Modes of Star Formation: A Retrospective

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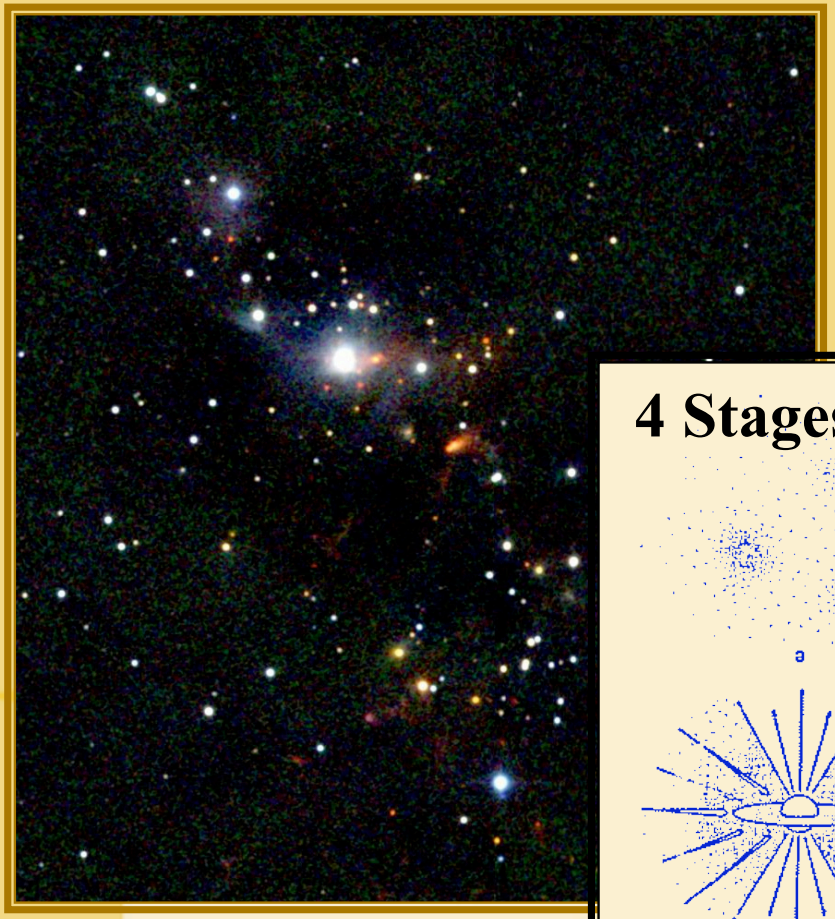
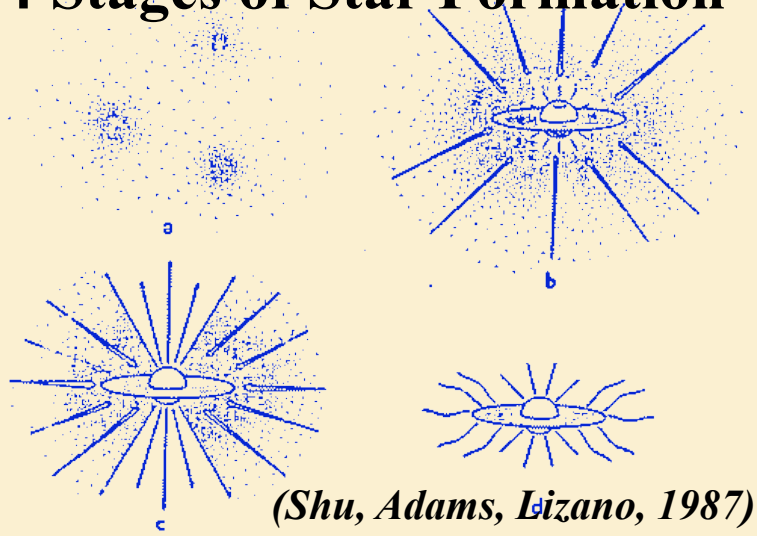
DENSE CORES LXV

NEWPORT, RI, OCTOBER 2009

A Brief History



4 Stages of Star Formation



(Shu, Adams, Lizano, 1987)

Ambipolar Diffusion

$$\frac{\partial \Sigma}{\partial t} + \frac{1}{r}\frac{\partial}{\partial r}\left(ru\Sigma\right) = 0$$

$$\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial r} + \frac{a^2}{\Sigma}\frac{\partial}{\partial r}\left(\Theta\Sigma\right) = g + l$$

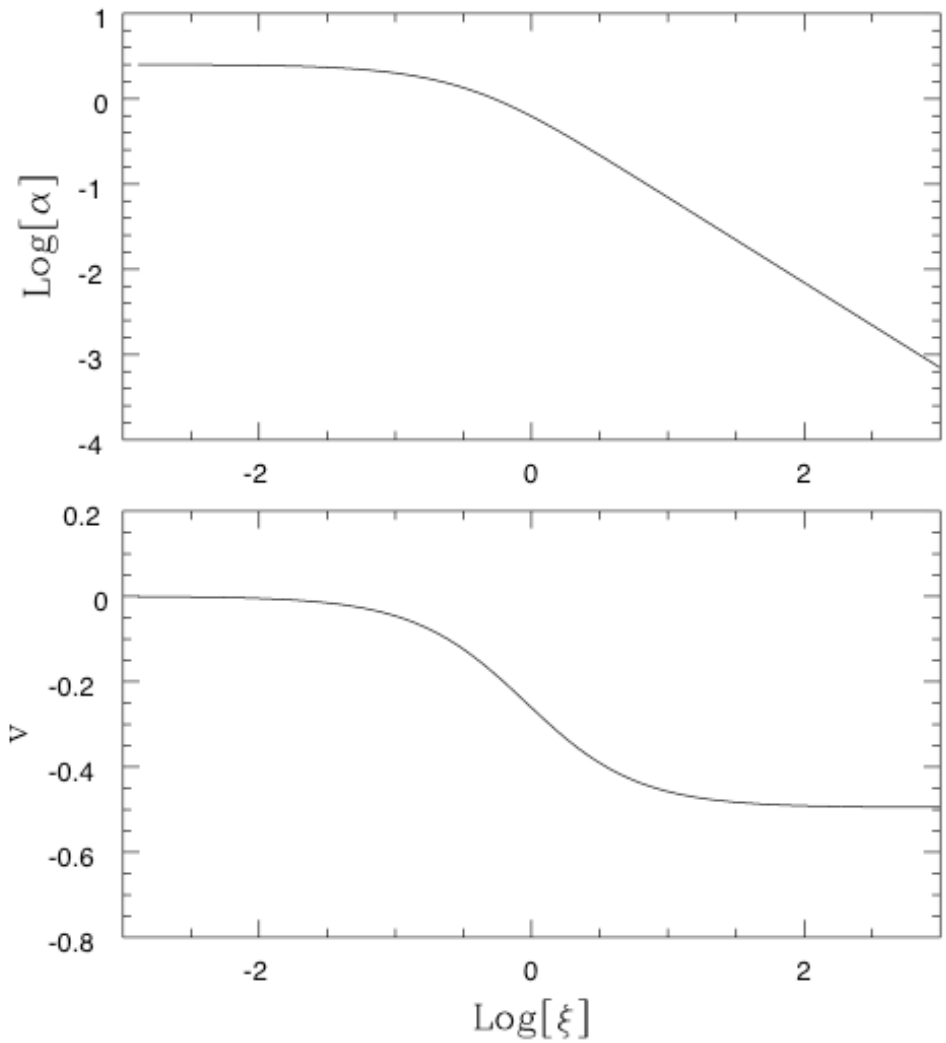
$$g + l = \frac{1}{r^2\Sigma}\int_0^\infty 2\pi r' dr' K_0(r'/r)\left[-G\Sigma(r)\Sigma(r') + \frac{B_z(r)B_z(r')}{(2\pi)^2}\right]$$

$$\left[\frac{\partial B_z}{\partial t} + \frac{1}{r}\frac{\partial}{\partial r}\left(urB_z\right)\right] = \frac{1}{r\Sigma}\left[\frac{\left(2z_0\right)^{1/2}}{2\pi\gamma C}\frac{rB_z^2 B_r^+}{\sqrt{\Sigma}}\right]$$

$$B_r^+ = \frac{1}{r^2}\int_0^\infty K_0(r'/r)B_z(r')r' dr'$$

$$K_0(q) = \frac{1}{2\pi}\int_0^{2\pi} d\varphi \frac{1 - q\cos\varphi}{\left(1 + q^2 - 2q\cos\varphi\right)^{3/2}}$$

Monopole Solution



$$v_\infty = 0.495 \ a_S$$

Fred: Your measurements of only `half the sound speed' must be wrong: you should get 0.495 times a_s. You need to get more accurate measurements…

