HII regions:
the classical view

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Payne-Scott workshop on
Hyper Compact HII regions

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Aim

Review the characteristics of regions of ionized gas within young massive star forming regions.

Will focus the discussion on the smaller regions thought to signpost the earliest evolutionary stages in the formation of high-mass stars.

HII regions

Massive O and B stars:

- Emit copious amount of Lyman continuum photons ($\lambda < 912$ Å).
- Are born within the dense cores of giant molecular clouds.

⇒ While still embedded, their UV photons excite the surroundings giving rise to regions of ionized gas: HII regions.

- Emission mechanism: Thermal free-free emission.
  Detectable as bright radio sources.

In addition, the non-ionizing radiation ($\lambda > 912$ Å) is absorbed in a zone beyond the HII region giving rise to a warm region of dust and molecular gas: IR cocoons.

Emission mechanism: Dust emission.
Detectable as bright infrared sources.

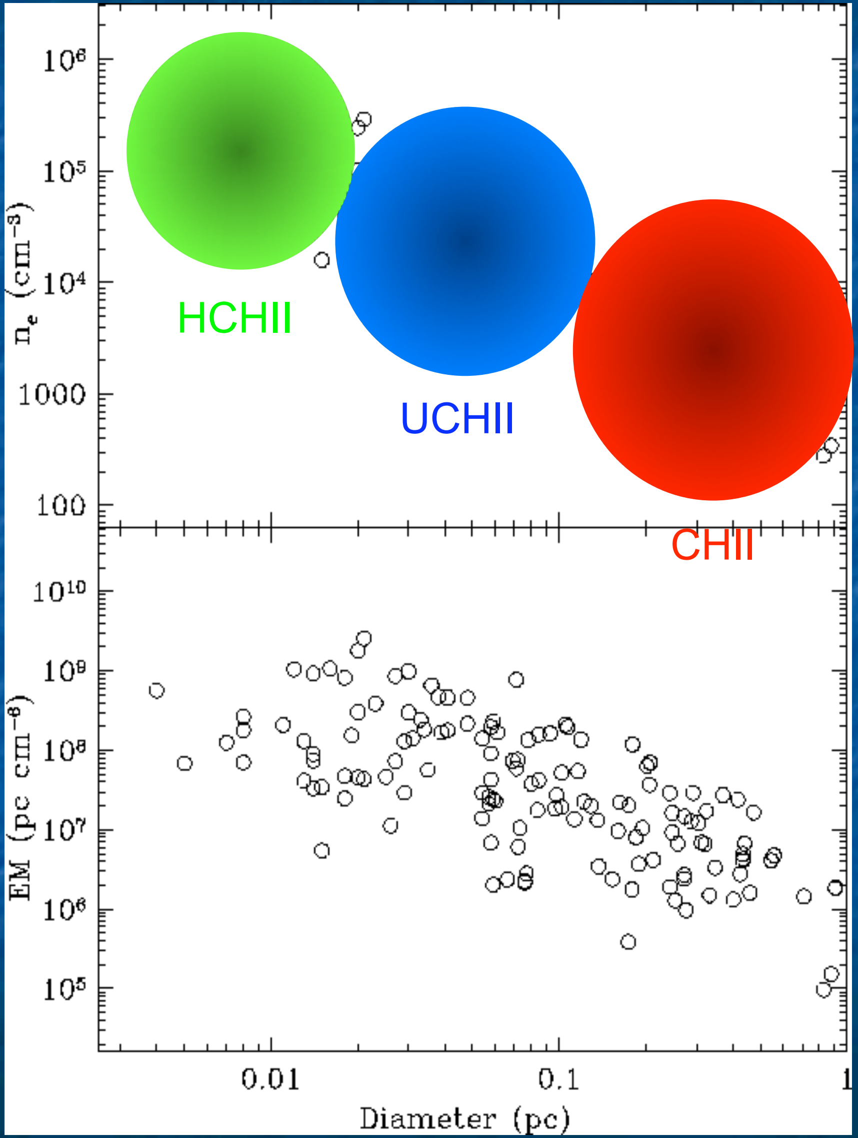
✧ Physical parameters of HII regions

- Based on their sizes, densities and emission measures, three classes of HII regions have been identified :

Class	Diameter (pc)	Density (cm^{-3})	EM ($pc\ cm^{-6}$)	Ref.
Compact	$0.1 < D < 0.5$	$>10^3$	$>10^6$	Mezger et al. (1967)
Ultracompact	$0.02 < D < 0.1$	$>10^4$	$>10^7$	Wood & Churchwell (1989)
Hypercompact	$D< 0.02$	$>10^5$	$>10^8$	Kurtz (2004) Hoare et al. (2007)

Time discovery line ⇔ increase in angular resolution, observing frequency and sensitivity.

- Rather than discrete, there is a continuous distribution in the value of the parameters



Garay & Lizano (1999)
(see also Churchwell 2002)

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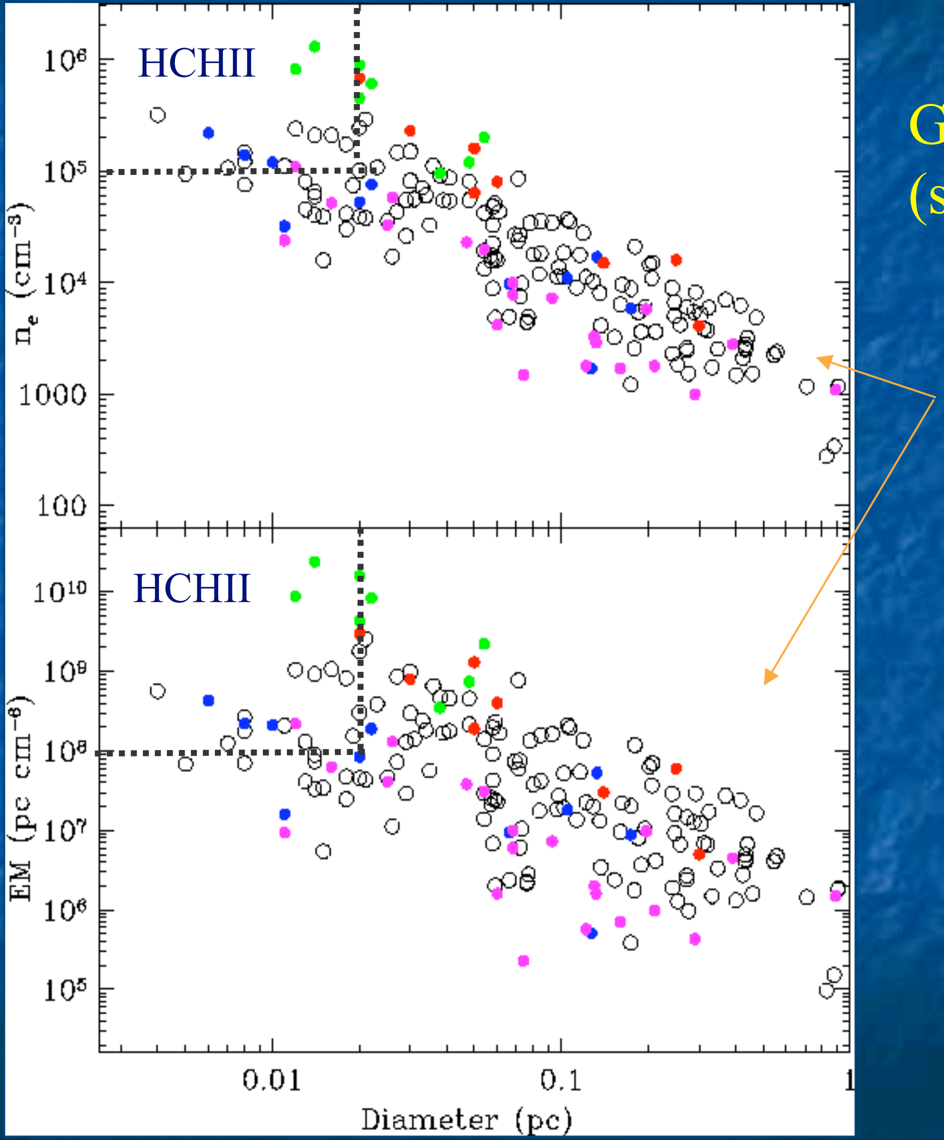


