Effects of Young Clusters on Forming Solar Systems

Fred C. Adams
University of Michigan

Star Formation: Then and Now
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WITH: Eva M. Proszkow, Anthony Bloch (Univ. Michigan)
Philip C. Myers (CfA), Marco Fatuzzo (Xavier University)
David Hollenbach (NASA Ames), Greg Laughlin (UCSC)

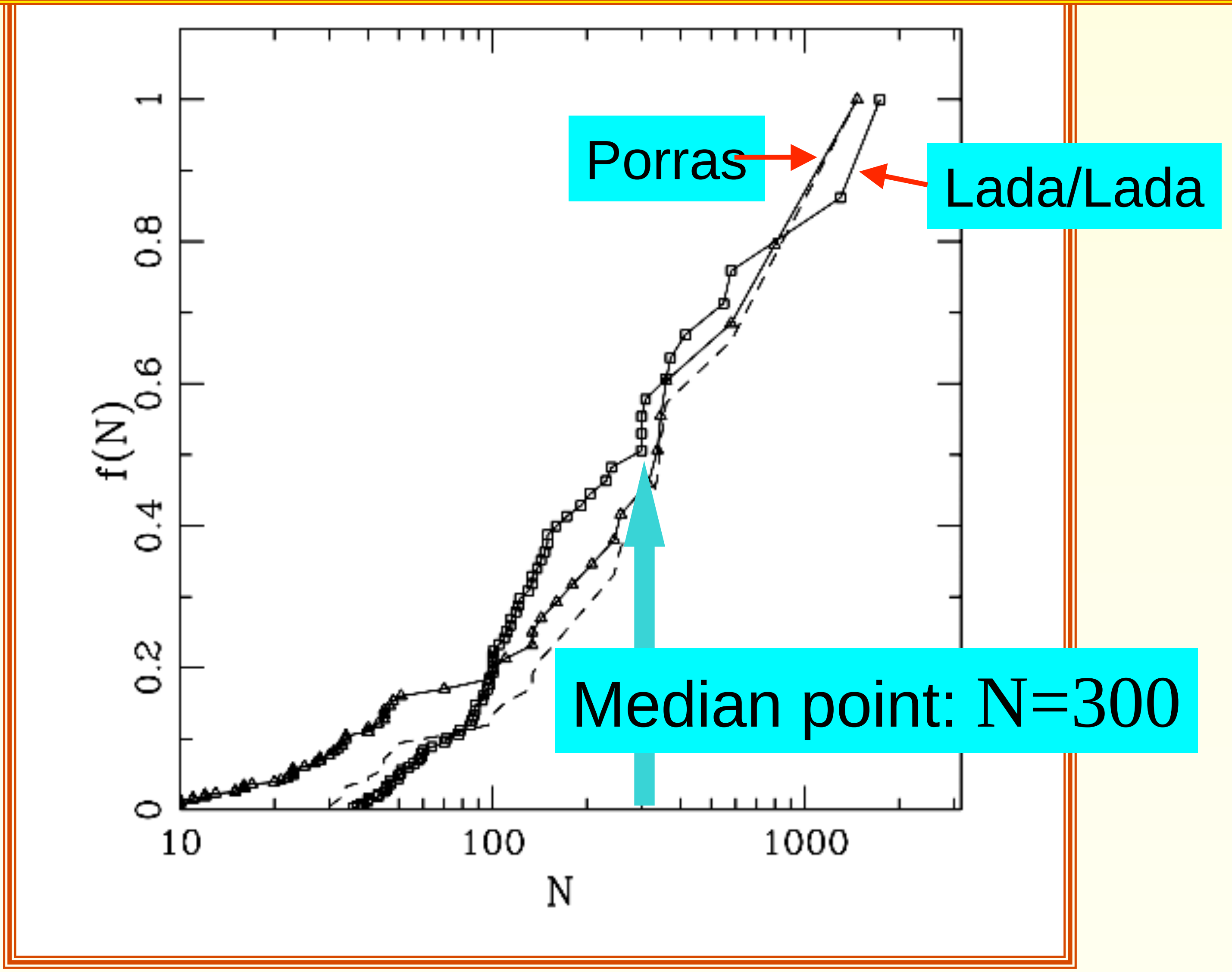
Most stars form in clusters:

→ How does the cluster environment affect process of star/planet formation?

Outline

- Distribution of Clusters
- N-body Simulations of Clusters
- UV Radiation Fields in Clusters
- Disk Photoevaporation Model
- Scattering Encounters

Cumulative Distribution: Fraction of stars that form in stellar aggregates with N < $\mathcal{N}$ as function of $\mathcal{N}$



Simulations of Embedded Clusters

- **Modified NBODY2(and 6) Codes** ***(S. Aarseth)***
- **Simulate evolution from embedded stage out to ages of 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**

Simulation Parameters

Cluster Membership

N = 100, 300, 1000

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

Initial Stellar Density $\rho_* \propto r^{-1}$

Gas Distribution

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

Star Formation Efficiency 0.33

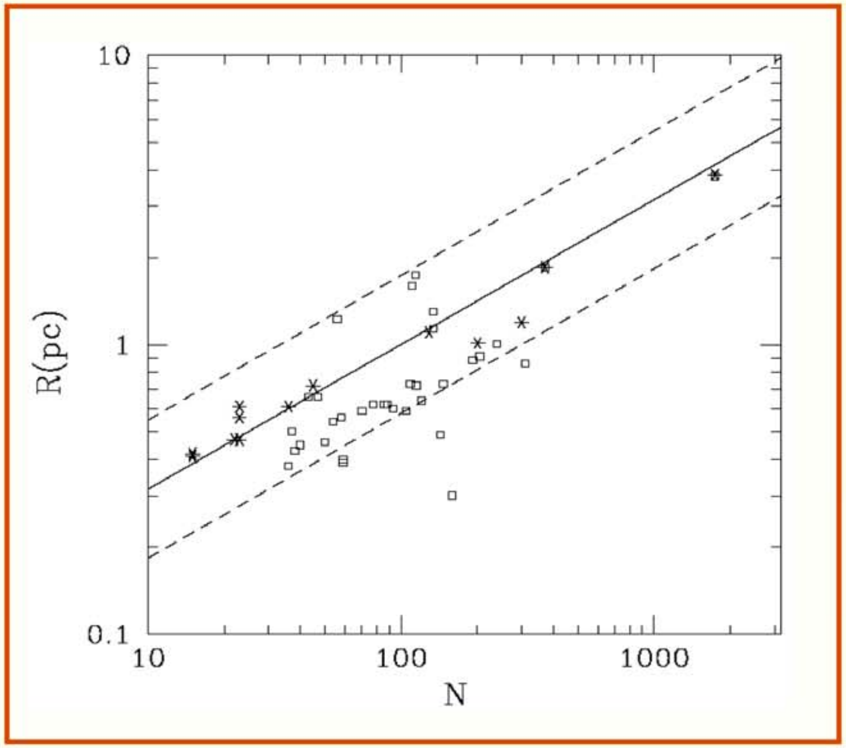
Embedded Epoch t = 0–5 Myr

Star Formation 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



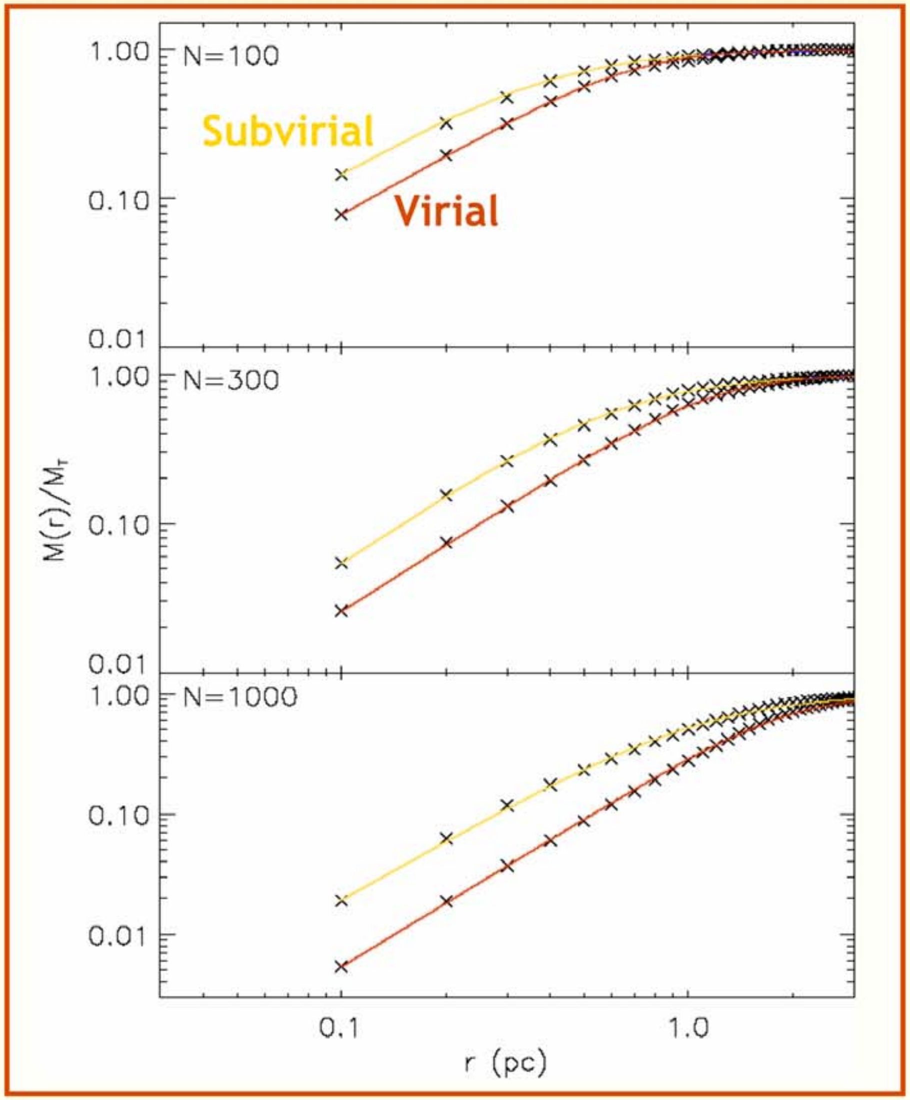
Dynamical Results

I. Evolution of clusters as astrophysical objects

II. Effects of clusters on forming solar systems

- **Distribution of closest approaches**
- **Radial position probability distribution (given by cluster mass profiles)**

Mass Profiles



$$\frac{M(\xi)}{M_T} = \left(\frac{\xi^a}{1+\xi^q}\right)^p \qquad \xi = r/r_0$$

Simulation	p	r_0	a
100 Subvirial	0.69	0.39	2
100 Virial	0.44	0.70	3
300 Subvirial	0.79	0.64	2
300 Virial	0.49	1.19	3
1000 Subvirial	0.82	1.11	2
300 Subvirial	0.59	1.96	3

