Evolution of infall, accretion and outflows in protostars

Results from Herschel Orion Protostar Survey (HOPS)

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ESAC, Madrid
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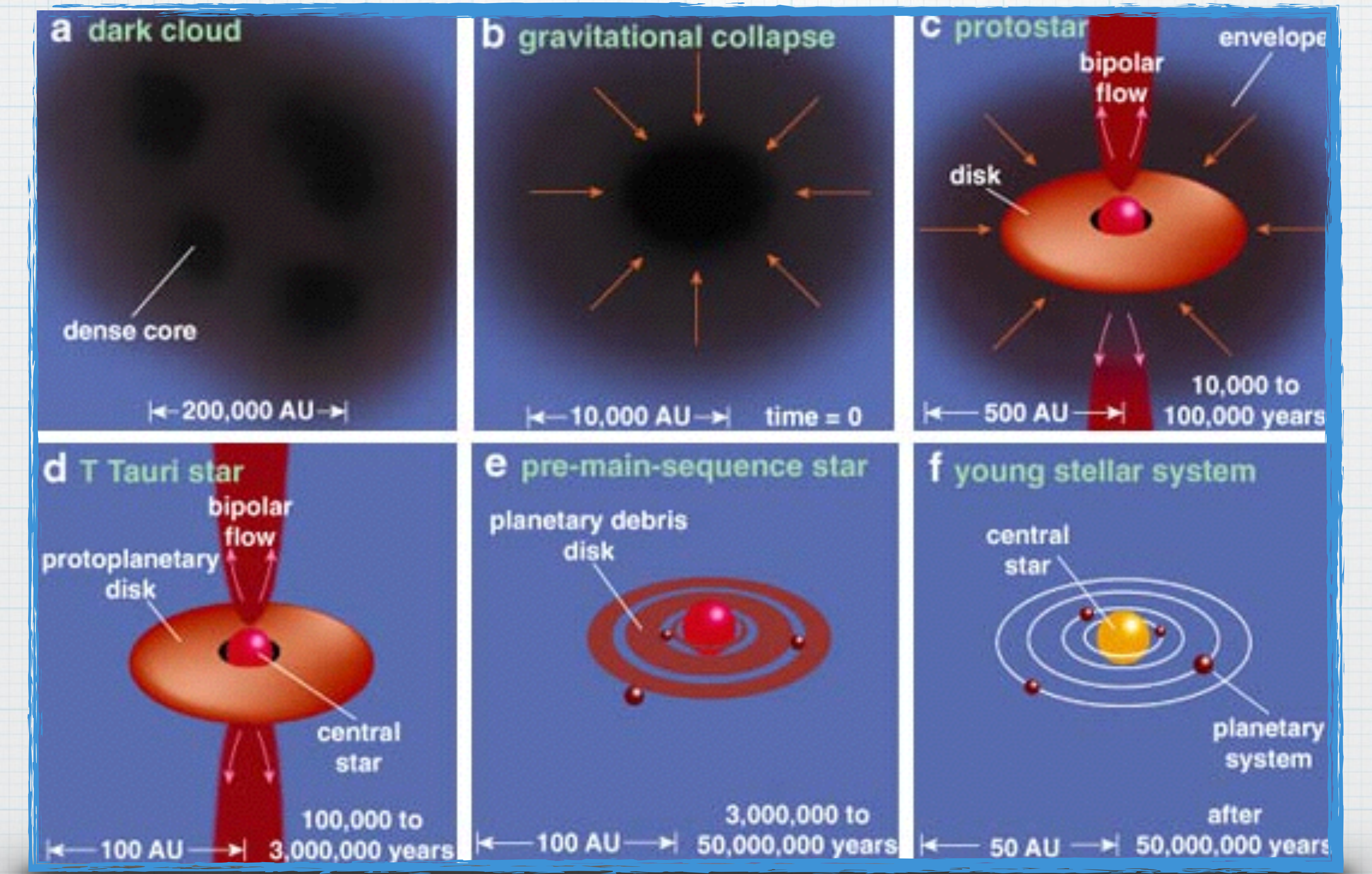
Star & planet formation: overview



Greene (2001)

HERSCHEL ORION PROTOSTAR SURVEY

Orion: over half of the YSOs within 500 pc

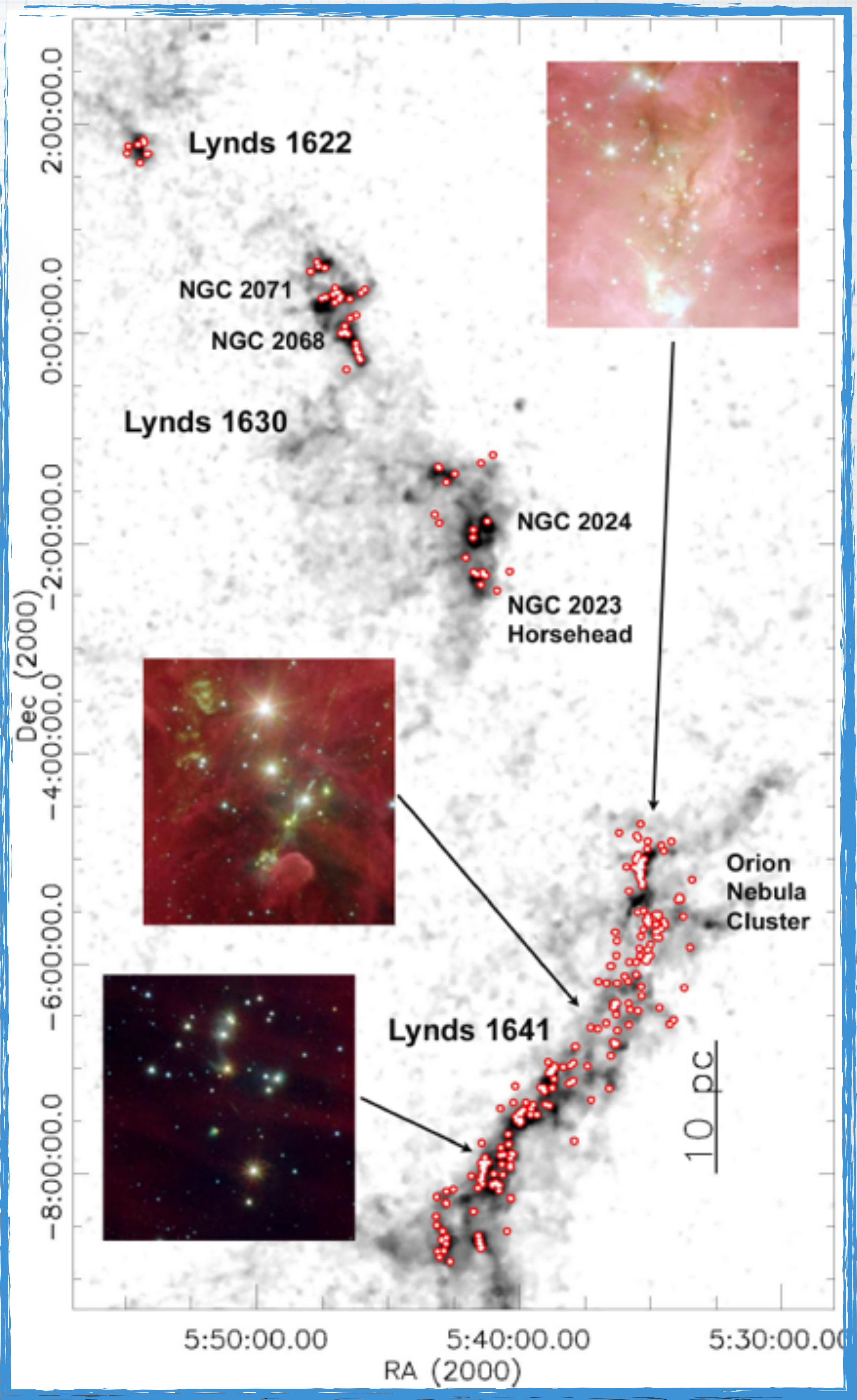
HOPS program:

- 200 hr on Herschel
- ~ 400 Spitzer identified protostars
- imaging @70 & 160 µm
- 54 — 200 µm spectroscopy of 50 protostars

