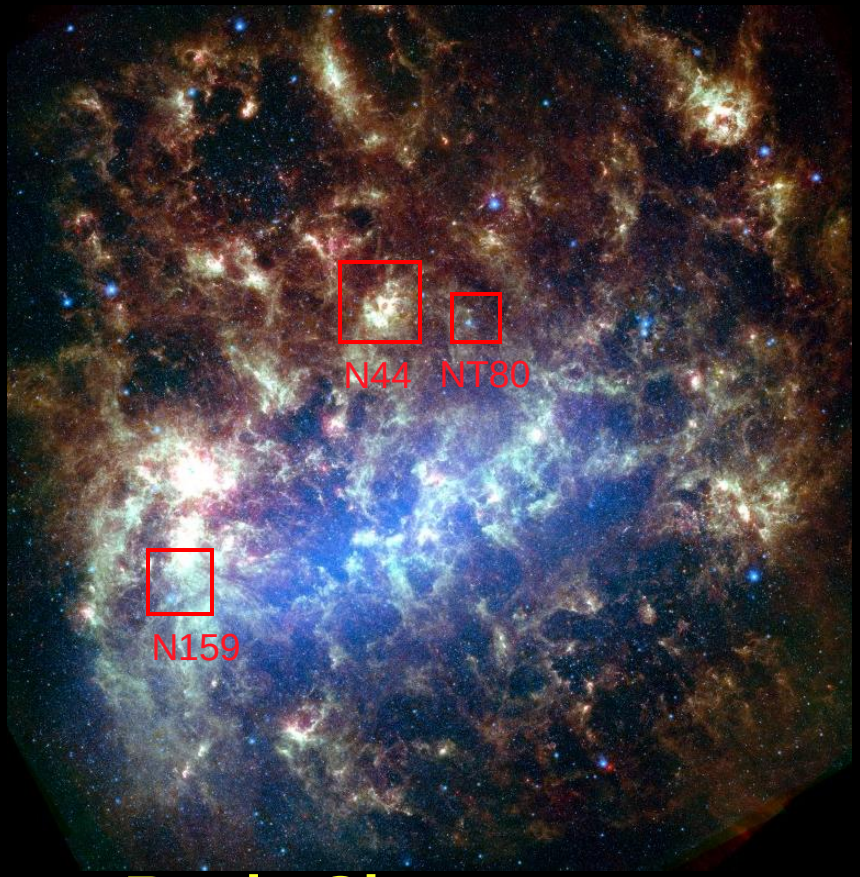
Massive Star Formation in the LMC Resolved at Clump Scales



Rosie Chen (MPIfR)

R. Indebetouw, A. Hughes, C. Henkel, R. Güsten, K. Menten, Z. Zhang, G. Li, J. Urquhart, M. Requena Torres, L. Looney

Motivation

- **What is the realistic SFE of GMCs?**

  -- GMCs are far from homogenous; SF actively occurs in clumps

  ⇒ *evolution of clumps/GMCs* determines the total SFE of GMC

- **Are massive stars formed in special conditions?**

  -- not all massive GMCs form massive stars.

  e.g., kpc-long molecular ridge in the LMC (Indebetouw+ 2008; Chen+2010)

  ⇒ are such GMCs young or unable to form massive stars?

- **How does stellar energy feedback affect MSF?**

  -- negative effect: GMCs can be dispersed ~ 10 Myr (Kawamura et al. 2009)

  -- positive effect: triggered MSF

Need resolved data of stellar & gas content in GMCs

Probing gas on clump scales

- APEX 9”-28”-resolution: 2-7pc @ LMC, a nearby 1/3 $Z_\odot$ dwarf

^{12}CO+^{13}CO J=2-1,3-2, ^{12}CO(4-3) & C I (1-0) mapping of 4 GMCs, ^{12}CO(6-5) & C I (2-1) of N44C

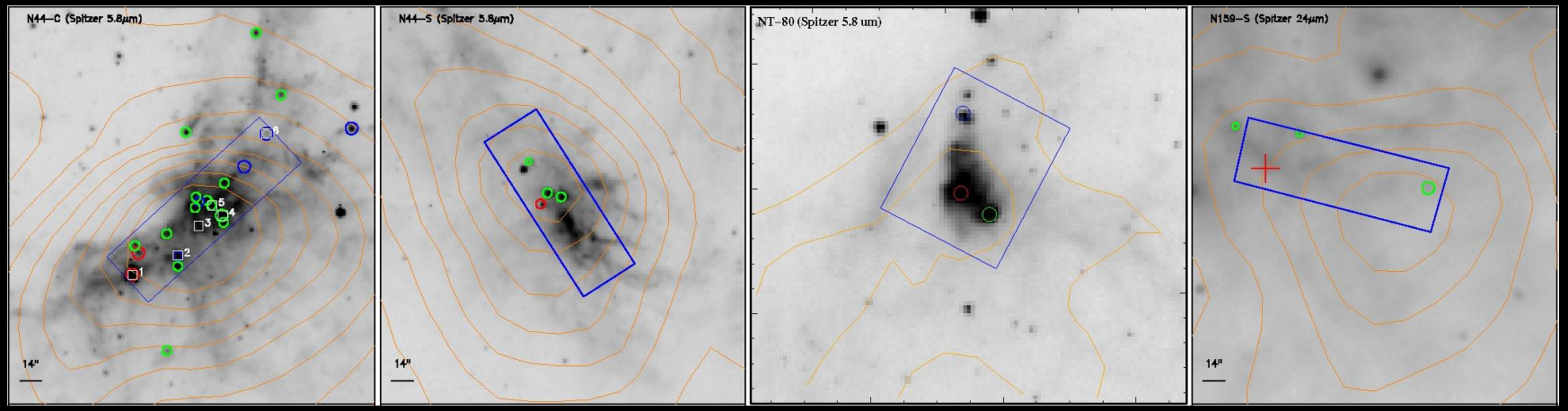
-- tracing n~ 10^2-10^5 cm^{-3} , better T constraint

(v.s. fewer lines in Seale+ 2012, Indebetouw+ 2014)

-- covering MYSO mass 5-50 M⊙ & age 0.1-3 Myr (Chen+ 2009, 2010, 2011); wide range of feedback

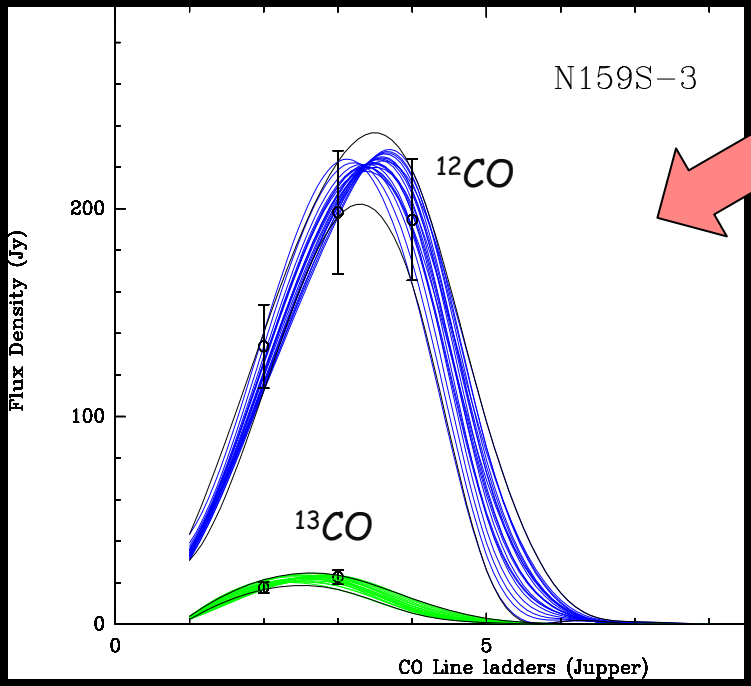
⇒ Examine feedback effect on clump evolution ; Search for requirement for MSF

