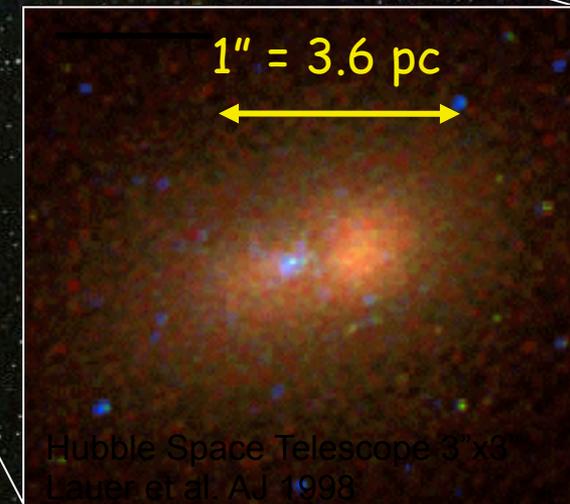


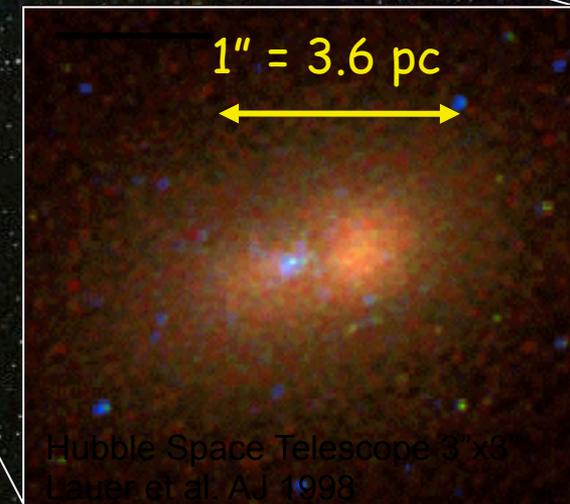
Dynamics of galaxy centers

$1000'' = 3600 \text{ pc} = 3.6 \text{ kpc}$



Dynamics of galaxy centers

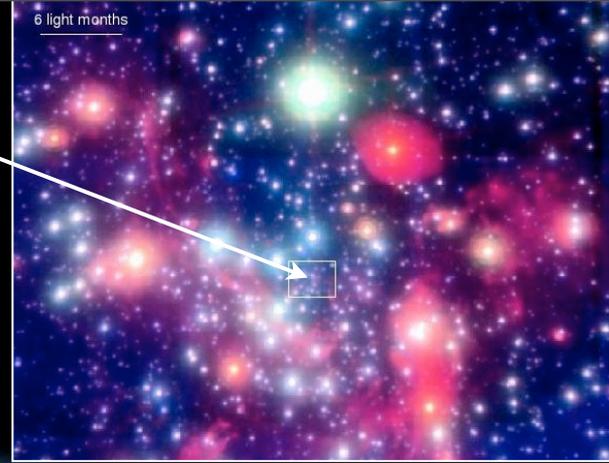
based in part on work with:
Bence Kocsis (CfA)
Hiranya Peiris (UC London)
Qingjuan Yu (KIAA, Beijing)



Milky Way

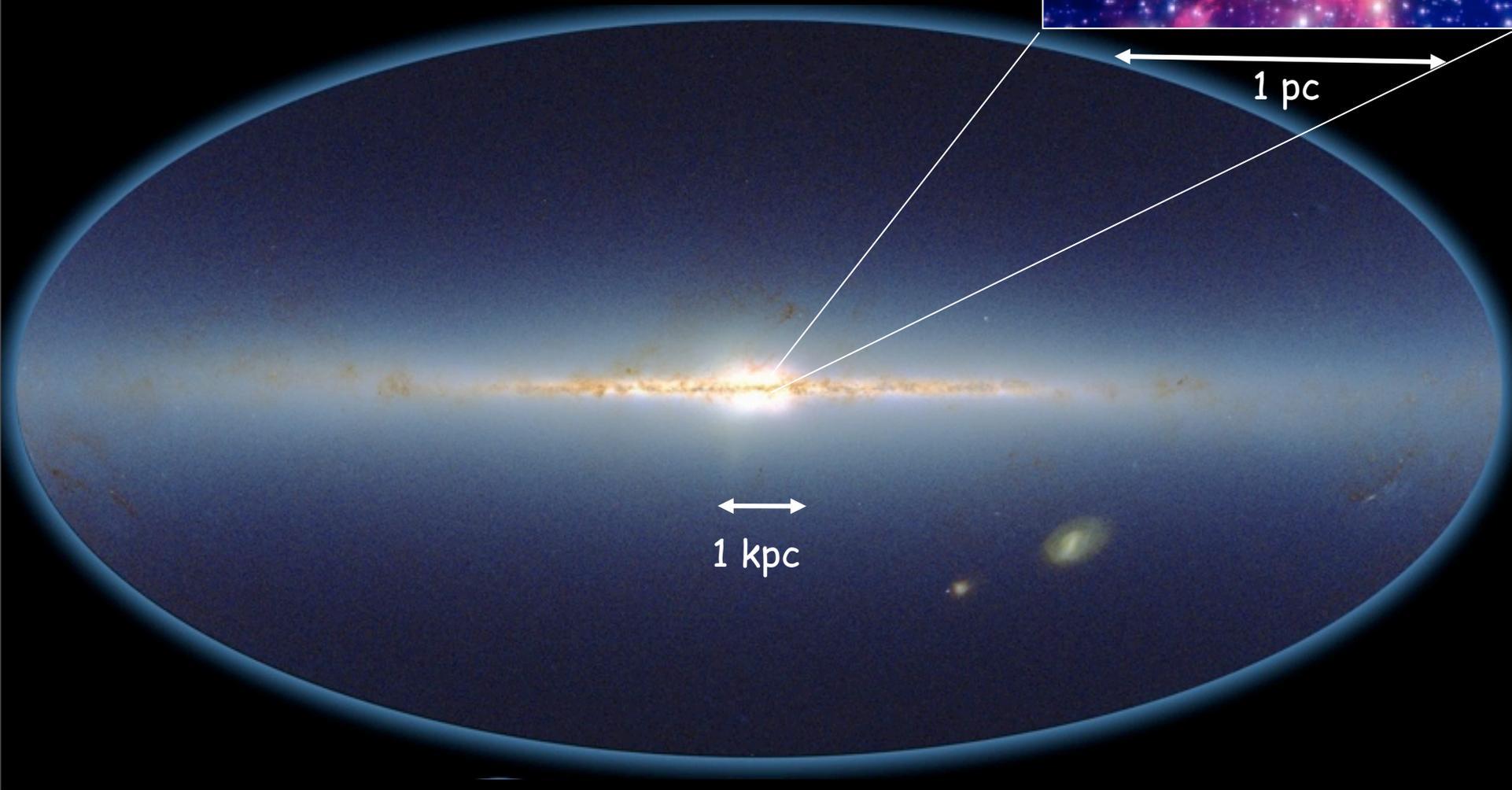
2MASS all-sky catalog of 5×10^8 stars

Sagittarius A*



1 pc

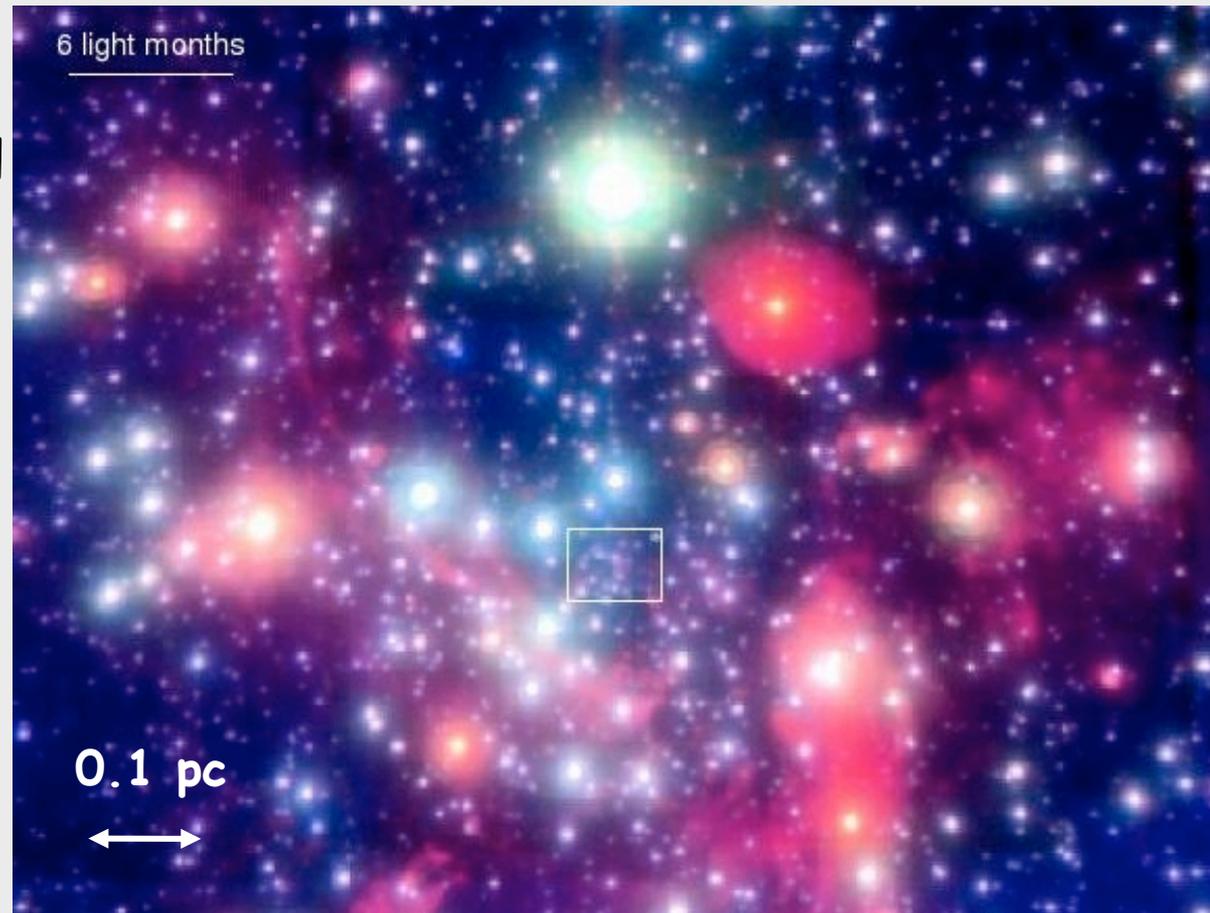
1 kpc



Why are the centers of galaxies interesting?

- these are the densest known stellar systems - at 0.1 pc from the center of our Galaxy the density of stars is 10^8 times higher than around the Sun

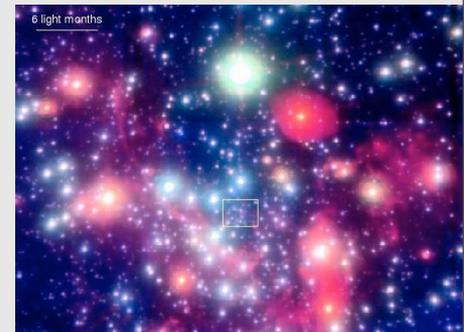
⇒ all interesting dynamical processes occur faster



infrared astronomy group, MPE,
Garching

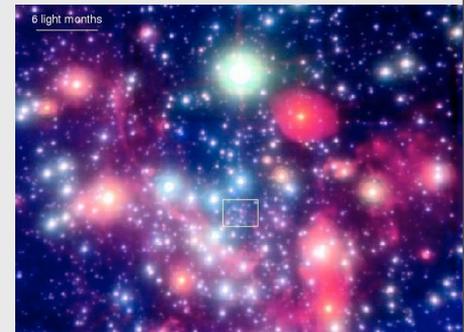
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- they're the bottom of the potential well of the galaxy
 - promising sites for archaeology



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 - however the relaxation time is shorter than the age at less than a few pc from *Galactic center* \Rightarrow statistical equilibrium of some kind
- they're the bottom of the potential well in the galaxy
- the centers of most galaxies contain black holes
 - laboratories for testing general relativity and extreme physics
 - sources for gravitational radiation

1. Hypervelocity stars
2. The nucleus of M31
3. Statistical mechanics in galaxy centers
4. Star formation in the central parsec

Hypervelocity stars

- Hills (1988):

“A close...encounter between a tightly bound binary and a $10^6 M_{\odot}$ black hole causes one binary component to become bound to the black hole and the other to be ejected at up to 4,000 km/s. The discovery of even one such hyper-velocity star coming from the Galactic center would be nearly definitive evidence for a massive black hole”

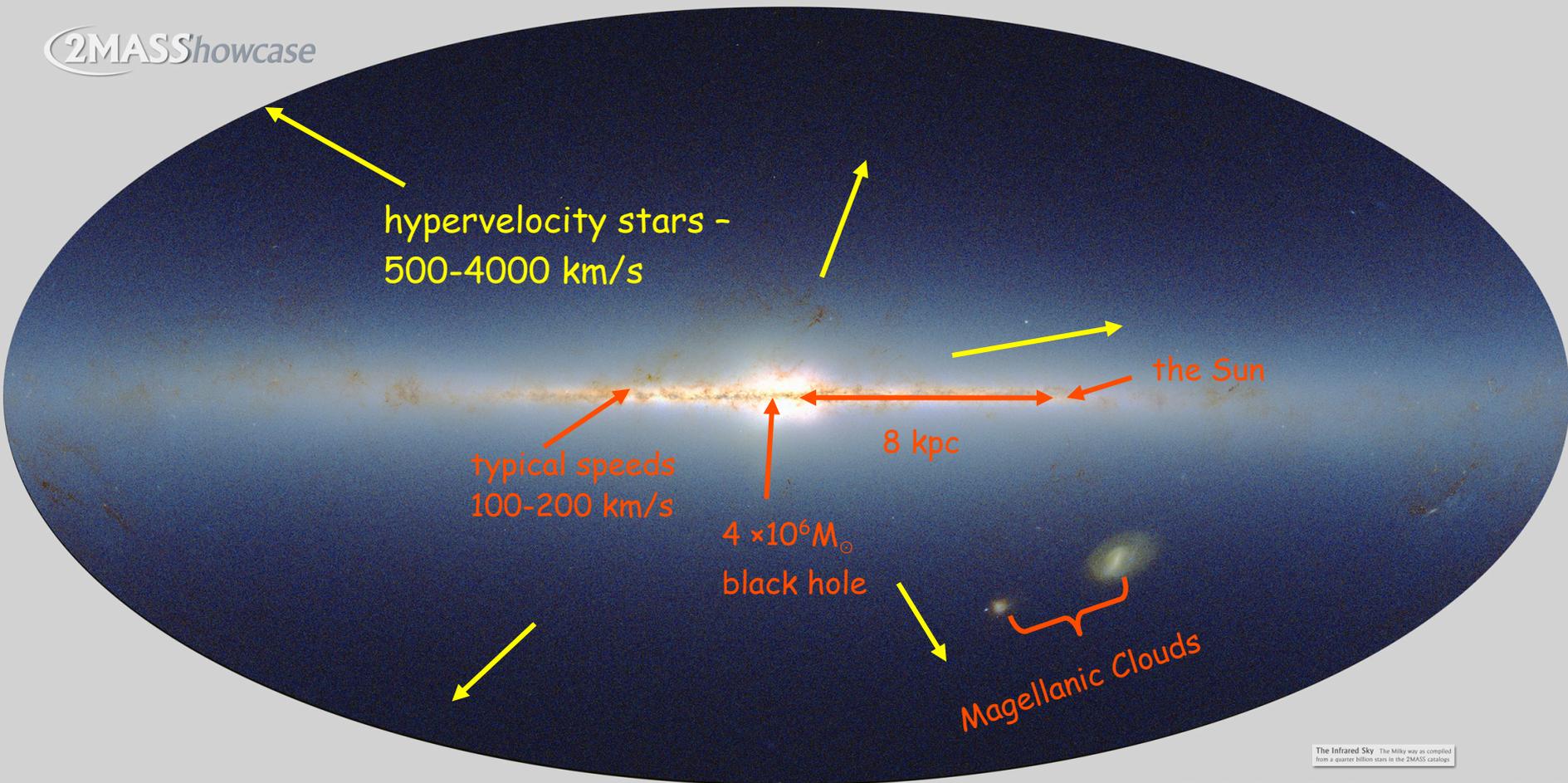


- ejection velocity scales as

$$v \sim v_{\text{binary}} (M_{\text{bh}} / M_{\star})^{1/6}$$

where v_{binary} is the binary orbital speed, M_{bh} is the black-hole mass, and M_{\star} is the star mass.

