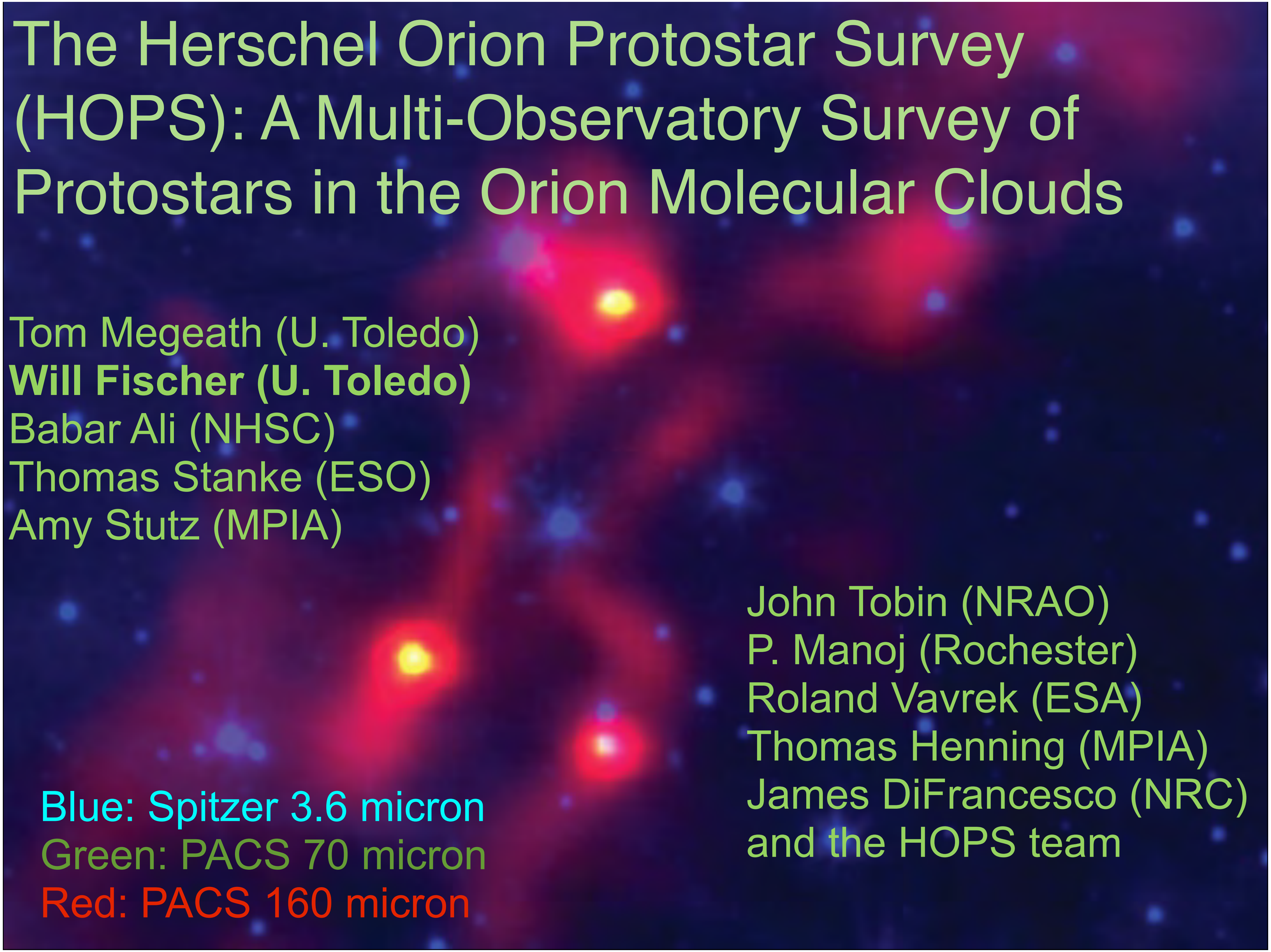
The Herschel Orion Protostar Survey (HOPS): A Multi-Observatory Survey of Protostars in the Orion Molecular Clouds

Tom Megeath (U. Toledo)
Will Fischer (U. Toledo)
Babar Ali (NHSC)
Thomas Stanke (ESO)
Amy Stutz (MPIA)

John Tobin (NRAO)
P. Manoj (Rochester)
Roland Vavrek (ESA)
Thomas Henning (MPIA)
James DiFrancesco (NRC)
and the HOPS team



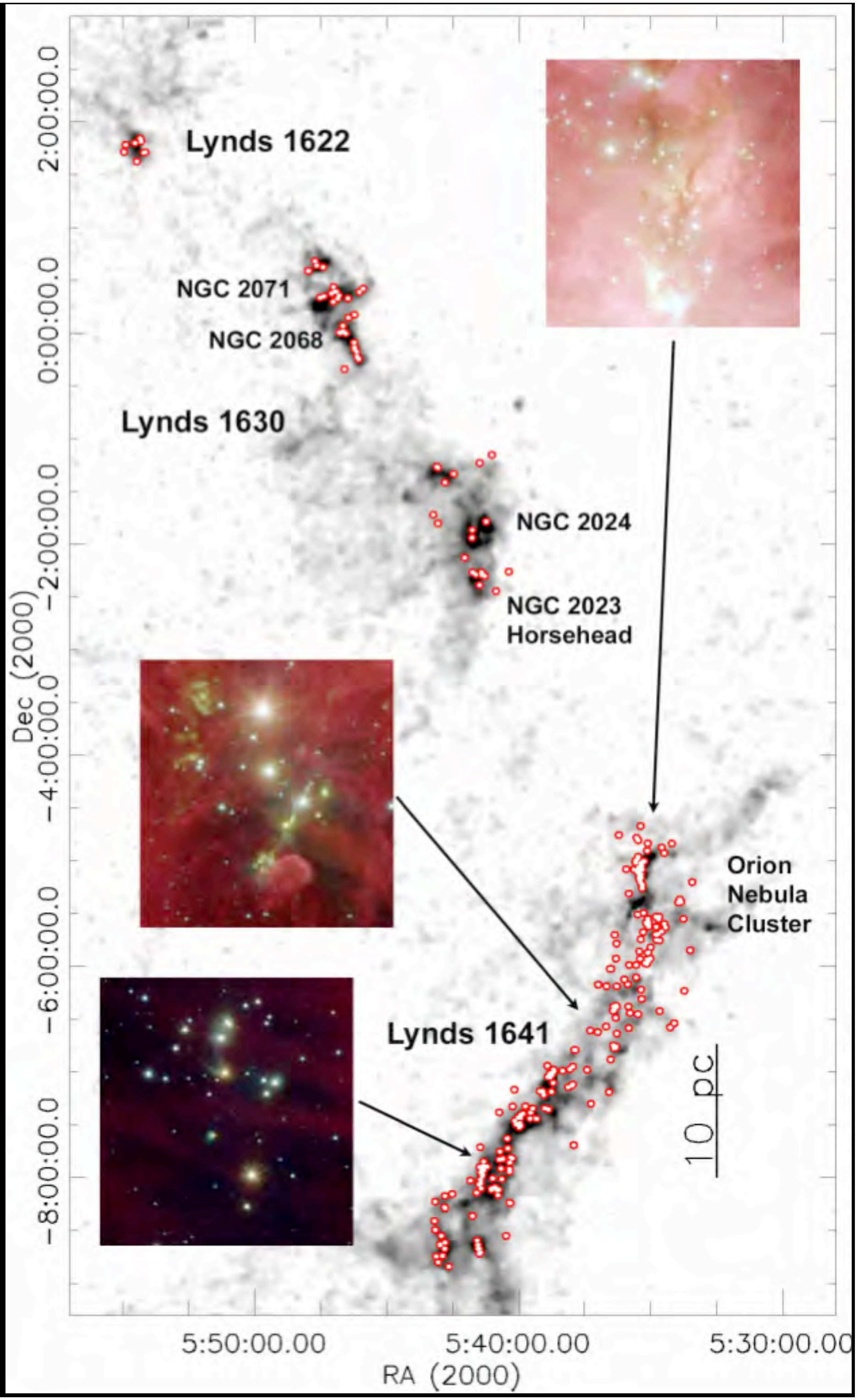
HOPS: Herschel Orion Protostar Survey

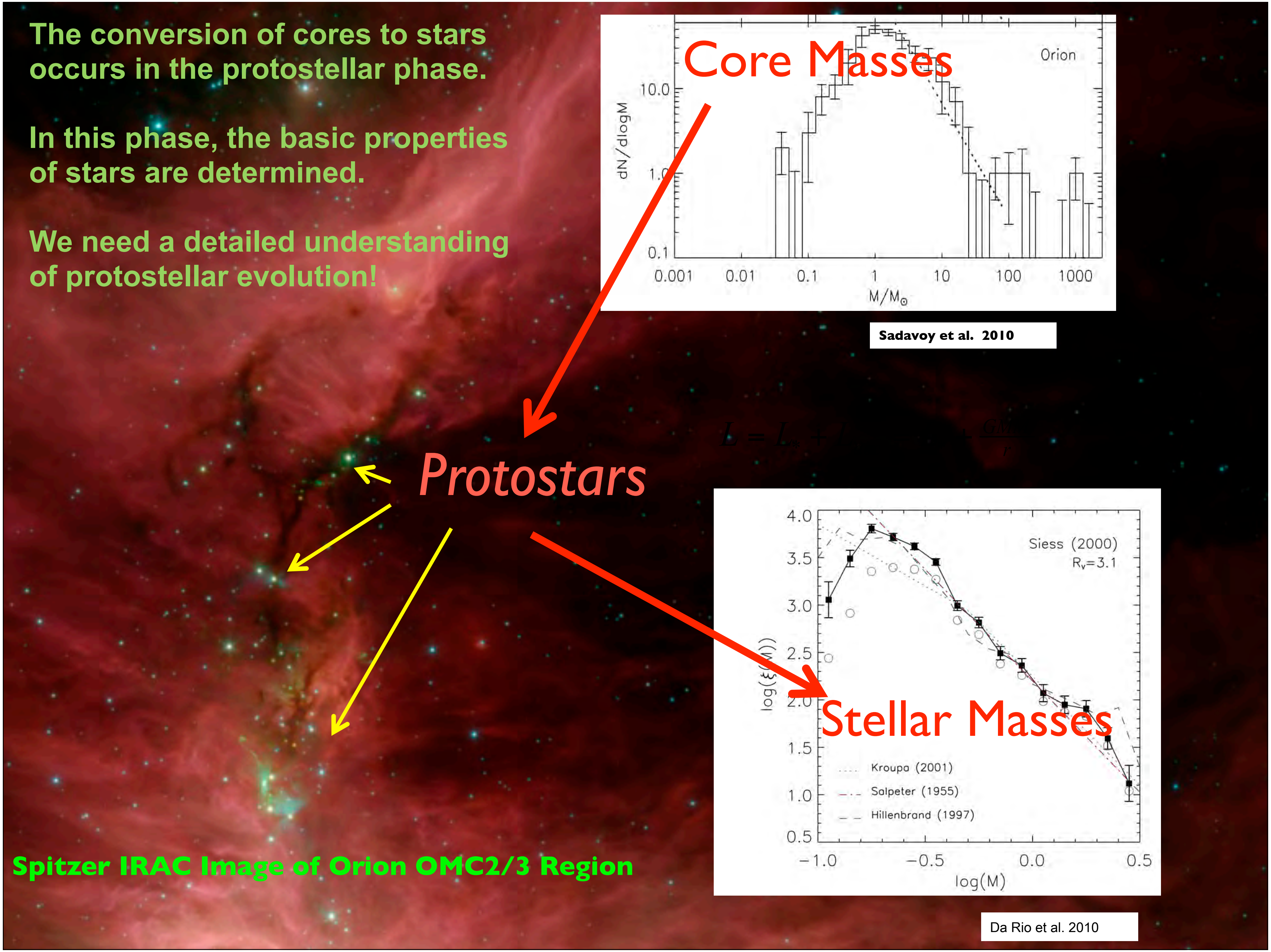
- •PACS imaging: 298 protostars at a common distance and in a variety of environments
  - Spitzer-identified protostars down to ~0.2 L_{sun}
  - 70 and 160 μm
  - 114 fields of 5’ to 8’
  - Medium (20”/s) scan rate

- •PACS range spectroscopy of 33 protostars (see P. Manoj Poster!!!)

And.........