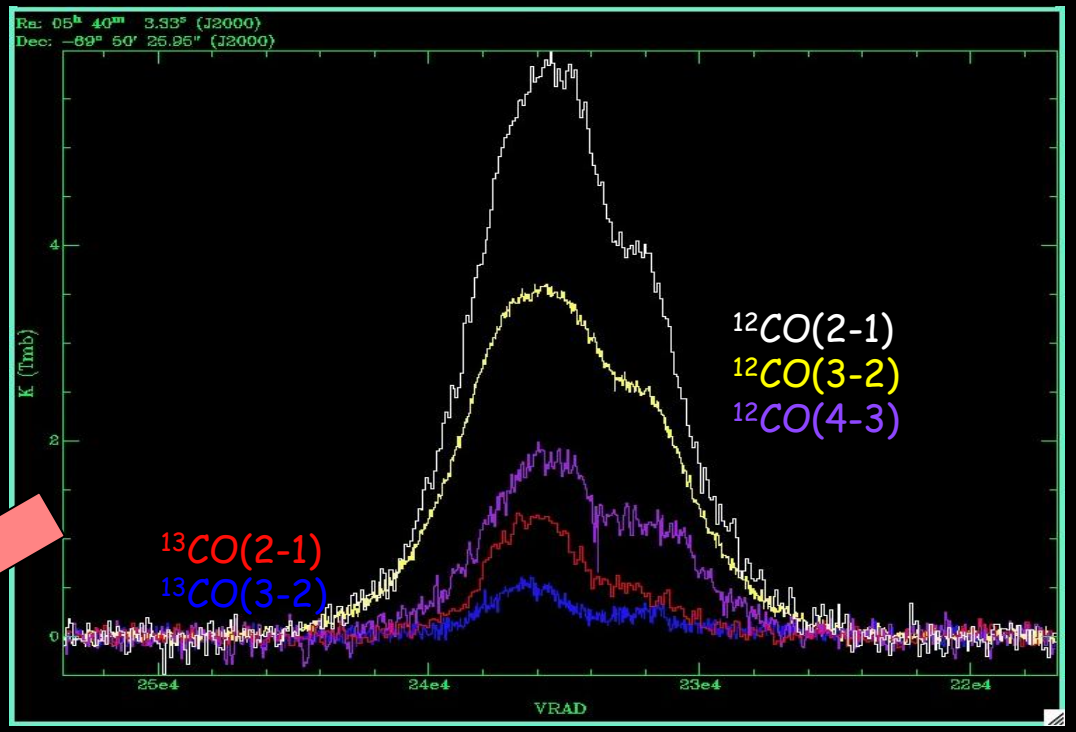
N44C N44S NT80 N159S



Estimate n & T of clumps

- Large velocity gradient (LVG) modeling on fluxes of ^{12}CO+^{13}CO J=2-1,3-2, & ^{12}CO J=4-3 (+J=6-5 for N44C) to derive n, T, dv/dr

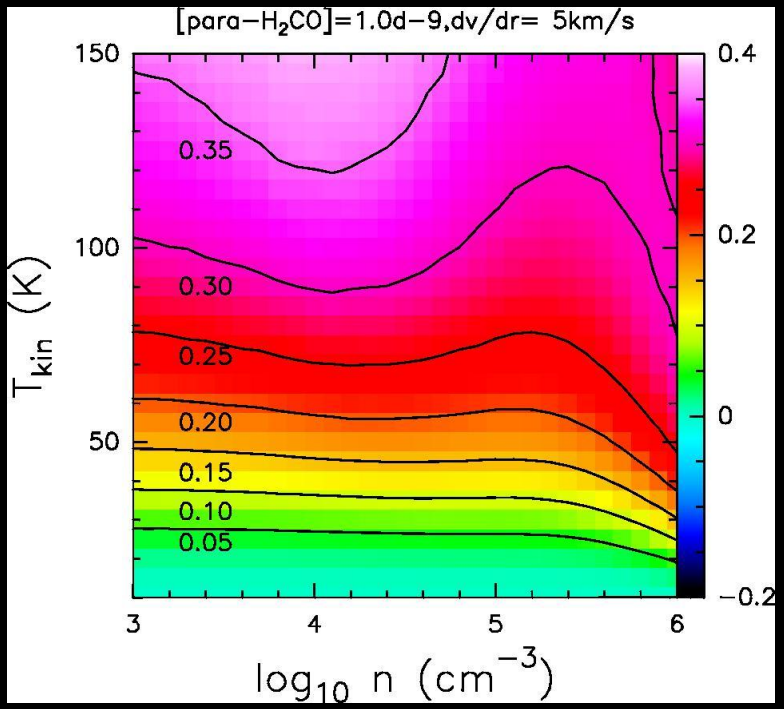




- Clump-finding: CO(4-3) channel maps
  Flux extraction: clump peaks from all maps smoothed to ^{13}CO(2-1)-res

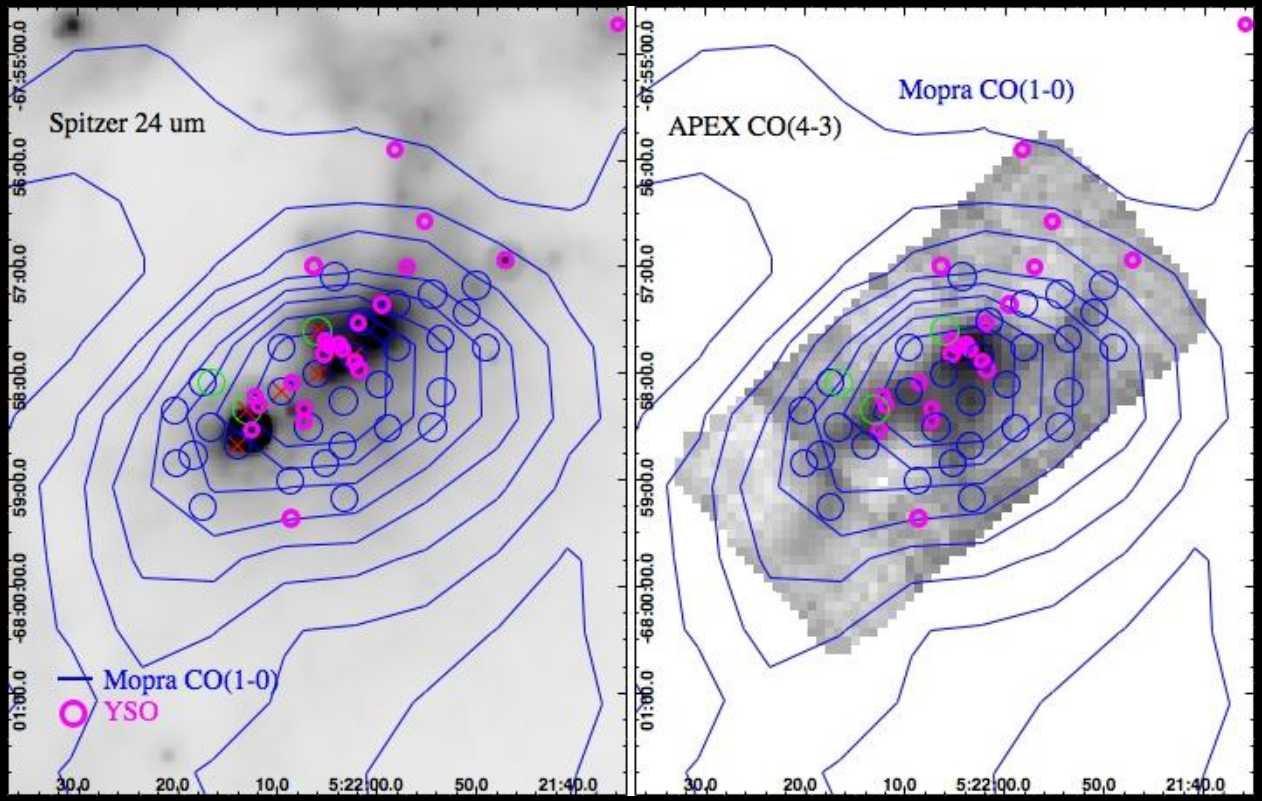
Consistency check on T

- Thermometer H_2CO: (Mangum & Wootten 1993; Mühle+ 2007)
- simultaneous obs in para-H_2CO $J_{K_AK_C}$ = 3_{02}-2_{02}, 3_{22}-2_{21}, & 3_{21}-2_{20} of selected positions in GMCs N44C, N159E, N159W, N159S, N113, 30 Dor-10.
- In N44C, T_{LVG} ~ 50-60 K.
  H_2CO 3_{22}-2_{21}/3_{02}-2_{02} =0.23±0.02
  $\Rightarrow$ 60-80 K
  $\Rightarrow$ in good agreement.