Stellar Gravitational Potential

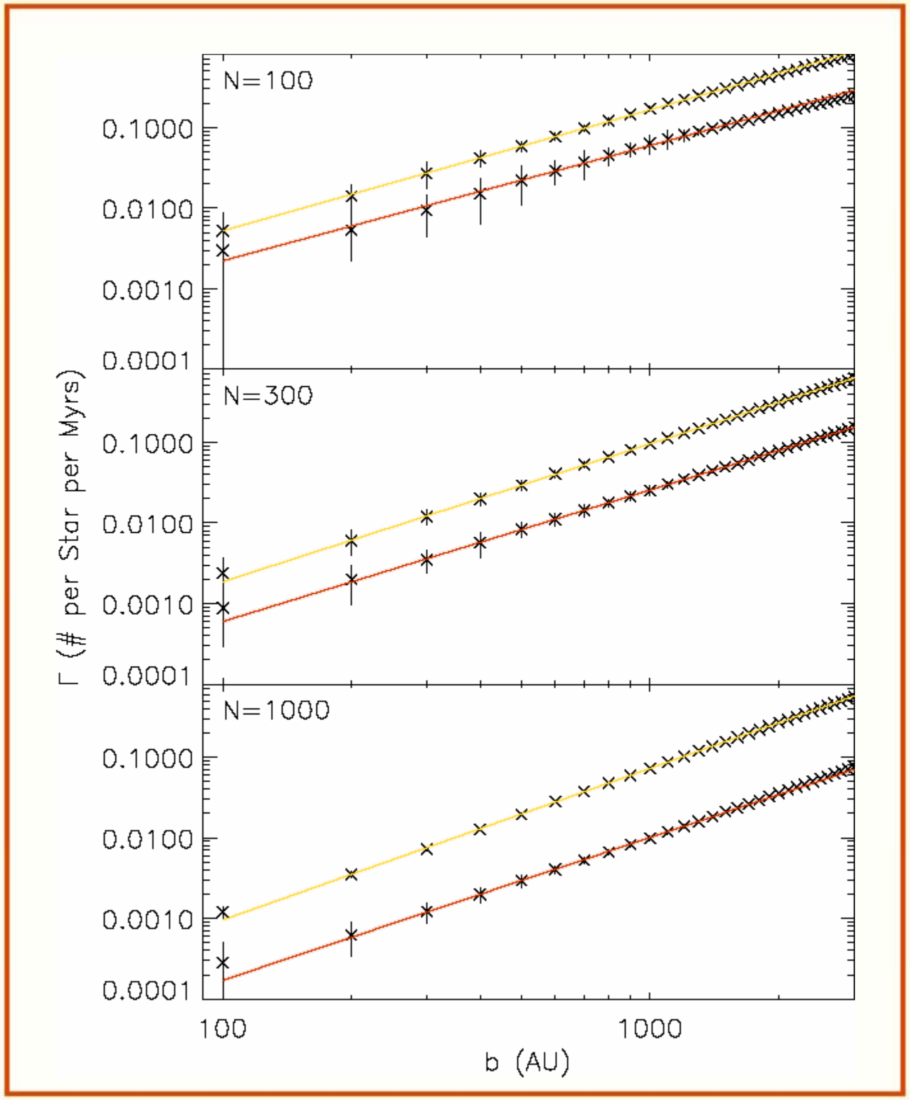
$$\Psi_* = \frac{GM_T}{r_0}\psi_0 \qquad \psi_0 = \int_0^\infty \left(\frac{1}{1+u^a}\right)^p du$$

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 during 10 Myr time span



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

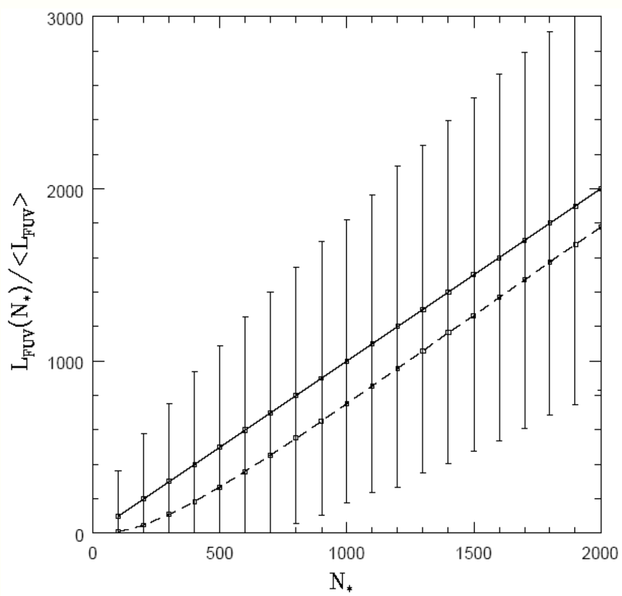
$$r_d = 36AU\left[\frac{M_*}{M_{sun}}\right]$$

Calculation of the Radiation Field

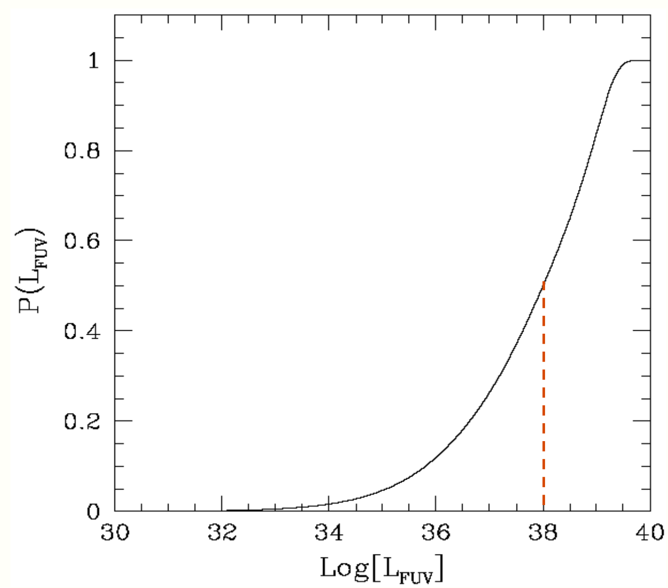
Fundamental Assumptions

- Cluster size N = N primaries (ignore binary companions)
- No gas or dust attenuation of FUV radiation
- Stellar FUV luminosity is only a function of mass
- Meader's models for stellar luminosity and temperature

