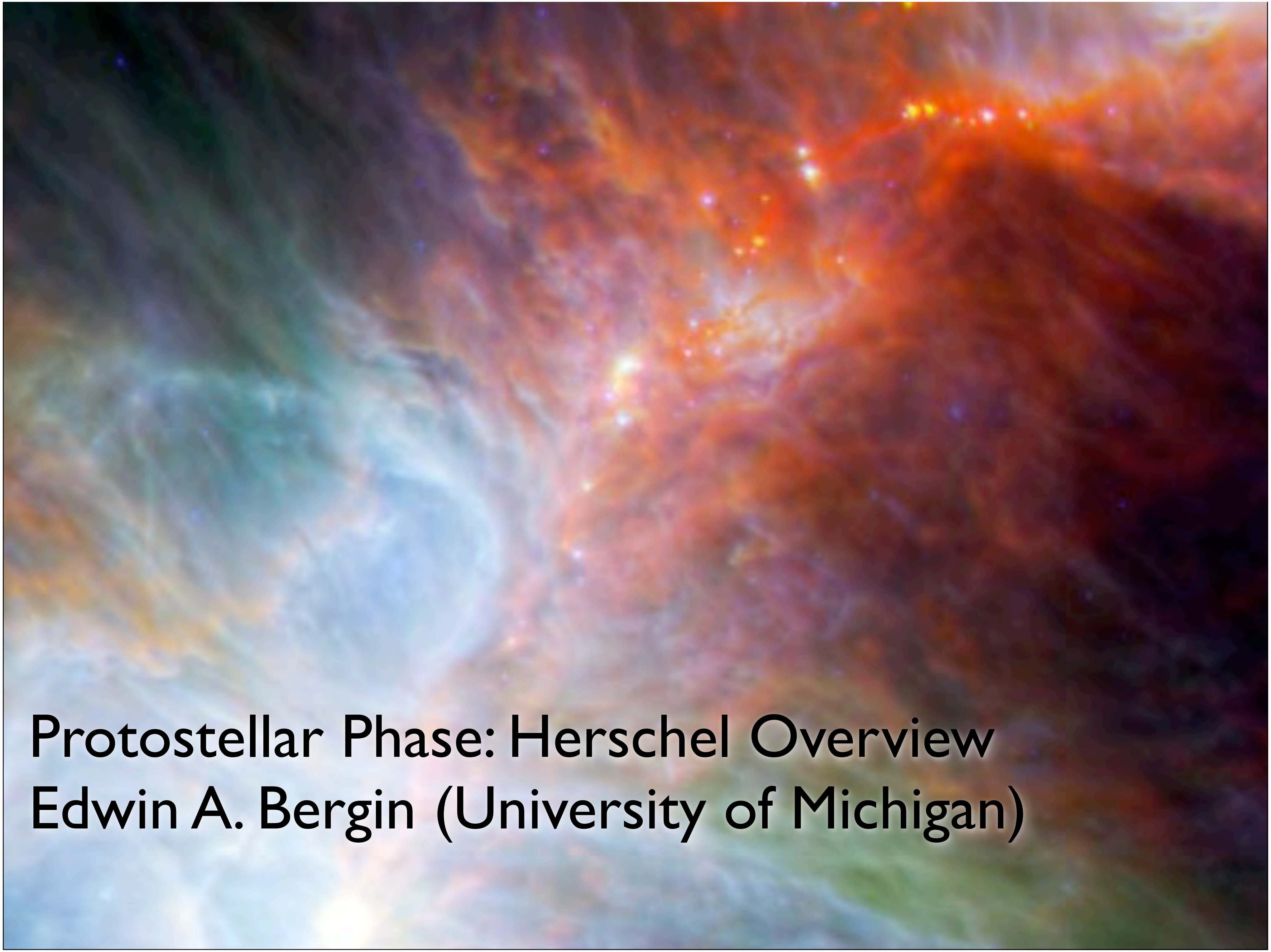


Protostellar Phase: Herschel Overview

Edwin A. Bergin (University of Michigan)

Contributions from:

- HOBYS (Motte)
- Goulds Belt (André)
- EPOS (Krause, Ragan)
- HOPS (Megeath, Puravankara, Fischer)
- DIGIT (Evans, Green)
- CHESS (Ceccarelli)
- WISH (van Dishoeck)
- HEXOS (Bergin)

- Will cover both low mass and high mass protostars
- Will not talk about physical structure (covered by R. Visser)

Herschel and Protostars

- Most of the emission from embedded young stars is in the far-infrared
  - ➡ dust thermal continuum emission (SPIRE, PACS)
- Warm envelope, heated outflow cavity, and shocked outflowing gas produces molecular emission from low to very high energy states -- regime of submm/far-infrared
  - ➡ spectroscopy (SPIRE, PACS, HIFI)
- Herschel is and will continue to make significant advances in our understanding of this crucial stage.

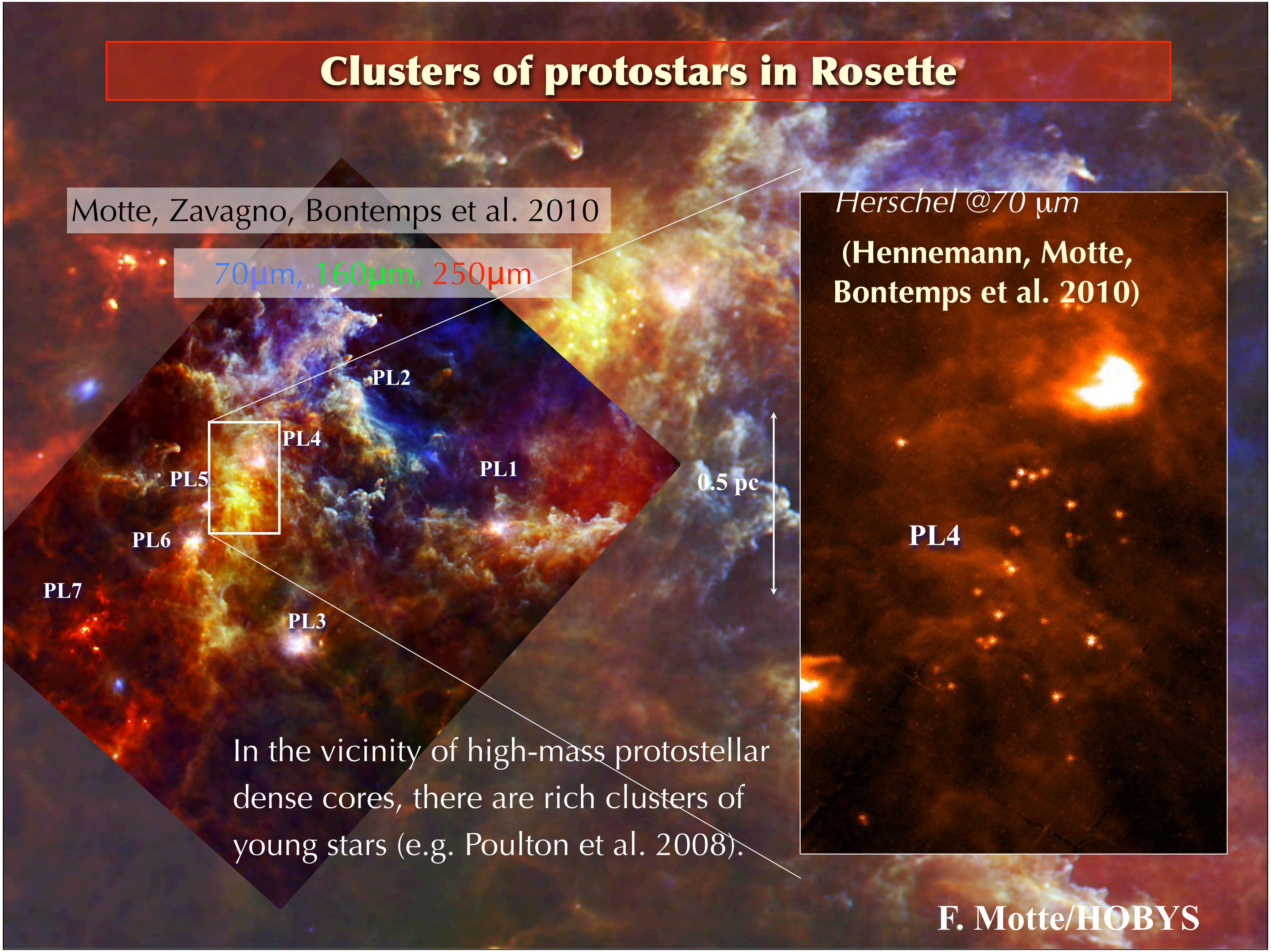
Herschel and Protostars Photometry

- trace the full observable SED (when combined with ground-based and Spitzer data)
  - ➡ *bolometric luminosity, envelope mass, temperature - unlocks evolutionary state*
- mapping surveys trace these parameters over the cloud probing entire protostellar population
  - ➡ *lifetimes and the ability to search for objects with short lifetimes (early stages of massive star evolution)*
  - ➡ *new objects (not seen by Spitzer…)*
- variability

Herschel and Protostars Spectroscopy

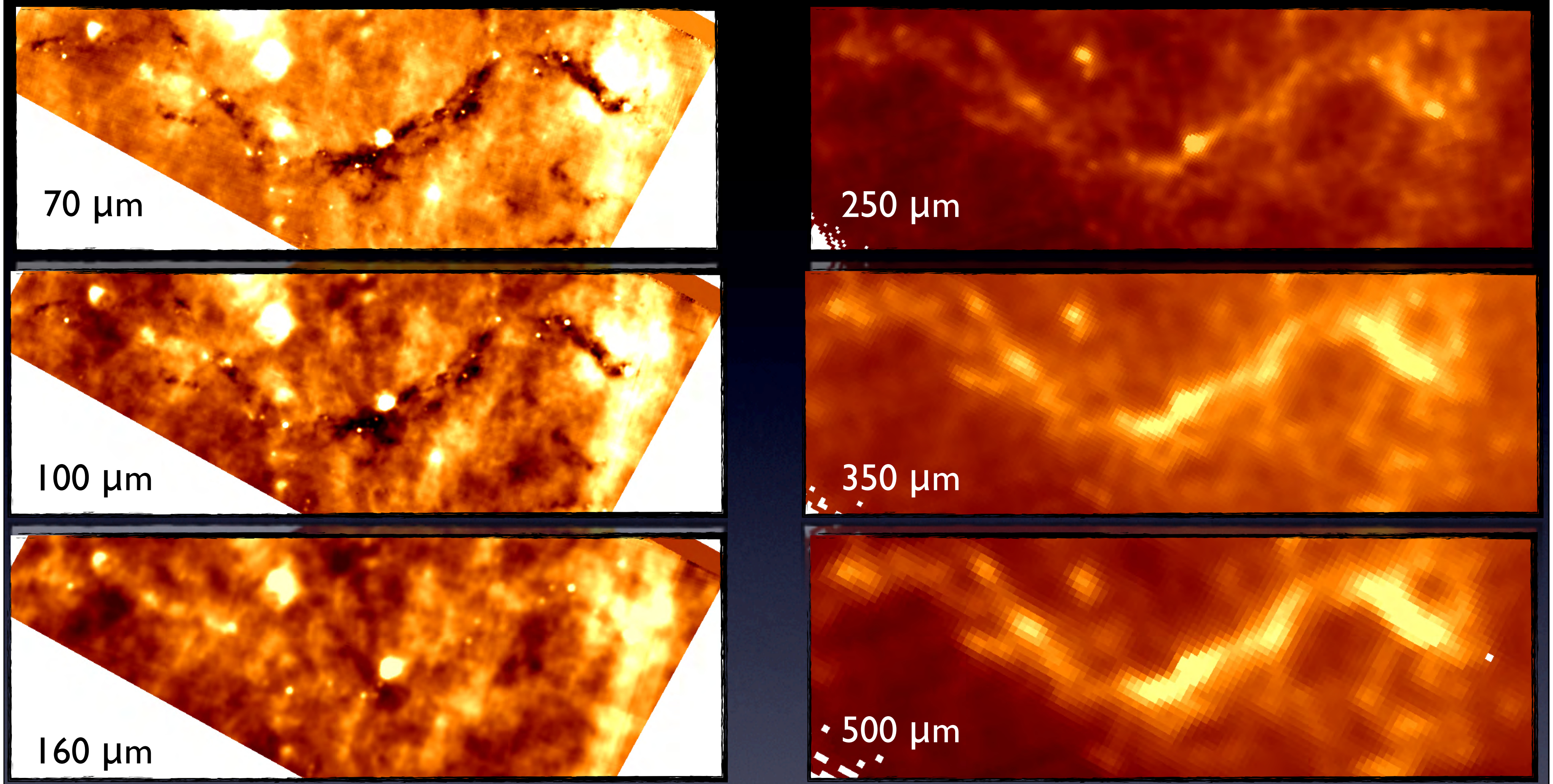
- hot envelope/infall/outflow - rich excitation and chemistry
- water, water, water...
  - ➡ *where is emission arising - hot envelope, shocks, quiescent gas (all of the above -- need for spectral resolution)*
  - ➡ *how much and what is its story (other talks)*
- Carbon monoxide
  - ➡ *Seeing J_u from 1 to ~40 -- Spectral Line Energy Distribution (SLED) -- rich information source*
- Overall spectrum - rich chemistry - what can we learn?

Clusters of protostars in Rosette



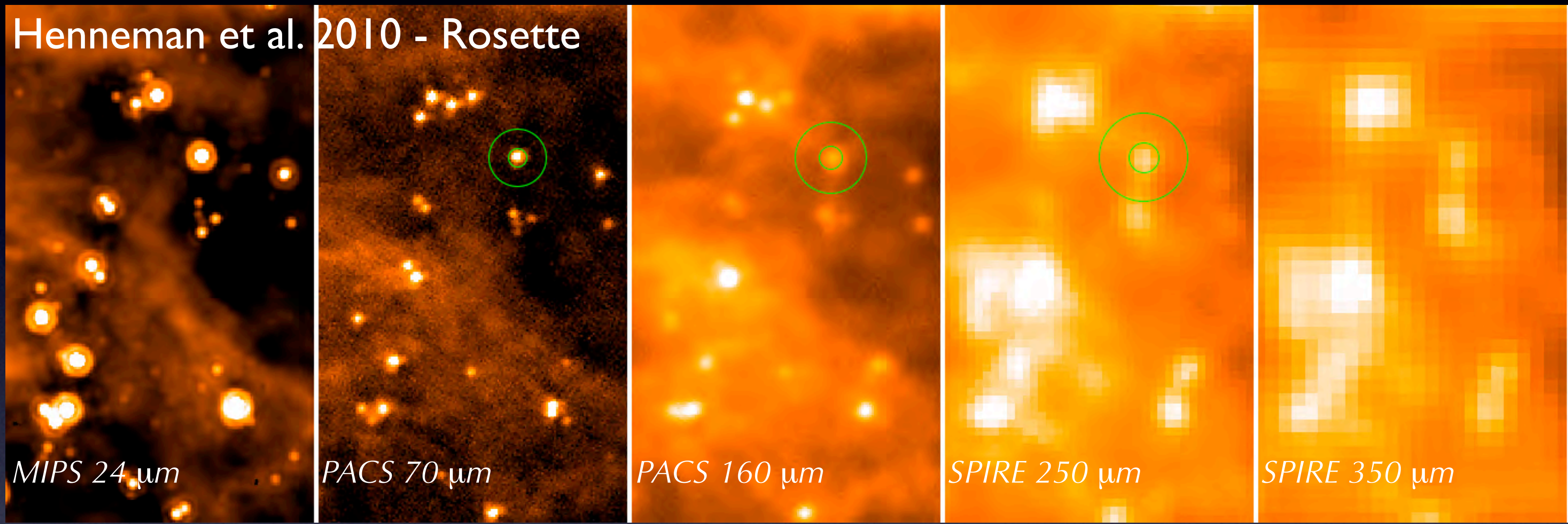
In the vicinity of high-mass protostellar dense cores, there are rich clusters of young stars (e.g. Poulton et al. 2008).

F. Motte/HOBYS



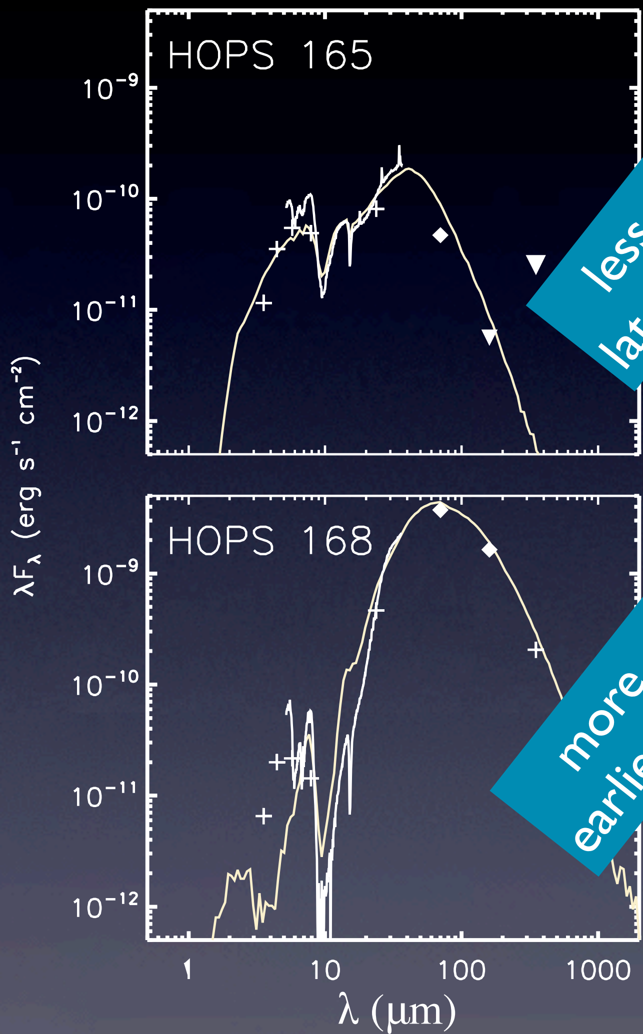
PACS (70/100/160 µm) and SPIRE (250/350/500 µm) scan mapping of G11 Infrared Dark Cloud

Henning et al. (2010)



Spectral Energy Distribution

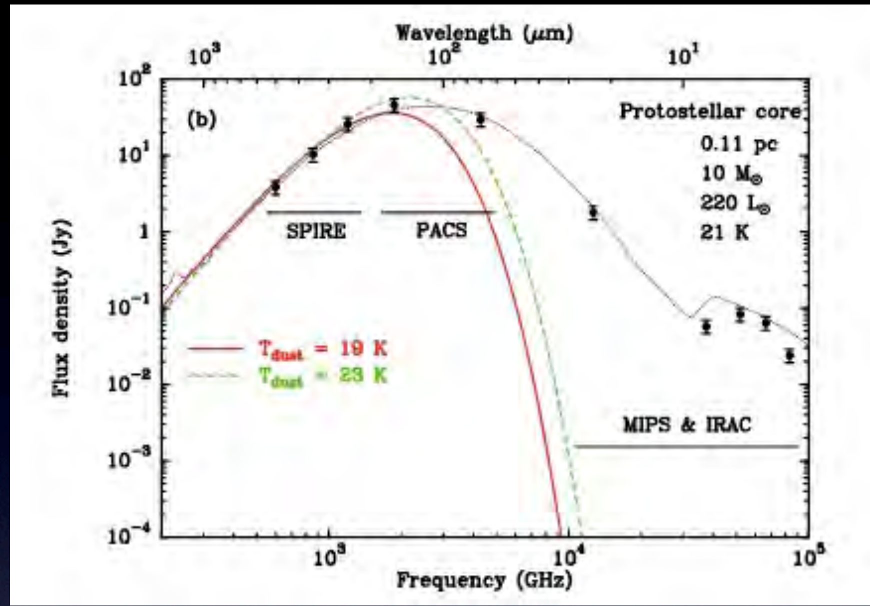
Spectral Energy Distribution



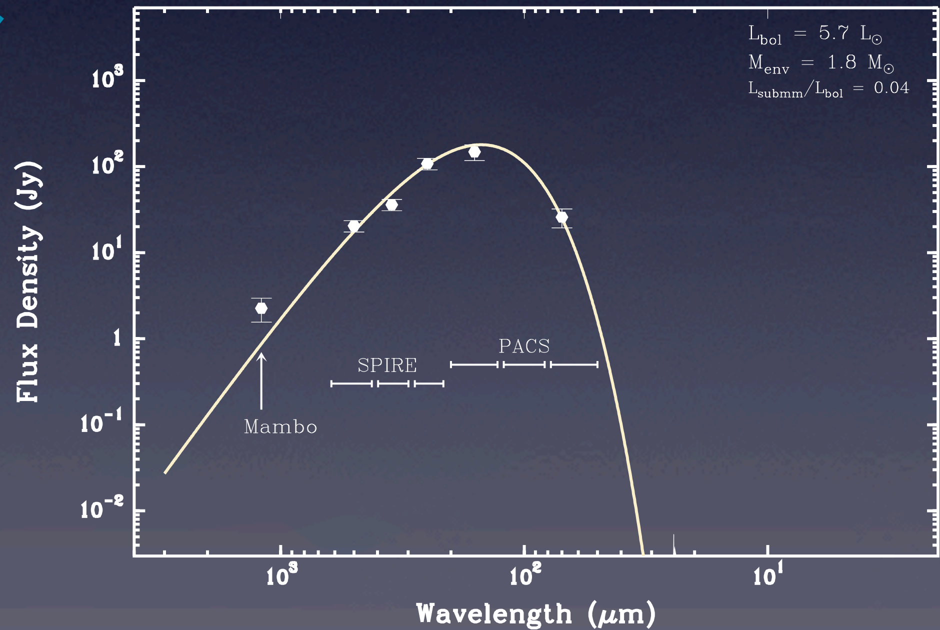
less envelope/
later stage (class I)

more envelope/
earlier stage (class 0)

