Dynamical Schwarzschild models of globular clusters

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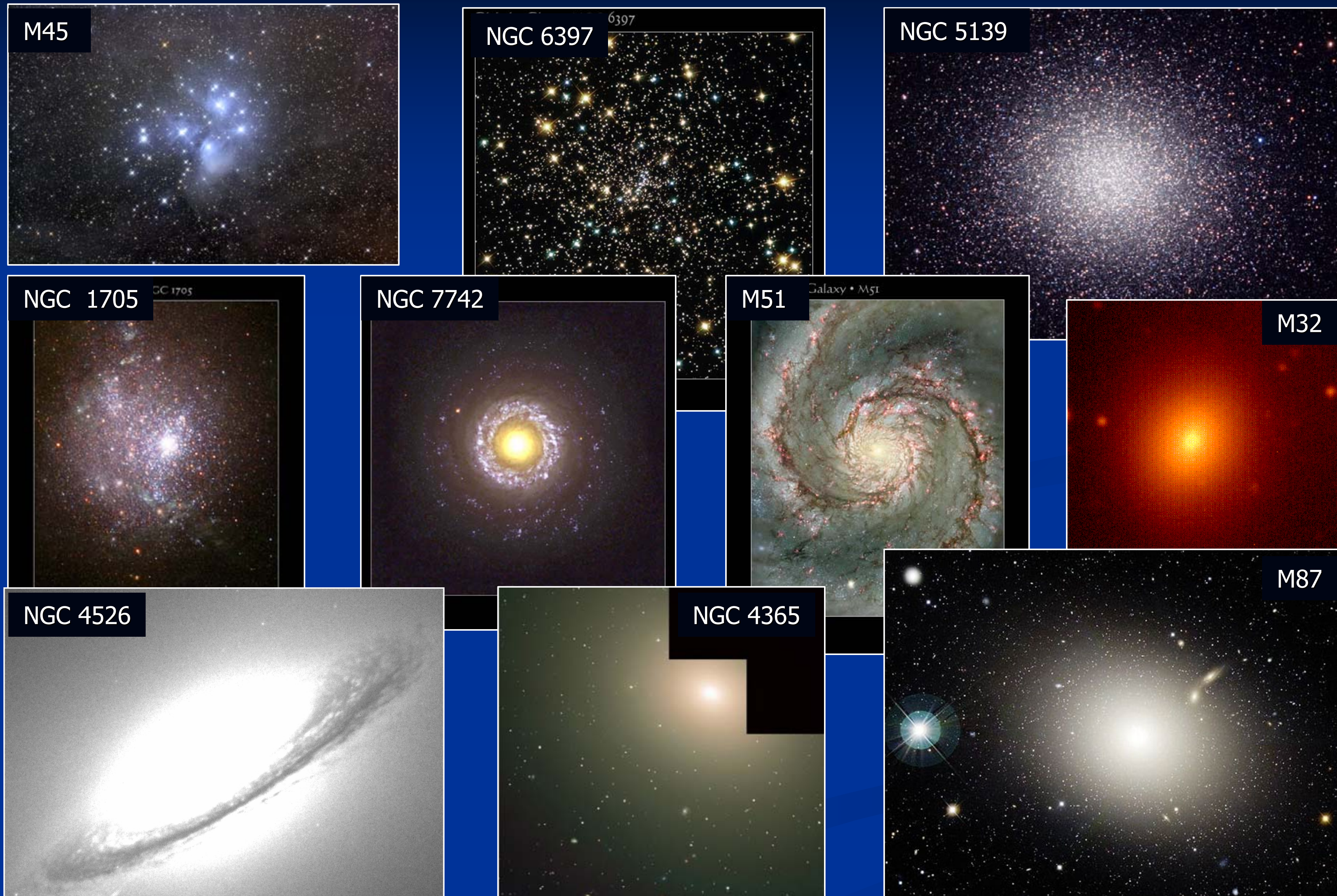
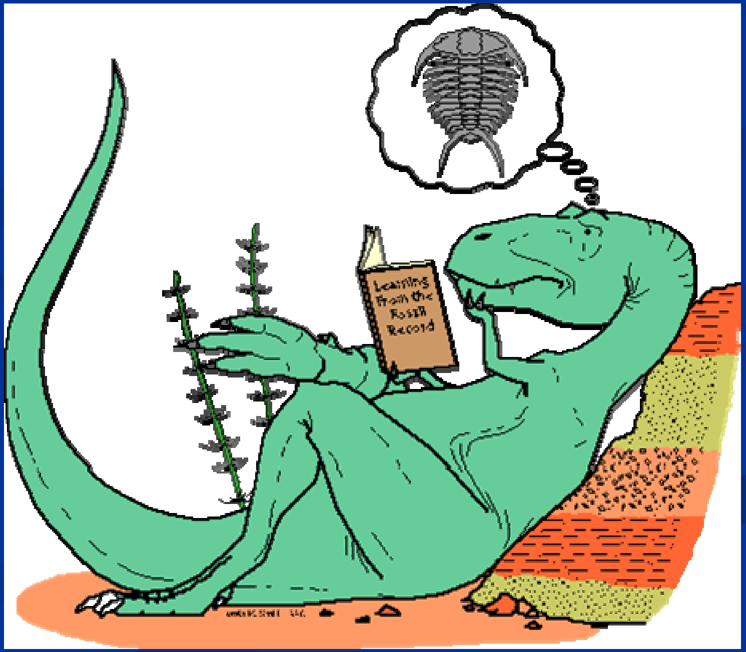
Stellar systems



Fossil record

- How do stellar systems form and evolve?
- Wealth of structure in morphology and kinematics
- Range in stellar population properties (age, metallicity, …)
- Link between dynamics and stellar populations?

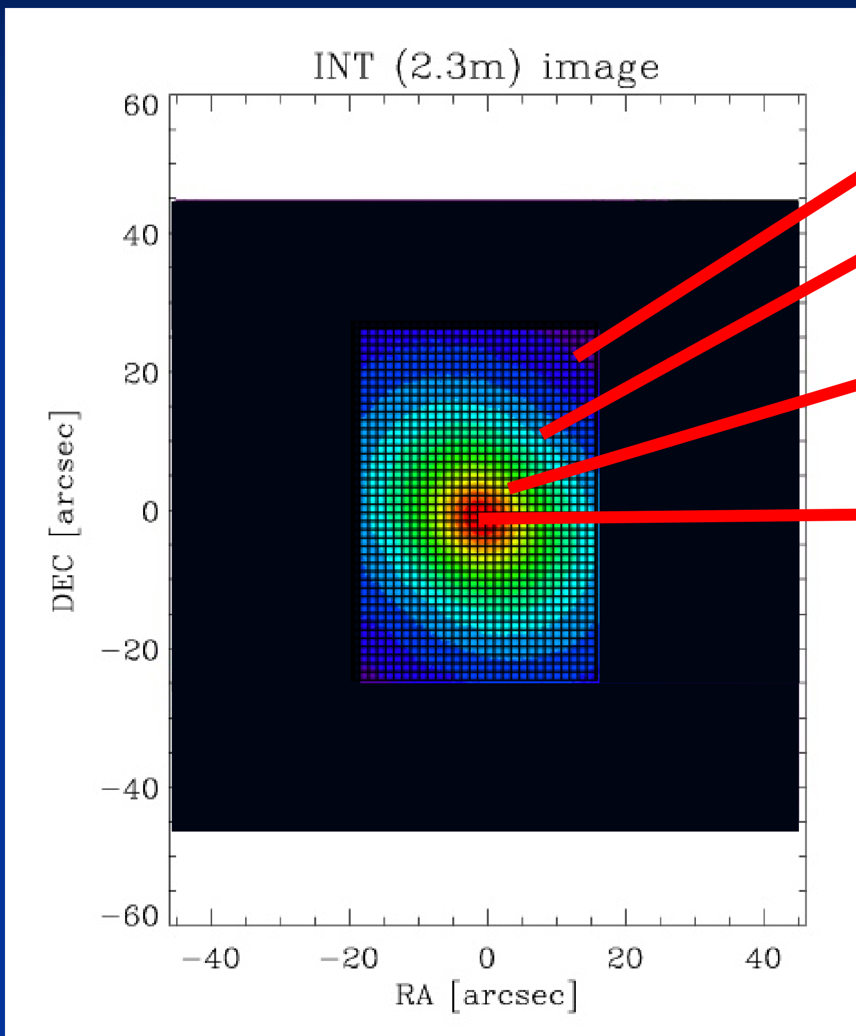
- Clean fossil record in early-type galaxies and globular clusters
- Galaxies: integral-field spectroscopy
- Globular clusters: discrete stellar kinematics + population properties



Early-type galaxies

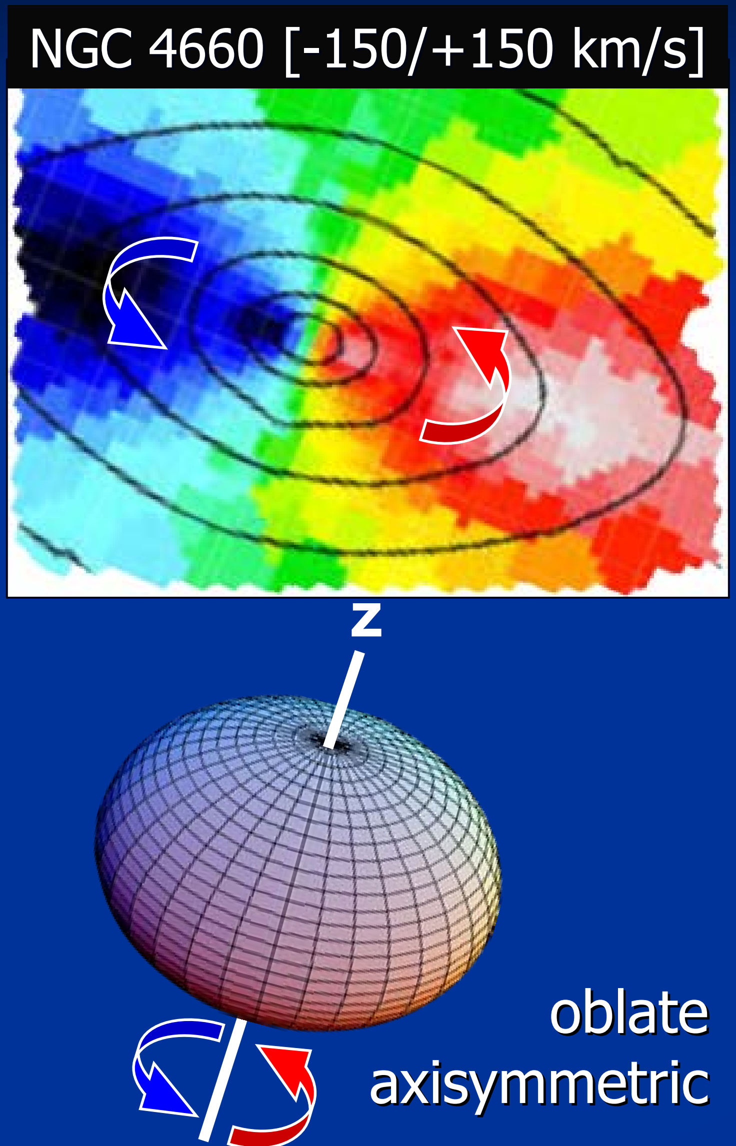
- Integral-field spectroscopy
- Schwarzschild’s method
- Triaxial dynamical model of NGC4365

Integral-field spectroscopy



… a spectrum at every position on the plane of the sky

Stellar velocity fields



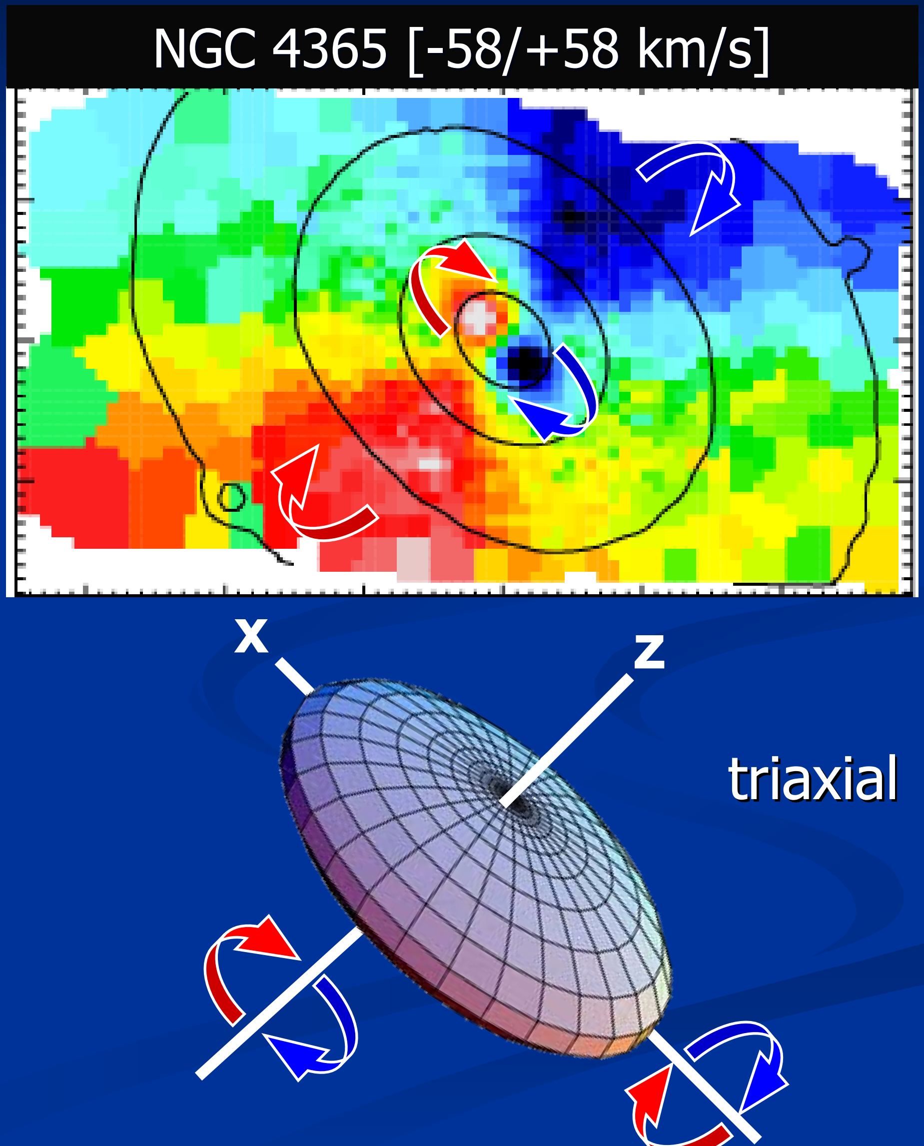
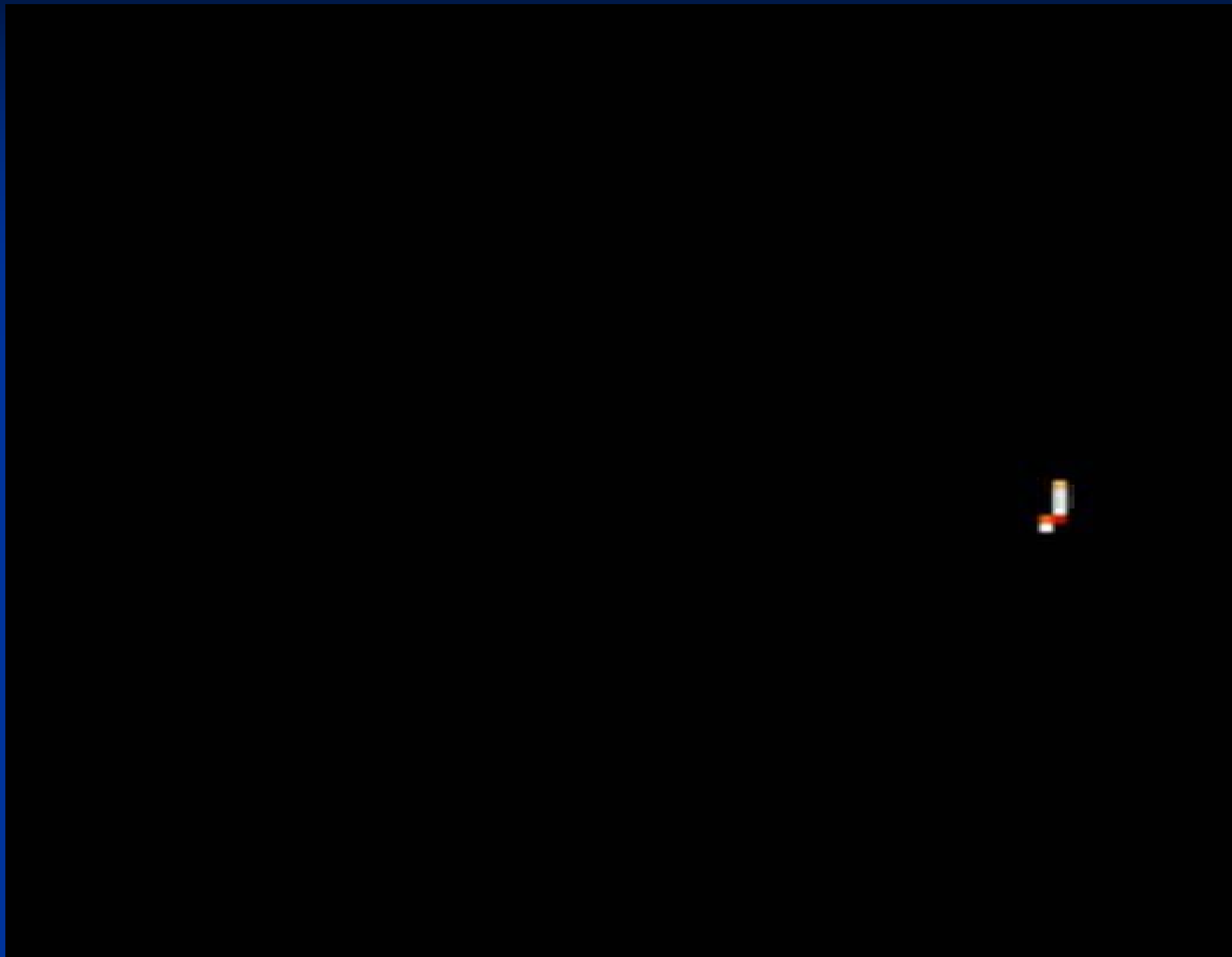
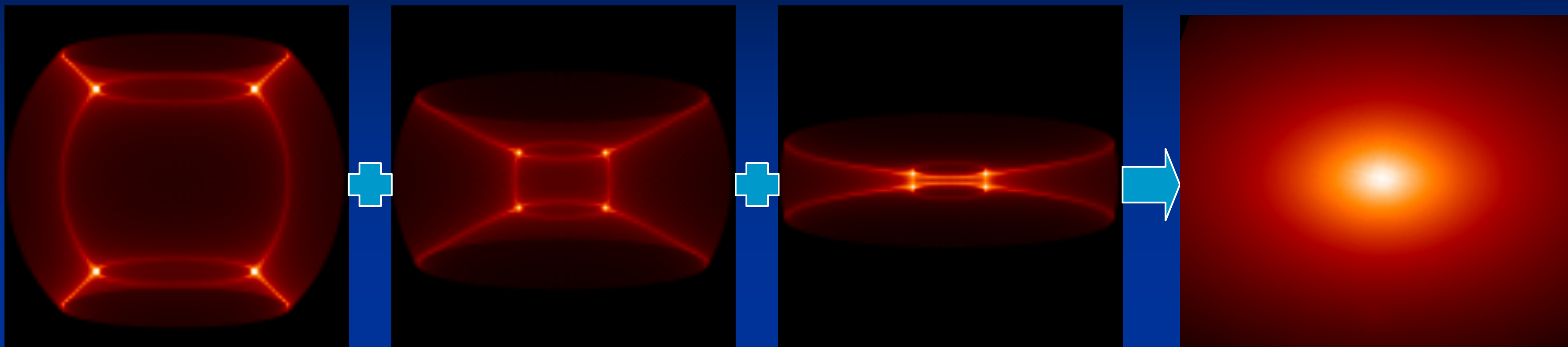