Sample IMF → $L_{FUV}(N)$



Sample Cluster Sizes → Expected FUV Luminosity in SF Cluster



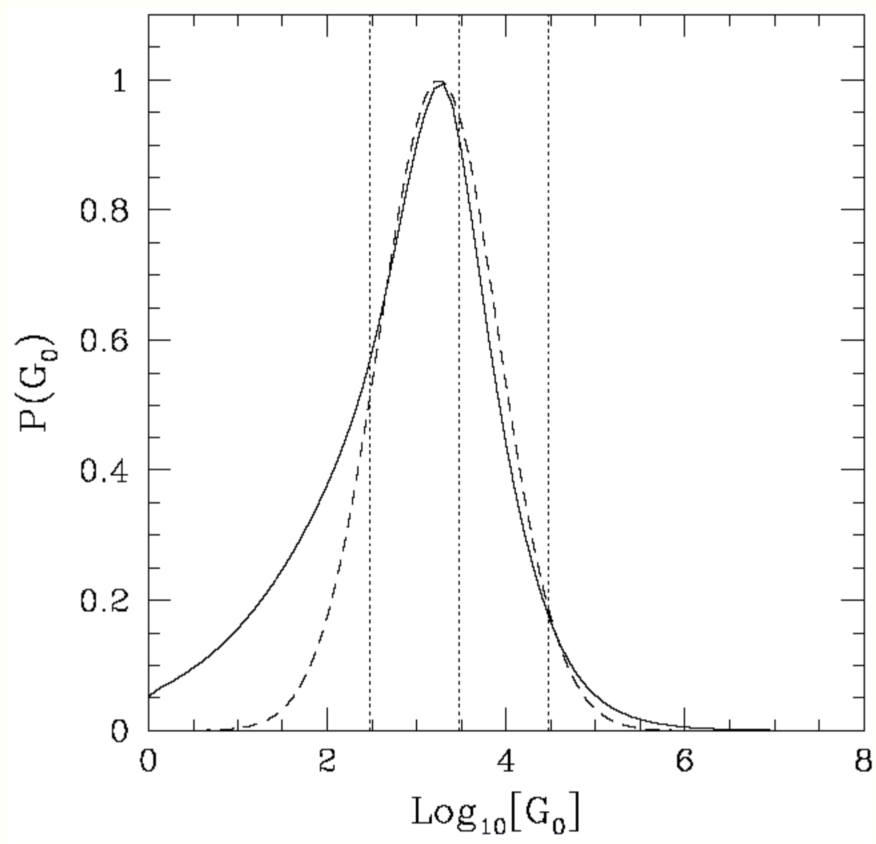
Photoevaporation of Circumstellar Disks

FUV Flux depends on:
- Cluster FUV luminosity
- Location of disk within cluster

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

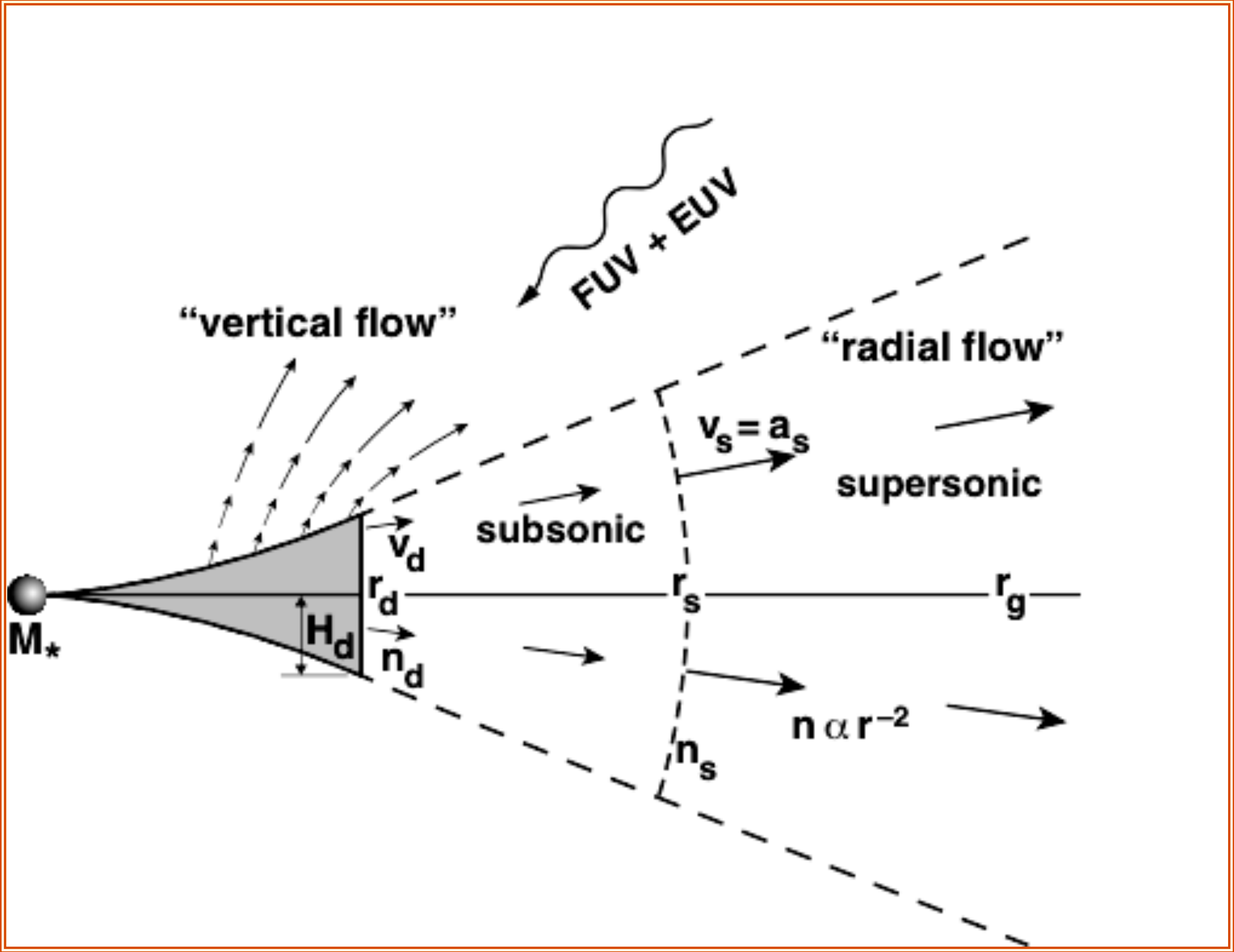
G_0 Distribution

Median	900
Peak	1800
Mean	16,500



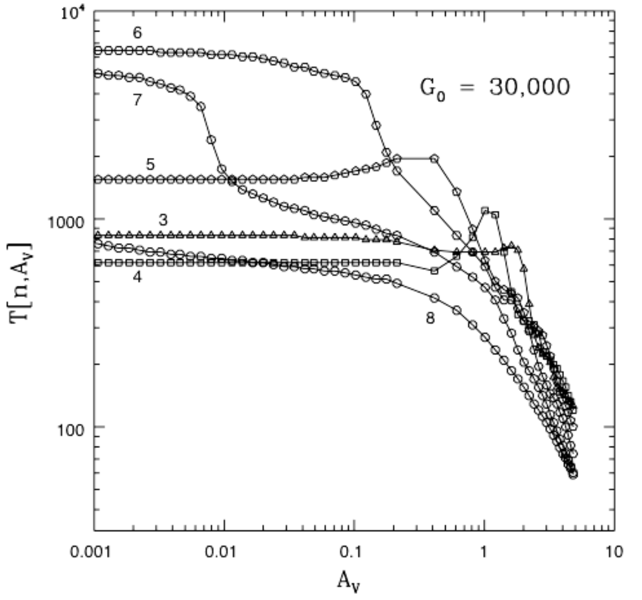
G_0 = 1 corresponds to FUV flux 1.6×10^{-3} erg s^{-1} cm^{-2}

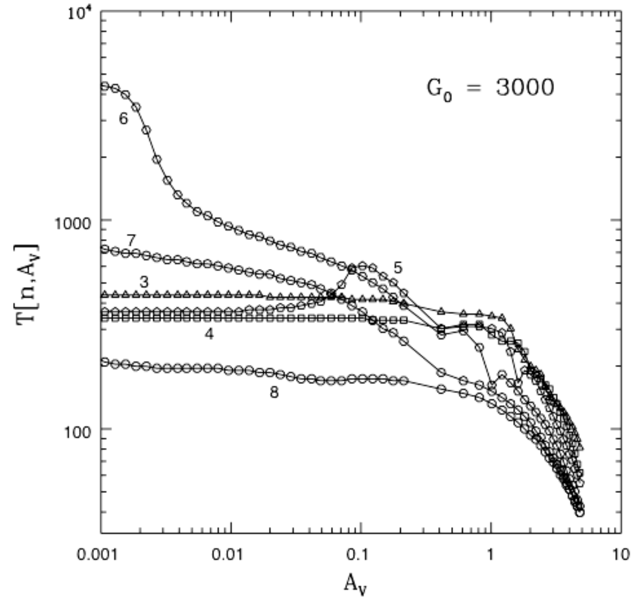
Photoevaporation Model

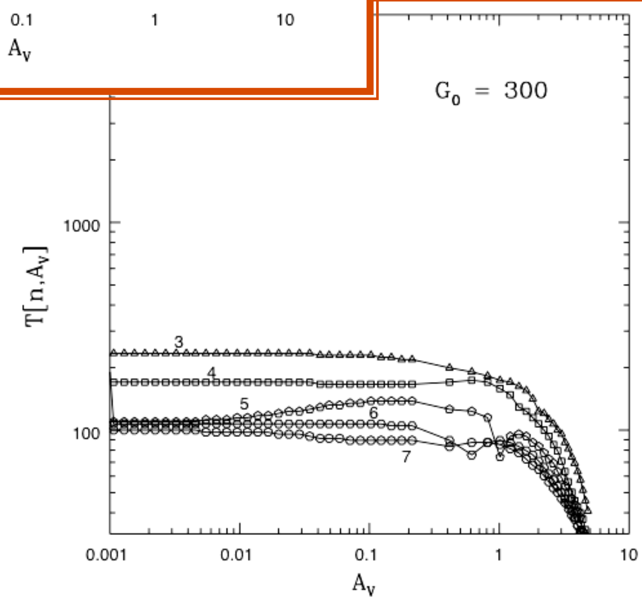


(Adams et al. 2004)

