Could the Galactic Center Stars have Formed in Situ?

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Goals:

- Assess the plausibility of in situ star formation within the black hole's dynamical sphere of influence
- Argue that star formation is a generic consequence of the AGN phenomenon
- Briefly discuss observational tests of in situ formation hypothesis

Star Formation in a Nutshell

Gas must overcome 4(5) barriers to form a (massive) star:

Thermal barrier $M_J \sim c_s^3 / G^{3/2}\, r_{gas}^{1/2}$
- does not stop collapse
- regulates accretion rate following collapse

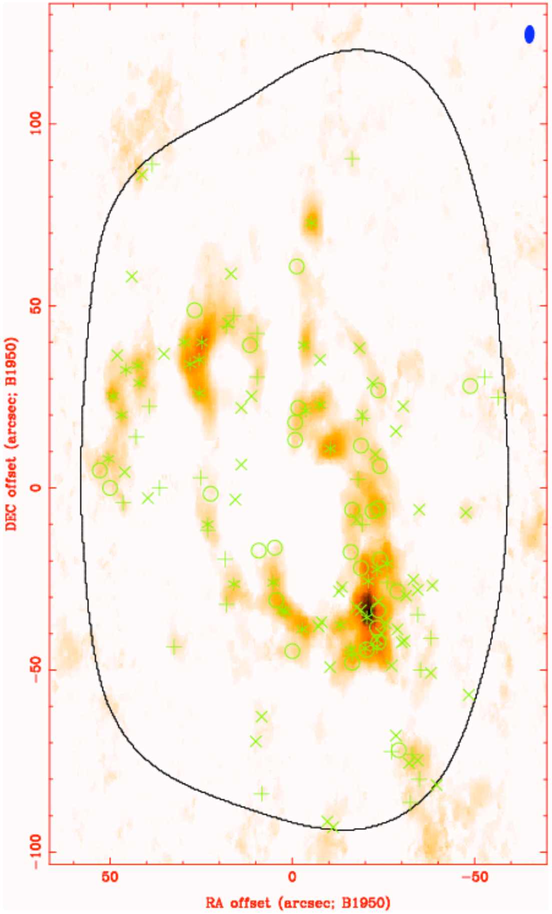
Magnetic barrier
- does not stop collapse;
- regulates accretion onto the core

Centrifugal barrier
- determines the nature of collapsed objects, including multiplicity

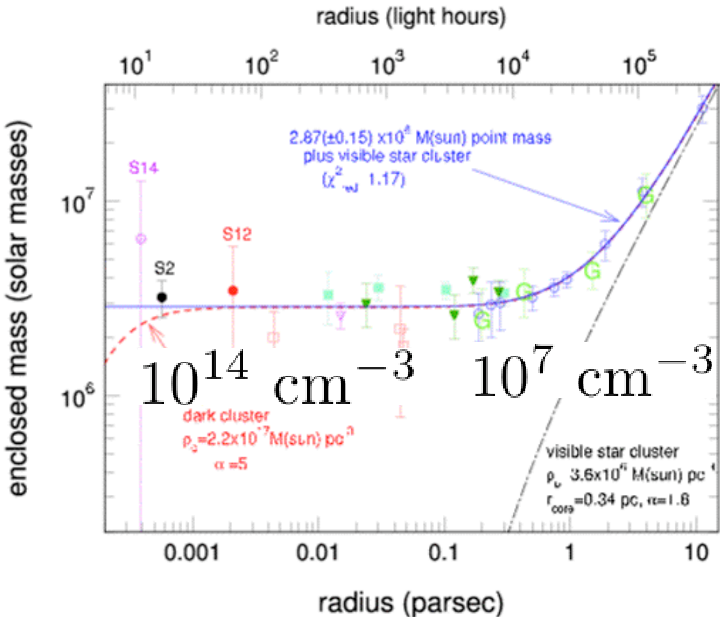
Tidal barrier $r_{gas} > M_{bh} / r^3$
- must be overcome!

Supply barrier
- multiple accreting objects compete for gas

Molecular Gas at the Galactic Center: The Circumnuclear Disk (e.g., Jacskon et al. 1993) and HLR gas (Herrnstein et al. 2005)

