Sgr A* young massive stars: the first evidence for star formation in AGN disks.

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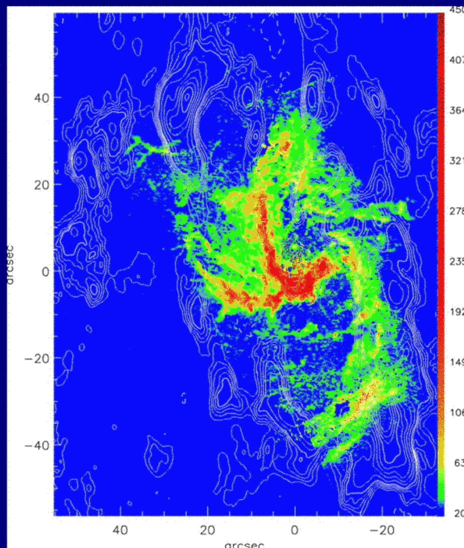
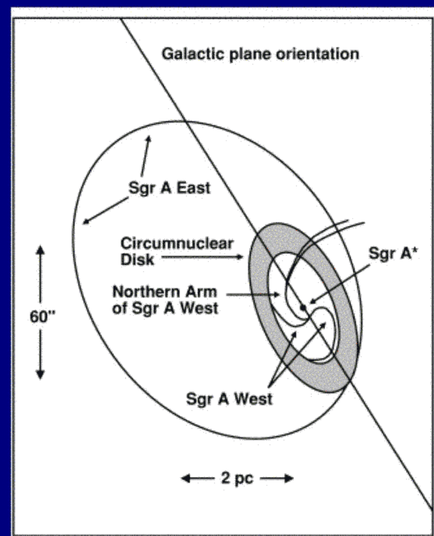
Outline of the talk

- Introduction to Sgr A* for beginners.
- The paradox of youth for high mass stars
  - Infall of a massive cluster model
  - Star formation in a massive disk
- Disk warping constraints
- X-ray emission from YSOs: where is it?
  - Top-heavy IMF for Sgr A* star formation event
- Implications for AGN
- Implications for star formation theories

Sgr A*: AGN number 1

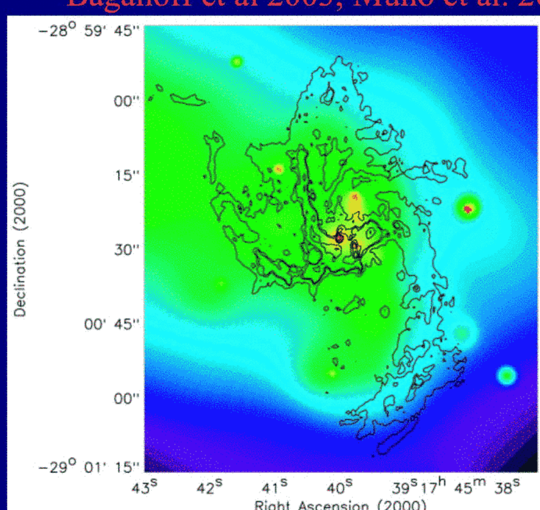


IR (Scoville et al. 2003)