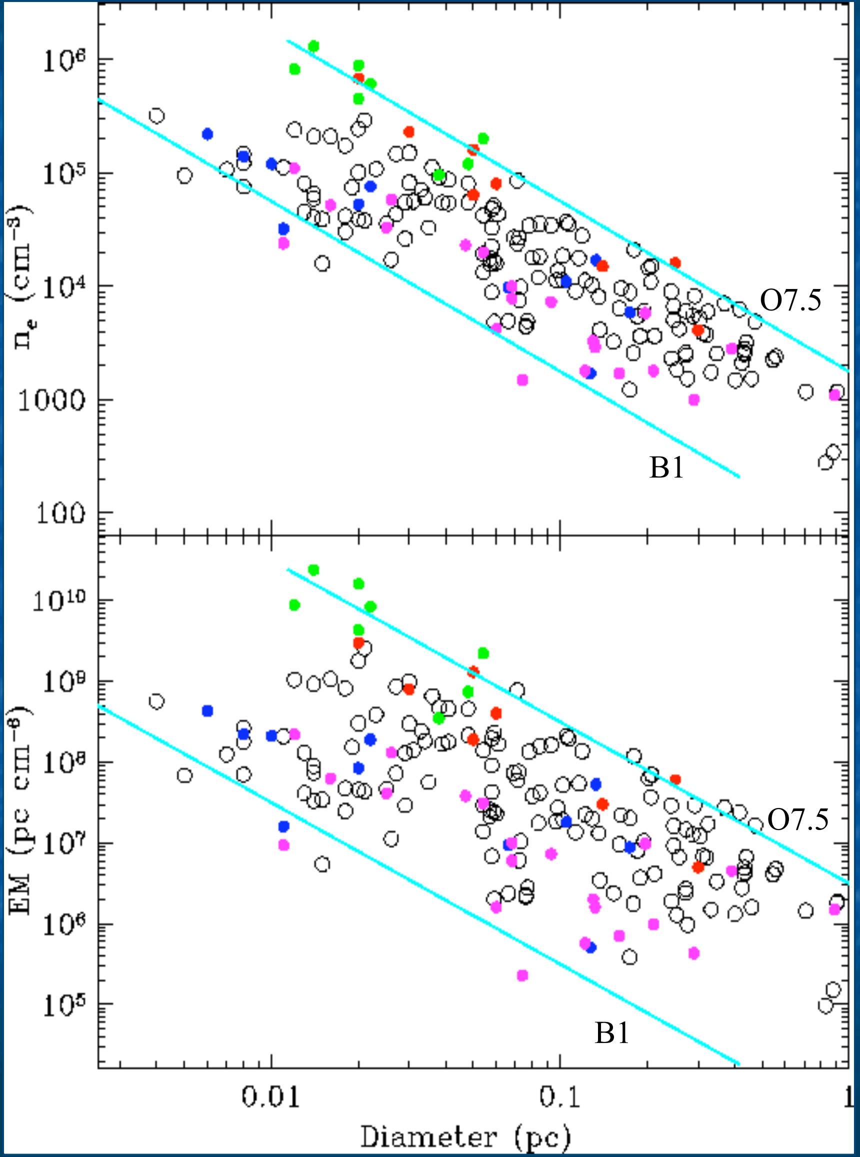
Garay & Lizano (1999)
(see also Churchwell 2002)

+ more data from recent surveys:

● DePree et al. (2004)
● Sewilo et al. (2004)
● Garay et al. (2006)
● Murphy et al. (2010)

⇒ HCHII are uncommon

- There is a significant correlation between the parameters



How do we explain these trends?

Dynamical evolution

Classical model: spherical bubble expanding in a uniform density medium (Spitzer 1978)

$$R(t) = R_S \left(1 + \frac{7}{4}\frac{c_s t}{R_s}\right)^{\frac{4}{7}}$$

$$n_e(t) = 2\,n_o \left(1 + \frac{7}{4}\frac{c_s t}{R_s}\right)^{-\frac{6}{7}}$$

n_o: ambient density, c_S: sound speed

R_S: initial Stromgren radius

$$R_S = 0.0032 \left(\frac{N_U}{10^{48}\,s^{-1}}\right)^{\frac{1}{3}} \left(\frac{10^6\,cm^{-3}}{n_o}\right)^{\frac{2}{3}} pc$$

Lines indicate model relations for:

- $n_o = 10^6$ cm^{-3} and $N_u = 3\times10^{48}$ s^{-1} (upper)
- $n_o = 10^6$ cm^{-3} and $N_u = 3\times10^{45}$ s^{-1} (lower)

This simple dynamical model ⇒

- Massive stars are born in a high density ambient medium.

  Densities are similar to those of hot molecular cores
  ⇨ Hot cores are the precursors of UCHII regions.

- HII regions reach pressure equilibrium with ambient medium in a time scale of a few 10^4 yrs.

  ⇨ Age of compact HII regions could be much larger than this value.

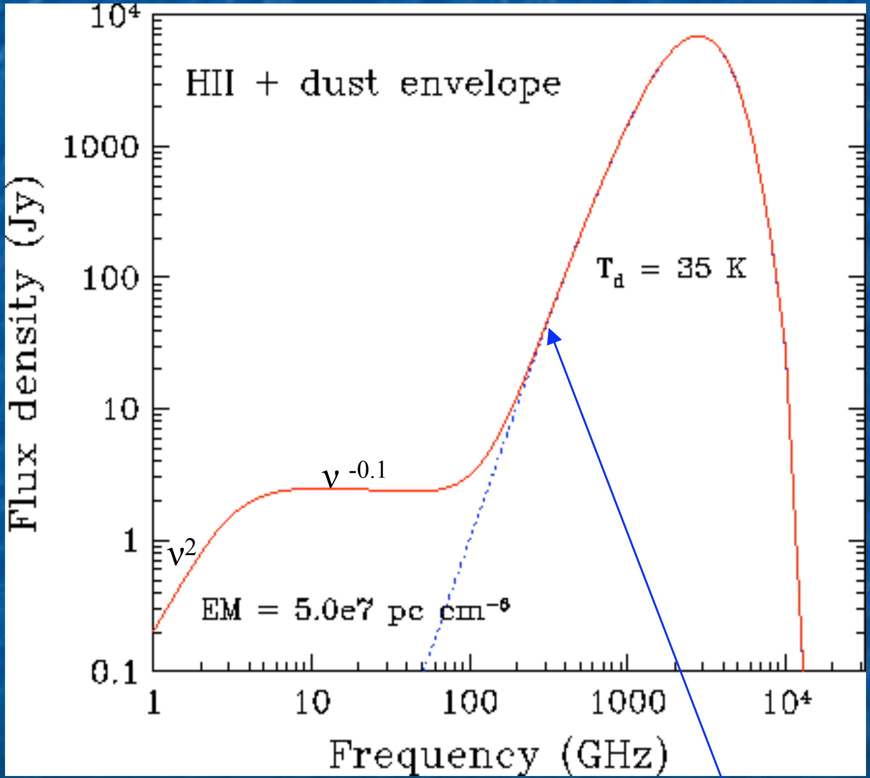
- Hypercompact are the youngest, smaller and denser versions of UCHII regions.

⇨ They should give us information about the process of high-mass star formation in the earliest evolutionary stages

1. Ultracompact HII regions

✧ Spectral energy distribution

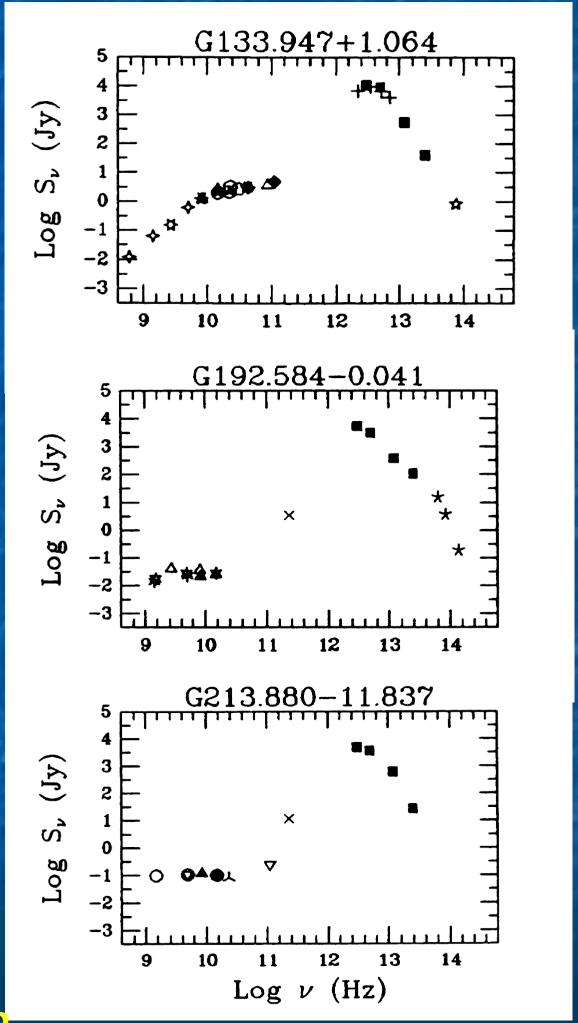
- At $\nu < 30$ GHz ($\lambda > 1$cm):
  free-free emission from ionized gas



- At $\nu > 300$ GHz ($\lambda < 1$ mm):
  thermal dust emission from warm cocoon

Modified Planck function

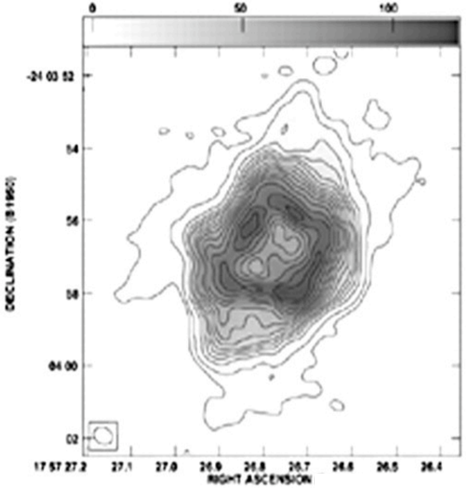
SEDs of UCHII regions



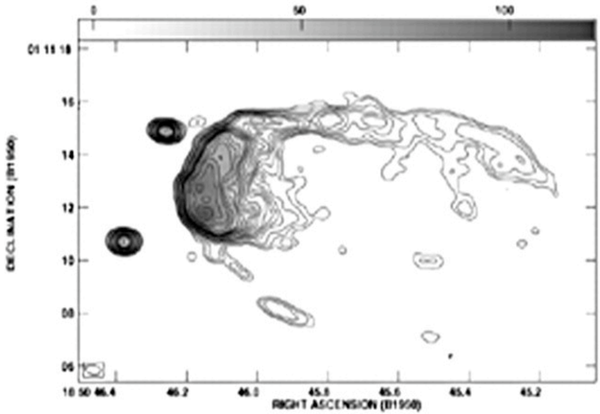
Kurtz et al. 1994

✧ Morphologies

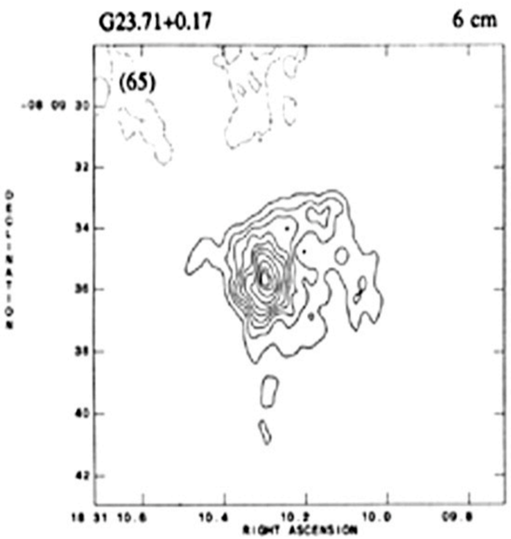
UCHII regions exhibit a variety of morphologies



