The Origin of the Young Stars in M31

P.C., Ruth Murray-Clay, Eliot Quataert, Eugene Chiang

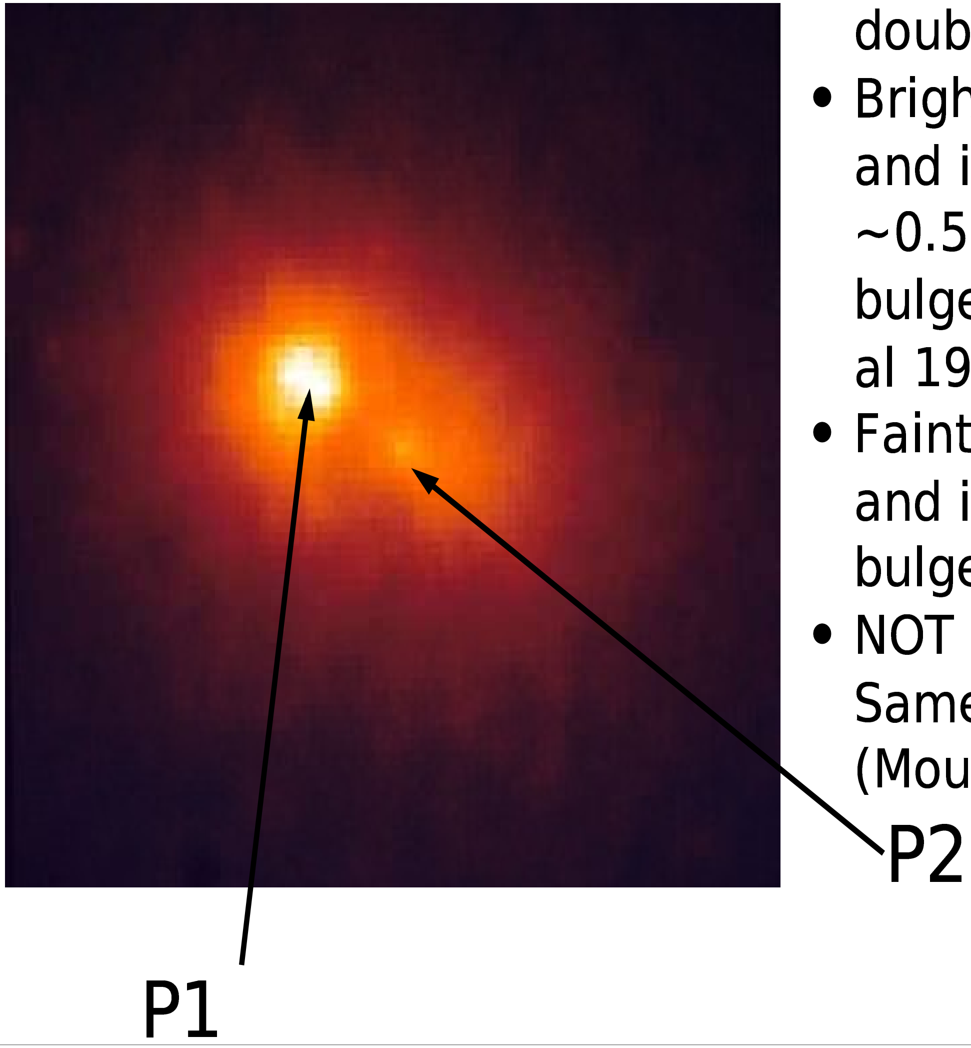
ArXiv:0704.3831

Outline

- The double nuclei of M31
  - Tremaine (95)'s model for the double nuclei
    - Double nuclei is made of an eccentric disk of old stars.
  - Surprise! Young stellar disk around the SMBH similar to the Galactic Center (GC)
- Our model: the eccentric disk determines the structure of the young stellar disk
  - Analogy with binary Roche-filling systems
    - The non-axisymmetric potential of the eccentric stellar disk determines the radial extent of the young stars
  - Stellar winds from the eccentric disk supply the gas which generates the young stars
  - Other galactic nuclei (?)
- Conclusions

The Double Nuclei of M31

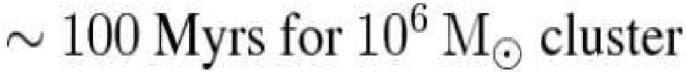
HST image from Lauer et al 1993



- The nucleus of M31 is double
- Brighter nucleus is P1 and is displace by ~0.5" (~2 pc) from bulge center (Lauer et al 1993)
- Fainter nucleus is P2 and is roughly at the bulge center
- NOT due to dust. Same structure in IR (Mould et al 1989)

What is the Double Nuclei?

- Cannot be star clusters!
  - dynamical friction time is too short (Tremaine 1995).

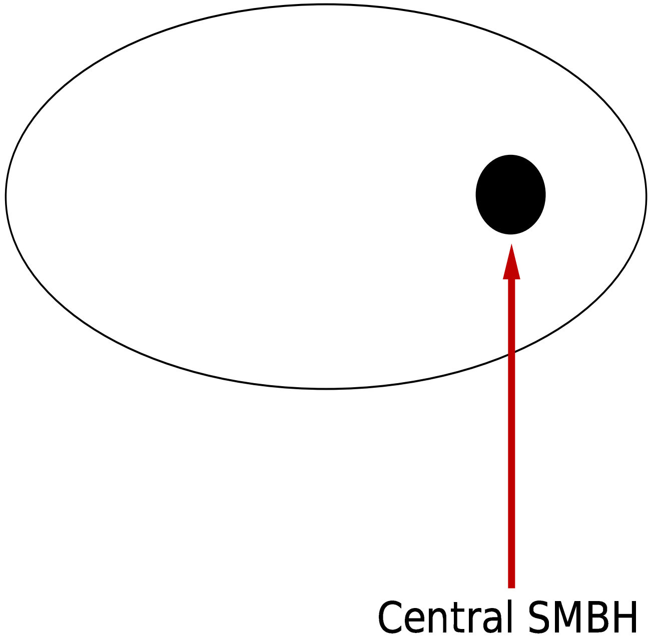


~ 100 Myrs for 10^6 $M_\odot$ cluster

- Tremaine (1995) proposed that the double nuclei is the result of a eccentric disk of stars.

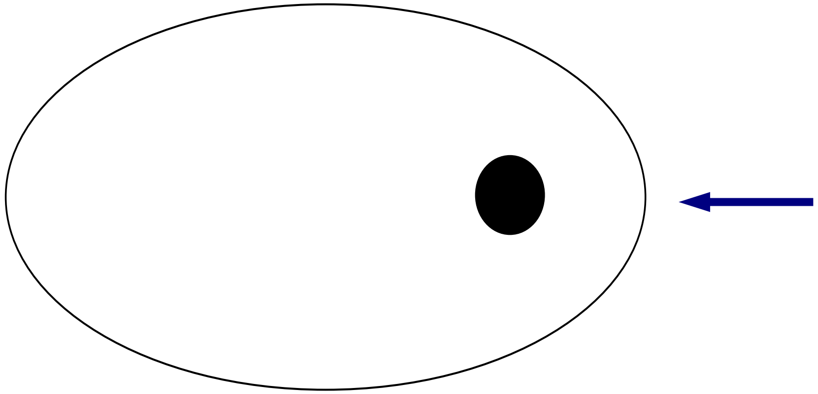
Eccentric Stellar Disk Model

- Suppose a number of stars are orbiting in an elliptical orbit.
- Line density of stars scales like ~1/v ~ $\sqrt{r}$



Eccentric Stellar Disk Model

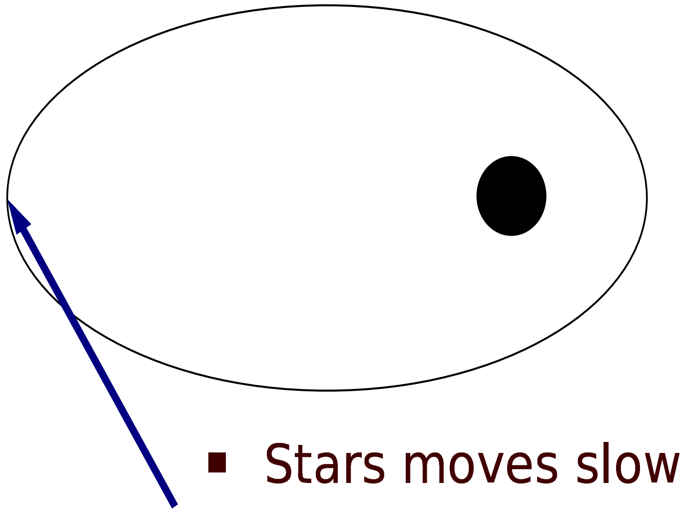
- Suppose a number of stars are orbiting in an elliptical orbit.
- Line density of stars scales like ~1/v ~



- Stars move quickly through periapse.
- Reduced line density of stars.

