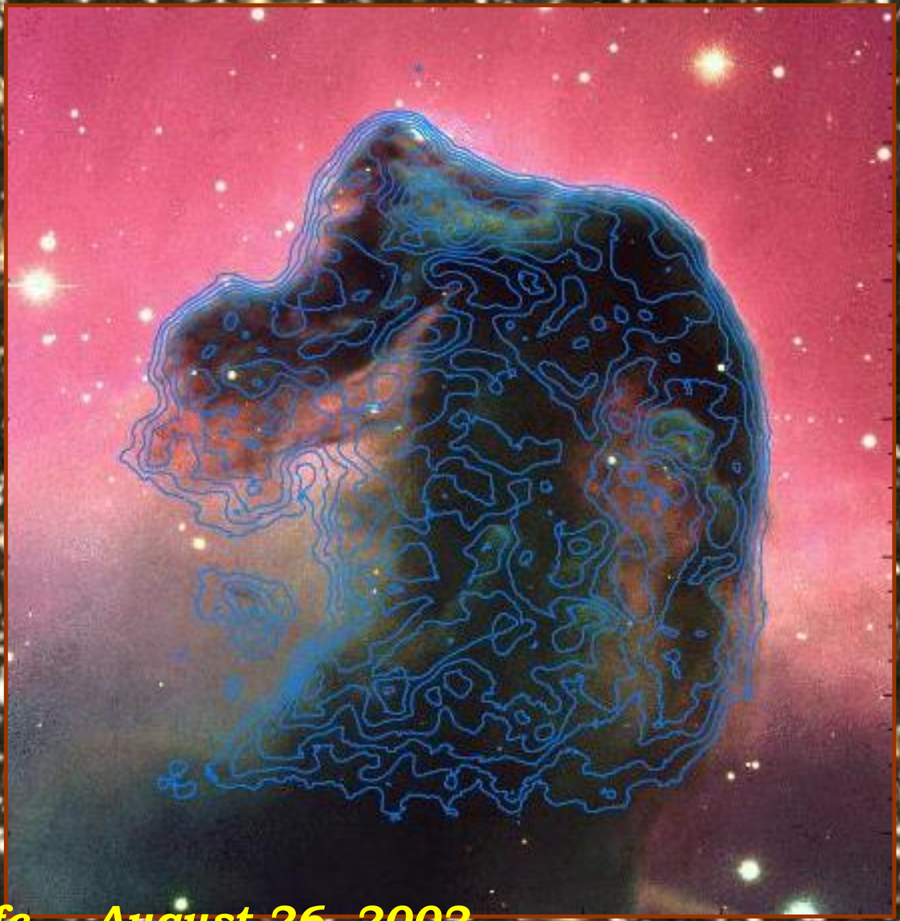
The Early Stages of Star Formation

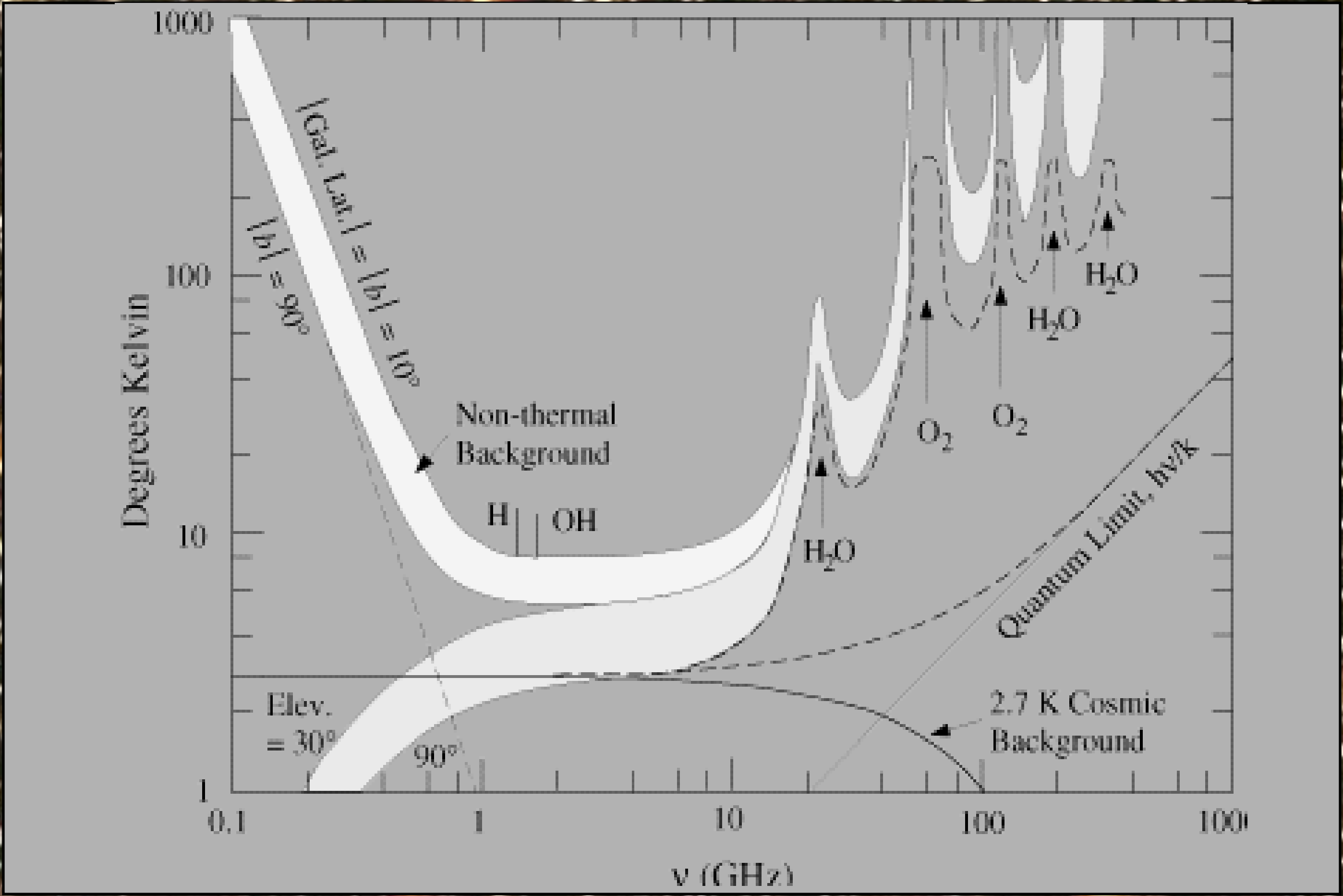
Leo Blitz

UC Berkeley



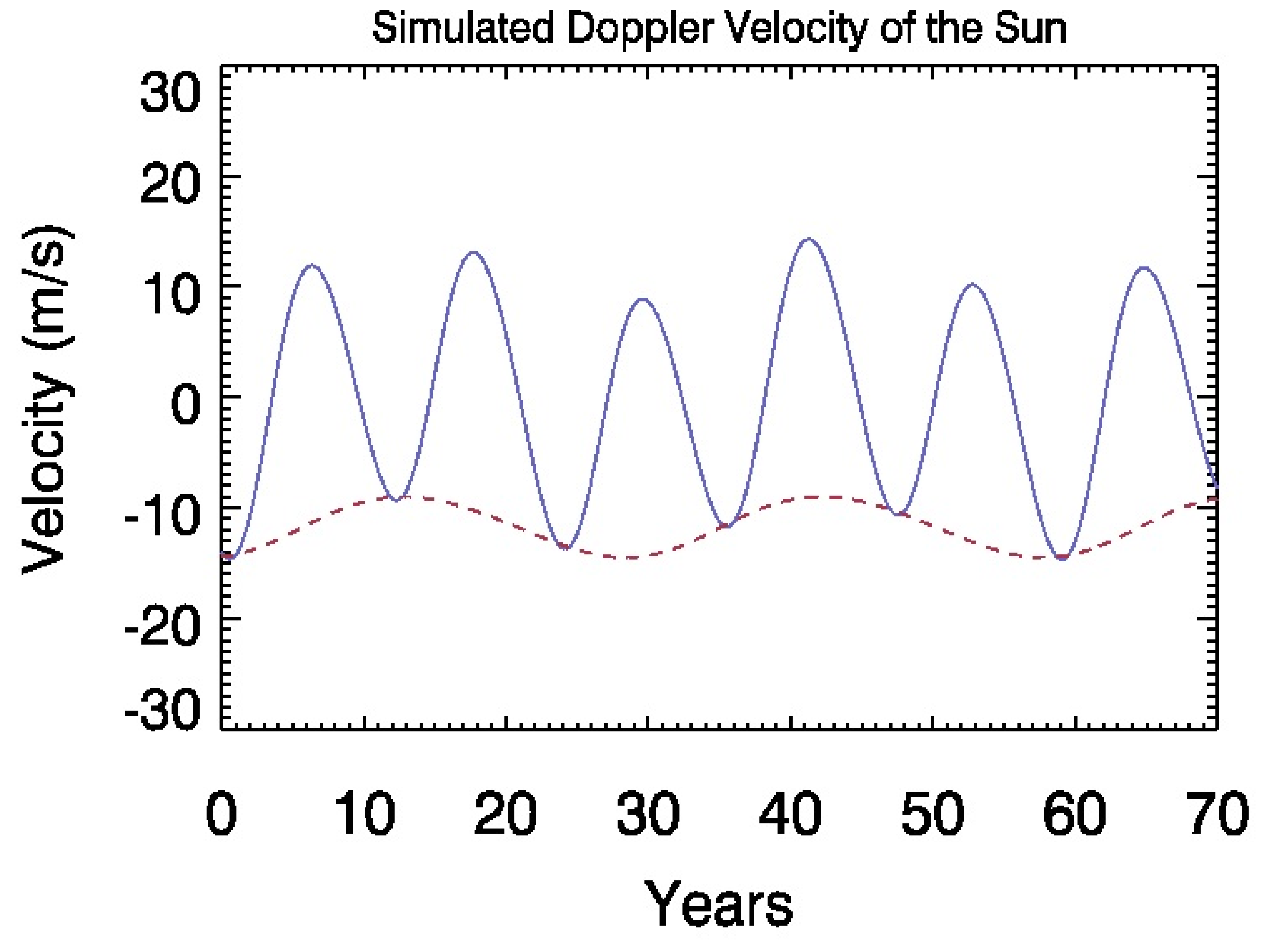
The Allen Telescope front and back

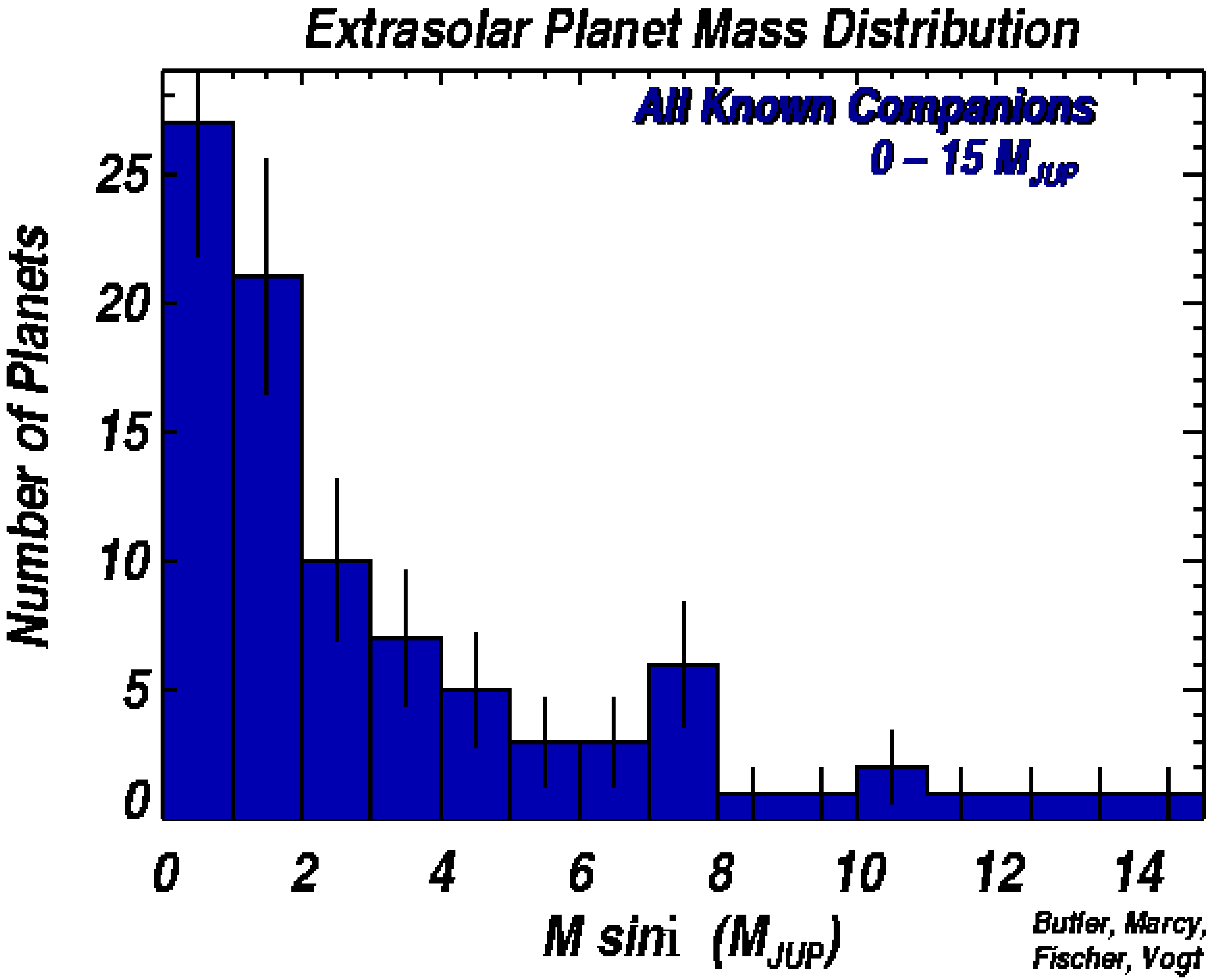
- Microwave search from 500 MHz to 11.2 GHz



