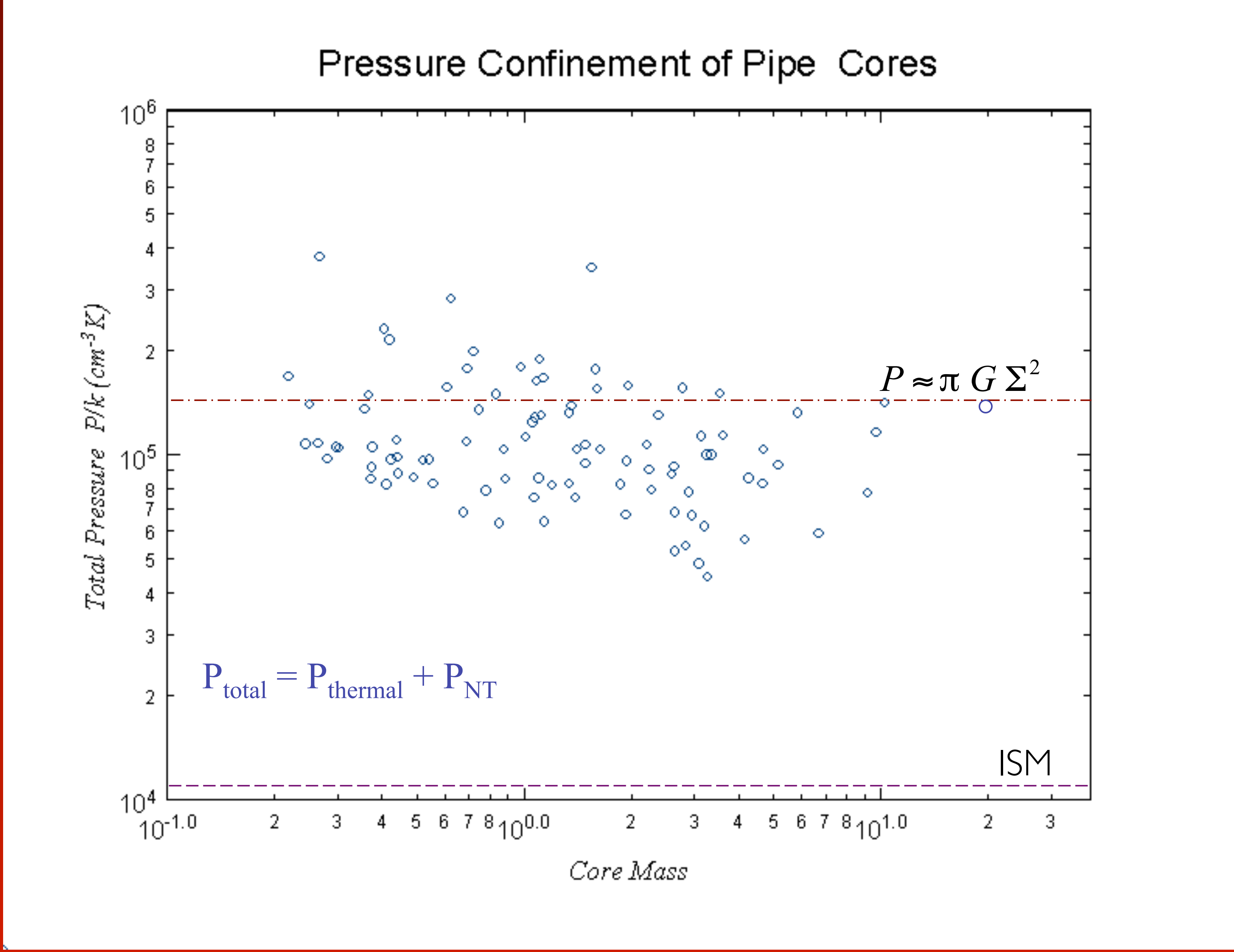


Pressure Confinement of Pipe Cores
Total Pressure P/k (cm^-3 K)
Core Mass
$P_{total} = P_{thermal} + P_{NT}$



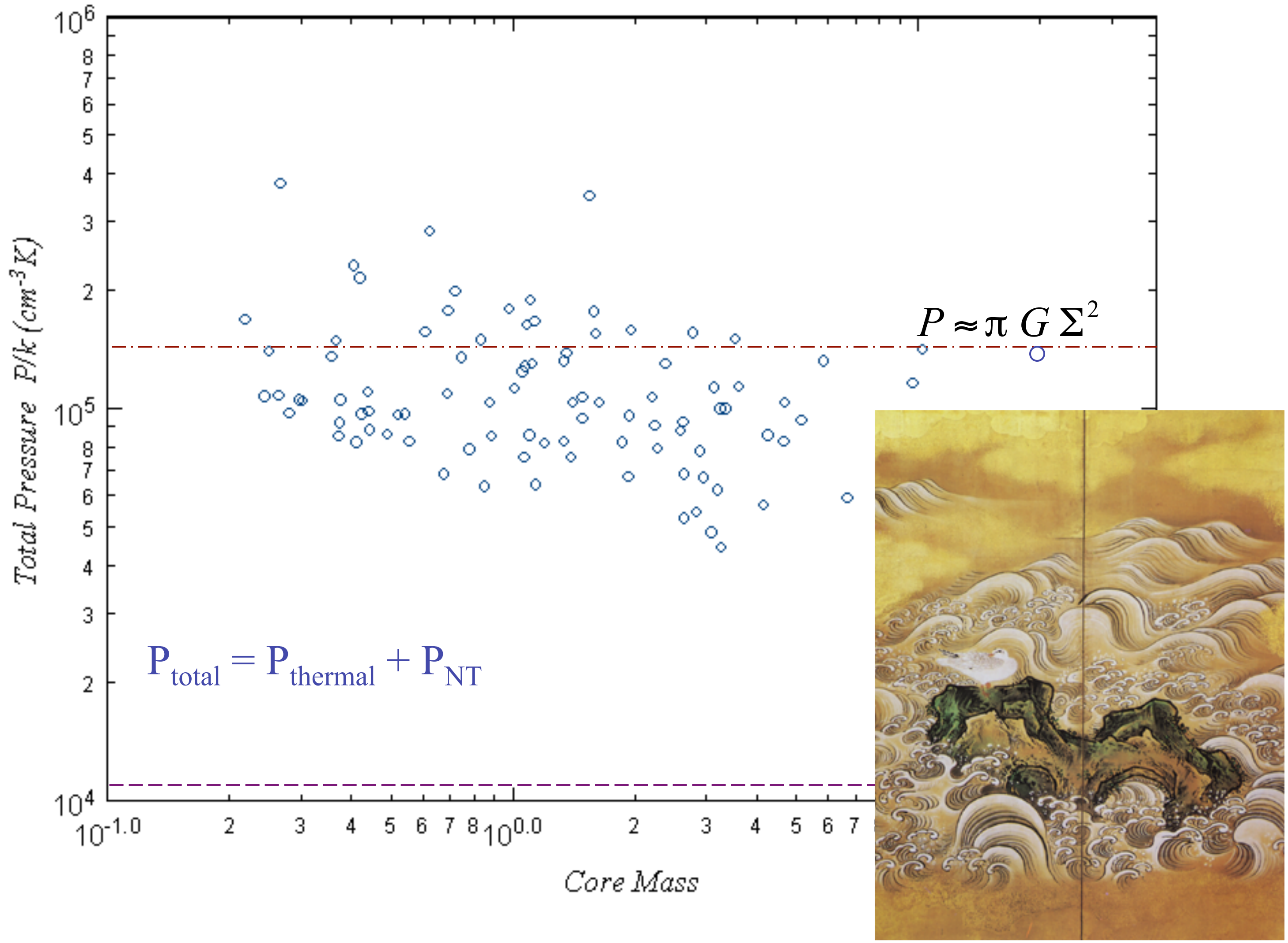
Pressure Confinement of Pipe Cores
Total Pressure P/k (cm^-3 K)
Core Mass
$P_{total} = P_{thermal} + P_{NT}$
ISM

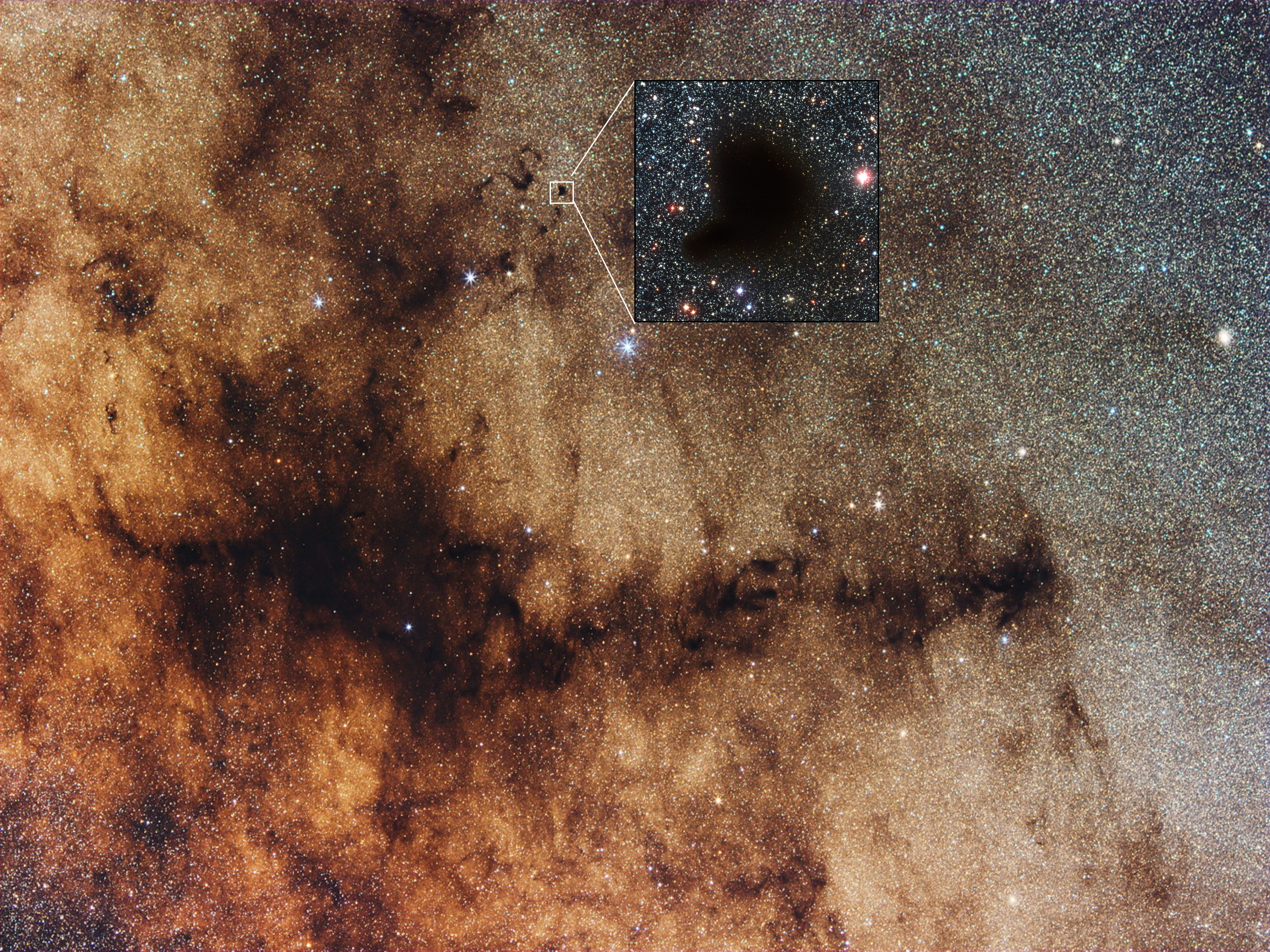

Pressure Confinement of Pipe Cores
Total Pressure P/k (cm^-3 K)
Core Mass
$P_{total} = P_{thermal} + P_{NT}$
ISM
10^6
10^5
10^4
10^-1.0
10^0.0
10^1.0



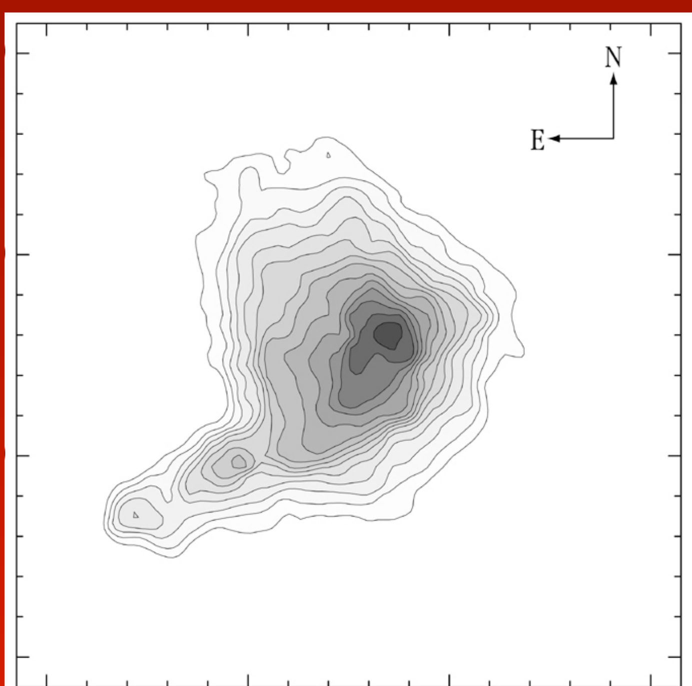
Pressure Confinement of Pipe Cores
Total Pressure P/k (cm^-3 K)
Core Mass
$P \approx \pi G \Sigma^2$
$P_{total} = P_{thermal} + P_{NT}$
ISM