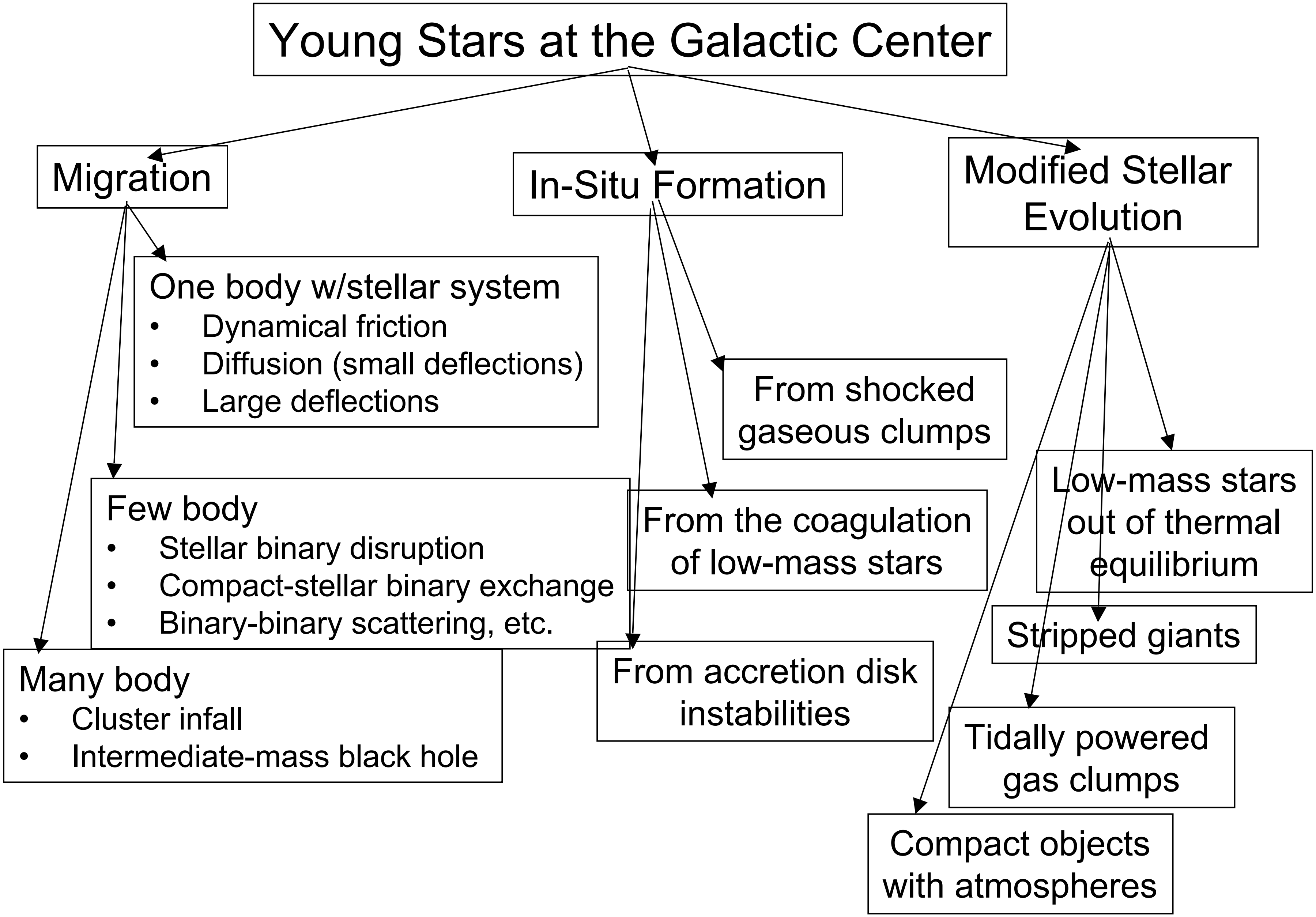


Christopher, Scoville, Stolovy & Yun 2004



$10^{14}\ \mathrm{cm}^{-3}$ $10^{7}\ \mathrm{cm}^{-3}$

Schoedel et al. 2003, Genzel et al. 2004



Young Stars at the Galactic Center

Migration

One body w/stellar system
- Dynamical friction
- Diffusion (small deflections)
- Large deflections

Few body
- Stellar binary disruption
- Compact-stellar binary exchange
- Binary-binary scattering, etc.

Many body
- Cluster infall
- Intermediate-mass black hole

In-Situ Formation

From shocked gaseous clumps

From the coagulation of low-mass stars

From accretion disk instabilities

Modified Stellar Evolution

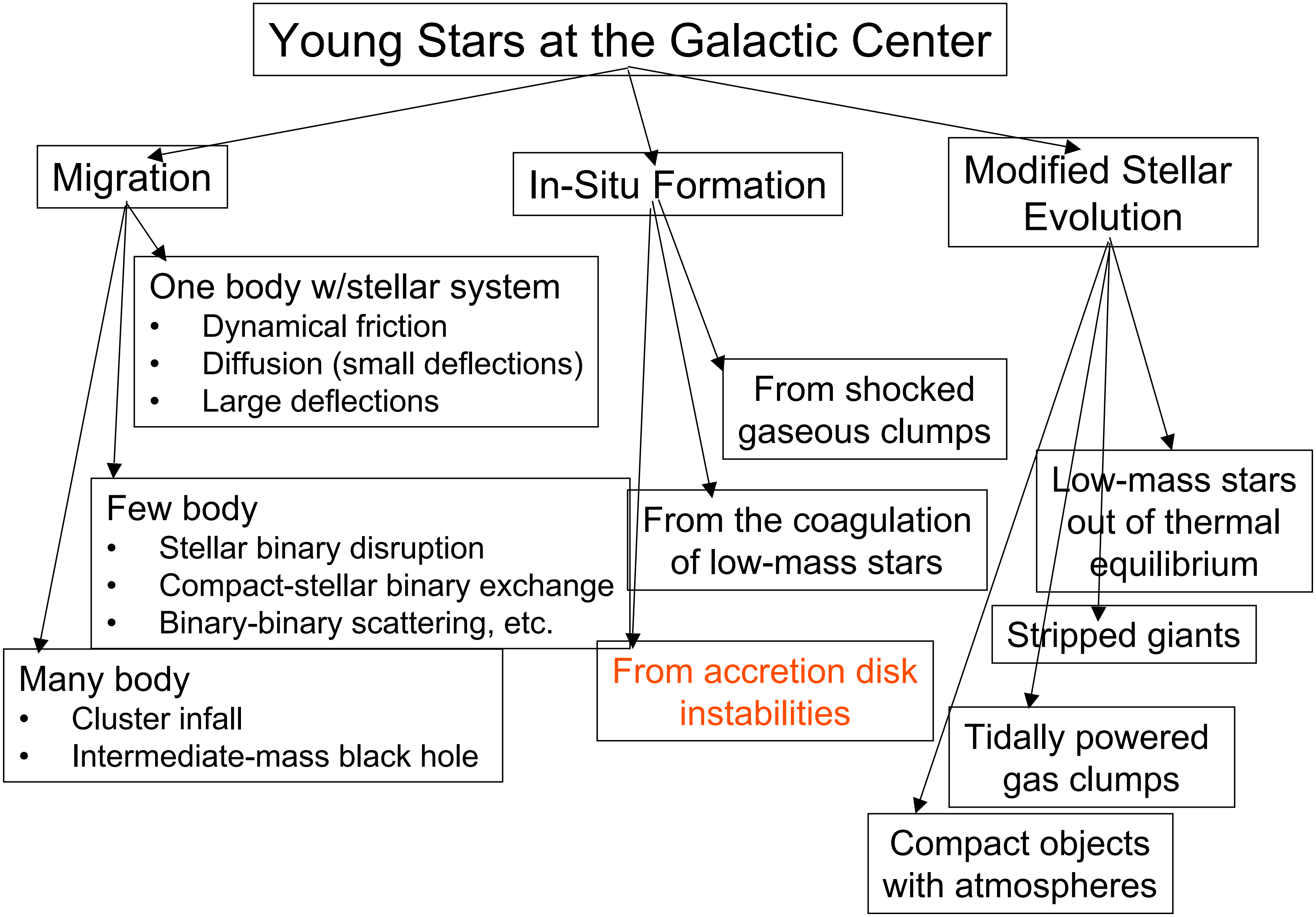
Low-mass stars out of thermal equilibrium

