Disruption of a Young Dense Cluster at the Galactic Center

Resolving the Youth Paradox

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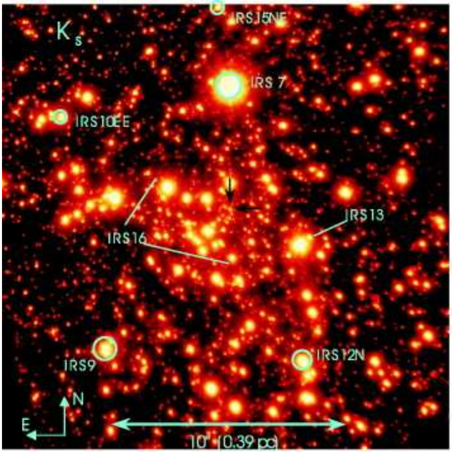
Outline

- Young Stars near the Galactic Center
- Monte Carlo Simulations of Young Dense Star Clusters and Formation of an Intermediate Mass Black Hole by Runaway Collisions
- Inspiral of a Young Dense Cluster to the Galactic Center

Central Parsec



- Young, He I line emission stars
- ~3-7 Myr old (?)
- Rotating disks and clustering (IRS13E)

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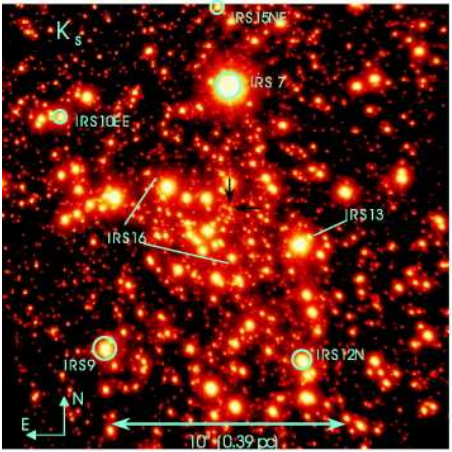

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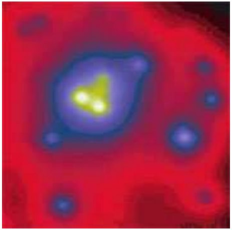
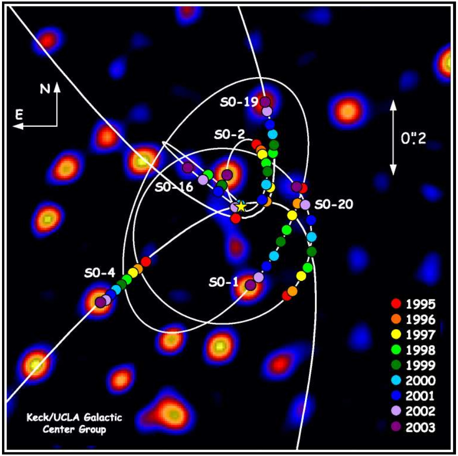


Central Cluster



- Somewhat older but still young ($\lesssim 10\,\mathrm{Myr}$) stars
- Approach as close as 100 AU to the Galactic center black hole
- Higher than normal eccentricities

The Problem

Observations of Young Stars at the Galactic Center:

- The environment is too hostile for stars to form there
- Stars are too young to form somewhere else and migrate there
  $\Rightarrow$ a paradox of youth
- Peculiar dynamical properties

The Solution?