Results from PDR Code

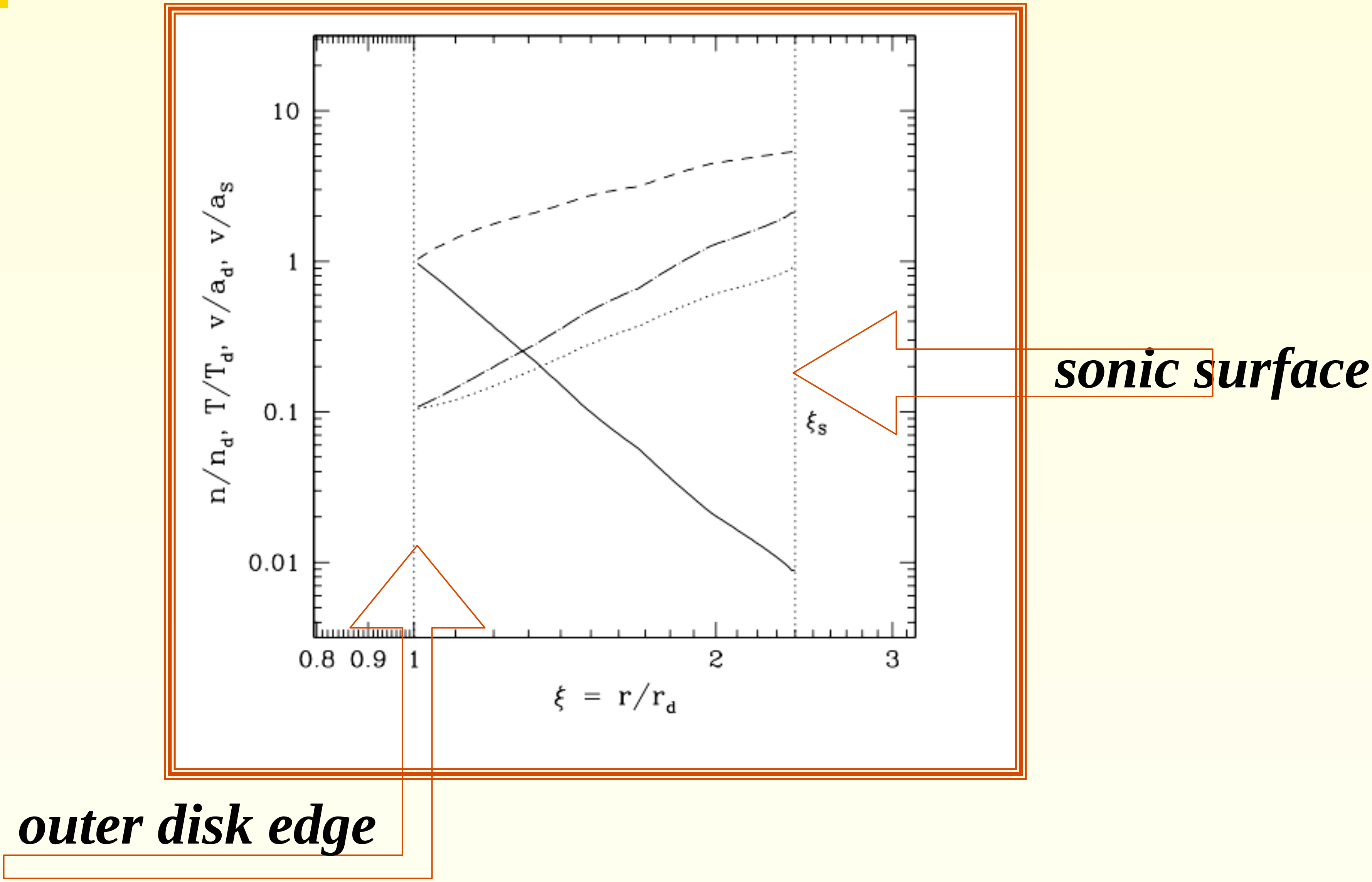




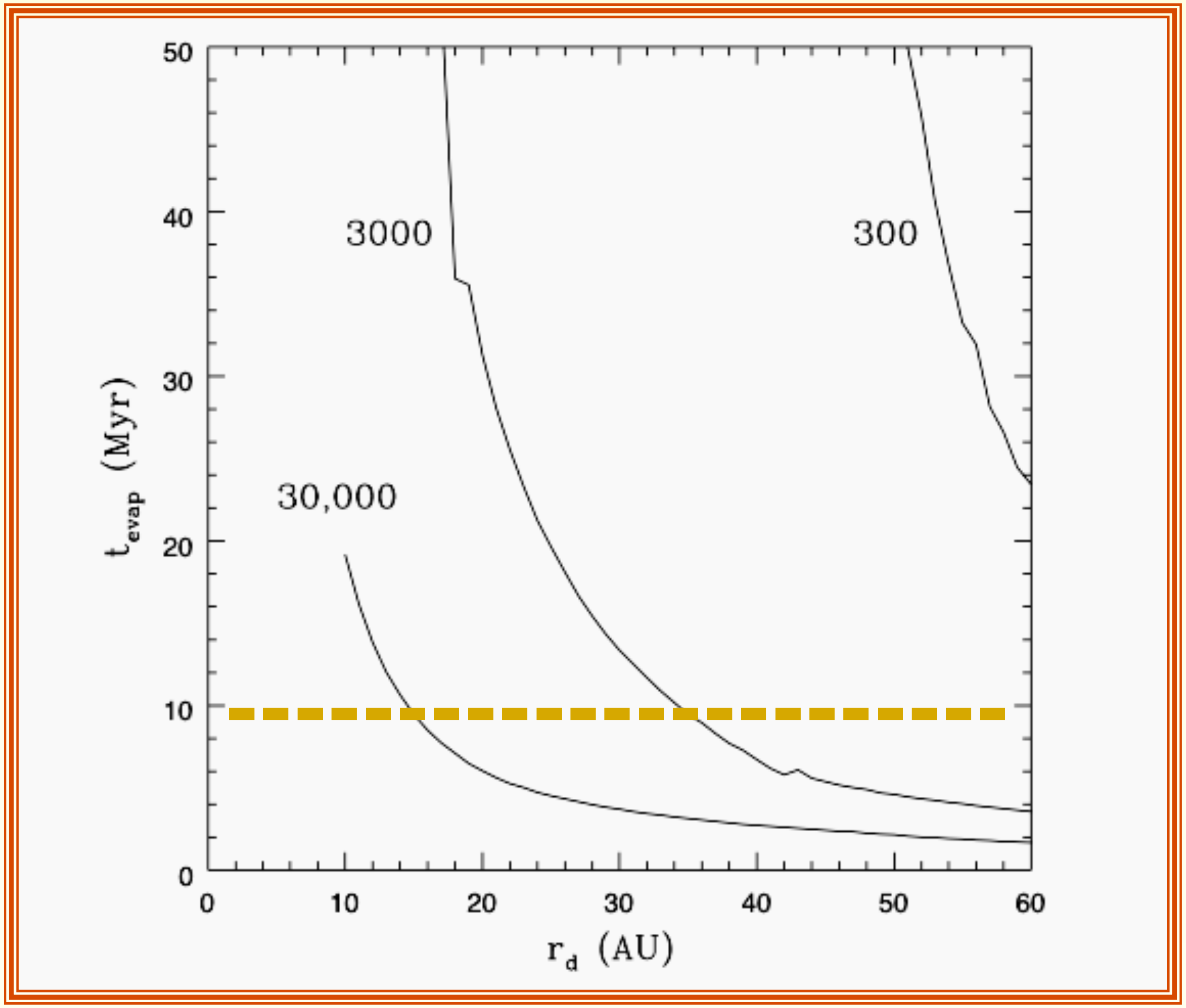


Lots of chemistry and many heating/cooling lines determine the temperature as a function of G, n, A

Solution for Fluid Fields



Evaporation Time vs FUV Field



(for disks around solar mass stars)

Photoevaporation in Simulated Clusters

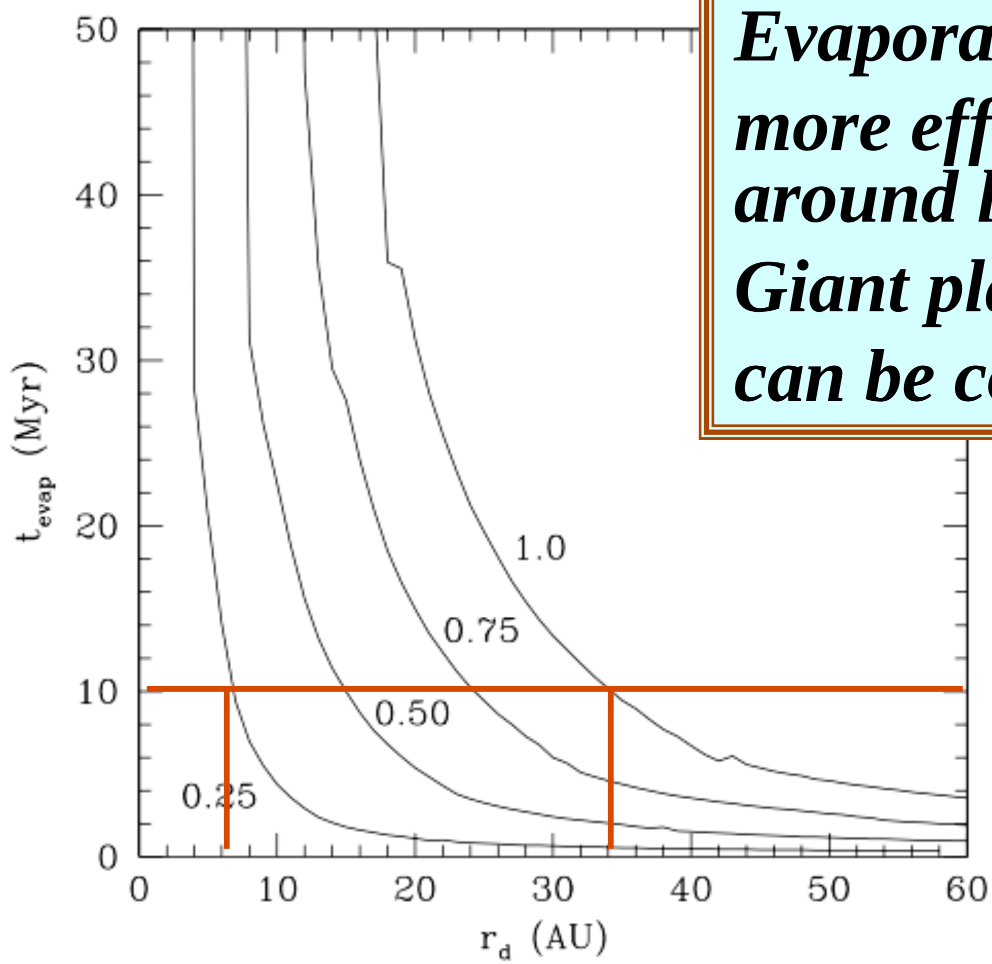
Radial Probability Distributions

$$\frac{N(r)}{N_T} = \left[\frac{\xi^a}{1+\xi^a}\right]^p \quad where \quad \xi = \frac{r}{r_0}$$

Simulation	r_{eff} (pc)	G_0 mean	r_{med} (pc)	**G_0 median**
100 Subvirial	0.080	66,500	0.323	**359**
100 Virial	0.112	34,300	0.387	**250**
300 Subvirial	0.126	81,000	0.549	**1,550**
300 Virial	0.181	39,000	0.687	**992**
1000 Subvirial	0.197	109,600	0.955	**3,600**
1000 Virial	0.348	35,200	1.25	**2,060**

FUV radiation does not evaporate enough disk gas to prevent giant planet formation for Solar-type stars

