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Formation of Star-Planet Systems

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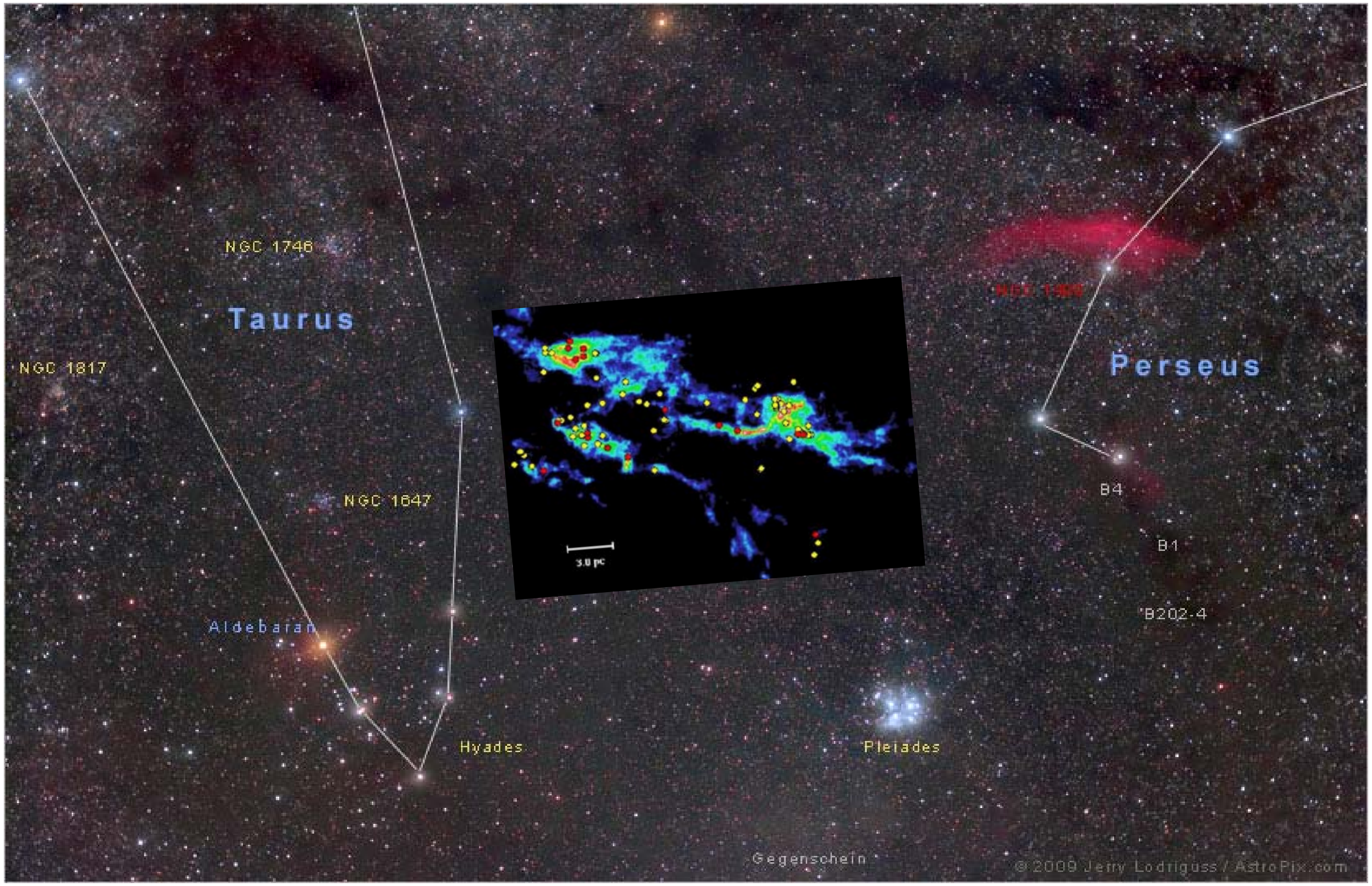
- Star-planet System formation from molecular cloud cores