- *In situ* formation, including infall of two clouds
- They are not young at all, including rejuvenation
- Accelerated inspiral via a cluster

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- *In situ* formation, including infall of two clouds
- They are not young at all, including rejuvenation
- Accelerated inspiral via a cluster
  that contains an intermediate mass black hole

Properties

- *Collisional* dense star clusters
- Relaxation plays an important role
- Systems are in quasi-equilibrium
- Initial numbers of stars easily reach hundreds of thousands

Assumptions

- Spherical symmetry
- Quasi-equilibrium $\Leftrightarrow$ Relaxation is the dominant process

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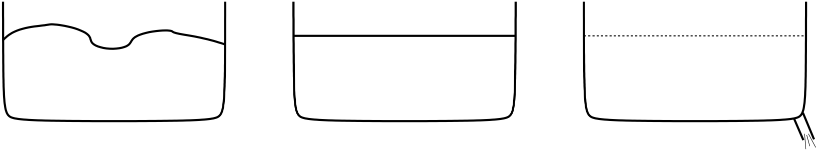
- All stars are represented as *spherical shells*
- Coordinate is represented by r
- Velocity is represented by v_r and v_t
- $r, v_r, v_t \Leftrightarrow E, A$
- Fast calculation of potential
- Fast calculation of orbits, $r_{\mathrm{min}}, r_{\mathrm{max}}$

Assumptions

- Spherical symmetry
- Quasi-equilibrium ⇔ Relaxation is the dominant process

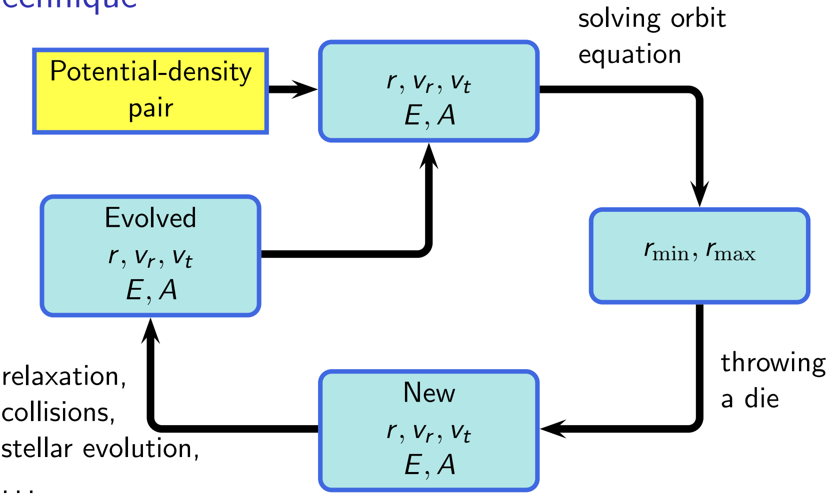


Initial violent relaxation

Equilibrium

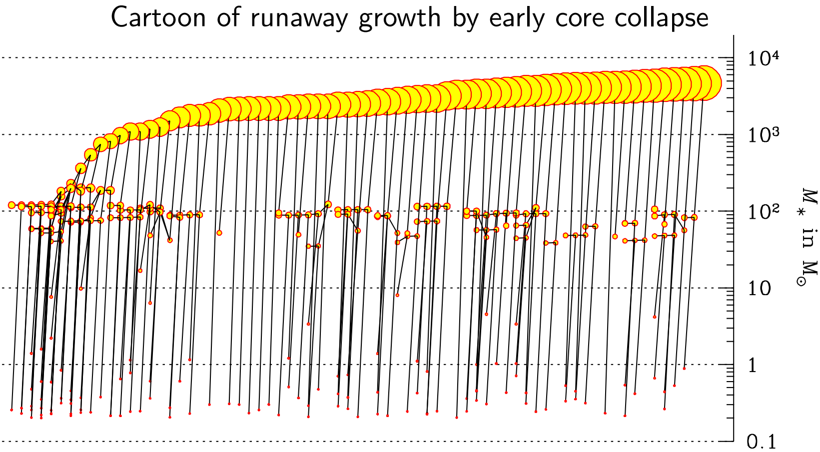
Evolution with relaxation

Technique


Potential-density pair
r, v_r, v_t
E, A
solving orbit equation
$r_{\min}, r_{\max}$
throwing a die
New
r, v_r, v_t
E, A
relaxation,
collisions,
stellar evolution,
...
Evolved
r, v_r, v_t
E, A

