Submillimeter observations of high-mass star formation

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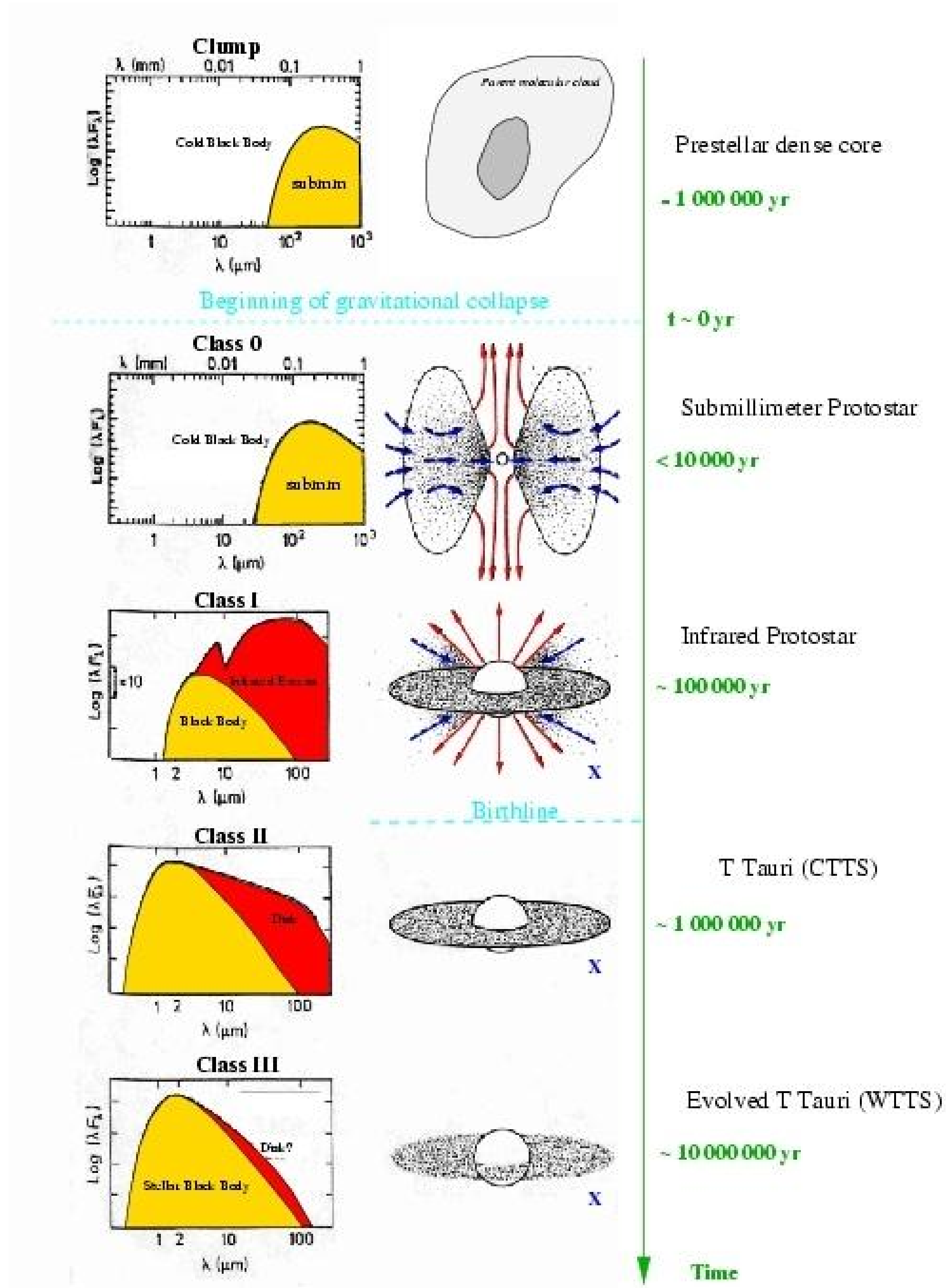
Outline

- Introduction
  - Low mass star formation
  - High mass stars and stellar clusters
- Methodology
  - Observations: wavelengths and scales
  - Models: gas and dust
- Results
  - Chemical clocks
  - Tracing invisible radiation
  - Multiple deuteration: Initial conditions
  - AFGL 2591: A massive disk of dust and water
  - Cosmic-ray ionization
- Conclusions

“Standard model” of low-mass star formation



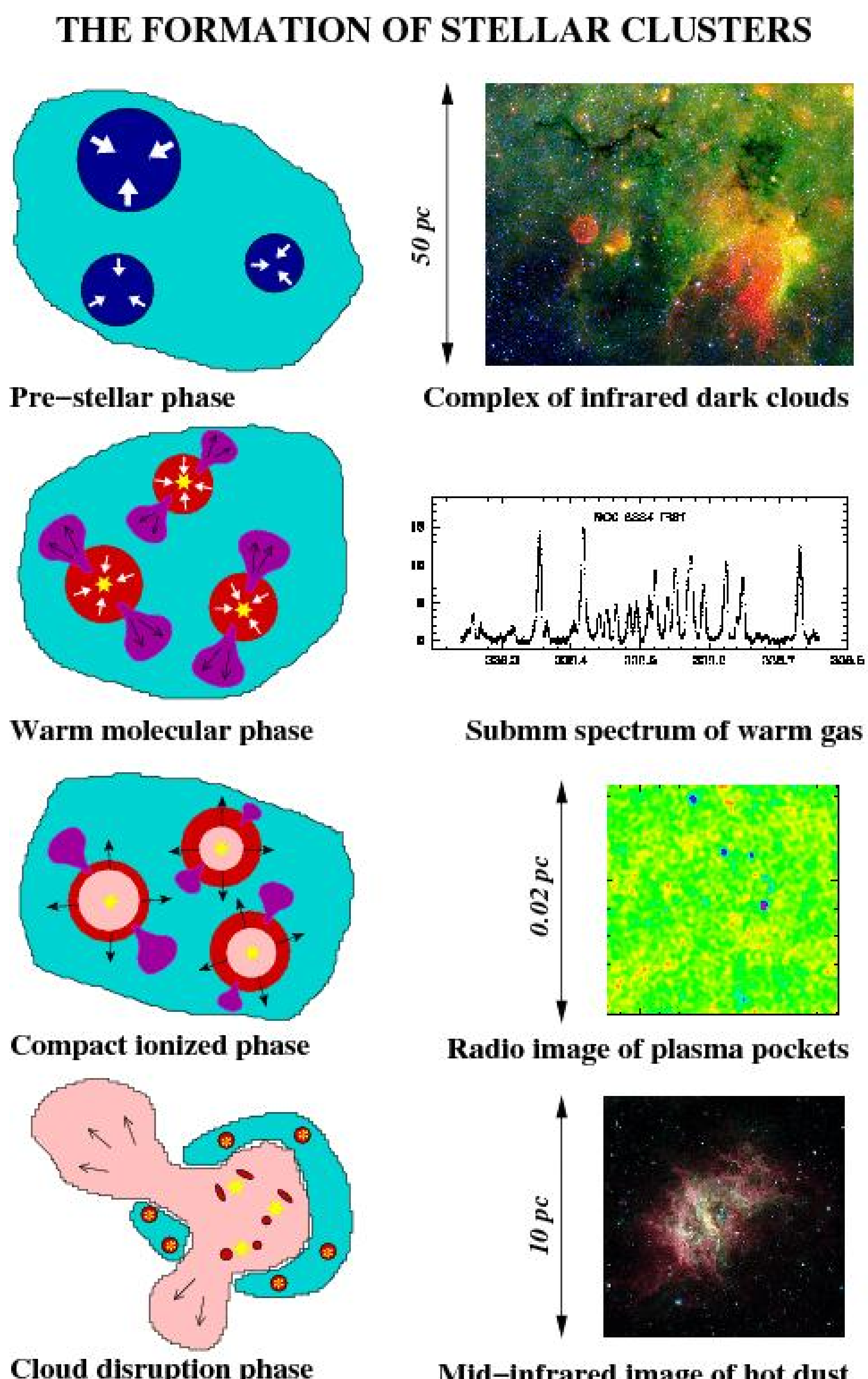
~1 pc

~10,000 AU

~1000 AU

binary?

+ planets?



Challenges:

more rapid (<0.1 Myr)
more distant (> 1 kpc)
more crowded
entirely embedded ($A_V > 100$)