Detectability of the Solar System

Precision: 3 m/s

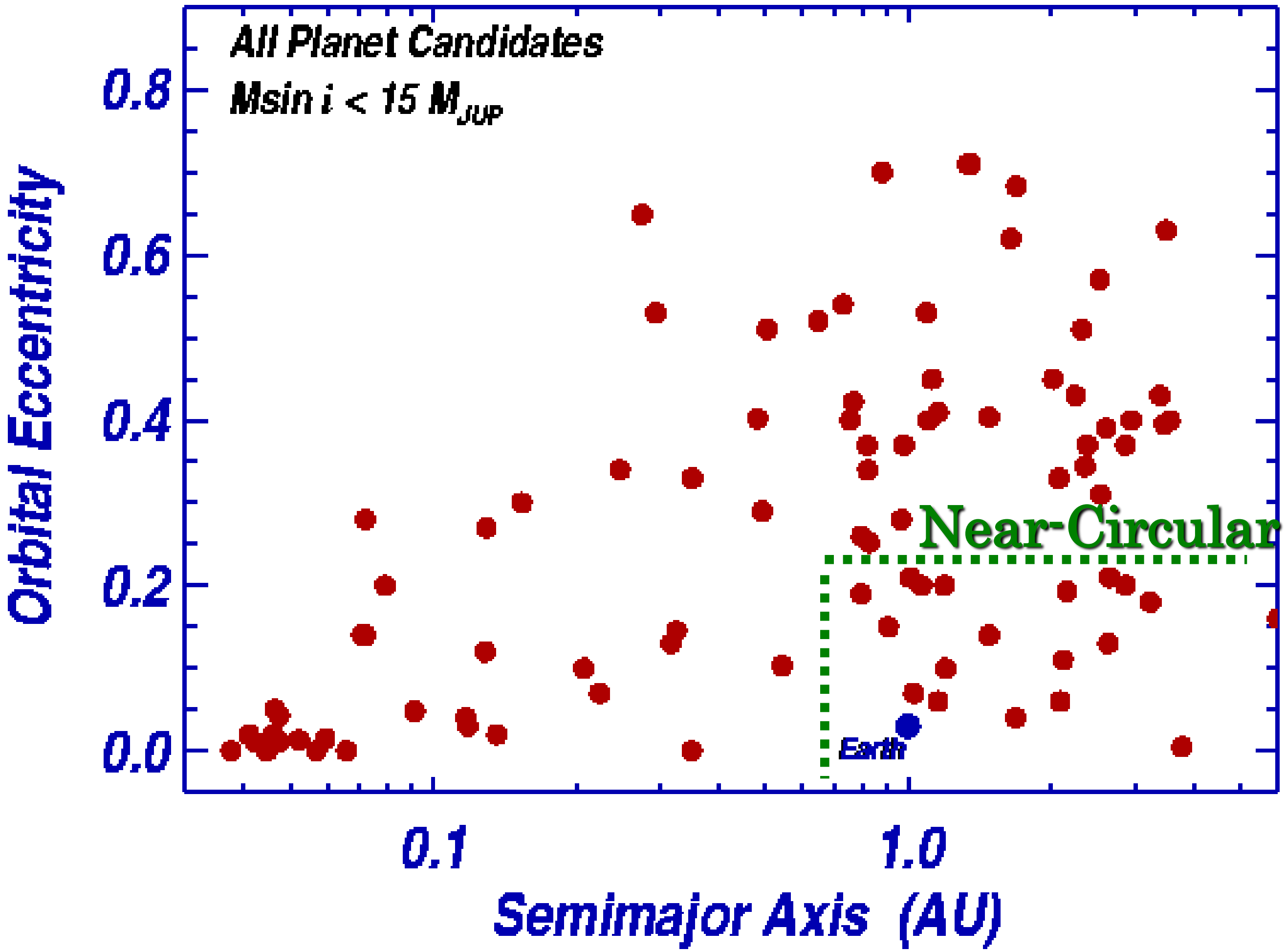


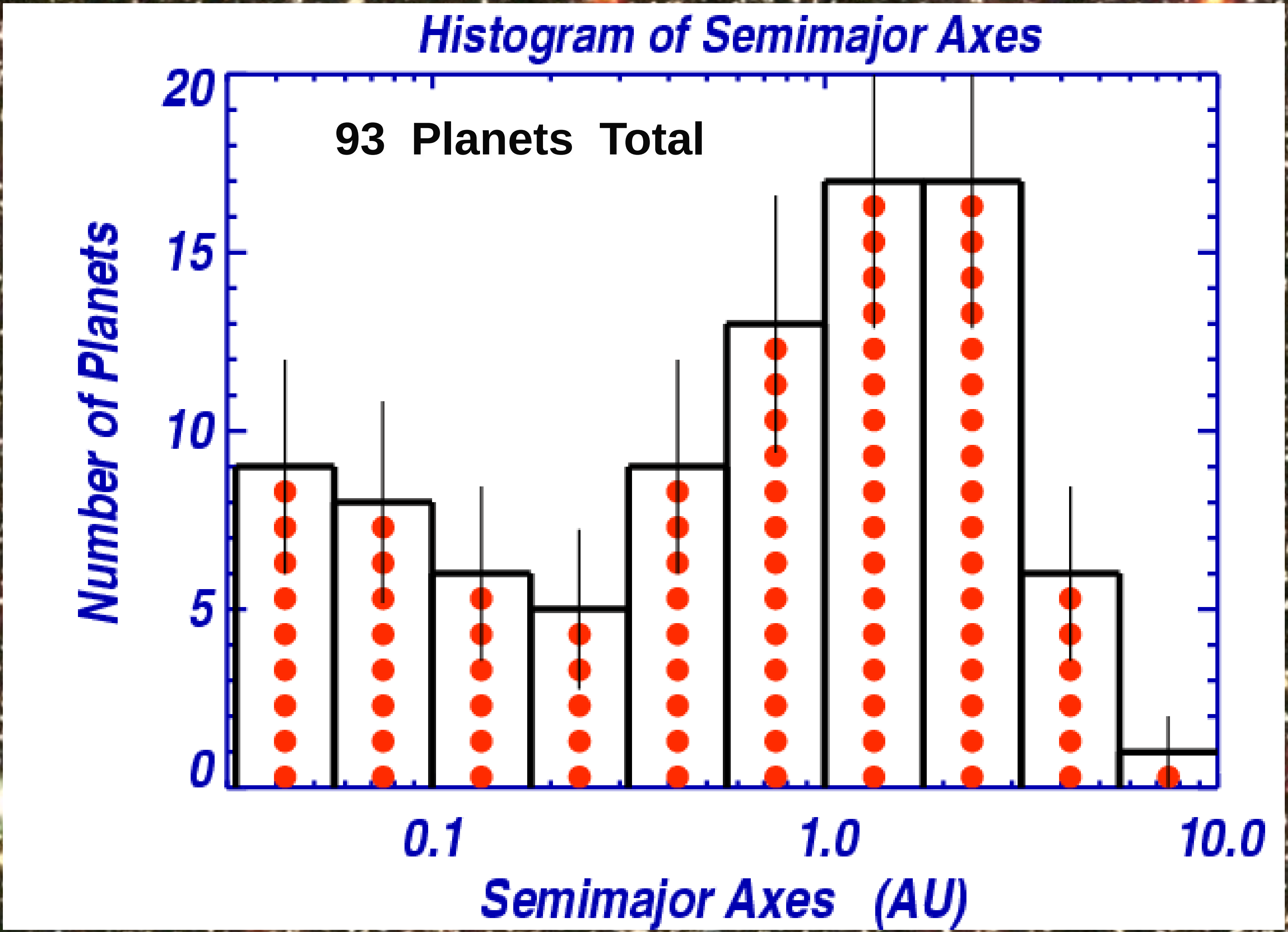


Extrasolar Planet Mass Distribution

Butler, Marcy, Fischer, Vogt

ECCENTRICITIES of PLANETS

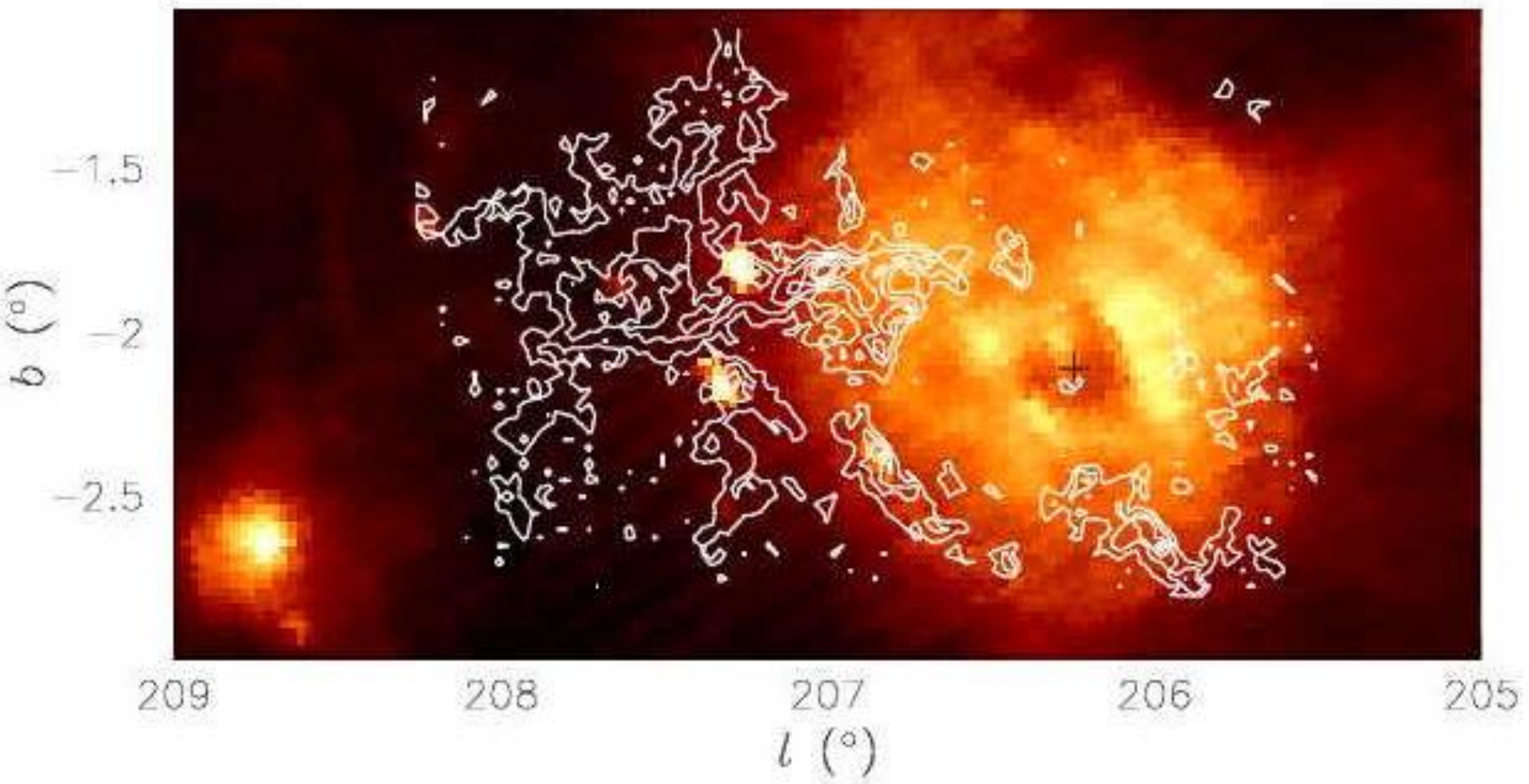



Histogram of Semimajor Axes
93 Planets Total
Number of Planets
20
15
10
5
0
0.1
1.0
10.0
Semimajor Axes (AU)

Approach the question in the following way: if we can understand how planets (and solar type stars) form, we can ask how variable are the conditions in which they form. So, we wish to examine the physics and phenomenology of star and planet formation.

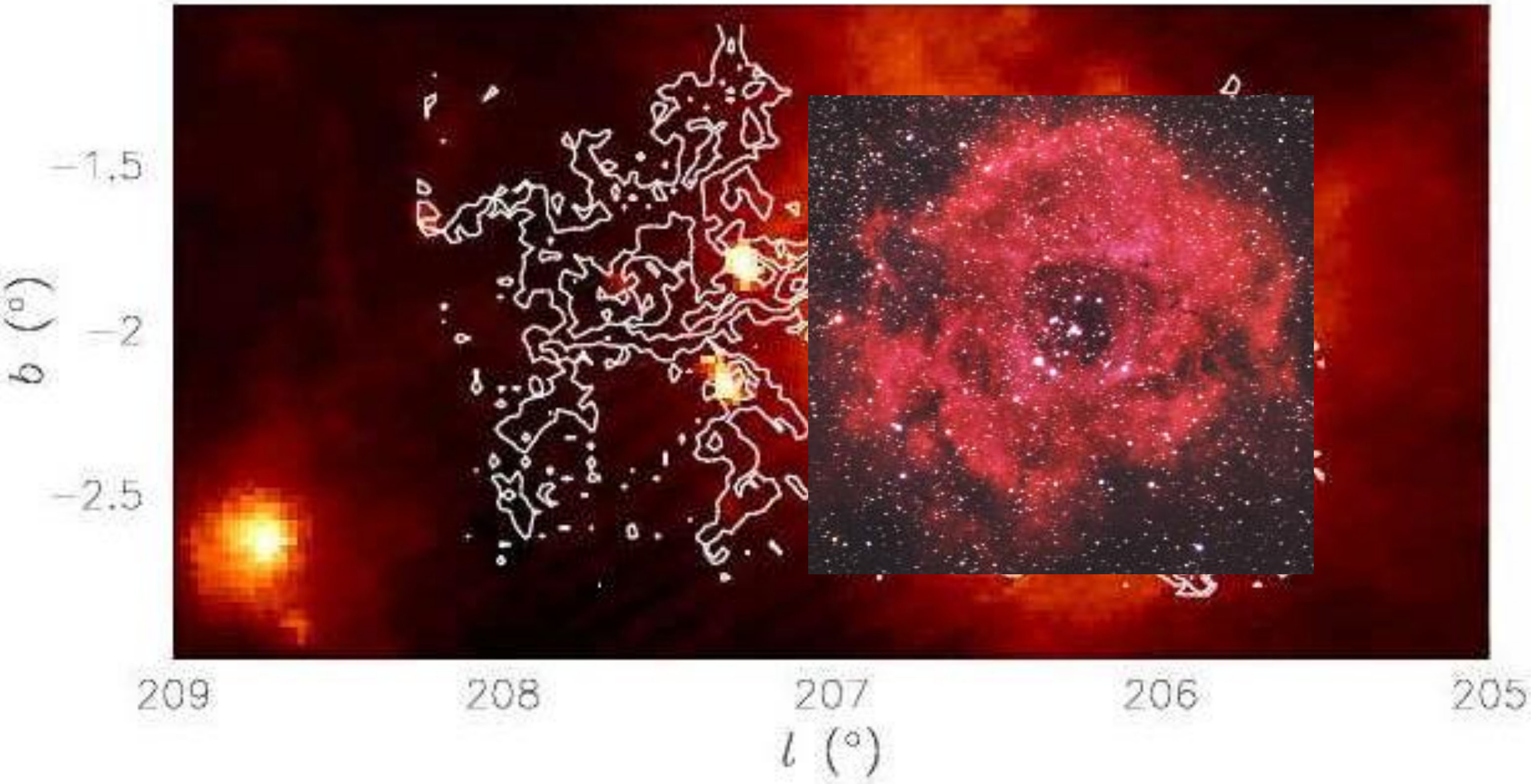
***Find regions where stars are known to be forming*.**

Rosette Molecular Cloud



Example of a Giant Molecular Cloud

Rosette Molecular Cloud



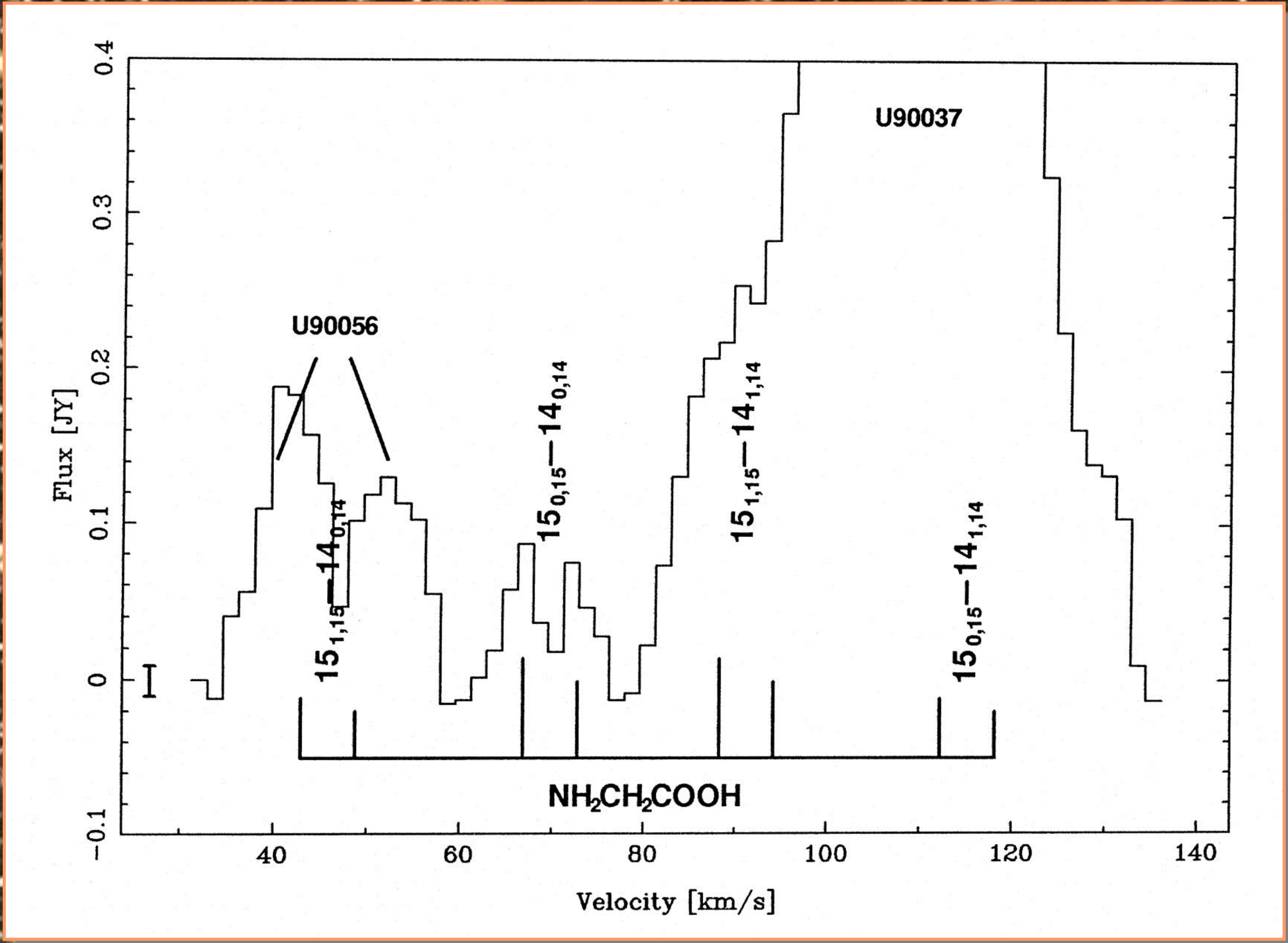
All stars from in molecular clouds

There are no known exceptions

Most stars form in the most massive clouds

- Molecular clouds are overwhelmingly molecular rather than atomic.
- Molecules are > 99% H_2; next most abundant molecule is CO at 10^{-4} abundance of H_2.
- They contain about 1% in solid dust particles by mass. This 1% is very important because it's what makes terrestrial planets.
- They are very cold ~10 K away from sources of heating.
- H_2 cannot generally be directly detected, so use surrogates such as CO, HCN, *et al.*
- More than 100 molecules have been detected in interstellar space.

Possible Glycine Spectrum (90.050 GHz)



All stars from in molecular clouds

Most stars form in the most massive clouds

Molecular clouds are self-gravitating.

Internal pressures exceed external pressure by order of magnitude.

To form a solar mass star by means of a gravitational instability requires very cold gas – so cold that the gas *must* be molecular.

We may think of the instability as a race between pressure (sound) waves and gravity.

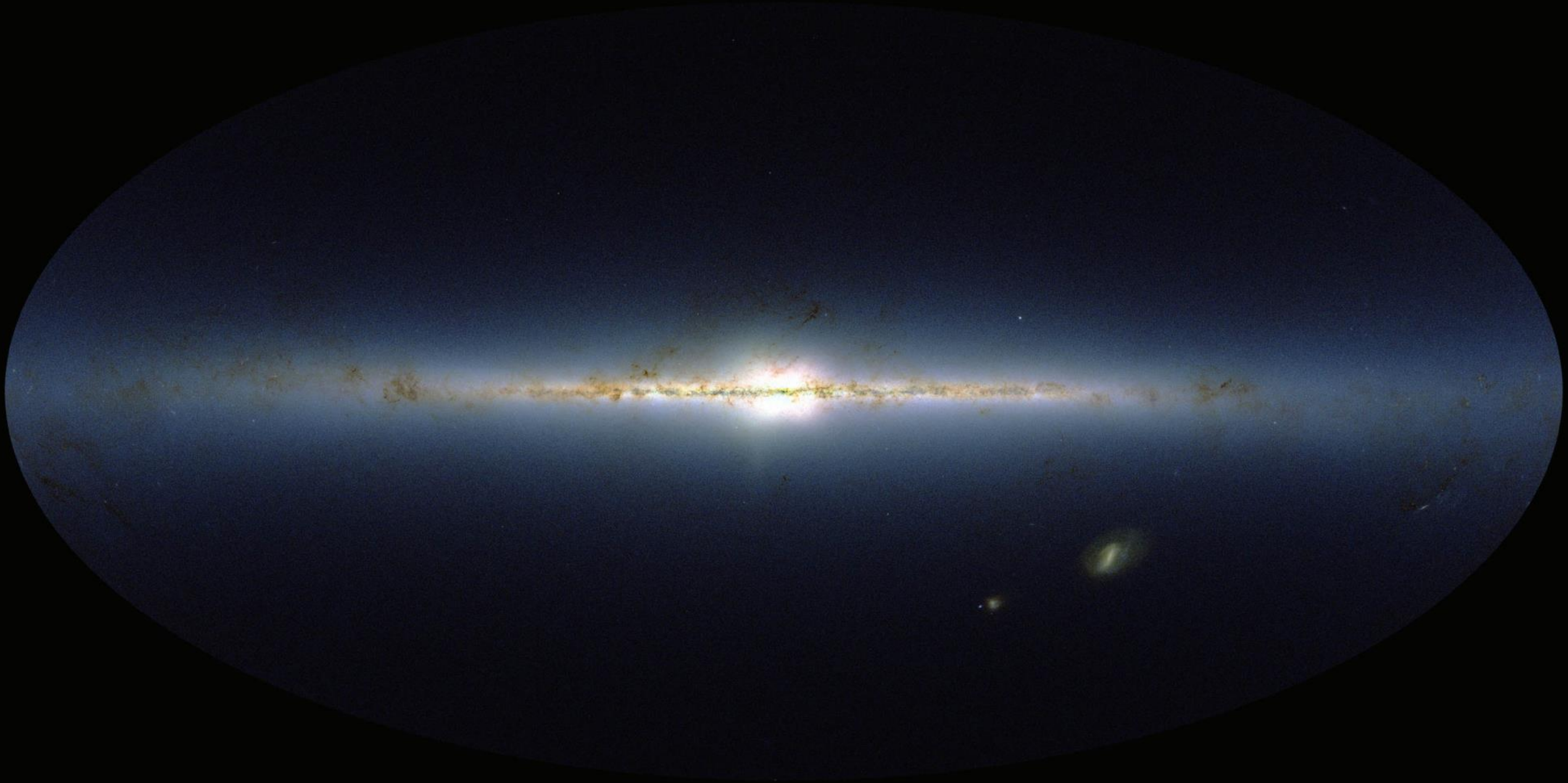
$$M_J \sim T^{3/2}$$
$$M_J \sim \rho^{-1/2}$$

All stars from in molecular clouds

Most stars form in the most massive clouds

How different are GMCs from one another, especially in different environments?

How well does a tracer such as CO trace out total molecular mass?