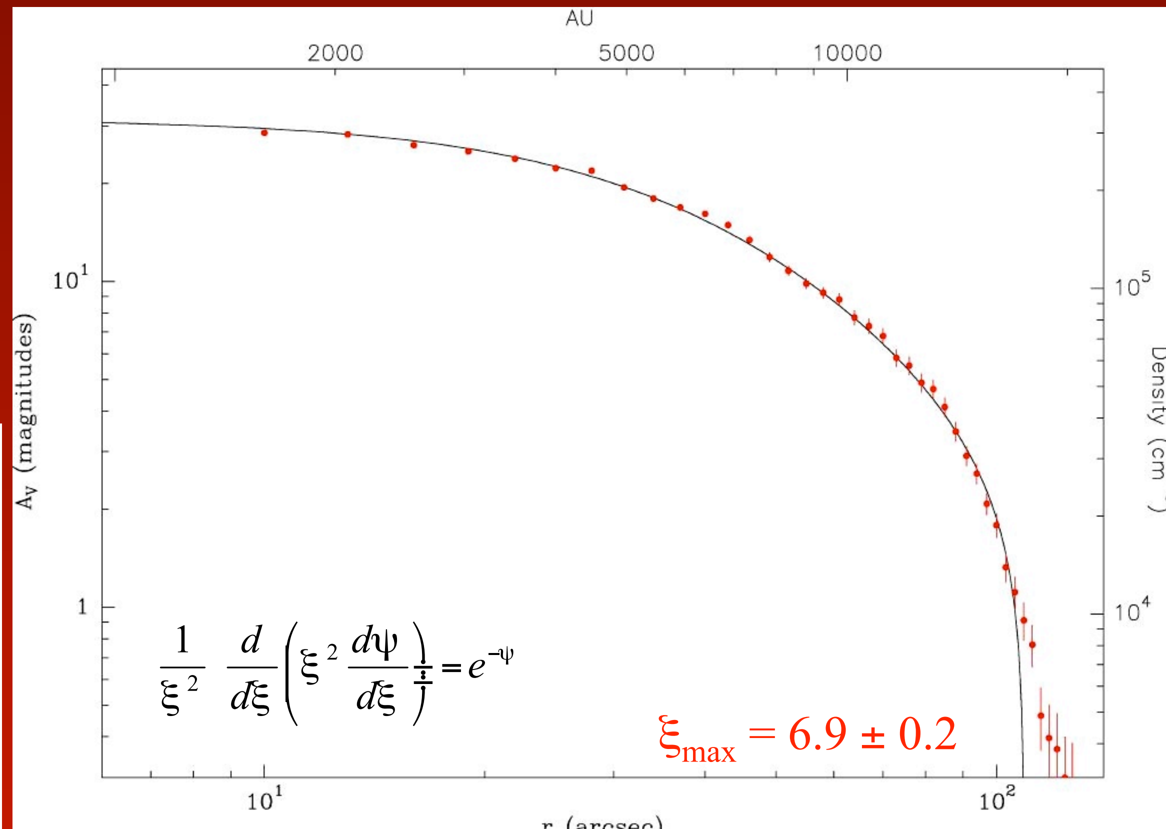
Pressure Confinement of Pipe Cores



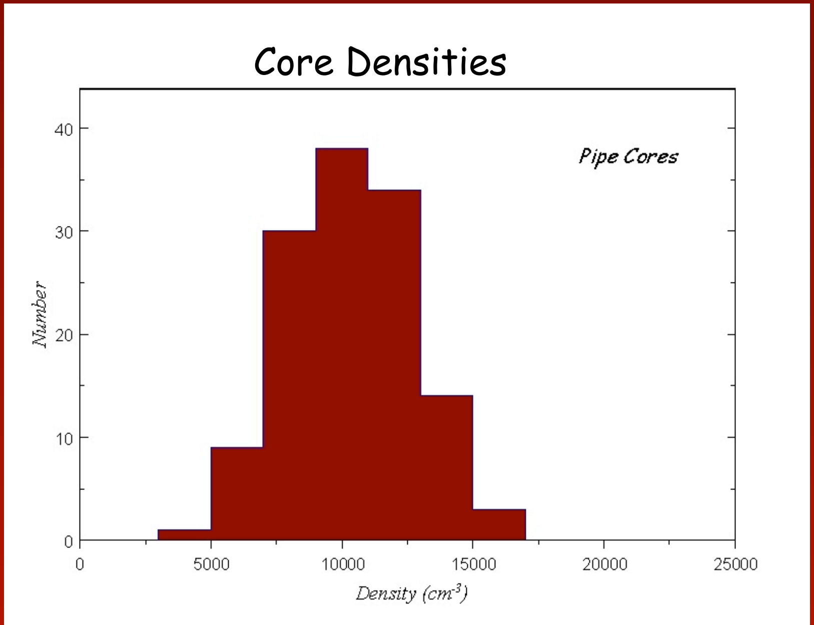


B 68: Radial Density Profile

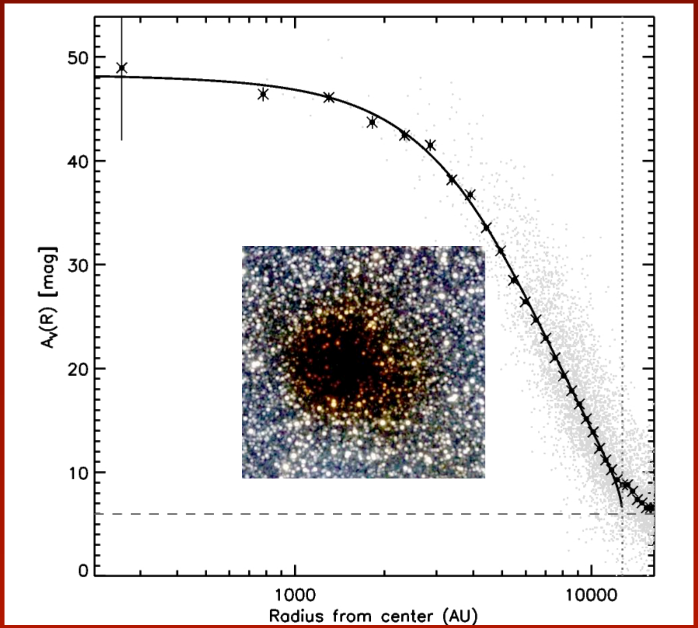




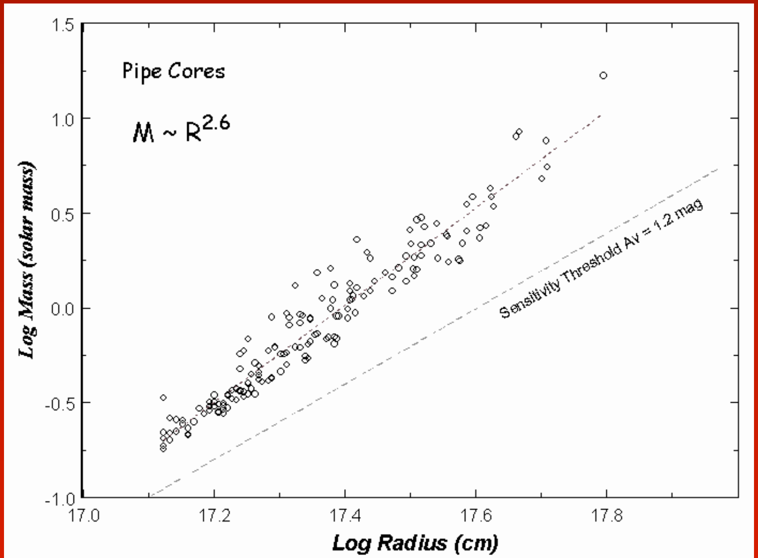
Critical Bonnor-Ebert Sphere



Core Densities
Pipe Cores
Number
Density (cm^{-3})
0
10
20
30
40
0
5000
10000
15000
20000
25000

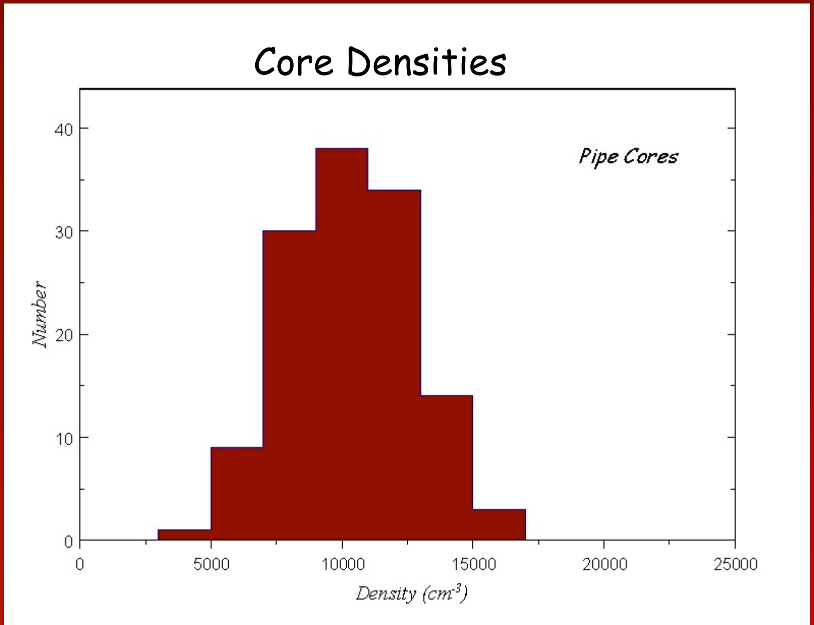


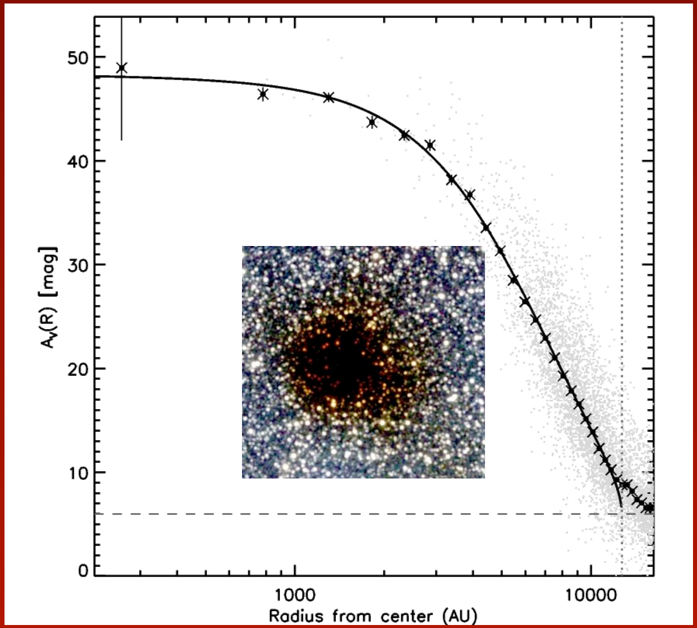
$A_V(R)$ [mag]
Radius from center (AU)
0
10
20
30
40
50
1000
10000

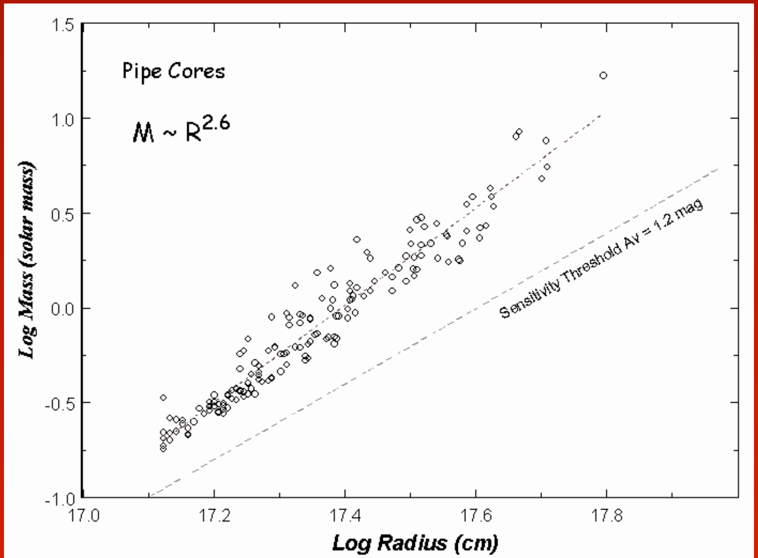


Pipe Cores
$M \sim R^{2.6}$
Sensitivity Threshold Av = 1.2 mag
Log Mass (solar mass)
Log Radius (cm)
1.5
1.0
0.5
0.0
-0.5
-1.0
17.0
17.2
17.4
17.6
17.8

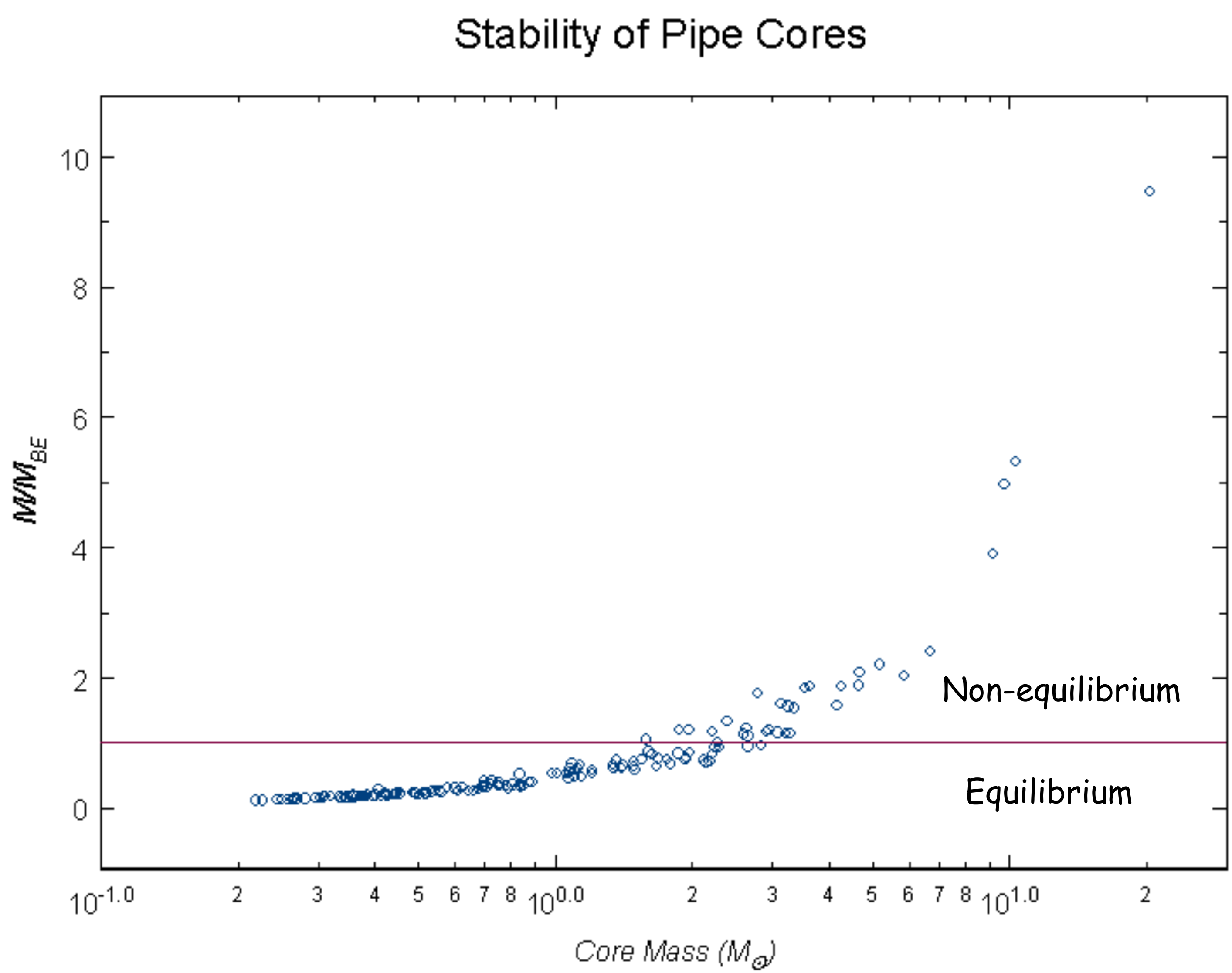
Core structure is set by the requirement of pressure equilibrium with external medium!





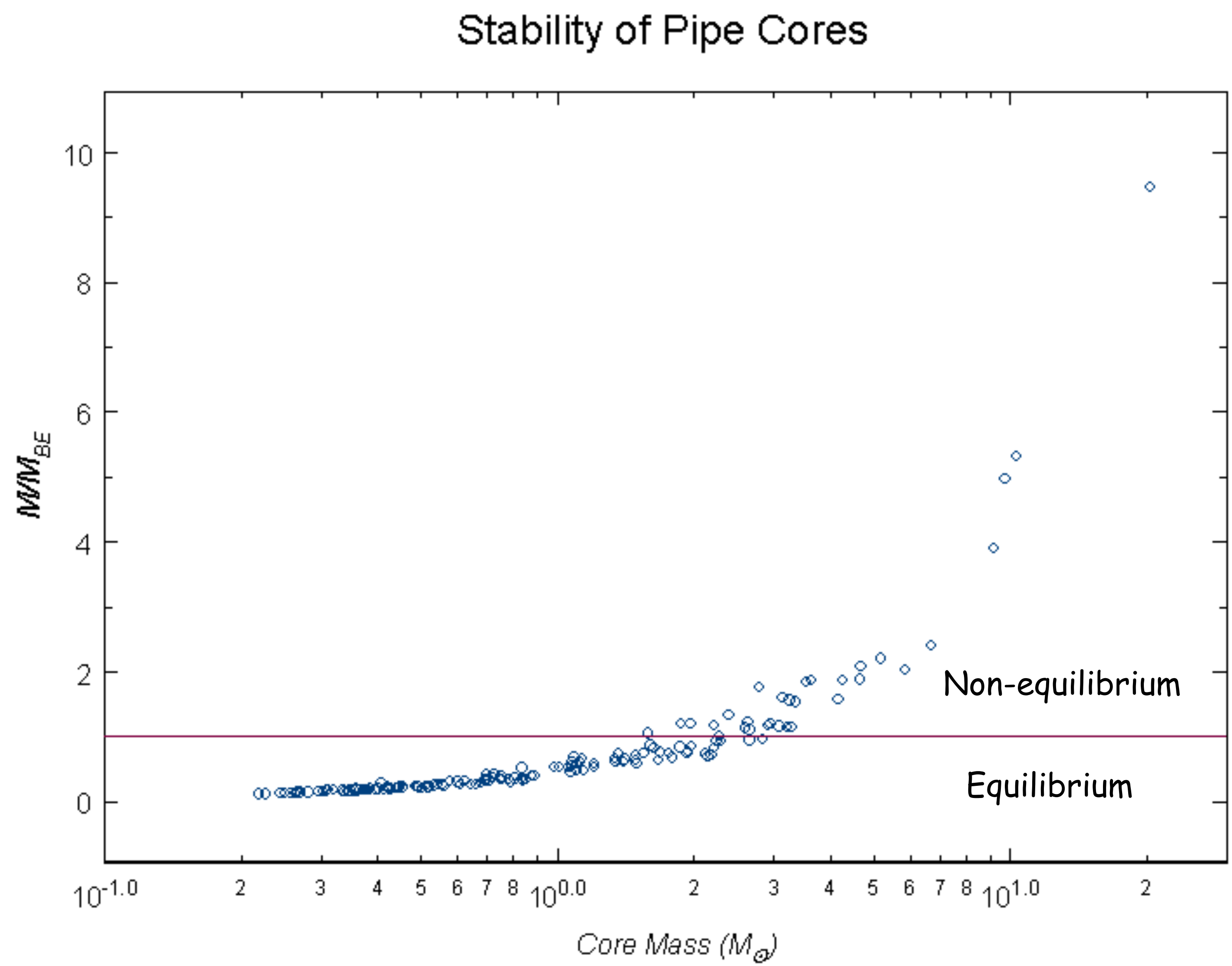


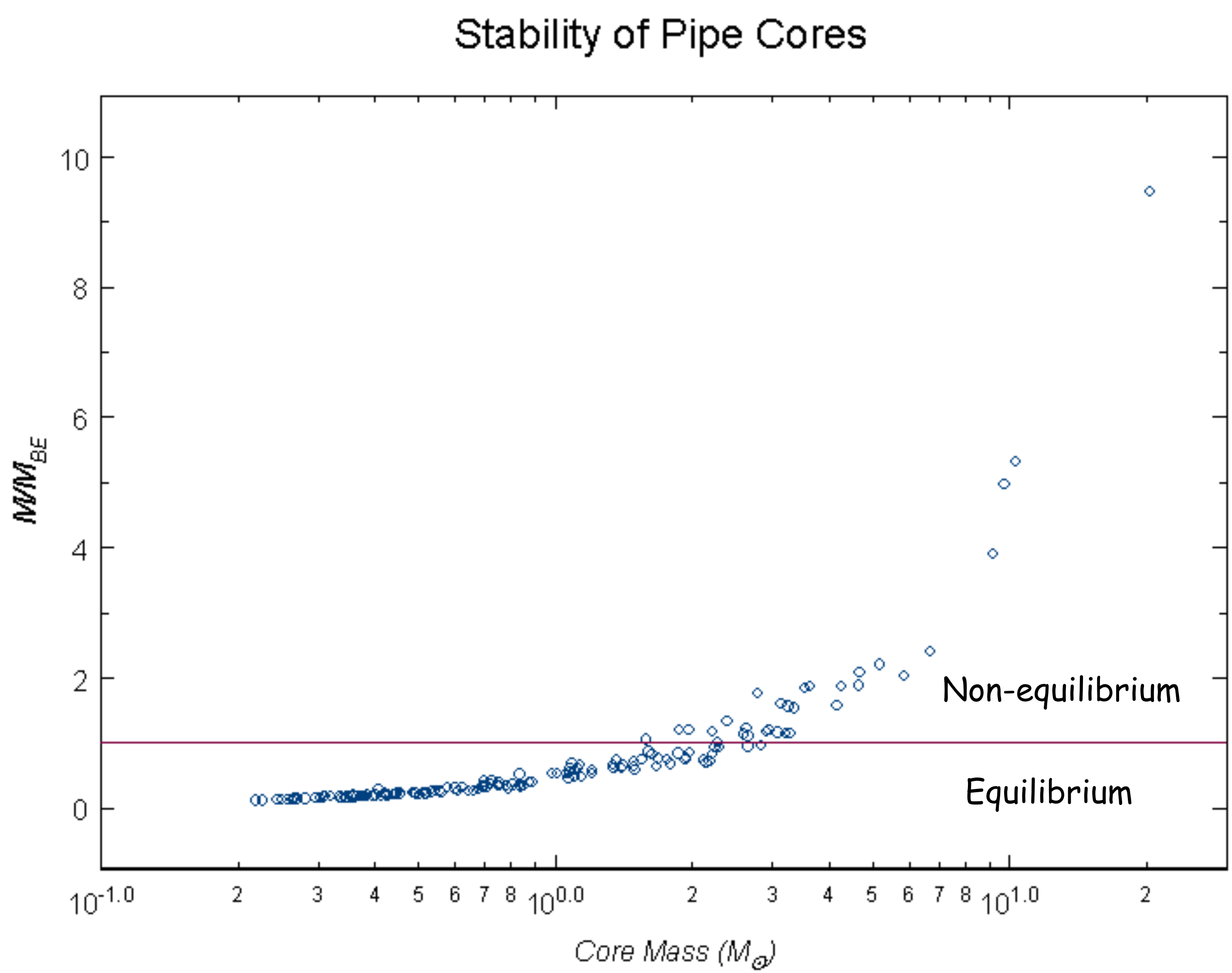
On the Origin of the Core and Stellar Masses



