The formation of the most massive stars in the Galaxy

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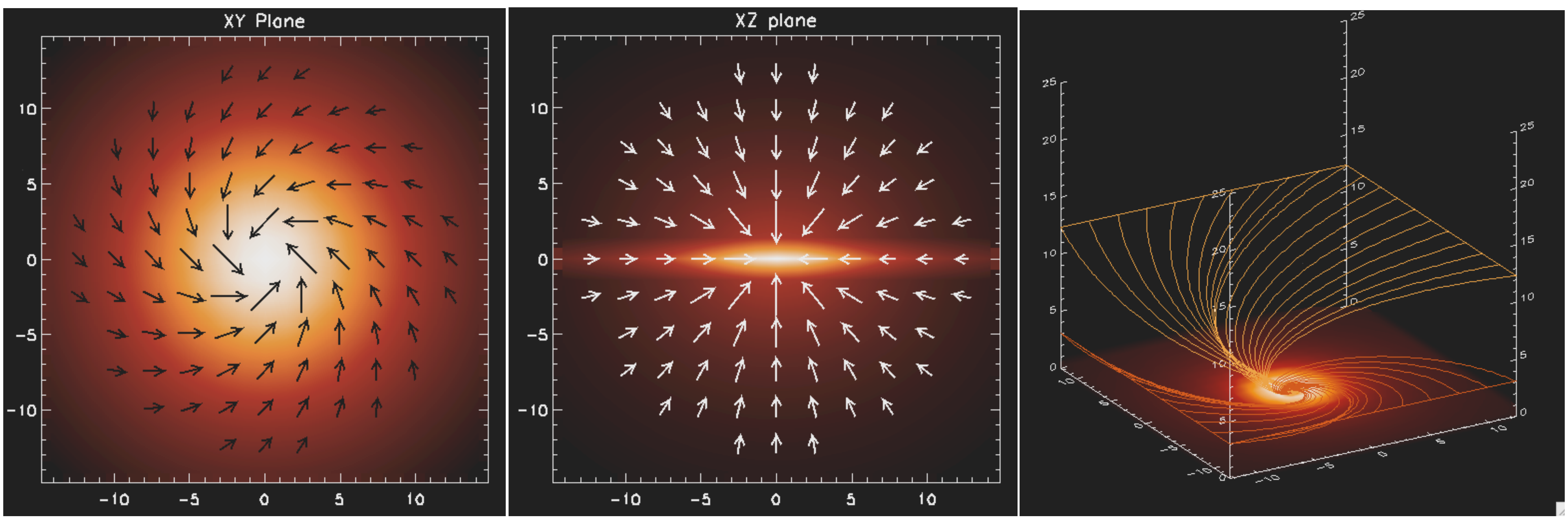
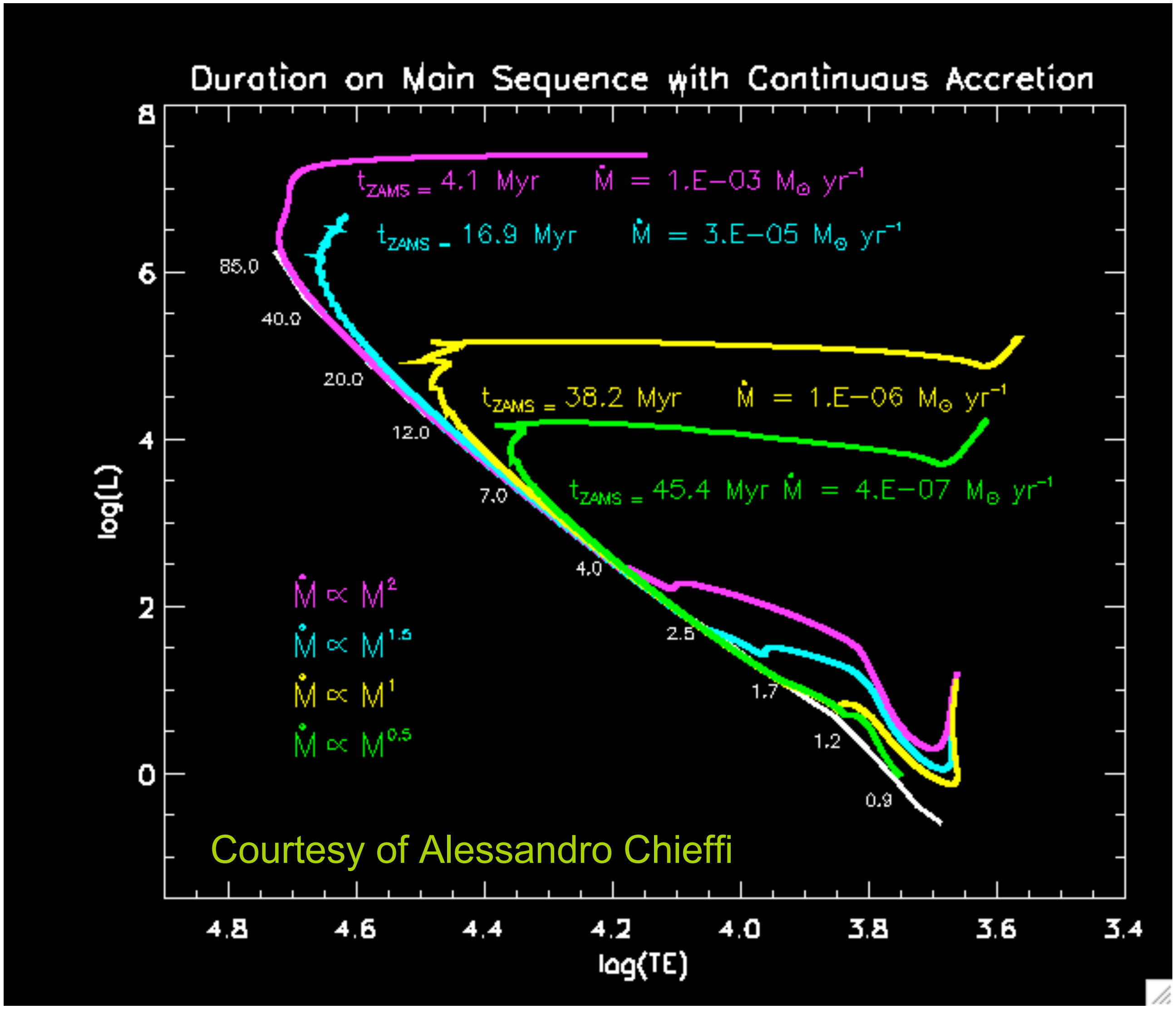
A model for observations of massive star formation

