The formation of massive star clusters by cooperative accretion

Eric Keto

Gene Avrett

Center for Astrophysics
Harvard University
Smithsonian Astrophysical Observatory

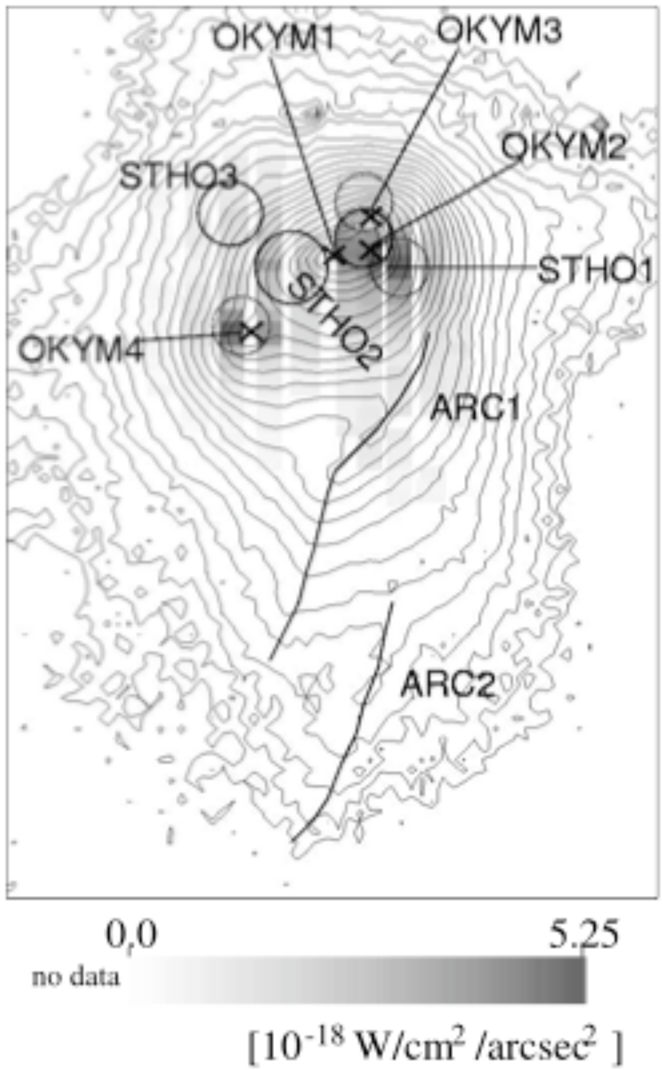
Wd2: A massive open cluster

Westerlund 2
Spitzer GLIMPSE

12 x O6 - O7 stars

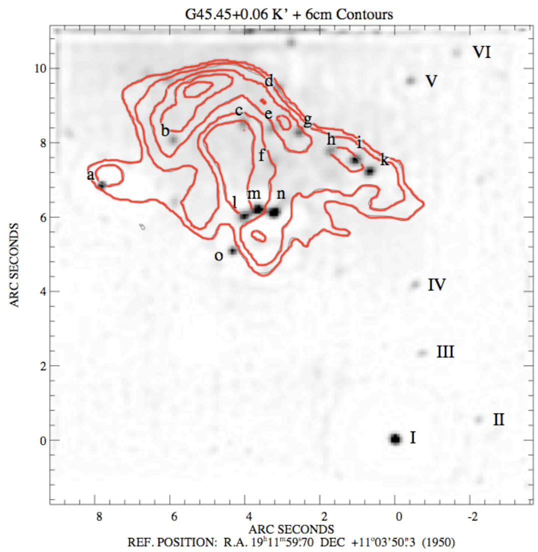
1-2 x 10^6 yrs old

K3-50 A
A group of O stars in an UCHII region

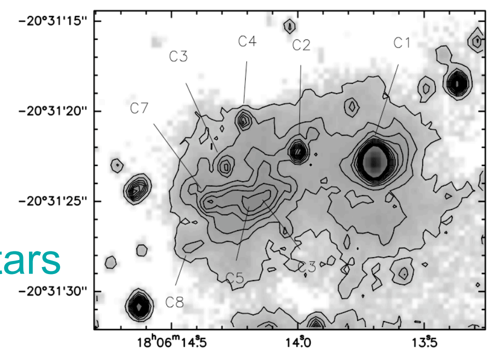


Mid-IR at Subaru telescope
Okamoto+ 2003

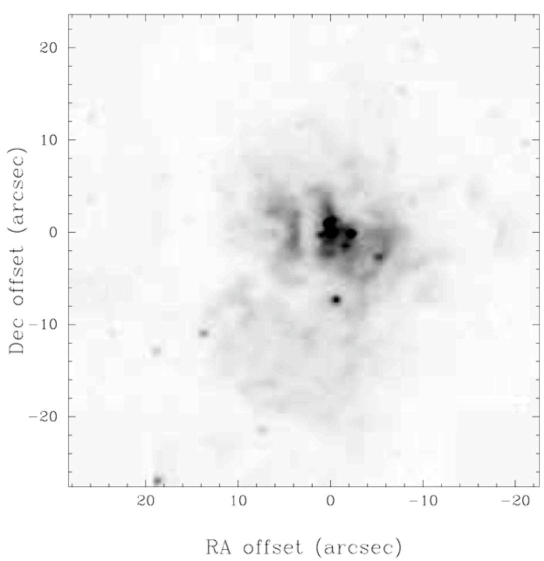
More examples of multiple O stars in UCHII regions



