What we learn about the earliest phase of star formation from Herschel's detection of water vapor in L1544

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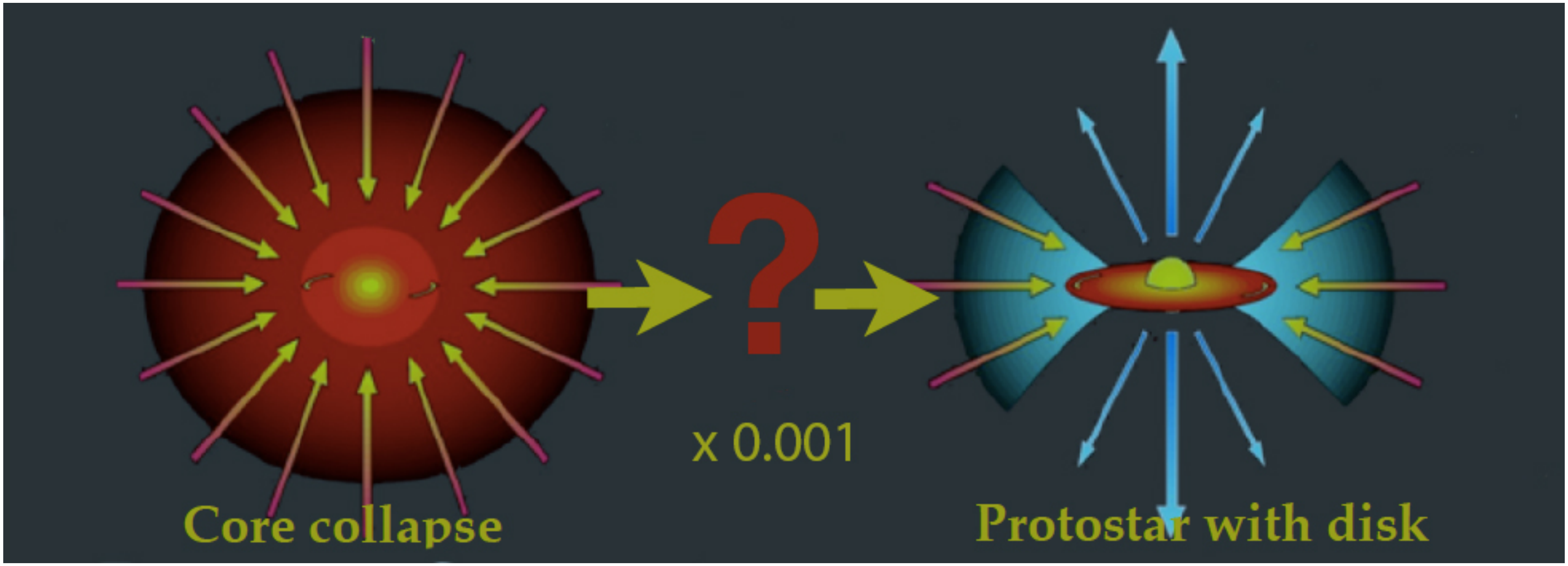
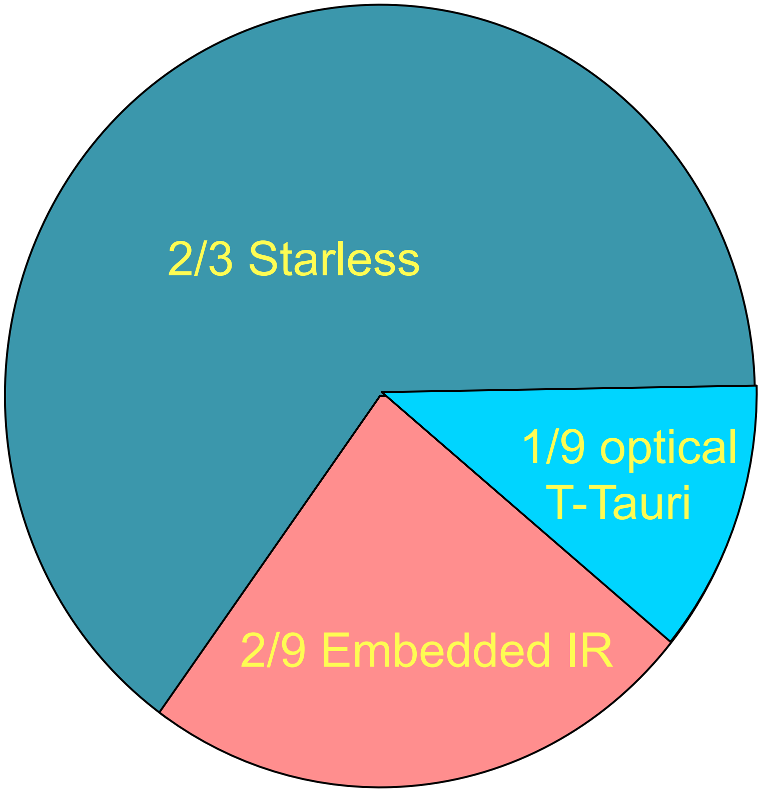
How?



Source selection

- Starless cores
    - The birthplaces of solar-mass stars

Starless cores and protostars



IRAS data for 100 dense molecular cores in Taurus.

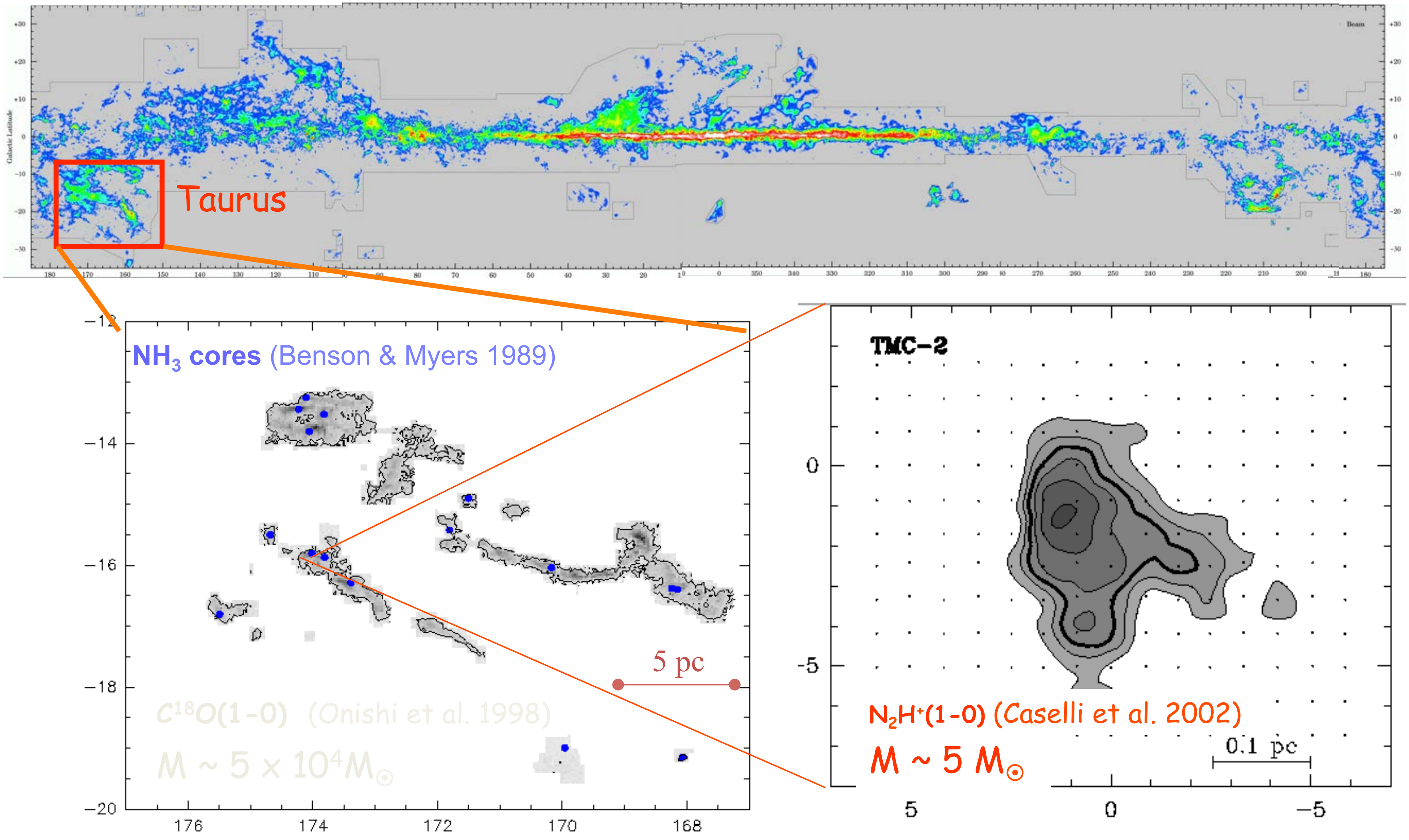
IRAS All Sky Survey (1983)
Spitzer Cores to Disks Survey (C2D) (2003)
Herschel Goulds Belt Survey (2009)