- •Spitzer imaging + spectra
- •Hubble and ground based near-IR imaging + spectra
- •Ground-based sub-mm data



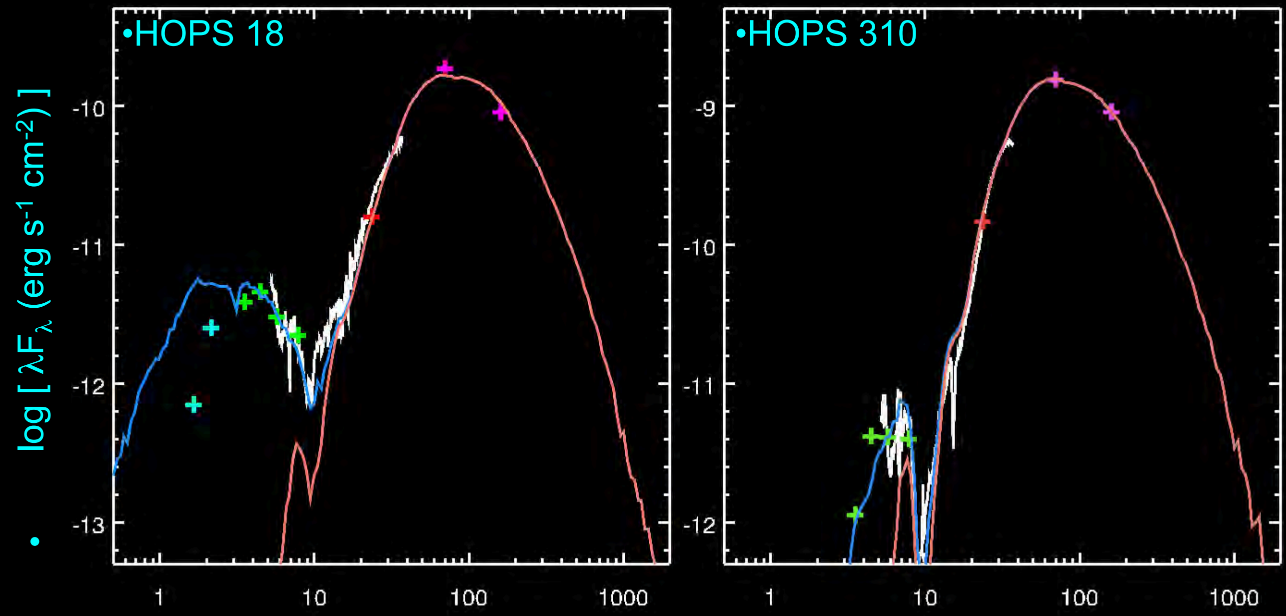

The conversion of cores to stars occurs in the protostellar phase.
In this phase, the basic properties of stars are determined.
We need a detailed understanding of protostellar evolution!
Core Masses
Orion
dN/dlogM
10.0
1.0
0.1
0.001
0.01
0.1
1
10
100
1000
M/M⊙
Sadavoy et al. 2010
Protostars
Siess (2000)
R_V=3.1
log(ξ(M))
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
Stellar Masses
Kroupa (2001)
Salpeter (1955)
Hillenbrand (1997)
−1.0
−0.5
0.0
0.5
log(M)
Spitzer IRAC Image of Orion OMC2/3 Region
Da Rio et al. 2010

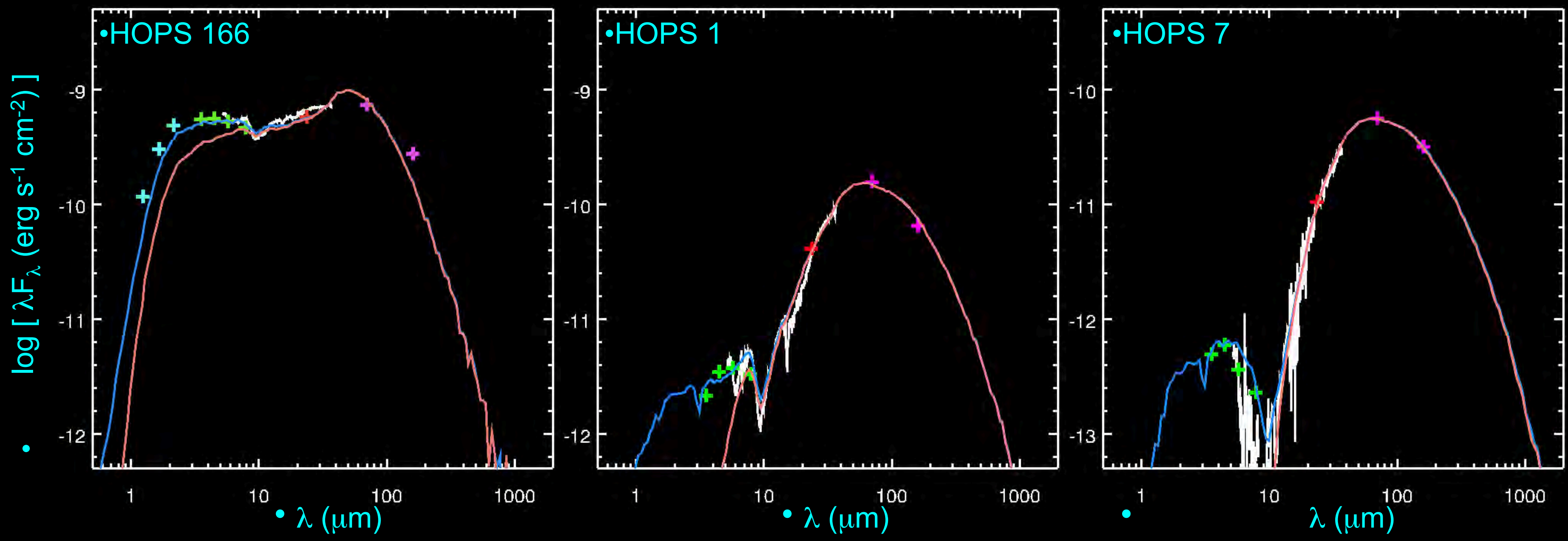
Goals of HOPS

- Dependence of Protostellar Properties on "Environment"
  - Properties of surrounding core (this talk)
  - Presence of binary or cluster
  - Properties of parental filament (poster by T. Stanke)
- Auditing infall and outflow
  - Infall estimated from SED
  - Outflow from PACS spectroscopy and ground-based data (poster by P. Manoj)
- Providing definitive data set for testing models of protostellar evolution (this talk and Amy Stutz's talk)
  - Understand connection between evolution and environment due to feedback (this talk).

The HOPS Model Grid (John Tobin)

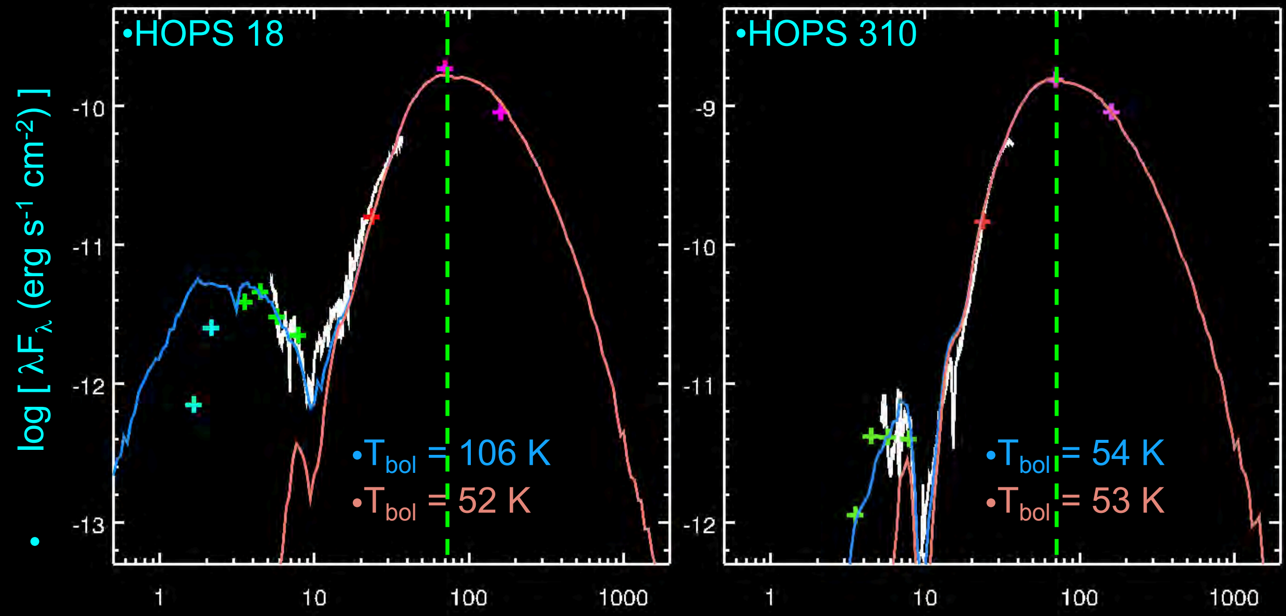
- Generated with Whitney Monte-Carlo code
- 3600 models viewed from 10 angles - giving 36000 SEDs
- Vary envelope density, outflow cavity angle, centrifugal flattening, luminosity.