High-mass star formation: outstanding questions

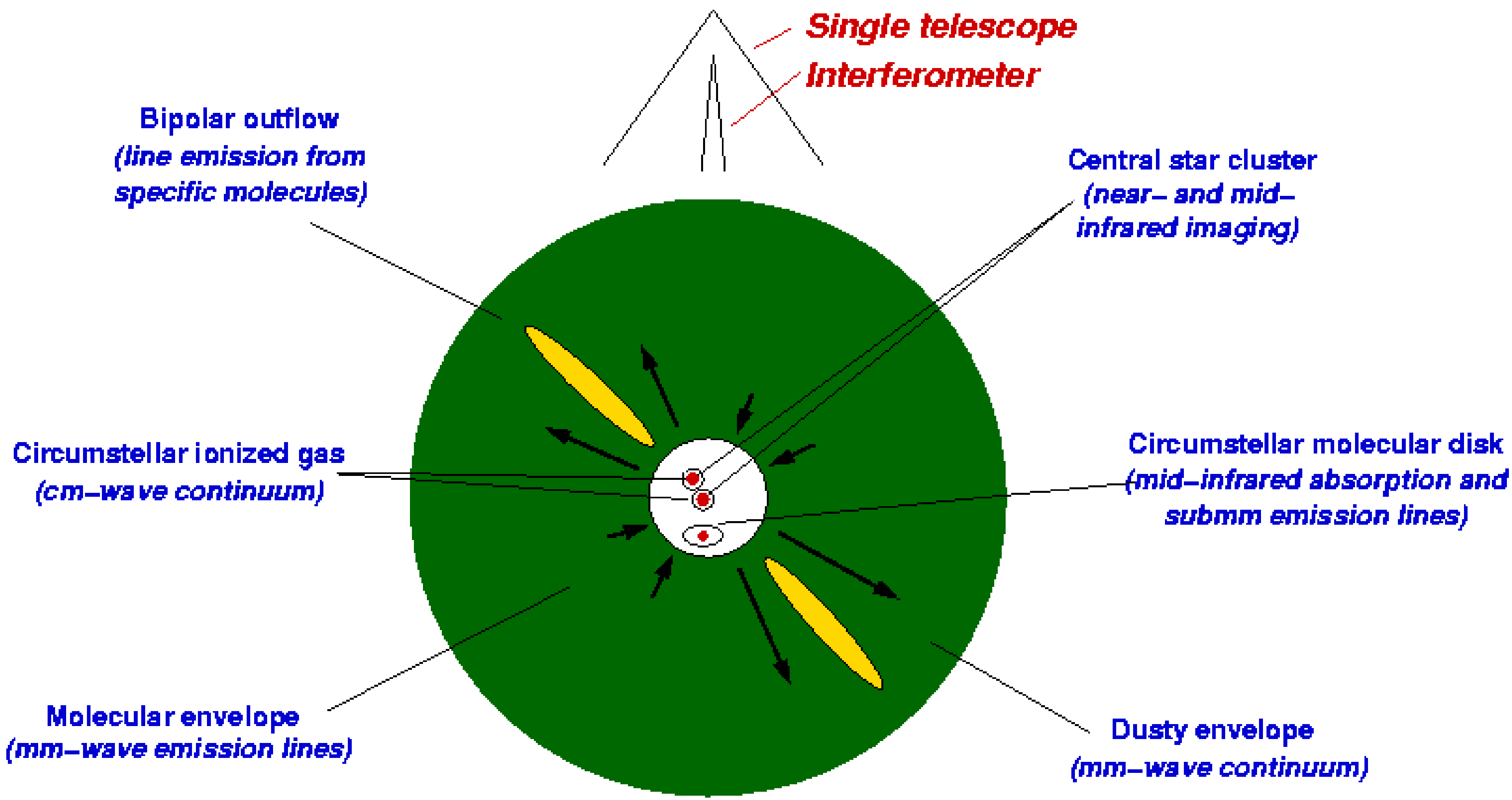
How does collapse begin ?
loss of turbulent / magnetic support; triggering

Feedback effects in clustered star formation ?
does mass spectrum (IMF) depend on stellar density

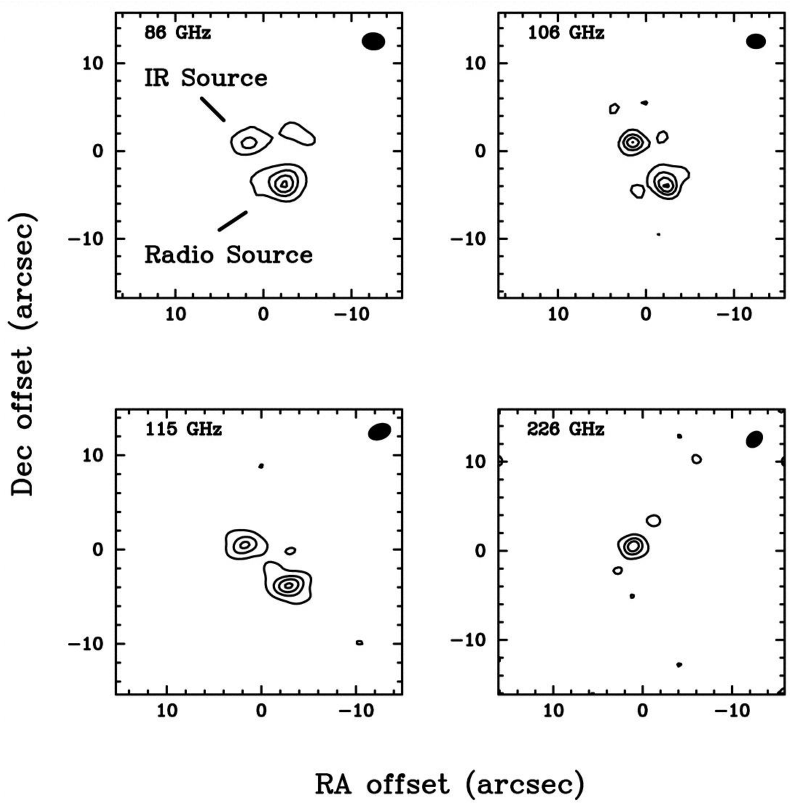
Nature of star-disk interaction?
prospects of forming planets