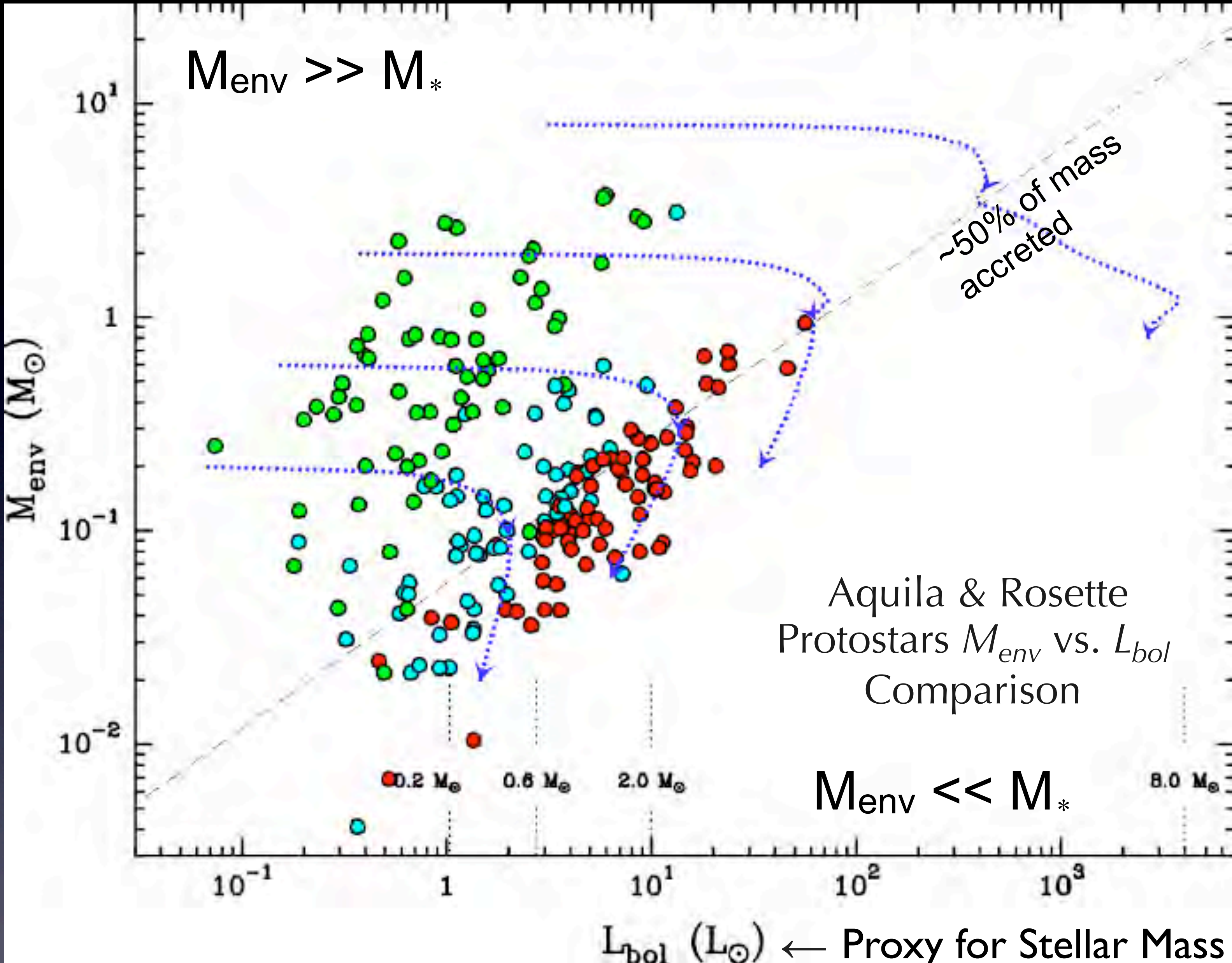
Fischer et al. 2011



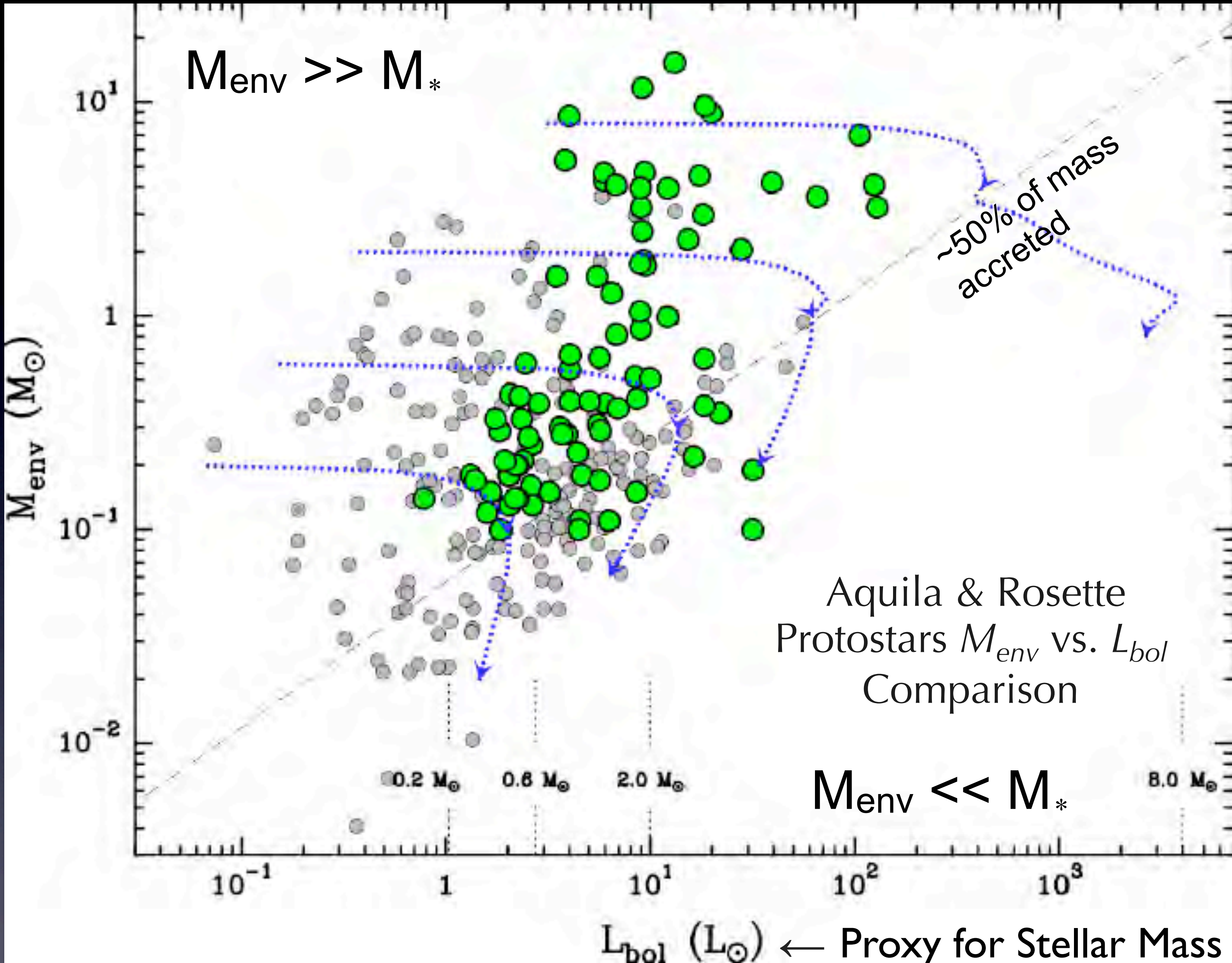
Motte et al. 2011



Bontemps et al. 2011



Better classification → Better statistics → ex. revised Class 0 lifetime 4 - 9 x 10^4 yrs (Maury et al. 2012 -- shorter than Evans et al. 2009)



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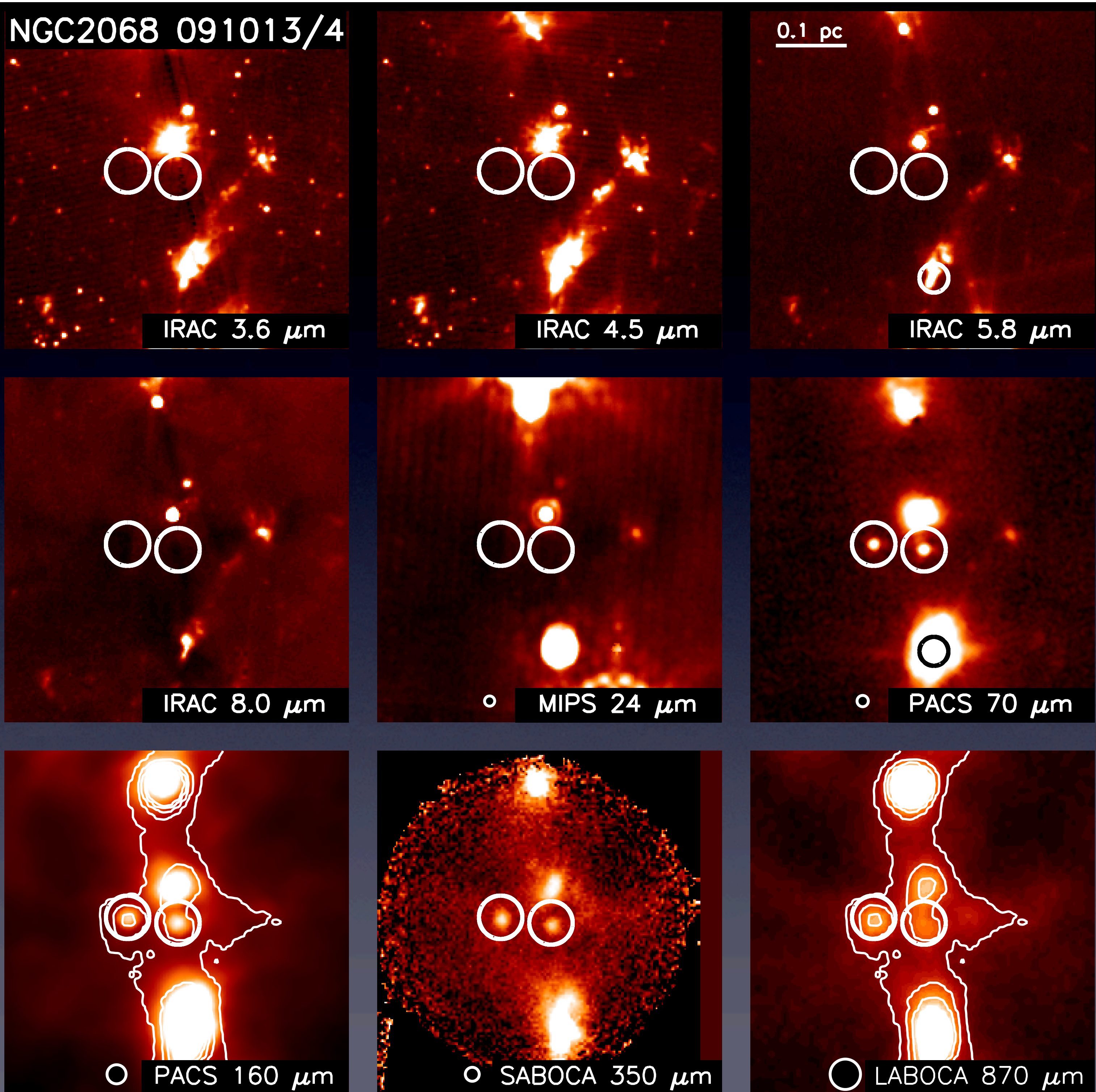

NGC2068 091013/4
0.1 pc
IRAC 3.6 μm
IRAC 4.5 μm
IRAC 5.8 μm
IRAC 8.0 μm
MIPS 24 μm
PACS 70 μm
PACS 160 μm
SABOCA 350 μm
LABOCA 870 μm

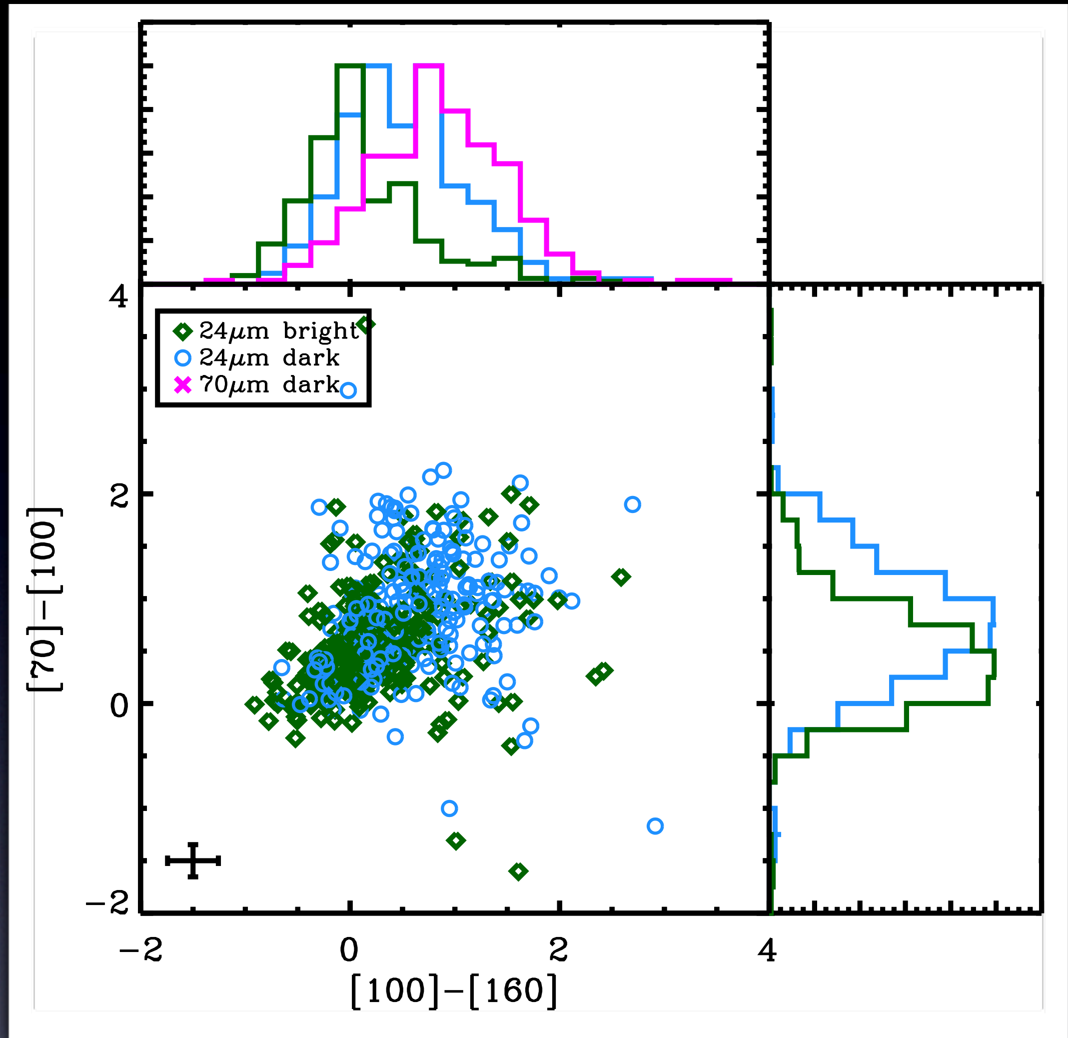
A. Stutz

• 500 cores extracted from EPOS PACS images (45 mapped regions)

< T > ~ 20K

• 24um-bright cores are warmer than 24um-dark cores - likely host protostars

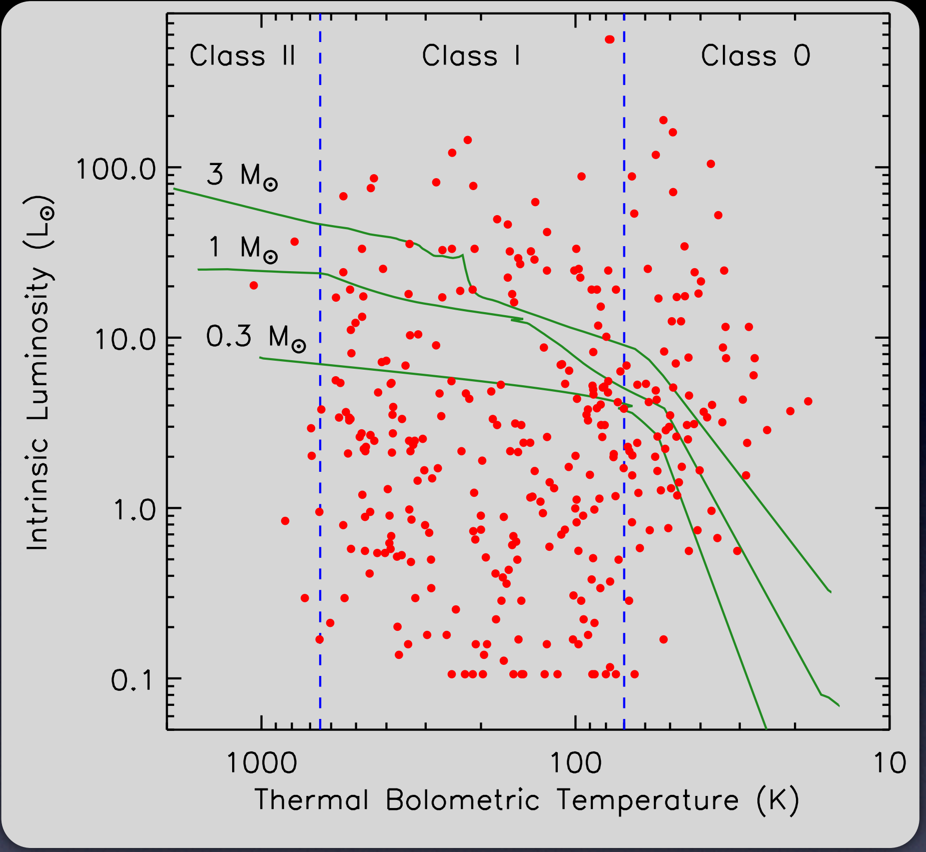
• 70um-dark cores unlikely to host protostars → candidates for elusive prestellar cores in IRDCs



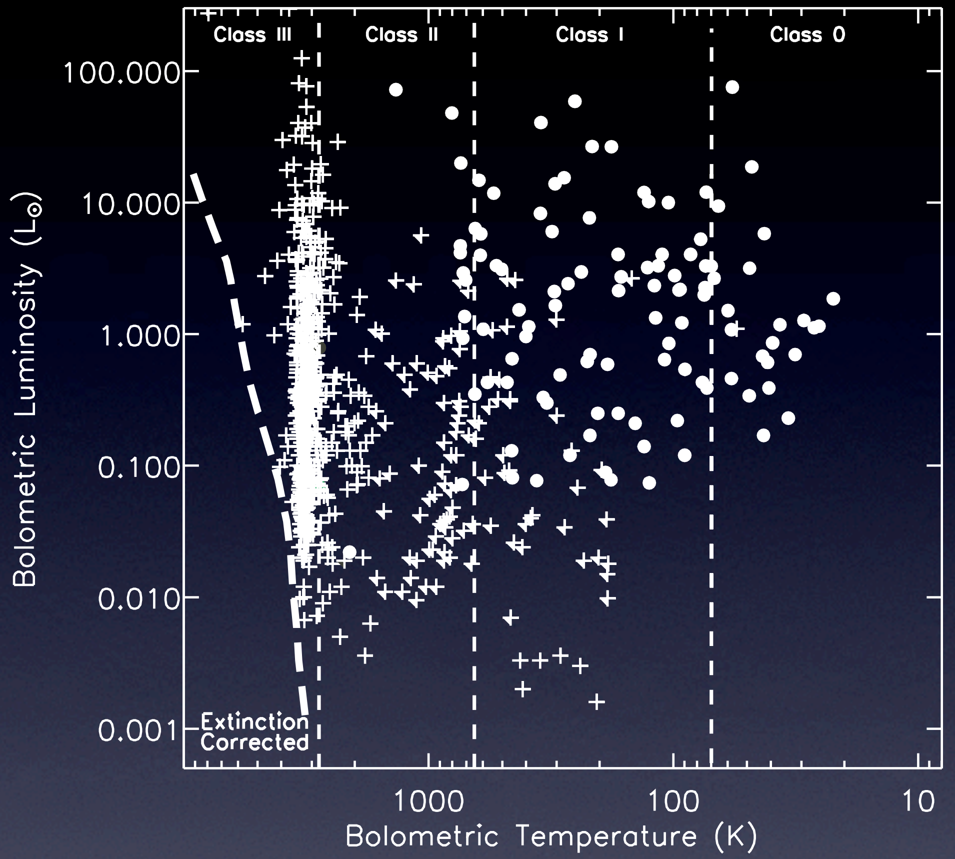
Demographics of Cold ?Protostars?