Molecular Clouds: Cradles of Stars

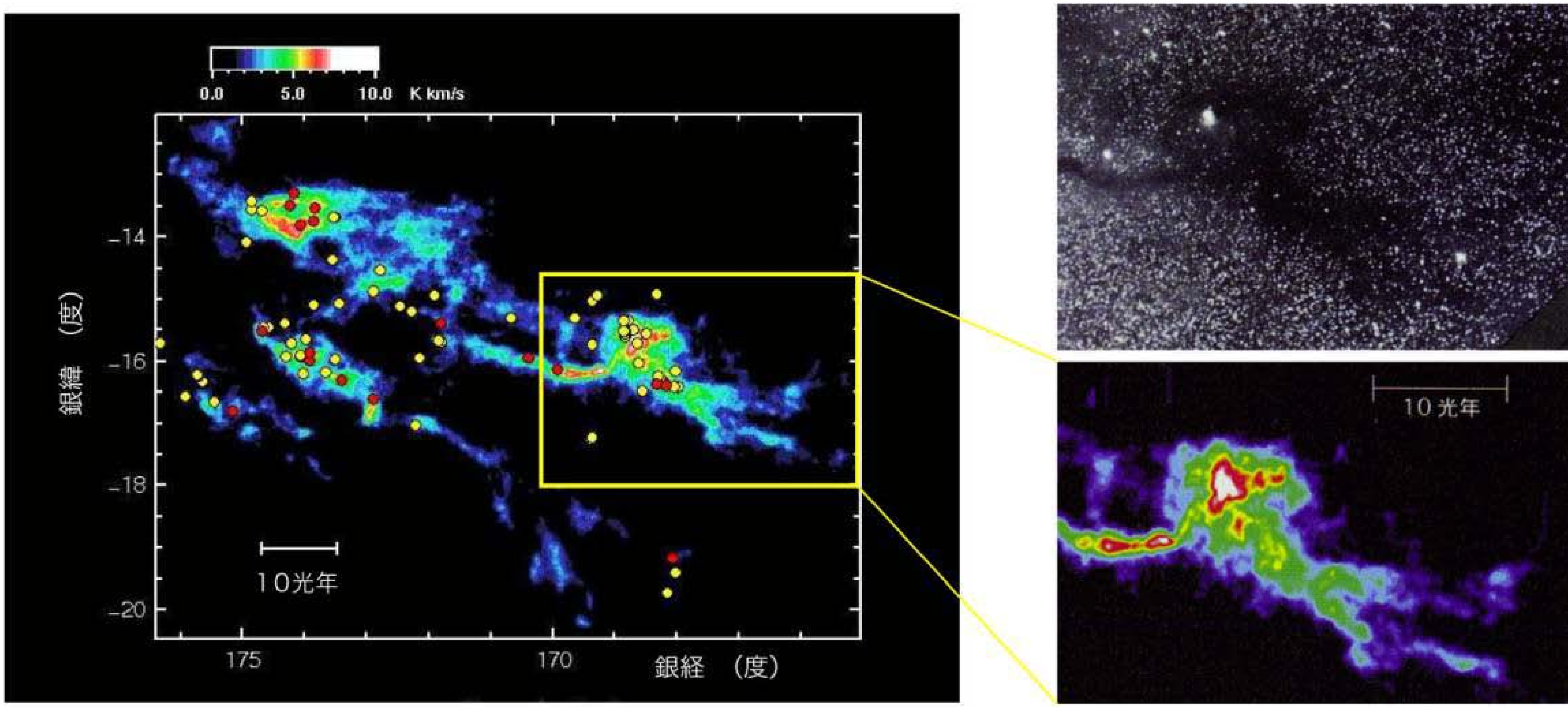


Molecular Clouds:

$M \sim 10^3 - 10^6\ M_{sun}$; $n \sim 100 cm^{-3}$; $T \sim 10K$

Molecular Cloud Cores

Taurus molecular cloud（^{13}CO observation） Mizuno+（1995）

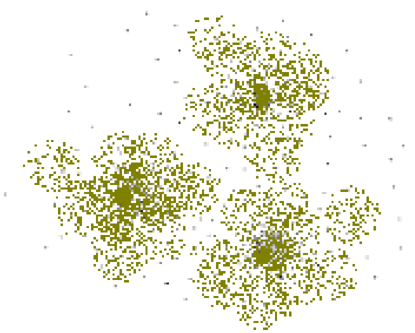


- molecular cloud (10$^{4\text{-}6}$M$_{sun}$; >10^{2}cm^{-3})
- molecular cloud core (1-10M$_{sun}$; >10^{4}cm^{-3})
  =direct progenitor of a single /binary star(s).

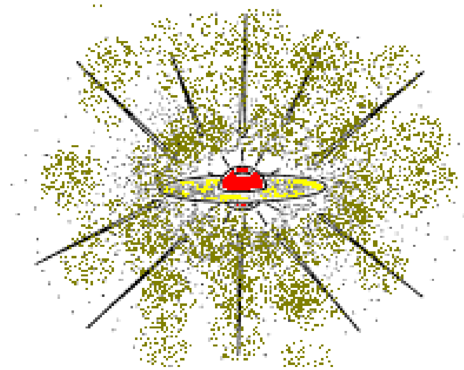
Standard scenario of low-mass star formation

Established in 1980's

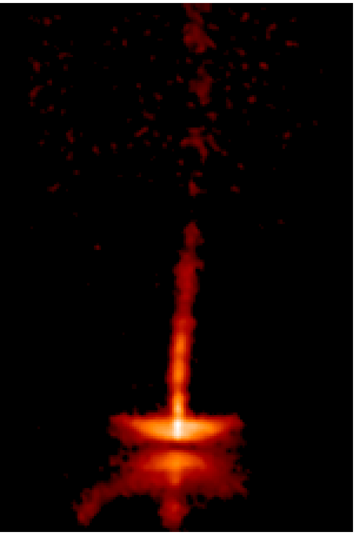
Shu, Adams & Lizano (1987)



A. Dense cores form within molecular clouds.



B. A protostar forms at the center of a core, growing in mass by accretion of ambient matter.



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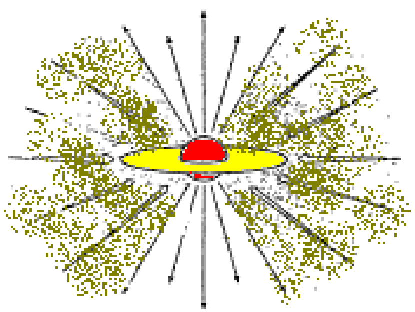
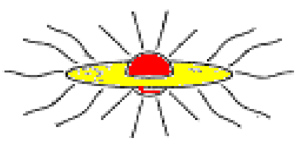
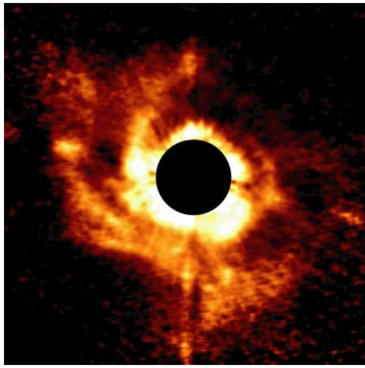