Stripped giants

Tidally powered gas clumps

Compact objects with atmospheres

Young Stars at the Galactic Center



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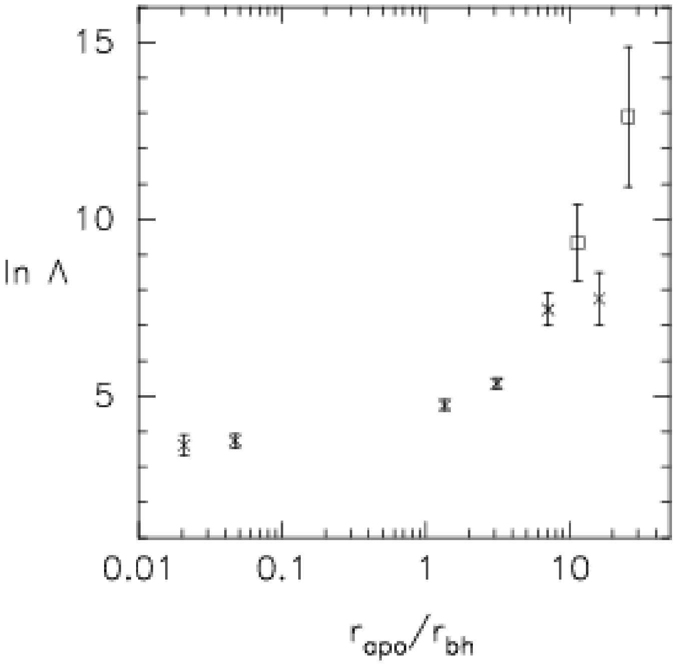
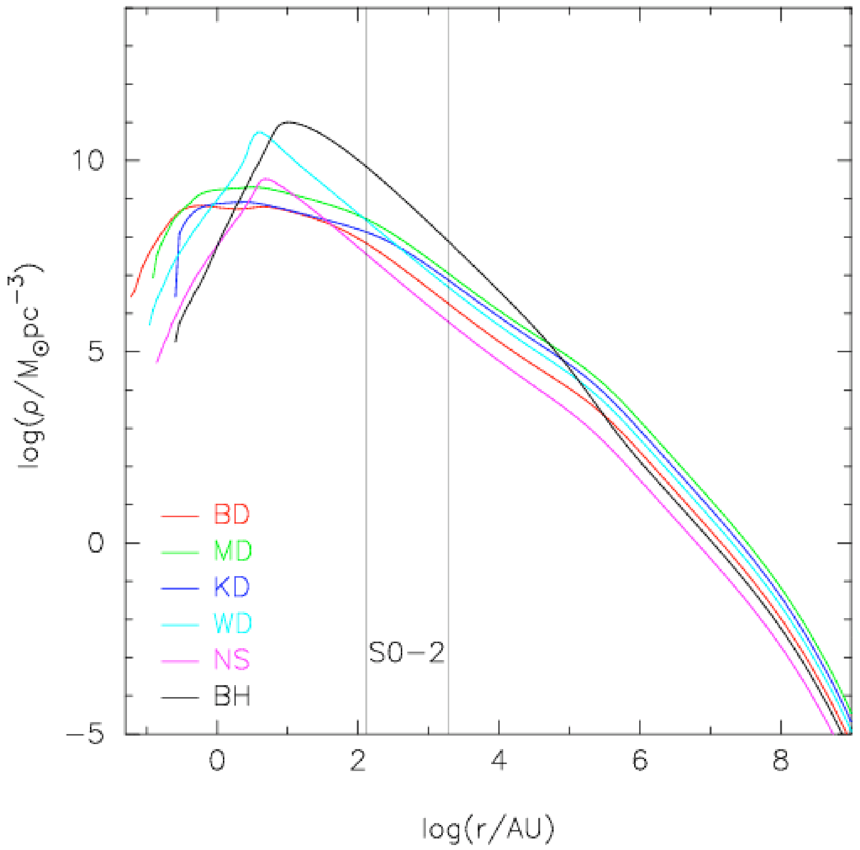
Diffusion Due to Discrete Stellar Encounters

$$t_{\rm E} \approx 2\times10^{8}\left(\frac{r}{1{\rm pc}}\right)^{1/4}\left(\frac{M_{\rm bh}}{4\times10^{6}M_{\rm Sun}}\right)^{3/2}\left(\frac{m}{10M_{\rm Sun}}\right)^{-1}$$

$$\times\left(\frac{\rho(1{\rm pc})}{2\times10^{5}M_{\rm Sun}{\rm pc}^{-3}}\right)^{-1}\left(\frac{\ln\Lambda}{10}\right)^{-1}\quad {\rm for}\ \ \rho\propto r^{-7/4}$$