- a second possible mechanism is ejection of single stars by a binary black hole (Yu & Tremaine 2003)

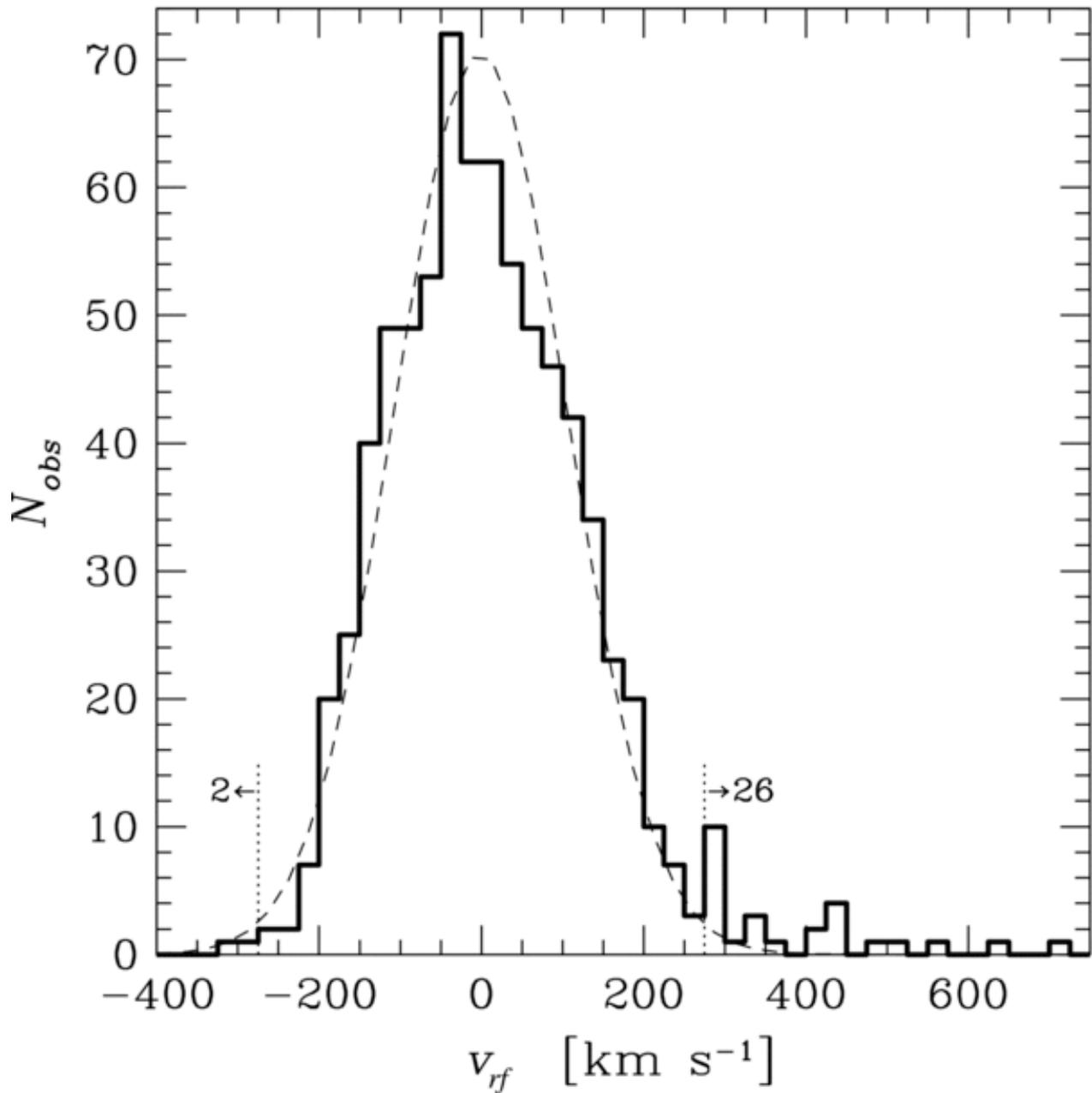


Two Micron All Sky Survey Image Mosaic: Infrared Processing and Analysis Center/Caltech & University of Massachusetts

look for stars that are:

- high above Galactic plane (less confusion)
- young (bright, so easy to find; also normal halo stars are all old)
- moving at high speed (either line-of-sight velocity or proper motion)
- if at distances \gg 8 kpc and on escape orbit, must be moving away from us

not yet practical



line-of-sight velocities
of a sample of young
stars at 25-100 kpc
Brown et al. (2009)

velocity along line of sight, in Galactic rest frame

Hypervelocity stars

Were these stars really ejected by the central black hole?

- NOT runaway stars (produced if a supernova goes off in a close binary or from binary-binary encounters) --- these have kick velocity < 200 km/s
- travel times from the Galactic center are $<$ stellar lifetime (200 Myr) so formation in Galactic center is possible
- rate ($\sim 1/\text{Myr}$) is roughly consistent with theoretical predictions
- velocities are positive, i.e., traveling outward
- $N(< r) \sim r$, as expected for uniform ejection rate

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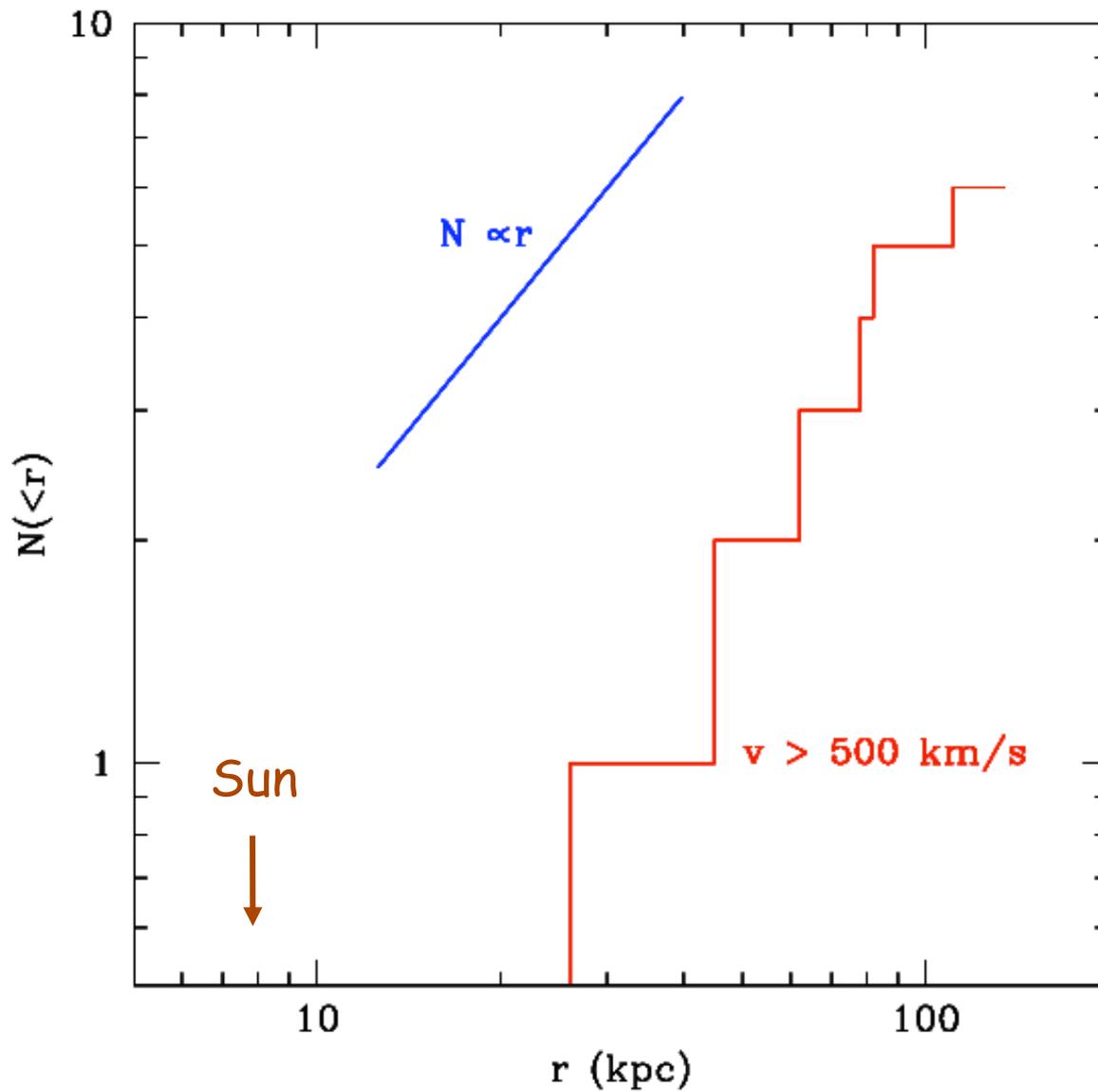
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distance from Galactic center

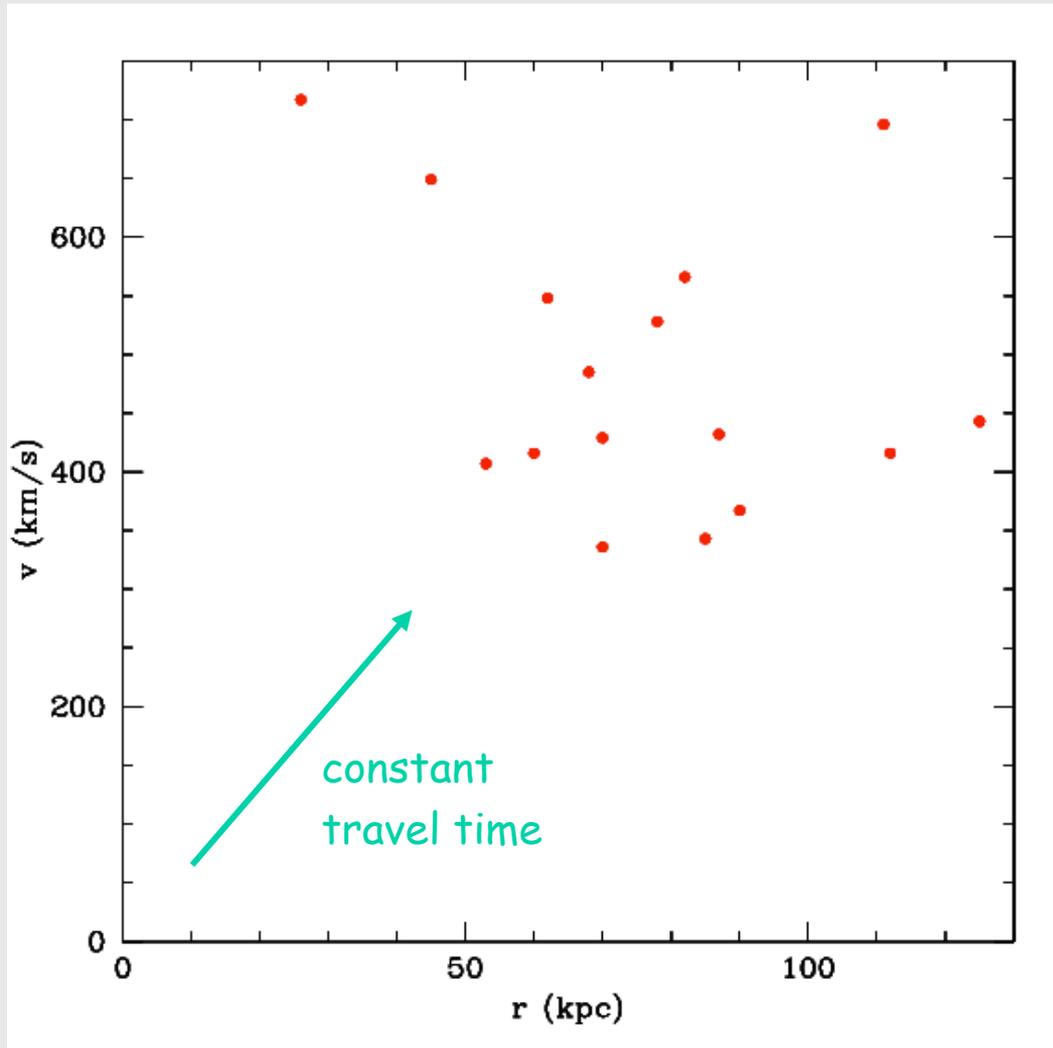
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- some stars don't fit:
 - **HD 271971**: B2-B3, 7.4 kpc above the plane, heliocentric $v = 442$ km/s; solar abundance; proper motion indicates that it came from the outer disk, not the Galactic center (Heber et al. 2008) 
 - **HE 0437-5439**: has a rest-frame velocity of 548 km/s but its main-sequence lifetime of 18 Myr is much shorter than travel time of 110 Myr. 

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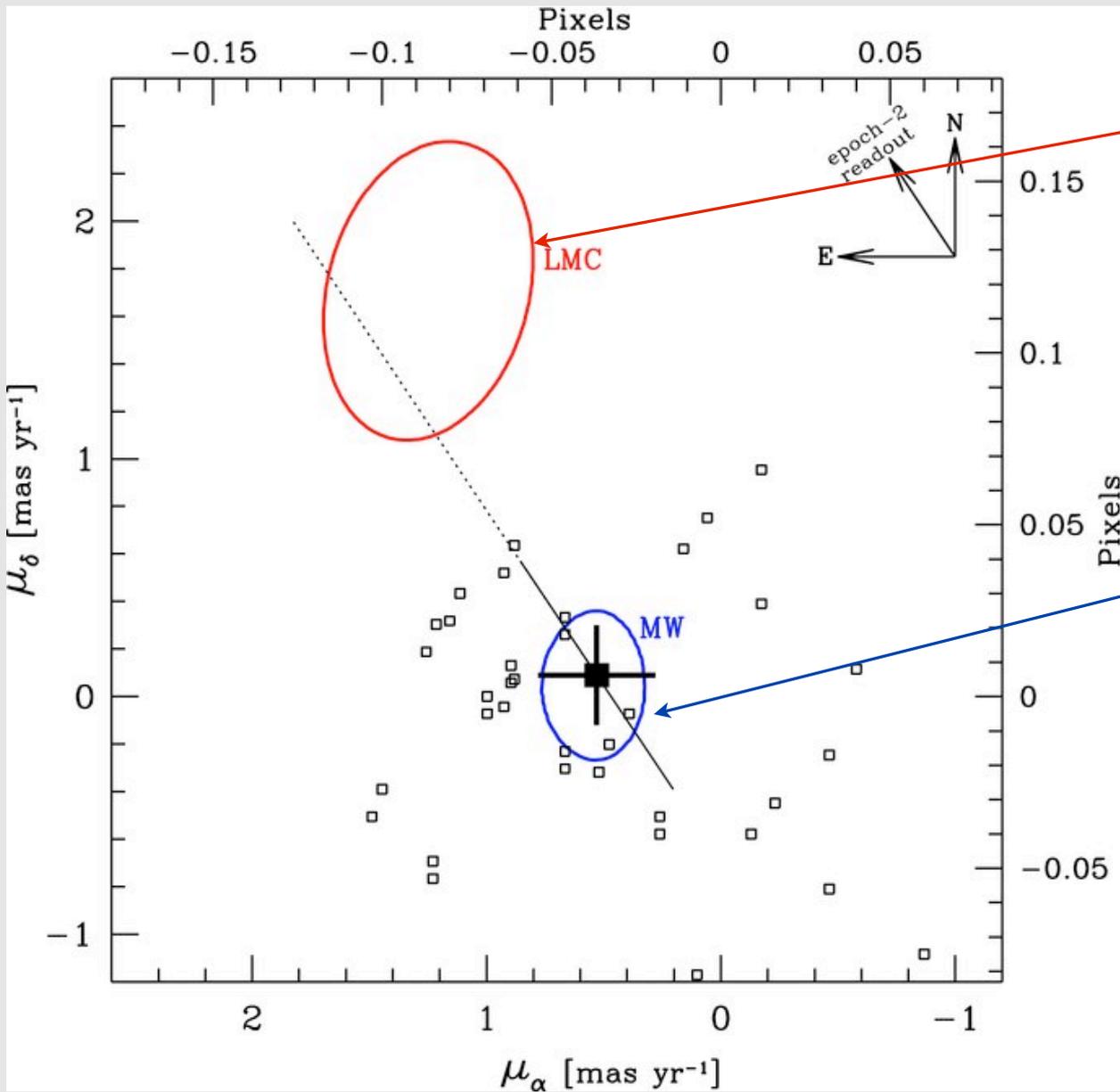
distance from *Galactic center*

- if hypervelocity stars originate from any single catastrophic event near the Galactic center the travel times should all be the same
- possible example is tidal spray from a recently disrupted satellite galaxy (Abadi et al. 2009)

Hypervelocity stars

Future observations:

- new photometric surveys will find more (e.g., Pan-STARRS, SkyMapper, LSST)
- chemical abundances should be characteristic of the Galactic center
- accurate proper motions of hypervelocity stars will constrain their origin - difference in proper motion between source at solar radius and source at Galactic center is ~ 0.5 mas/yr
- larger surveys will constrain spatial distribution
- are there hypervelocity binaries? If so then ejection by binary black hole is favored



3 kpc from LMC

8 kpc from the Galactic center

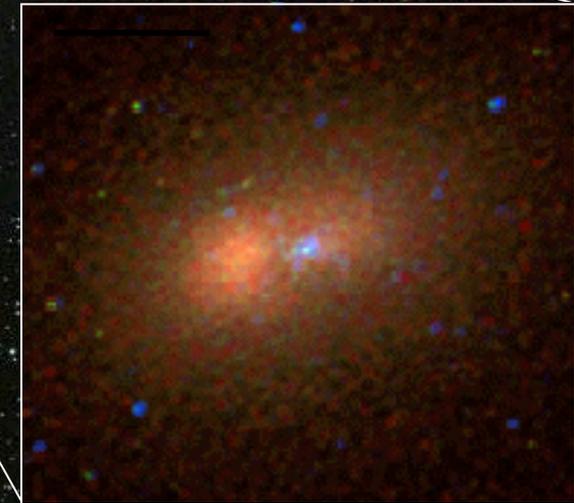
HE 0437-5439

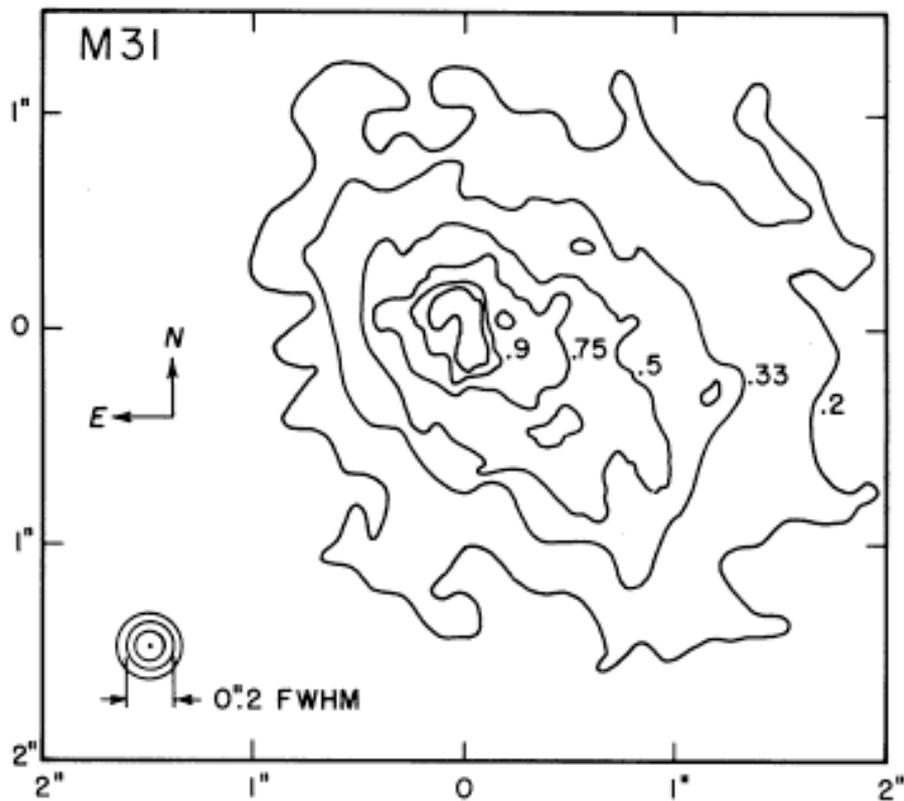
(Brown et al. 2010)