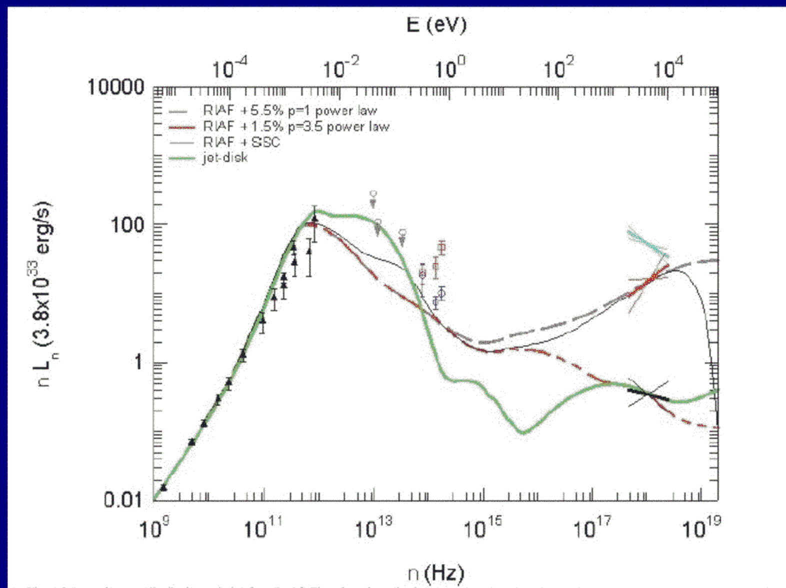
Sgr A* in X-rays

Baganoff et al 2003, Muno et al. 2004



Cold gas can't get rid of its angular momentum;
Hot gas is too hot to be bound

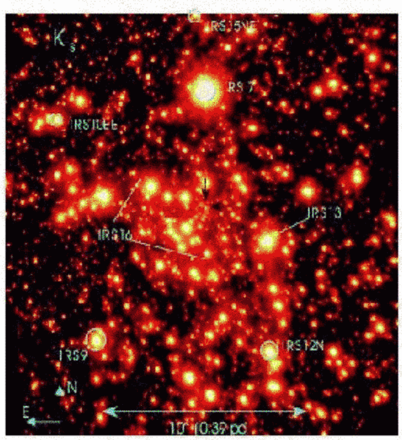
Sgr A*: the miserable AGN.

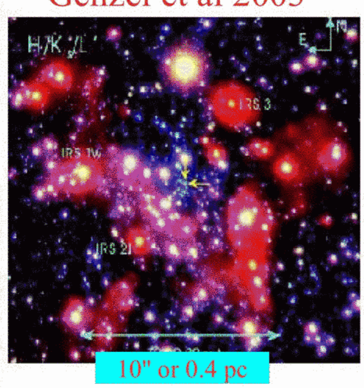


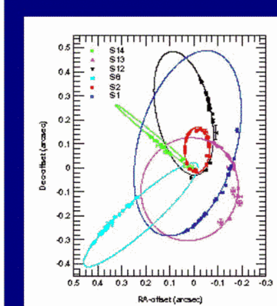
Forget about gas and disks
Think stars

The stars near Sgr A*

Genzel et al 2003







Eisenhauer et al 05

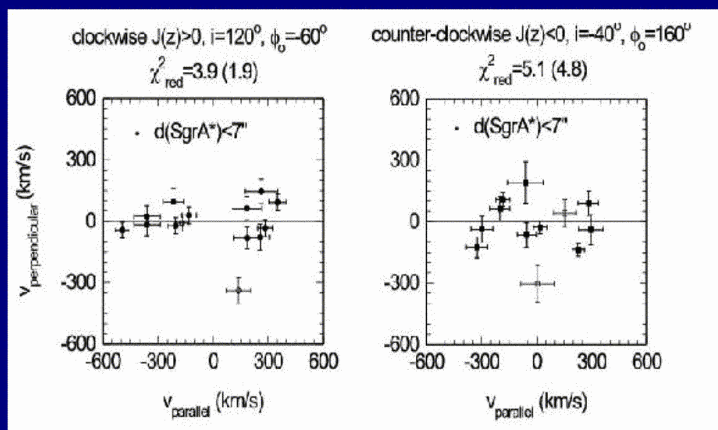
- Individual stellar orbits can be resolved down to ~ 1000 R_S !!!
- M_BH = 3.5 million solar masses (Genzel et al, Ghez et al)

- ***Young (t < few Myr) stars: how did they get within ~ 0.2 parsec of a SMBH? Need n_H > 10^10 particles/cm^3***

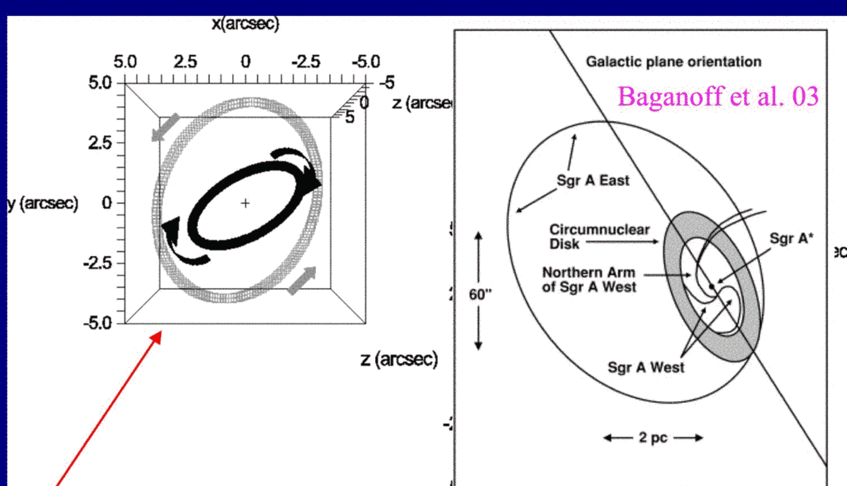
`Outer' young stars: two stellar rings.

$$\chi^2 = \frac{1}{N-1} \Sigma_{i=1}^{N} \frac{(\boldsymbol{n} \cdot \boldsymbol{v}_i)^2}{(n_x \sigma_{xi})^2 + (n_y \sigma_{yi})^2 + (n_z \sigma_{zi})^2}, \qquad (1)$$

- ***Levin & Beloborodov 03, Genzel et al. 2003: The young stars belong to one of the two rings, not alligned with the Galactic plane***



Two young stellar rings



View of the rings on the plane of the sky (Genzel et al. 03)

In situ star formation?