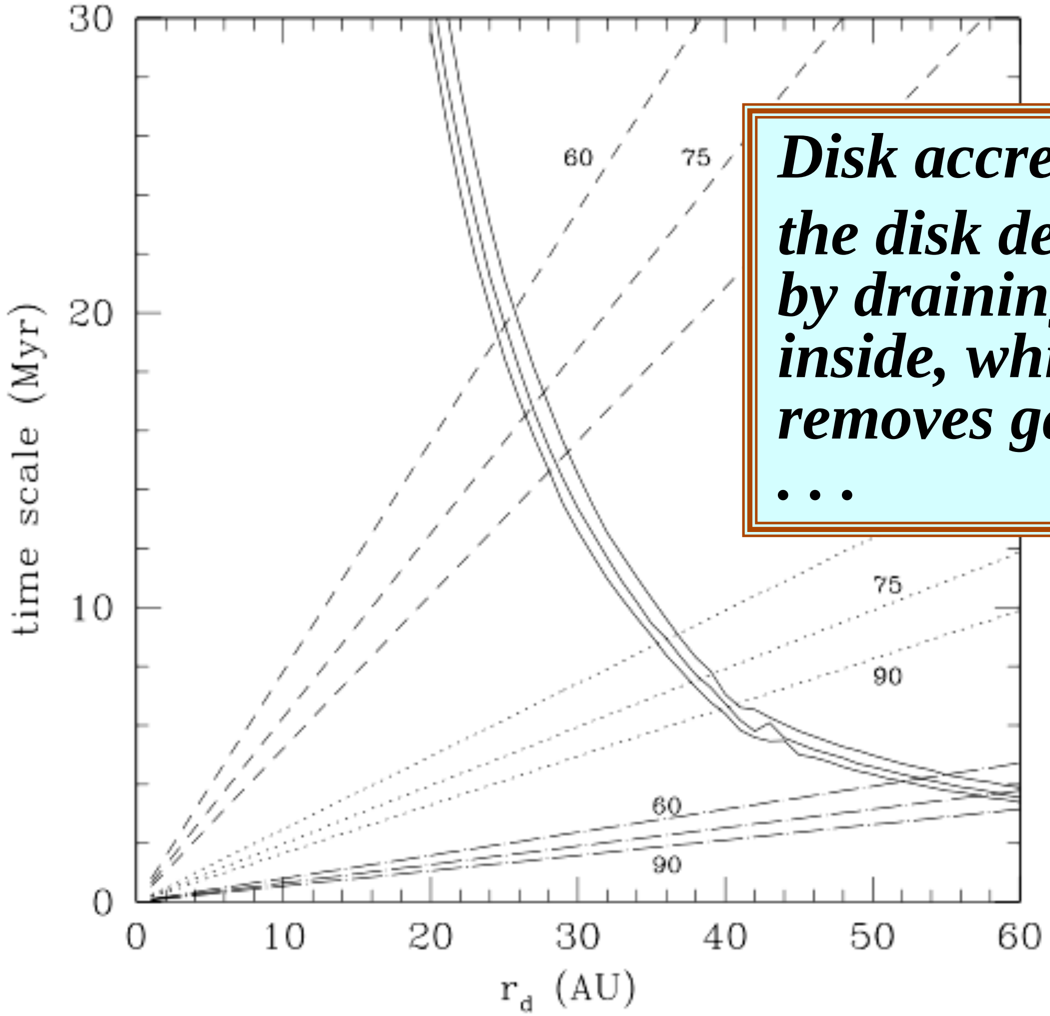
Evaporation Time vs Stellar Mass



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

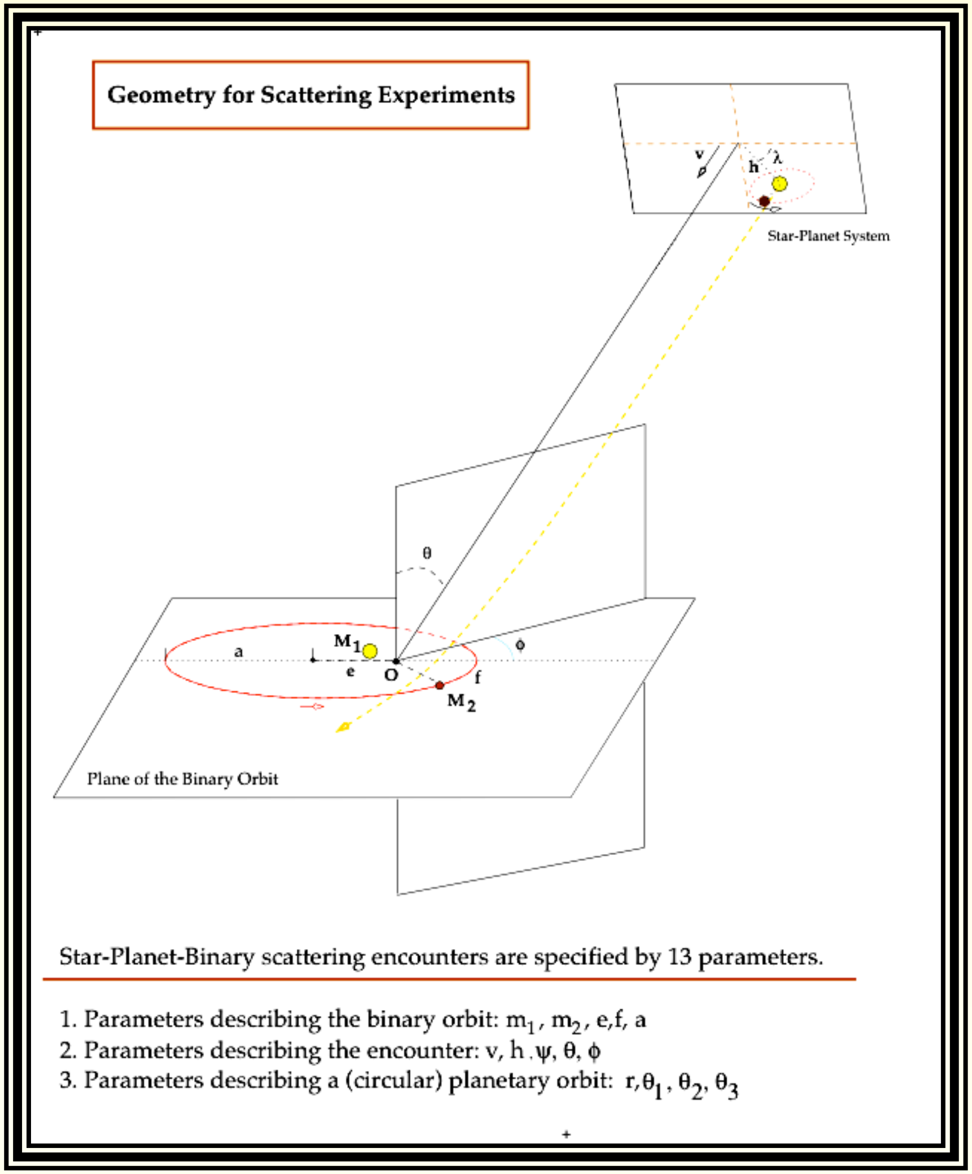
G=3000

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 . . .

Solar System Scattering



Many Parameters

+

Chaotic Behavior

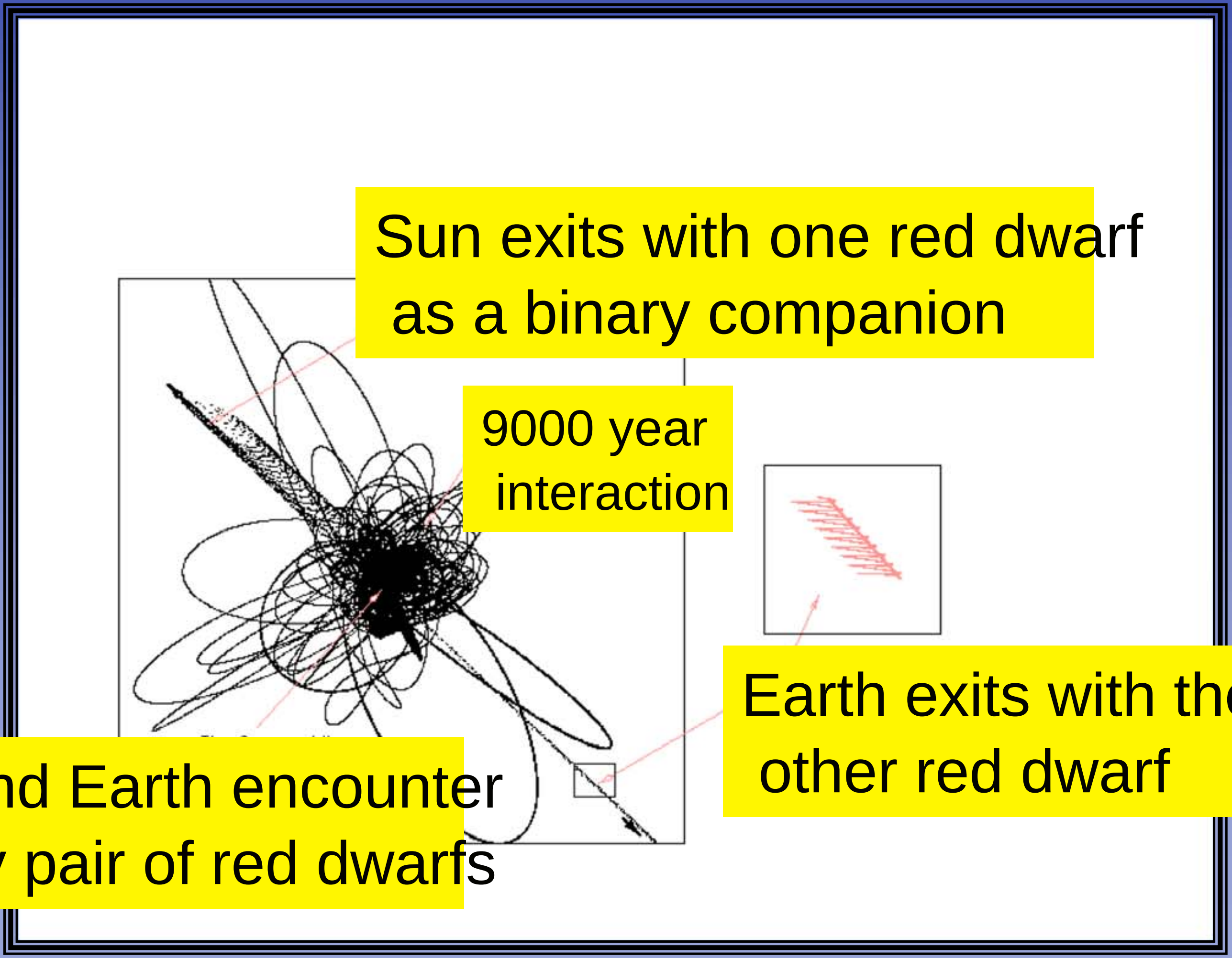
Many Simulations

Monte Carlo

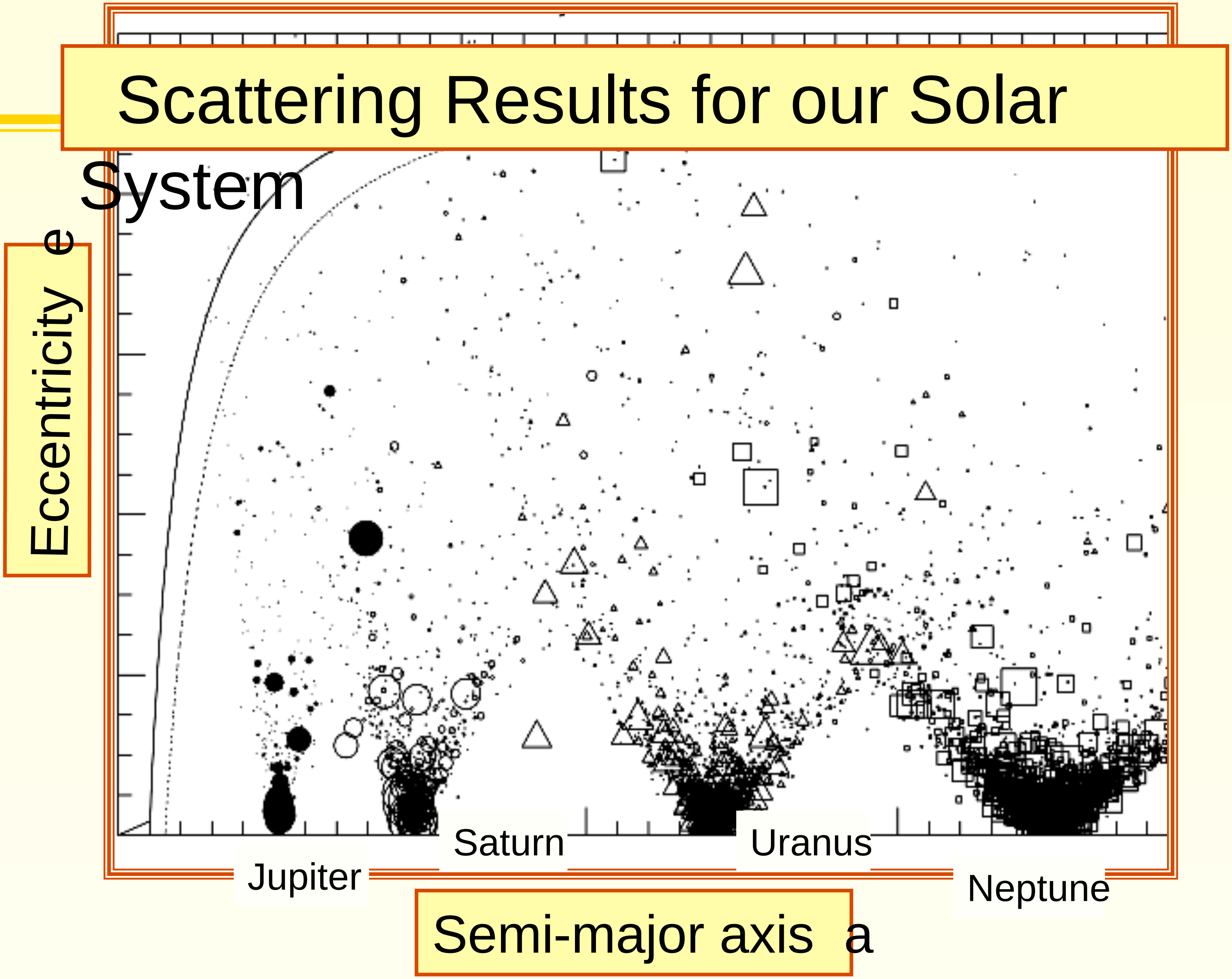
Monte Carlo Experiments

- Jupiter only, v = 1 km/s, N=40,000 realizations
- 4 giant planets, v = 1 km/s, N=50,000 realizations
- KB Objects, v = 1 km/s, N=30,000 realizations
- Earth only, v = 40 km/s, N=100,000 realizations
- 4 giant planets, v = 40 km/s, Solar mass, N=100,000 realizations
- 4 giant planets, v = 1 km/s, varying stellar mass, N=100,000 realizations