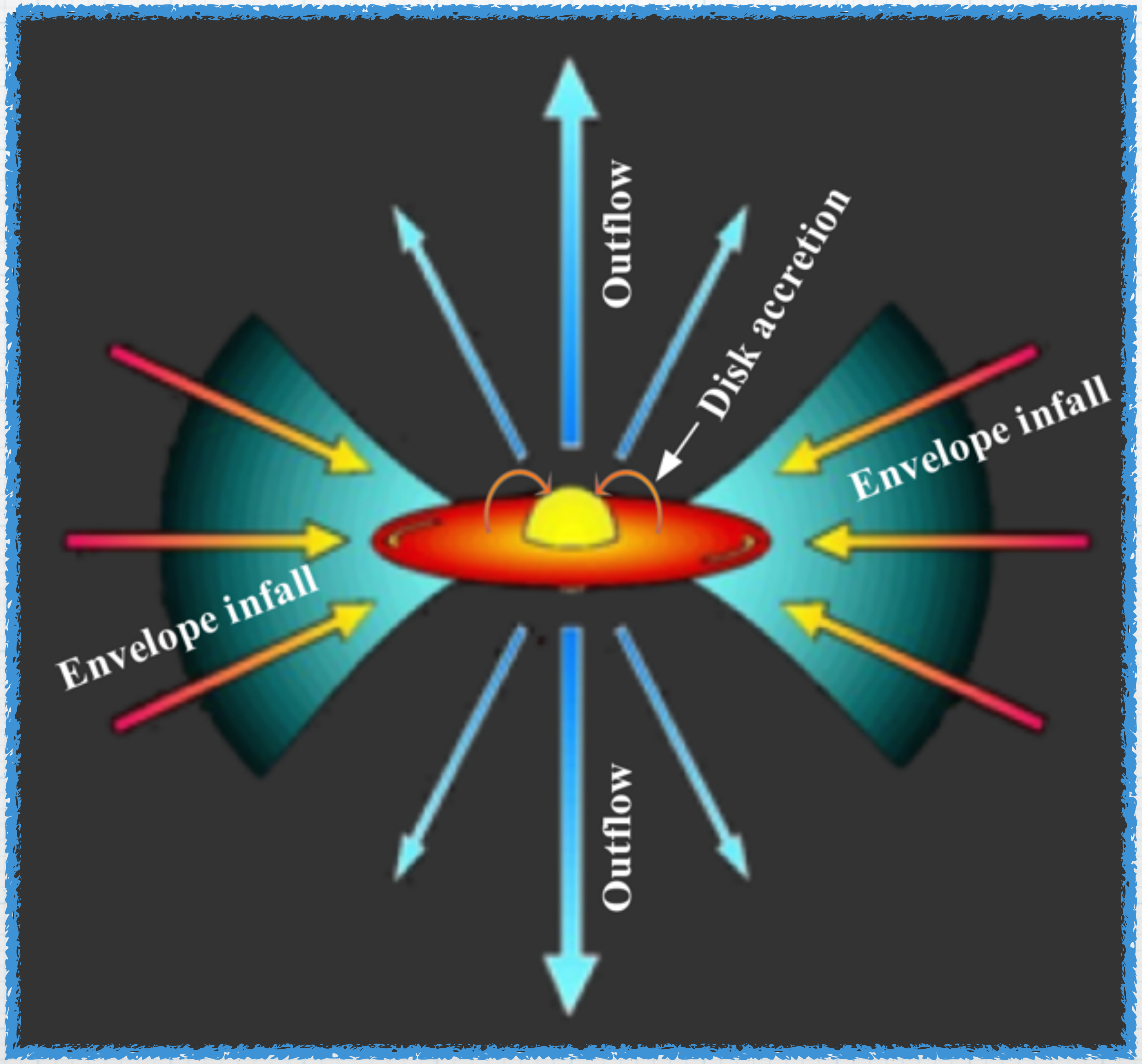
Additional observations

- HST, IRTF, Spitzer, APEX, IRAM, CARMA ALMA

GOAL: Study protostellar evolution with the large sample of protostars & diverse range of environments found in Orion.



Protostellar evolution is driven by the competition between three mass flows: envelope infall, disk accretion & outflow



Results from HOPS

- Evidence for higher infall/accretion rate in the early stages of protostellar evolution *(Fischer et al. in prep)*

- PACS Bright Red sources (PBRs): the reddest protostars known *(A. Stutz et al. 2013)*

- The origin of high-excitation CO line emission in protostars *(Manoj et al. 2013; Manoj et al. in prep.)*

- Role of environment in regulating star formation *(Megeath et al. in prep.)*

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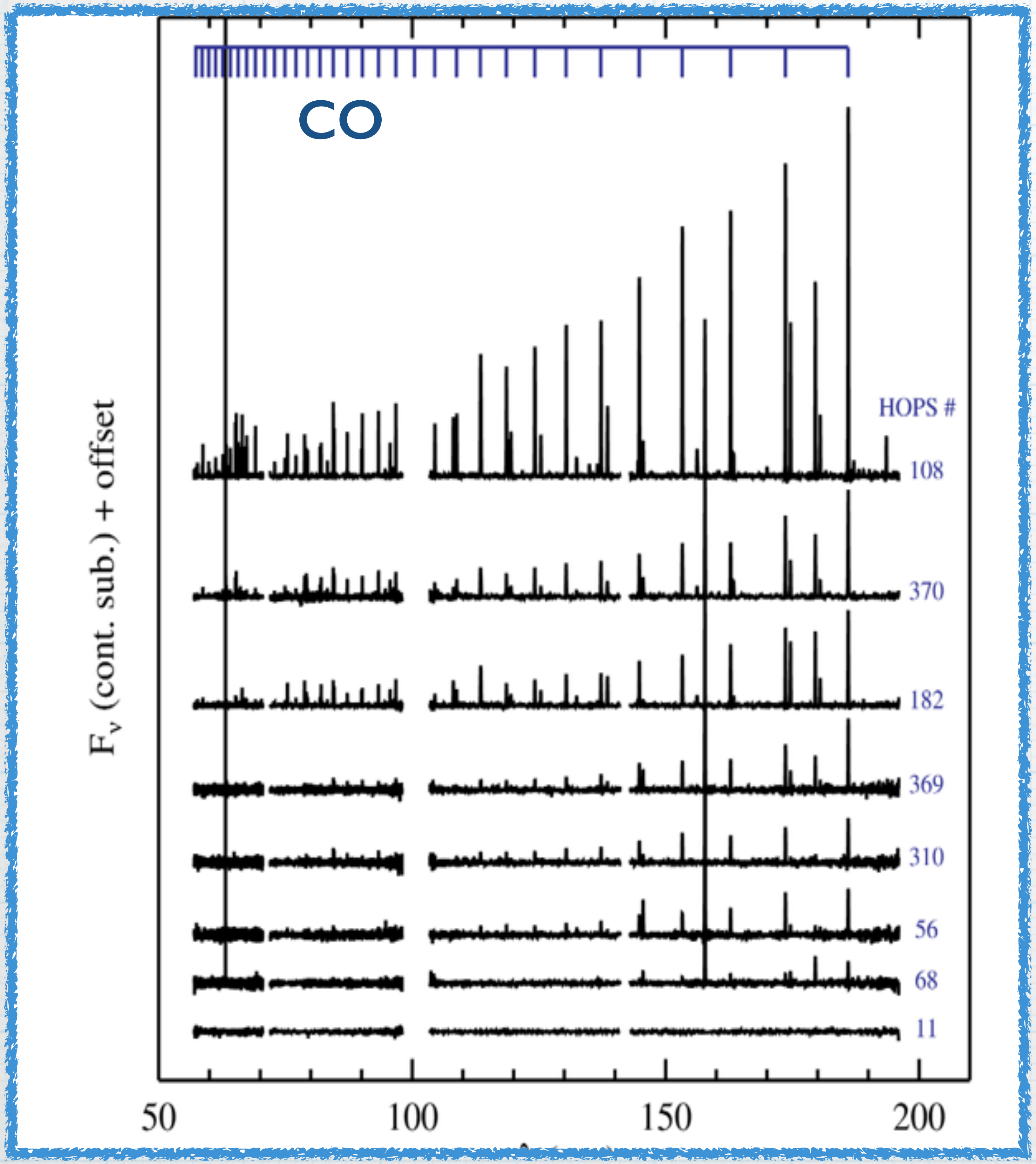
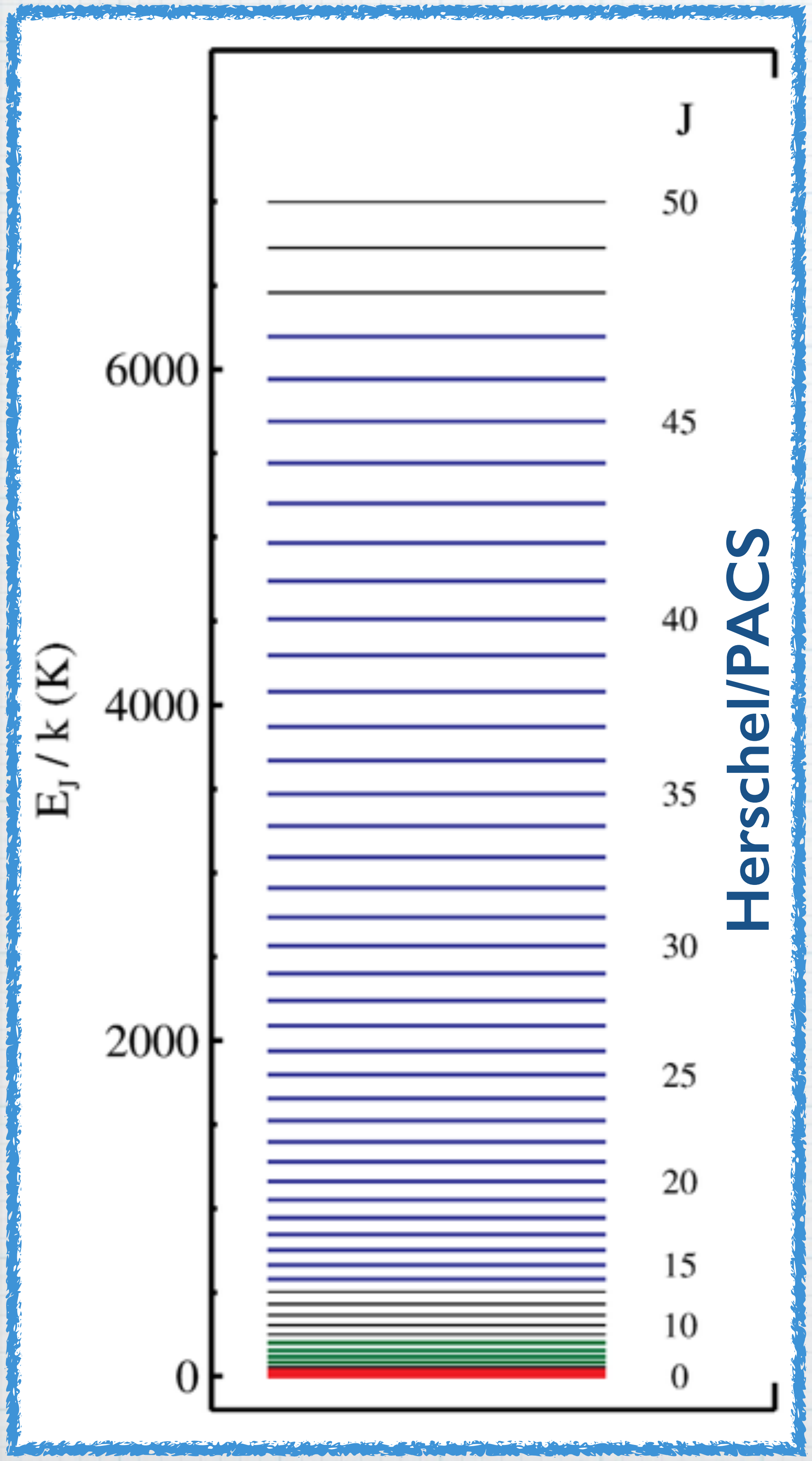
FIR (PACS) spectra of protostars



- Primary coolants of the warm & hot gas
  - [OI], [CII]
  - CO, H_2O, OH
- Provide powerful diagnostics of the emitting gas
  - density, temperature, elemental abundances etc.