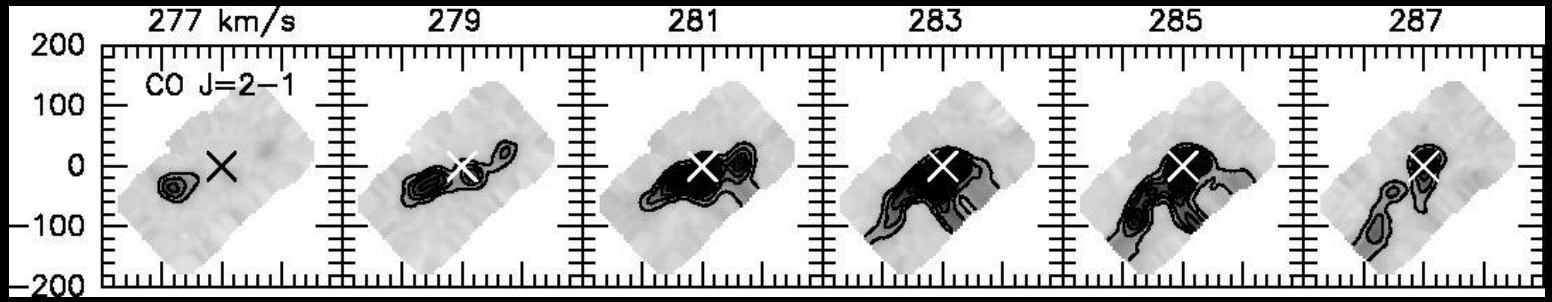


courtesy of Y. Gong

Clump properties in N44C

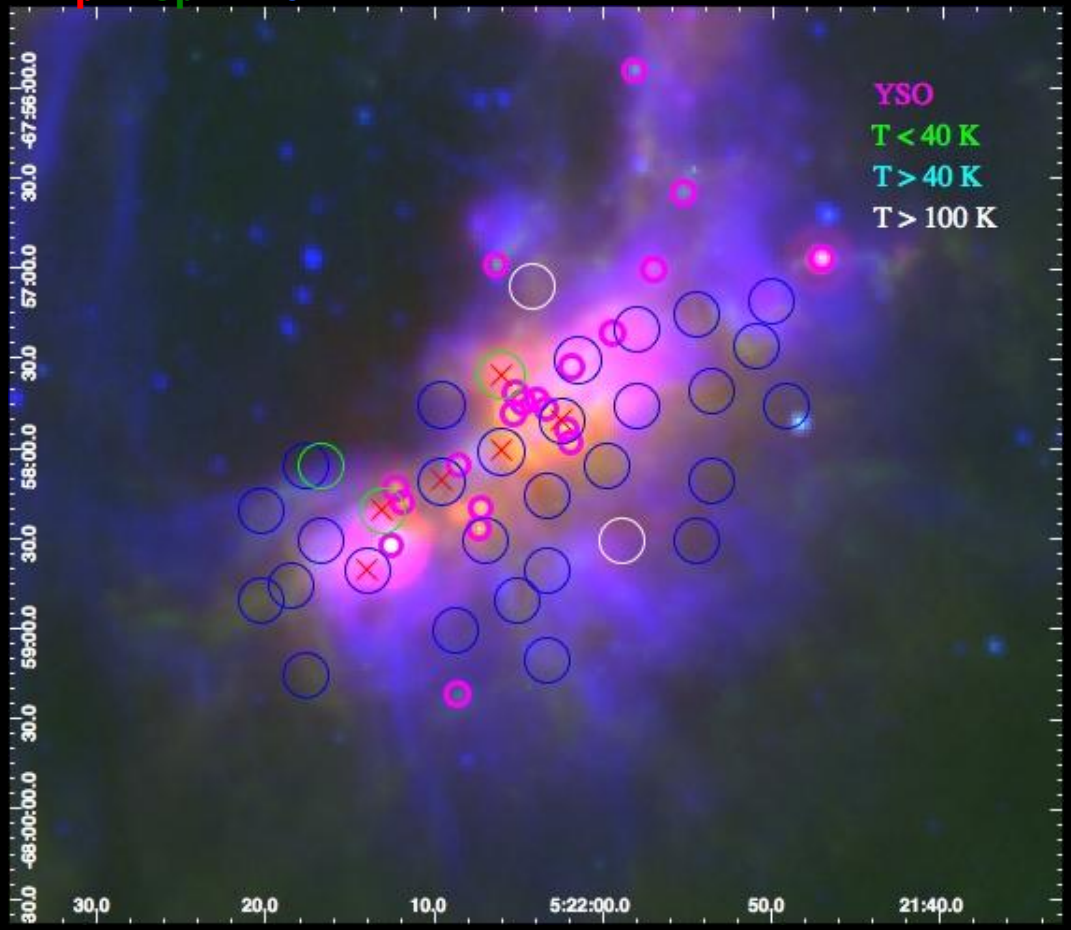


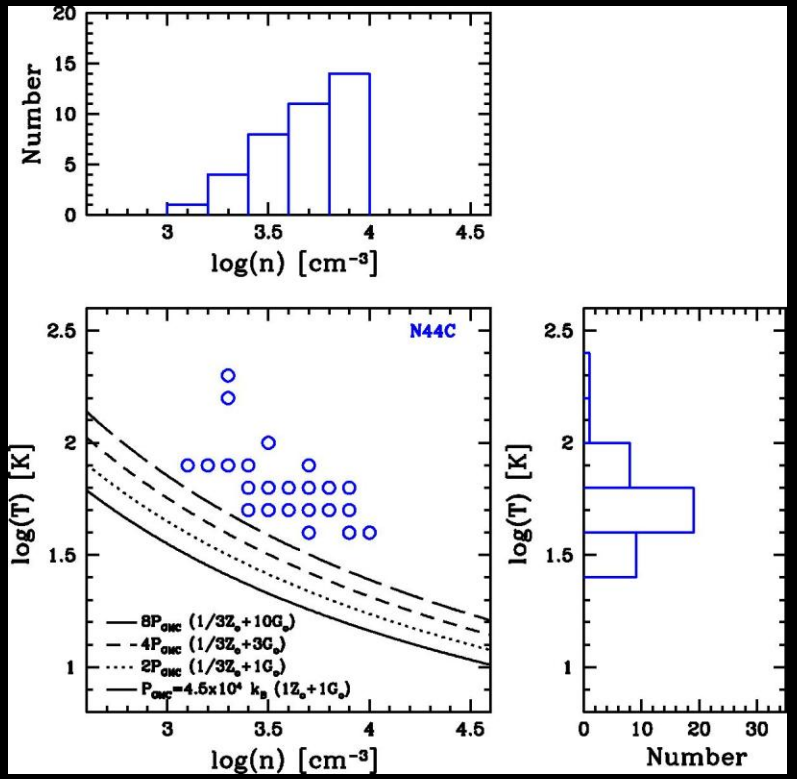
- 47 peaks found in CO(4-3) channel map
- LVG analysis on 38 peaks detected in ≥ 5 transitions in CO & ^{13}CO