Passive Evolution of 10^{10} Years



- The central few arcsec are dominated by ~10 M_{Sun} black holes (e.g. Morris 93, Miralda-Escude & Gould 01)
- Collisions set the maximum central density of dwarfs < 1 M_{Sun} at 10^9 M_{Sun}/pc^3
- Some low-mass stars remain in the central parsec
- Anisotropy parameter moderate b_{min} ~ -0.2
- Diffusion time remains > 10^8 yr

Collision Rate

$$\frac{d^2N}{d\log_2 r\,dt} \sim \left(10^4\,\mathrm{yr}\right)^{-1}\left(\frac{r}{0.01\mathrm{pc}}\right)^{-1}\left(\frac{R}{R_{\mathrm{Sun}}}\right)^{2}\left(\frac{m}{M_{\mathrm{Sun}}}\right)^{-2}$$

$$+\left(10^5\,\mathrm{yr}\right)^{-1}\left(\frac{R}{R_{\mathrm{Sun}}}\right)\left(\frac{m}{M_{\mathrm{Sun}}}\right)^{-1}$$

Unrealistic absolute maximum!

Departures from Thermal Equilibrium

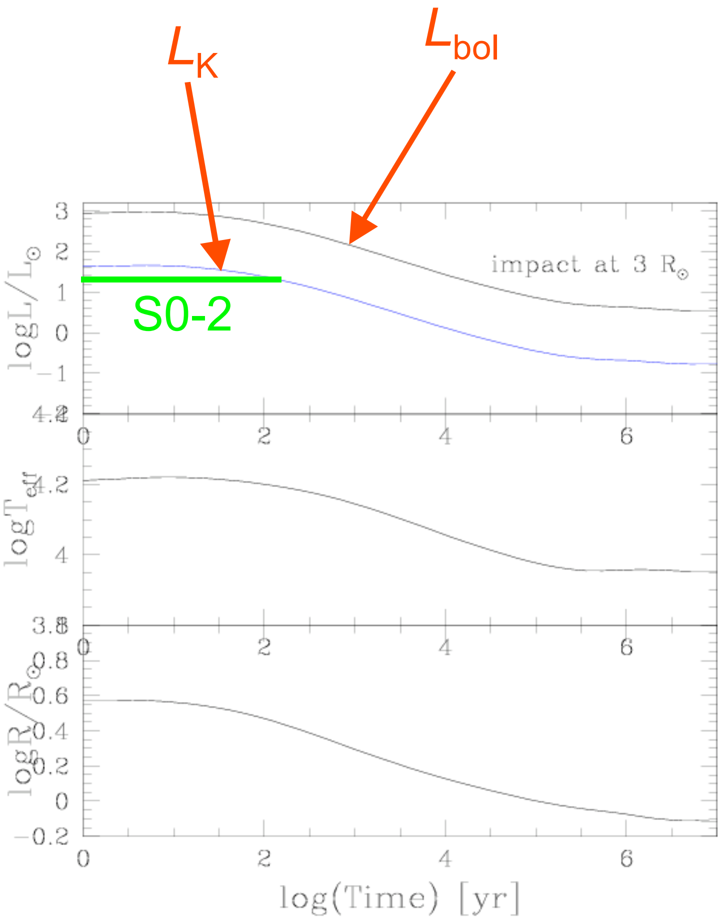


Fig. Ivanova, Faber, & Rasio

$$\frac{L_K}{L_{K,Sun}} \sim \frac{T}{T_{Sun}}\left(\frac{R}{R_{Sun}}\right)^2 \sim 100$$

$$\frac{L}{L_{Sun}} \sim \left(\frac{T}{T_{Sun}}\right)^4\left(\frac{R}{R_{Sun}}\right)^2 \sim \frac{t_{KH,Sun}}{t_{KH}}$$