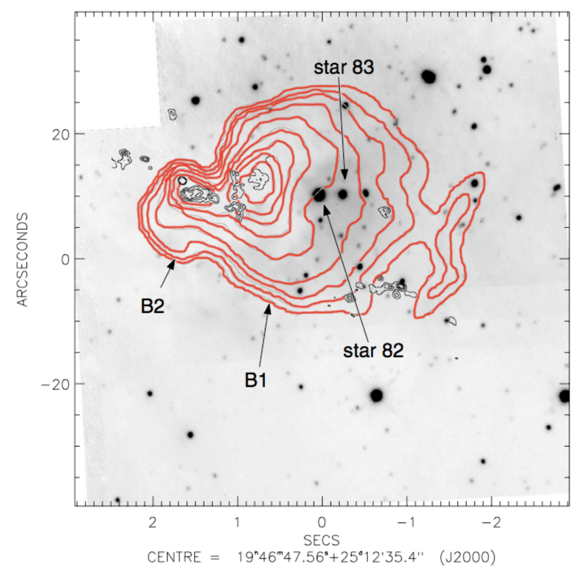
G45.45+0.06
Feldt+ 1998
6 x mid-early O stars
Blum & McGregor 2008



G9.62+0.19
3 x O9 - O6 stars
Persi+ 1998

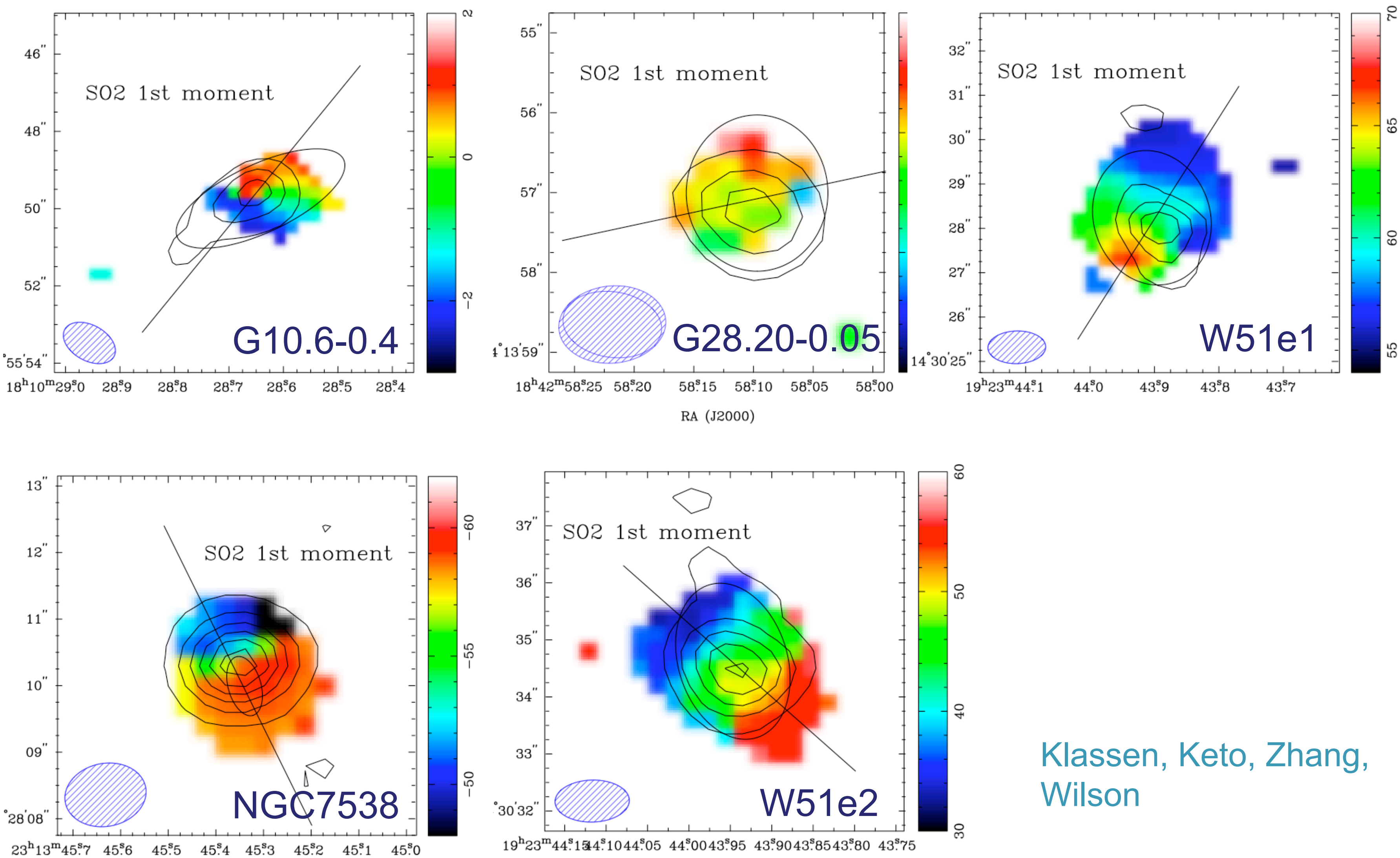


G333.6-0.2
19 x O7 stars:
Fujiyoshi+ 2006

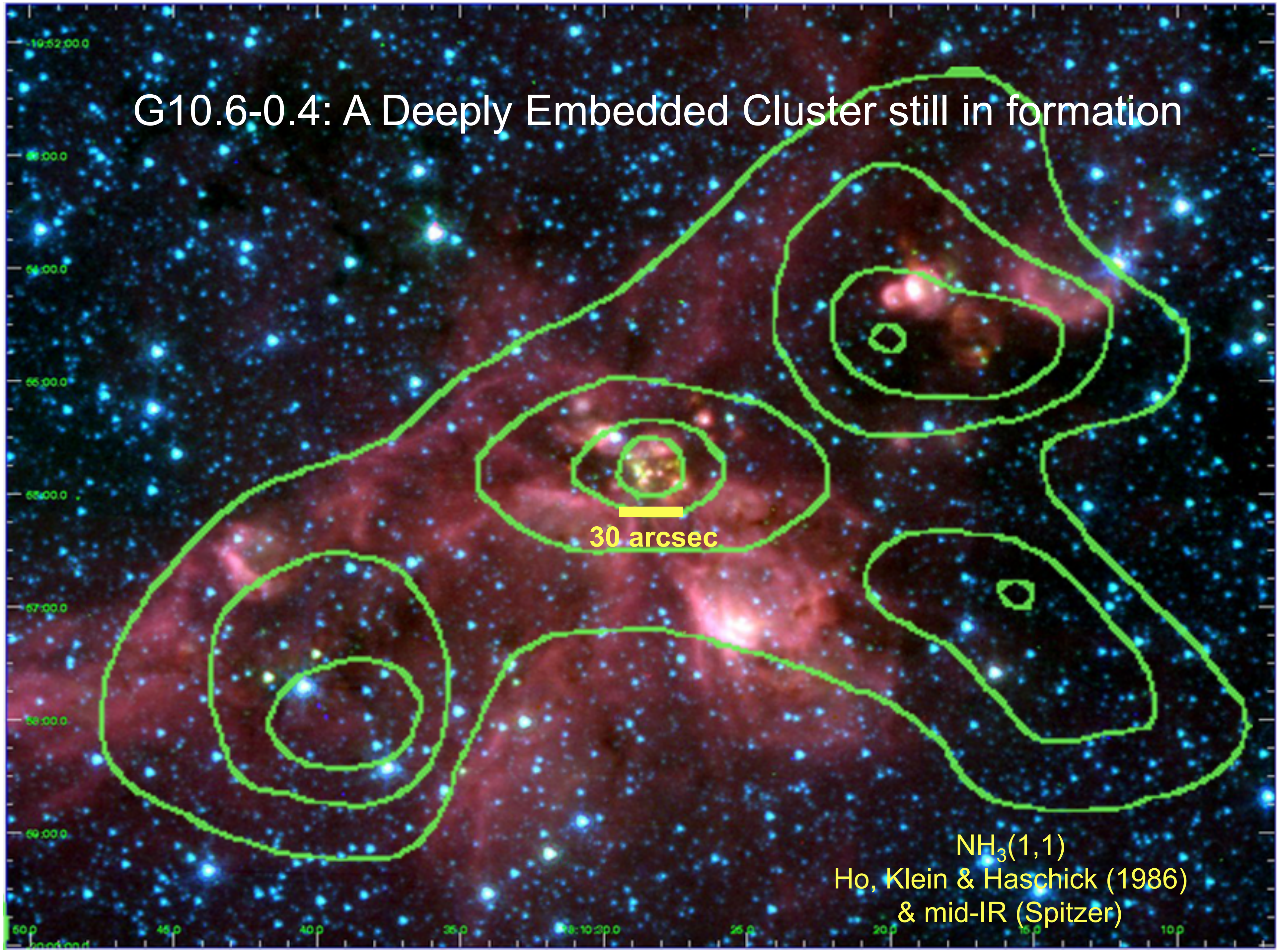


G61.48+0.09