- Start with simplest accretion flow with rotation
- Ionize the center of the flow
  - Streamlines on ballistic trajectories
    - Ulrich (1976 T-Tauri),
    - Terebey, Shu, Cassen (1984 inside out collapse),
    - Jijina & Adams (1996 radiation pressure),
    - Mendoza et al (2004 stellar winds)

$$R_D = \frac{GM}{v_k^2}$$



Massive stars grow up the ZAMS



Stahler, Palla

Yorke

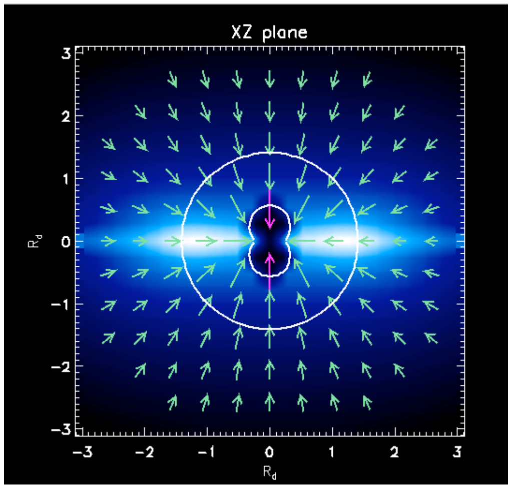
Maeder,Norberg
Berhrend

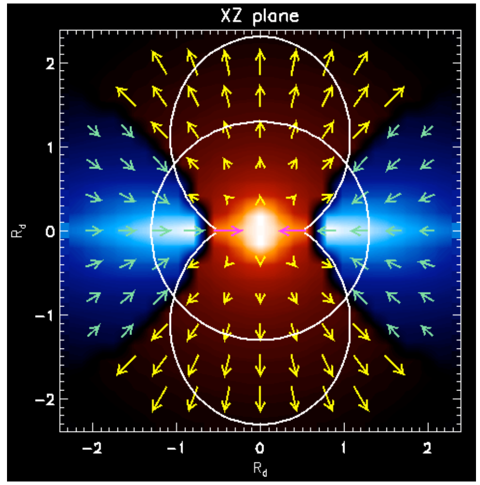
Chieffi

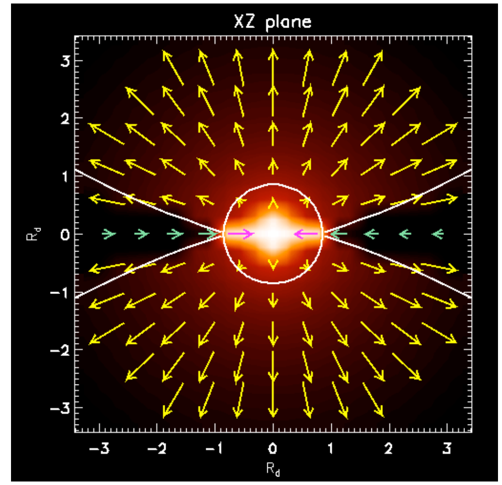
McKee, Tan

Ionizing flux increases as a star gains mass by accretion

HII Evolution with increasing ionization





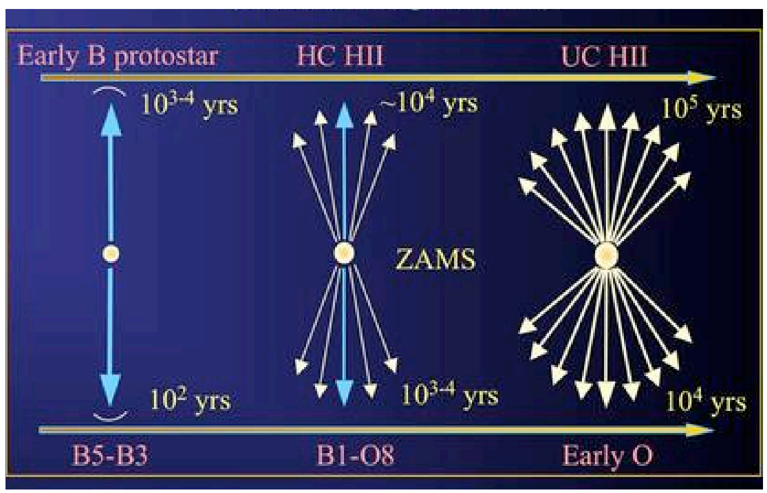


$$R_{HII} < R_S = \frac{GM}{2c^2}$$

$$R_{HII} \sim R_S :$$

$$R_{HII} > R_S :$$

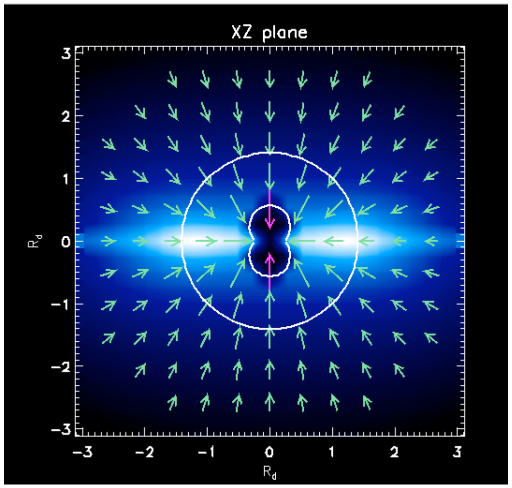
Beuther & Shepherd 2005

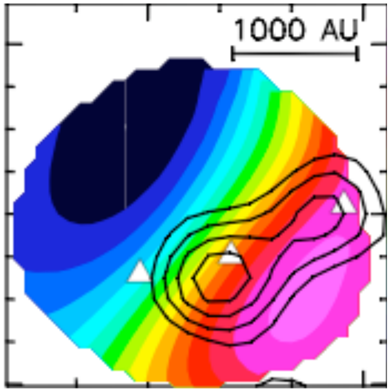


Ionization depends on

1) the flux of ionizing radiation
2) gas density.