$$T \sim T_{Sun}\left(\frac{t_{KH}}{10^5\,\mathrm{yr}}\right)^{-1/3}$$

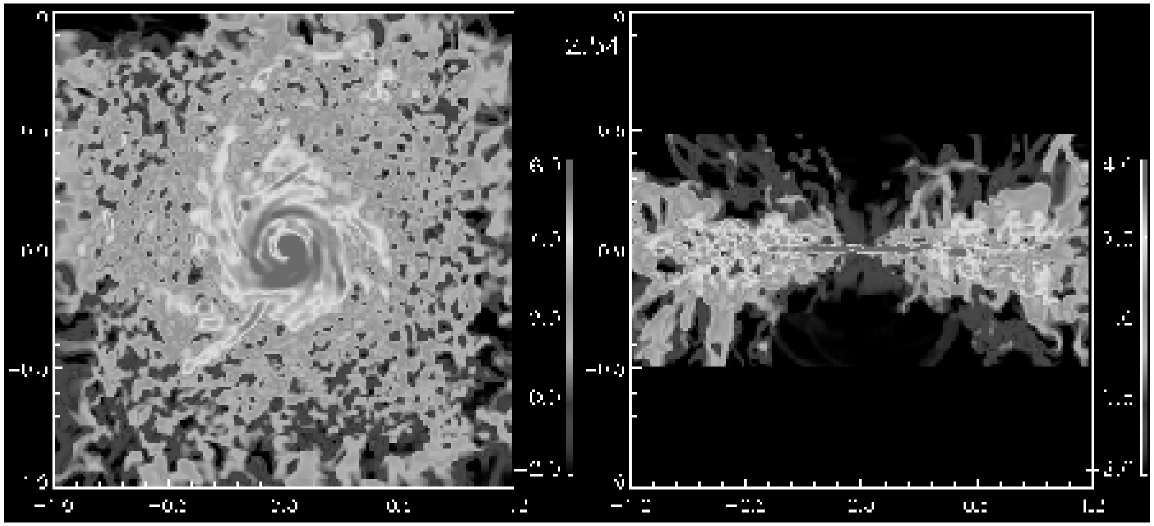
$$\therefore R \sim 10 R_{Sun}$$

Must be maintained between successive collisions!

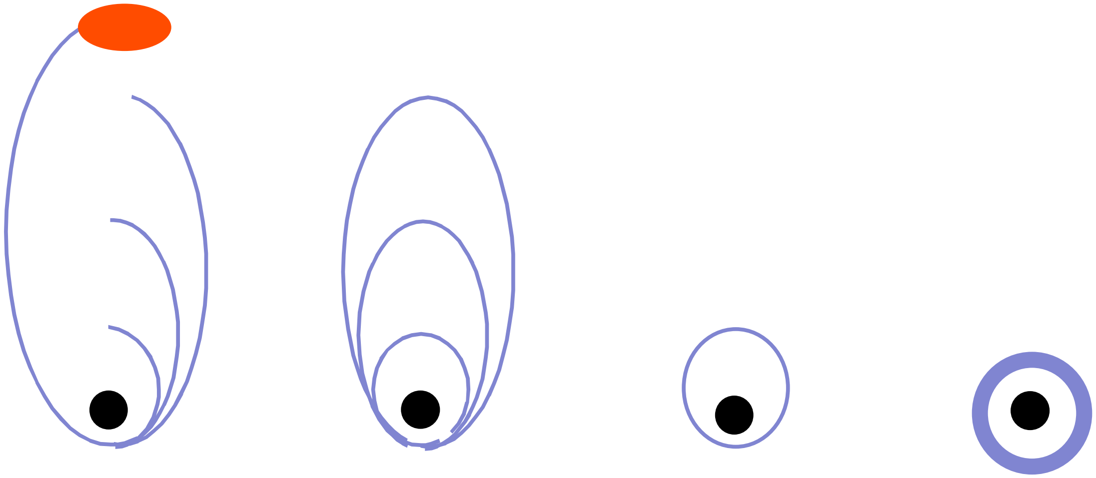
Sgr A* Cluster and the Copernican Principle

- The star formation mechanism is universal to the gas-rich nuclei of disk galaxies and is related to accretion.
- Star formation in the central parsec is continuous or intermittent and possibly favors massive stars.