Image of numerical orbit



Schwarzschild's method

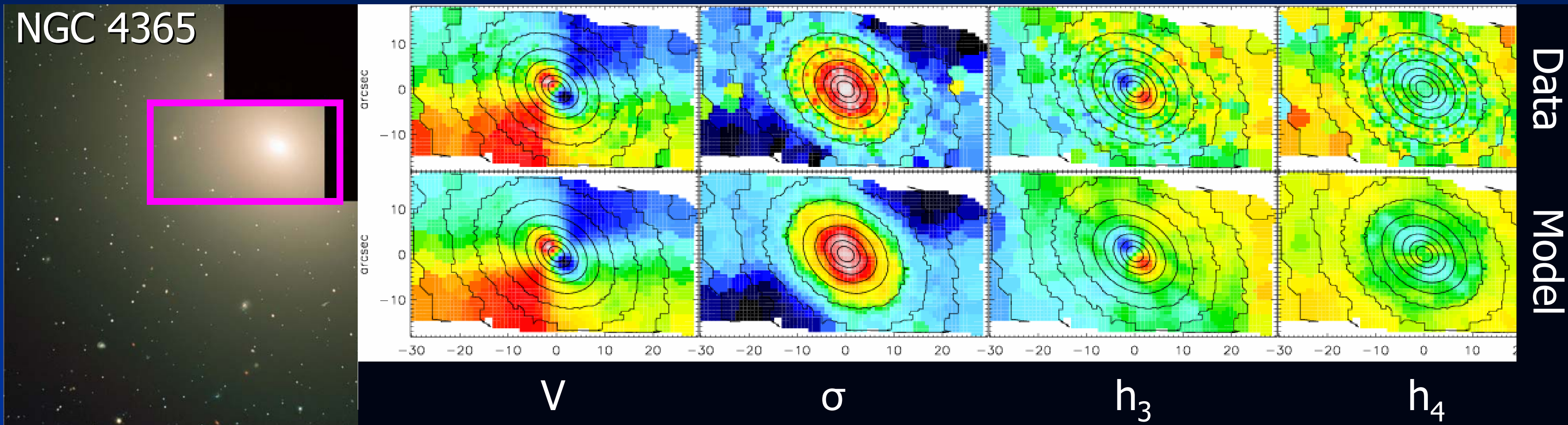


images of model orbits   observed image

- Surface brightness → (MGE) gravitational potential
- Grid of (E, I_2, I_3) → initial orbit conditions → orbit library
- Weighted superposition of orbits that best fits photometry and kinematics → dynamical model

Schwarzschild (1979), Richstone & Tremaine (1988), Rix et al. (1997), van der Marel (1998), Cappellari et al. (2002), Gebhardt et al. (2003), …

Dynamical model elliptical galaxy



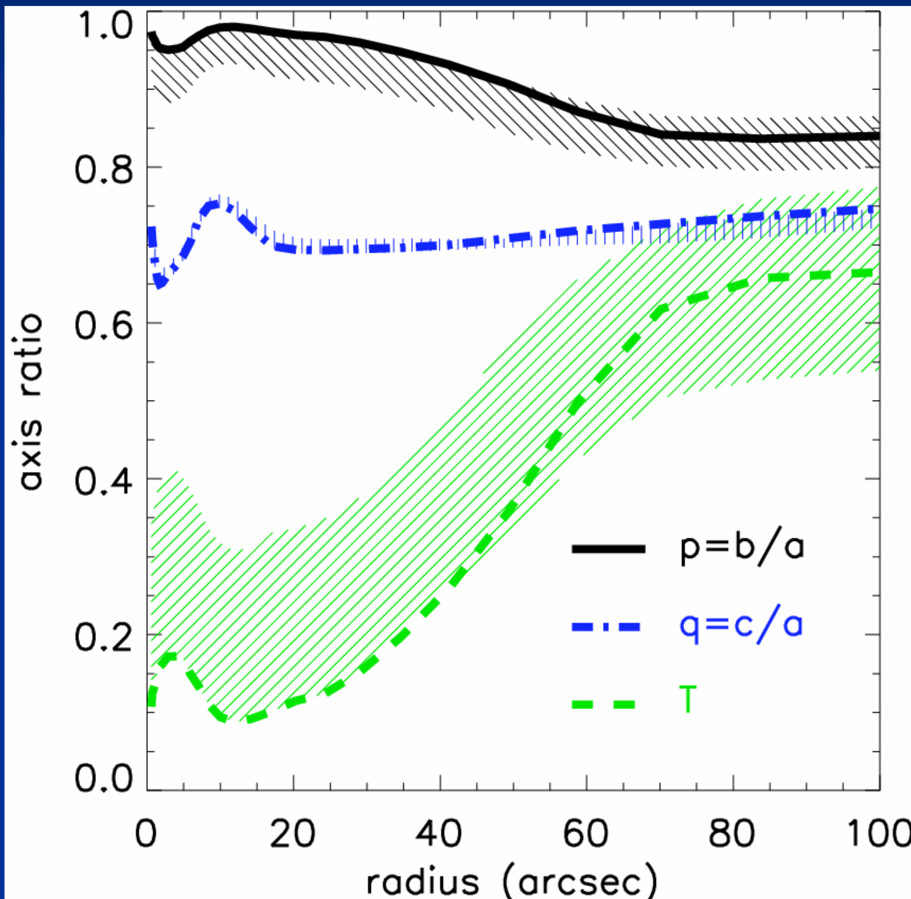
~skewness ~kurtosis

Fitting simultaneously photometry and kinematics in triaxial geometry, including a possible black hole and/or dark matter halo

van den Bosch, van de Ven, et al. (2008,MNRAS,385,647)
van de Ven, de Zeeuw & van den Bosch (2008,MNRAS,385,614)
van den Bosch & van de Ven (2008,MNRAS,arXiv:0811.3474)

Intrinsic shape

oblate … triaxial



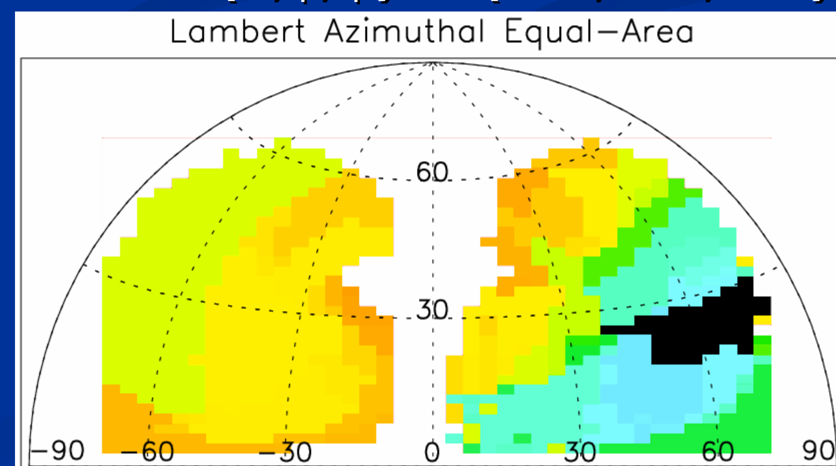
$T = (1-p^2)/(1-q^2)$

Oblate: p=1 (a=b>c), T=0

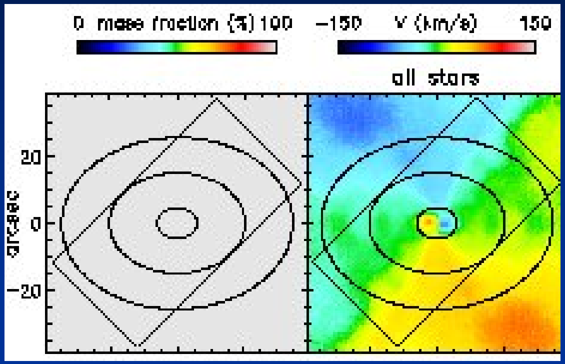
Prolate: p=q (a>b=c), T=1

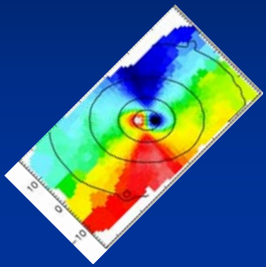
… and viewing direction

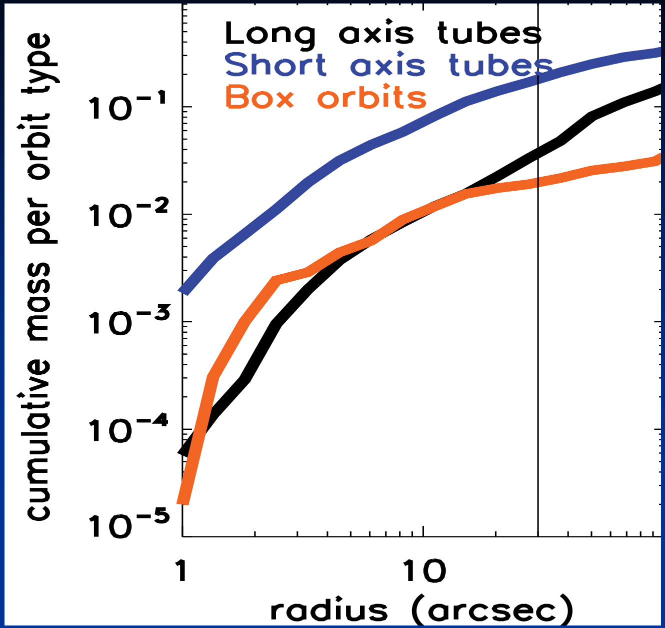
$(\theta,\phi,\psi) = (68°,73°,91°)$

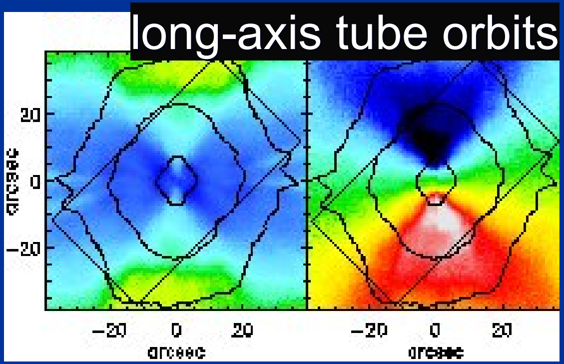


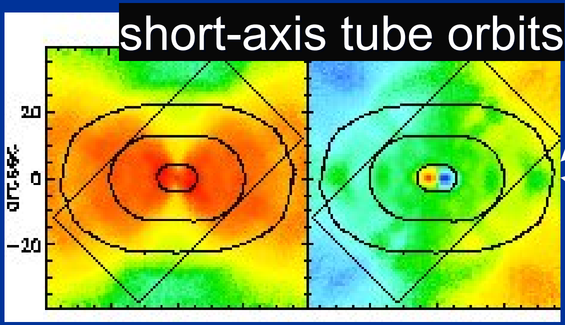
Orbital decomposition

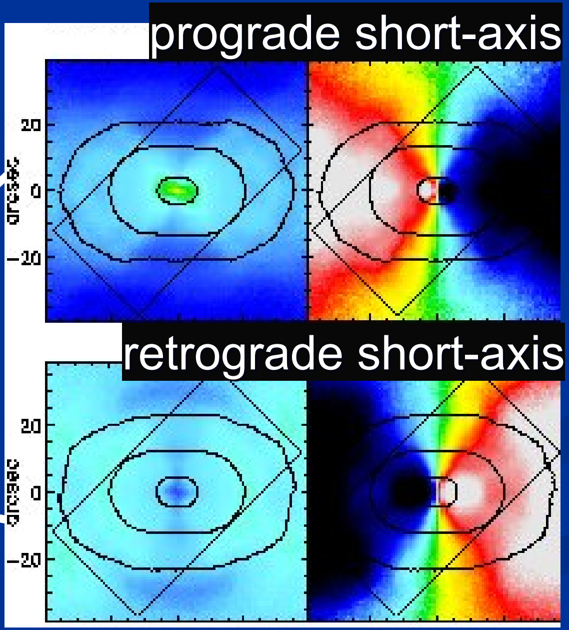












rotation cancels except center

Globular clusters: ω Cen

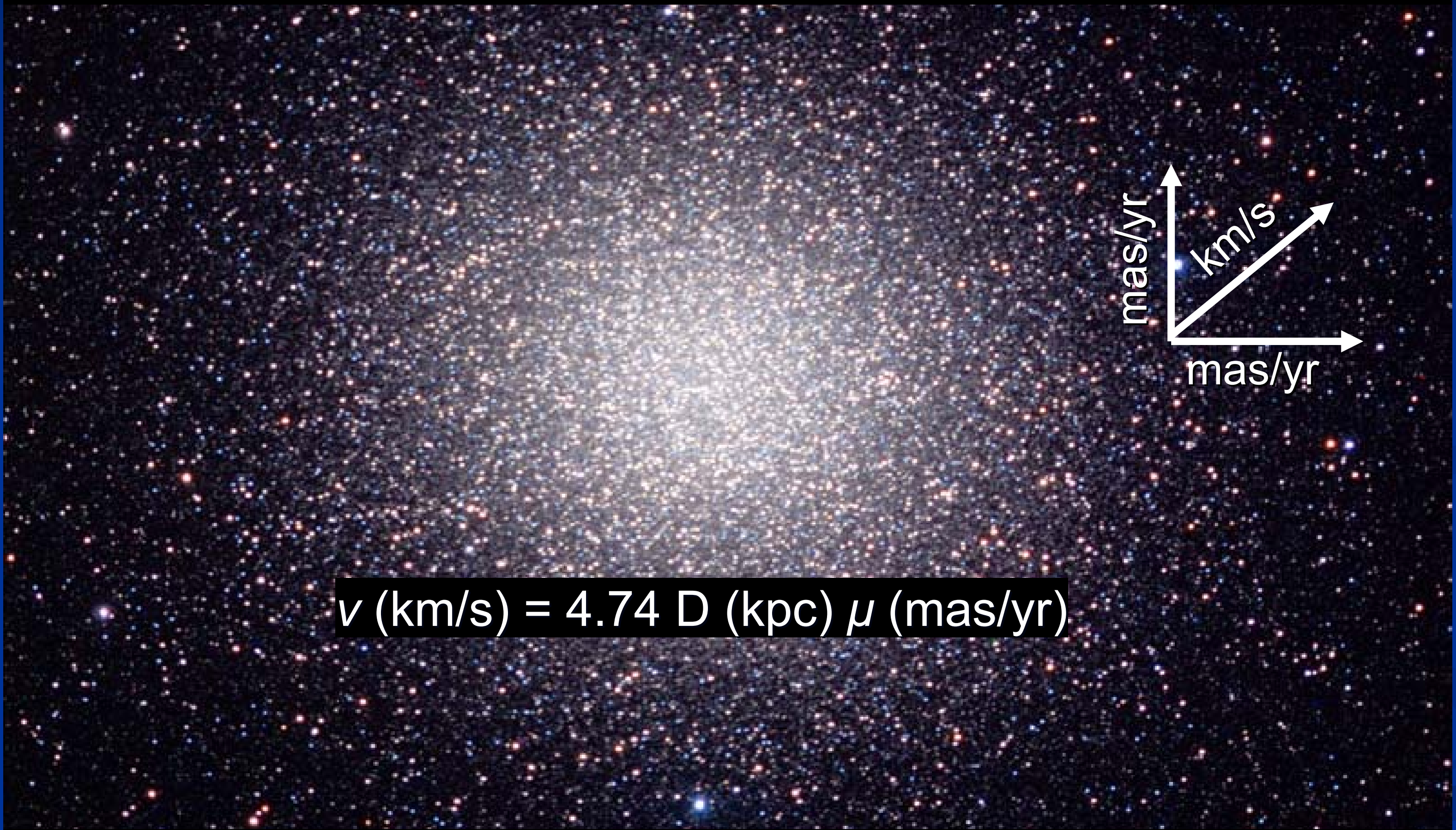
- discrete kinematics: proper motions and line-of-sight velocities
- distance, inclination, M/L
- inner disk and tidal striping

van de Ven et al. (2006,A&A,445,513)

ω Cen (NGC 5139)

proper motions ~ 10000 (van Leeuwen et al. 2000)

l.o.s. velocities ~ 4000 (4 data-sets)