Paczynski 1978, Kolykhalov & Sunyaev 1980, Shlossman & Begelman 1989, Collin & Zahn 1999, Gammie 2001, Goodman et al. 2003

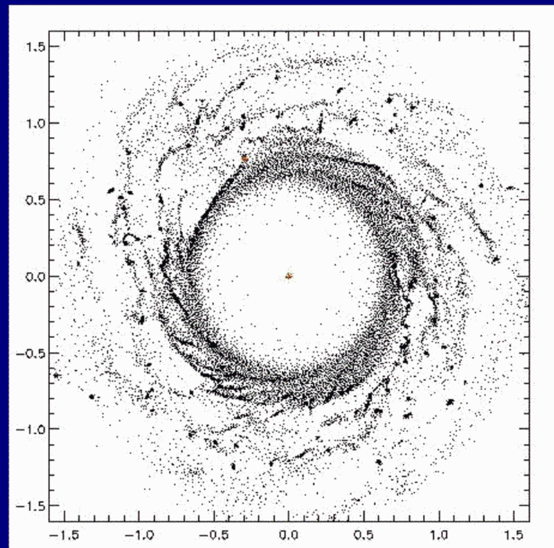
Disks are self-gravitating if

Q = M_bh H / M_disk R < 1

(Toomre 1964)

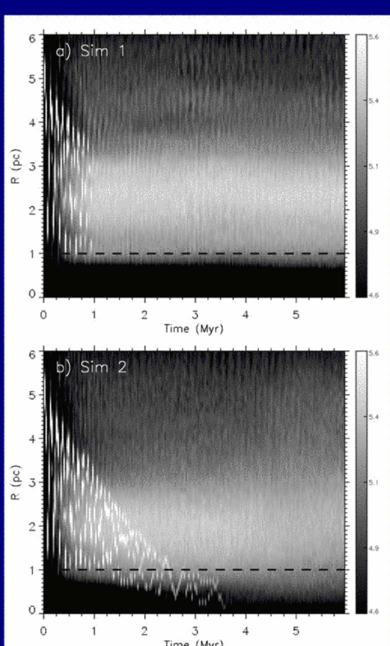
M_disk > M_bh (H/R)

(In addition, efficient cooling, no magnetic fields or turbulent support against gravity)