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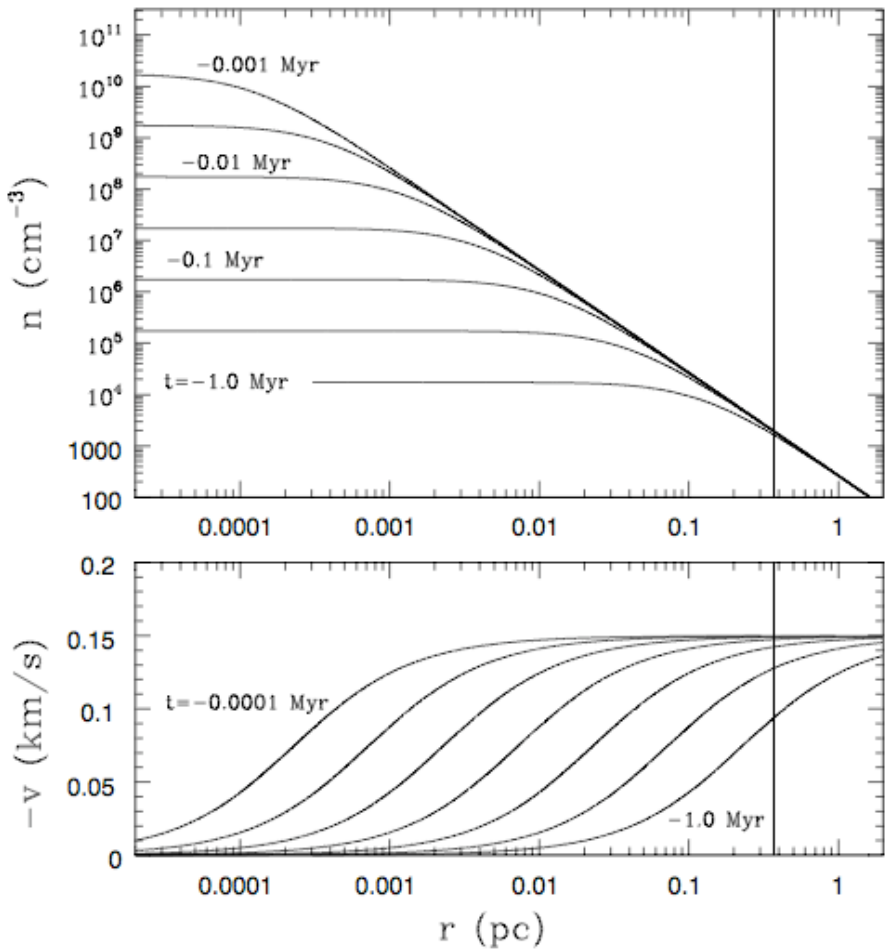
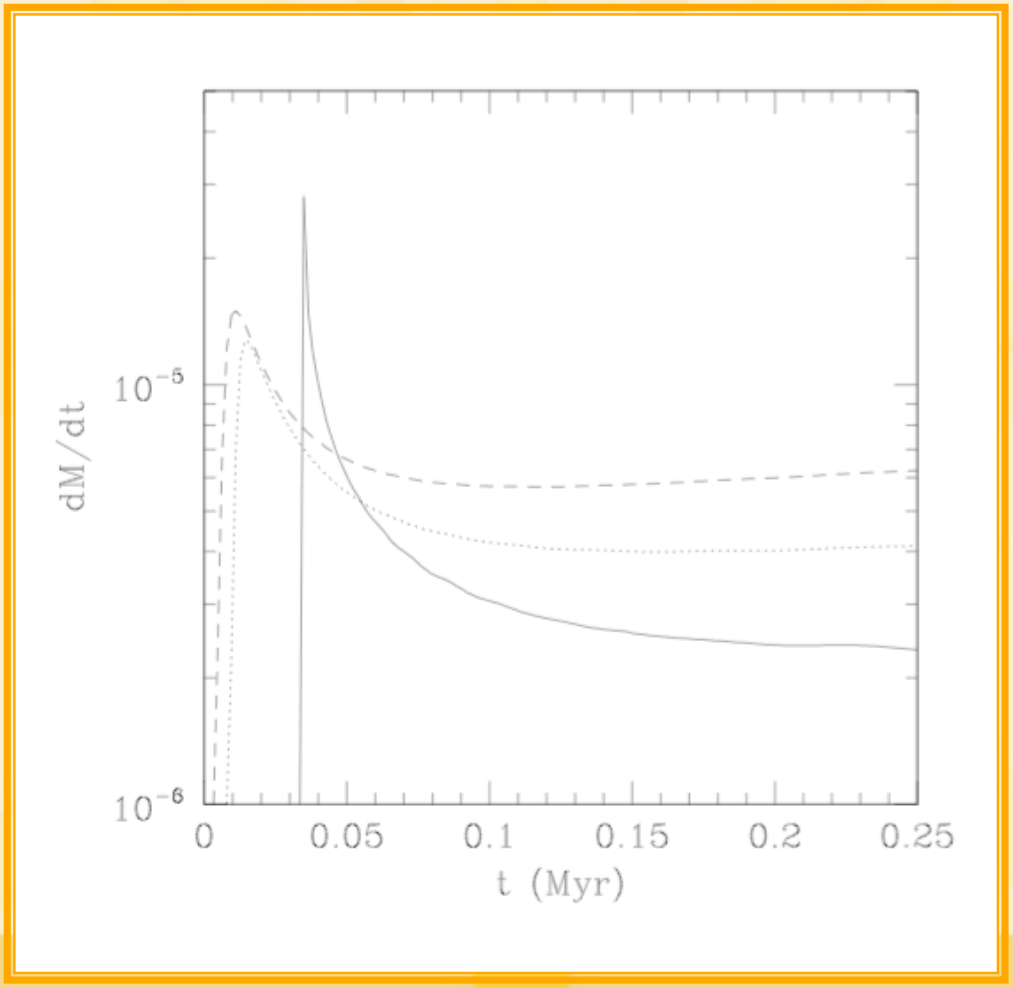
Phil: … you and Frank never do anything 0.495-hearted or 0.495-assed…

Physical Diffusion Solutions



Mass Infall Rates with Nonzero Head Start Velocity



Most Stars Form in Clusters:

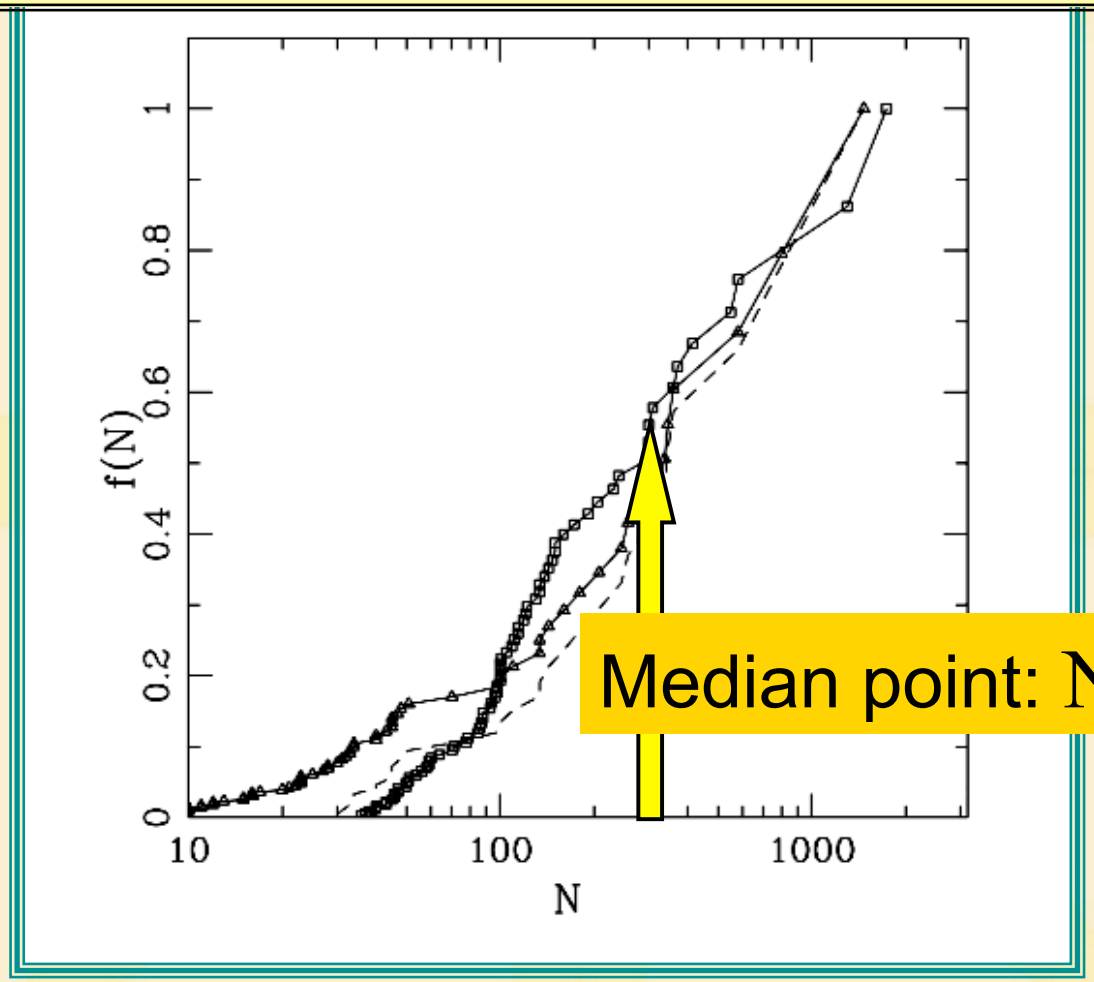
[1] What is the distribution of cluster environments?

[2] How does the cluster environment affect the formation of stars/planets?

Conjecture:

Cluster environments actively affect the formation of planets more than the formation of stars themselves.

Cumulative Distribution: Fraction of stars that form in stellar aggregates with N < N as function of N



(Adams, Proszkow, Fatuzzo, & Myers 2006, ApJ)

Dynamical Studies

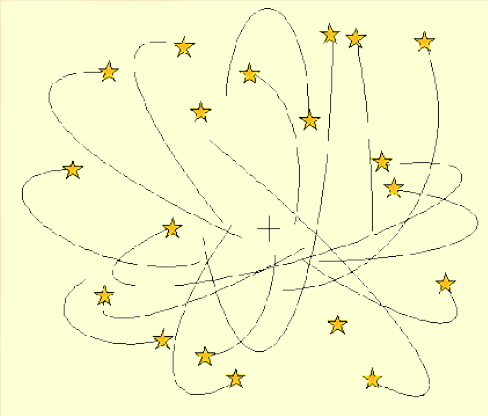
I. Evolution of clusters as astrophysical objects

II.Effects of clusters on forming solar systems

- Distribution of closest approaches
- Radial position probability distribution

Simulations of Embedded Clusters

- **Modified NBODY2(and 6) Codes *(S. Aarseth)***
- **Simulate evolution from embedded stage to age 10 Myr**
- **Cluster evolution depends on the following:**
  - cluster size
  - initial stellar and gas profiles
  - gas disruption history
  - star formation history
  - primordial mass segregation
  - initial dynamical assumptions



- **100 realizations are needed to provide robust statistics for output measures**

(E. Proszkow thesis - work with Phil!)