2. The center of the Andromeda galaxy

Why M31 is important:

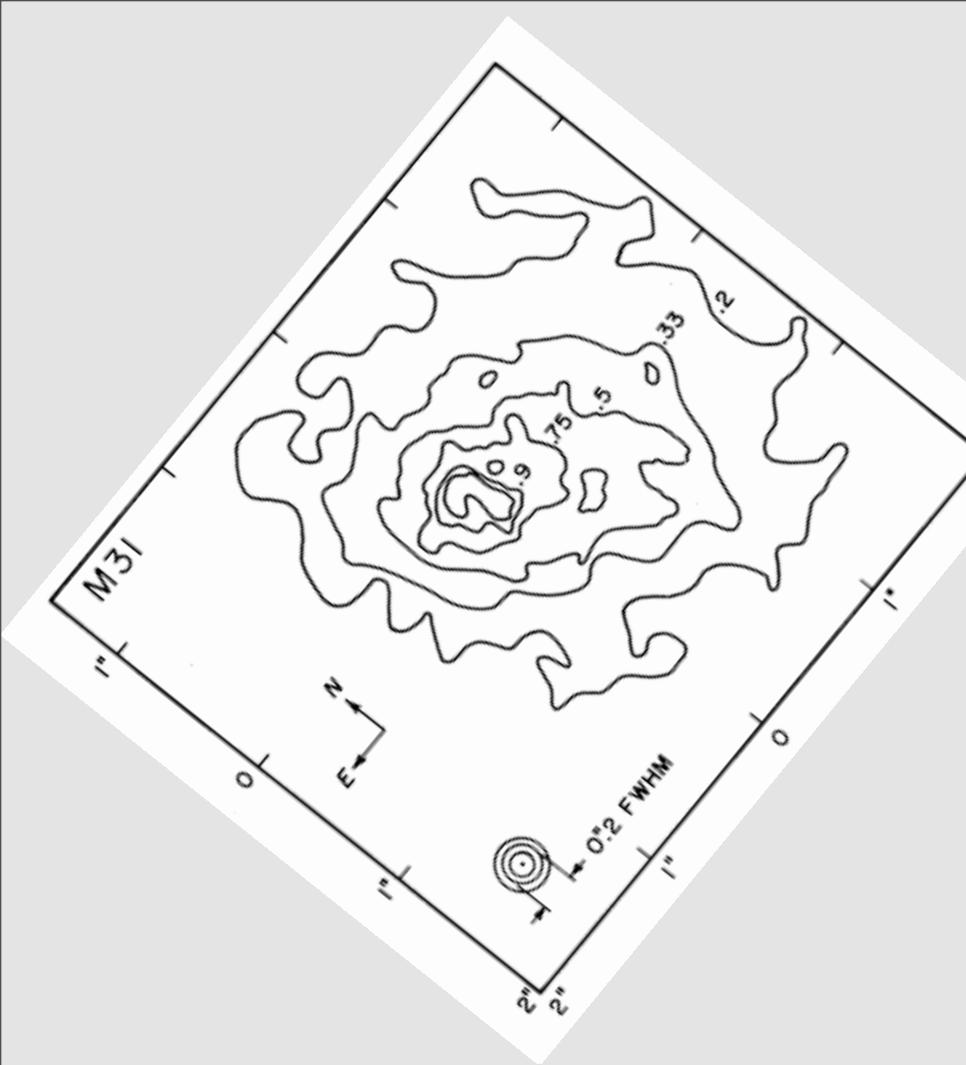
- angular size of region in which black hole dominates the gravitational field is larger than in any other galaxy except Milky Way
- little or no gas, dust, recent star formation so stellar distribution is easy to interpret



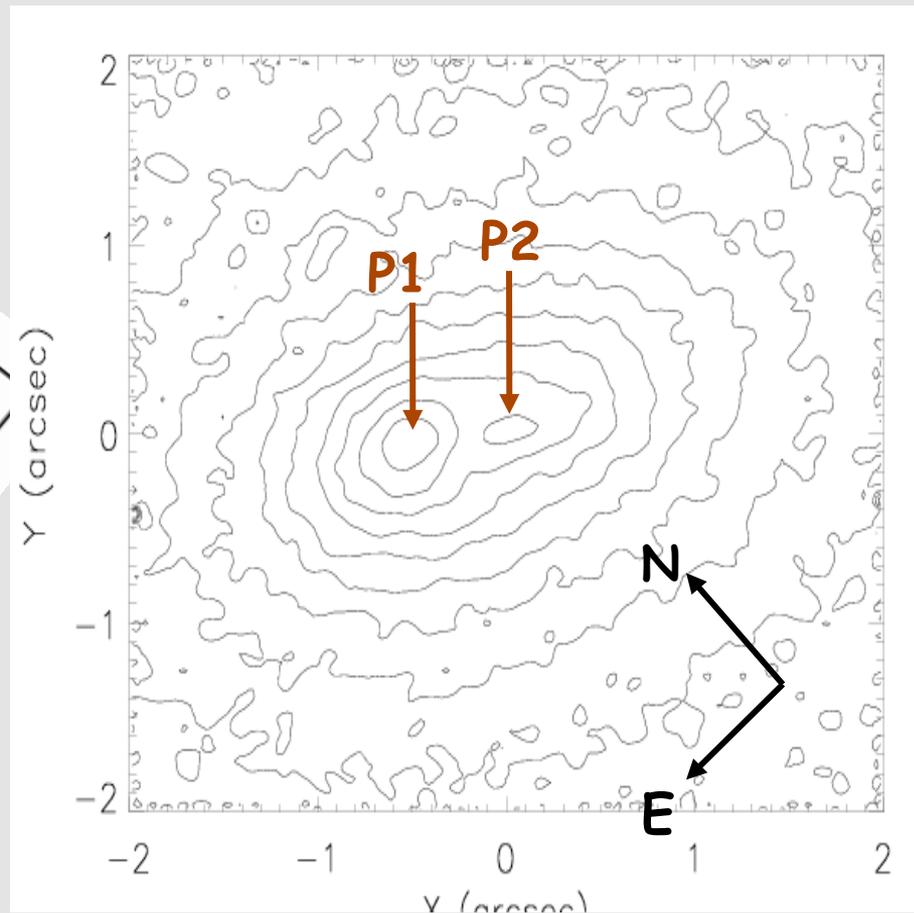


Light, Danielson & Schwarzschild (1974)

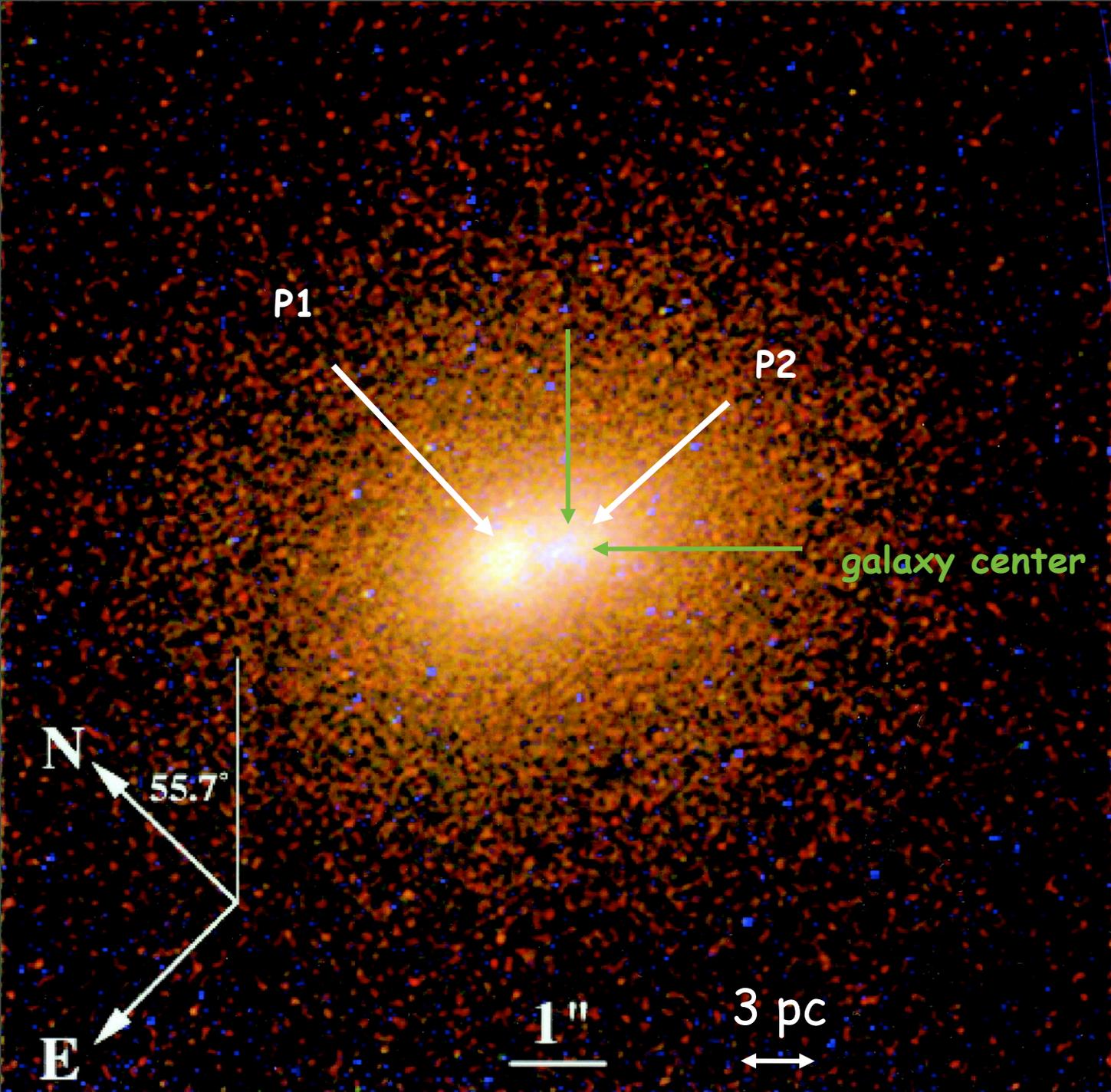
"A puzzling aspect of the high-resolution images is the offset of the peak brightness with respect to the outer portions of the nucleus...if no significant dust is present, the observed asymmetry is an intrinsic property of the nucleus which will probably require a dynamical explanation."



Stratoscope



Hubble Space Telescope



further curiosities:

- faint component (P2) is at the galaxy center, not the bright component
- P2 is cuspy, P1 is not
- colors of P1 and P2 are the same
- P2 has a compact blue component at its center (P3)

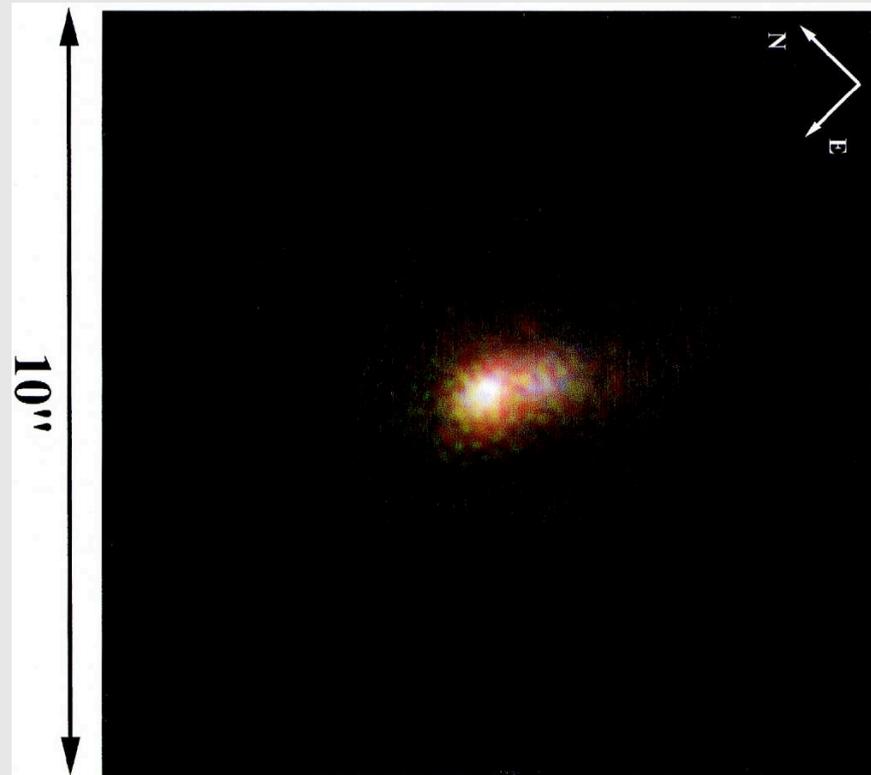
Lauer et al. (1998)

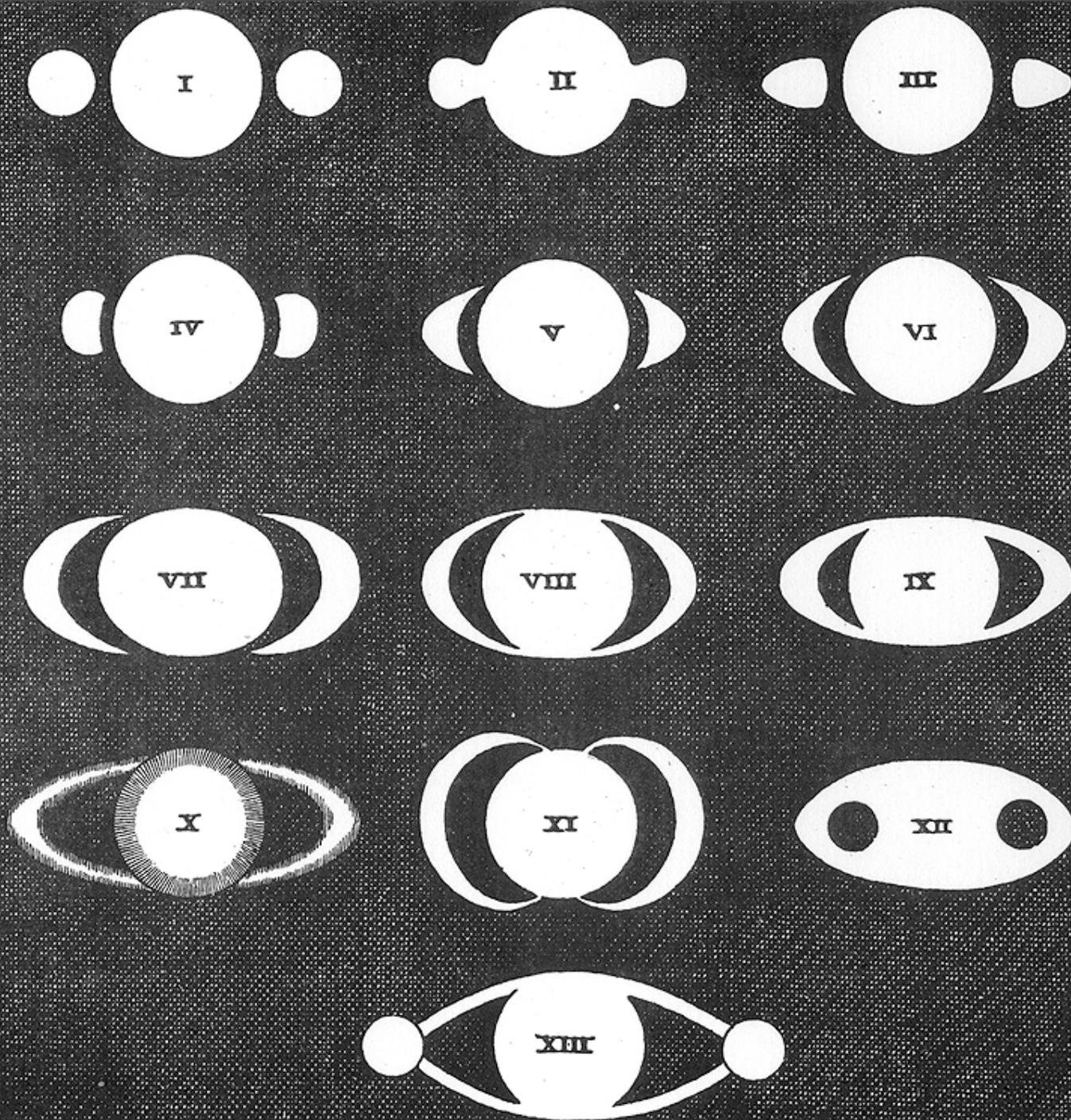
A binary stellar system?

- P1 and P2 have the same colors, except for the compact source P3
- orbital period only 50,000 yr and inspiral time due to dynamical friction from the surrounding galaxy is $\sim 10^8 \times (10^6 M_{\odot}/M)$ yr

Dust?