FIR CO emission from protostars

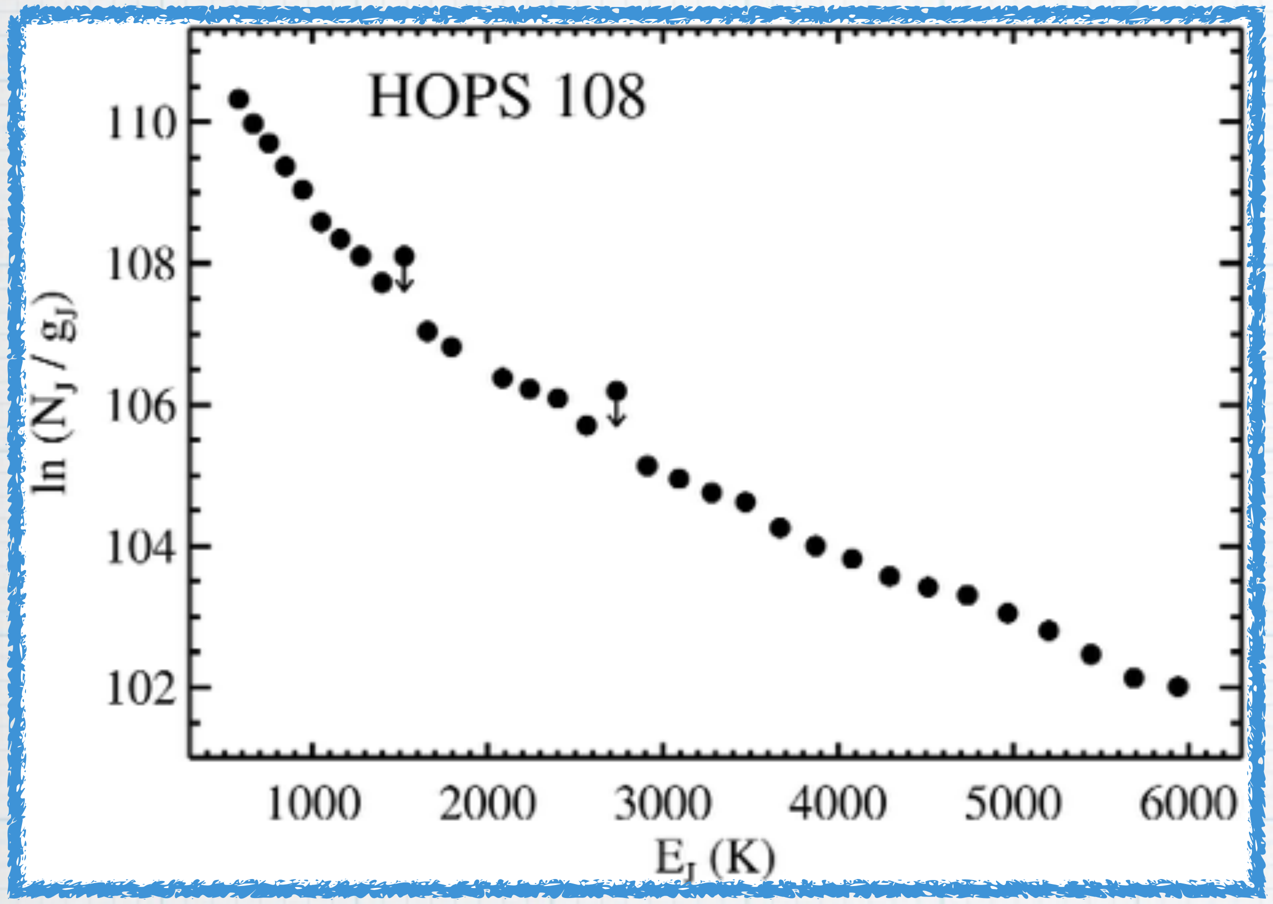


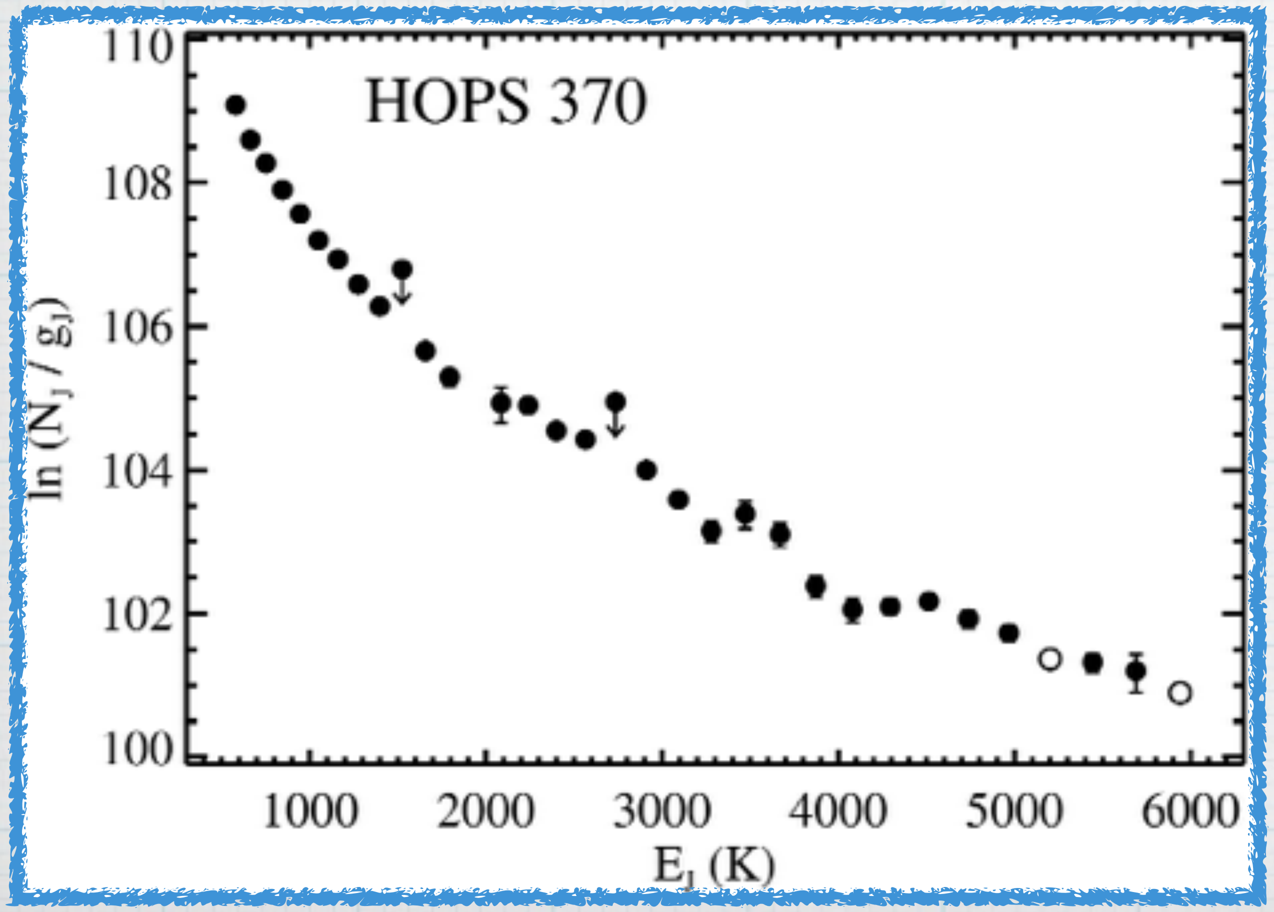
more than 30 rotational transitions of the ground vibrational state of CO in the PACS wavelength range

What are the excitation conditions in the FIR CO emitting gas ?

Where does the FIR CO emission originate in the vicinity of protostars ?

CO rotational diagrams





Boltzmann eqn:

$$N_J \propto g_J \, e^{-\left(E_J/k\,T_{rot}\right)}$$

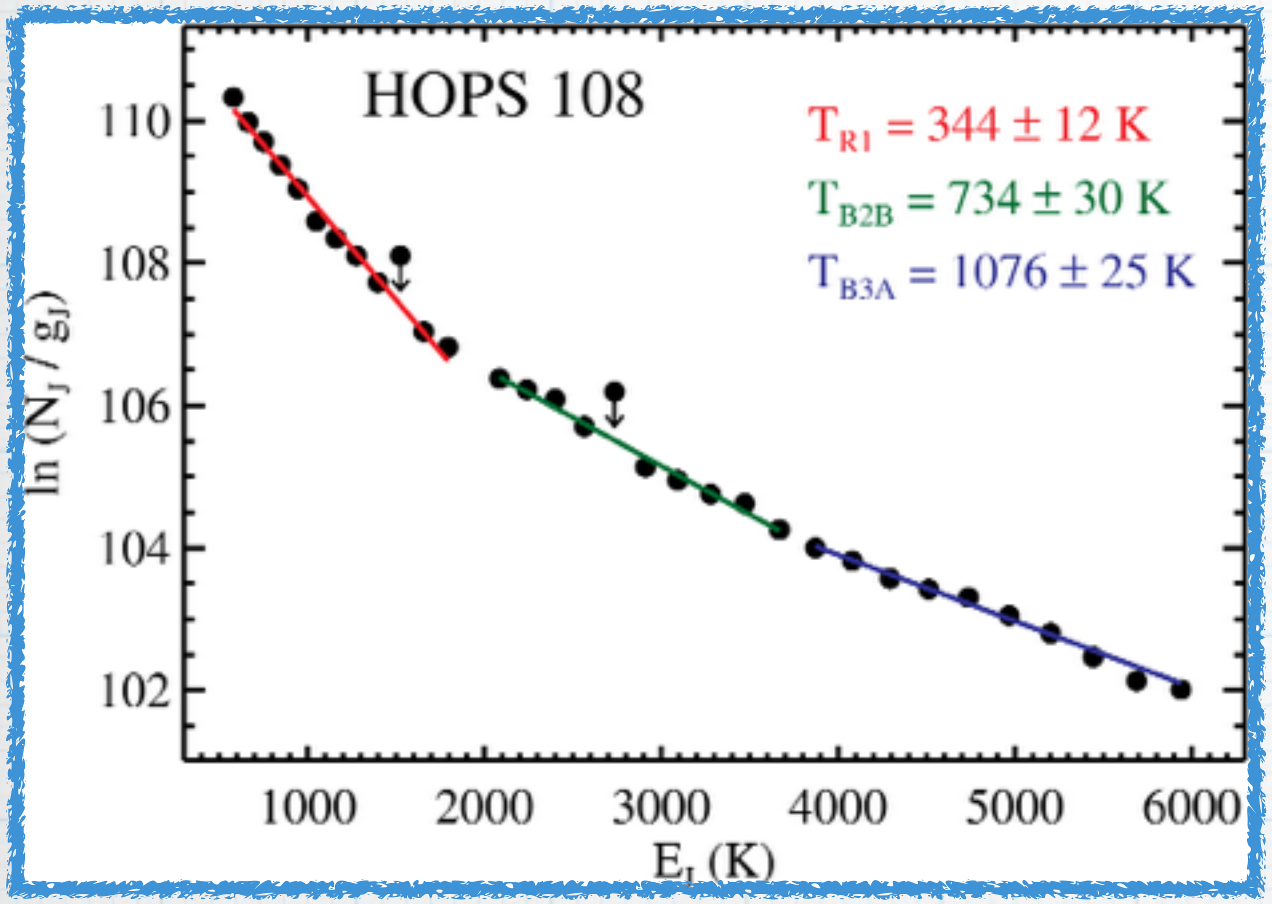
Optically thin line emission:

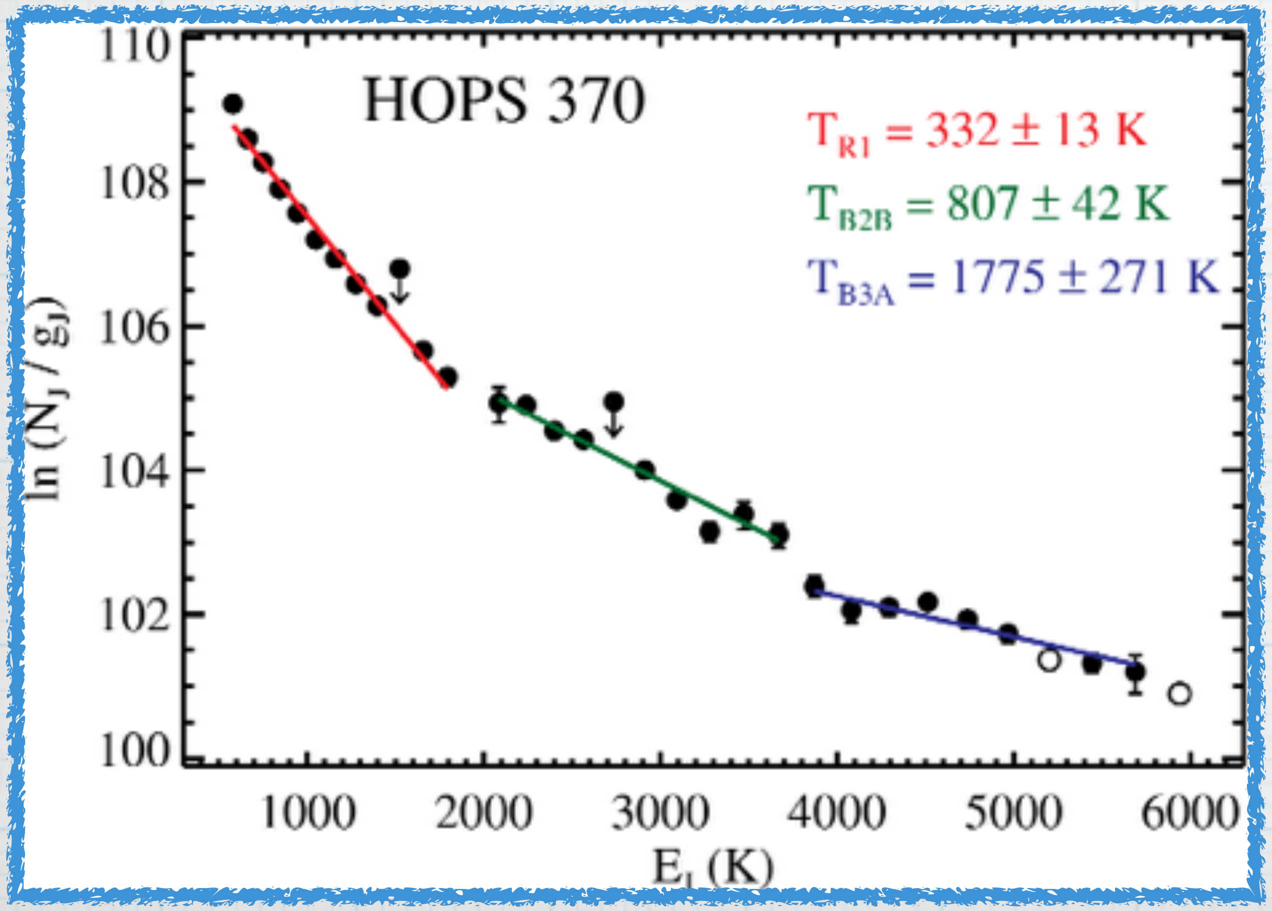
$$N_J = \frac{4\,\pi\,d^2\,F_J}{h\,\nu_{J,J\text{-}1}\,A_{J,J\text{-}1}}$$

Rotational temperature:

$$T_{rot} = -\left(\frac{k\,\mathrm{d}\ln\left[N_J/g_J\right]}{\mathrm{d}E_J}\right)^{-1}$$

CO rotational diagrams





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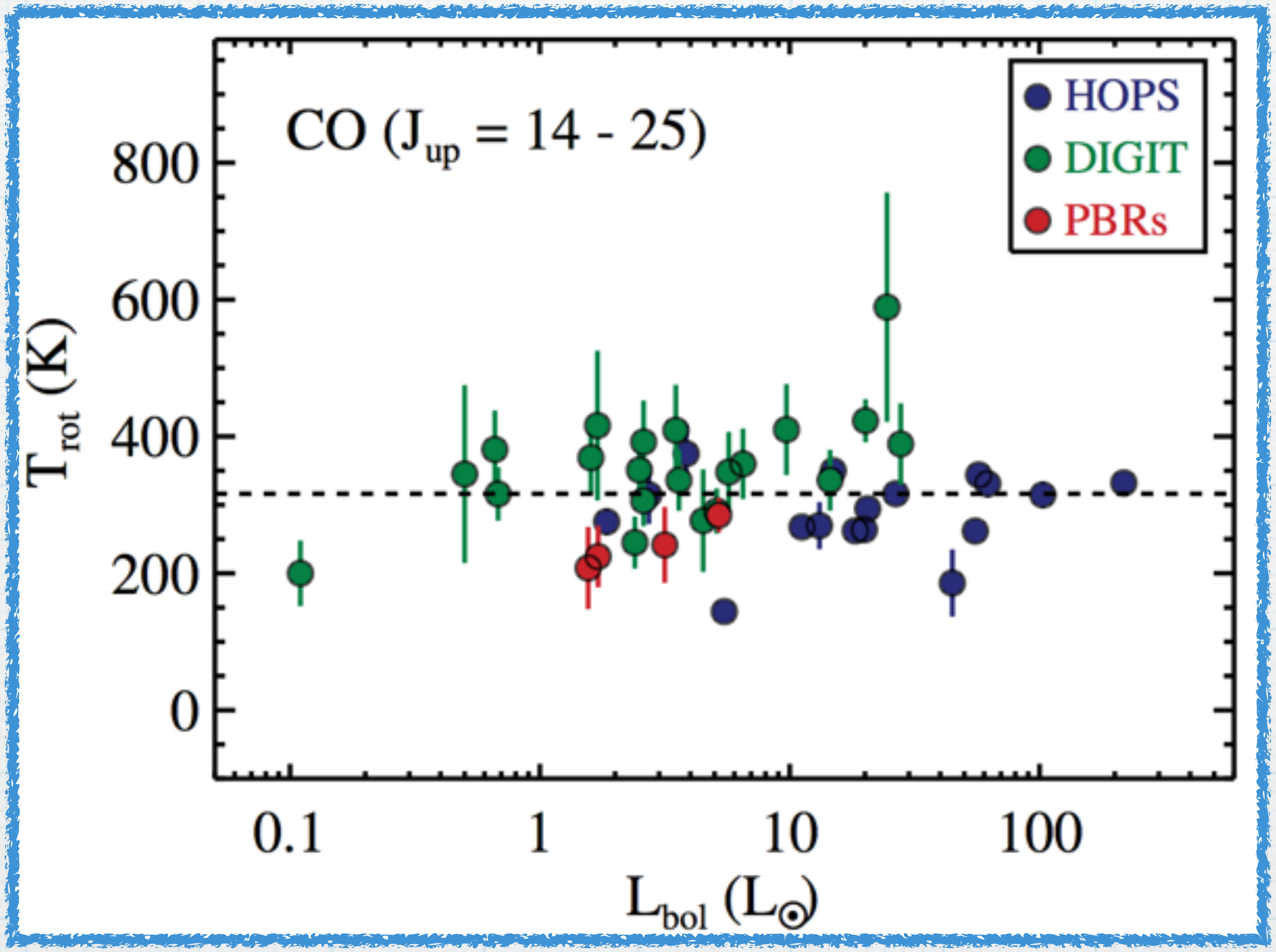
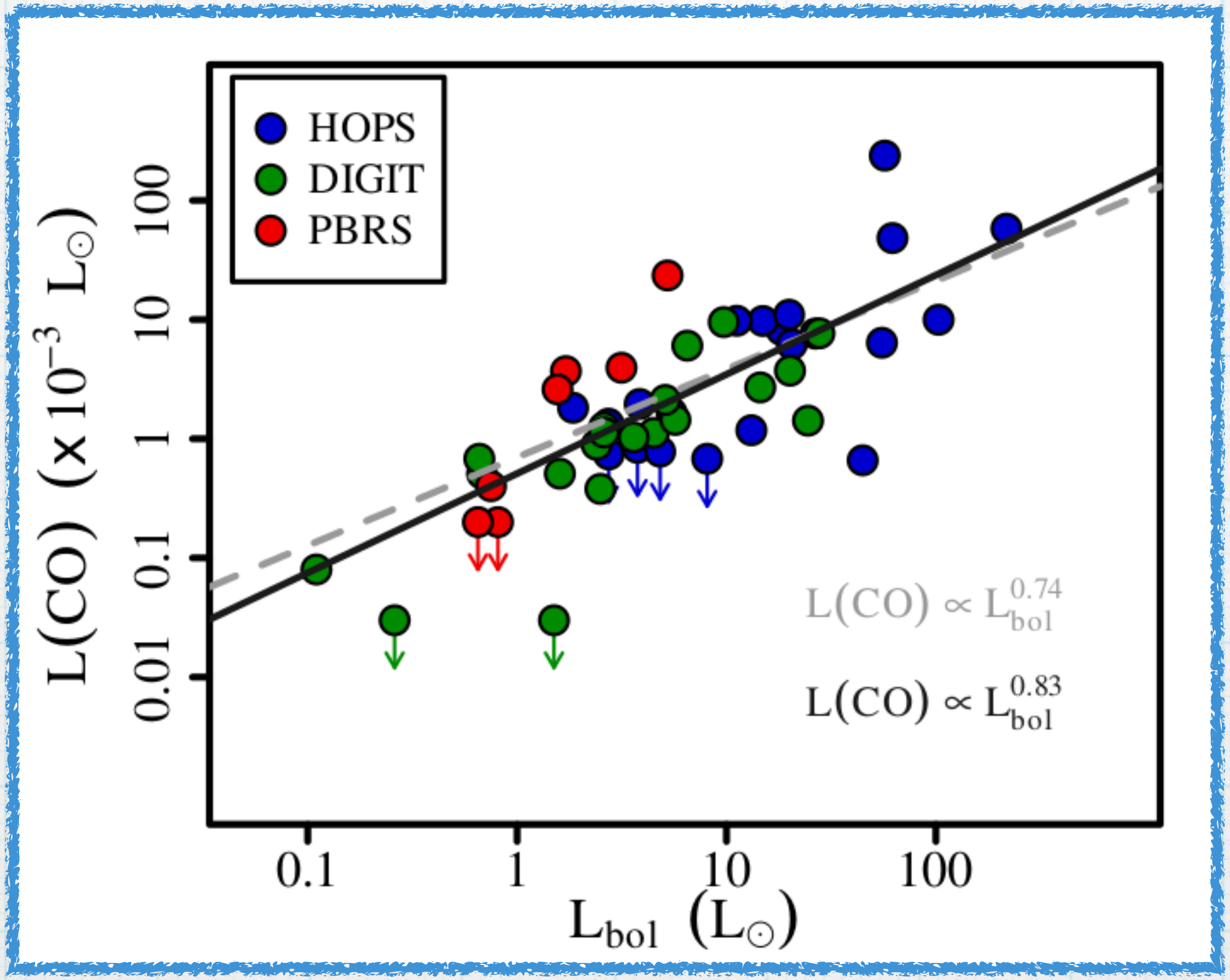
CO rotational (excitation) temperature remains constant over 3 orders of magnitude in protostellar luminosity