C. A stellar wind breaks out, creating a bipolar flow



D. The infall terminates, revealing a newly formed star with a disk.



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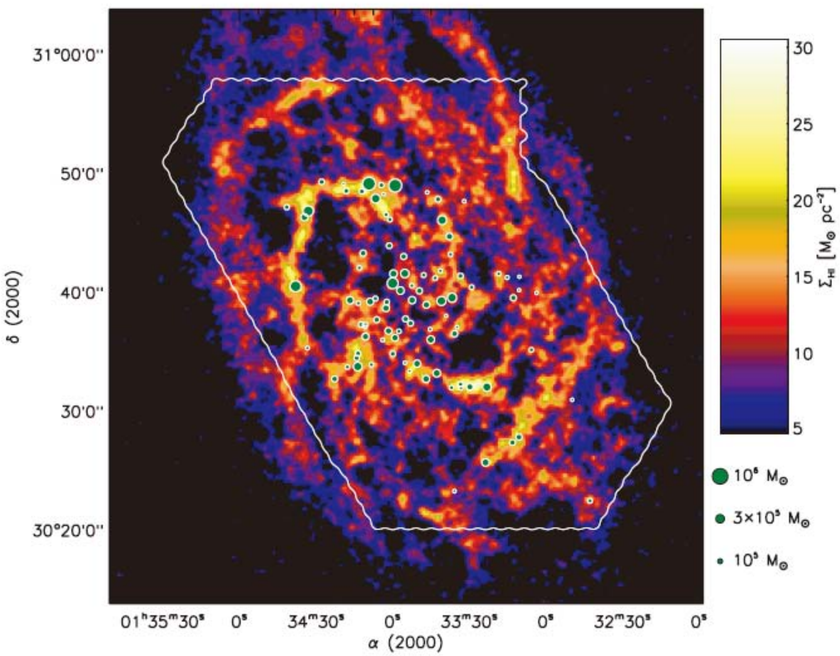
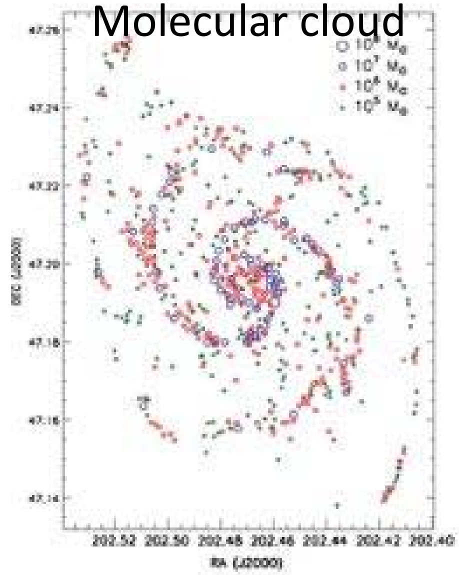
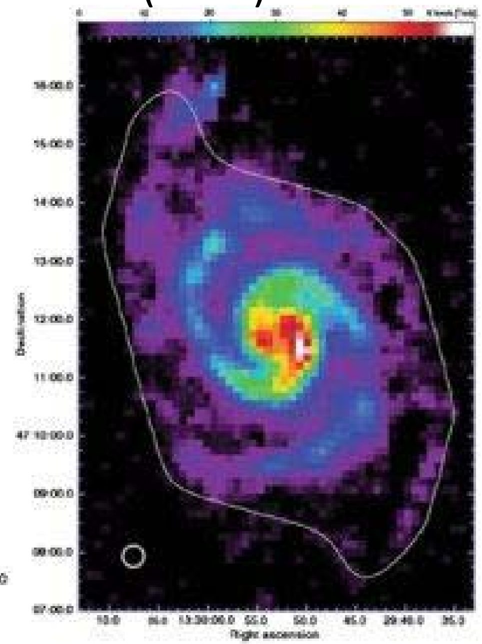
Molecular clouds in galaxies

M33 Engargiola+ (2003)



M51 Koda+(2011)

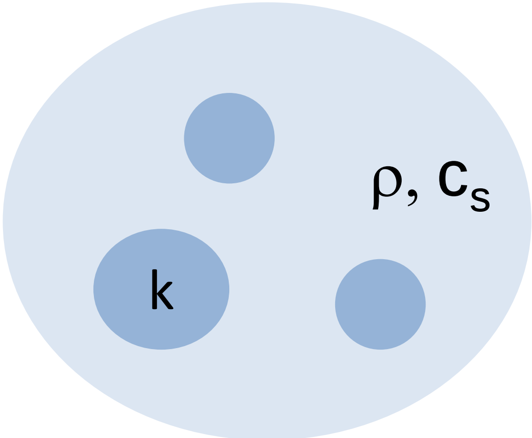




- Molecular clouds (MCs) are distributed mainly along the spiral arms.
- MCs are presumably formed by gravitational instability due to compression by the spiral wave.