Gadget run with M_disk = 0.02 M_bh

Infall of a massive cluster



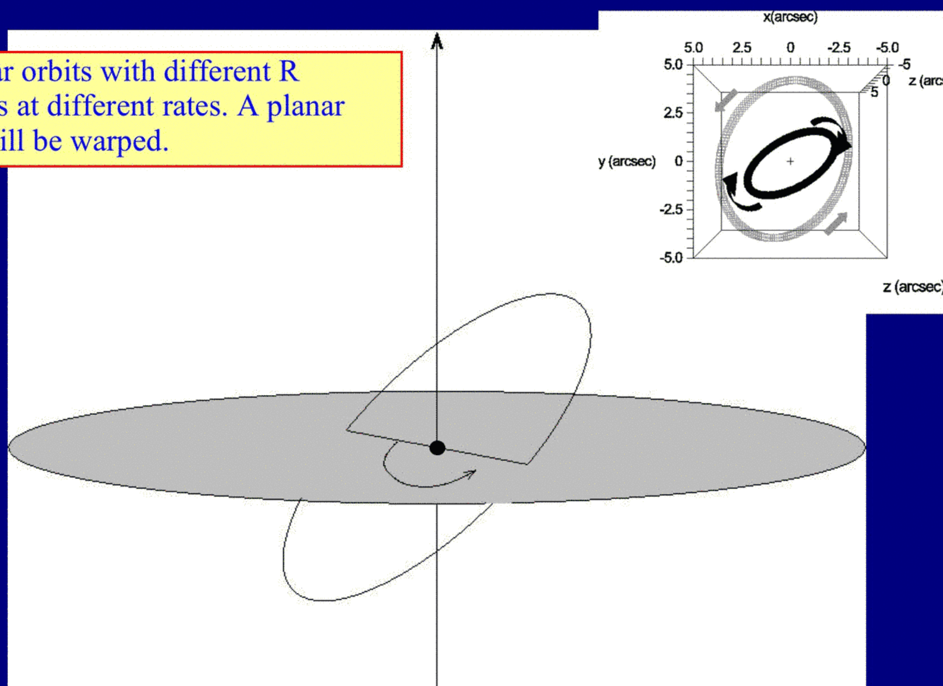
Kim, Figer & Morris 2004

$$\tau_{df} = \frac{1.17}{\ln(0.4N)} \frac{R_i^2 v_c}{G m_c} = 3.1 \times 10^6 R_{30}^2 v_{130} m_6^{-1} \lambda_{10}^{-1} \text{ yr},$$

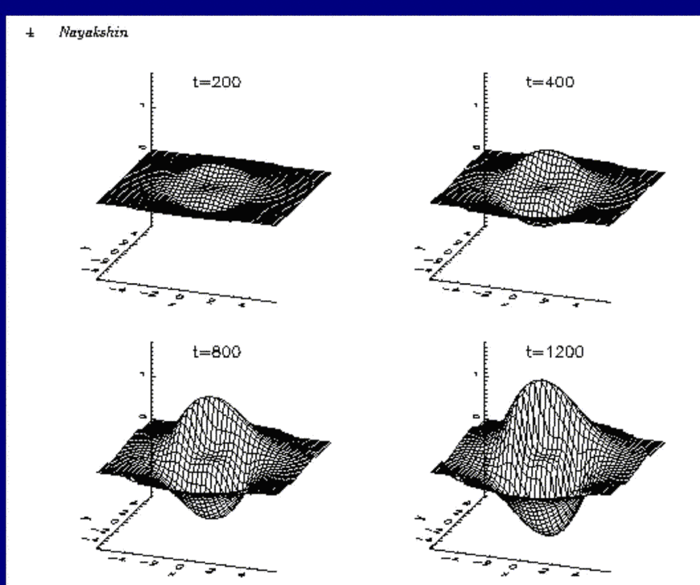
- Need ~ 10^5 to 10^6 M_sun star cluster, to infall rapidly enough (Gerhard 01)
- Need to be within < 30 pc of the GC
- Need to be very compact or would dissolve before reaching the inner parsec.
- Without IMBH cluster is dissolved too early.
- IMBH should be ~ 10^4 M_sun to delay core destruction.
- Two such events are needed

Orbital precession in axisymmetric potential

Circular orbits with different R precess at different rates. A planar disk will be warped.



Warping by a stellar ring



$$\frac{M_r}{M_{BH}} = 0.01$$

Side comment:

Such warped disks could contribute to AGN obscuration (type I / type II division)

(N 2005)

Warping by a stellar ring

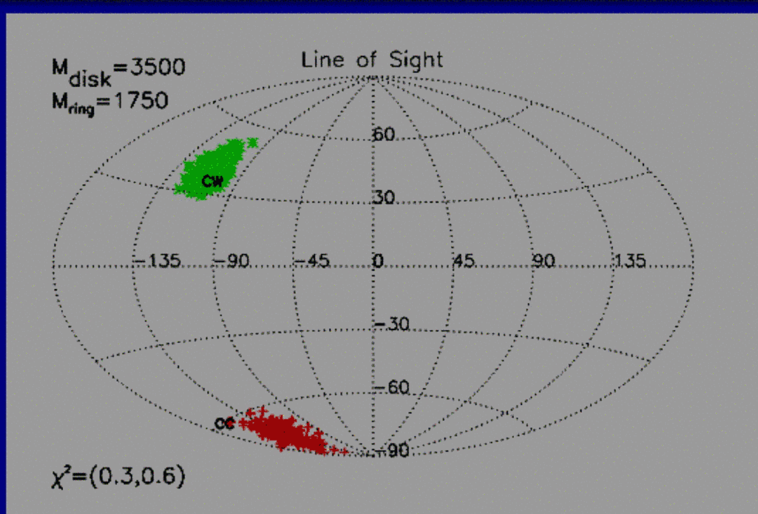
$$\frac{\omega_p}{\Omega_K} \approx -\frac{3M_{\rm ring}}{4M_{\rm BH}} \cos\beta \, \frac{R^3 R_{\rm ring}^2}{\left[R^2 + R_{\rm ring}^2\right]^{5/2}}$$

$$\Delta\phi = \omega_p t \propto \frac{M_{\rm ring}}{M_{\rm BH}} \cos\beta \, \frac{t}{T} \, F(R/R_{\rm ring})$$