- colors of P1 and P2 are the same
- double structure is still present in near-infrared; no evidence of color gradient





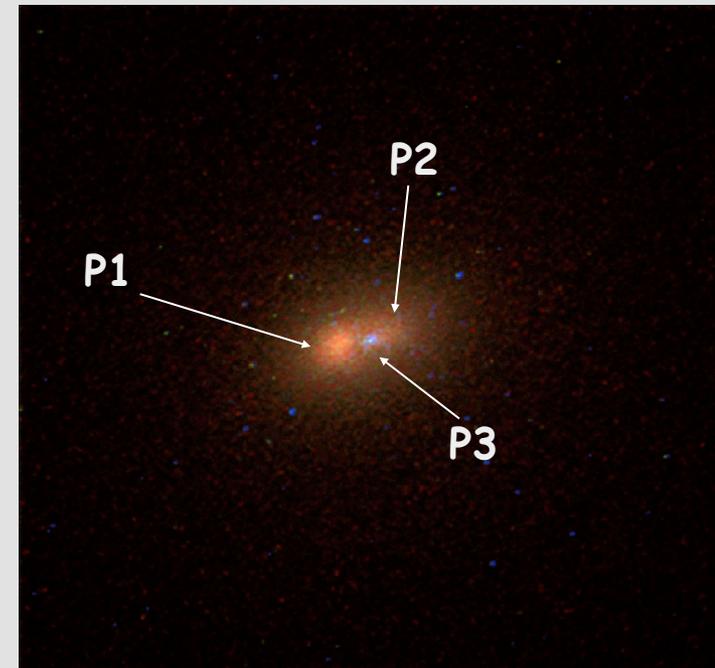
Huygens (1659)

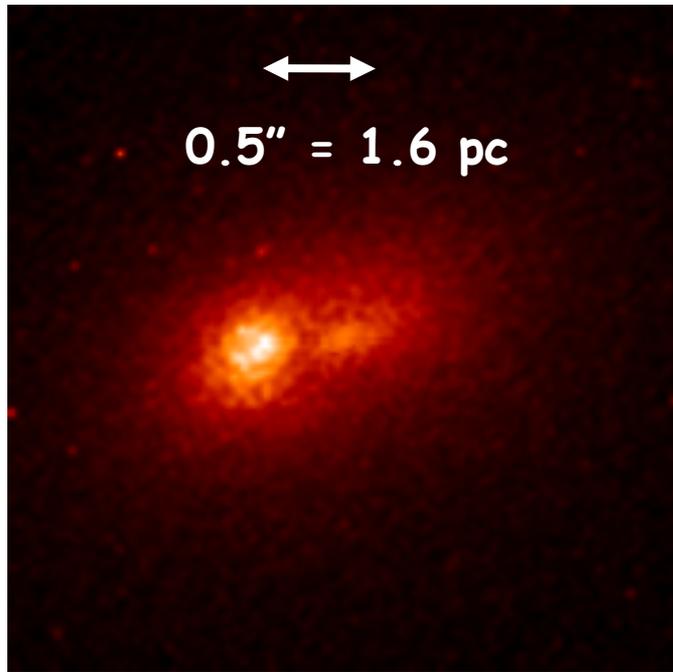
The eccentric-disk model

- nucleus consists of a single massive black hole at P3, surrounded by a disk of stars that is not far from edge-on
- stars in disk are on eccentric, nearly Keplerian orbits which are aligned so that apocenters point in the same direction
- P1 is the portion of the disc close to apocenter; stars move slowly near apocenter so most of them are found in this region at any given time
- P2 is the portion of the disk close to pericenter
- black hole dominates gravitational potential so orbits are approximately closed

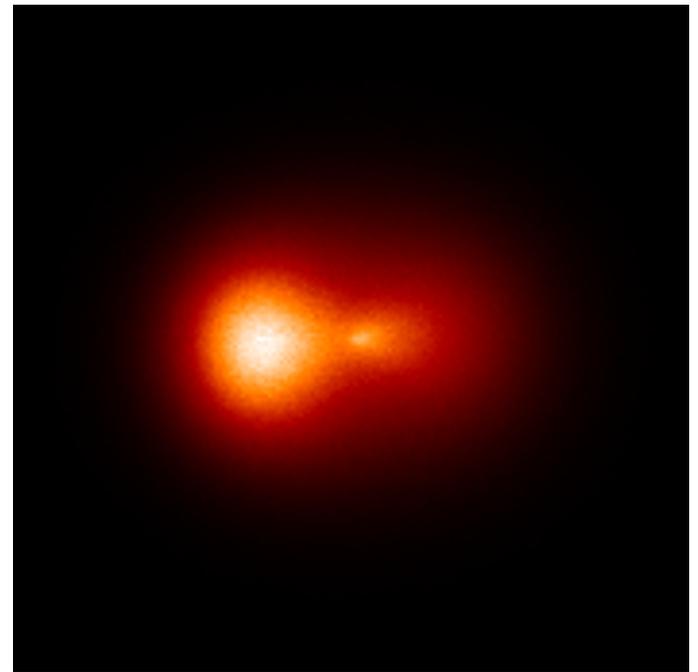
Correctly explains why:

- P2 is almost at the center of the galaxy (the black hole has most of the mass)
- colors of P1 and P2 are the same, and different from the surrounding stars (they're the same stars)
- P2 is cuspy but P1 is smooth (stars are bound to P3 which is near the center of P2)
- P3 is blue and compact (small AGN or cluster of young stars near the black hole)

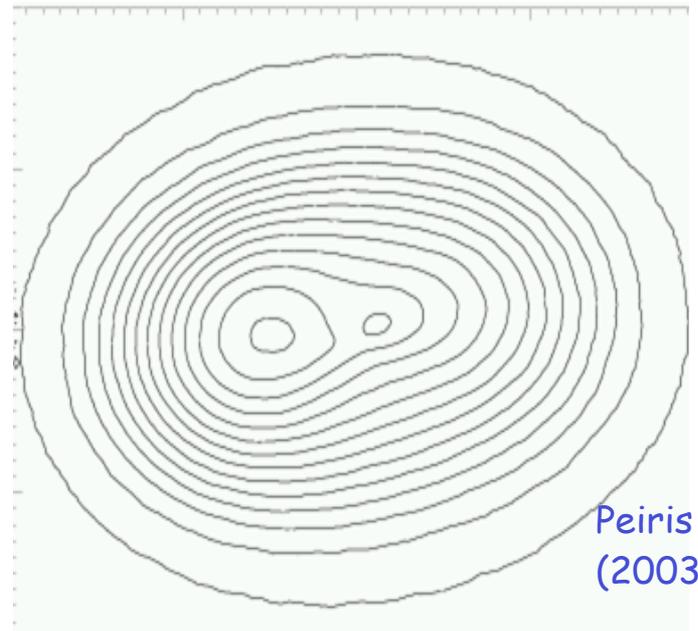




data

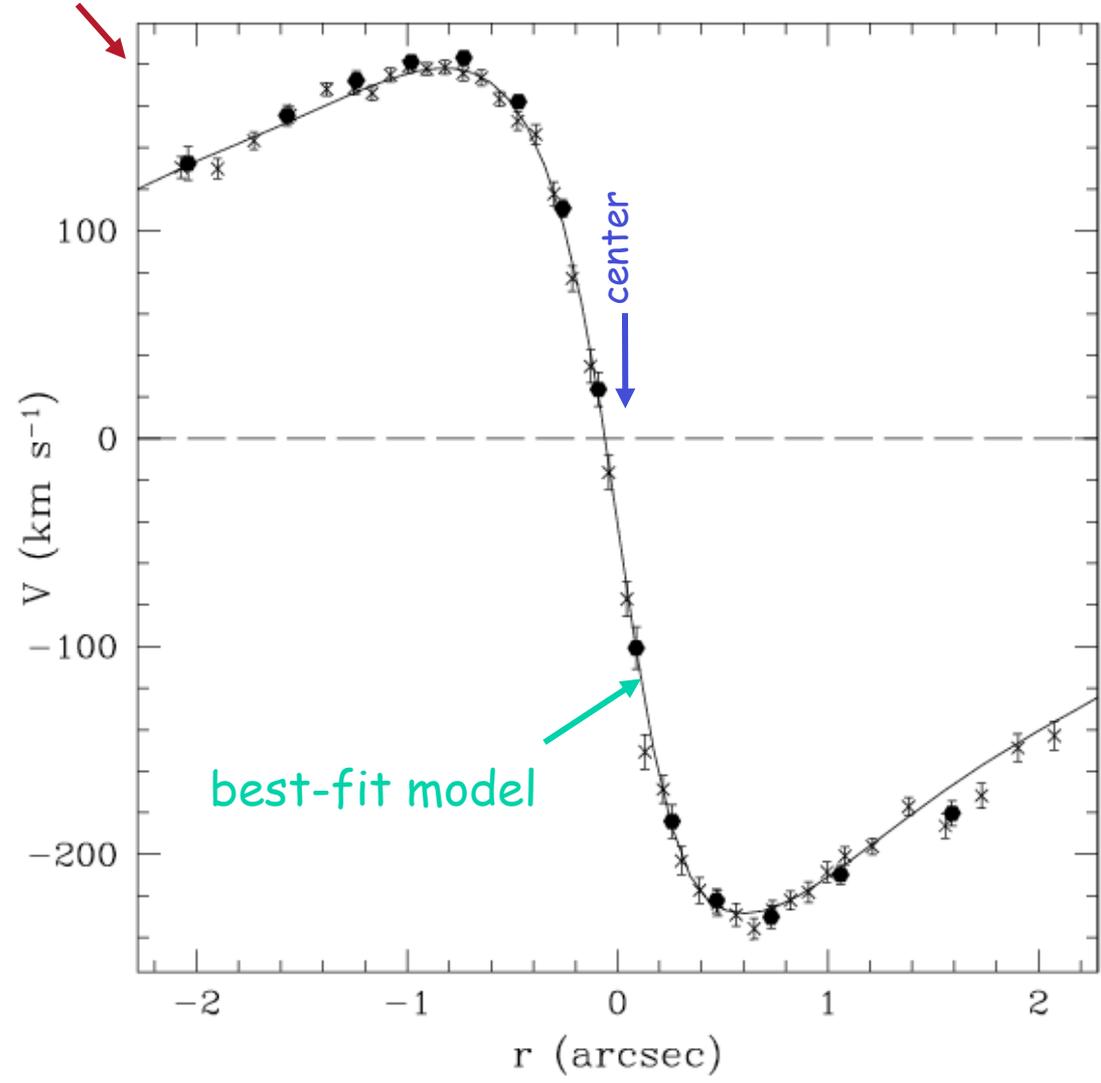


eccentric-disk model



Peiris & ST
(2003)

+180 km/s

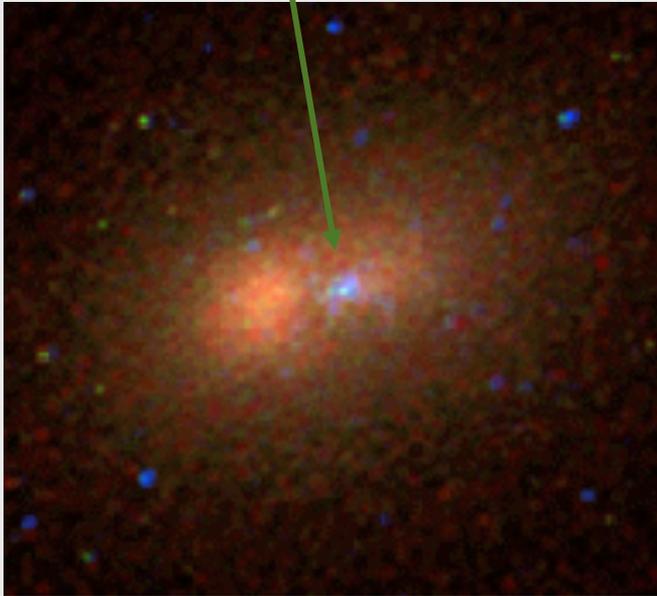


- eccentric disk model correctly and automatically reproduces rotation and dispersion curves
- required black-hole mass is $M_{\text{BH}} = 1 \times 10^8 M_{\odot}$

-230 km/s

data from Kormendy & Bender (1999)

HST spectra of P3

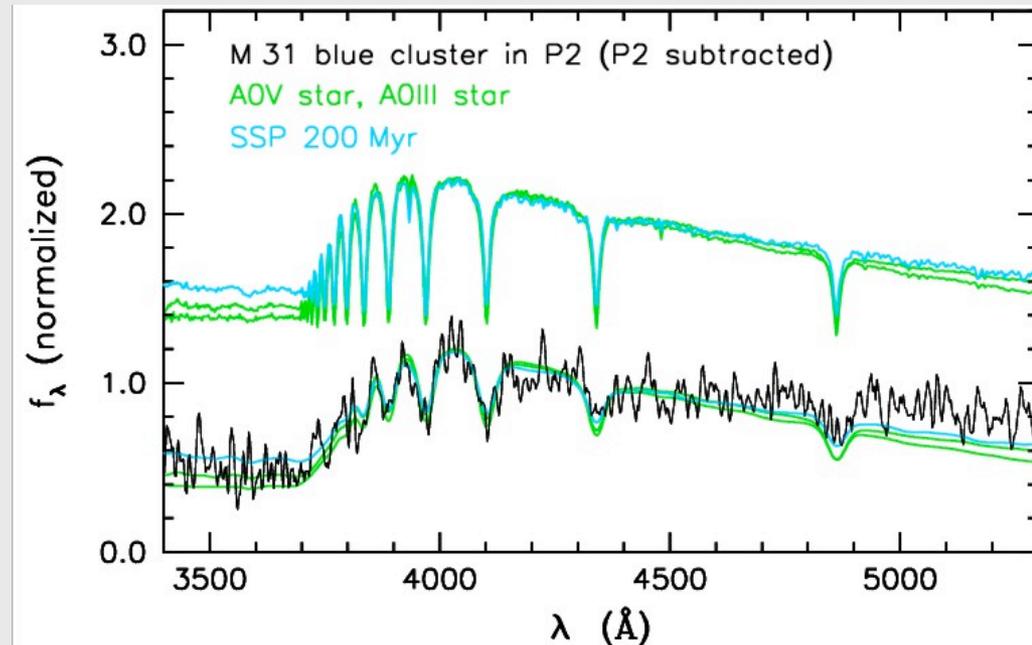


The blue nucleus is a cluster of stars with age ~ 200 Myr. Its mass is about $5000 M_{\odot}$. Its velocity dispersion within $0.1'' = 0.3$ pc is:

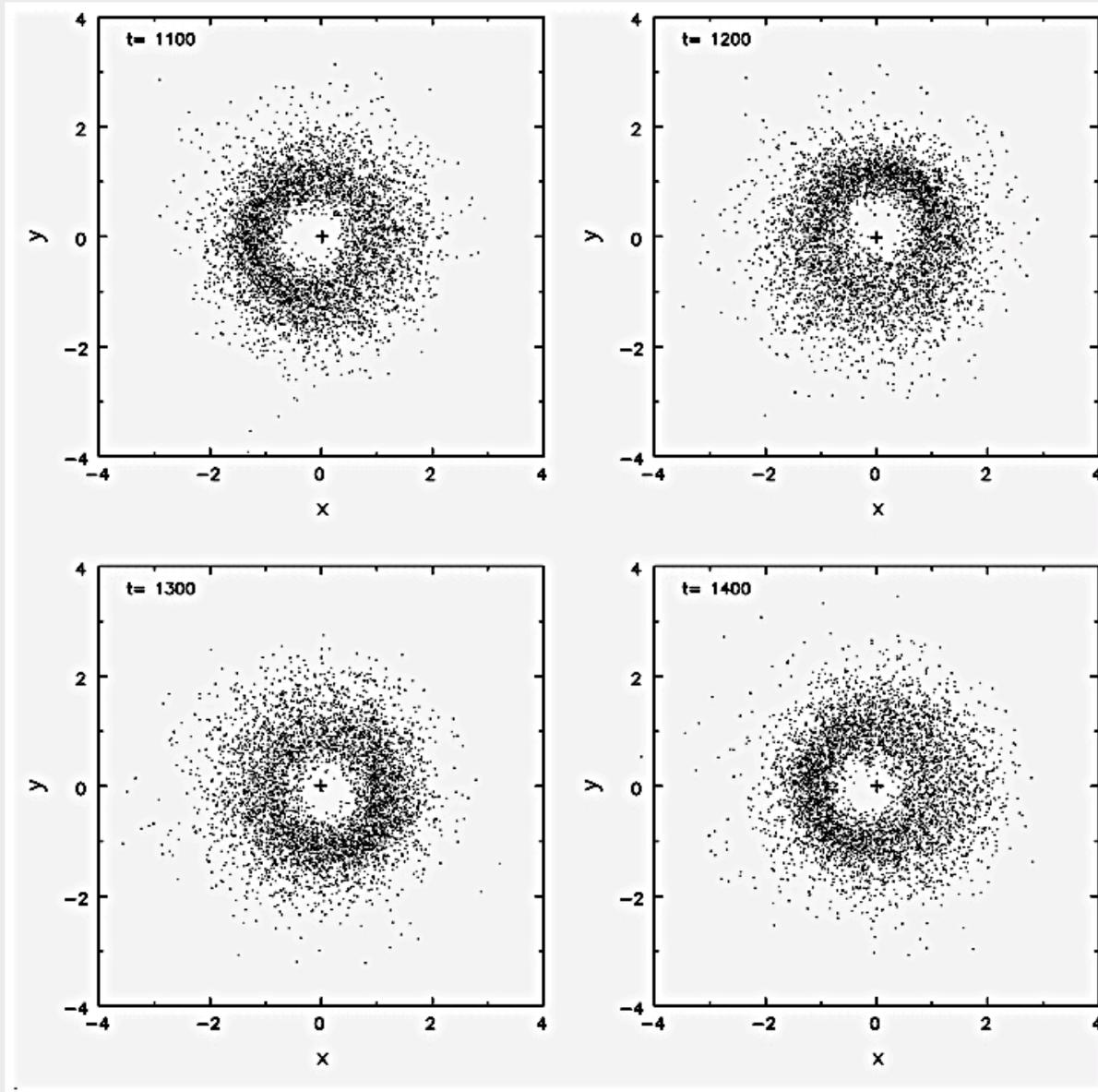
$$\sigma = 960 \pm 106 \text{ km/s}$$

compared to average M31 dispersion of 150 km/s (!)