Myers 1983
Beichman 1986
Benson+ 1986
Benson & Myers 1989

The starless cores

- The birthplaces of solar-mass stars
  - Small,
    - Few tenths of a pc
    - Few $M_{\odot}$
  - Dense
    - $10^{5}\ \mathrm{cm}^{-3}$
  - Quiet
    - Subsonic spectral line widths
  - Hydrostatic

The starless cores



Taurus

NH_3 cores (Benson & Myers 1989)

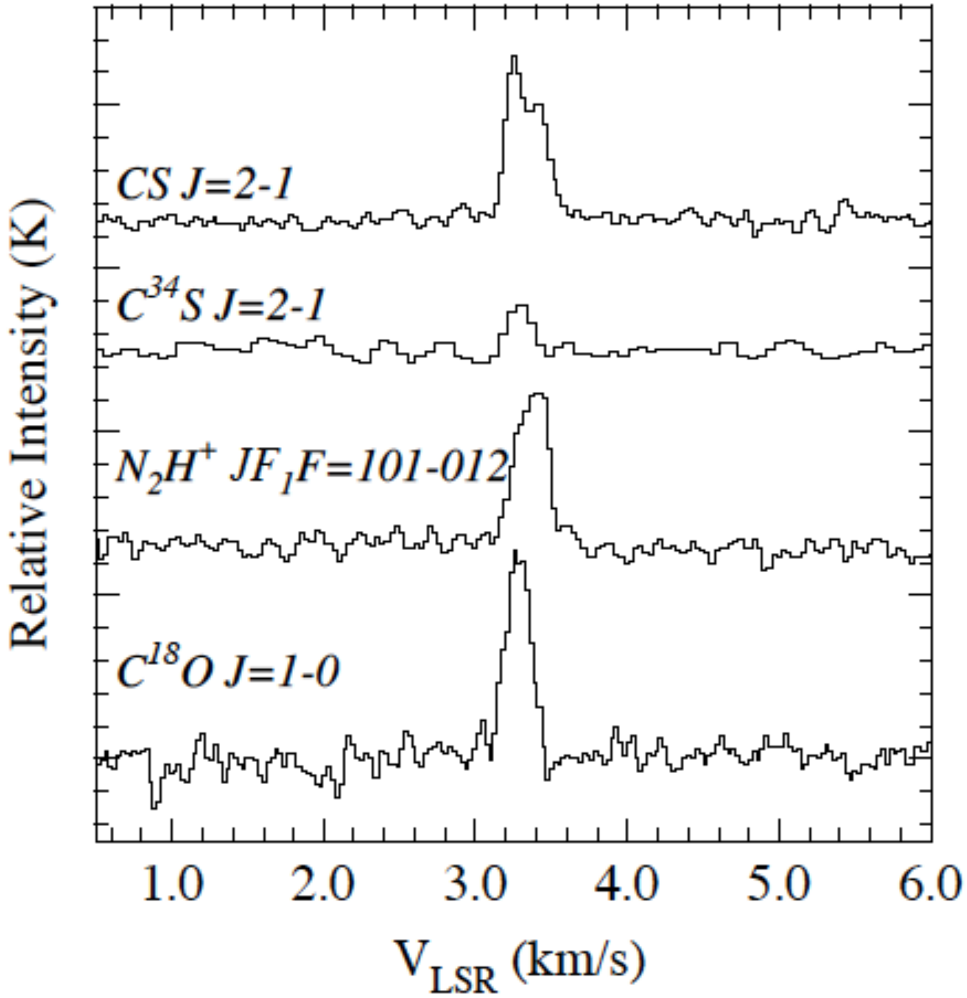
$C^{18}O(1-0)$ (Onishi et al. 1998)

$M \sim 5 \times 10^4 M_\odot$

$N_2H^+(1-0)$ (Caselli et al. 2002)