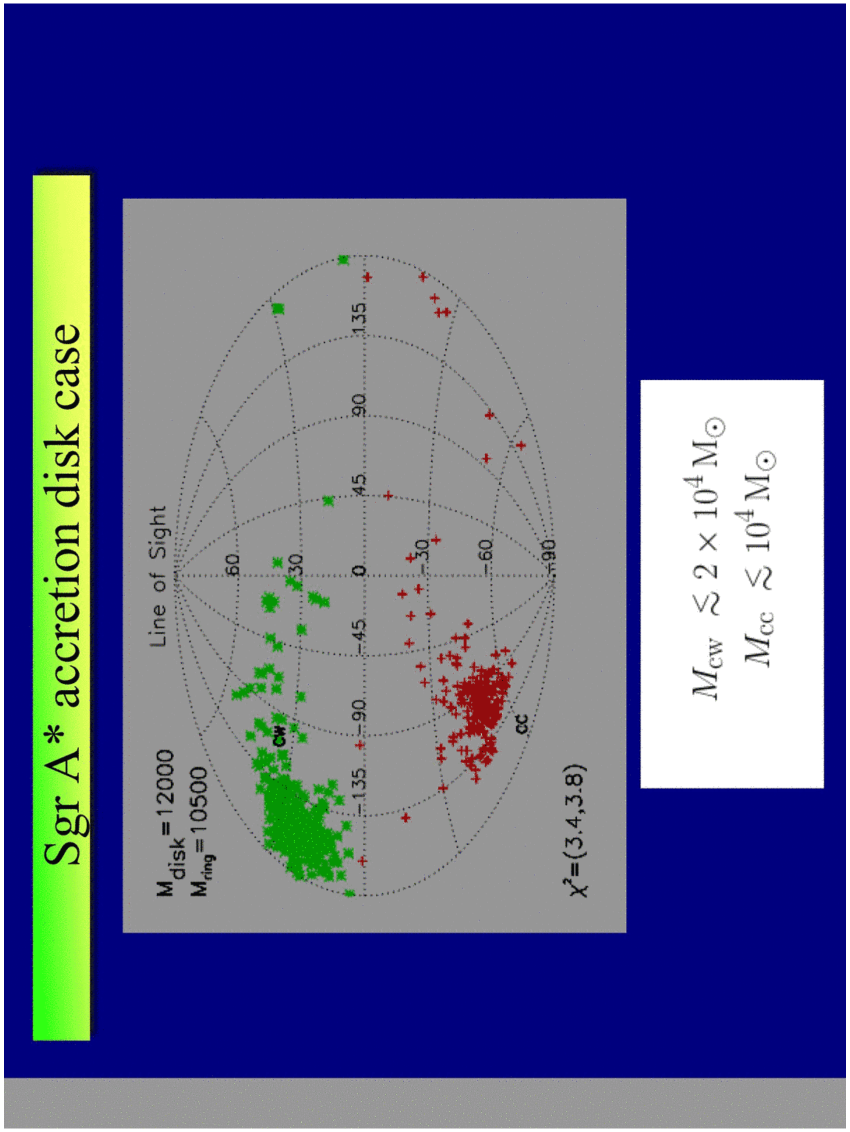
Since $\cos\beta F(R/R_{\rm ring}) < 1$,