Clump properties in N44C

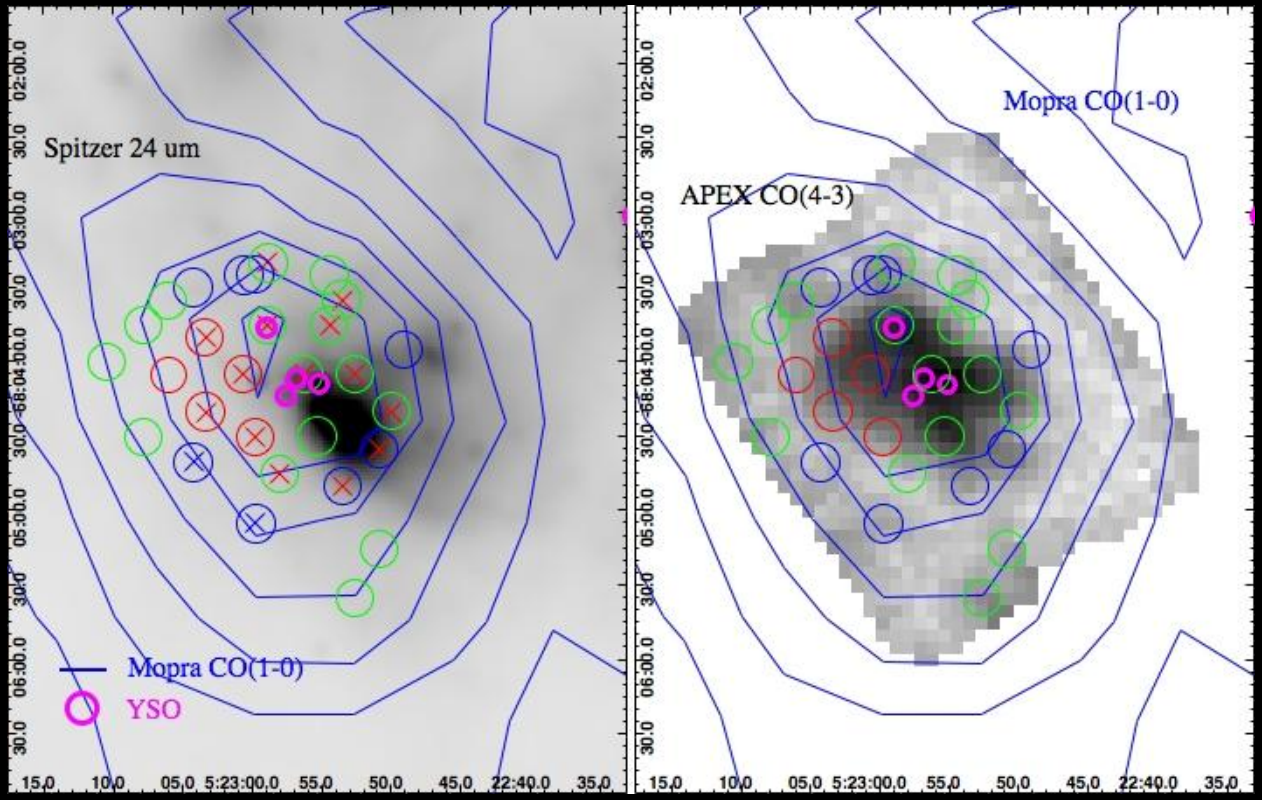
24μm 8μm Hα



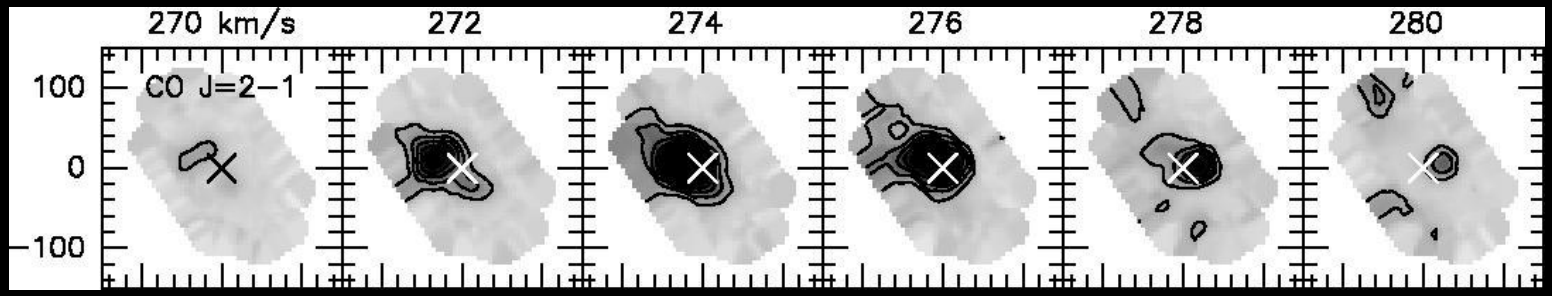


- mostly warm (40-80 K) clumps; high-T+low-n ← energy feedback
- n~10^4 cm^{-3} clumps only around MYSOs (5 O & 15 B0-3; Chen+ 2009)
- $P_{clump} > P_{Galactic\ GMC}$ or $P_{1/3\ Zo+10\ IRSF}$ (Elmegreen 1989; Wolfire+ 1995)

Clump properties in N44S

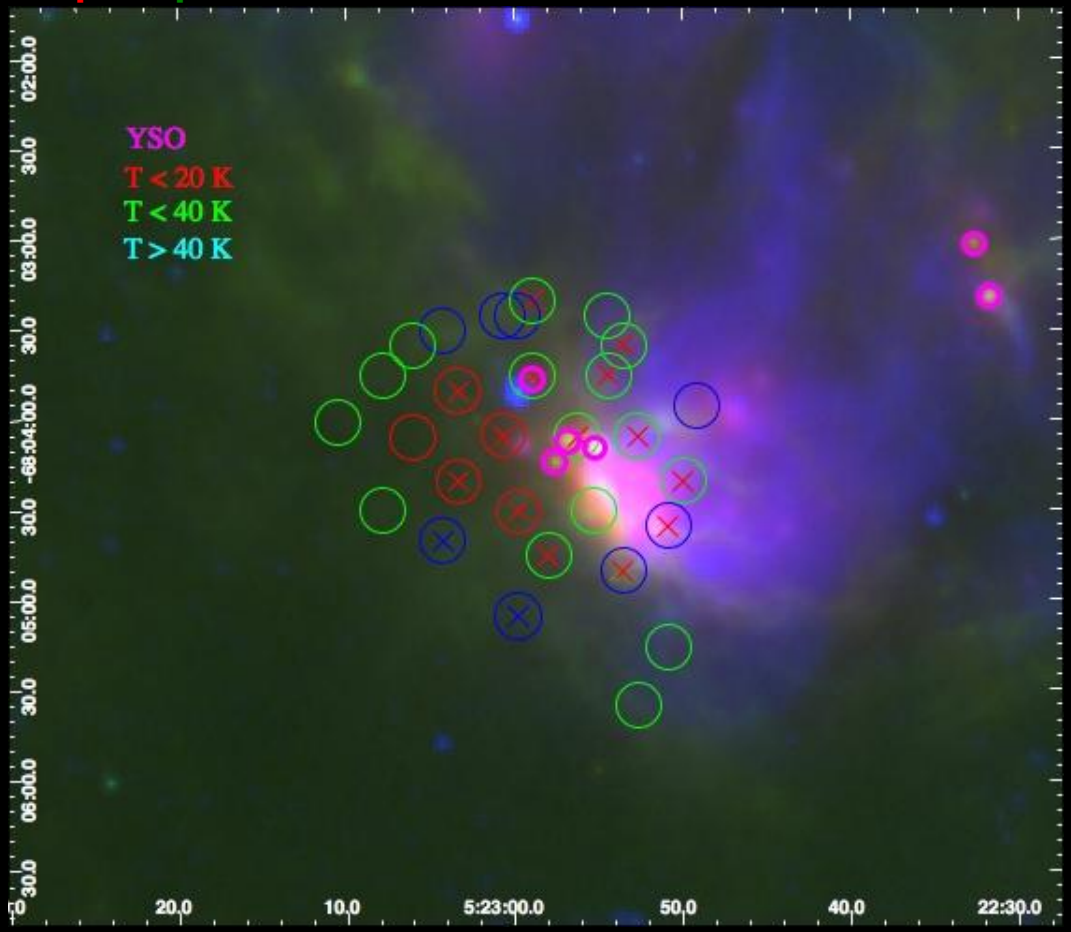


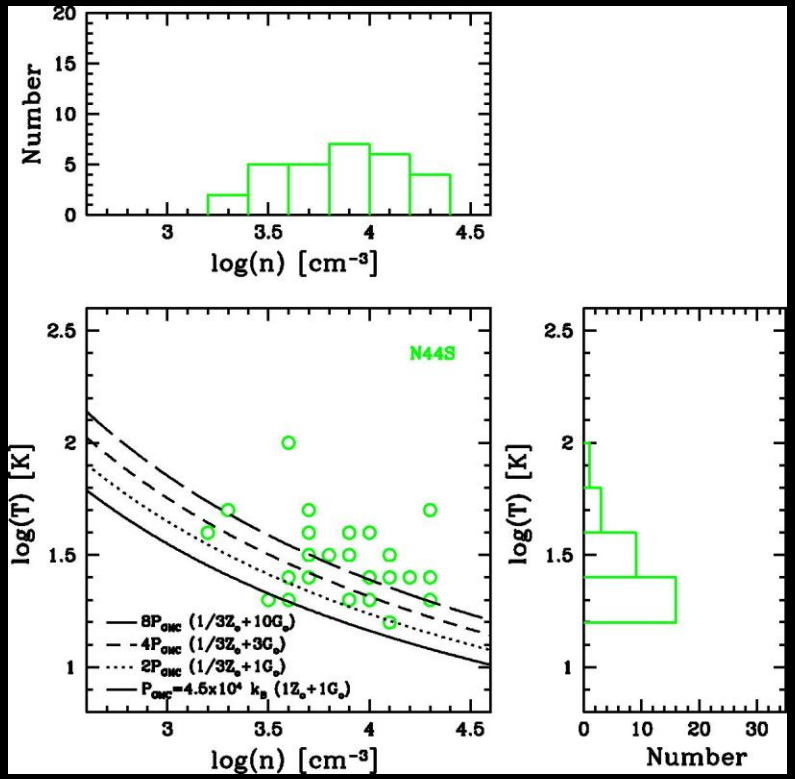
- 43 peaks found in CO(4-3) channel map
- LVG analysis on 29 peaks detected in all 5 transitions in CO &^{13}CO