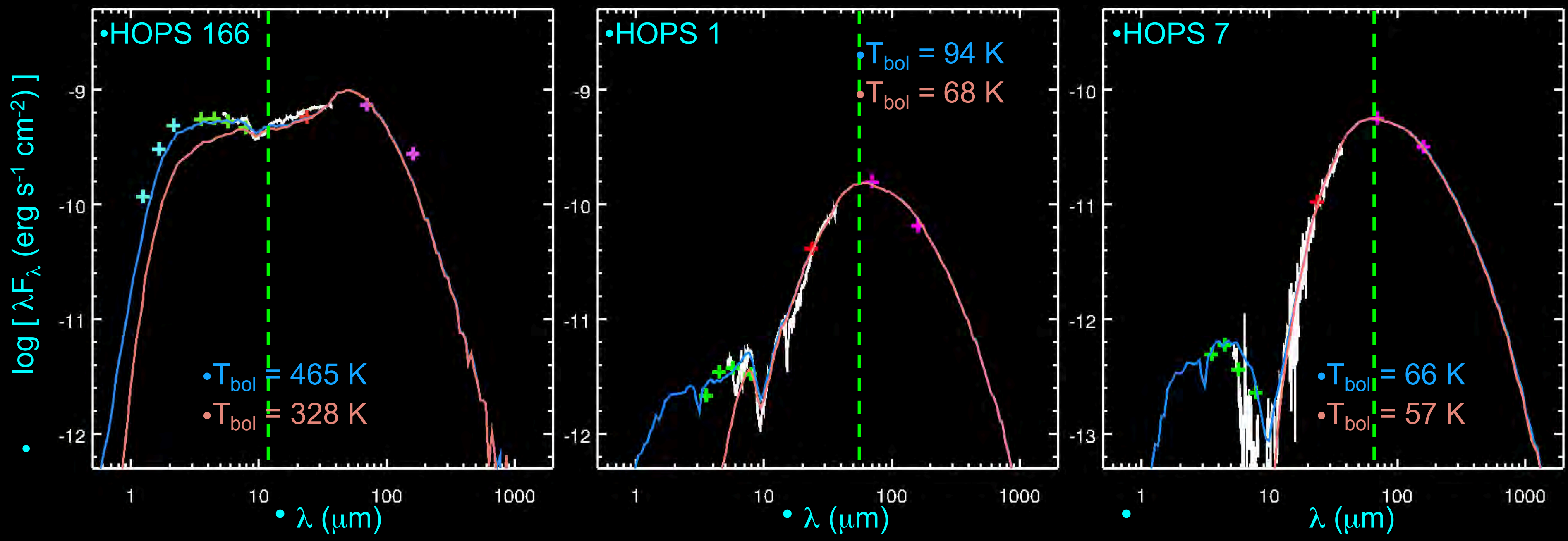




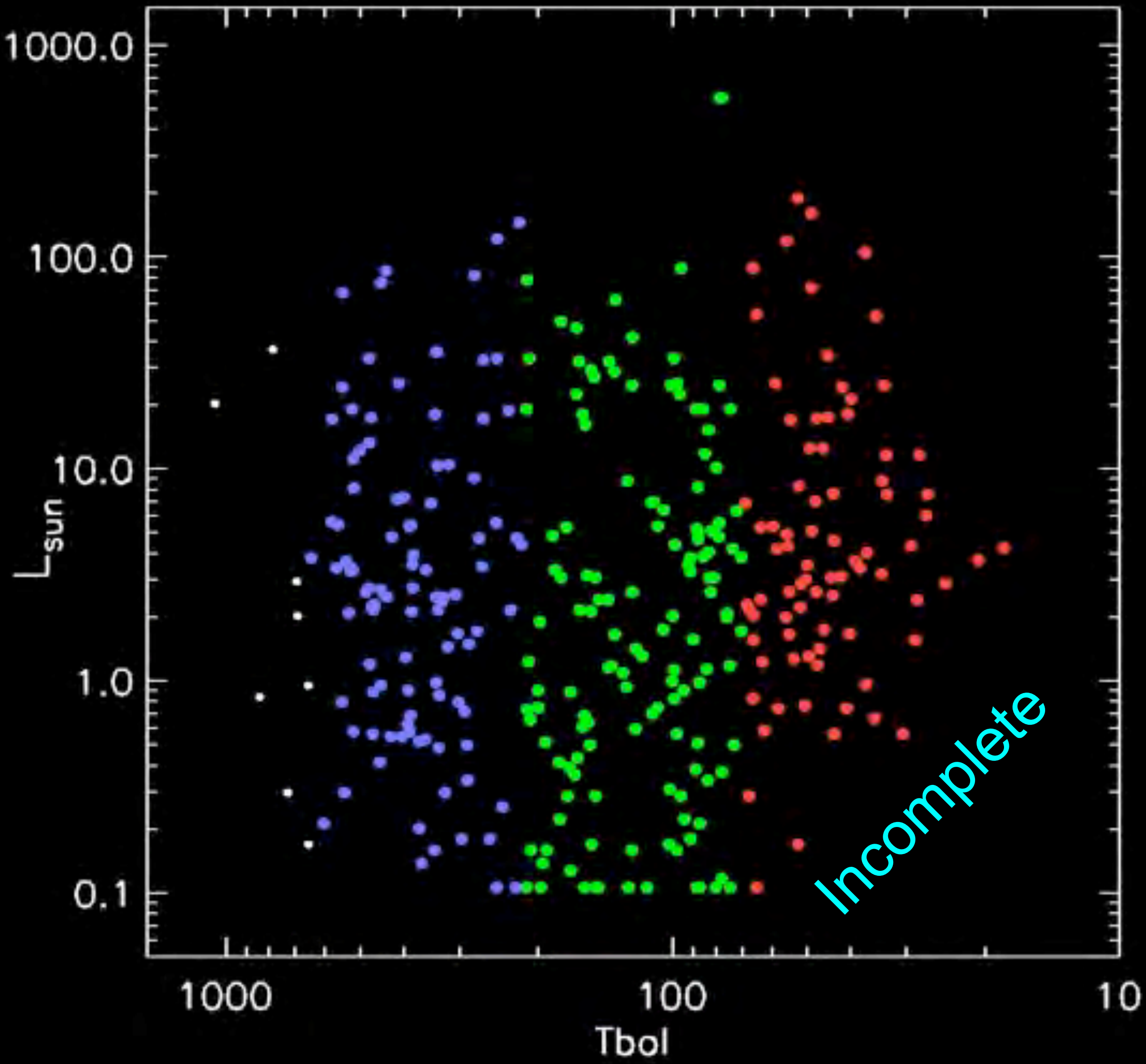
T_{bol} (Bolometric Temperature: temperature of a blackbody with the same mean frequency of the protostar)

- T_{bol} is intended to track envelope evolution
- Can be skewed upward by scattered light
- With model, count only the thermal emission



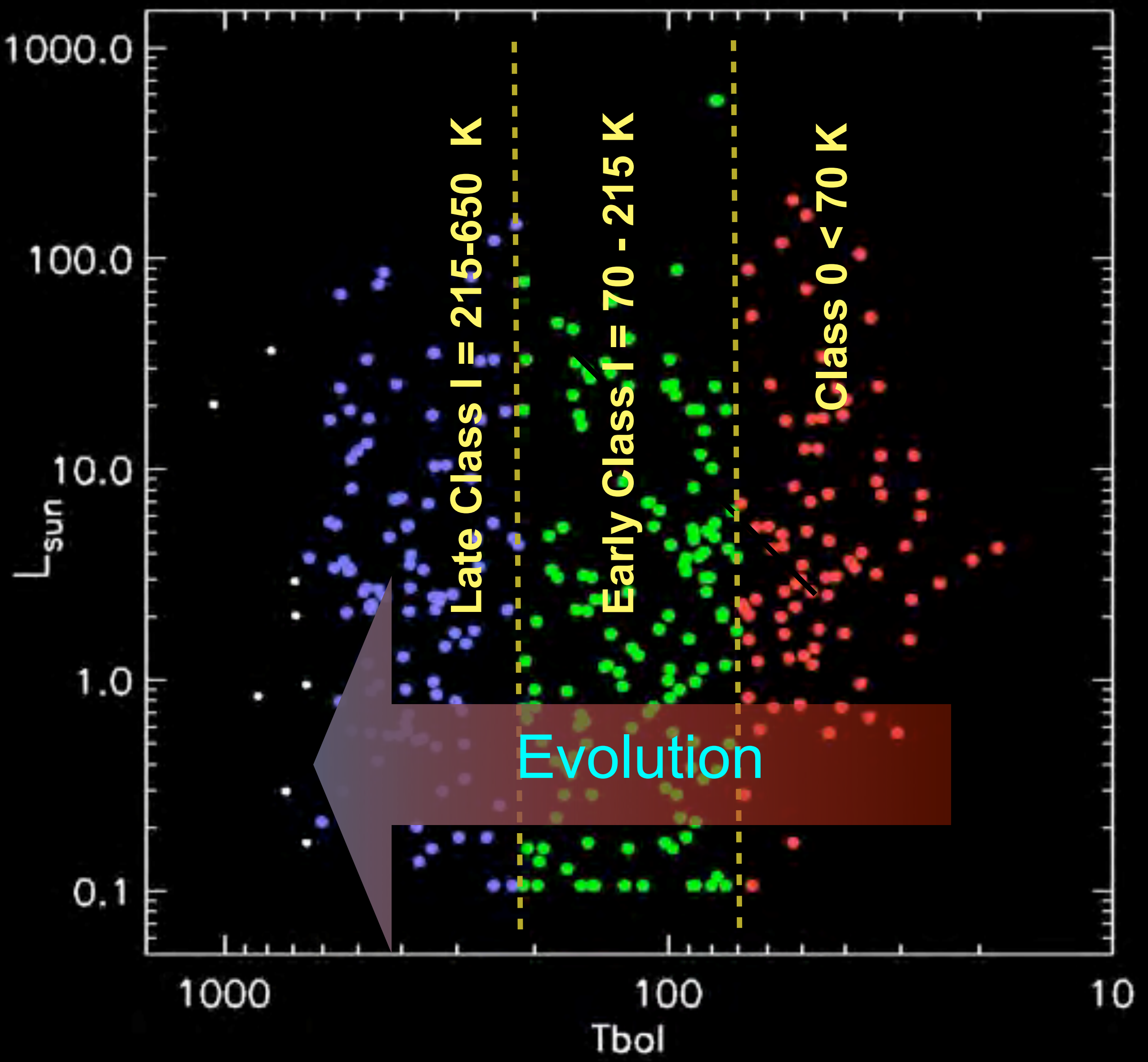


Tracing Protostellar Evolution with Bolometric Temperature

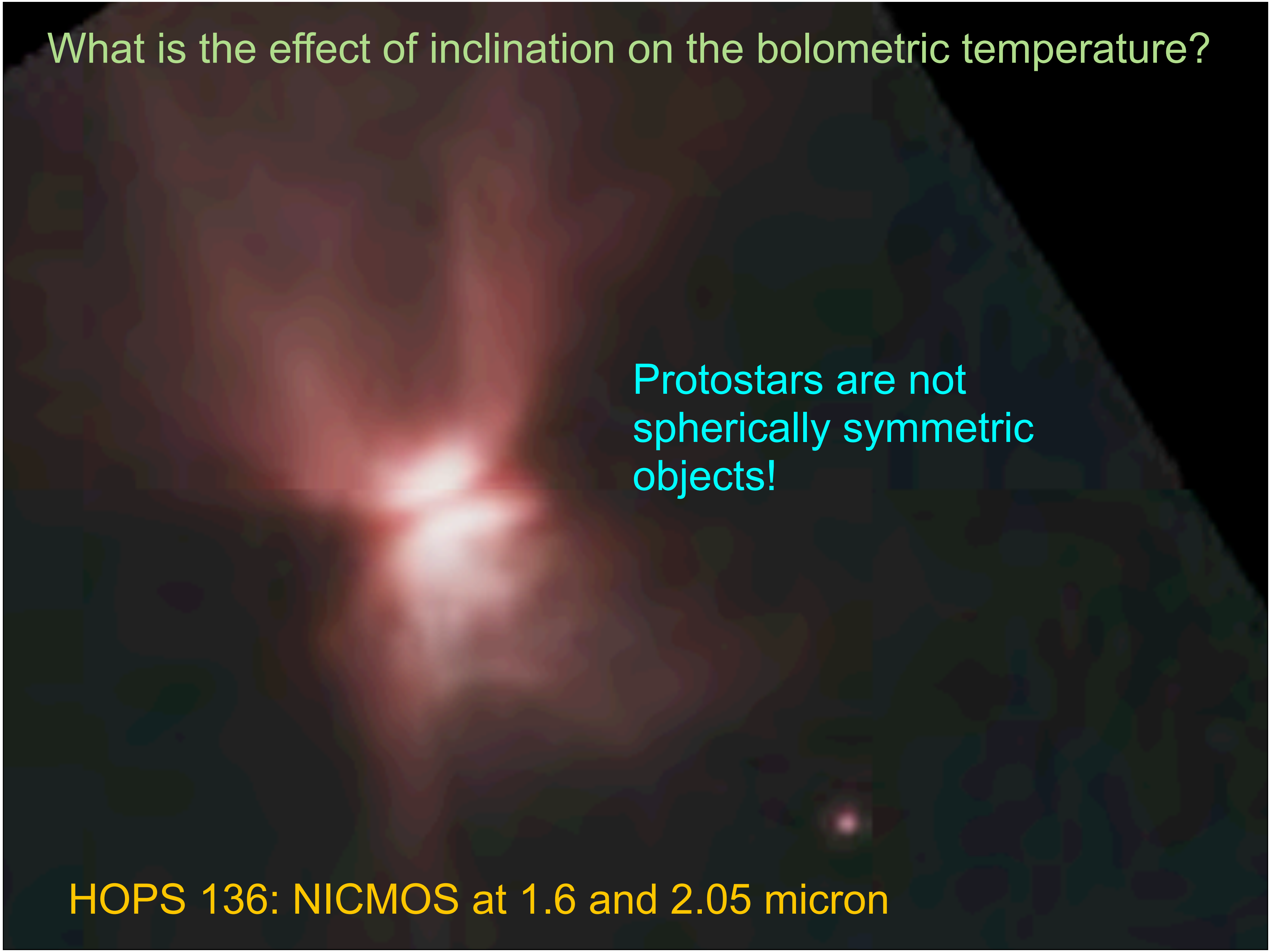


Bolometric Temperature vs Luminosity Plot for 298 Protostars

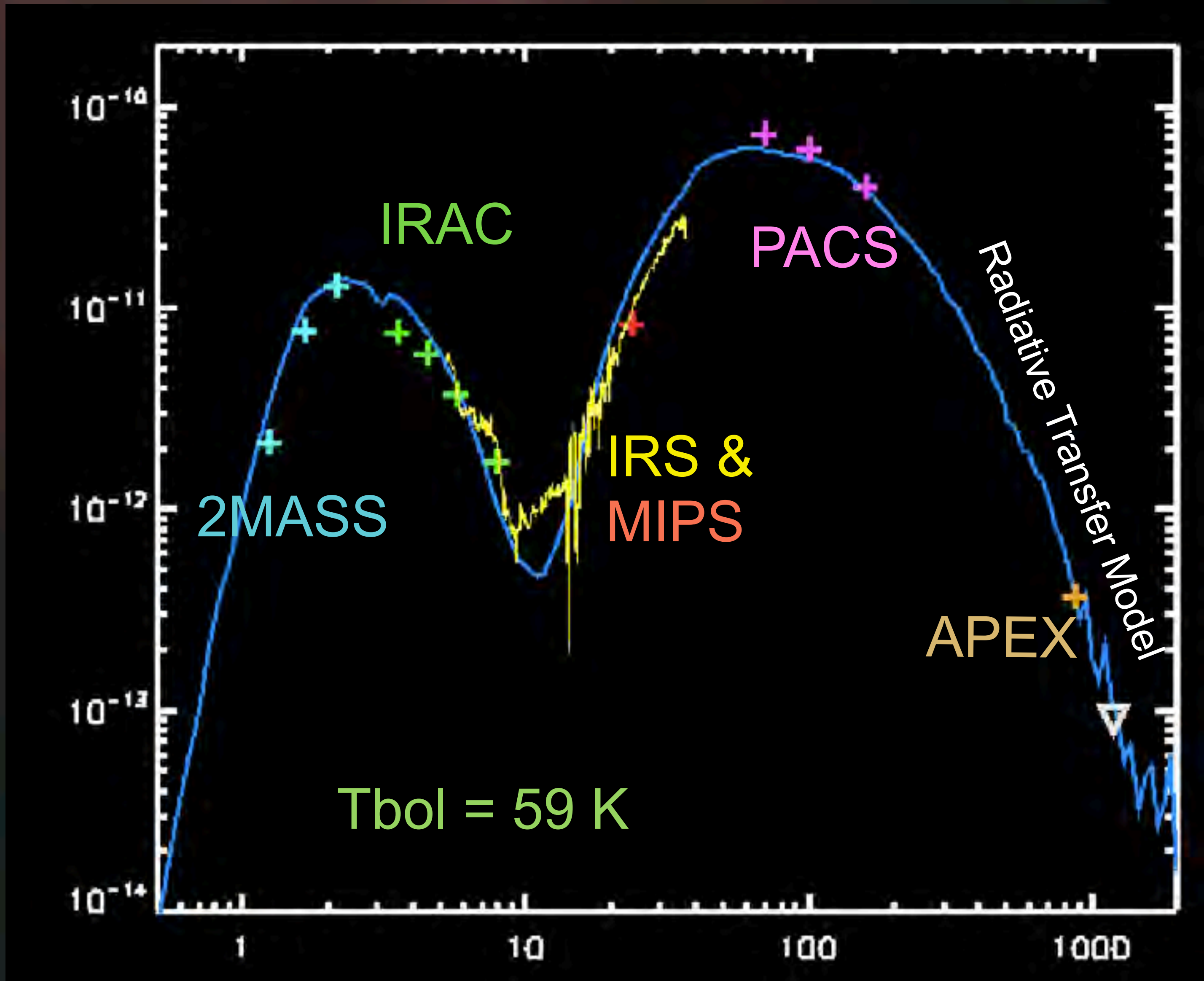
Tracing Protostellar Evolution with Bolometric Temperature