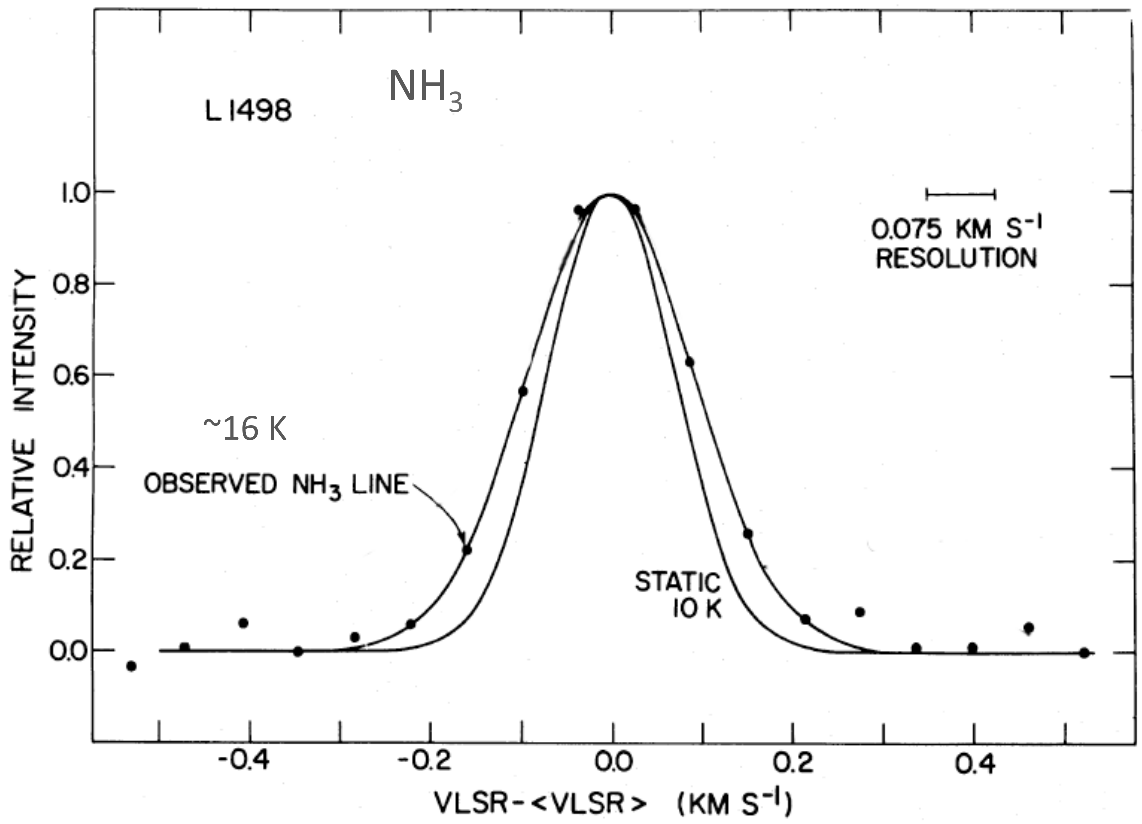
$M \sim 5\ M_\odot$

Subsonic internal velocities



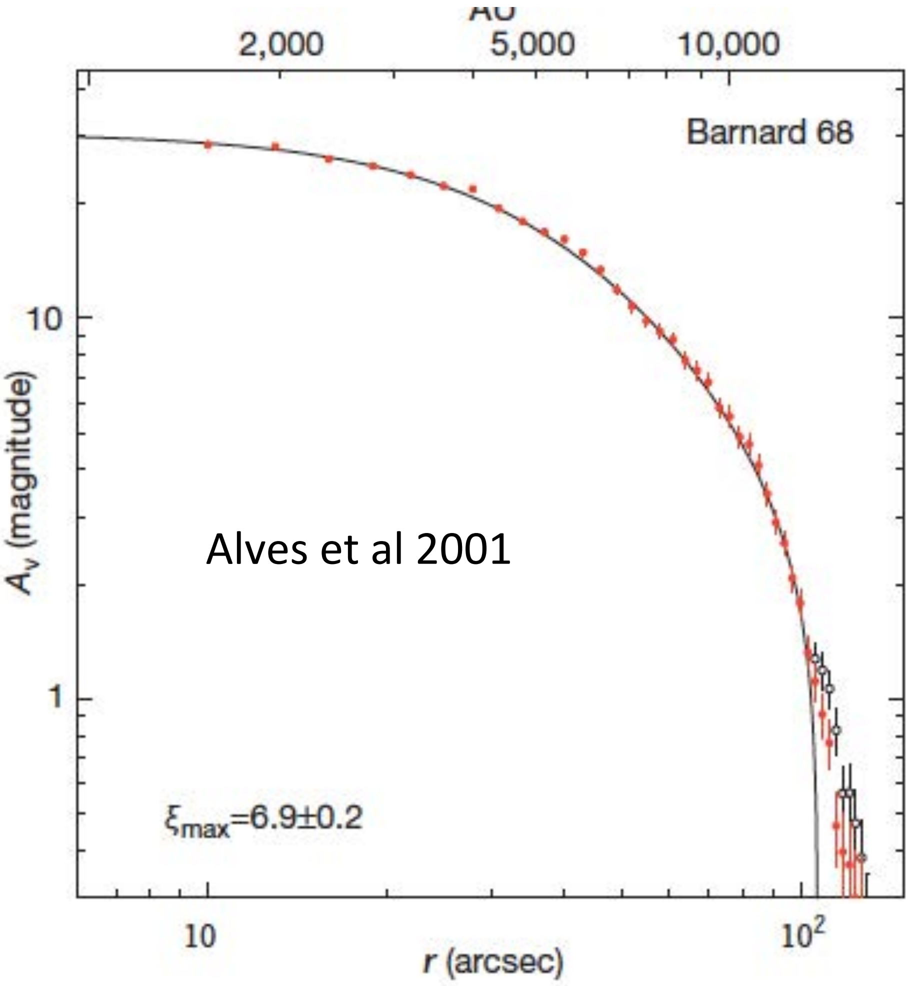
Redman, Keto,
Rawlings 2006

70% thermal
30% subsonic turbulence



Myers & Benson 1983

Hydrostatic density profiles
Bonnor-Ebert spheres



Alves et al 2001

Bonnor 1956
Ebert 1957

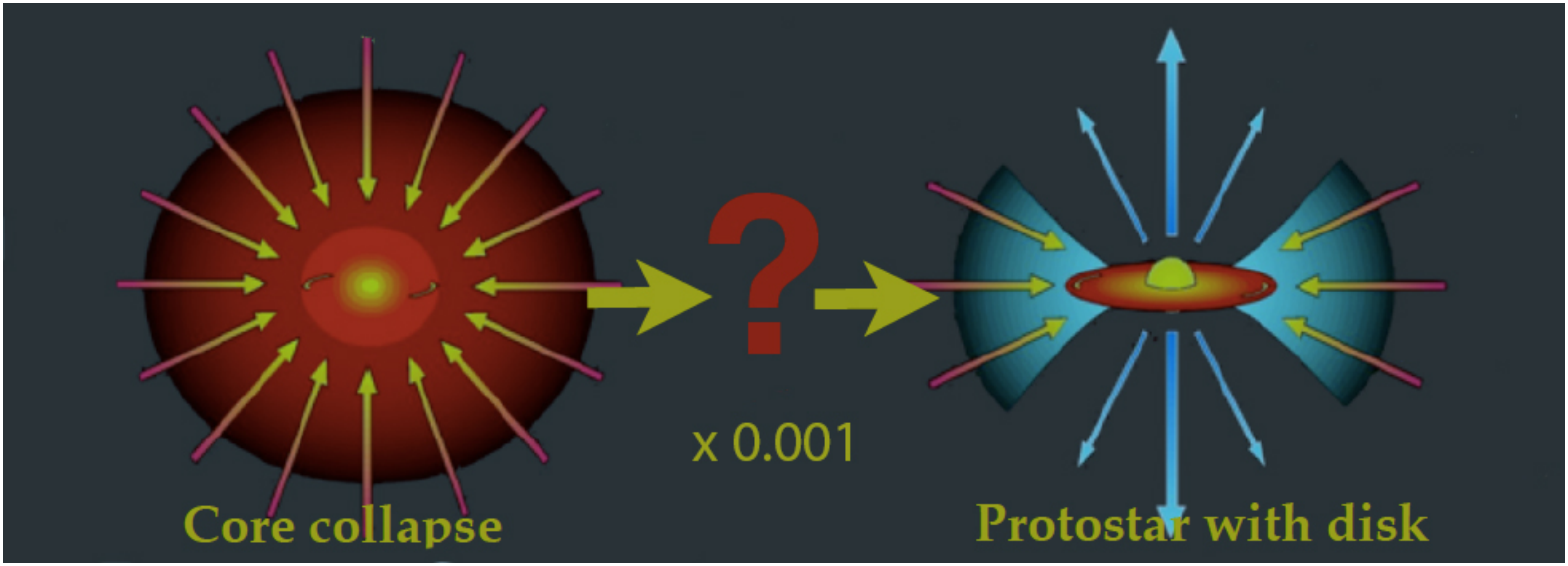
How do starless cores contract to form stars?

We know the relationship between the nearly hydrostatic cores and protostars.

We know that the star formation follows gravitational collapse.

We do not know how this collapse proceeds.

How?



3 example collapse solutions

- Larson-Penston flow
  - Larson (1969), Penston (1969)
  - Star formation in supersonic turbulence
- Singular isothermal sphere
  - Shu (1977)
- Quasi-equilibrium contraction of a Bonnor-Ebert sphere (Keto, Caselli, Rawlings 2015)

Collapse solutions

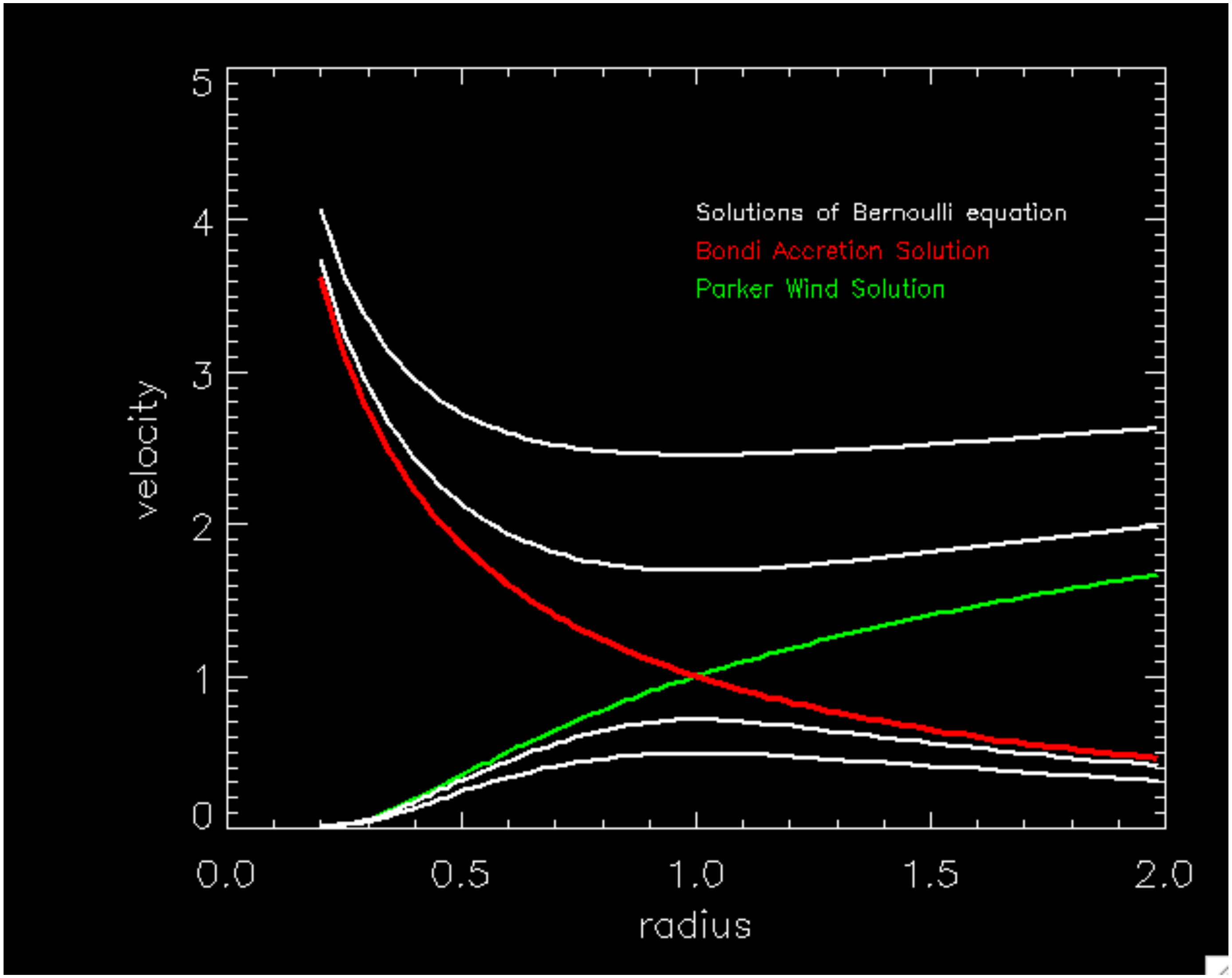
$$\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial r} = -\frac{a^2}{\rho}\frac{\partial \rho}{\partial r} - \frac{GM}{r^2}$$