Bender et al. (2005)



- The best fit is obtained for a point mass, i.e. a black hole of mass
 $M \sim 1.4 \times 10^8 M_{\odot}$
- an extended mass of radius $> 0.03'' \sim 0.1$ pc is 1-sigma off from the BH solution
- consistent with, and independent of, analysis of P1-P2 kinematics on 10 X larger scale ($M \sim 1 \times 10^8 M_{\odot}$)



Jacobs & Sellwood (2001)

- simulated low-mass disks around a point mass
- $N=100,000$ grid-based simulations
- “we were able to generate long-lived eccentric disks with quite remarkable ease”
- no spirality
- no sign of decay over ~ 700 orbits

eccentric disks could form through:

- disruption of cluster on eccentric orbit (but the disk mass is $\sim 10^7 M_{\odot}$, $\sim 10X$ larger than any single globular cluster)
- secular evolution due to dynamical friction from the bulge (if pattern speed of disk $>$ mean rotation of bulge)
- instabilities induced by counter-rotating stars (Touma 2002)
- fossil remnant of "feeding the monster" (Hopkins & Quataert 2010)

3. Statistical mechanics in galaxy centers

- near the centers of galaxies the relaxation time due to gravitational encounters can be less than the age \Rightarrow centers should be in some kind of thermodynamic equilibrium
- for an isolated self-gravitating system the virial theorem states that kinetic energy K , potential energy W , and total energy $E=K+W$ are related by

$$2K+W=0, \quad E=-K, \quad E=W/2.$$

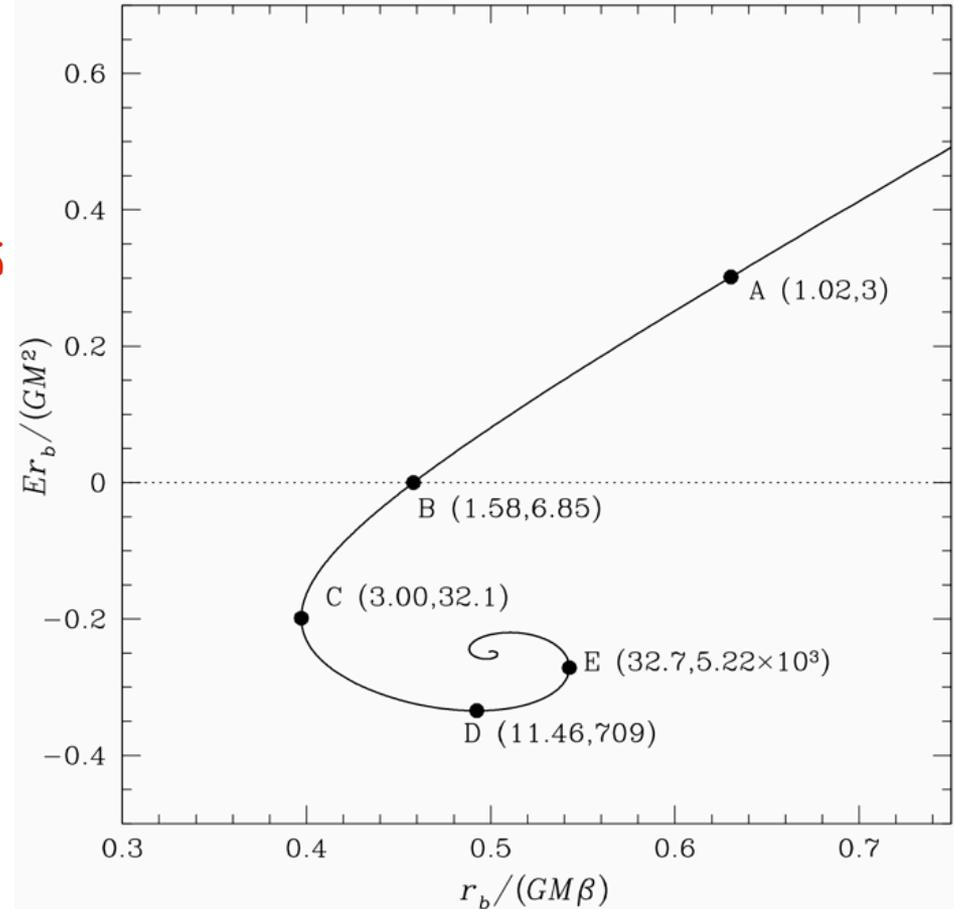
In a gas $K=3/2 NkT$. Then $E=-3/2 NkT$ and heat capacity is

$$C=dE/dT=-3/2 Nk.$$

Heat capacity is negative. Any system with negative heat capacity that is in contact with a heat bath is unstable.

- consider a spherical box of radius r_b containing a mass M of gas of energy E and temperature T , $\beta=1/kT$
- if the box is in contact with a heat bath it is unstable beyond point C
- if the box is insulating, imagine expanding it suddenly
 - an insulating box is unstable beyond point D
 - develops a core-envelope structure in which the envelope (positive heat capacity) and core (negative heat capacity) both grow steadily hotter (the "gravothermal catastrophe")

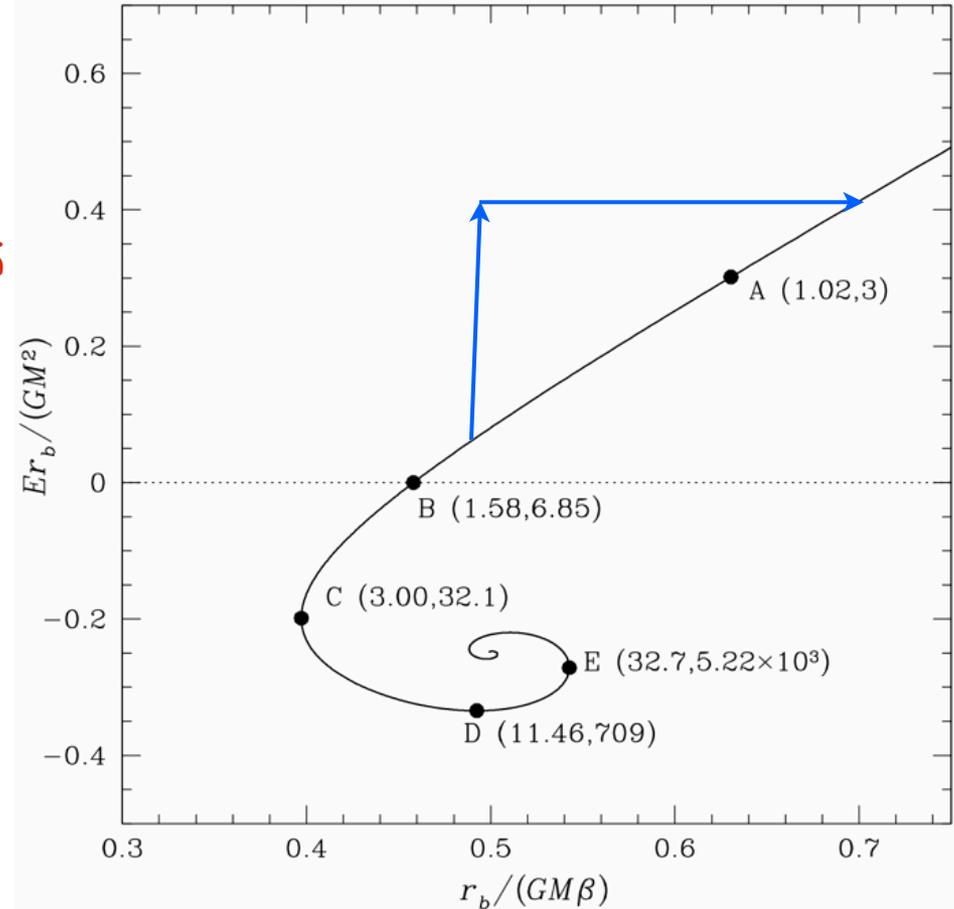
dimensionless energy



dimensionless temperature

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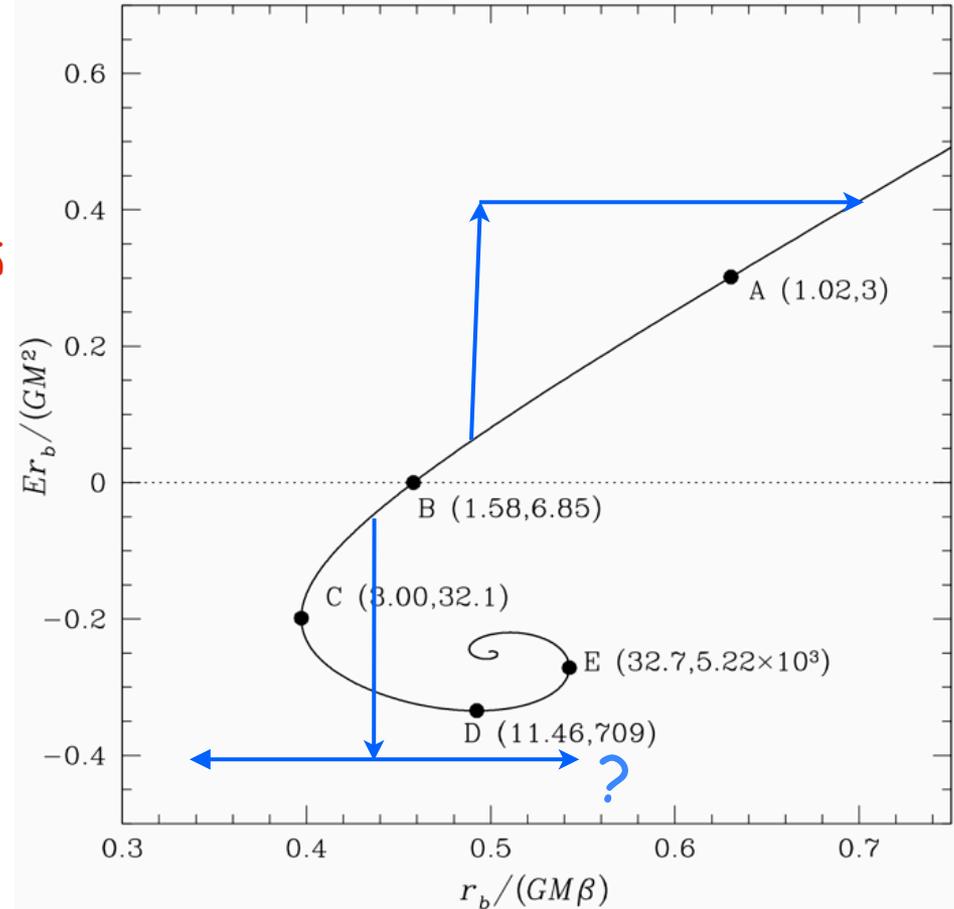
dimensionless energy



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dimensionless energy



dimensionless temperature

- what happens if a black hole is present?
- thermodynamic equilibrium in potential $\Phi = -GM/r$ yields density

$$n(r) \propto \exp\left(\frac{-\Phi}{kT}\right) \propto \exp\left(\frac{GMm}{kTr}\right)$$

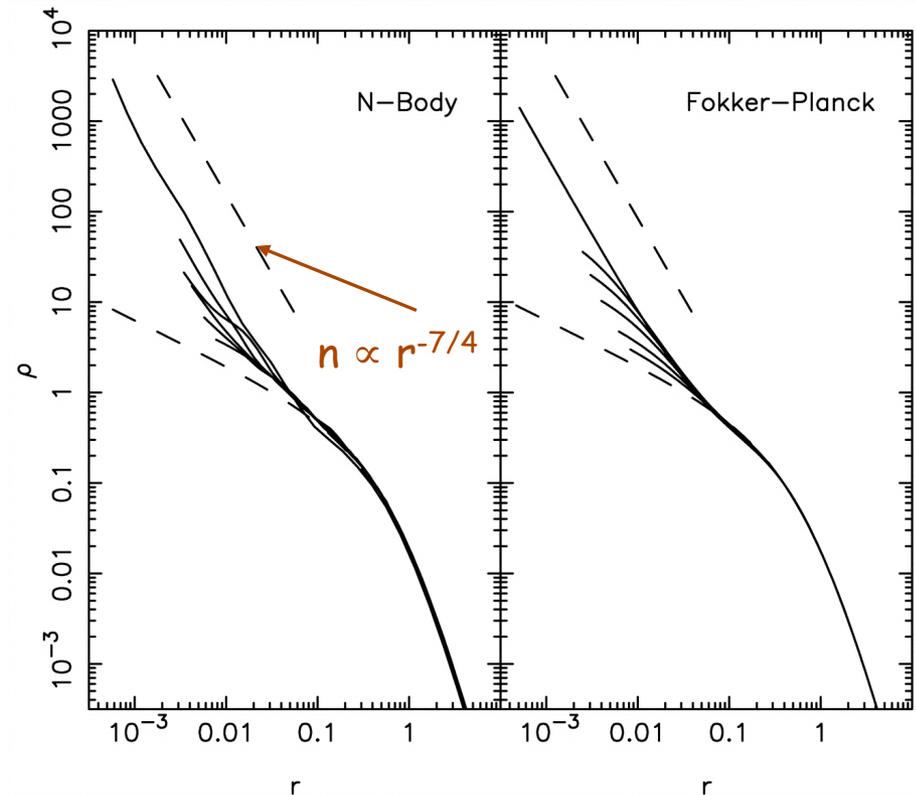
Boltzmann constant \rightarrow kT
temperature (10^{63}K) \rightarrow kTr
stellar mass \rightarrow GMm

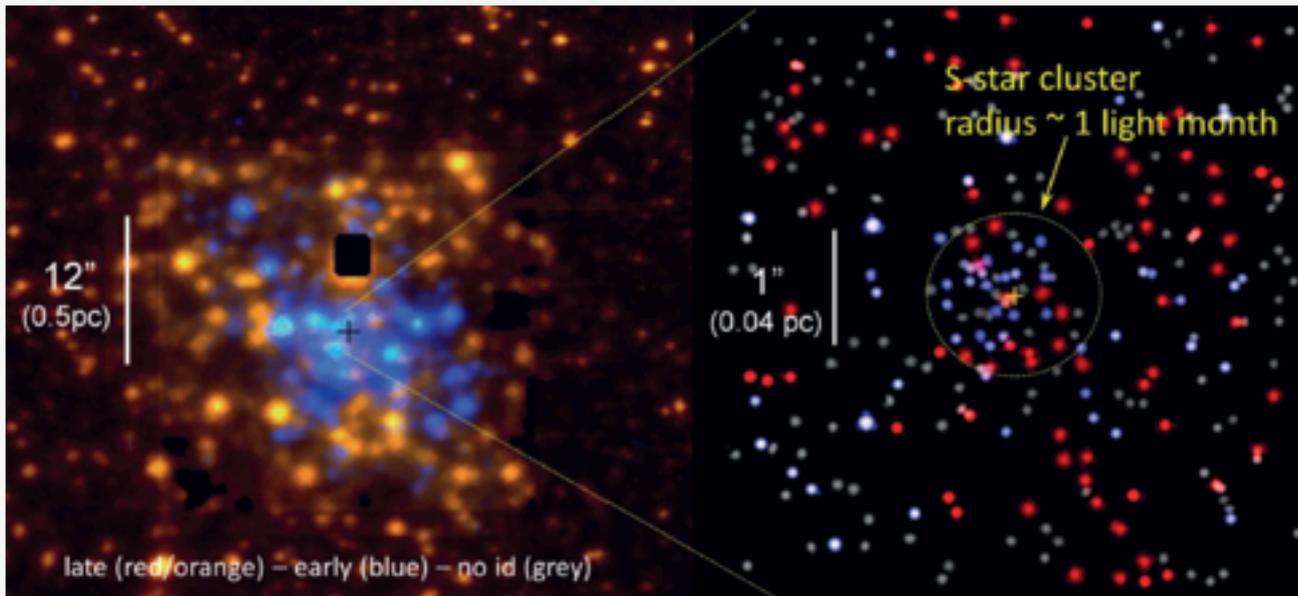
Preto et al. (2004)

- this doesn't apply because stars at small radii are eaten by the black hole
- correct solution for a single stellar mass, including absorbing boundary condition, is (Bahcall & Wolf 1976)

$$n(r) \propto r^{-7/4}$$

- this is not easy to test in Milky Way because (i) wide range of masses, distribution of masses not well known; (ii) recent star formation; (iii) possible dark remnants



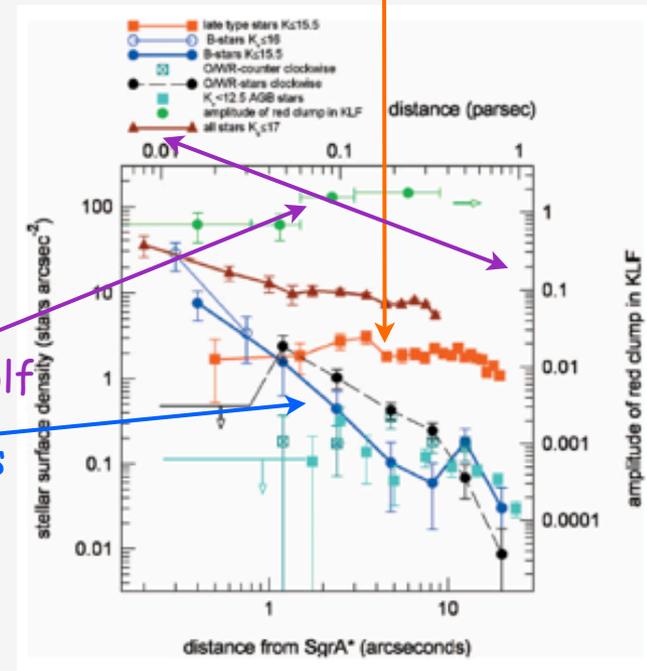


Genzel et al. (2010)

- massive, young, blue stars have $n(r) \sim r^{-2.5}$; cannot be Bahcall-Wolf cusp because ages shorter than relaxation time
- old stars have a flat distribution at $r < 0.5$ pc; cannot be Bahcall-Wolf cusp because even multi-mass cusps are steeper than r^{-1}
- collisions could deplete old stars?
- not yet relaxed?
- inspiral of intermediate-mass black hole?