Ragan et al. 2012, Submitted

Herschel HOPS

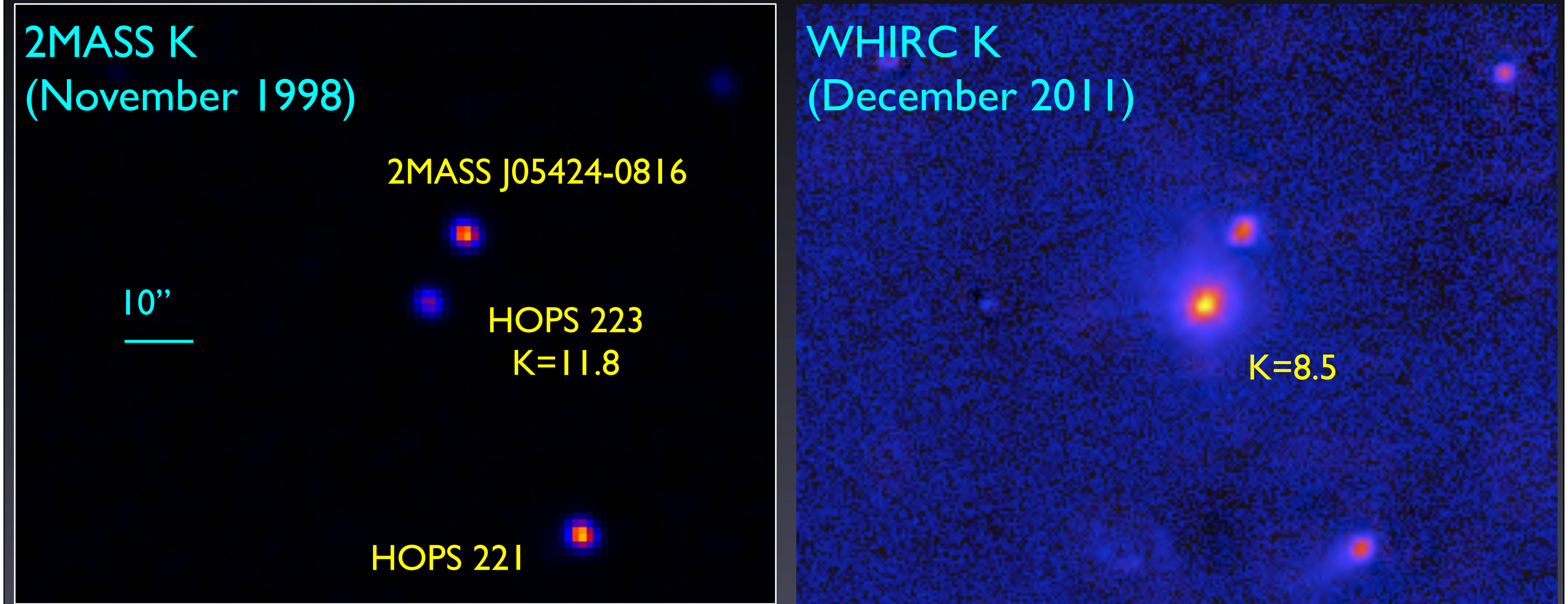


Spitzer C2D



Bolometric Temperature: the temperature of a blackbody that emits with the same mean frequency of the protostar. Lower bolometric temperatures imply a dense cocoon of cold dust indicative of the early stages of protostellar collapse.

HOPS 223 Luminosity Outburst



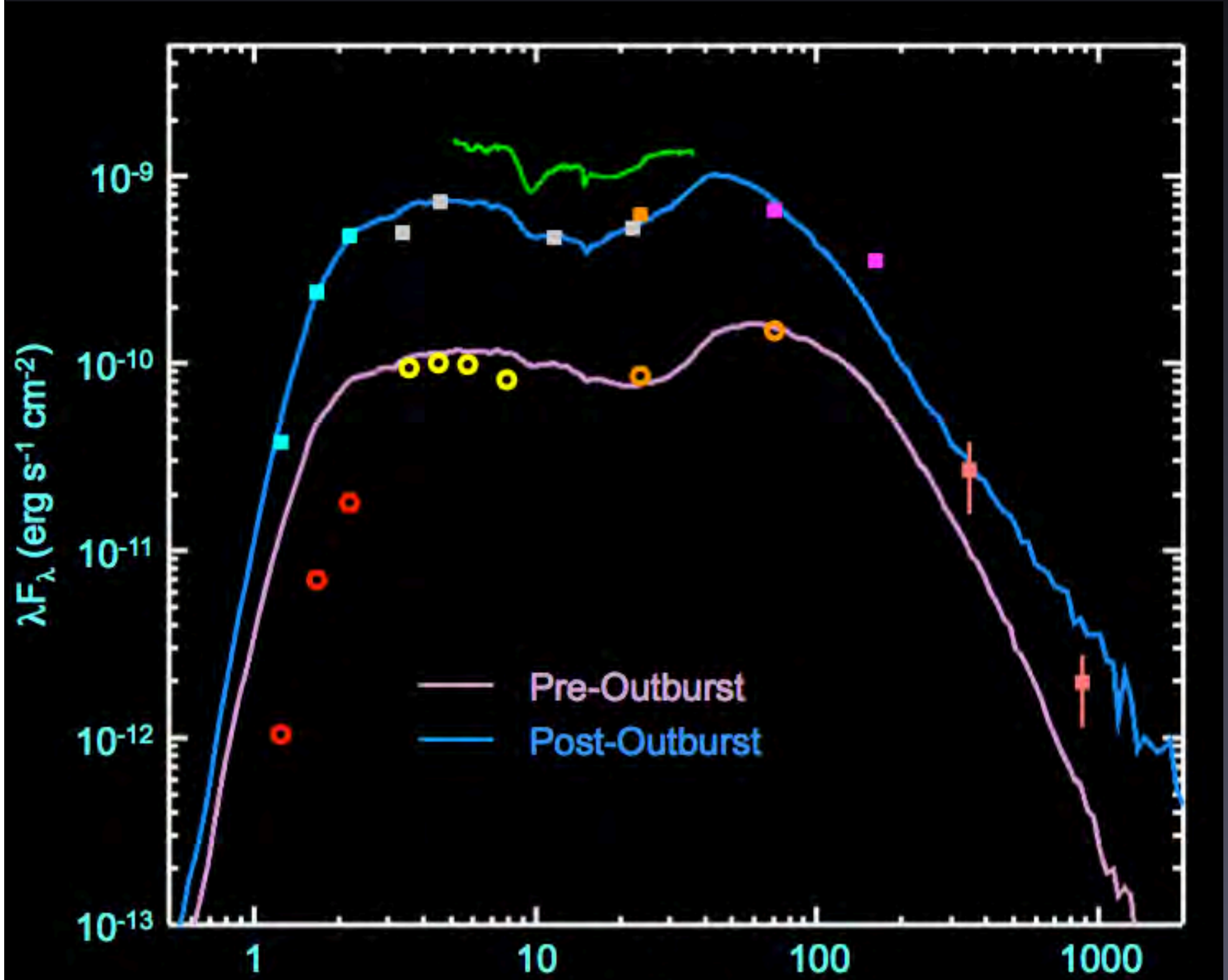
Babar Ali, Lori Allen

Discovered by Caratti o Garatti et al. (2011) in October 2010 imaging

W. Fischer

Best-Fit SED Models

W. Fischer



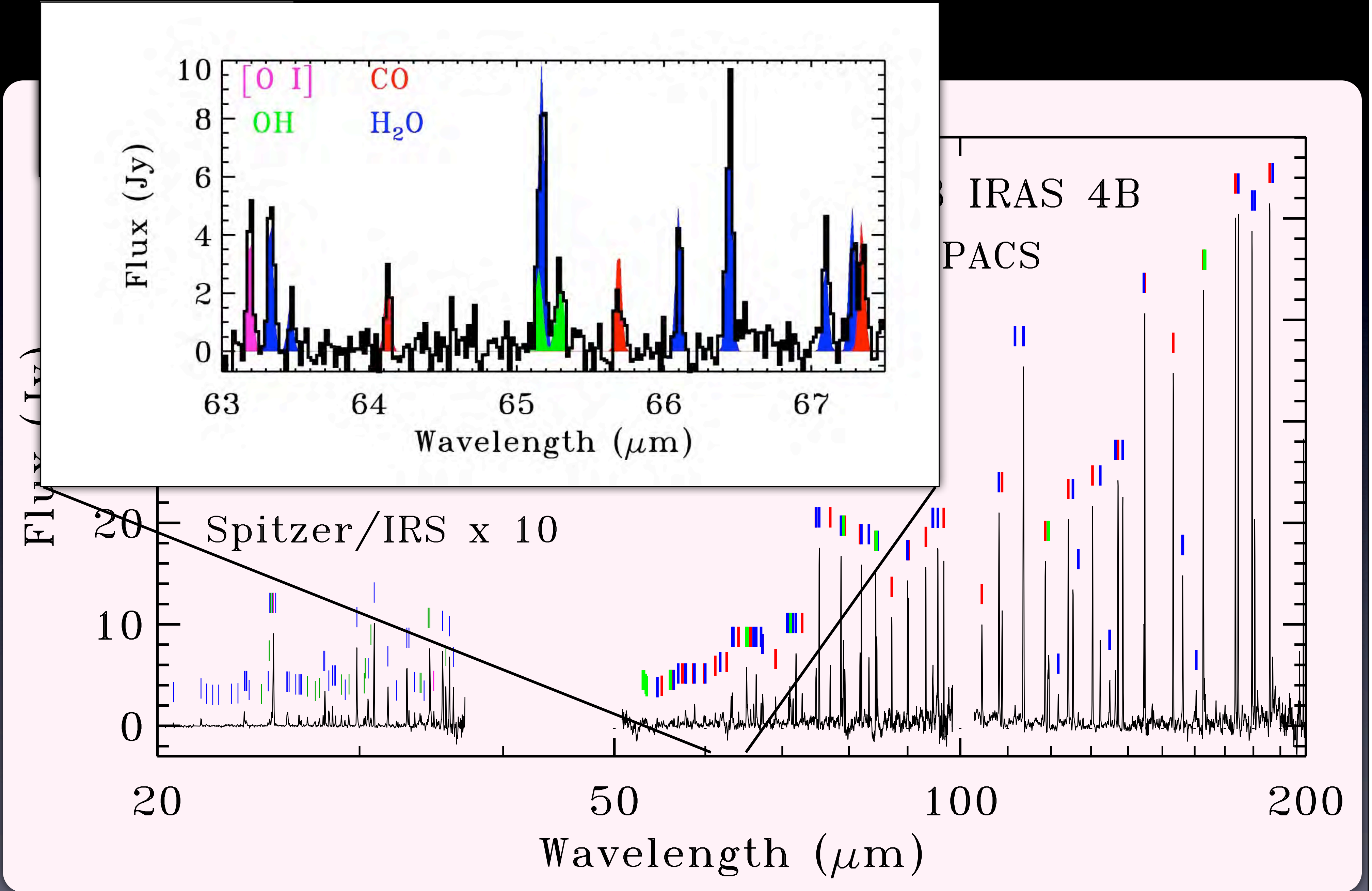
W. Fischer

- Luminosity:
  L_{pre} = 4.6 $L_{\odot}$
  L_{post} = 25.3 $L_{\odot}$
- Mass infall rate changes by order of magnitude (from star to disk)
- Protostar and FU Ori object

also talk by Billot

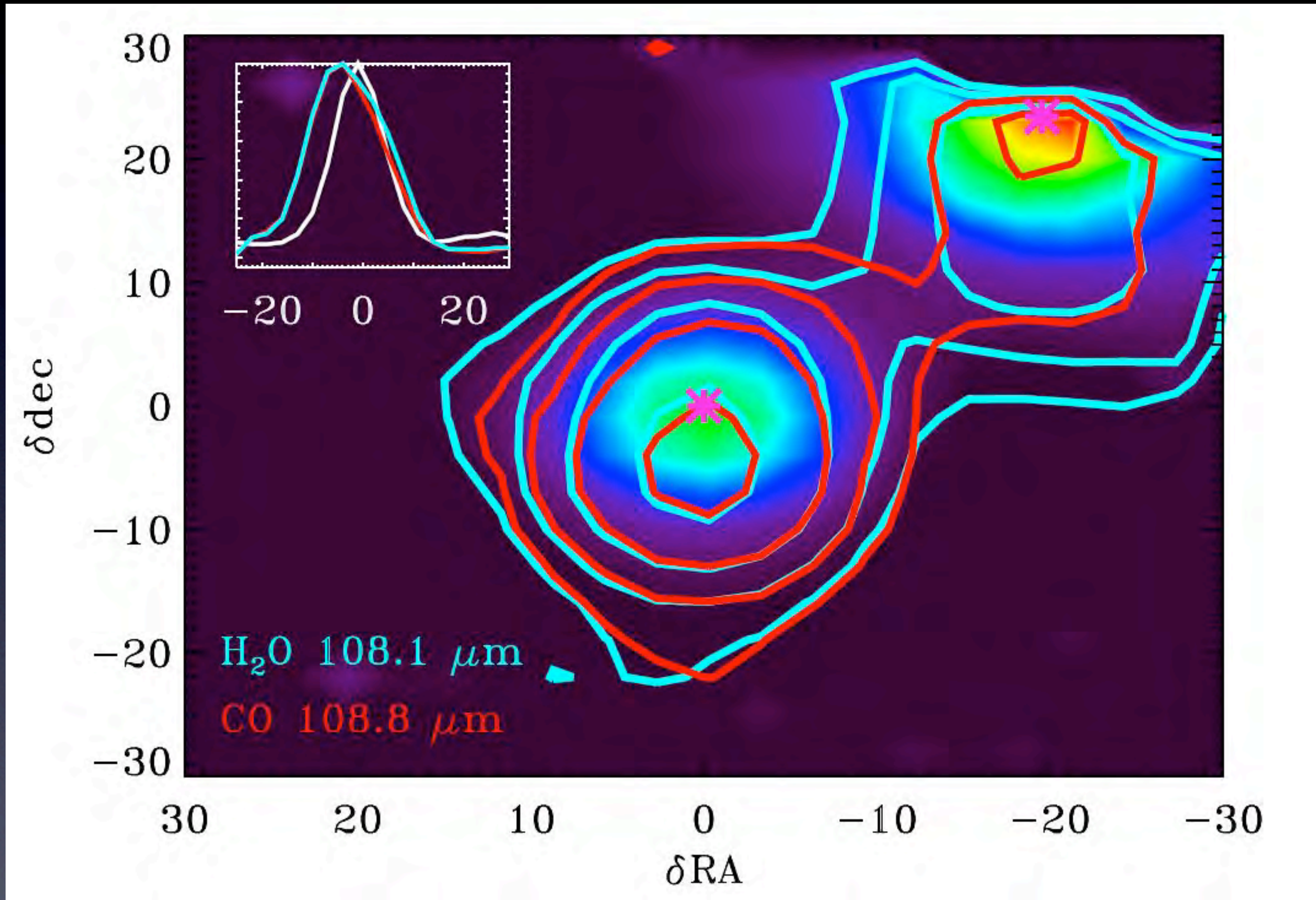
H_2O

NGC1333 IRAS 4B: Herczeg et al. 2012



H_2O and CO in outflow, not disk

Use PACS raster mode for fully sampled map



Herczeg et al. 2012

Hot CO and H_2O clearly displaced from far-infrared continuum → not disk

H_2O

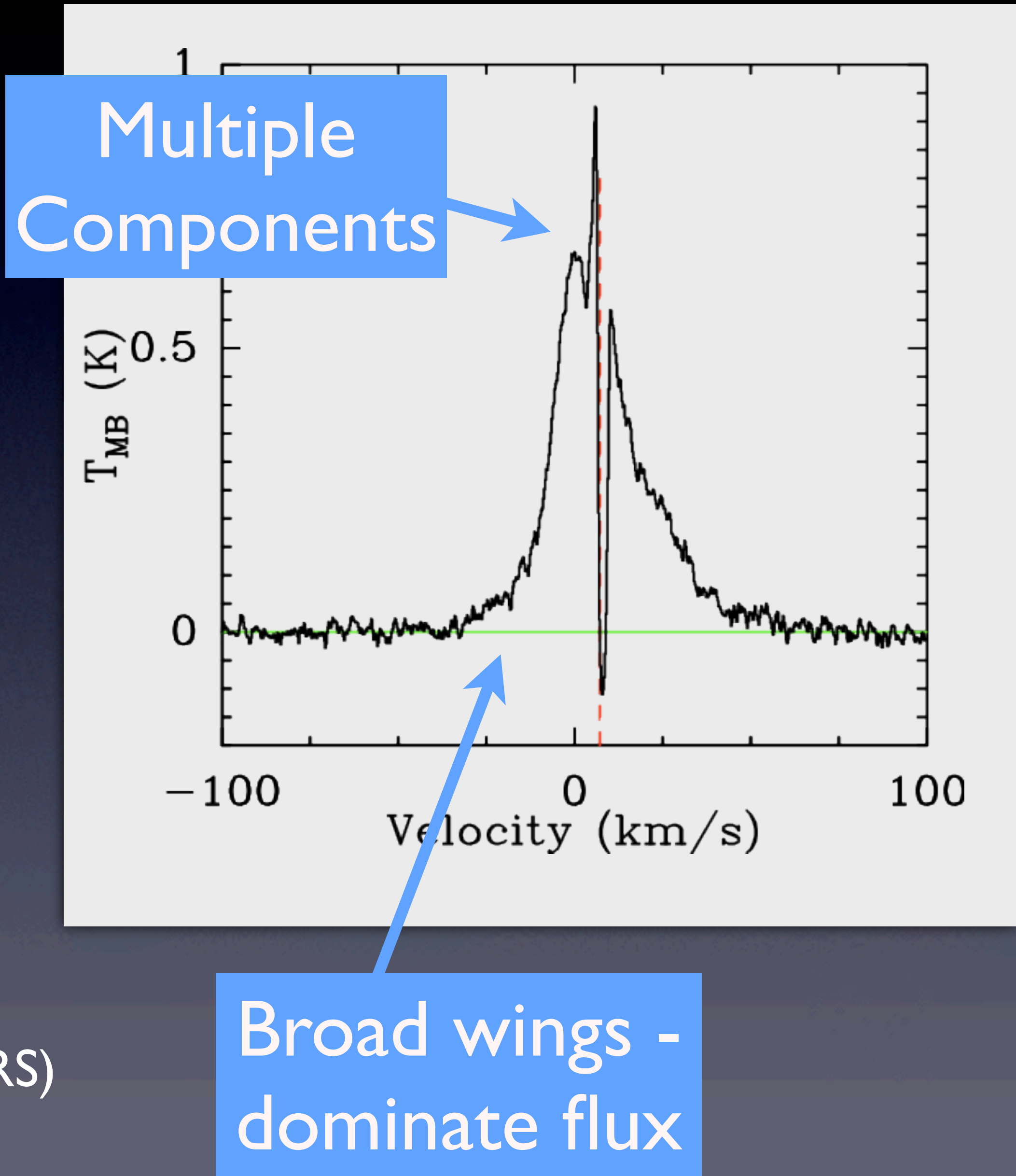
General expectations:

- Water will be abundant in hot gas
- Water will be less abundant in cold gas
- Lower column gives rise to more emission:
  - $N_{01} = 4.9 \times 10^{12} \tau_0 \Delta v$ (cm^{-2})
  - $\tau_0 = 1$ need 5×10^{12} cm^{-2}