IMBH formation

- For realistic initial mass function ($m_{\rm max}/<m>\sim 100$) core collapse will be very rapid
- If $t_{\rm cc} < 3\,{\rm Myr}$ runaway collisions will take place
- These will lead to a massive ($m >> 100\,M_\odot$) star which can turn into an intermediate mass black hole



- $M_{\mathrm{collapsed\,core}} \sim 0.002\,M_{\mathrm{cluster}}$

Formulation

Dynamical friction in Galaxy:

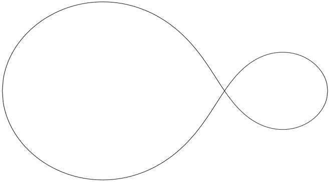
$$\frac{dR}{dt} = -2m_{\mathrm{clu}} \ln \Lambda \frac{\alpha\chi}{\alpha+1} \left(\frac{G}{A}\right)^{1/2} R^{-(\alpha+1)/2}$$

$$\text{with} \quad M(R) = AR^{\alpha}$$

or in dimensionless form:

$$\frac{d\xi}{d\tau} = \frac{4\pi\alpha}{\alpha+1} \chi \ln \Lambda \frac{m_{\mathrm{clu}}}{M_0} \xi^{-(\alpha+1)/2}$$

Formulation II



Tidal disruption:

- Evaporation from the cluster
- Adjusting the tidal boundary:

$$r_J = \left[\frac{m_J}{2M(R)}\right]^{1/3} R$$

Point-mass Approximation

Assumption:

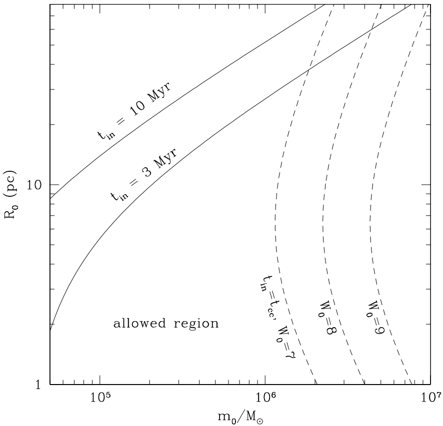
- No mass loss from tidal boundary

Conditions:

- Fast inspiral: $t_{\rm in} < 3\text{--}10\,\mathrm{Myr}$
- Fast collapse: $t_{\rm cc} < t_{\rm in}$

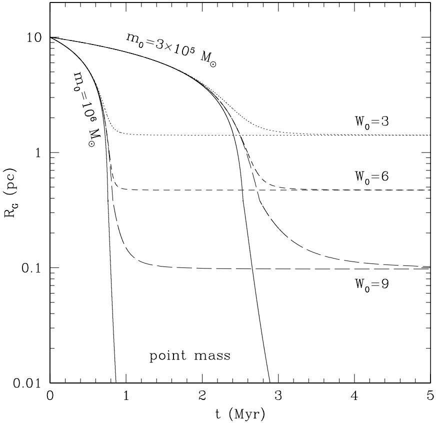
Point-mass Approximation

Constraints:

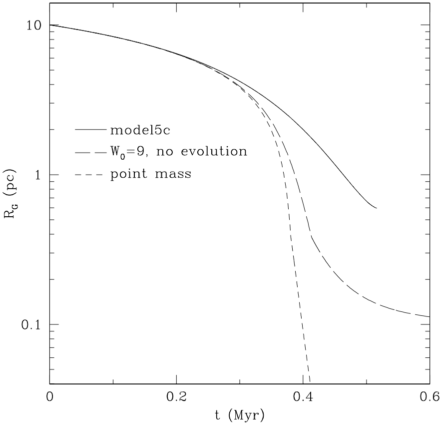


Static Cluster Approximation

No change in structure during inspiral



Comparison with Simulation



- Approximations provide necessary but not sufficient conditions
- Approximations cannot provide star demographics