➥ line ratios constant

Manoj et al. (2013); Green et al. (2013); Manoj et al. in prep.

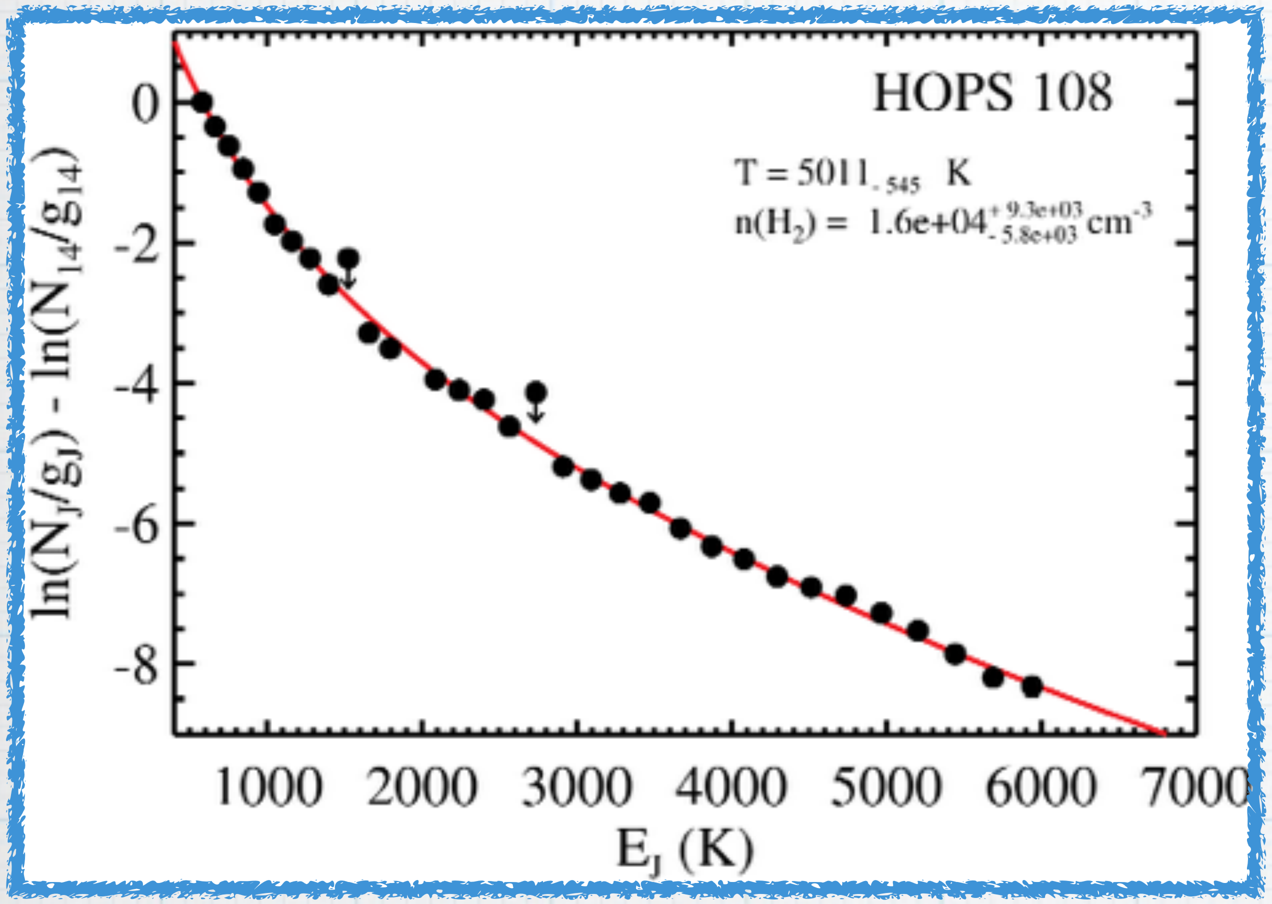
CO luminosity scales with protostellar luminosity

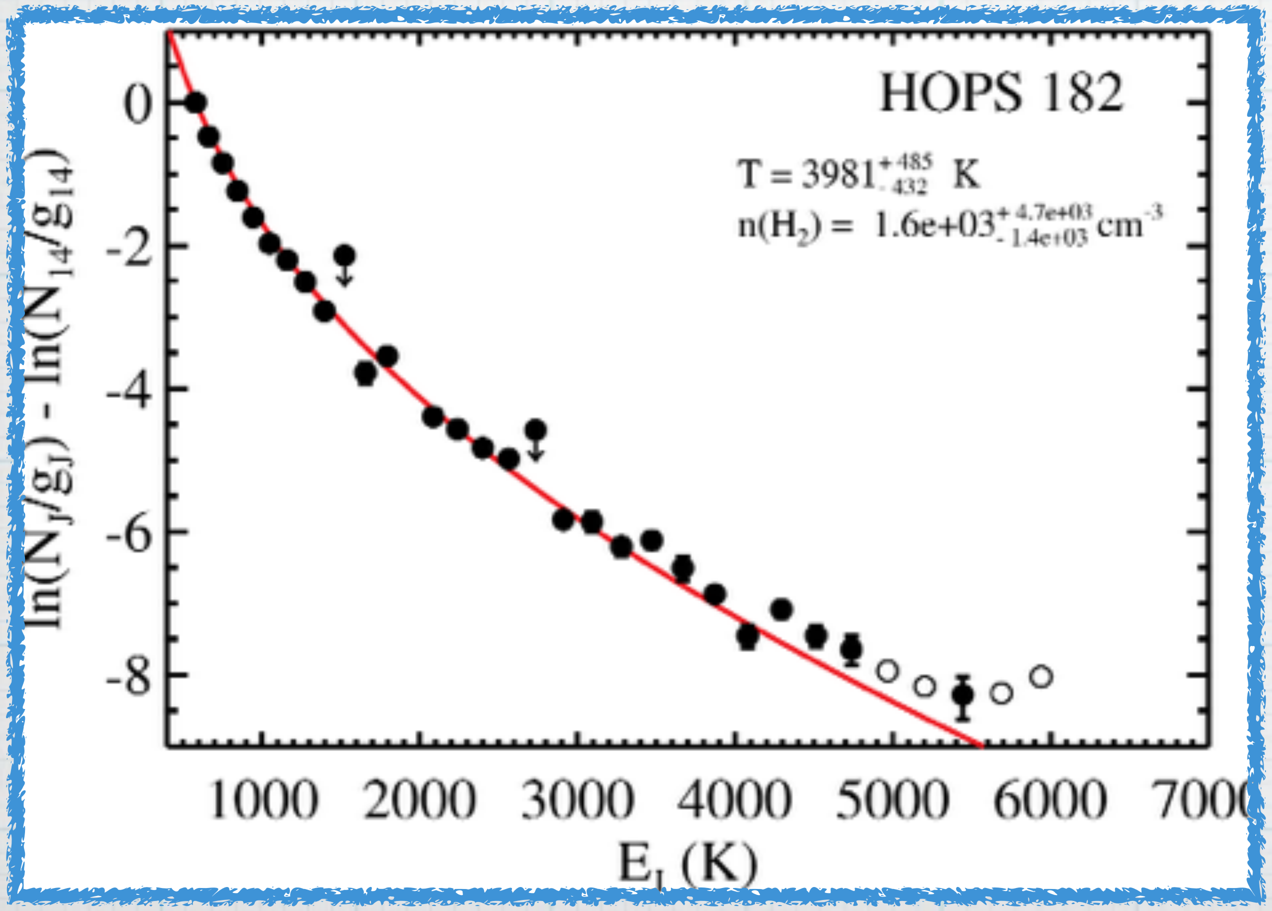


➥ line flux scales with L_{bol}

Manoj et al. (2013); Green et al. (2013); Manoj et al. in prep.