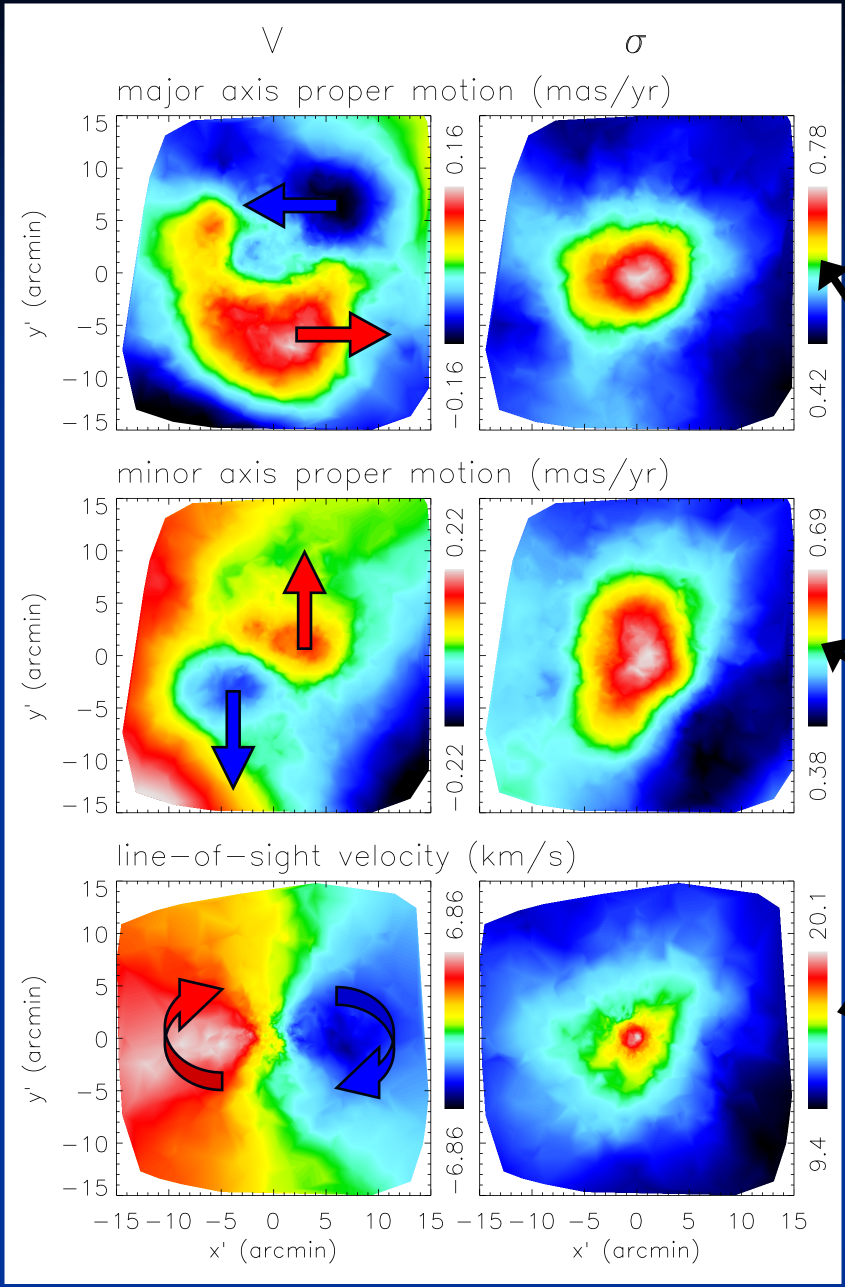


v (km/s) = 4.74 D (kpc) μ (mas/yr)

diameter ω Centauri ~ 2 x diameter full moon

Loke Kun Tan (StarryScapes)

Smooth velocity and dispersion fields



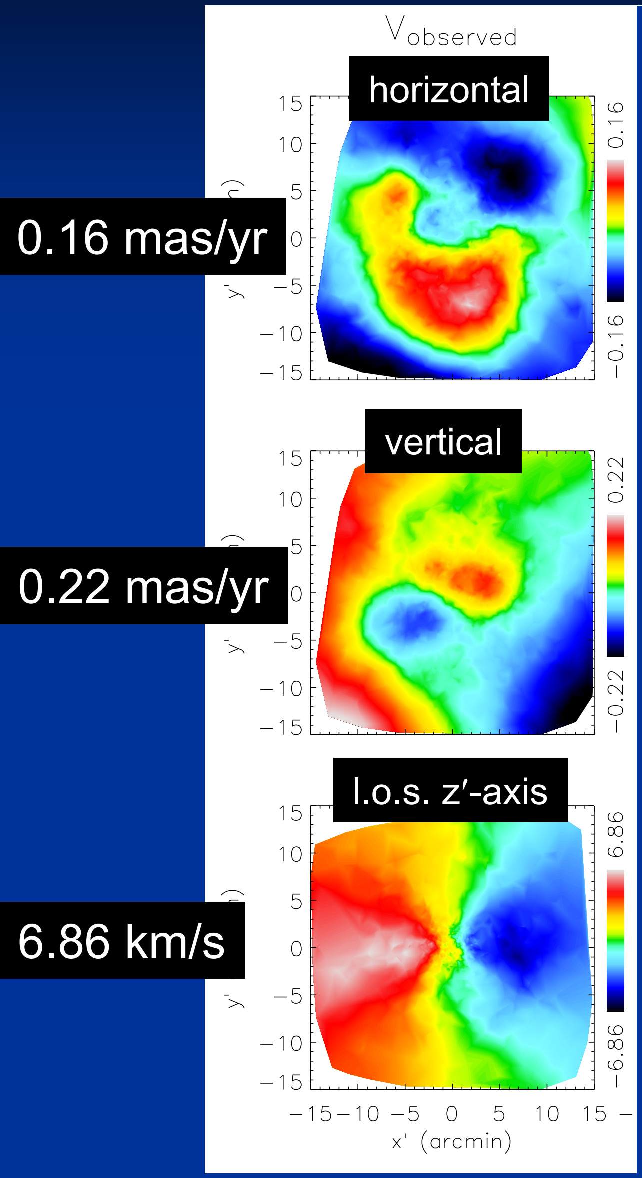
horizontal: in direction of major x′-axis