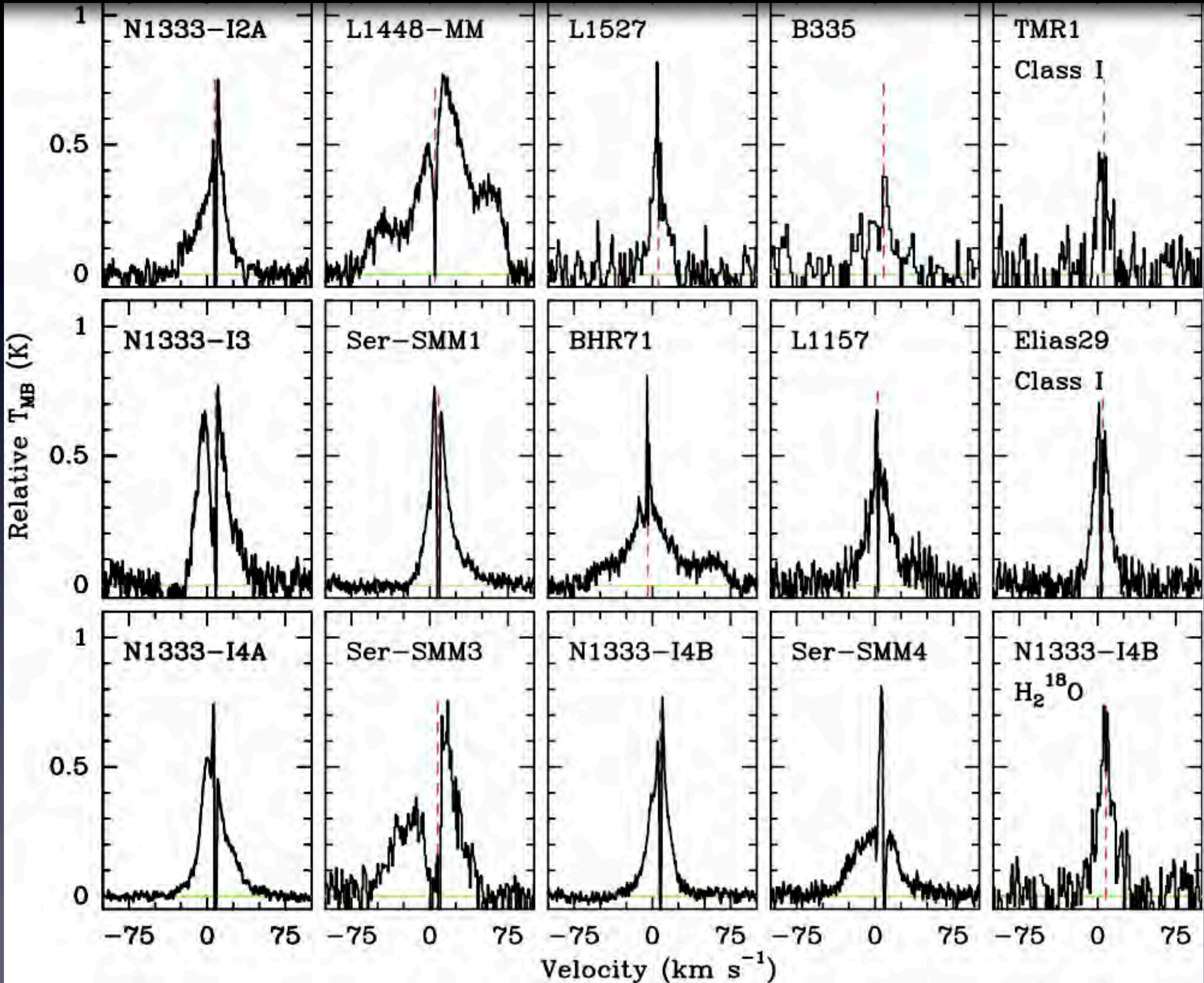
van Dishoeck et al. 2011 (PASP)
Bergin & van Dishoeck 2012 (Phil Trans RS)

Kristensen et al. 2010

NGC1333 IRAS 4A Class 0

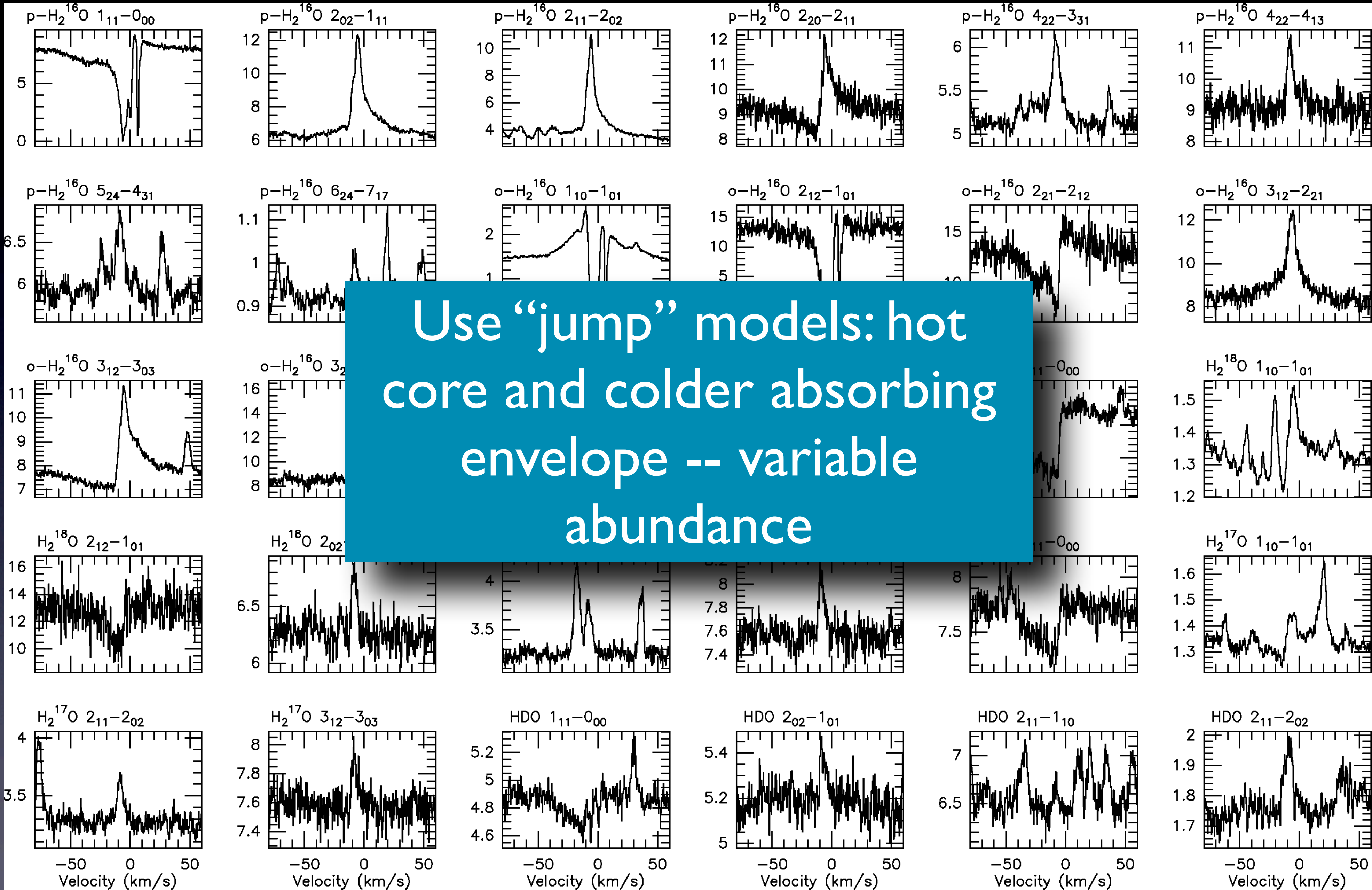


➡ Water ($H_2{}^{16}O$) emission is dominated by fast moving *shocked* gas



Kristensen et al. 2012

NGC6334I

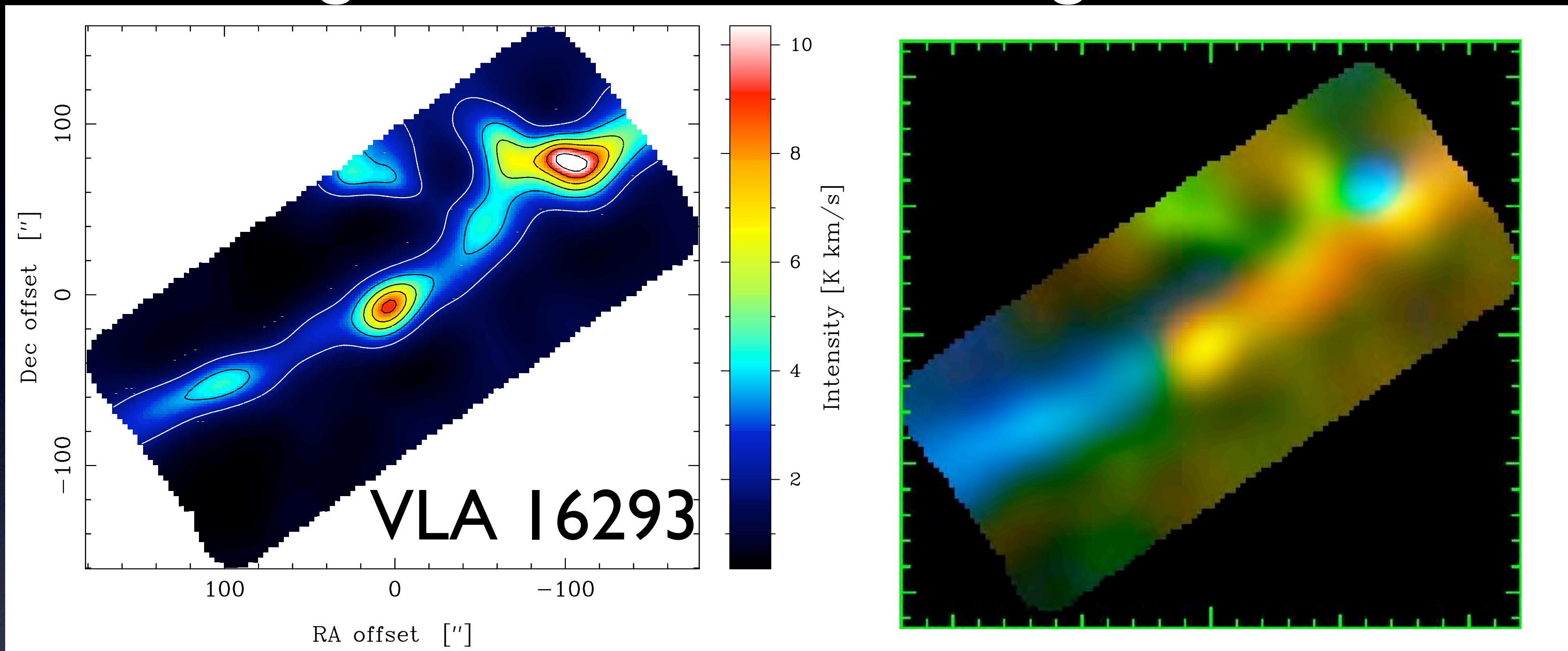


Use “jump” models: hot core and colder absorbing envelope -- variable abundance

Emprechtinger et al. 2010

Water in Outflows

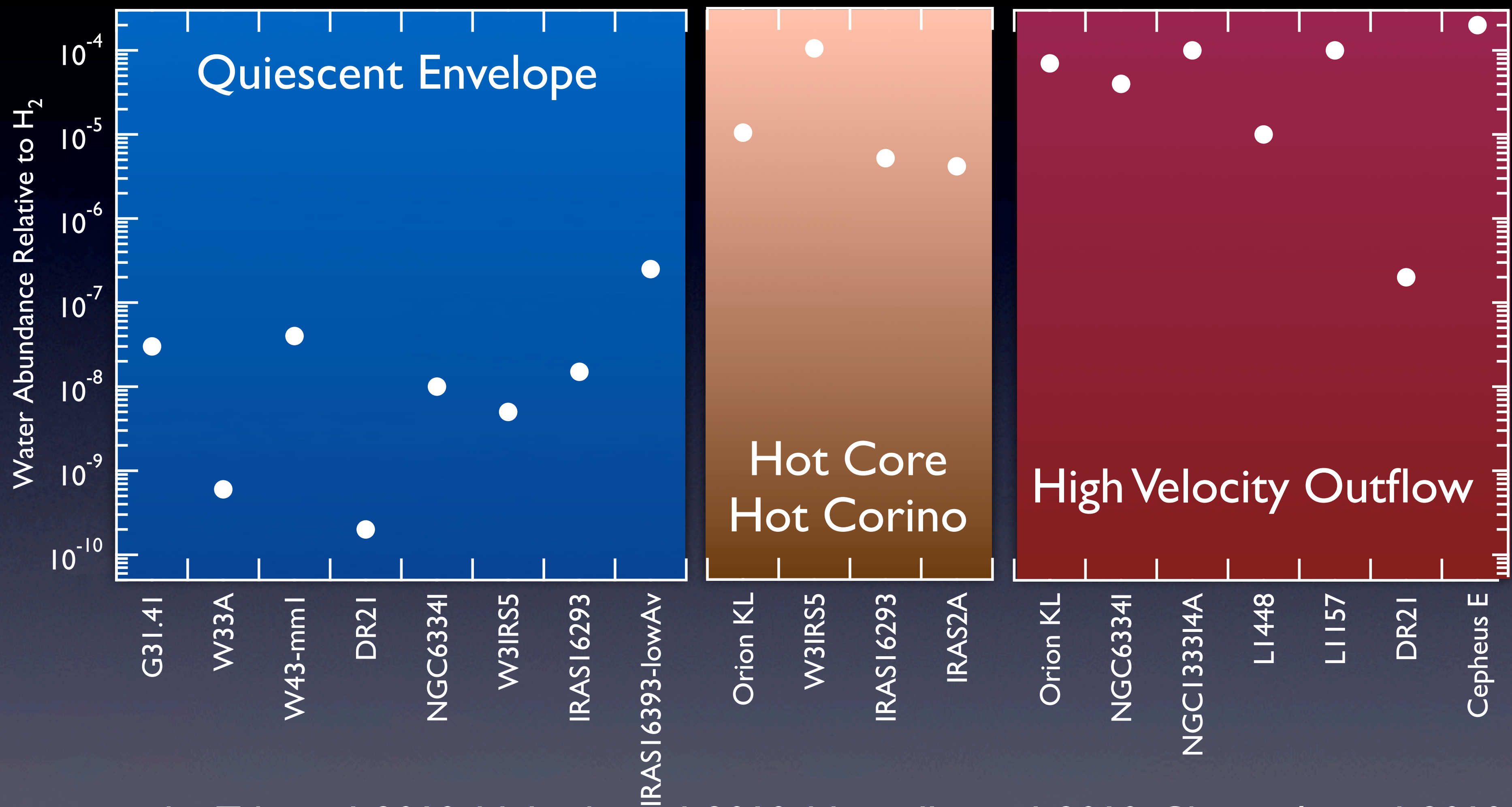
H_2O Integrated Emission Wing Emission



P. Bjerkeli

- Shocked gas in outflows are clearly a primary part of the water story (poster by Vasta, also Basquet)
- Many sources have H_2 rotational emission maps from Spitzer - water emission similar to molecular hydrogen and not low J CO (Nisini et al. 2010)

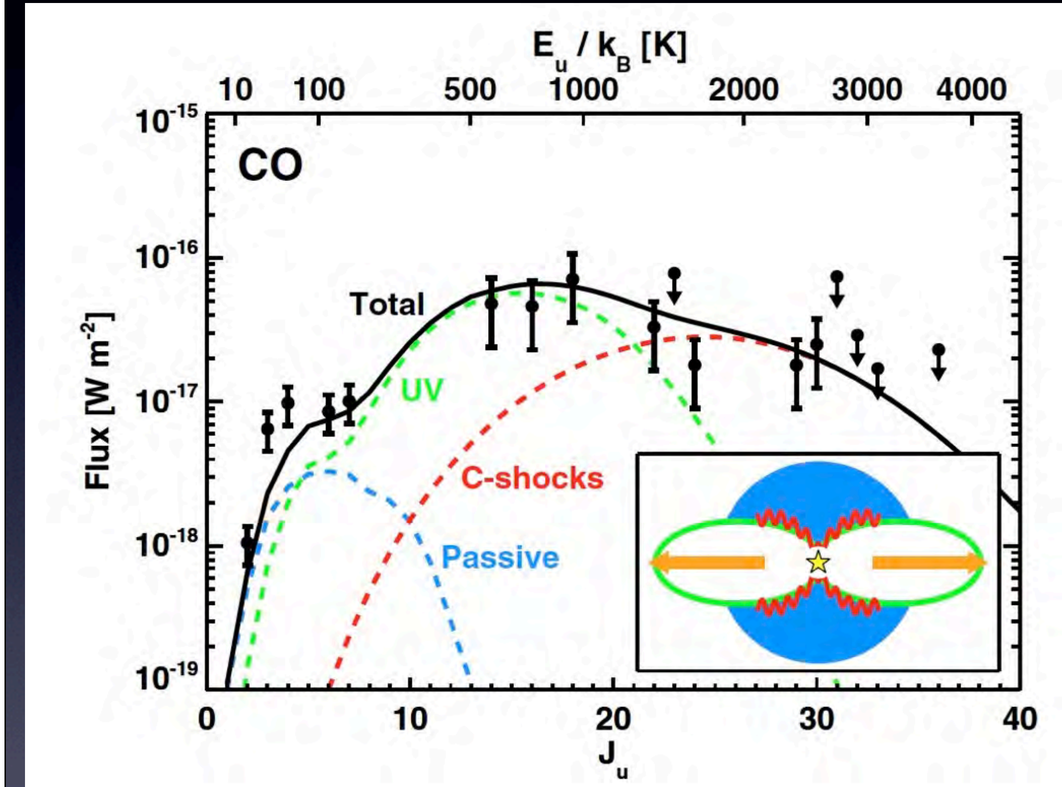
Water Abundance

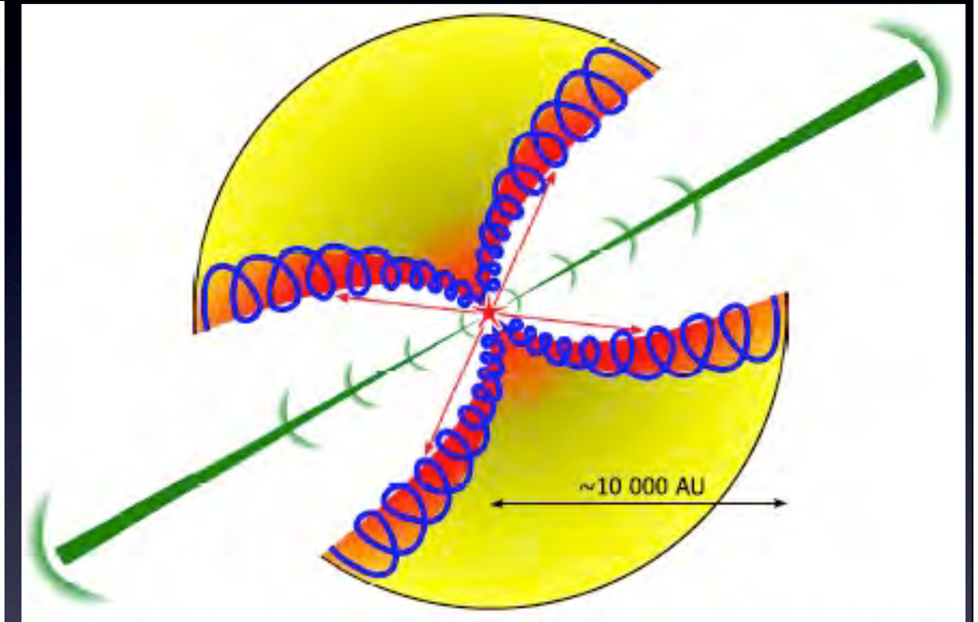


van der Tak et al. 2010; Melnick et al. 2010; Marseille et al. 2010; Chavarría et al. 2010; Emprechtinger et. al. 2010; Nisini et al. 2010; Kristensen et al. 2010, 2011; Lefloch et al. 2011; Coutens et al. 2012; Santangelo et al. 2012; Vasta et al. 2012