4 x O5 - O8 stars:
Puga+ 2006

Molecular accretion flows around UCHII regions

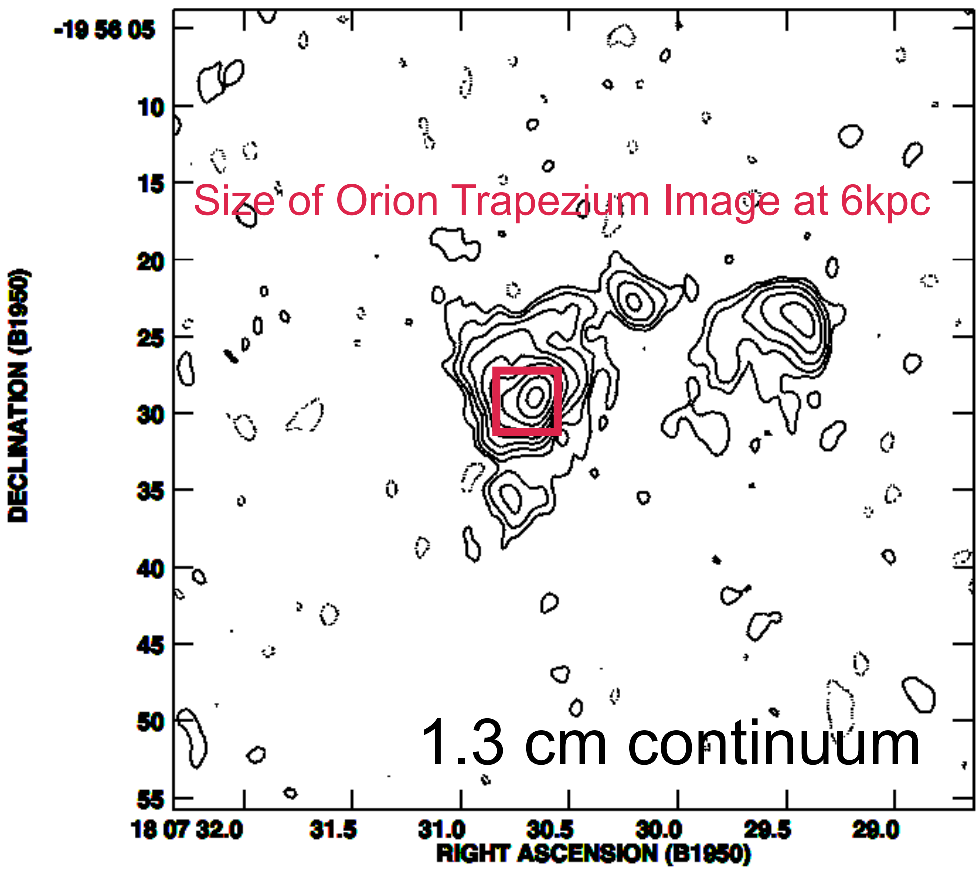


Klassen, Keto, Zhang, Wilson


G10.6-0.4: A Deeply Embedded Cluster still in formation
30 arcsec
NH_3(1,1)
Ho, Klein & Haschick (1986)
& mid-IR (Spitzer)