Eccentric Stellar Disk Model

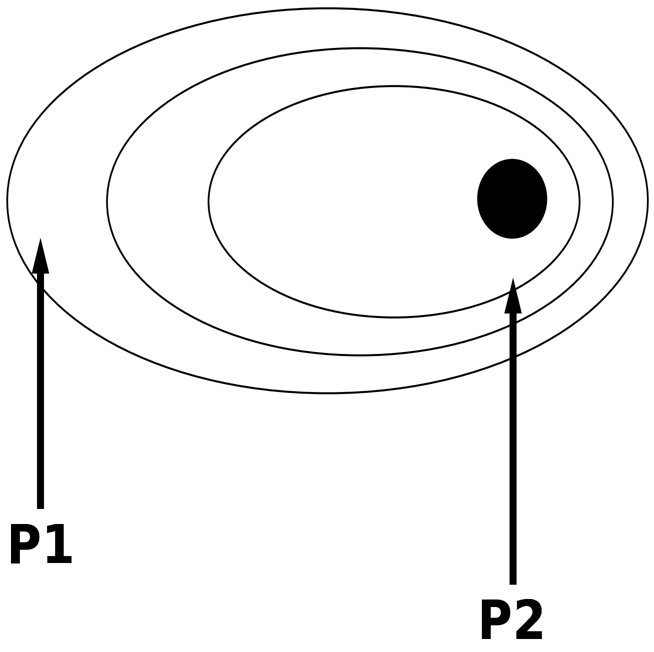
- Suppose a number of stars are orbiting in an elliptical orbit.
- Line density of stars scales like ~1/v ~ $\sqrt{r}$



- Stars moves slowly through apoapse.
- Traffic jams leads to increase stellar density

Eccentric Stellar Disk Model

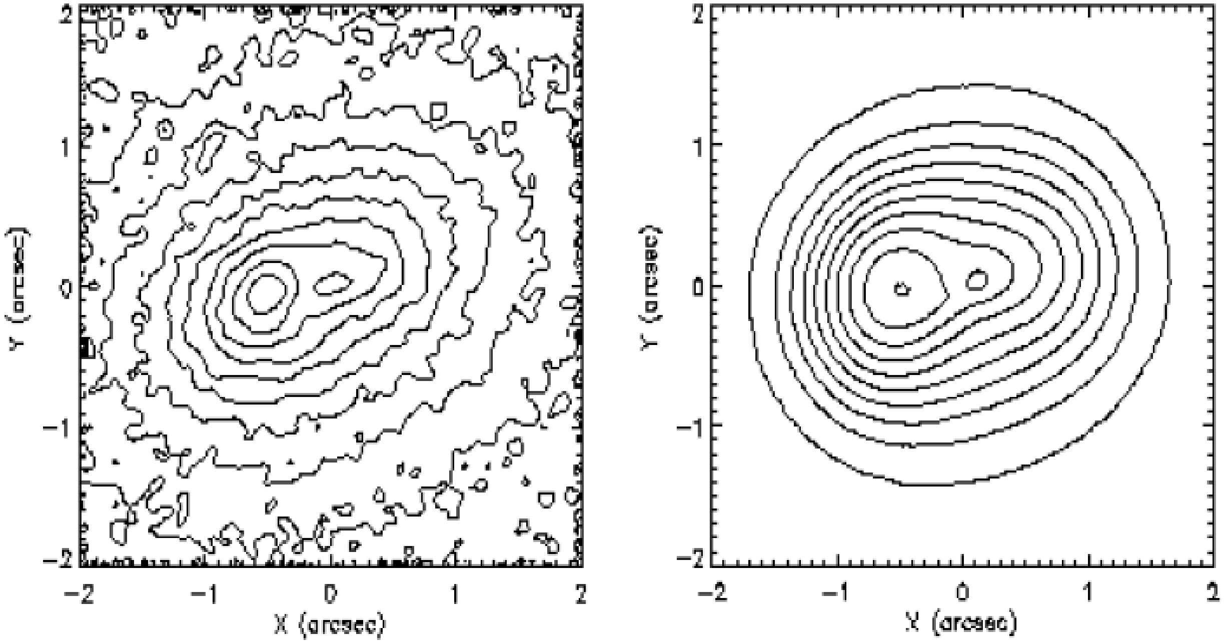
- Suppose a number of stars are orbiting in an elliptical orbit.
- Line density of stars scales like ~1/v ~ $\sqrt{r}$



- Generate a nested bunch of ***aligned*** ellipses with some normalized line density for each
- Identify apopase of these ellipses with P1
- Fit the normalized line density to get P2

Eccentric Stellar Disk Fits to the Data

- Pieris and Tremaine (2003) fit both kinematic data and photometry to the double nucleus
- Best fit model is a non-aligned (with respect to galactic disk) with an inclination of 54 degrees
- Consistent with independent modeling of the double nucleus as a thin disk (55 degrees; Bender 2001)
- Stellar mass is $\approx 2 \times 10^7\ \mathrm{M}_\odot$



Color Structure of the P1/P2

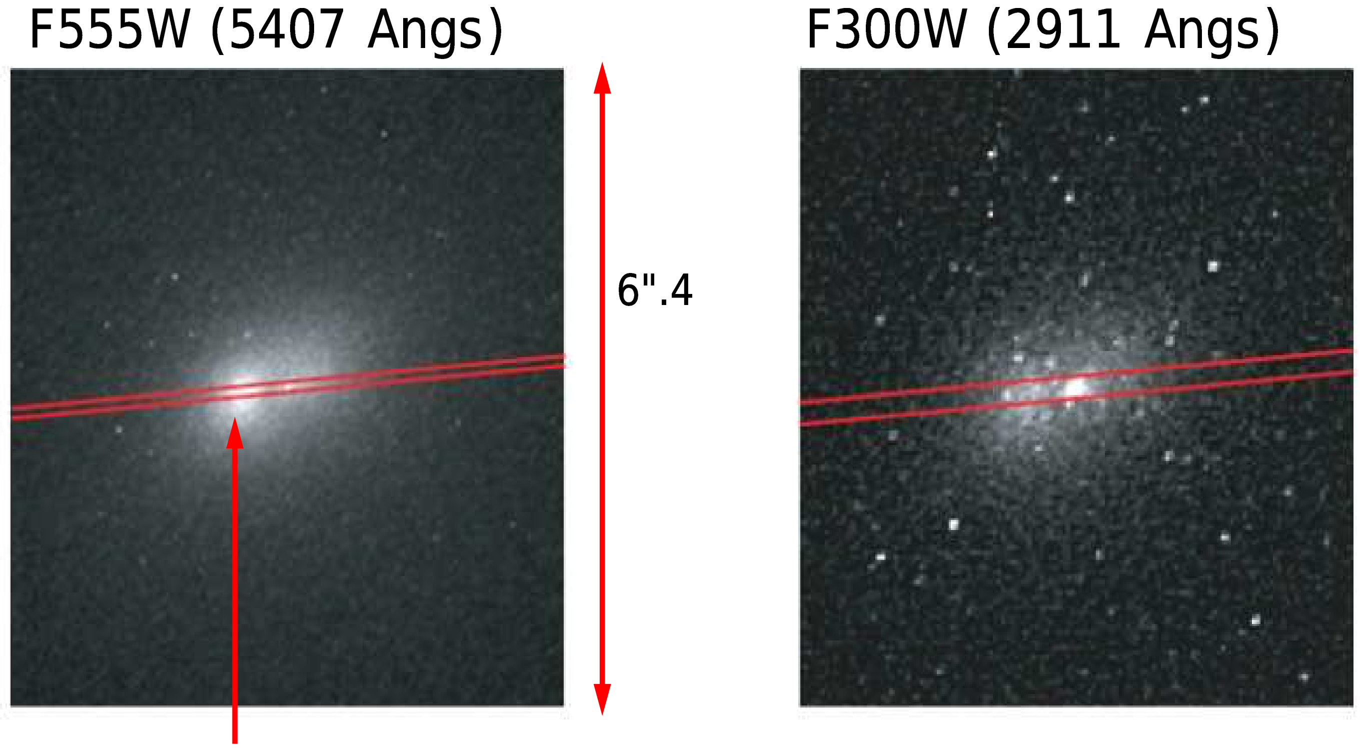
- An eccentric disk model for P1/P2 implies same populations of stars, which implies same colors

Color Structure of the P1/P2

- An eccentric disk model for P1/P2 implies same populations of stars, which implies same colors
- But this is not the case, P2 is bluer than P1.
  - P2 is brighter in the UV than P1!

Color Structure of the P1/P2

- An eccentric disk model for P1/P2 implies same populations of stars, which implies same colors
- But this is not the case, P2 is bluer than P1