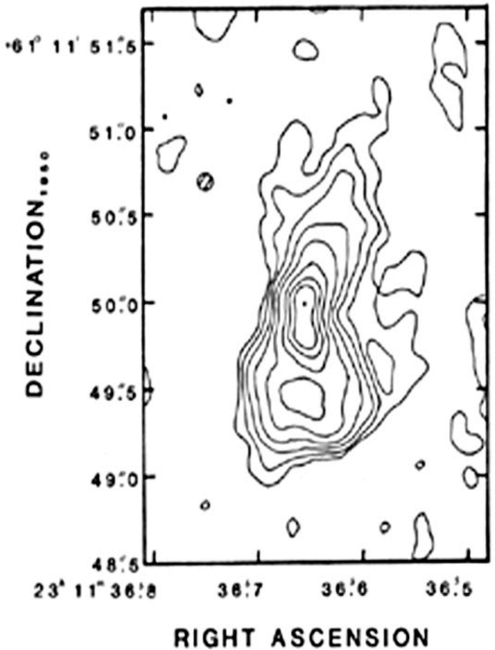
Shell 28%



Cometary 14%



Core-halo 16%



Bipolar 8%

+ spherical, irregular, and unresolved morphologies (Churchwell 2002)

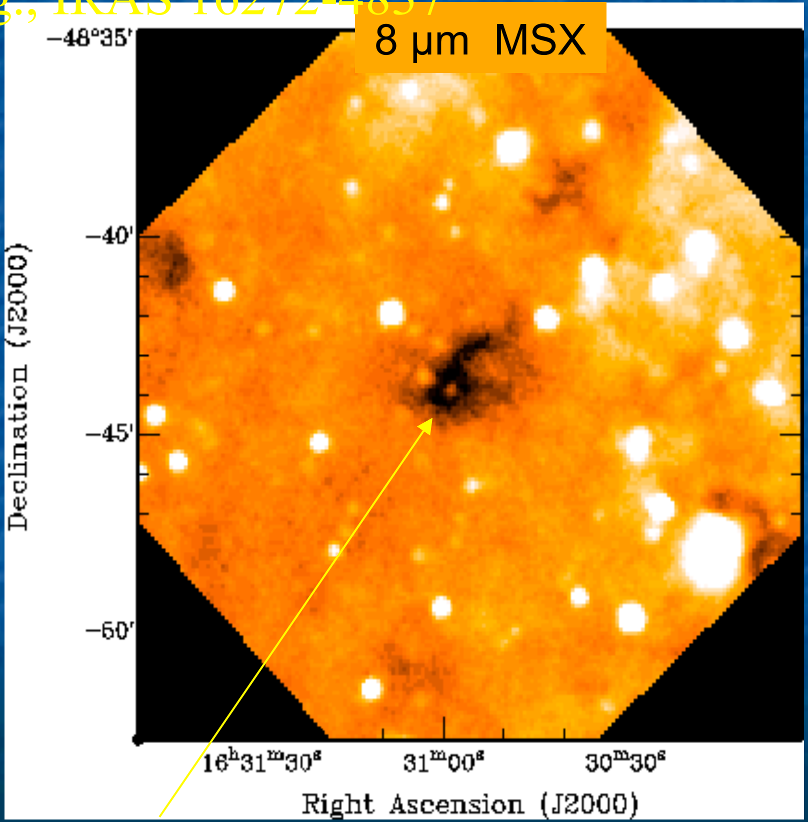
Morphologies depend on the characteristics of the exciting star and of the environment, as well as on their interaction.

2. Hypercompact HII regions

① Characteristics of their large scale (~1 pc) surroundings

Dust continuum and molecular line observations in high density tracers ⇒ HCHII are found inside massive and dense cores.

e.g., IRAS 16272-4837



Massive and dense core

Massive and dense cores

- ✧ Very dark even at IR (IRDCs)
- ✧ Physical parameters:
  - R ~ 0.4 pc
  - M ~ $4\times10^{3}\ M_{\odot}$
  - $n(H_2)$ ~ 6×10^{5} cm^{-3}
  - Δv ~ 6 km s^{-1}
- ✧ Highly centrally condensed
  - $n \propto r^{-1.5}$

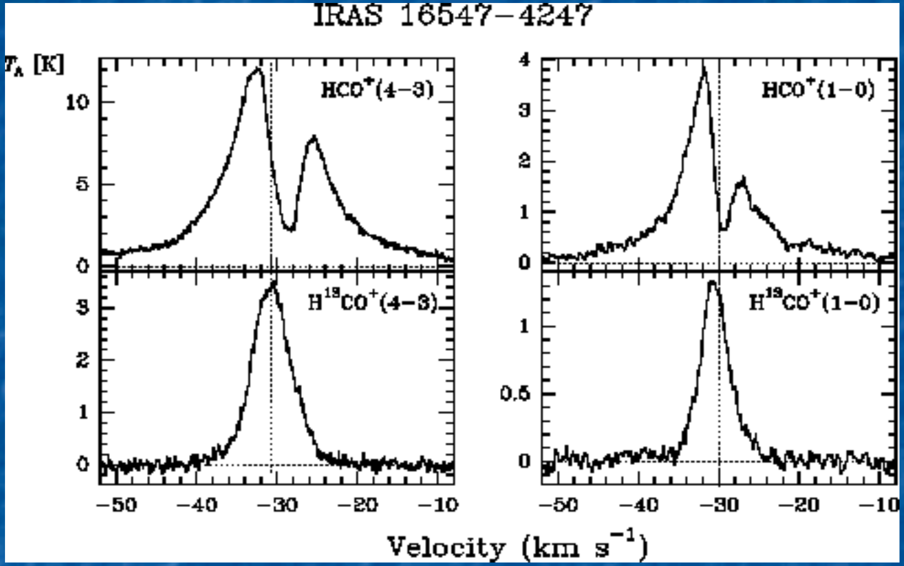
✧ Dynamical state:

- Most in virial equilibrium
- Few undergoing large scale inflow motions

e.g., IRAS 16547-4247

Optically thick lines ➞

Optically thin lines ➞



⇒ large scale infalling motions

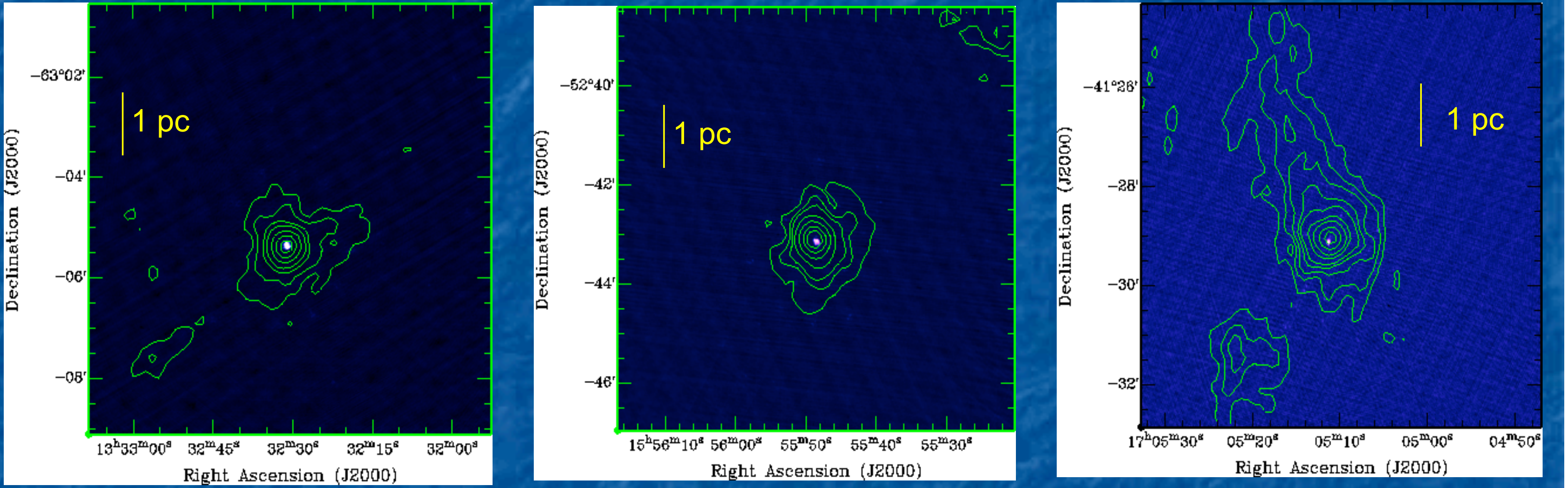
Massive and dense core undergoing intense accretion phase

$V_{inf} \sim 1$ km s^{-1} $\dot{M}_{inf} \sim 1\times10^{-3}$ $M_\odot$ yr^{-1}

About thirty massive dense cores known with infalling motions

Snell & Loren 1977, Welch et al. 1988, Garay et al. 2002, 2003, Wu & Evans 2003

② Where are HCHIIs located within massive and dense cores?