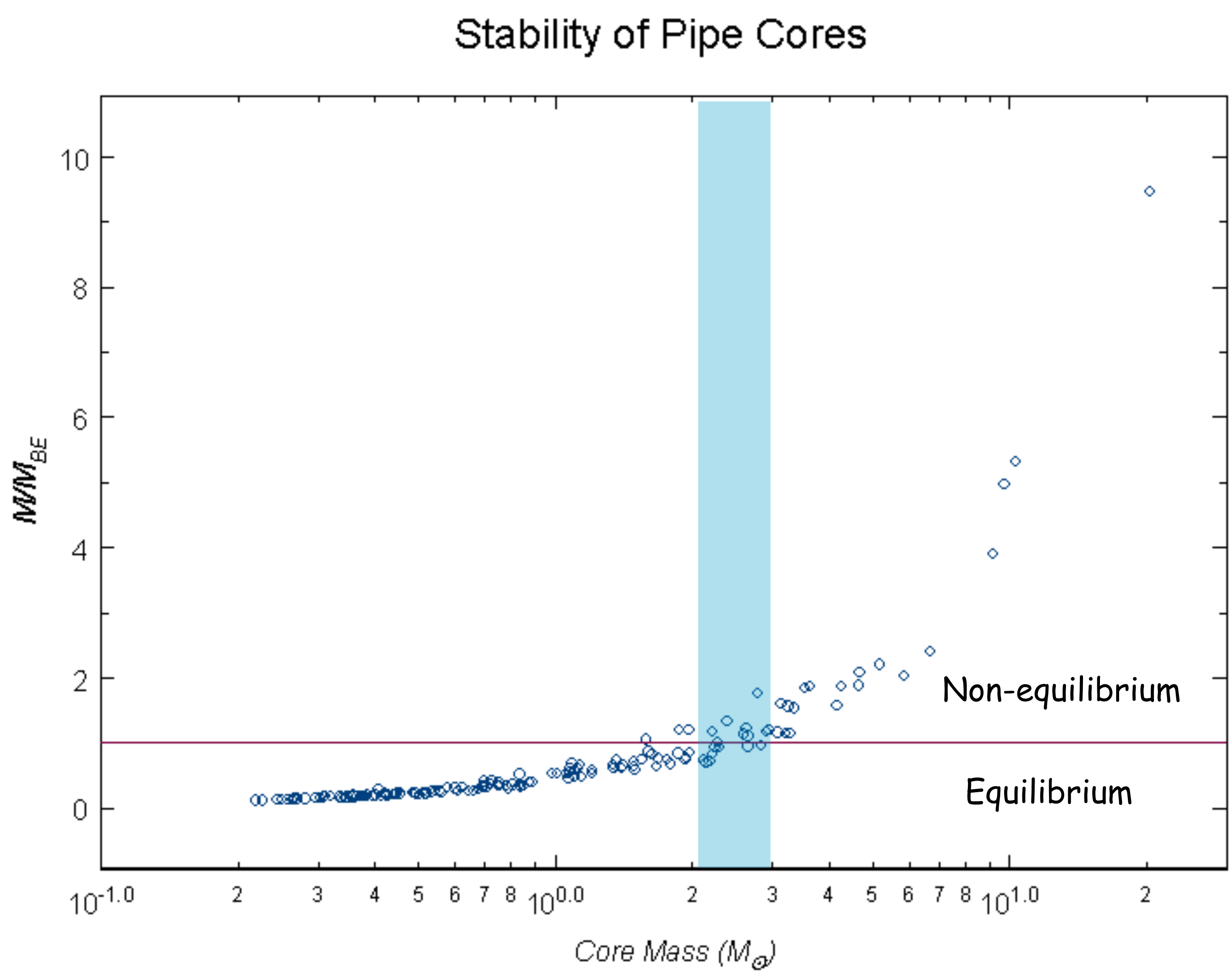
Stability of Pipe Cores
10
8
6
4
2
0
M/M_BE
Non-equilibrium
Equilibrium
10^-1.0
2
3
4
5
6
7
8
10^0.0
2
3
4
5
6
7
8
10^1.0
2
Core Mass (M_⊙)

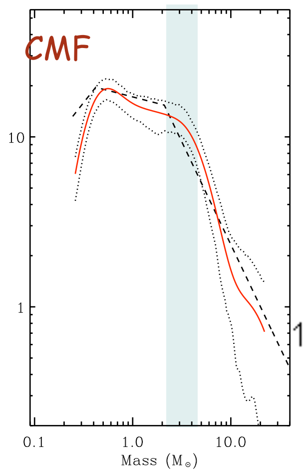
$M_{BE} = 1.82\ (n_4)^{-0.5}\ (T_{10})^{1.5}$ *(solar masses)*



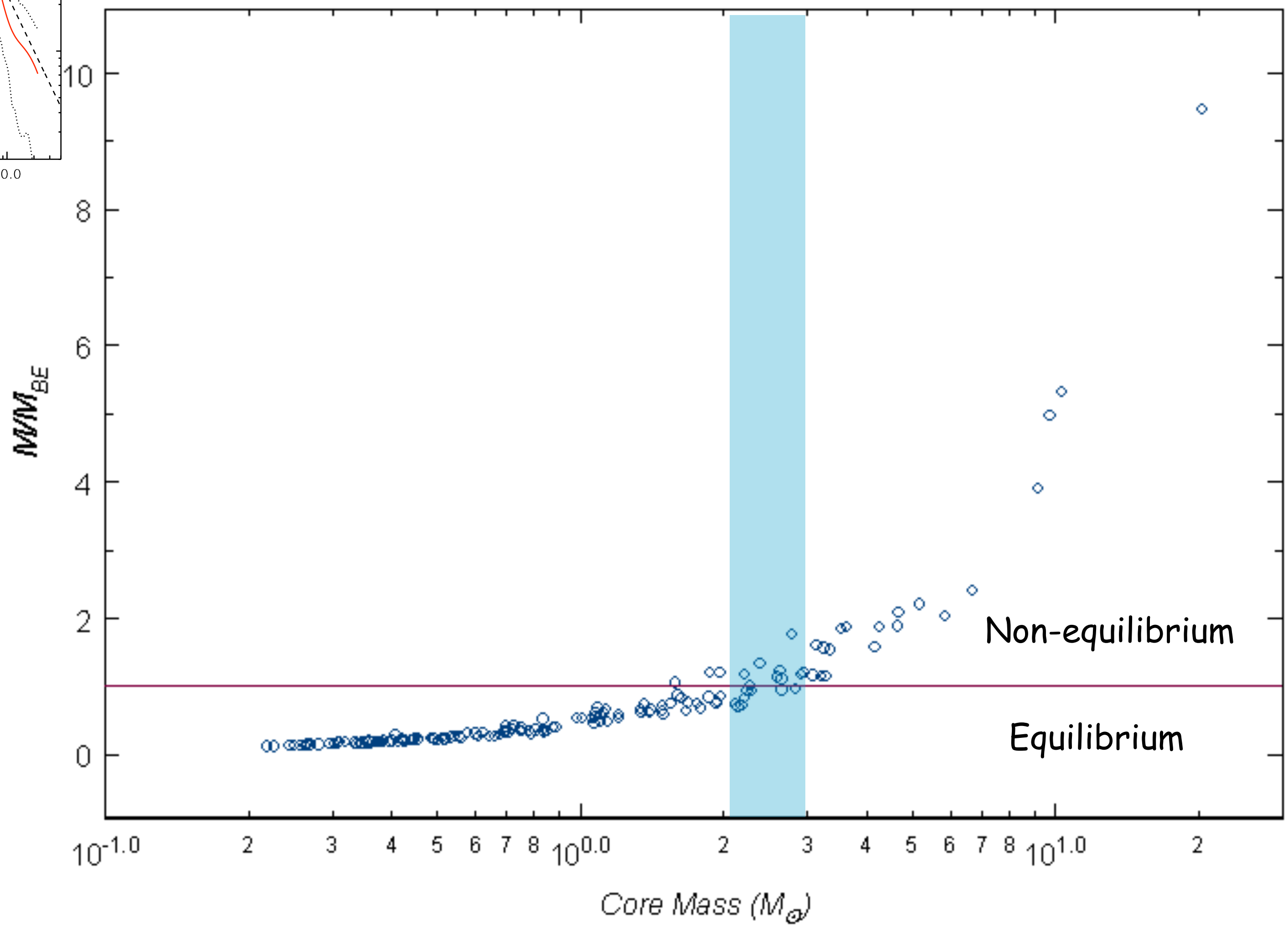


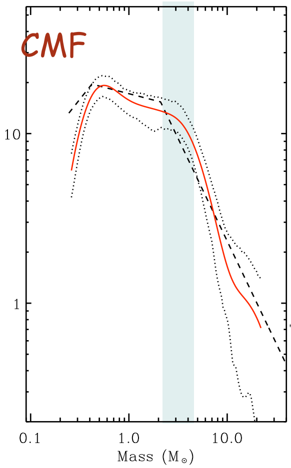
Stability of Pipe Cores
10
8
6
4
2
0
M/M_BE
Non-equilibrium
Equilibrium
10^-1.0
2
3
4
5
6
7
8
10^0.0
2
3
4
5
6
7
8
10^1.0
2
Core Mass (M_⊙)


Stability of Pipe Cores
M/M_BE
10
8
6
4
2
0
Non-equilibrium
Equilibrium
10^-1.0
2
3
4
5
6
7
8
10^0.0
2
3
4
5
6
7
8
10^1.0
2
Core Mass (M_⊙)