Simulation Parameters

Cluster Membership

N = 100, 300, 1000

Radius $R(N) = 1pc\left(N/300\right)^{1/2}$

Initial Stellar Density

Gas Distribution $\rho_* \propto r^{-1}$

$$\rho_{gas} = \frac{\rho_0}{\xi(1+\xi)^3}, \quad \rho_0 = \frac{2M_*}{\pi R^3} \quad \xi = \frac{r}{R}$$

SF Efficiency = 0.33

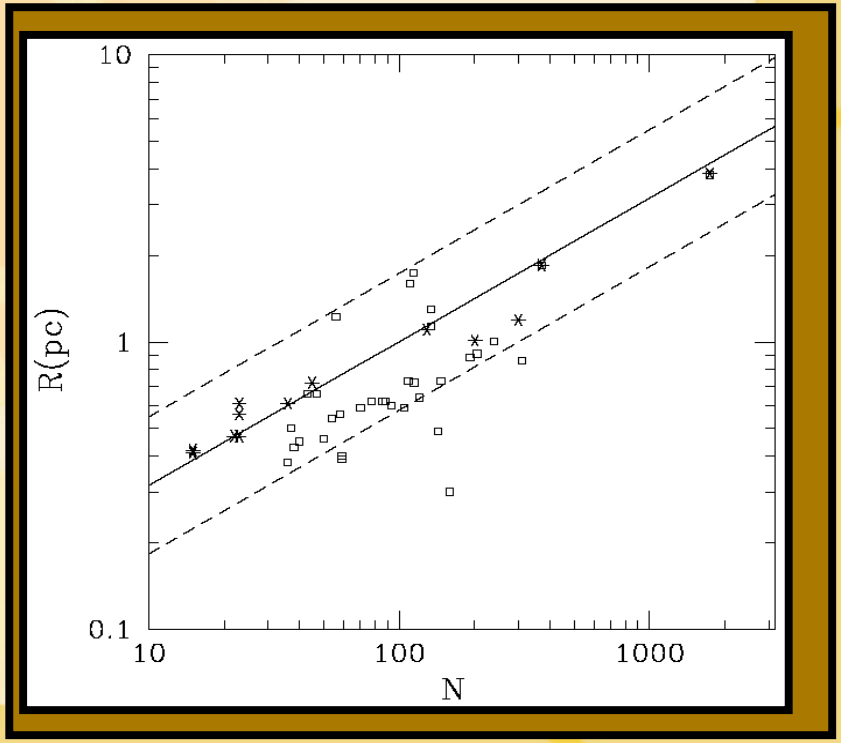
Embedded Epoch t = 0–5 Myr

SF time span t = 0-1 Myr

Virial Ratio $Q = |K/W|$

virial Q = 0.5; cold Q = 0.04

Mass Segregation: largest star at center of cluster

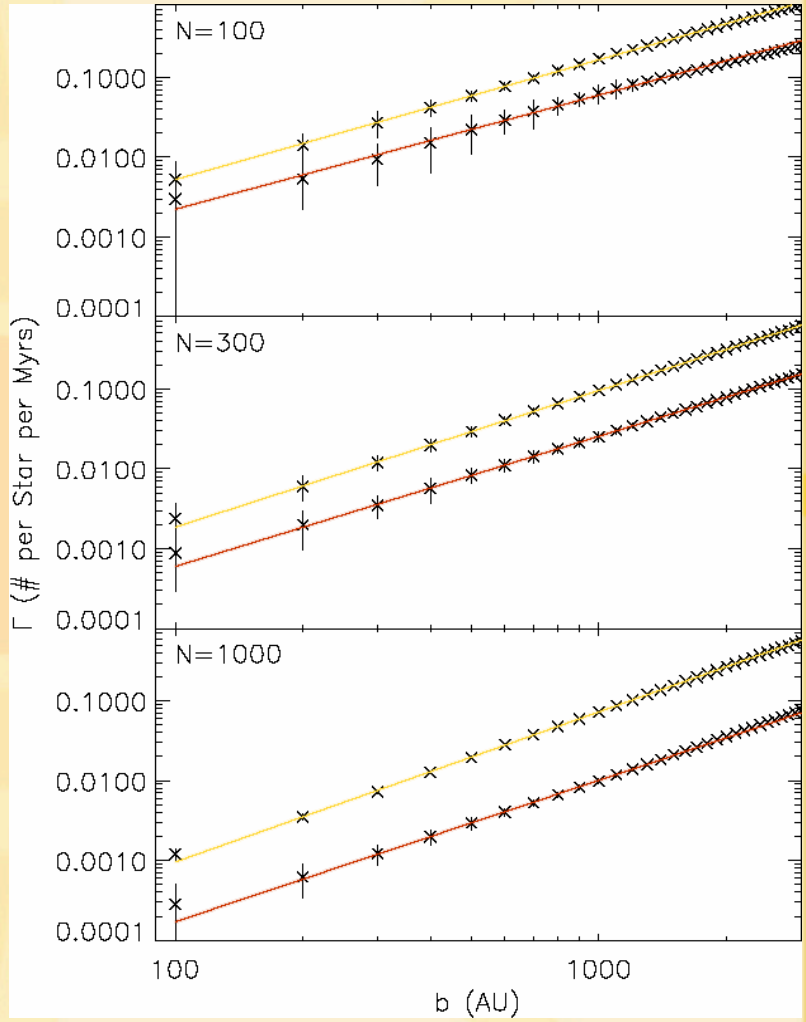


Closest Approach Distributions

$$\Gamma = \Gamma_0 \left[\frac{b}{1000\,AU} \right]^{\gamma}$$

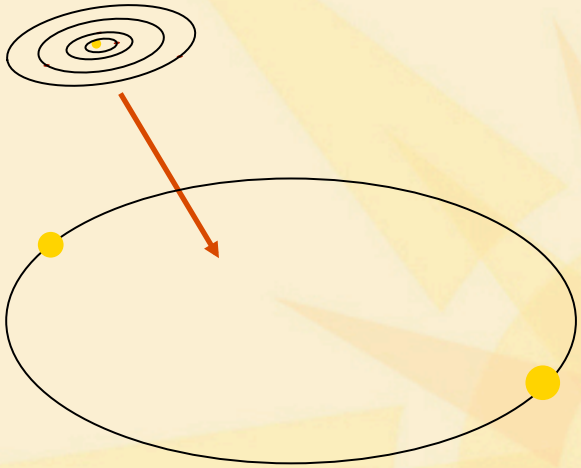
Simulation	Γ_0	γ	b_C (AU)
100 Subvirial	0.166	1.50	713
100 Virial	0.0598	1.43	1430
300 Subvirial	0.0957	1.71	1030
300 Virial	0.0256	1.63	2310
1000 Subvirial	0.0724	1.88	1190
1000 Virial	0.0101	1.77	3650

Typical star experiences one close encounter with impact parameter b_C over t = 10 Myr



Subvirial initial conditions matter - thanks Phil…

Interaction Cross Sections

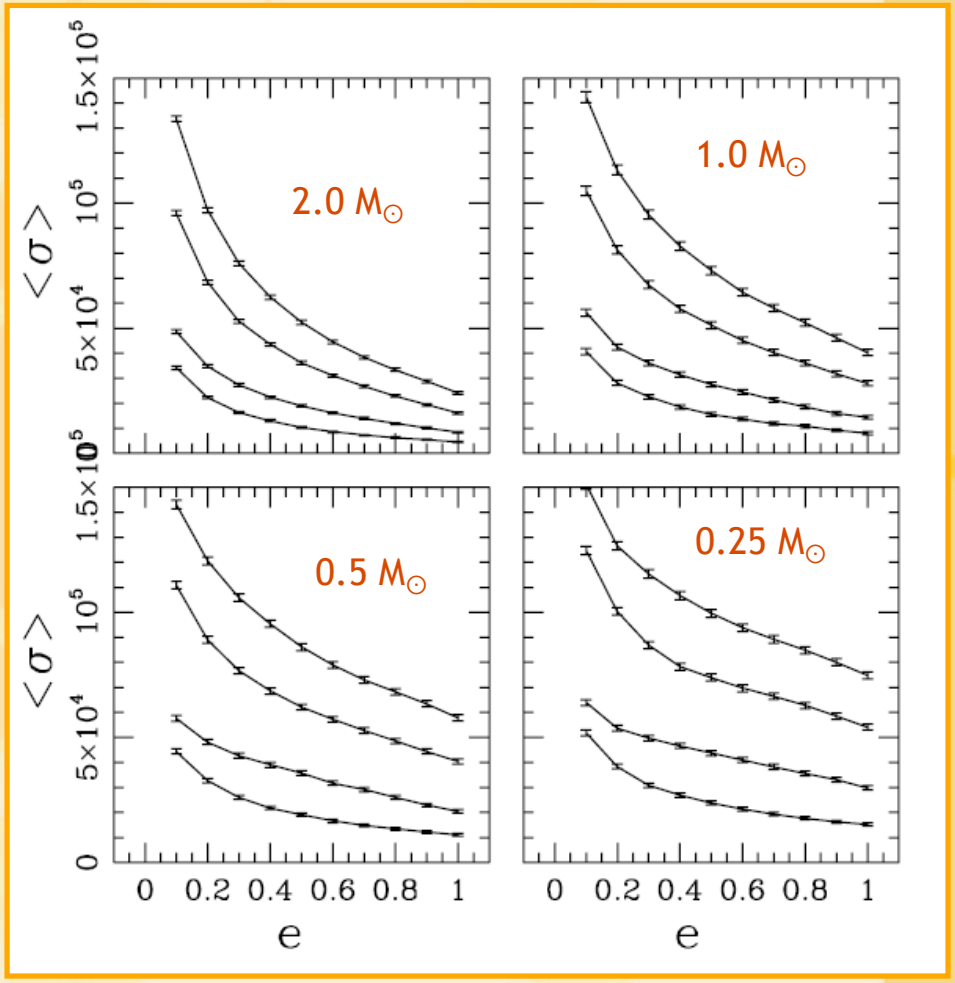


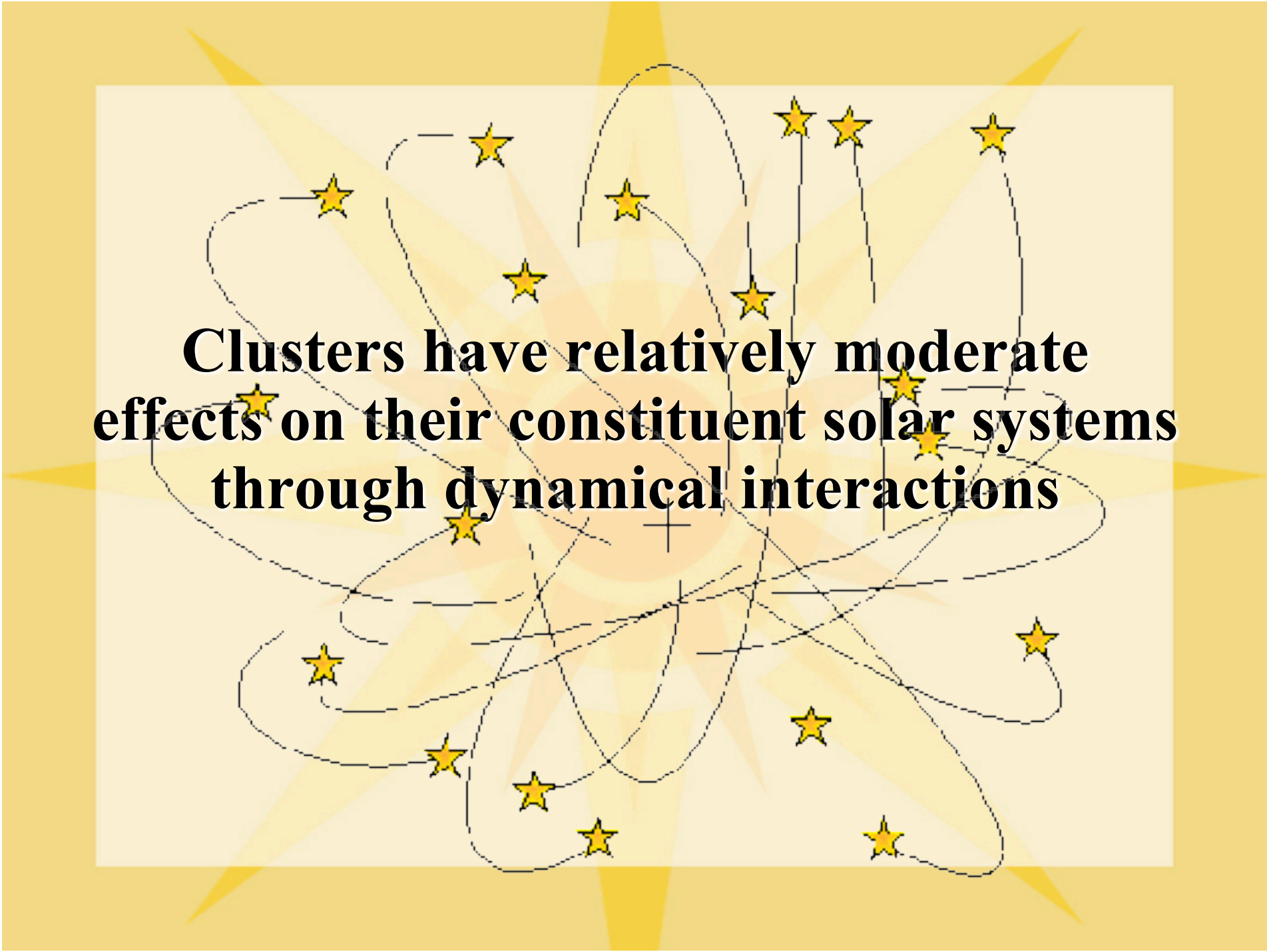
$$\langle \sigma \rangle_{ej} = C_0 \left(\frac{a_P}{AU} \right) \left(\frac{M_*}{M_{sun}} \right)^{-1/2}$$