FIR CO emission: excitation conditions





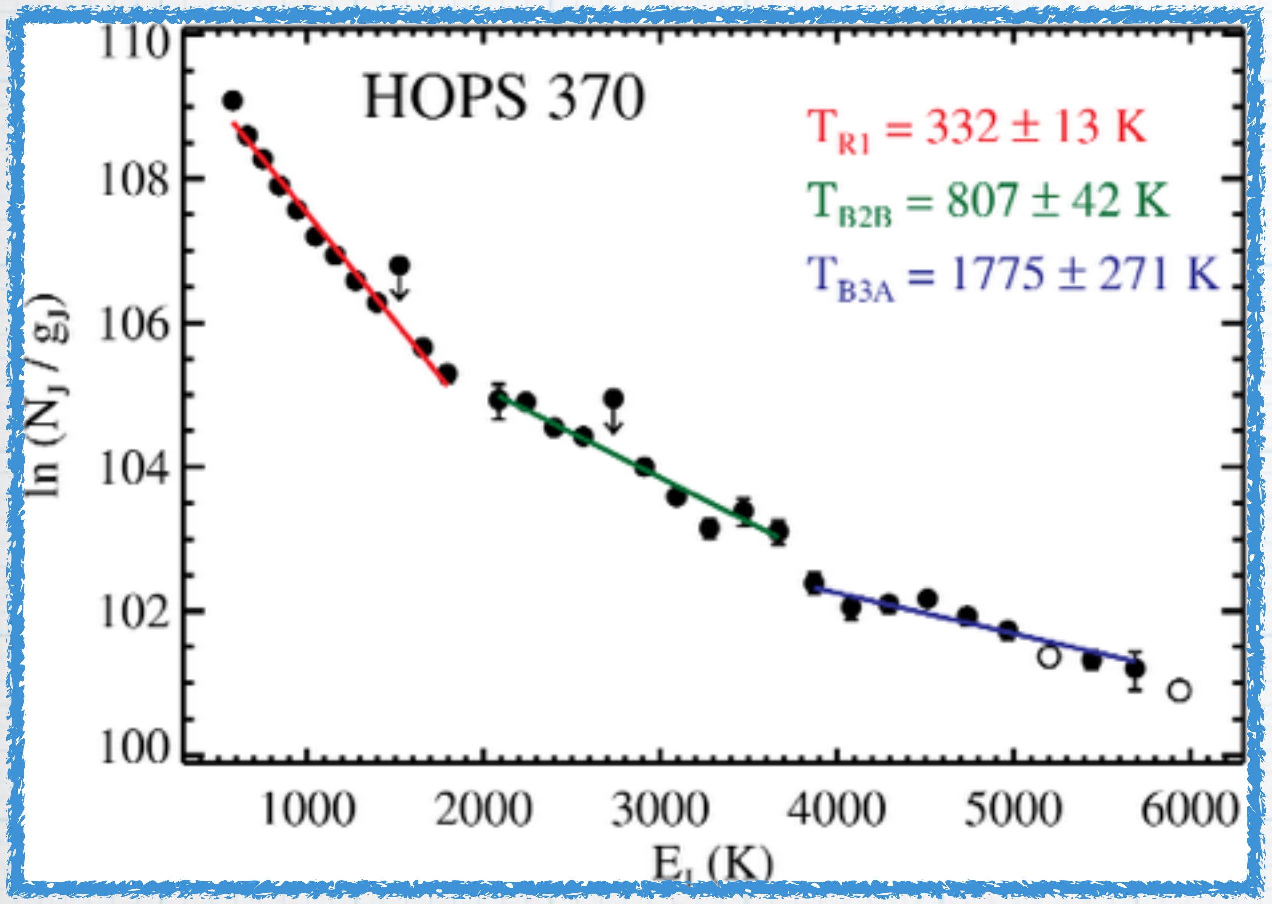
- CO emission from a medium of uniform temperature & density
  - grid of 50,000 (non-LTE) models
  - $n(H_2) \Rightarrow 100 - 10^{12}$ cm^{-3}
  - $T \Rightarrow 10 - 5000$ K

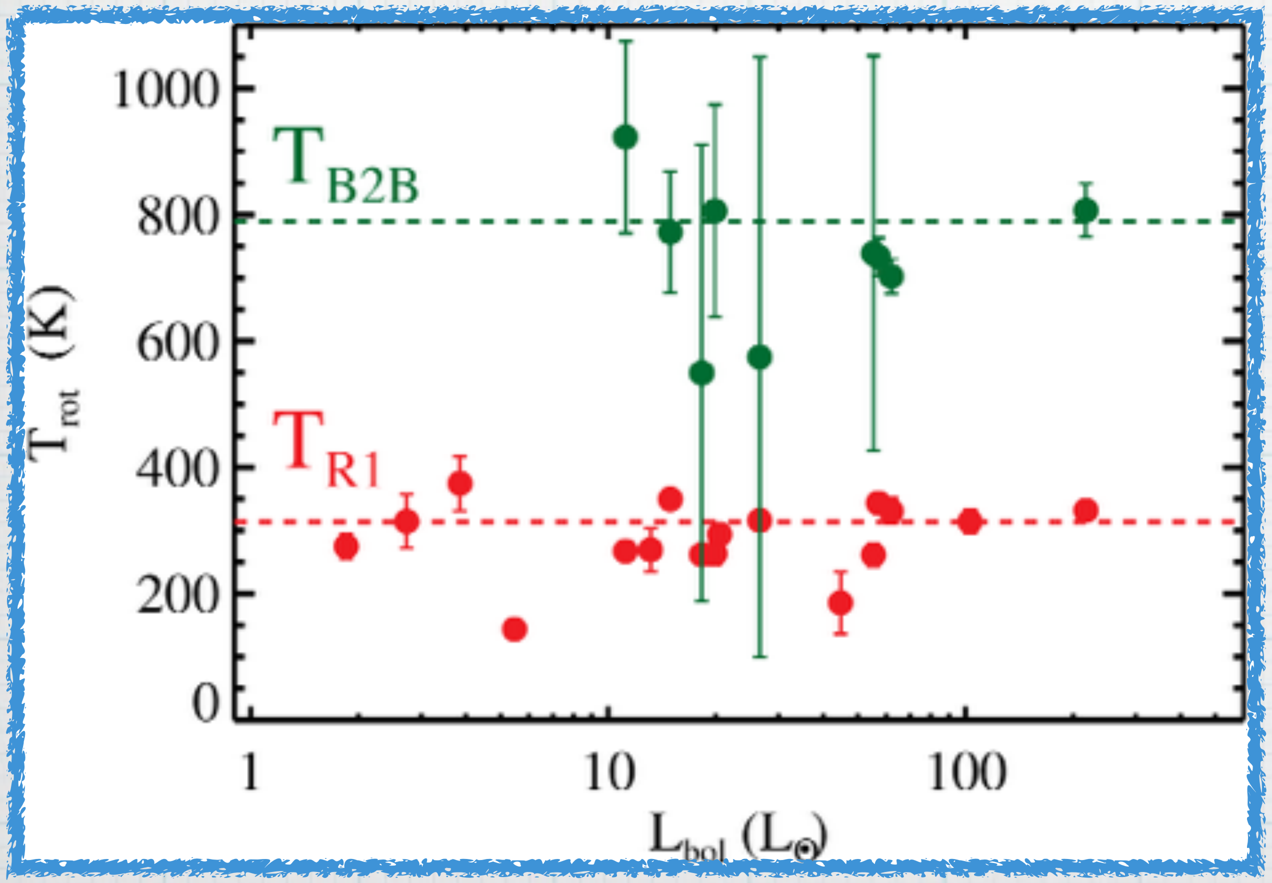
- Physical parameters for the CO emitting gas
  - $n(H_2) \leq 10^5$ cm^{-3}
  - $T > 2000$ K

FIR CO emission from sub-thermally excited hot gas

Neufeld (2012); Manoj et al. (2013)