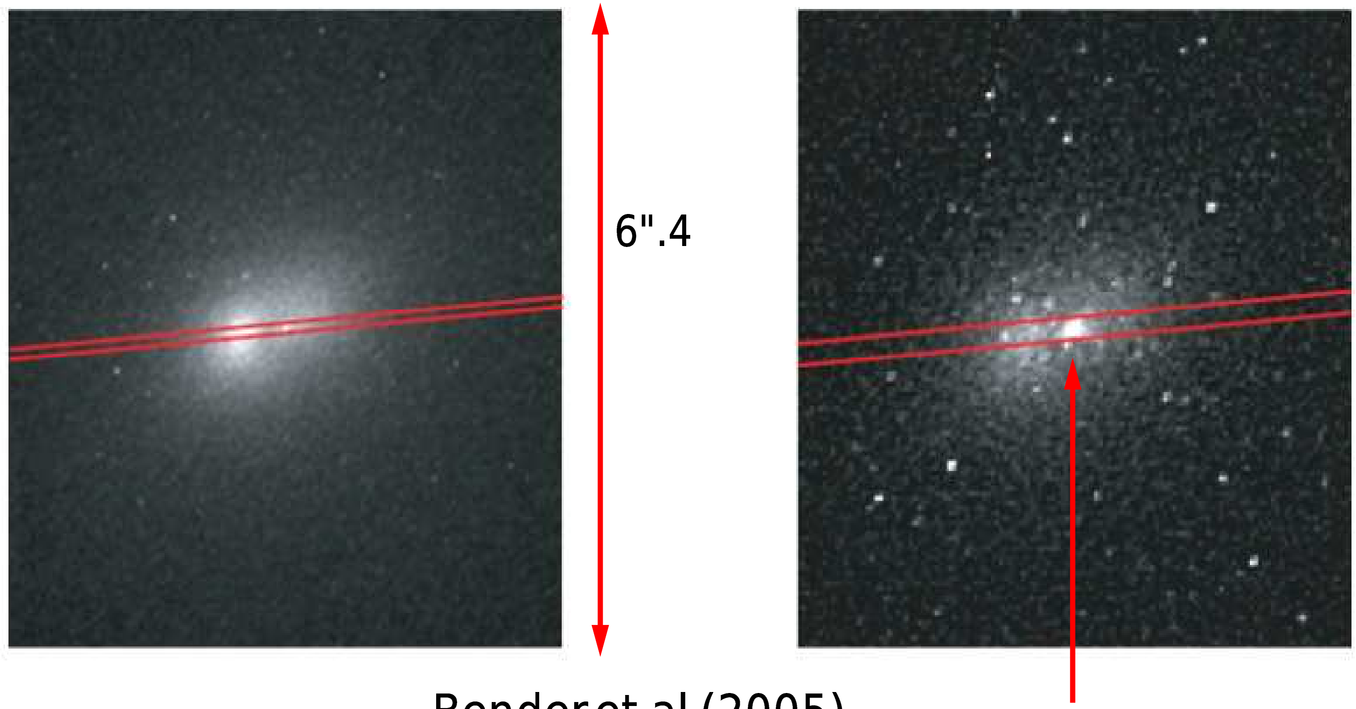


P1 is brighter

Bender et al (2005); data is from Lauer et al. (1998)

Color Structure of the P1/P2

- An eccentric disk model for P1/P2 implies same populations of stars, which implies same colors
- But this is not the case, P2 is bluer than P1

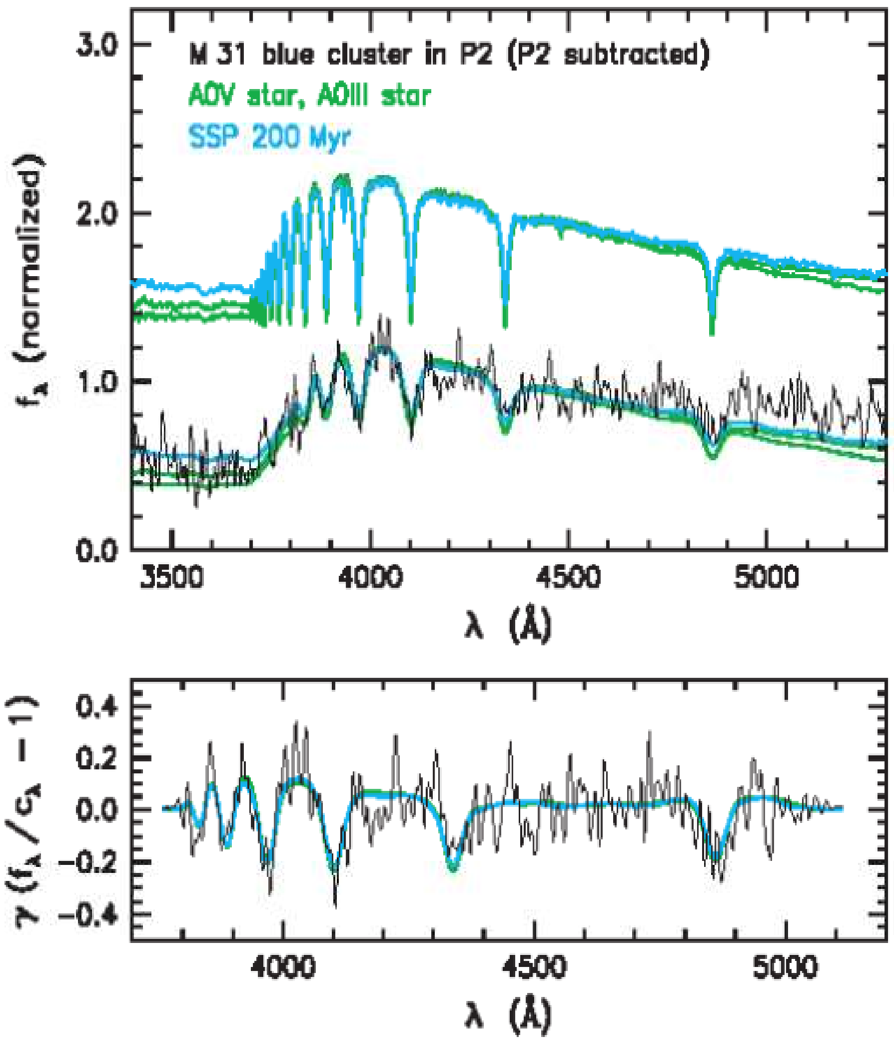

F555W (5407 Angs)

F300W (2911 Angs)

Bender et al (2005)

P2 is brighter

Young Stars around the SMBH



- Fitted with a A-star spectrum (giant and dwarf)
- Also fitted with a 200 Myr old starburst population (lots of A-stars)
- Because this population is distinct, it is named P3.
- Young stellar disk with the same inclination of the eccentric disk AND has a radial extent of ~ 1 pc.
- total stellar mass of .

$\approx 4000\,M_\odot$

Review of Observations and Questions

- An eccentric stellar disk of old (10 Gyr) stars orbits around the SMBH of M31 (the P1/P2 disk)
  - Mass of $2 \times 10^7 \, \mathrm{M}_\odot$

Review of Observations and Questions

- An eccentric stellar disk of old (10 Gyr) stars orbits around the SMBH of M31 (the P1/P2 disk)
  - Mass of $2 \times 10^7 \, \mathrm{M}_\odot$
- A younger (200 Myr) stellar population of A stars orbits within the P1/P2 disk.
  - Outer radial cutoff of ~1 pc.
  - Mass of $\approx 4000 \, \mathrm{M}_\odot$

Review of Observations and Questions

- An eccentric stellar disk of old (10 Gyr) stars orbits around the SMBH of M31 (the P1/P2 disk)
  - Mass of $2 \times 10^7\,\mathrm{M}_\odot$
- A younger (200 Myr) stellar population of A stars orbits within the P1/P2 disk.
  - Outer radial cutoff of ~1 pc.
  - Mass of $\approx 4000\,\mathrm{M}_\odot$
- ***Key Questions***
  - Where do the young stars come from?
  - What sets the outer cutoff?

Review of Observations and Questions

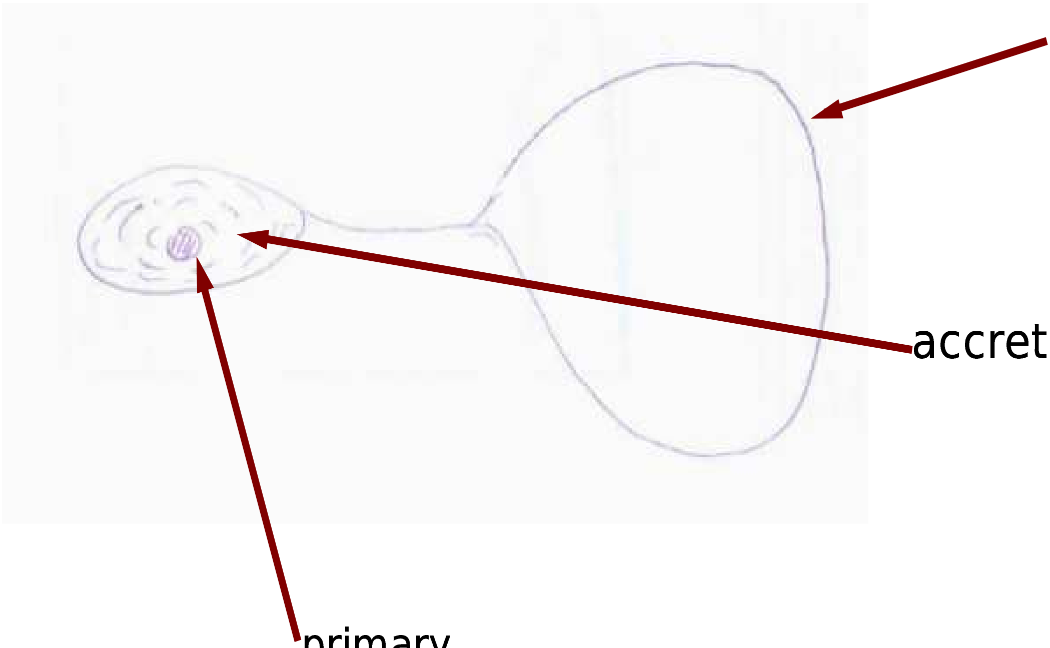
- An eccentric stellar disk of old (10 Gyr) stars orbits around the SMBH of M31 (the P1/P2 disk)
  - Mass of $2 \times 10^7 \, \mathrm{M}_\odot$
- A younger (200 Myr) stellar population of A stars orbits within the P1/P2 disk.
  - Outer radial cutoff of ~1 pc.
  - Mass of $\approx 4000 \, \mathrm{M}_\odot$
- ***Key Questions***
  - Where do the young stars come from?
  - What sets the outer cutoff?
  - Analogy with the GC
    - In-situ star formation
    - Infalling clusters

Review of Observations and Questions

- An eccentric stellar disk of old (10 Gyr) stars orbits around the SMBH of M31 (the P1/P2 disk)
  - Mass of $2 \times 10^7 \, \mathrm{M}_\odot$
- A younger (200 Myr) stellar population of A stars orbits within the P1/P2 disk.
  - Outer radial cutoff of ~1 pc.
  - Mass of $\approx 4000 \, \mathrm{M}_\odot$
- ***Key Questions***
  - Where do the young stars come from?
  - What sets the outer cutoff?
  - Analogy with the GC
    - In-situ star formation
    - Infalling clusters
    - In both scenarios, young stars should be observed at all radii; same problem in GC.
    - For in-situ star formation, where does the gas come from?