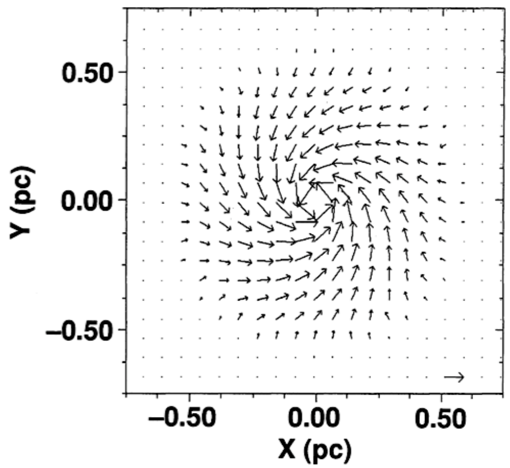
G10.6-0.4

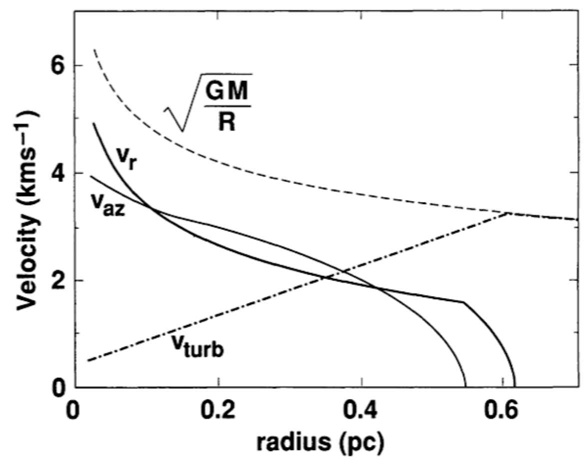
UCHII regions with 9 x O6 - B0

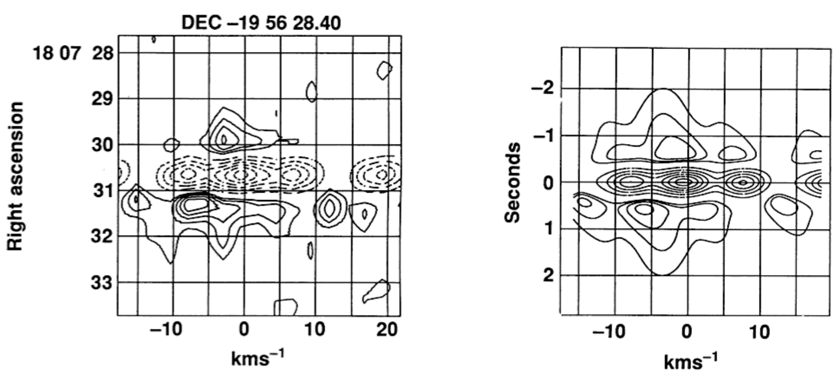


Ho & Haschick 1981
Keto 2002

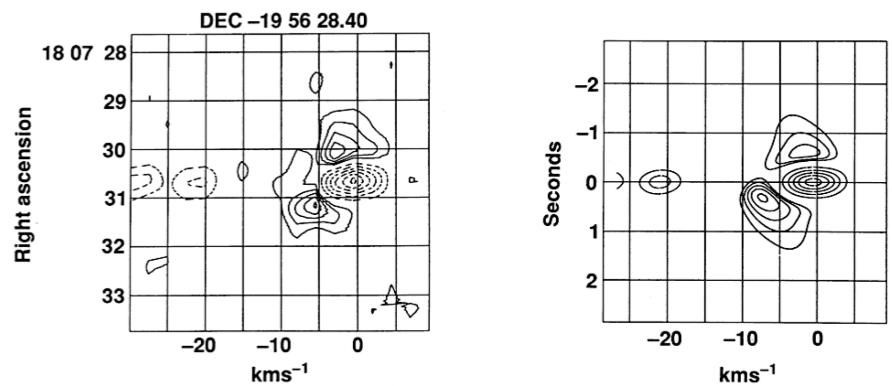
$M = RV^2/G > 250\ M_\odot$ implies Cooperative Accretion