Spectral Line Energy Distribution

Visser et al. 2012

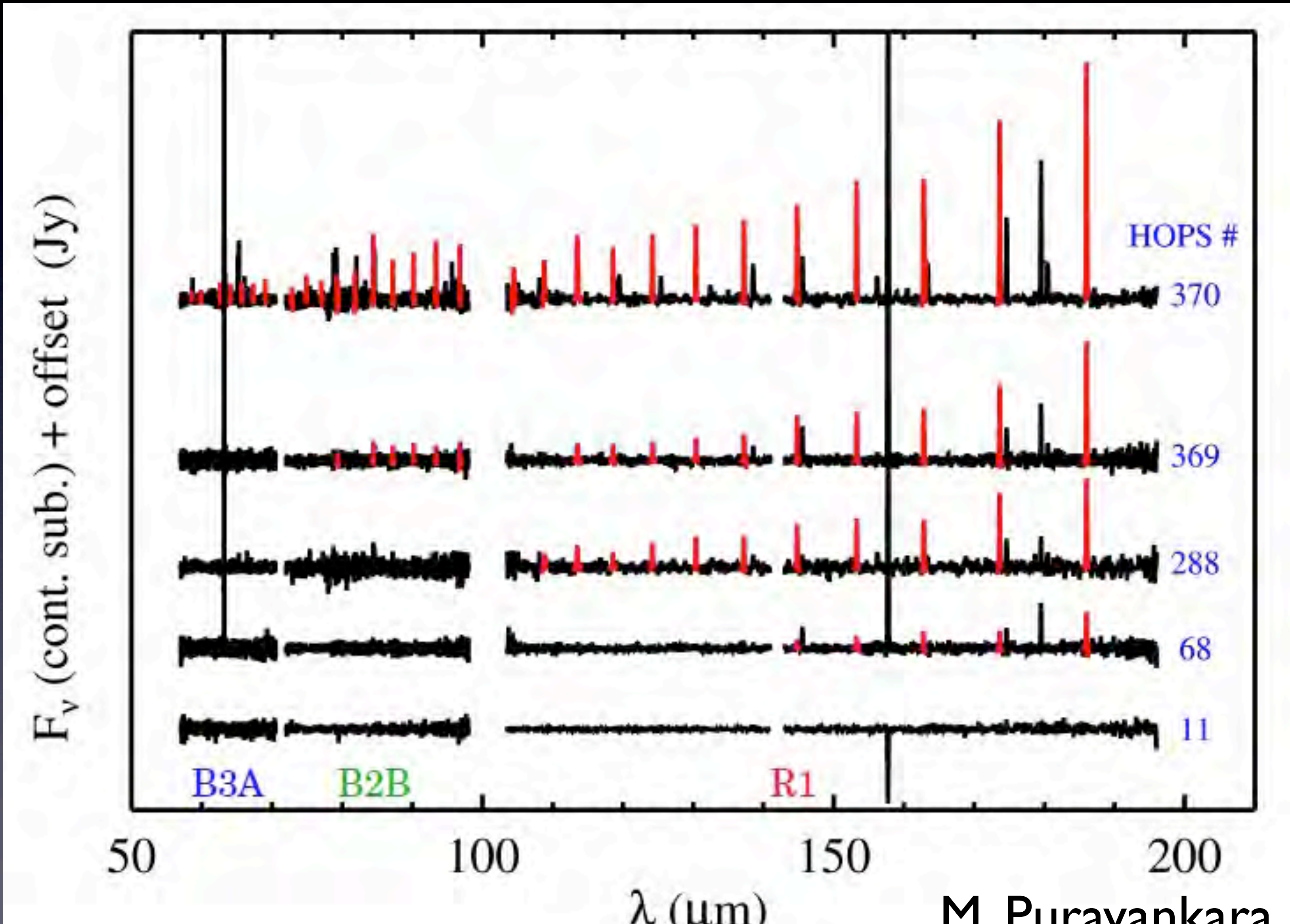




van Kempen, Kristensen et al. 2010
Visser et al. 2012

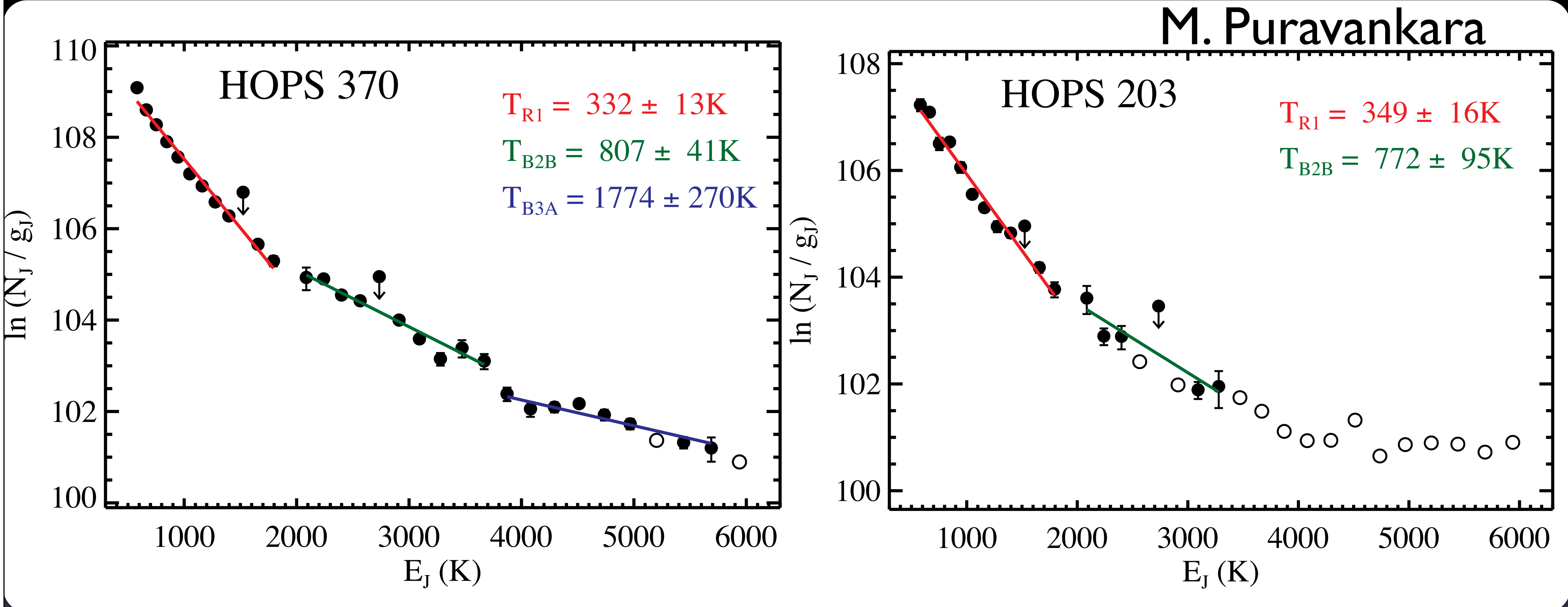
yellow: passive heated envelope
green: bipolar jet
red: UV heated cavity walls
blue: small scale shocks along cavity walls

Surveys



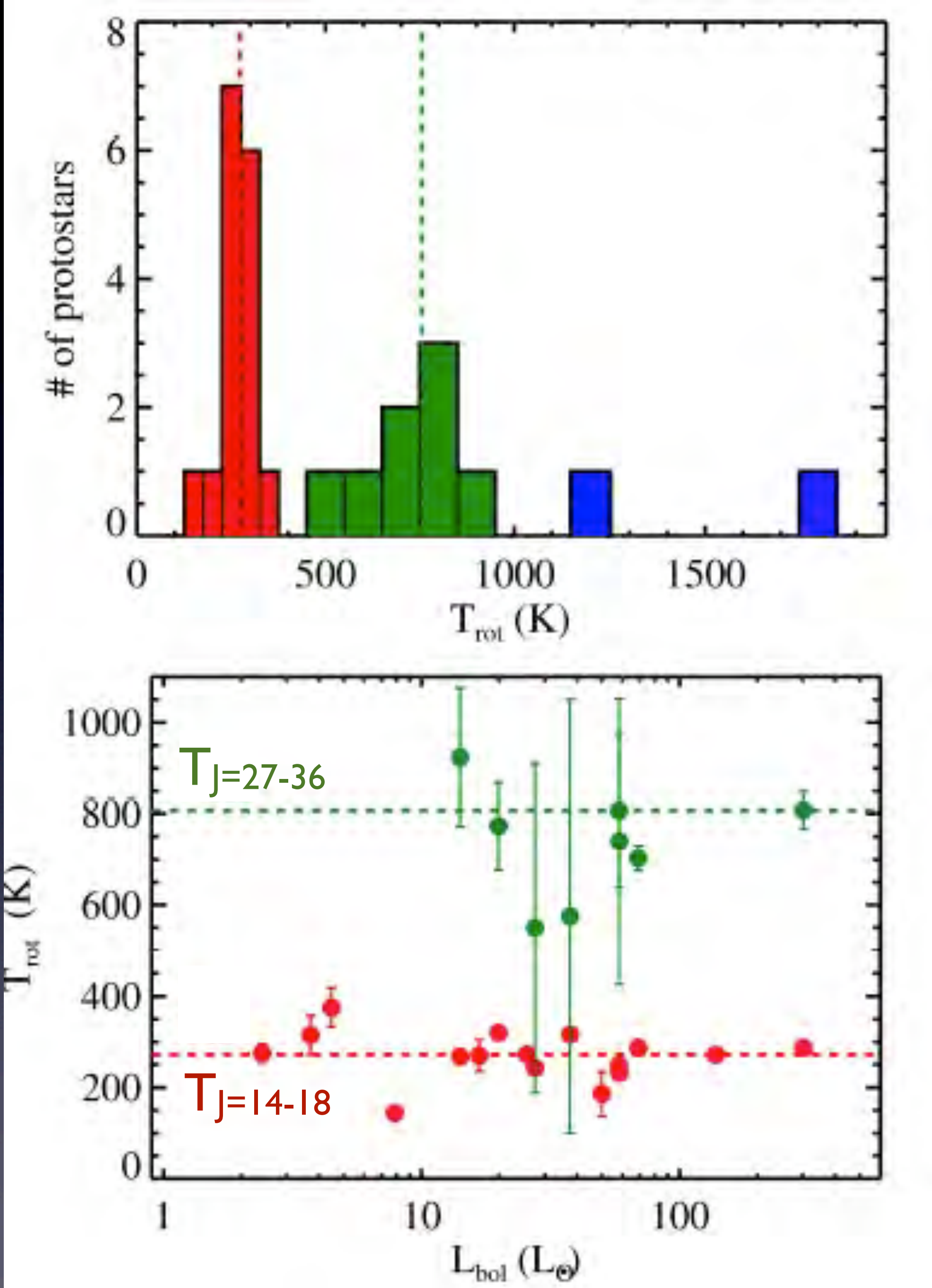
M. Puravankara

Correlations and Rotation Diagrams



- CO Luminosity is not correlated with envelope mass, bolometric temperature, or density
- CO Luminosity is correlated with the L_{bol}

Protostars

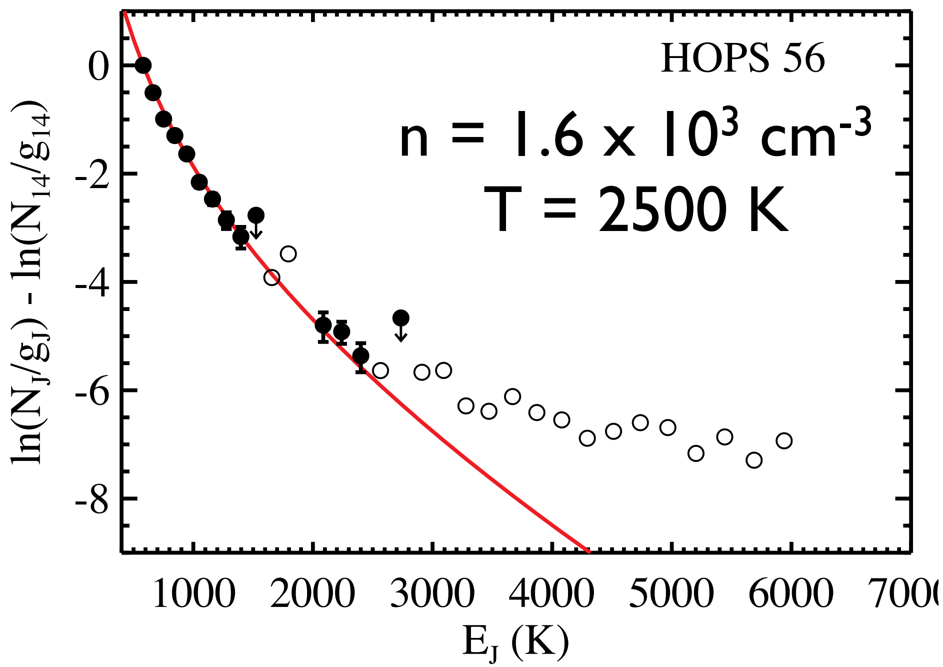


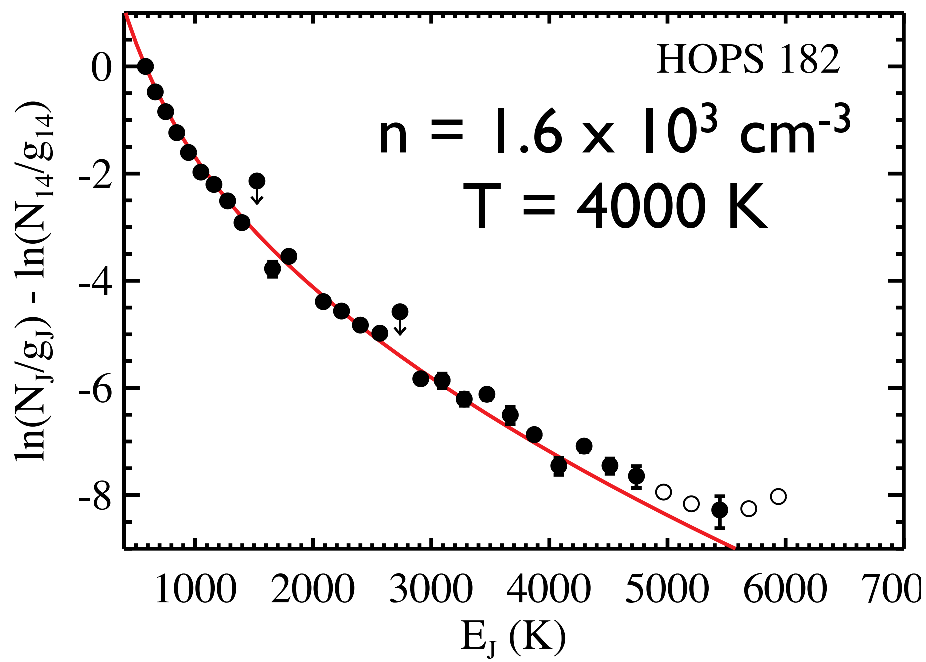
- DIGIT (J. Green) AND HOPS sample - statistics
- In each source find at least two components: one warm (~300 K) and the other hot (>600 K)
- very common!!!!! why 300 K?
- T_{rot} constant across L_{bol}

More consistent with ^{12}CO tracing shocked gas...

M. Puravankara

Excitation Analysis





- Grid of 50,000 CO LVG models from Neufeld (2012)

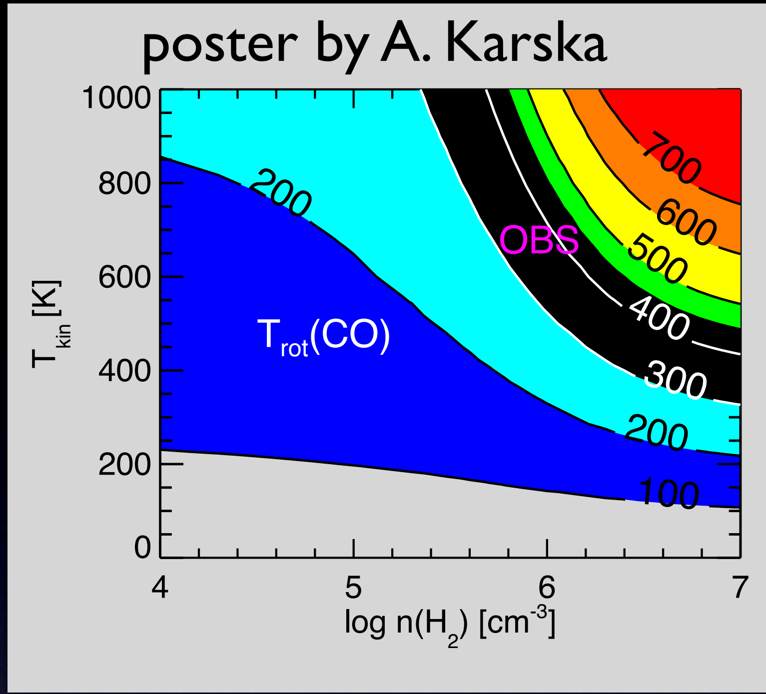
M. Puravankara

Density?

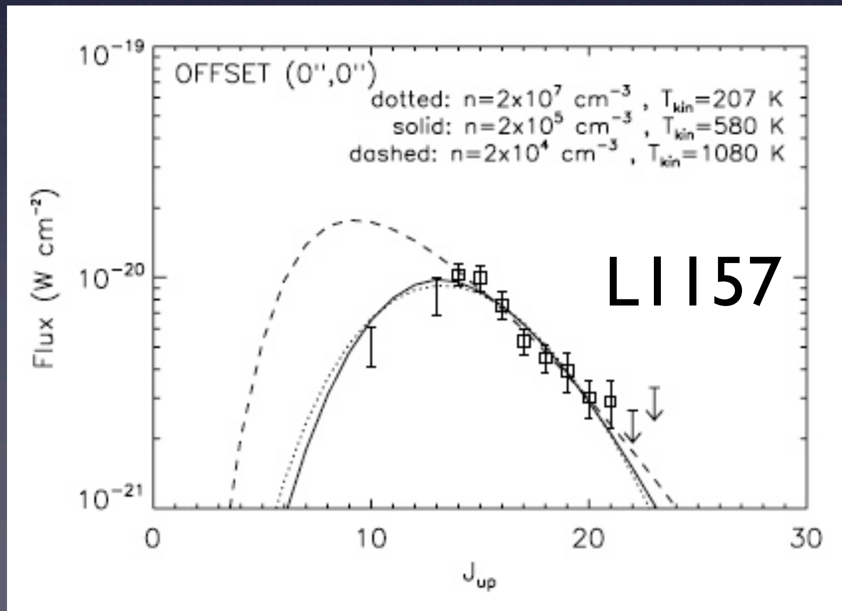
- CO emission is sub-thermal excitation of hot gas
  - ➡ represents a wider range of conditions that give rise to excitation temps of a few hundred K

OR

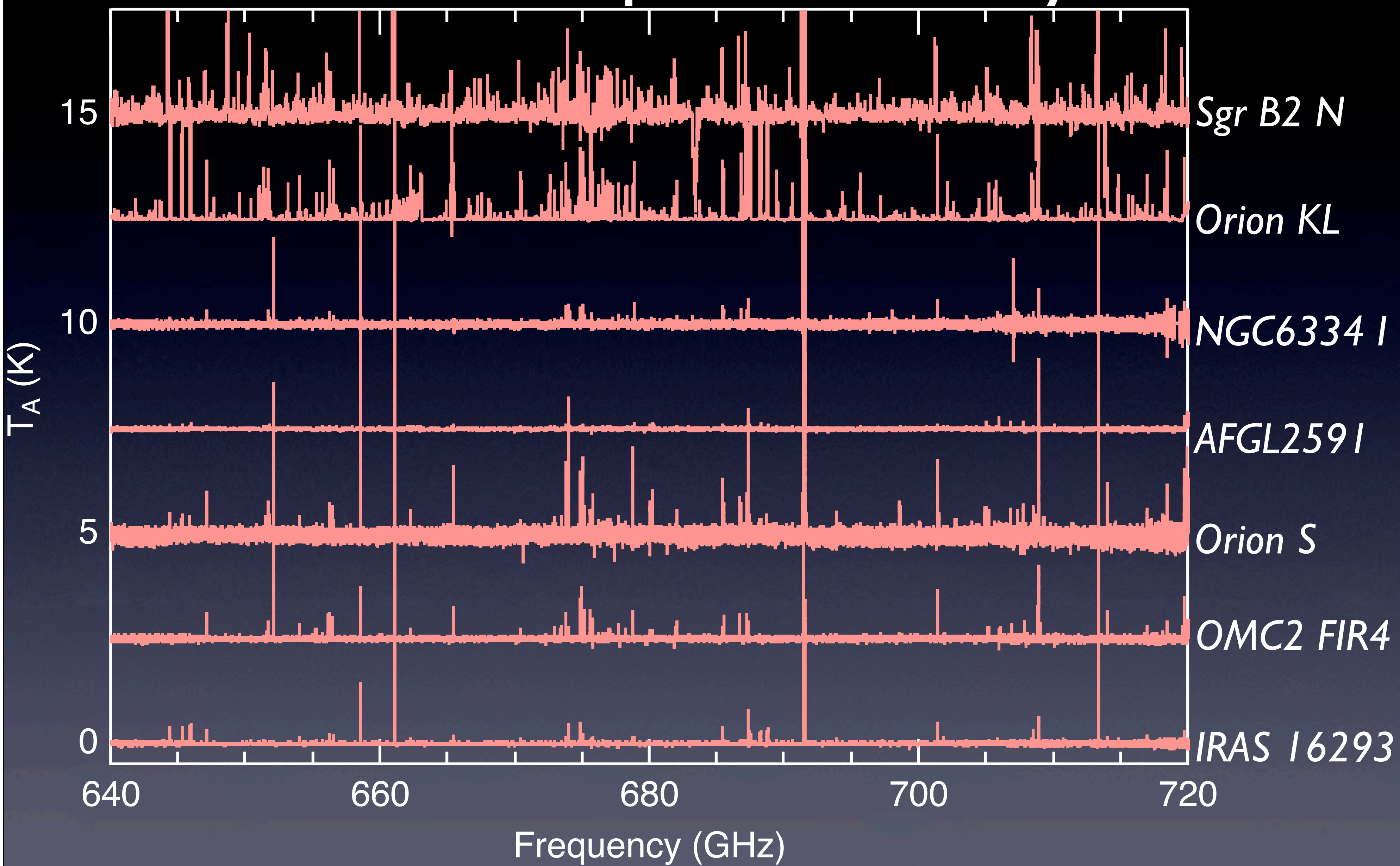
- CO is emitting from higher density gas with T ~600 K
  - ➡ ^{13}CO??
  - ➡ spatial distribution???
  - ➡ what about H_2??