Effect on galaxy evolution?
origin & evolution of winds / outflows

Observational tools

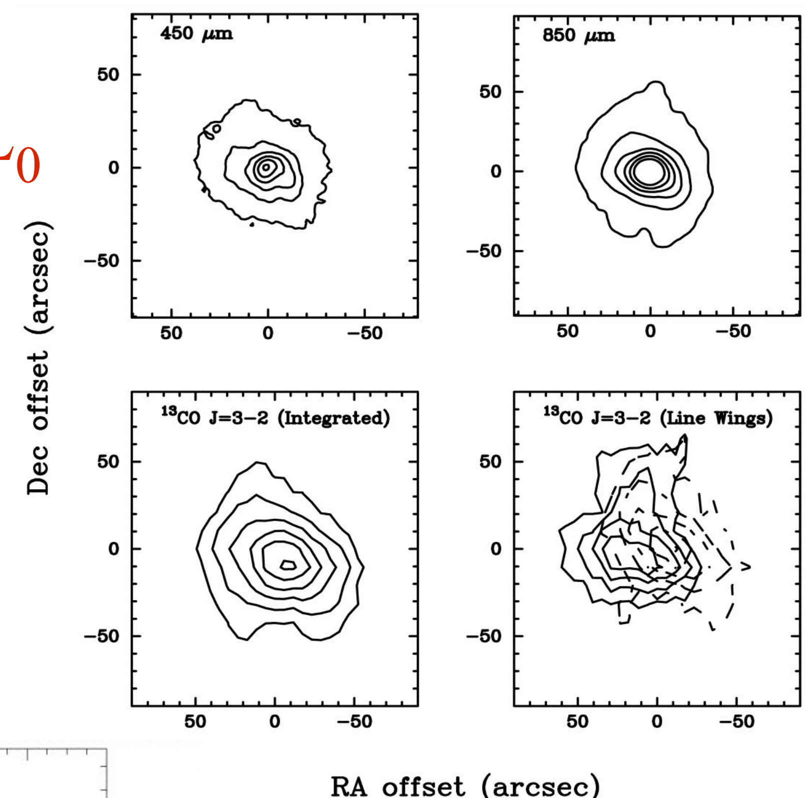


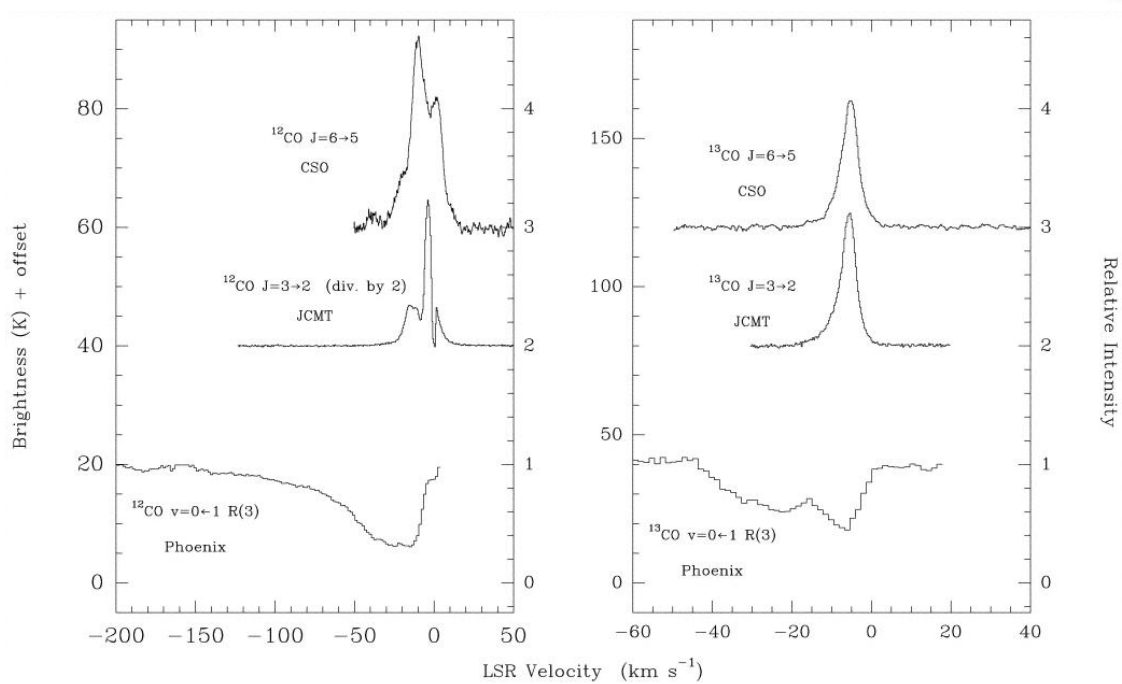
Prototype AFGL 2591



$d = 1$ kpc

$L = 20{,}000\ L_0$



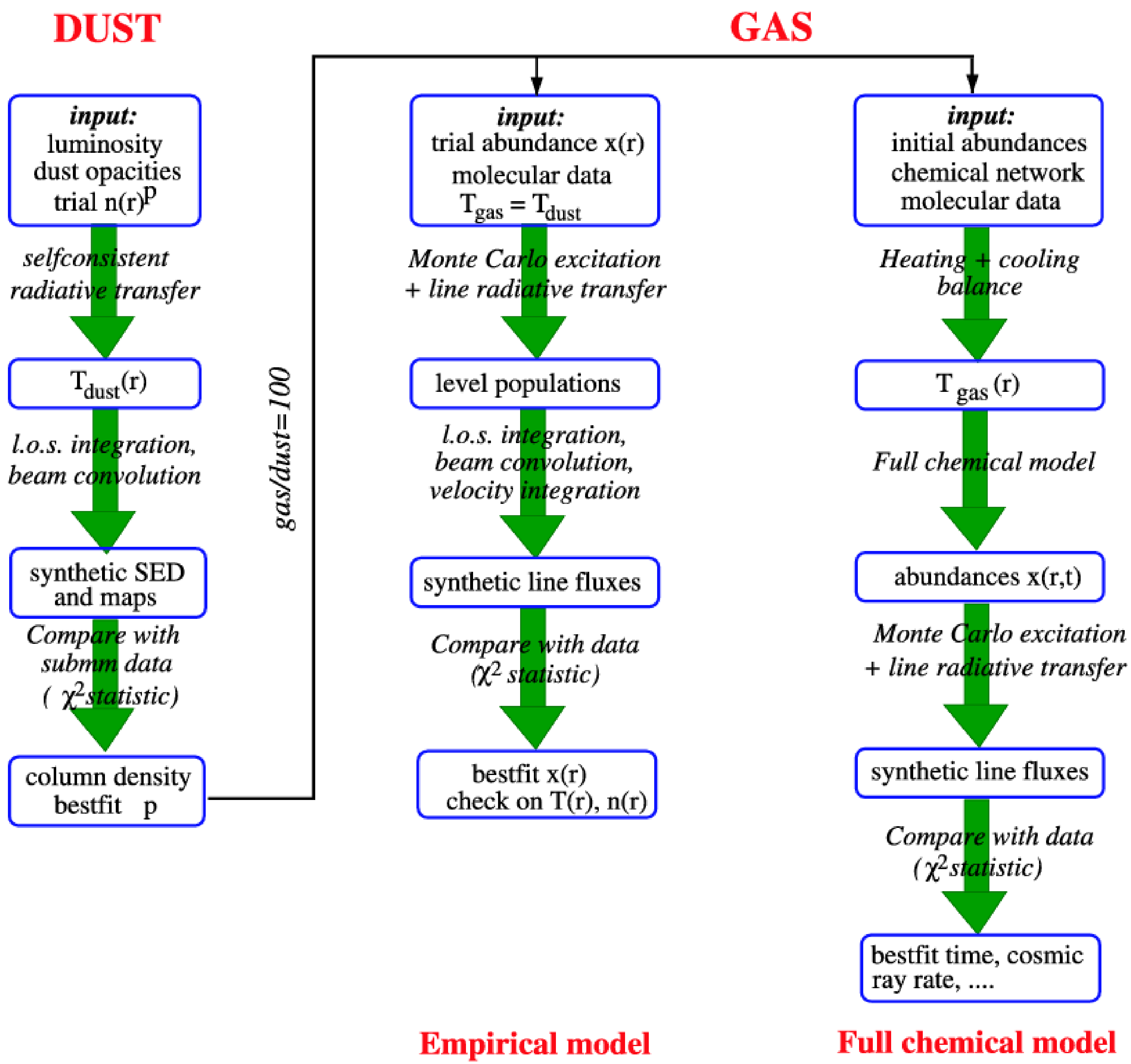


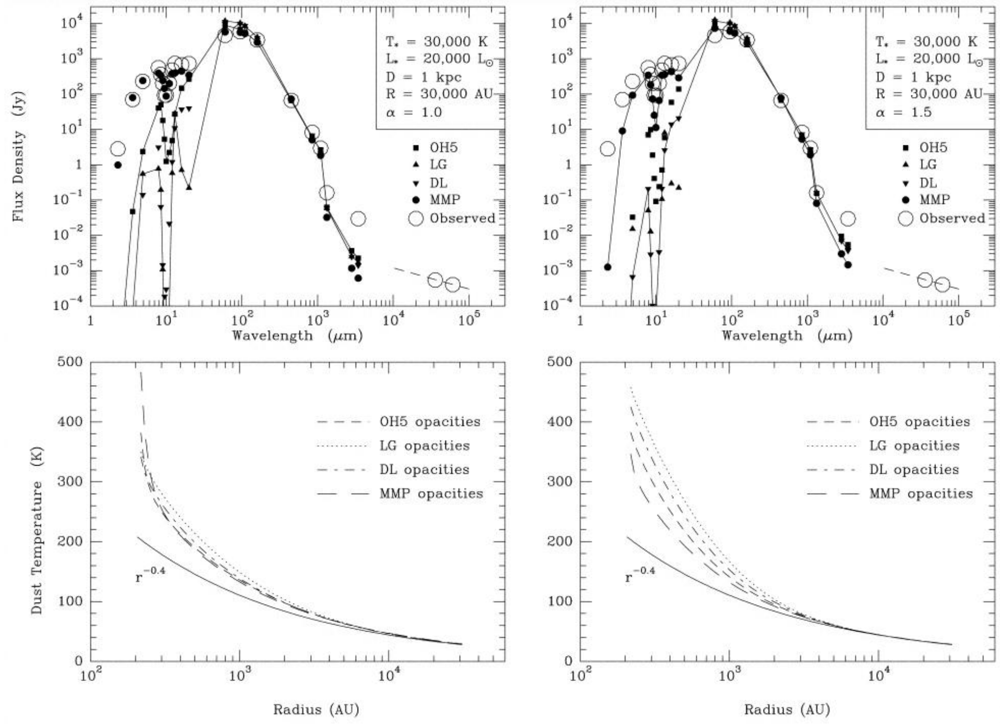
spherical on large scales, not on small

CO = main gas tracer

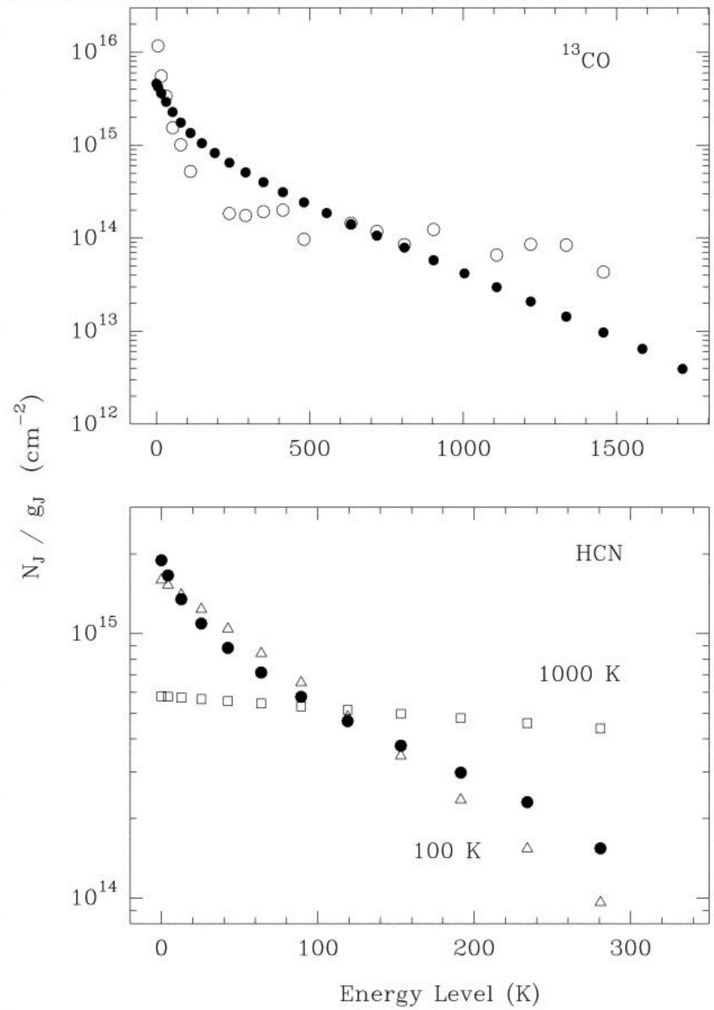
active kinematics

Modeling approach