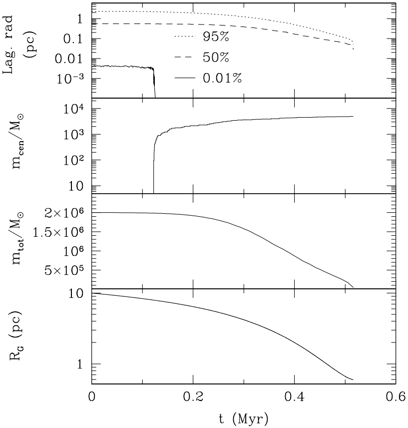
Inspiral and Disruption

Simulations with $W_0 = 9$

m_0 $(M_\odot)$	R_0 (pc)	$R_{\rm dis}$ (pc)	$t_{\rm dis}$ (Myr)	$m_\bullet$ $(M_\odot)$
3×10^6	20	1.23	1.10	5500
3×10^6	10	0.56	0.35	4500
3×10^6	5	0.28	0.14	3000
2×10^6	20	1.20	1.70	6000
2×10^6	10	0.60	0.52	4900
2×10^6	5	0.33	0.20	4200
10^6	20	1.89	3.23	4700
10^6	10	0.76	1.04	3500
10^6	5	0.43	0.34	3600
5×10^5	20	3.14	6.50	2900
5×10^5	10	1.26	1.95	2700
3×10^5	20	4.18	11.0	1900
3×10^5	10	1.91	3.04	2000
2×10^6	30	1.96	3.54	6800
2×10^6	60	5.17	13.8	6800
2×10^6	50	3.81	9.63	6600

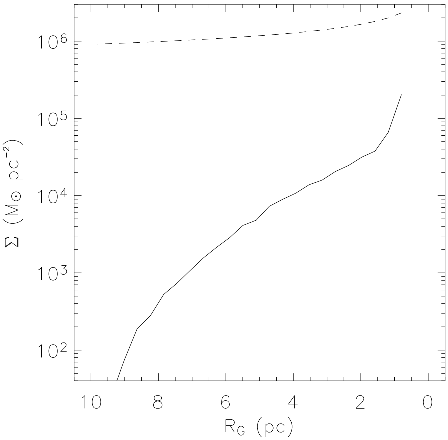
- It is possible to reach the inner parsec
- It is not possible to reach 0.1 pc with dynamical friction
- High concentrations ($W_0 \gtrsim 6$) are necessary
- Large masses ($m_0 \gtrsim 10^6\, M_\odot$) are necessary

Inspiral and Disruption II



- A King model with $W_0 = 9$
- $m_0 = 2 \times 10^6\, M_\odot$, $R_0 = 10\,\mathrm{pc}$
- $t_{\rm dis} = 0.5\,\mathrm{Myr}$, $R_{\rm dis} = 0.6\,\mathrm{pc}$, $m_{\rm collapsed\ core} = 5000\, M_\odot$