vertical: in direction of minor y′-axis

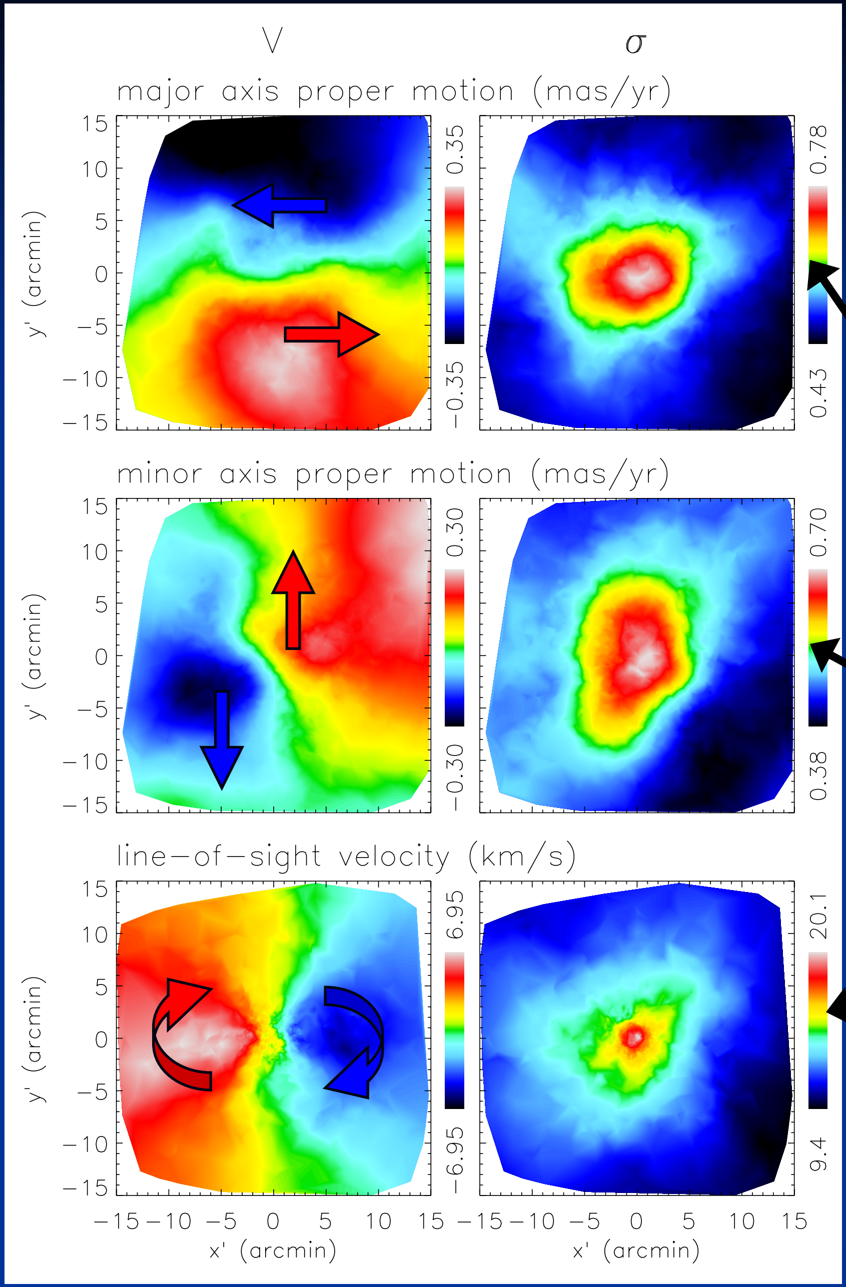
in direction of l.o.s. z′-axis

1 arcmin ~ 1.45 pc

Corrected velocity field



Smooth velocity and dispersion fields



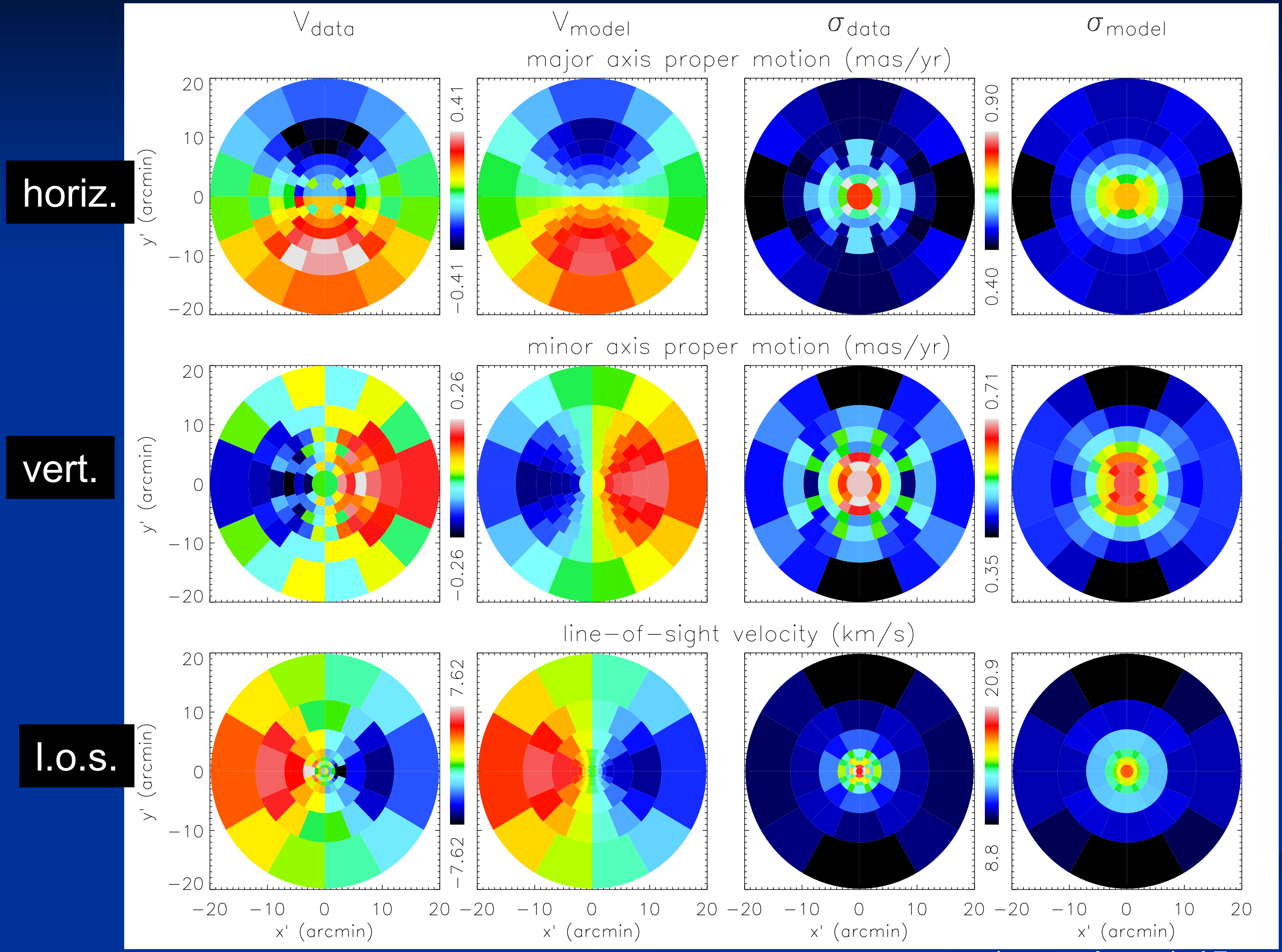
horizontal: in direction of major axis

vertical: in direction of minor axis

in direction of line-of-sight axis

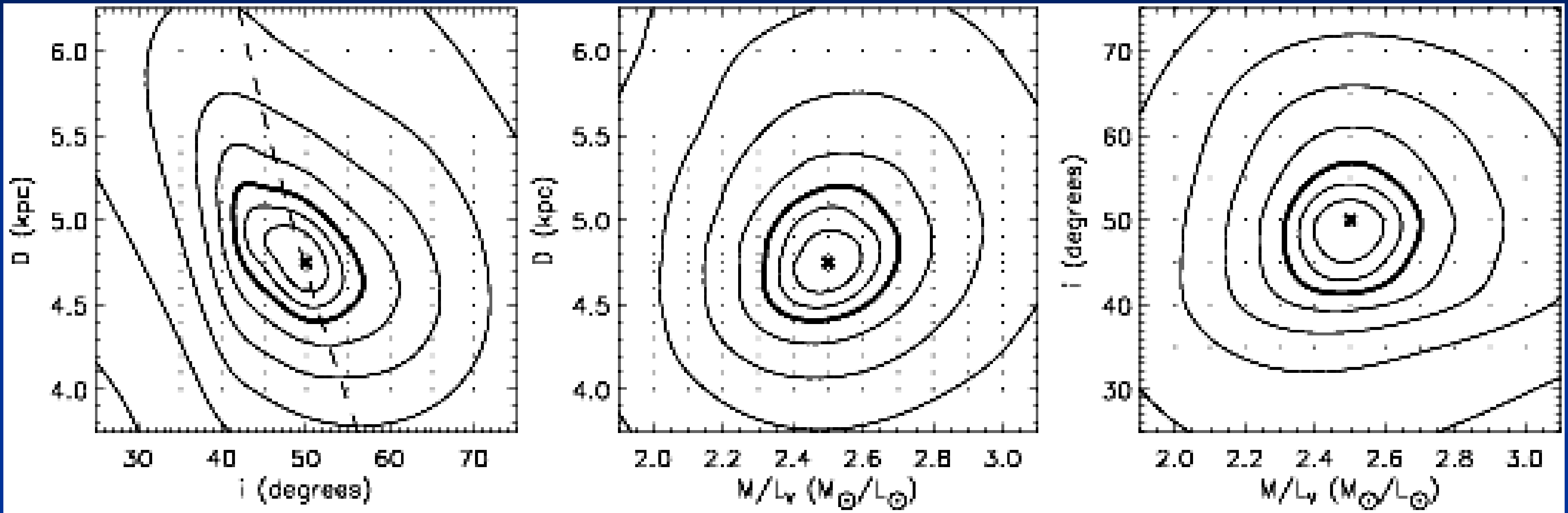
1 arcmin ~ 1.45 pc

Schwarzschild model



1 arcmin ~ 1.45 pc

Best-fit parameters



$D = 4.8 \pm 0.3$ kpc,

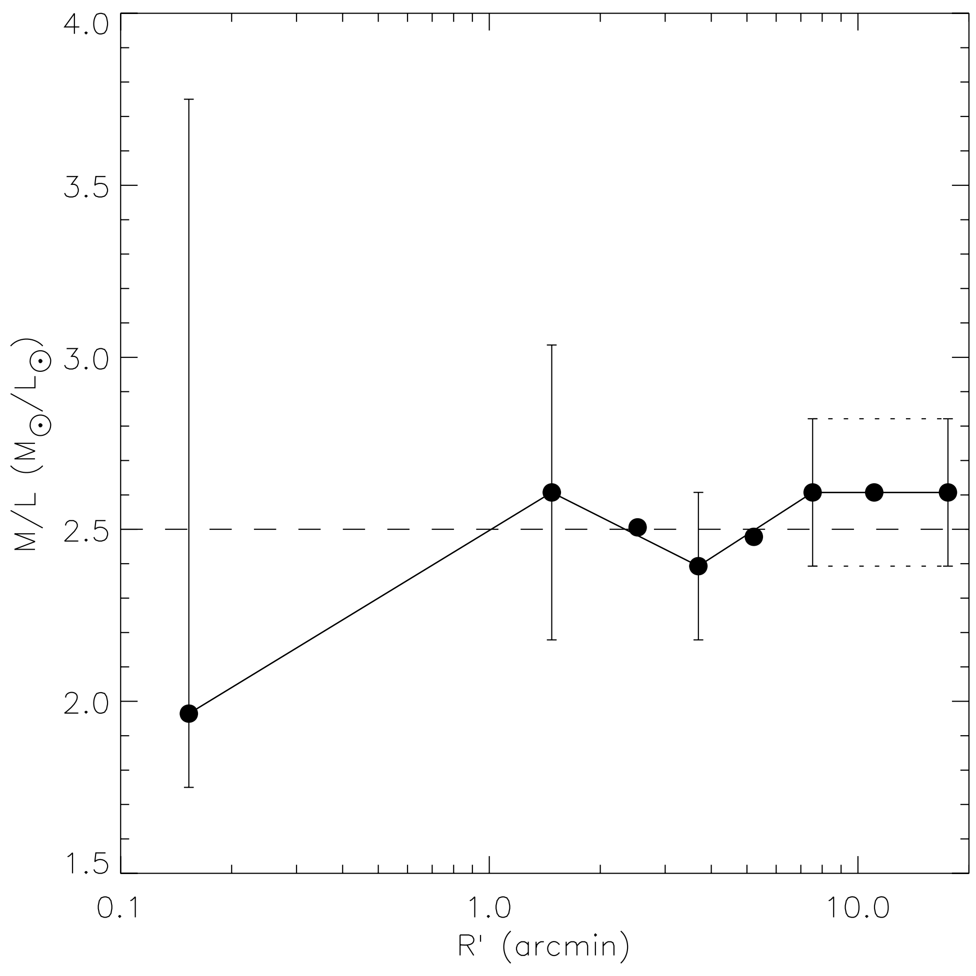
$i = 50° \pm 4°$

$M/L_V = 2.5 \pm 0.1 \; M_\odot/L_\odot$

$L_V = 1.0 \pm 0.1 \times 10^6 \; L_\odot$

$M = 2.5 \pm 0.3 \times 10^6 \; M_\odot$

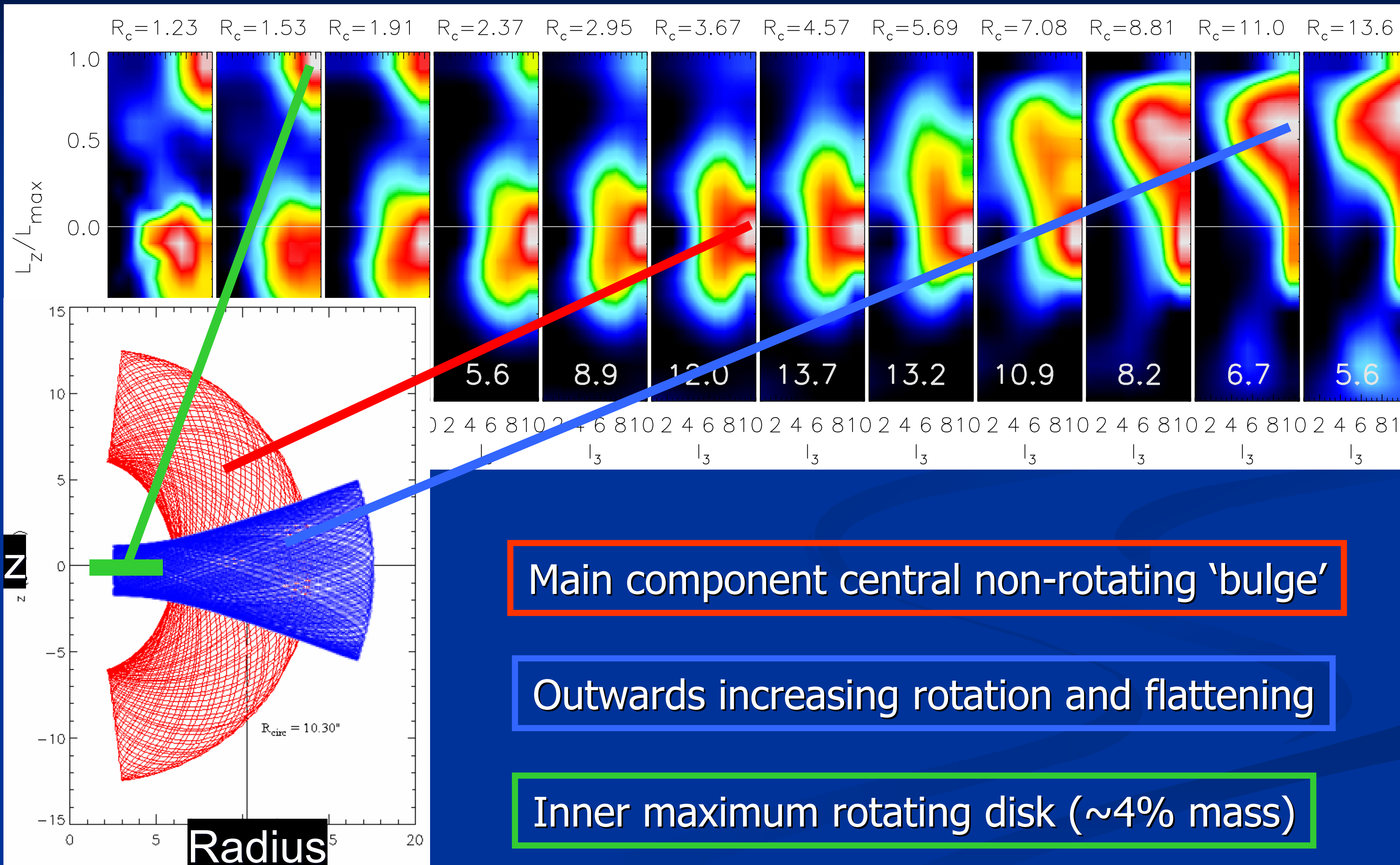
M/L variation with radius?



1 arcmin ~ 1.45 pc

Consistent with constant $M/L_V = 2.5 \pm 0.1\ M_\odot/L_\odot$

Phase-space distribution



Main component central non-rotating ‘bulge’

Outwards increasing rotation and flattening

Inner maximum rotating disk (~4% mass)

Tidal interaction and multiple populations

- ω Centauri mean rotation (L_z>0) and orbit around Milky Way center opposite → prograde orbits (L_z<0) tidally removed?
- Impulse approximation: |Δv| ~ σ around 16 arcmin (tidal radius around 45 arcmin) Dinescu et al. (1999)
- Multiple stellar populations
  (Freeman & Rodgers 1975, Norris et al. 1997, Pancino et al. 2003, …)

Metal-rich [Ca/H] > -1.2
- Centrally concentrated
- No apparent rotation
- Nearly round

⇩

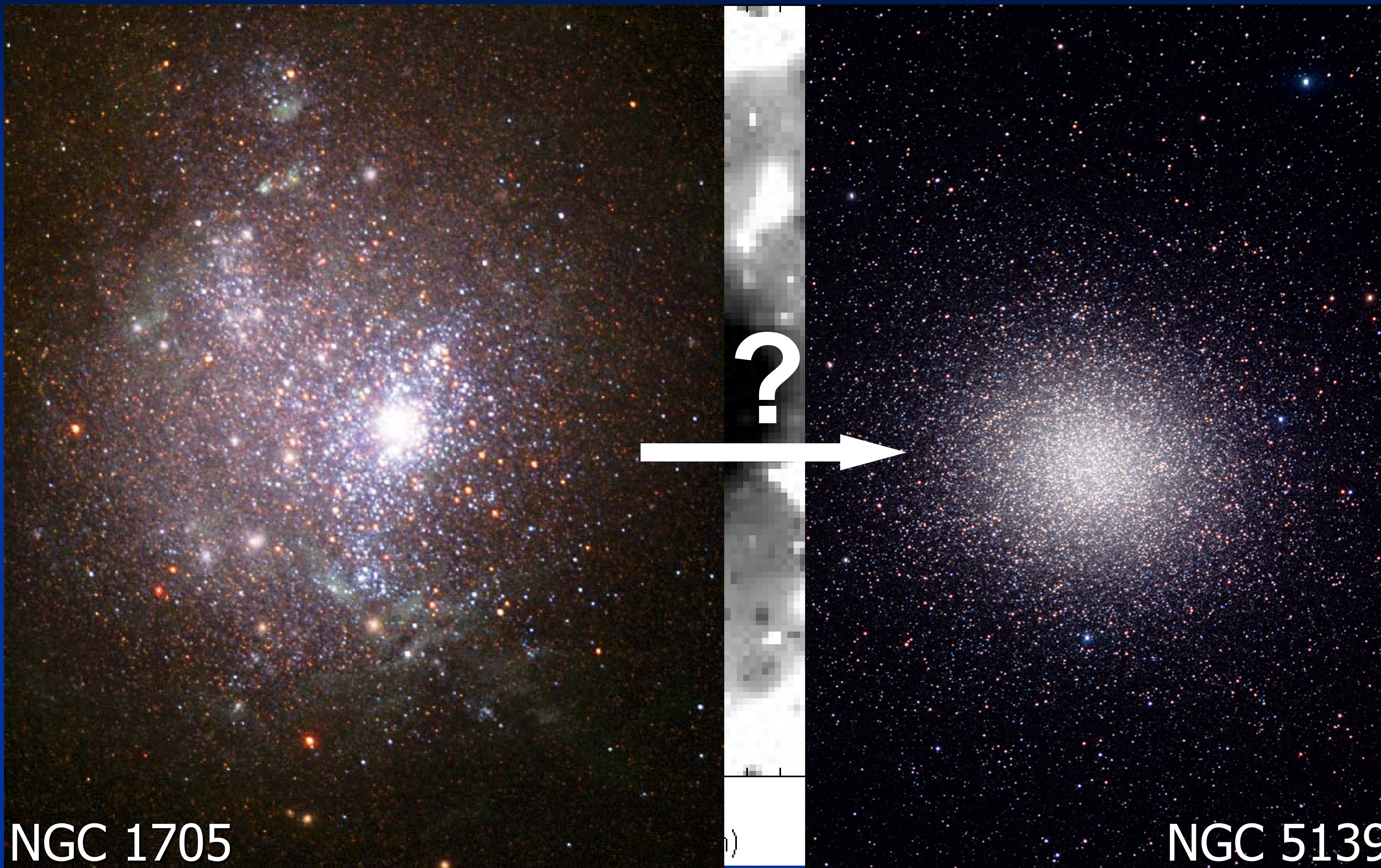
Non-rotating 'bulge' ?

Metal-poor [Ca/H] < -1.2
- Throughout galaxy
- Rapidly rotating
- Flattened

⇩

Rotating flattened component?

Tidally stripped dwarf galaxy?

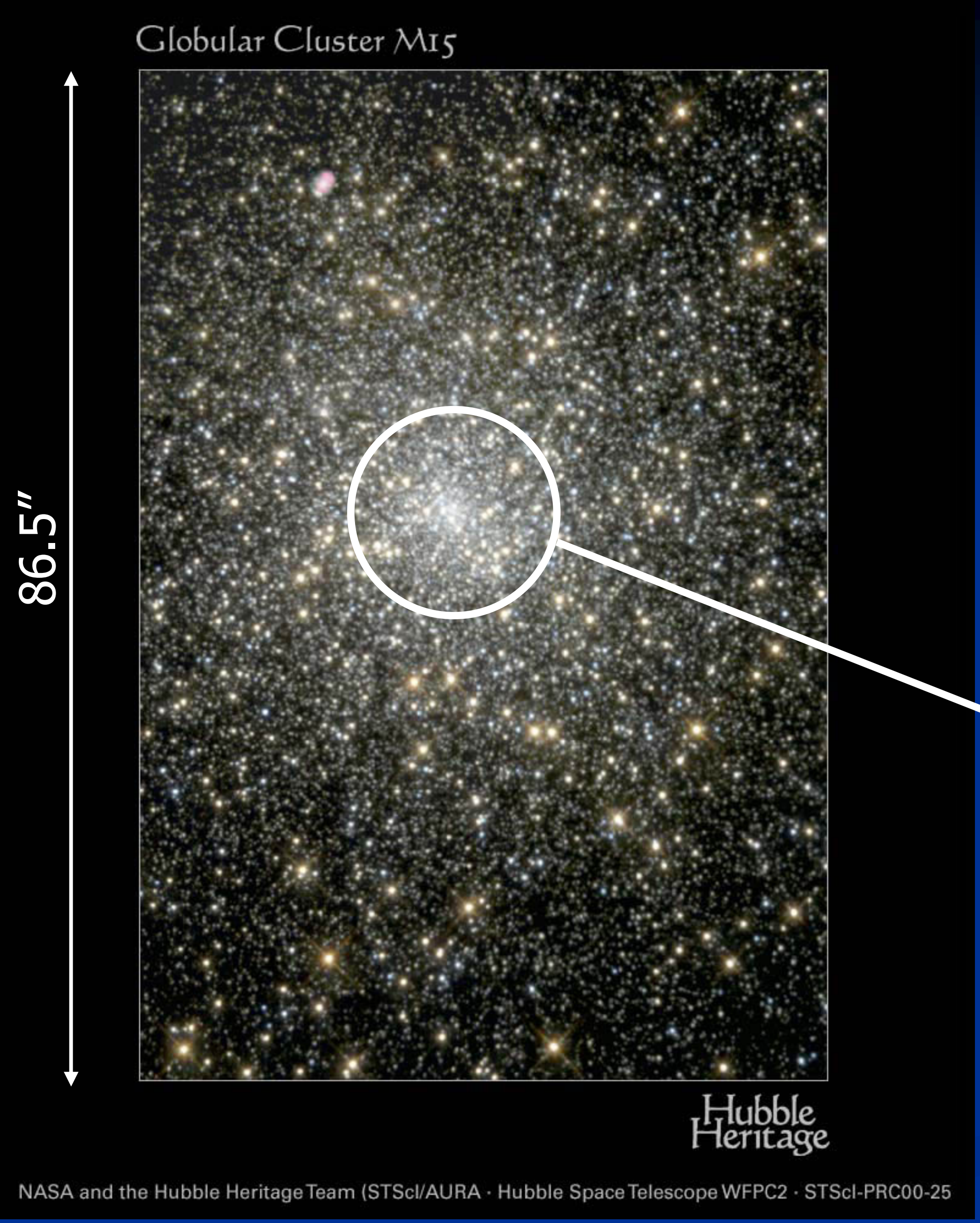


Leon, Meylan & Combes (2000)

Globular clusters: M15

- mass-to-light ratio
- IMBH or dark remnants?

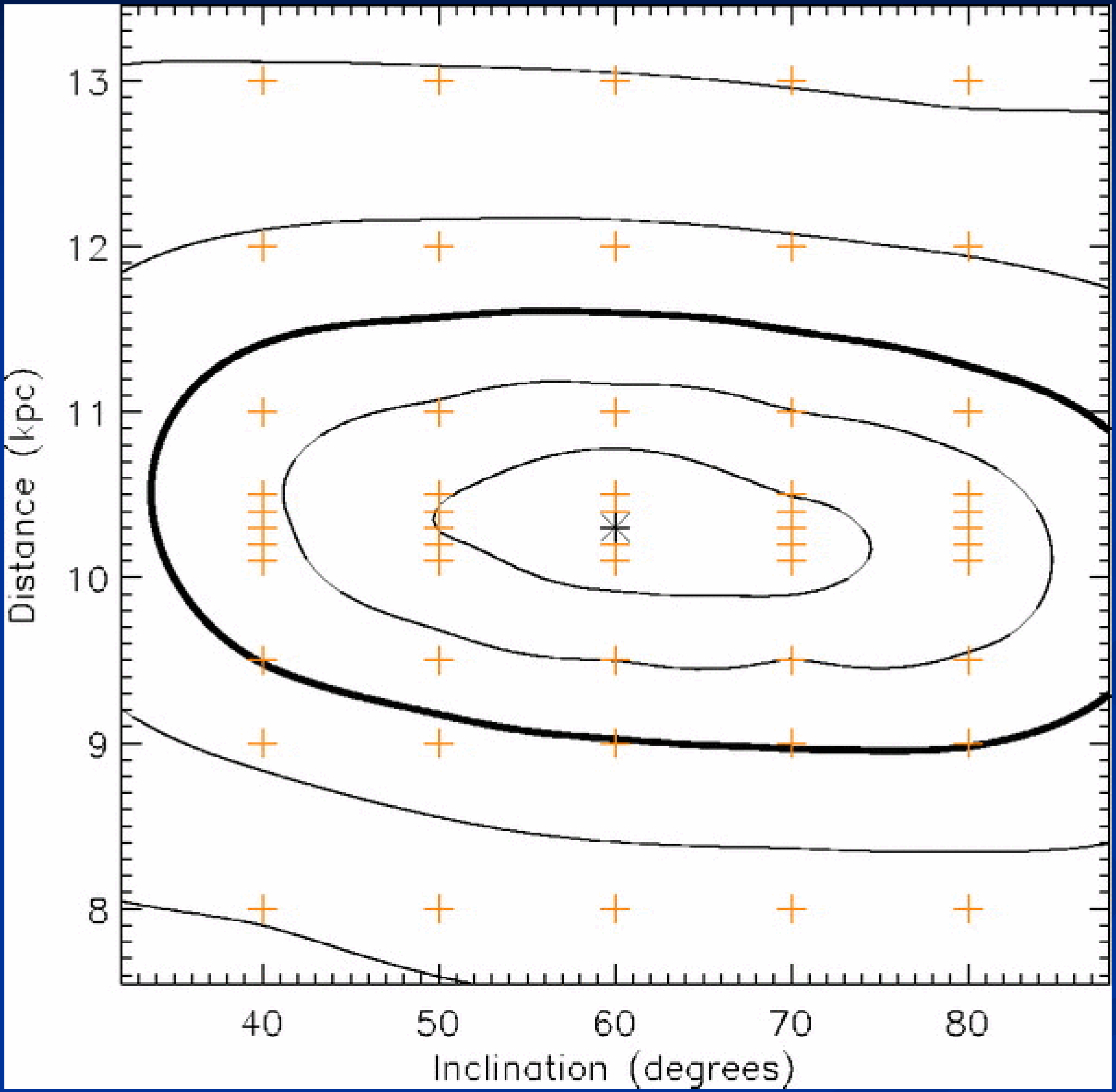
van den Bosch et al. (2006,ApJ,641,852)



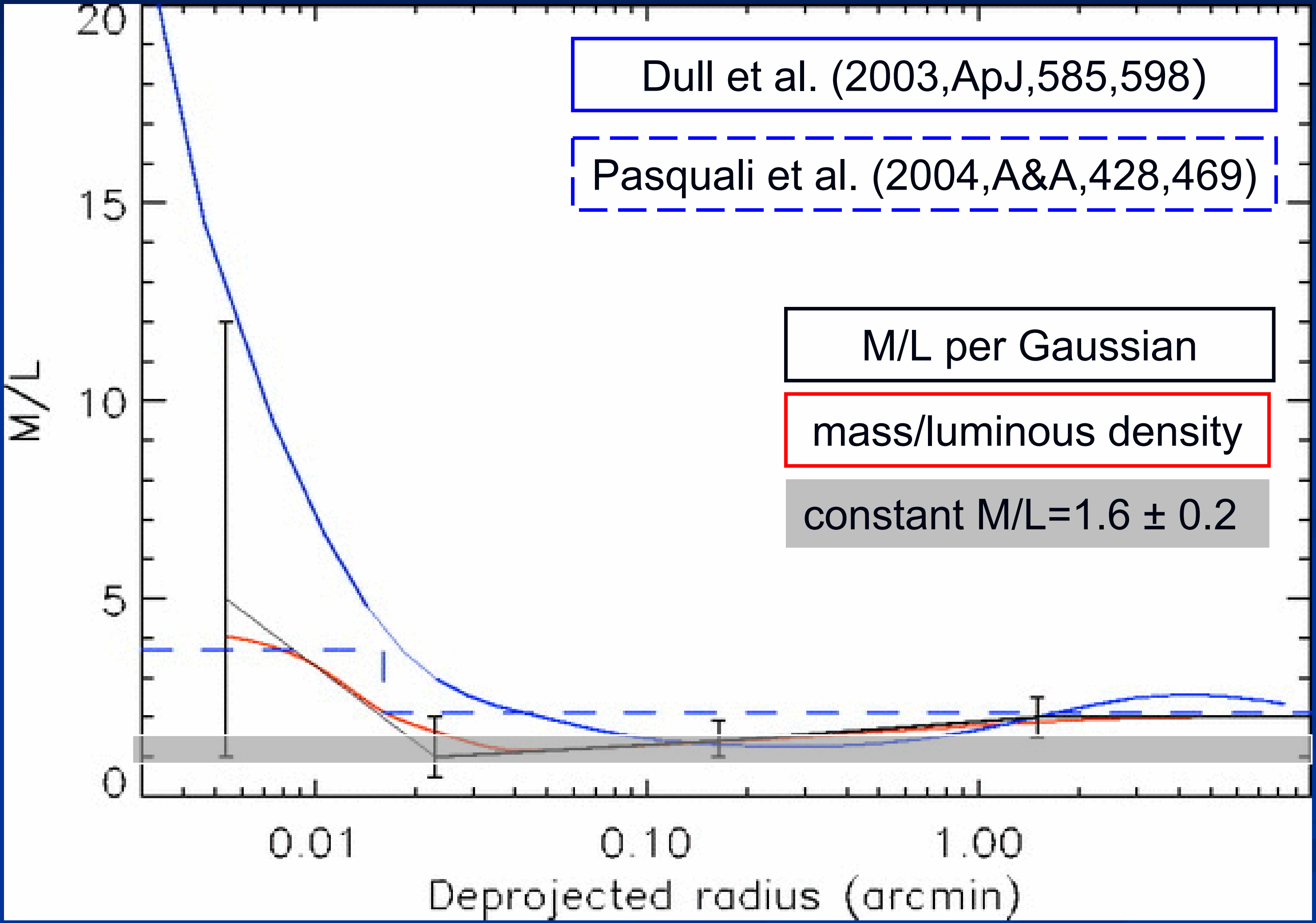
M15 (NGC 7078)