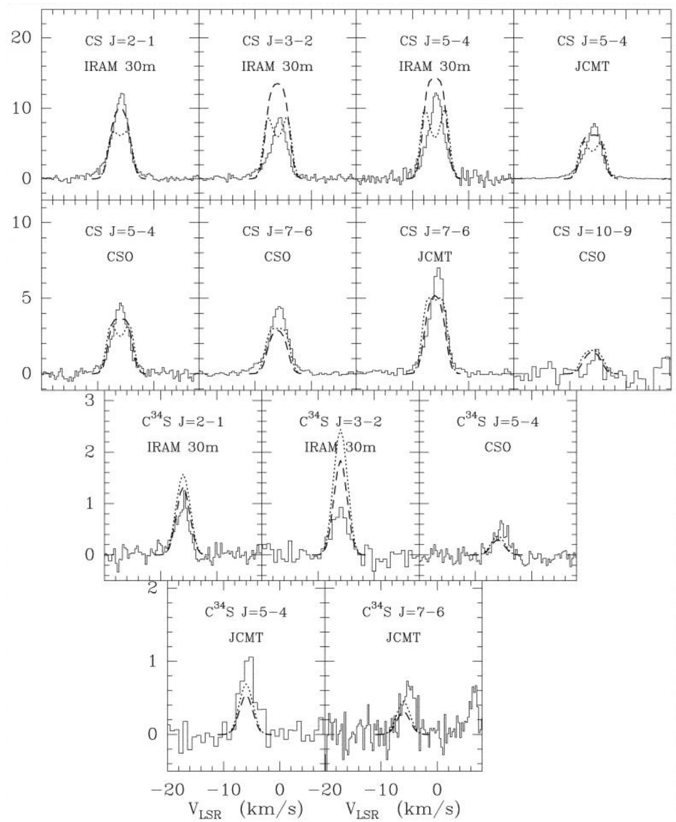




Mid-IR absorption lines:
Inner region

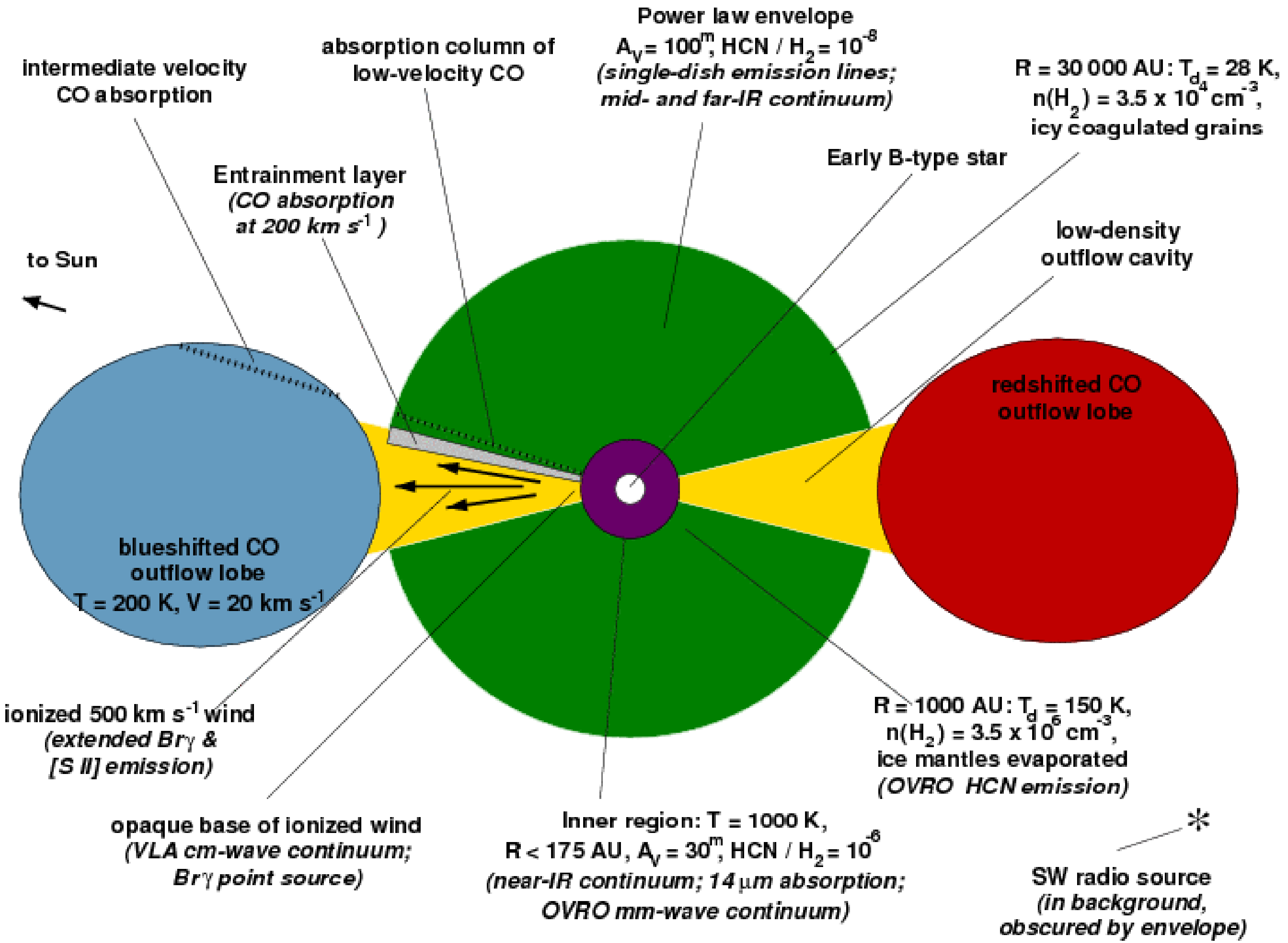


Dust continuum:
Temperature structure
Grain properties

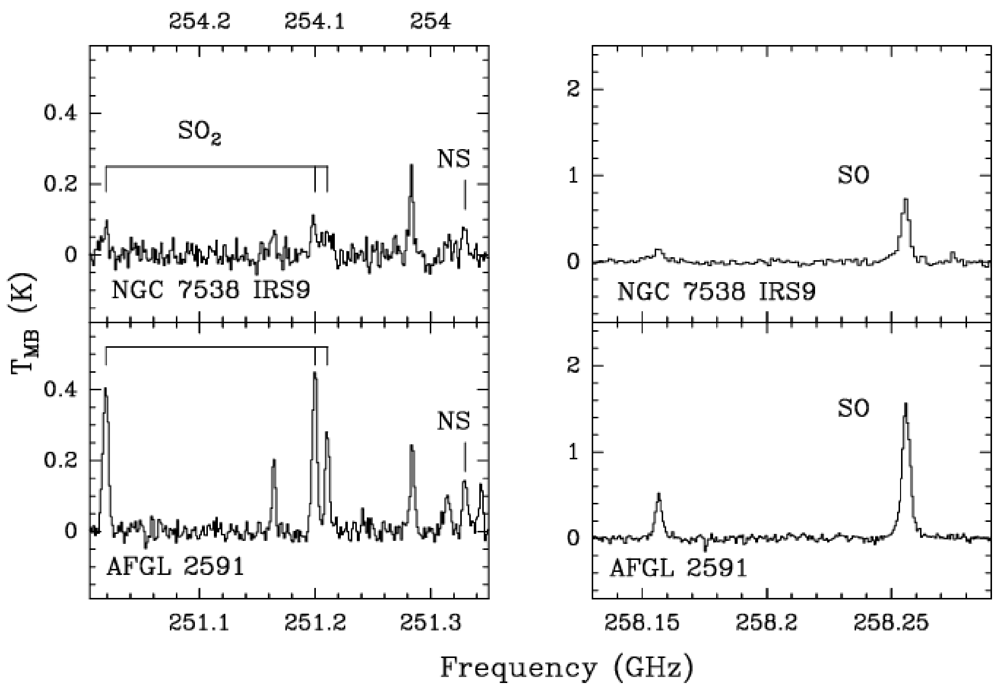


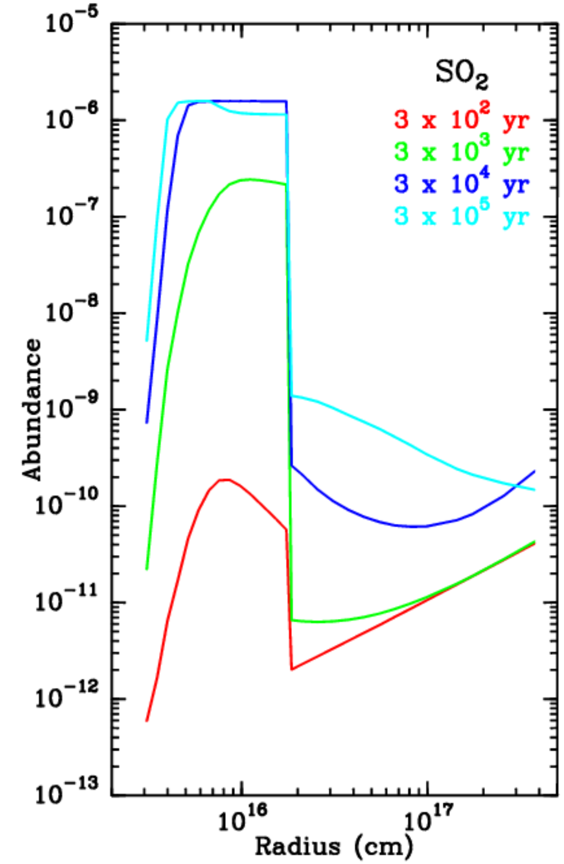
Submm emission lines:
Density structure

Model for AFGL 2591



Sulphur: A chemical clock





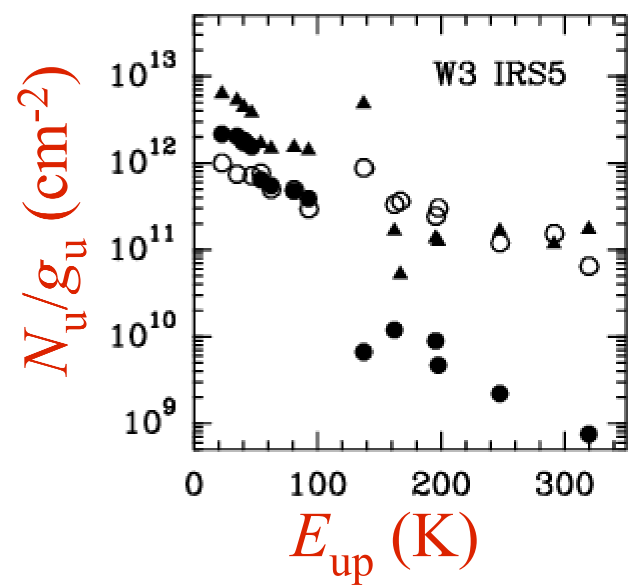
Molecules freeze onto dust in dense clouds