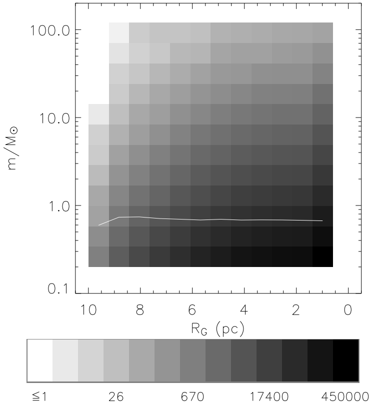
Stars Left Behind: Surface Density

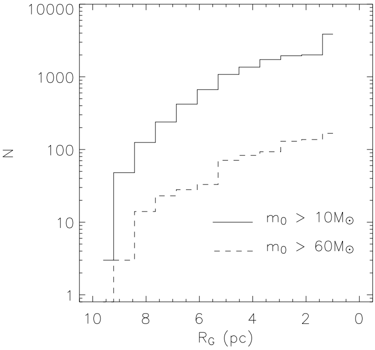


- The remnants of the cluster will not be detectable

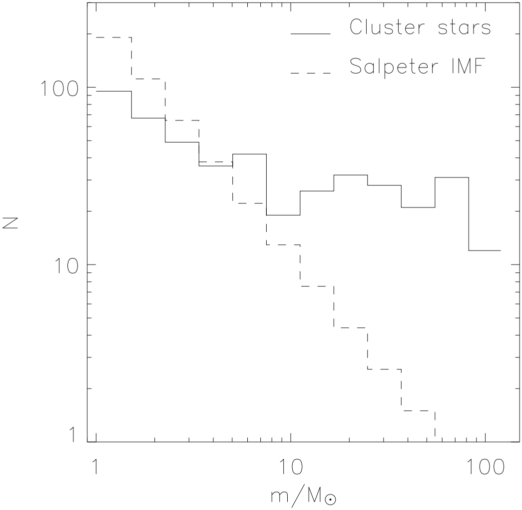
Stars Left Behind: Masses

Heavy stars near the center:





Disruption and Retained Cusp



- Heaviest stars are retained in the cluster
- Density is higher than the background
- Velocity dispersion is lower than the background
  ⇒ clumping

Conclusions

- It is possible to bring a star cluster from $R_0 \gtrsim 10\,\mathrm{pc}$ to $R_{\mathrm{dis}} \lesssim 1\,\mathrm{pc}$ in $\lesssim 3\,\mathrm{Myr}$.
- This requires $m_0 \gtrsim 10^6\,M_\odot$ and $W_0 \gtrsim 6$.
- Heaviest stars are deposited closest to the center of the Galaxy.
- Clusters that are concentrated enough not to be disrupted will undergo core collapse and may form an IMBH

Future Work

- Evolution of the retained cusp,
- Dynamics of the IMBH, and
- The inner 0.1 pc stars

still need quantitative analysis

End of talk.
The following is additional material.

Formation of an Intermediate Mass Black Hole by Runaway Collisions

- Large mass difference ⇒ mass segregation
- Increased density ⇒ dynamical instability
- Rapid core collapse ⇒ runaway collisions

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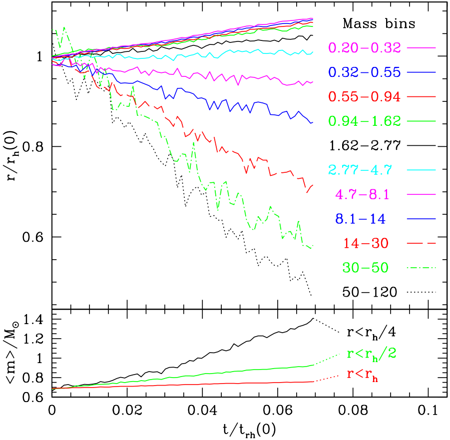
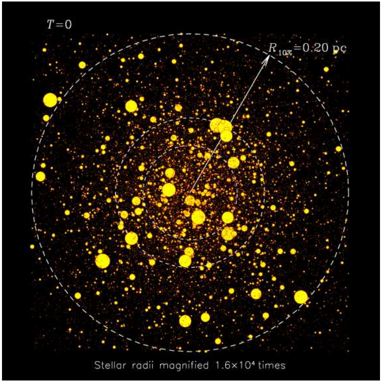
- Large mass difference ⇒ mass segregation
- Increased density ⇒ dynamical instability
- Rapid core collapse ⇒ runaway collisions
  if core collapse is faster than stellar evolution