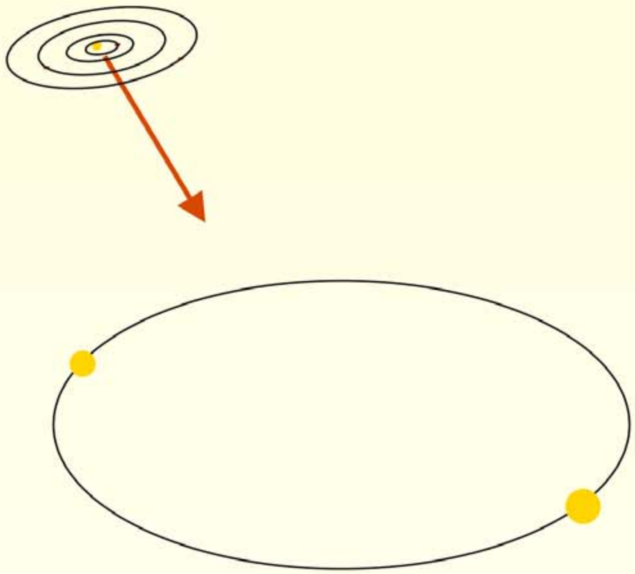
Red Dwarf captures the Earth

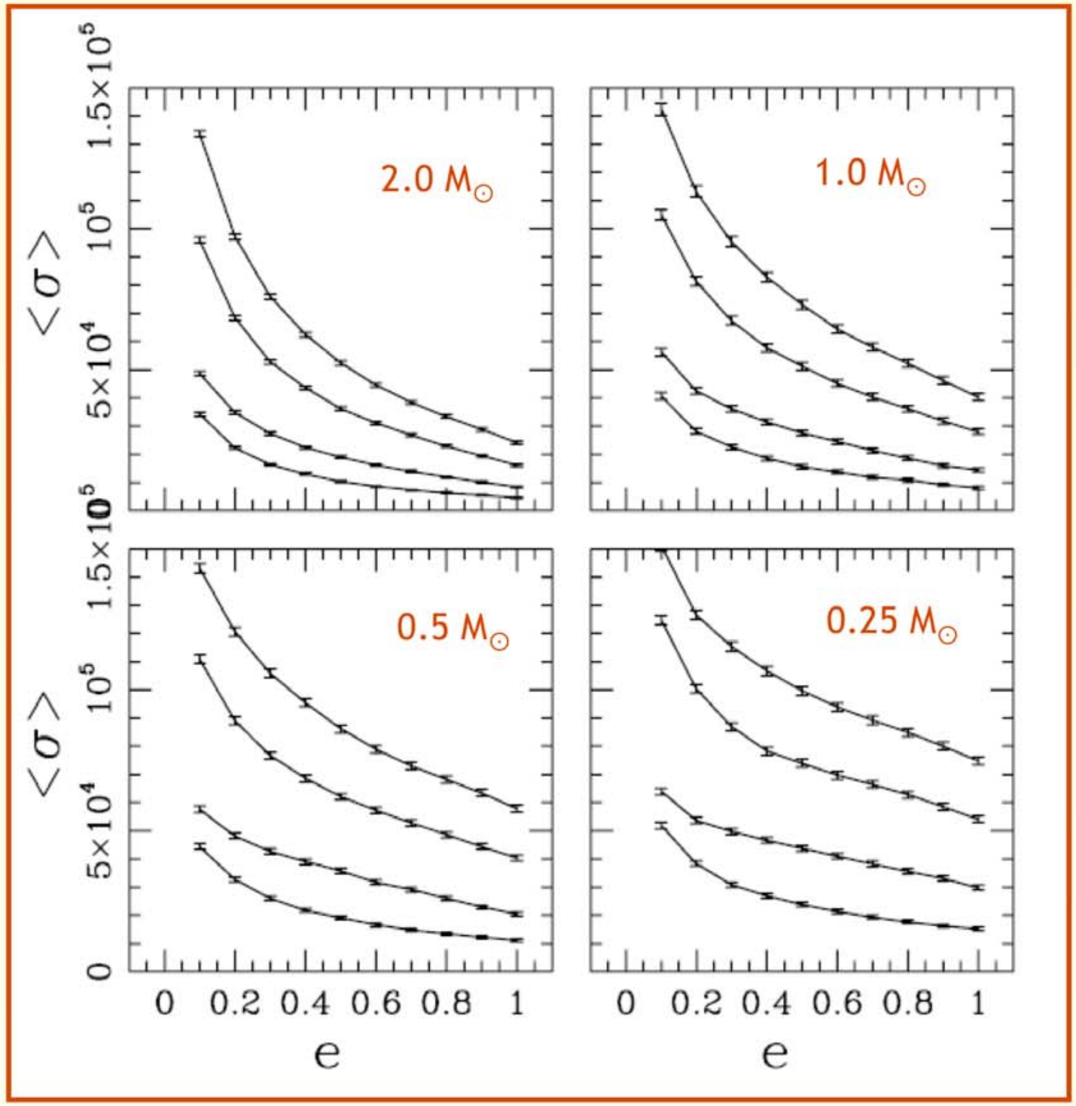


Scattering Results for our Solar System



Cross Sections





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

where

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

Solar System Scattering in Clusters

Ejection Rate per Star
(for a given mass)

$$\Gamma_{\text{eject}} = \Gamma_0 \left(\frac{C_0 (a_p / \text{AU})}{\pi (1000\ \text{AU})} \right)^{\gamma/2} \left(\frac{M_*}{M_\odot} \right)^{-\gamma/4}$$

↓

Integrate over IMF
(normalized to cluster size)

$$\int dm \left(\frac{dN}{dm} \right) m^{-\gamma/4} \text{ where } N = \int dm \left(\frac{dN}{dm} \right)$$

Subvirial N=300 Cluster

$\Gamma_0 = 0.096$, $\gamma = 1.7$

$\Gamma_J = 0.15$ per Myr

1-2 Jupiters are ejected in 10 Myr

Less than number of ejections from internal solar system scattering

(Moorhead & Adams 2005)

Conclusions

- Clusters have moderate effects on star formation:
  - FUV fluxes significantly shorten total disk lifetime (but still allow for Jovian planet formation)
  - Disruption of planetary systems rare, $b_C \sim 700\text{-}4000$ AU
  - Planet ejection rates via scattering encounters are low
  - All modes of destruction more important for M stars

- Photoevaporation model for external FUV radiation
- Distributions of FUV flux and luminosity
- Distributions of radial positions and closest approaches
- Cross sections for solar system disruption
- [Orbit solutions, triaxial effects, spirographic approx.]

Bibliography

- *Adams et al. 2007, ApJ, in press*
- *Adams & Bloch 2007, SIAM J. Ap. Math*
- *Adams, Proszkow, Fatuzzo, Myers 2006, ApJ, 641, 504*
- *Adams & Bloch 2005, ApJ, 629, 204*
- *Adams, Hollenbach, Laughlin, Gorti 2004, ApJ, 611, 360*
- *Adams & Myers 2001, ApJ, 553, 744*
- *Adams & Laughlin 2001, Icarus, 150, 151*

Orbits in Cluster Potentials

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

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

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

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

Orbits (continued)

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

(angular momentum of the circular orbit)

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

(effective semi-major axis)

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

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

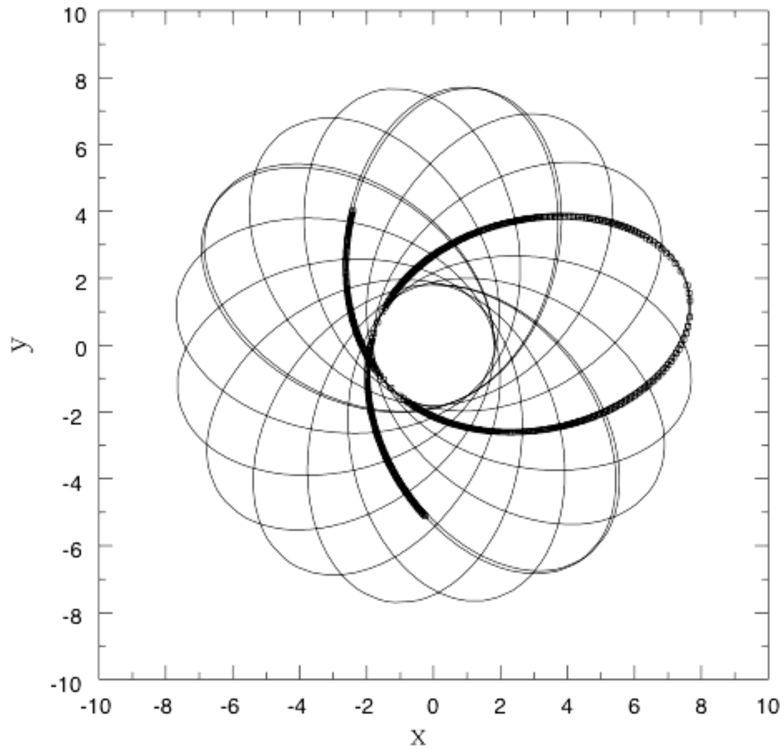
(circular orbits do not close)

These results can be used to determine the radiation exposure of a star averaged over its orbit, as a function of energy, where the result is nearly independent of angular momentum:

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

$$where \quad 1 \le A \le \sqrt{2}$$

Spirographic Orbits!