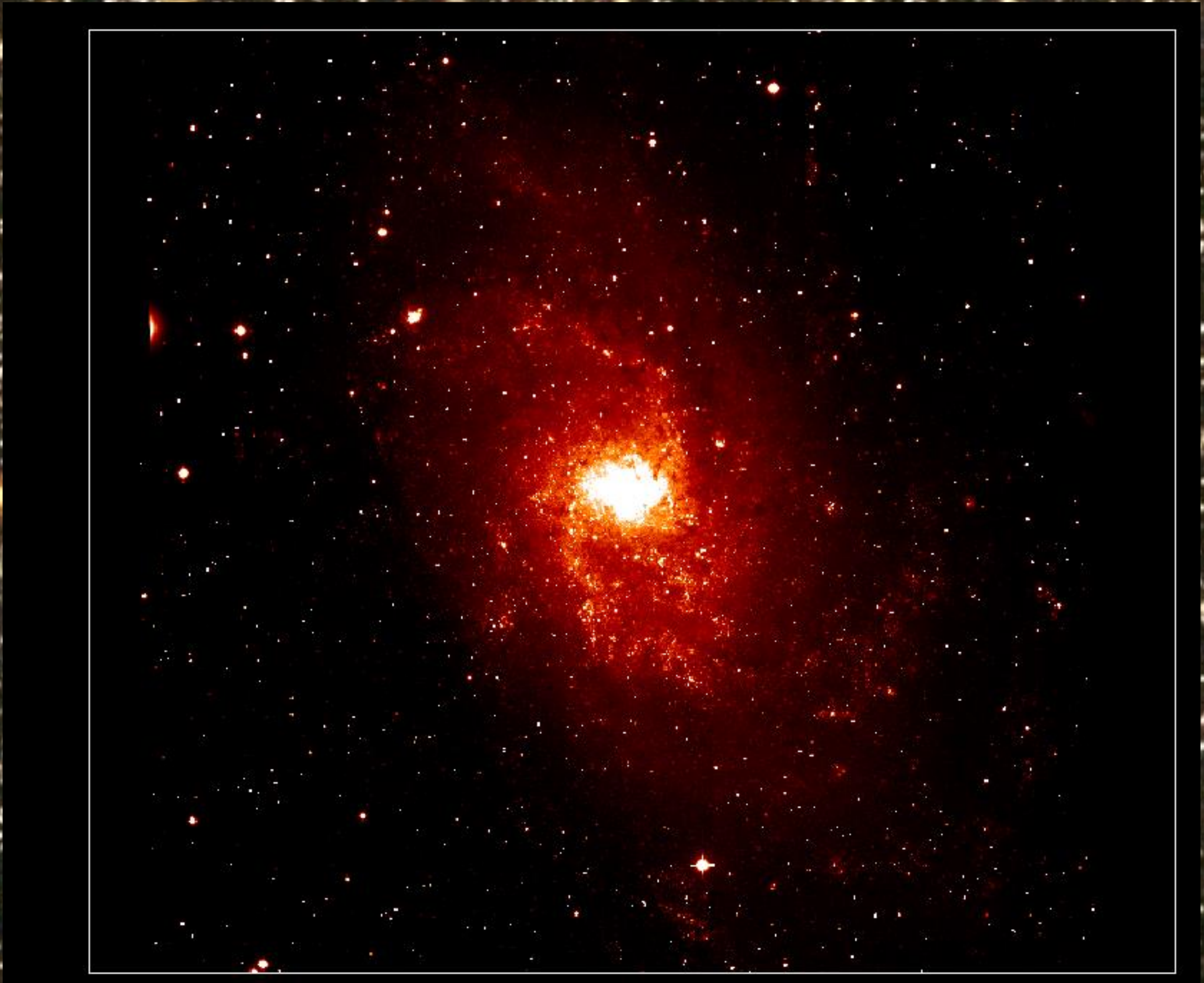


For a complete survey of Giant Molecular Clouds, need to observe another galaxy

BIMA

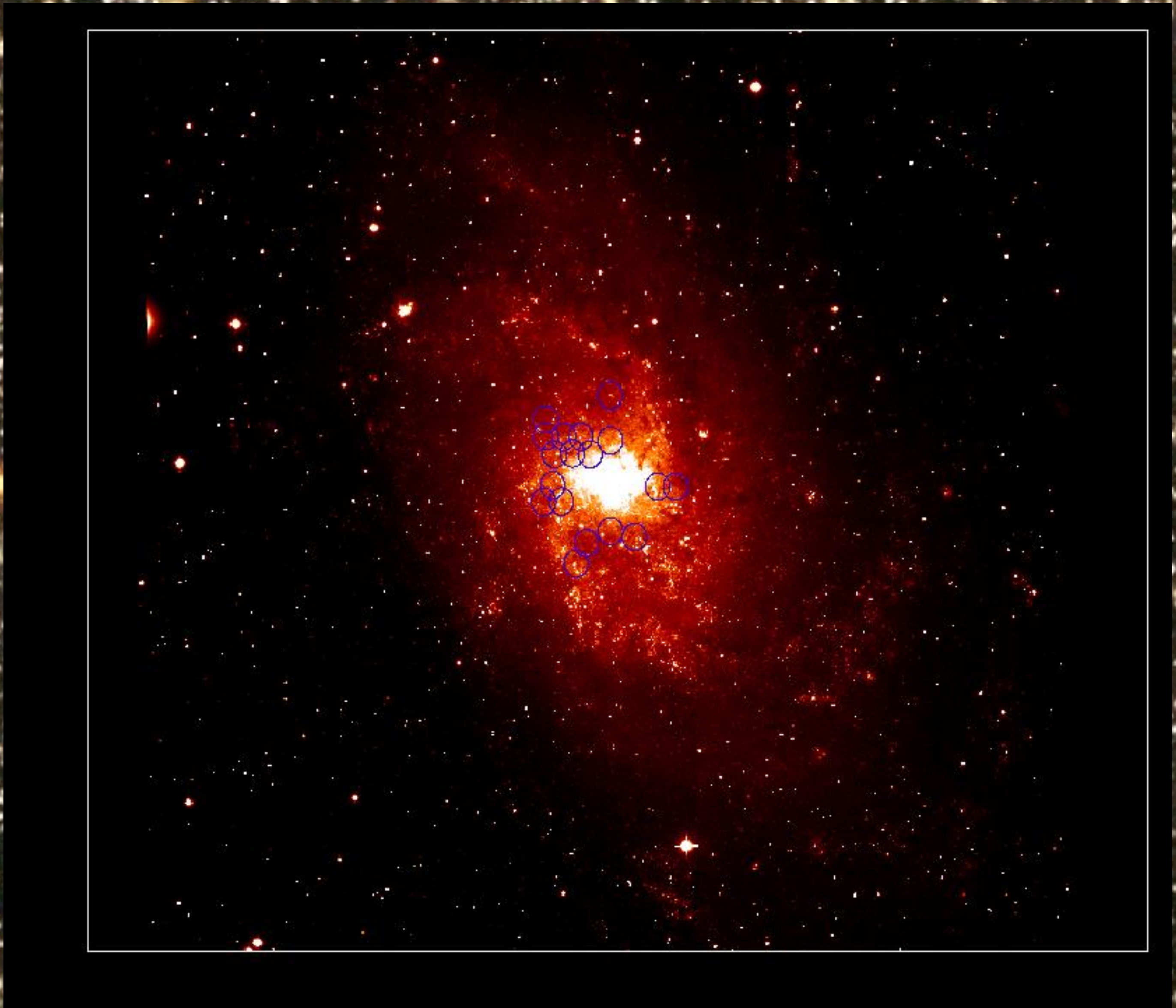
BIMA

M33 in Hα

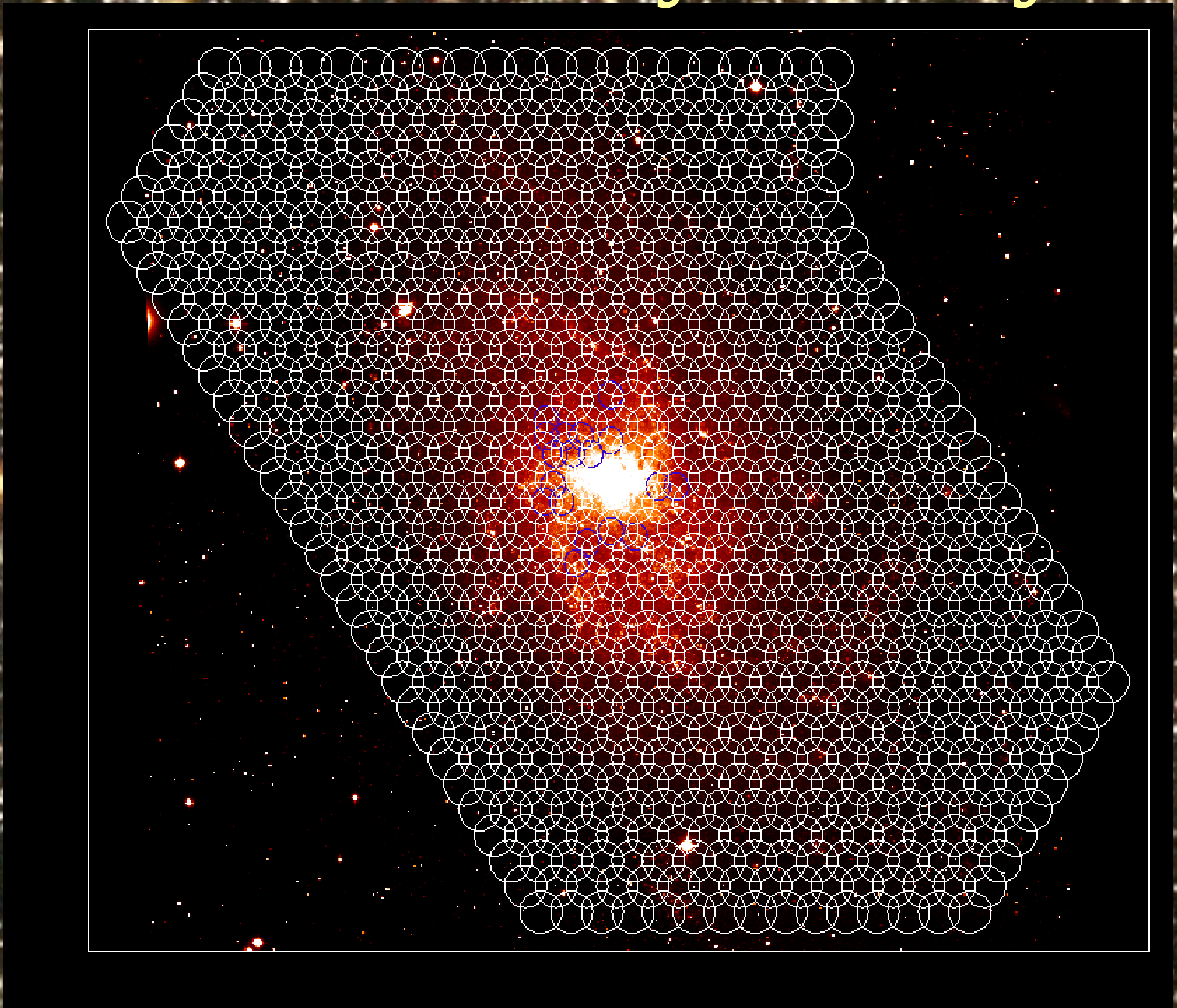


Cheng *et al.* (1993)