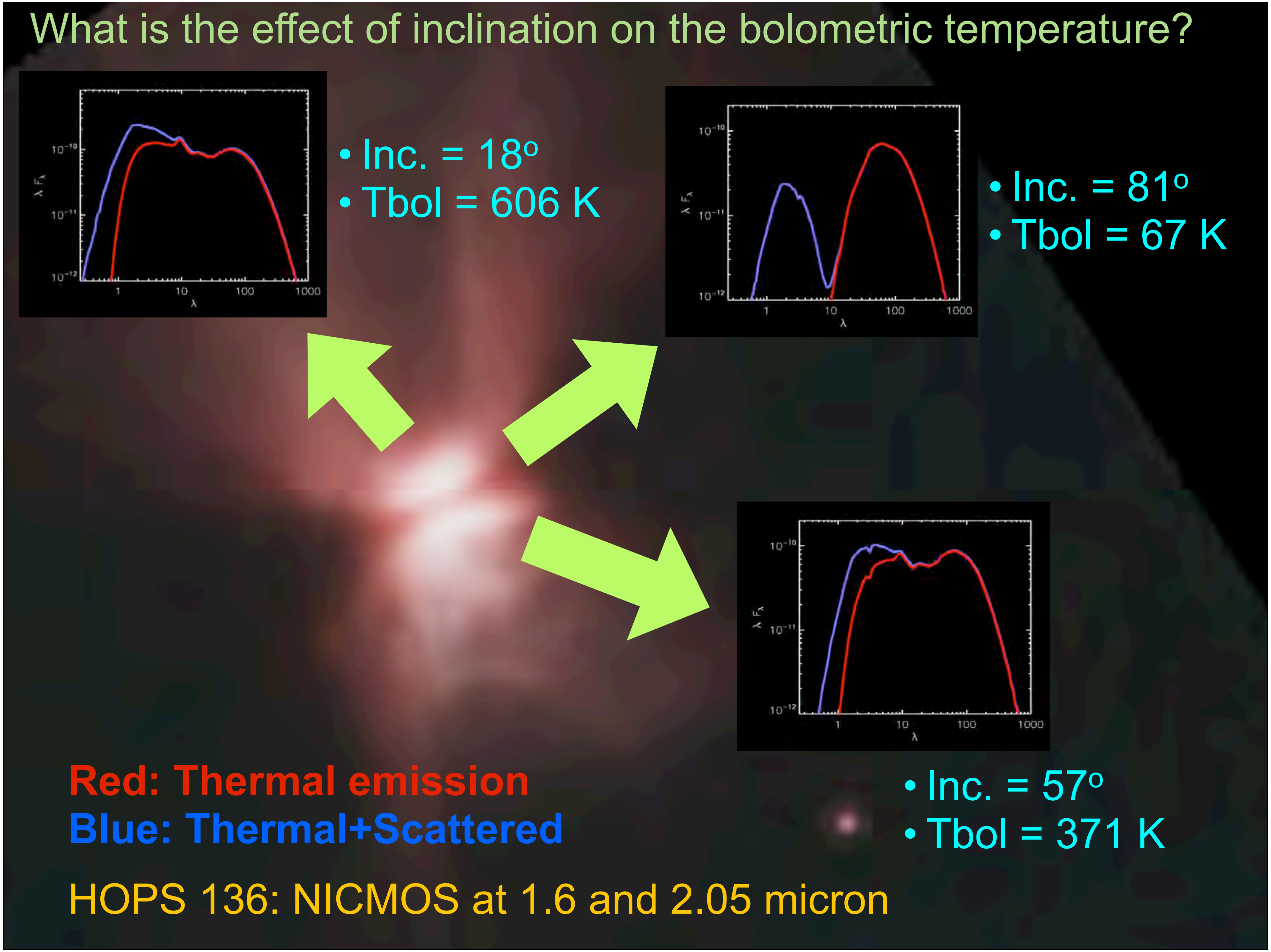
Is this the HR diagram for protostars?


What is the effect of inclination on the bolometric temperature?
Protostars are not spherically symmetric objects!
HOPS 136: NICMOS at 1.6 and 2.05 micron

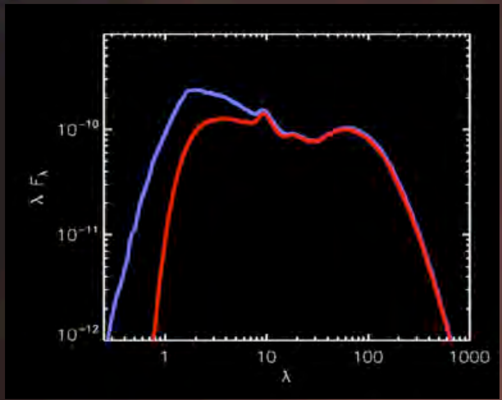
What is the effect of inclination on the bolometric temperature?



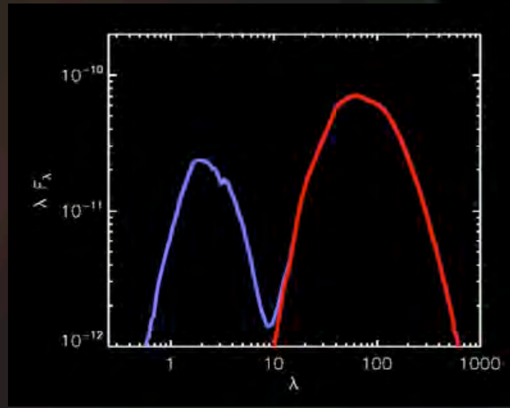
HOPS 136: NICMOS at 1.6 and 2.05 micron


What is the effect of inclination on the bolometric temperature?
• Inc. = 18o
• Tbol = 606 K
• Inc. = 81o
• Tbol = 67 K
• Inc. = 57o
• Tbol = 371 K
Red: Thermal emission
Blue: Thermal+Scattered
HOPS 136: NICMOS at 1.6 and 2.05 micron
λ F_λ
λ
1
10
100
1000

What is the effect of inclination on the bolometric temperature?