Basics of Gravitational Instability

Gravitational instability



Jeans criterion

Linear perturbation of homogeneous gas

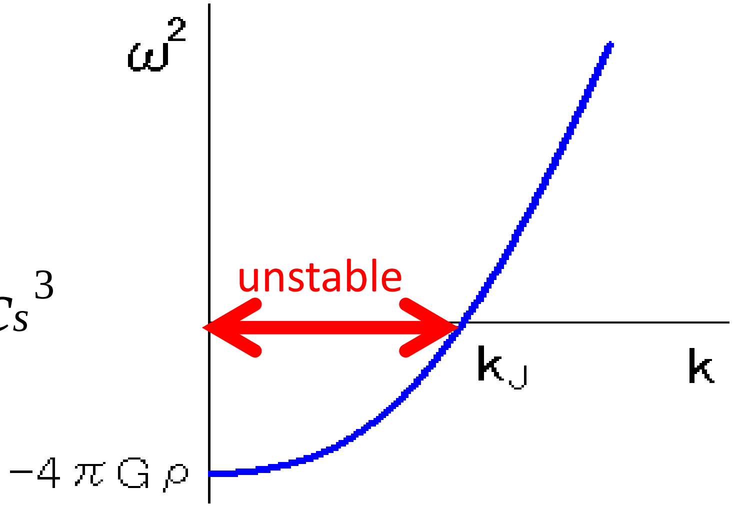
Unstable if

$$\omega^2 = c_s{}^2 k^2 - 4\pi G\rho$$

$$k < k_J = \sqrt{4\pi G\rho} / c_s$$

$$\lambda > \lambda_J = 2\pi / k_J = c_s \sqrt{\pi / G\rho}$$

$$M > M_J = \rho \lambda_J{}^3 = \pi^{3/2} G^{-3/2} \rho^{-1/2} c_s{}^3$$



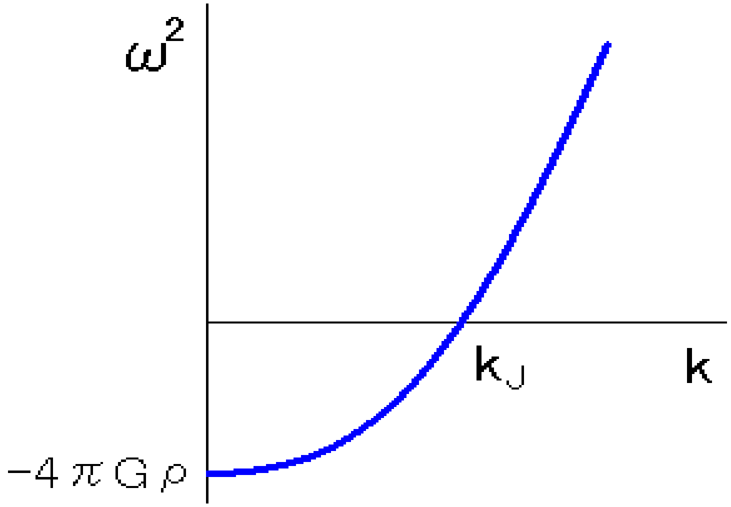
Problem of Jeans' analysis

- max. growing mode k=0
  🡸 global contraction of the cloud

$$(gravity) \sim \frac{GM}{L^2} \sim G\rho L$$

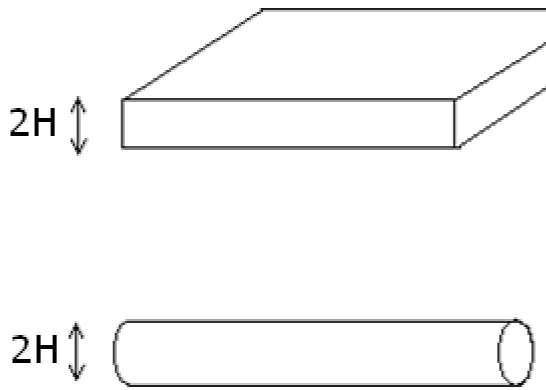
$$(pressure) \sim \frac{P}{\rho L} \sim \frac{{c_s}^2}{L}$$

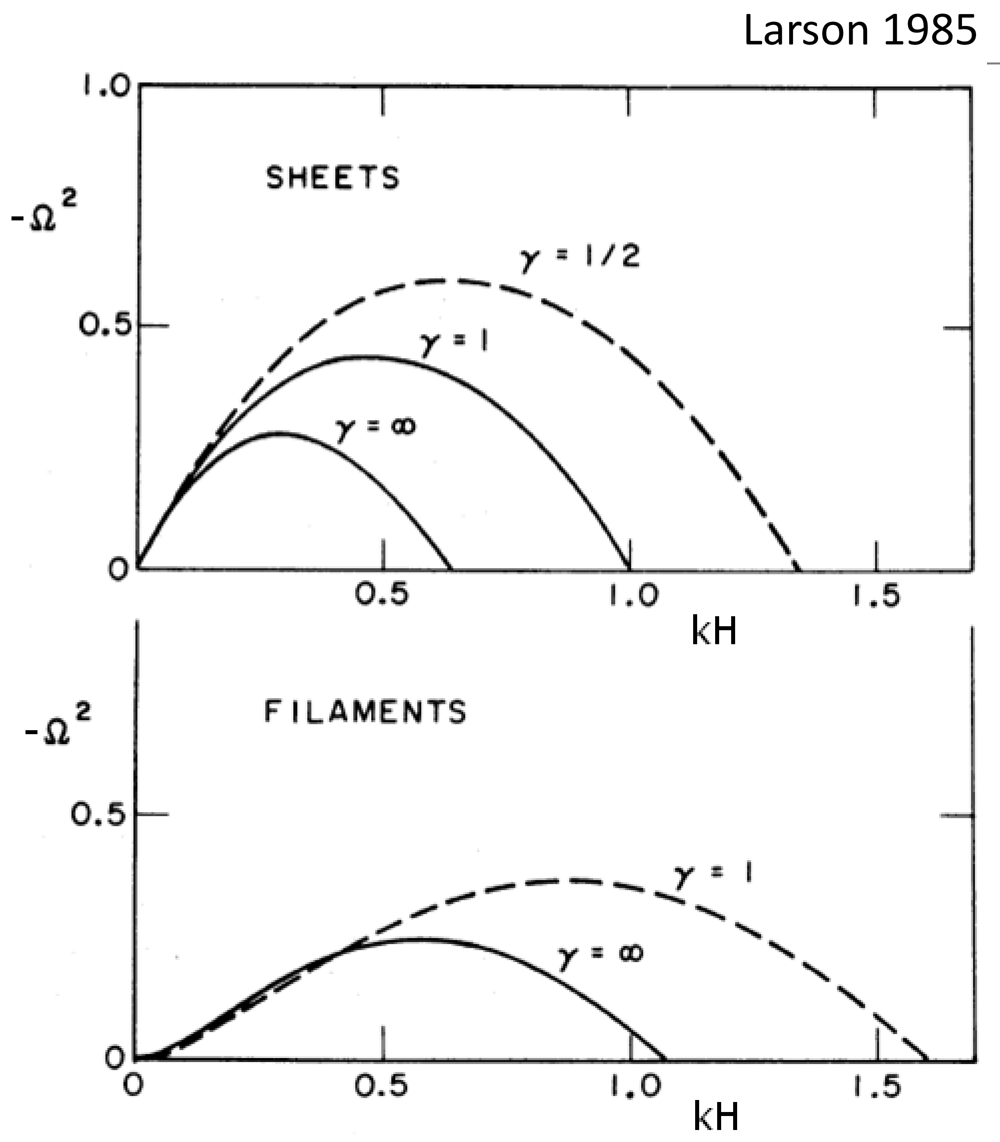
- In larger scale, gravity becomes more and more important and so the collapse is faster.