Clump properties in N44S

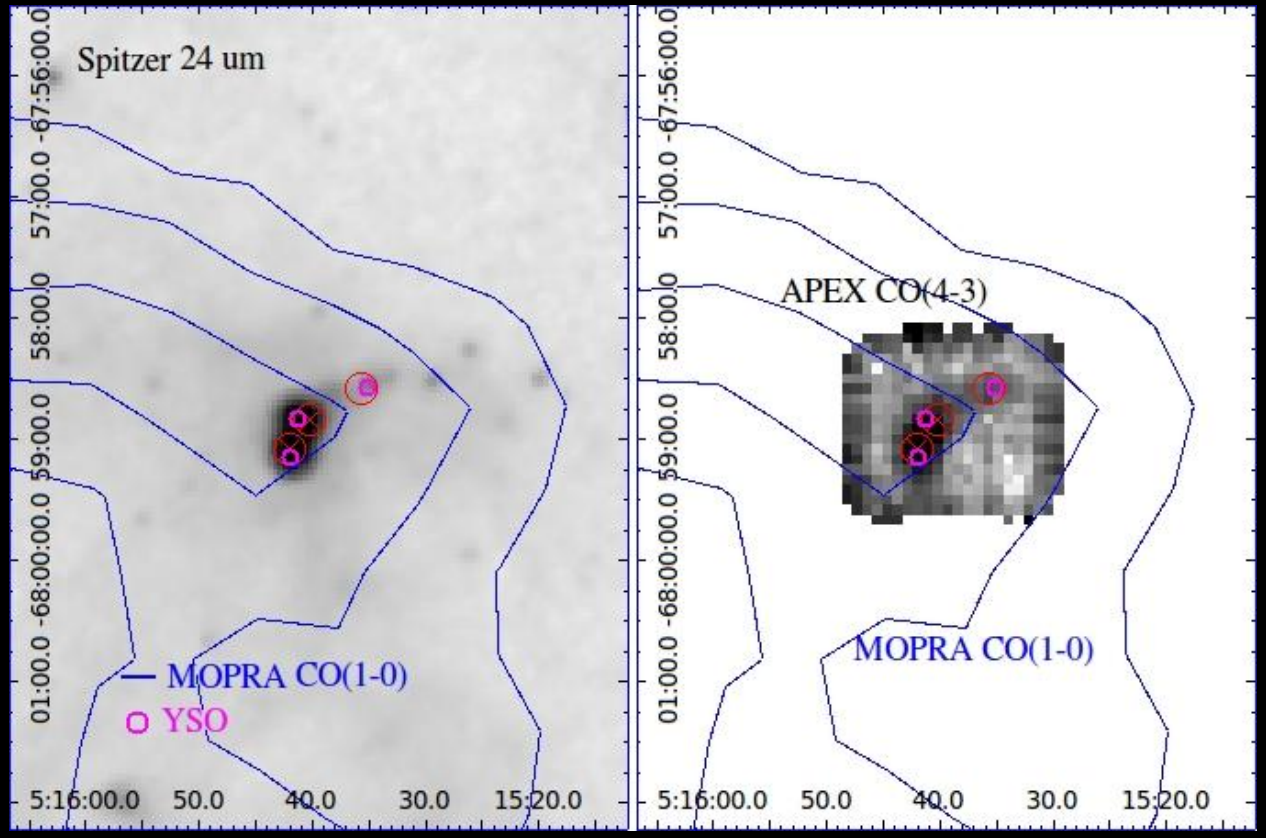
24μm 8μm Hα



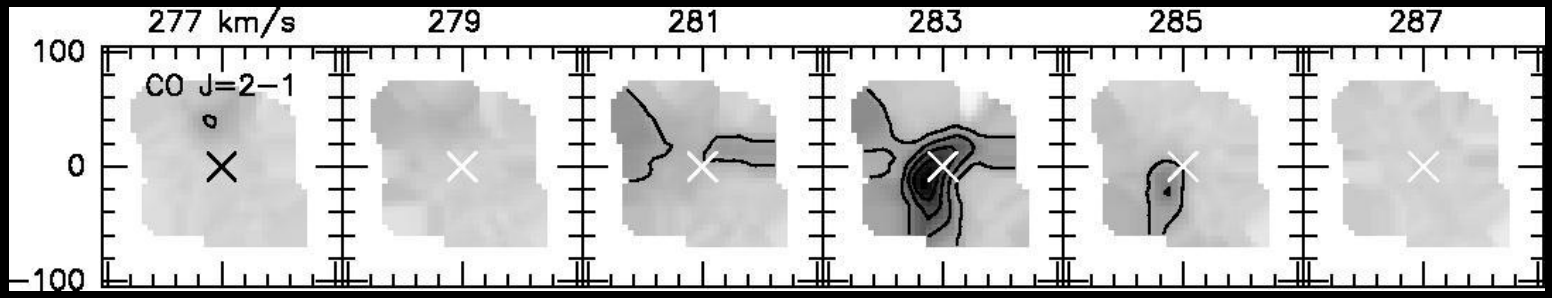


- large # of dense (~10^4 cm^{-3}) clumps
- cold (< 20 K), dense (n~10^4 cm^{-3}) clumps offset from MYSOs & HIIs ⇒ significant energy feedback from MYSOs (3 B0-3; Chen+2009)

Clump properties in NT80

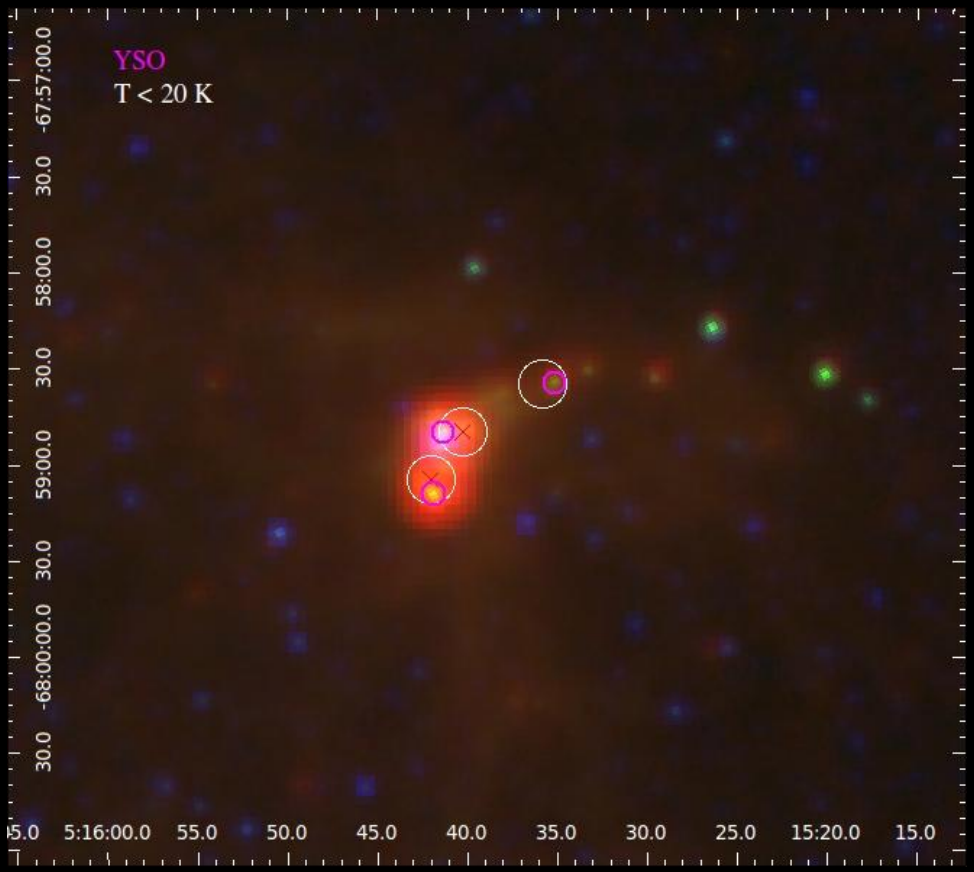


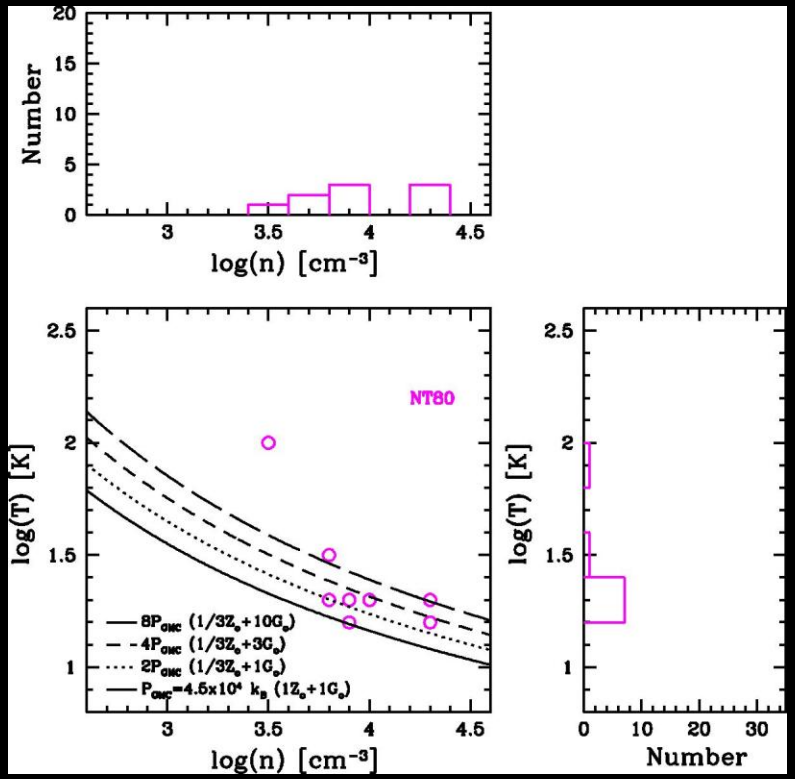
- 14 peaks found in CO(4-3) channel map
- LVG analysis on 8 peaks detected in all 5 transitions in CO & ^{13}CO