Protostar warms up: evaporate & react

Use abundance profile to estimate $t \sim 30{,}000$ yr

Jumps confirmed by recent SMA images

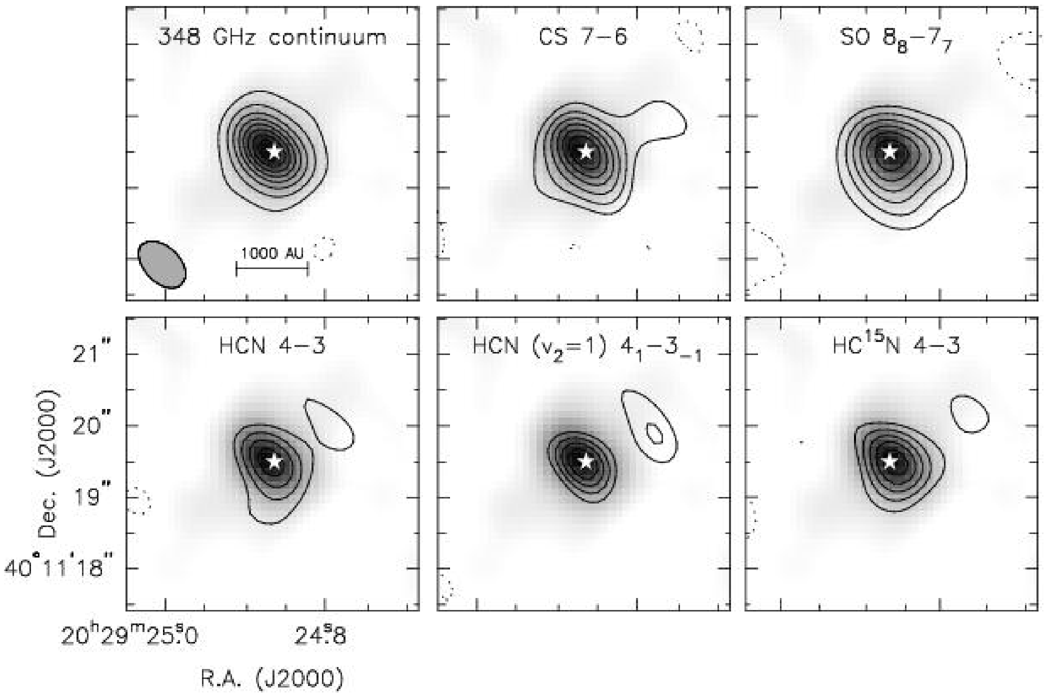
Next: include stellar evolution and gas dynamics into model

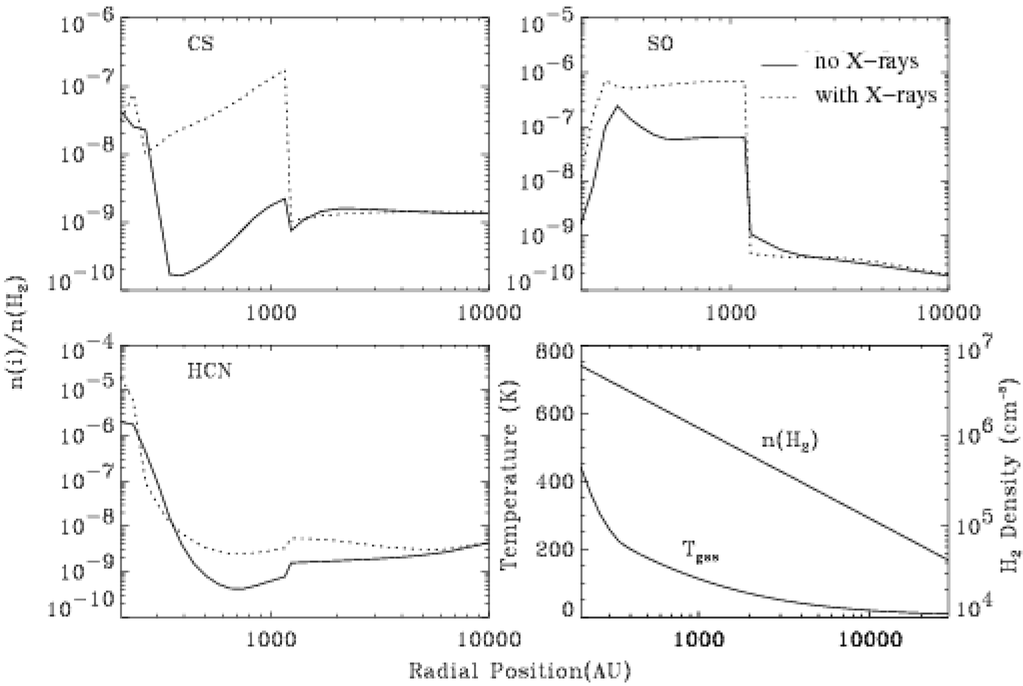


Chemistry tracing invisible radiation

Massive stars emit strong X-rays, but when do they start?

- Protostellar X-rays affect chemistry on <1000 AU scales
- Pronounced peaks in SO and CS seen in SMA data of AFGL 2591: $L_X / L_{bol} >\sim 10^{-6}$

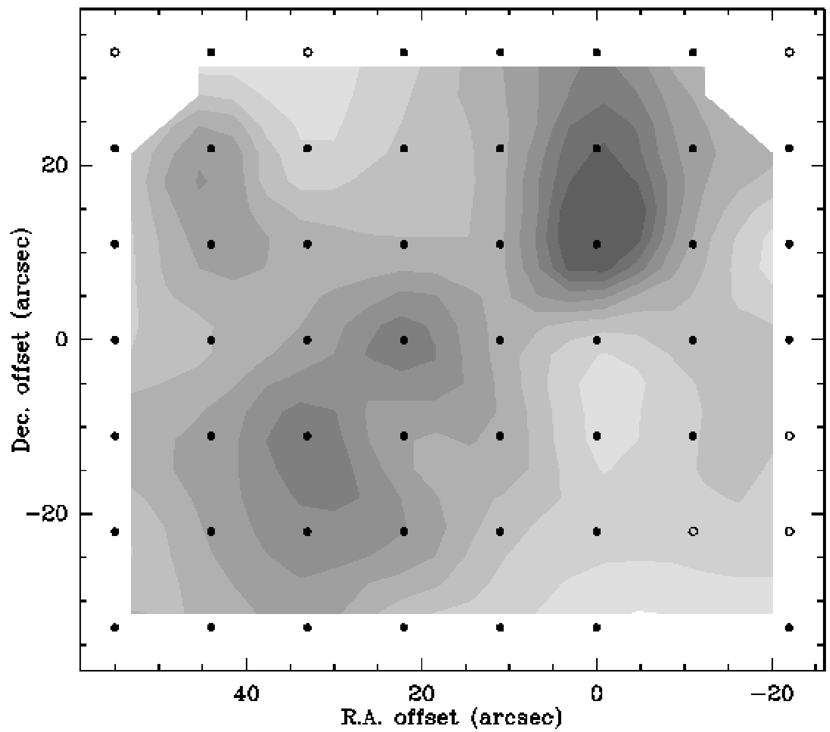


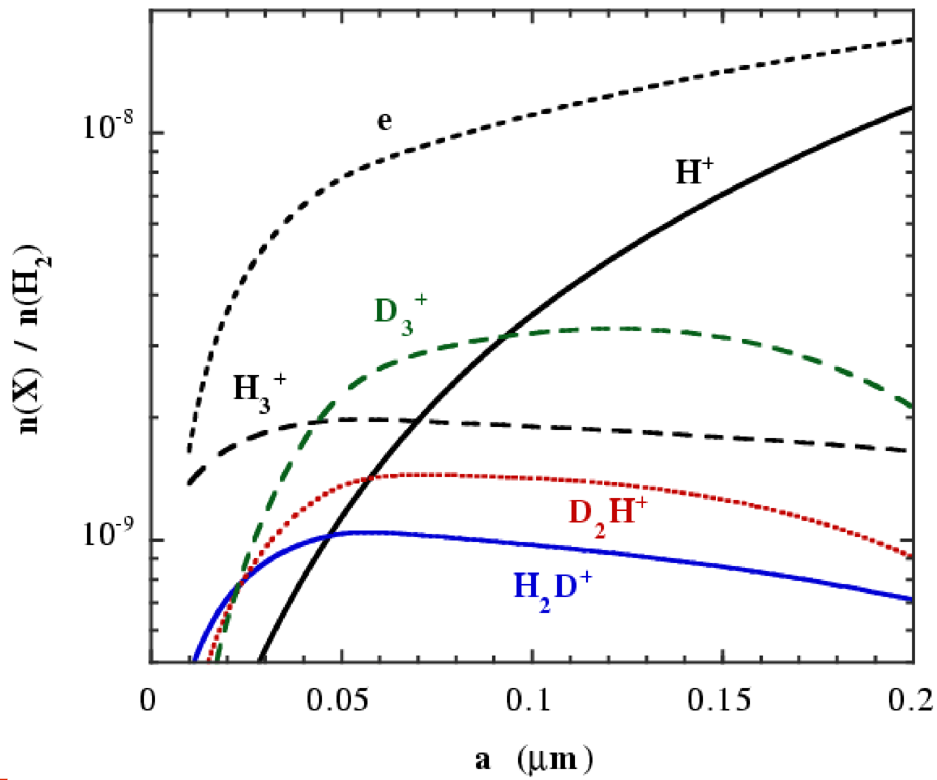


Benz et al 2007

Pre-stellar cores: Initial conditions of star formation

NH_2D in NGC 1333





Molecular D/H ratios enhanced by 10^{15} driven by >99% CNO freeze-out

Major charge carriers: H_2D^+ & D_2H^+ and grains. CO not a good gas tracer!

Chemistry gives handle on grain sizes:

- charge balance magnetic pressure
- thermal balance support against gravitational collapse
- grain growth will continue within protoplanetary disks!