Issues with thermal excitation of CO

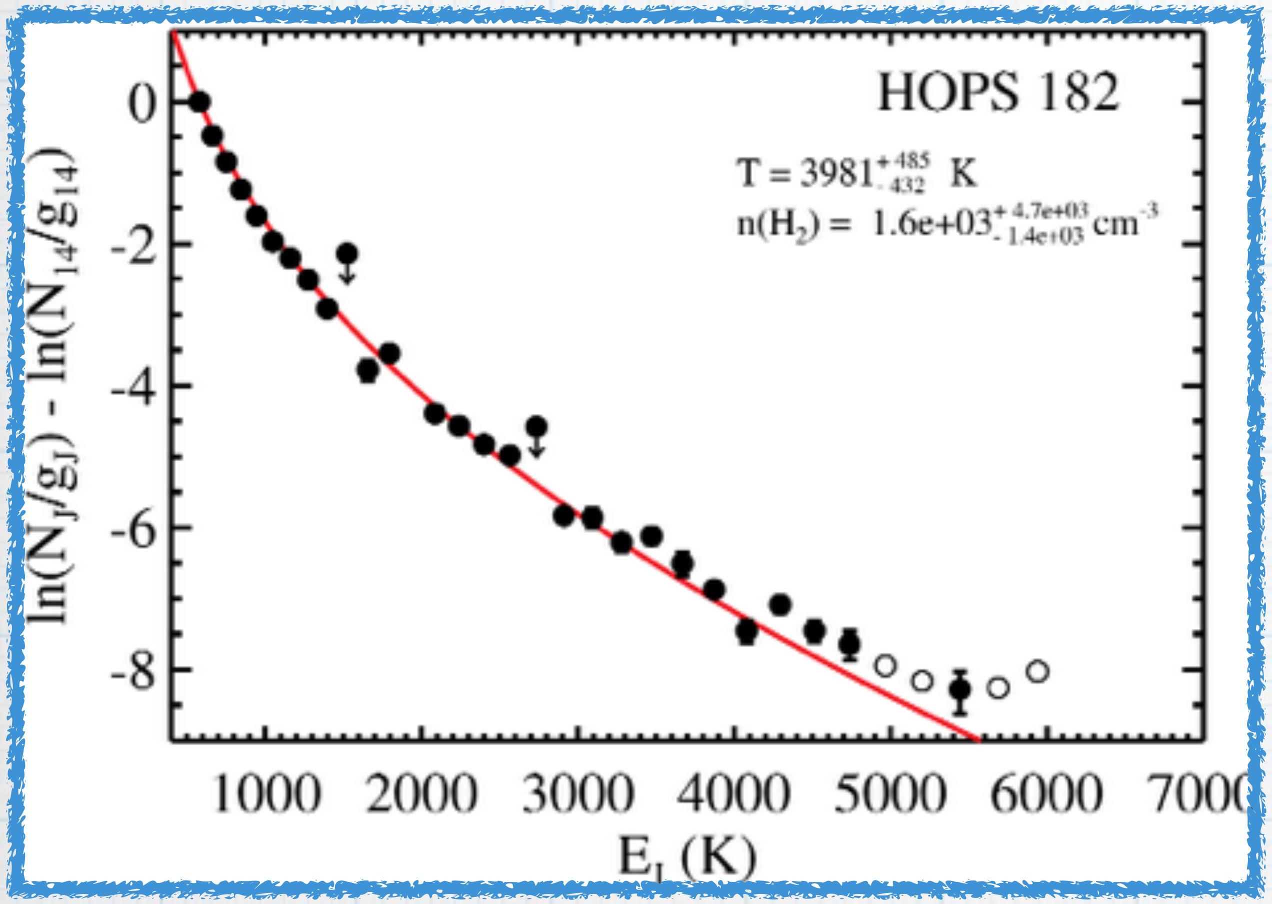


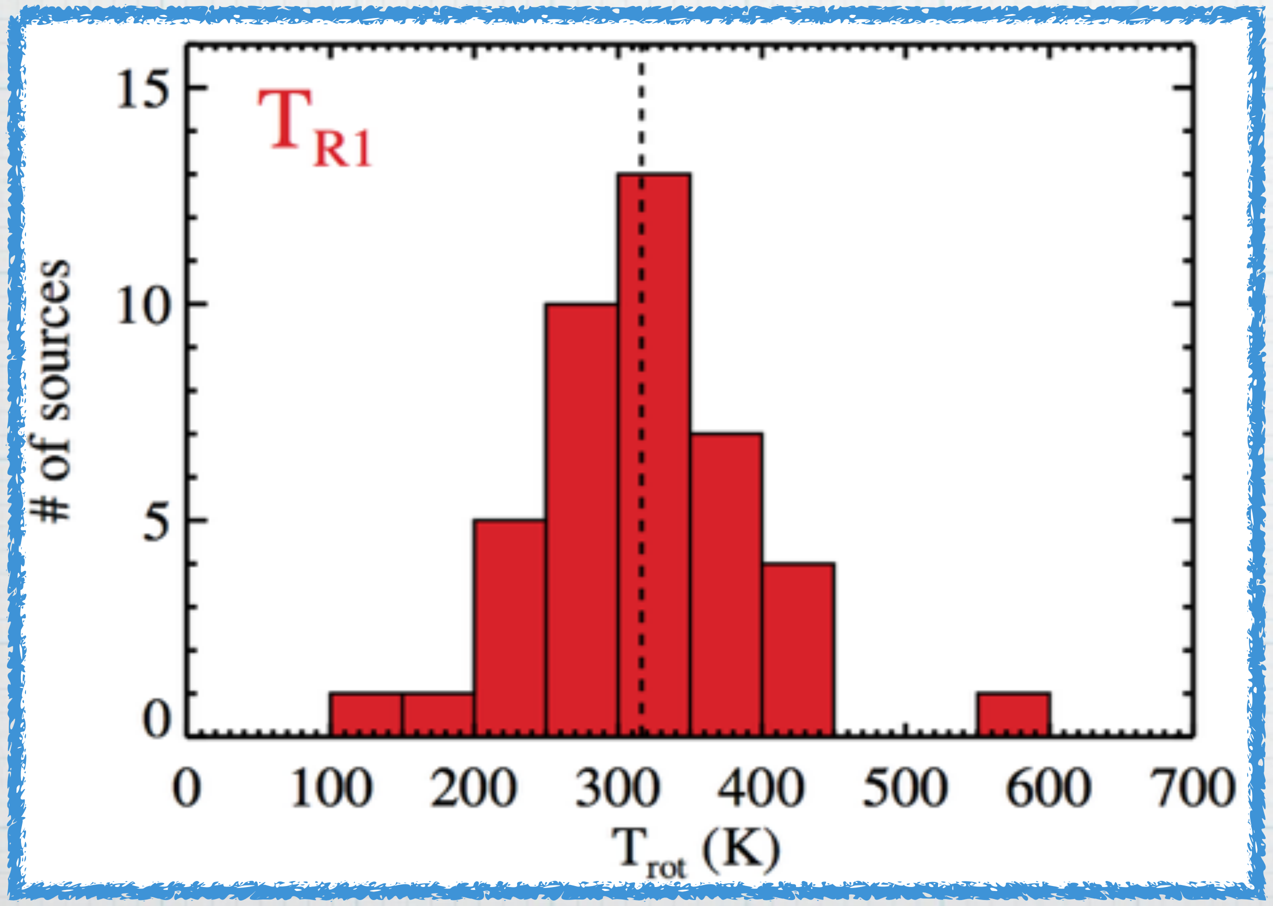


- $T_{rot} = T_{gas}$
- requires at least 3 or more temperature components
- these multiple temperature components must remain the same for the protostars over a large range in luminosity

Manoj et al. (2013)

Sub-thermal excitation of CO



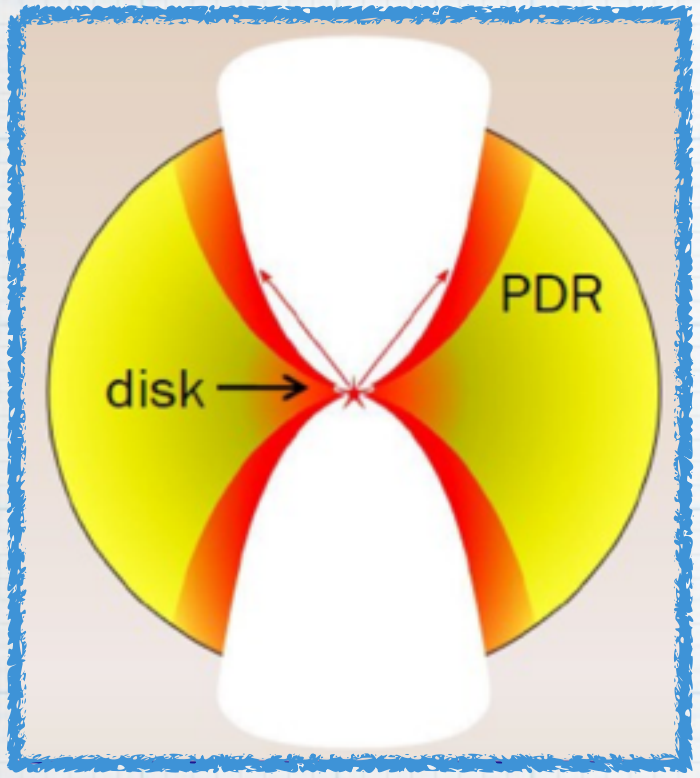


- $T_{rot} \ll T_{gas}$
- for n(H$_2$) ≤ 10^5 cm^{-3}, T_{rot} is only weakly sensitive to the temperature of the emitting gas.
- e.g. T_{gas} = 800 - 5000 K

➥ T_{R1} = 230 - 380 K

Manoj et al. (2013)

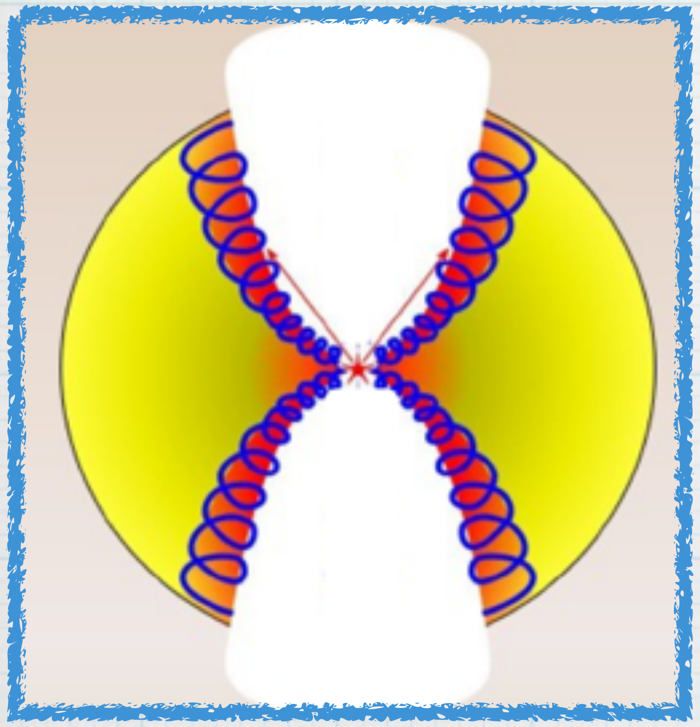
The origin of FIR CO emission in protostars



UV-heated PDRs along envelope cavity walls

(e.g. van Kempen+ 2010; Visser+ 2012; Karska+ 2013)

- LTE $\Longrightarrow$ $n(H_2) >> 10^6\ cm^{-3}$
- $T_{gas} < 2000$ K
- $T_{gas} = T_{rot}$ constant over $L_{bol} = 0.1 - 300\ L_\odot$
- $T_{gas} \propto L_{UV}/n(H_2) \sim L_{bol}/n(H_2)$



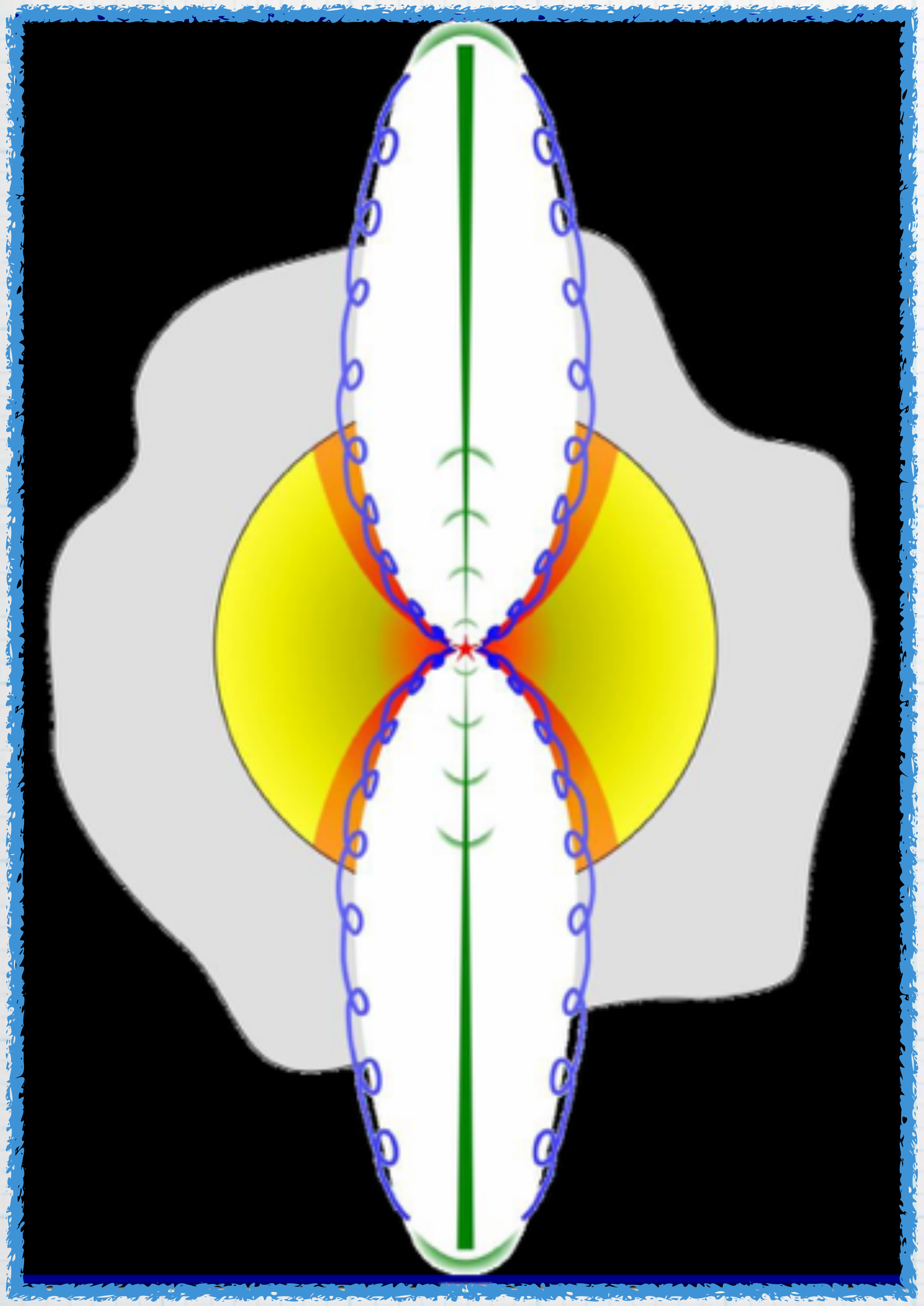
small-scale shocks along cavity walls

(e.g. van Kempen+ 2010; Visser+ 2012; Karska+ 2013)