- D=10 kpc (1″=0.05 pc)
- SB profile: r_c=0.05 pc, central slope=-0.62±0.06
  (Noyola & Gebhardt 2006,AJ,132,447)
- 1540 l.o.s. velocities
  (Gebhardt et al. 2009,AJ,119,1268)
- 703 HST proper motions
  (McNamara et al. 2003,ApJ,595,187)

Distance and inclination



M/L variation with radius



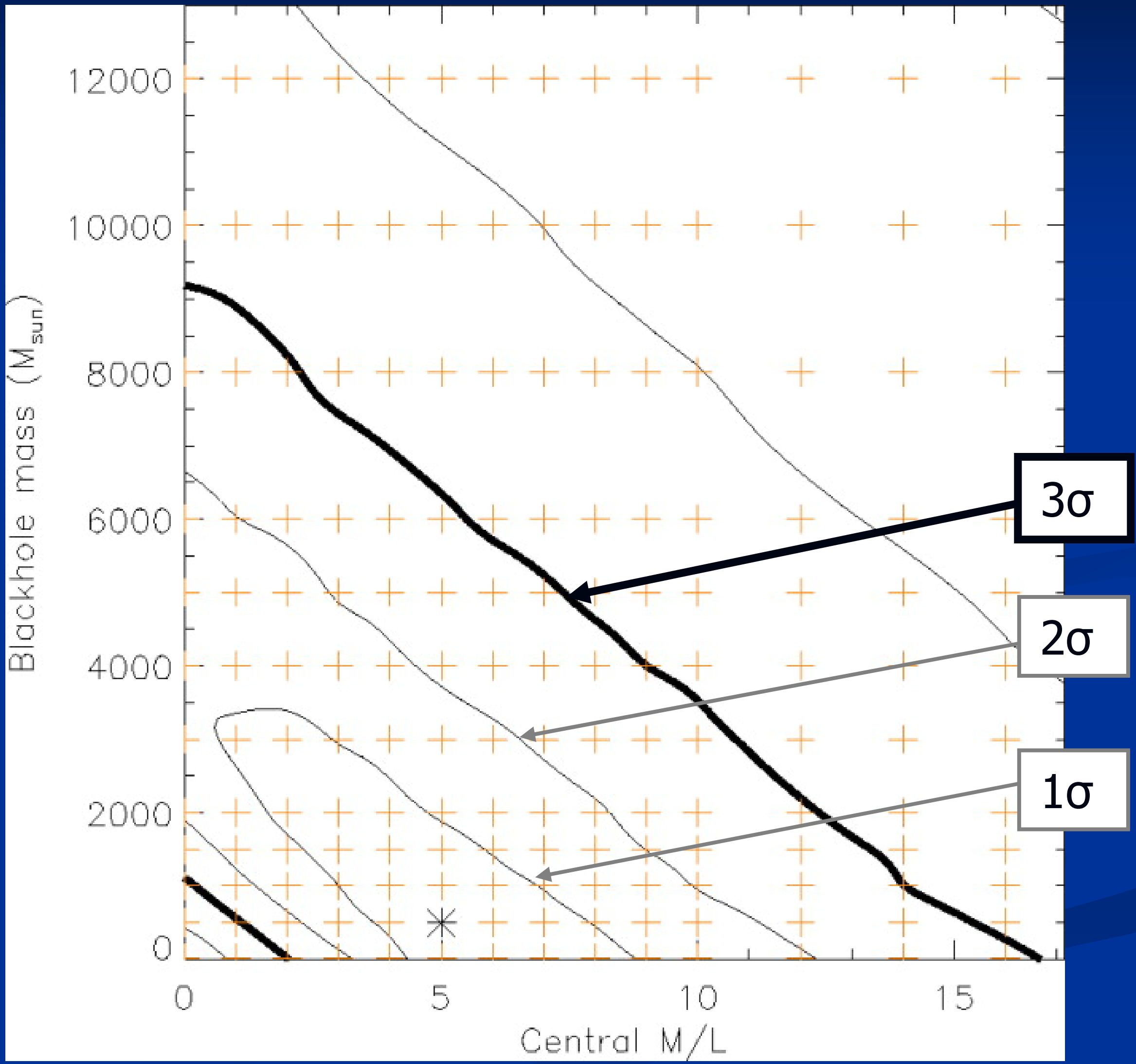
1 arcmin ~ 3 pc

IMBH or dark remnants?

- D = 10.3±0.05 kpc
- i = 60±15 degrees

- From M_{BH}-σ relation: $\sim 10^3\ M_\odot$ (σ~11 km/s)
- $r_{BH} \sim 0.5'' \sim 0.025$ pc

- Within r_c=0.05 pc
  $M_c = 3.4 \times 10^3\ M_\odot$
  $\rho_c = 7.4 \times 10^6\ M_\odot/pc^3$
- $M_{tot} = 4.4 \times 10^5\ M_\odot$

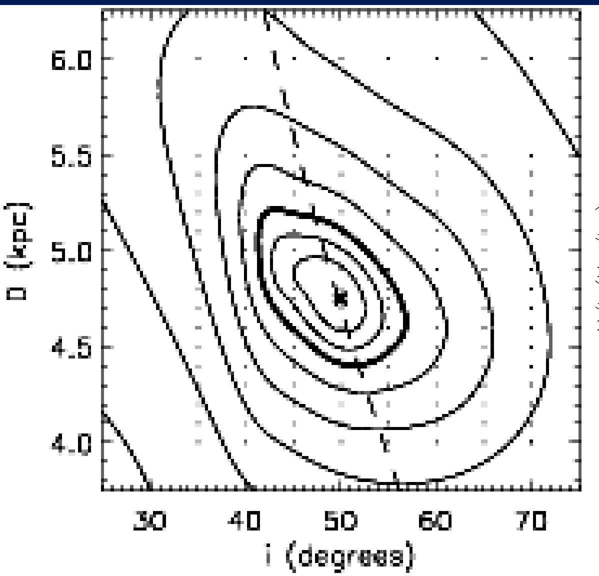


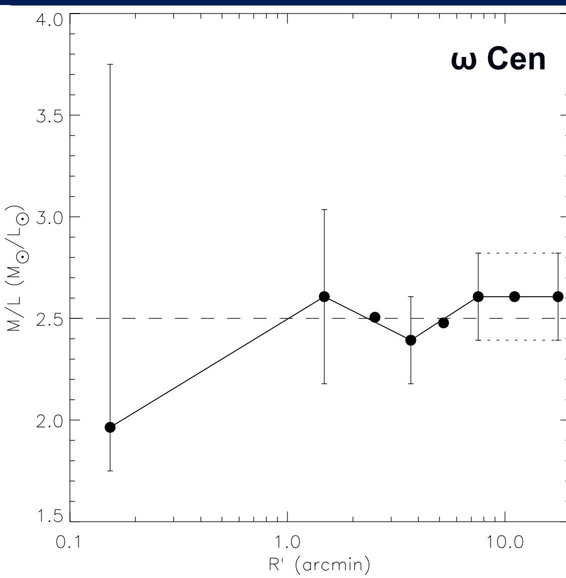
Outlook and summary

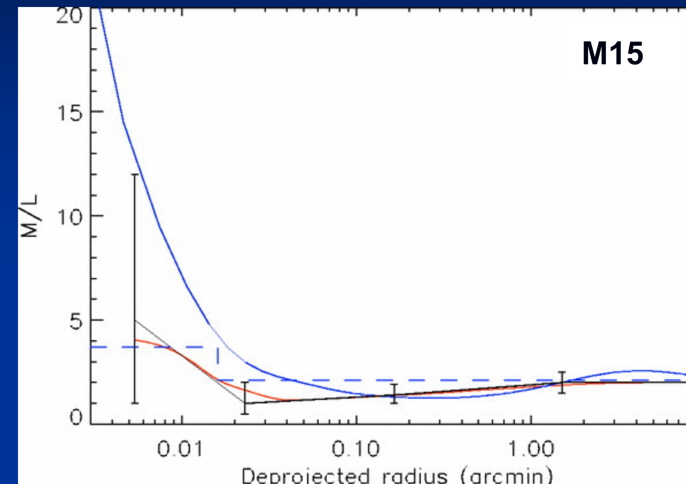
Next steps

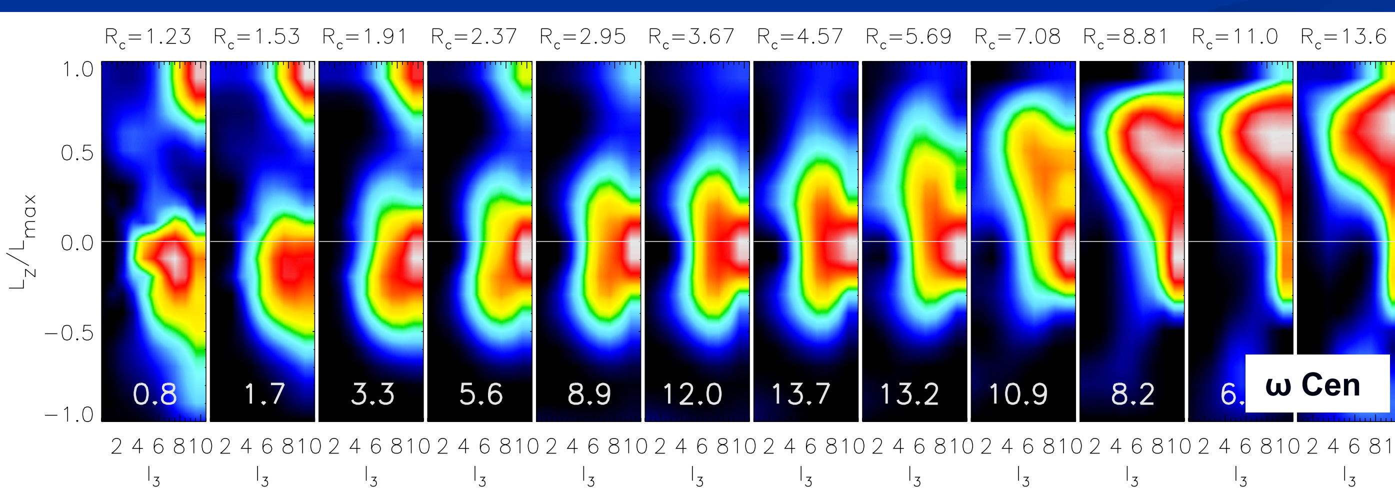
- HST proper motions: IMBH?
- Correlated and higher order velocity moments, or…
- Fitting directly discrete kinematics with Max. Likelihood methods
- Including color, metallicity and age indicators, etc.:
  link kinematics and stellar properties in single model
- Synergy with particle-based models?

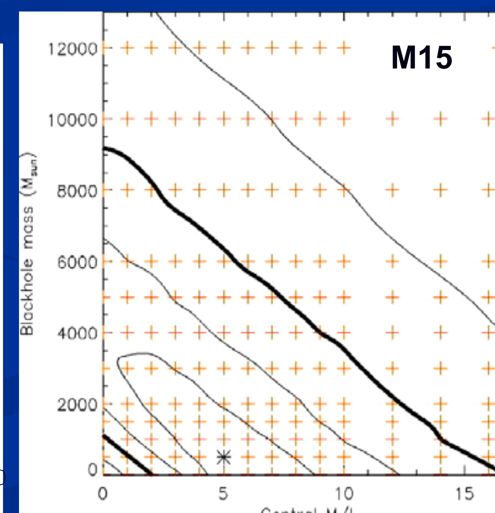
Summary in figures











...the end

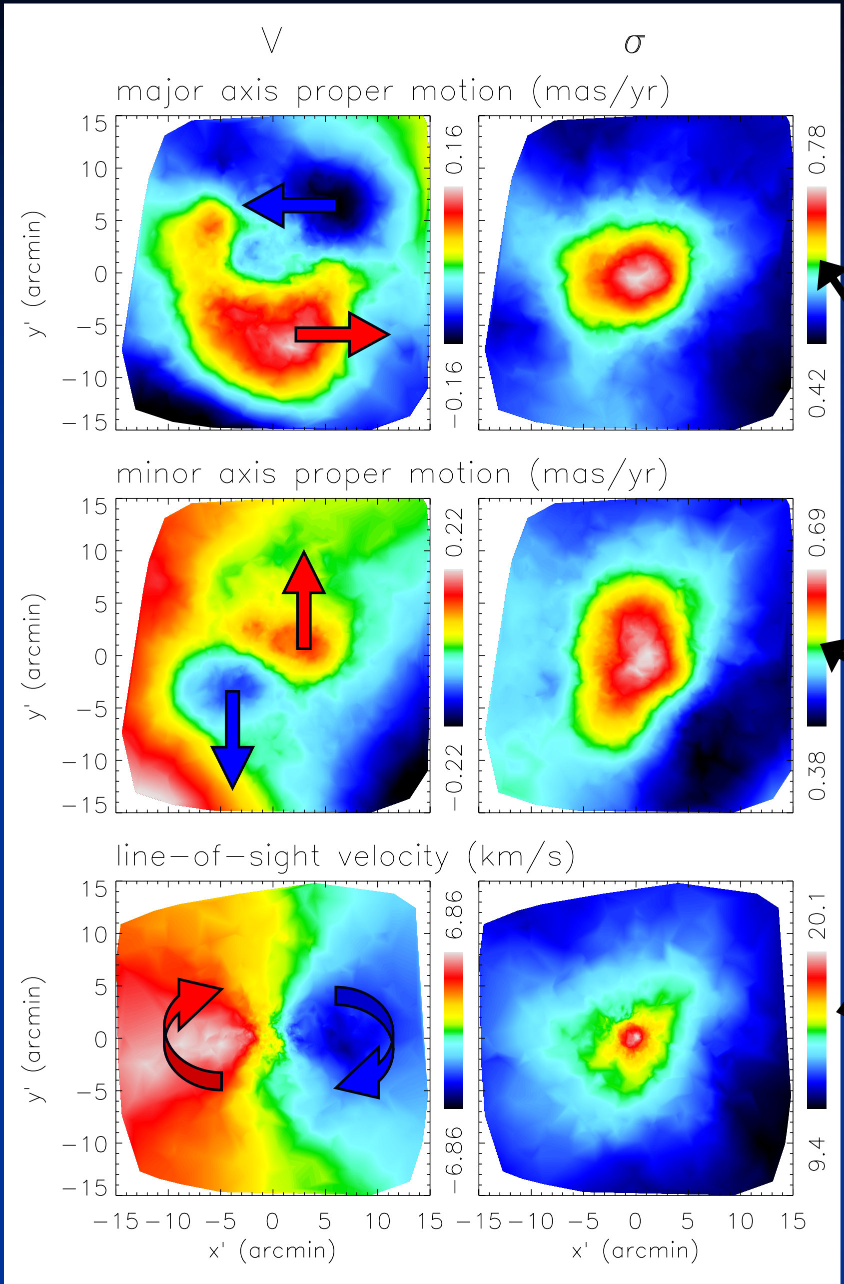
Extra: ω Cen

Some properties

- Most massive GC in Milky Way: $M \sim 2\text{-}5 \times 10^6\ M_\odot$
- One of most flattened GCs: $q' \sim 0.9$
- Relatively loosely bound: $\log(r_t/r_c) \sim 1.24$
  tidal radius r_t ~45′, core radius r_c ~2.6′
- Small heliocentric distance: D ~ 5 kpc
  RR Lyrae and eclipsing binary
- Complicated composition with multiple stellar populations
  - Self-enrichment (isolated cluster/nucleus dwarf galaxy)?
  - (Subsequent) interaction/merger GCs?