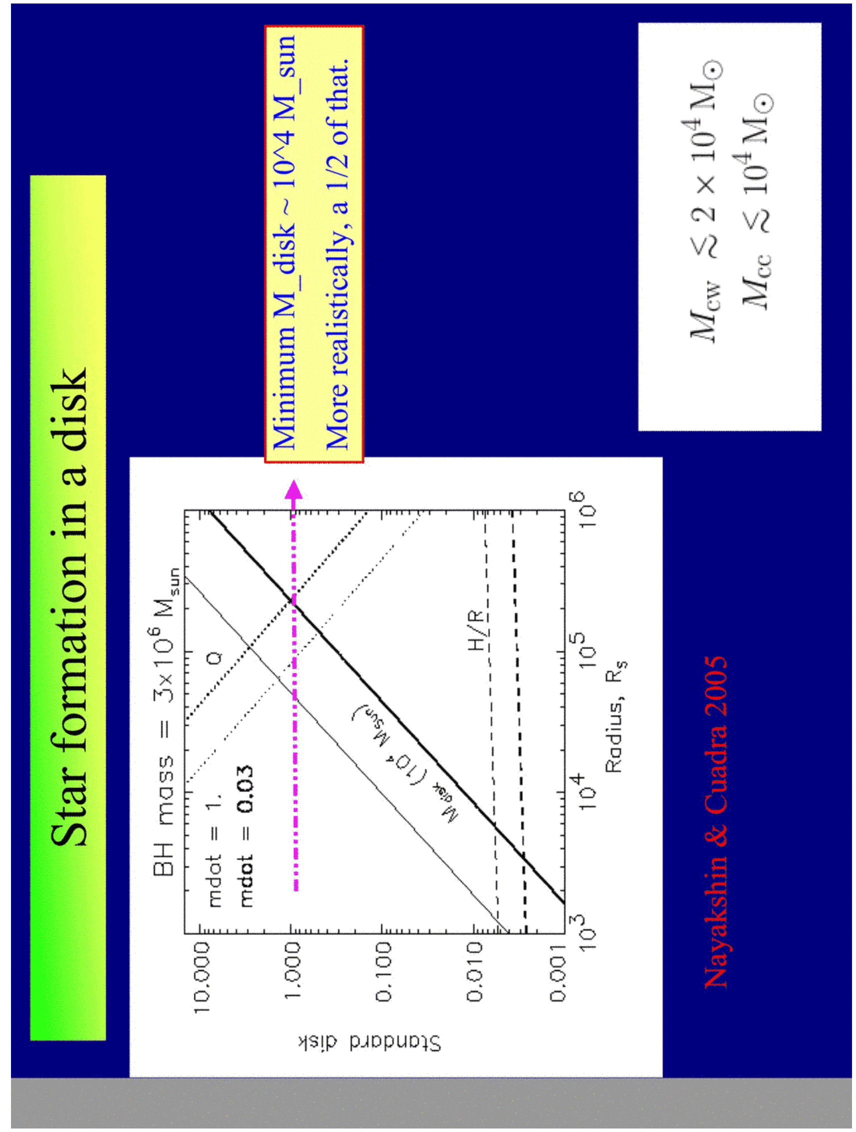
$$\Delta\phi \sim \frac{M_{\rm ring}}{M_{\rm BH}} N_{\rm orb} \sim 10^3 \frac{M_{\rm ring}}{M_{\rm BH}}$$

Sgr A* accretion disk case



N-body simulations with W. Dehnen’s (U of Leicester) code


Sgr A* accretion disk case
Line of Sight
M_disk=12000
M_ring=10500
CW
CC
χ²=(3.4,3.8)
M_cw ≲ 2 × 10^4 M⊙
M_cc ≲ 10^4 M⊙


Star formation in a disk
Minimum M_disk ~ 10^4 M_sun
More realistically, a 1/2 of that.
BH mass = 3×10^6 M_sun
mdot = 1.
mdot = 0.03
Q
H/R
M_disk (10^4 M_sun)
Standard disk
Radius, R_s
M_cw ≲ 2 × 10^4 M⊙
M_cc ≲ 10^4 M⊙
Nayakshin & Cuadra 2005

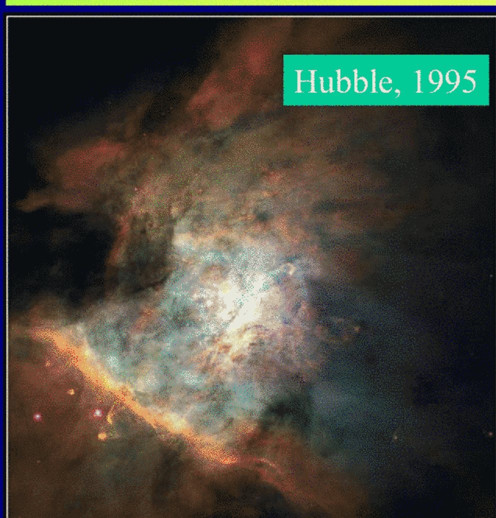
Sgr A* infalling star cluster case

- As stars are peeled of the IMB/cluster, they scatter via close passages into eccentric orbits.
- Levin et al. 2005: e > 0.5 for circular cluster's orbit.

$$M_{\rm cw} \lesssim 8 \times 10^3 \, {\rm M}_\odot$$
$$M_{\rm cc} \lesssim 6 \times 10^3 \, {\rm M}_\odot$$

- If cluster's orbit is eccentric, the limits will be even lower.
- **More "IFs" for the cluster infall model, but it still isn't ruled out!**