Low ionization $R_{HII} < R_S$
Gravitationally Trapped HII regions



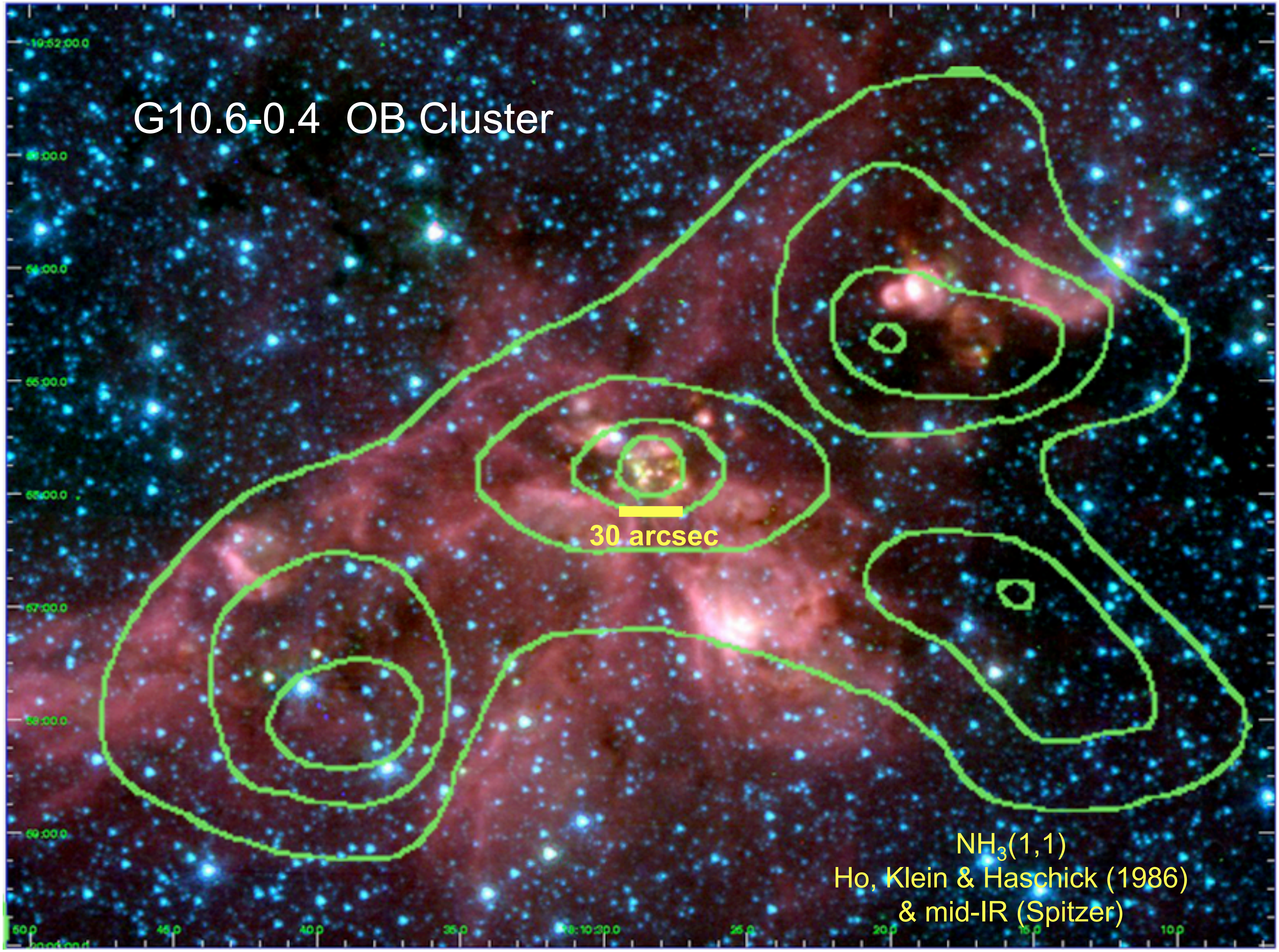


IRAS 20126
Cesaroni, Hofner, Zhang

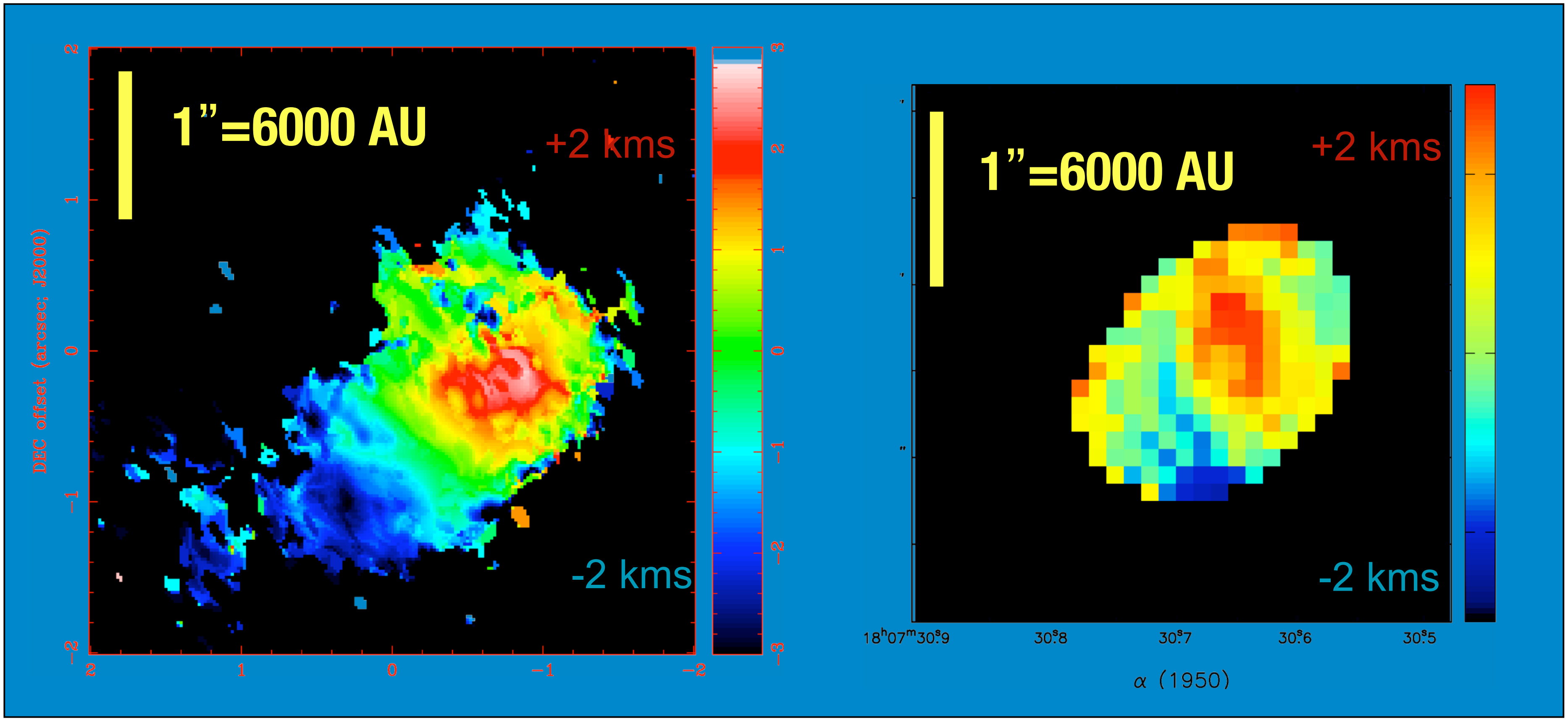
1) Only outflow is through the magnetically driven bipolar wind.
   Outflow-confined HII regions
   Tan & McKee 2003

2) The precursor of an O star is a B star.

3) Almost every core with a B star does or will contain a gravitationally trapped HCHII region (and also an ionized jet).