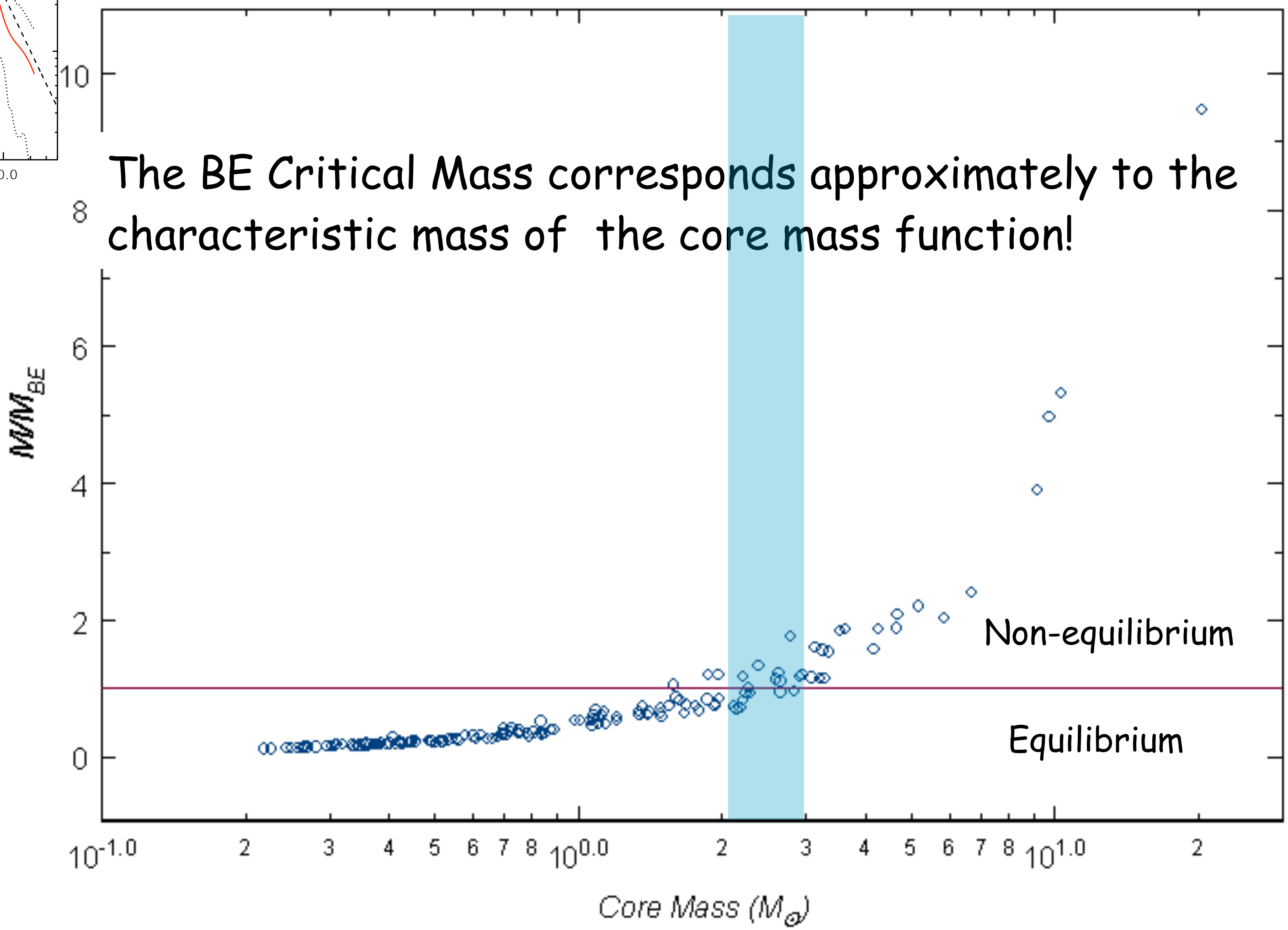
Stability of Pipe Cores

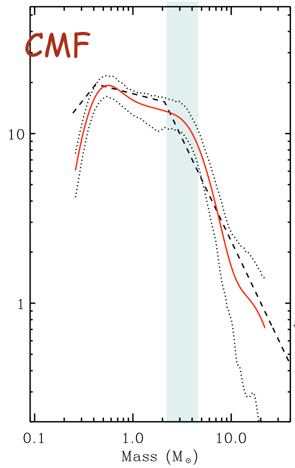


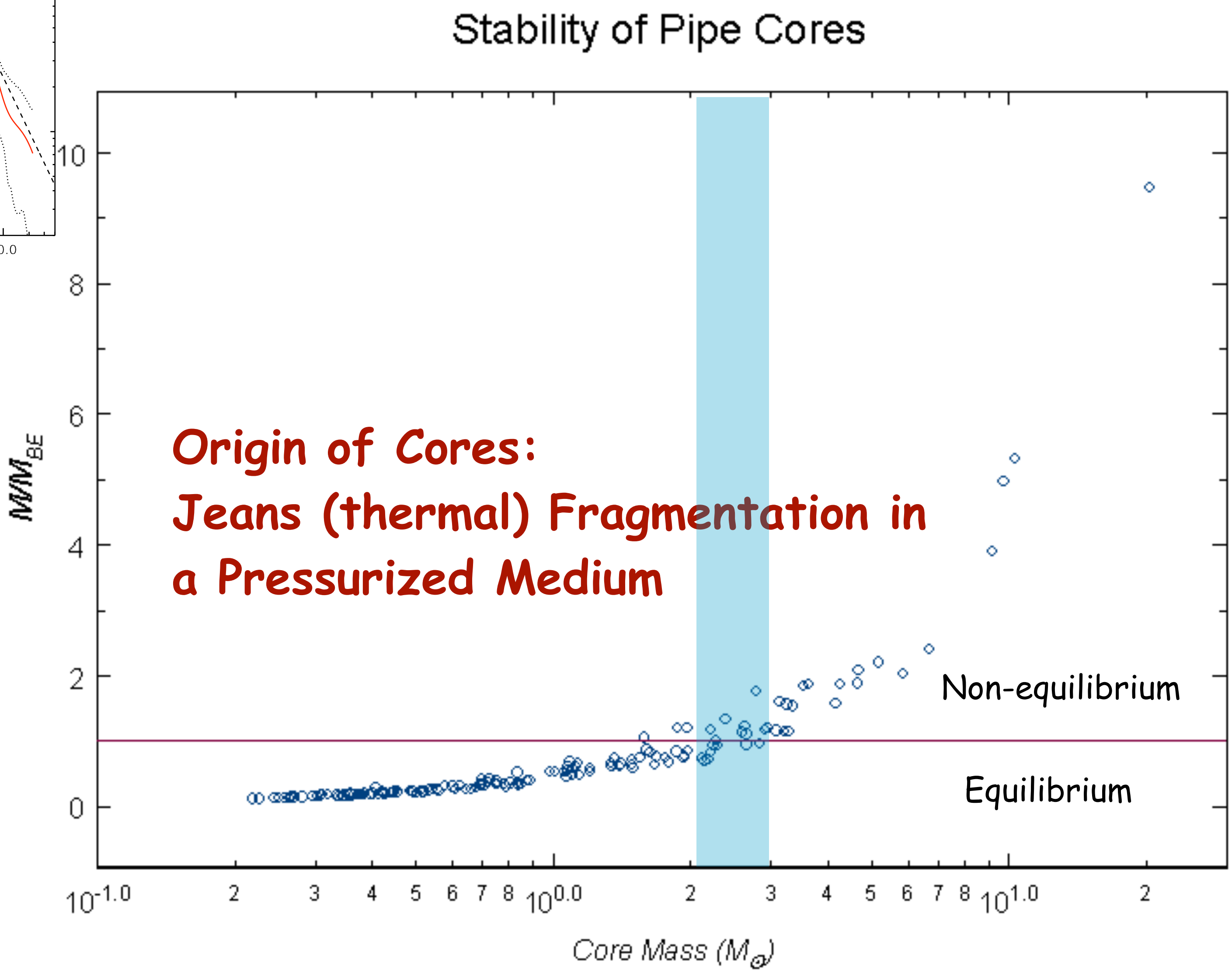


Stability of Pipe Cores

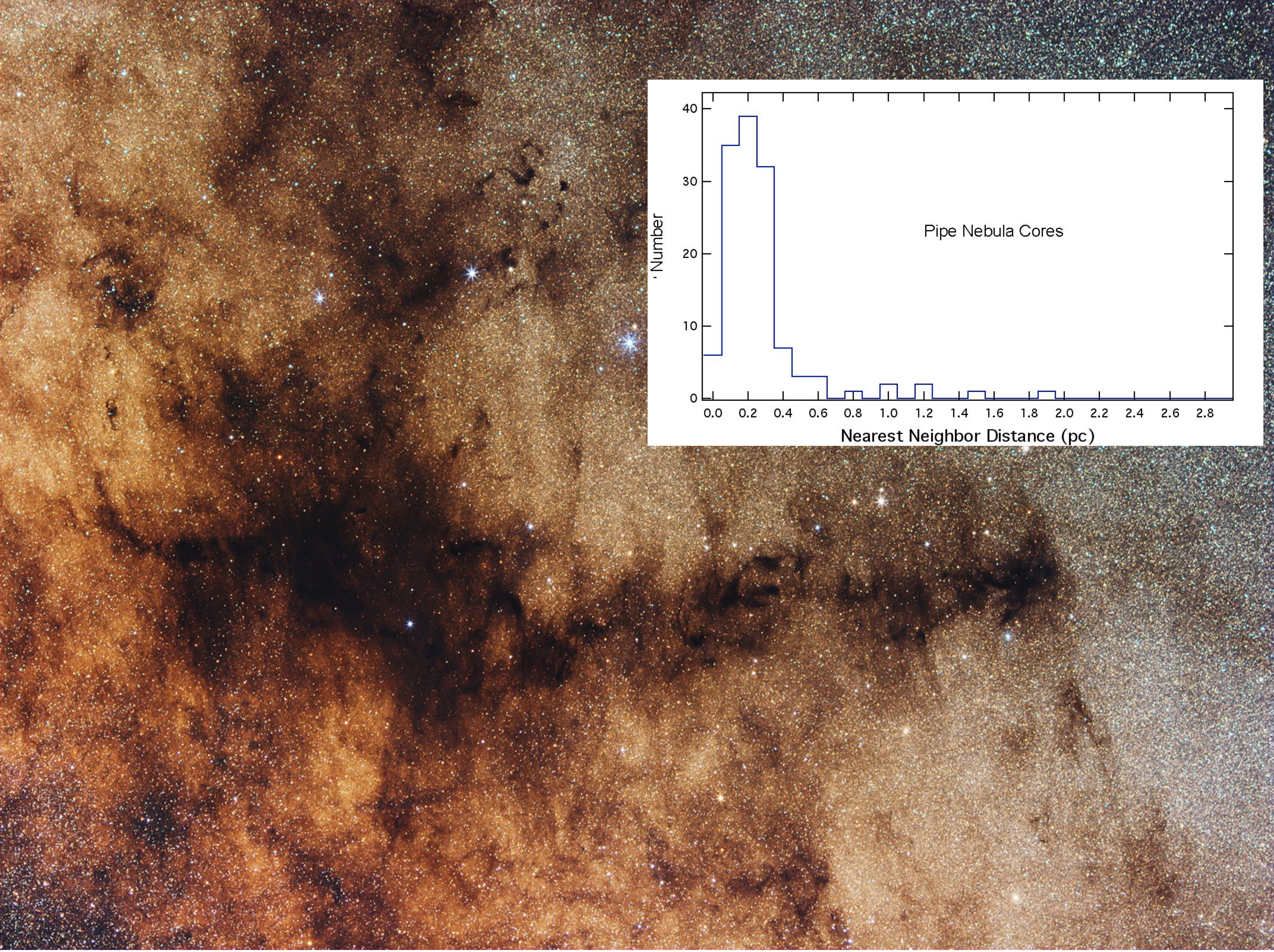
The BE Critical Mass corresponds approximately to the characteristic mass of the core mass function!



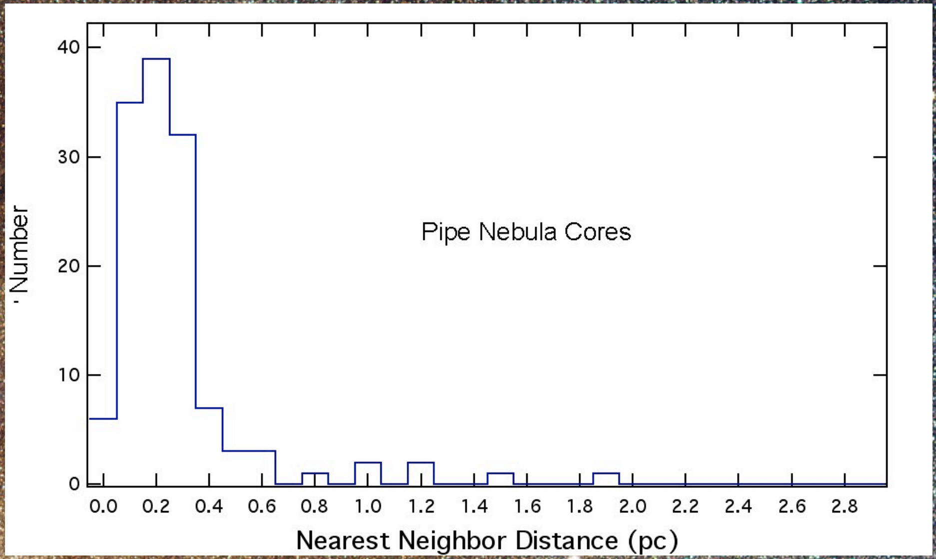




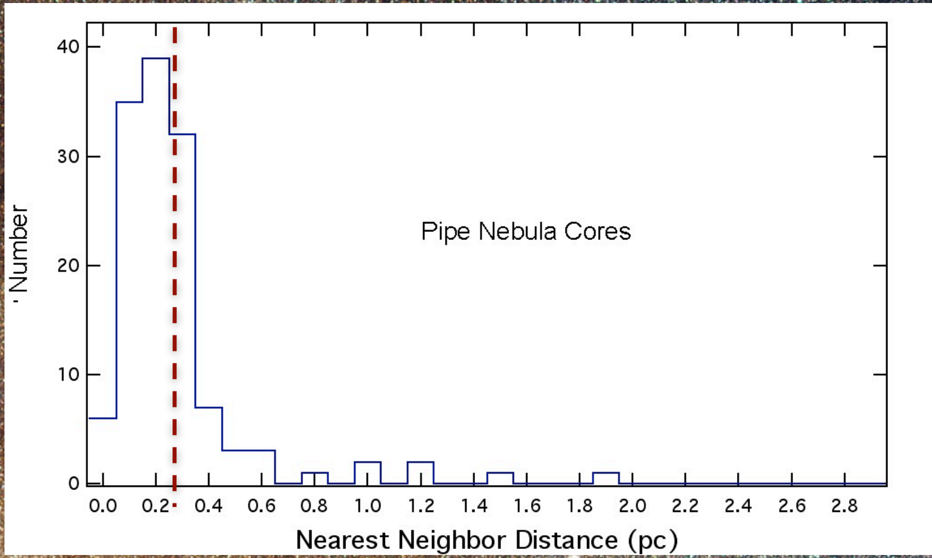
Origin of Cores:
Jeans (thermal) Fragmentation in a Pressurized Medium


Pipe Nebula Cores
Number
Nearest Neighbor Distance (pc)
0.0 0.2 0.4 0.6 0.8 1.0 1.2 1.4 1.6 1.8 2.0 2.2 2.4 2.6 2.8
0 10 20 30 40

Nearest Neighbors



Nearest Neighbors



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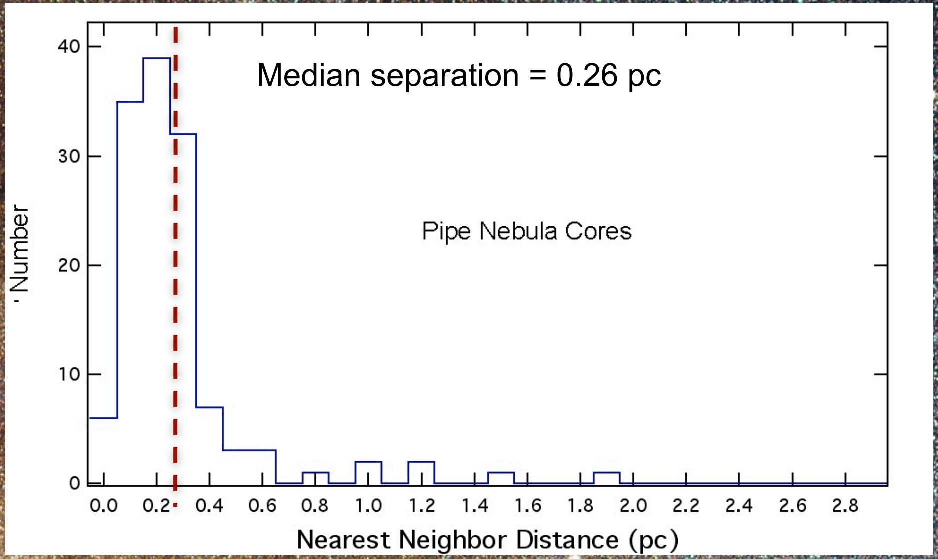

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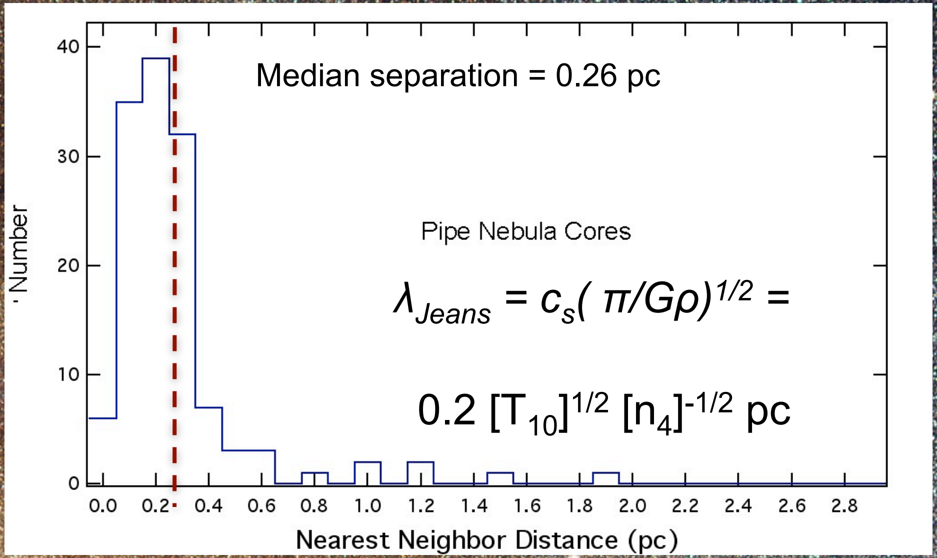

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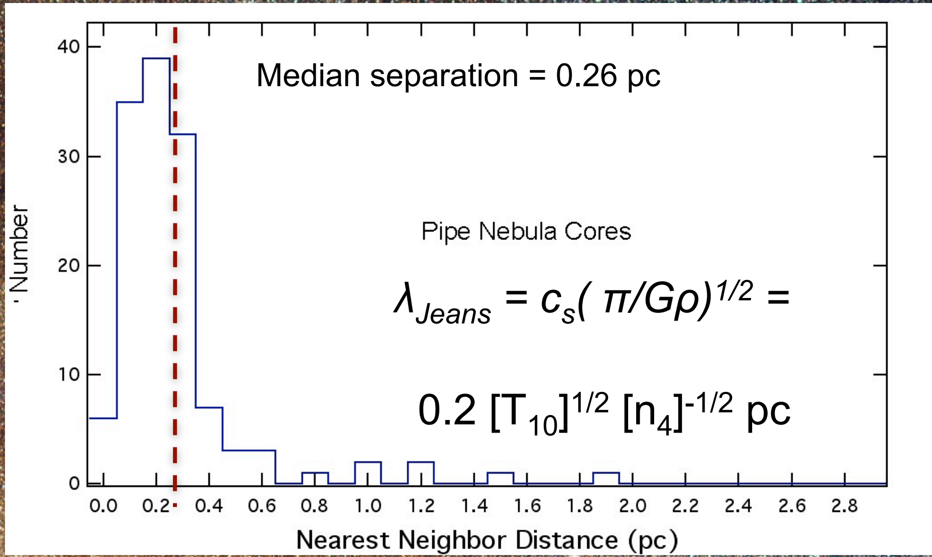

Thermal (Jeans) Fragmentation !

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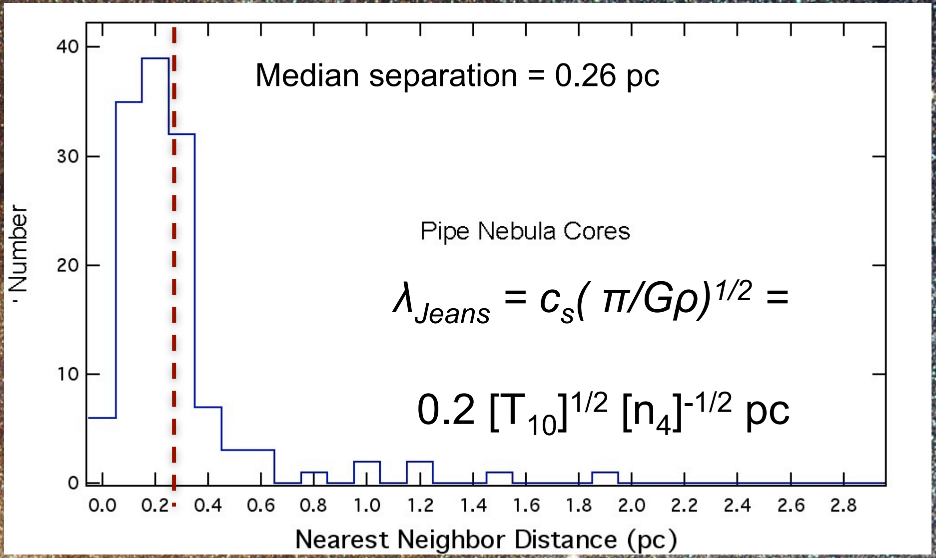
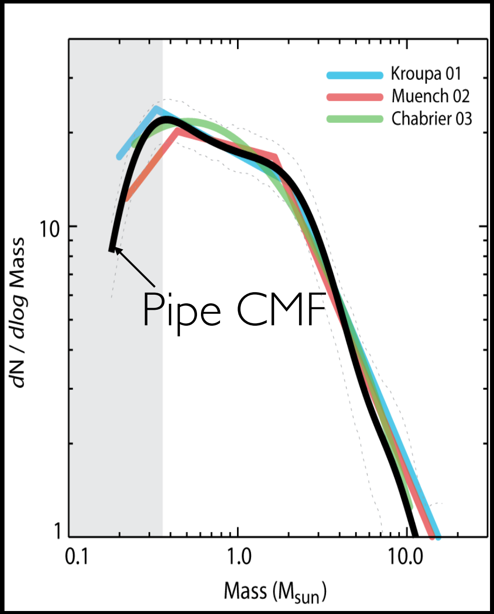


Thermal (Jeans) Fragmentation !

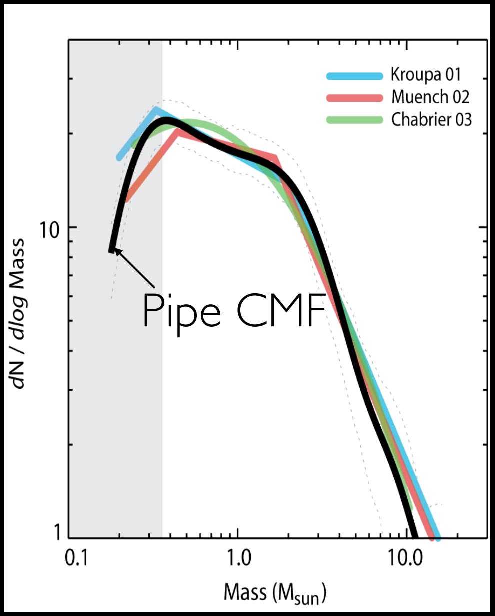
"The Jeans scale must therefore play a key role in at least the final stages of star formation process regardless of what happens during earlier evolution of star-forming clouds." Larson (2005)

On the ORIGIN OF THE CMF/IMF:



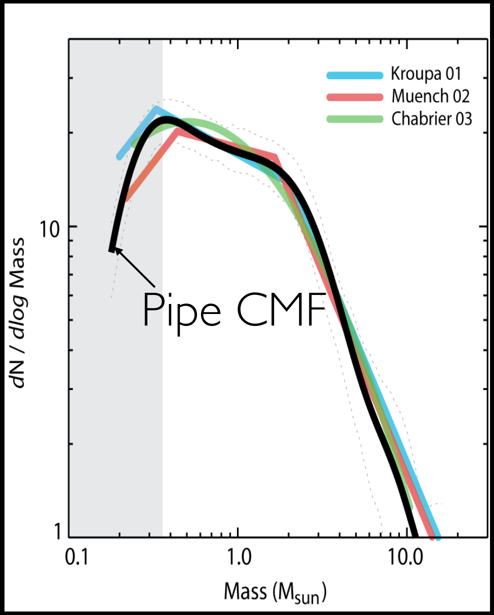
On the ORIGIN OF THE CMF/IMF:

A process of thermal-Jeans fragmentation?