- LTE $\Longrightarrow$ $n(H_2) >> 10^6\ cm^{-3}$
- $T_{gas} = T_{rot}$ constant over $L_{bol} = 0.1 - 300\ L_\odot$
- FIR CO emission from outflow lobes indistinguishable from on-source emission

Manoj et al. (2013)

FIR CO emission in protostars from shock-heated gas at high temperatures and low densities, located within the cavity along the molecular outflow or along the cavity walls at radii > 1000 AU

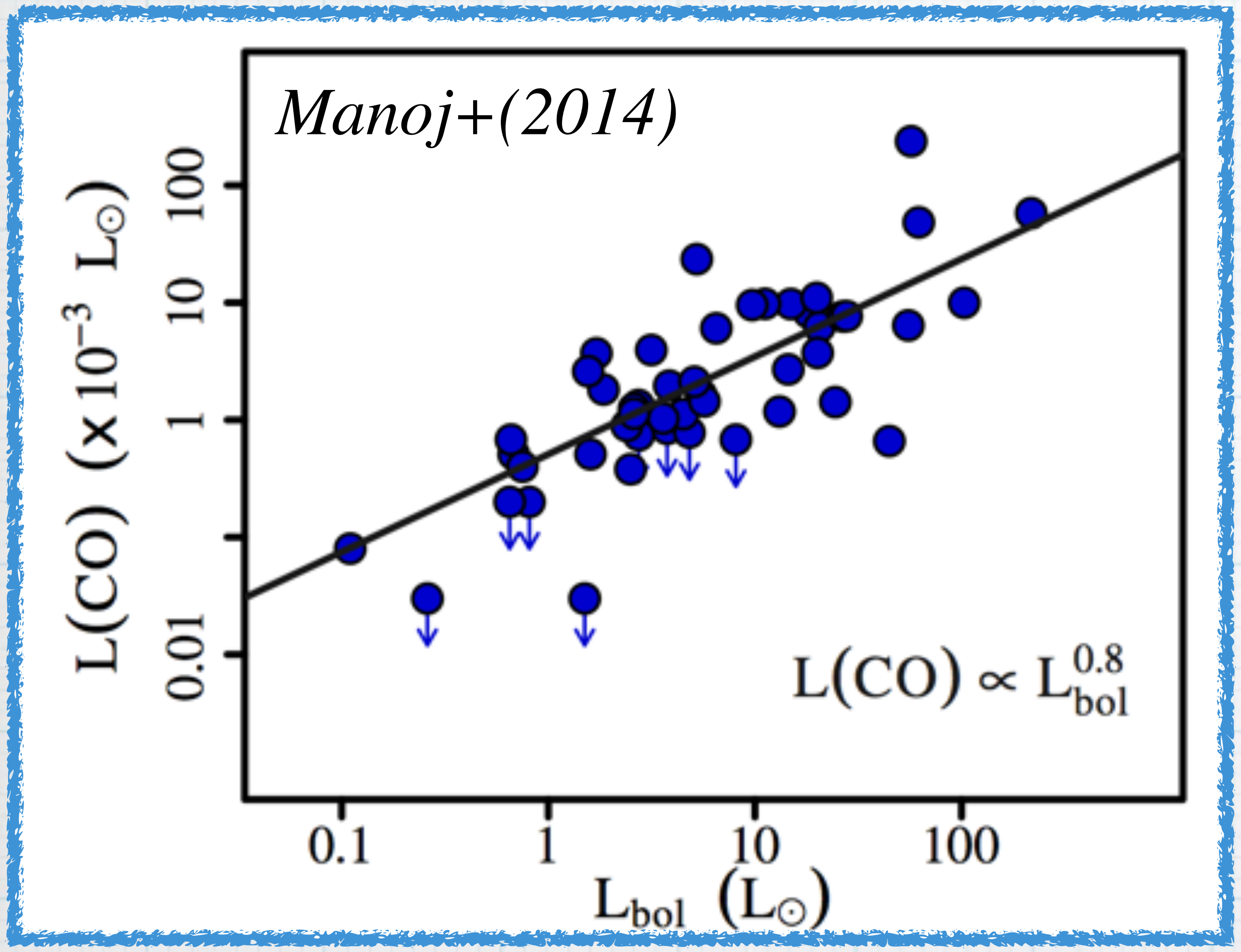


- sub-thermal excitation ($n(H_2) < 10^5$ cm^{-3}) of hot ($T < 2000$ K) gas
- T_{rot} constant over large range in L_{bol}

CO emission in protostars as a probe for outflow properties !

(Manoj et al. 2013, Manoj et al. in prep)

L(CO) as a proxy for outflow rate

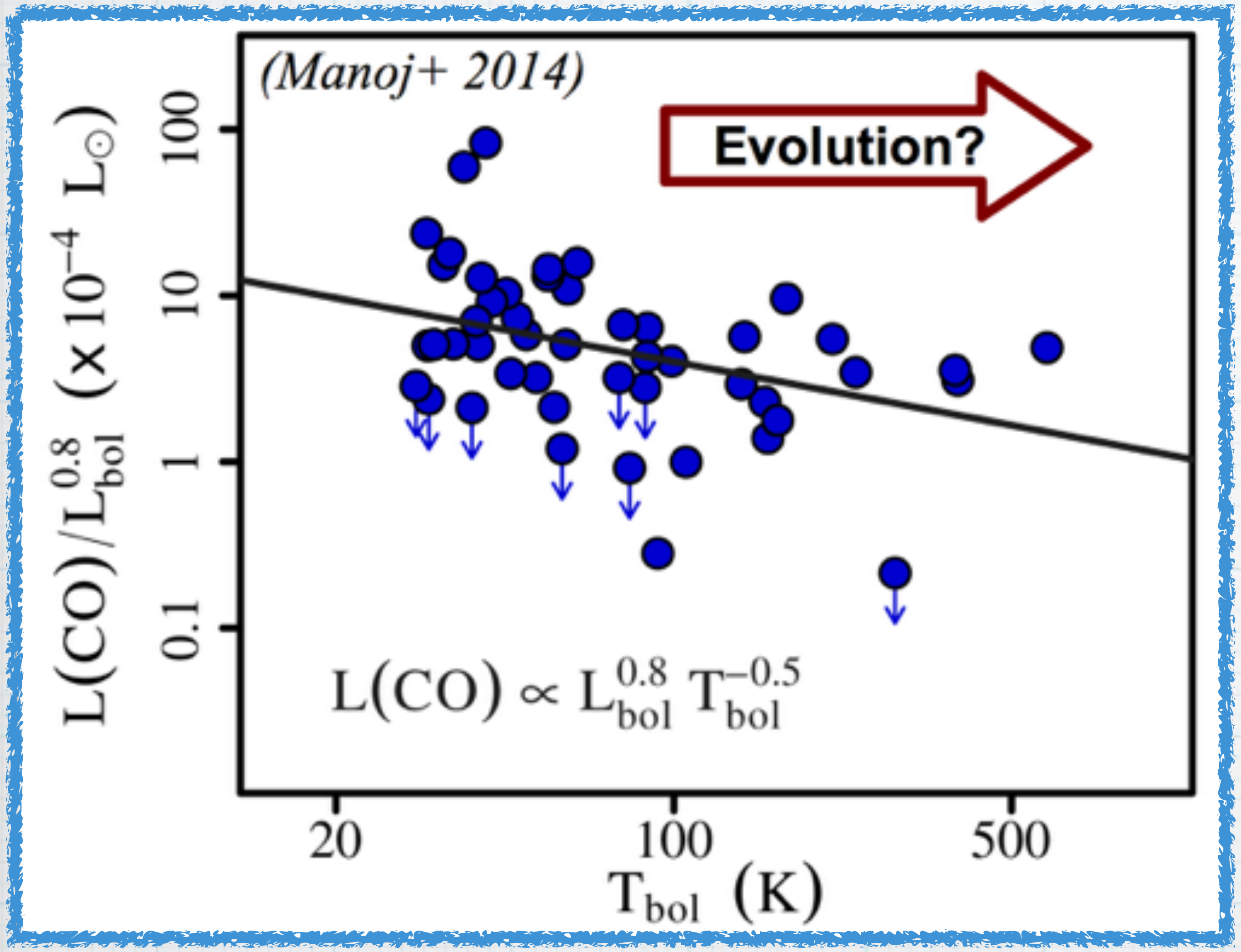


$$L(CO) \;\propto\; \frac{1}{2}\dot{M}_{out}\,v^2 \;\propto\; \dot{M}_{out}$$

and $L_{bol} \;\propto\; \dot{M}_{acc}$, early on

$\dot{M}_{out} \;\propto\; \dot{M}_{acc}$ over 3 orders of magnitude

CO luminosity: evolution



- L(CO) decreases as T_{bol} increases
- again, large scatter

on average, $\dot{M}_{out}$ drops with system age

Summary

1) Median L_{bol} ($\dot{M}_{acc}$?) and $L(CO)$ ($\dot{M}_{out}$?) decreases as T_{bol} increases, with substantial scatter.

2) L_{bol} ($\dot{M}_{acc}$?) and $L(CO)$ ($\dot{M}_{out}$?) appear to be tightly correlated.

3) Mass flow rates in protostars are not steady, monotonic functions of system age (evolution). Protostellar evolution appears to be much more dynamic.