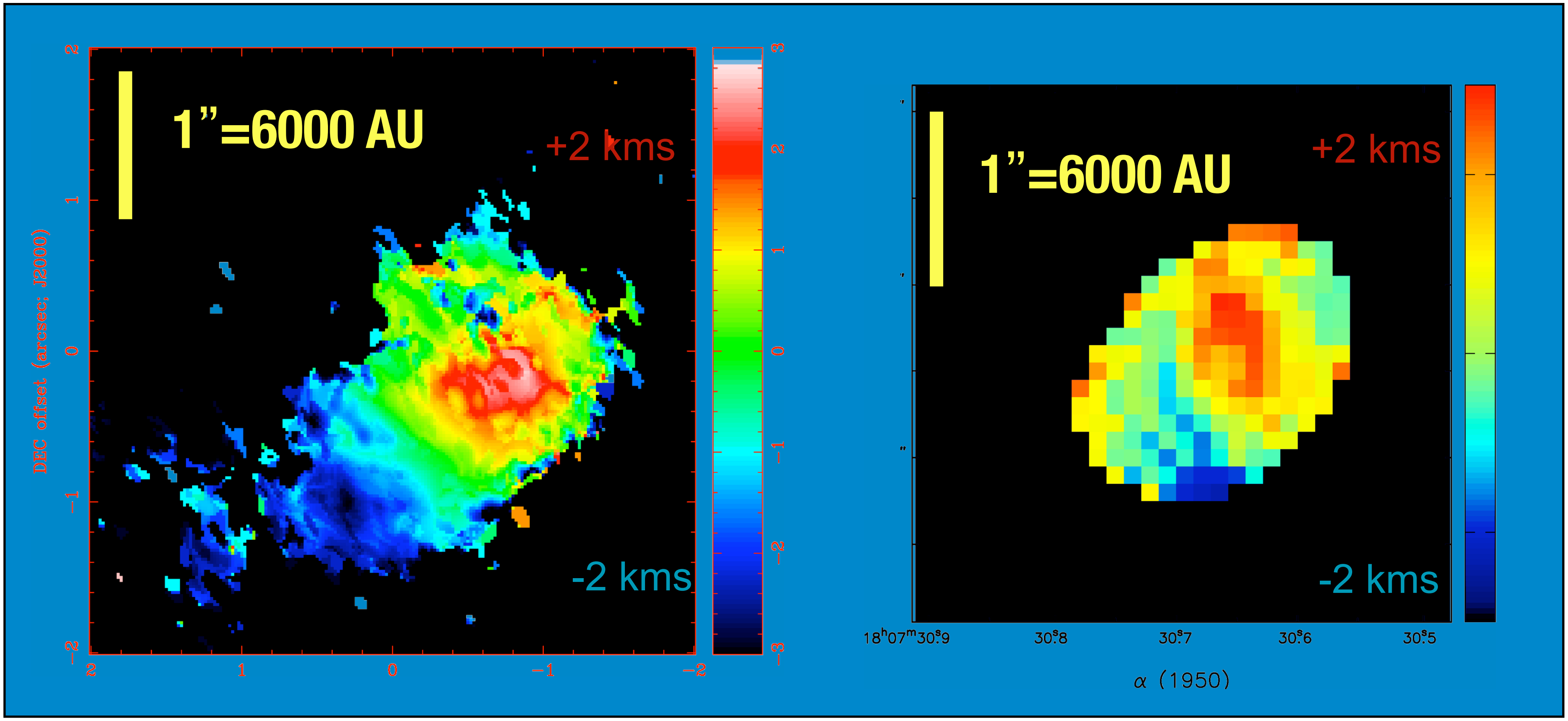
NH_3(1,1) data and model



NH_3 (3,3) data and model

Keto 1990

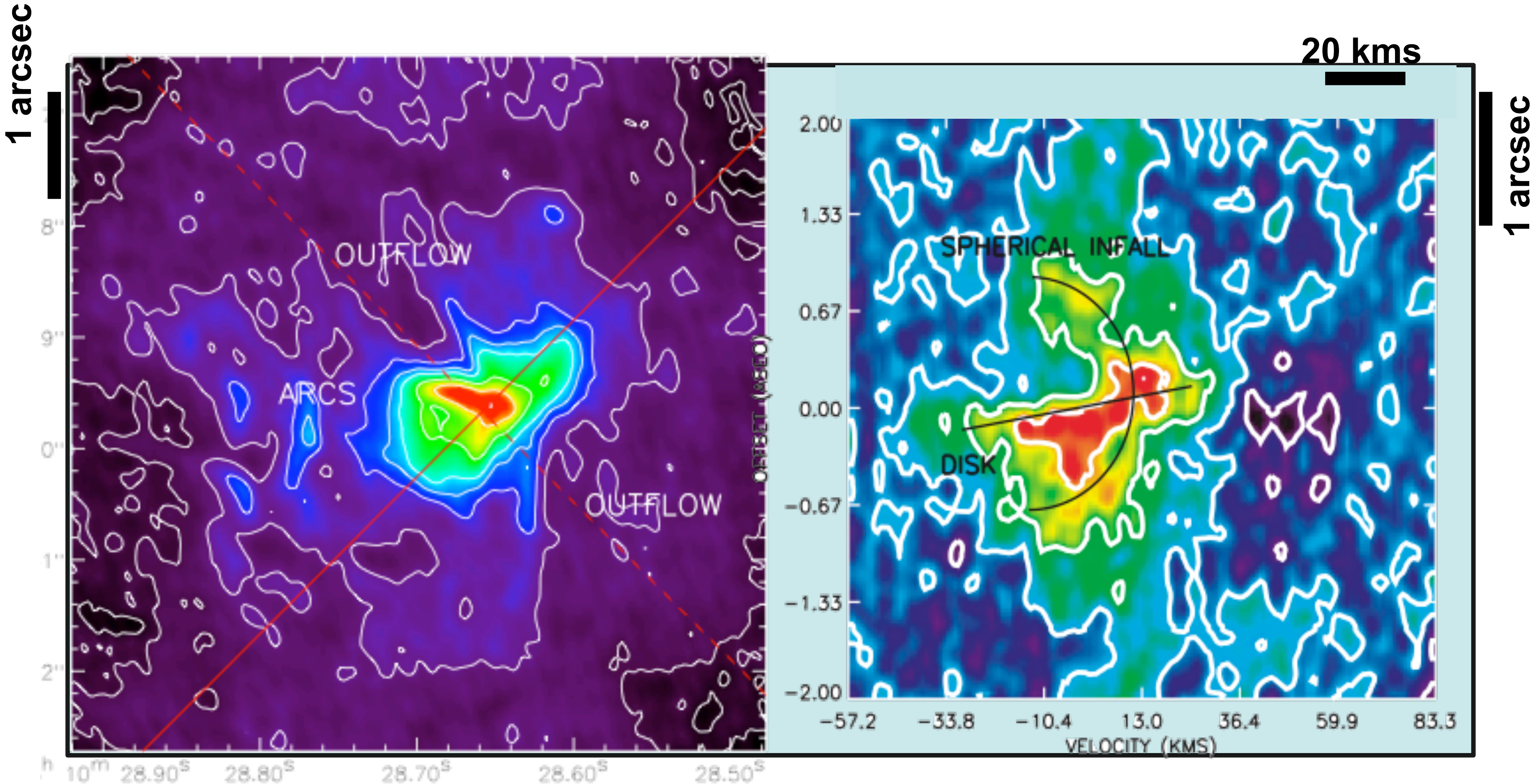
Molecular to Ionized
2-Phase Cooperative Accretion Flow



Mean velocity of molecular gas (NH_3)
Sollins, Zhang, Keto, Ho (2005)

Mean velocity of ionized gas (H66a)
Keto (2002)

A rotating disk in ionized line emission



1.3 cm continuum

H66a recombination

Summary of the flow structure forming an open cluster