where

$$C_0 = 1350 \pm 160 \ (AU)^2$$

$$\langle \sigma \rangle_{disrupt} \approx (400 \ AU)^2$$





Clusters have relatively moderate effects on their constituent solar systems through dynamical interactions

Effects of Cluster Radiation on Forming/Young Solar Systems

- Photoevaporation of a circumstellar disk
- Radiation from the background cluster often dominates radiation from the parent star *(Johnstone et al. 1998; Adams & Myers 2001)*
- FUV radiation (6 eV < E < 13.6 eV) is more important in this process than EUV radiation
- FUV flux of G_0 = 3000 will truncate a circumstellar disk to r_d over 10 Myr, where $r_d = 36AU\left[M_*/M_{sun}\right]$

Composite Distribution of FUV Flux

FUV Flux depends on:

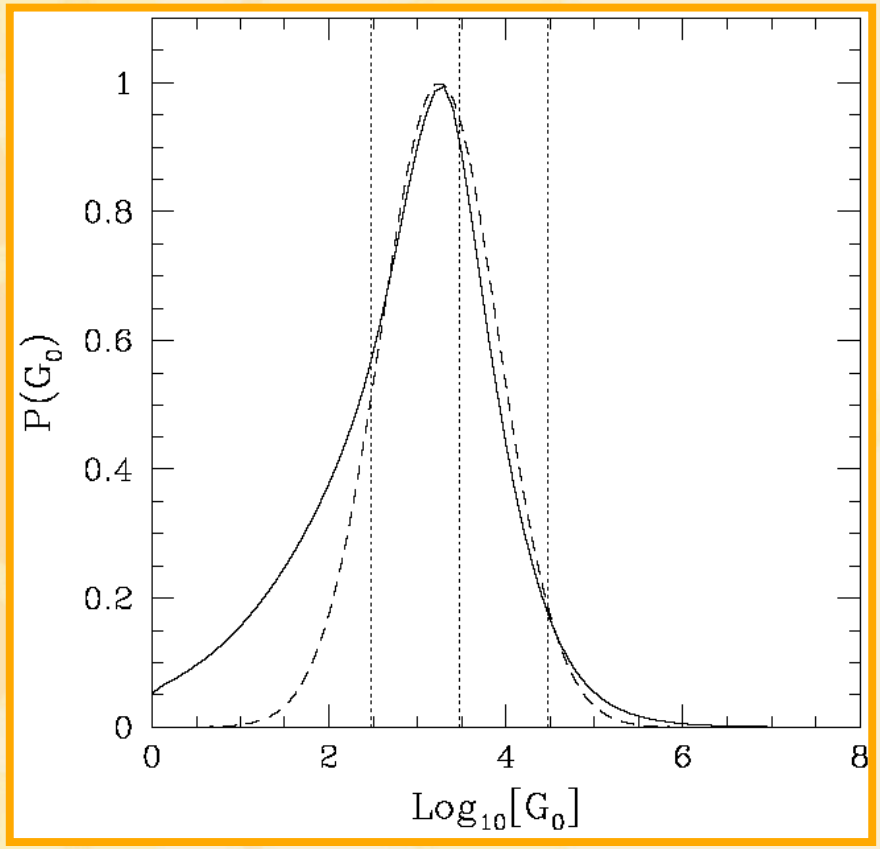
- Cluster FUV luminosity
- Location of disk within cluster

Assume:

- FUV point source at center of cluster
- Stellar density $\rho \sim 1/r$

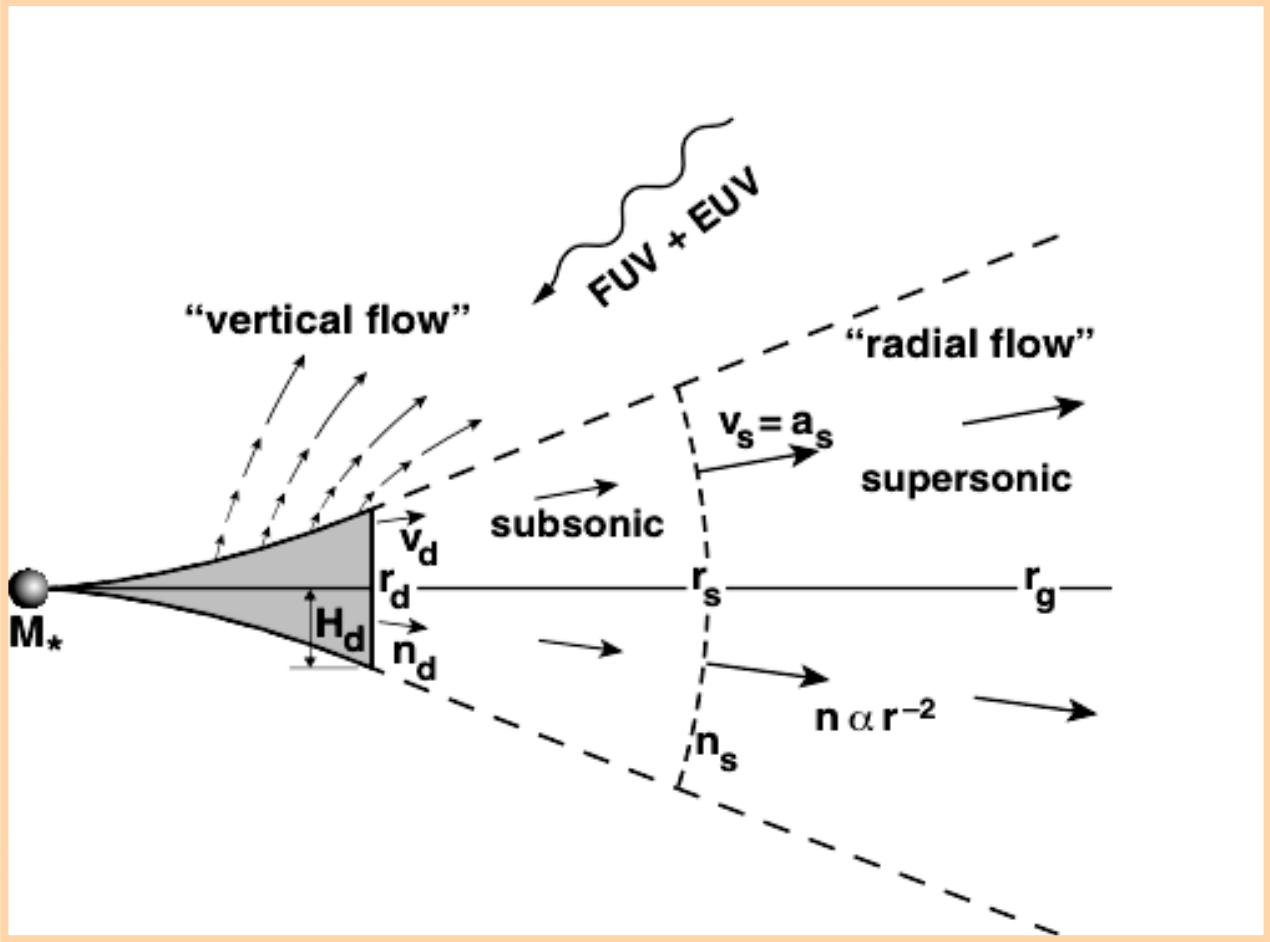
G_0 Distribution

Median	900
Peak	1800
Mean	16,500



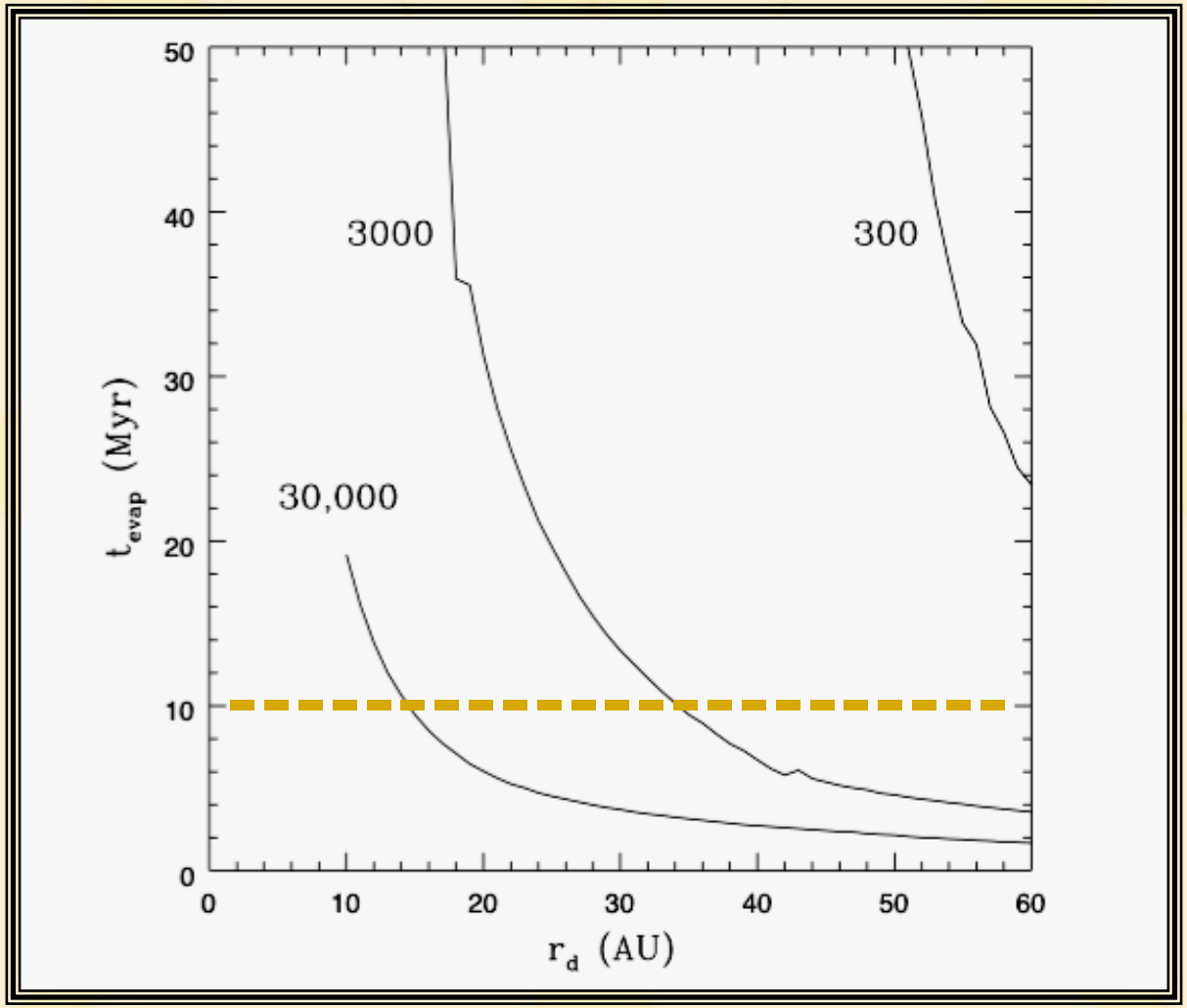
G_0 = 1 corresponds to FUV flux 1.6×10^{-3} erg s^{-1} cm^{-2}

Photoevaporation Model



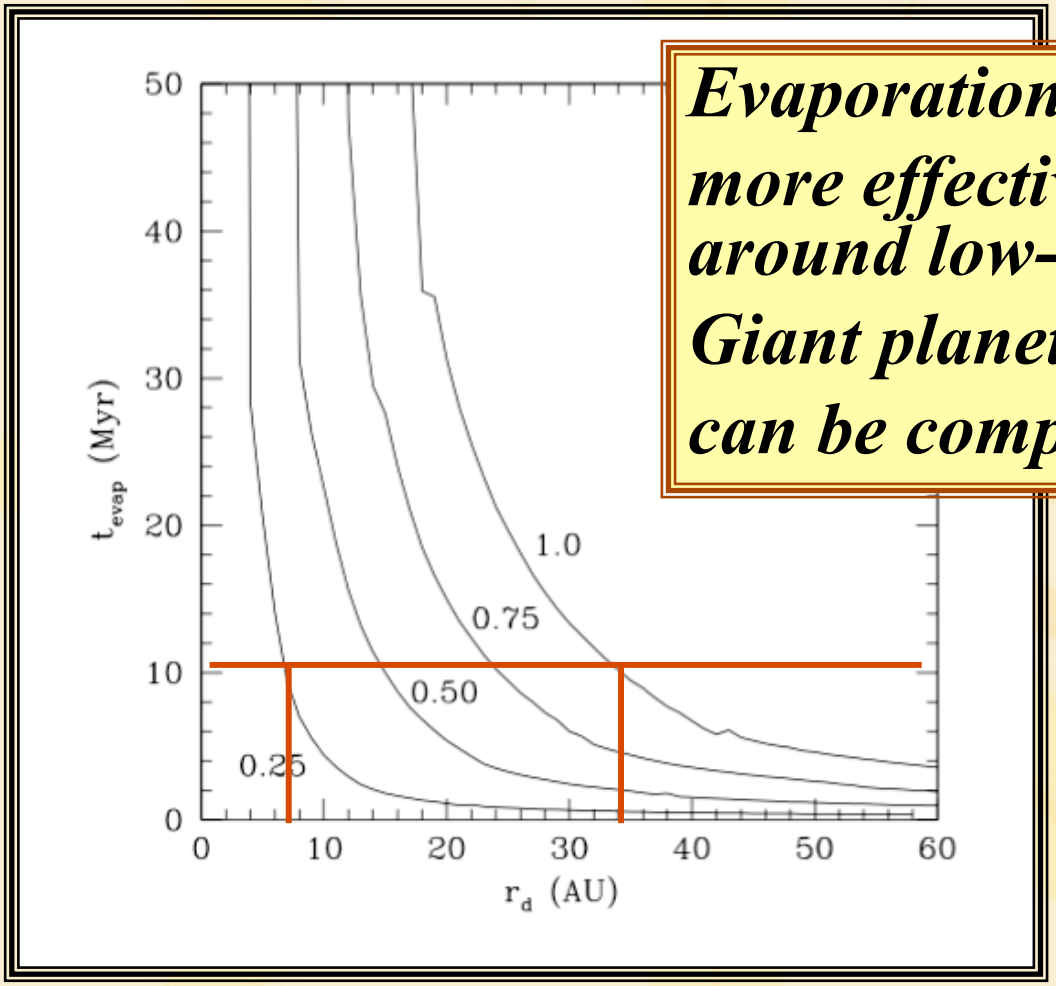
(Adams et al. 2004)

Evaporation Time vs FUV Field



(for disks around solar mass stars)

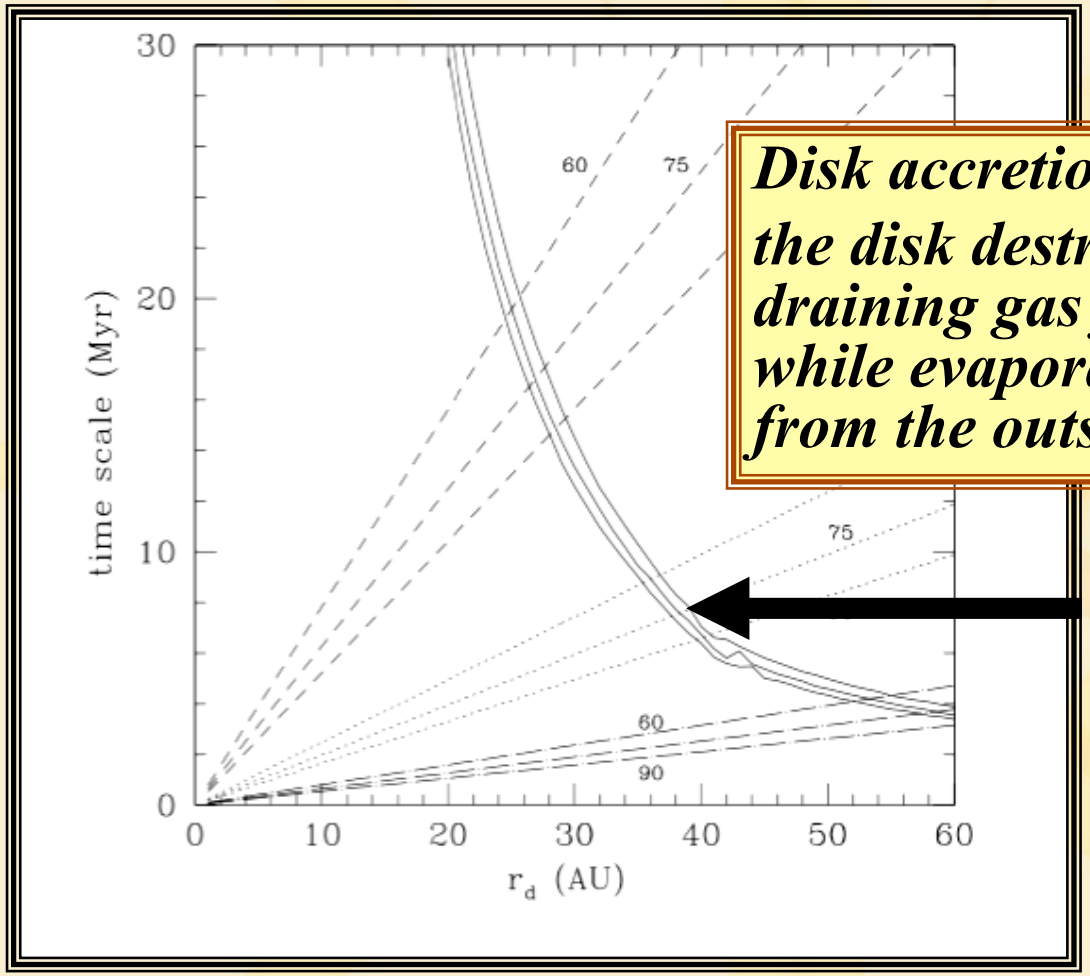
Evaporation Time vs Stellar Mass



Evaporation is much more effective for disks around low-mass stars: Giant planet formation can be compromised