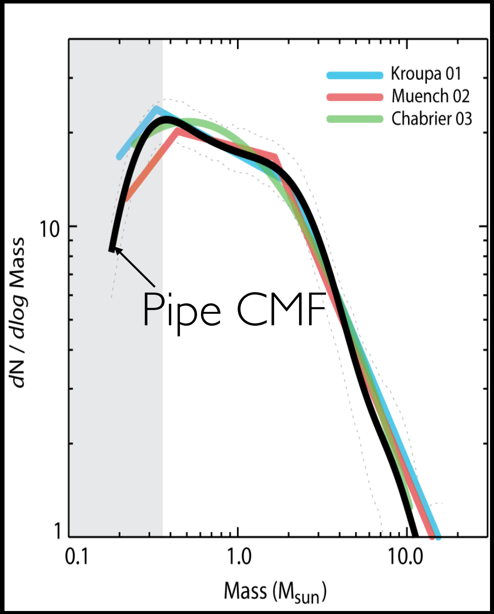
On the ORIGIN OF THE CMF/IMF:

$$\mathrm{CMF}\{\log m\} = c_1\, \psi(\log\{m/m_0\},\, s_i);$$



On the ORIGIN OF THE CMF/IMF:

$CMF\{\log m\} = c_1 \psi(\log\{m/m_0\}, s_i);$ $m_0 = m_{BE}$**



$^{**}m_{BE}$ = Constant x a^4 $(P_{surface})^{-0.5}$ Bonnor-Ebert Mass Scale

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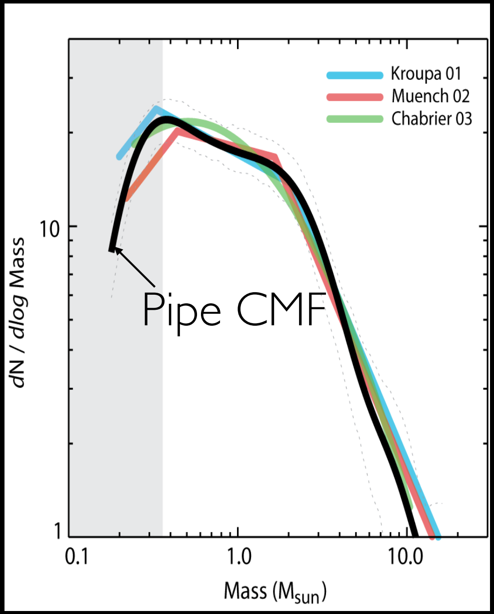

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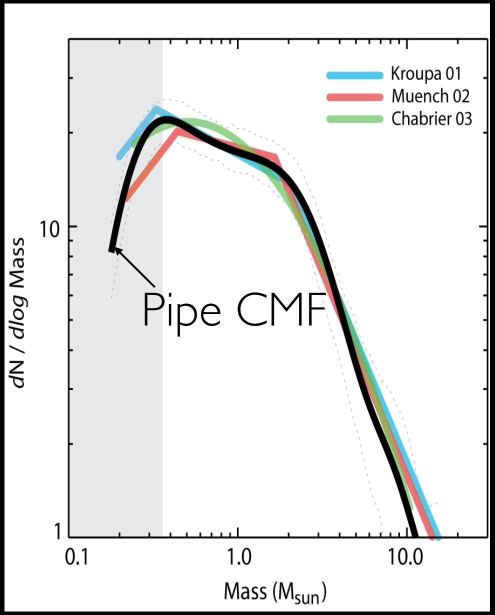

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The Star Formation Rate: Scaling the IMF

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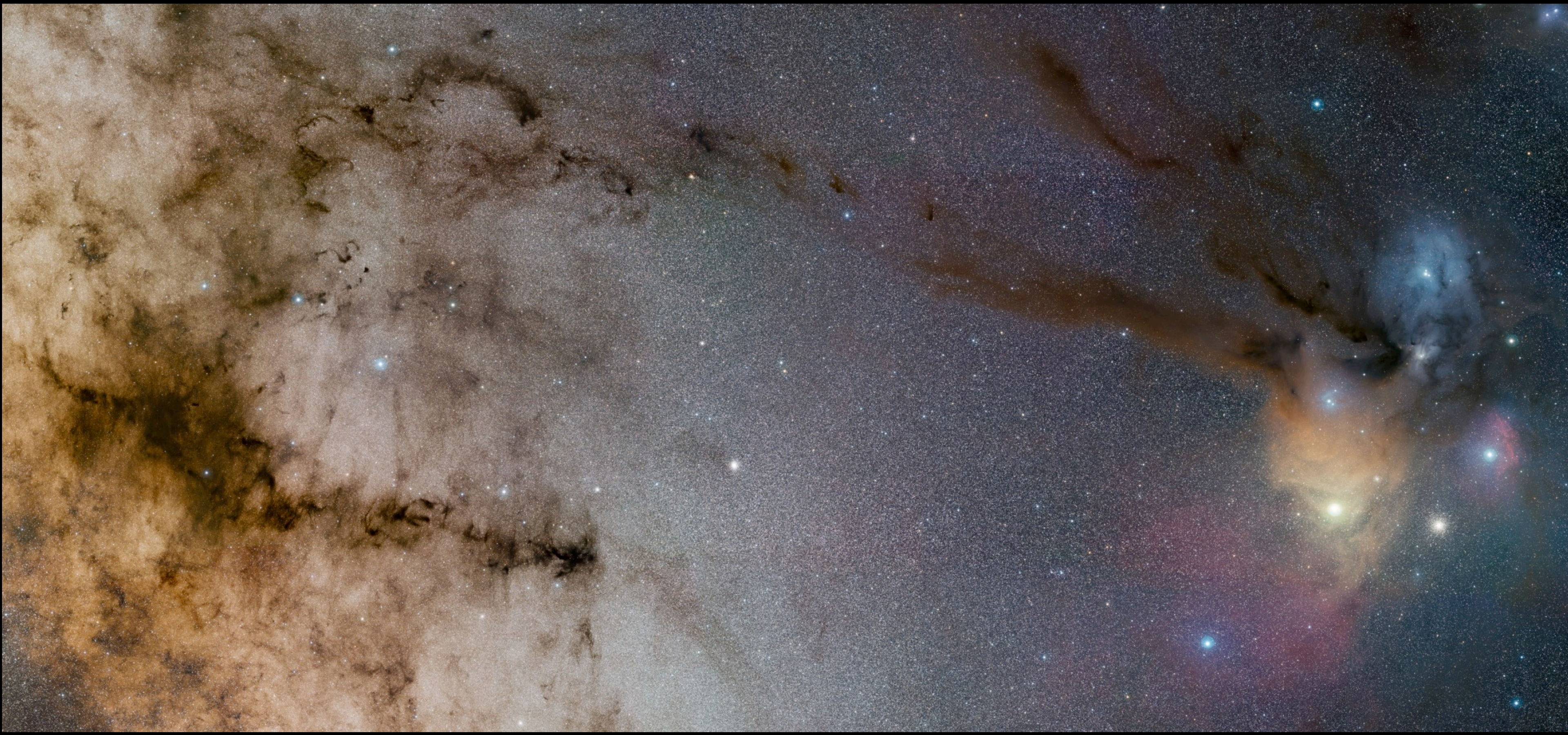
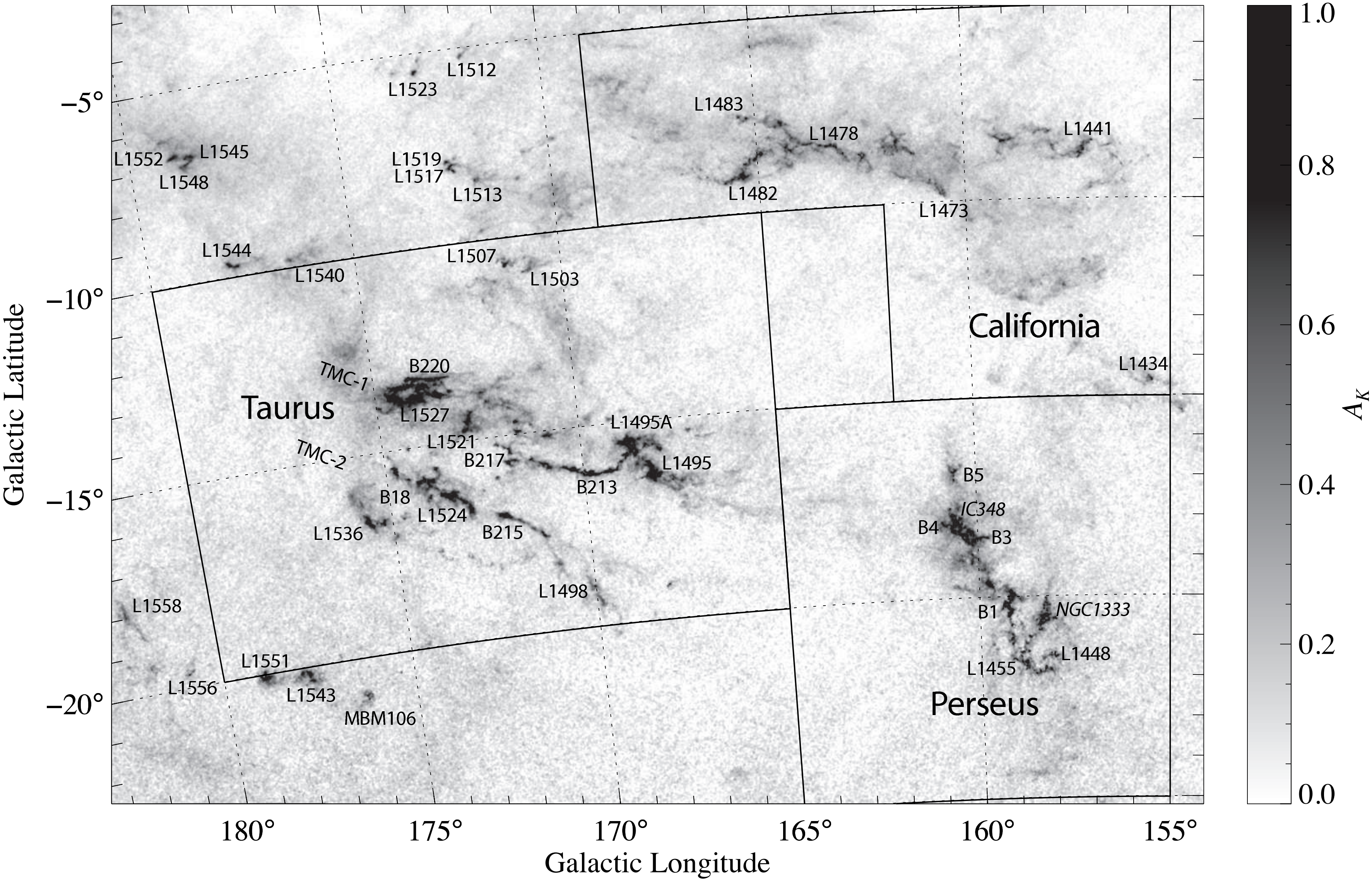
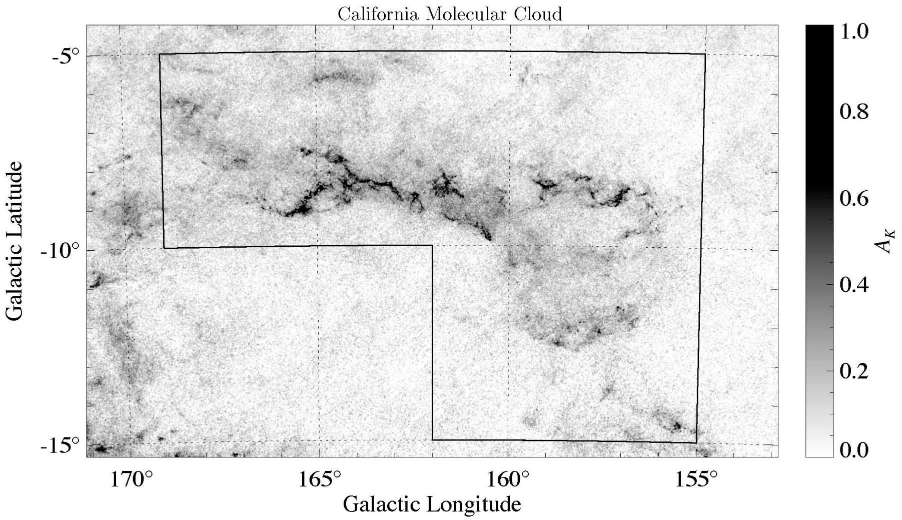


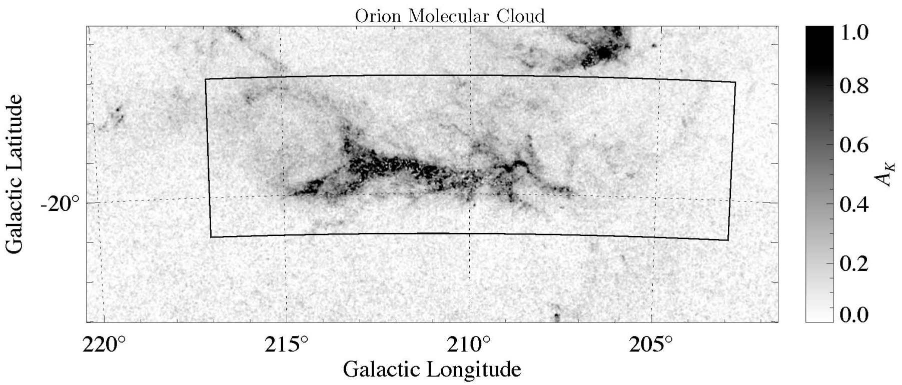
The California Molecular Cloud



Lombardi, Lada & Alves 2009 A&A, in press

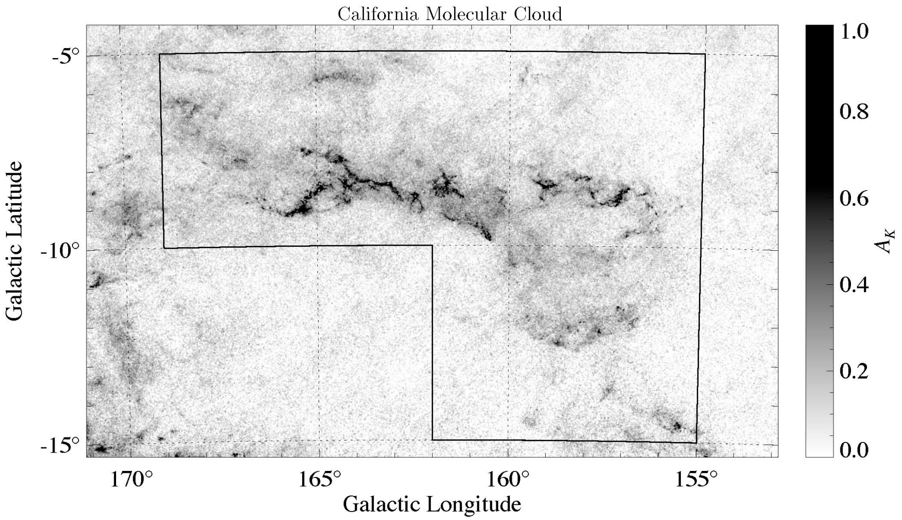
Comparing the California and Orion Molecular Clouds

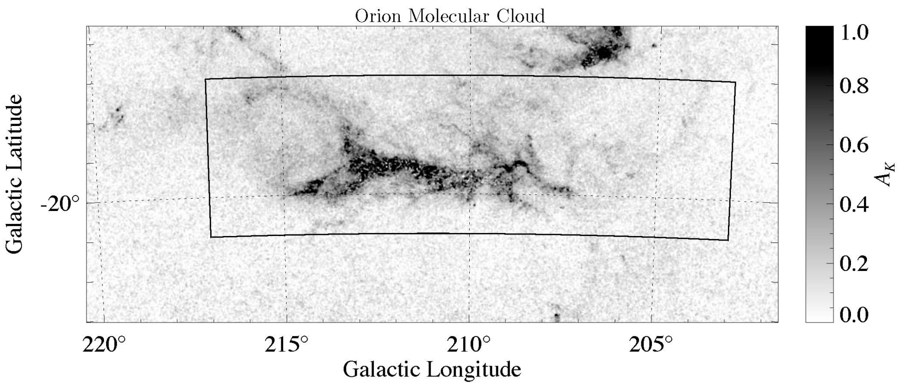




Comparing the California and Orion Molecular Clouds

The two clouds are nearly identical in mass & size





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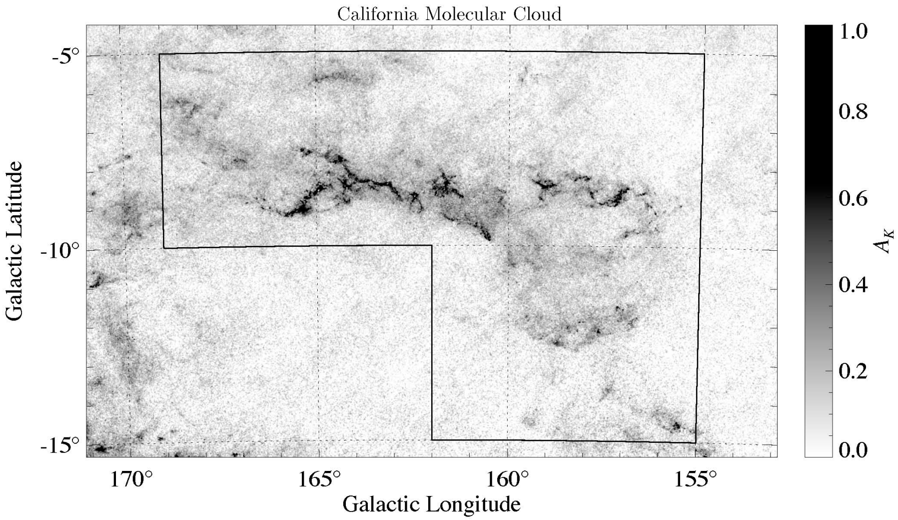