IRAS 13291-6249

IRAS 15520-5234

IRAS 17016-4124

Images: 4.8 GHz emission (HCHII region) Contours: 1.2-mm emission (Massive core)

⇒ HCHII regions typically found at the center of massive cores

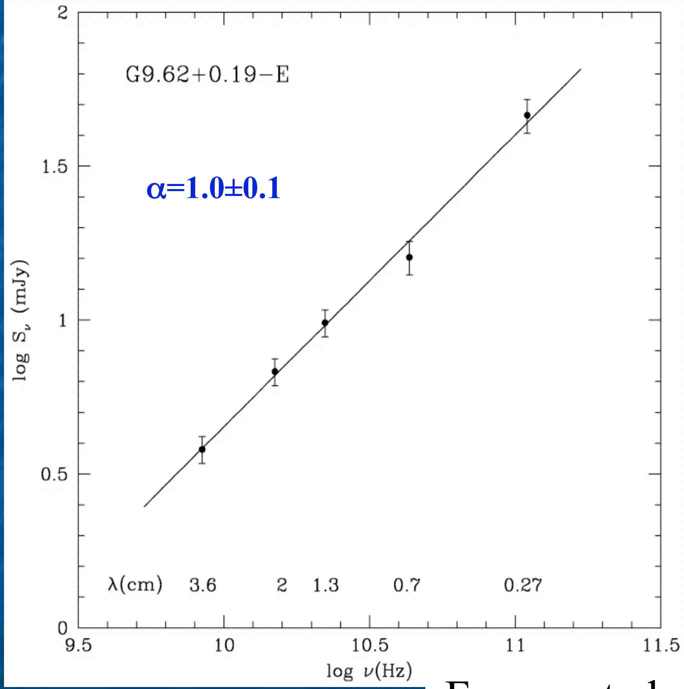
Whether massive stars are formed at the center or migrate there is still an open question.

③ Continuum spectra

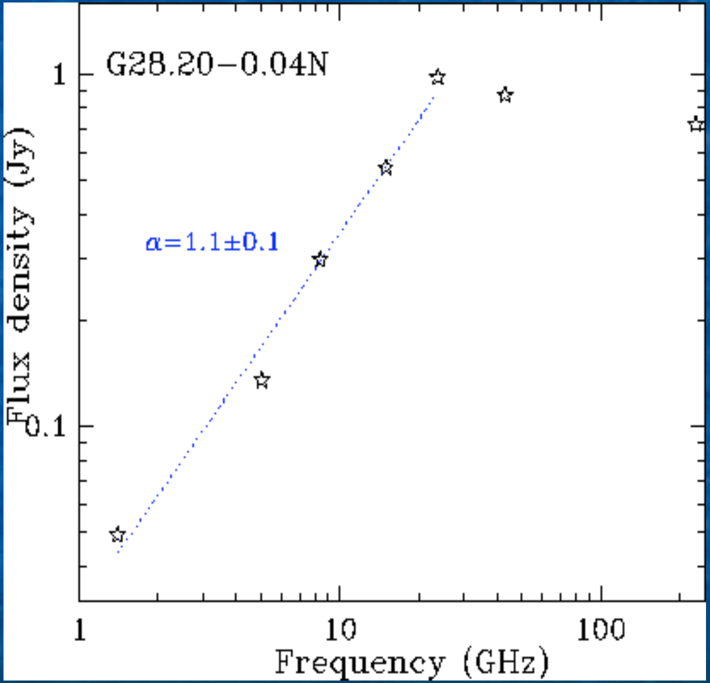
Due to their high emission measure HCHIIs are expected to have turnover frequencies, ν_{to} , greater than 10 GHz.

$$\nu_{to} = 16.0 \left(\frac{EM}{10^9 \, pc \, cm^{-6}} \right)^{0.48} \left(\frac{T_e}{10^4 \, K} \right)^{-0.64} GHz$$

Below ν_{to}, HCHII regions frequently show power-law spectra over a wide frequency range, $S_\nu \propto \nu^\alpha$, with α typically ~1.



Franco et al. (2000)



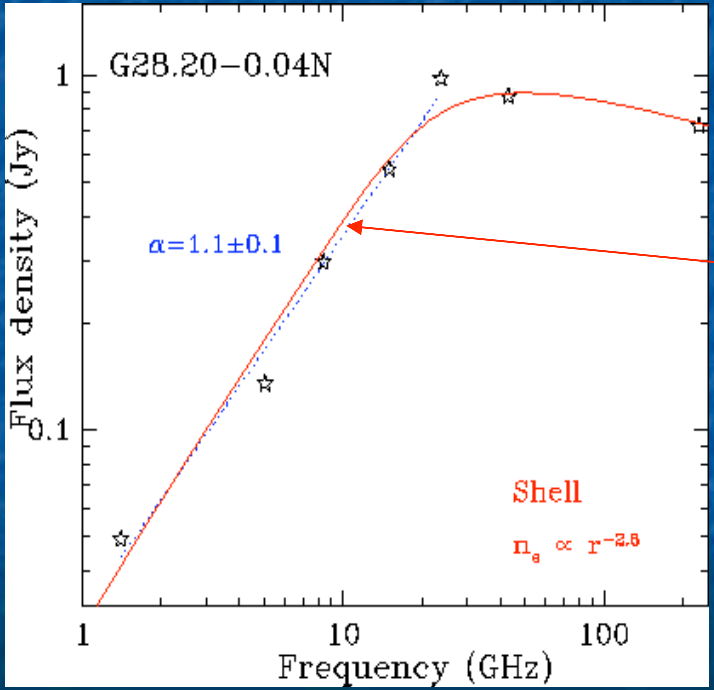
Range of power-law too wide to correspond to the transition from optically thick to optically thin regimes in a constant density region.

Possible explanations for the power-law:

✧ HCHIIs possess density gradients.

For a region in which the electron density goes as $n \propto r^{-\beta} \Rightarrow$
Flux density depends with ν as $S_\nu \propto \nu^\alpha$, with $\alpha=(4\beta-6.2)/(2\beta-1)$
Angular size depends with ν as $\theta_\nu \propto \nu^\gamma$, with $\gamma = -2.1/(2\beta-1)$

e.g. HCHII G28.20-0.04:



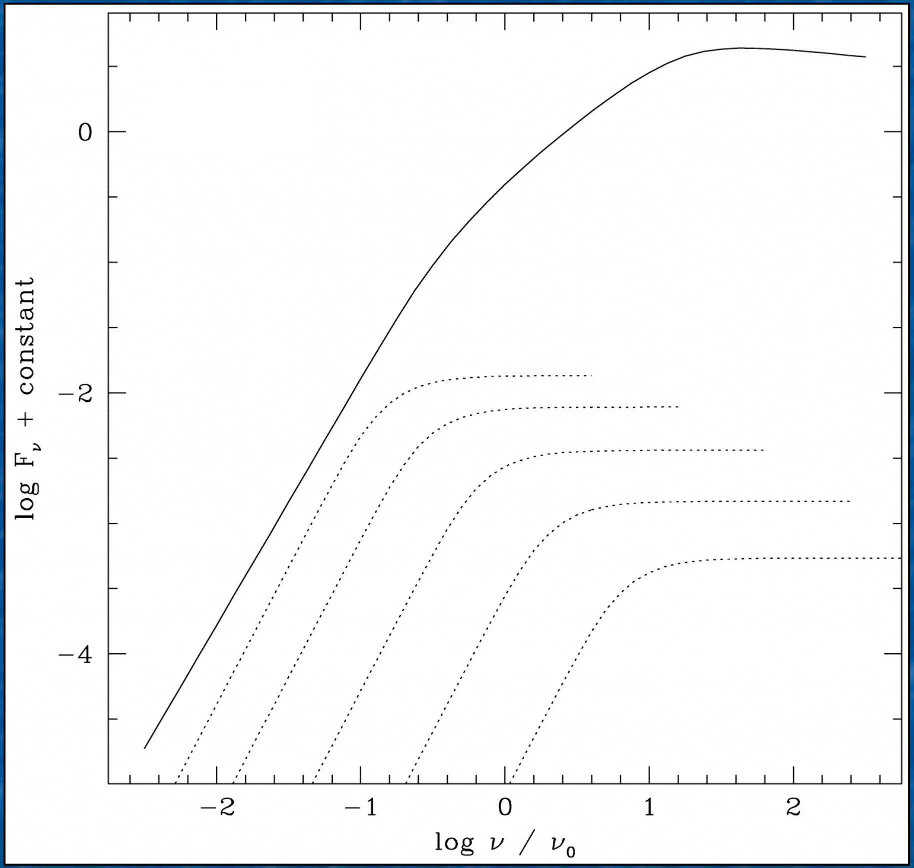
$S_\nu \propto \nu^{1.1} \Rightarrow n \propto r^{-2.8}$
$(\theta \propto \nu^{-0.5})$

Shell model: $R_i = 0.0063$ pc
$R_o = 0.055$ pc
$n_i = 6\text{x}10^5$ cm^{-3}
$\beta = 2.8$

Is the expected size dependence with ν actually observed?