Kinematics of molecular ions toward the pre-stellar core L1544

Double-peaked H_2D^+ line profile

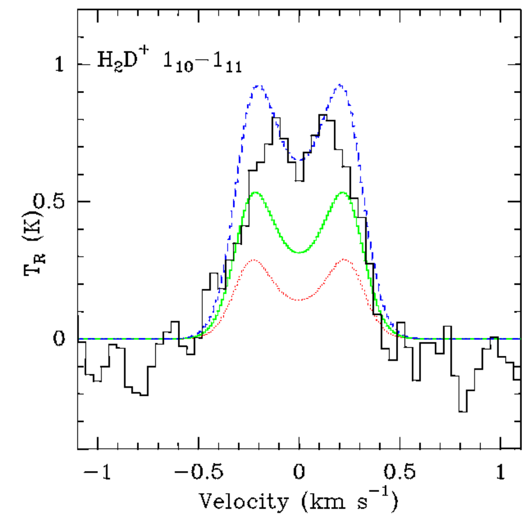
like HCO^+ and N_2H^+

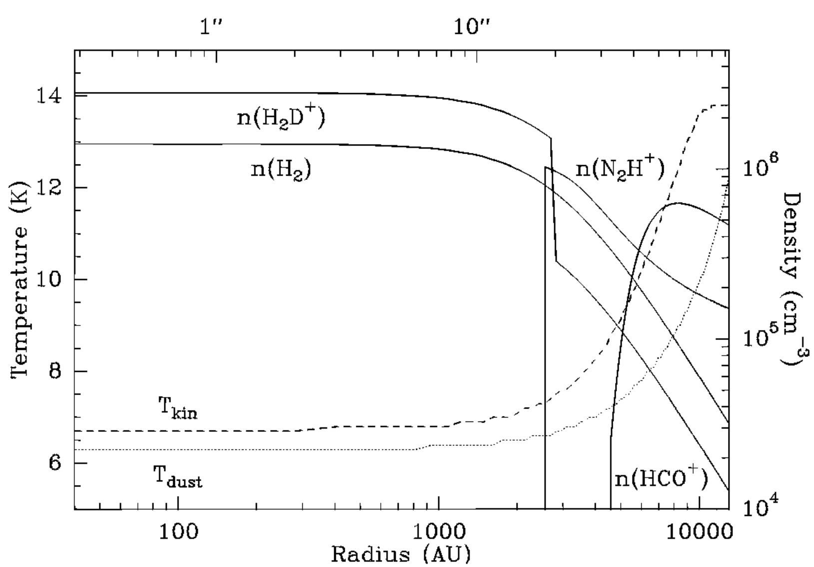
but probes smaller radii

Several major implications:

1. density centrally peaked (no flattening)
   expect ~constant accretion rate
2. gas temperature does not decrease
   decoupled from dust: grain growth
3. infall velocity increases inward
   inside-out collapse
4. motion outer layers < thermal speed
   limits role of turbulence (unlike IRDC!)

Van der Tak et al 2005

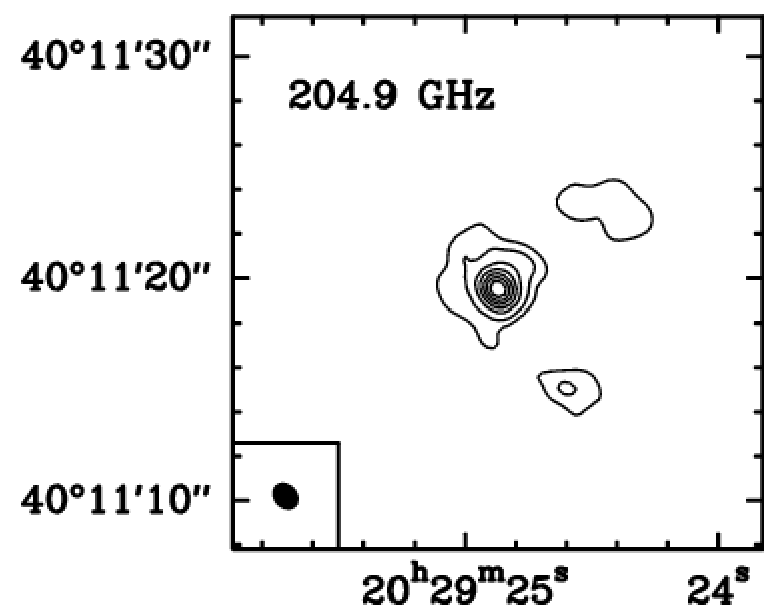




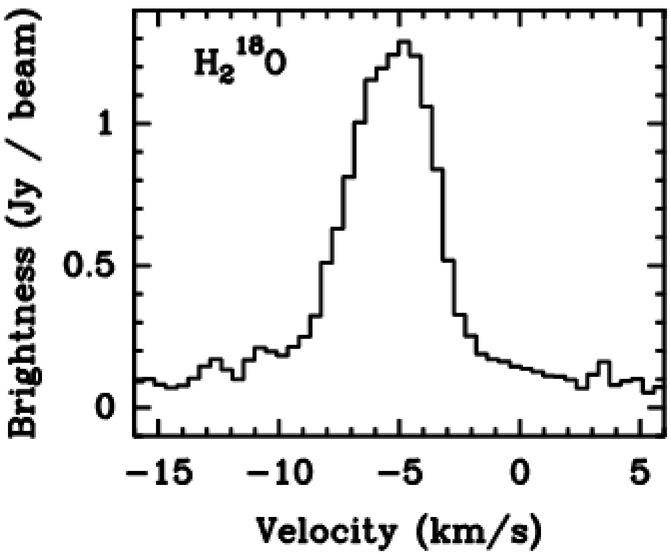
A dust and water disk around AFGL 2591

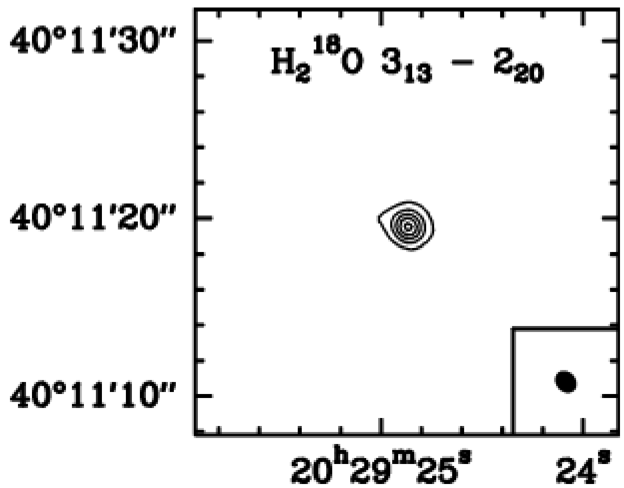
- High-mass stars may form through disk accretion
  - like low-mass stars (coagulation is exception)
  - but massive circumstellar disks hard to see
- Need high spatial and spectral resolution
  - and avoid foreground gas
- Bure 1.3 mm map:
  - $M = 0.8\ M_0 = 5\%$ of M_*

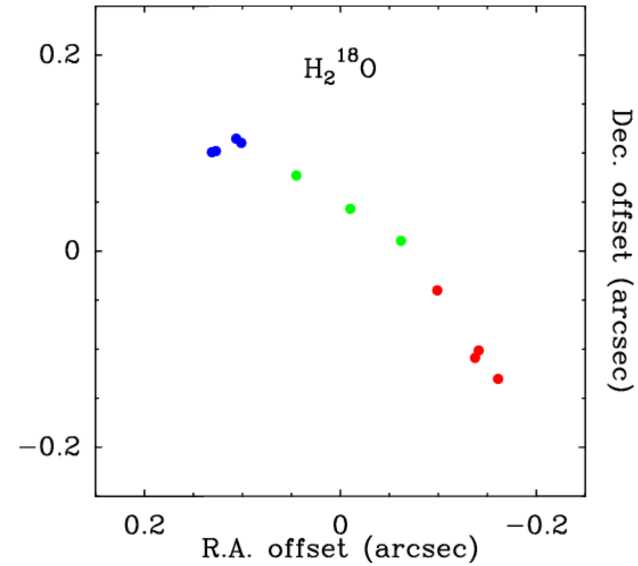
    << MHD simulations: evolved?
  - $a/b = 0.8$, so $i = 30^0$
  - dust $\beta = 1$: grain growth



IRAM PdB observations of $H_2^{18}O$ at 203 GHz



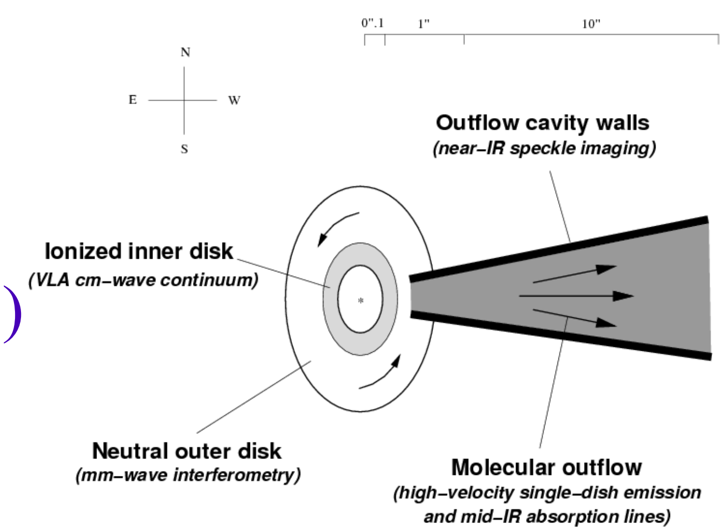




Velocity gradient ~ Kepler speed around 16 M_0 star

- Column too high and orientation wrong for outflow
- H_2O / H_2 ~ 10^{-4}: evaporated ice
- Next step is to resolve velocity field (ALMA)

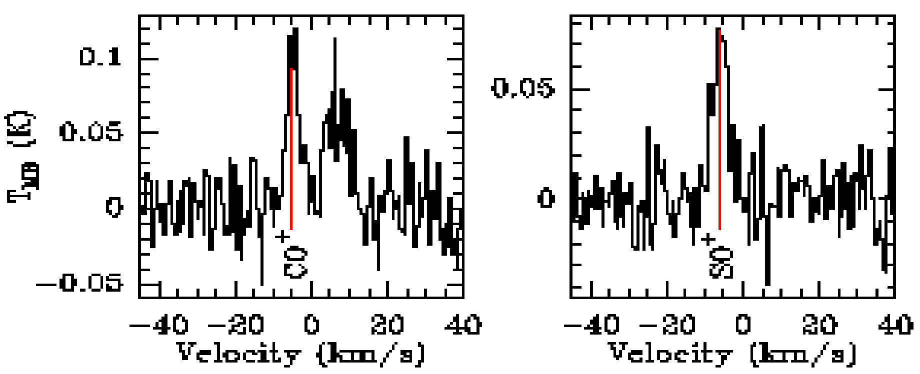
Can now get good handle on disk properties!
(e.g., massive = unstable = high accretion rate?)