Analogy with Roche-filling Binary Systems

- Donor star overfills its Roche lobe and sends a stream of material through the inner Lagrange point.
- The material circularizes and forms an accretion disk around the primary.



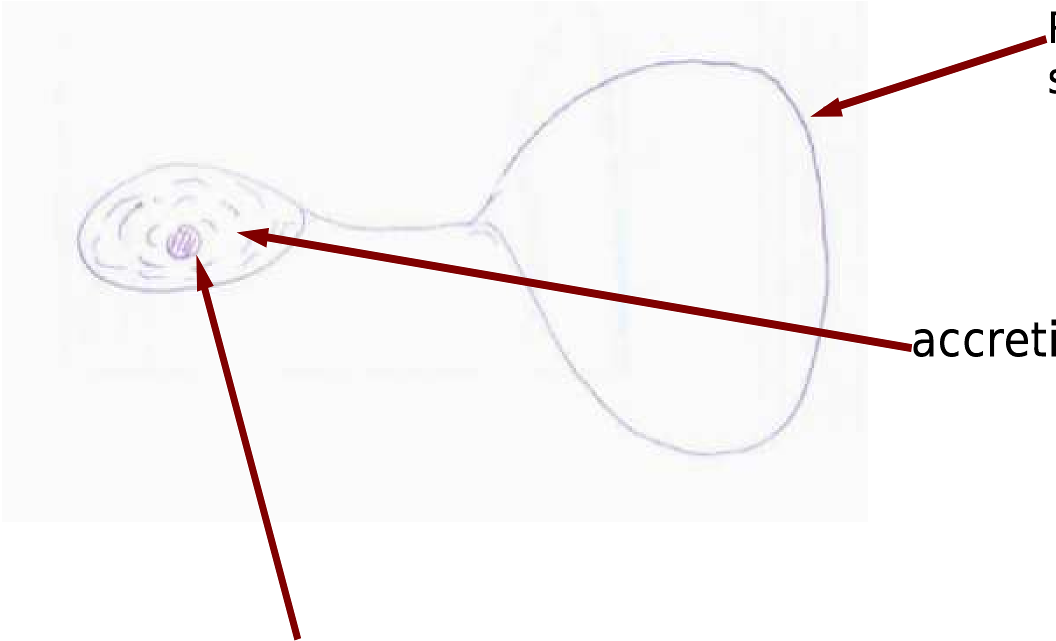
Roche-filling secondary

accretion disk

primary

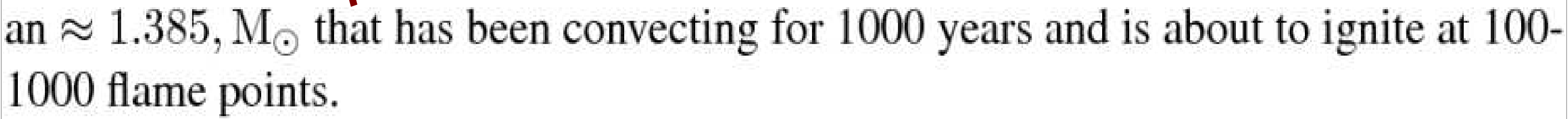
Analogy with Roche-filling Binary Systems

- Donor star overfills its Roche lobe and sends a stream of material through the inner Lagrange point.
- The material circularizes and forms an accretion disk around the primary.



Roche-filling secondary

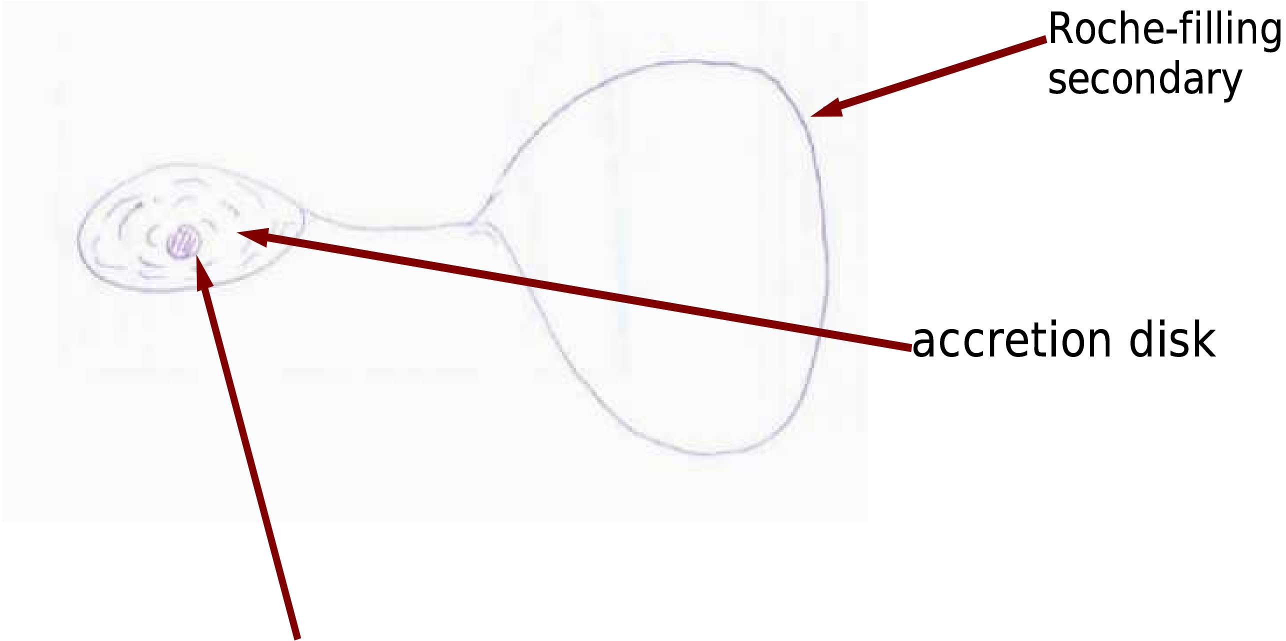
accretion disk

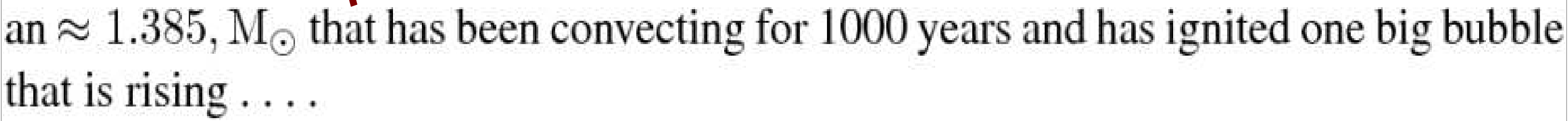


an ≈ 1.385, $M_\odot$ that has been convecting for 1000 years and is about to ignite at 100-1000 flame points.

Analogy with Roche-filling Binary Systems

- Donor star overfills its Roche lobe and sends a stream of material through the inner Lagrange point.
- The material circularizes and forms an accretion disk around the primary.





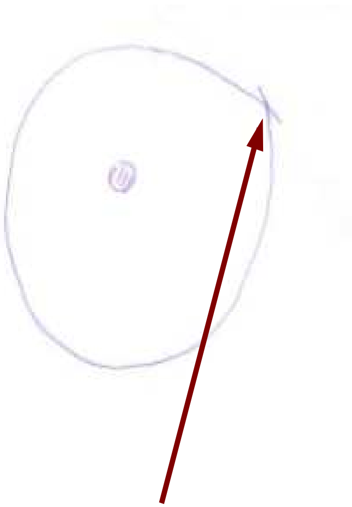
an $\approx$ 1.385, $M_\odot$ that has been convecting for 1000 years and has ignited one big bubble that is rising . . . .

Analogy with Roche-filling Binary Systems

- Donor star overfills its Roche lobe and sends a stream of material through the inner Lagrange point.
- The material circularizes and forms an accretion disk around the primary.
- What is the maximum size of the accretion disk?
  - Order of magnitude expectation is that it is the Roche radius.
  - But this depends on the nature of gas orbits

Analogy with Roche-filling Binary Systems

- Gas orbits cannot cross each other or themselves
  - Otherwise they will shock!



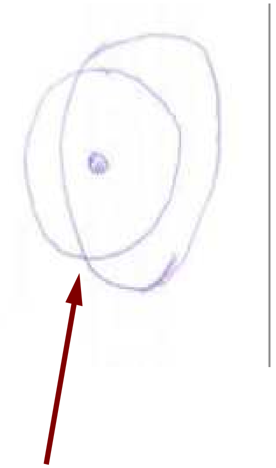
Gas shocks as it crosses itself.

Gas shocks as it intersects it neighbor.

Analogy with Roche-filling Binary Systems

- Gas orbits cannot cross each other or themselves
  - Otherwise they will shock!
- Gas streams cannot cross, a.k.a. the GhostBusters' rule.
- So gas orbits must be nested and simply closed .