Benedettini et al. 2012,
poster by Busquet

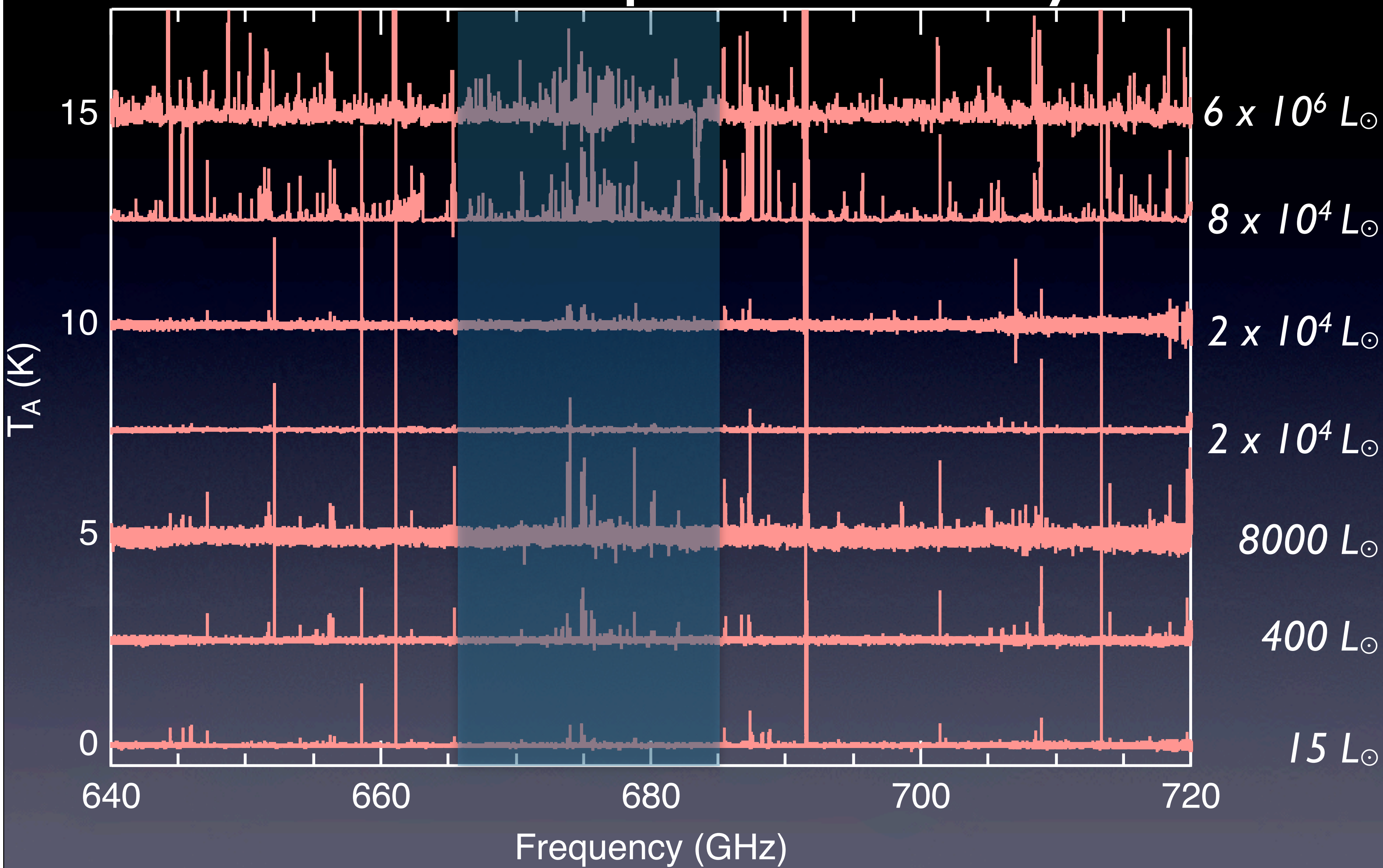


Herschel Spectral Surveys



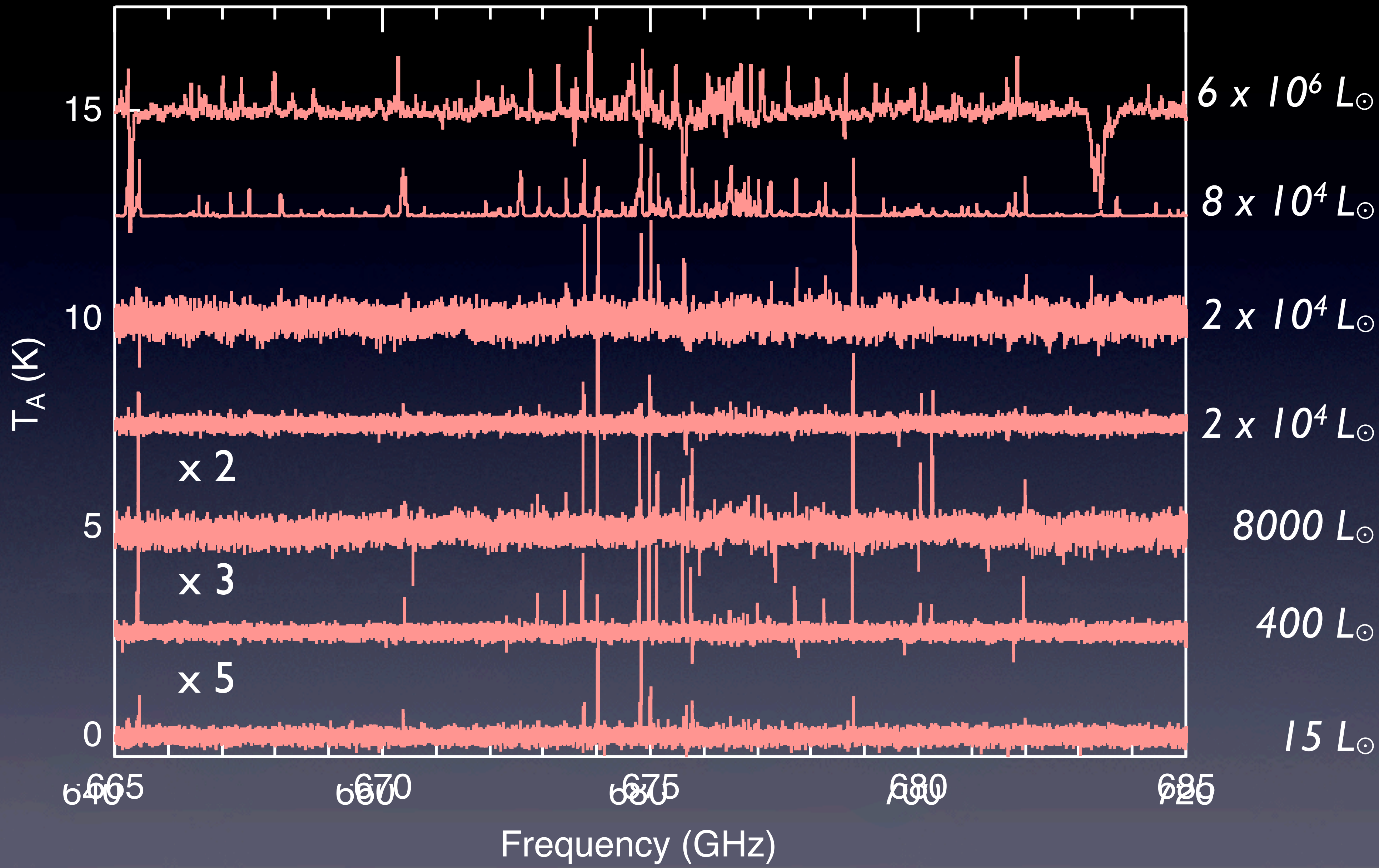
CHESS/HEXOS

Herschel Spectral Surveys



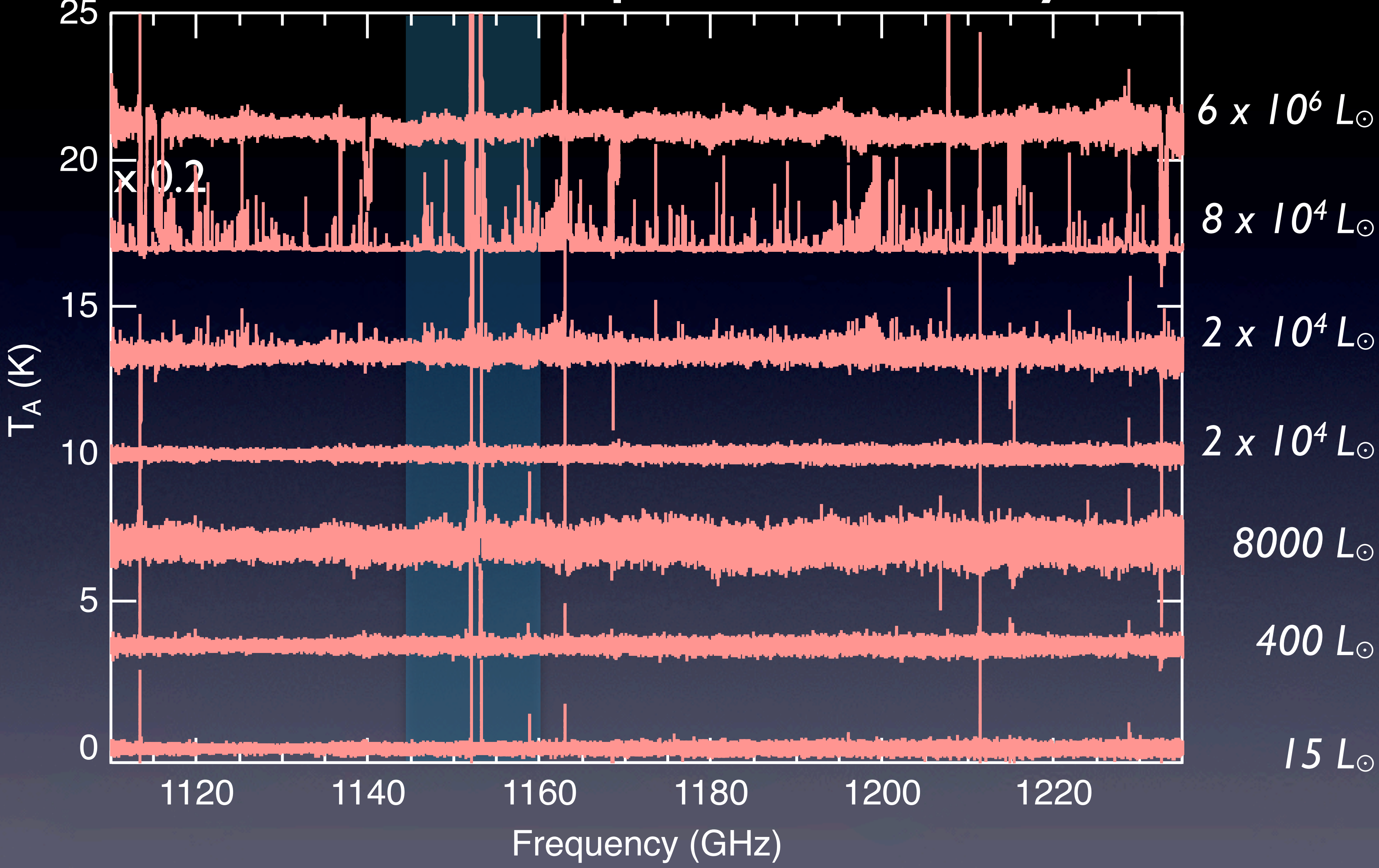
CHESS/HEXOS

Herschel Spectral Surveys



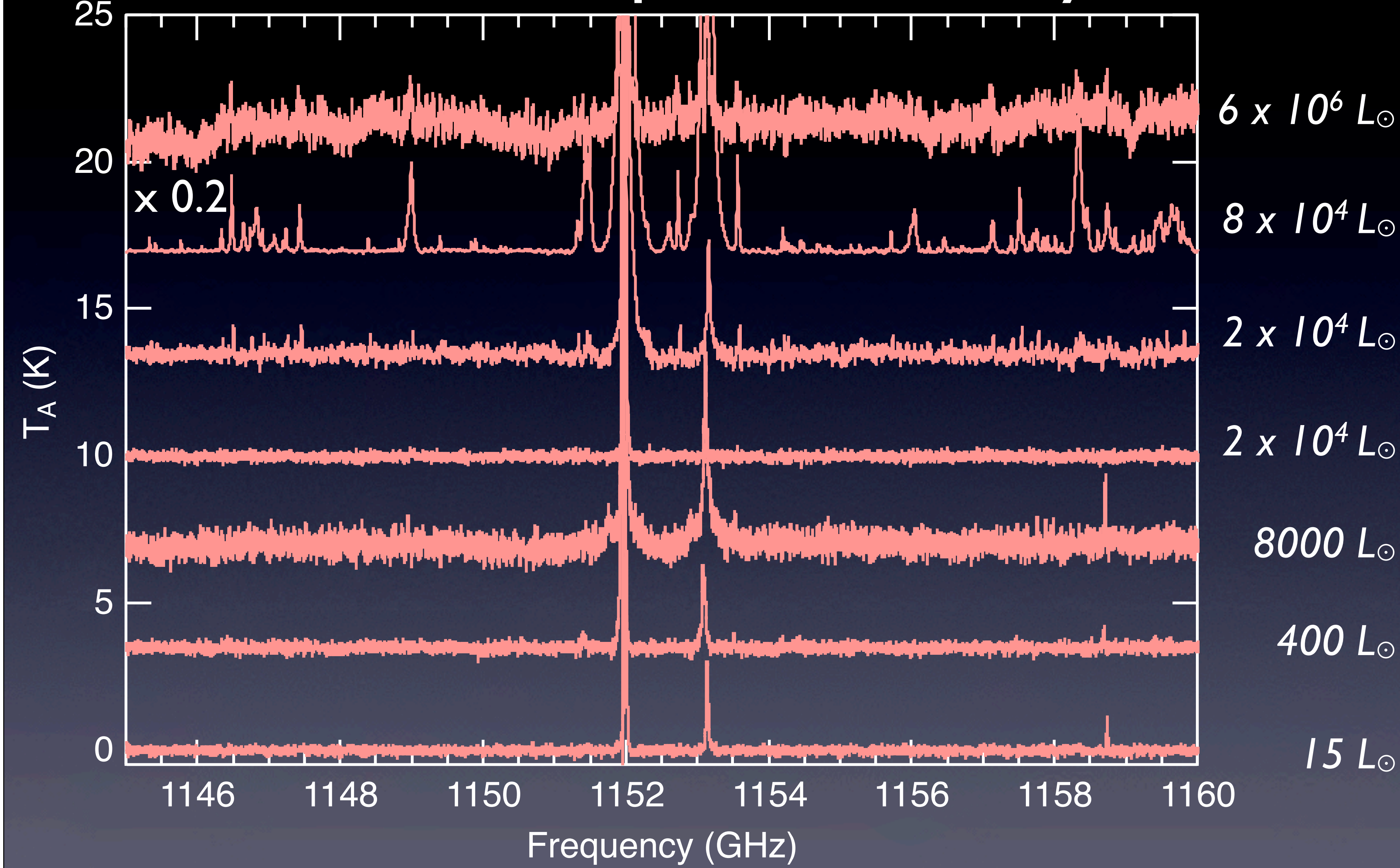
CHESS/HEXOS

Herschel Spectral Surveys



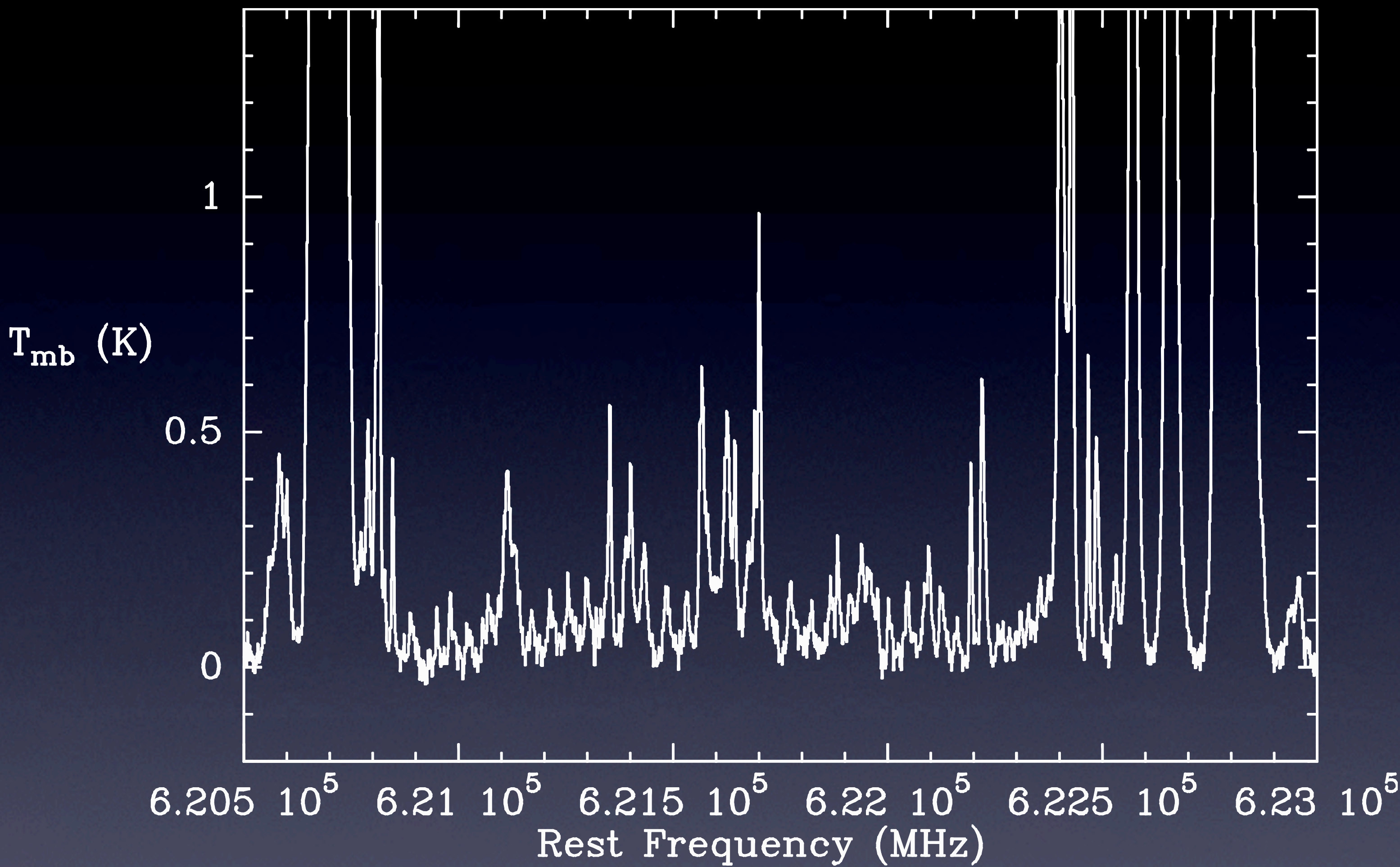
CHESS/HEXOS

Herschel Spectral Surveys