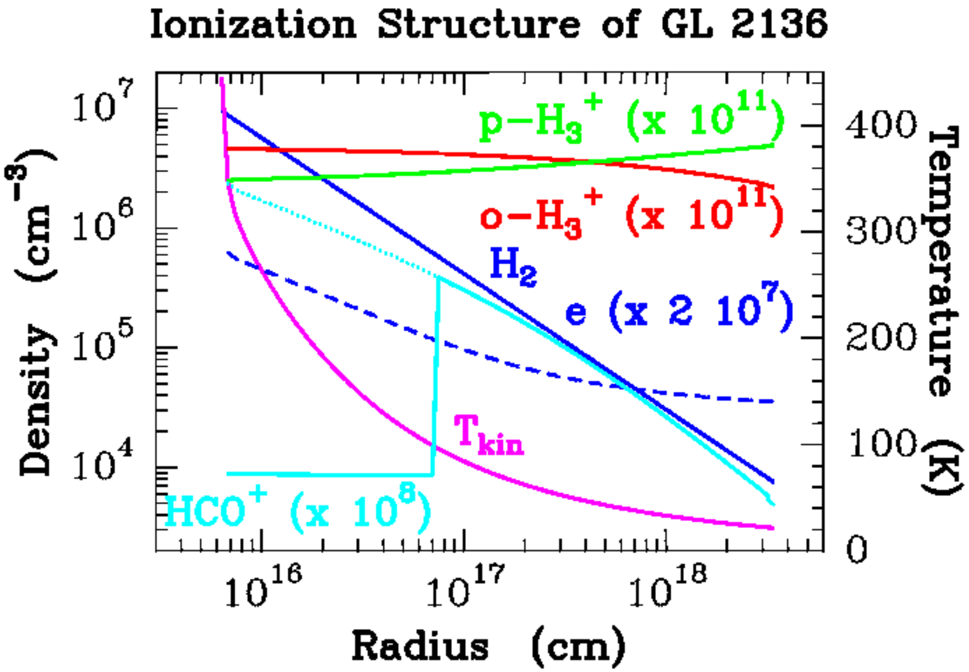
Ionization rate of molecular gas

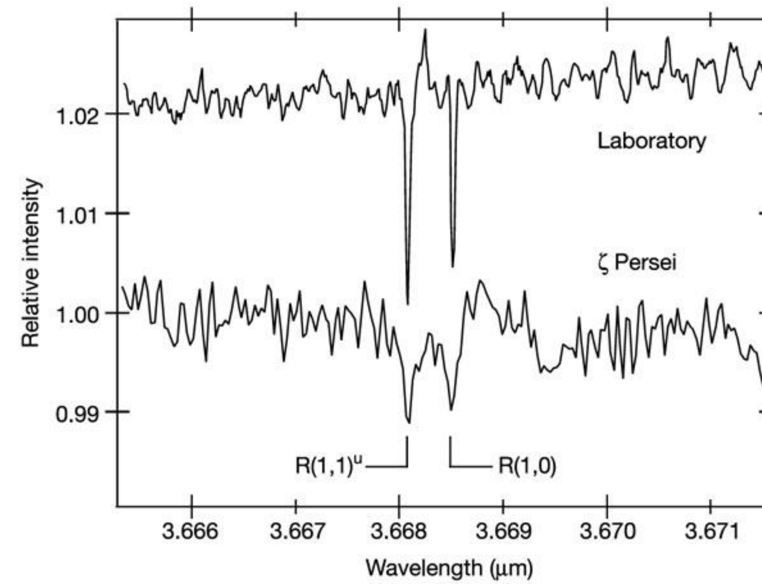
- Influence of magnetic fields on dynamics
  - efficiency of support against gravitational collapse
- Time scale of ion-molecule reactions
  - dominate gas-phase chemistry at $T \sim 10$ K, $n \sim 10^4$ cm^{-3}
- Mostly by cosmic rays except close to stars
  - low-*E* (~100 MeV) p from SNR

Detection of CO^+ and SO^+ toward AFGL 2591: Stäuber et al 2007



Probing the cosmic-ray ionization rate





Dense clouds: $\zeta \sim 3 \times 10^{-17}$ s^{-1} (Van der Tak & van Dishoeck 2000)

in good agreement with Voyager / Pioneer results at 65 AU

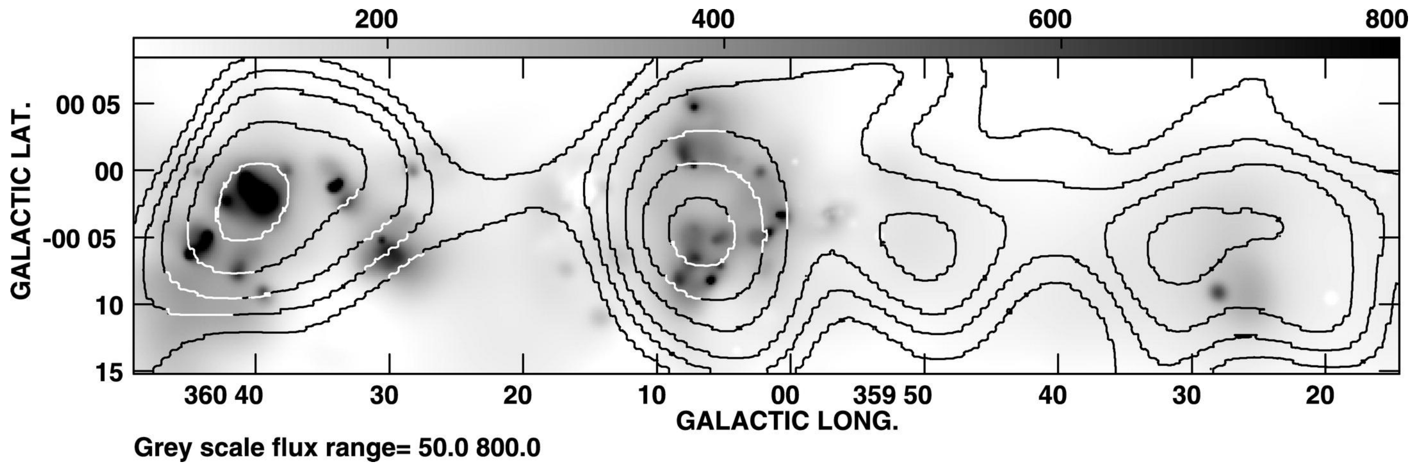
Local diffuse clouds: 10 x more (McCall et al 2003; Le Petit et al 2004)

Local pre-stellar core: 10 x less (Caselli et al 2002)

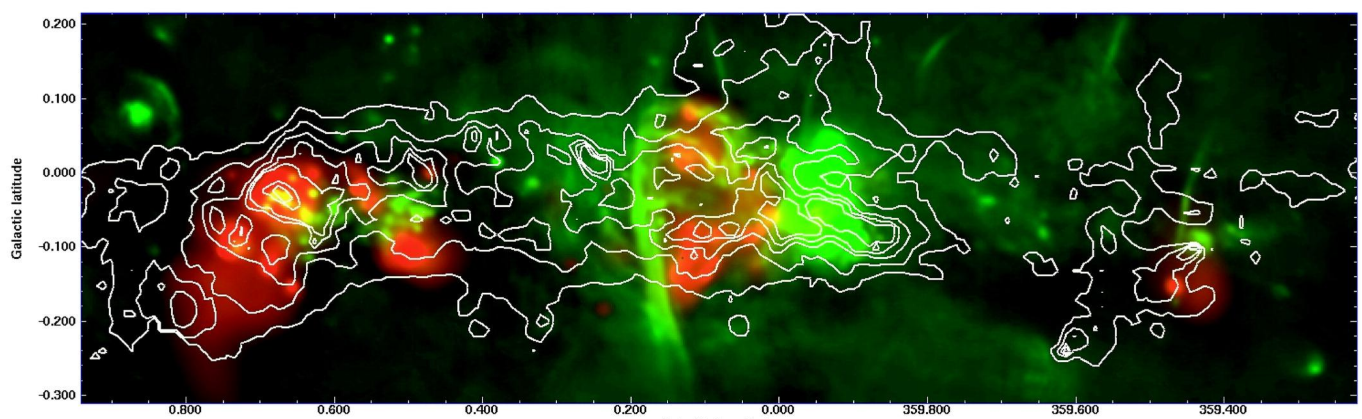
Sgr A region: 100 x more (Oka et al 2005)

Variation linked to propagation effects or CR flux?