F. van Leeuwen, G. Piotto & J. Huyghes, 2001, ASP Conf. Ser. 265

Smooth velocity and dispersion fields



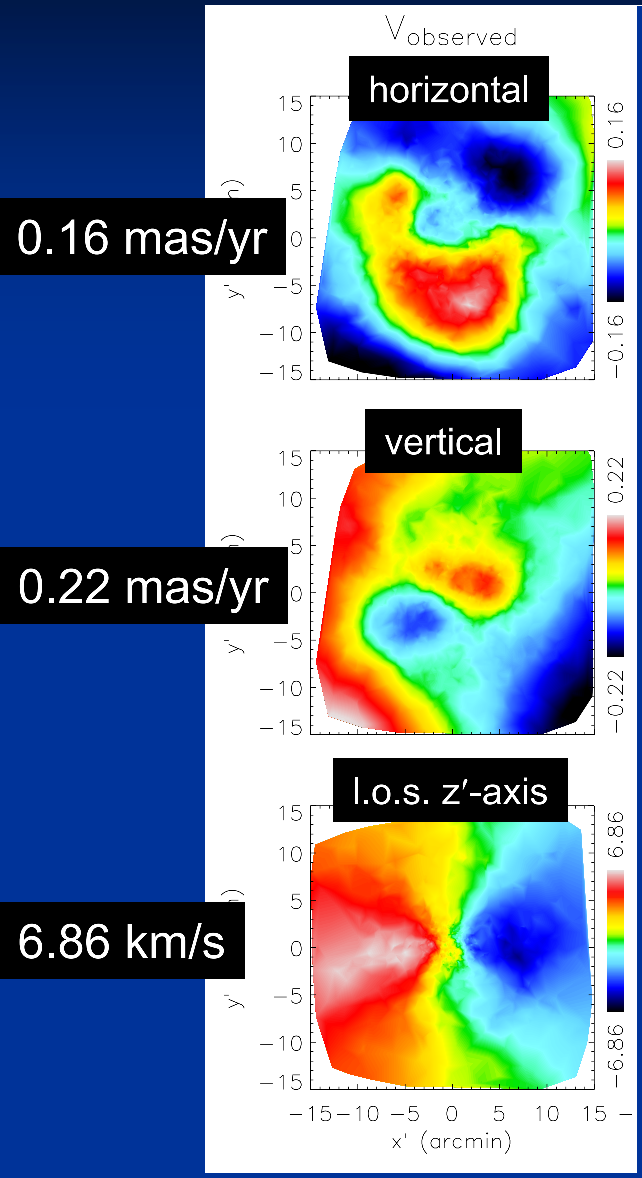
horizontal: in direction of major x'-axis

vertical: in direction of minor y'-axis

in direction of l.o.s. z'-axis

1 arcmin ~ 1.45 pc

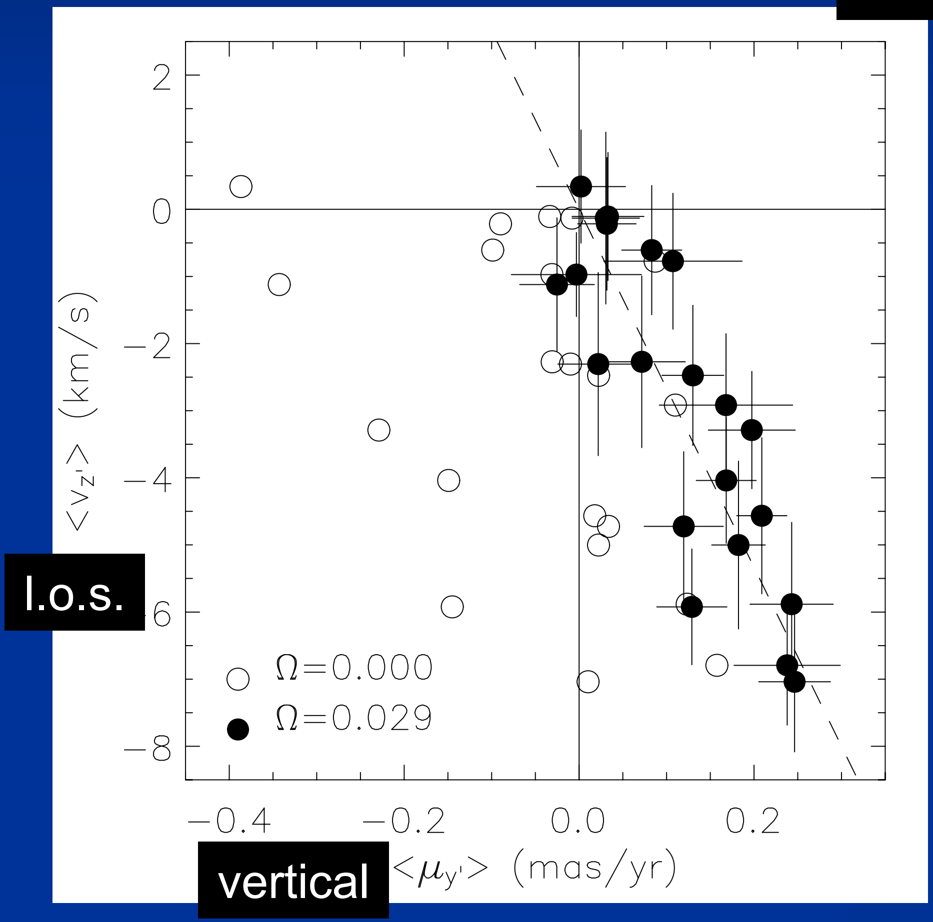
Corrected velocity field

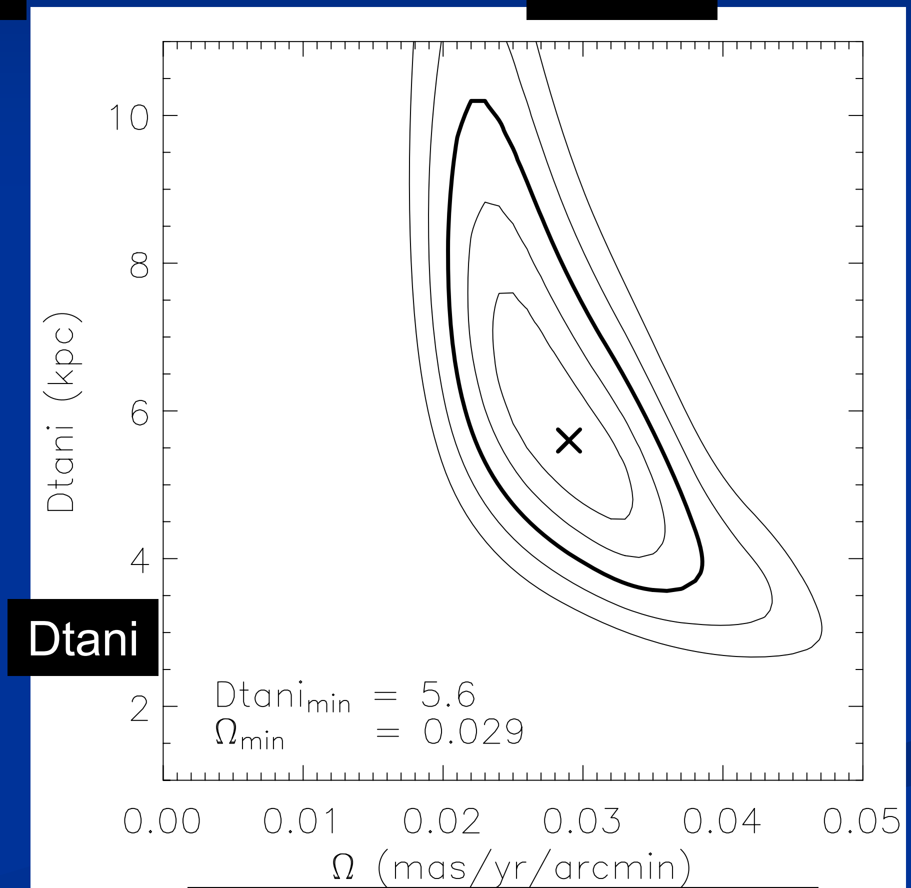


Measuring 'solid-body' rotation

Any axisymmetric object: $\langle v_{z'} \rangle (x', y') = -4.74 D \tan i \langle \mu_{y'} \rangle (x', y')$

l.o.s. vertical

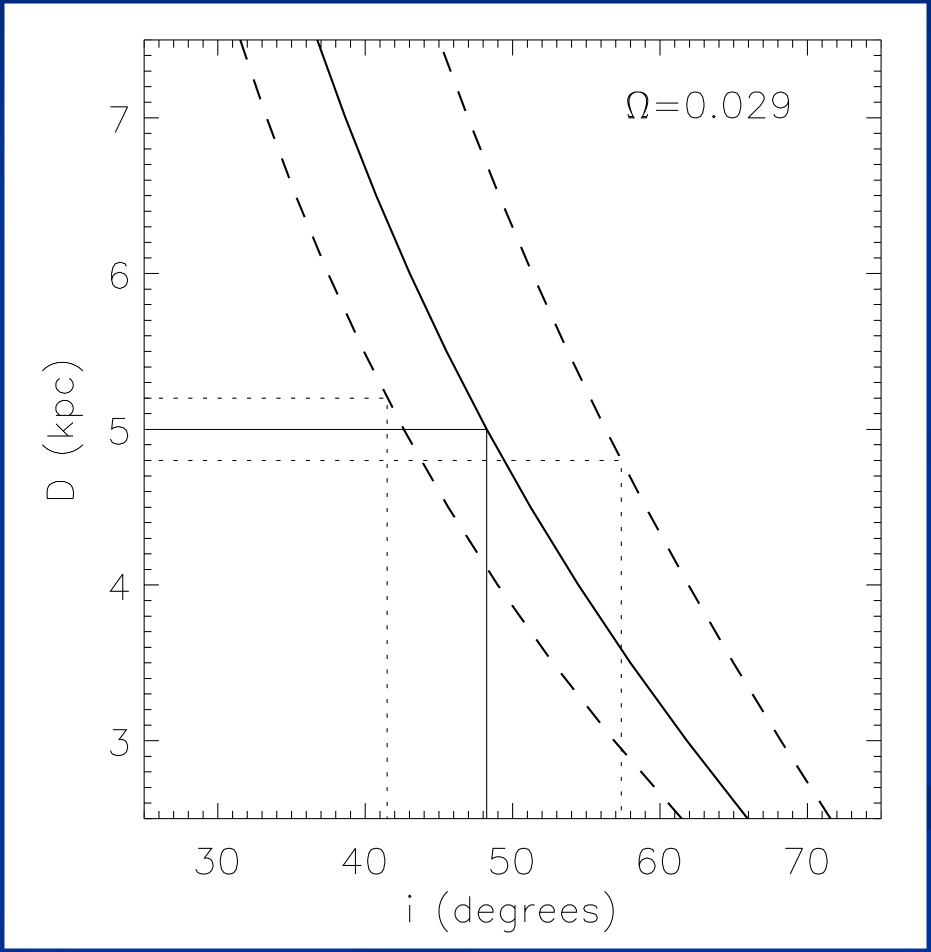




Residual solid-body rotation

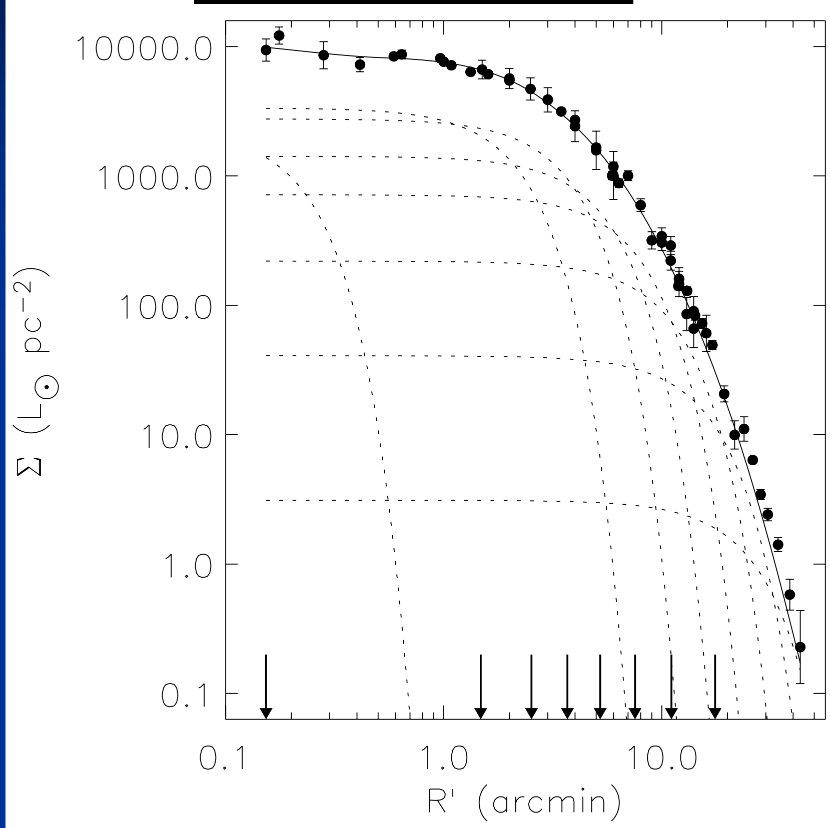
Constraint on inclination

- Best-fit solid-body rotation
  sbr = 0.029 mas/yr/arcmin
- canonical D = 5.0±0.2 kpc
  inclination i = 41 - 57°
- flattening:
  observed q′ = 0.88 ± 0.01
  intrinsic q = 0.78 ± 0.03

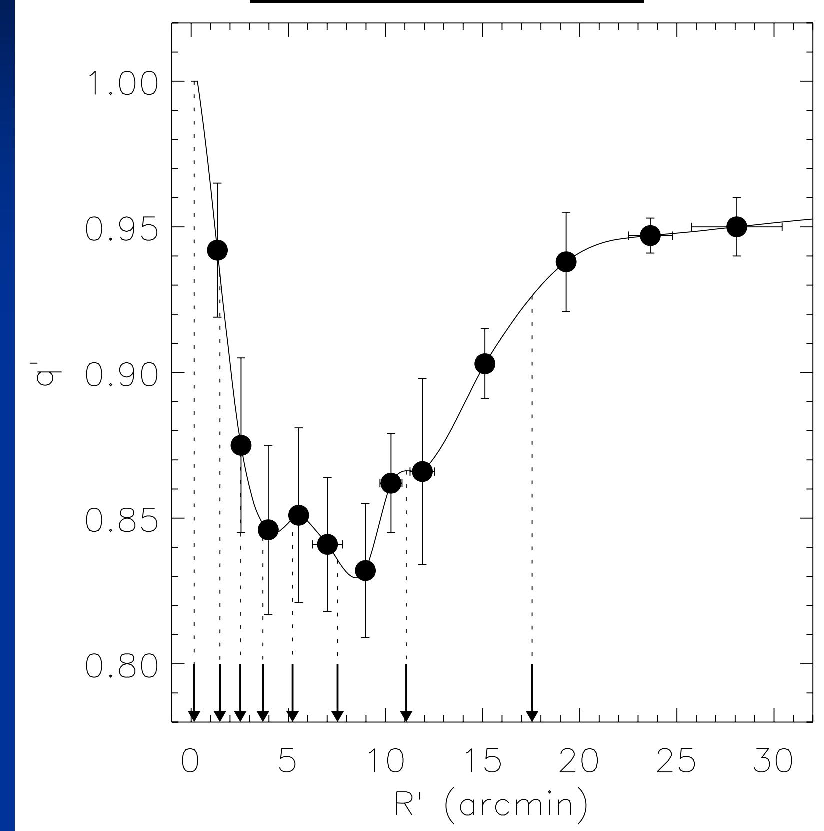


MGE mass model

Surface brightness



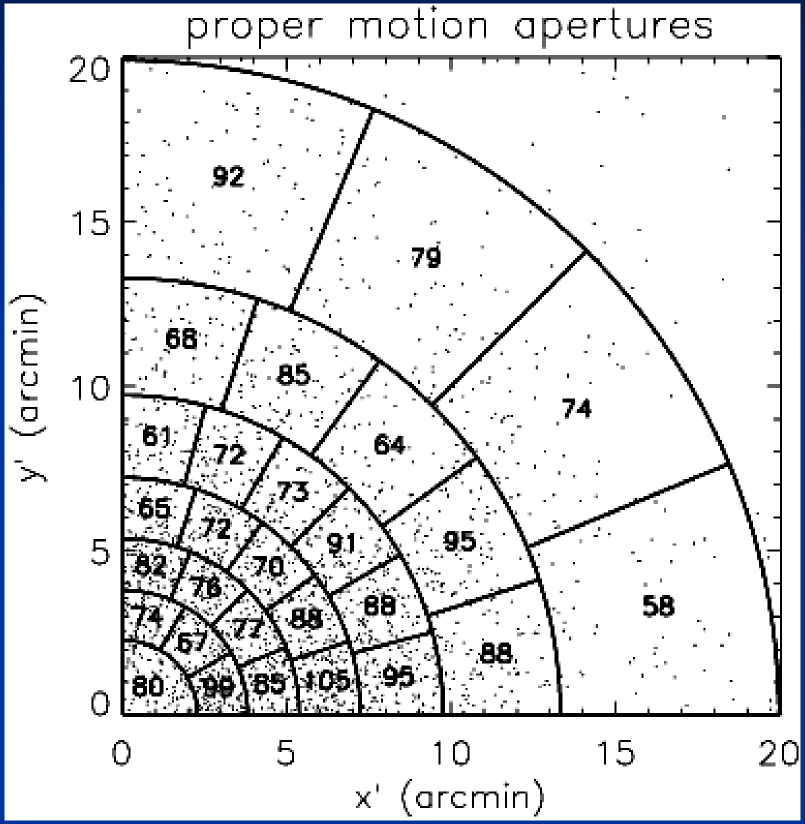
Flattening profile

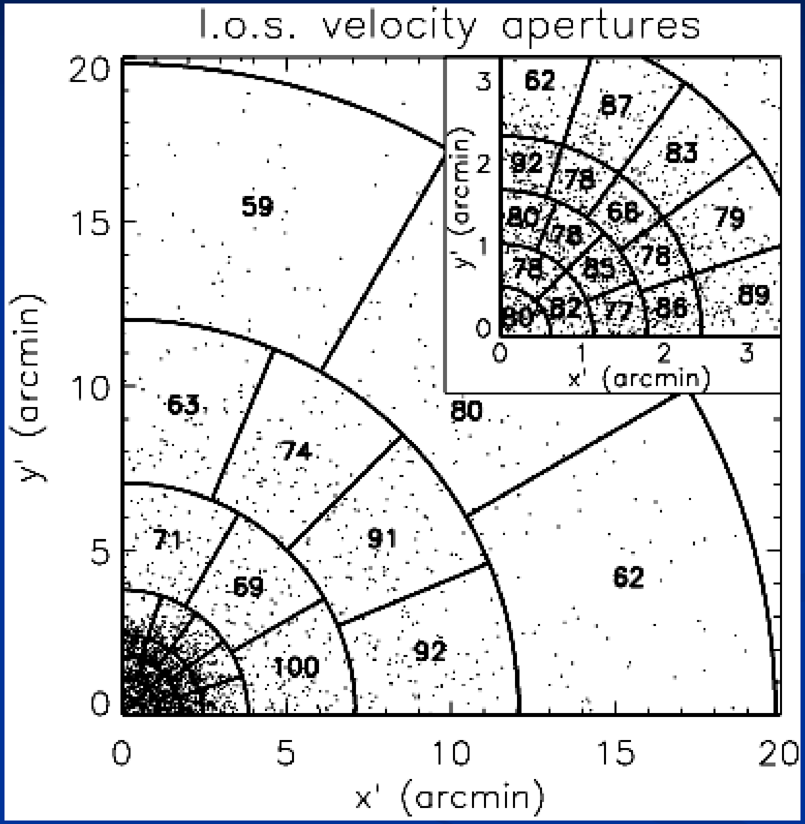


1 arcmin ~ 1.45 pc

- 1D: 8 Gaussians → 2D: flattening profile Geyer et al. (1983)
- E(B-V) = 0.11, D = 5.0±0.2 kpc: $L_V \sim 1.0 \pm 0.1 \times 10^6\ L_\odot$