$$\rho v r^2 = \dot{M} = \mathrm{constant}$$

$$\frac{r^2}{u}\frac{du}{dr} = \frac{2a^2 - GM}{u^2 - a^2}$$

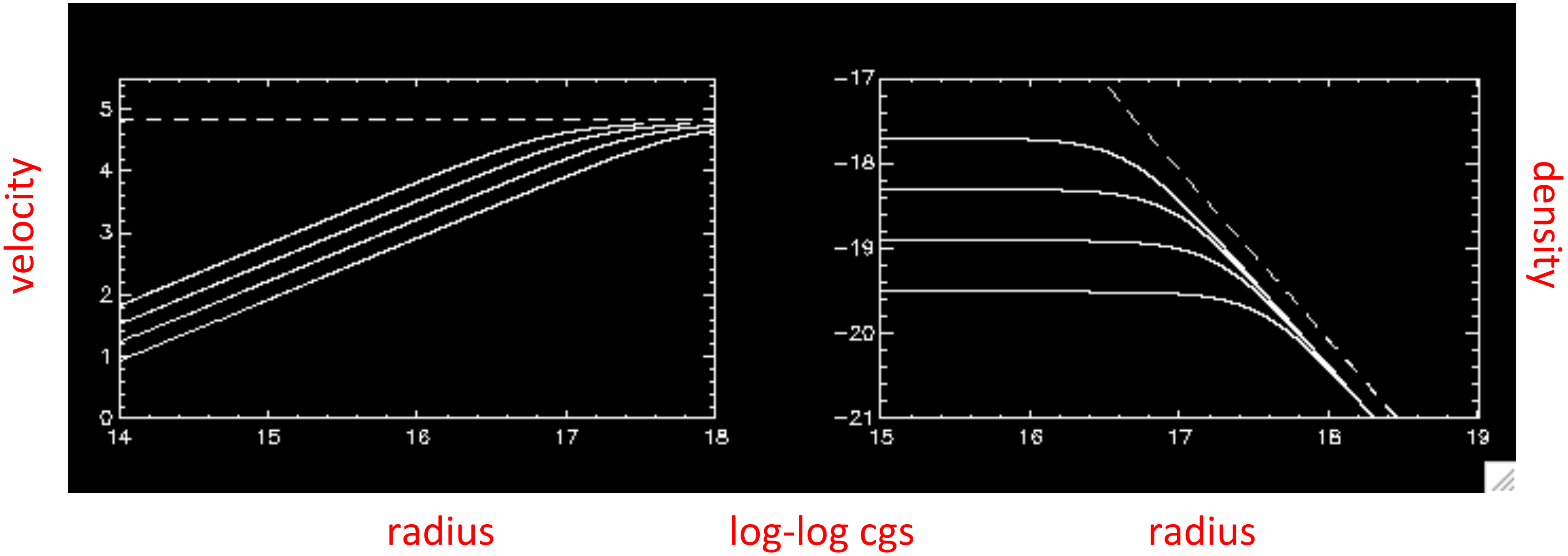
$$r_c = GM/2a^2$$

Collapse solutions



LP flow

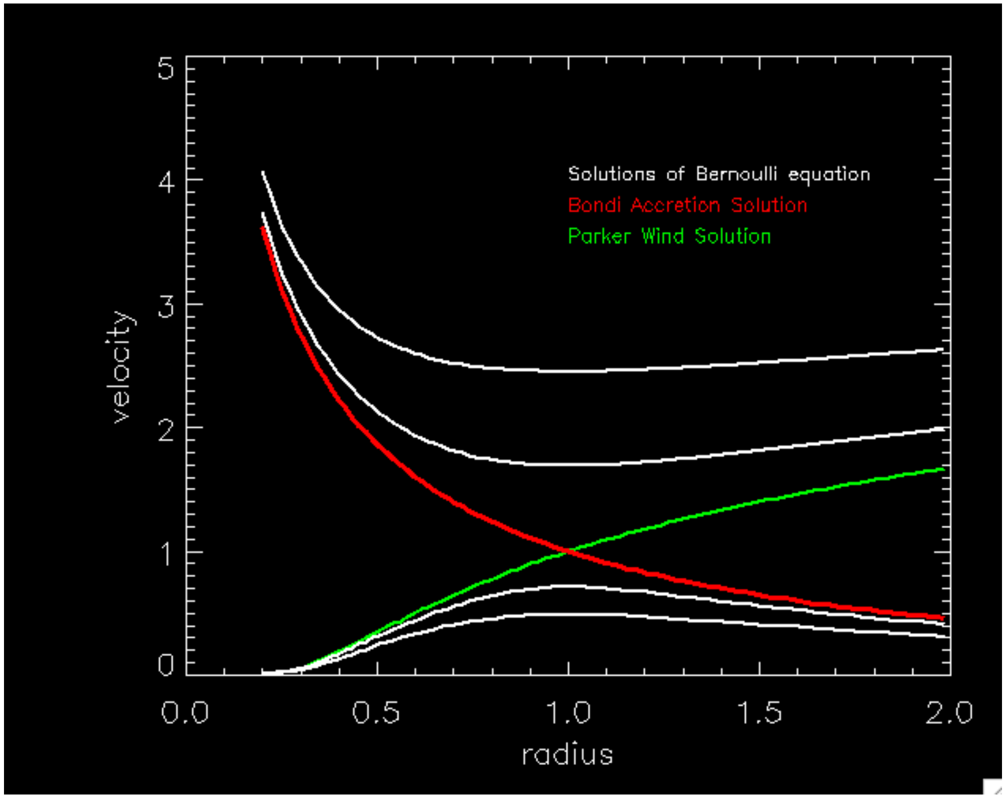
$$\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial r} = -\frac{a^2}{\rho}\frac{\partial \rho}{\partial r} - \frac{GM}{r^2}$$