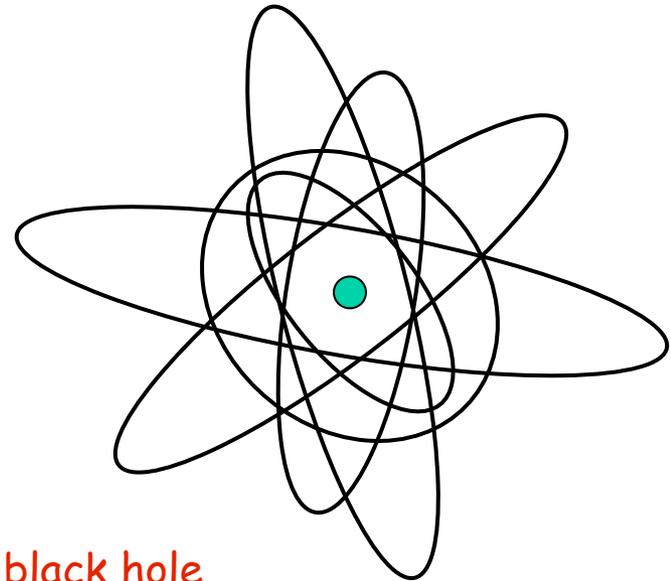
Bahcall-Wolf
young stars

old stars



Resonant relaxation

- inside ~ 0.5 pc gravitational field is dominated by the black hole ($M_{\text{stars}} < 10^5 M_{\odot}$, $M_{\text{BH}} \sim 4 \times 10^6 M_{\odot}$) and therefore is nearly spherical
- on timescales longer than the apsidal precession period each stellar orbit can be thought of as a disk or annulus
- each disk exerts a torque on all other disks, leading to precession or wobble
- mutual torques can lead to relaxation of orbit normals or angular momenta
- energy (semi-major axis) and scalar angular momentum (or eccentricity) of each orbit is conserved, but vector angular momentum or orbit normal is not



$$t_{\text{relax}} \simeq t_{\text{orbital}}(r) \frac{M}{mN^{1/2}(r)}$$

← mass of the black hole
← number of stars inside radius r
← orbital period
← mass of a star

Rauch & Tremaine (1996)

Resonant relaxation

- interaction energy between stars i and j is $m_i m_j f(a_i, a_j, e_i, e_j, \cos \mu_{ij})$ where μ_{ij} is the angle between the orbit normals



- simplify this drastically by assuming equal masses, equal semi-major axes, circular orbits, and neglecting all harmonics other than quadrupole

Resulting interaction energy between two stars i and j is just

$$- C \cos^2 \mu_{ij}$$

where μ_{ij} is the angle between the two orbit normals \mathbf{n}_i and \mathbf{n}_j

$$\frac{d\mathbf{n}_i}{dt} = - \frac{2C}{\sqrt{GMa}} \sum_{j \neq i} (\mathbf{n}_i \cdot \mathbf{n}_j) \mathbf{n}_i \times \mathbf{n}_j$$

Resonant relaxation

Interaction energy between two stars is

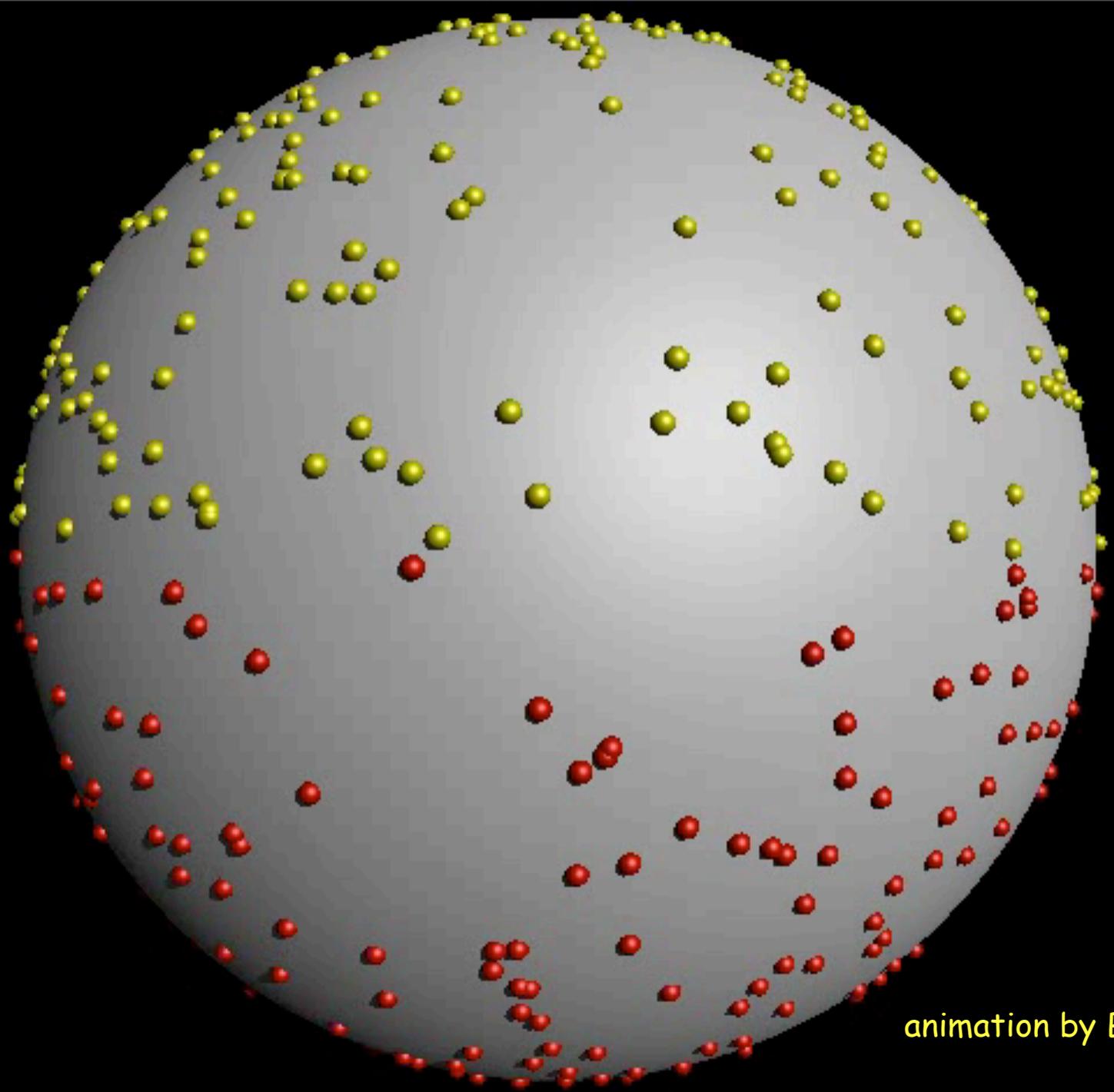
$$H = -C \cos^2 \mu$$

where μ is the angle between the two orbit normals

- 800 stars
- each point represents tip of orbit normal
- orbit normals initially in northern hemisphere are yellow, south is red

$$\frac{d\mathbf{n}_i}{dt} = -\frac{2C}{\sqrt{GMa}} \sum_{j \neq i} (\mathbf{n}_i \cdot \mathbf{n}_j) \mathbf{n}_i \times \mathbf{n}_j$$

animation by B. Kocsis



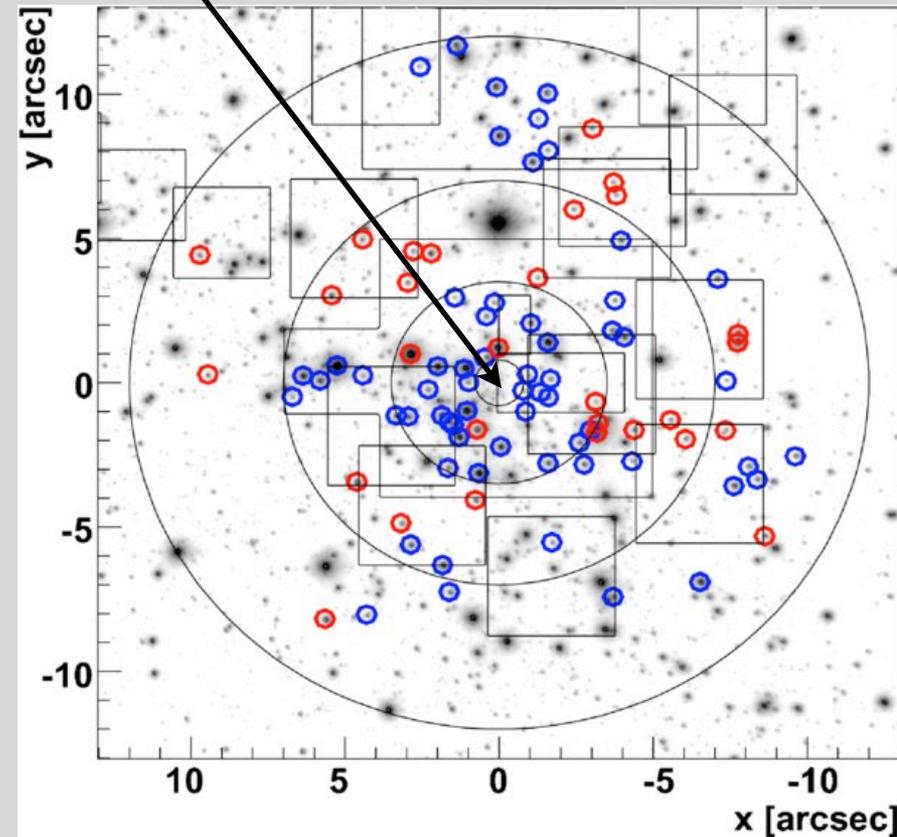
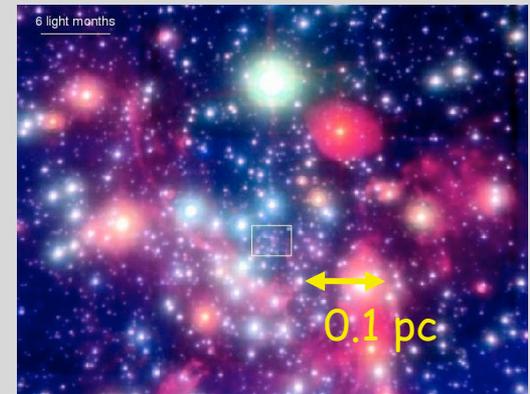
animation by B. Kocsis

The disk(s) in the Galactic center

- ~ 100 massive young stars found in the central parsec (at larger radii than the S stars); estimated total mass $5-10 \times 10^3 M_{\odot}$
- disks are embedded in a spherical cluster of old, fainter stars with $M(0.2 \text{ pc}) \sim 2 \times 10^5 M_{\odot}$
- age $6 \times 10^6 \text{ yr}$
- line-of-sight velocities measured by Doppler shift and angular velocities measured by astrometry → five of six phase-space coordinates
- many of velocity vectors lie close to a plane, implying that many of the stars are in a disk or perhaps 2 disks (Levin & Beloborodov 2003)

blue = clockwise orbits

red = counter-clockwise orbits

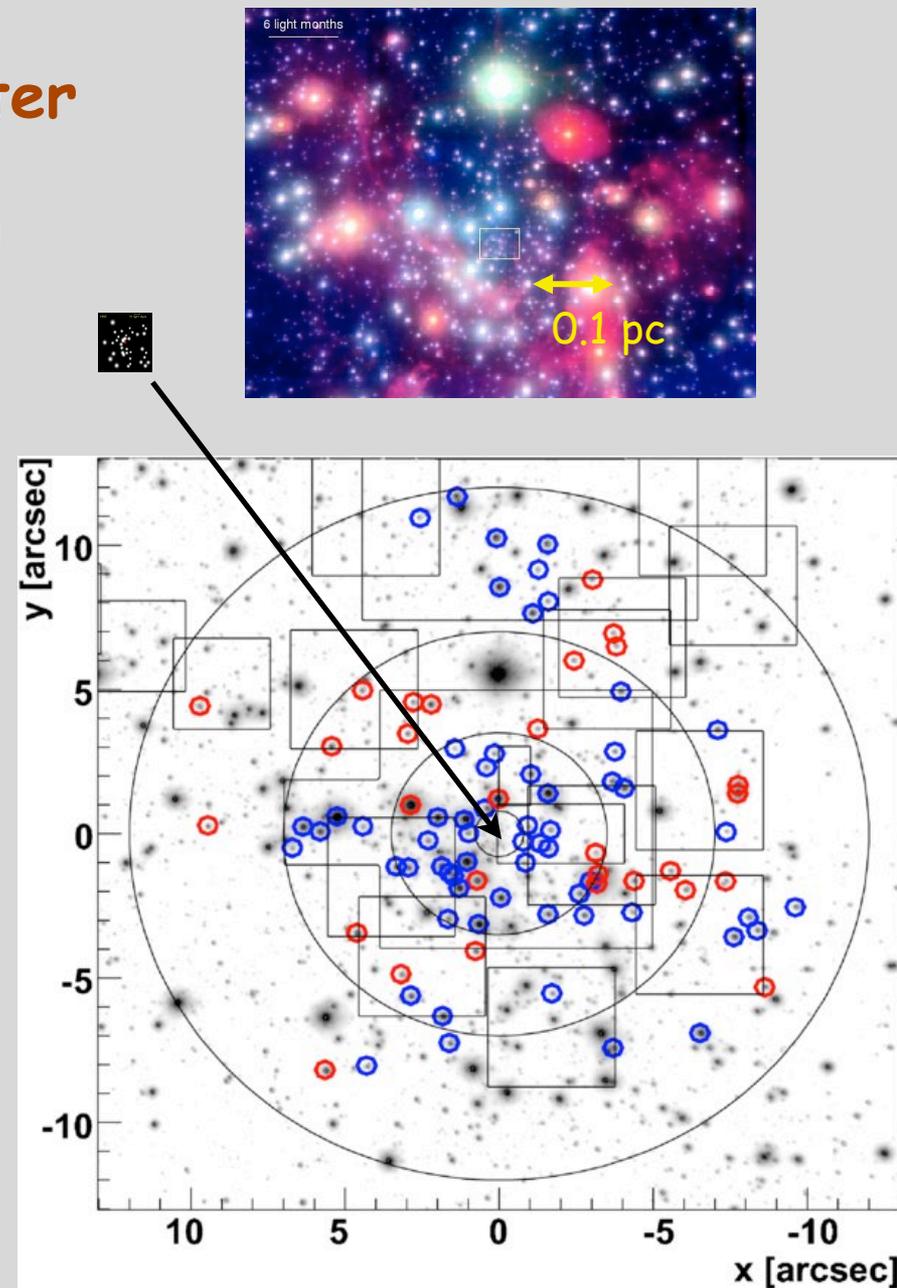


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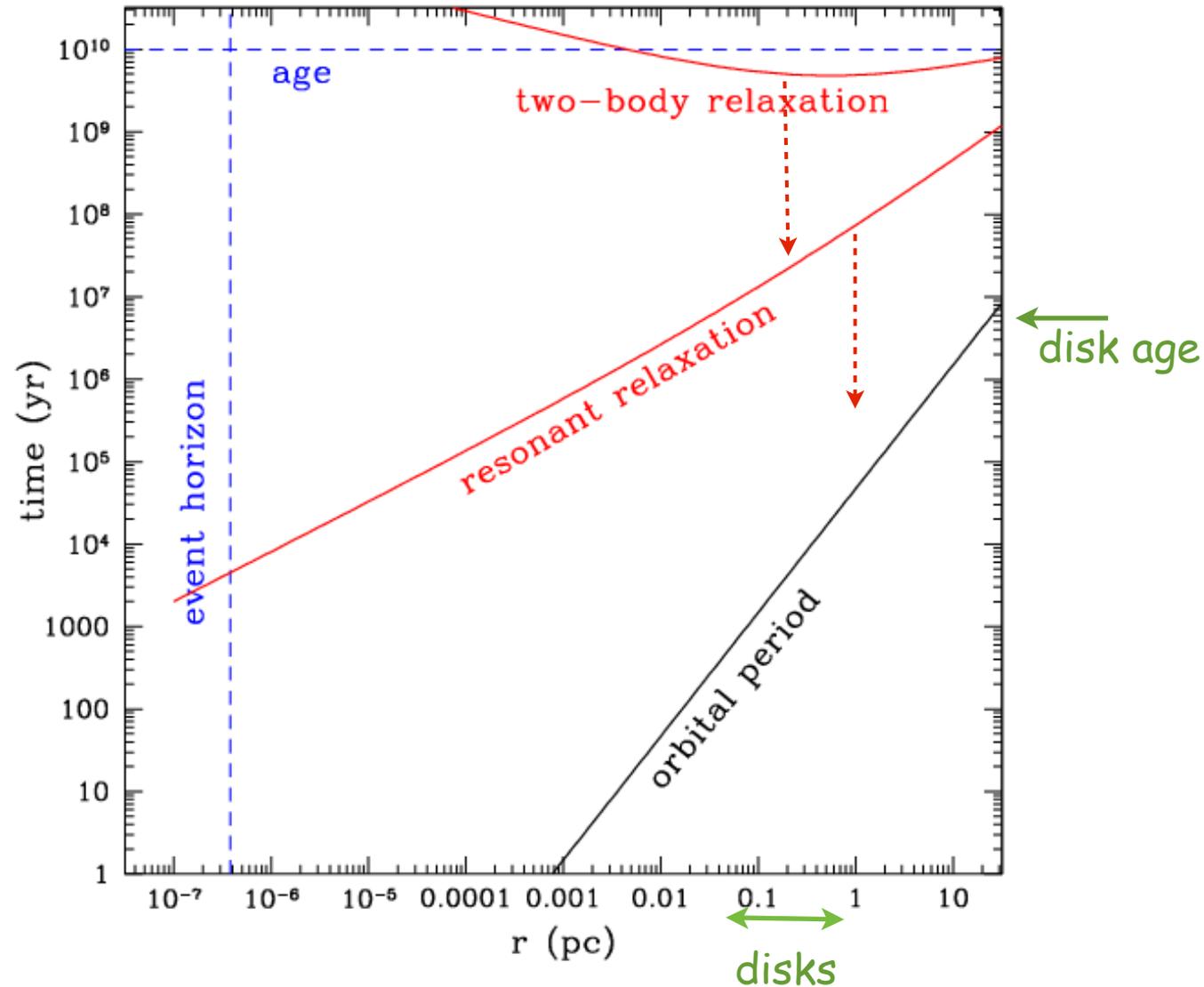
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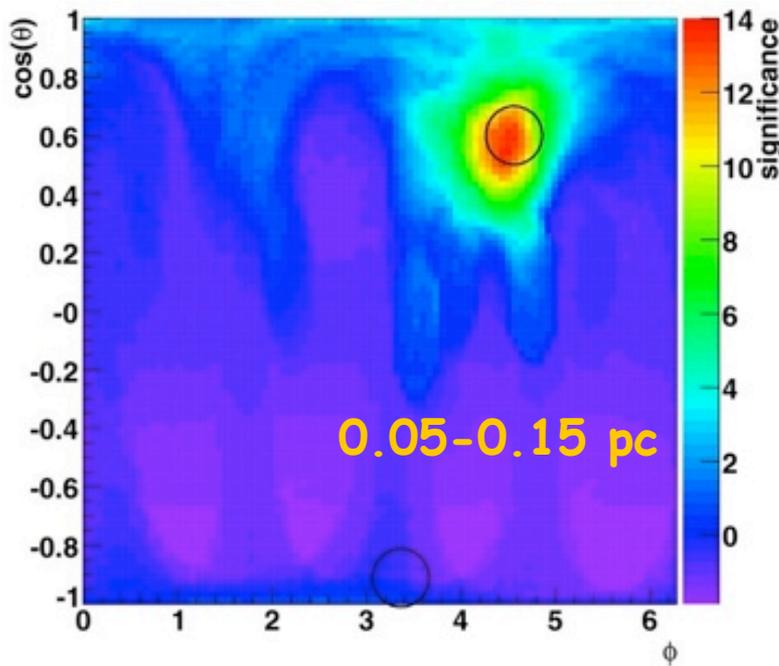