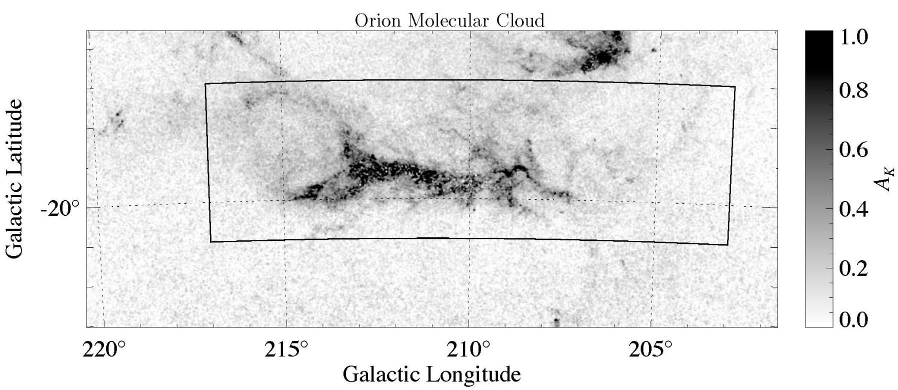

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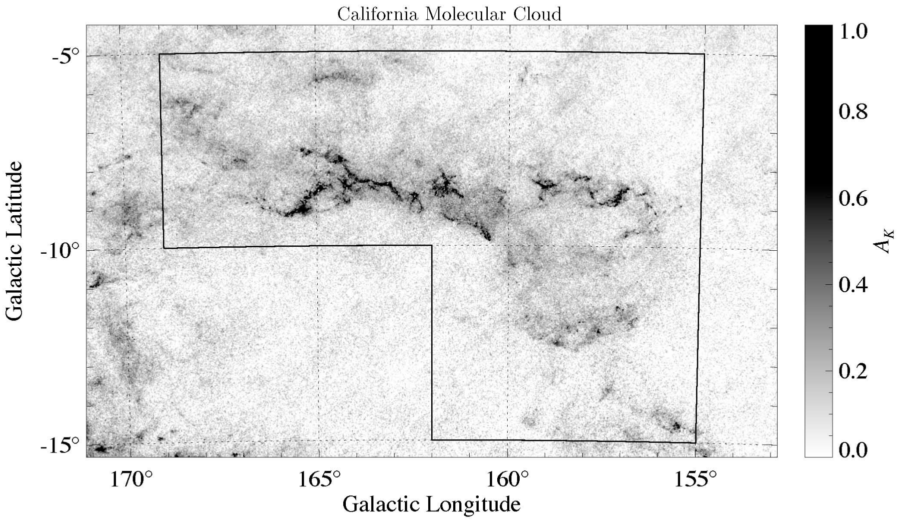

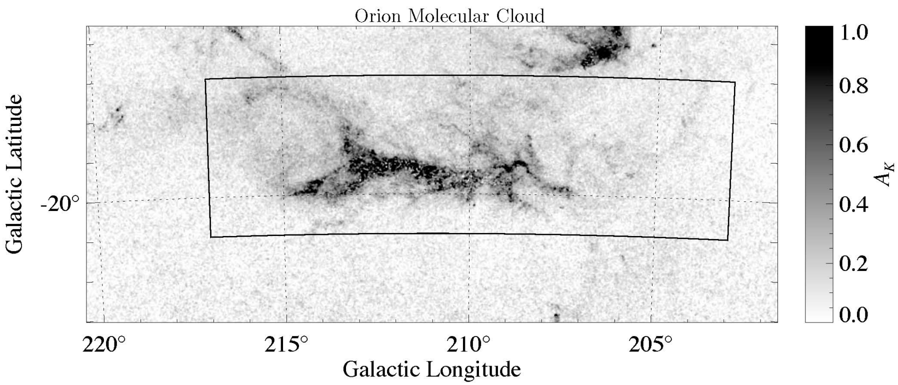

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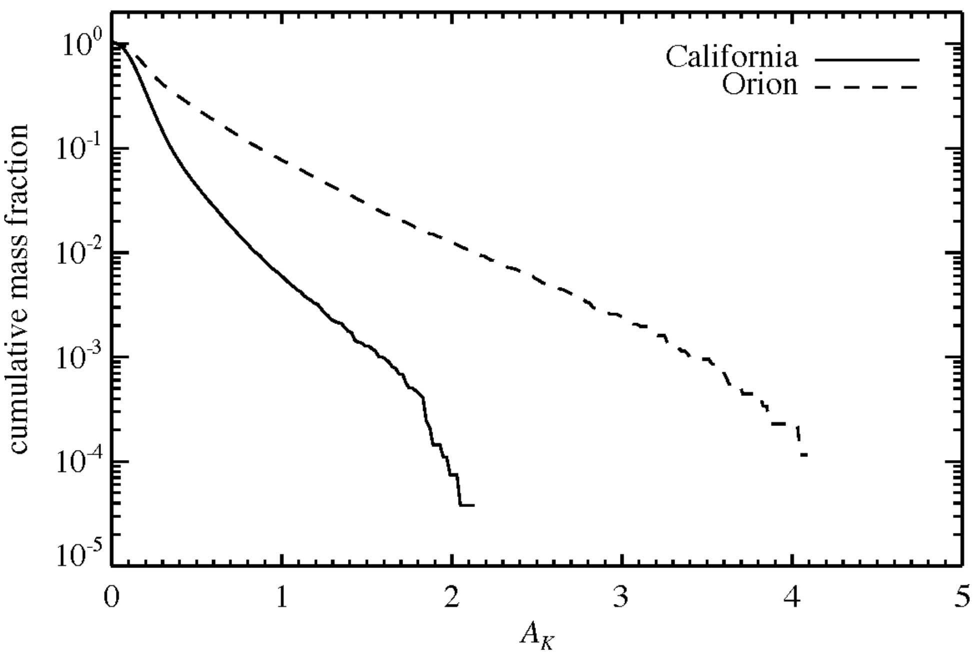

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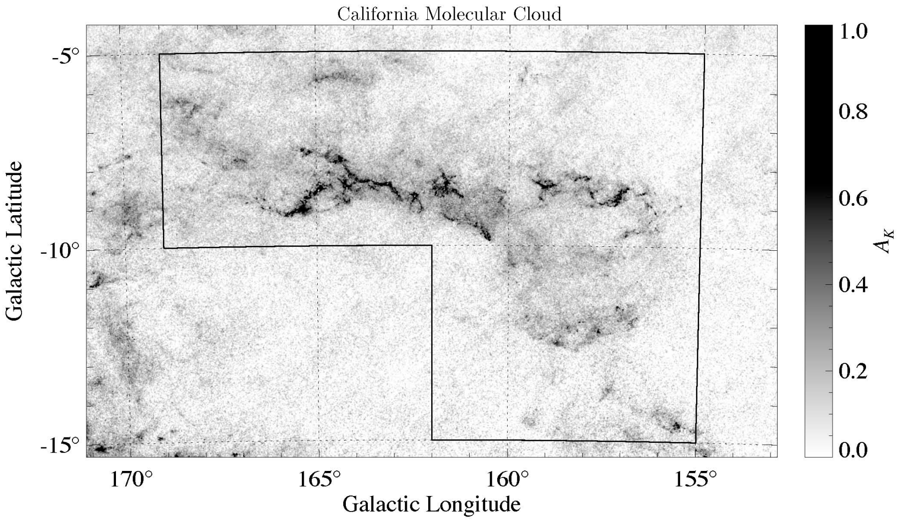

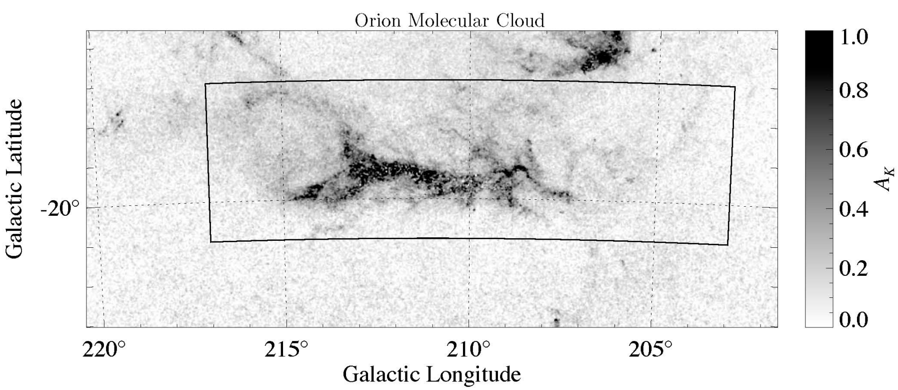

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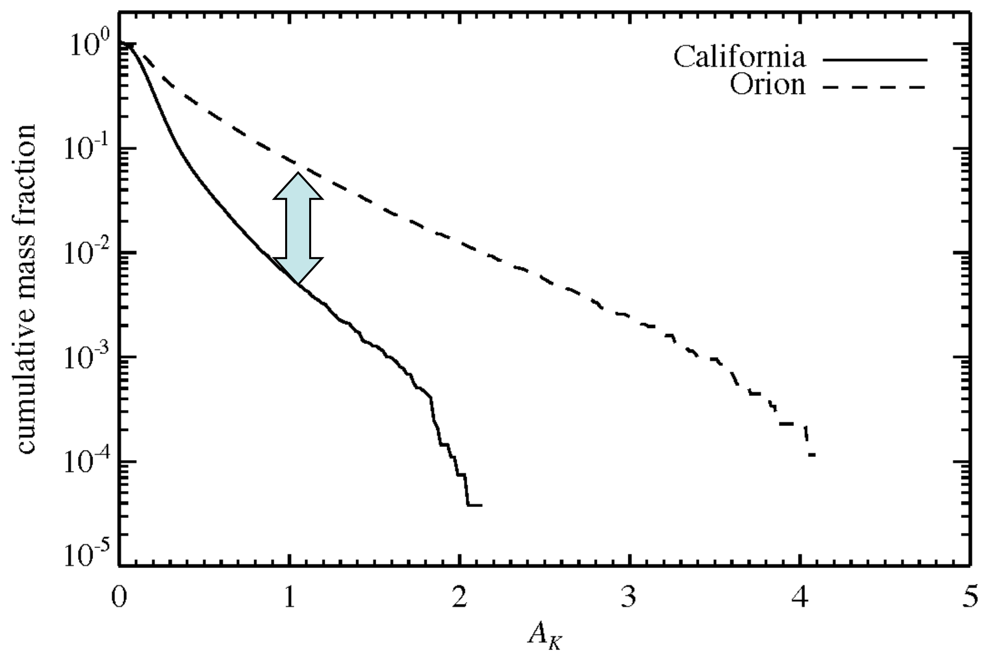

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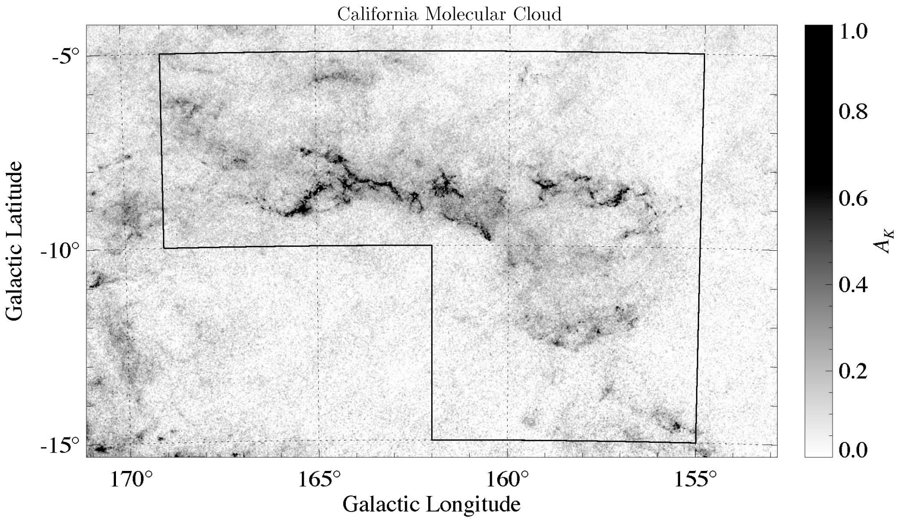

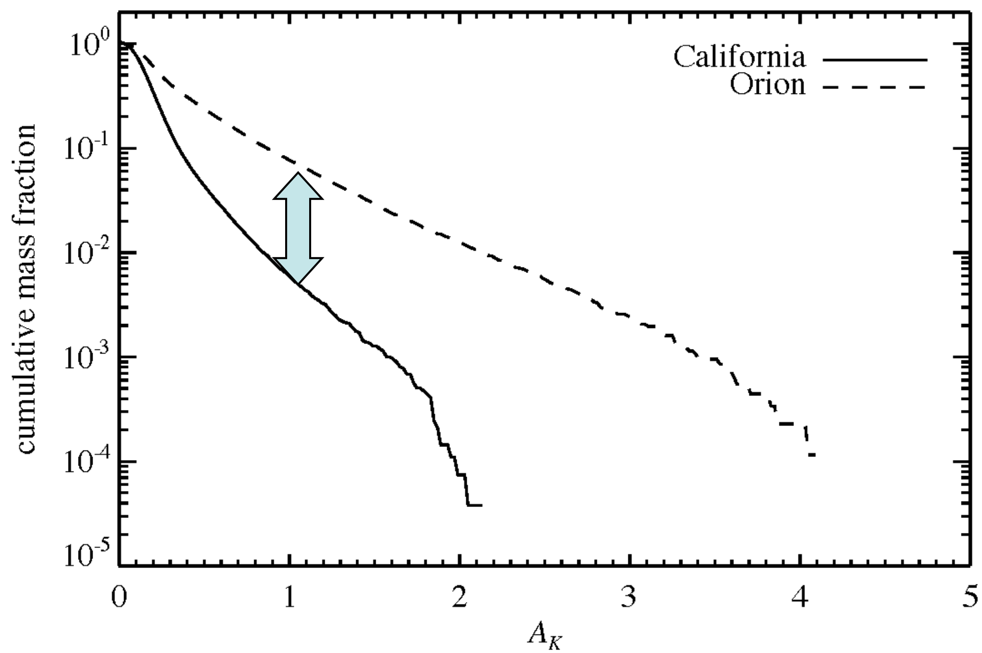

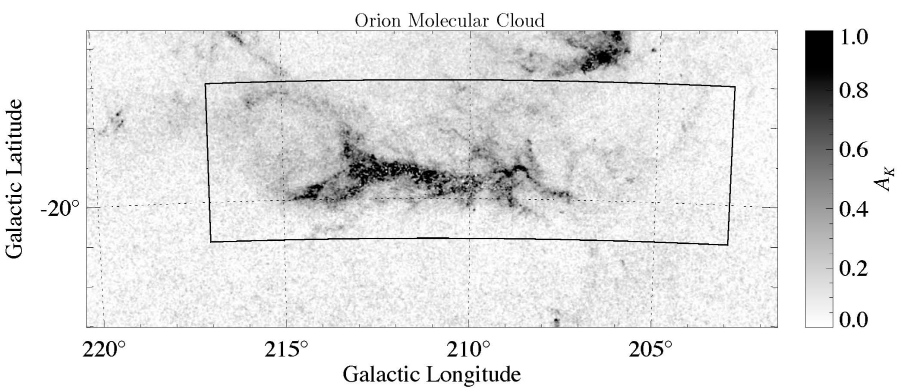

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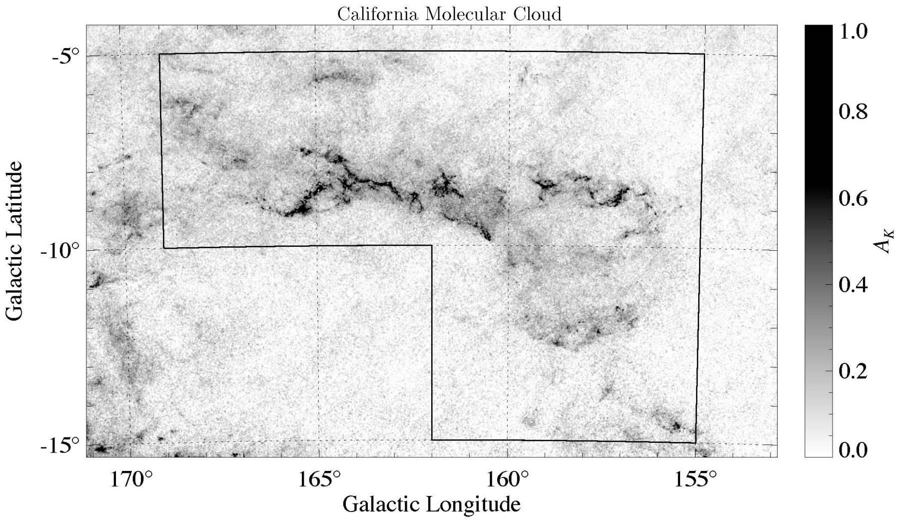