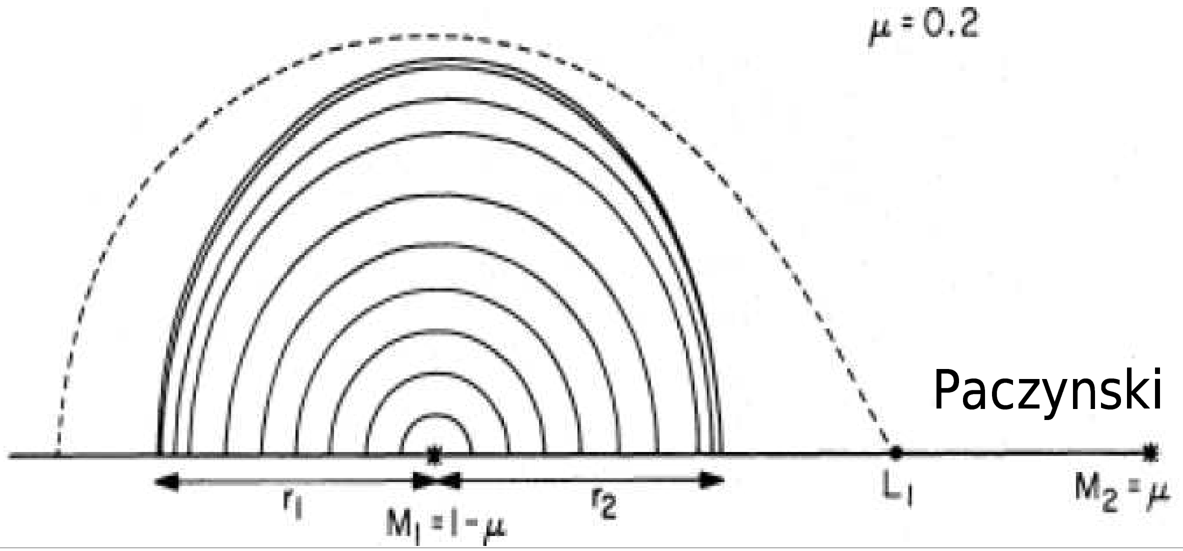
Gas shocks as it crosses itself.



Gas shocks as it intersects it neighbor.

Analogy with Roche-filling Binary Systems

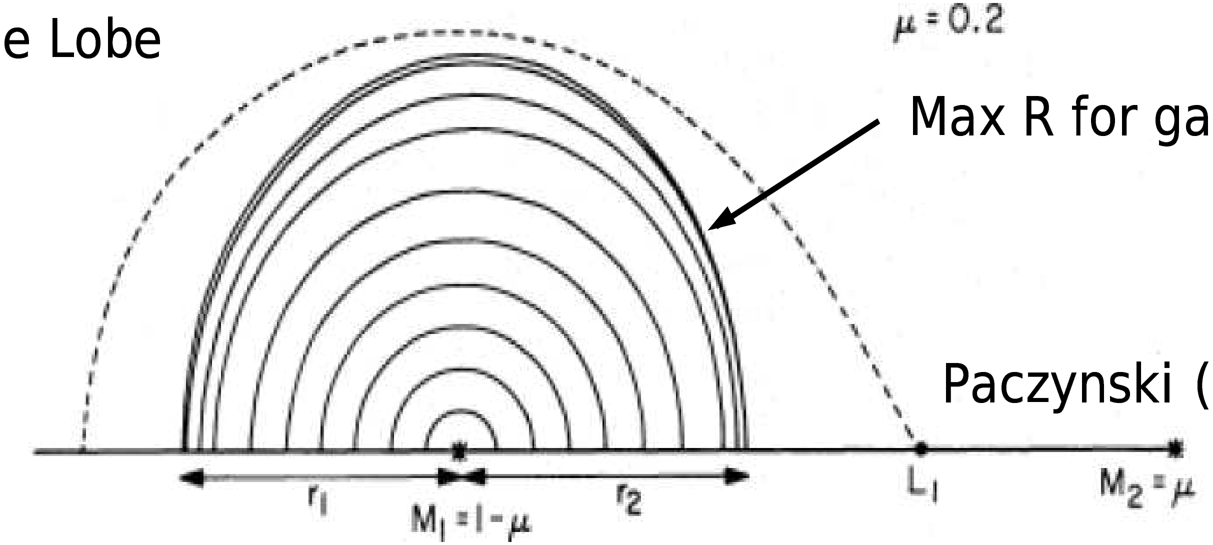
- Gas orbits cannot cross each other or themselves
  - Otherwise they will shock!
- So gas orbits must be nested and simply closed.
  - Close to the primary, orbits are circular
  - Farther out orbits begin to become less circular because of the perturbation of the secondary.
  - But they must still be nested and *simply* closed (in the rotating frame).



Paczynski (1977)

Analogy with Roche-filling Binary Systems

- Gas orbits cannot cross each other or themselves
  - Otherwise they will shock!
- So gas orbits must be nested and simply closed.
  - Close to the primary, orbits are circular
  - Farther out orbits begin to become less circular because of the perturbation of the secondary.
  - But they must still be nested and *simply* closed (in the rotating frame).
- These conditions can no longer be fulfilled beyond a maximum radius, the tidal trucation radius R_t



Roche Lobe

Max R for gas orbits

Paczynski (1977)

Analogy with Roche-filling Binary Systems

- Gas orbits cannot cross each other or themselves
  - Otherwise they will shock!
- So gas orbits must be nested and simply closed.
  - Close to the primary, orbits are circular
  - Farther out orbits begin to become less circular because of the perturbation of the secondary.
  - But they must still be nested and *simply* closed (in the rotating frame).
- These conditions can no longer be fulfilled beyond a maximum radius, the tidal trucation radius R_t
- To complete the analogy
  - primary <-----> SMBH
  - secondary <-----> eccentric disk

Solving F=ma Until Your Face Turns Blue

- Solve the equation of motion in the rotating frame

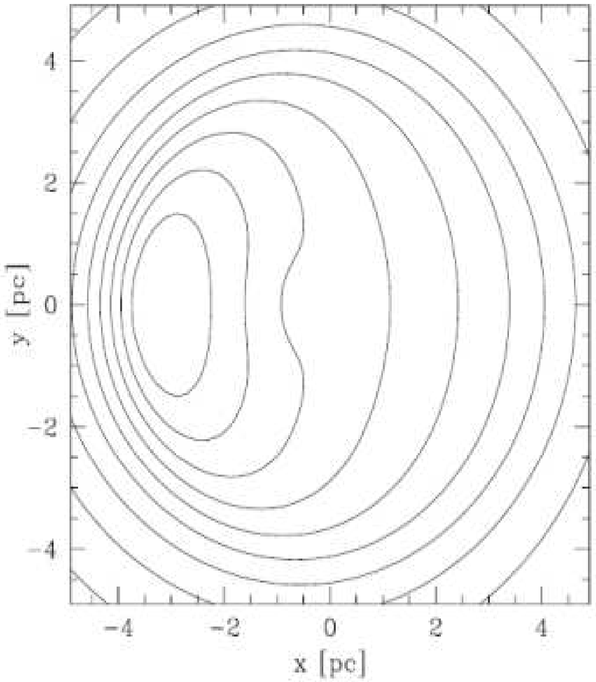
$$\ddot{x} = -\frac{d\Phi}{dx} + \Omega_p^2\left(x - x_{\rm cm}\right) + 2\Omega_o\dot{y}$$
$$\ddot{y} = -\frac{d\Phi}{dy} + \Omega_p^2 y - 2\Omega_o\dot{x}$$

$$\Phi = \Phi_{\rm SMBH} + \Phi_{\rm disk}$$

The potential of the eccentric stellar disk

The eccentric stellar disk is lopsided (m=1), so we expect a lopsided contribution to the potential.

$$\Phi_{\rm disk}(x,y) = -G\int dx'dy'\,\frac{\Sigma(x',y')}{|r-r'|+h}$$



- The potential from the stellar disk is concentrated around the mass peak (P1).
- h is the softening length, which here we set to h = 0.1 pc and 0.1-0.4 r

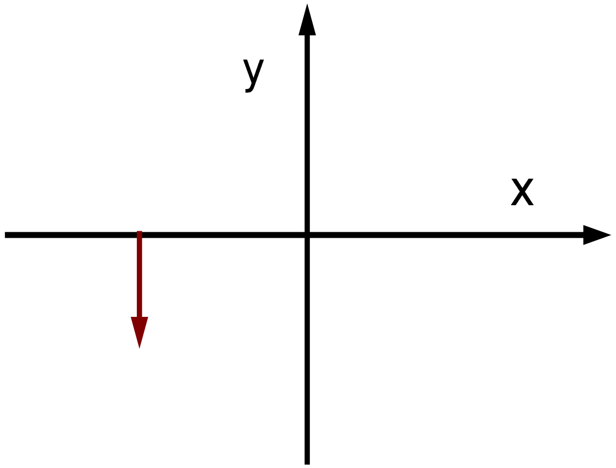
Solving F=ma Until Your Face Turns Blue

- Solve the equation of motion in the rotating frame

$$\ddot{x} = -\frac{d\Phi}{dx} + \Omega_p^2\left(x - x_{\rm cm}\right) + 2\Omega_o\dot{y}$$
$$\ddot{y} = -\frac{d\Phi}{dy} + \Omega_p^2 y - 2\Omega_o\dot{x}$$

$$\Phi = \Phi_{\rm SMBH} + \Phi_{\rm disk}$$

- Start on the x-axis $v_x = v_{x,0}, \quad v_y = 0$



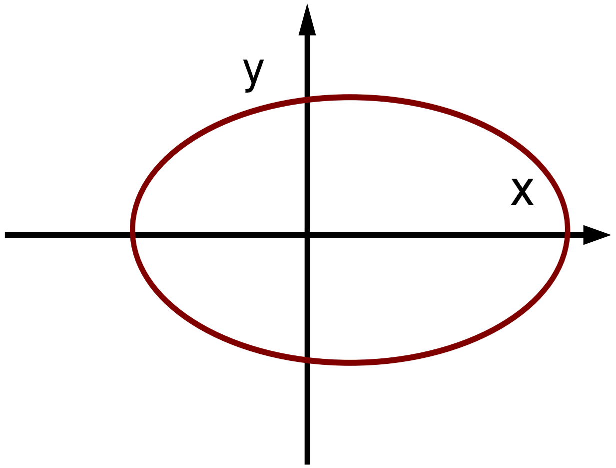
Solving F=ma Until Your Face Turns Blue

- Solve the equation of motion in the rotating frame

$$\ddot{x} = -\frac{d\Phi}{dx} + \Omega_p^2 (x - x_{\mathrm{cm}}) + 2\Omega_o \dot{y}$$
$$\ddot{y} = -\frac{d\Phi}{dy} + \Omega_p^2 y - 2\Omega_o \dot{x}$$

$$\Phi = \Phi_{\mathrm{SMBH}} + \Phi_{\mathrm{disk}}$$

- Start on the x-axis
- Iterate until we reproduce the starting conditions.