☹ e.g., Avalos et al. (2005)

✧ HCHIIs are hierarchically clumped structures.



Ignace & Churchwell (2004)

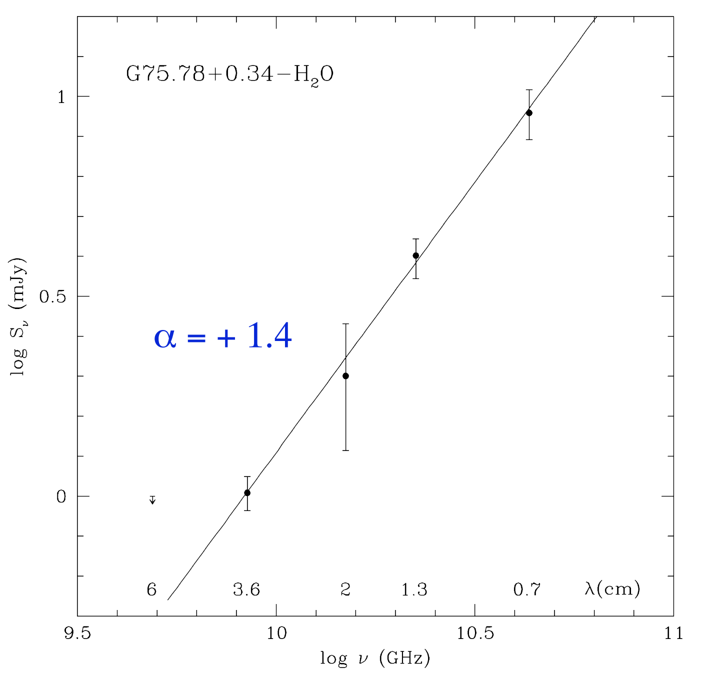
Ensemble of clumps with a distribution of optical depths produce:

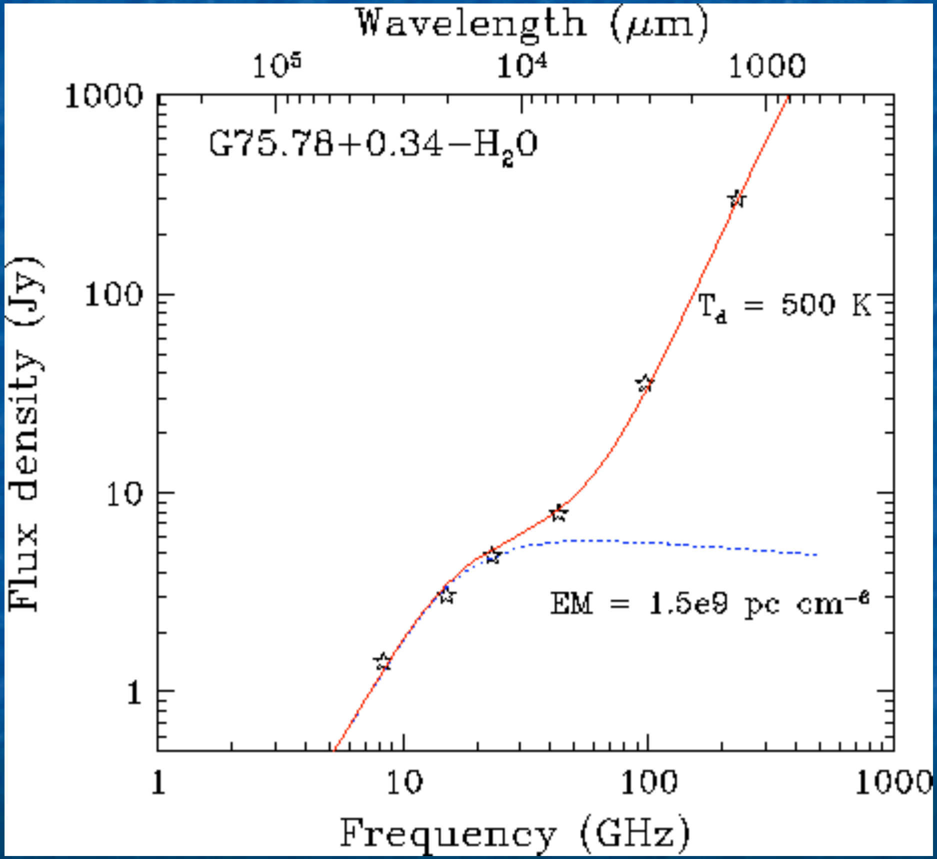
- Power-law spectral index covering a wide frequency range
- No dependence of angular size with frequency

☺

Caveat: Contribution from dust and free-free emission at frequencies of ~50 GHz can be of the same order, affecting the spectral index interpretation.

e.g., G75.78+0.34-H_2O





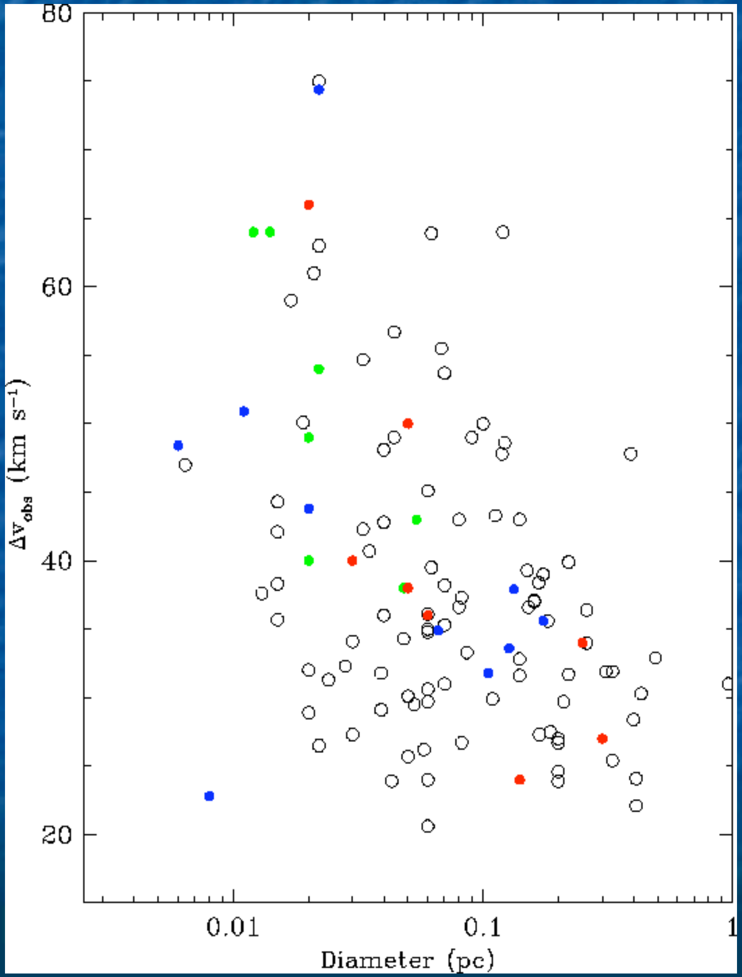
$\Rightarrow n \propto r^{-4}$ ☹

Franco et al. (2000)

Cte. density HCHII region + hot dust disk

④ Radio recombination lines

HCHII regions often have broader line widths than UCHII regions.



$\Delta v_{HCHII} > 40$ km s^{-1}

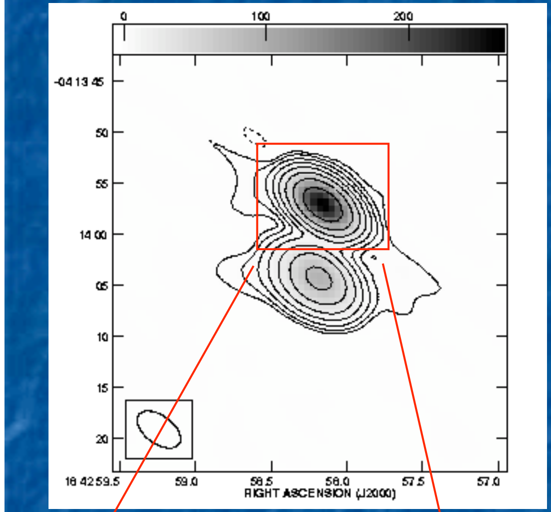
Origin of line broadening?