Polar grid of apertures



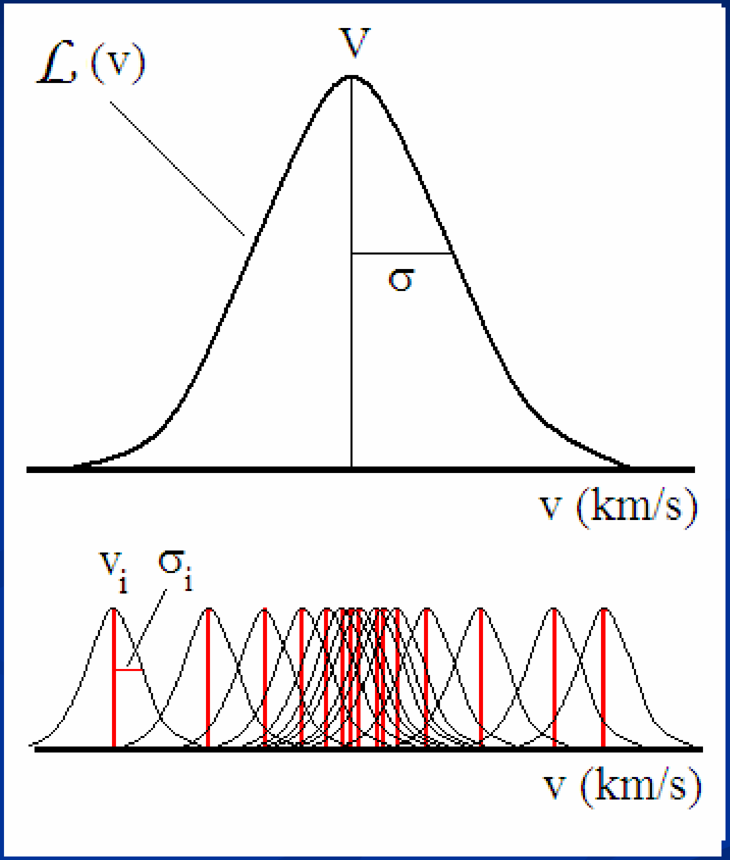


Reflected to first quadrant, around 80 stars per aperture

- Proper motions: 28 apertures, total 2295 stars
- L.o.s. velocities: 27 apertures, total 2223 stars

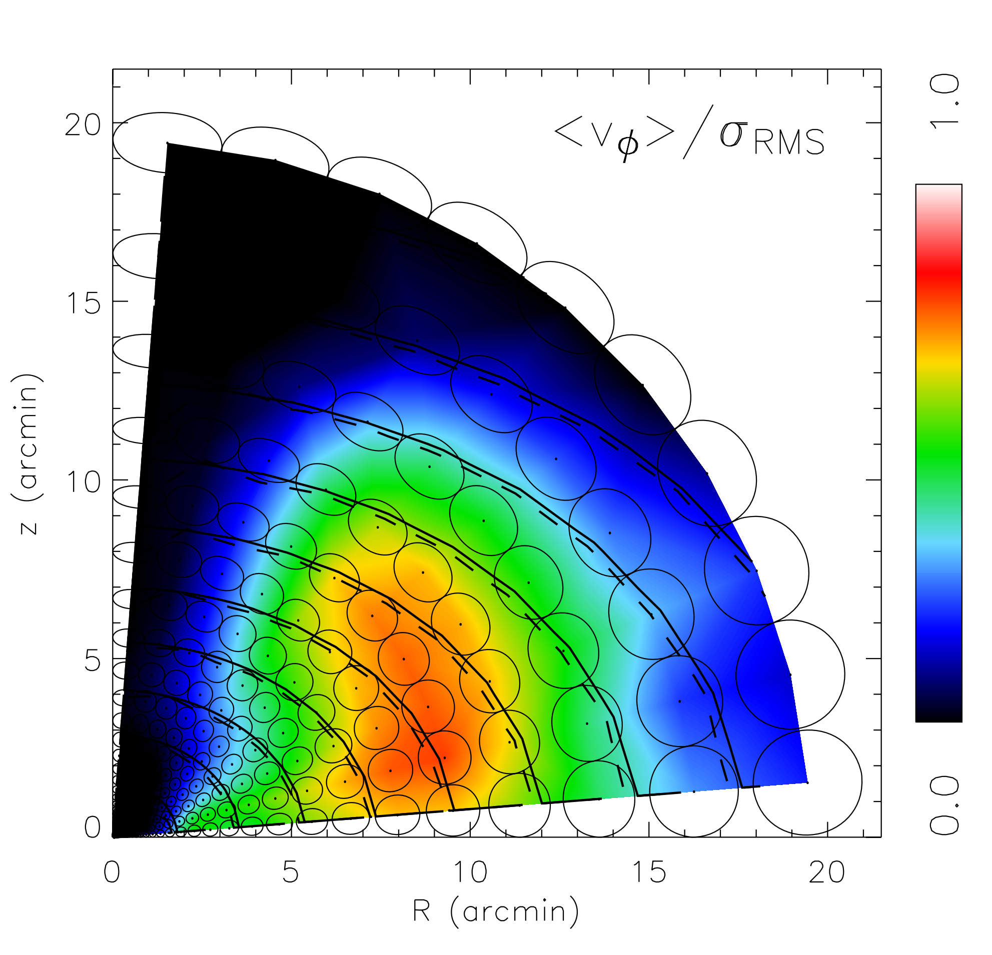
Averaged kinematics

- Fitting to average kinematics (V,σ,…) of stars within aperture:
  - Linear method ensures global best-fit
  - Faster than using discrete velocities
- How to extract velocity moments?
  - Gaussian fit to velocity histograms
  - Instrumental dispersion: $\sigma^2_{fit}=\sigma^2+\sigma^2_{ins}$
  - Maximum likelihood estimation:



$$L(V,\sigma,\ldots)=\prod_{i=1}^{n}\int_{-\infty}^{\infty}\mathcal{L}(v)\frac{e^{-\frac{1}{2}\left(\frac{v_i-v}{\sigma_i}\right)^2}}{\sqrt{2\pi}\sigma_i}dv$$

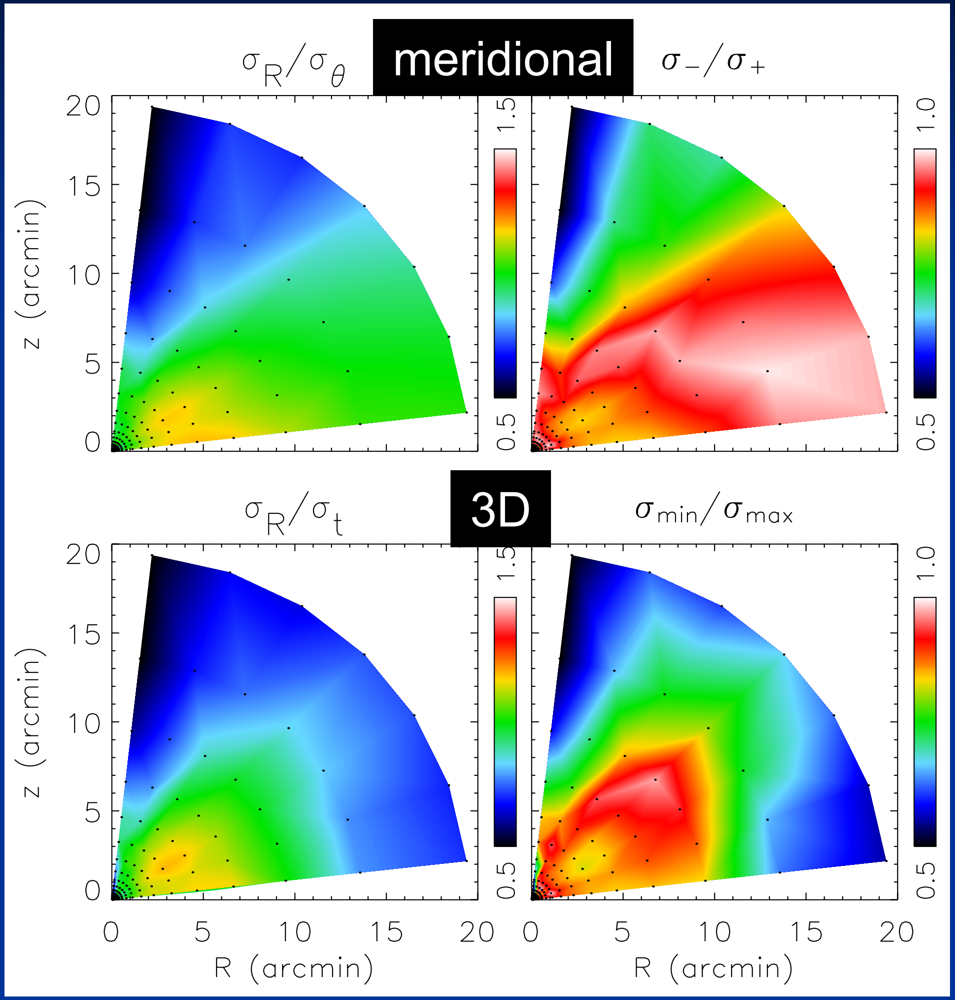
Rotational/pressure supported



$$\sigma_{RMS}^2 = \left(\sigma_R^2 + \sigma_\theta^2 + \sigma_\phi^2\right)/3$$

- max V/σ at R ~ 8 arcmin ~ at maximum v_{los}
- V/σ > 0.5 above isotropic oblate rotator in (V/σ,ε) ~ rotational support
- Outwards (partly) pressure supported

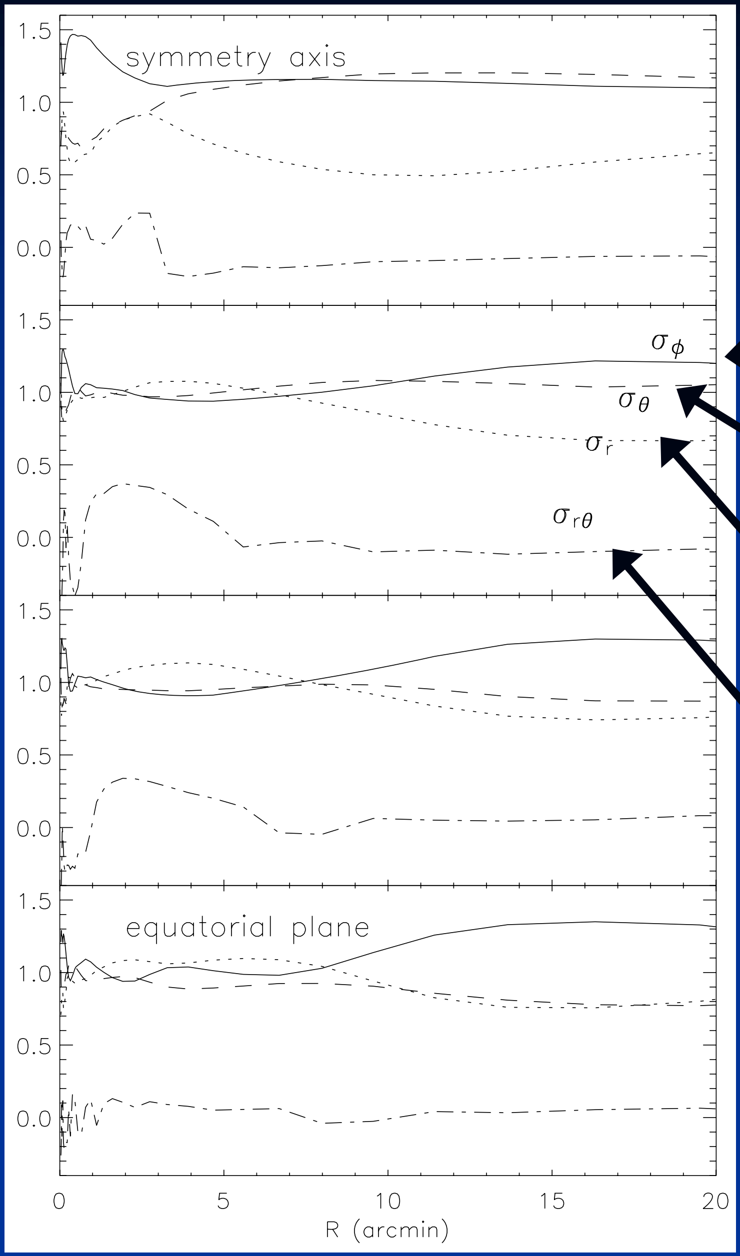
Anisotropy



$$\sigma_t^2 = \left(\sigma_\theta^2 + \sigma_\phi^2\right)/2$$

- Principal axis velocity ellipsoid σ_+ , σ_- , and σ_ϕ
- In meridional plane:
  - Almost isotropic near equatorial plane
  - Tangential anisotropic towards symmetry axis
- 3D (including azimuthal)
  - Radial anisotropic center
  - Tangential ansiotropic in outer parts
- Not two-integral $F(E,L_z)$

Intrinsic velocity moments



$$\sigma_\varphi^2 = \langle v_\varphi^2 \rangle - \langle v_\varphi \rangle^2$$

$$\sigma_\theta^2 = \langle v_\theta^2 \rangle$$

$$\sigma_R^2 = \langle v_R^2 \rangle$$

$$\sigma_{R\theta}^2 = \langle v_R v_\theta \rangle$$

Axisymmetric:

$$\langle v_R \rangle = \langle v_\theta \rangle = \langle v_R v_\phi \rangle = \langle v_\theta v_\phi \rangle = 0$$

Conclusions ω Centauri

- Significant perspective and residual solid-body rotation
- Amount solid-body rotation and D·tan(i) directly from data
- Axisymmetric anisotropic Schwarzschild model:

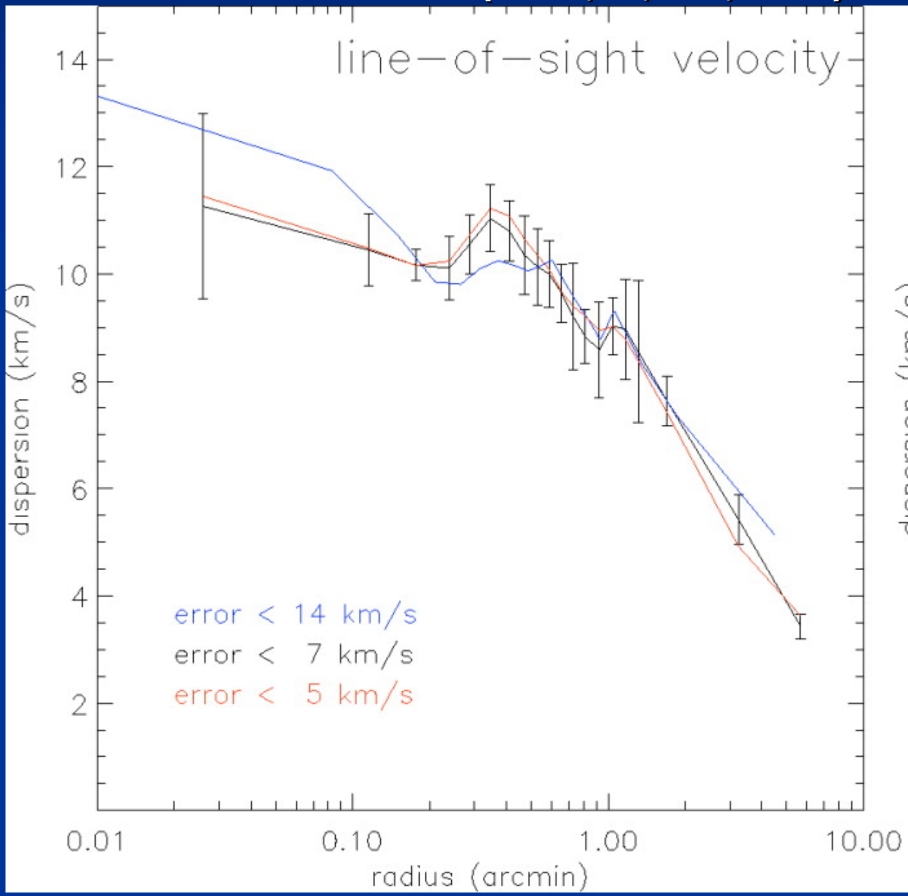
  $D=4.8\pm0.3$ kpc, $M/L_V=2.5\pm0.1\ M_\odot/L_\odot$, $M=2.5\pm0.3 \times 10^6\ M_\odot$
- Substructure in distribution function:
  - Main component center non-rotating ‘bulge’
  - Outwards increasing rotation and flattening
  - Inner (~1-3 arcmin) maximum rotating disk ~ 4% mass

  … linked with multiple stellar populations?
  … tidally stripped dwarf galaxy?

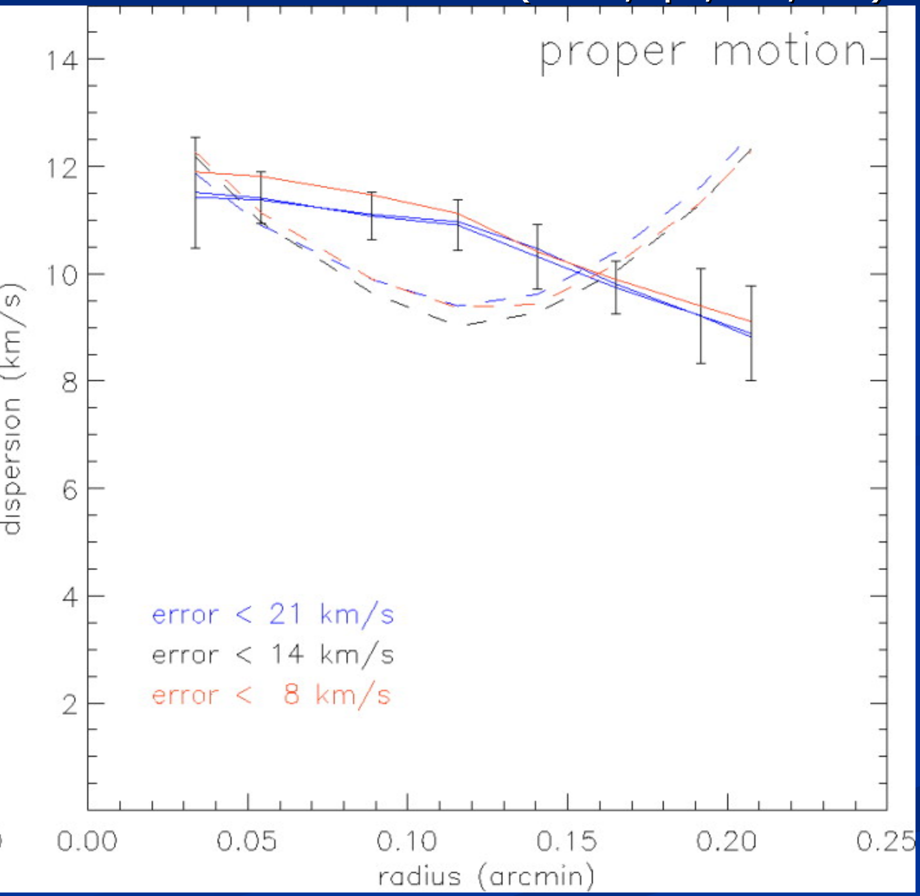
Extra: M15

Dispersion profiles

#1773 Gebhardt et al. (2009,AJ,119,1268)



#703 McNamara et al. (2003,ApJ,595,187)