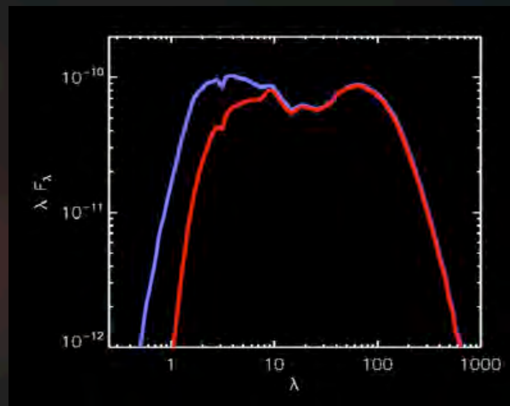


- Inc. = 18°
- Tbol = 606 K



- Inc. = 81°
- Tbol = 67 K

Inclination averaged bolometric temperature is <Tbol> = 393 K

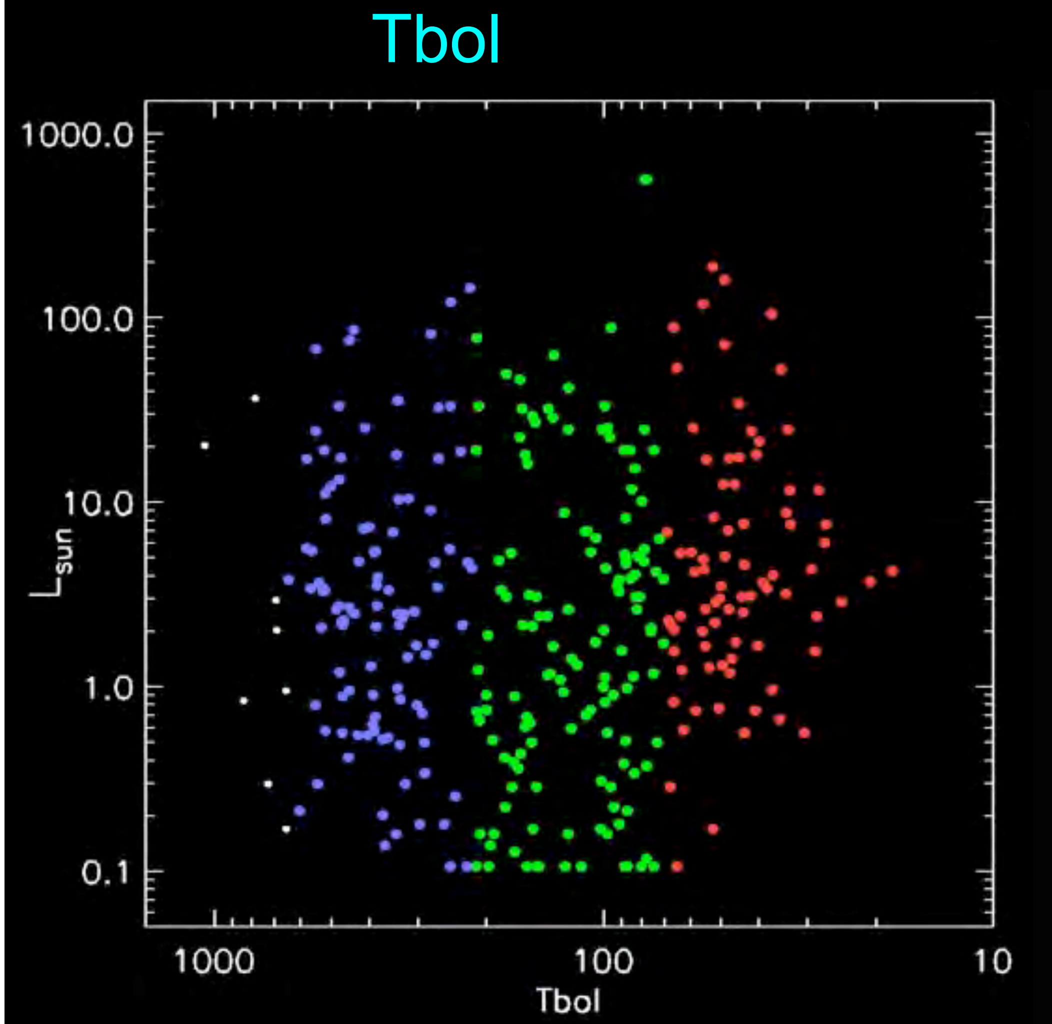


- Inc. = 57°
- Tbol = 371 K

Red: Thermal emission
Blue: Thermal+Scattered

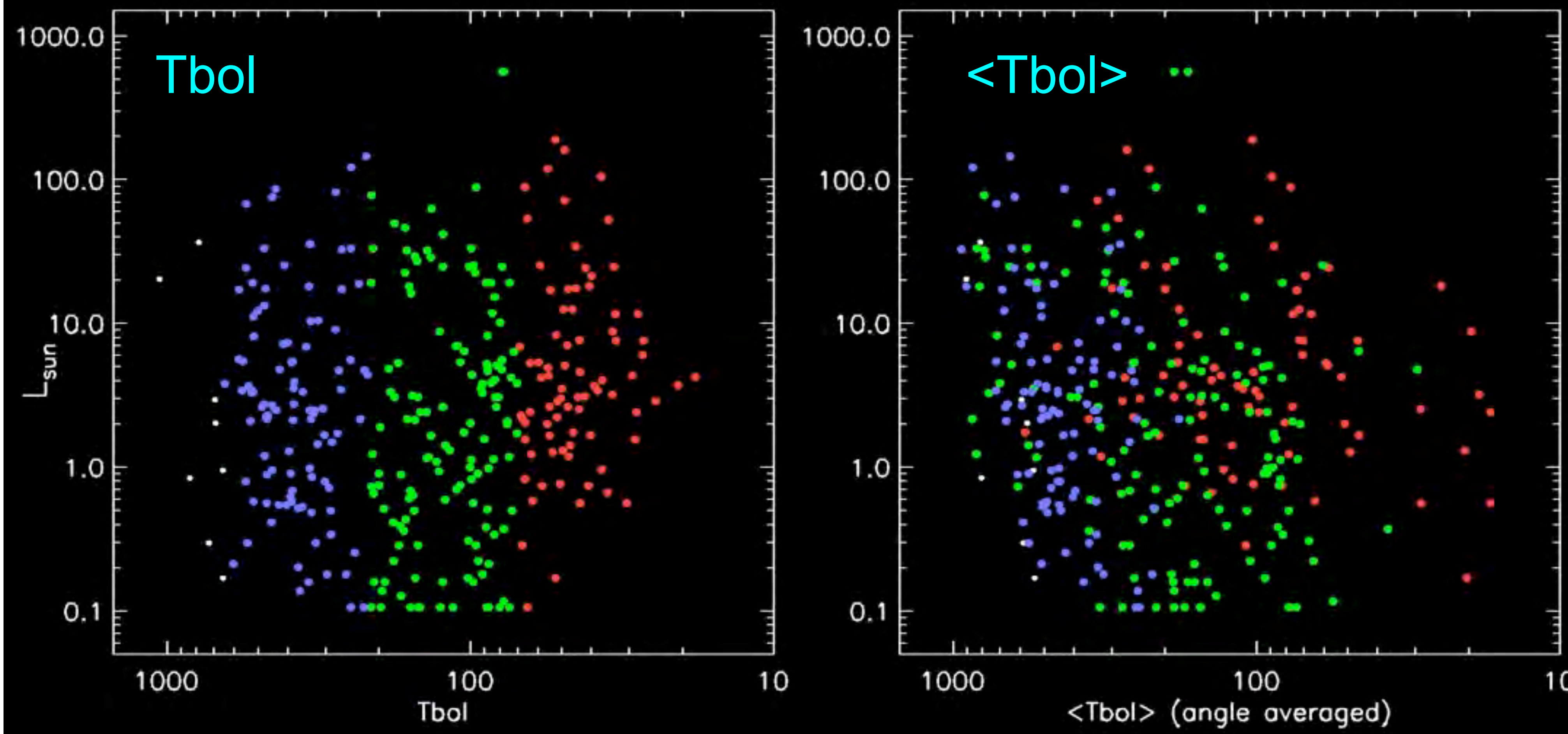
HOPS 136: NICMOS at 1.6 and 2.05 micron

Tracing Protostellar Evolution with Inclination Averaged Bolometric Temperature



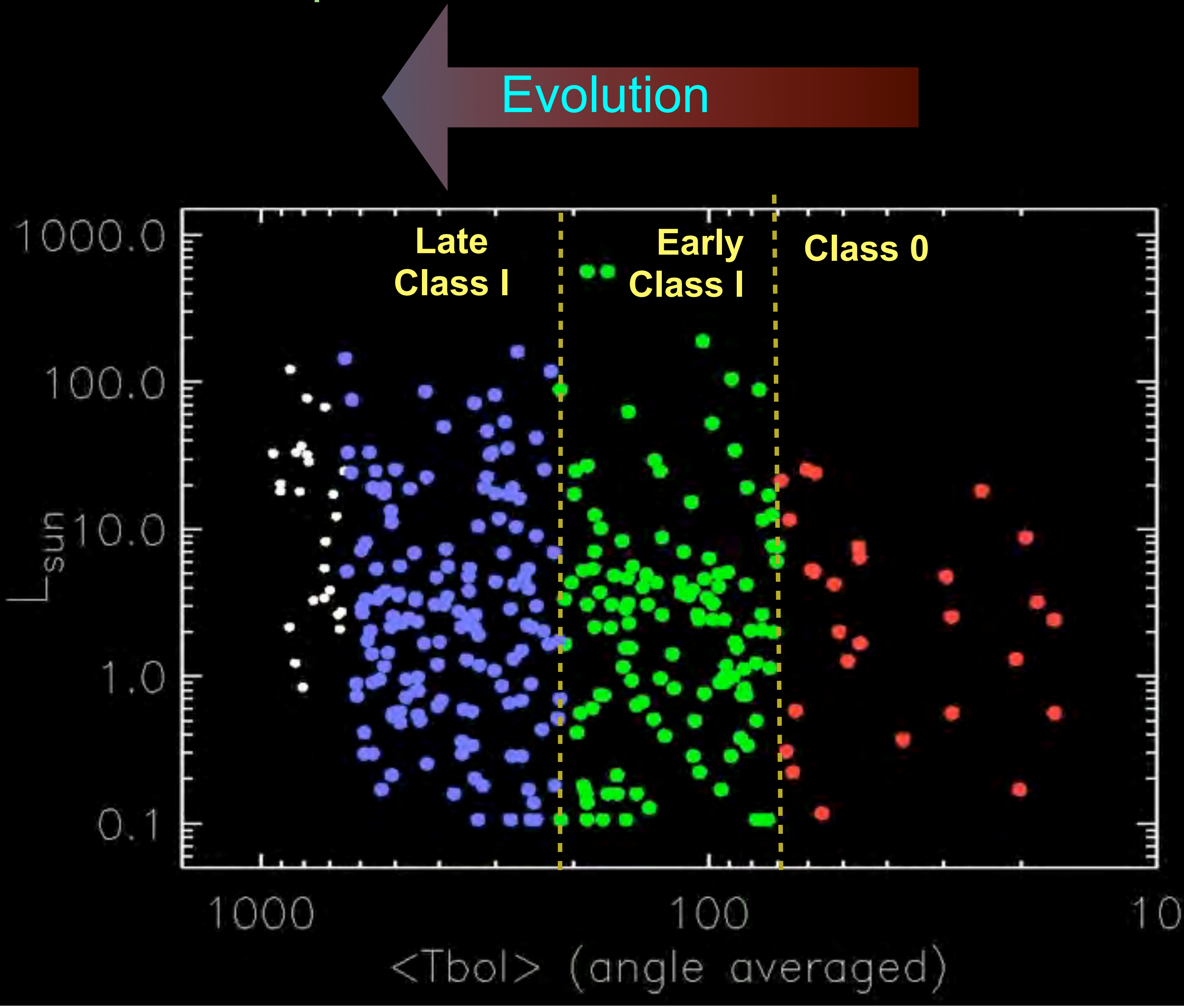
Tracing Protostellar Evolution with Inclination Averaged Bolometric Temperature

Fit model and use Tbol averaged over 10 inclinations: <Tbol>

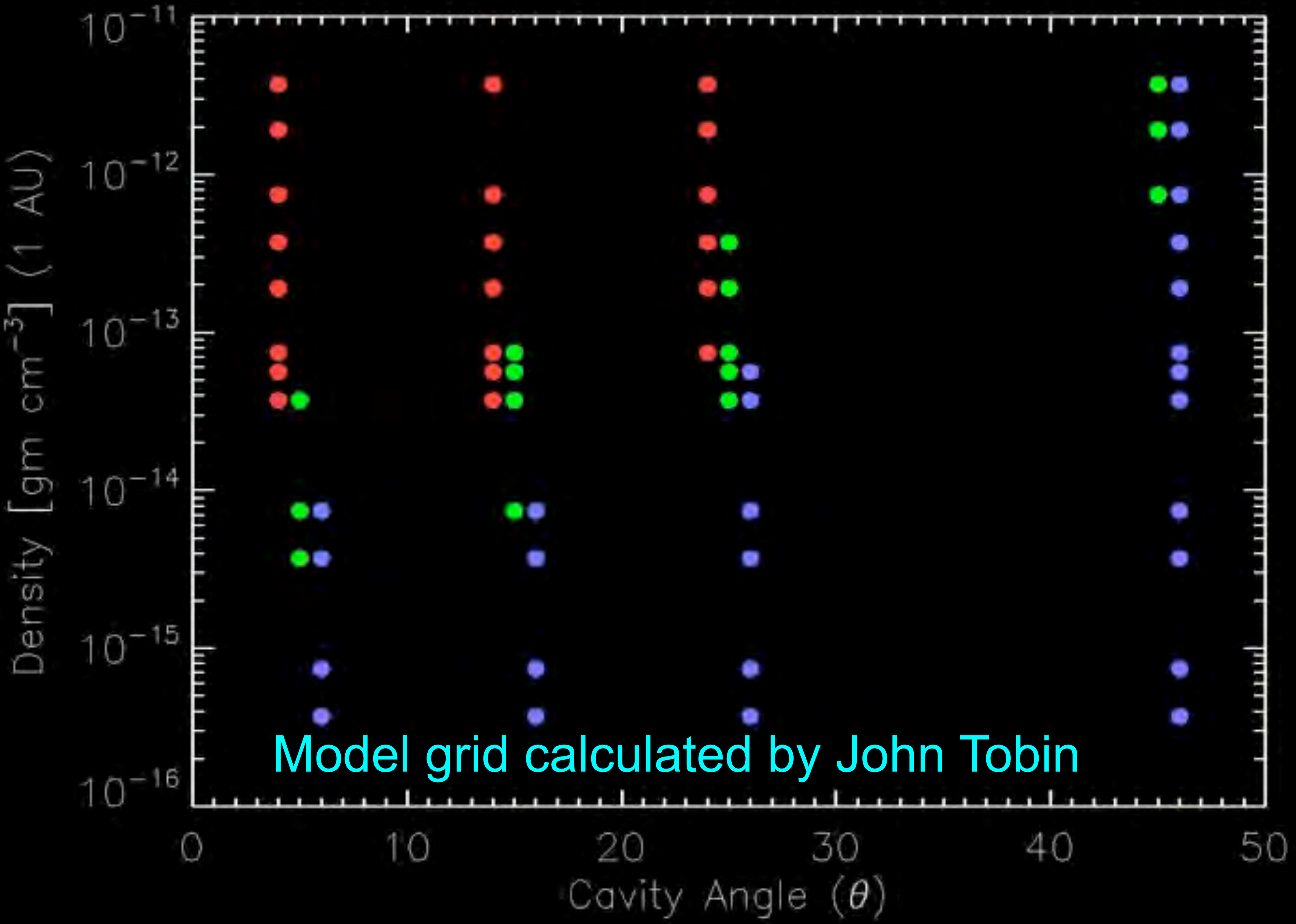


Many Class 0 objects may be highly inclined Class I sources

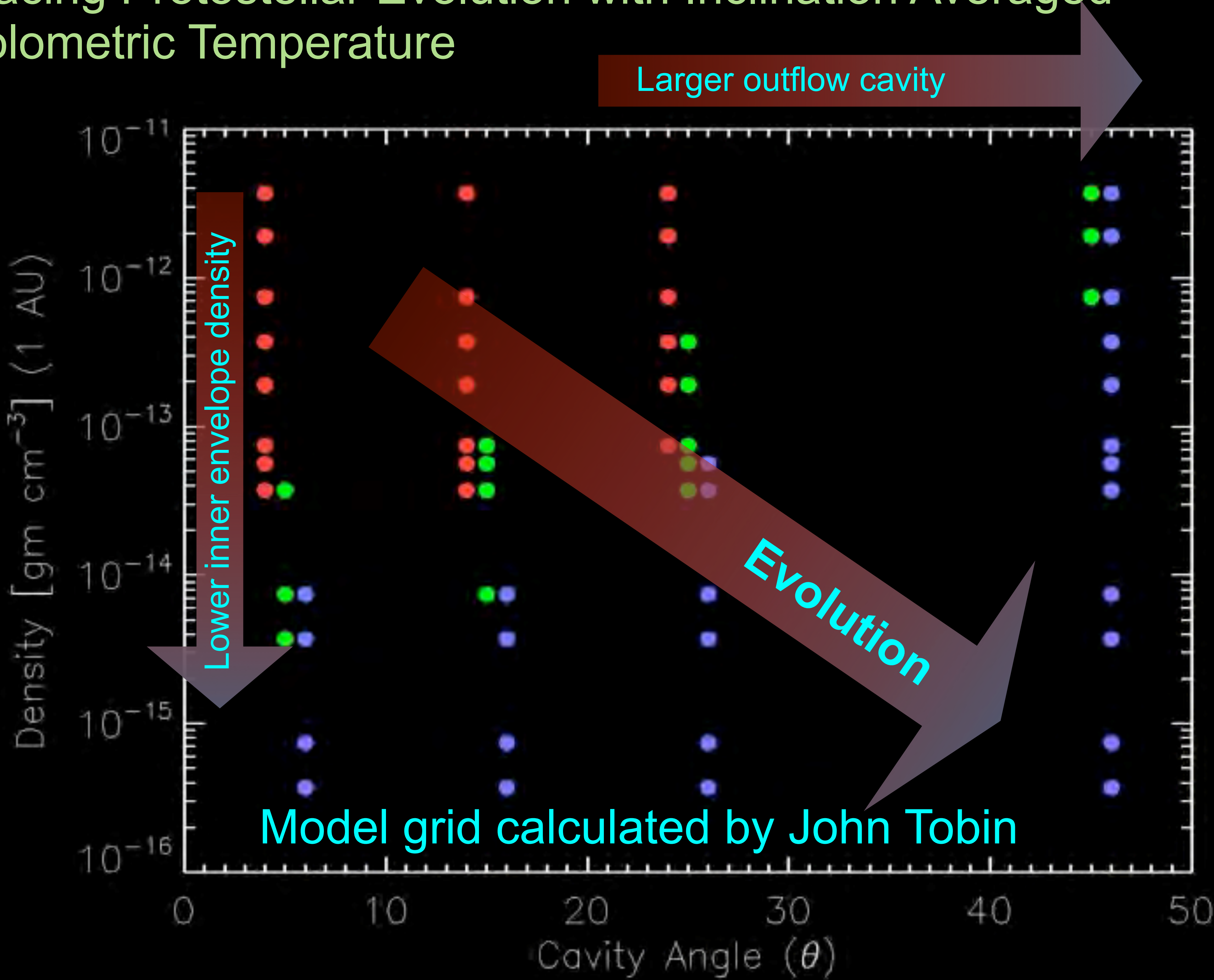
Tracing Protostellar Evolution with Inclination Averaged Bolometric Temperature