- Large, cluster scale molecular accretion flow
  - 1 pc, 1000 $M_\odot$
  - Similar to T-Tauri model accretion flow (angular momentum consv.)

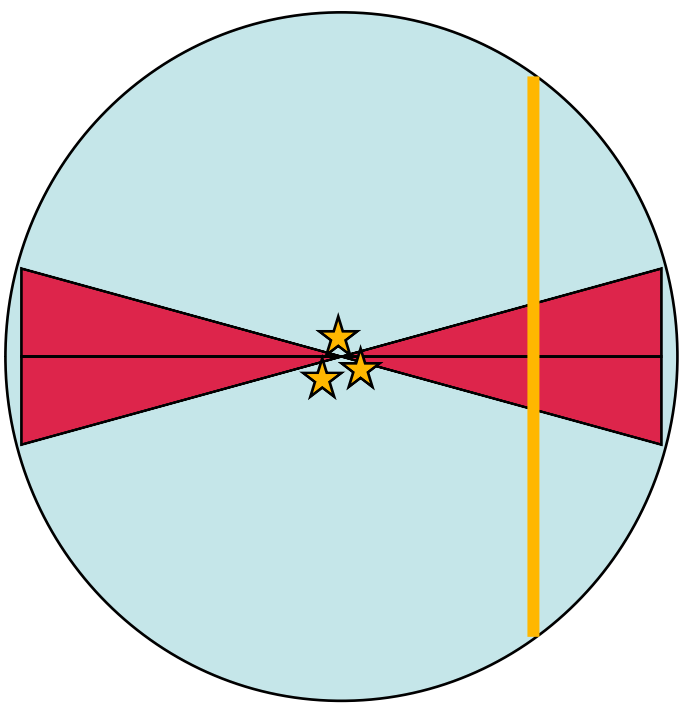
- Center of the accretion flow is ionized by a cluster of O stars
  - As long as HII region is not too big then the increased pressure of the hot ionized gas is negligible compared to the gravitational pull of all the stars in the cluster.