Solving F=ma Until Your Face Turns Blue

- Solve the equation of motion in the rotating frame

$$\ddot{x} = -\frac{d\Phi}{dx} + \Omega_p^2\left(x - x_{\rm cm}\right) + 2\Omega_o\dot{y}$$
$$\ddot{y} = -\frac{d\Phi}{dy} + \Omega_p^2 y - 2\Omega_o\dot{x}$$

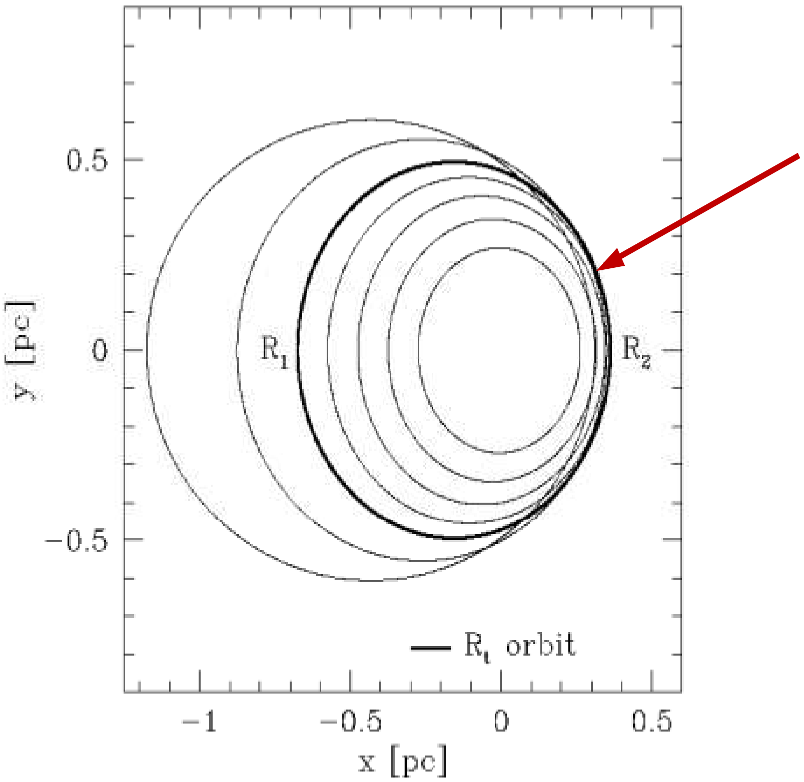
$$\Phi = \Phi_{\rm SMBH} + \Phi_{\rm disk}$$

- Start on the x-axis
- Iterate until we reproduce the starting conditions.
- The pattern speed of the P1/P2 disk is unknown.
  - Qualitative differences between low and high pattern speeds.

Orbits at low pattern speeds

- For low pattern speeds, there exists a tidal truncation radius.

- Gas outside of the tidal truncation radius will be forced inside of the tidal trucation radius because of shock dissipation.



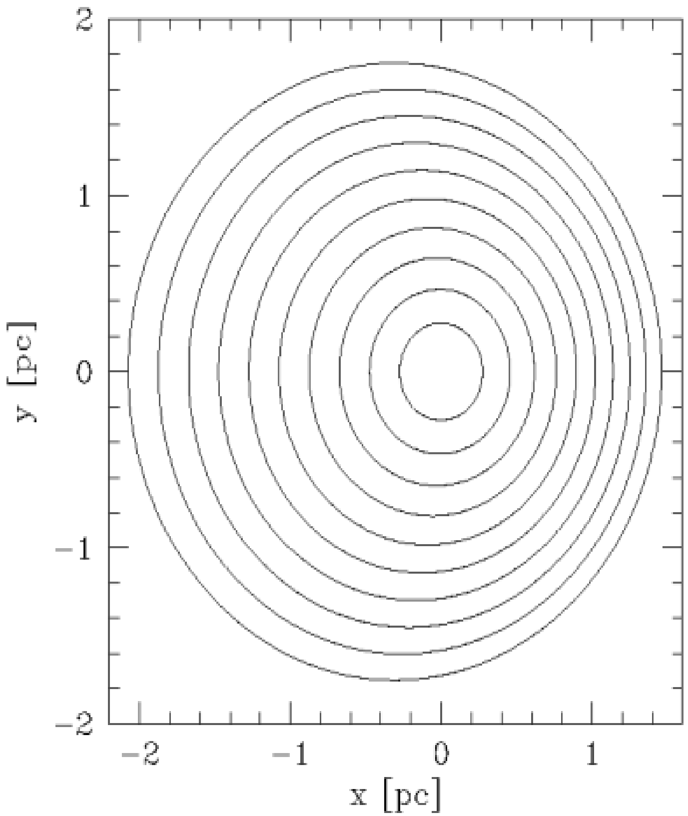
R_t orbit

$R_t \approx 0.6\,\mathrm{pc}$

$\Omega_p = 3\,\mathrm{km\,s^{-1}\,pc^{-1}}$

Orbits at high pattern speeds

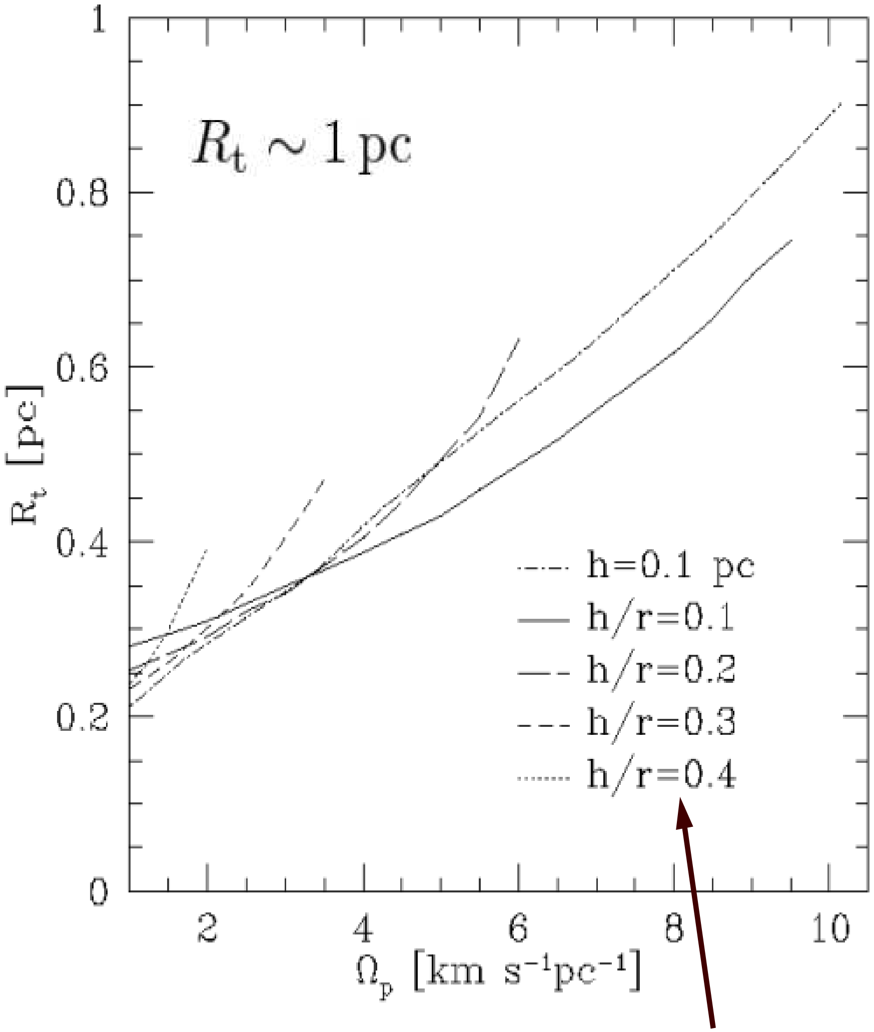
- In contrast to low pattern speeds, no tidal truncation radius exists for high pattern speeds.
- Gas orbits can span the entire disk.



$\Omega_p = 30\,\mathrm{km\,s^{-1}\,pc^{-1}}$

No R_t orbit

Radial Extent of P3 and Pattern Speed



different scale heights for the eccentric disk.