Orbital Elements

$$(\varepsilon,\ q)$$

$$(\xi_{1,}\xi_{2})$$

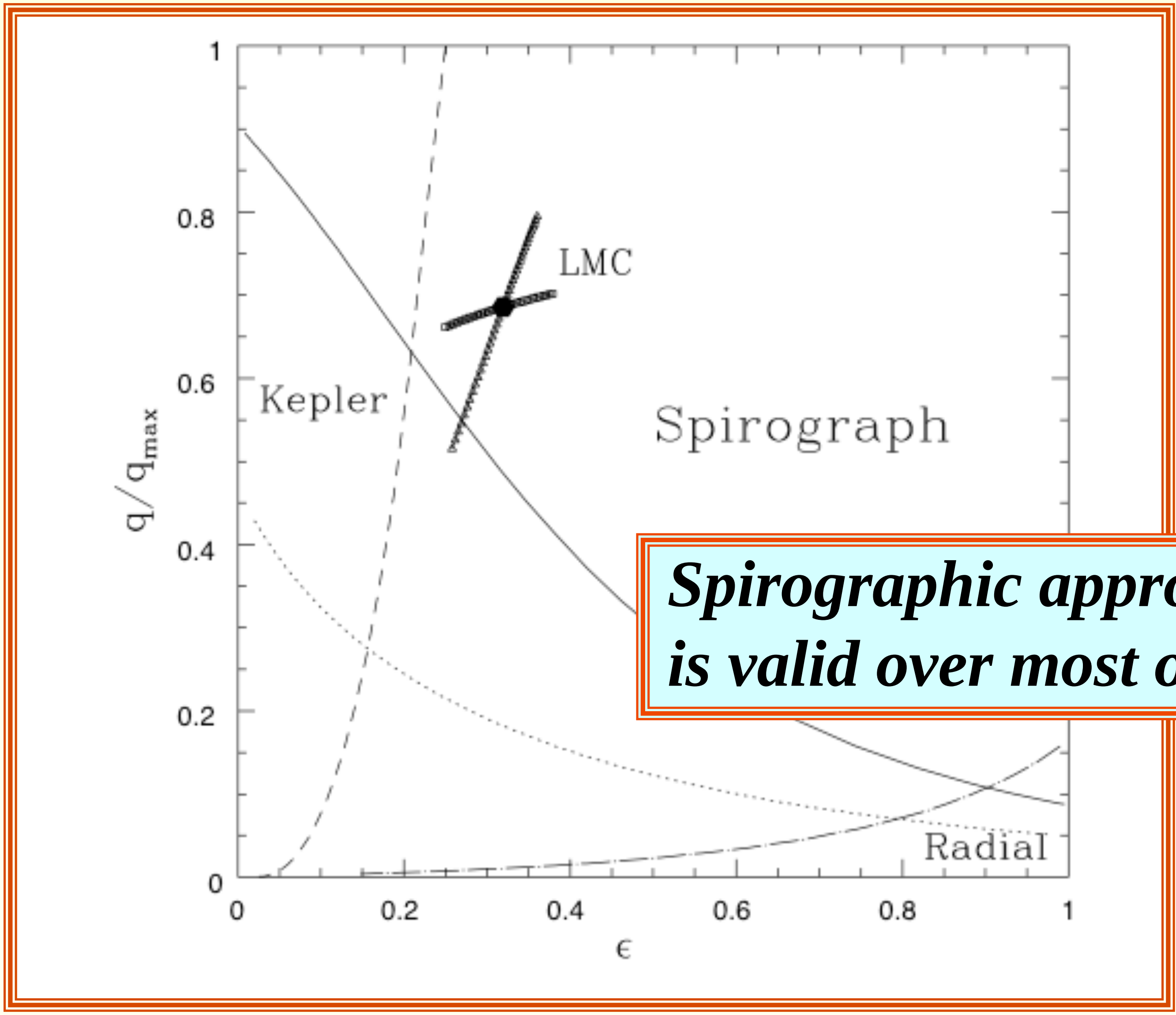
$$(\alpha,\beta,\gamma)$$

$$x(t_p) = (\alpha - \beta)\cos t_p + \gamma \cos[(\alpha - \beta)t_p / \beta]$$

$$y(t_p) = -(\alpha - \beta)\sin t_p + \gamma \sin[(\alpha - \beta)t_p / \beta]$$

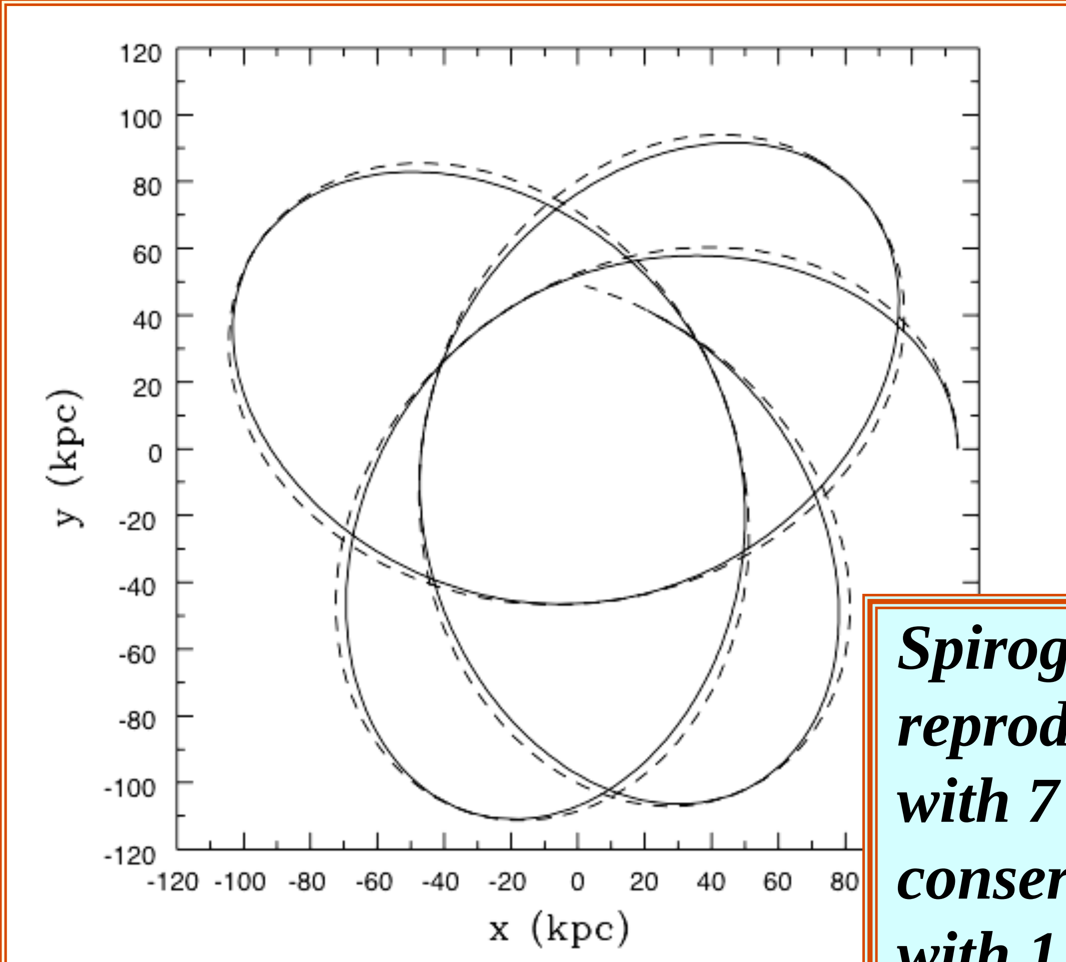
(Adams & Bloch 2005)

Allowed Parameter Space



Spirographic approximation is valid over most of the plane

Application to LMC Orbit



Spirographic approximation reproduces the orbital shape with 7 percent accuracy & conserves angular momentum with 1 percent accuracy. Compare with observational uncertainties of 10-20 percent.

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

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

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

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

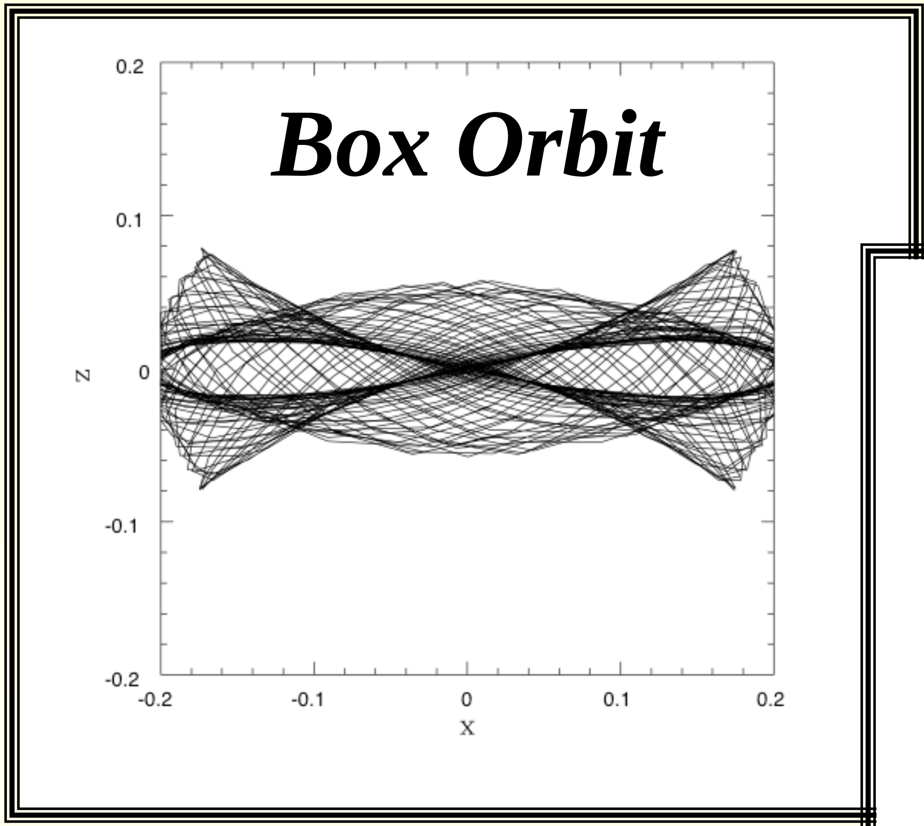
$$G(u) = \xi^2u^4-\Lambda u^2+\Gamma$$

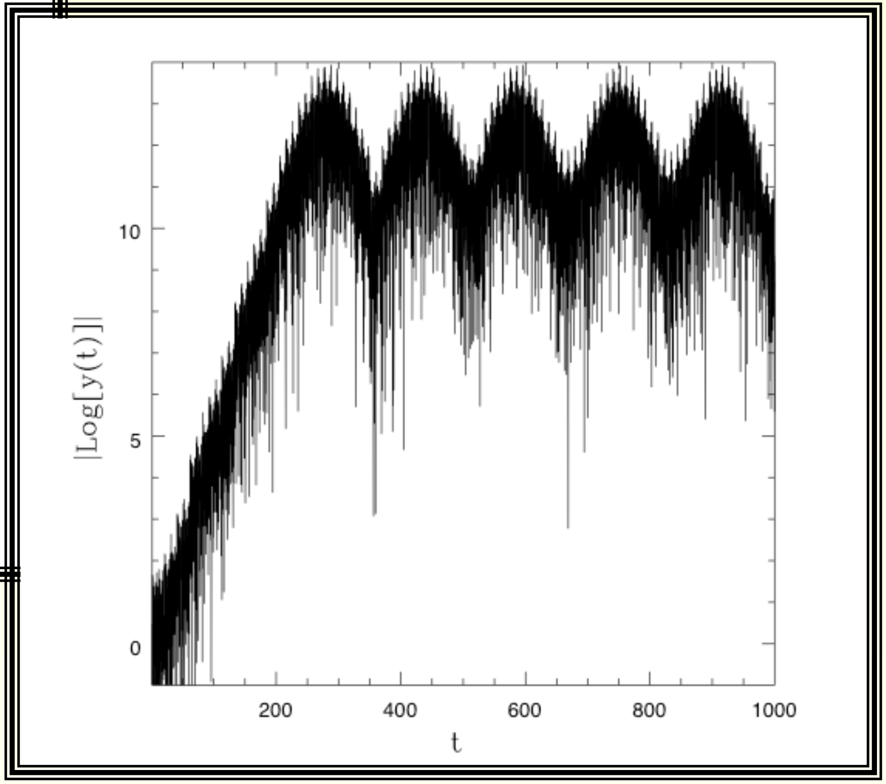
$$\xi^2 = x^2+y^2+z^2$$

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

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

Triaxial Potentials in Clusters





Growth of perpendicular coordinate

Where did we come from?