Tracing Protostellar Evolution with Inclination Averaged Bolometric Temperature

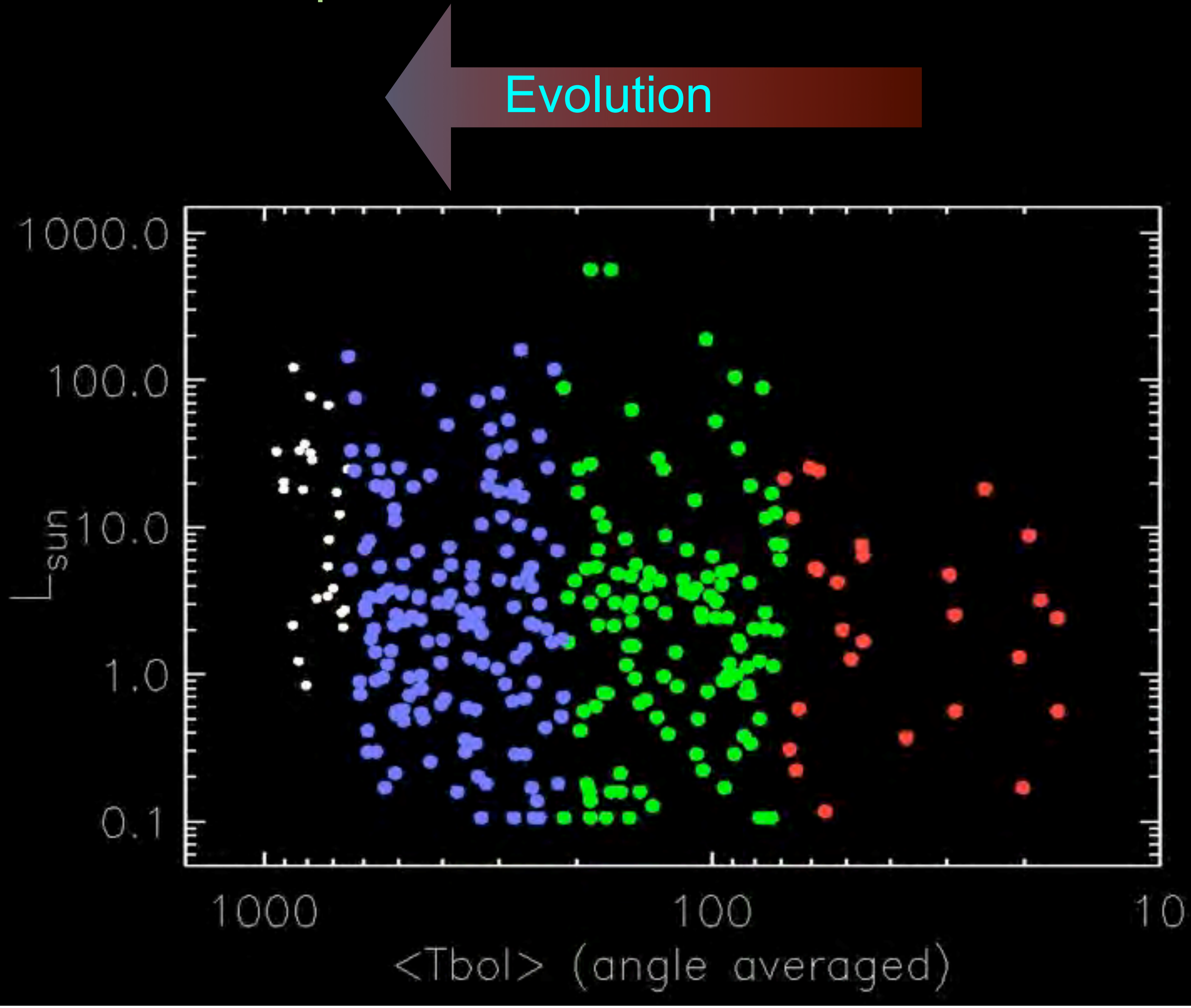


Tracing Protostellar Evolution with Inclination Averaged Bolometric Temperature



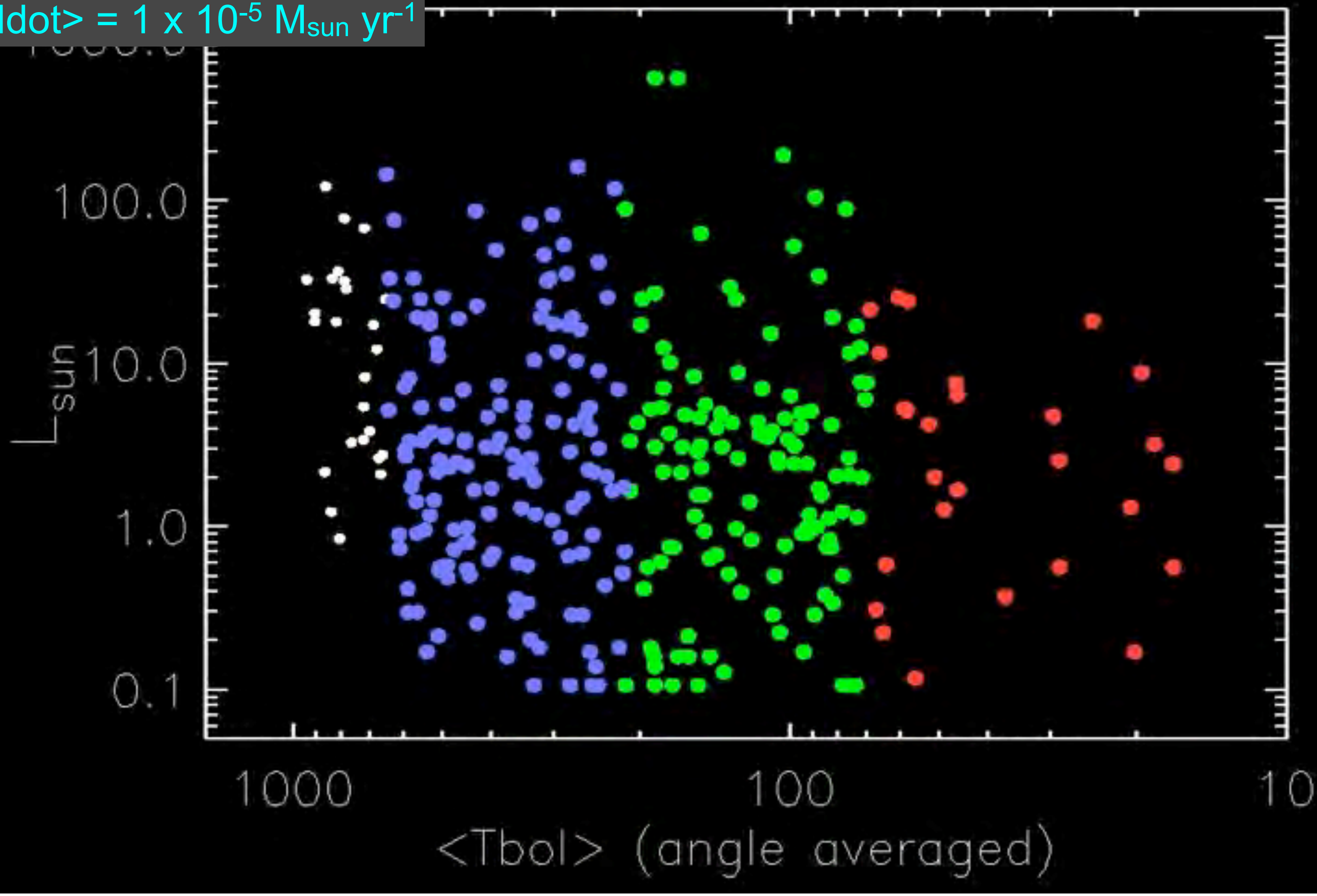
Model grid calculated by John Tobin

Tracing Protostellar Evolution with Inclination Averaged Bolometric Temperature



Tracing Protostellar Evolution with Inclination Averaged Bolometric Temperature

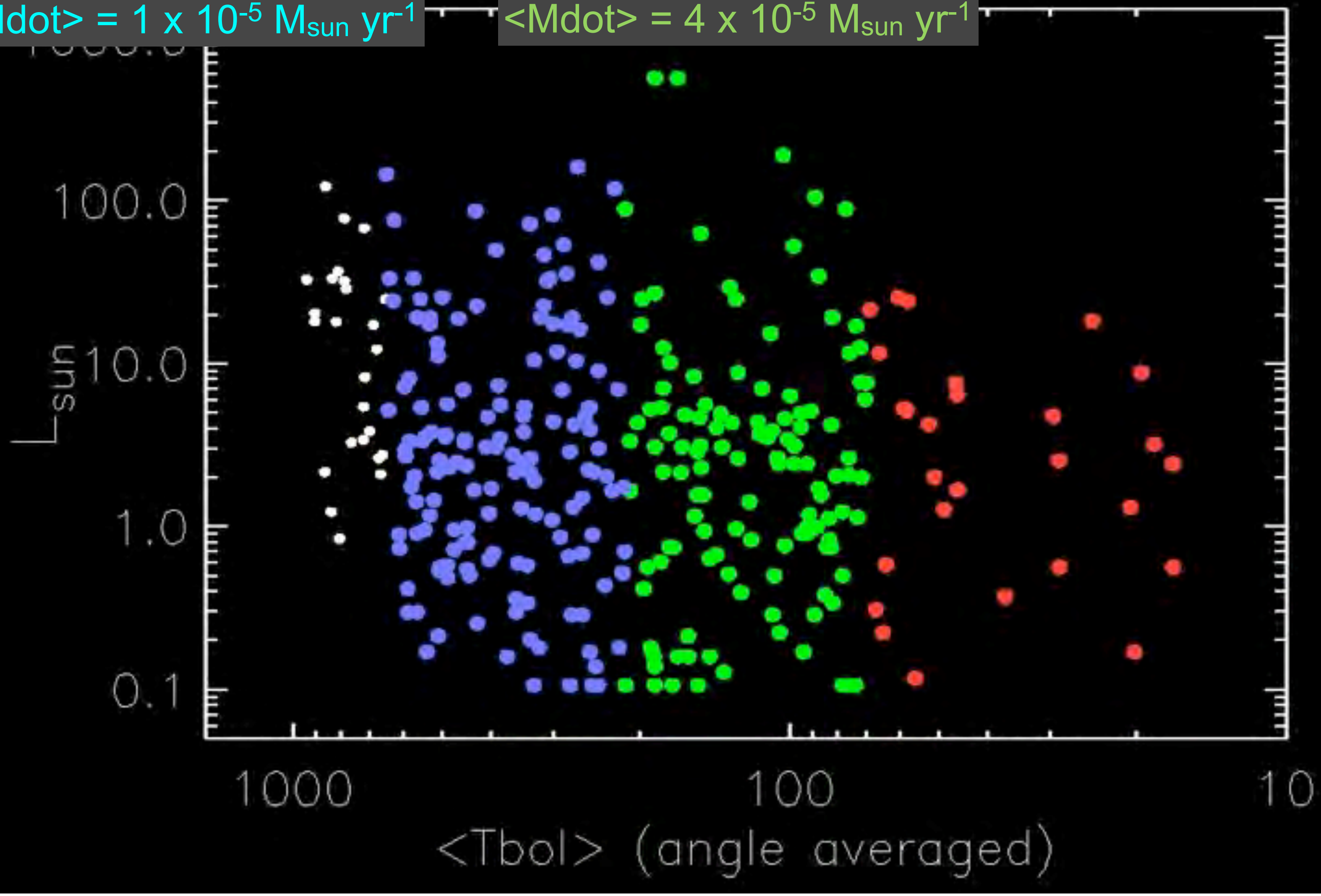
Number = 155
<inc> = 62°
Median Lsun = 2.5
<Mdot> = 1 x 10^{-5} M_{sun} yr^{-1}