This does not lead to fragmentation

Gravitational instability of sheets and filaments





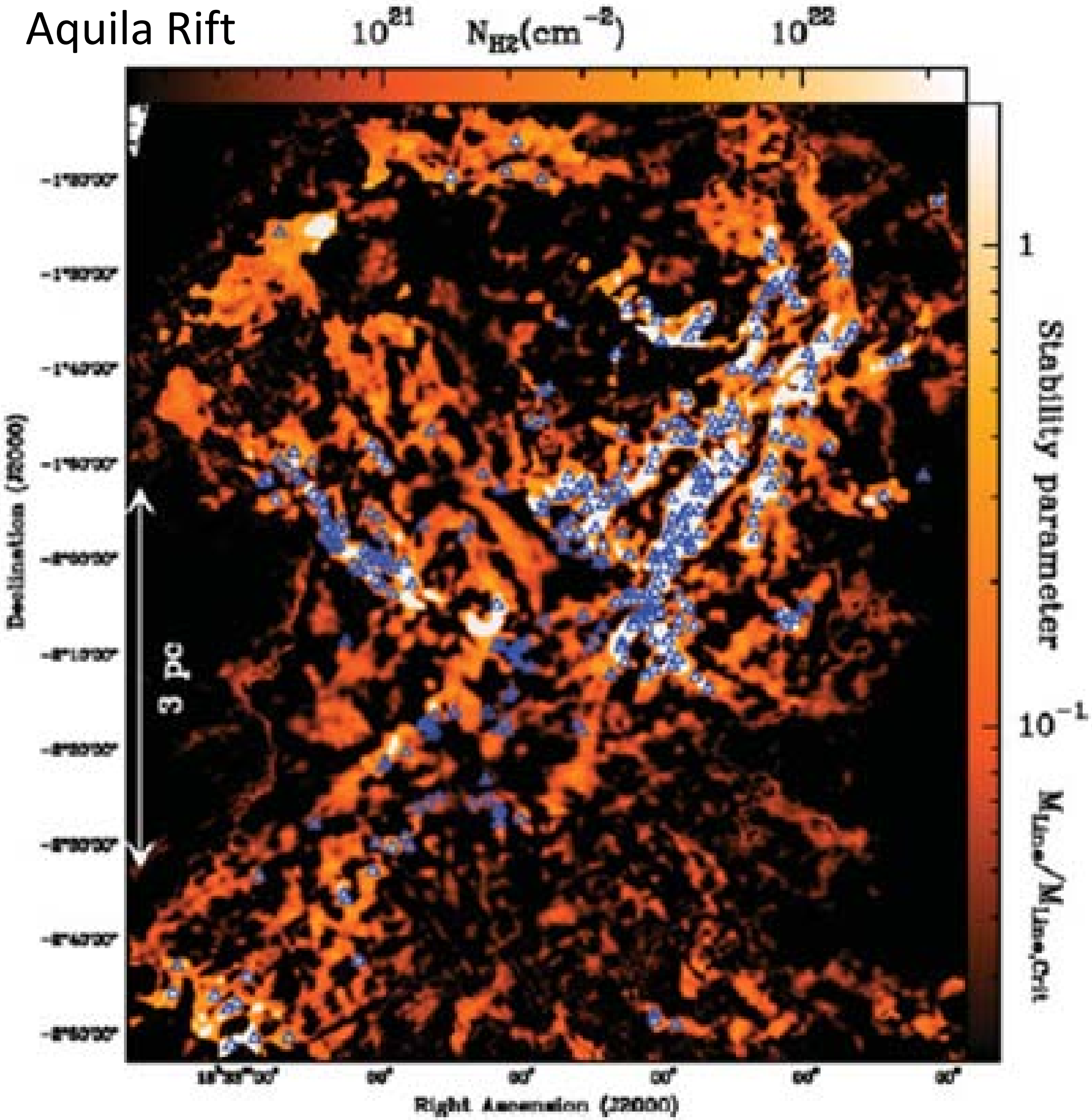
- Perturbation with wavelength ~H grows fastest k_{max}~1/H~k_J