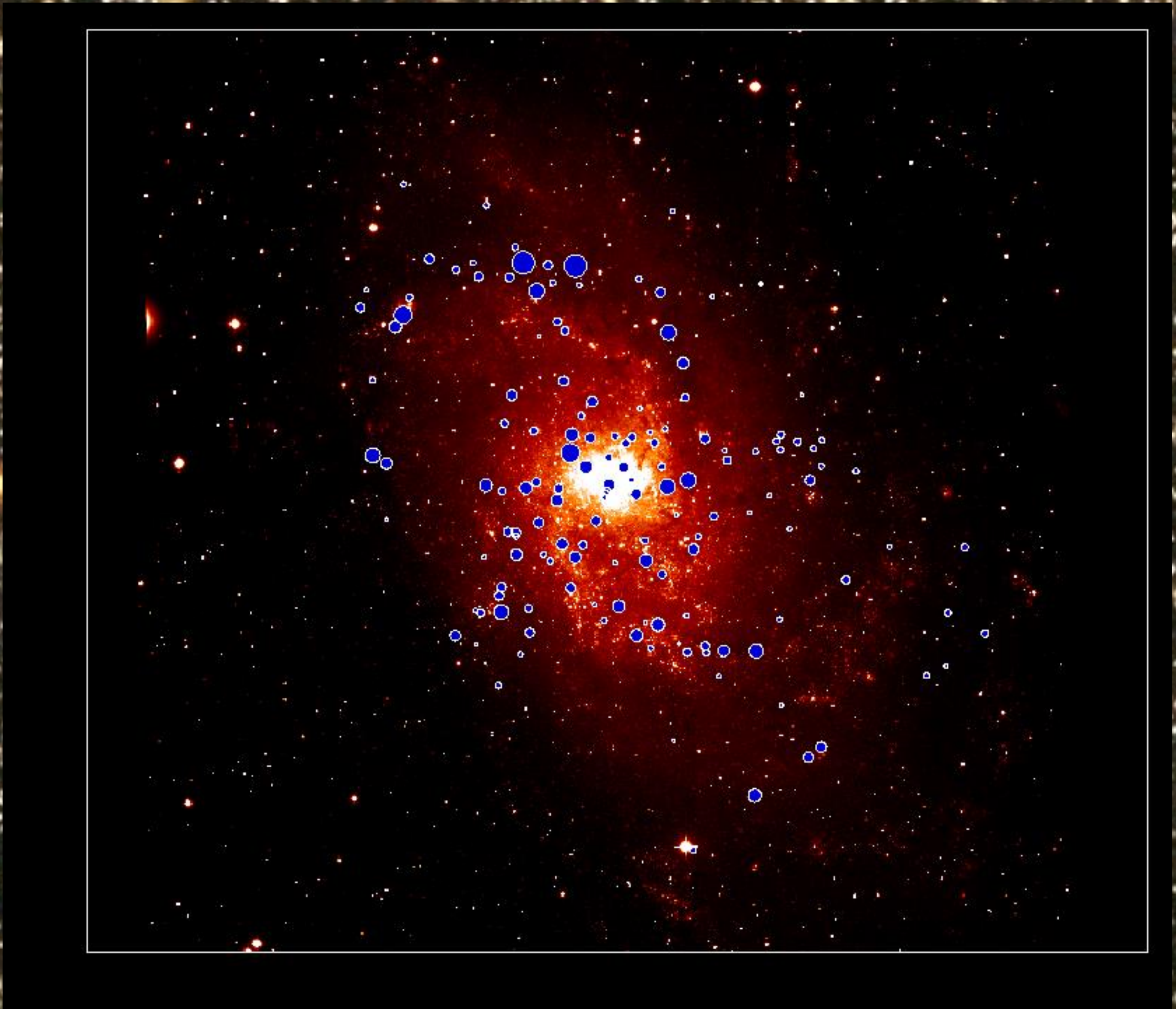
The State of the Art



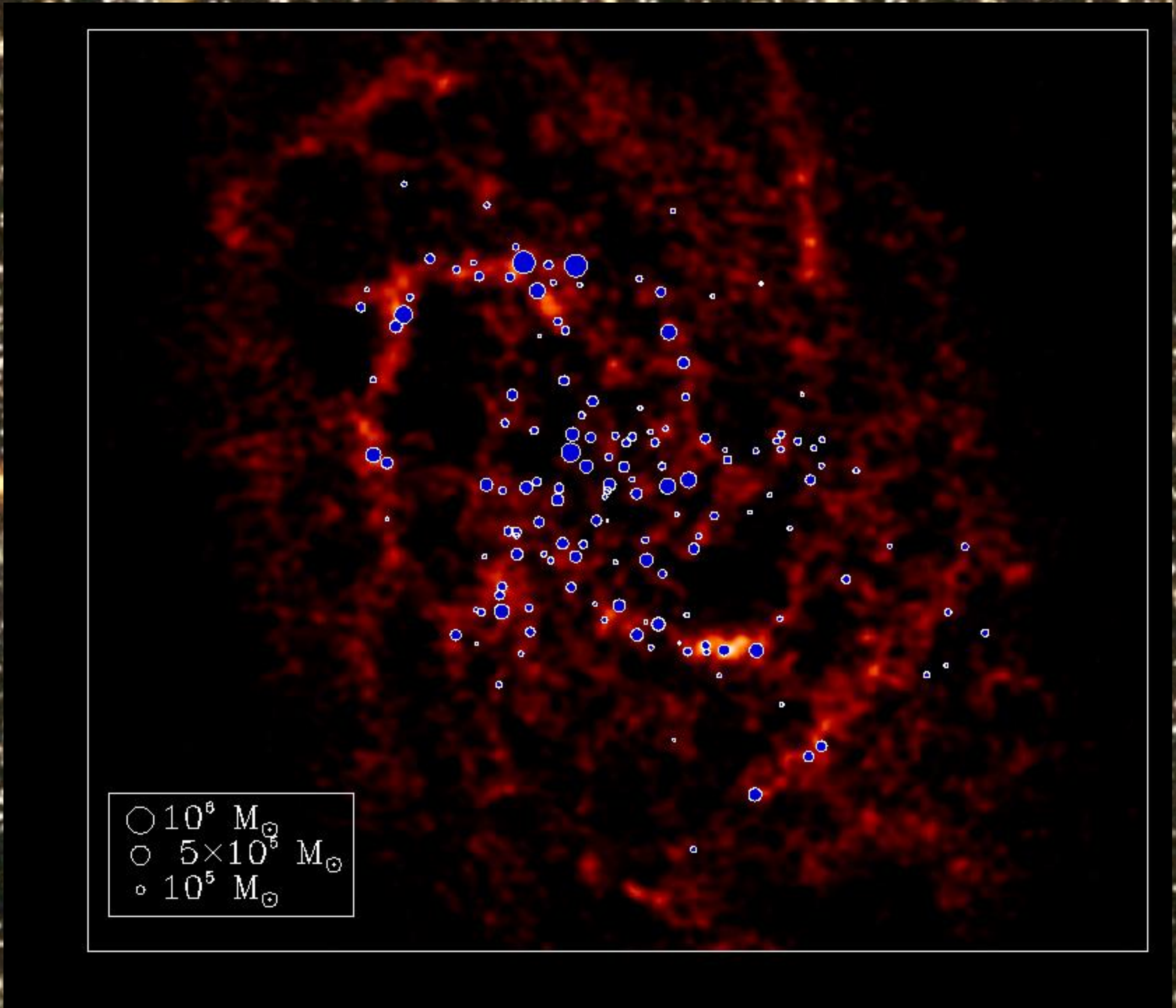
The D-array Survey



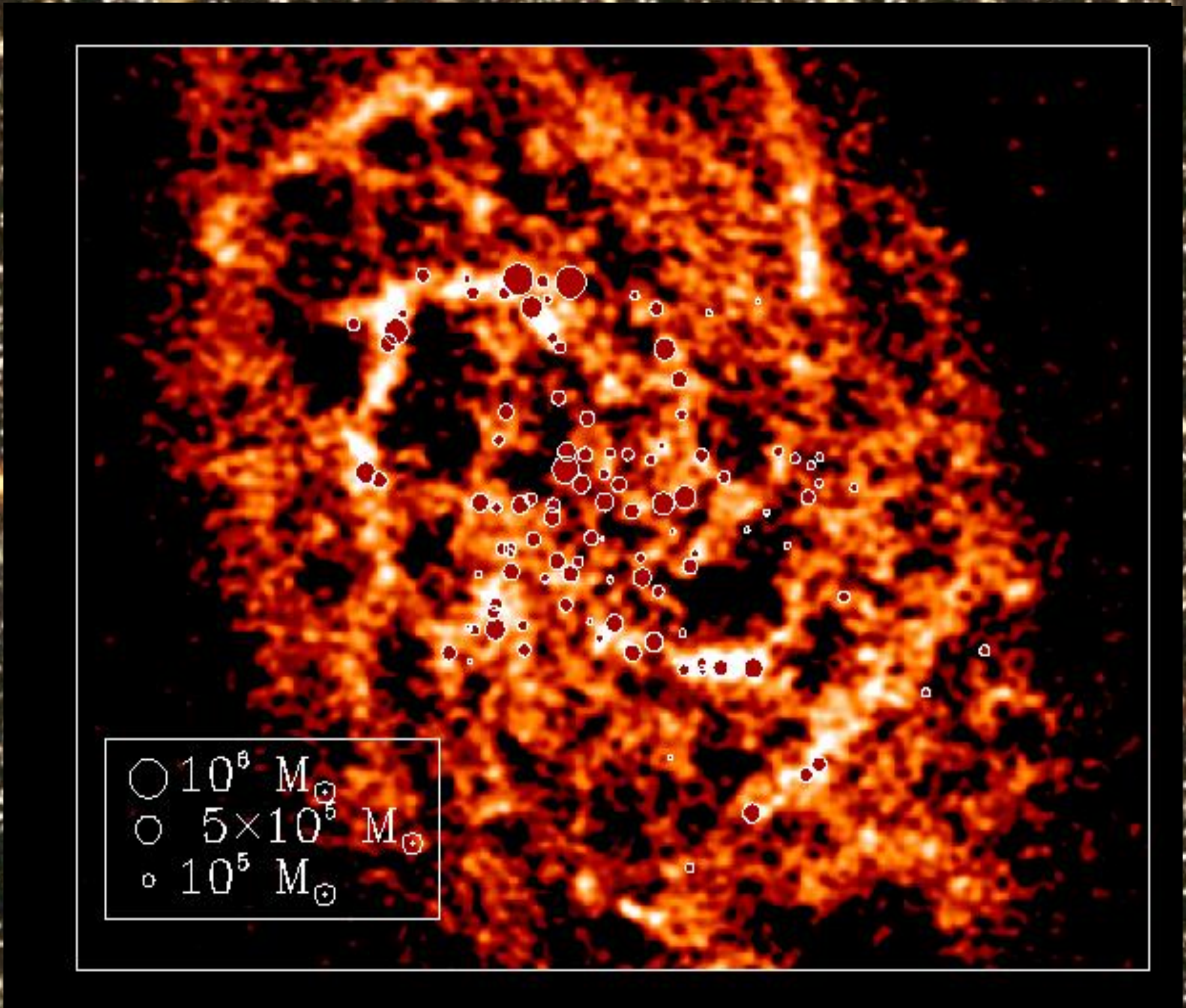
The GMCs in M33



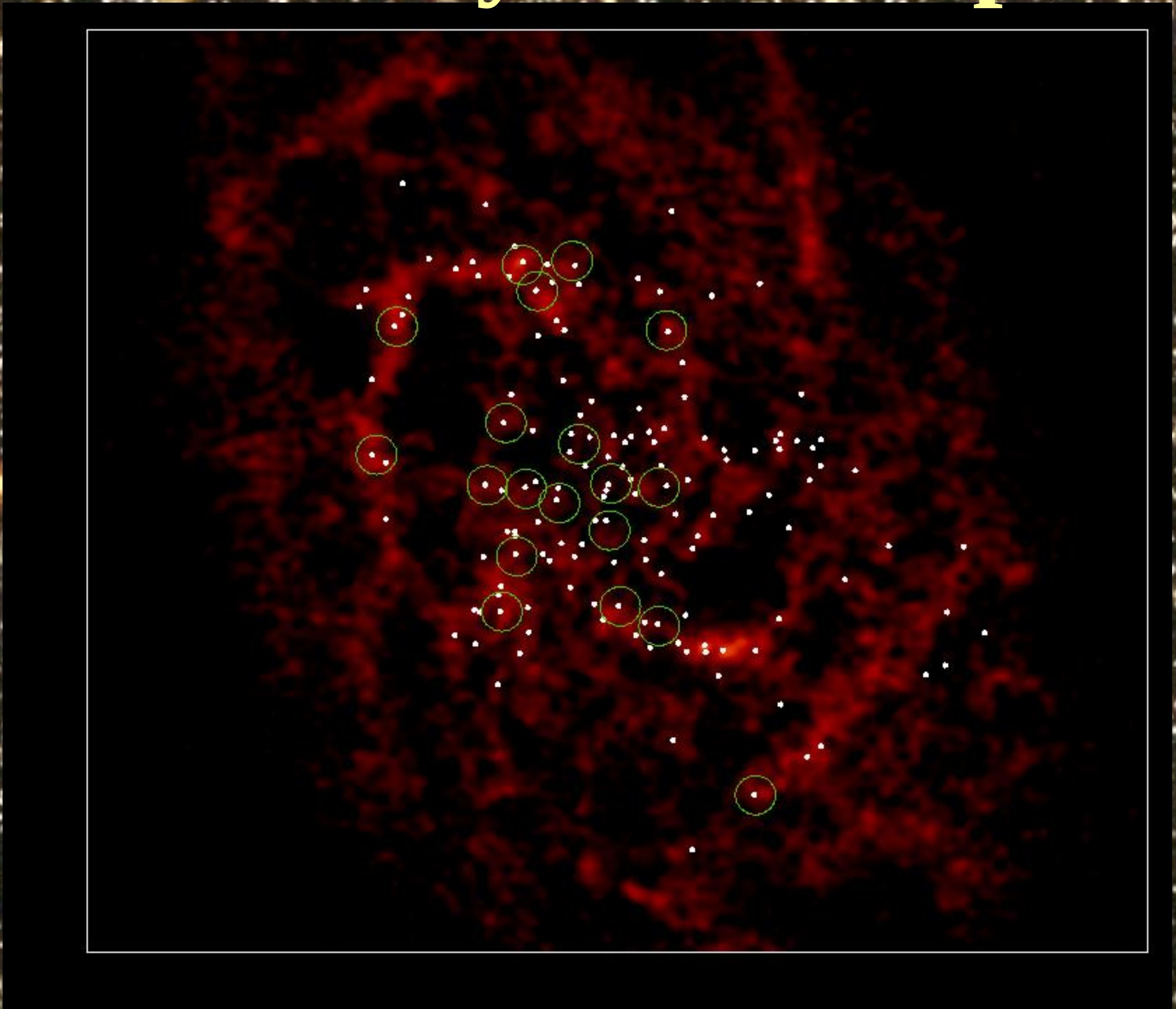
Correlation with HI



Correlation with HI

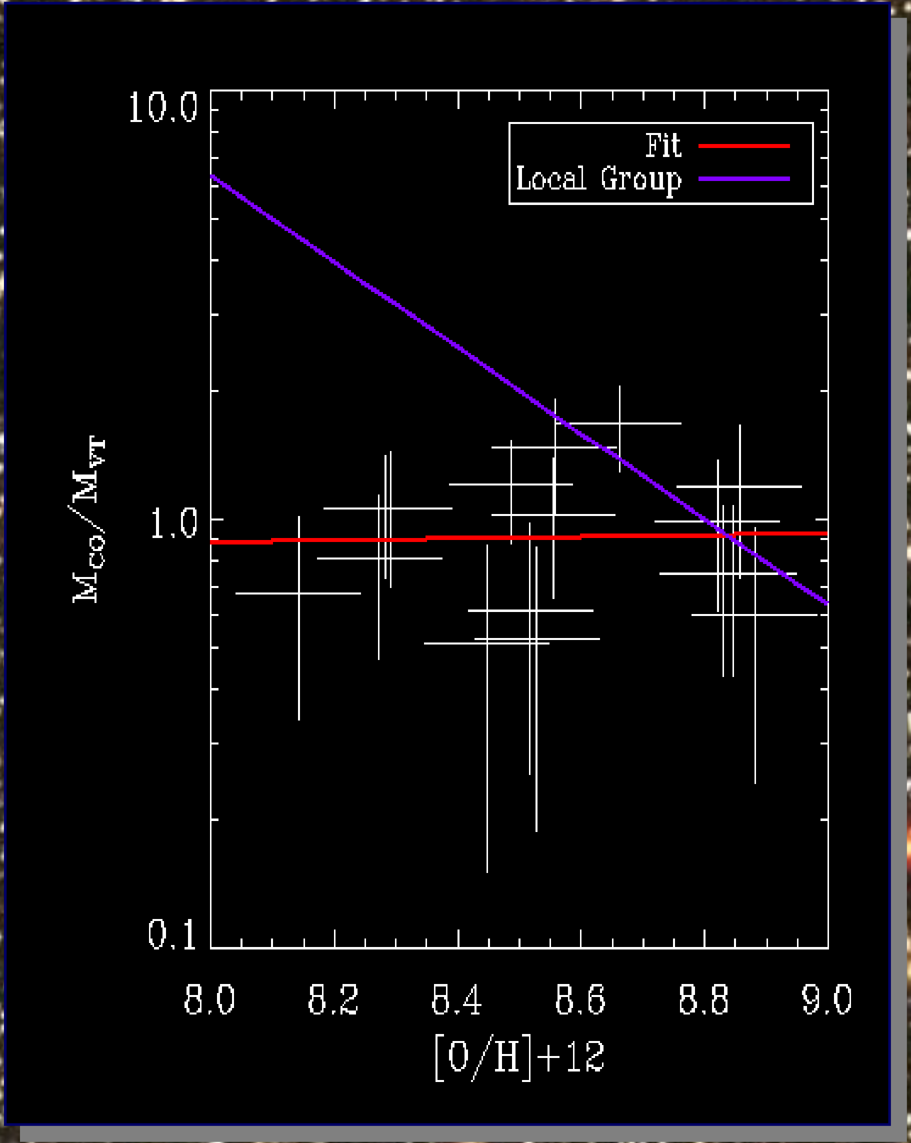


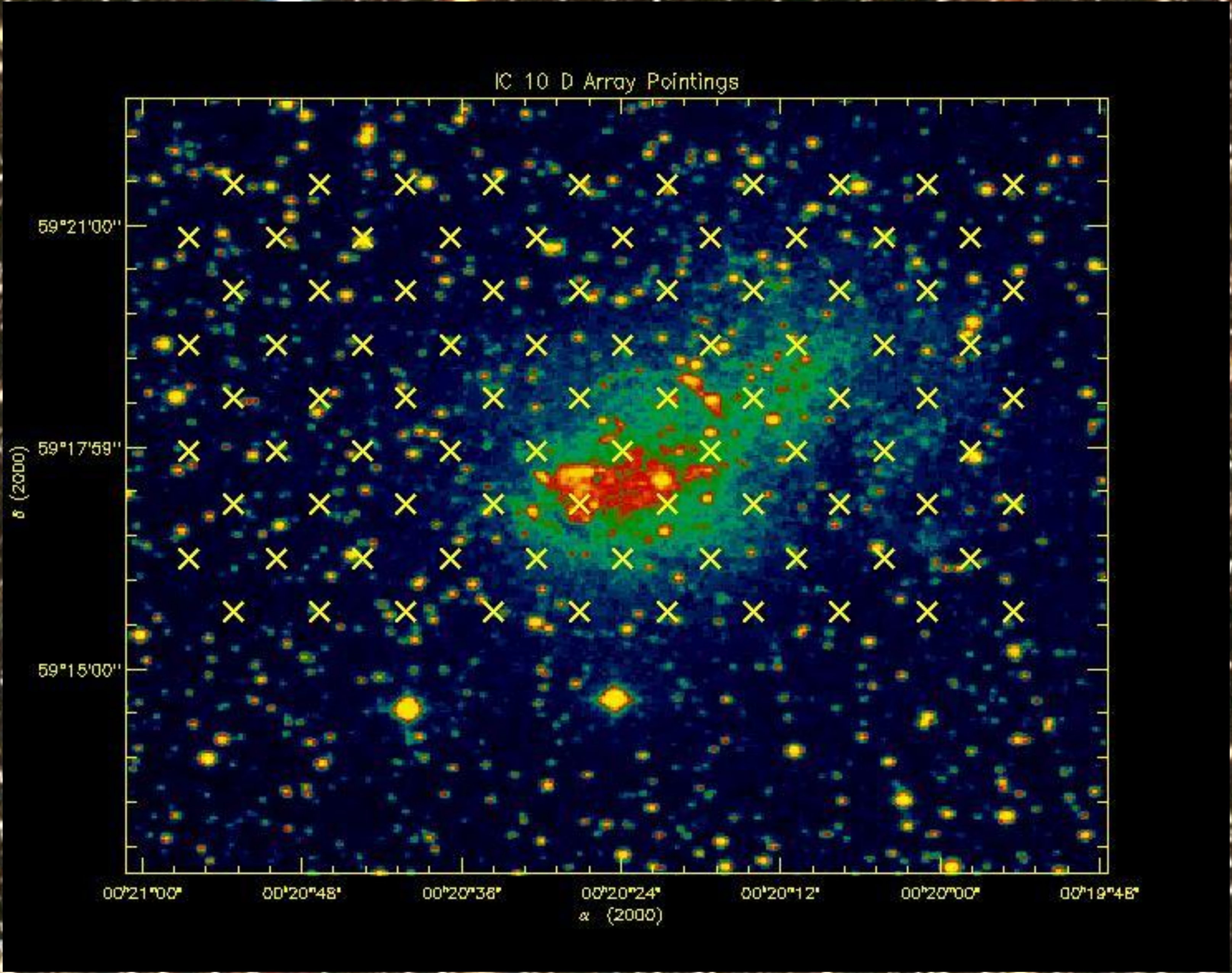
C-array Follow-up



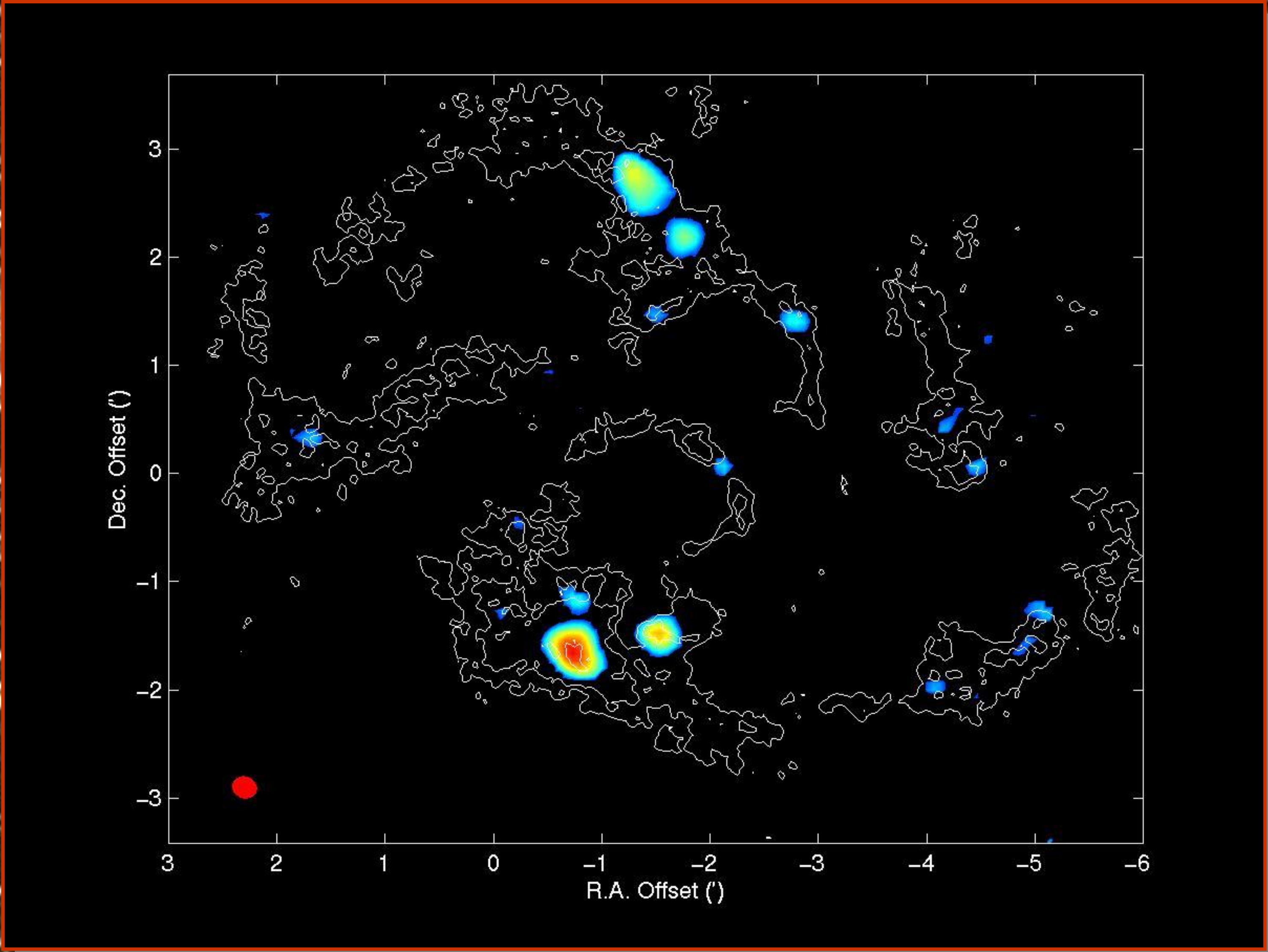
Constant CO-to-H_2 Conversion

- Compare virial (gravitational) and CO (luminous) masses of clouds
- The ratio of masses does not change with heavy element abundance
- The conversion factor is indistinguishable from that found in the inner Milky Way
- The conversion factor is independent of external pressure