G=3000

Evaporation vs Accretion

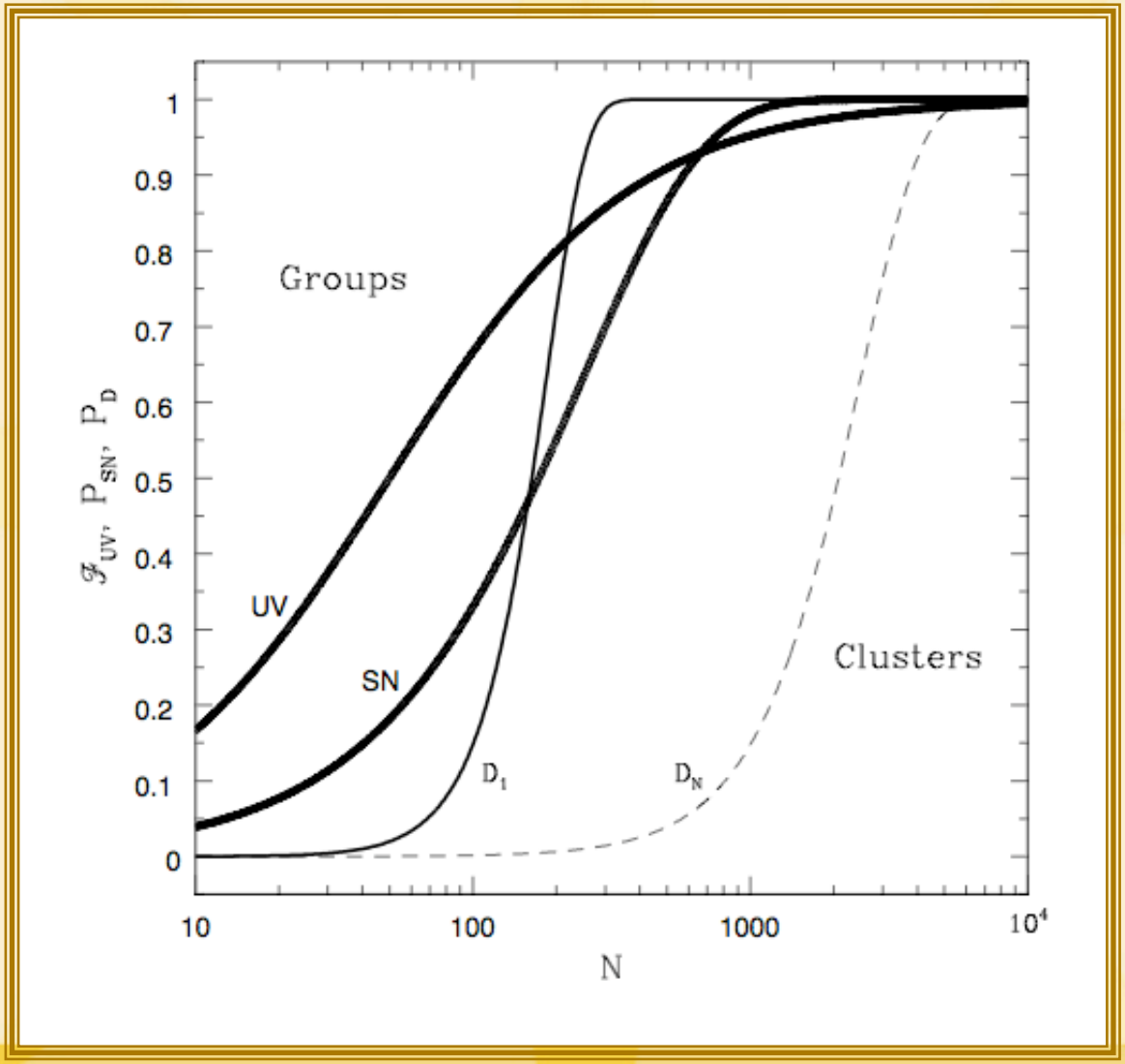


Disk accretion aids and abets the disk destruction process by draining gas from the inside, while evaporation removes gas from the outside . . .

Total time scale of 8 Myr, consistent with observations…

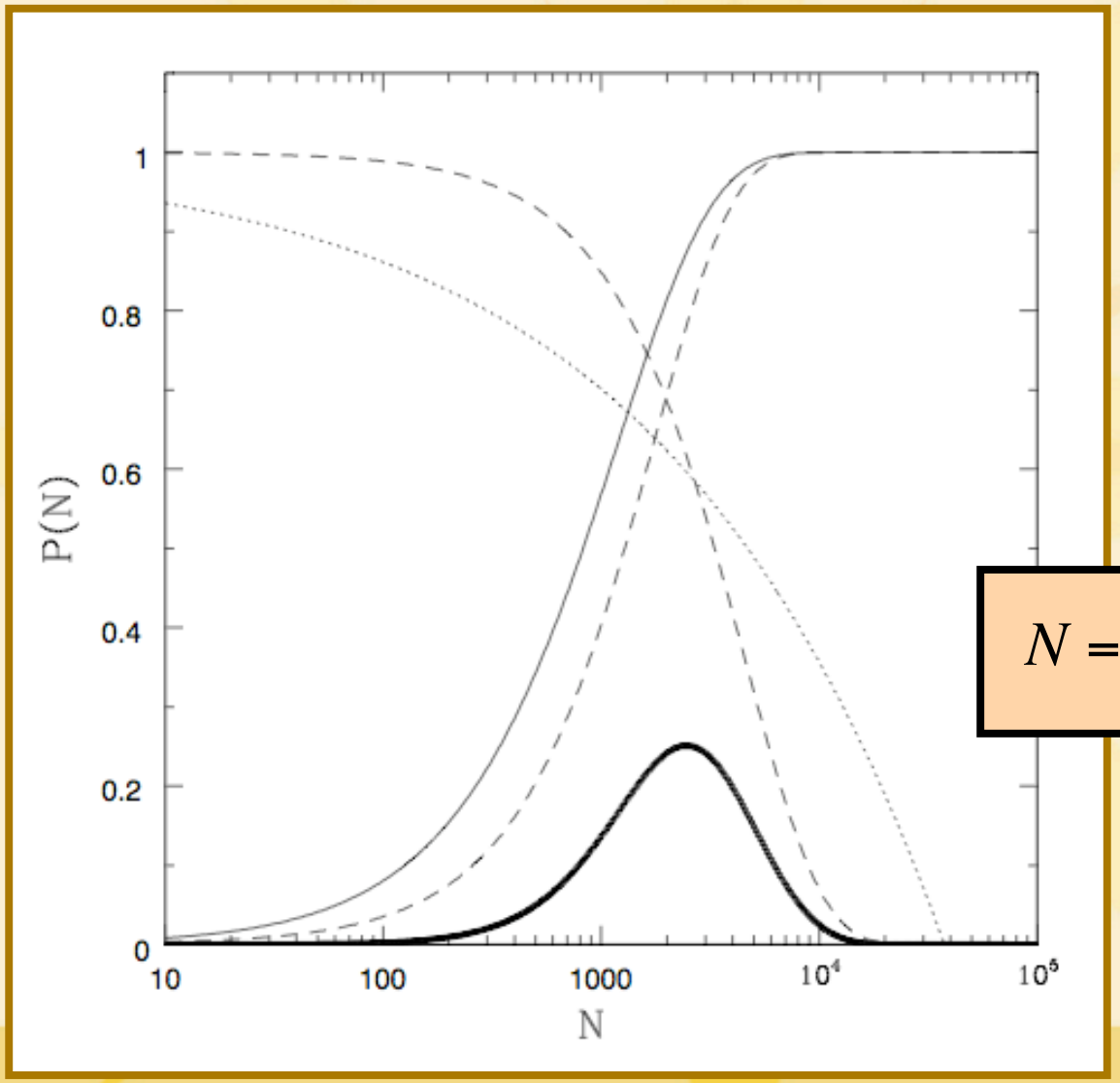
Radiation effects Dominate over Dynamical effects in Clusters

Group/Cluster Transition



(Adams & Myers 2001, ApJ)

Constraints on Solar Birth Cluster



Supernova
Neptune
Sedna
Radiation

$$N = 4300 \pm 2800$$

CONSISTENT SCENARIO for Solar Birth Aggregate

Cluster size: N = 1000 - 7000

Reasonable *a priori* probability (few percent)

Allows meteoritic enrichment and scattering survival

UV radiation field evaporates disk down to 30 AU

Scattering interactions truncate Kuiper belt at 50 AU leave Sedna and remaining KBOs with large (a,e,i)

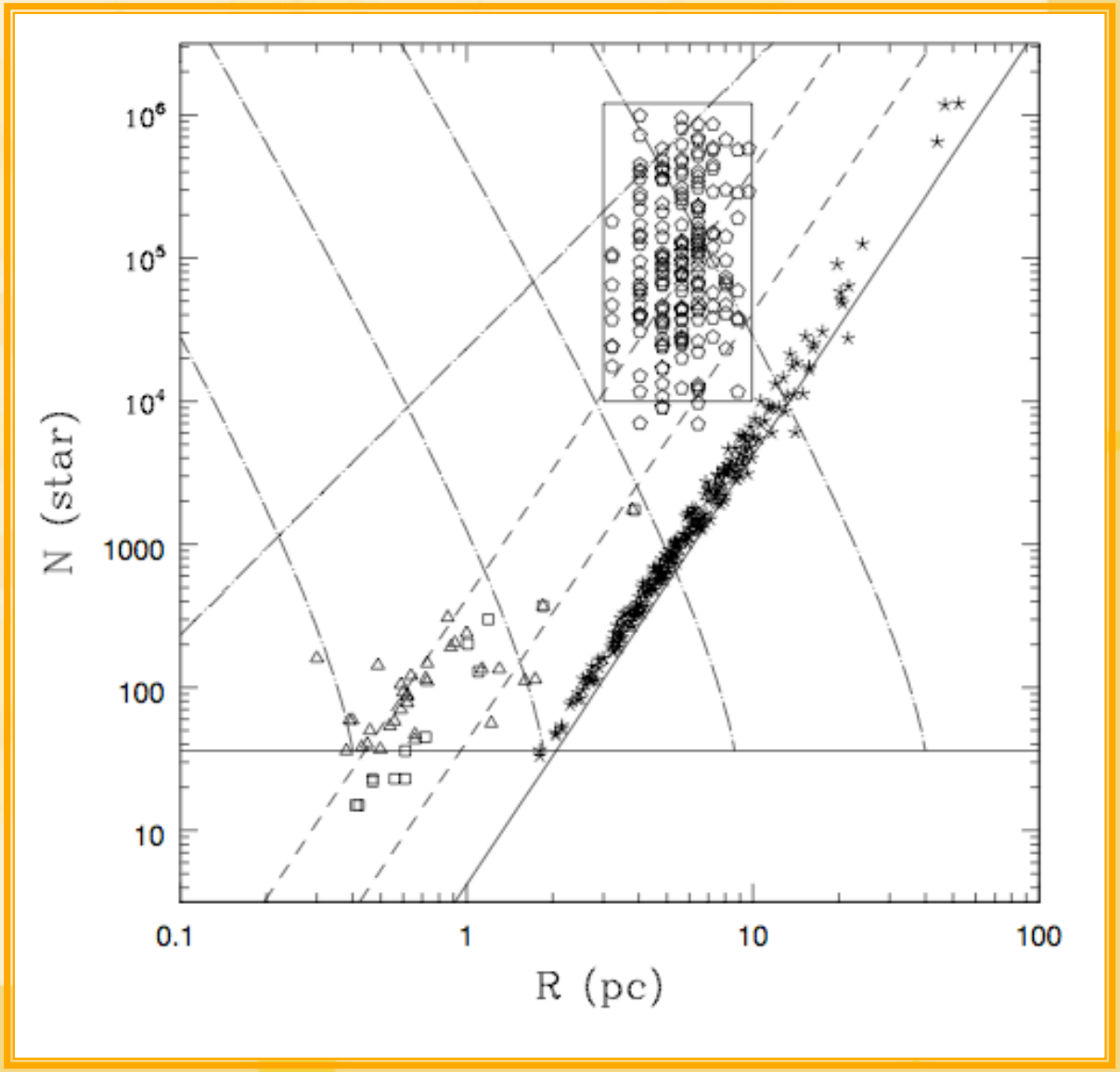
Bottom Line:

Clusters in solar neighborhood exert an intermediate level of influence on their constituent solar systems: Neither Dominant Nor Negligible.