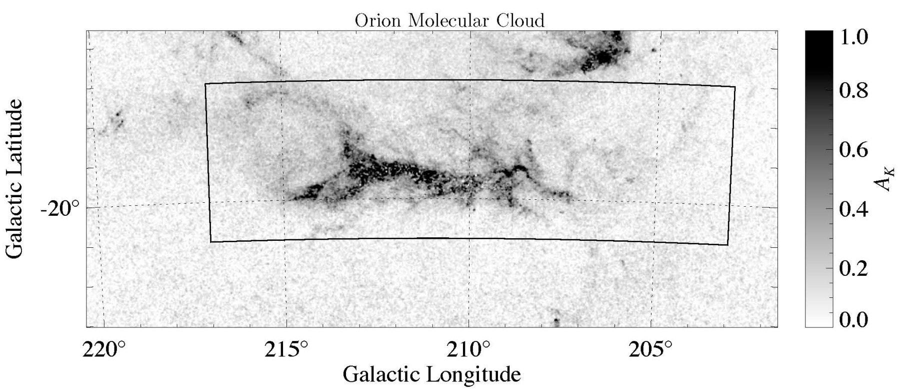

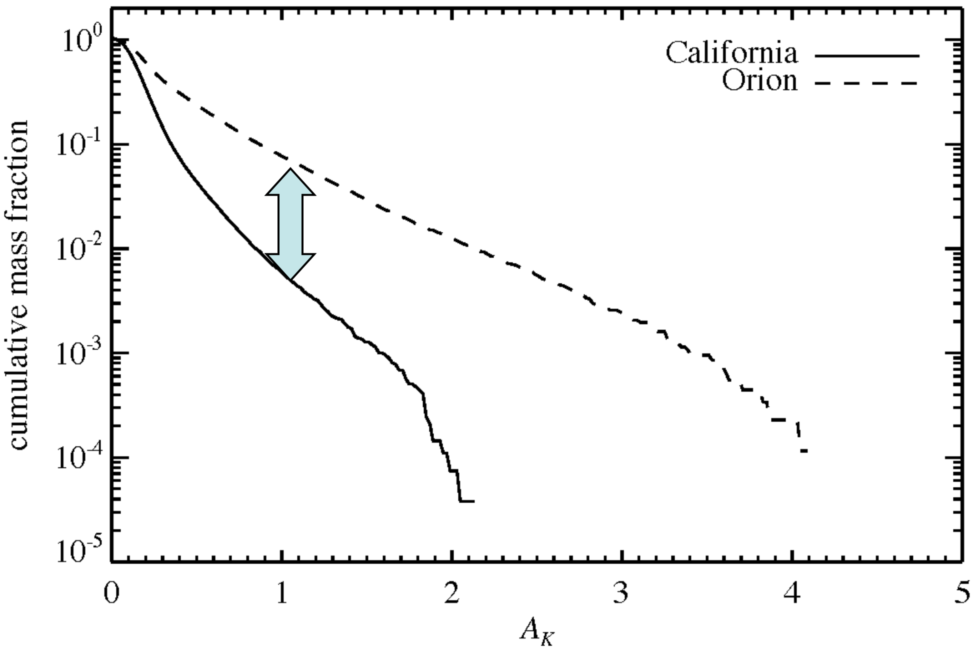

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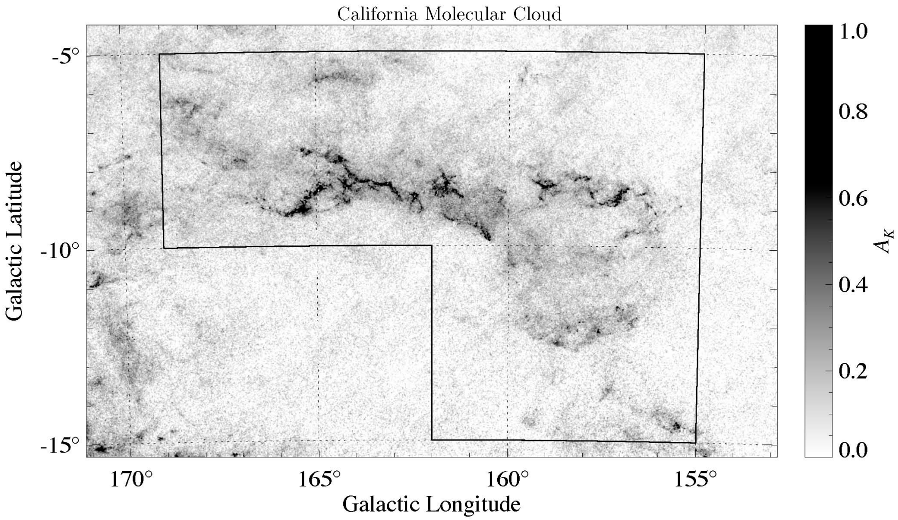

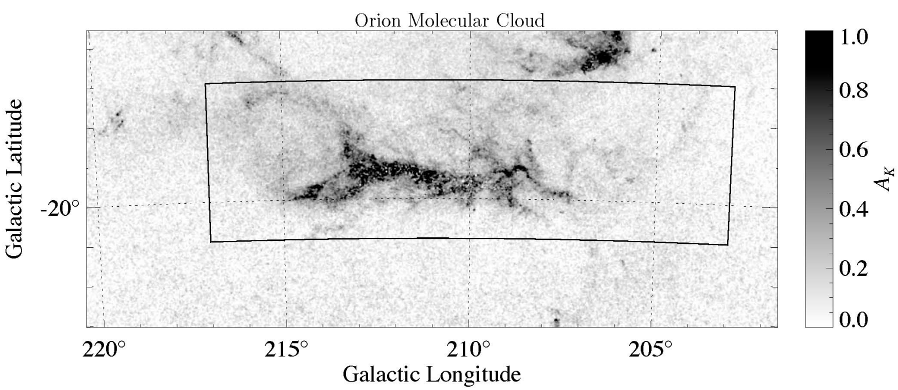

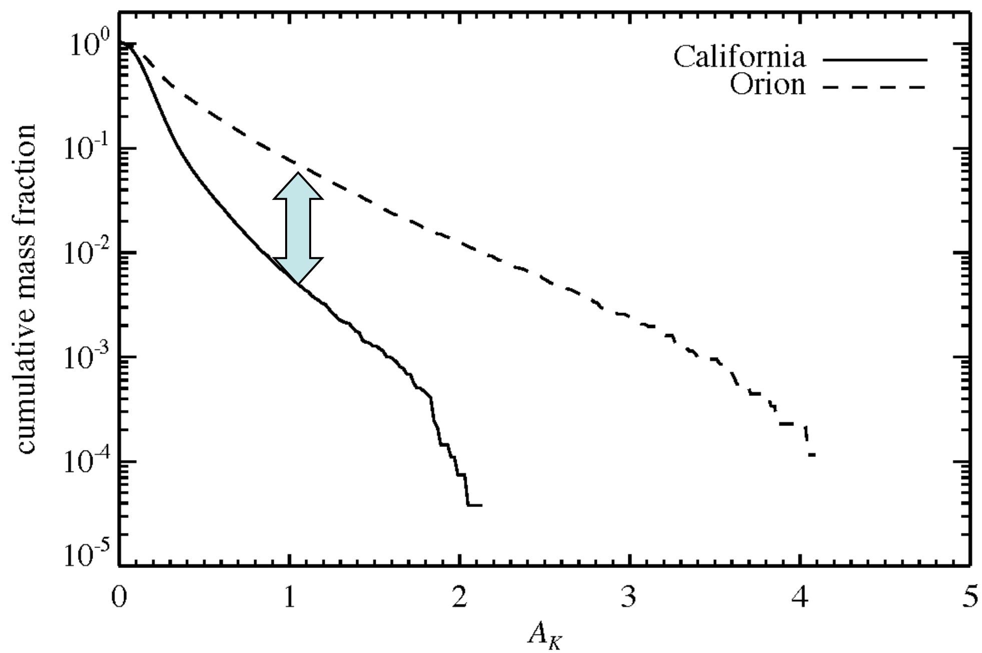

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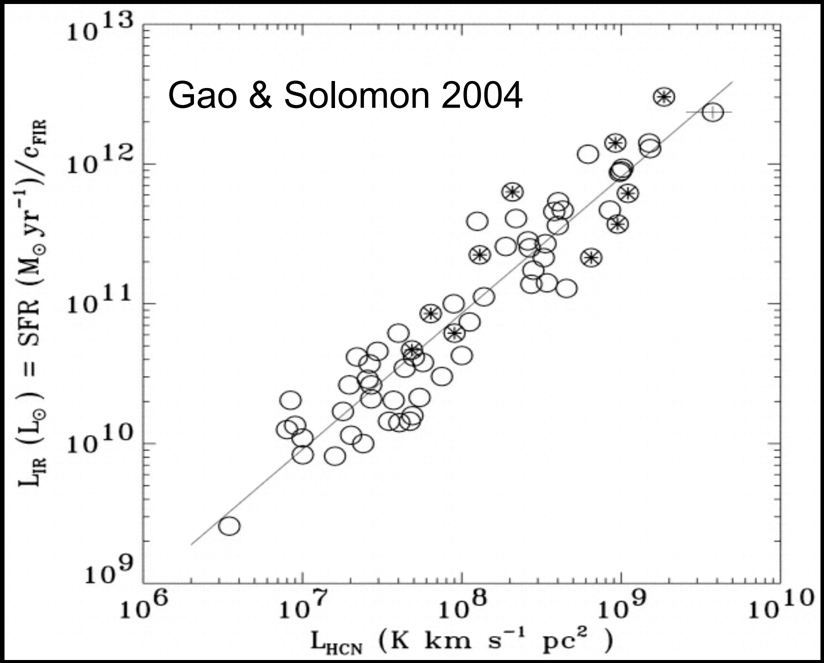
What determines the Star Formation Rate?



In external galaxies global star formation rate correlates directly with amount of dense gas

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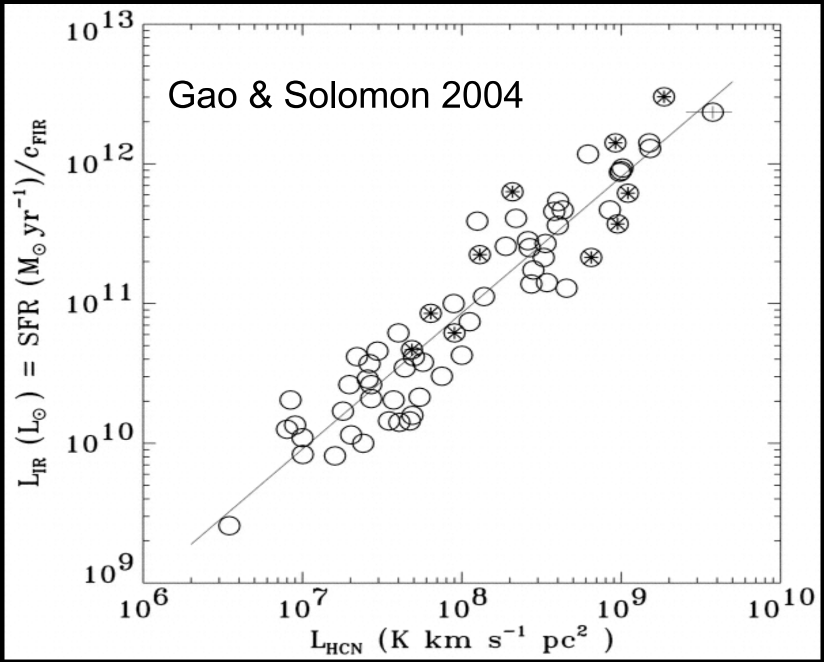
SFR ~ $\mathcal{M}_{DG}$



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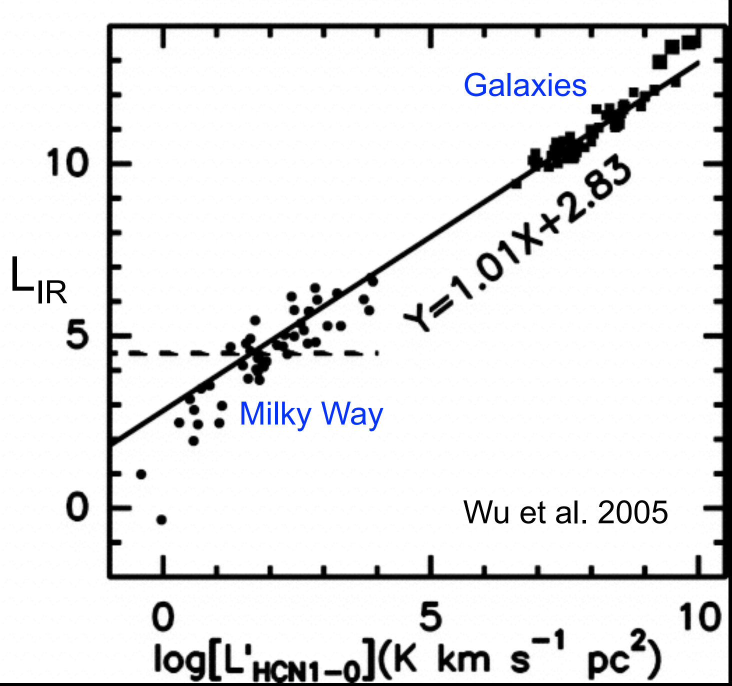

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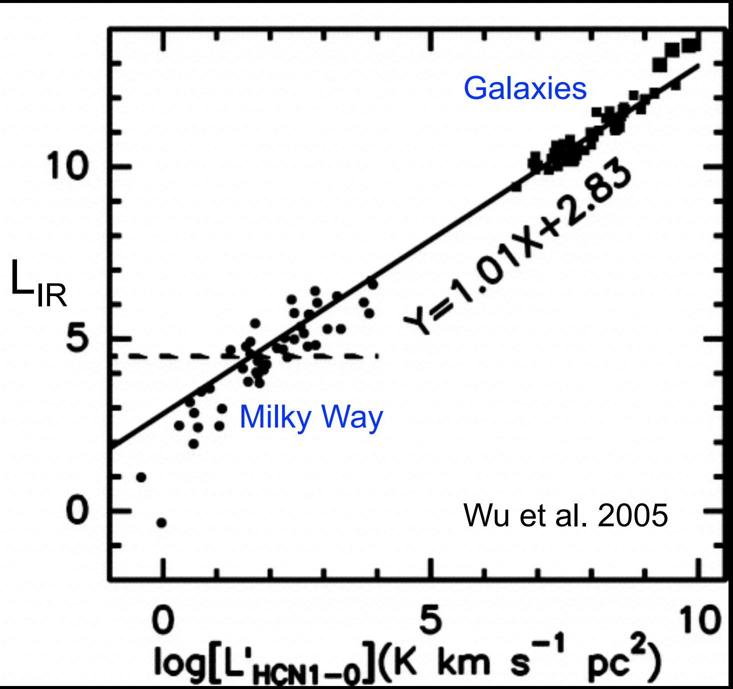

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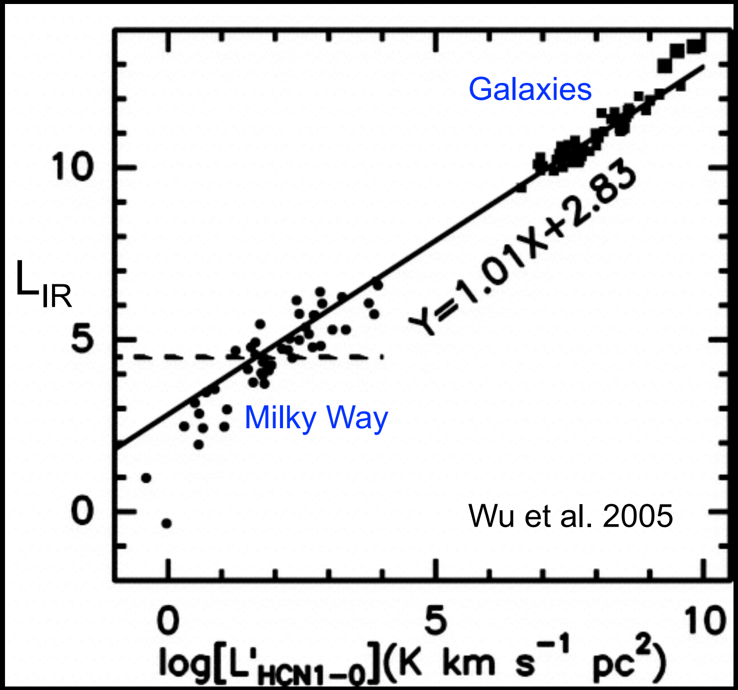

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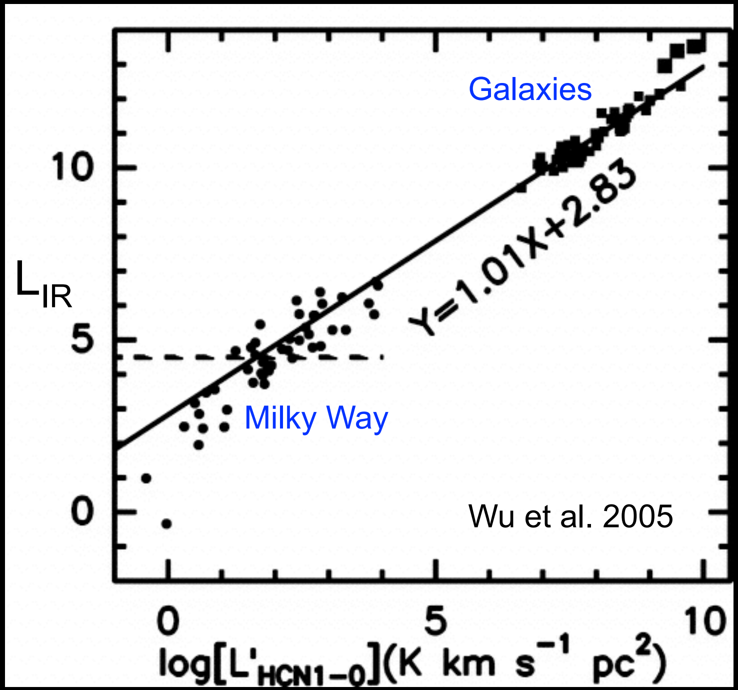