Resonant relaxation in dense stellar systems

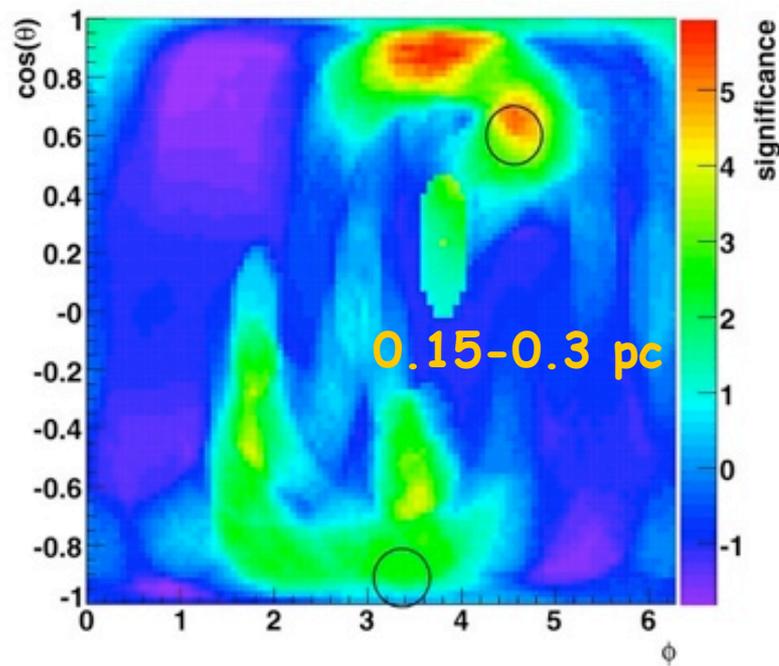
plot shows relaxation time for solar-mass stars but actual relaxation rate varies as $M\langle m^2 \rangle$ where M is disk-star mass and $\langle m^2 \rangle$ is mean-square mass in surrounding cluster

- visible disk stars are $M > 20 M_{\odot}$



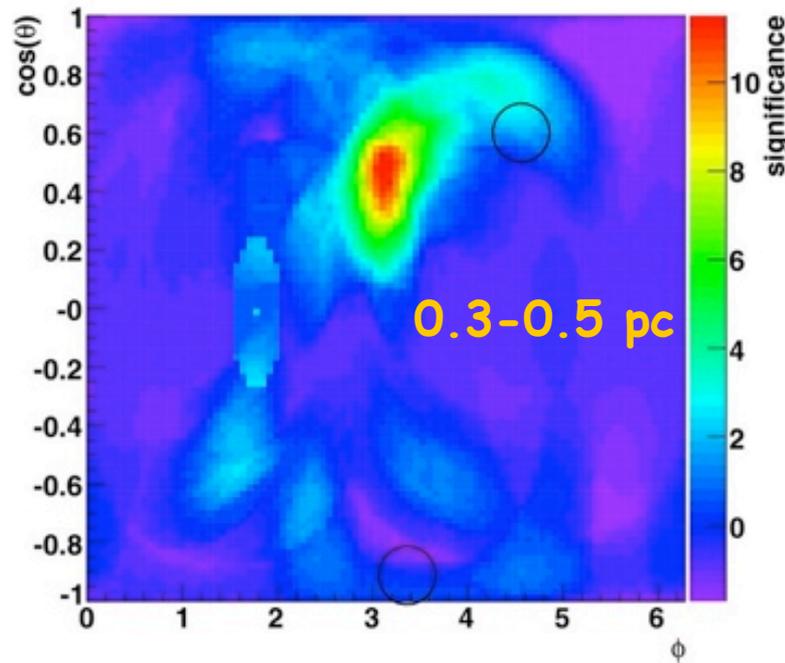


0.05-0.15 pc



0.15-0.3 pc

~30 stars
per panel;
data from
Bartko et al.
(2009)



0.3-0.5 pc

• **clockwise disk:**

- warped (best-fit normals in inner and outer image differ by 60°)
- disk is less well-formed at larger radii

• **counter-clockwise disk:**

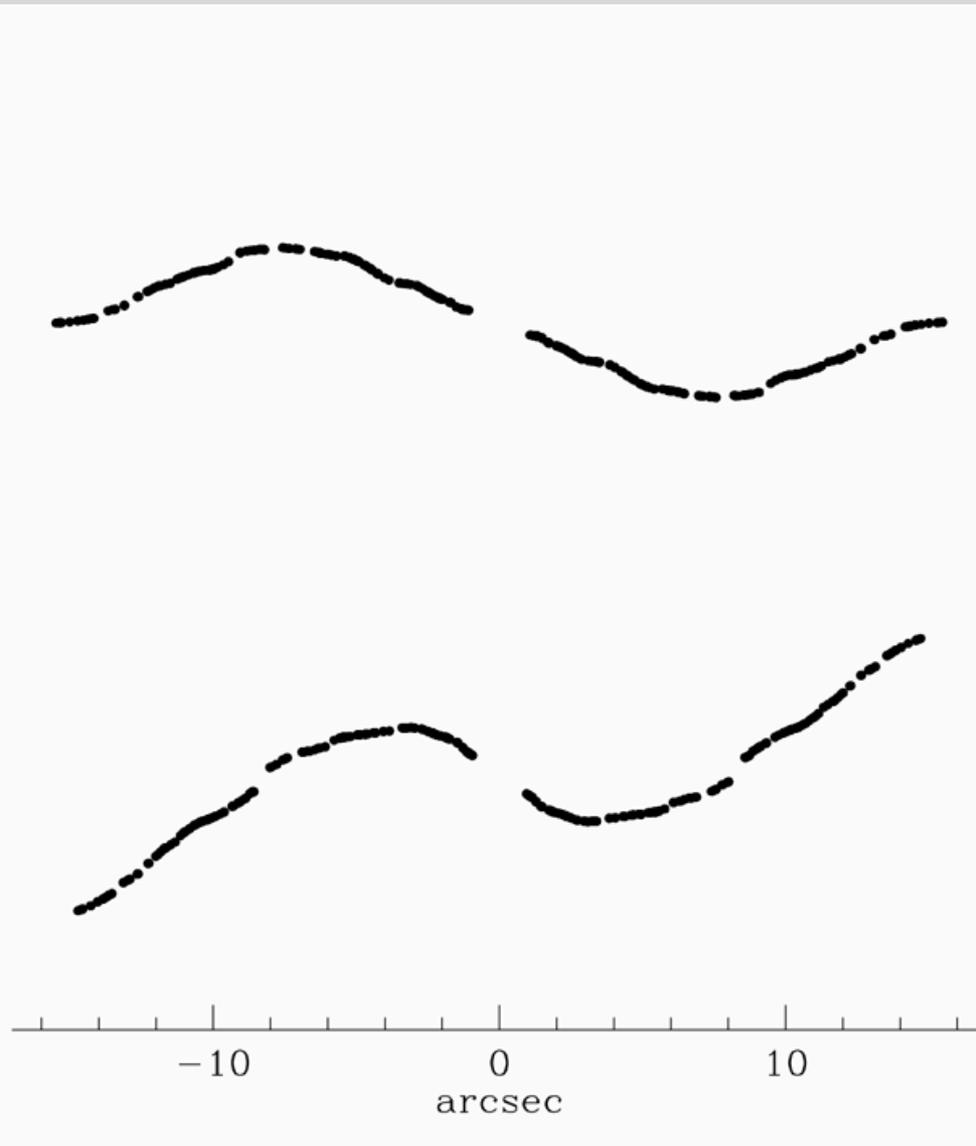
- weaker evidence
- localized between 0.1 and 0.3 pc

The disk(s) in the Galactic center

- take initially thin, flat disk with the same surface density and stellar mass distribution as the observed disks
- embed in a spherical cluster of old stars with the same properties as the nuclear stars in the Milky Way
- evolve for 6 Myr under resonant relaxation
- principal uncertainty: relaxation rate scales as $\langle m^2 \rangle / \langle m \rangle$ which depends on IMF, fate of massive remnants, globular clusters, molecular clouds, etc.
- method 1: semi-analytic perturbation theory
- method 2: N-body integrations ("bodies" = orbit-averaged disks)

The disk(s) in the Galactic center

$$\langle m^2 \rangle / \langle m \rangle = 10 M_{\odot}$$



- shows two orthogonal edge-on cuts through the disk after 6 Myr

- the surrounding cluster warps the disk but doesn't thicken it

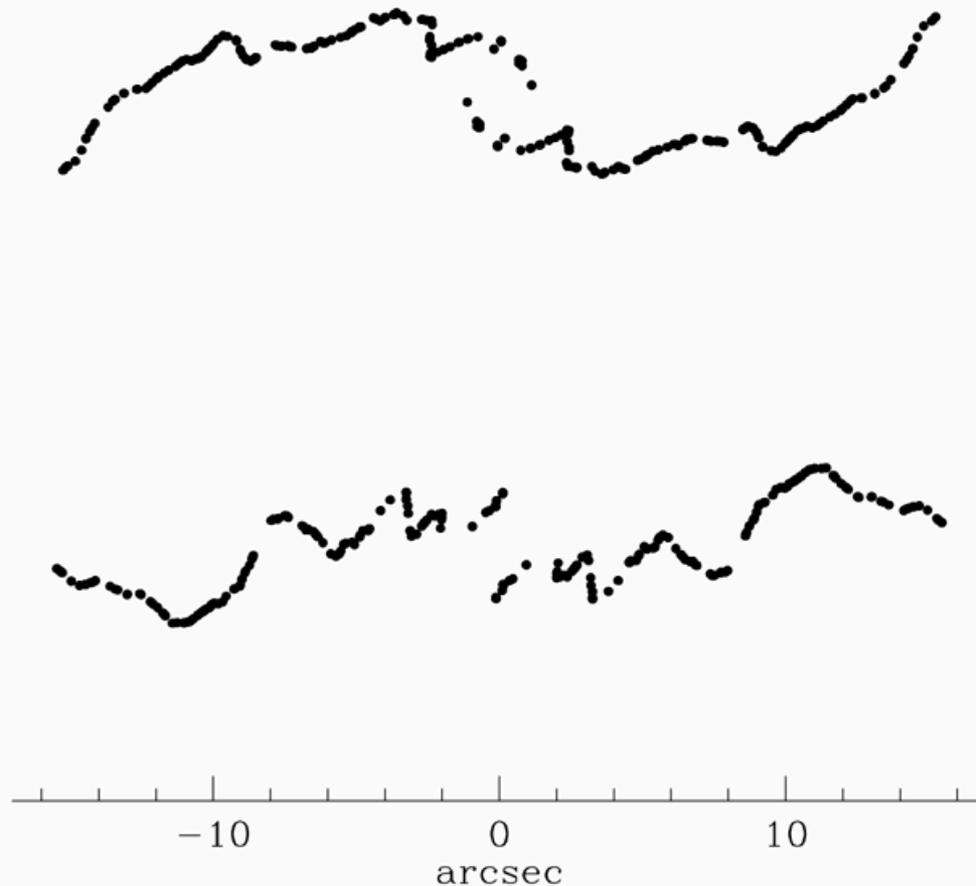
- ordinary two-body relaxation thickens the disk but it remains flat; resonant relaxation warps the disk but it remains thin, because:

- orbit-averaged perturbers have less small-scale power than point masses

- because of the disk self-gravity, small-scale normal modes have high frequency so are adiabatically invariant

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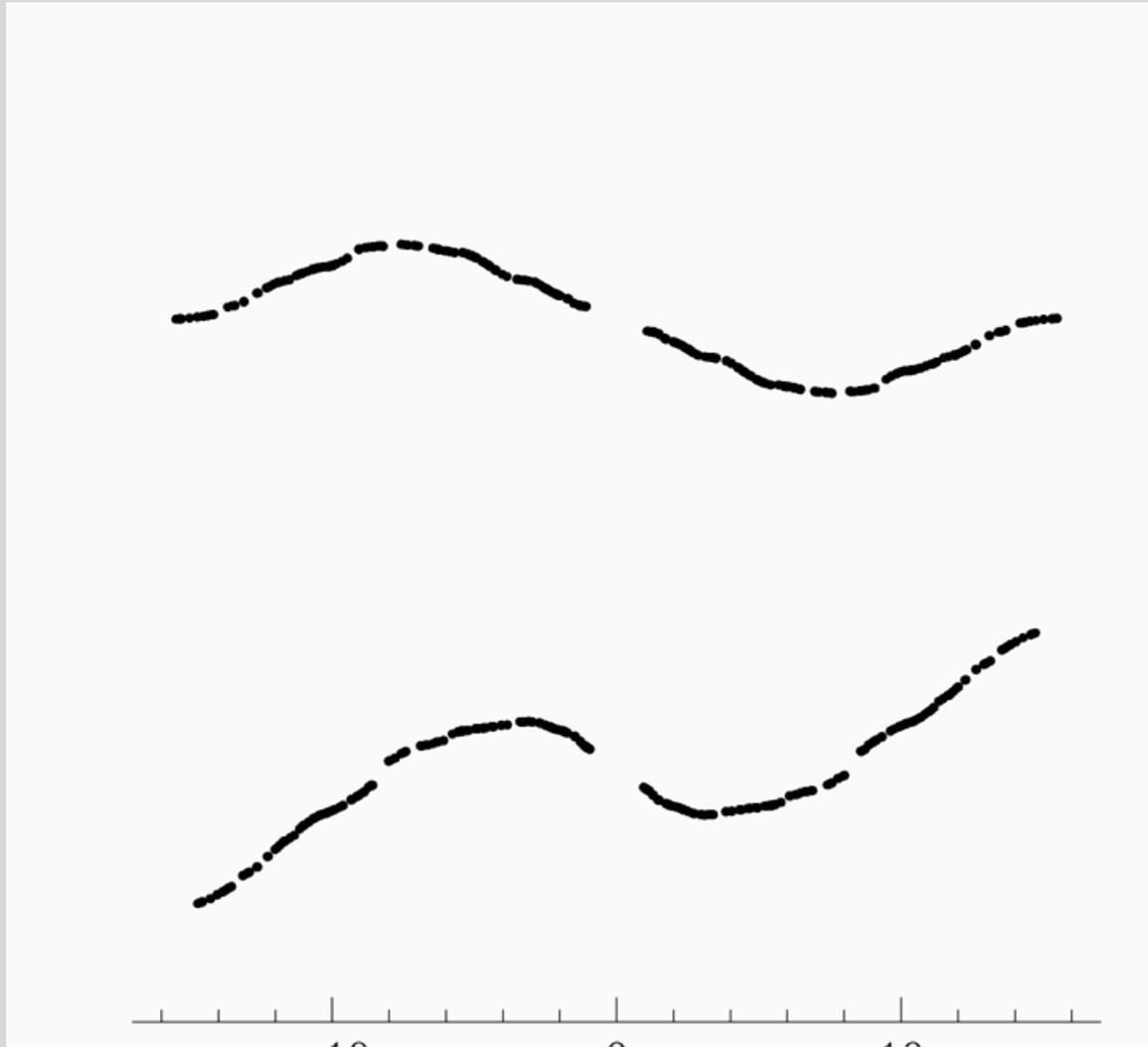
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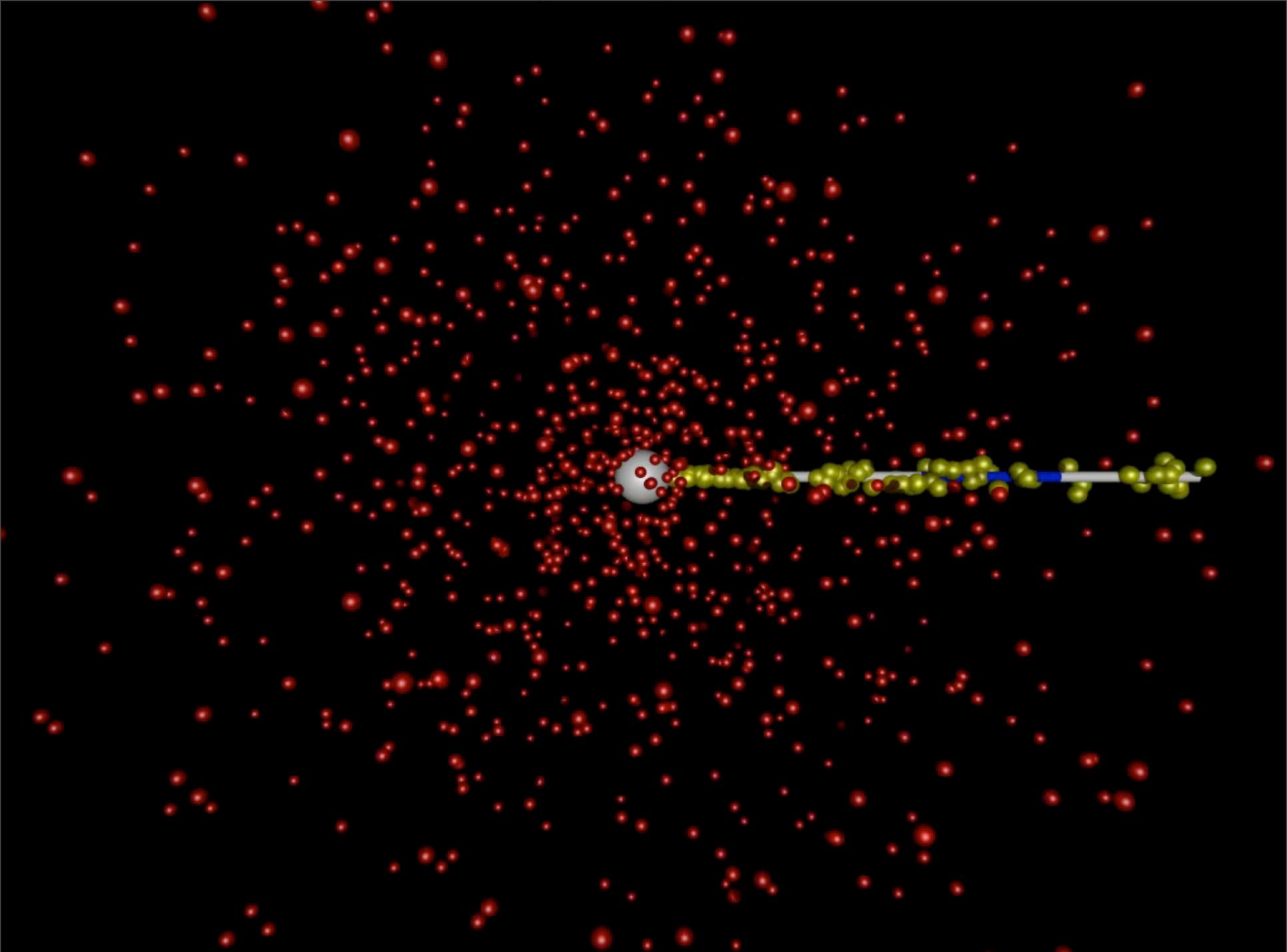