What's next:

Extend analysis to larger N
Distribution of cluster sizes N

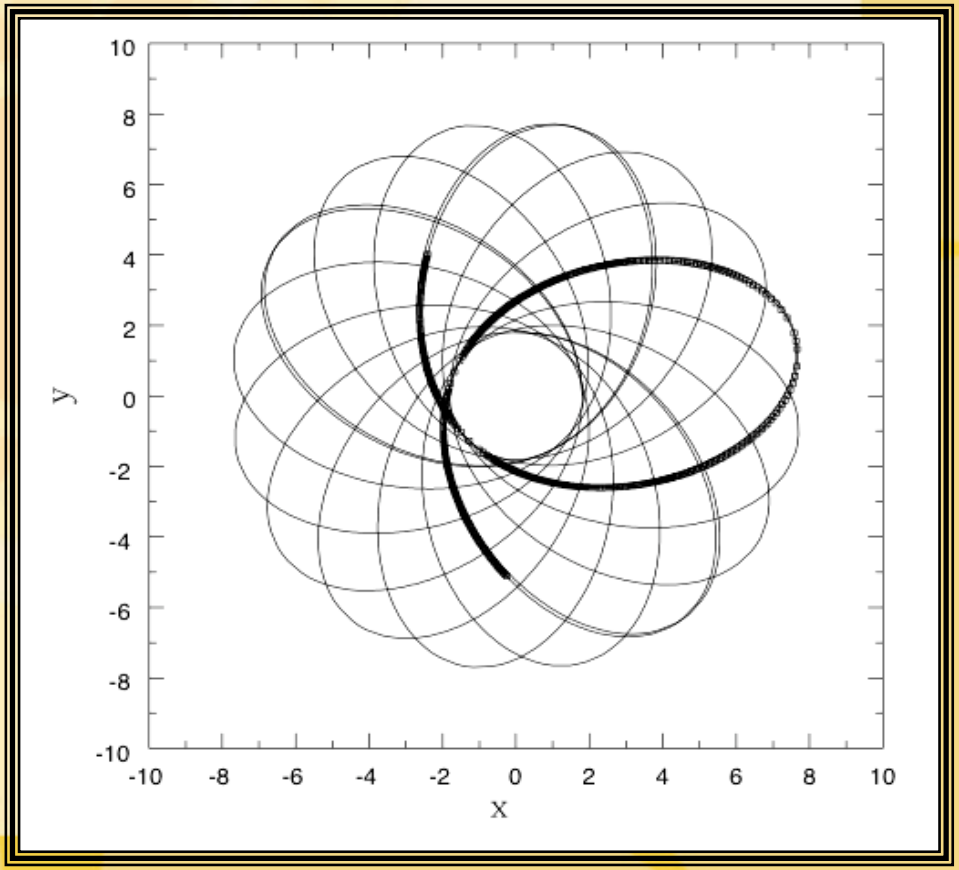
Fundamental Plane for Clusters



Density: 1,10,100
Relax time: 1-1000 Myr

WHAT ABOUT ORBITS?

In spherical limit, orbits are Spirographs:



Orbits in Spherical Potential

$$\rho = \frac{\rho_0}{\xi(1+\xi)^3} \Rightarrow \Psi = \frac{\Psi_0}{1+\xi}$$

$$\varepsilon \equiv |E|/\Psi_0 \quad and \quad q \equiv j^2/2\Psi_0 r_s^2$$

$$\varepsilon = \frac{\xi_1 + \xi_2 + \xi_1\xi_2}{(\xi_1+\xi_2)(1+\xi_1+\xi_2+\xi_1\xi_2)}$$

$$q = \frac{(\xi_1\xi_2)^2}{(\xi_1+\xi_2)(1+\xi_1+\xi_2+\xi_1\xi_2)}$$

$$q_{\max} = \frac{1}{8\varepsilon}\frac{(1+\sqrt{1+8\varepsilon}-4\varepsilon)^3}{(1+\sqrt{1+8\varepsilon})^2}$$

(angular momentum of the circular orbit)

$$\xi_* = \frac{1-4\varepsilon+\sqrt{1+8\varepsilon}}{4\varepsilon}$$

(effective semi-major axis)

$$\frac{\Delta\theta}{\pi} = \frac{1}{2} + \left[(1+8\varepsilon)^{-1/4} - \frac{1}{2}\right]\left[1+\frac{\log(q/q_{\max})}{6\log 10}\right]^{3.6}$$

$$\lim_{q\to q_{\max}} \Delta\theta = \pi(1+8\varepsilon)^{-1/4}$$

(circular orbits do not close)

These results determine the radiation exposure of a star, averaged over its orbit, as a function of energy and angular momentum:

$$\left\langle F_{fuv} \right\rangle \approx \frac{L_{fuv}}{8 r_s^2 \sqrt{q}} \frac{A \varepsilon^{3/2}}{\cos^{-1}\sqrt{\varepsilon} + \sqrt{\varepsilon}\sqrt{1-\varepsilon}}$$

$$where \quad 1 \le A(q) \le \sqrt{2}$$

Triaxial Density Distributions

- Relevant density profiles include NFW and Hernquist

$$\rho_{nfw} = \frac{1}{m(1+m)^2} \qquad \rho_{Hern} = \frac{1}{m(1+m)^3}$$

- Isodensity surfaces in triaxial geometry

$$m^2 = \frac{x^2}{a^2} + \frac{y^2}{b^2} + \frac{z^2}{c^2} \qquad a > b > c > 0$$

- In the inner limit both profiles scale as 1/r

$$m << 1 \quad \Rightarrow \quad \rho \propto \frac{1}{m}$$

Triaxial Potential

$$\Phi = \int_0^\infty du \frac{\psi(m)}{\sqrt{(u+a^2)(u+b^2)(u+c^2)}} \qquad \psi(m) = \int_\infty^{m^2} \rho(m) dm^2$$

- In the inner limit the above integral can be simplified to

$$\Phi = -I_1 + I_2$$

where I_1 is the depth of the potential well and the effective potential is given by

$$I_2 = 2\int_0^\infty du \frac{\sqrt{\xi^2 u^2 + \Lambda u + \Gamma}}{(u+a^2)(u+b^2)(u+c^2)}$$

ξ, Λ, Γ are polynomial functions of x, y, z, a, b, c

Triaxial Forces

$$F_x = \frac{-2\,\mathrm{sgn}(x)}{\sqrt{\left(a^2-b^2\right)\left(a^2-c^2\right)}}\ln\left(\frac{2G(a)\sqrt{\Gamma}+2\Gamma-a^2\Lambda}{2a^2\xi G(a)+\Lambda a^2-2a^4\xi^2}\right)$$

$$F_y = \frac{-2\,\mathrm{sgn}(y)}{\sqrt{\left(a^2-b^2\right)\left(b^2-c^2\right)}}\left[\sin^{-1}\left(\frac{\Lambda-2b^2\xi^2}{\sqrt{\Lambda^2-4\Gamma\xi^2}}\right)-\sin^{-1}\left(\frac{2\Gamma/b^2-\Lambda}{\sqrt{\Lambda^2-4\xi^2\Gamma}}\right)\right]$$

$$F_z = \frac{-2\,\mathrm{sgn}(z)}{\sqrt{\left(a^2-c^2\right)\left(b^2-c^2\right)}}\ln\left(\frac{2G(c)\sqrt{\Gamma}+2\Gamma-c^2\Lambda}{2c^2\xi G(c)+\Lambda c^2-2c^4\xi^2}\right)$$