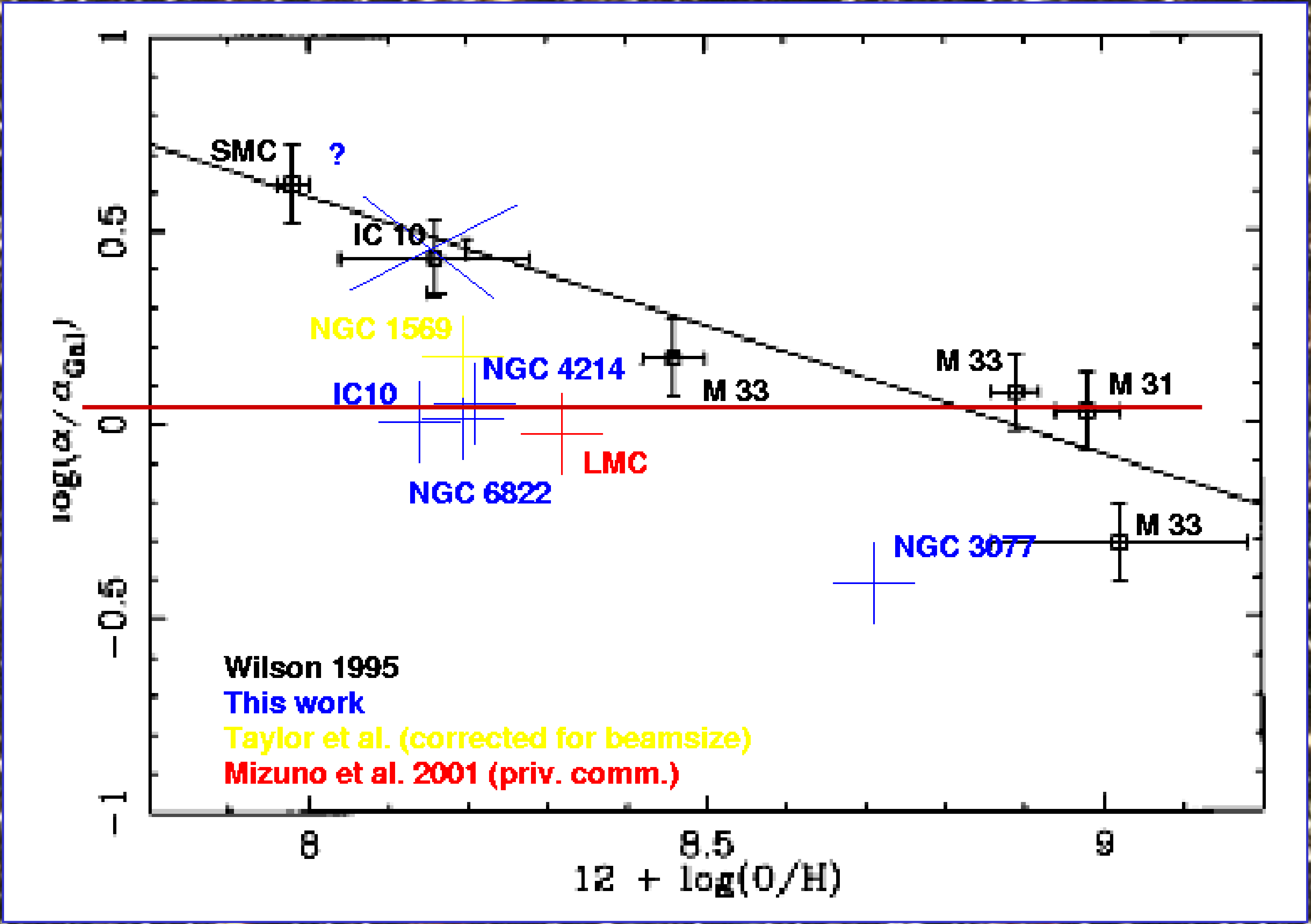

IC 10 D Array Pointings
59°21'00"
59°17'59"
59°15'00"
δ (2000)
00h21m00s
00h20m48s
00h20m36s
00h20m24s
00h20m12s
00h20m00s
00h19m48s
α (2000)

IC 10

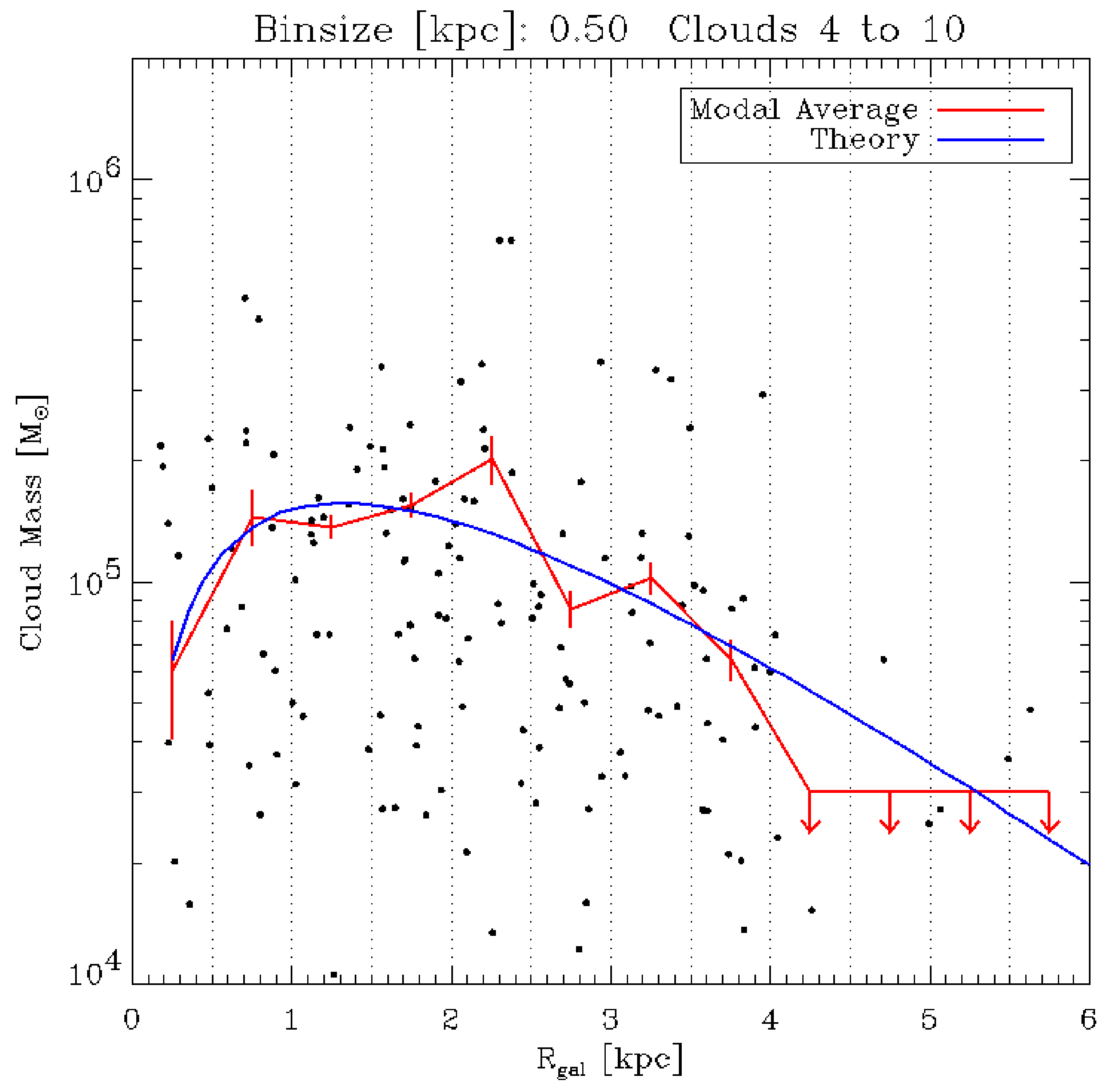


BIMA and OVRO dwarf surveys:

CO/H2 conversion factor is constant



From Walter, et al. (in prep.)


Binsize [kpc]: 0.50   Clouds 4 to 10
Modal Average
Theory
Cloud Mass [$M_\odot$]
10^6
10^5
10^4
0
1
2
3
4
5
6
R_{gal} [kpc]

GMCs are self gravitating.

- Internal pressures exceed surface pressure by an order of magnitude.

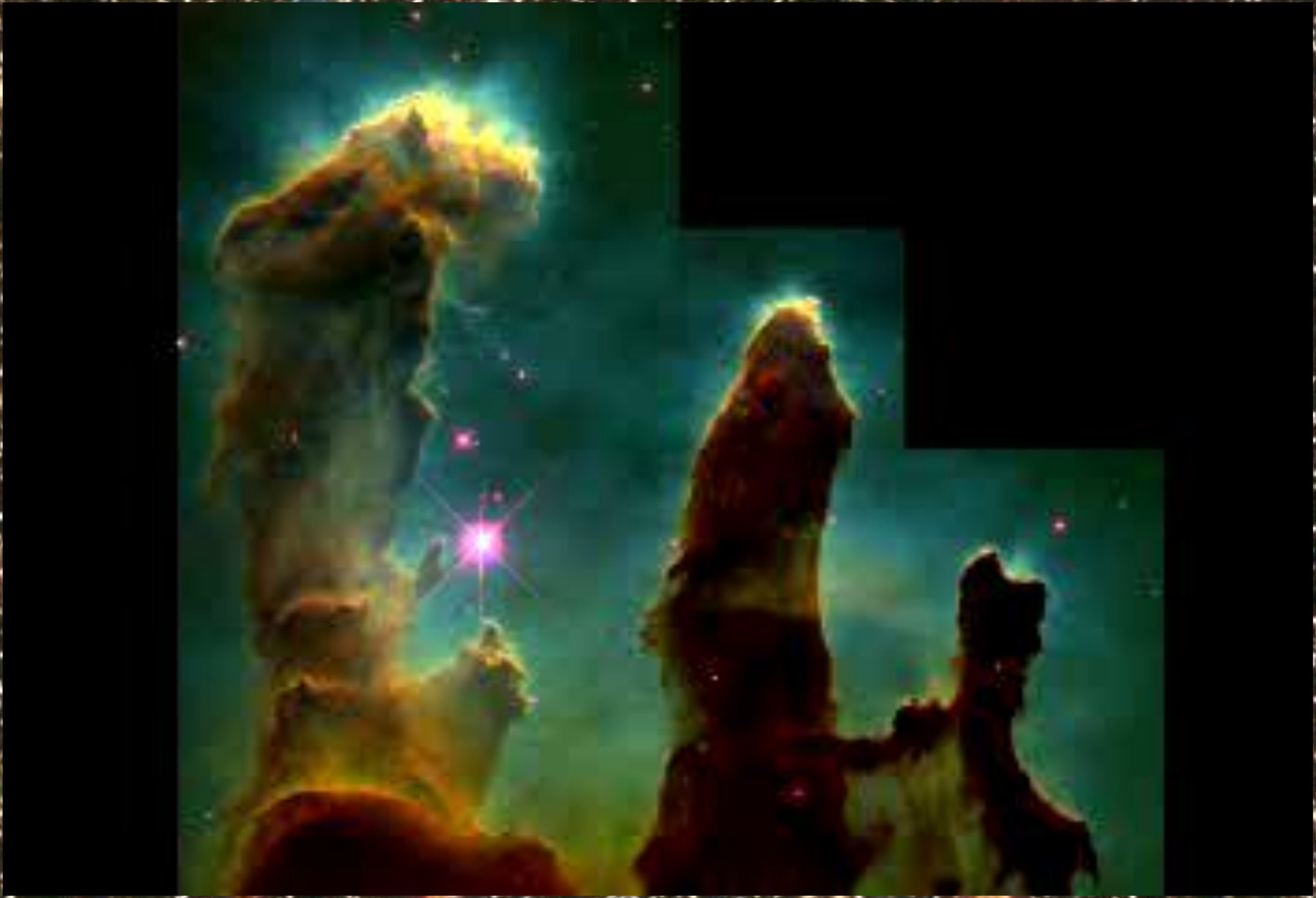
Combined with linewidth-size relation implies constant average surface density.

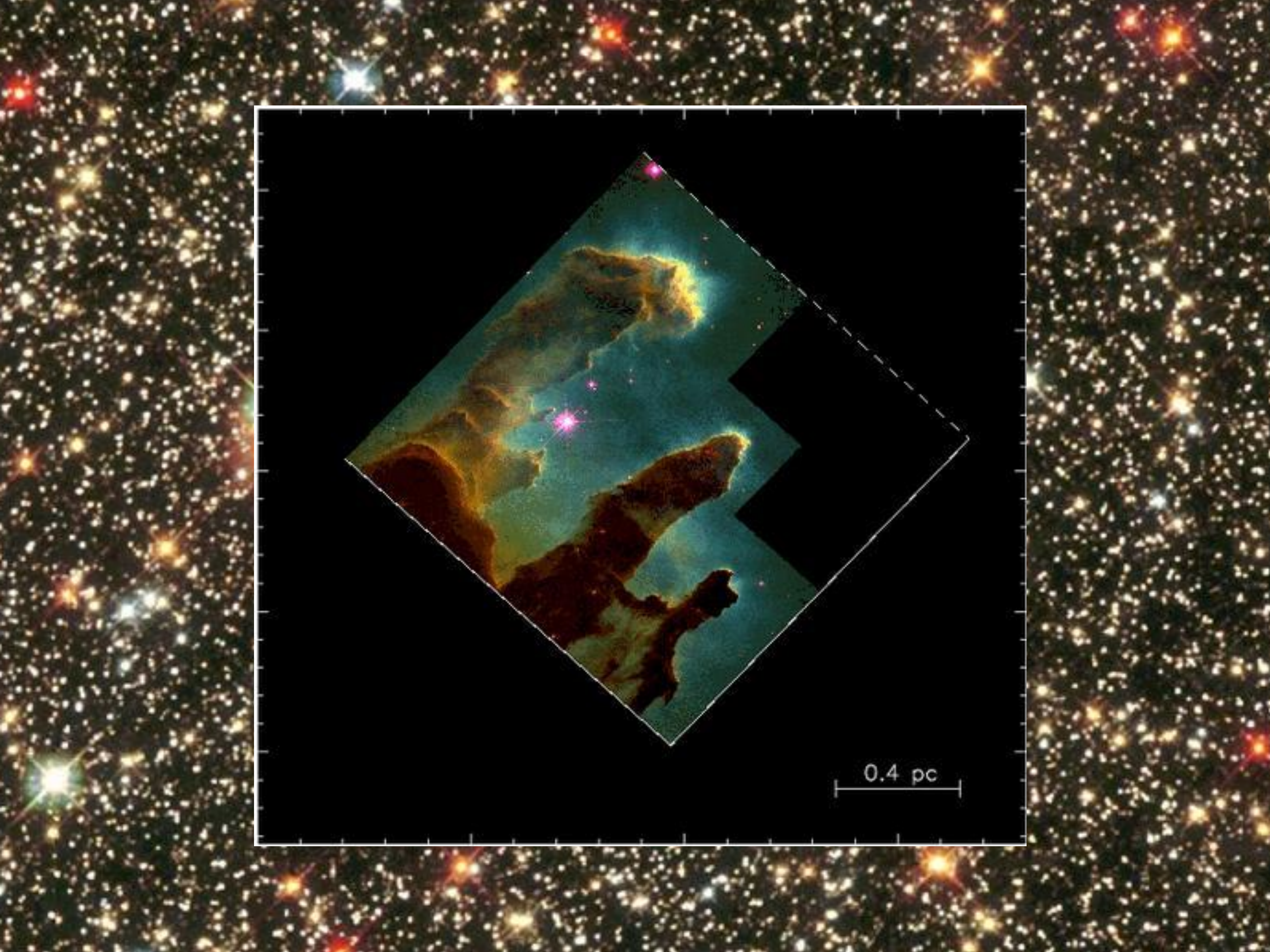
- Confirmed by observations in the Milky Way, M33, and IC10.

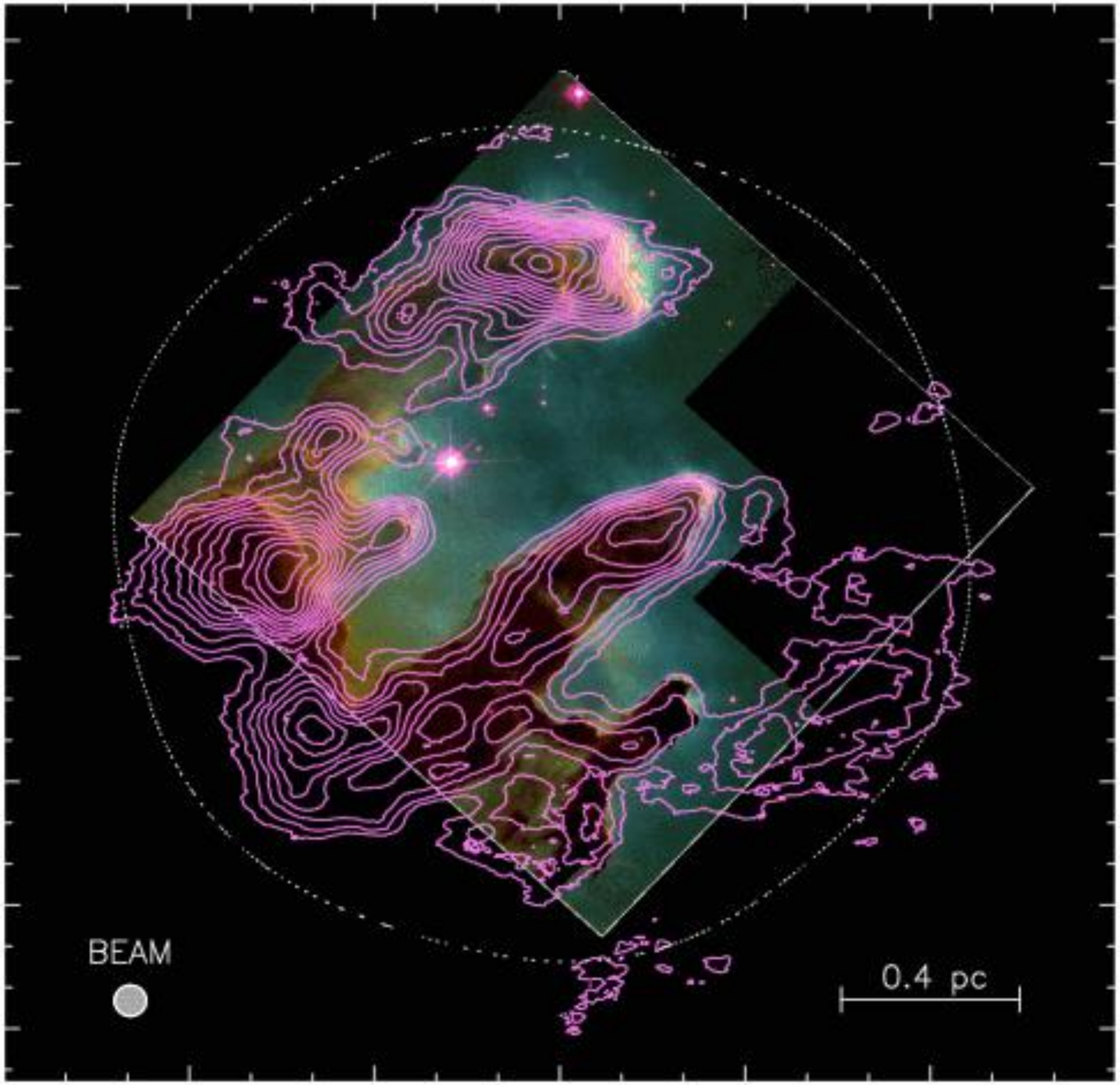
This implies that they have about have the same mean internal pressure.

Statistics suggest that they are all drawn from the same population, regardless of external pressure and heavy element content, or other variables.

Self-gravitating GMCS are remarkably similar to one another.