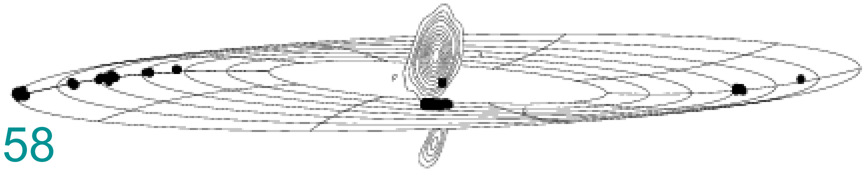
Circularization



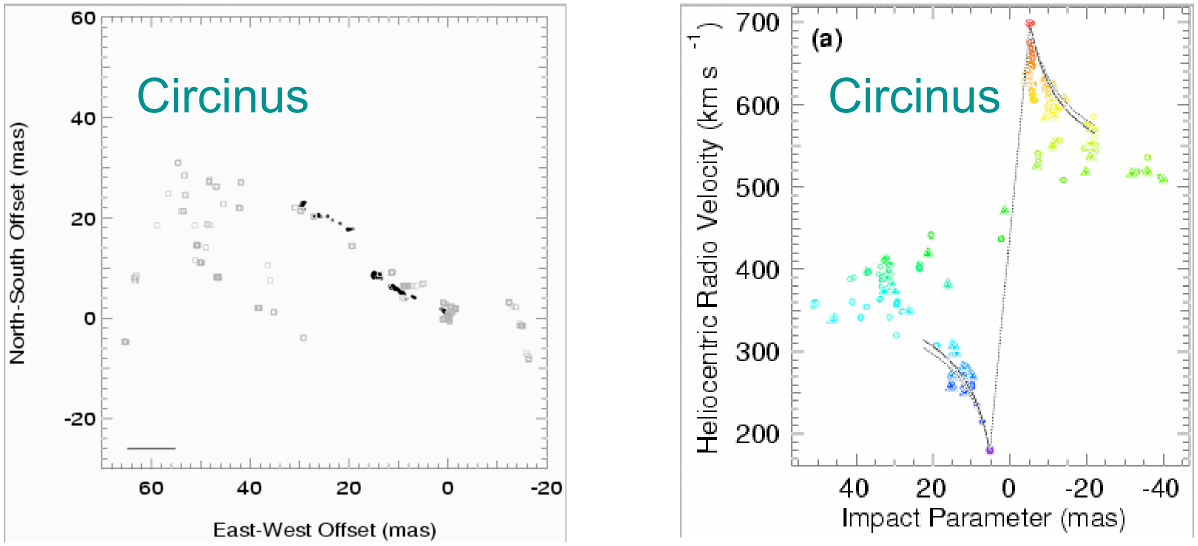
Wada 2003



Extragalactic Water Masers



Herrnstein et al



Greenhill et al

Conditions of the Operation of Water Masers and the Disk Parameters

- $n_{gas} > 10^7$ cm^{-3} easily achieved in a disk!
- $n_{gas} \sim 10^{10}$ cm^{-3} levels thermalized
- $T_{gas} > 400$ K difficult – what keeps the gas hot?
- r ~ 0.1 – 0.5 pc
- We choose: $n_{gas} \sim 10^9$ cm^{-3}
- $N \sim 10^{25}$ cm^{-2} X-ray abs. but geometry uncertain
- $M_{disk} \sim 10^4$ $M_{Sun,}$ $M_{bh} \sim 10^{6-7}$ M_{Sun}
- Maser emission – Uniform or localized?
- Illumination by X-rays from the AGN
- Accretion time – long! Accretion rate varies with radius.

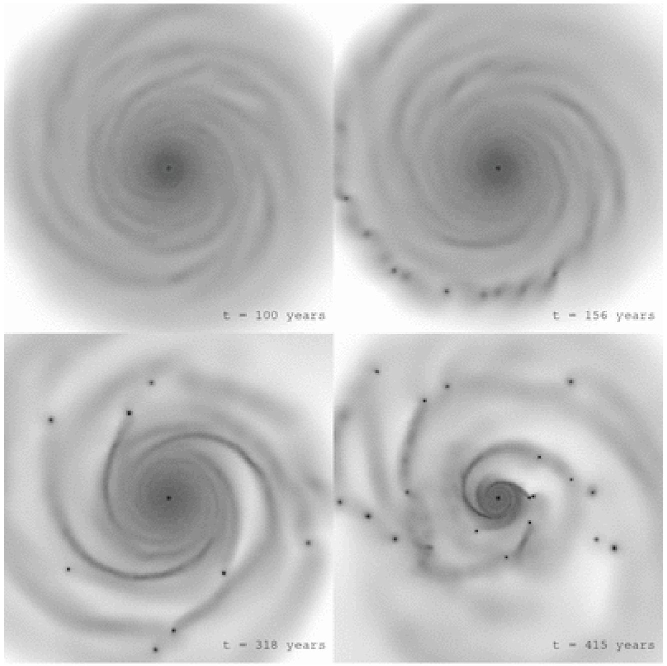
What keeps the gas warm?

- Irradiation by X-rays from the AGN (Neufeld, Maloney & Conger 1994)?
- Spiral shocks (Maoz & McKee 1998)?
- Ionizing radiation from nearby stars? $R_{Stromgren}\sim10^{15}$ cm
- Dissipation of turbulence (Desch, Wallin & Watson 1998)?
- Magnetic reconnection in disk corrona?

Fragmentation

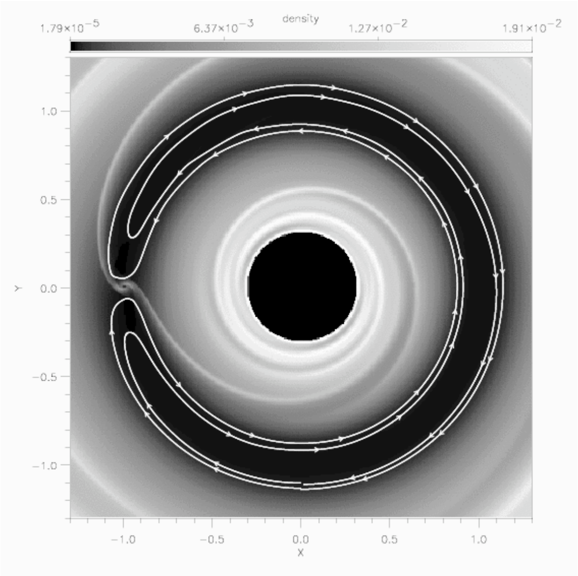
$$Q \sim \left(\frac{n}{10^9\,\mathrm{cm}^{-3}}\right)^{-1}\left(\frac{r}{0.4\,\mathrm{pc}}\right)^{-3}\left(\frac{M_{\mathrm{bh}}}{10^7 M_{\mathrm{Sun}}}\right)$$

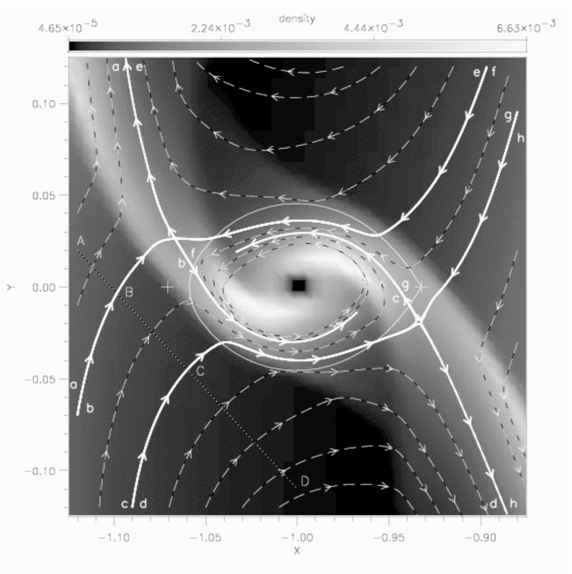
$$M_{\mathrm{Jeans}} \sim 2M_{\mathrm{Sun}}\left(\frac{n}{10^9\,\mathrm{cm}^{-3}}\right)^{-1}\left(\frac{T}{400\mathrm{K}}\right)^{3/2}\left(\frac{r}{0.4\,\mathrm{pc}}\right)^{-3/2}\left(\frac{M_{\mathrm{bh}}}{10^7 M_{\mathrm{Sun}}}\right)^{1/2}$$