$$G(u) = \xi^2u^4-\Lambda u^2+\Gamma$$

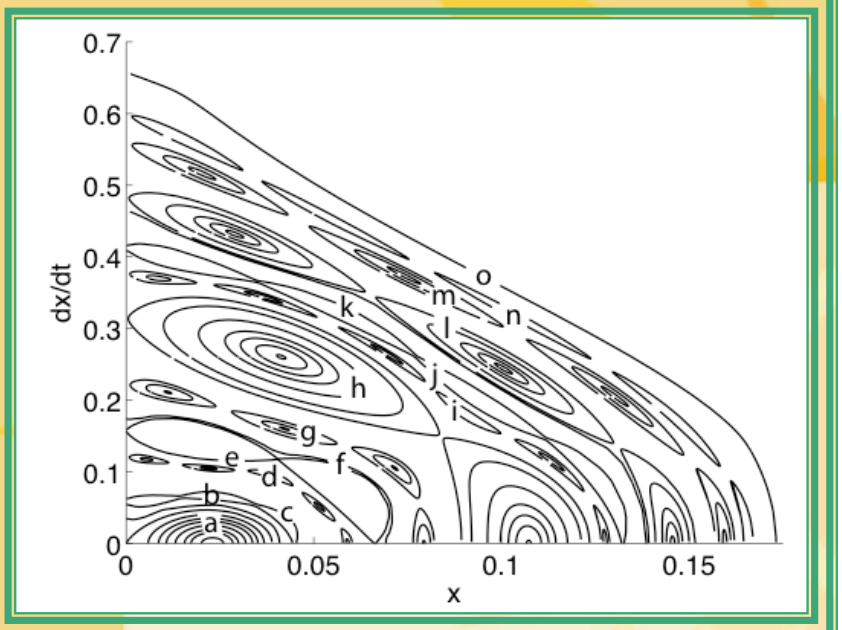
$$\xi^2 = x^2+y^2+z^2$$

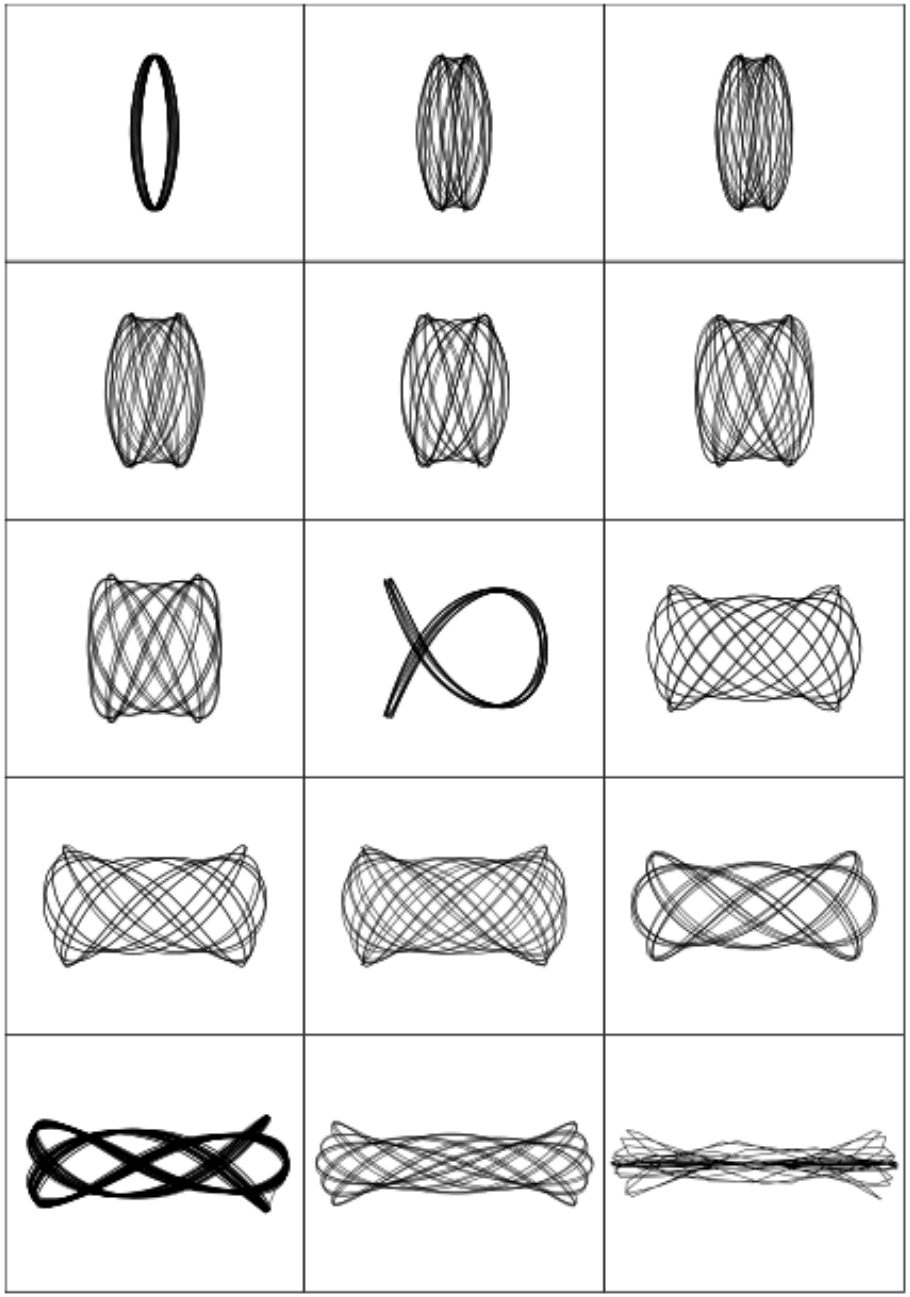
$$\Lambda = \left(b^2+c^2\right)x^2+\left(a^2+c^2\right)y^2+\left(a^2+b^2\right)z^2$$

$$\Gamma = b^2c^2x^2+a^2c^2y^2+a^2b^2z^2$$

(Adams, Bloch, Butler, Druce, Ketchum 2007)

Orbit Gallery





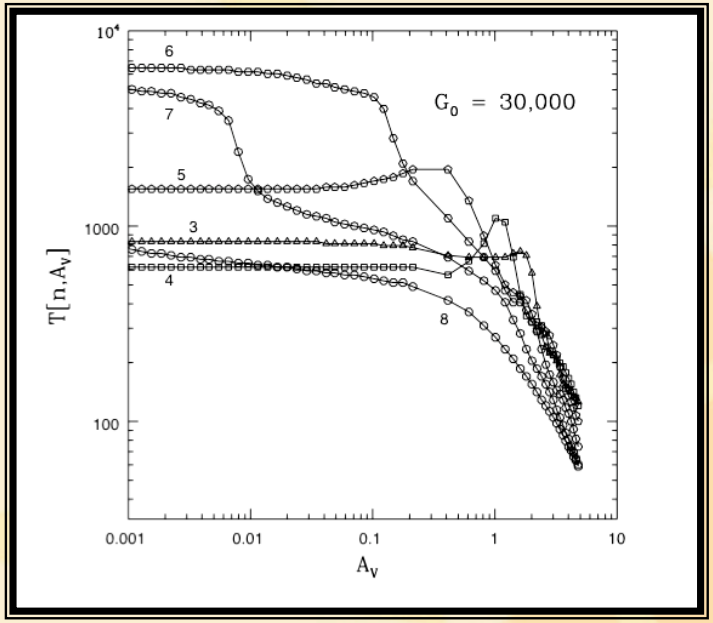
New Cluster Result

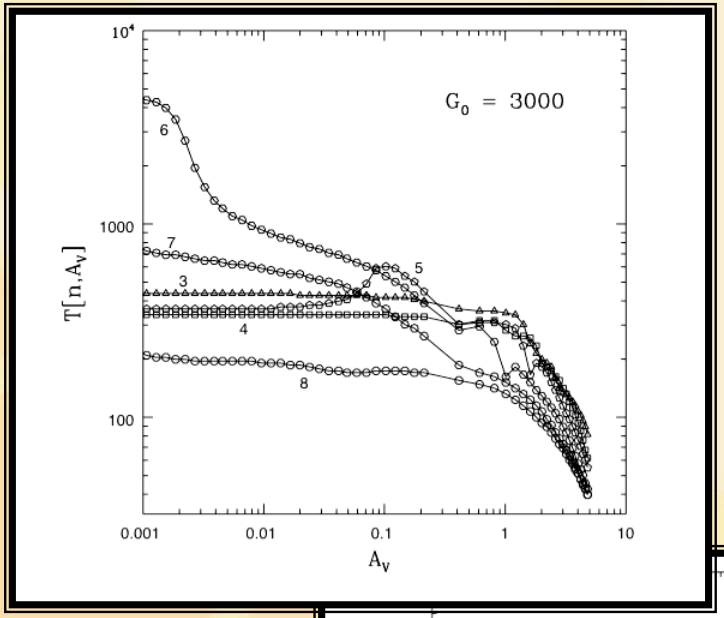
Kinematic observations of the Orion Nebula Cluster show that the system must have:

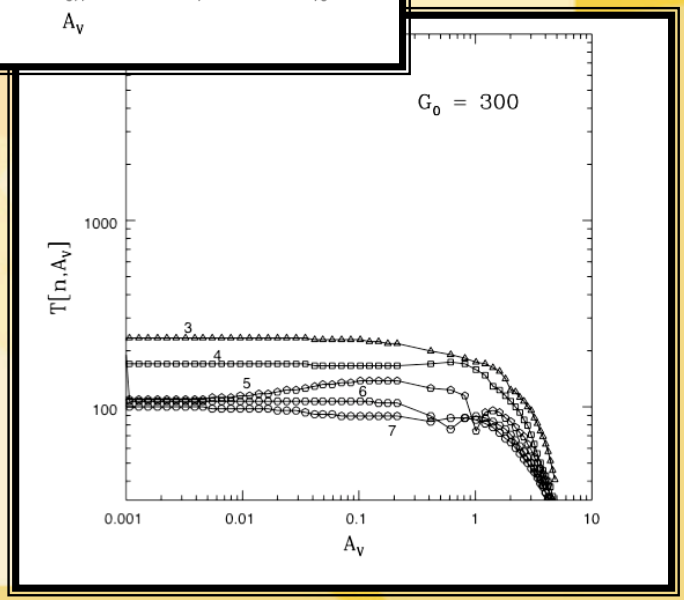
- Non-spherical geometry
- Non-virial initial conditions
- Viewing angle not along a principal axis

(with E. Proszkow, J. Tobin, and L. Hartmann, 2009)

Results from PDR Code

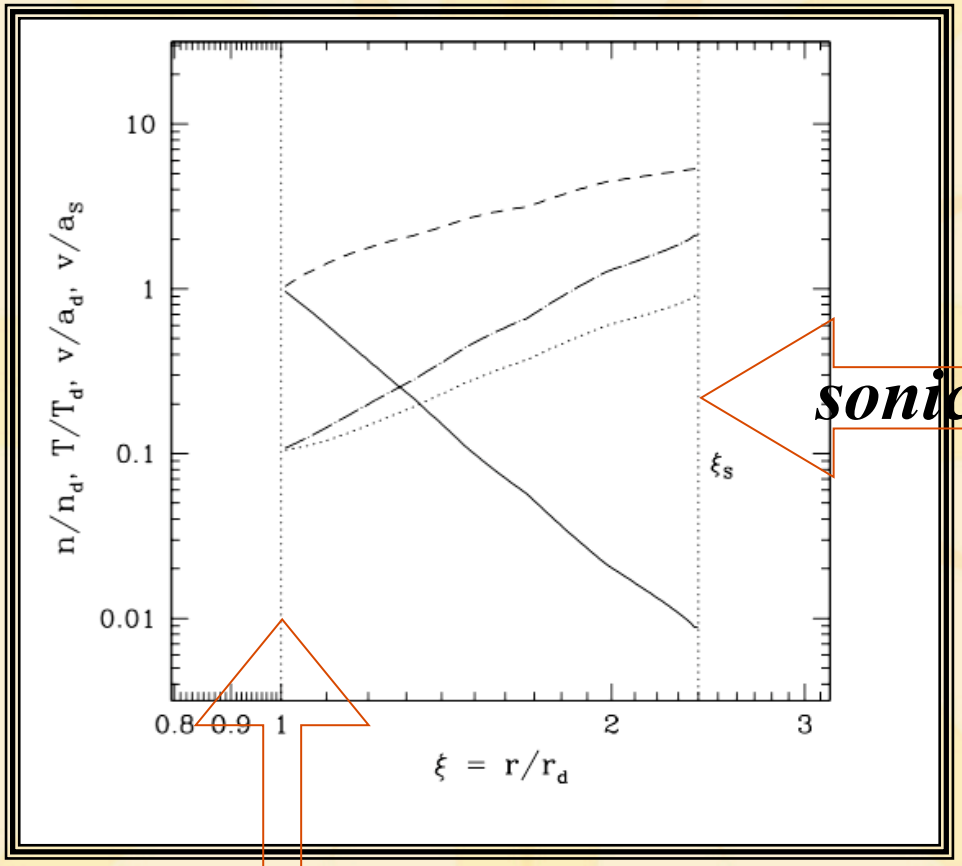






Lots of chemistry and many heating/cooling lines determine the temperature as a function of G, n, A

Solution for the Fluid Fields



sonic surface

outer disk edge