Clump properties in NT80

24μm 8μm Hα

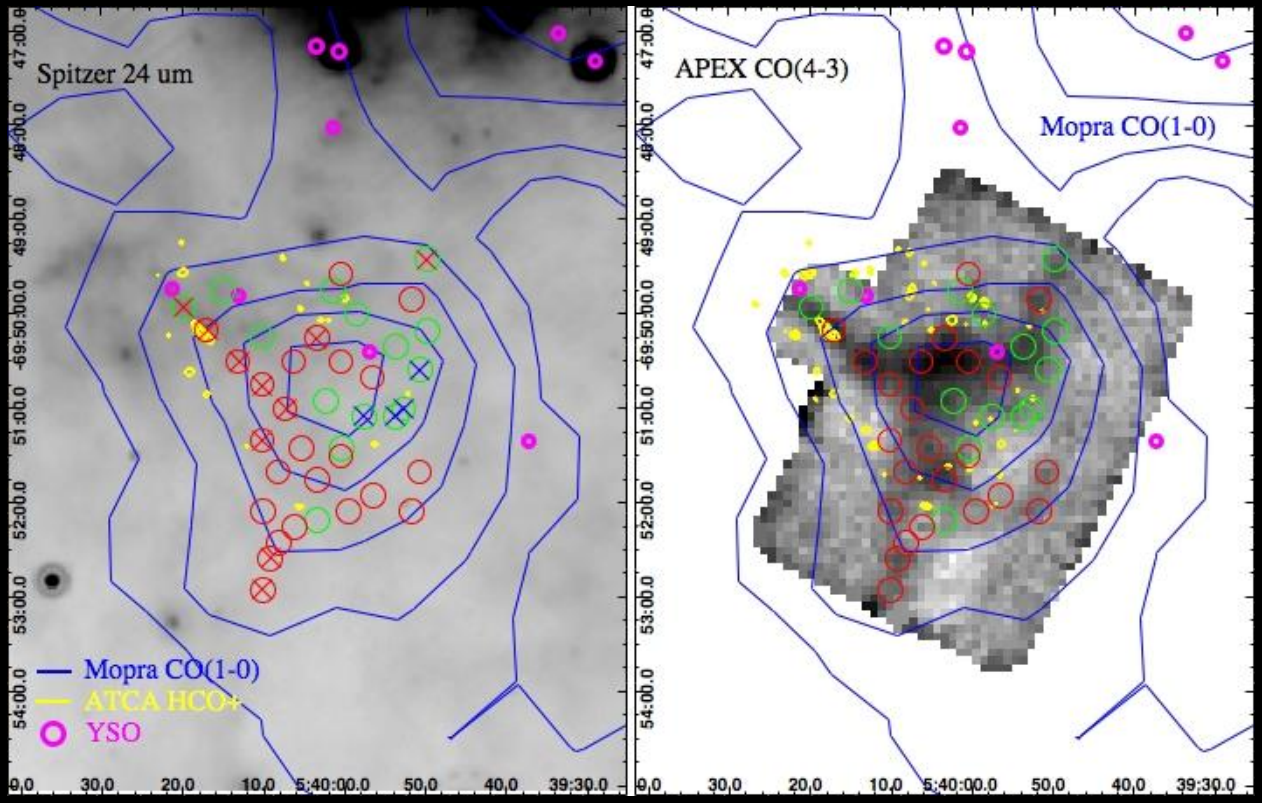




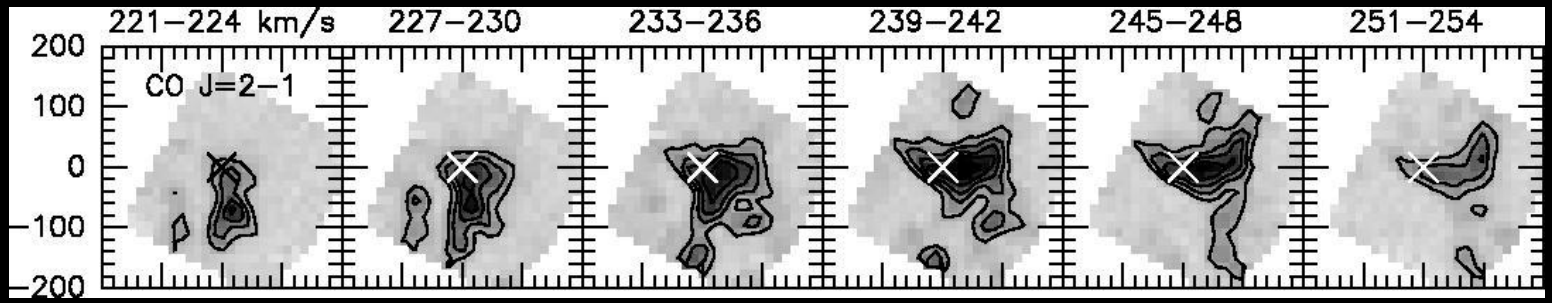
- mostly cold (< 20 K) clumps, no obvious HII regions
- cold (T< 20 K), n~10^4 cm^{-3} clumps near less massive YSOs

  ⇒ modest energy feedback from YSOs (2 B2-3; Chen+2011)

Clump properties in N159S

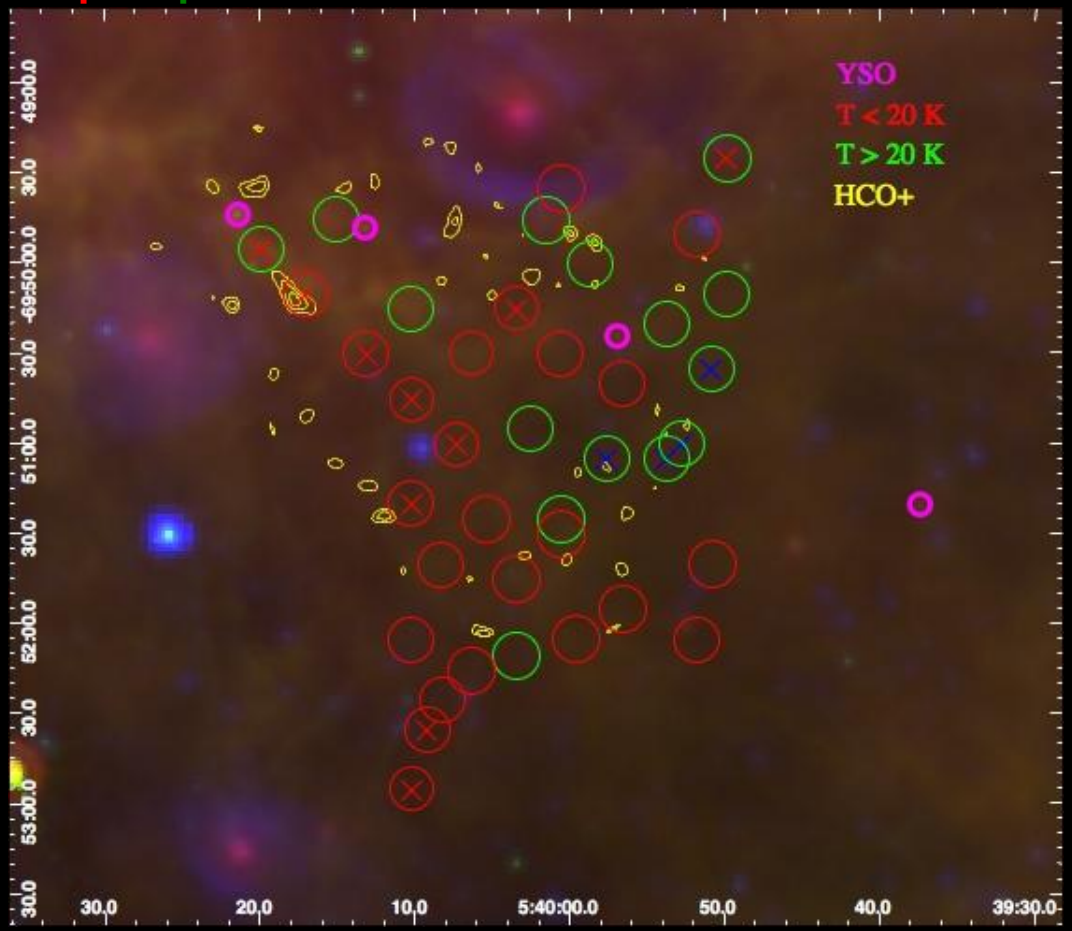


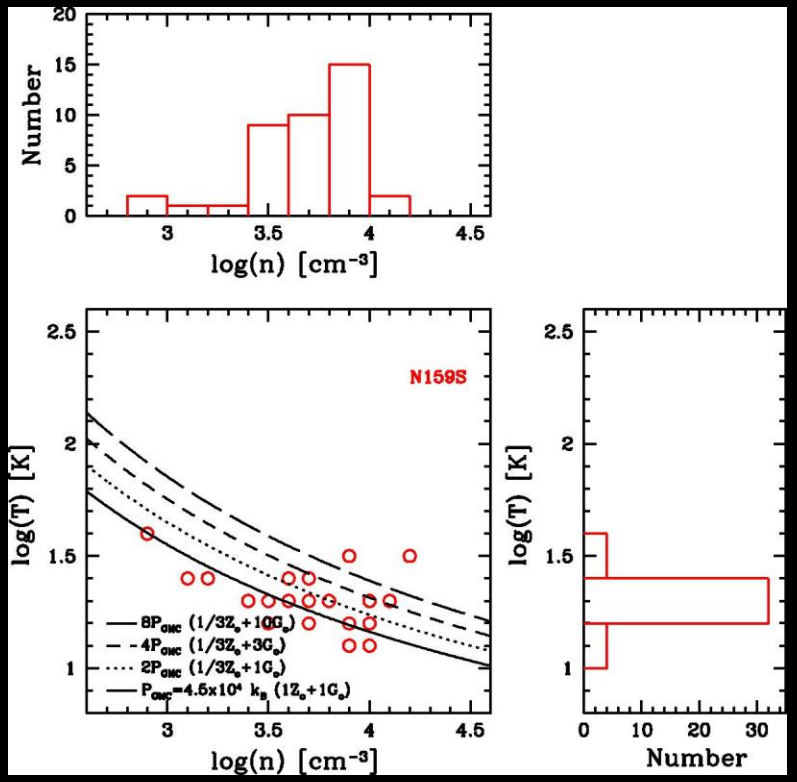
- 60 peaks found in CO(4-3) channel map
- LVG analysis on 40 peaks detected in all 5 transitions in CO & ^{13}CO