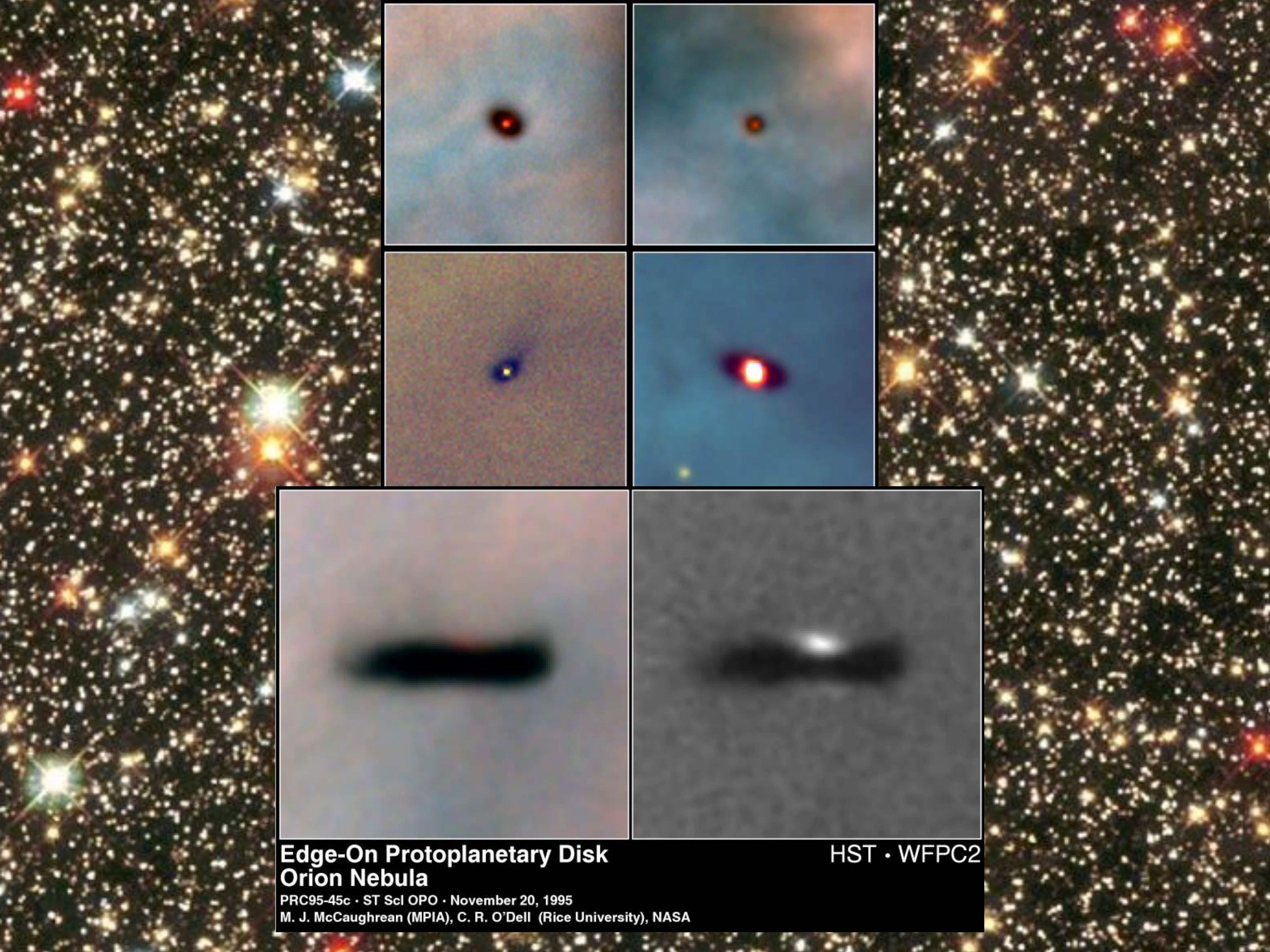



0.4 pc


BEAM
0.4 pc

Orion Nebula Mosaic HST · WFPC2

PRC95-45a · ST ScI OPO · November 20, 1995
C. R. O'Dell and S. K. Wong (Rice University), NASA



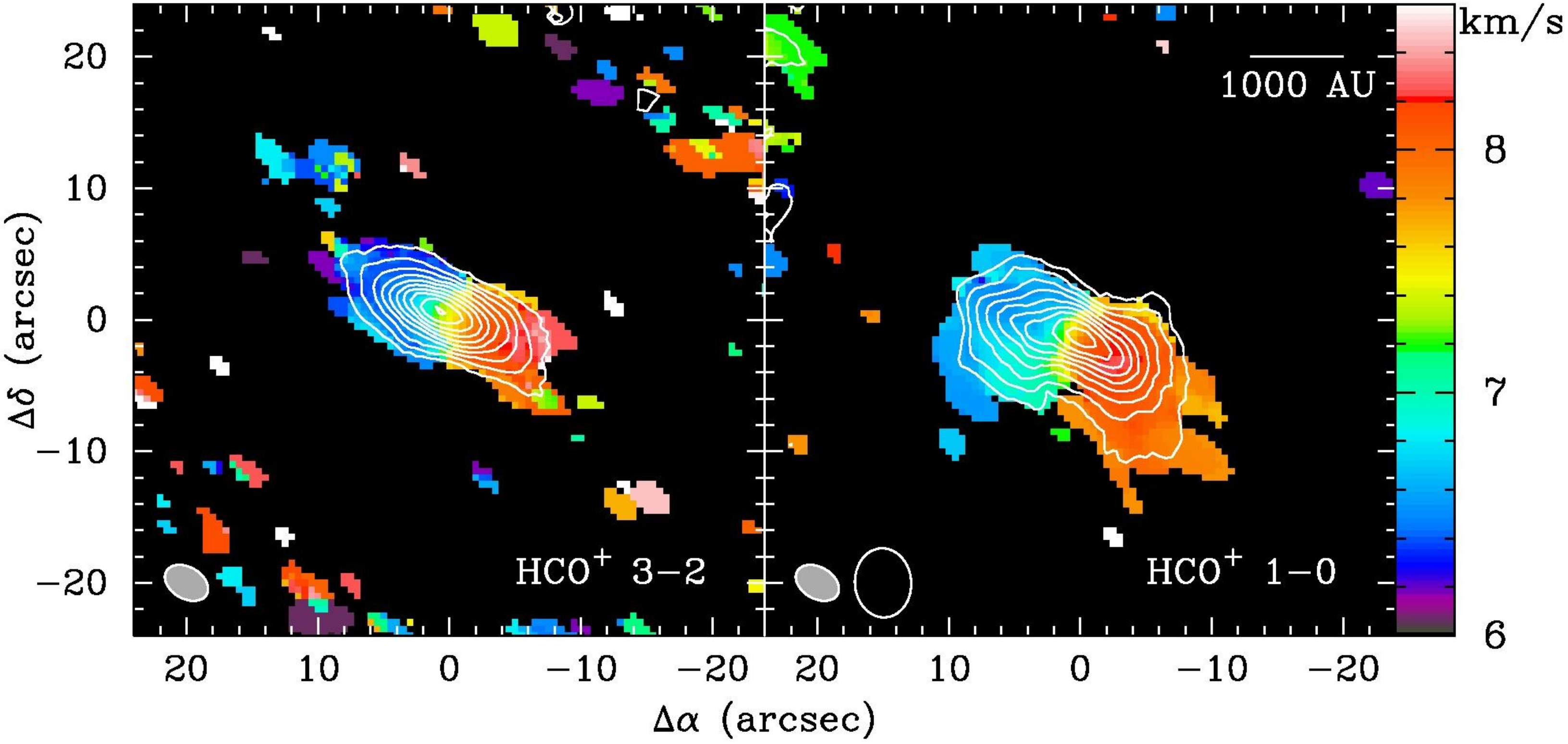
Edge-On Protoplanetary Disk
Orion Nebula

HST • WFPC2

PRC95-45c · ST ScI OPO · November 20, 1995
M. J. McCaughrean (MPIA), C. R. O'Dell (Rice University), NASA

DISKS

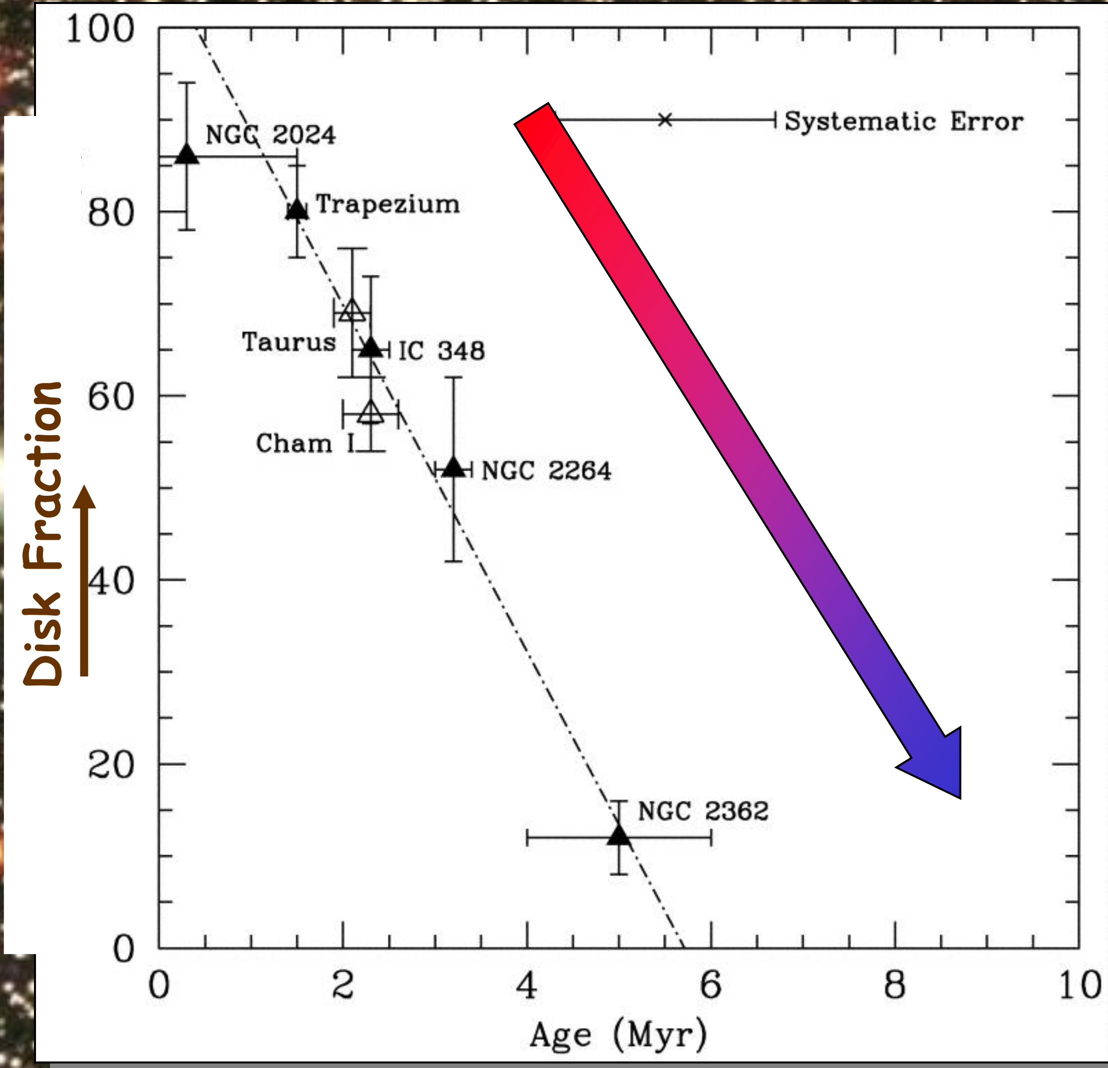
A rotating infalling disk around the young stellar object L1489 IRS imaged at 267 and 89 GHz with the Berkeley–Illinois–Maryland Array



(Hogerheijde 2000)

Protoplanetary Disk Frequency in Young Clusters

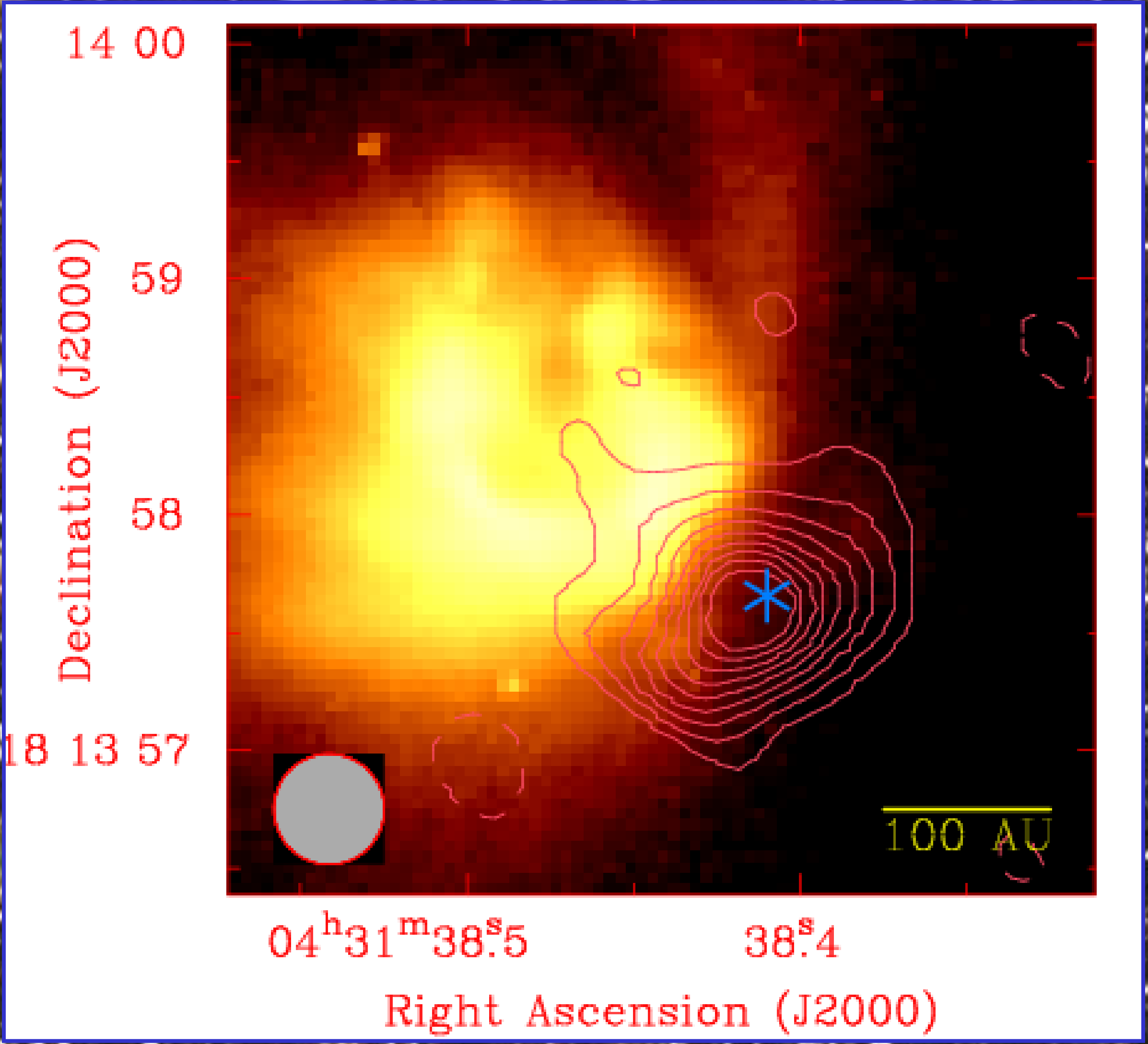
Essentially all stars are born with circumstellar disks and the potential to form planetary systems!!



Haisch, Lada & Lada (2001)

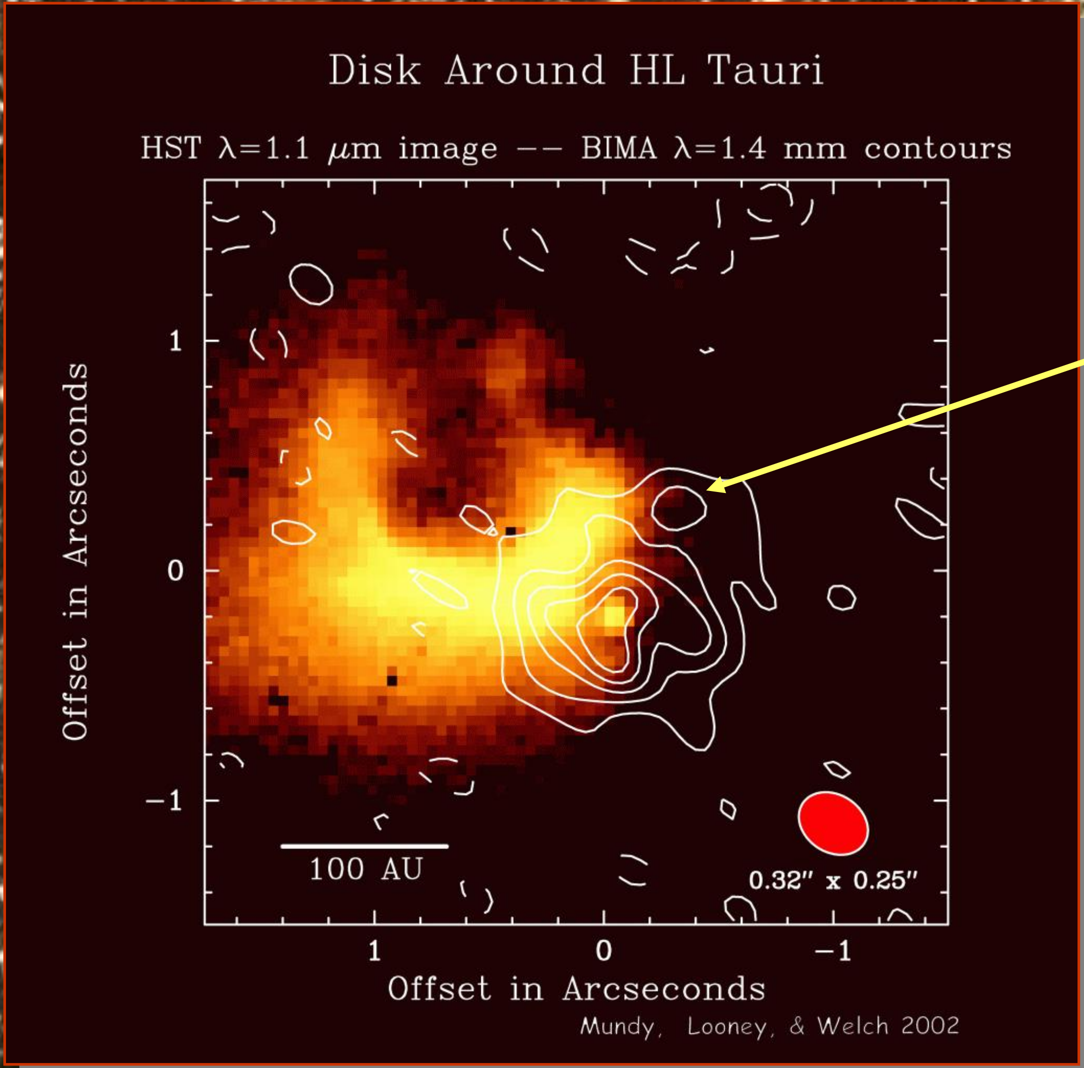
But Protoplanetary disks have short lifetimes!