- Fragmentation into Jeans scale pieces

From a molecular cloud to stars

Omnipresence of Filaments in MC

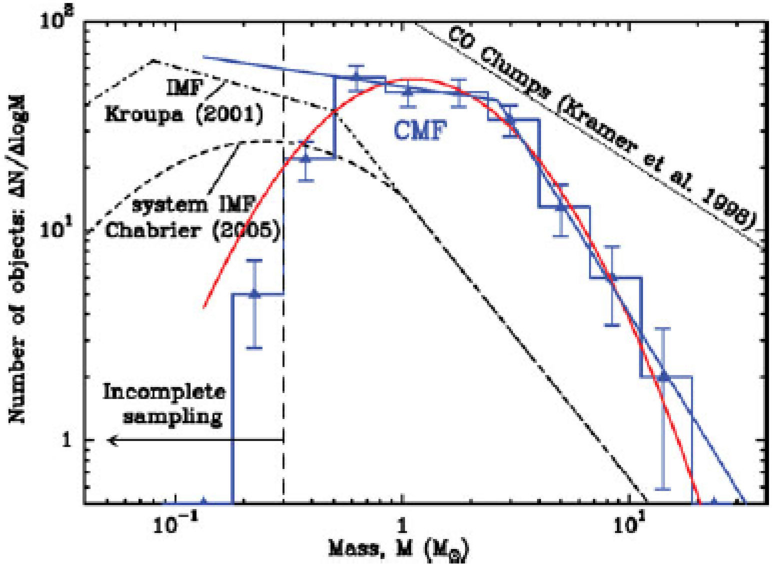
Aquila Rift

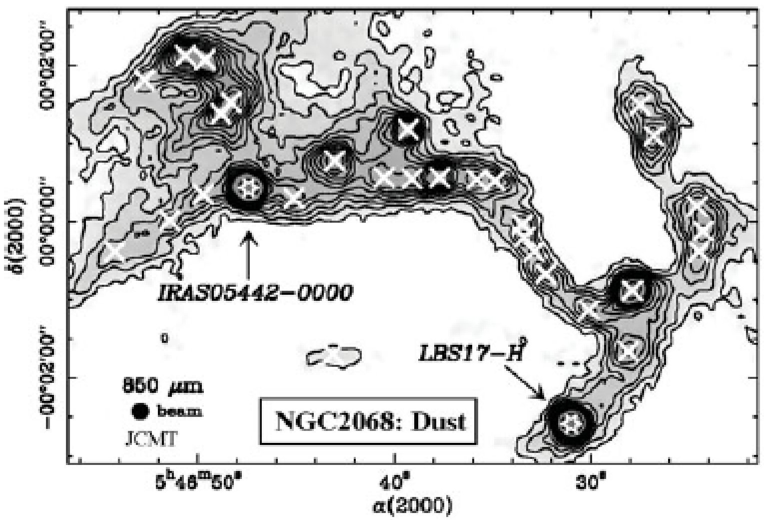


- Gravitationally bound cores form only in unstable filaments.

Andre et al. 2011

core mass function (CMF) and stellar initial mass function (IMF)



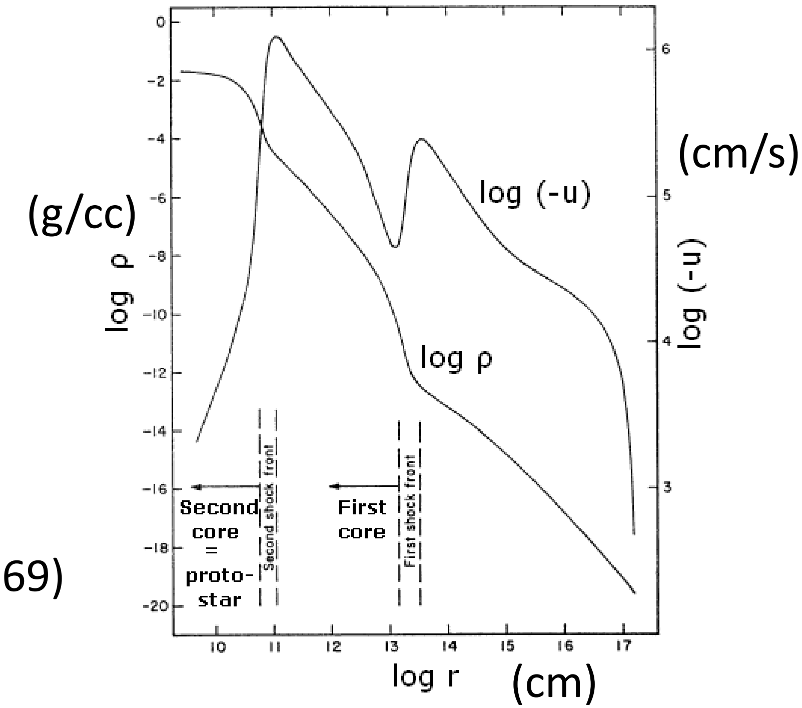


Mass distribution of dense cores resembles that of stars at their birth.

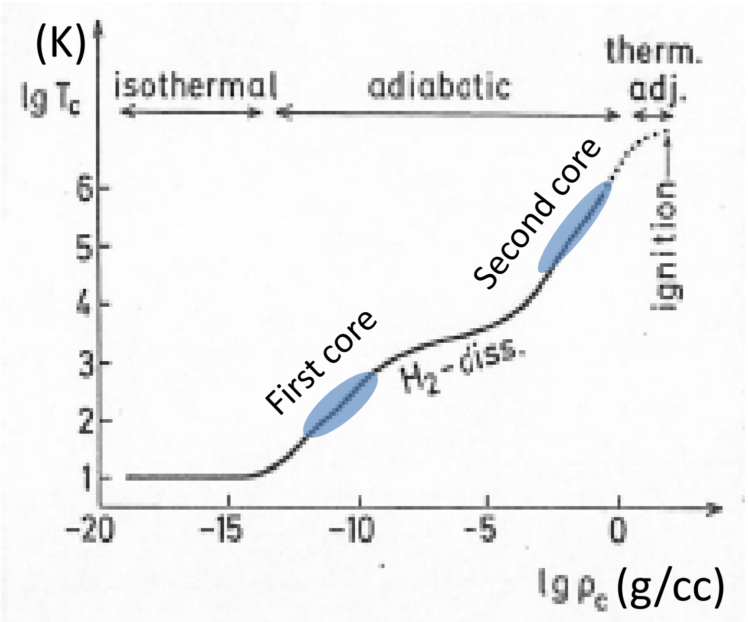
Fragmentation appears to set both CMF and IMF.