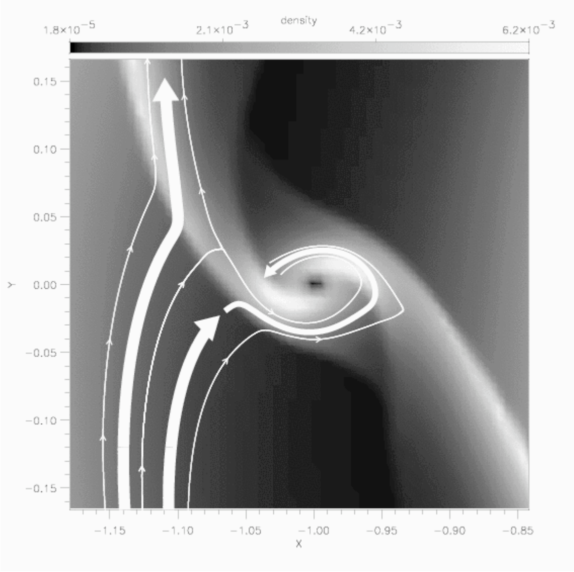


Lufkin et al 2004

Structure of the Roche (Corotation) Annulus







Lubow, Seibert, & Artymowicz 1999

Hill (Roche) radius $R_H \sim r\,(m/M_{bh})^{1/3}$

Growth of Protostars in a Gas Disk

(Kolykhalov & Sunyaev 1980, Shlosman & Begelman 1989, Levin & Beloborodov 2003, Tan & Goodman 2004)

Material arriving into the Roche lobe at the rate:

$$\dot{m} \sim 10^{-4}\,\frac{M_{\rm Sun}}{\rm yr}\left(\frac{m}{2M_{\rm Sun}}\right)^{2/3}\left(\frac{n}{10^{9}{\rm cm}^{-3}}\right)\left(\frac{T}{400{\rm K}}\right)^{1/2}\left(\frac{r}{0.4{\rm pc}}\right)^{2}\left(\frac{M_{\rm bh}}{10^{7}M_{\rm Sun}}\right)^{-2/3}$$

The Roche lobe could accrete an ``isolation mass'':

$$M_{\rm iso} \sim \frac{M_{\rm disk}^{3/2}}{M_{\rm bh}^{1/2}}$$

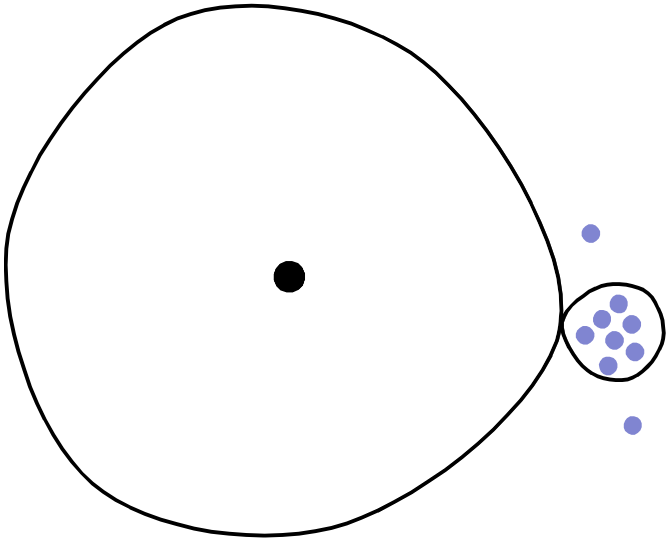
The isolation mass by far exceeds the Jeans mass.
Isolation mass may not be reached if multiple Roche annuli overlap.

Sub-Fragmentation

(MM & Loeb 2004)