Larson 1969
Penston 1969

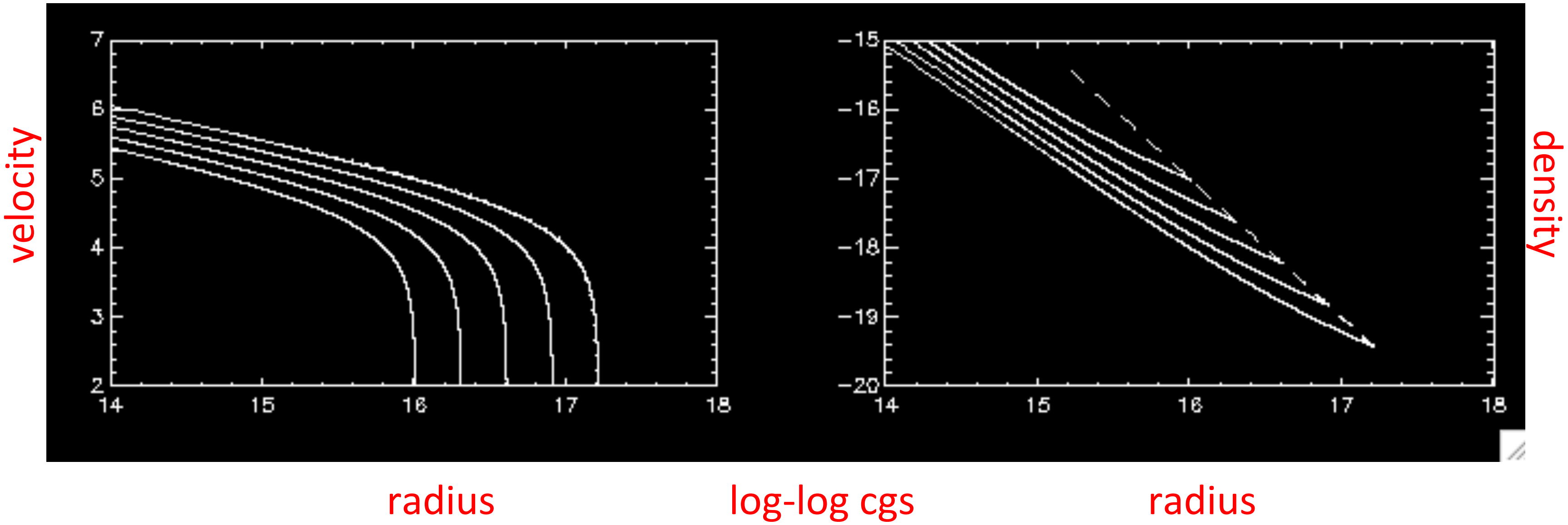
Collapse solutions

$$\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial r} = -\frac{a^2}{\rho}\frac{\partial \rho}{\partial r} - \frac{GM}{r^2}$$



SIS inside-out collapse

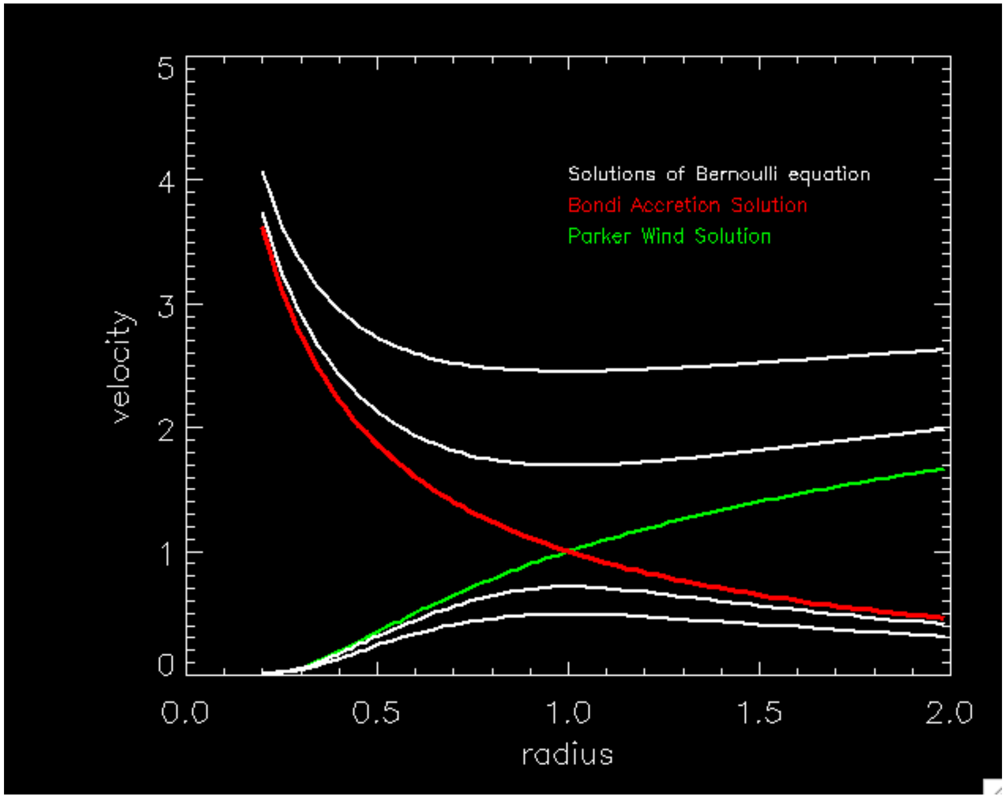
$$\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial r} = -\frac{a^2}{\rho}\frac{\partial \rho}{\partial r} - \frac{GM}{r^2}$$



Shu 1977

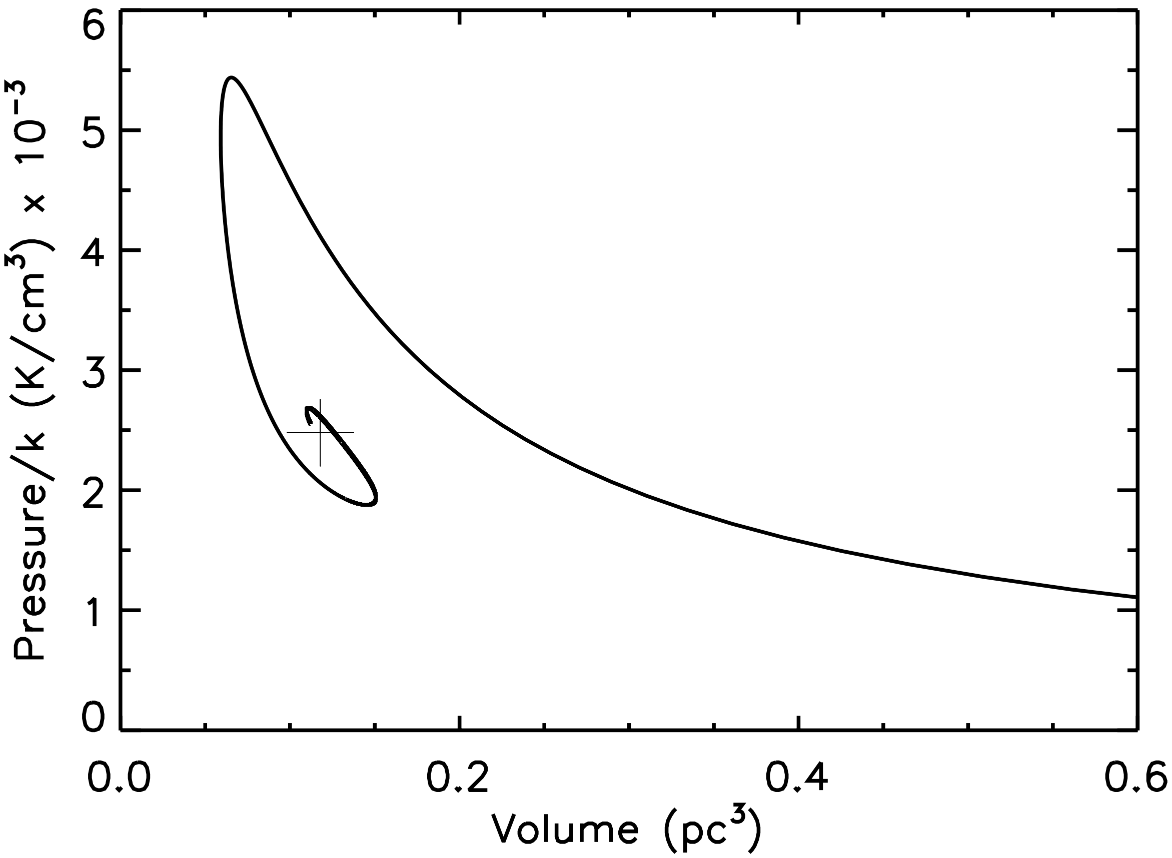
Collapse solutions

$$\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial r} = -\frac{a^2}{\rho}\frac{\partial \rho}{\partial r} - \frac{GM}{r^2}$$