Clump properties in N159S

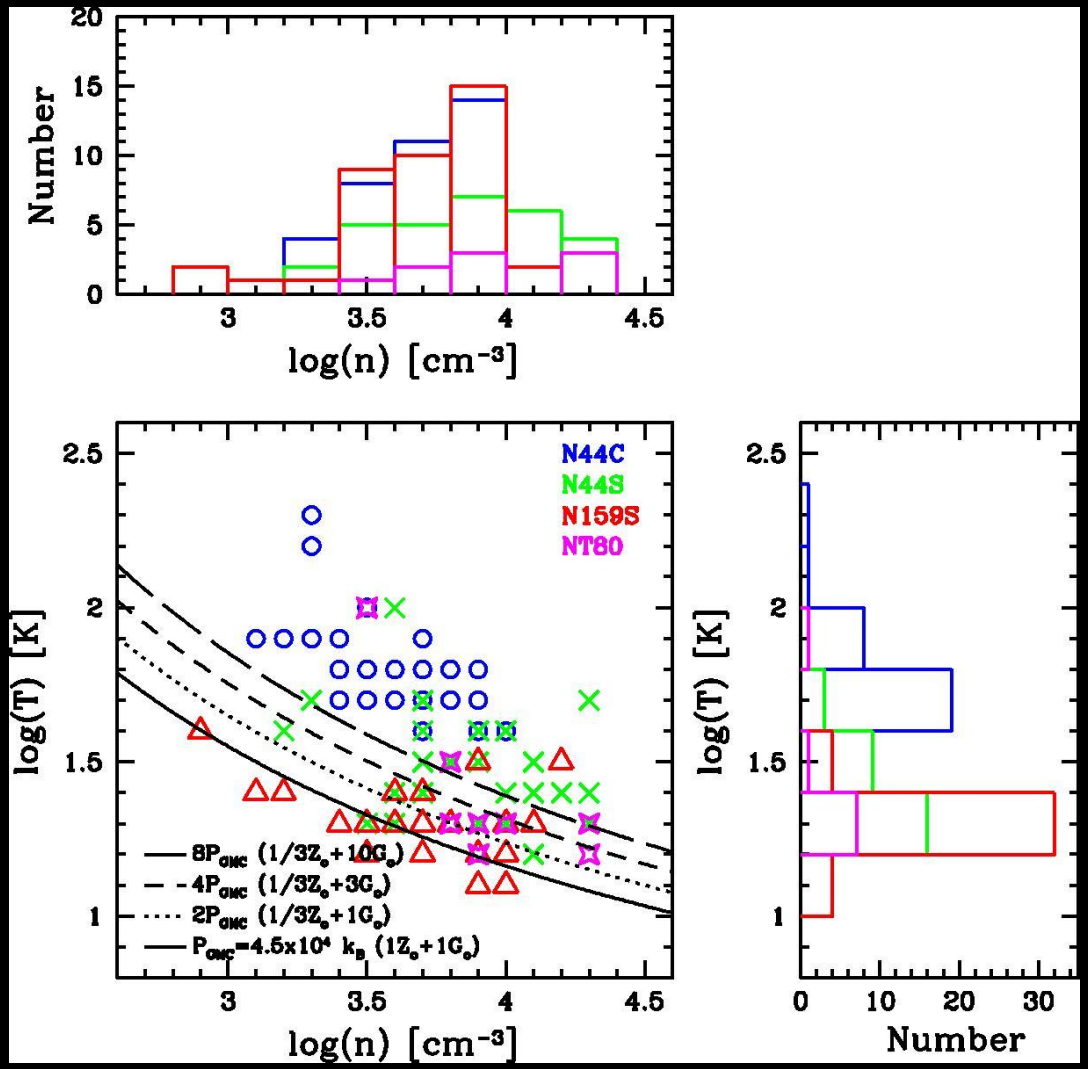
24μm 8μm Hα





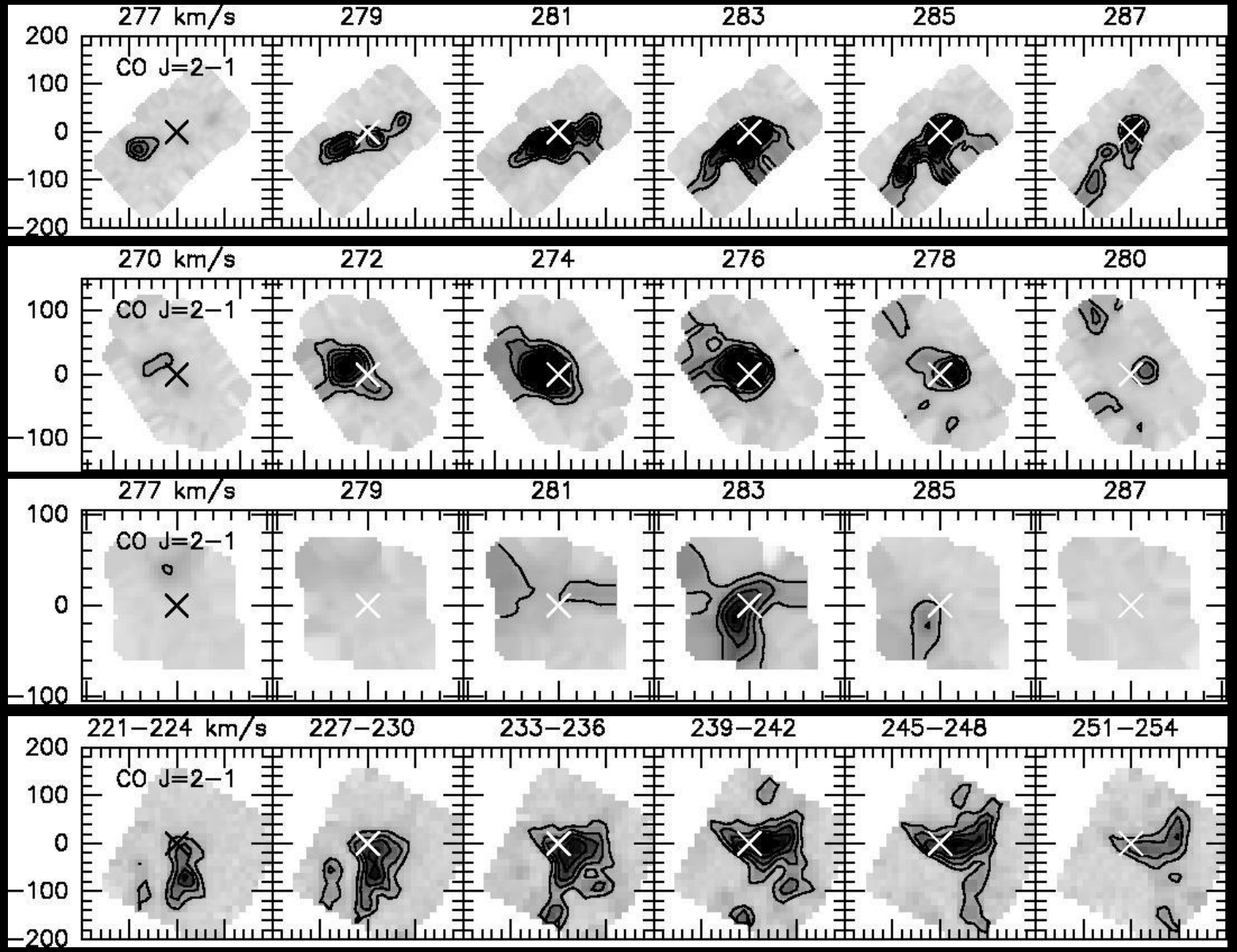
- large # of cold (< 20 K) clumps; no YSOs w/ $M_\star > 8\ M_\odot$ (Chen+ 2010)
- distributed ~10^4 cm^{-3} clumps; 2 highest-n clumps coincide w/ the only ATCA HCO+ clump detected in N159S

Clump properties in 4 GMCs



- n_{max}~10^4 cm^{-3} in 4 GMCs
  ⇒ minimum for MSF
- T varies from 10-15 to 200 K, depending on energy feedback from massive stars+MYSOs.
- P_{clump} varies w/ energy feedback; highest P_{clump} in N44C superbubble.