HL Tau at 2.7mm



Δθ = 0.5 sec

HL Tau at 1.4 mm



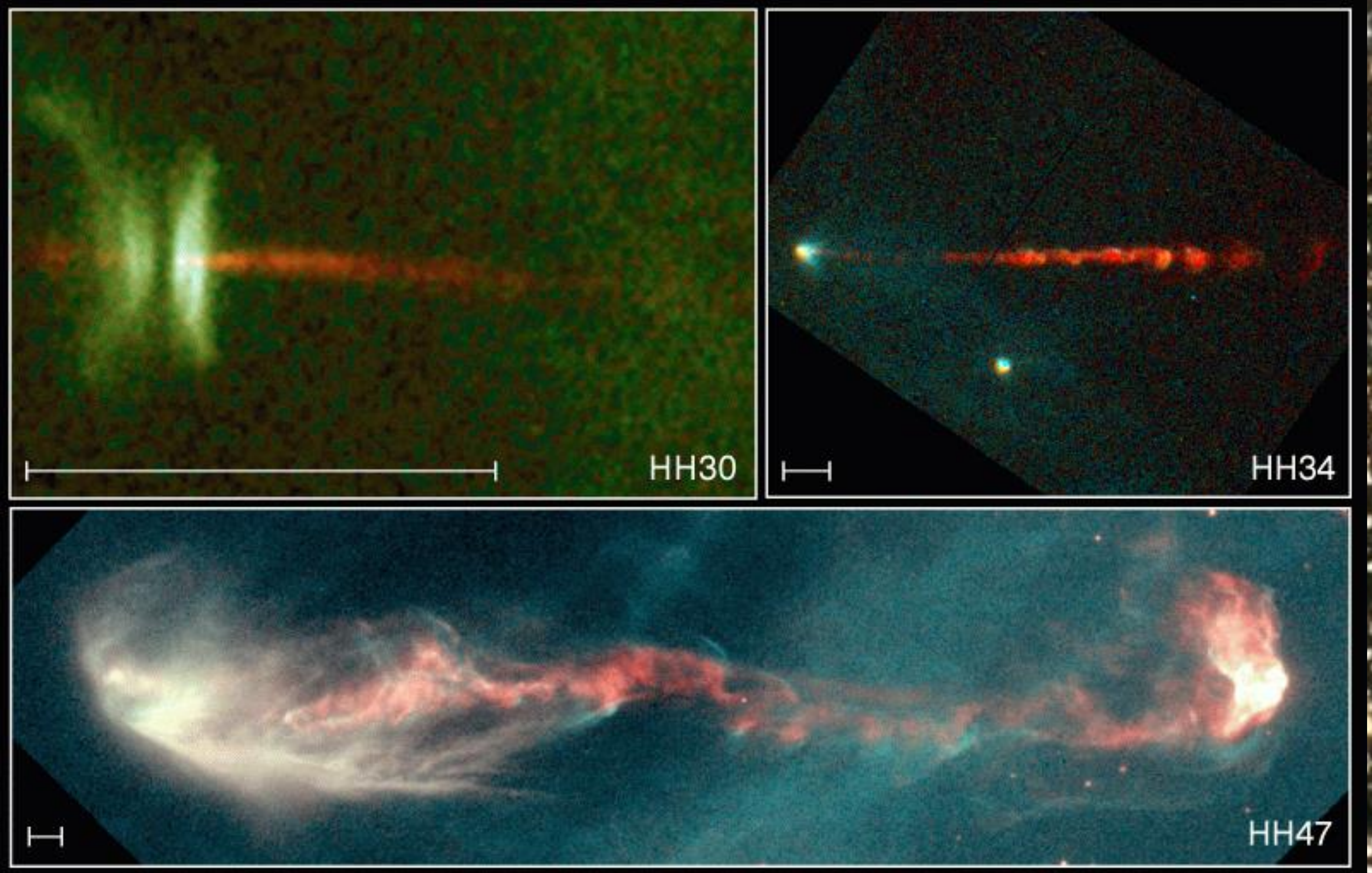
What is it?

Δθ = 0.3 sec

BIPOLAR MOLECULAR OUTFLOWS & JETS

The formation of a star appears to begin with the energetic *ejection* of matter into bipolar jets or outflows!

The bipolar outflow requires the presence of a circumstellar disk to provide the power and directionality of the outflow.

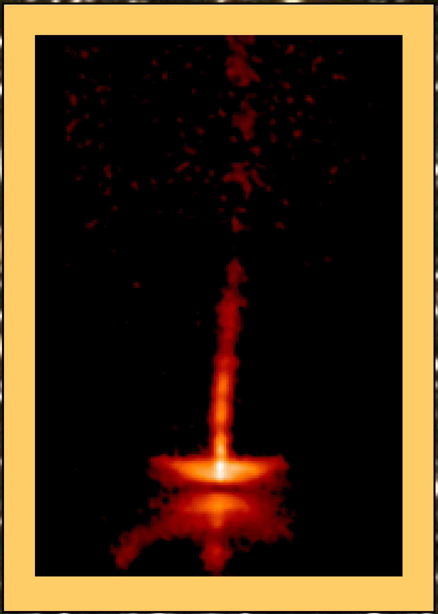


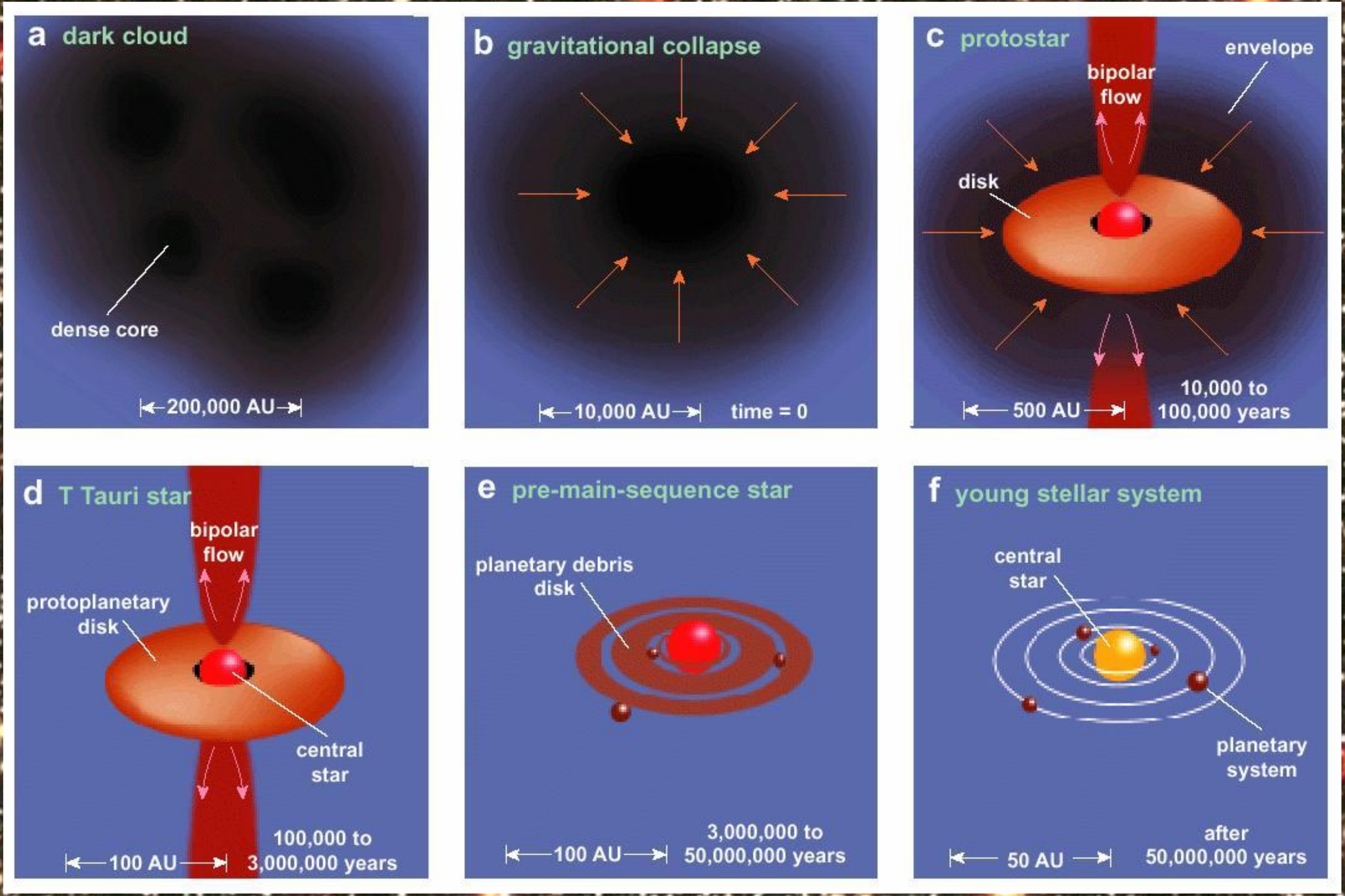
Jets from Young Stars

HST • WFPC2

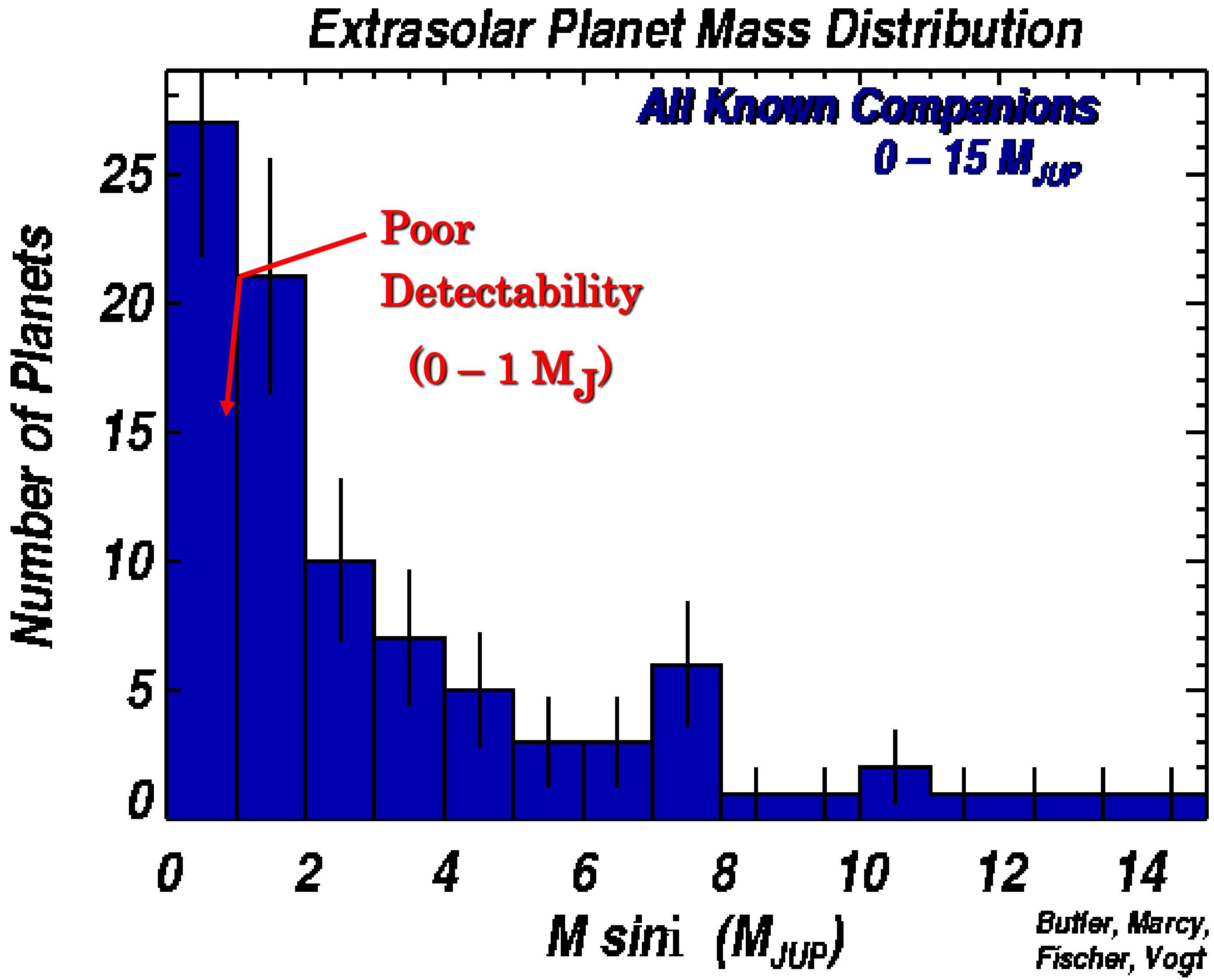
PRC95-24a • ST ScI OPO • June 6, 1995

C. Burrows (ST ScI), J. Hester (AZ State U.), J. Morse (ST ScI), NASA





Green, 2001 *American Sceintist* 89, 316



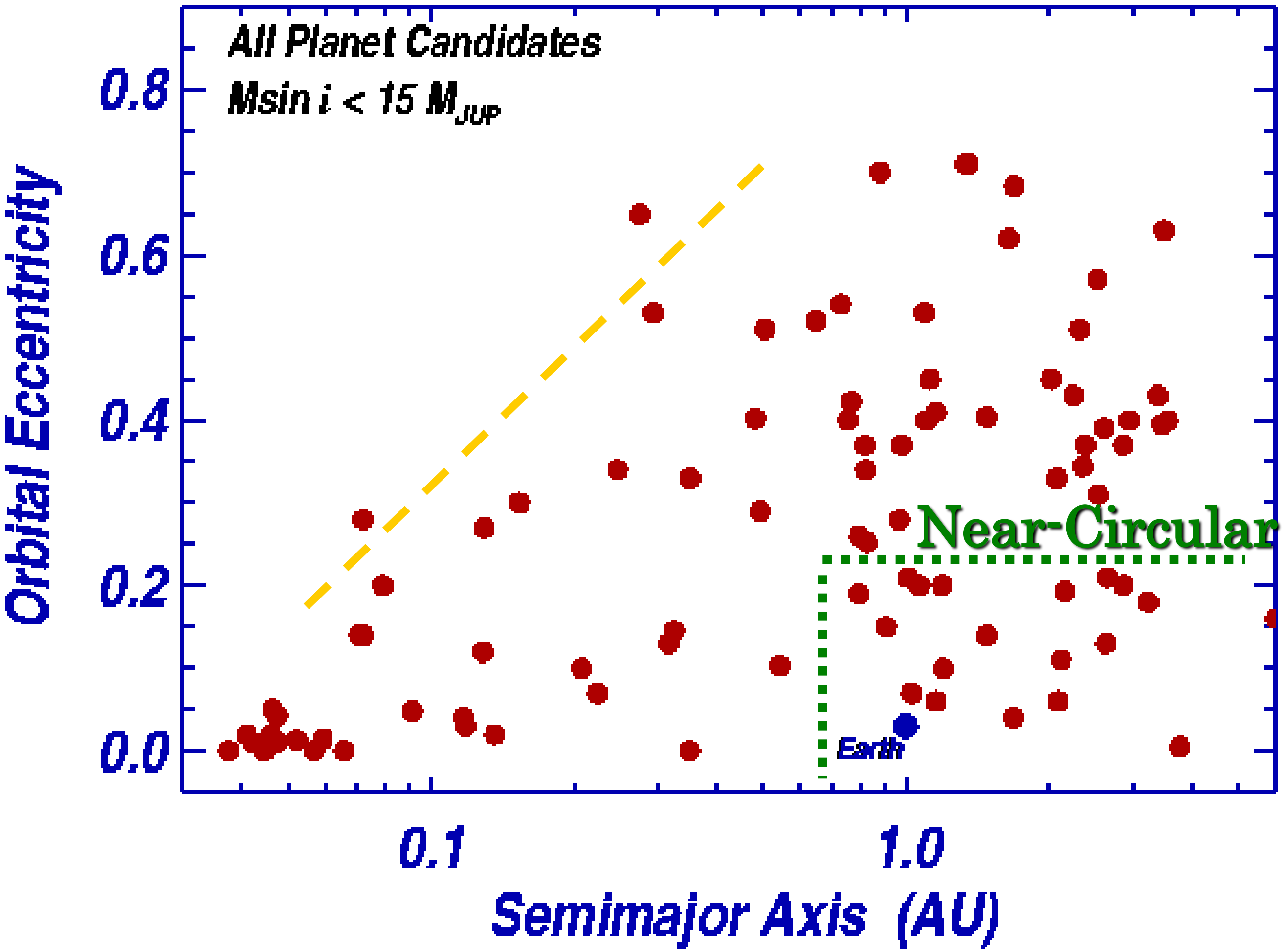
Extrasolar Planet Mass Distribution

Poor Detectability

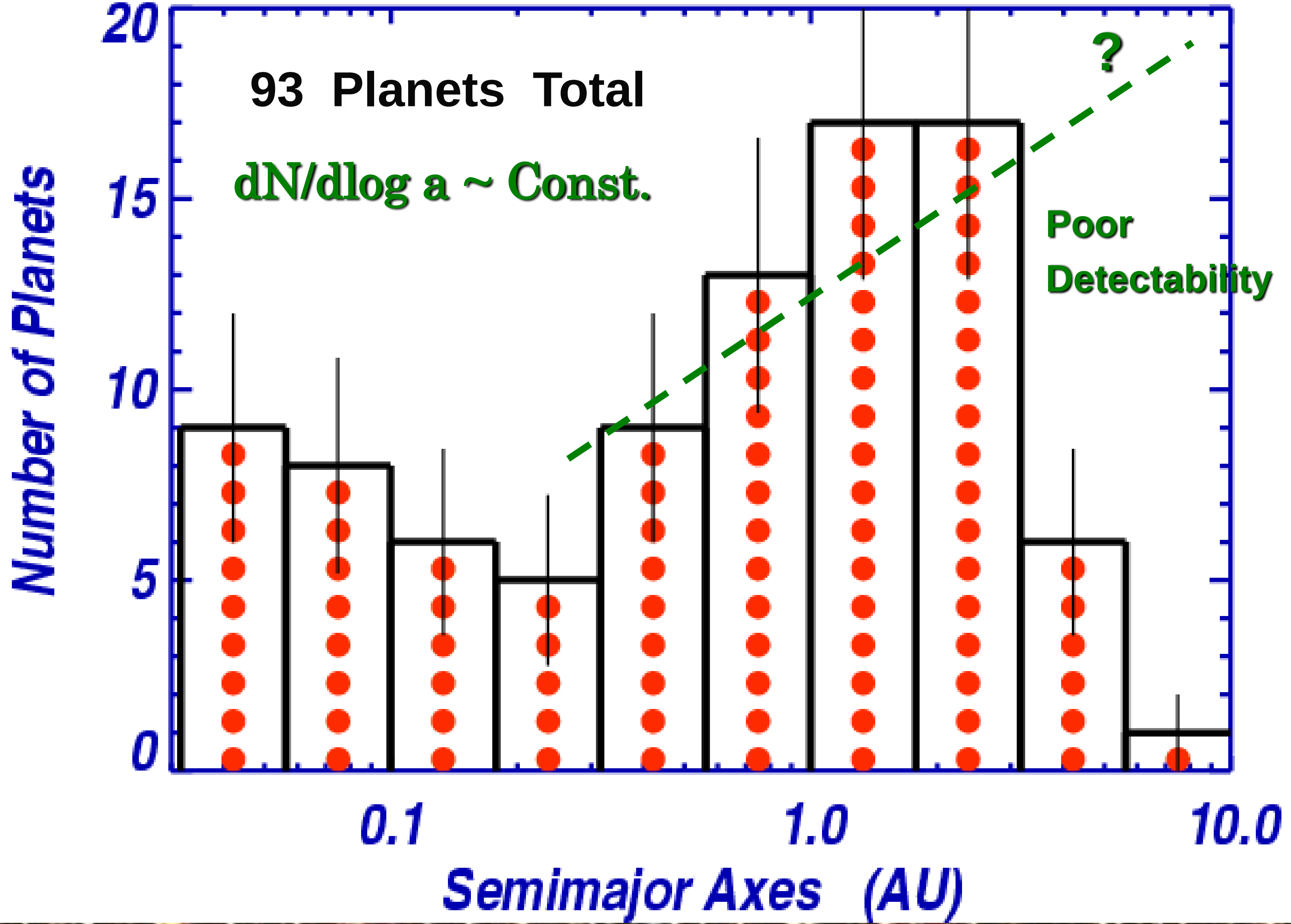
(0 – 1 M_J)