QE and NE BES

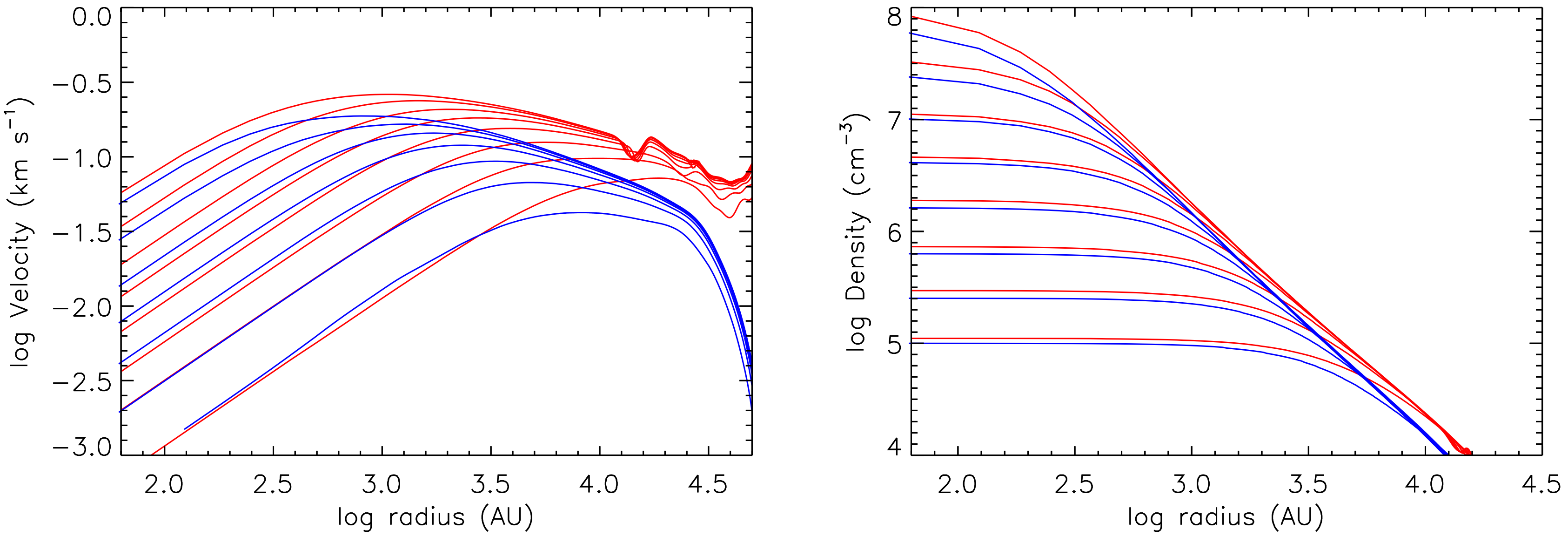
Bonnor 1956 -- Ebert 1957



QE and NE BES

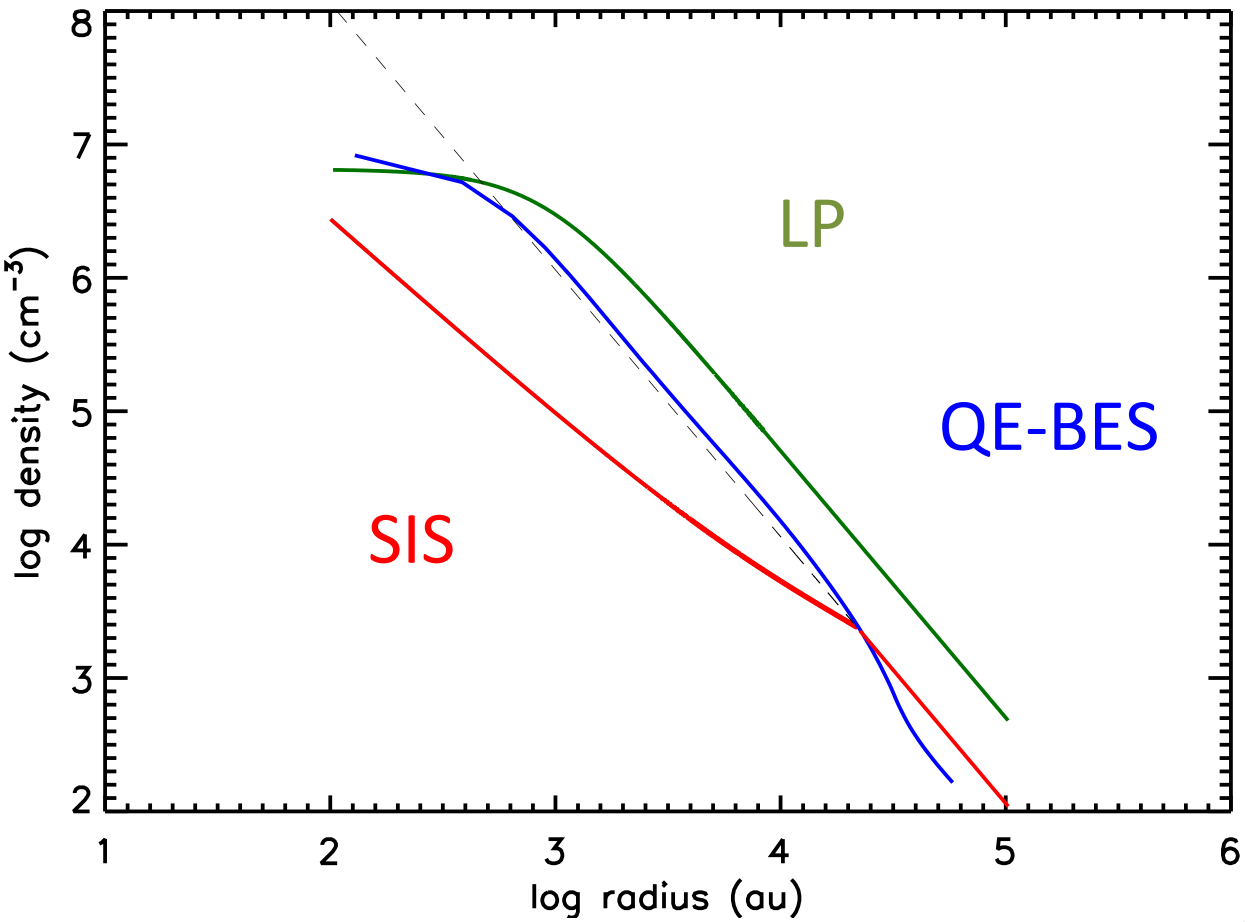
Unstable equilibrium

Unstable equilibrium + 10%



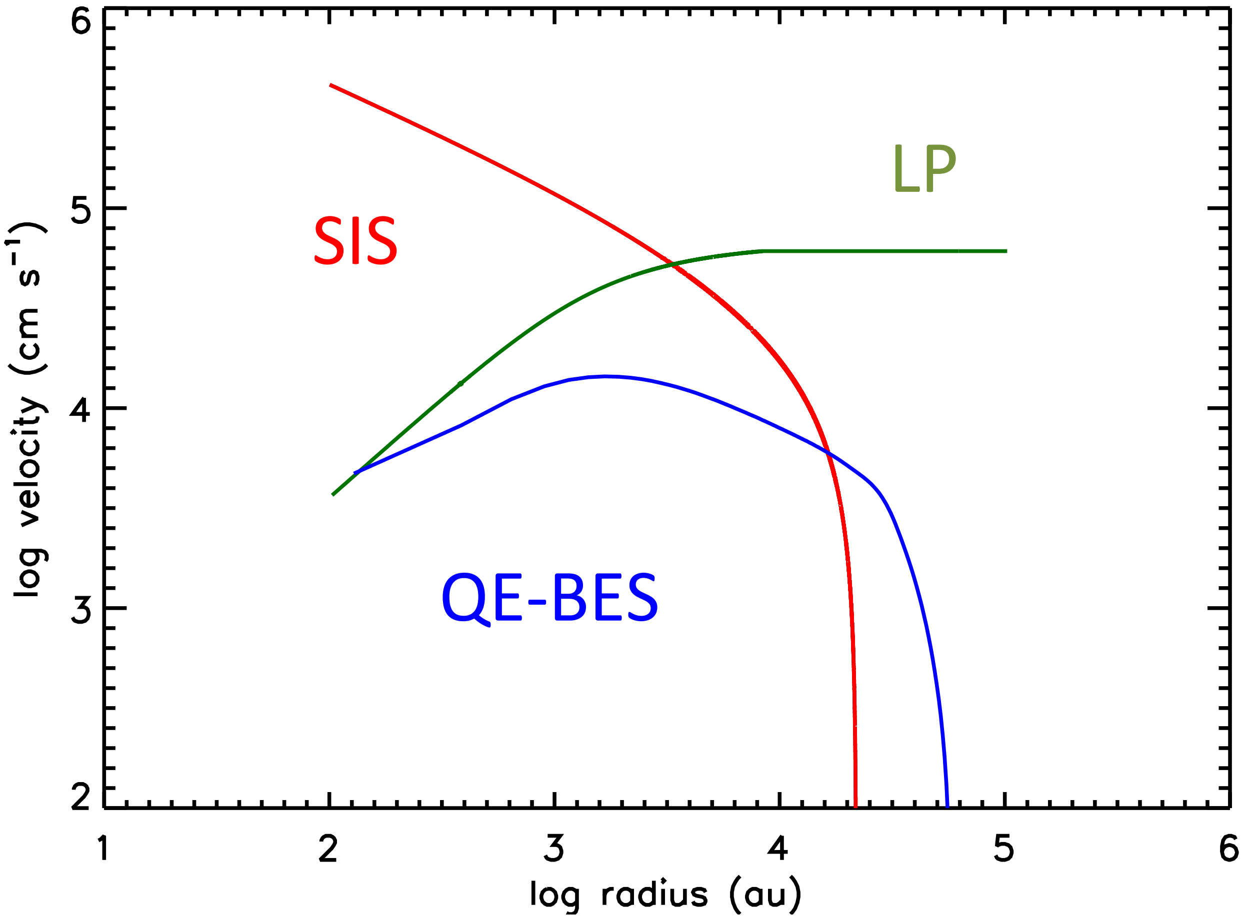
Keto, Rawlings, Caselli 2014

Problem: All self-gravitating spherical clouds have similar R^{-2} density profiles.