Andre et al. 2011

Gravitational collapse of dense cores and birth of protostars



Larson (1969)



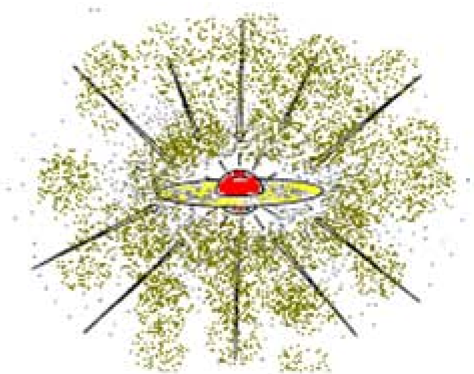
Appenzeller & Tsuarnuter (1975)

- Molecular cloud core

  ＝self-similar dynamical collapse⇒
- Formation of the first core @10^{11}cm^{-3}

  ＝dynamical collapse by H_2 dissociation⇒
- Formation of the second core (=protostar)@10^{22}cm^{-3}

Accretion evolution of a protostar



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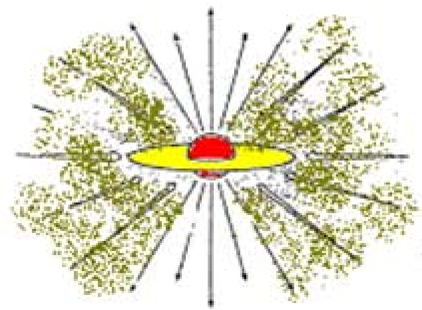

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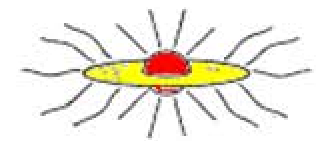