G10.6-0.4 OB Cluster
30 arcsec
NH3(1,1)
Ho, Klein & Haschick (1986)
& mid-IR (Spitzer)

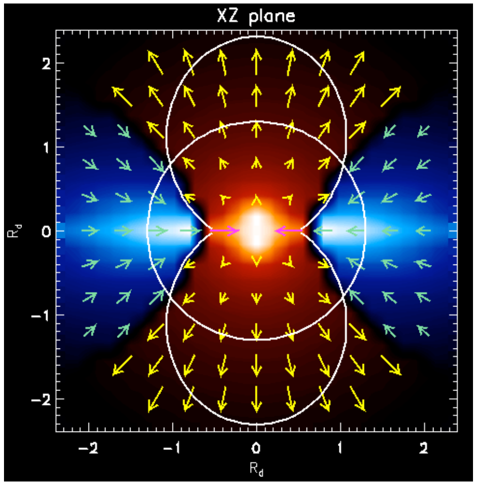
Supermassive Accretion Flow
Gravitationally Trapped by Cluster Potential



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

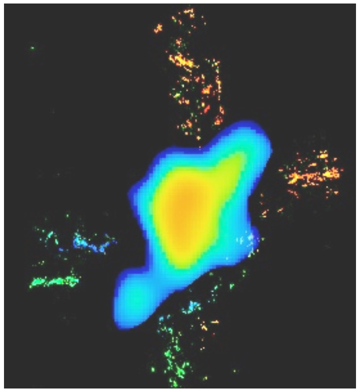
Mean velocity of ionized gas (H66a)
Keto (2002)

Medium ionization $R_{HII} \sim R_s$
Molecular-Ionized Accretion Flows
Pressure-driven winds



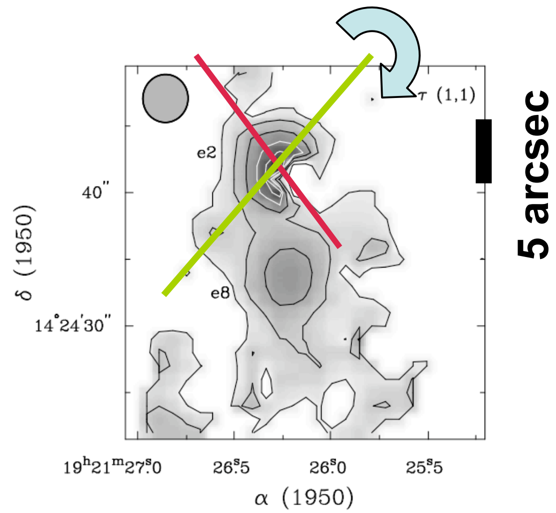
1) HII is fed by the accretion flow along the mid-plane
   Example: Ionized Accretion DISK

2) The HII expands by thermal pressure towards the poles
   Theory: Parker stellar wind
   Example: Pressure driven outflow