Keto, Caselli, Rawlings 2014

Solution: The collapse velocities are very different at large and small radii



Keto, Rawlings, Caselli 2015

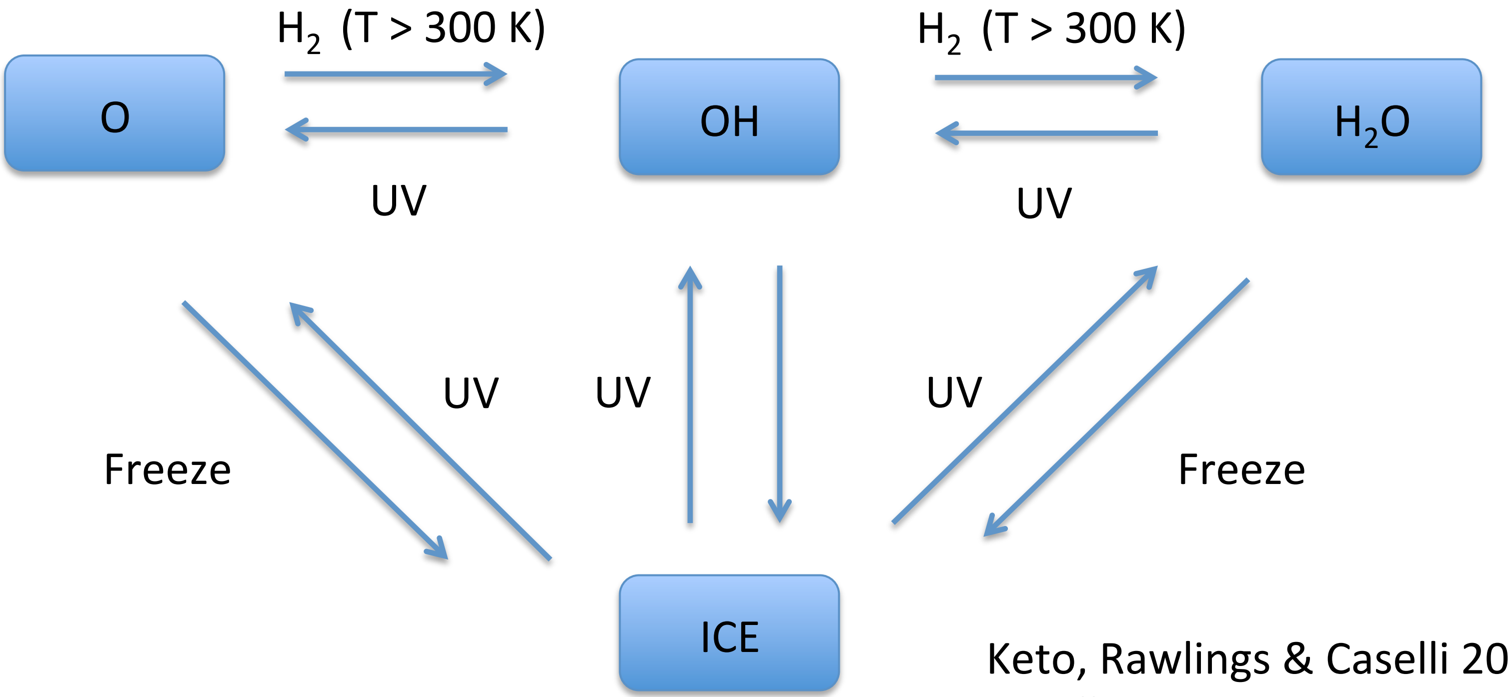
Use molecular lines that are emitted from the inner and outer core

- H_2O (110-101) 556 GHz
    - Einstein A = 10^{-3} s^{-1}
    - critical density 10^{8} cm^{-3}

- $C^{18}O$ (1-0) 110 GHz
    - Einstein A = 10^{-8} s^{-1}
    - critical density 10^{3} cm^{-3}