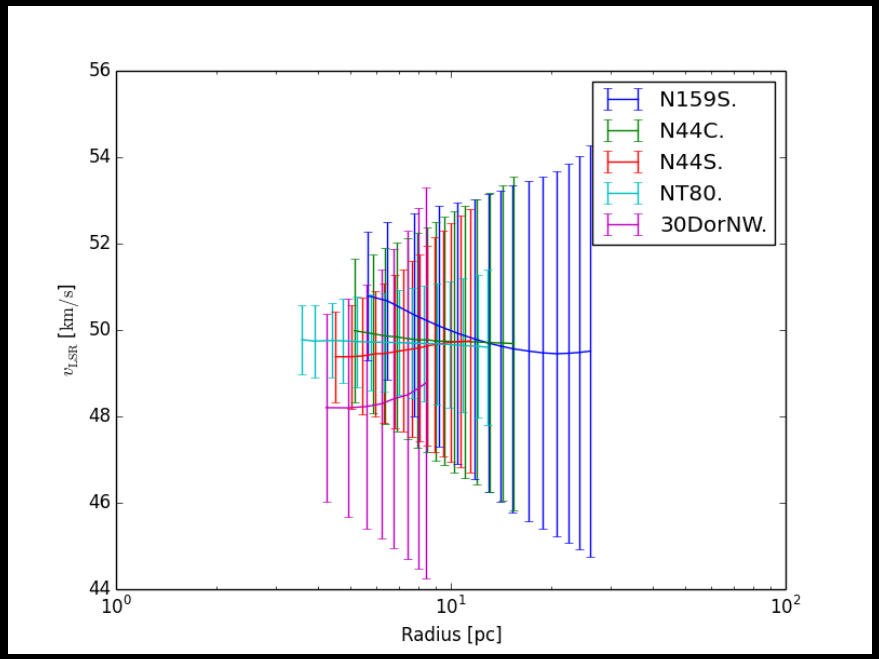
Kinetic Evolution of GMCs

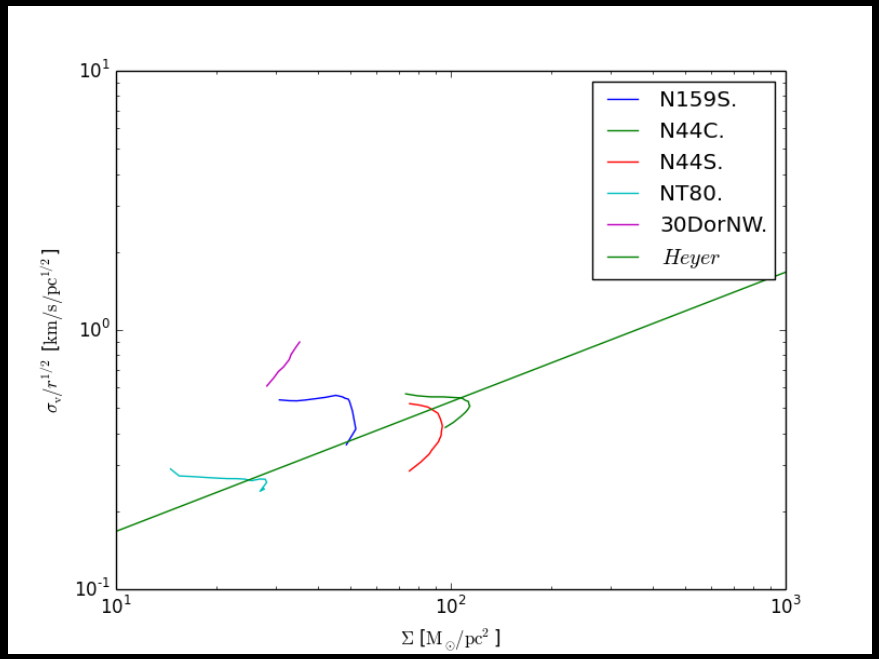


Rosie Chen

Ringberg, 2015.3.18

Kinetic Evolution of GMCs

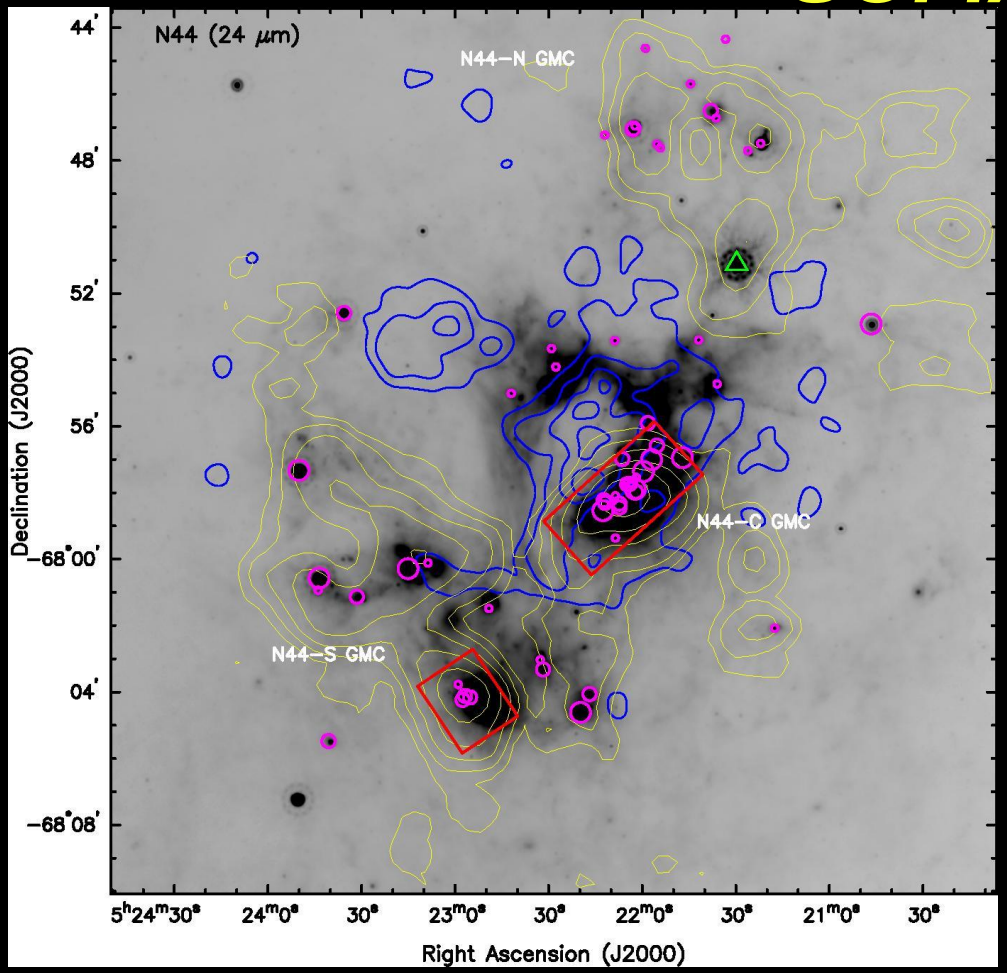




- **quantify structure & kinematics of GMCs w/ ^{13}CO (2-1) channel map: L(^{13}CO) ⇒ E_{grav}; V & σ ⇒ E_K (G-virial; Li+ 2014)**

- **N159S: V separation between GMC outer & center.**
  N159S & 30 Dor-10: less gravitationally bound (Heyer+ 2009)
  ⇒ Is N159S young or a large-volume collapse prevented?

GMC-clump interface to be examined by *SOFIA*



- Awarded Cycle 3 SOFIA GREAT [NII] 122+[CII] 157 μm obs of N44C & N44S to study physical conditions of PDRs

- N44C: PDRs in 10^6 K gas
  N44S: PDRs in 10^4 K gas

- Questions to be addressed:
  -- how gas reacts to different strengths of radiation field => clump dissipation time
  -- gas fraction in CO, CI, CII (Frank's talk)
  -- Examine if [CII] a good SFR tracer by comparing to resolved stellar content.

Rosie Chen

Ringberg, 2015.3.18

Concluding Remarks

- **What are the clump properties around MYSOs?**
  -- a wide range of n: <10^3- a few 10^4cm^{-3} , T: 10-200 K

- **Are special conditions required to form MYSOs?**
  -- n_{min}~10^4 cm^{-3} to form MYSOs
  -- no MYSOs in un-virialized N159S ⇒ young or unable to converge?

- **How does energy feedback affects MSF?**
  -- clumps near MYSO & massive stars have higher T & lower n
  -- clumps @ intense feedback have larger P ⇒ larger M to collapse?

What next?

-- Is GMC N159S really young?
⇒ SF duration from PMS stars in N159 (awarded *HST* program)
-- How will clumps evolve w/ external heating?
⇒ realistic physical conditions of inter-clumps (awarded *SOFIA* program)