Tracing Protostellar Evolution with Inclination Averaged Bolometric Temperature

Number = 155
<inc> = 62^{o}
Median Lsun = 2.5
<Mdot> = 1 x 10^{-5} M_{sun} yr^{-1}

Number = 123
<inc> = 61^{o}
Median Lsun = 2.4
<Mdot> = 4 x 10^{-5} M_{sun} yr^{-1}

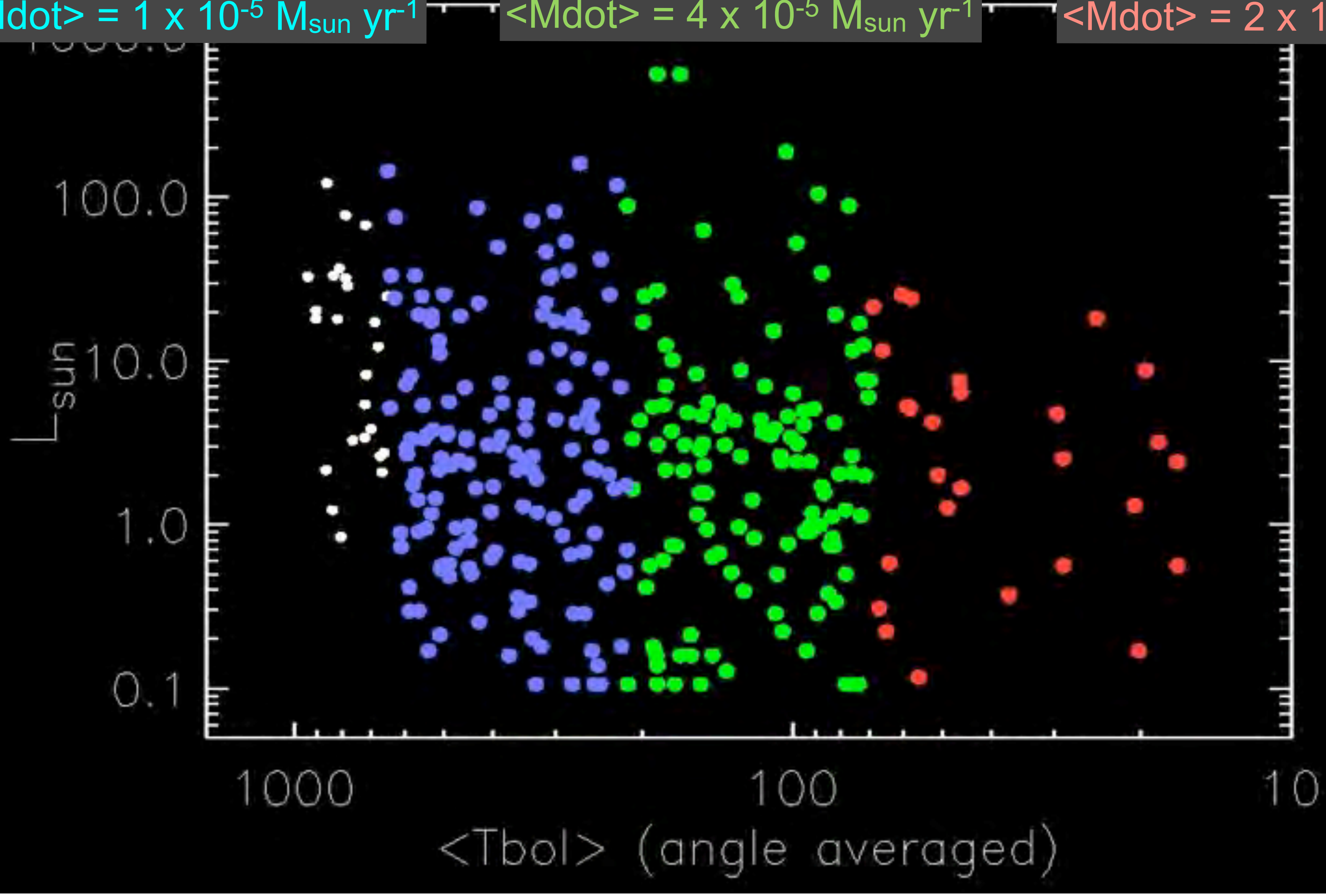


Tracing Protostellar Evolution with Inclination Averaged Bolometric Temperature

Number = 155
<inc> = 62^o
Median Lsun = 2.5
<Mdot> = 1 x 10^{-5} M_{sun} yr^{-1}

Number = 123
<inc> = 61^o
Median Lsun = 2.4
<Mdot> = 4 x 10^{-5} M_{sun} yr^{-1}

Number = 27
<Inc> = 30^o
Median Lsun = 2.5
<Mdot> = 2 x 10^{-4} M_{sun} yr^{-1}

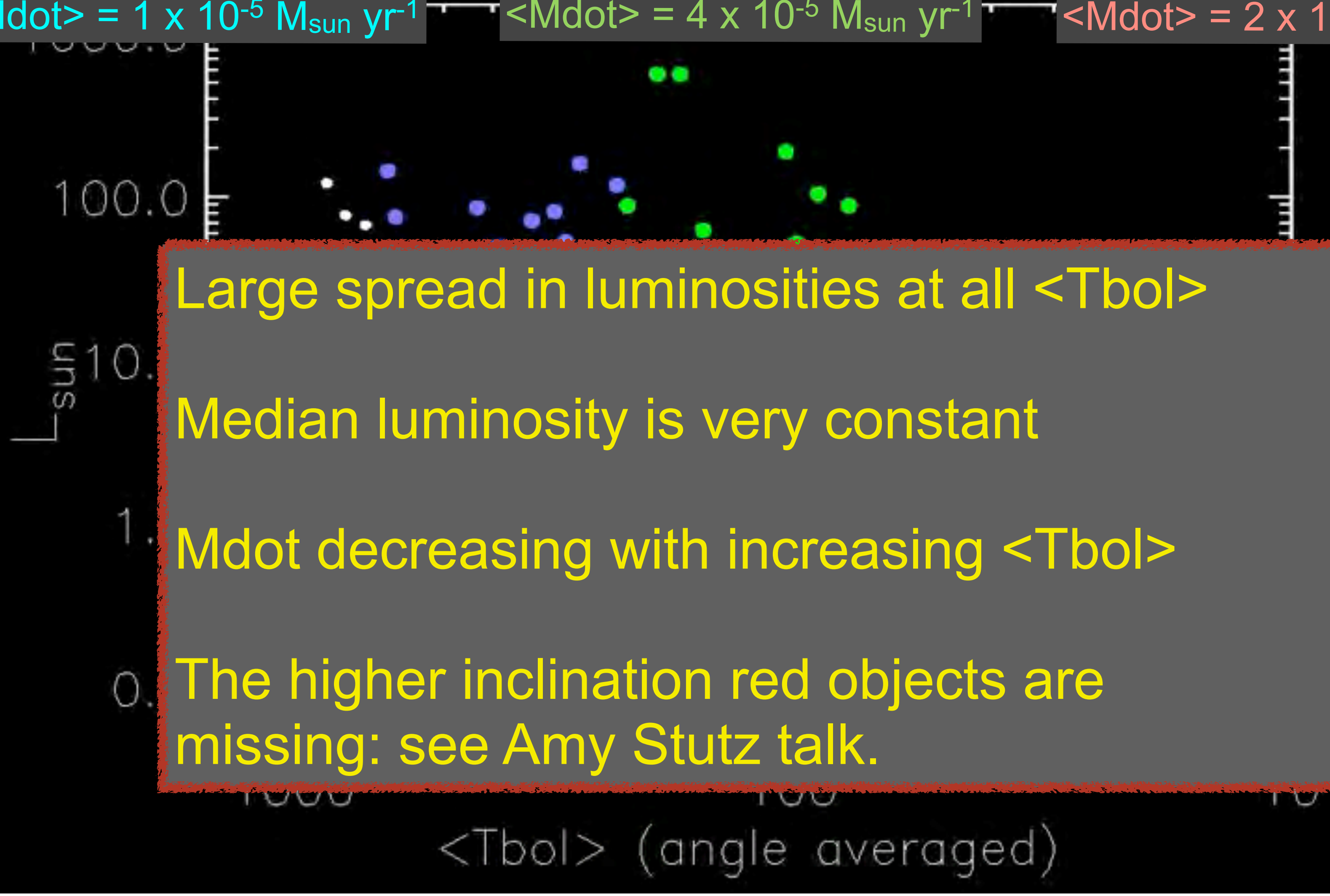


Tracing Protostellar Evolution with Inclination Averaged Bolometric Temperature

Number = 155
<inc> = 62°
Median Lsun = 2.5
<Mdot> = 1 x 10^{-5} M_{sun} yr^{-1}

Number = 123
<inc> = 61°
Median Lsun = 2.4
<Mdot> = 4 x 10^{-5} M_{sun} yr^{-1}

Number = 27
<Inc> = 30°
Median Lsun = 2.5
<Mdot> = 2 x 10^{-4} M_{sun} yr^{-1}



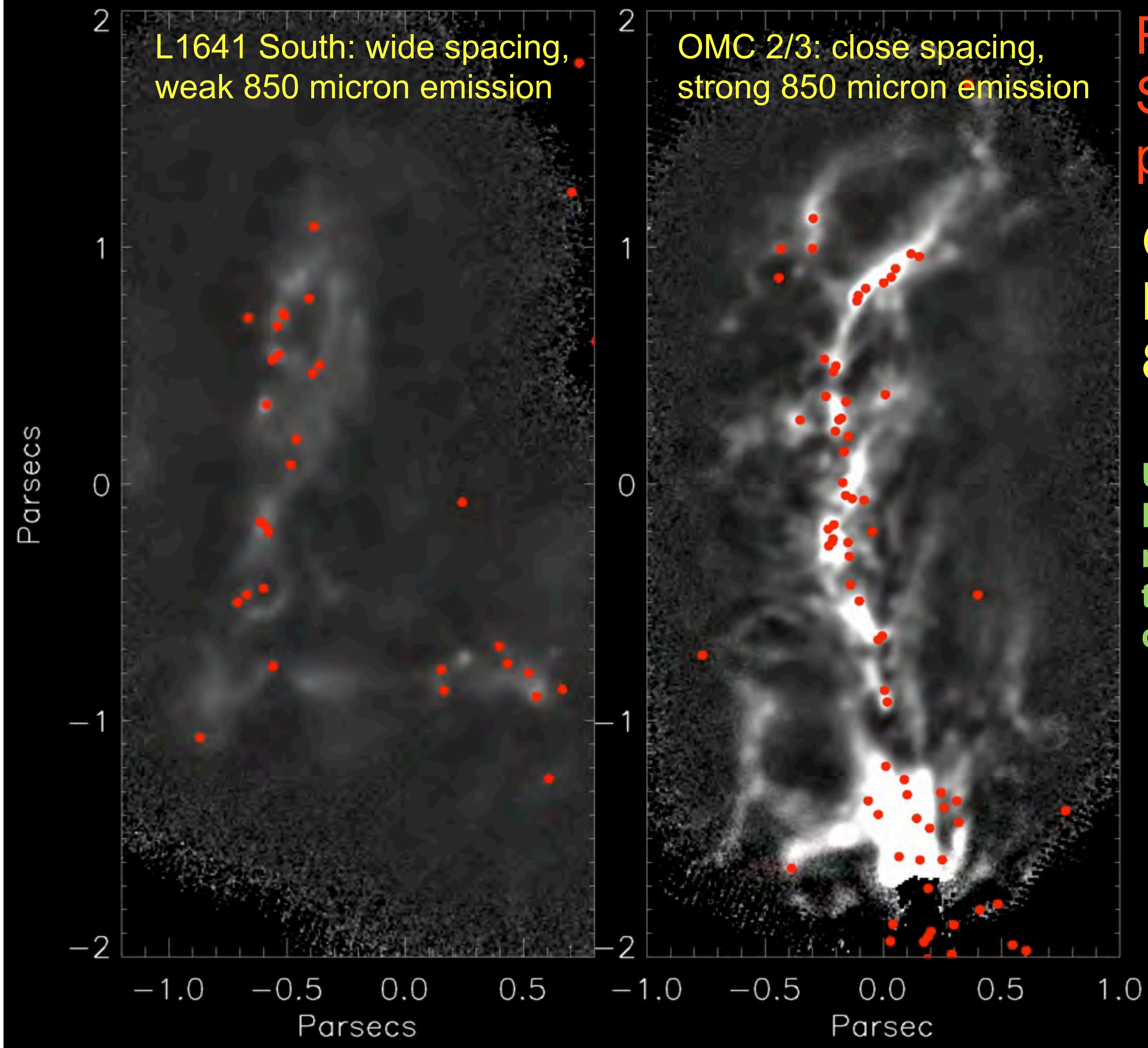
Large spread in luminosities at all <Tbol>

Median luminosity is very constant

Mdot decreasing with increasing <Tbol>

The higher inclination red objects are missing: see Amy Stutz talk.