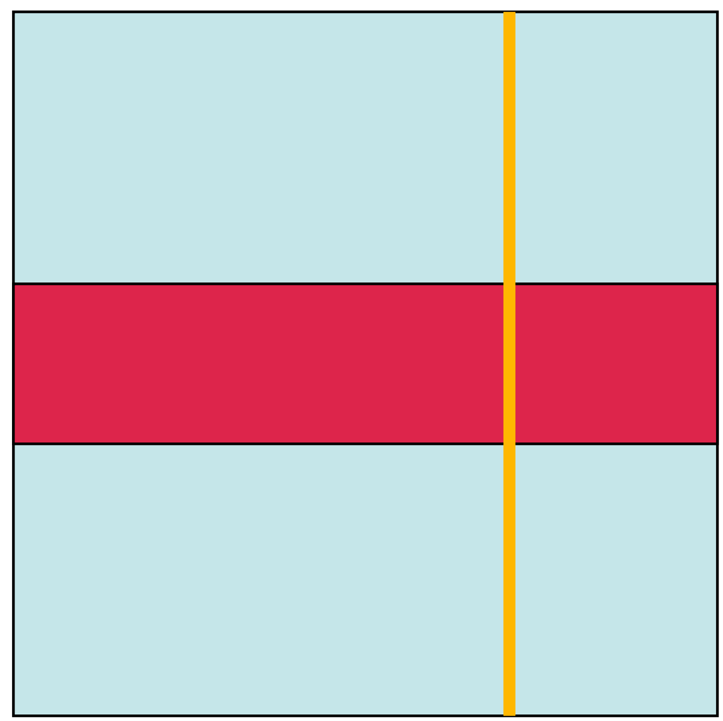
- An accretion disk forms at the centrifugal radius
  - Following the T-Tauri model with A.M. conservation
  - Inside the HII region, disk forms out of the inflowing ionized accretion flow

- What is the structure of this disk?

Cooperative accretion disk within a spherical HII region approximated in plane parallel geometry

- Disk structure from thin disk theory
  - Flared hydrostatic disk with exponential scale height
- All ionizing radiation reaching the disk emitted by the HII region.

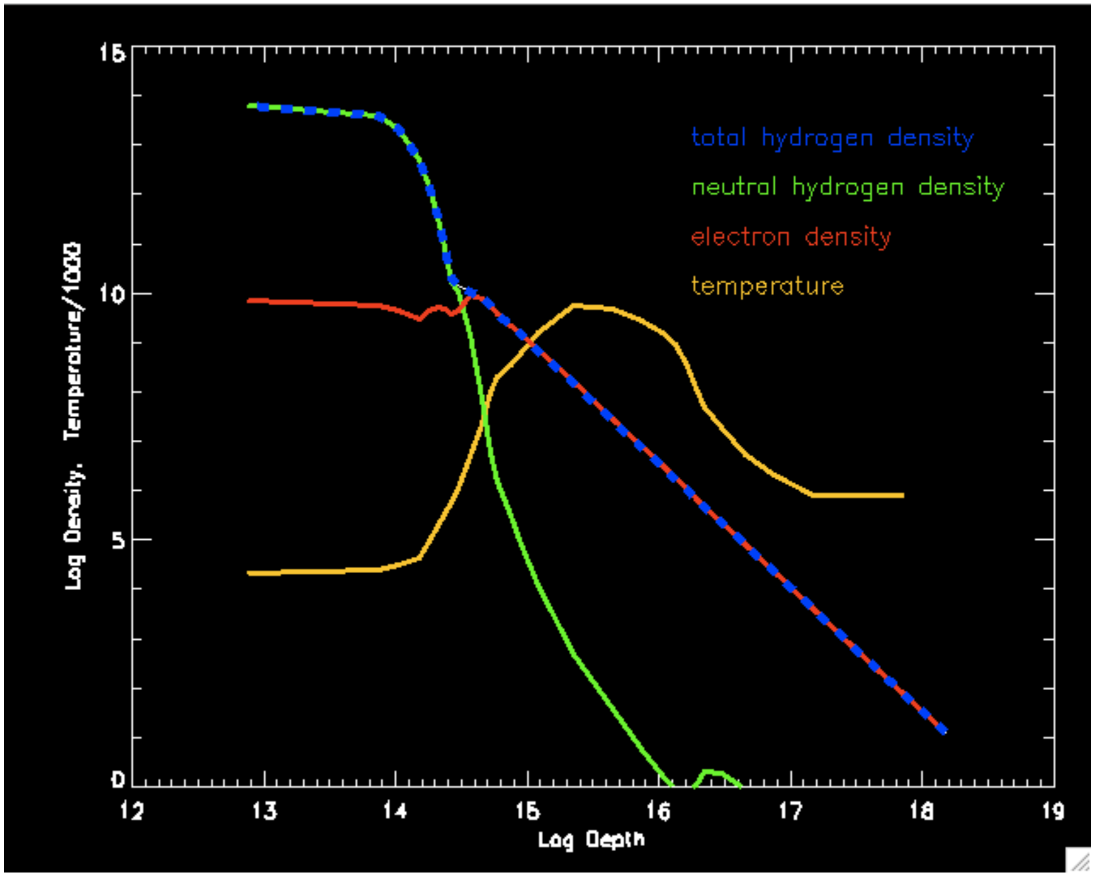




The structure of the accretion disk

- Ionization and radiative equilibrium from Gene Avrett's PANDORA code for stellar atmospheres

- At high densities, the gas cannot remain ionized
- The gas cannot cool too much
  - Optically thick in the IR
  - Surrounded by 10^4 K ionized gas
- The disk is high temperature, neutral gas, HI at few 1000 K,



Implications

- What limits the maximum stellar mass?