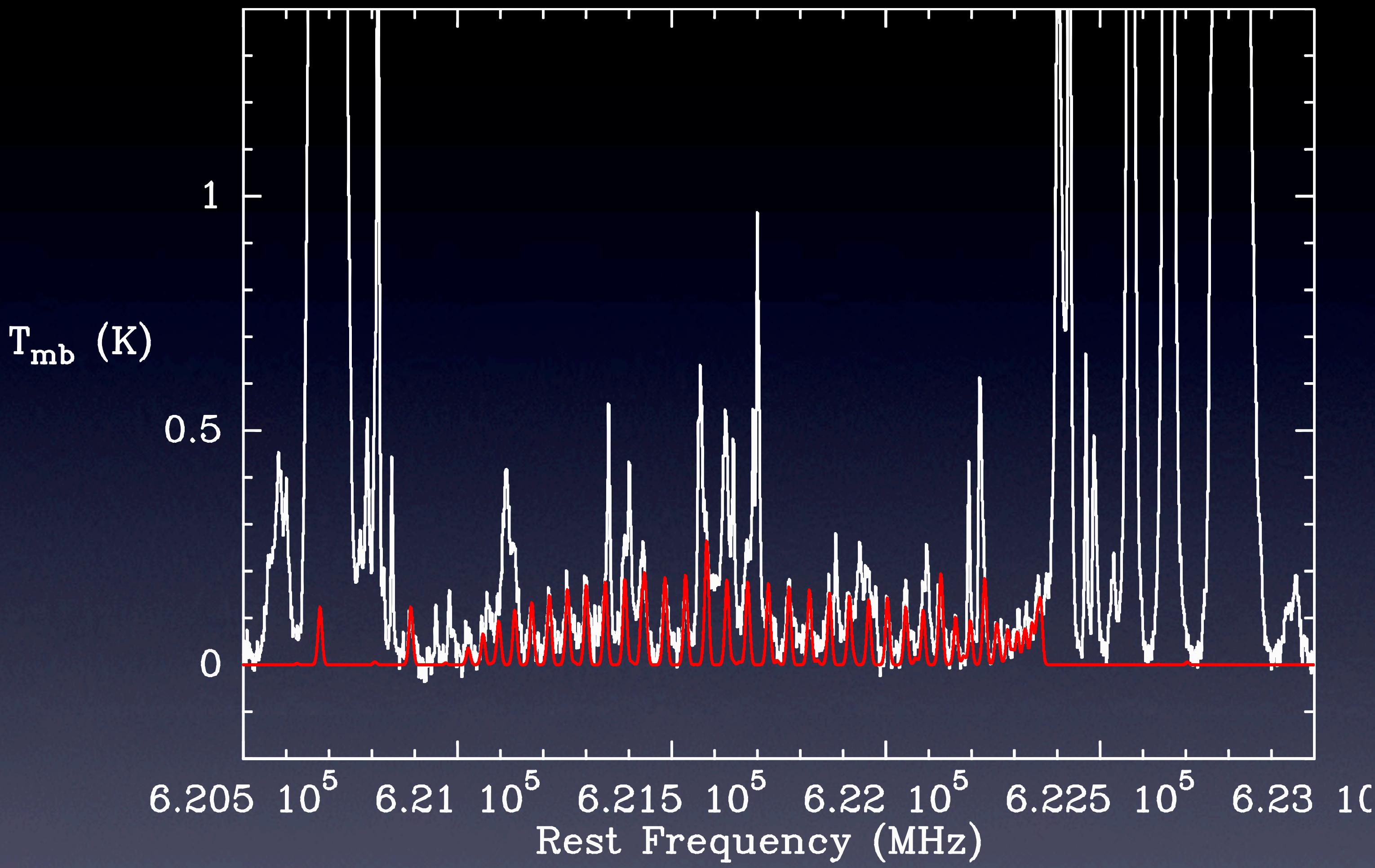
CHESS/HEXOS

N. Crockett

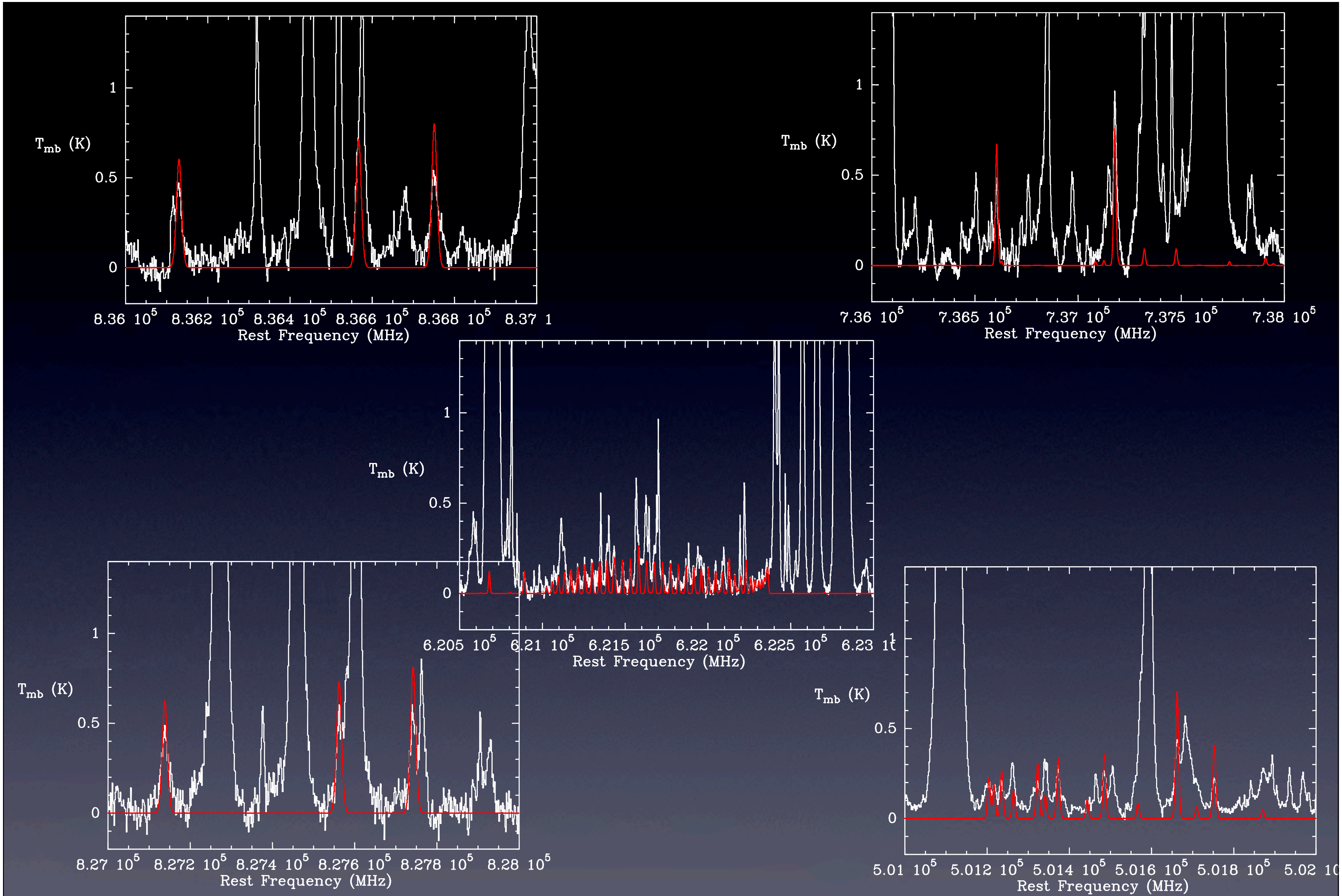


Ethyl Cyanide: C_2H_5CN

N. Crockett



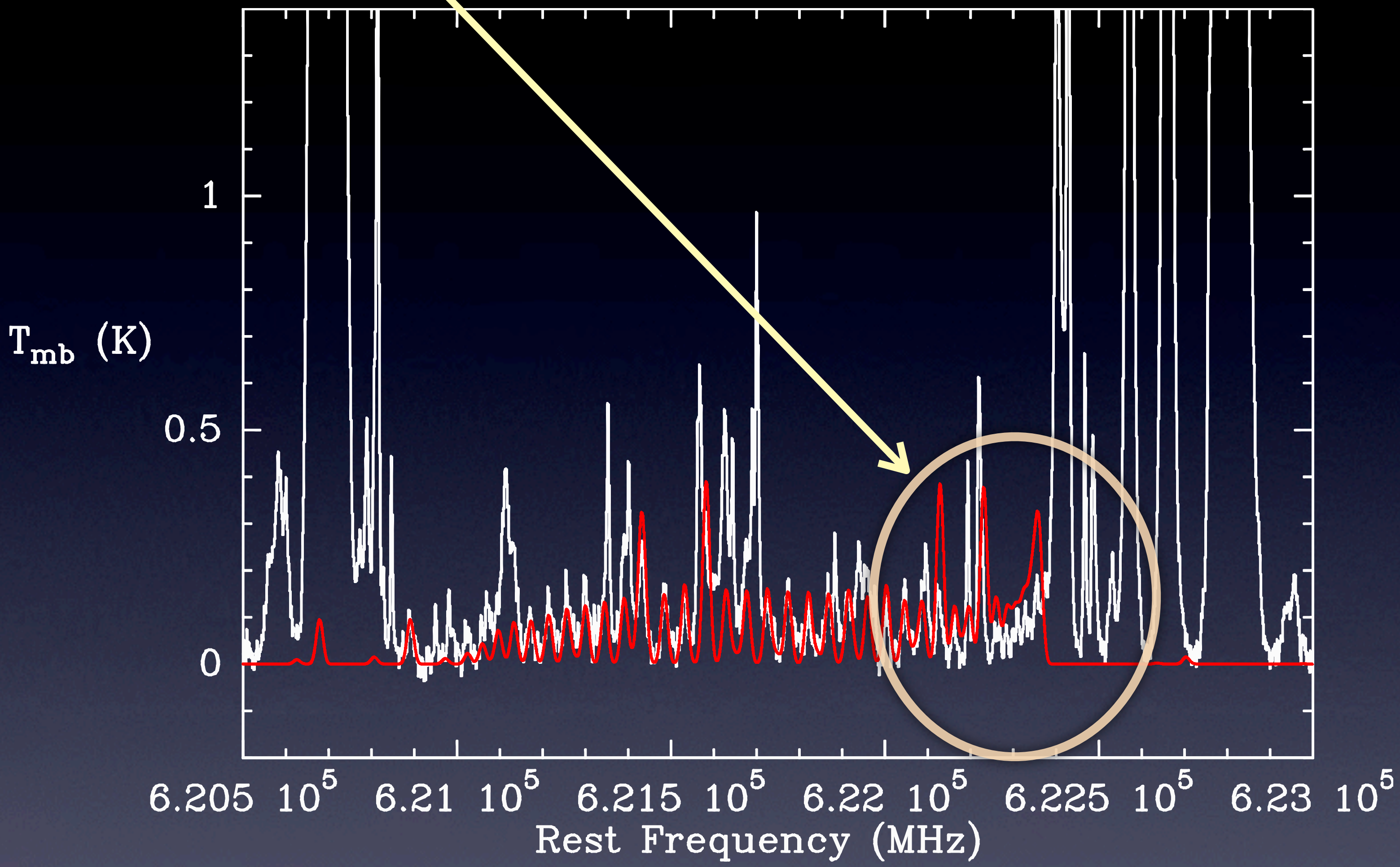
Ethyl Cyanide: C_2H_5CN



Ethyl Cyanide: C_2H_5CN

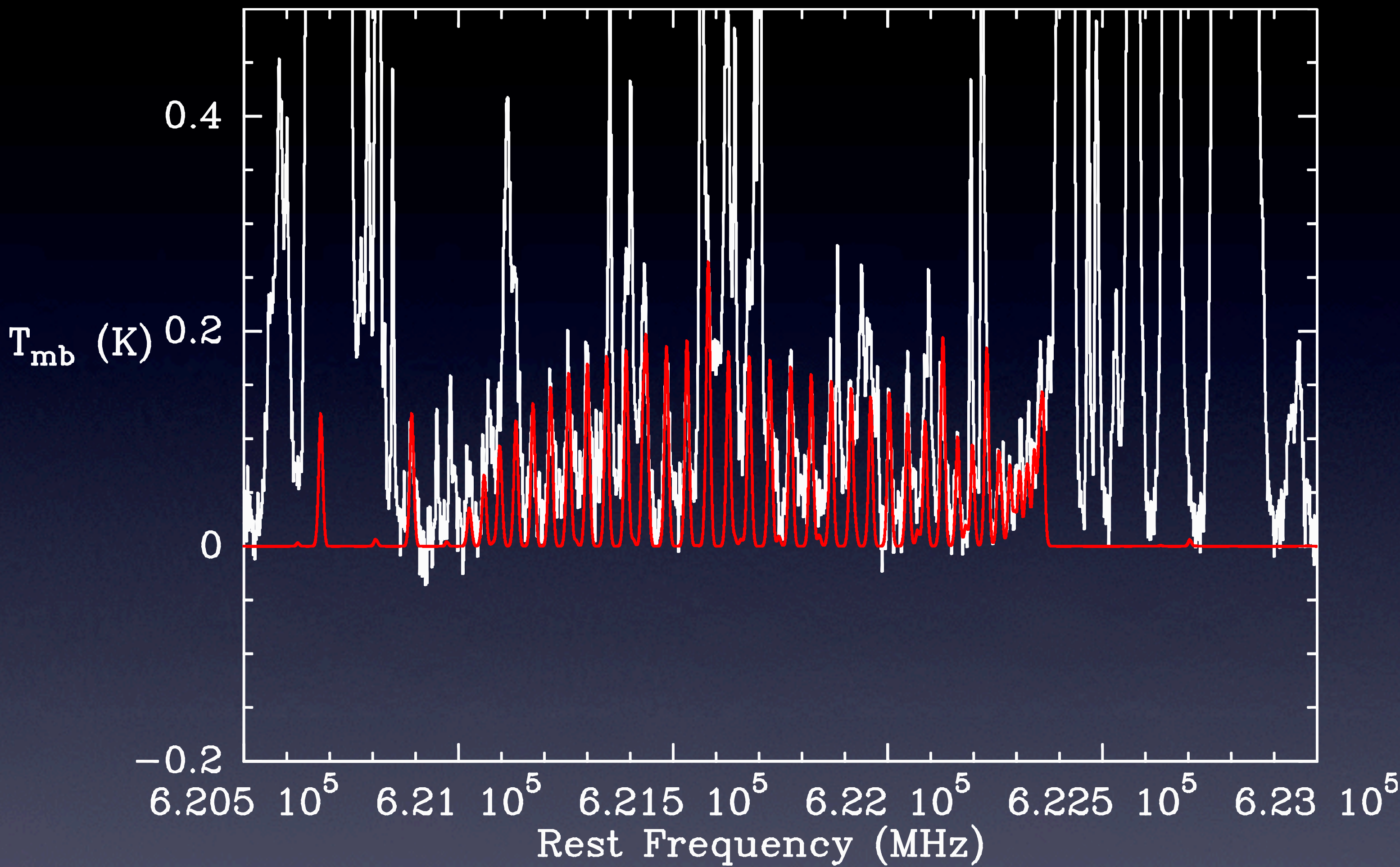
N. Crockett

Requires compact warmer component



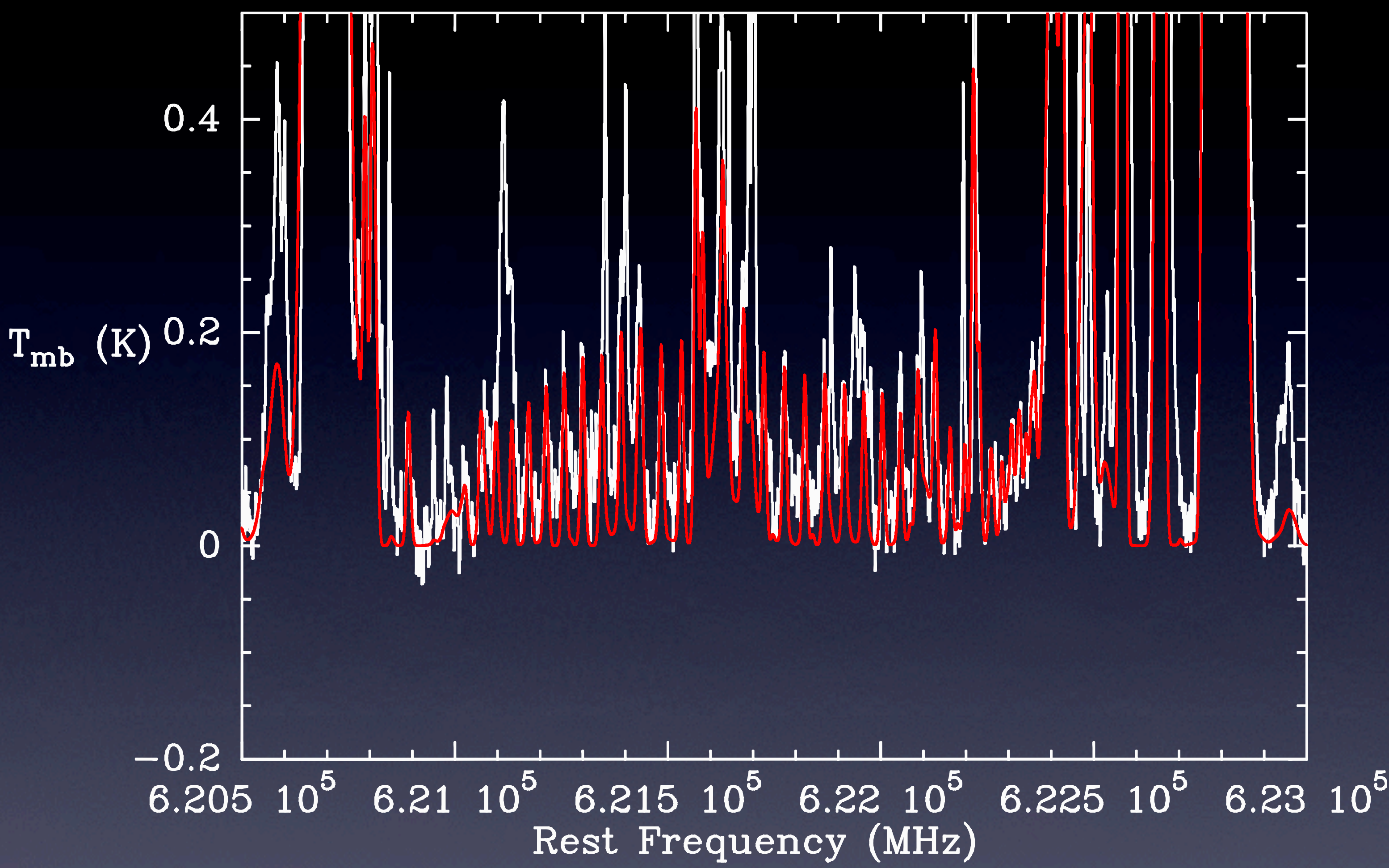
Science: Original Fit from Ground-Based Data