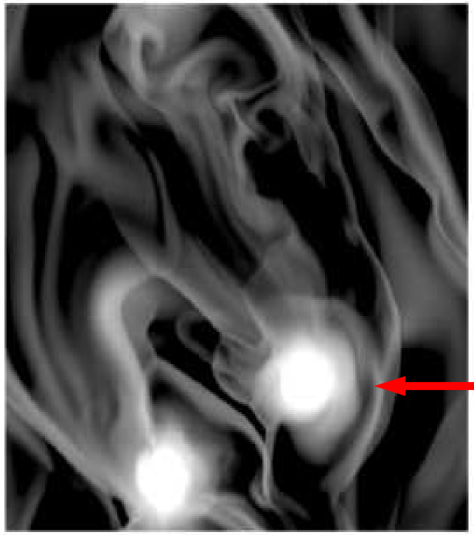
- The tidal truncation radius is a function of pattern speed
- For sufficiently low pattern speeds, we find tidal trucation radii < 1 pc similar to the radial extent of P3
- Predicts a low pattern speed for the P1/P2 disk.

$$\Omega_p \lesssim 3 - 10\,\mathrm{km\,s^{-1}pc^{-1}}$$

- Gives a gaseous disk a natural radial extent, but what happens to the gas and where does it come from?

Star Formation in a Gaseous Disk

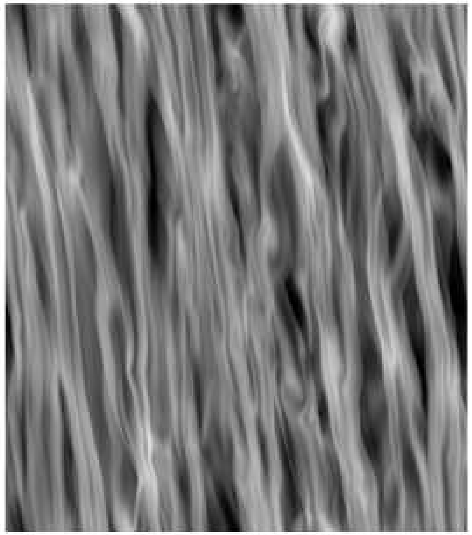
- Gas disk builds up mass and become gravitational unstable.
  - Toomre $Q = \frac{\kappa c_s}{\pi G \Sigma} \sim 1 \rightarrow \frac{M_{\rm disk}}{M_{\rm BH}} \sim \frac{h}{R}$
- If cooling is fast, disk will break up into smaller clumps, which themselves collapse and form stars.


Clumps form

Gammie (2001)

Star Formation in a Gaseous Disk

- Gas disk builds up mass and become gravitational unstable.
  - Toomre $Q = \frac{\kappa c_s}{\pi G \Sigma} \sim 1 \rightarrow \frac{M_{\rm disk}}{M_{\rm BH}} \sim \frac{h}{R}$
- If cooling is fast, disk will break up into smaller clumps, which themselves collapse and form stars.
- If cooling is slow, disk will enter a gravitoturbulent state, I.e. no fragmentation.



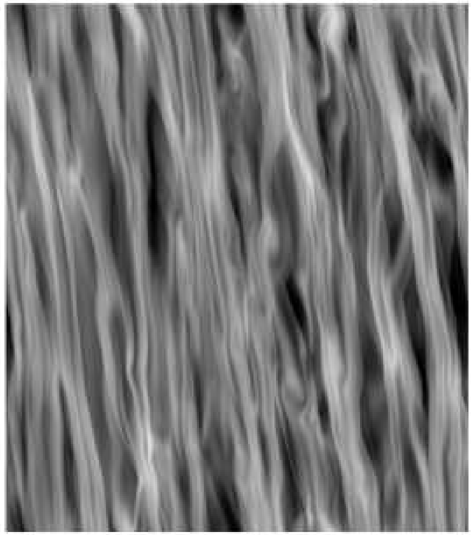
Gammie (2001)

No clumps form.

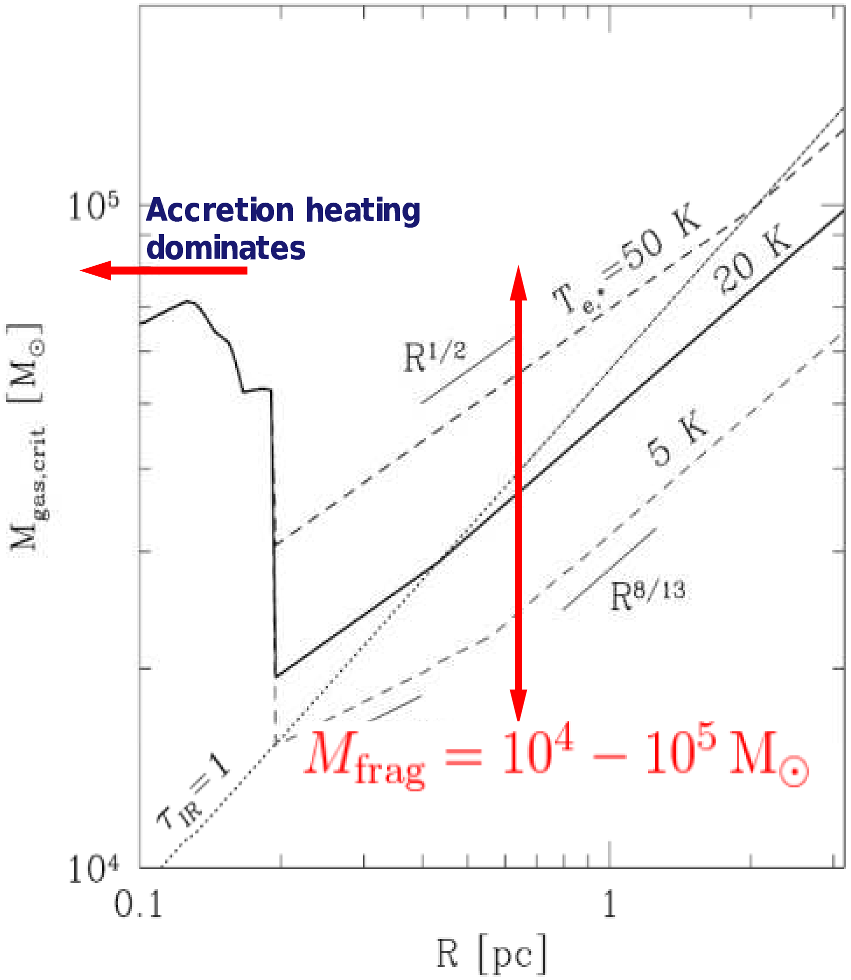
Disk enters a gravitoturbulentstate.

Star Formation in a Gaseous Disk

- Gas disk builds up mass and become gravitational unstable.
  - Toomre $Q = \frac{\kappa c_s}{\pi G \Sigma} \sim 1 \rightarrow \frac{M_{\rm disk}}{M_{\rm BH}} \sim \frac{h}{R}$
- If cooling is fast, disk will break up into smaller clumps, which themselves collapse and form stars.
- If cooling is slow, disk will enter a gravitoturbulent state, I.e. no fragmentation.
- Boundary between the two situations is $t_{\rm cool} < 3t_{\rm dyn}$



Disk Fragmentation Mass



- Solve for when

$$Q \sim 1 \rightarrow \frac{M_{\rm gas}}{M_{\rm BH}} \sim \frac{h}{R} \sim \frac{c_s}{v_{\rm orb}}$$

$$t_{\rm cool} \lesssim 3t_{\rm dyn}$$

- Cooling is via IR-dust emission
- Heating is via gravitoturbulence or starlight
- Starlight heating is dominant.

$$\sigma T_{e,*}^4 = \frac{L}{4\pi R^2}\frac{h}{R} \rightarrow T_{e,*} \approx 20\,{\rm K}$$