Dynamical Friction

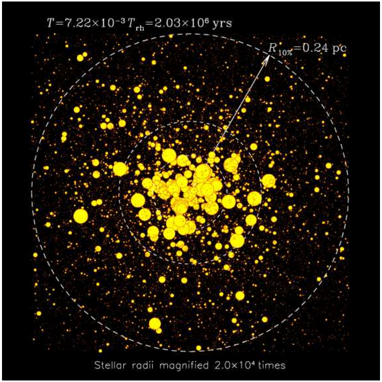
Evolution of half-mass radii:



Accumulation of Masses at the Center



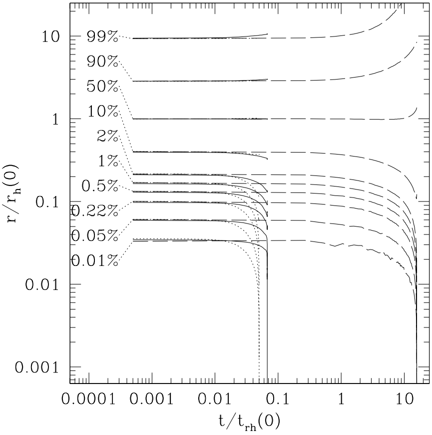
Initial Conditions



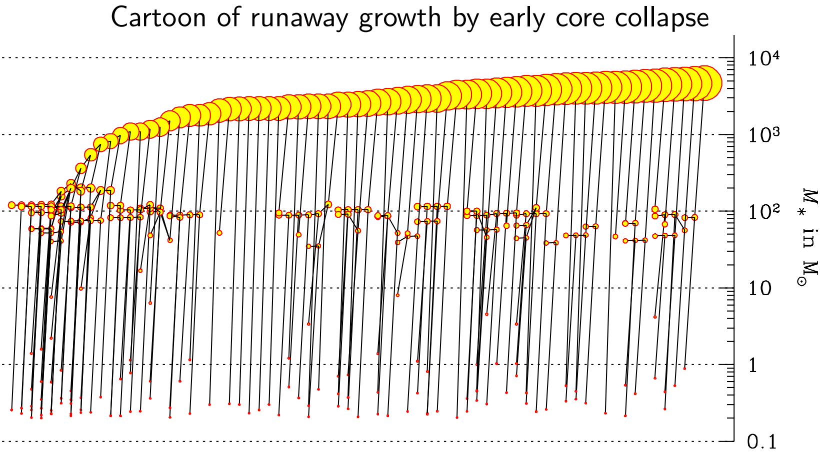
After 2 Myr

Figures courtesy of Marc Freitag

Comparison with single mass cluster



- $t_{cc} \sim 0.15\, t_{rc}$
- Faster by two orders of magnitude
- Independent of structure
- "Independent" of initial mass function



- $M_{\text{collapsed core}} \sim 0.002\, M_{\text{cluster}}$

Monte Carlo Method

Basics:

- Hénon, M. 1971, Ap&SS, 13, 284
- Hénon, M. 1971, Ap&SS, 14, 151
- Hénon, M. 1973, Dynamical Structure and Evolution of Stellar Systems, 183
- Hénon, M. 1975, IAU Symp. 69: Dynamics of the Solar Systems, 69, 133

MIT/NU code:

- Joshi, K. J., Rasio, F. A., & Portegies Zwart, S. 2000, ApJ, 540, 969
- Joshi, K. J., Nave, C. P., & Rasio, F. A. 2001, ApJ, 550, 691
- Fregeau, J. M., Gürkan, M. A., Joshi, K. J., & Rasio, F. A. 2003, ApJ, 593, 772
- Gürkan, M. A., Freitag, M., & Rasio, F. A. 2004, ApJ, 604, 632

Freitag-Benz code:

- Freitag, M. & Benz, W. 2001, A&A, 375, 711
- Freitag, M. & Benz, W. 2002, A&A, 394, 345

See also works by Giersz and Stodolkiewicz.