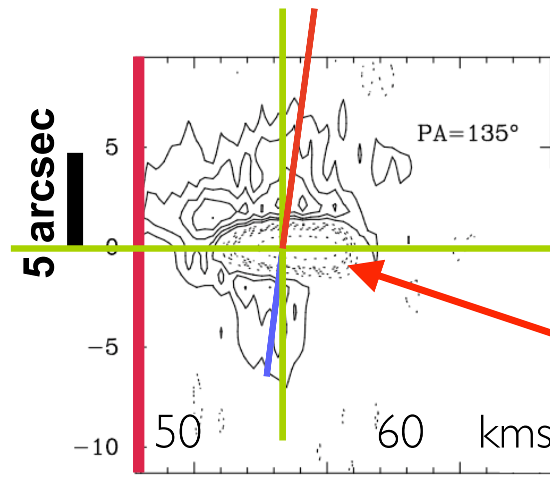


ORION I
Reid, Greenhill

Molecular and ionized accretion DISKS



NH_3(1,1) optical depth

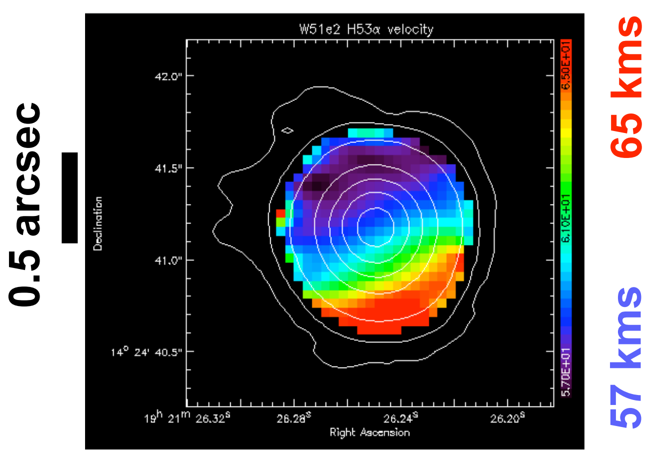


NH_3(1,1) velocity

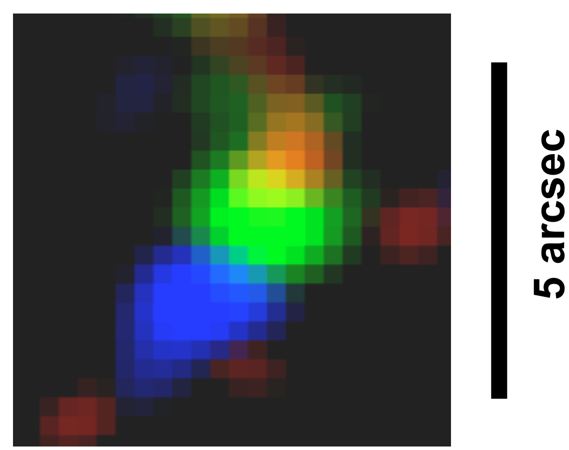
Red-Blue emission
Rotation

Red-shifted
absorption = infall

W51e2   O star
Zhang et al 1997
Klaassen 2007



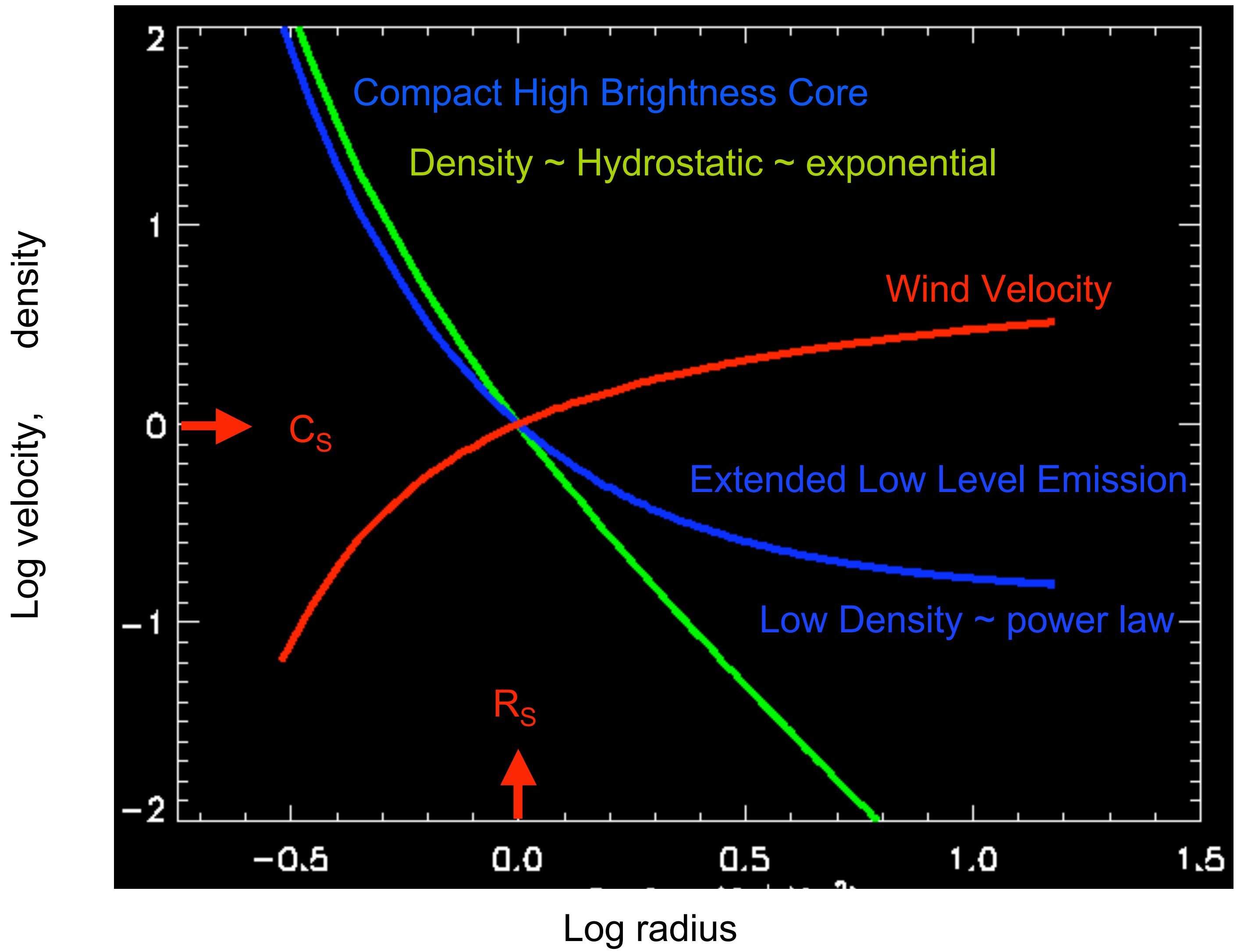
H53a velocities



CO(2-1) velocities

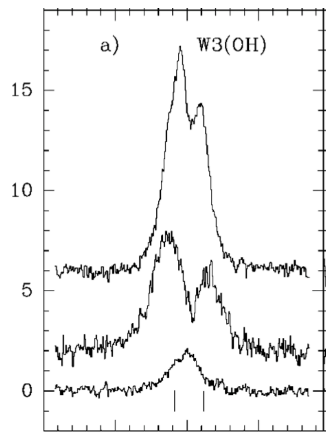
Pressure Driven Winds:
Compact & Extended Emission

Parker isothermal wind (Parker 1958)