- No Pressure differential
  – HI is close to the temperature of the ionized gas. Small thermal pressure differential between neutral and ionized gas

- No Dust -- No radiation pressure on dust close to the star

- Maximum stellar mass is set by radiation pressure on electrons, Thompson scattering

- If nothing else happens first, stars inside a cooperative accretion flow grow to the Eddington limit ~ 100 $M_{\odot}$. The flow then forms another star.

- Ionization of the large-scale molecular gas ultimately limits growth of the cluster.

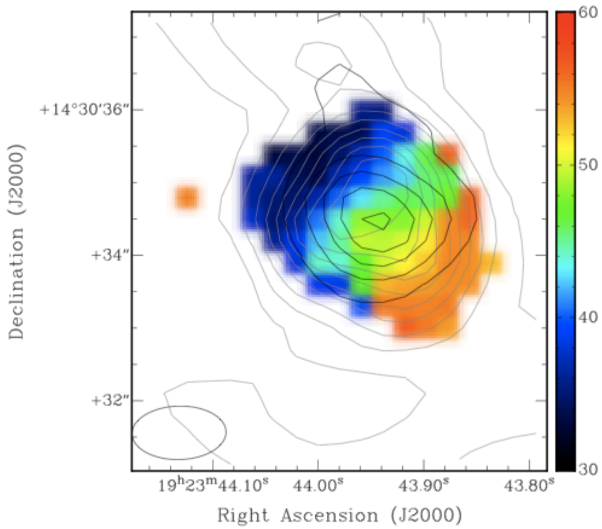
Implications

- Disks around O stars may have large scale heights.
  - Nothing about the structure of the cluster scale accretion flow depends on scale.

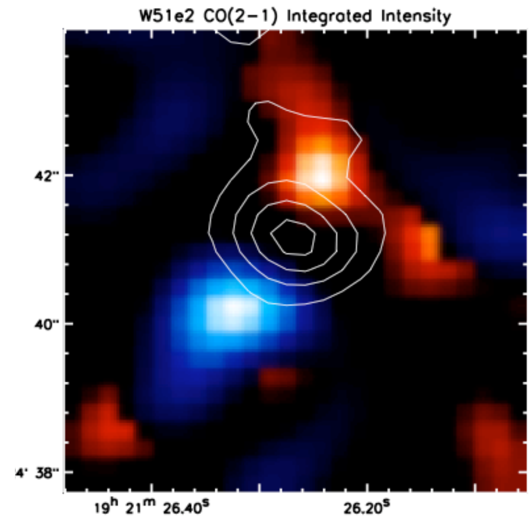
- Around isolated O stars / binaries
  - Expect to detect the rotationally flattened molecular flow outside the HII region (fat toroids).
  - Ionization may make the accretion disk (scale $< R_d$) difficult to detect apart from the HII region

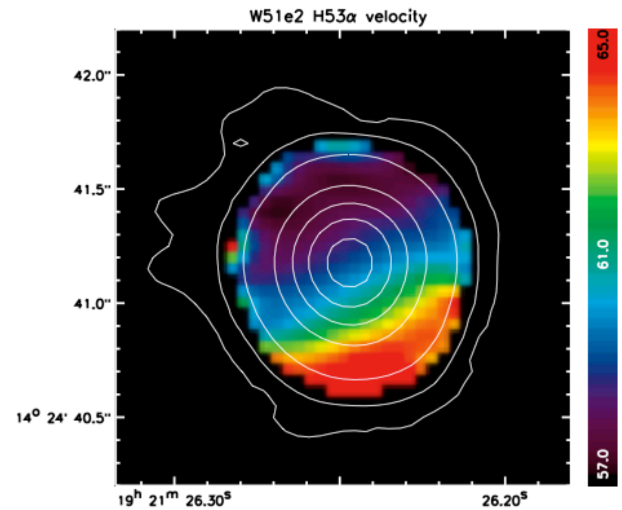
    - Cesaroni + 2007 PPV, No disks around O stars?

Molecular Accretion Flow, Bipolar Outflow, Ionized flow in W51e2 >20 $M_\odot$ O star



(c) W51e2





Rotating Envelope in SO_2 velocities

Bipolar Outflow in CO

Rotating Ionized flow in H53a velocities

Keto & Klaassen 2008

Star Formation in Clusters

- Cooperative accretion into cluster center
  - Accretion driven by the combined mass of stars in the cluster
  - 3-phase accretion flow:
    - large scale molecular accretion flow outside the HII region
    - ionized accretion flow within HII region
    - formation of a high density, neutral accretion disk at the centrifugal radius of the ionized accretion flow

- High pressure accretion disk
  - Accretion flow supplying more than one star
    - Stars grow up to the Eddington limit (Thompson scattering)
      - As radiation pressure “zeroes” out the gravitational mass of one star, the larger scale accretion flow forms a new star

- Cluster formation ends when co-op HII > co-op transonic R_b

ALMA Opportunities

- Higher Angular Resolution
  - Currently limited by the angular resolution of the VLA (0.1”)
- H Recombination Lines at higher frequency
  - Currently limited by the optical depth of the ionized gas at 7mm
- Identify density structure within the ionized accretion flow. Give us a good understanding of the dynamics of cooperative accretion flows that form around and within massive star clusters.
- Super Star Clusters in Starbursts. Gravitationally bound ionized gas illuminated by 10^6 O stars (Turner+ 2003). 1” = 15 pc at 3 Mpc (M82 - NGC253). ALMA will see inside SSCs.