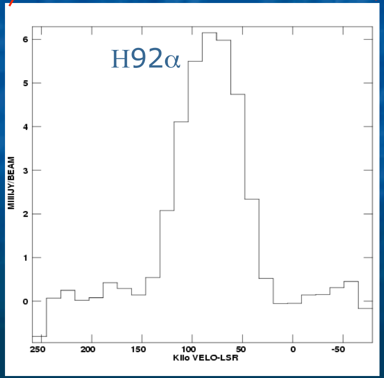
Possible mechanisms:

- Large-scale organized motions:
  rotation
  expansion
  infall
- Pressure broadening
  $\Delta v \propto n^{7.4}\, n_e$

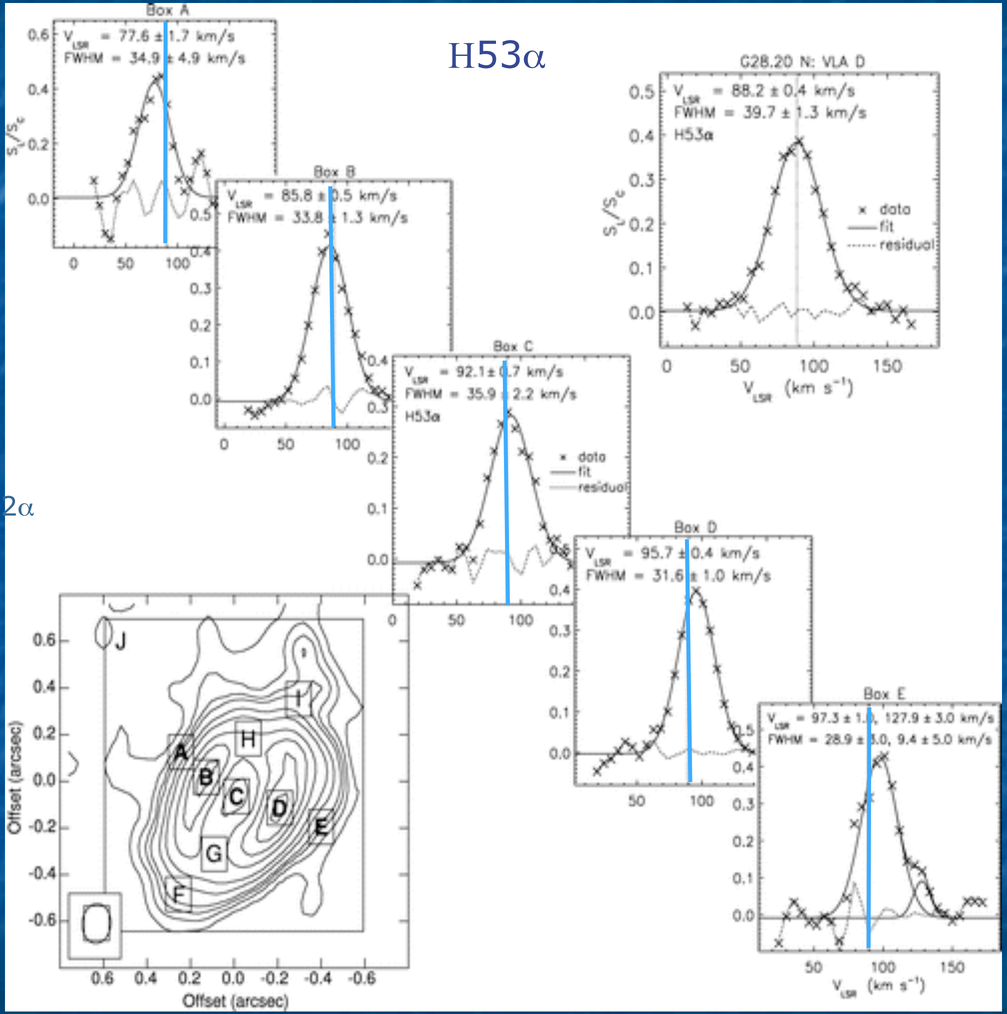
✧ High angular resolution observations indicate that ordered motions are present.

e.g. G28.20-0.04 N





Δv
74 km s^{-1}



H92α

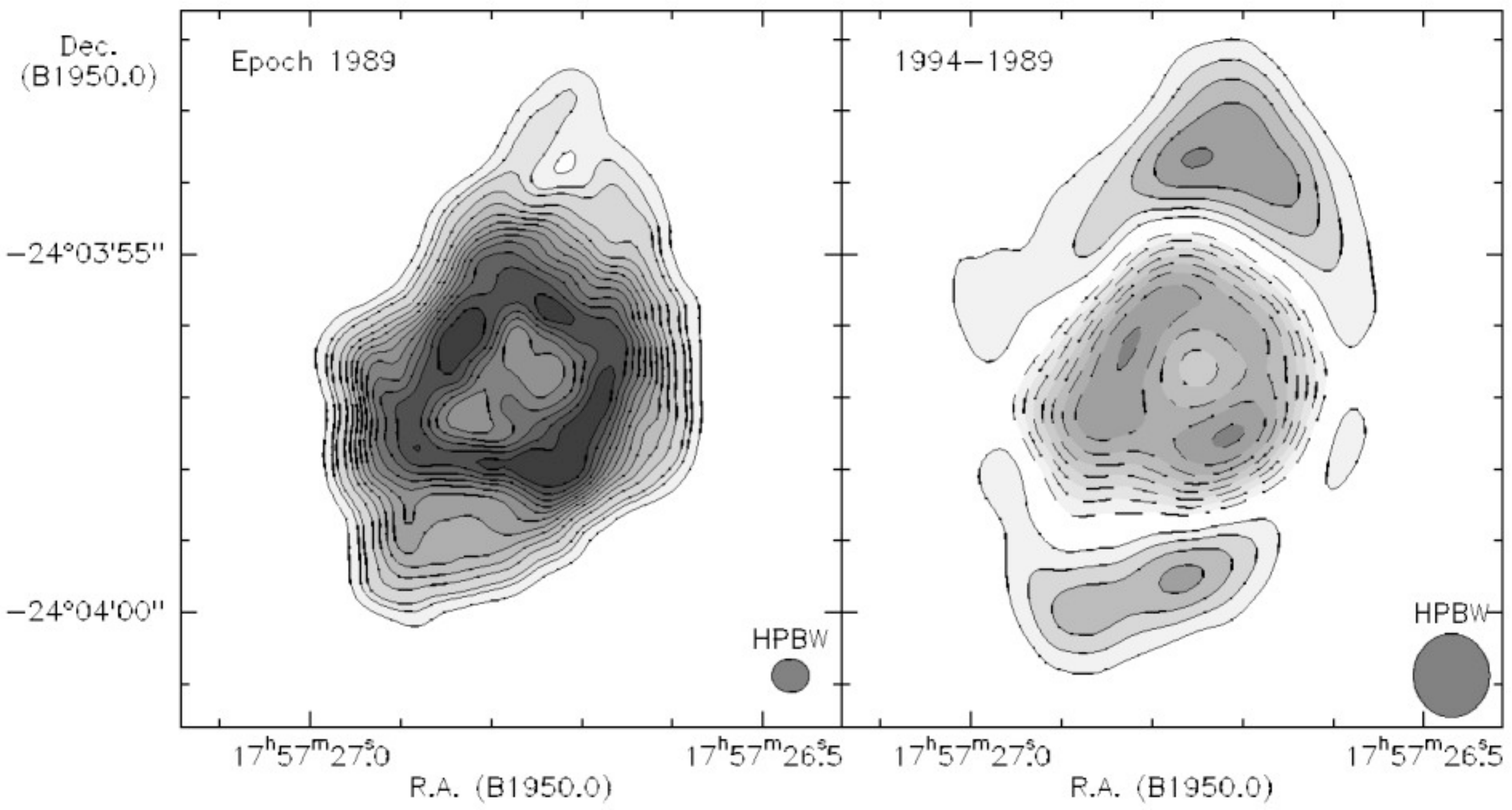
Sewilo et al. (2008)

Sewilo et al. (2004)

Velocity gradient of 10^3 km s^{-1} pc^{-1}.

⇨ Rotating torus with a velocity of 5 km s^{-1} at 0.005pc

- G5.89-0.39



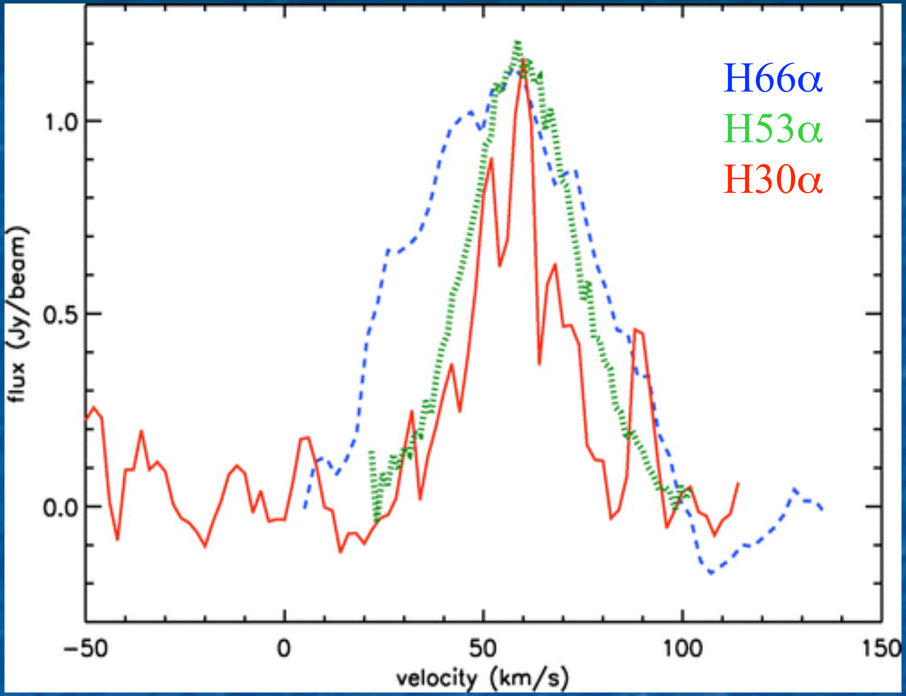
VLA observations in two epochs with Δt = 5 years, Acord et al. (1998)

⇒ Expansion motions with a velocity of about 35 km s^{-1}.

In most cases the bulk motions are not able to explain the observed linewidths.

✧ Pressure broadening is the most important contributor.

e.g. W51e2



Line	Δv ($\mathrm{km\ s^{-1}}$)	n_e ($\mathrm{cm^{-3}}$)
H66α	50.9	2.2e6
H53α	32.5	4.7e6
H30α	26.8	---

For G28.20-0.04 N:

Line	Δv ($\mathrm{km\ s^{-1}}$)	n_e ($\mathrm{cm^{-3}}$)
H92α	74 .4	3e5
H76α	57.6	9e5
H53α	39.7	7e6

In addition to the high densities, the RRL observations indicate the presence of density gradients (at the higher frequency seeing deeper into the region).