disk warps arise naturally and inevitably from resonant relaxation

Resonant relaxation

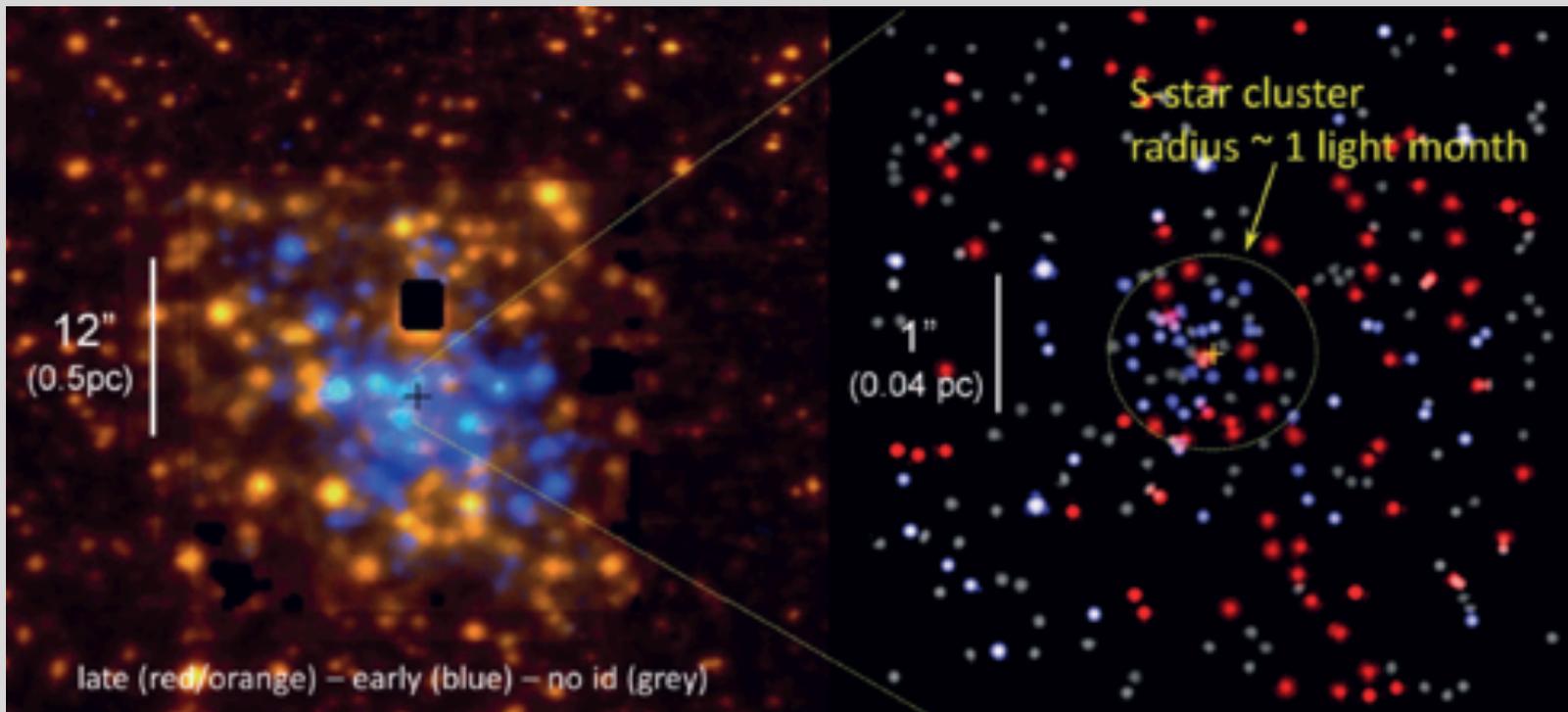
- interaction energy between stars i and j is $m_i m_j f(a_i, a_j, e_i, e_j, \cos \mu_{ij})$ where μ_{ij} is the angle between the orbit normals
- integrate orbit-averaged equations of motion for 6 Myr
- yellow = disk stars, red = stars in spherical cluster
- direction and radius of each point represents direction of angular-momentum vector and semi-major axis of star

animation by B. Kocsis



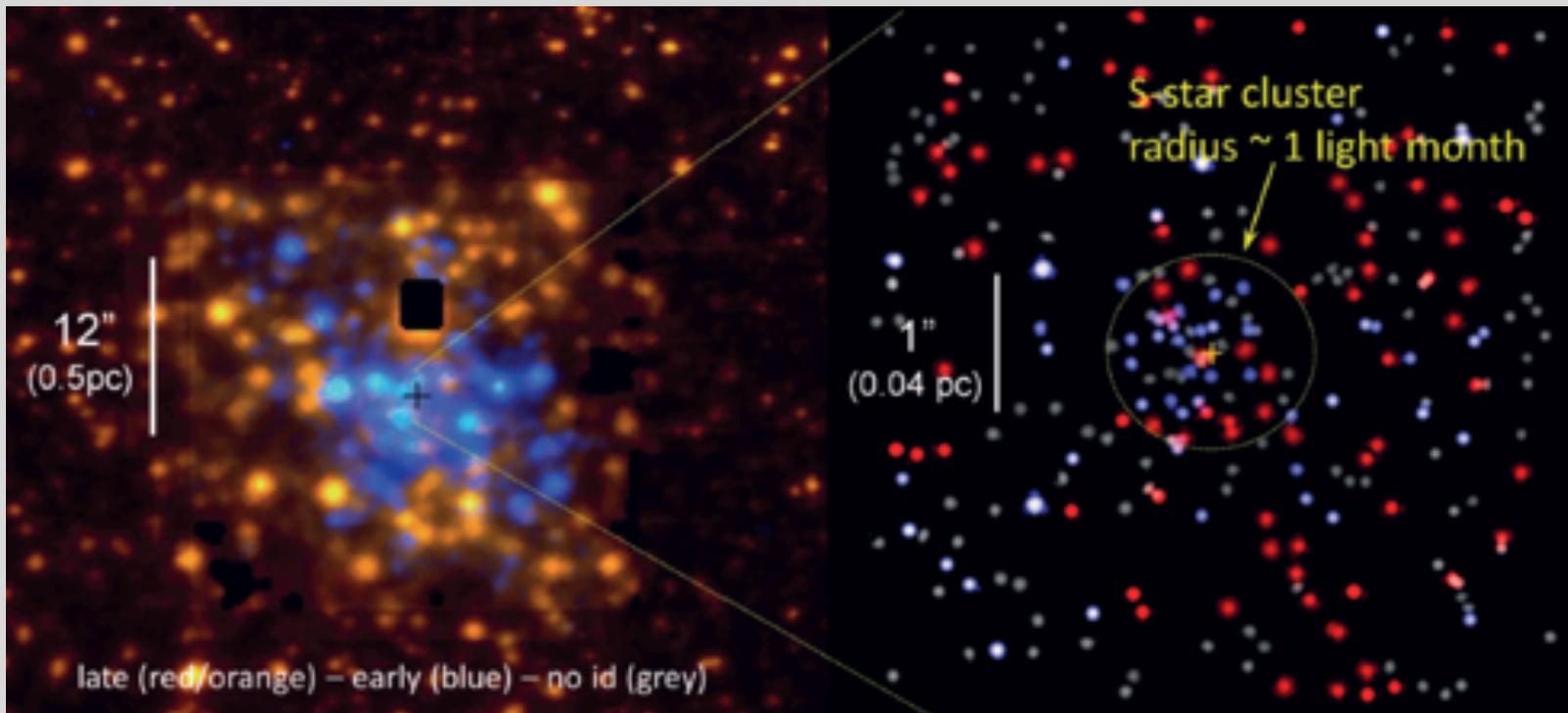
Star formation in the central parsec

- there are many young (< 10 Myr) stars in the central pc of the Milky Way (blue supergiants, main-sequence O and B stars, Wolf-Rayet stars, etc.)
 - clockwise and counter-clockwise disks at 0.1-0.5 pc
 - the S-star cluster at < 0.03 pc
- how did they get there?



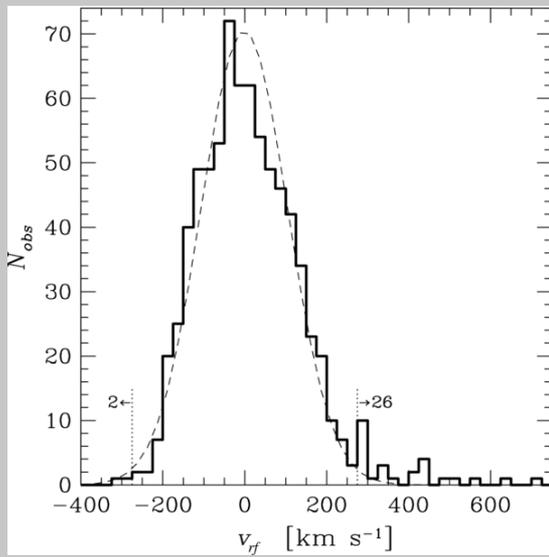
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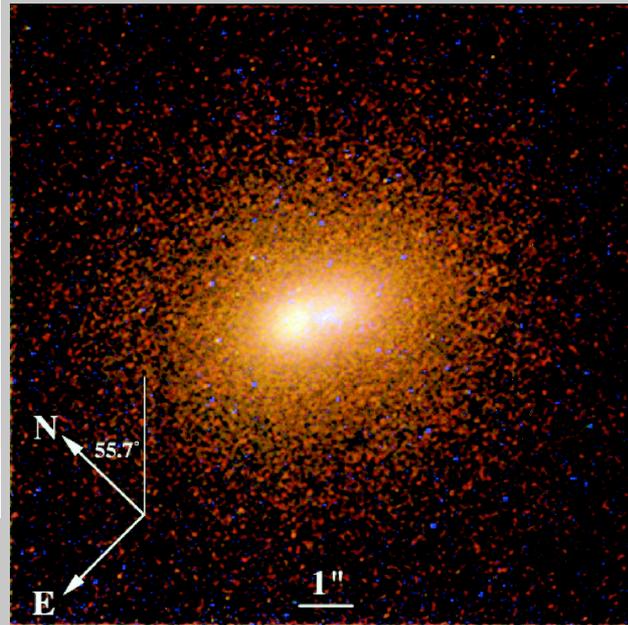


Star formation in the central parsec

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- how did they get there?
- strong tidal shear makes gravitational collapse difficult (required density $\sim 10^4$ X larger than in surrounding gas clouds)
- possible solutions:
 - star formation in cooling shocks in an infalling molecular cloud
 - inspiral of a dense star cluster (but needs densities larger than in any known cluster)
 - inspiral of an $10^4 M_{\odot}$ black hole surrounded by stars
 - migration in a gas disk
 - Hills mechanism (sisters of the hypervelocity stars)

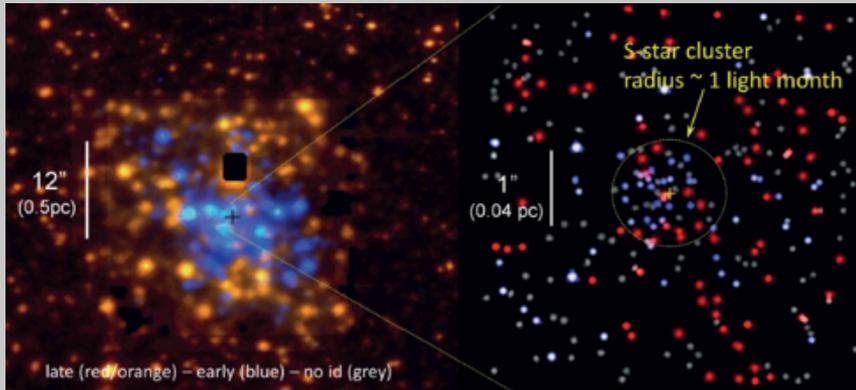
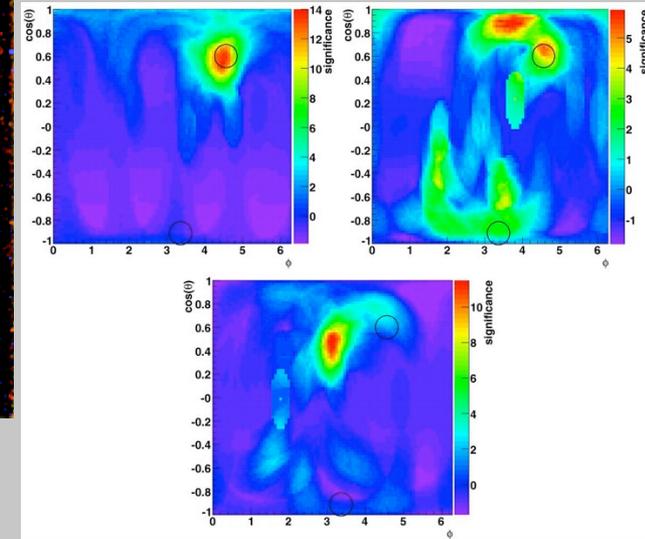


hypervelocity stars



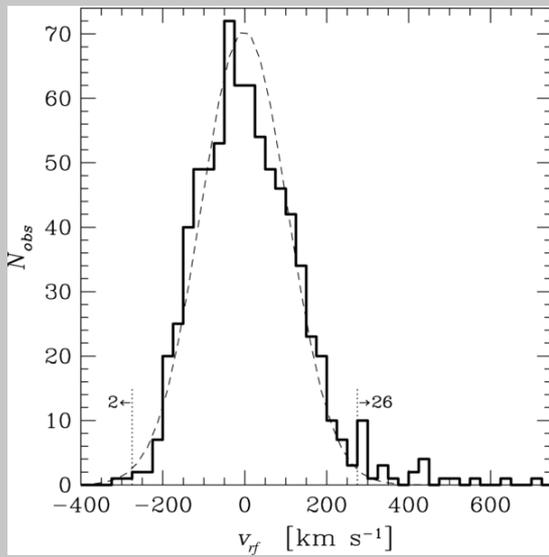
double nucleus of M31

young disks in the Galactic center

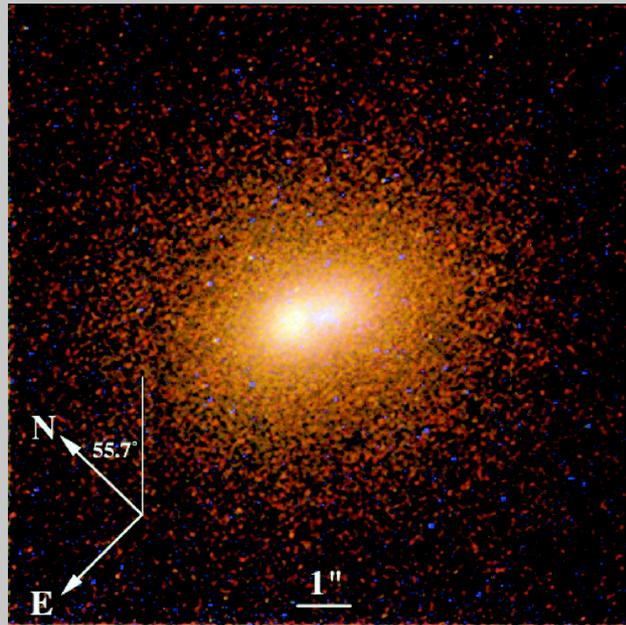


distribution of old stars in the central pc of the Galaxy

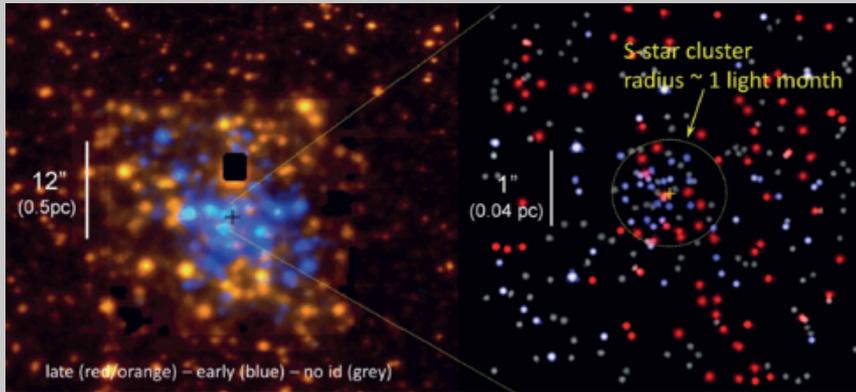
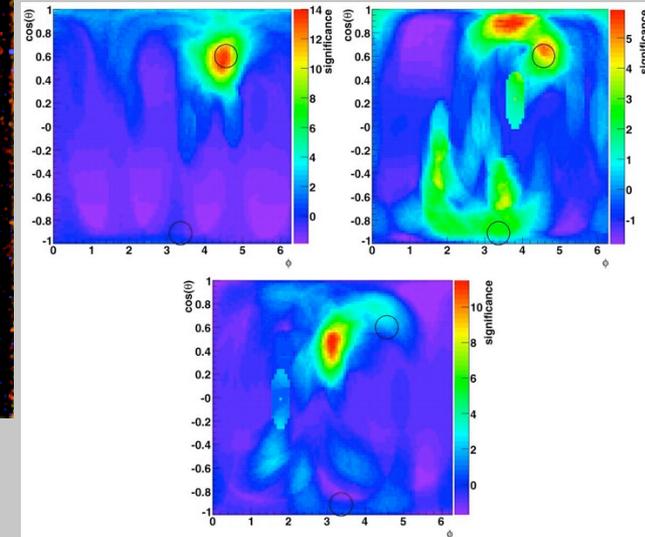
resonant relaxation



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double nucleus of M31
young disks in the Galactic center



distribution of old stars in the central pc of the Galaxy

resonant relaxation