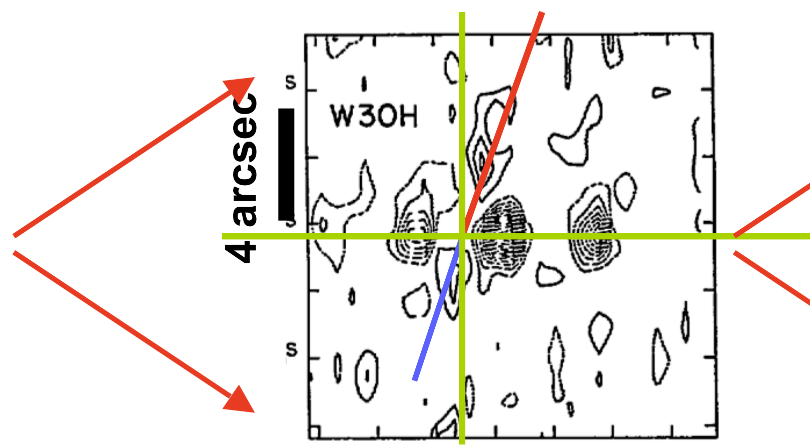


Compact and Extended Wind Emission

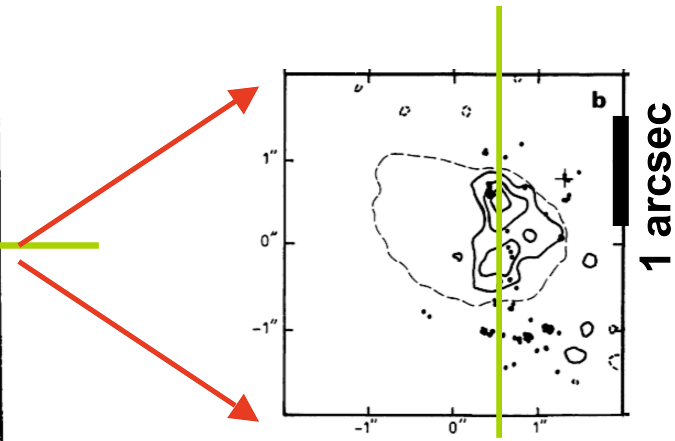
W3(OH) O7 star



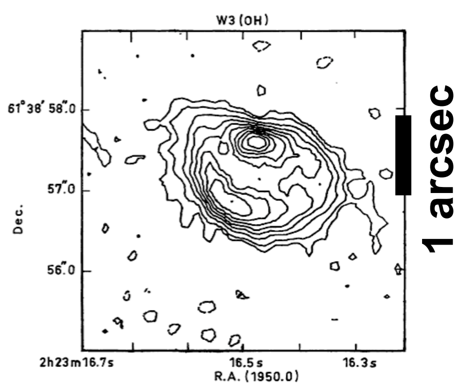
CS & HCN



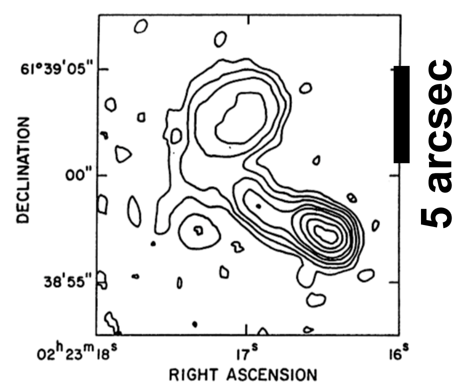
$NH_3(1,1)$ velocity



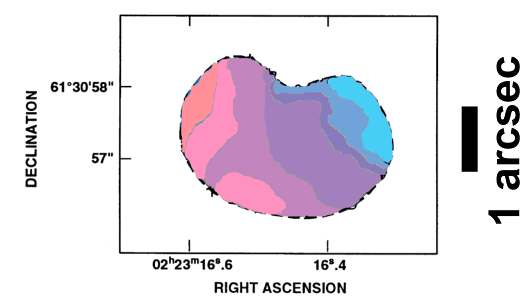
$NH_3(2,2)$



1.3 cm



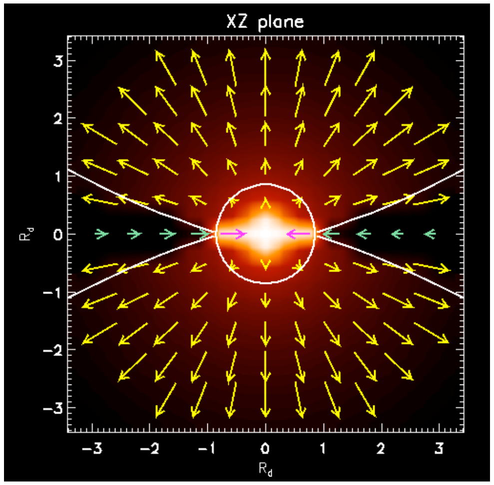
21 cm



H92α Velocity

Guilloteau et al (1984) Keto et al (1987, 1995) Wu et al (2003)