- Typical fragmentation mass is $10^4 - 10^5\,{\rm M}_\odot$

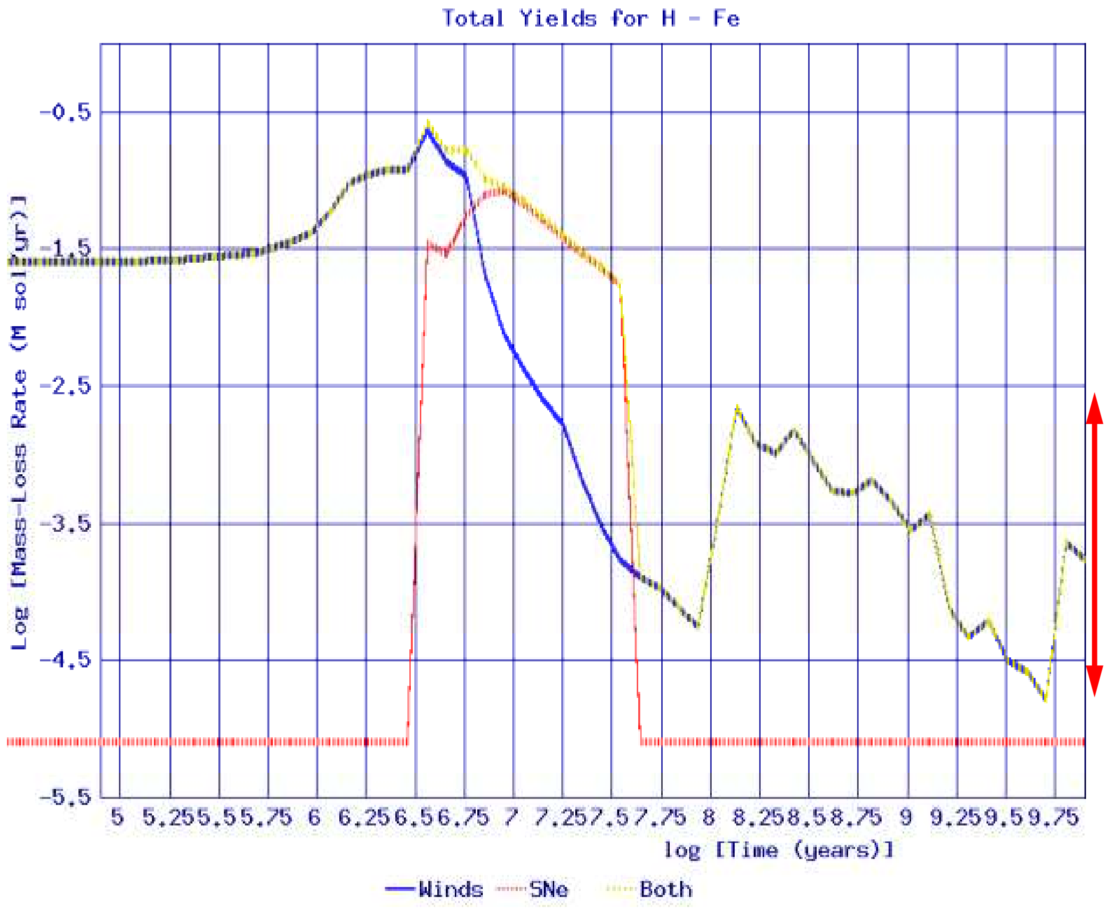
Mass Supply via Stellar Winds

- Stellar mass loss from the P1/P2 disk can supply the gas to form the A stars.
- Typical stellar mass loss rate is $\dot{\mathrm{M}} \sim 10^{-4} \mathrm{M}_{\odot}\,\mathrm{yr}^{-1}$ for a $2 \times 10^{7} \mathrm{M}_{\odot}$ star cluster

Stellar Mass Loss Rates at 0.1-10 Gyrs

- Dominated by AGB stars. Slow winds $\sim 20\,\mathrm{km\,s^{-1}}$
- Typical Mass Loss Rates are

0.1 - 10 Gyrs



$2 \times 10^{-3}\,\mathrm{M_\odot\,yr^{-1}}$

$2 \times 10^{-5}\,\mathrm{M_\odot\,yr^{-1}}$

- For a 10 million solar mass cluster, we compute the stellar mass loss rate from Starburst99

Mass Supply via Stellar Winds

- Stellar mass loss from the P1/P2 disk can supply the gas to form the A stars.
- Typical stellar mass loss rate is $\dot{\mathrm{M}} \sim 10^{-4}\mathrm{M}_{\odot}\,\mathrm{yr}^{-1}$ for a $2 \times 10^{7}\mathrm{M}_{\odot}$ star cluster
- Stellar winds shock, cool and are forced inside R_{t}
- Fragmentation mass is typically $10^{4} - 10^{5}\mathrm{M}_{\odot}$

- So the timescale (i.e., starburst timescale) is

$$t_{\mathrm{accum}} = \frac{\mathrm{M}_{\mathrm{frag}}}{\dot{\mathrm{M}}} \sim 10^{8} - 10^{9}\,\mathrm{yr}$$

Mass Supply via Stellar Winds

- Stellar mass loss from the P1/P2 disk can supply the gas to form the A stars.
- Typical stellar mass loss rate is $\dot{\mathrm{M}} \sim 10^{-4}\mathrm{M}_\odot\,\mathrm{yr}^{-1}$ for a $2 \times 10^7\mathrm{M}_\odot$ star cluster
- Stellar winds shock, cool and are forced inside R_t
- Fragmentation mass is typically $10^4 - 10^5\mathrm{M}_\odot$

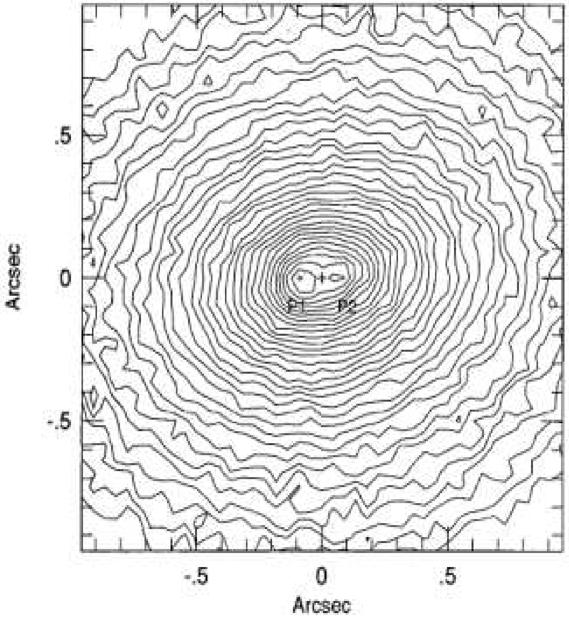
- So the timescale (i.e., starburst timescale) is

$$t_\mathrm{accum} = \frac{\mathrm{M}_\mathrm{frag}}{\dot{\mathrm{M}}} \sim 10^8 - 10^9\,\mathrm{yr}$$

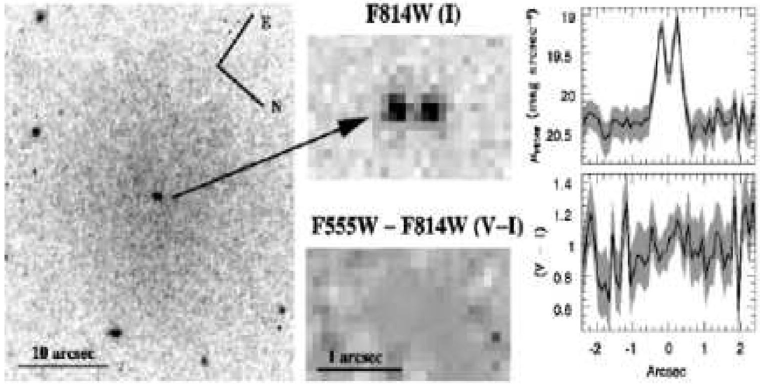
- Consistent with the age of the A stars of 200 Myr!

- Not so consistent with the mass of P3 of $\sim 4000\,\mathrm{M}_\odot$
  - Top heavy IMF?
  - Not all the mass fragments.
- Since the last starburst was 200 Myr ago $\sim 10^4 - 10^5\,\mathrm{M}_\odot$ of molecular gas in P3

Double Nuclei in Other Galaxies



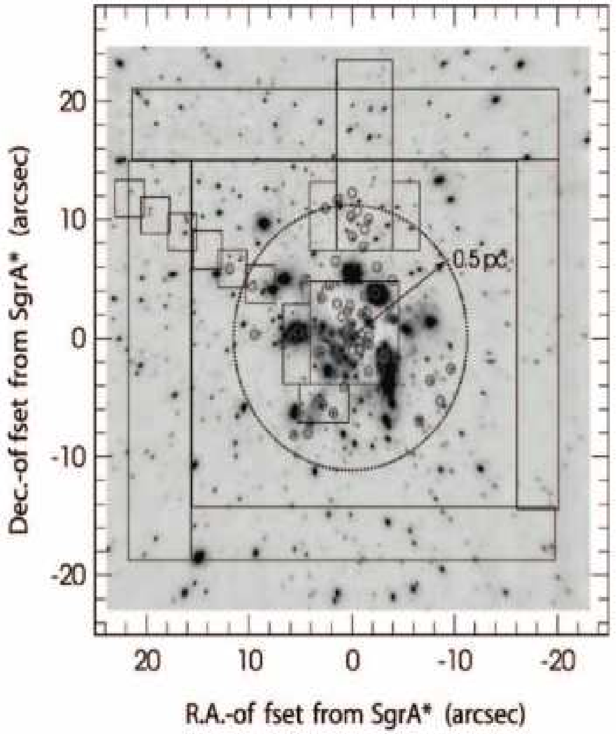
- Double nuclei seen in NGC4486B by Lauer et al (1996)
- Spatial separation ~ 12 pc



- Also seen in VCC128 by Debattista et al (2006)
- separation ~ 32 pc

Application to the GC?

(or big page of speculations)



Paumard et al 2006

- OB stars are observed in the GC inside of the central 0.5 pc. (Paumard et al 2006)
- Given the top-heavy IMF (Nayakshin & Sunyaev 2005), this is most of the stellar mass.
- Eccentric potential due to mass concentration around R~1 pc may be responsible. (CND?, eccentric stellar disk)
- Stellar mass loss rate inside of bulge isn't responsible for starburst timescale of ~ 10 Myrs (inflowing molecular clouds, cloud-cloud collisions in CMZ)

Conclusions

- The radial structure and origin of the A stars (P3) in M31 is intimately tied to the eccentric stellar disk of old stars (P1/P2)
  - Non-axisymmetric potential gives an outer radial cutoff of $\sim 1\,\mathrm{pc}$ if $\Omega_p < 3 - 10\,\mathrm{km\,s^{-1}\,pc^{-1}}$
  - Stellar winds from the eccentric disk are able to supply the mass for a disk to fragment and form P3
    - This gas shocks, cools, and is then forced inside the tidal truncation radius where it collects.
    - After an accumulation time of 100-1000 Myr, gas fragments and forms stars.
- Our model predicts $\sim 10^4 - 10^5\,\mathrm{M}_\odot$ in molecular gas.
  - Observable via molecular lines ~ 2 mJy in CO
  - Stellar remnants from previous starbursts (?)
- Possible applications to other galactic nuclei (the GC?)