Connecting Protostellar Evolution with "Environment"

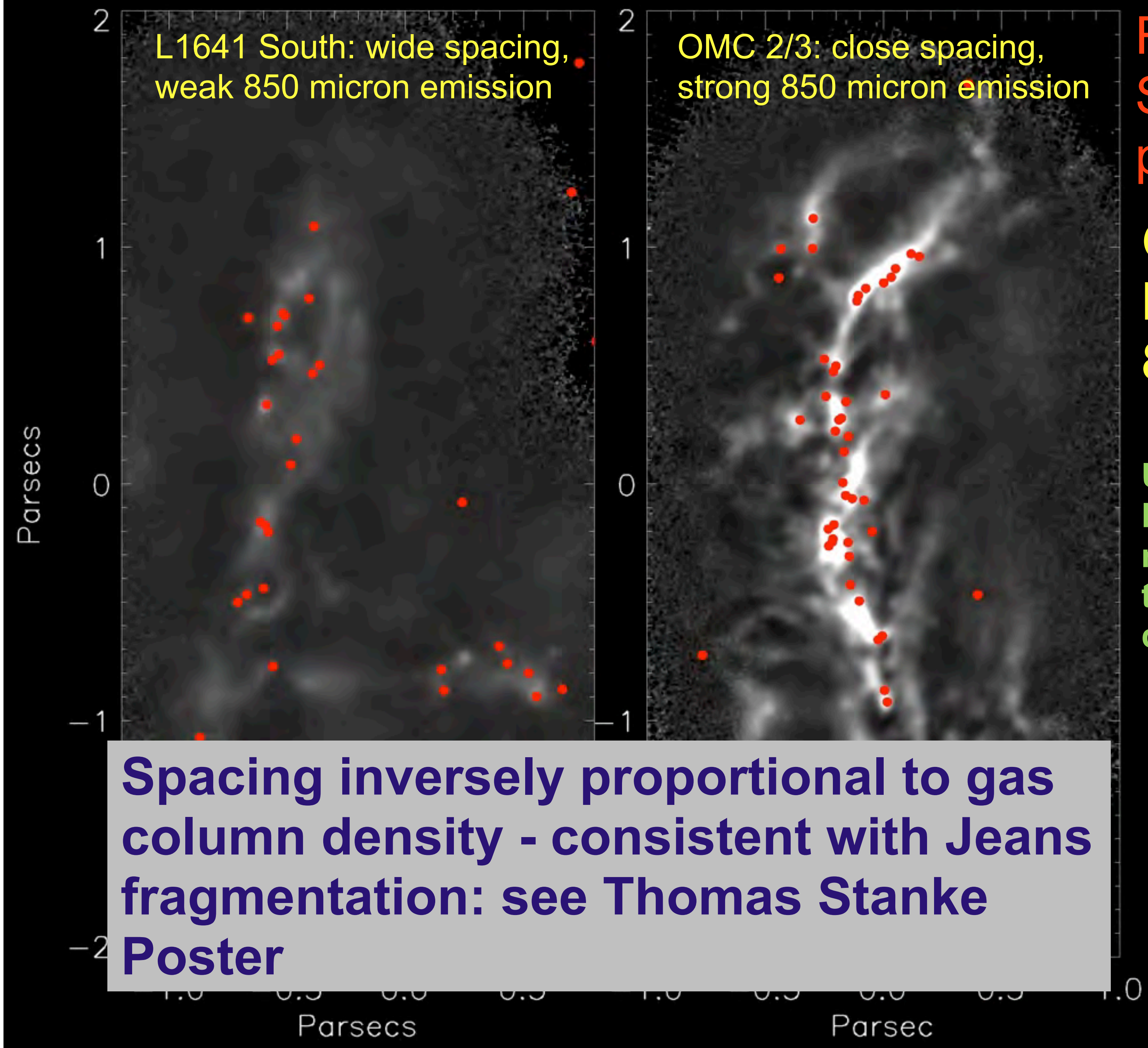


Red dots:
Spitzer identified protostars

Greyscale:
LABOCA
850 micron

Used LABOCA and Herschel PACS 160 micron data to find temperature and column densities.

Connecting Protostellar Evolution with "Environment"



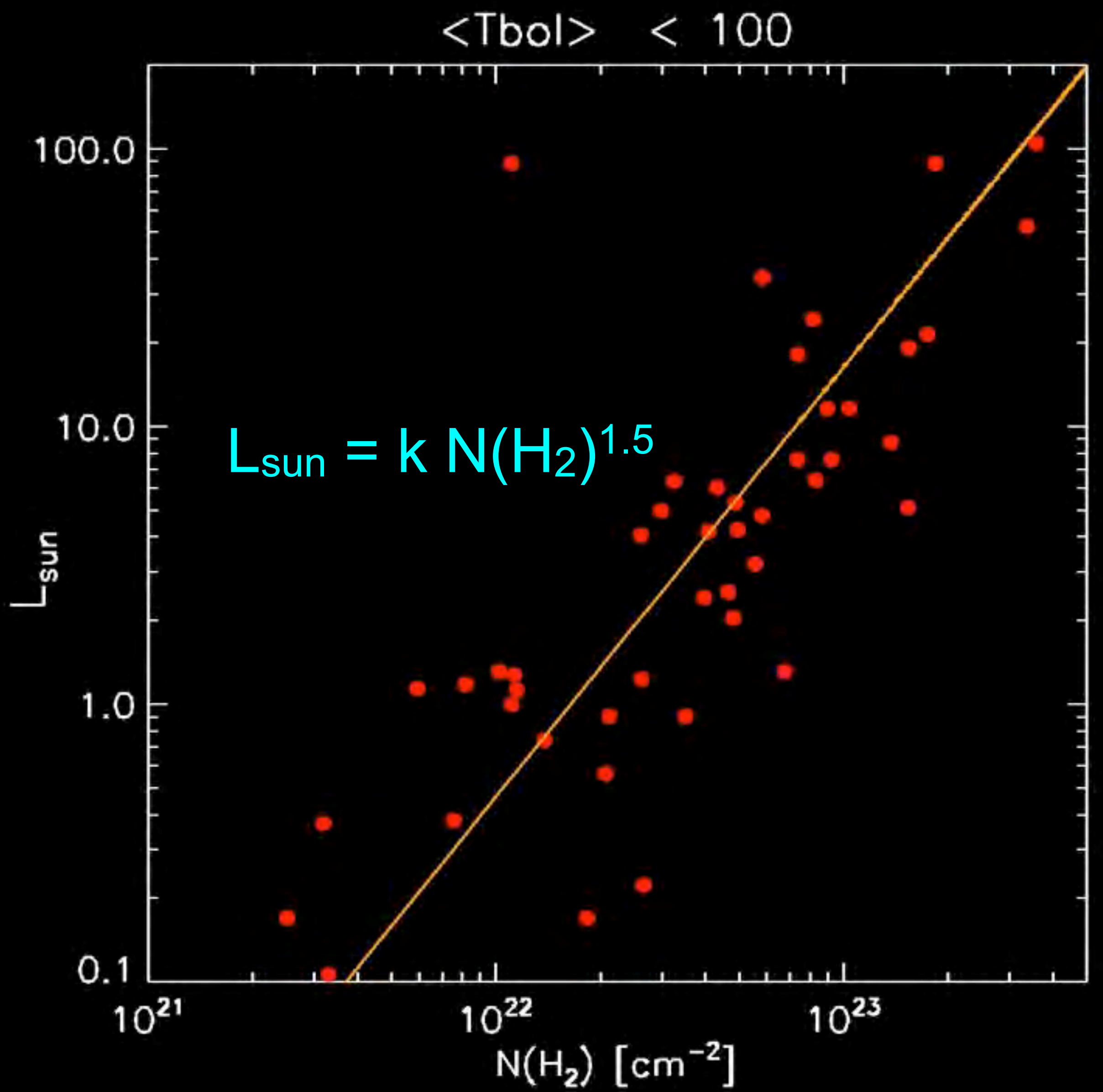
Spacing inversely proportional to gas column density - consistent with Jeans fragmentation: see Thomas Stanke Poster

Red dots: Spitzer identified protostars

Greyscale: LABOCA 850 micron

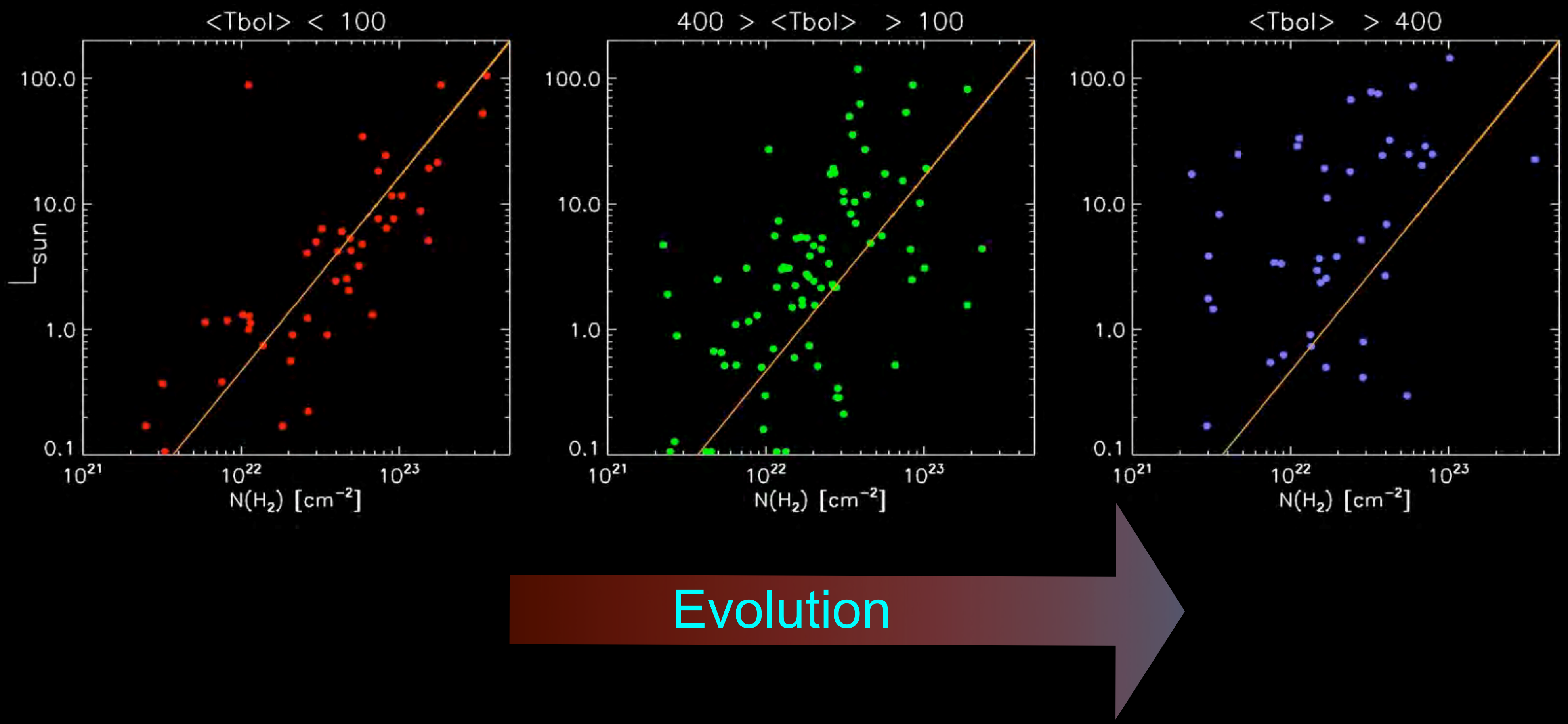
Used LABOCA and Herschel PACS 160 micron data to find temperature and column densities.

Luminosity vs Column Density



Approximately consistent with Mdot = Mass/t_{ff}

Luminosity vs Column Density



This shows a clearing of the surrounding gas with increasing <Tbol>, probably the result of feedback.

Summary

Presented a preliminary examination of indicators of evolution

- Tbol is strongly affected by inclination

- Inclination averaged Tbol, <Tbol>, a much better indicator of evolution
  - <Tbol> decreases as envelope density decreases and cavity opening angle increases.
  - *Caution*: much more model dependent.

- Wide spread in luminosities at all <Tbol>

- Median luminosity constant with <Tbol>

- Higher inclination Class0 objects not detected with Spitzer (see Amy Stutz talk)

- We find that for the reddest objects, the Luminosity = $k\ N(H_2)^{1.5}$

- For a given luminosity - gas column density decreases with increasing <Tbol>

Posters by Thomas Stanke and P. Manoj