Solar Birth Aggregate

Supernova enrichment requires large N

$$M_* > 25 M_\odot$$

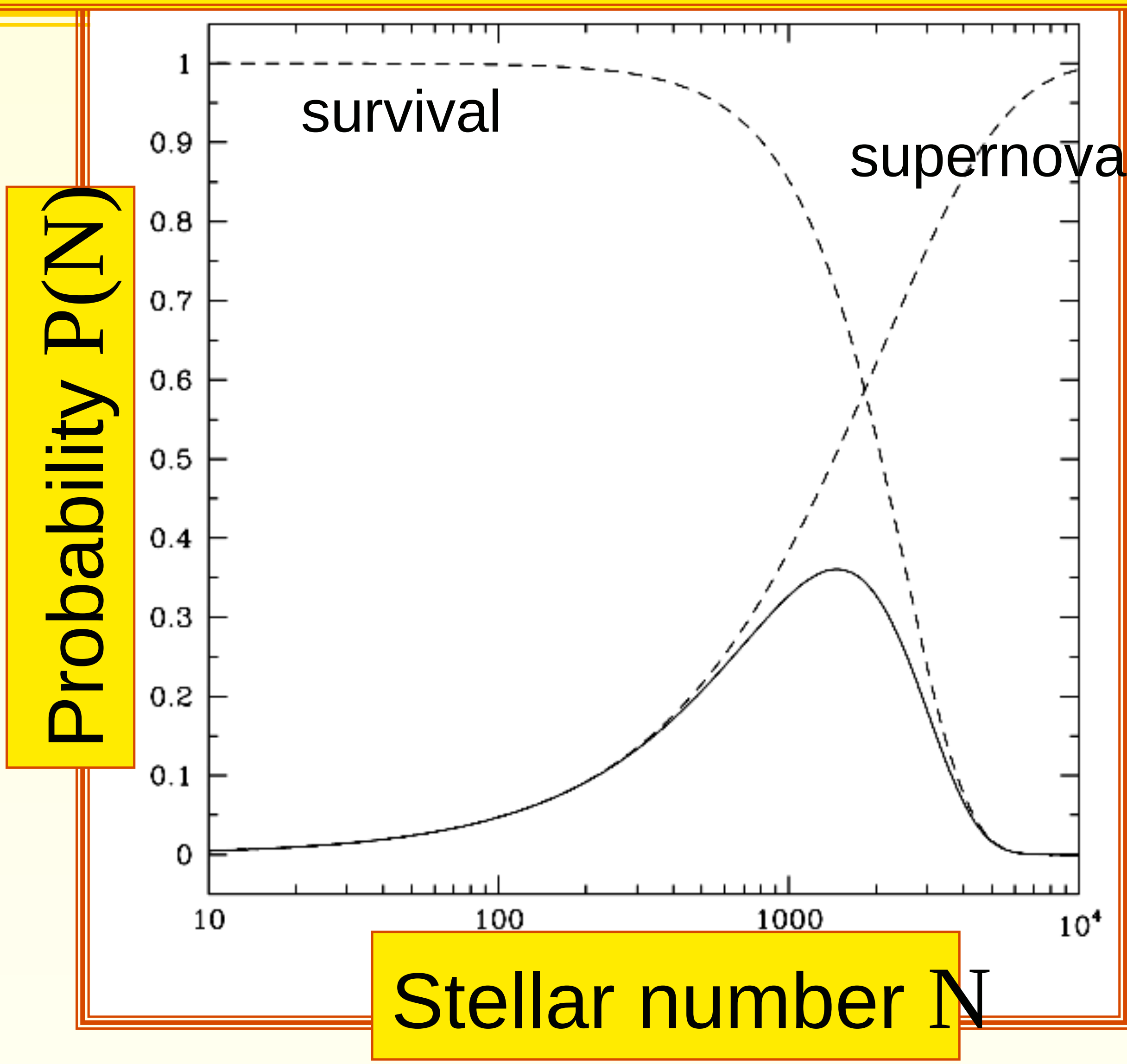
$$F_{SN} = 0.000485$$

Well ordered solar system requires small N

$$\varepsilon(Neptune) < 0.1$$

$$\Delta\Theta_j < 3.5^\circ$$

Expected Size of the Stellar Birth Aggregate



Adams & Laughlin, 2001, Icarus, 150, 151

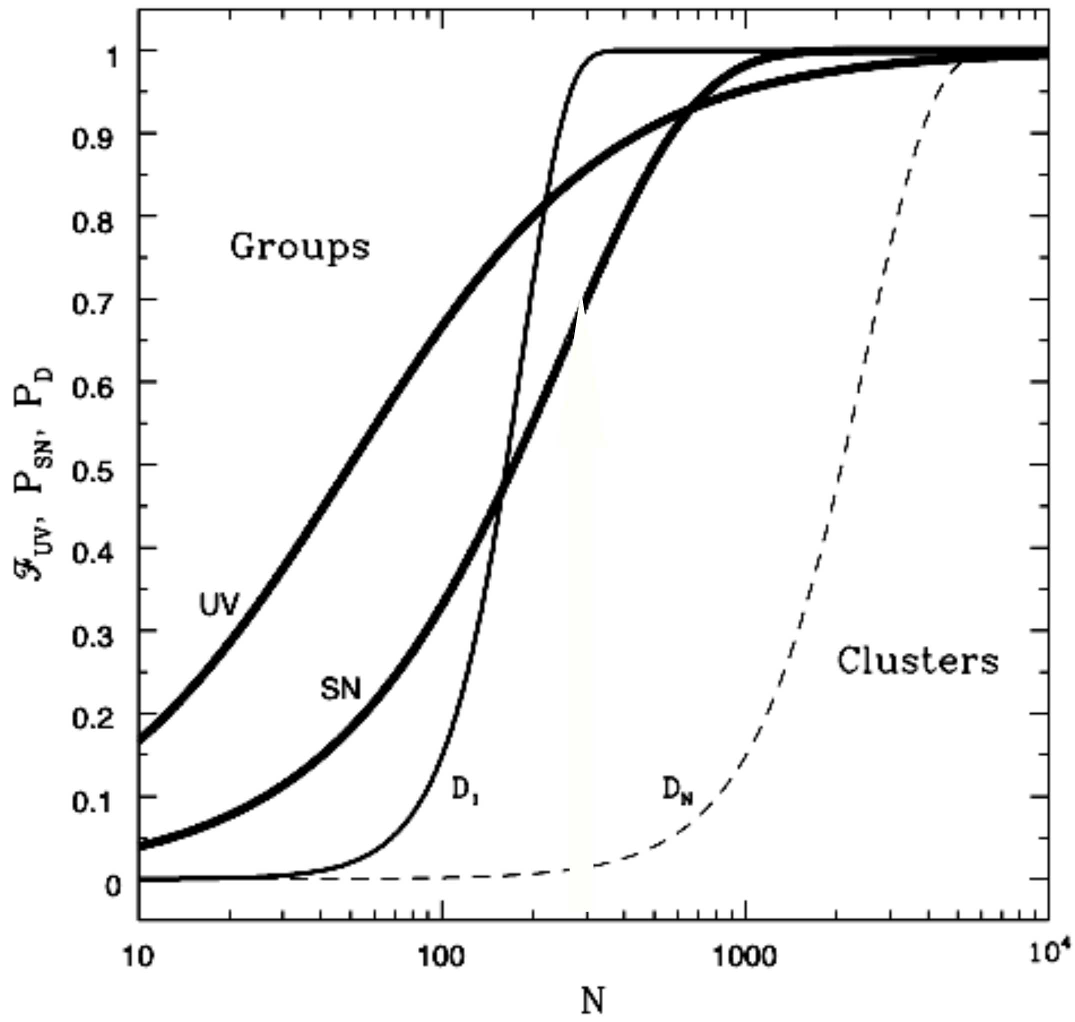
Constraints on the Solar Birth Aggregate

$$\langle N \rangle \approx 2000 \pm 1100$$

$$P \approx 0.017$$ (1 out of 60)

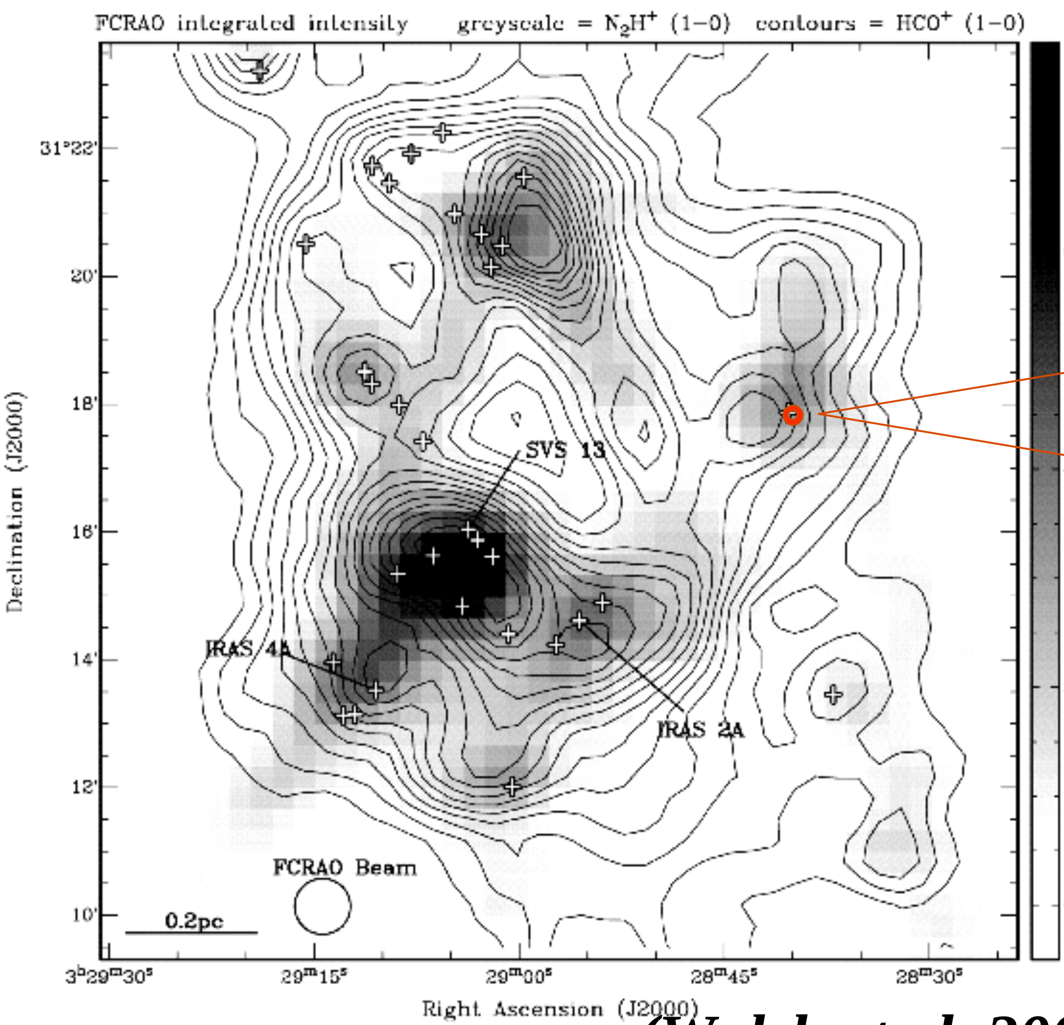
(Adams & Laughlin 2001 - updated)

Probability as function of system size N



(Adams & Myers 2001)

NGC 1333 - cold start



(Walsh et al. 2006)

$$(\Delta v)_Z \approx 0.1 \ km/s$$

$$(\Delta v)_T (\Delta t)_{SF} \approx 0.02\, pc$$