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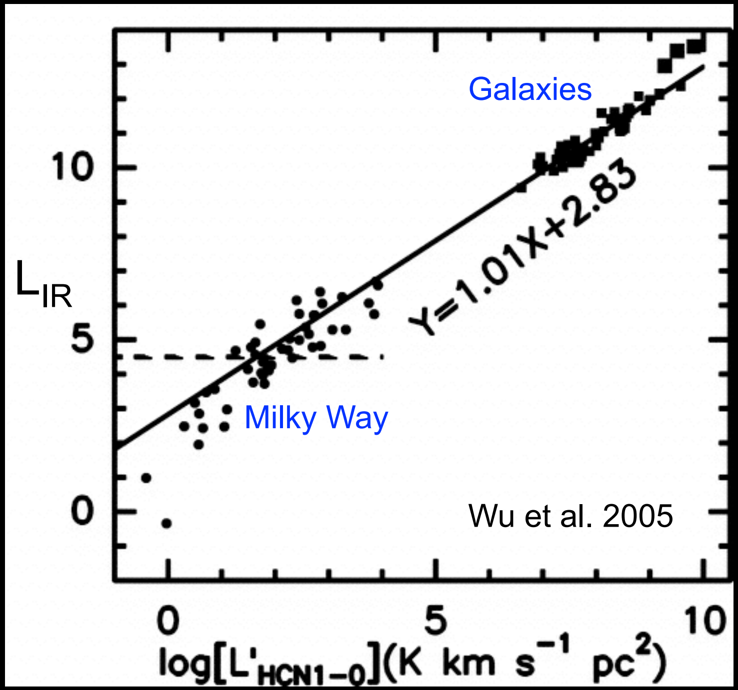

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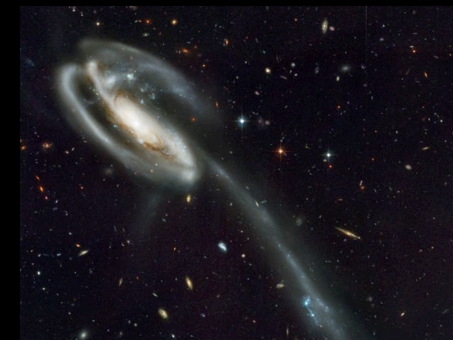

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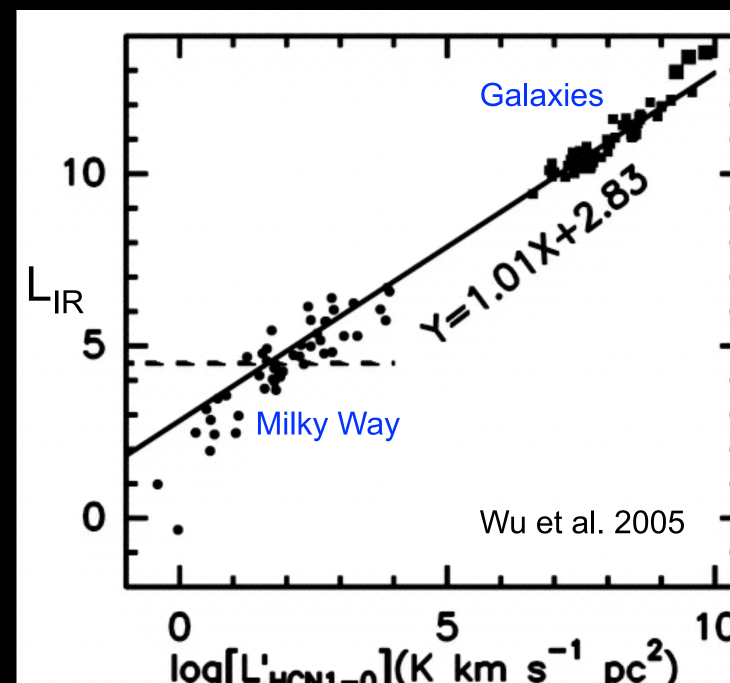

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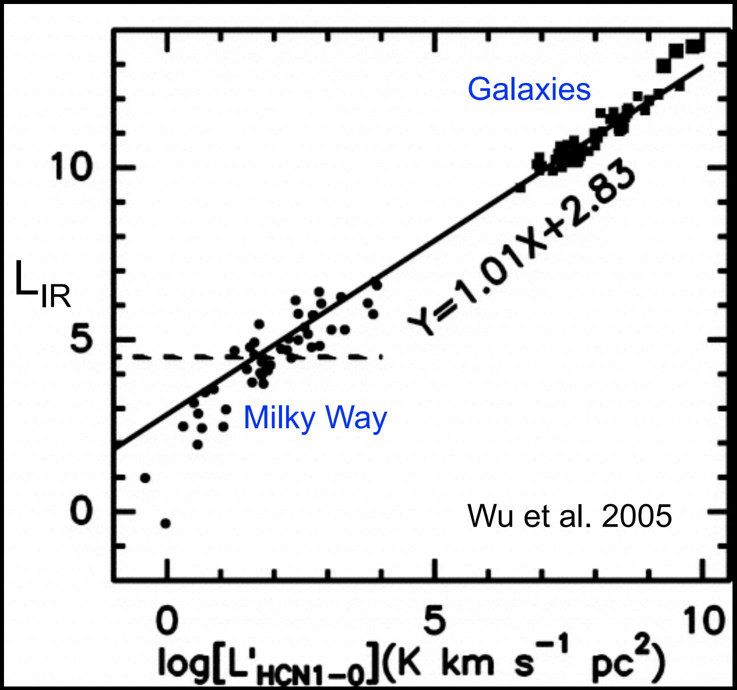

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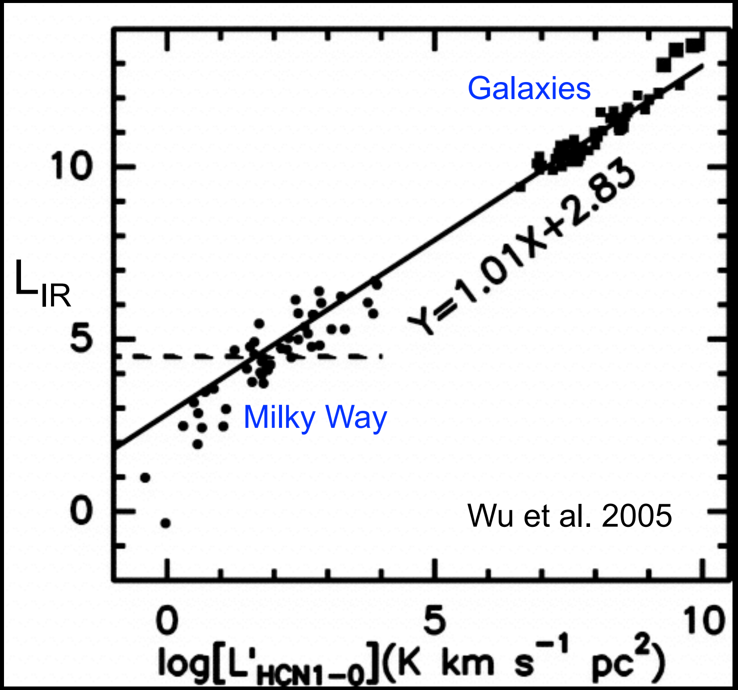

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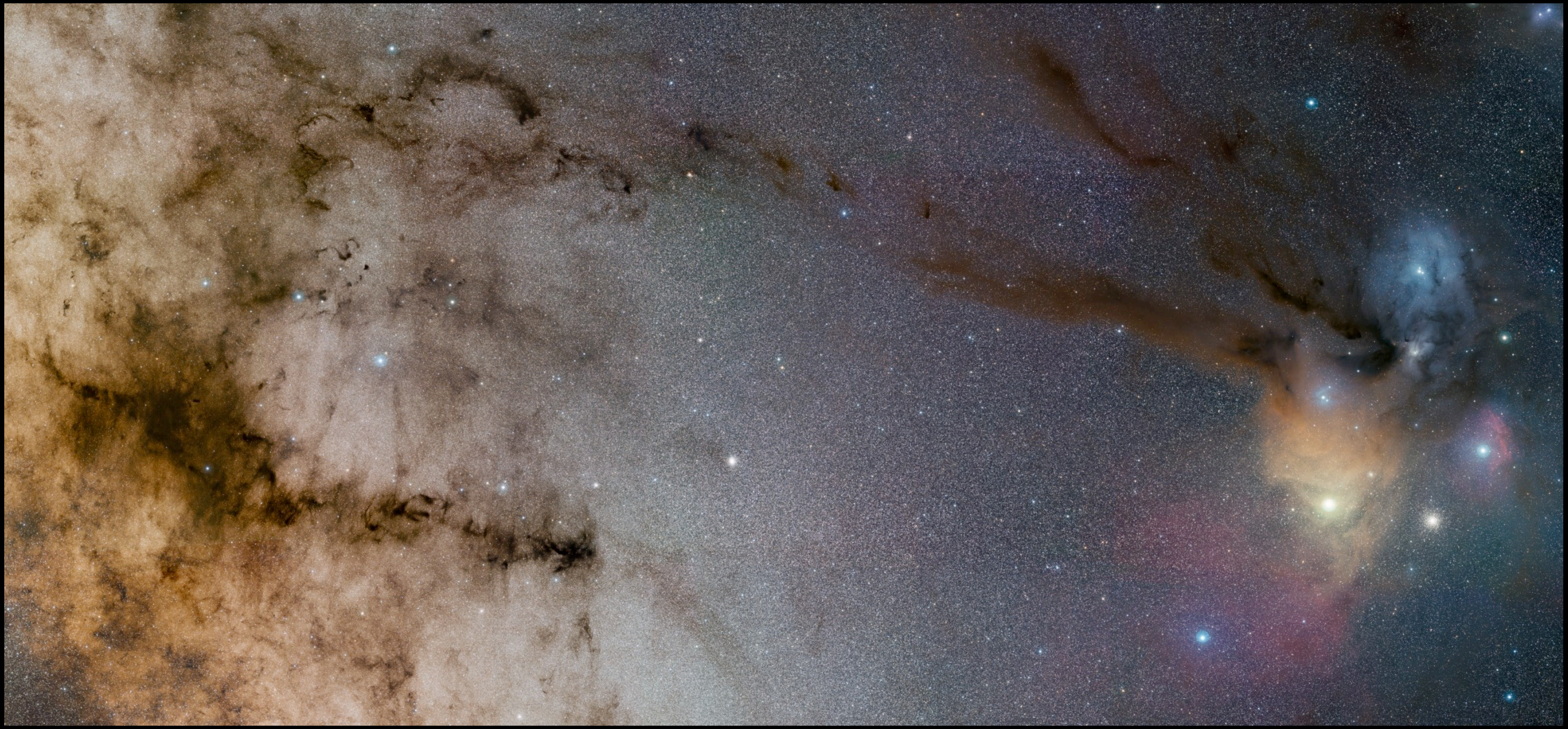

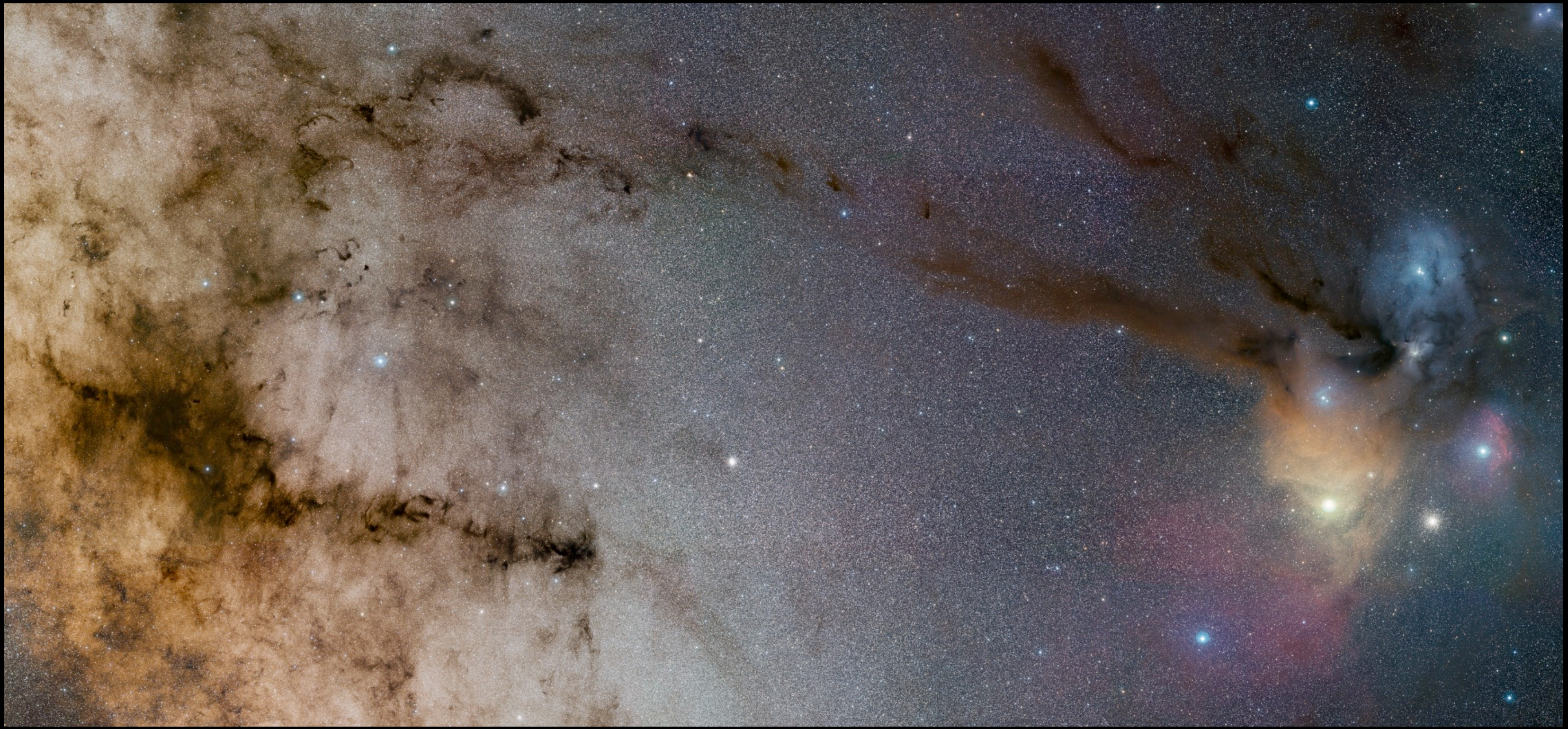


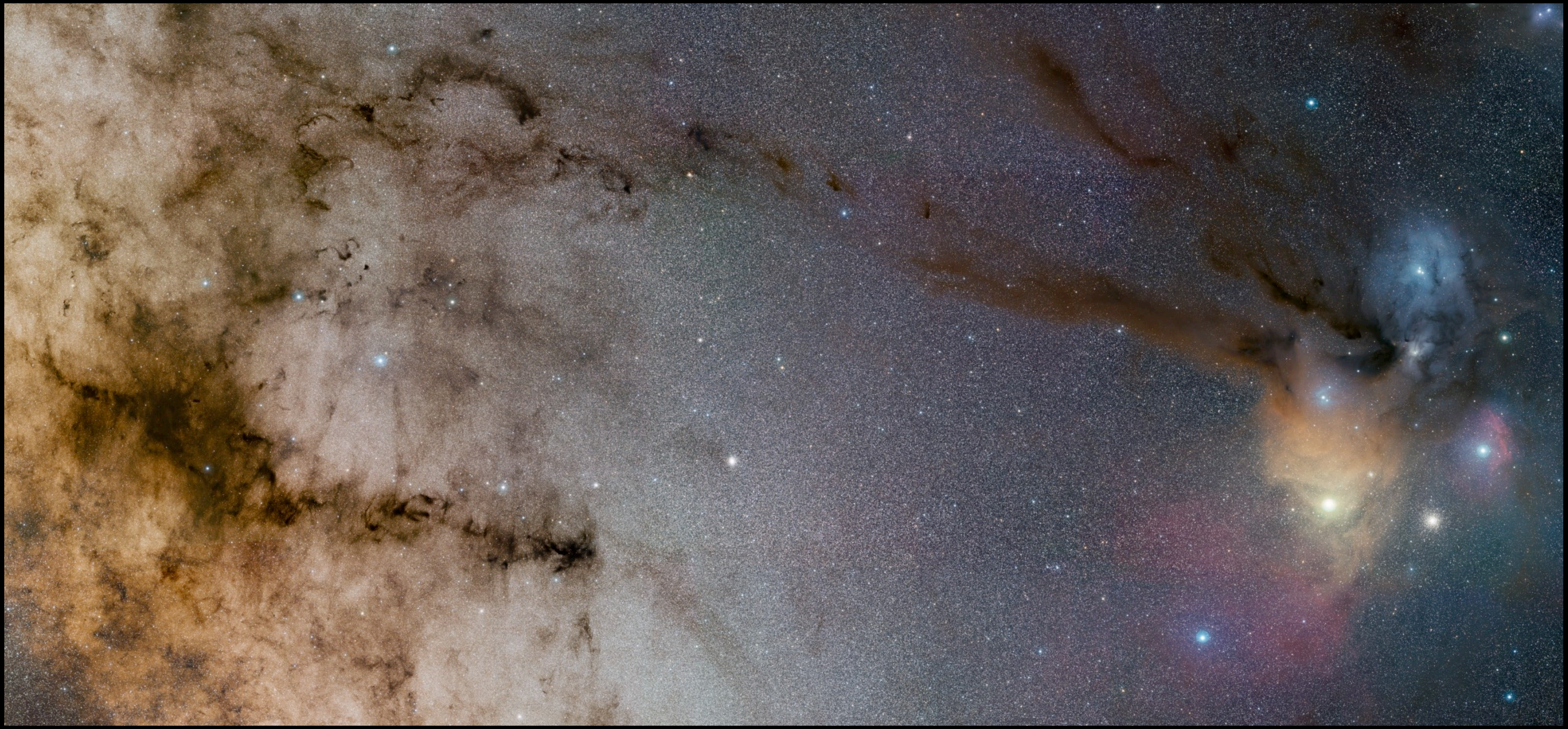

The End

KPNO Summer 1970

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