N. Crockett

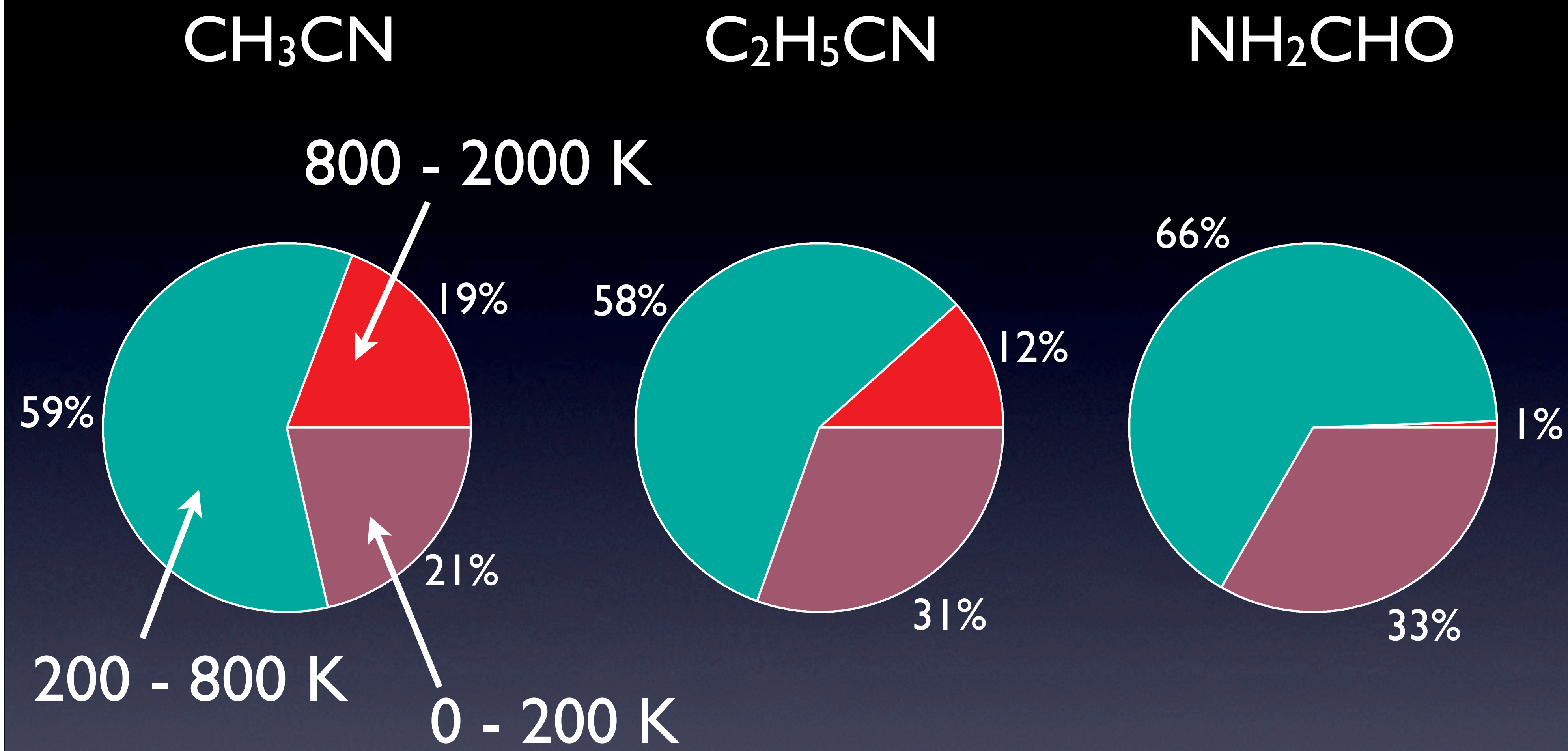


Ethyl Cyanide: C_2H_5CN

N. Crockett



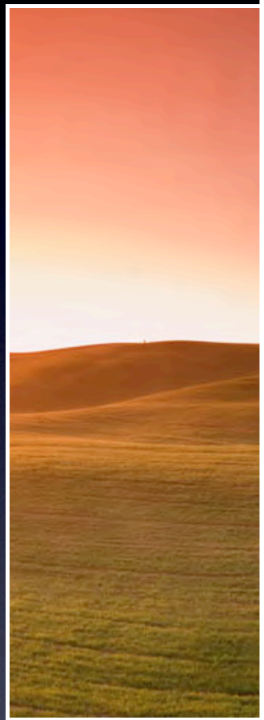
Ethyl Cyanide: C_2H_5CN

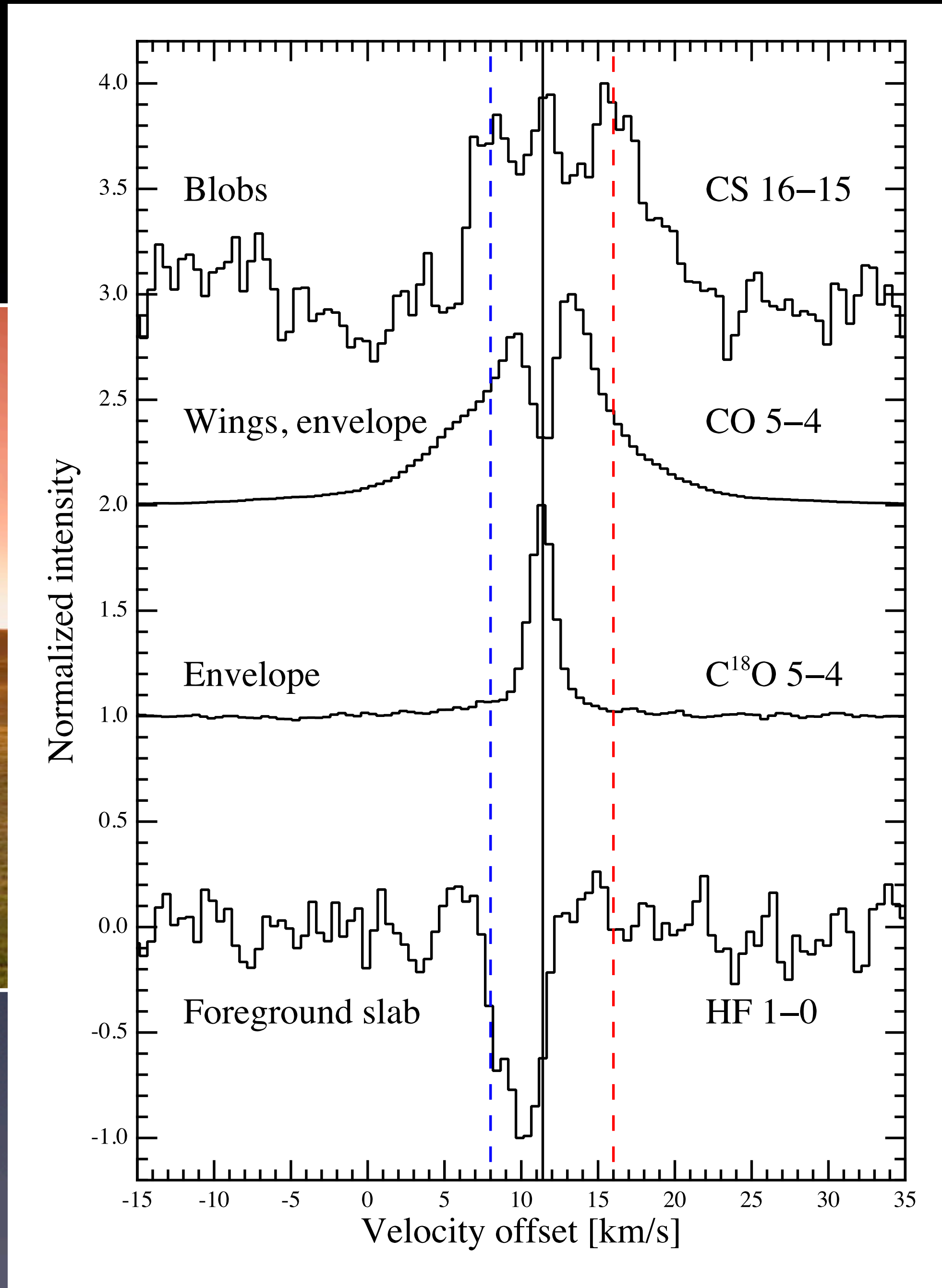


Herschel and Organics

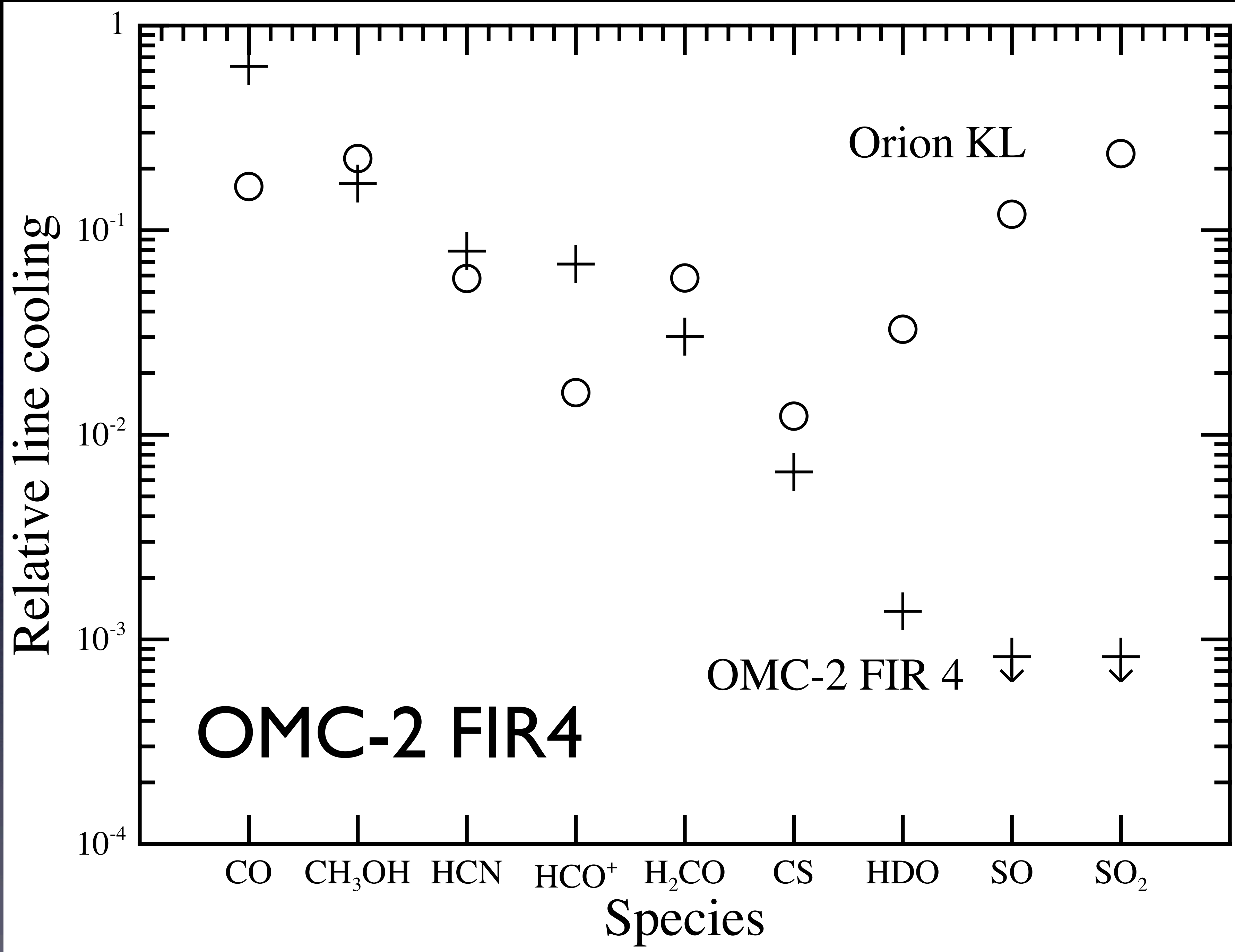
Orion KL - HEXOS - N. Crockett

OMC-2 FIR4





M. Kama


1
10-1
10-2
10-3
10-4
Relative line cooling
Orion KL
OMC-2 FIR 4
OMC-2 FIR4
CO
CH3OH
HCN
HCO+
H2CO
CS
HDO
SO
SO2
Species

M. Kama

Deuterium As a Fossil

- Hydrogen (H) is the most abundant element
- Deuterium (D) has an abundance 100,000 times below that of hydrogen (relic from big bang)

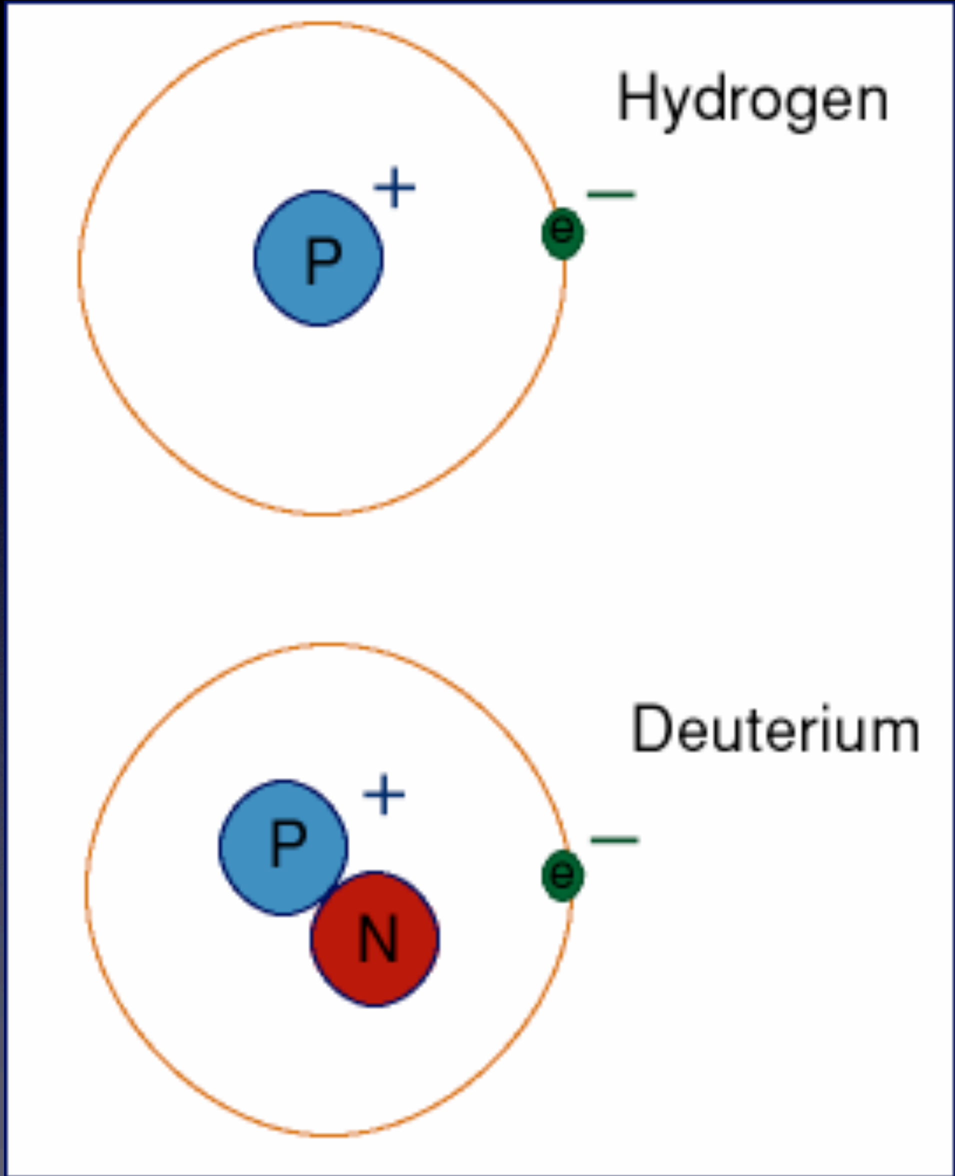
➡ at low temp. ($T < 50$ K) chemistry favors transfer of D as opposed to H

➡ if $T < 50$ K then

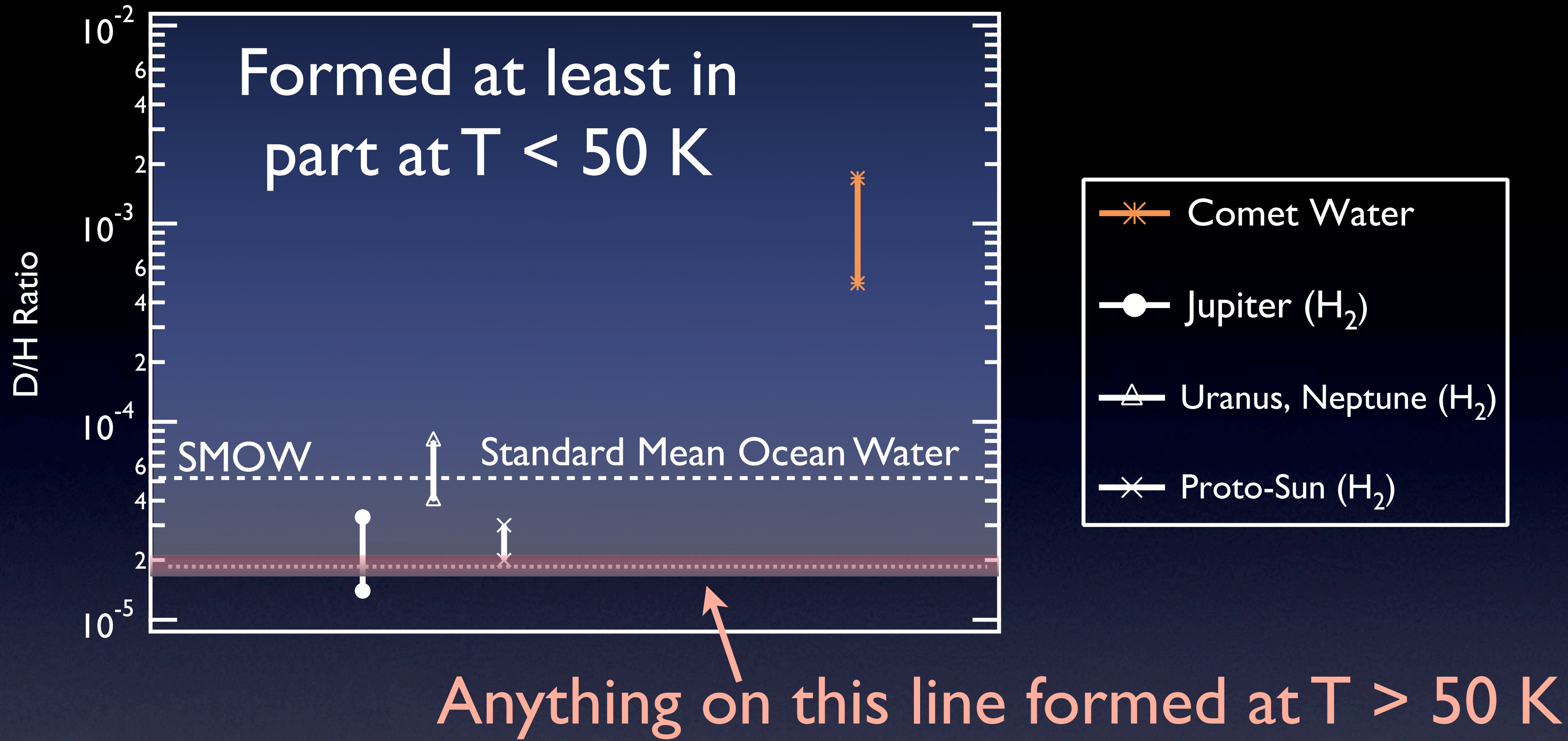
$HDO/H_2O > D/H$

➡ if $T > 50$ K then

$HDO/H_2O = D/H$

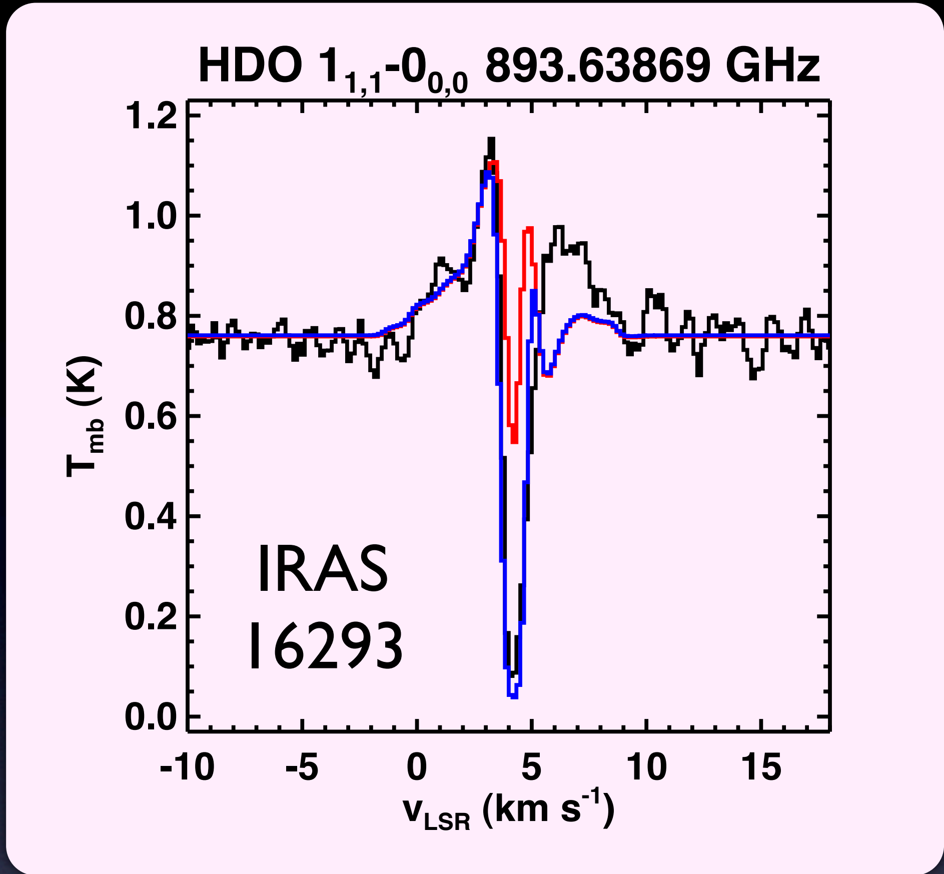


Deuterium as a Fossil



- *Earth water (SMOW) partially formed at very low temperatures - T < 50 K*

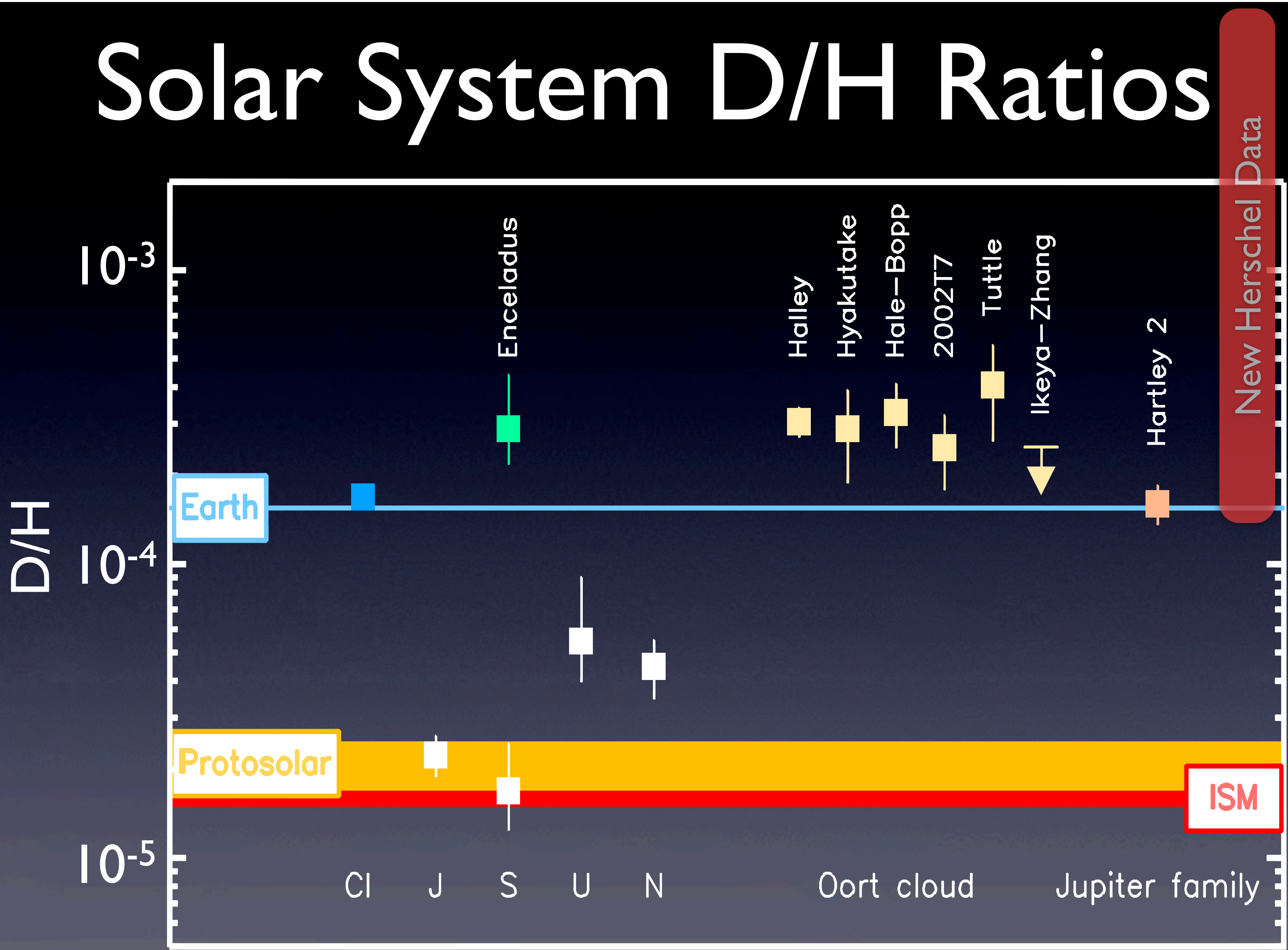
- Numerous transitions of HDO and $H_2{}^{18}O$
- more robust D/H
- Ability to probe structure in HDO/H_2O
  - ➡ Hot Corino: ~0.03
  - ➡ Outer Envelope: ~0.005
  - ➡ Photodesorbing layer: ~0.05



Coutens et al. 2012
see also Liu et al. 2010, Bergin et al. 2010

Revisiting D/H

Solar System D/H Ratios



Hartogh et al. 2011, *Nature*, Oct. 5

Herschel and Protostars

- Beautiful data with more to come!
- Protostars are a key part of the Herschel Legacy - which is still being written!