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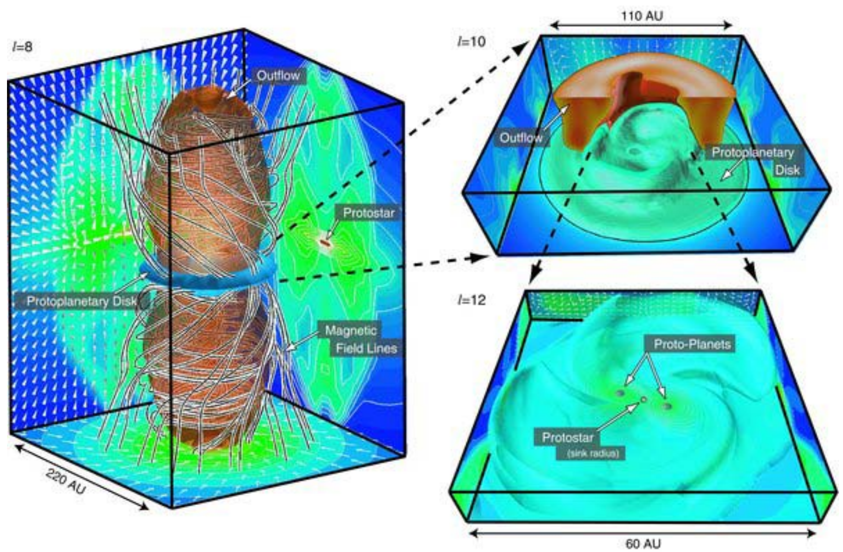
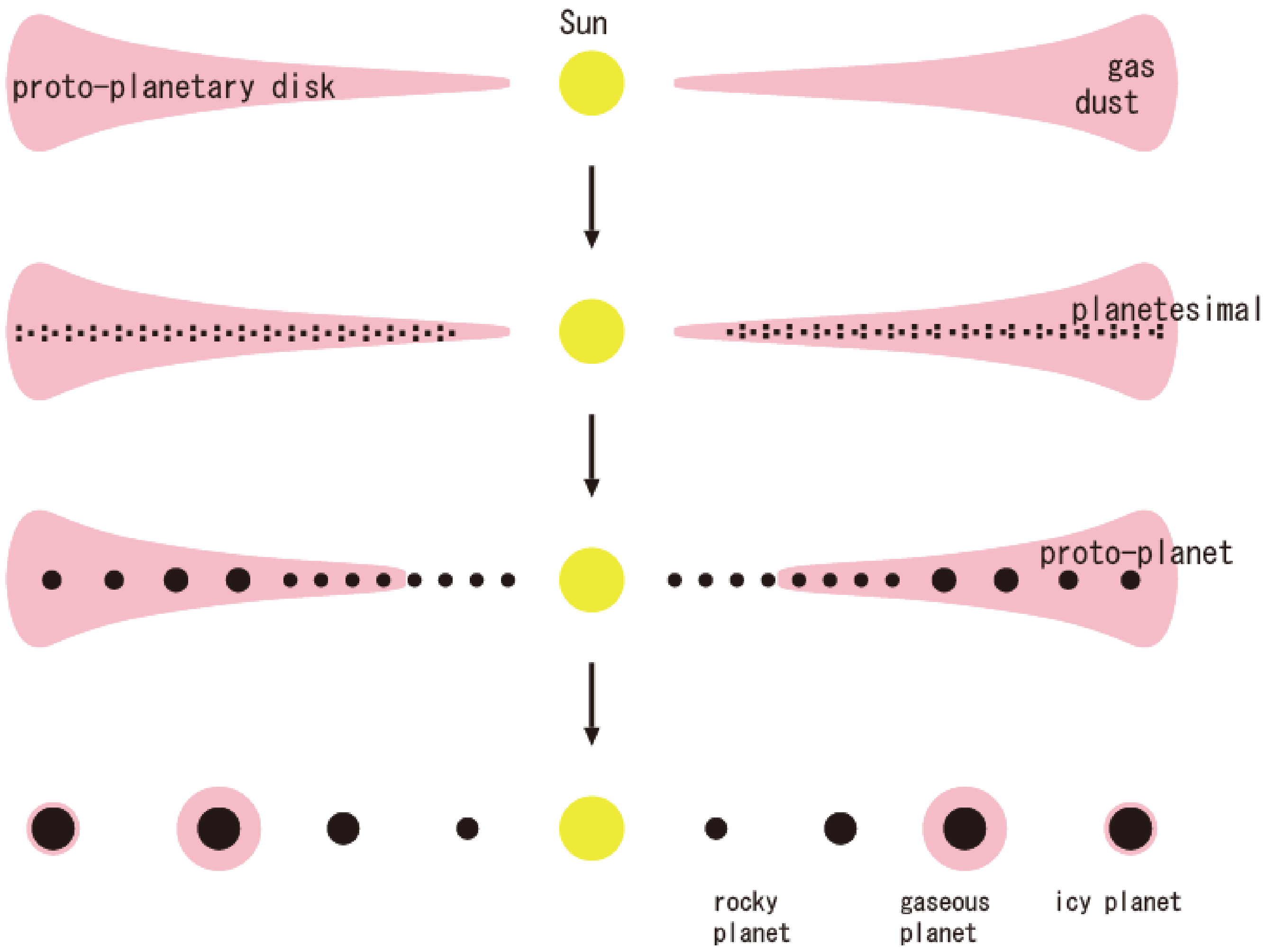
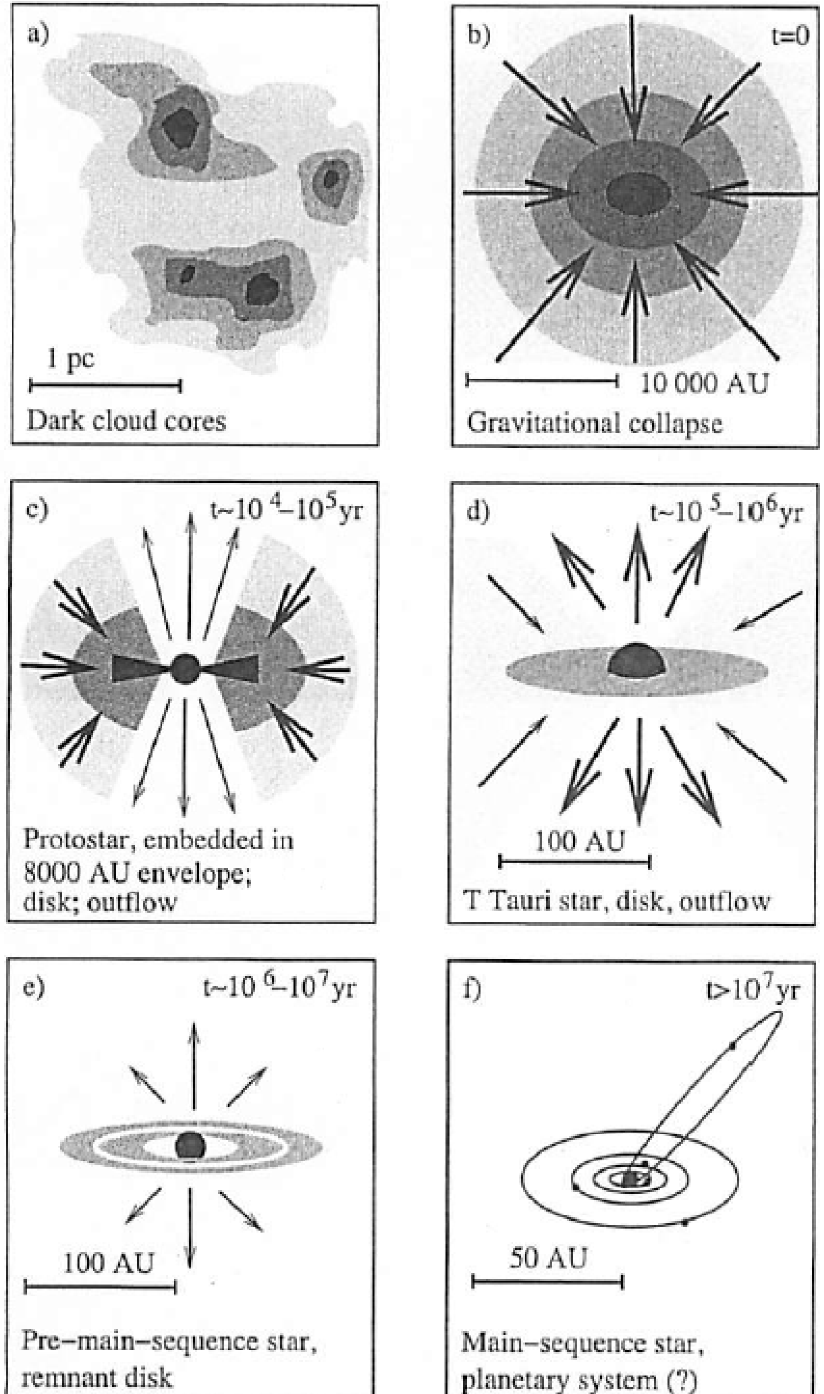


- •The protostar grows in mass by accretion.
- •The mass of the star is fixed when the accretion terminates.
- •A circumstellar disk remains for a while ➔ the formation site of planets.

Inutsuka + 2010

Standard scenario of Solar system formation : Kyoto Model





Summary
Big picture for the birth of star-planet systems

- Molecular clouds have filamentary structures.
- Filamentary clouds fragment to produce dense cores.
- A dense core collapses gravitationally to form a single/binary star system.
- The disks surrounding the stars eventually evolve to planetary systems.

Ward-Thompson & Whitworth 2011