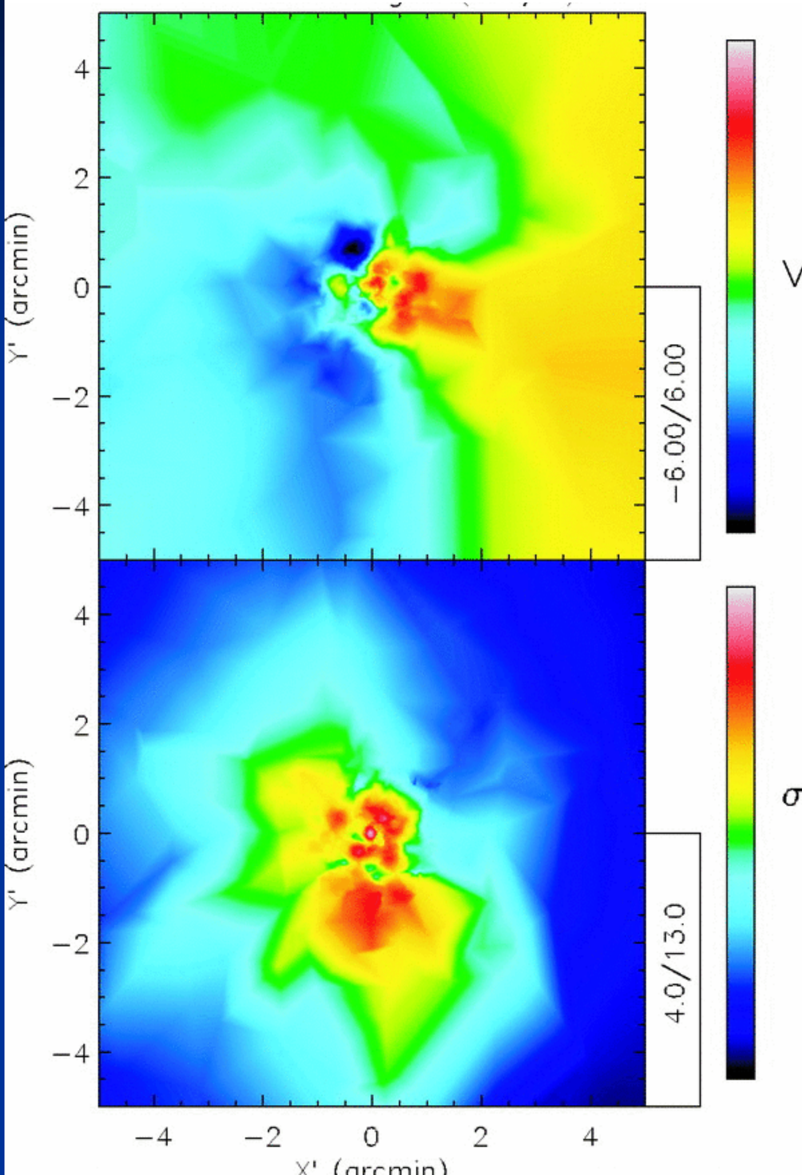


1 arcmin ~ 3 pc

Kinematic maps

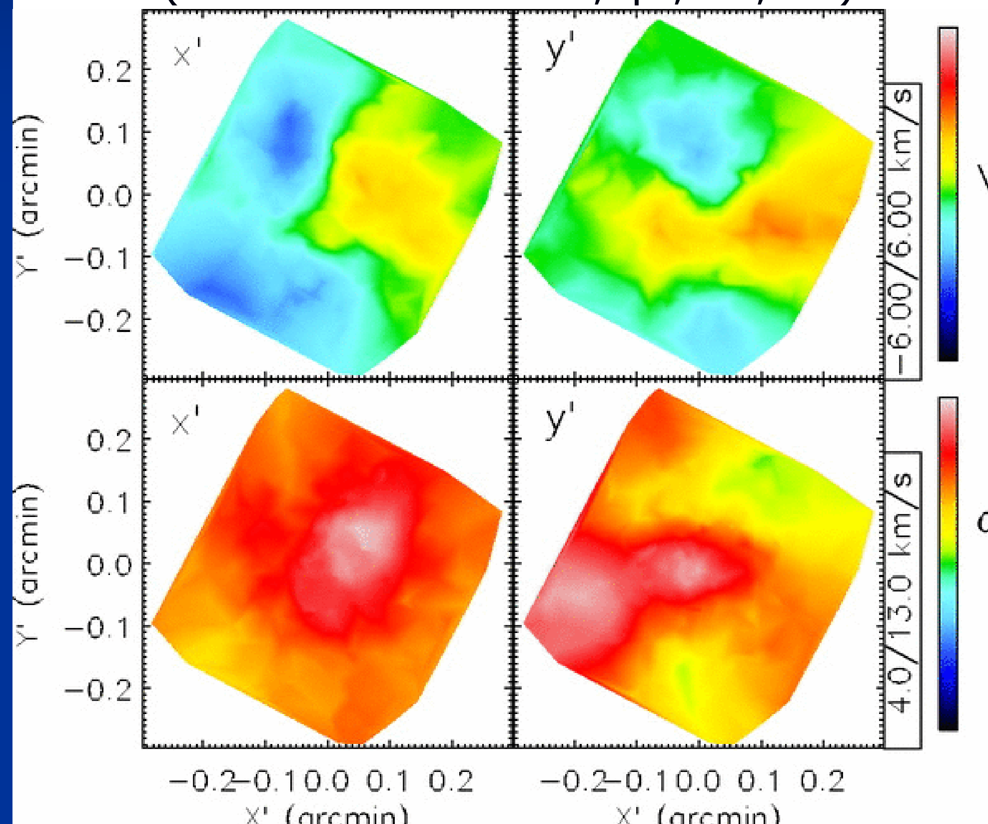
1540 l.o.s. velocities

(Gebhardt et al. 2009,AJ,119,1268)



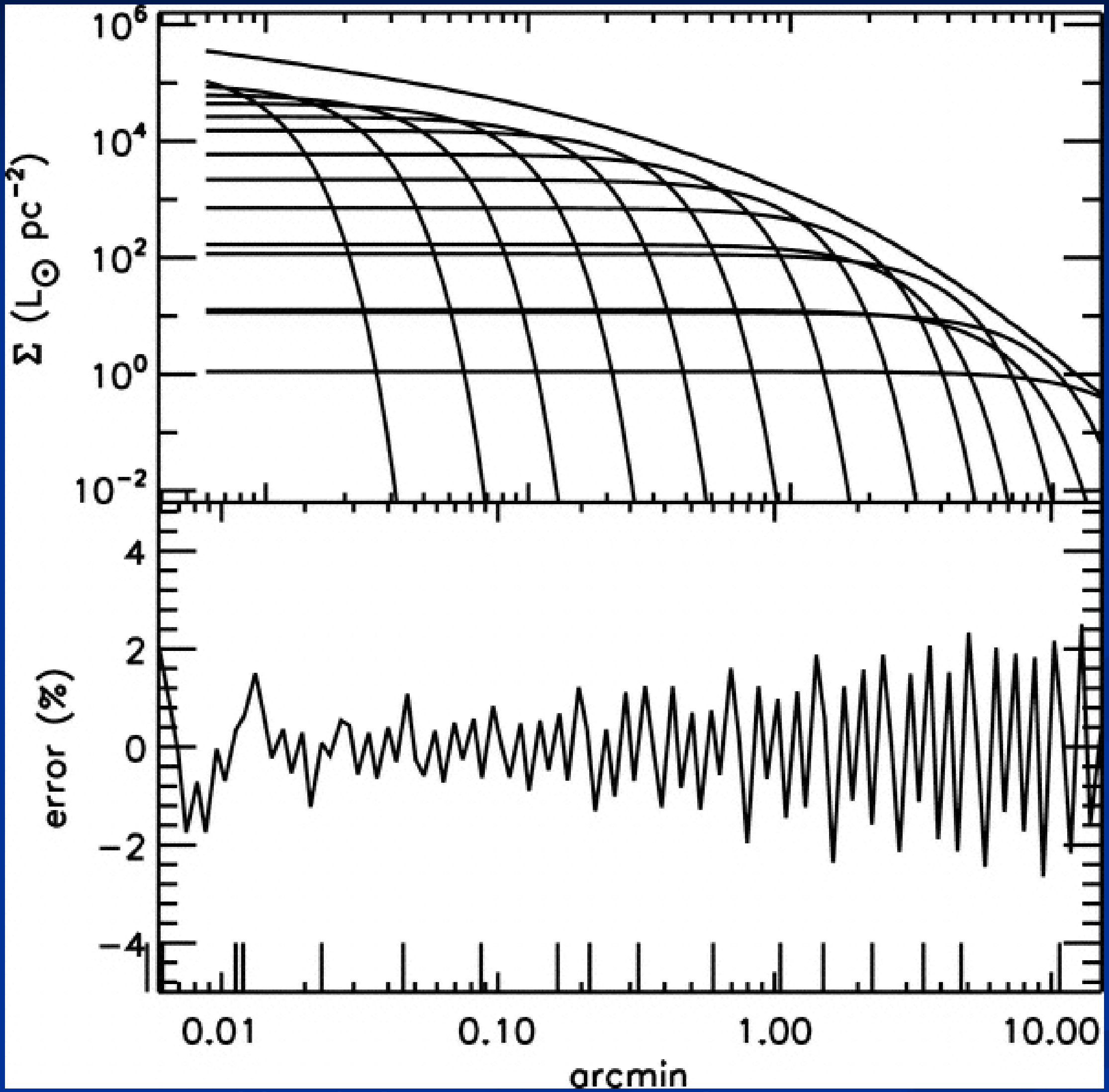
703 HST proper motions

(McNamara et al. 2003,ApJ,595,187)



1 arcmin ~ 3 pc

MGE mass model



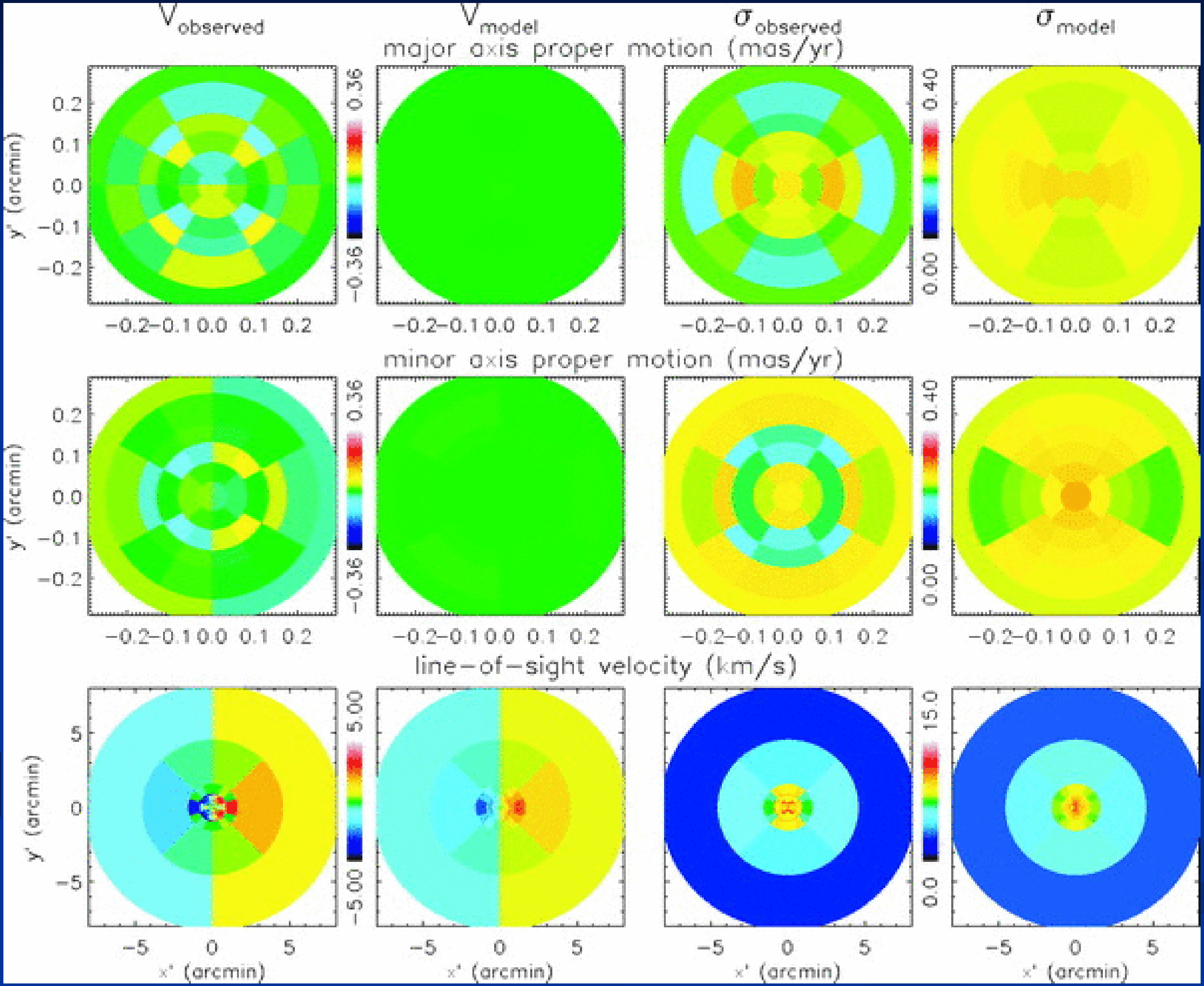
Noyola & Gebhardt (2006,AJ,132,447) 1 arcmin ~ 3 pc

Schwarzschild model

horiz.

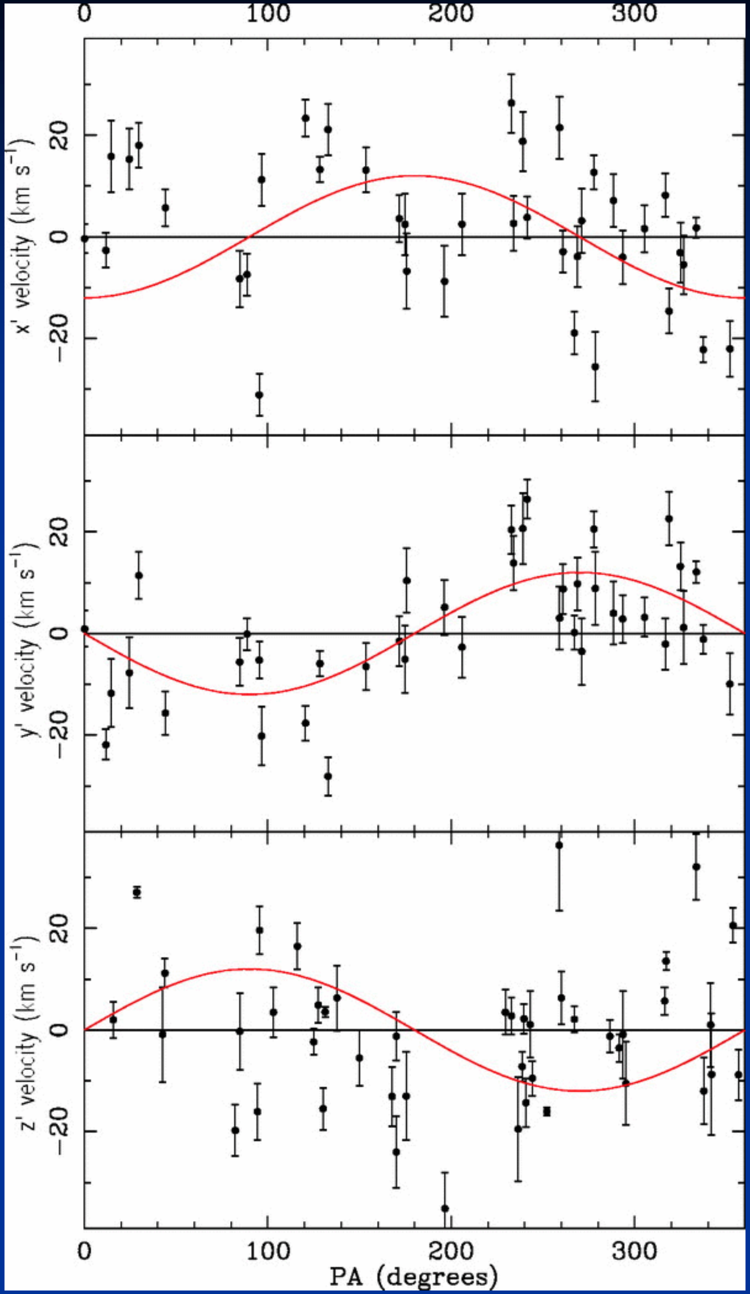
vert.

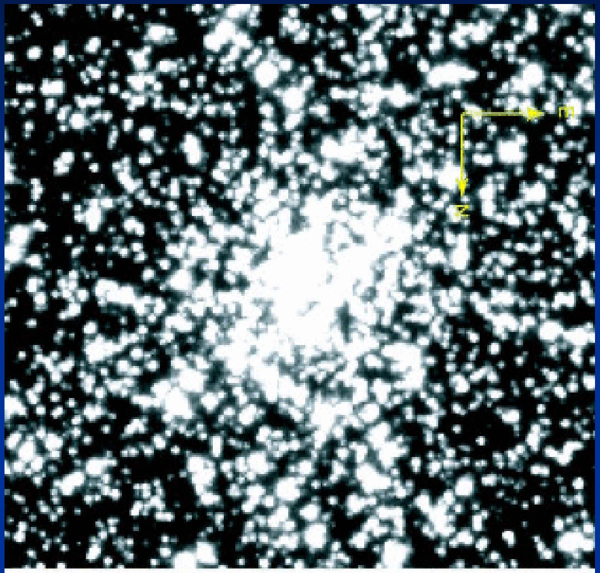
l.o.s.

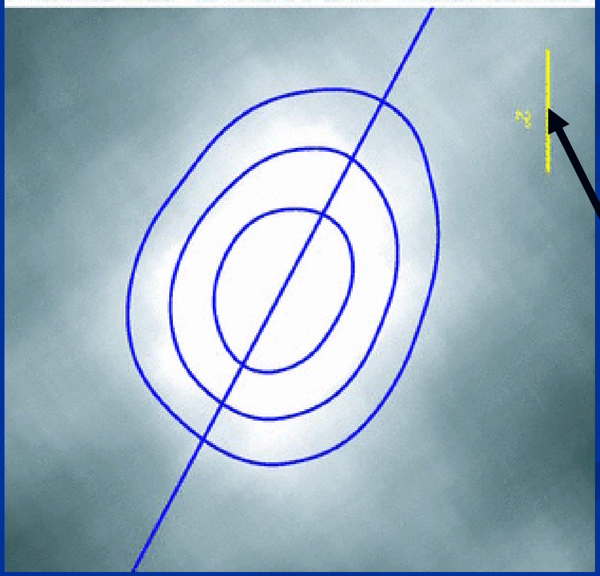


1 arcmin ~ 3 pc

Decoupled core?







2″=0.1 pc