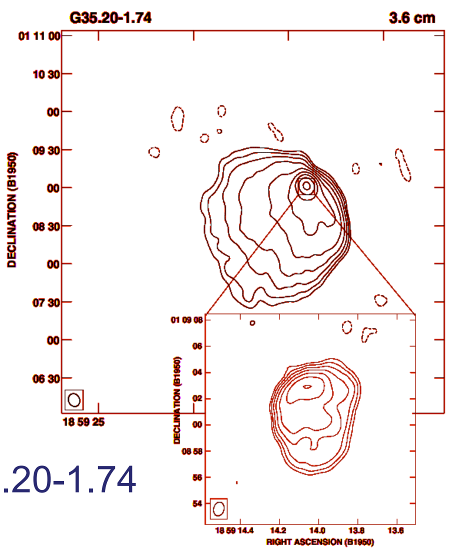
High ionization $R_{HII} > R_b$
flow + photo-evaporating disks



❖UCHII region = hydrostatic core

❖Extended emission = wind + transition to classical (zero G) HII

❖Accretion has ended or will end soon



G35.20-1.74

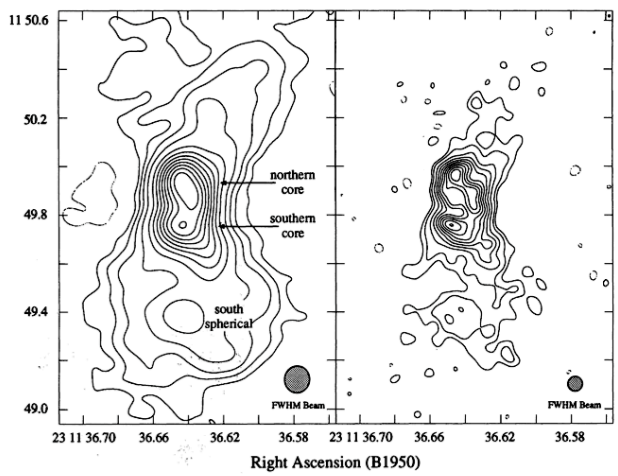
Kurtz 2000

Similar to photo-evaporating disk model (Hollenbach, Lizano, Garay et al)

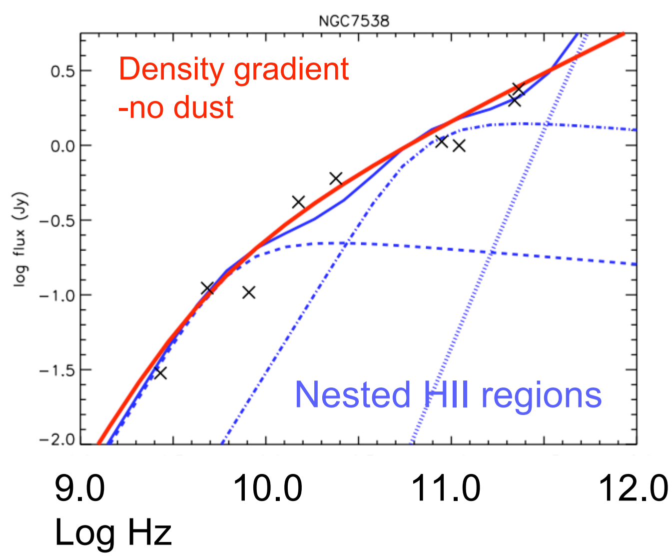
Spectral Energy Distributions

- ❖Density gradients stretch the turnover
- ❖Free-free emission at 100 - 200 GHz

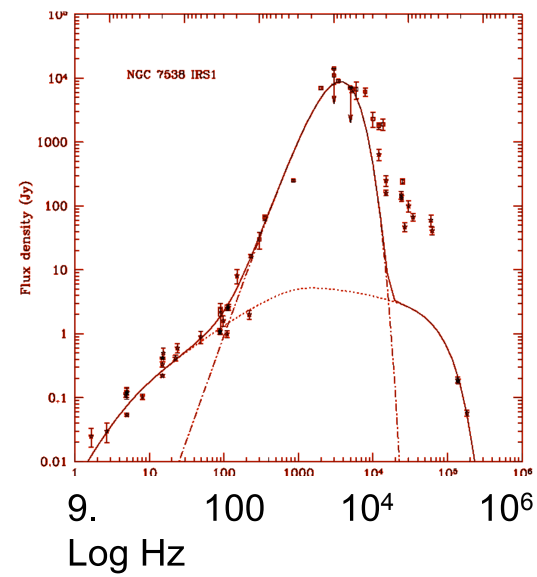
NGC 7538
3.6 cm   1.3 cm



Gaume et al 1995



Pratap et al 1992
Keto 2003
Keto, Zhang, Kurtz 2007



PED + dust
Lugo, Lizano, Garay 2004

Summary

❖The pre-cursor to a massive star is a smaller ZAMS massive star

❖HCHII regions are the ionized portions of flows associated with accretion processes. We observe:

- ❖Rotating ionized disks
- ❖Pressure driven ionized outflows
- ❖Quasi-spherical collapse of ionized envelope (cluster scale)
- ❖If the G force is large enough, P_{HII} not dominant

❖We observe molecular flows with large-scale envelope collapse, spin-up and flattening, outflows, and ionization simultaneously.

- ❖If the G force is high enough, the time scale is compressed

❖HCHII regions are characterized by density gradients and supersonic flows, not constant density and subsonic expansion.

❖There is no life time problem because the gas continuously crosses the HII region.

❖A theory without an observation is not a theory, it is an hypothesis.