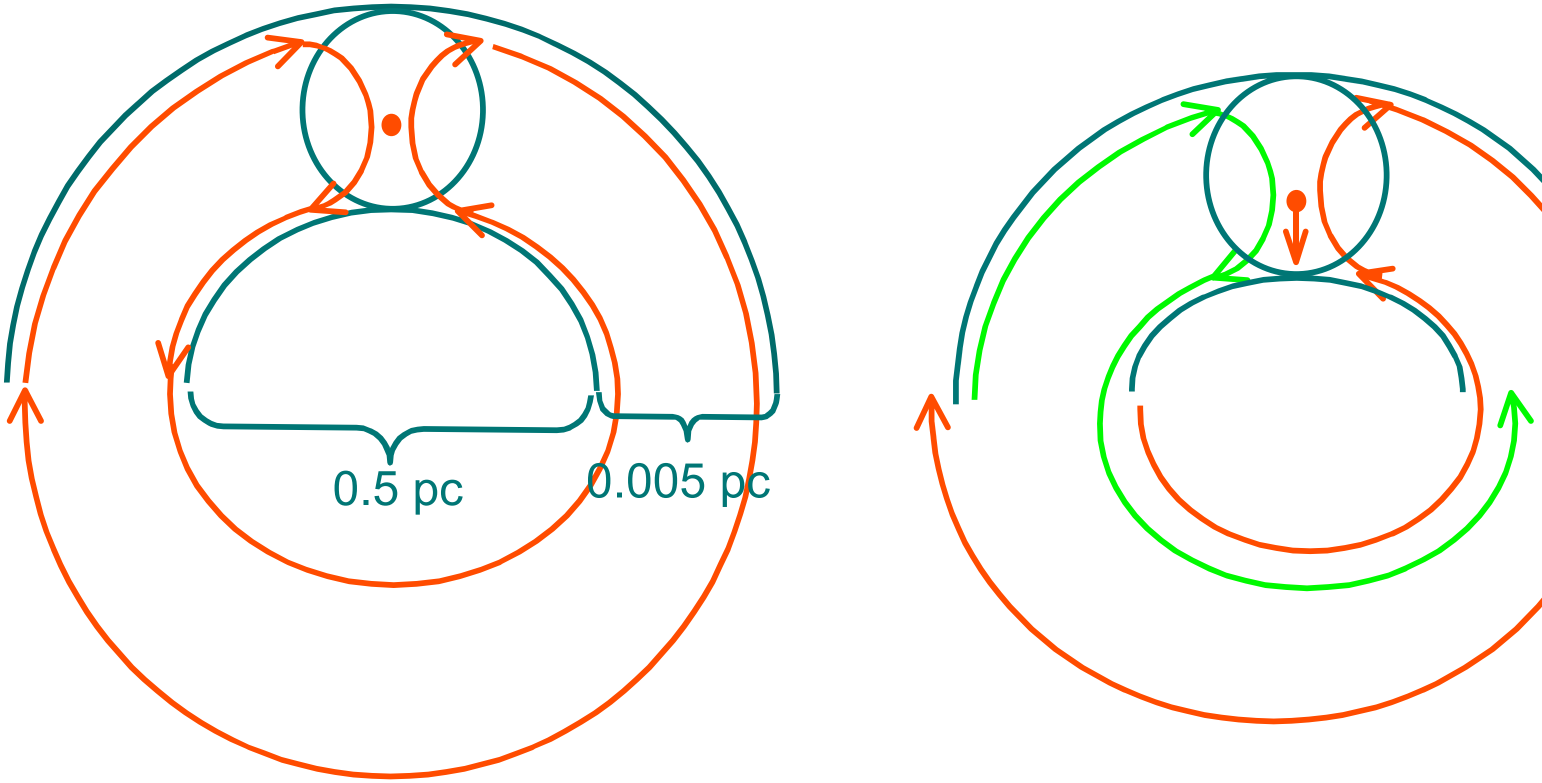
- The “protostar” is fed from an accretion disk of its own
- Protostellar disk spans >4 decades in radius
- As mass is added at the disk’s outer edge, the disk becomes unstable, unless angular momentum transport is efficient
- Transport mechanisms: magnetorotational instability, magnetic braking, winds (magnetized disks), vortices (unmagnetized disks), etc.
- MRI: $a \sim 0.01$ implies $Q \sim 0.01$ at R_H
- MB: $Q_{Roche} < Q_{disk}$
- Conclusion: The protostellar disk is unstable and susceptible to fragmentation!

Origin of IRS-13?



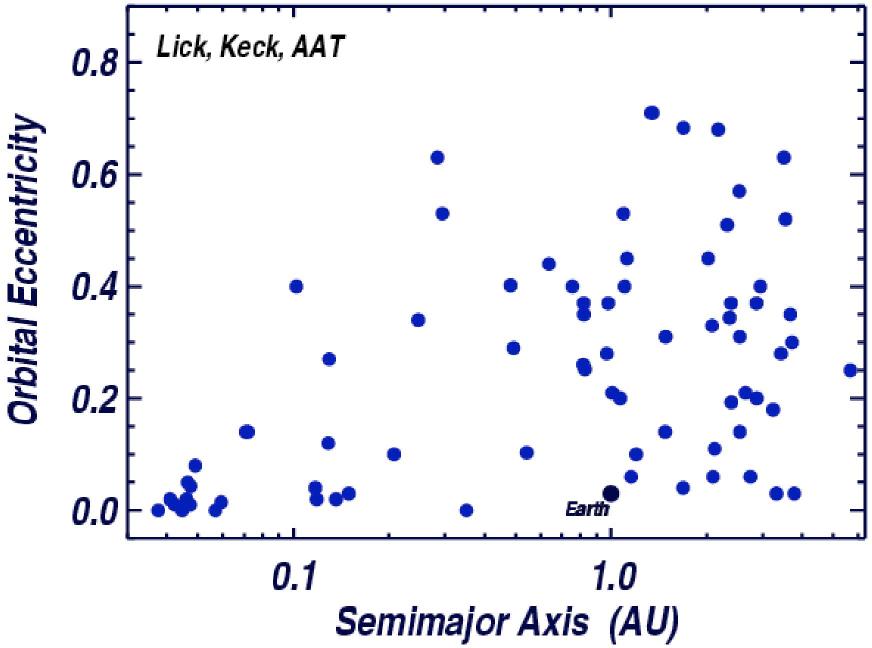
$$t_{\mathrm{shear}} \sim \left(\frac{M}{Nm}\right)^{1/3} t_{\mathrm{orbital}} \qquad t_{\mathrm{evap}} \sim N t_{\mathrm{orbital}}$$

Migration



Eccentricity

- Disk-star interactions
  - mutual excitation of disk and stellar eccentricity
- Star-star interactions
  - scattering (?)
  - secular resonances



Conclusions

- The Galactic center stars could have formed from a transient molecular disk
- Current conditions in the maser nuclei, and those at the Galactic Center, represent consecutive, recurrent phases
- The warm molecular disks that give rise to the maser emission fragment into stellar-size objects, which form mini-clusters. The clusters migrate due to cluster-disk interactions
- Internal dynamics of the clusters can be used to place constraints on the plausibility of this scenario