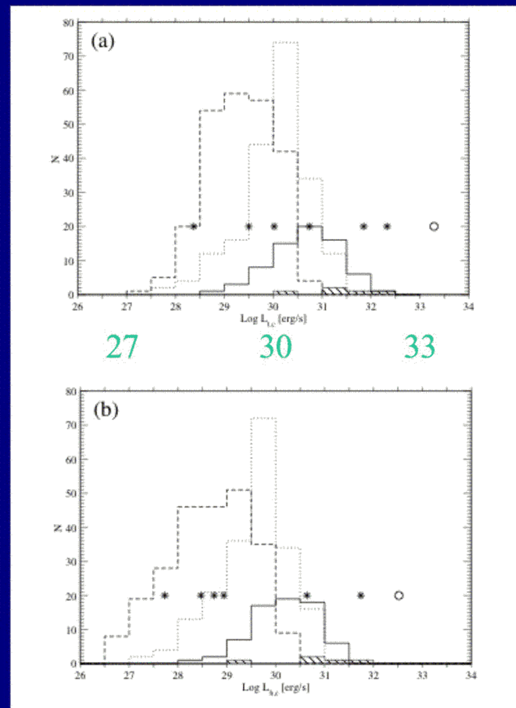
Great Orion Nebula



- *ON has around 2000 young (PMS) stars; M_total ~ 1000 M_sun*
- *Stellar ages are from 0.5 Myears < t < few Myears*
- *0.1 < M_star /M_Sun < 50*
- *ON stellar IMF is close to the "universal" IMF (Hillenbrand 97)*

Orion X-ray emitting stars

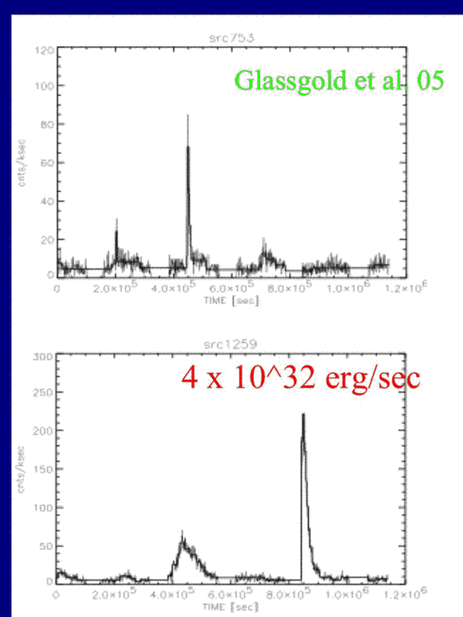
- *Chandra spent ~ 1 Million sec(!) looking at Orion Nebula*
- ***97%** of stars are detected in X-rays*
- *X-ray emission rotationally modulated: magnetic flares on stellar surface, not disk*
- *X-ray luminosity actually decreases when an accretion disk present*
- *L_x/L_bol up to 0.001*



Feigelson et al 05.

Orion X-ray flaring stars

- ***Some sources produce X-ray flares up to 0.1 L_solar !***
- ***Frequency ~ 0.1 %***



...ure 3. X-ray light curves for two COUP sources showing several types ...lares. The second flare for source #1259 (bottom) has a peak luminosity ...$.1 L_{\odot}$, one of the most powerful ever observed from a YSO.

Where are the YSOs ?

- *Chandra spent about 1 Msec on Sgr A* as well*
- ***If IMF is standard**, then L_exp ~ 10^3 L_Orion*

$$L_{\rm exp} \approx 10^{36}\,\frac{M_{\rm cl}}{10^6\,{\rm M}_\odot}\quad {\rm erg/sec}\ . \qquad (1)$$

$$L_{\rm diff} \simeq 3.5\times 10^{33} R_{\rm cl}^2\quad {\rm erg/sec}\ . \qquad (2)$$

- ***Could be hidden in a 30 parsec disk***
- ***But what about X-ray flares?***
- ***Muno et al. 2004 -- no more than ~ 5000 YSO***
- ***If IMF is top-dominated, there should be ~ 10^4 -10^5 OB stars, but there are only hundreds***
- ***Cluster model is ruled out***

YSOs inside the stellar disks.

- ***For a standard IMF,***

$$L_{\rm exp} \approx 2.5\times 10^{34}\,\frac{M_{10}}{3000}\quad {\rm erg/sec}\ .$$

The limit from observations is

$$L_{\rm stellar} \lesssim 10^{33}\,\frac{R_{\rm disk}^2}{(5")^2}\quad {\rm erg/sec}\ .$$

- ***Low mass stars should be deficient by at least a factor of 10***
- ***Need $\Gamma < 2$ (Salpeter's IMF has $\Gamma = 2.35$)***

What does this mean?