⑤ Models

✦ Accretion flow (Keto 2002)

Ingredients: Gravity + Ionization

Two characteristic radii → R_i : radius of ionization equilibrium

→ R_g : gravitational radius (escape radius for ionized gas)

$$R_i = 0.0032 \left(\frac{N_U}{10^{48} s^{-1}}\right)^{\frac{1}{3}} \left(\frac{10^6 cm^{-3}}{n_o}\right)^{\frac{2}{3}} pc$$

$$R_g = \frac{GM_*}{c_s^2} = 0.0007 \left(\frac{M}{20\, M_\Theta}\right) pc$$

If $R_i < R_g$ ⇒ ionized gas can not expand

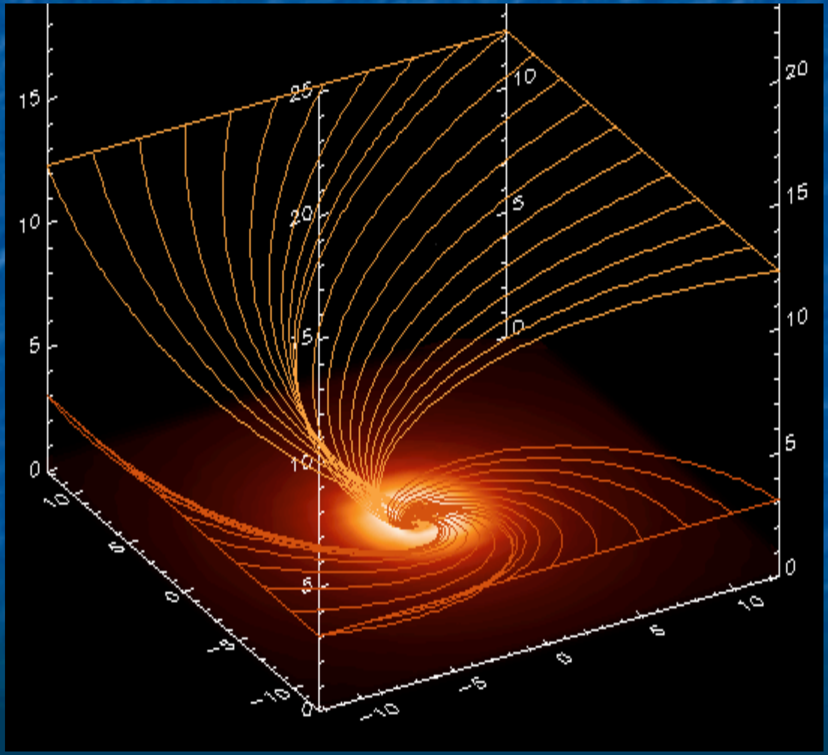
gravitationally trapped HII region

✦ Accretion disk (Keto 2007)

Ingredients: Gravity + Ionization + Rotation of primordial cloud

Third characteristic: radius ⟶ radius at which centrifugal and gravitational forces balance

$$R_d = \left(\frac{5}{6G}\right)\frac{L^2}{M^3}.$$



Actual situation depends on the relative values of the three R's.

If $R_i > R_d$, Rg
⇒ radial wind driven by the thermal pressure of the ionized gas.

✦ Photoevaporating disks

Ingredients: Keplerian circumstellar disk + luminous YSO

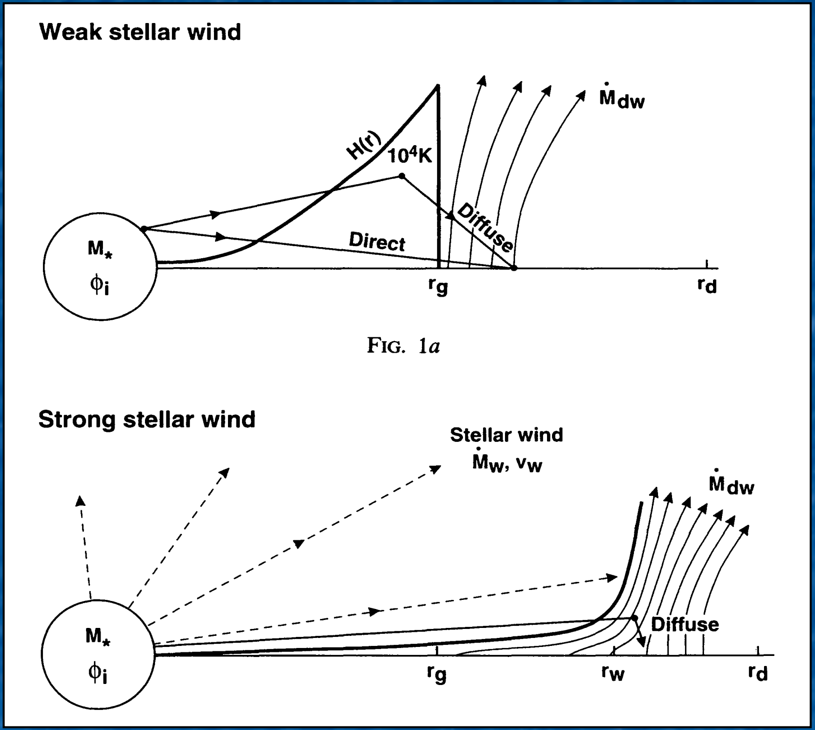
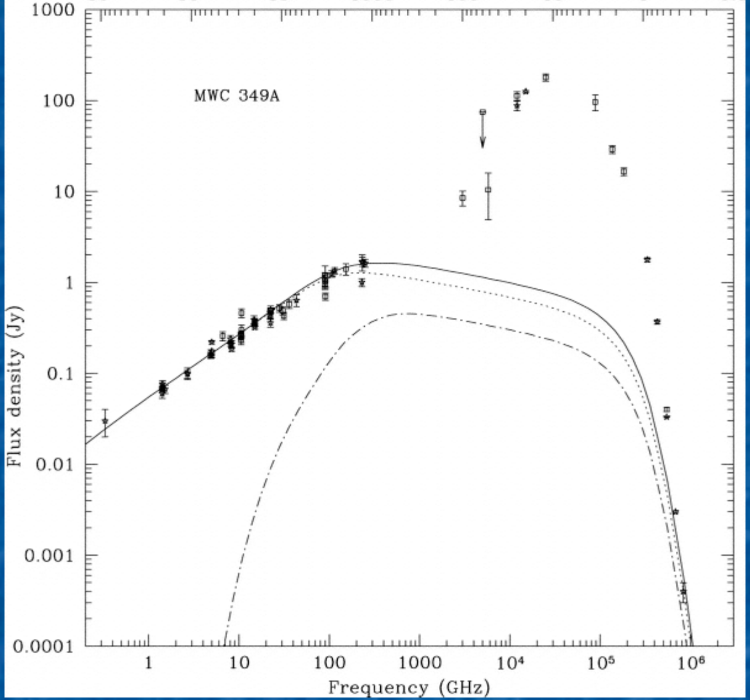


FIG. 1*a*



Hollenbach et al. (1994)
Lizano et al (1996)

R_g = 0.0007 pc , R_d = 0.0015 pc
Density gradient of photoevaporated wind produce spectral index of ~ 0.8.

Lugo et al. (2004)

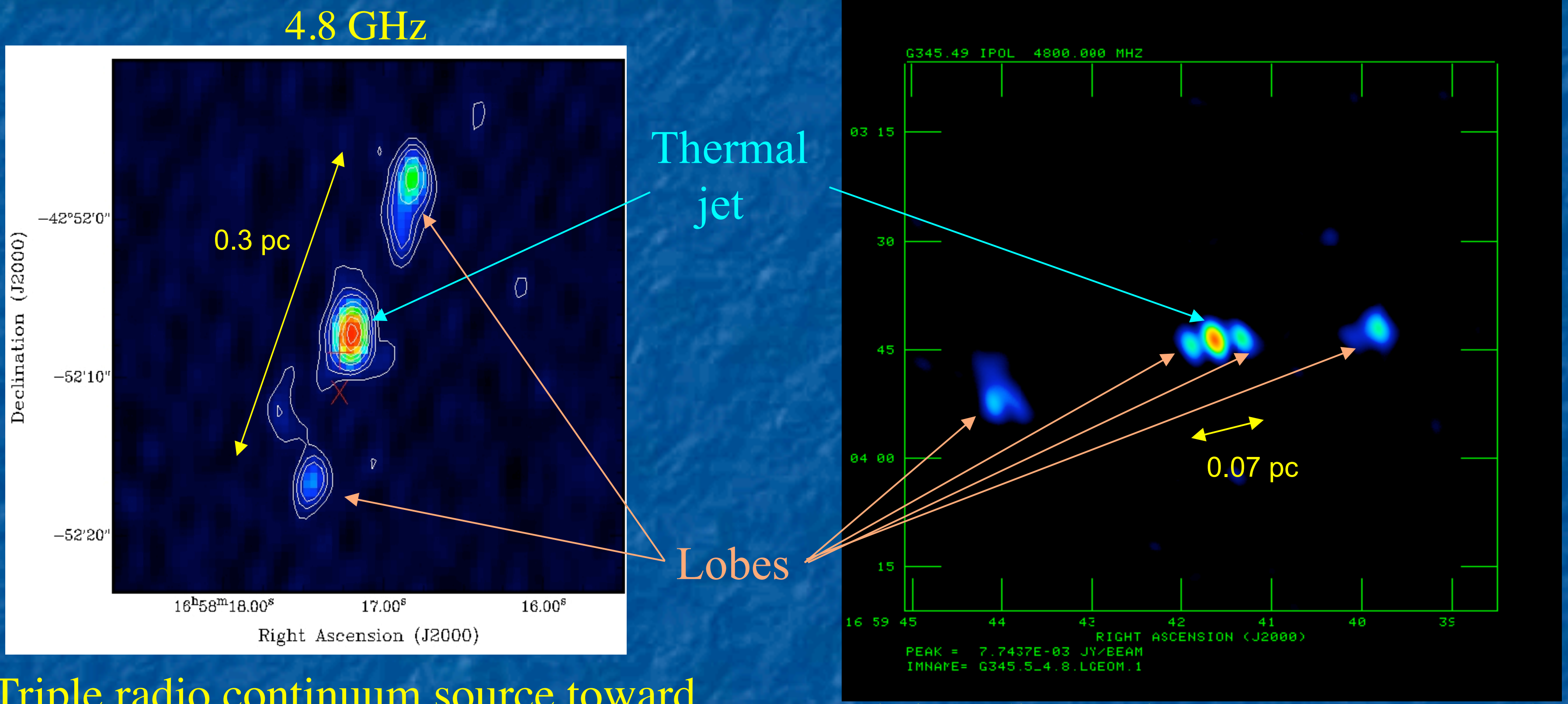
In the case of low-mass protostars, observations clearly show a Disk-Jet symbiosis.