Galactic center: high cosmic-ray flux seen in many other tracers



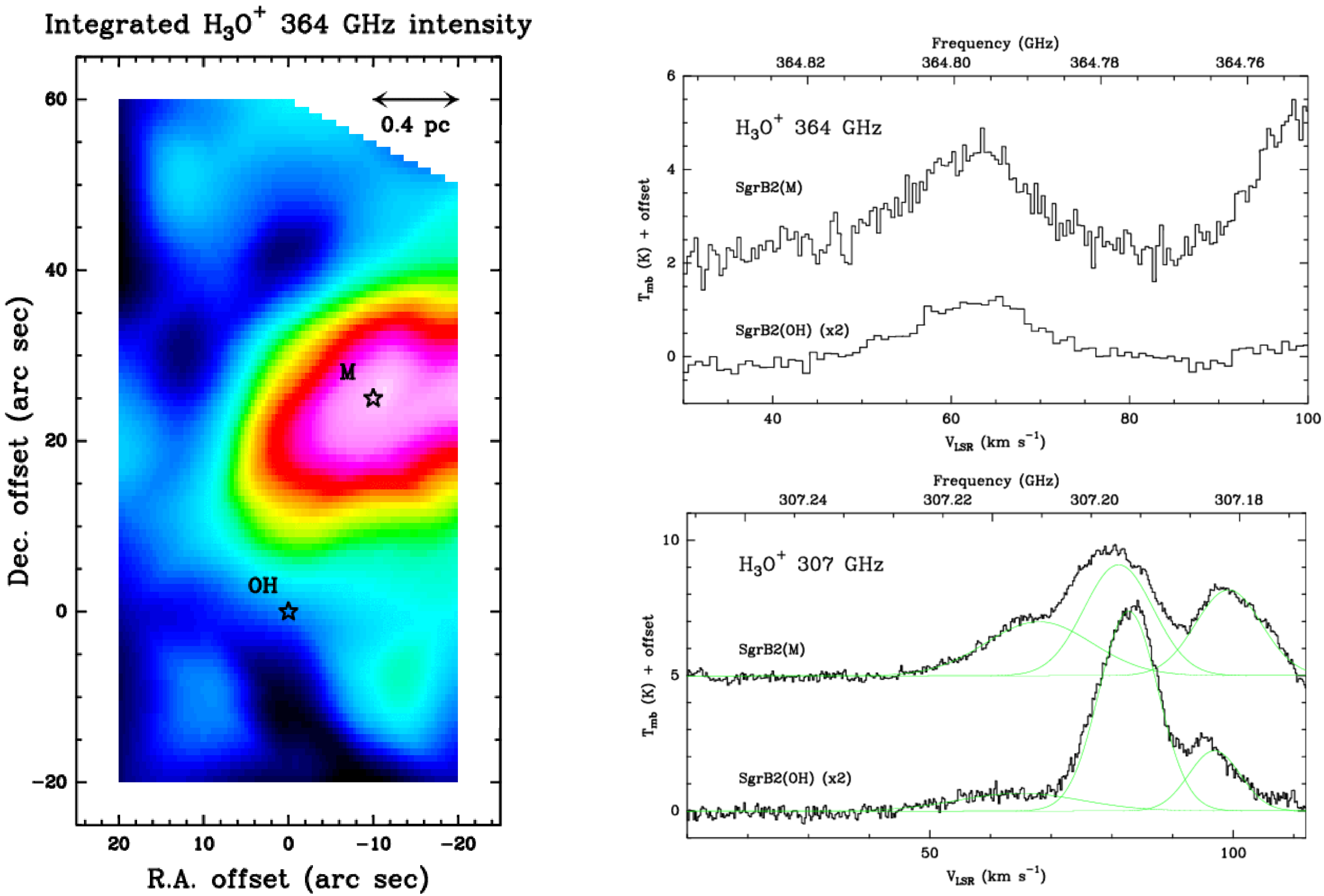
HESS contours on Fe Kα image (Aharonian et al 2006)



Submm + *VLA* 20 cm + *Chandra* 6.4 keV *(Yusef-Zadeh et al 2007)*

Sgr B2: strong widespread H_3O^+ emission

$H_3O^+ / H_2O = 1/50$, $\zeta = 3.5 \times 10^{-16}\ s^{-1}$



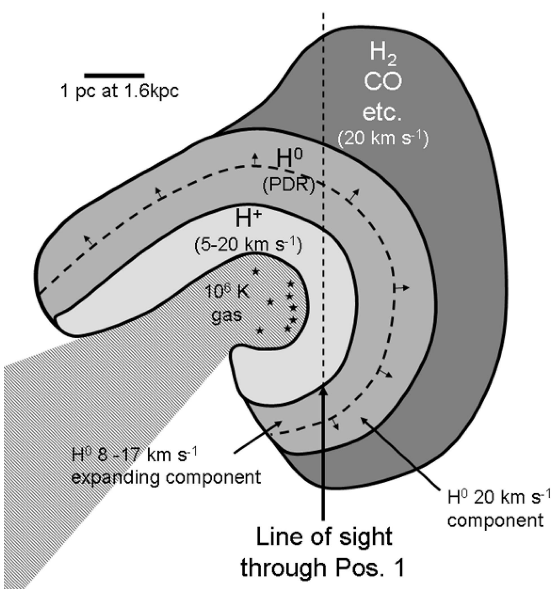
Implications for ζ

- Ionization rate in Galactic Center 10x higher than in Solar neighbourhood: effect of cosmic-ray flux
  - consistent with γ-ray and synchrotron data
  - possibly extra ionization by X-rays
- Ionization rate of dense gas 3x lower than for diffuse clouds: propagation effect
  - absorption takes $\Sigma = 50$ g/cm^2: unlikely
  - scattering off plasma waves: more efficient in denser clouds with stronger magnetic fields (Padoan & Scalo 2005): explains observed trend

An alternative view

- Orion, M17 PDRs: HI Zeeman data indicate strong B : structure dominated by magnetic not gas pressure?
  - gas pushed out by starlight momentum
  - B-field lines compressed: CR density enhanced
- High CR rate = result not cause of star formation
  - need to measure ζ in regions of known B to find out
  - expect correlation of CR flux with stellar *L*

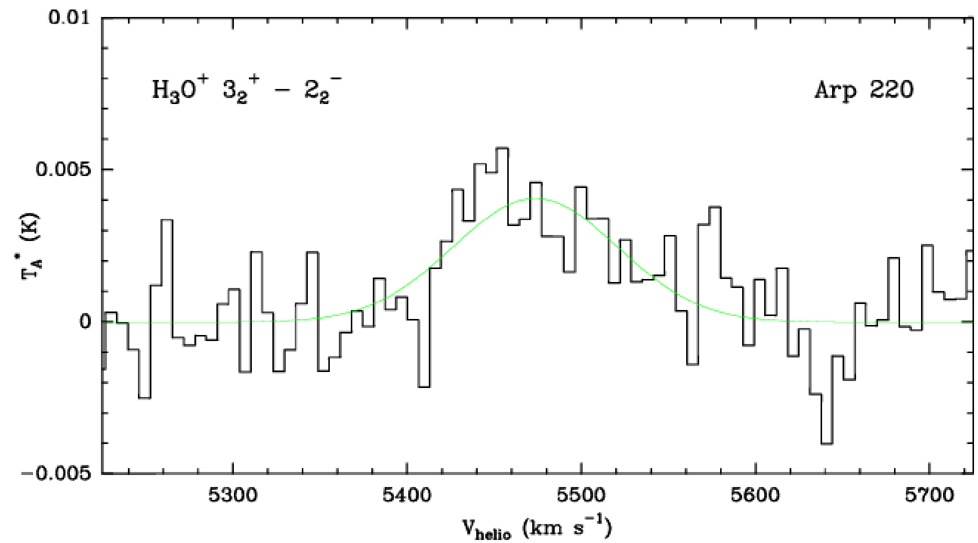
Pellegrini et al 2007

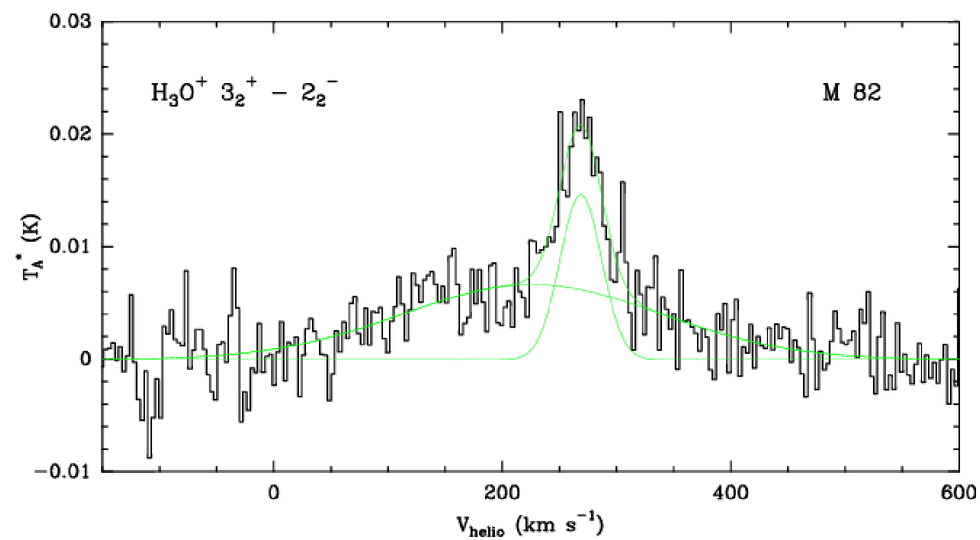


Detection of extragalactic H_3O^+

- Arp 220: prototype merger
  -- ISO detection of H_2O
  -- $d = 72$ Mpc
  -- ULIRG
- M82: prototype starburst
  -- IRAM 30m detection of CO^+
  -- $d = 4$ Mpc
- Detect the line in both nuclei!
  -- Central velocity and width as expected; no other plausible ID
  -- Two *V*-components in M82

Abundance ~few 10^{-9} exceeds Sgr B2!





Scale: 10″ = 100 pc

Origin of high ionization

- For M82, a PDR model with $G_0 = 10^{3.5}$ & $\zeta = 100\zeta_0$ reproduces the H_3O^+ column density and abundance.

--> evolved starburst (UV from stars, CR from supernovae)

--> consistent with earlier models (Förster Schreiber et al 2003)

- The Arp 220 data require an XDR with $F_X = 16$ erg/s/cm^2: Sign of AGN activity.

--> very high $N(H_2) = 10^{24}$ cm^{-2} should attenuate any radiation?

--> H_3O^+ located in surrounding CO-absorbing torus?

Van der Tak et al 2007

Conclusions

- Submm observations: A cornerstone of astrophysics
  - essential to probe origin of stars and planets
  - applications from comets to high-z galaxies
  - measure fundamental physical parameters
- Molecular studies of star-forming regions useful to:
  - estimate ages of protostars
  - probe kinematics of star formation
  - measure properties of circumstellar disks
  - measure ionization rate across the Galaxy .. if not the Universe!