Butler, Marcy, Fischer, Vogt

ECCENTRICITIES of PLANETS



Histogram of Semimajor Axes



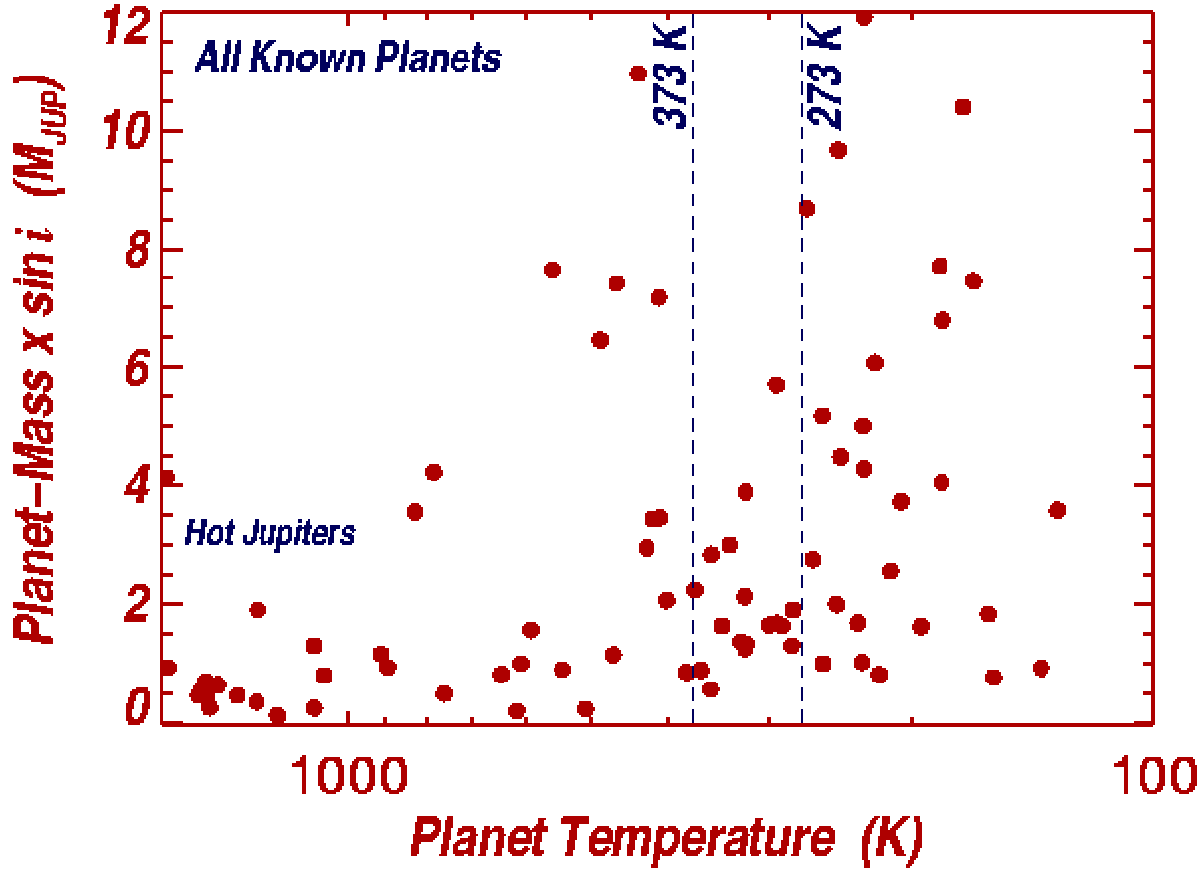
93 Planets Total

dN/dlog a ~ Const.

?

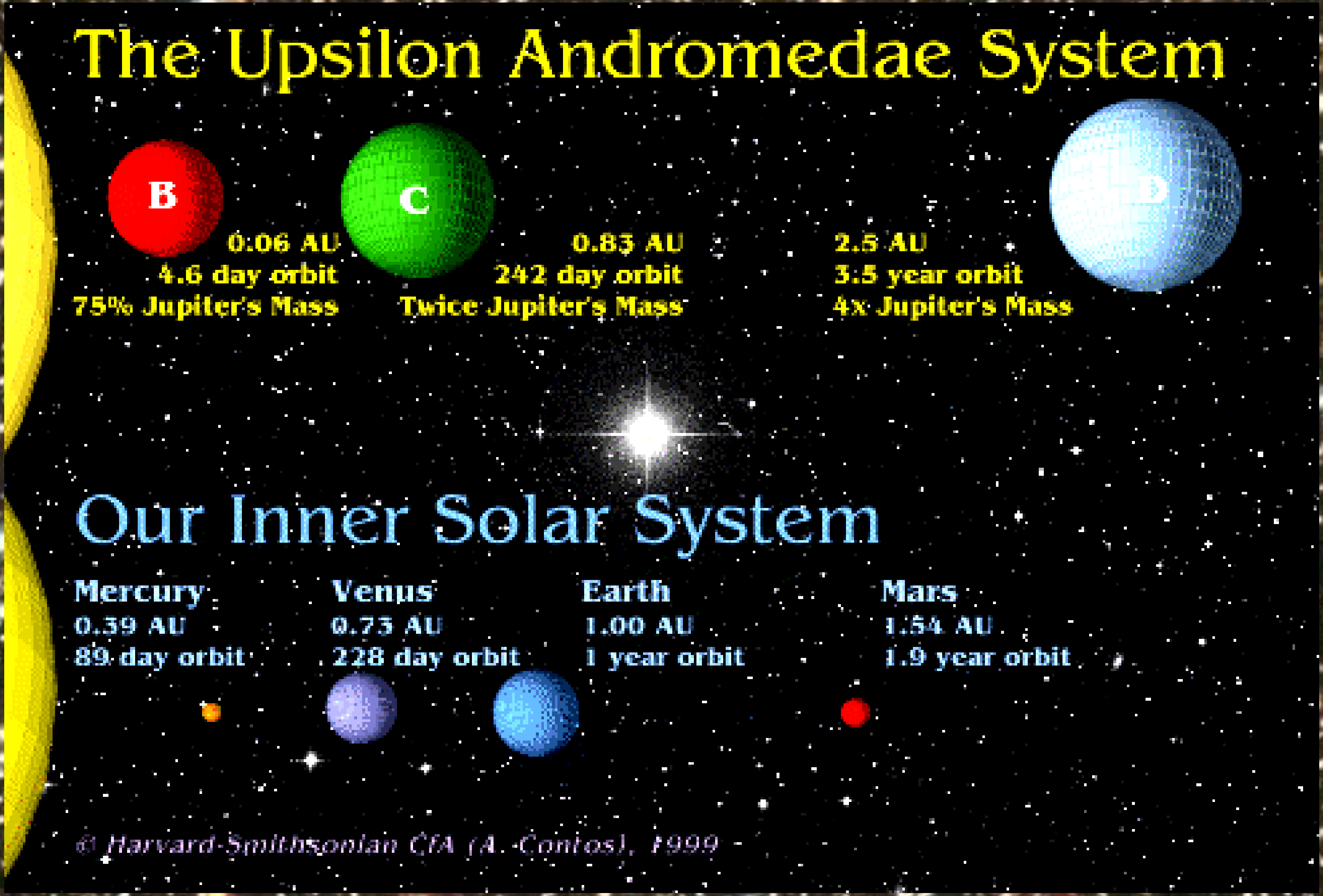
Poor Detectability

Temperatures of Planets



$T \sim L^{1/4}/d^{1/2}$

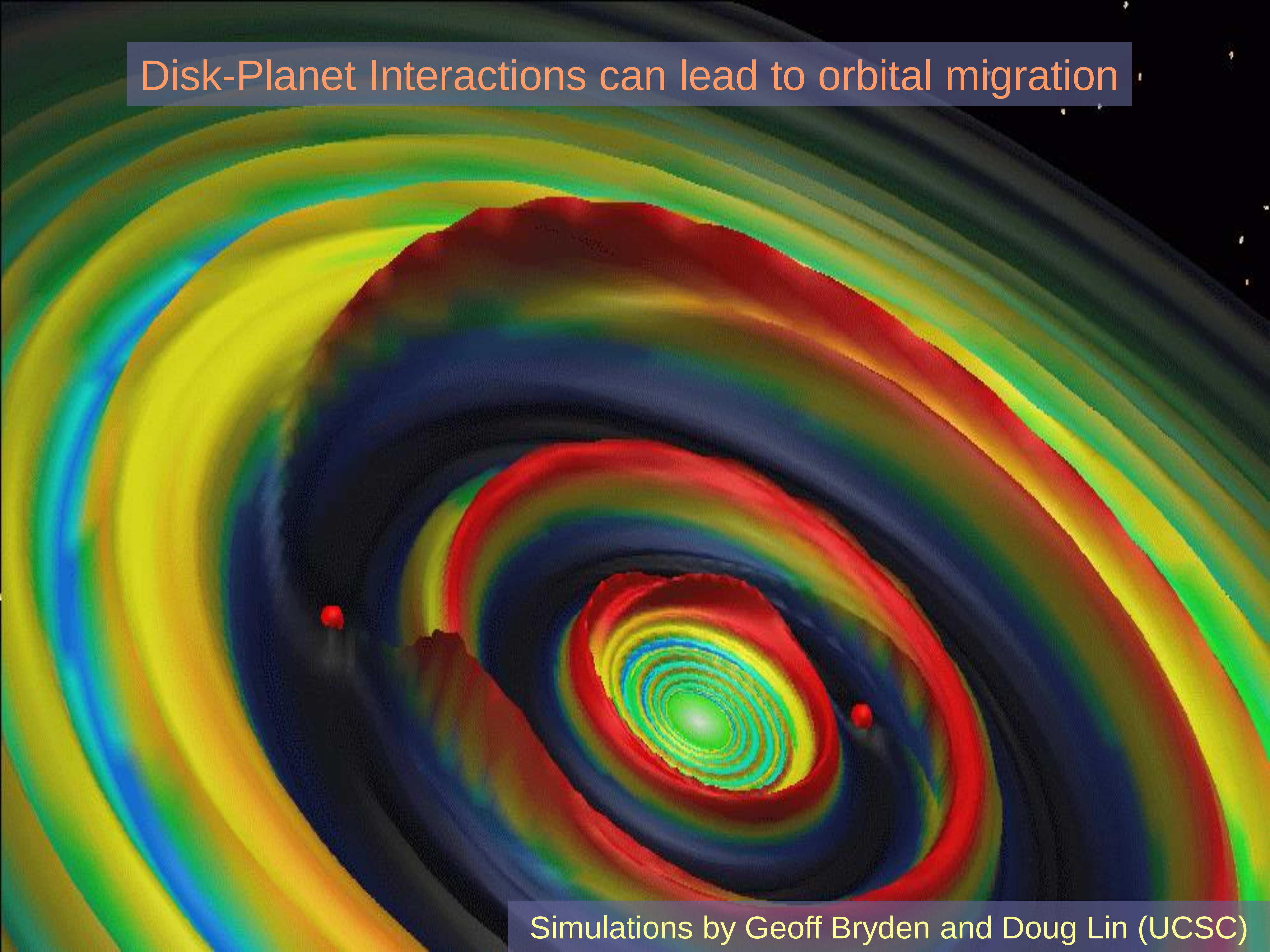
So Far, Unlike Our Own



Roughly 50% of stars that have one planet eventually reveal a second planet.

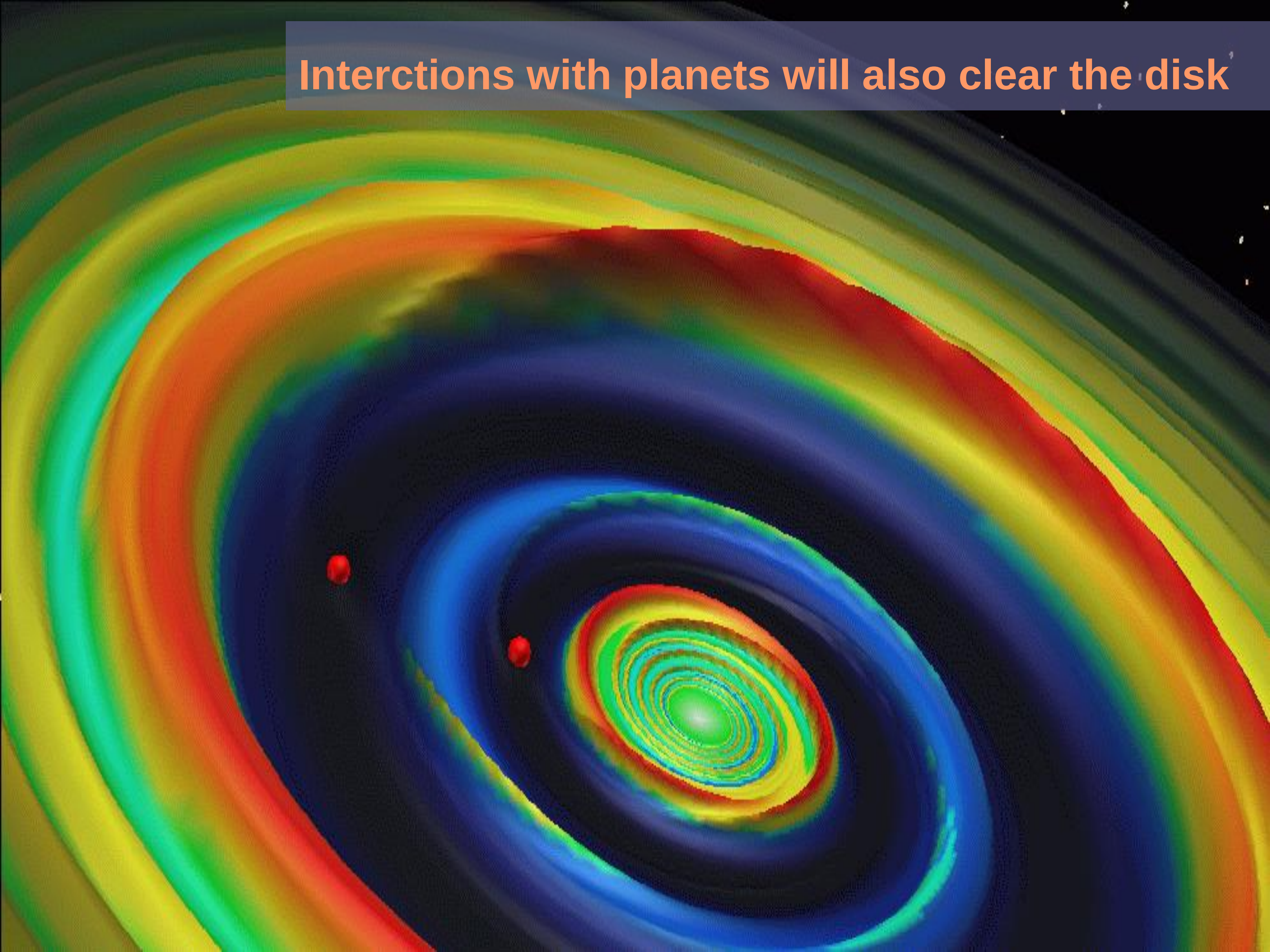
Fischer et al. 2001

Disk-Planet Interactions can lead to orbital migration

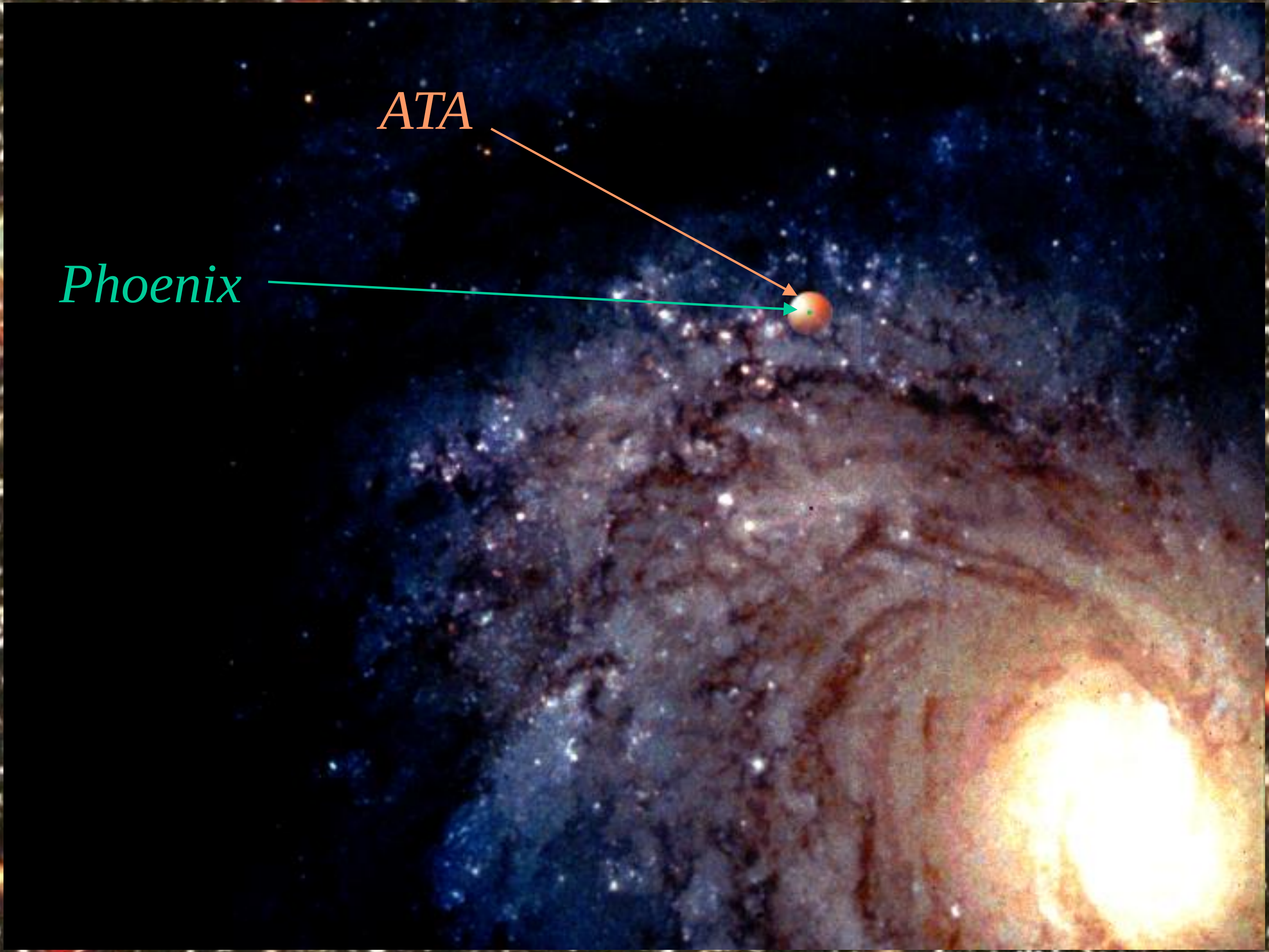


Simulations by Geoff Bryden and Doug Lin (UCSC)

Interctions with planets will also clear the disk



Exploring The Galaxy



Expand The Galactic Exploration