Disk: Protostar grows by accreting from disk.

Jet: Carries away angular momentum and mechanical energy from disk into the surroundings, allowing accretion to proceed.

- ✦ Are young massive stars associated with ionized jets?

ATCA survey of radio continuum emission toward luminous massive proto-stellar objects.



Triple radio continuum source toward IRAS 16547-4247 ($L = 6\times10^4\ L_\odot$)

Garay et al (2003)

Triple radio continuum source toward IRAS 16562-3959 ($L = 7\times10^4\ L_\odot$)

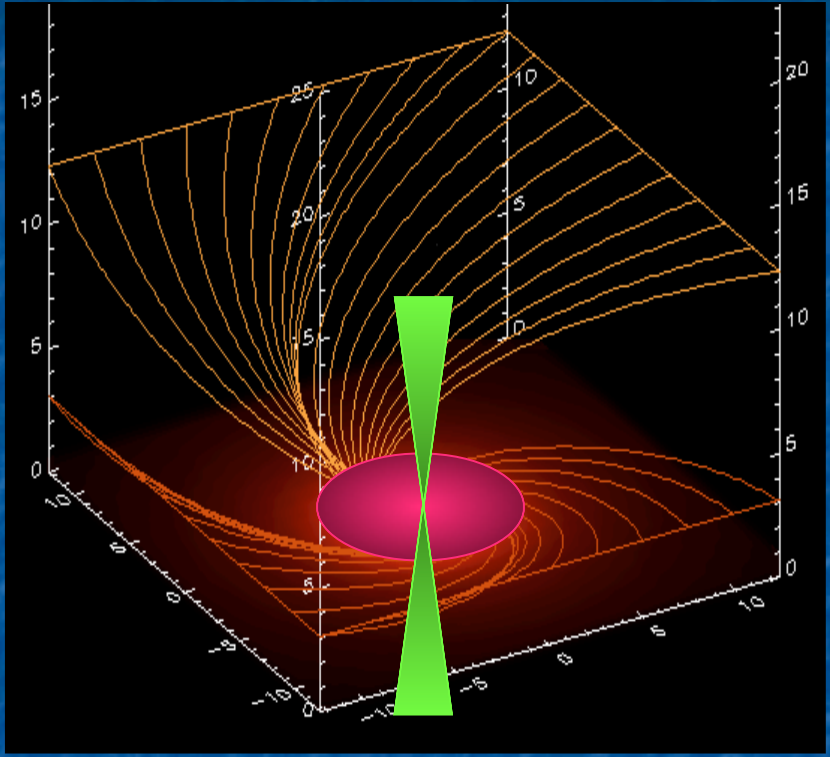
Guzman et al. (2010)

⇒ Jets are found associated with luminous YSOs.

Next model:

✦ Accretion disk + jet

Ingredients: Gravity
+ Ionization
+ Rotation
+ Magnetic field



Conclusions

✧ CHII, UCHII and HCHII regions are probes of the different phases of evolution of regions of ionized gas excited by young high-mass stars.

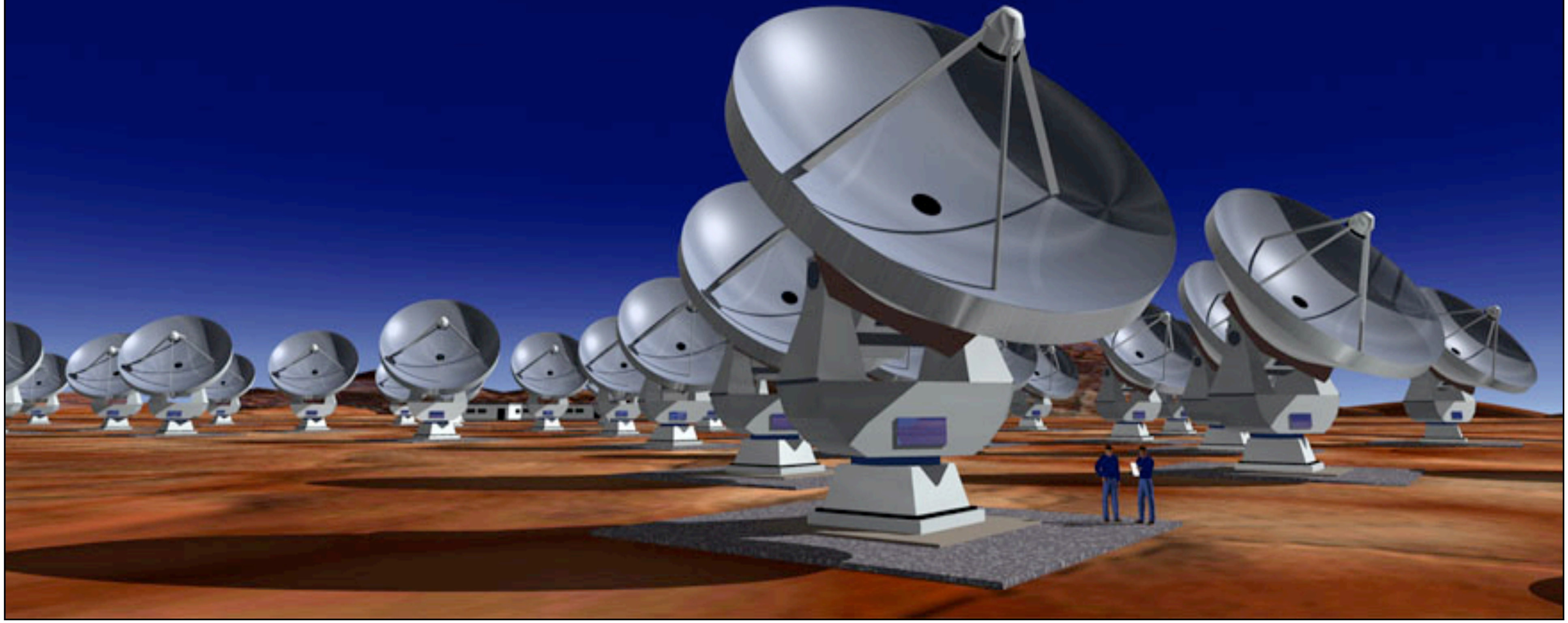
CHII : pressure equilibrium between ionized gas and ambient medium.
UCHII : dynamics is dominated by the thermal pressure of the ionized gas.
HCHII : dynamics is dominated by the stellar gravity and accretion.

✧Still far from understanding HCHIIs

- $S_\nu \propto \nu^{1.0}$
  - density gradients : $n \propto r^{-2.5}$?
  - ensemble of clumps ?
- Broad linewidths
  - Disk rotation ?
  - Outflows ?
  - Pressure broadening ?
- Morphologies ?
- Are the high-mass stars exciting HCHII regions formed at the center of massive and dense cores or they migrate there?

To address these questions we need to probe HCHIIs regions with spatial resolutions of < 50 AU.

ALMA



SCIENCE WITH ALMA

- Protostars and young stellar objects

Measurement of the motions associated with gravitational infall at scales of < 100 AU and with a velocity resolution of 0.02 km/s

⇨ rate of mass infall from the dense cores

- Accretion disks

Measurements of the velocity structure and mass distribution of the protostellar accretion disks

⇨ dynamics and rate of accretion from disk

- Outflows

Images of the acceleration very near the origin of the flow and of the entrainment region.

⇨ nature of driving source and driving mechanism

✦ Observational consideration

How many massive protostars we expect to see in our Galaxy?

Massive stars spend short time in the pre-main sequence:

$$\tau_{K-H} \approx 7\times10^4 \left(\frac{M}{20\,M_{SUN}}\right)^{-3} yr$$

Kelvin-Helmholtz time

Rate of massive star formation in the Galaxy:

$$\dot{N}(>M) \approx 0.003 \left(\frac{M}{20\,M_{SUN}}\right)^{-3}$$

➡ $$N_{PMS}(>M) \approx \tau_{K-H} \times \dot{N}(>M) \approx 200 \left(\frac{M}{20\,M_{SUN}}\right)^{-6}$$

⇨ Massive protostars are very rare