IMBHs in Star Clusters

Observations:

- Gerssen, J., van der Marel, R. P., Gebhardt, K., Guhathakurta, P., Peterson, R. C., & Pryor, C. 2002, AJ, 124, 3270
- Gerssen, J., van der Marel, R. P., Gebhardt, K., Guhathakurta, P., Peterson, R. C., & Pryor, C. 2003, AJ, 125, 376
- Gebhardt, K., Rich, R. M., & Ho, L. C. 2002, ApJ, 578, L41 Maillard, J. P., Paumard, T., Stolovy, S. R., & Rigaut, F. 2004, A&A, 423, 155

IMBHs in Globular Clusters Rebuttal:

- Baumgardt, H., Hut, P., Makino, J., McMillan, S., & Portegies Zwart, S. 2003, ApJ, 582, L21
- Baumgardt, H., Makino, J., Hut, P., McMillan, S., & Portegies Zwart, S. 2003, ApJ, 589, L25

IMBHs in Star Clusters (cont.)

IMBHs and Cluster Structure:

- Baumgardt, H., Makino, J., & Ebisuzaki, T. 2004, ApJ, 613, 1133
- Baumgardt, H., Makino, J., & Ebisuzaki, T. 2004, ApJ, 613, 1143

Formation of an IMBH by Runaway:

- Portegies Zwart, S. F. & McMillan, S. L. W. 2002, ApJ, 576, 899
- Rasio, F. A., Freitag, M., & Gürkan, M. A. 2004, Coevolution of Black Holes and Galaxies, 138
- Gürkan, M. A., Freitag, M., & Rasio, F. A. 2004, ApJ, 604, 632
- Baumgardt, H., Hut, P., Makino, J., & McMillan, S. L. W. 2004, Nature, 428, 724

Young stars at the Galactic Center

Observations:

(This is the most incomplete list since [a] There are a very large number of observation papers [b] I am not an observer myself)

- Krabbe, A., et al. 1995, ApJ, 447, L95
- Najarro, F., Krabbe, A., Genzel, R., Lutz, D., Kudritzki, R. P., & Hillier, D. J. 1997, A&A, 325, 700
- Genzel, R., Pichon, C., Eckart, A., Gerhard, O. E., & Ott, T. 2000, MNRAS, 317, 348
- Ghez, A. M. 2003, GCNews Invited Review "Recent Advances Made with a Decade of Diffraction-Limited Data From the W. M. Keck 10 meter Telescopes", at: `http://www.aoc.nrao.edu/ gcnews/gcnews/Vol.17/article2.shtml` last checked on November 17, 2004.
- Ghez, A. M., et al. 2003, ApJ, 586, L127
- Genzel, R., et al. 2003, ApJ, 594, 812
- Maillard, J. P., Paumard, T., Stolovy, S. R., & Rigaut, F. 2004, A&A, 423, 155

Scenarios

Various Scenarios:

- Levin, Y. & Beloborodov, A. M. 2003, ApJ, 590, L33
- Alexander, T. & Morris, M. 2003, ApJ, 590, L25
- Genzel, R., et al. 2003, ApJ, 594, 812
  (This contains a review of various scenarios)

Cluster Inspiral:

- Gerhard, O. 2001, ApJ, 546, L39
- Portegies Zwart, S. F., McMillan, S. L. W., & Gerhard, O. 2003, ApJ, 593, 352
- McMillan, S. L. W. & Portegies Zwart, S. F. 2003, ApJ, 596, 314
- Kim, S. S. & Morris, M. 2003, ApJ, 597, 312
- Kim, S. S., Figer, D. F., & Morris, M. 2004, ApJ, 607, L123
- Gürkan, M. A., & Rasio, F. A. 2004, in IAU Symposium 222: The interplay among Black Holes, Stars and ISM in Galactic Nuclei, eds. T. Storchi Bergmann, L. C. Ho and H. R. Schmitt (Cambridge: Cambridge Univ. Press), in press, `http://www.astro.northwestern.edu/~ato/publications/iau222pos1/`