- ***Was the Jeans mass very high? -- No.***

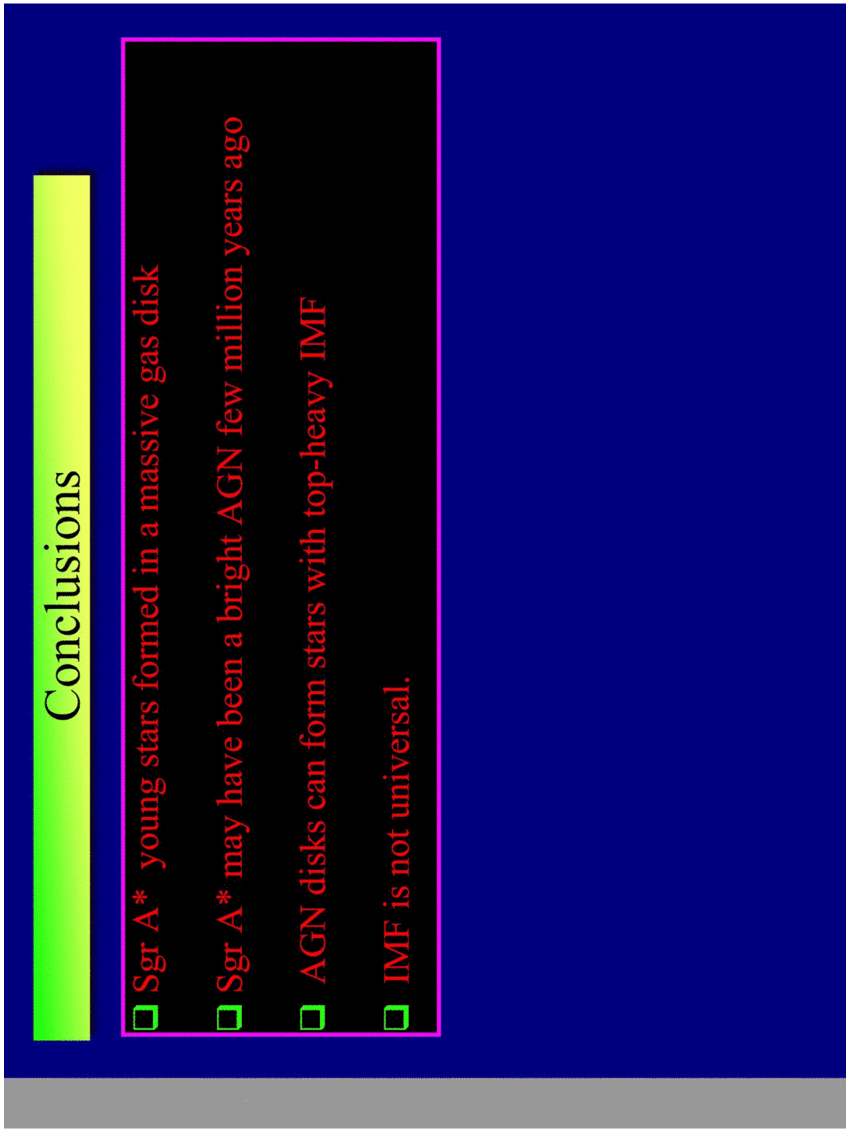
$$M_J \simeq \frac{\dot{M}}{3\pi\alpha\Omega}$$
$$= 1.8\ M_\odot \left(\frac{\alpha}{0.3}\right)^{-1} \frac{\dot{M}c^2}{L_{\rm Edd}} \left(\frac{M}{3\times10^6\ M_\odot}\right)^{0.5} \left(\frac{R}{0.2\ {\rm pc}}\right)^{1.5},$$

- ***Mergers of low mass stars? Gas assisted, probably.***
- ***Direct gas accretion? Likely.***

- ***IMF is not universal. It is a function of enviroment, at least in extreme conditions near SMBHs.***

Implications for AGN

- ✓ Star formation in AGN disks: reality.
- ✓ Not all AGN disks feed SMBHs.
- ✓ If IMF of stars is top-heavy, stellar feedback into the disk is stronger than thought. Then
  - ✓ important for AGN torii (Krolik & Begelman, Wada & Norman..)
  - ✓ fast metal enrichment of AGN disks
  - ✓ many stellar mass black holes in the inner parsec (GW radiation)


Conclusions
Sgr A* young stars formed in a massive gas disk
Sgr A* may have been a bright AGN few million years ago
AGN disks can form stars with top-heavy IMF
IMF is not universal.