Keto, Rawlings, Caselli 2015

Simplified Oxygen Chemistry

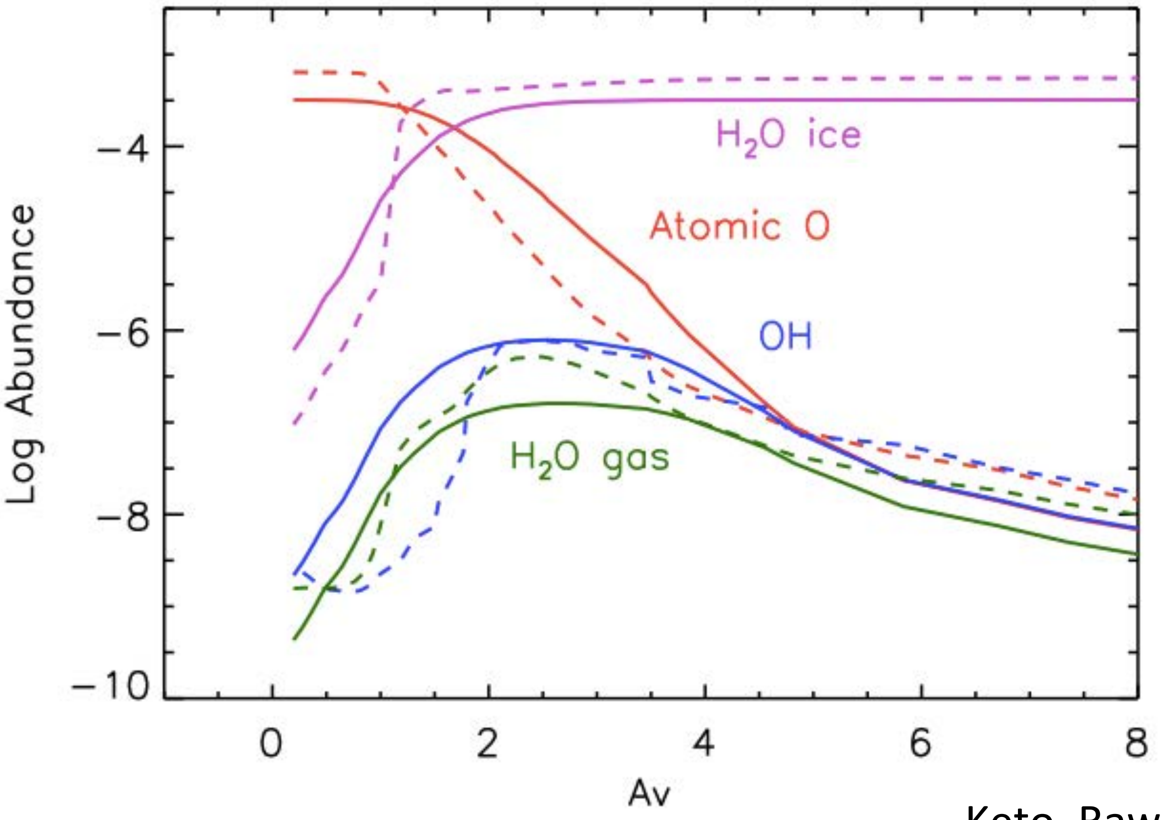


Keto, Rawlings & Caselli 2014
Caselli, Keto, + WISH 2010, 2012

Schmalzl et al 2014

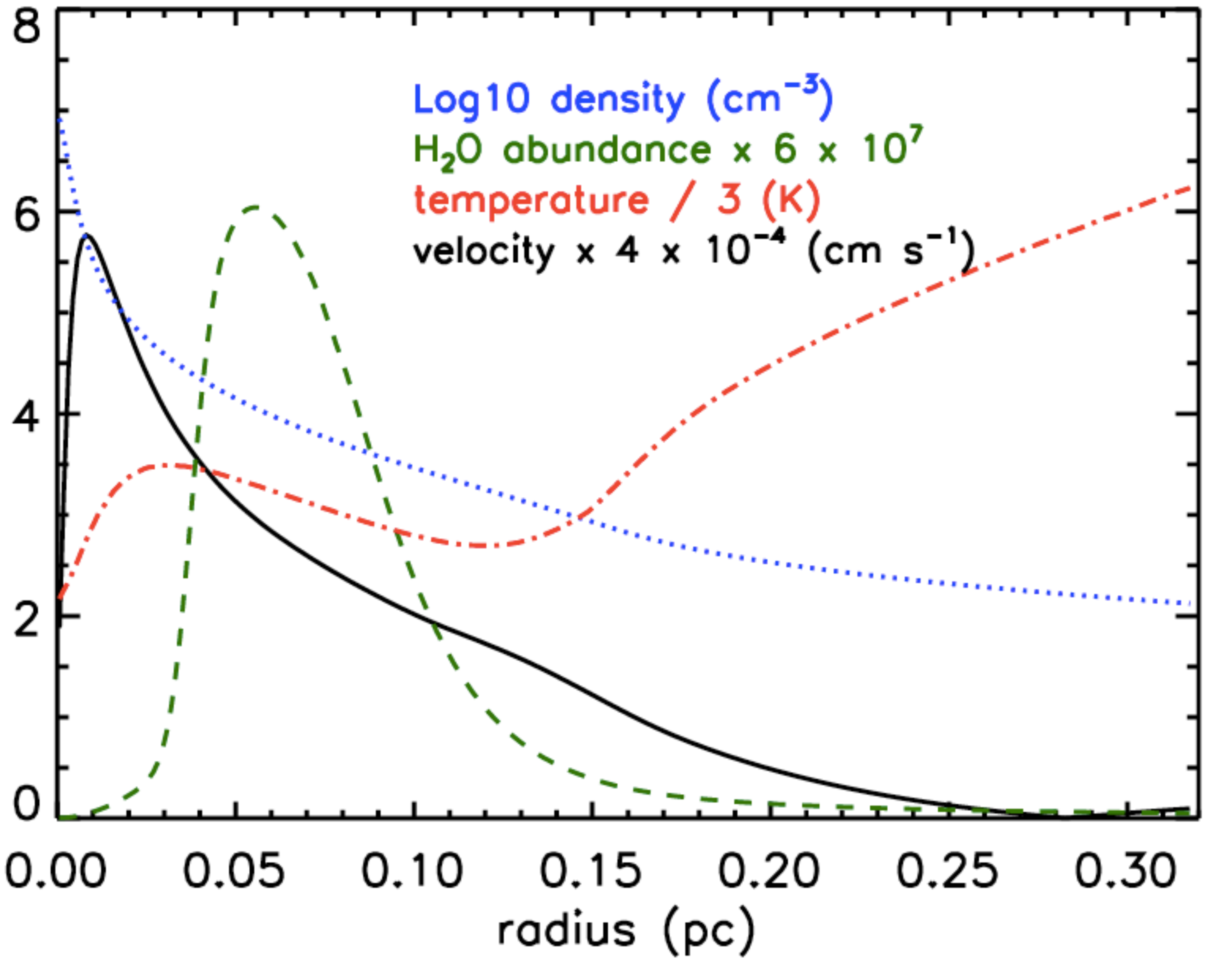
Simplified Oxygen in L1544

Desorption rates from
Hollenbach, Kaufman, Bergin, Melnick 2009



Keto, Rawlings & Caselli 2014
Caselli, Keto, + WISH 2012

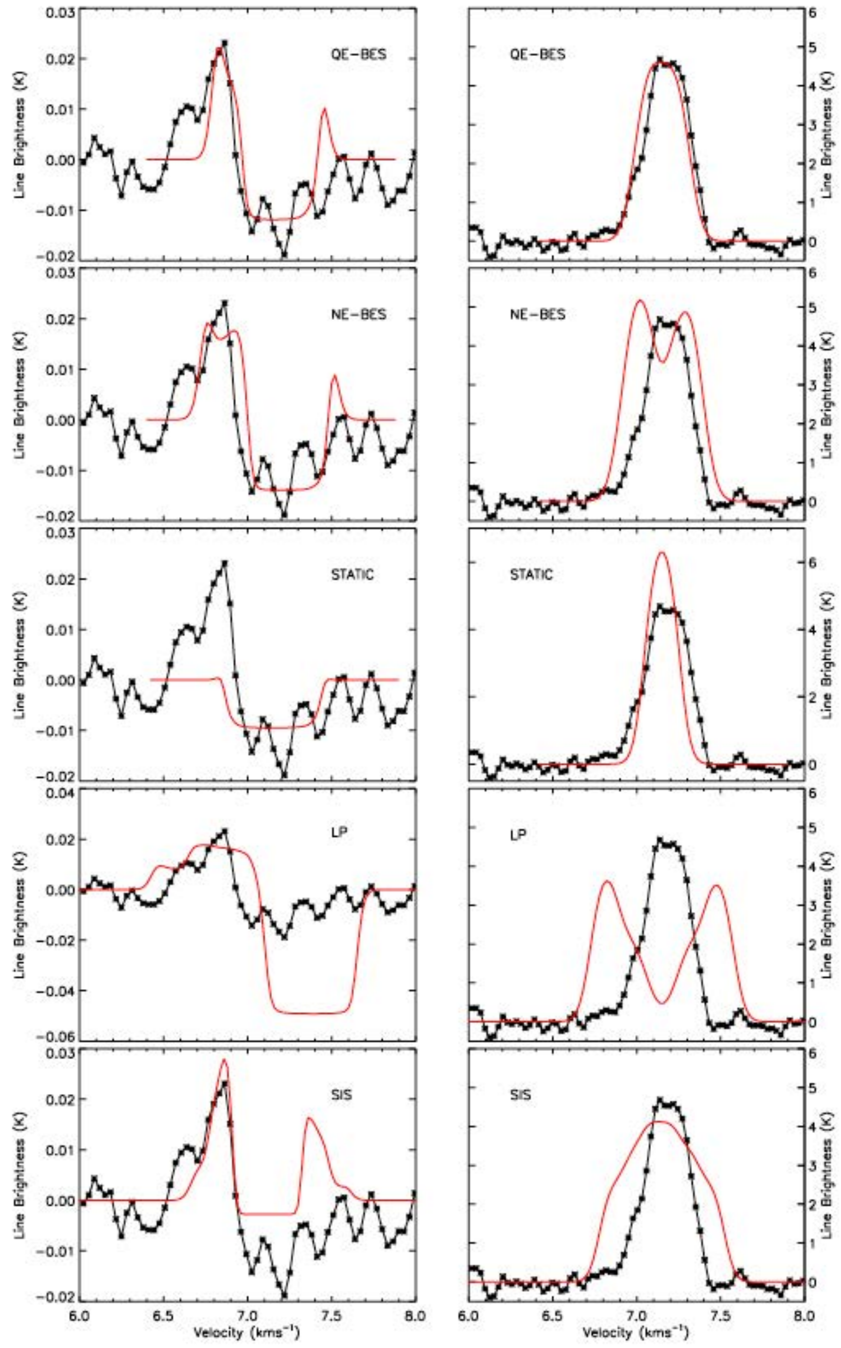
L1544



Log10 density (cm^{-3})
H_2O abundance x 6 x 10^7
temperature / 3 (K)
velocity x 4 x 10^{-4} ($cm\ s^{-1}$)
8
6
4
2
0
0.00
0.05
0.10
0.15
0.20
0.25
0.30
radius (pc)

5 dynamical models to compare

- SIS inside-out collapse
- LP flow
- Quasi-Equilibrium-BES
- Non-Equilibrium-BES
- static



Simulated and observed H_2O and $C^{18}O$ spectra

Keto, Rawlings, Caselli 2014

Conclusions

- There are several possible solutions for the gravitational collapse of starless cores
- These are observationally distinguishable by observational spectroscopy that measures the velocities in the inner and outer parts of the core.
- Only the slow collapse solution of a quasi-hydrostatic contraction matches the data.
- Only one core, L1544, so far.