Overview of Dynamical Modeling

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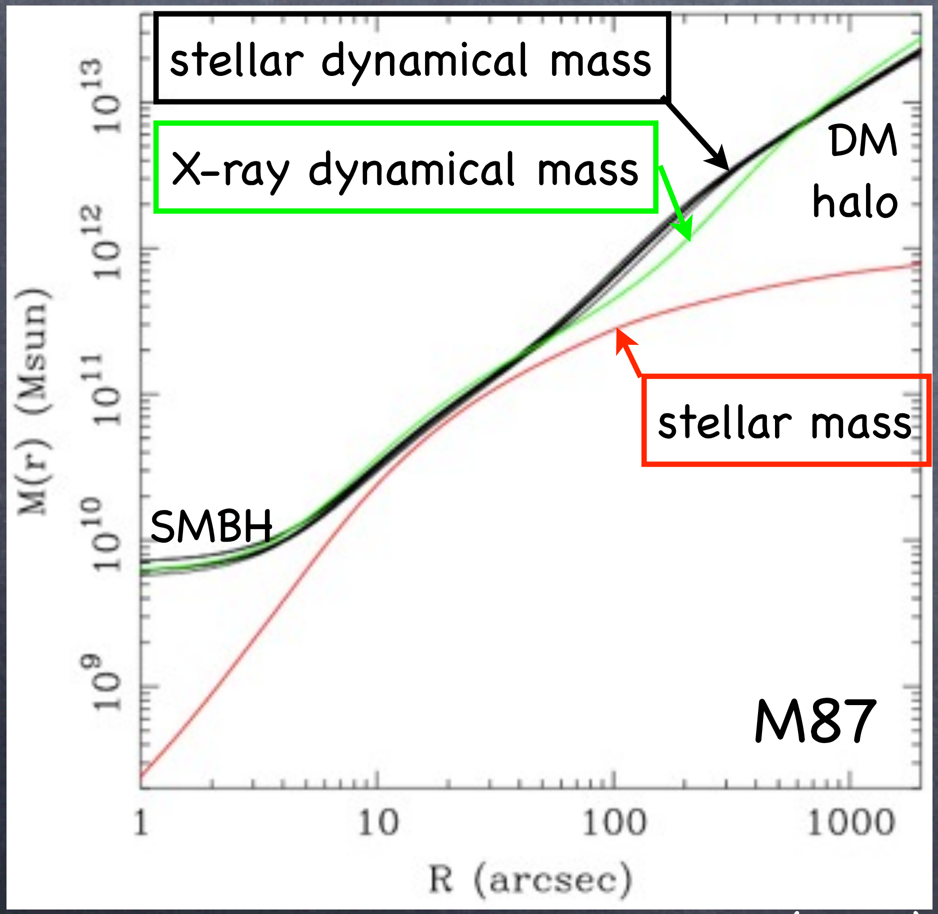
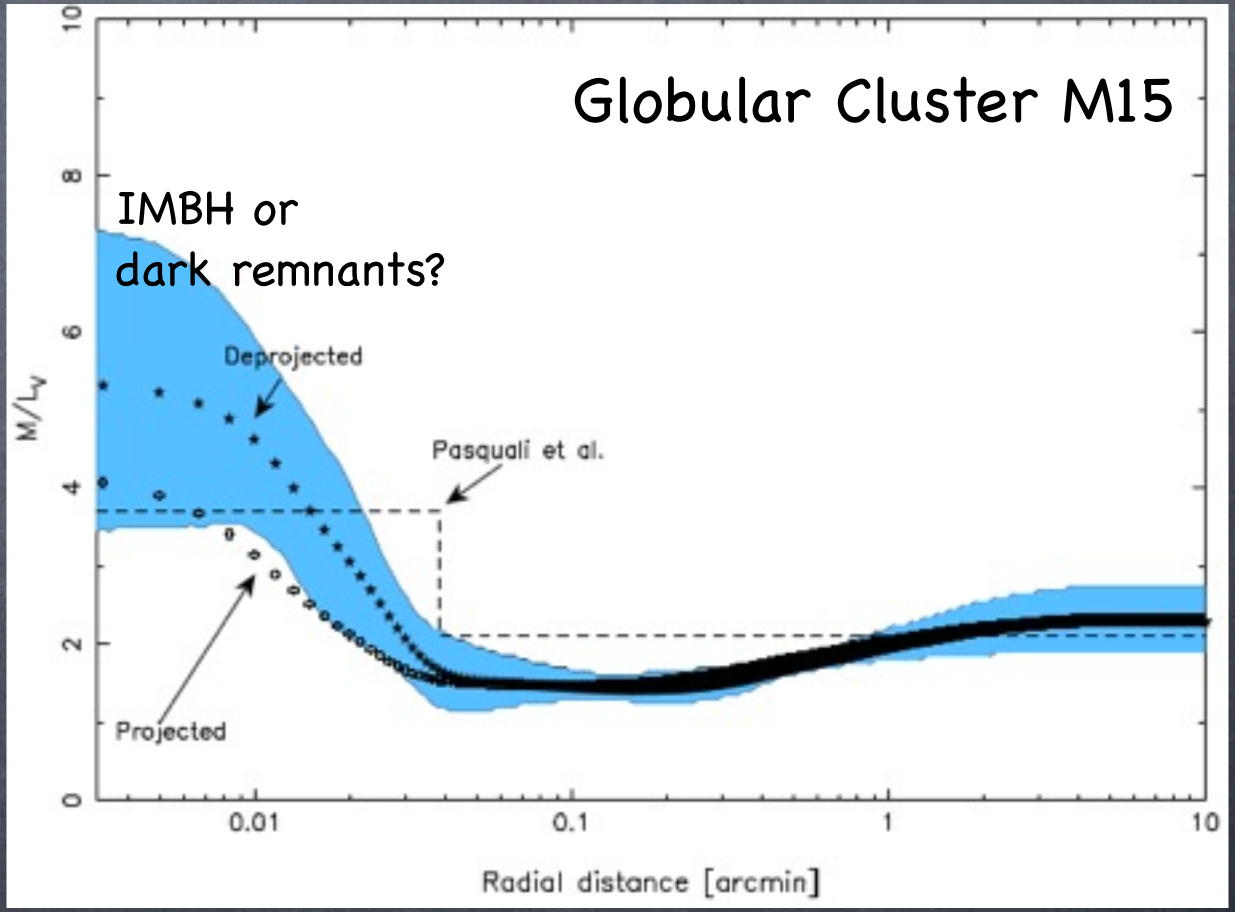
Why dynamical modeling? -- mass

- total mass stellar systems key is to their evolution
- compare luminous mass: constrain DM and/or IMF
- DM radial profile and shape agree with LCDM?
- central black hole mass



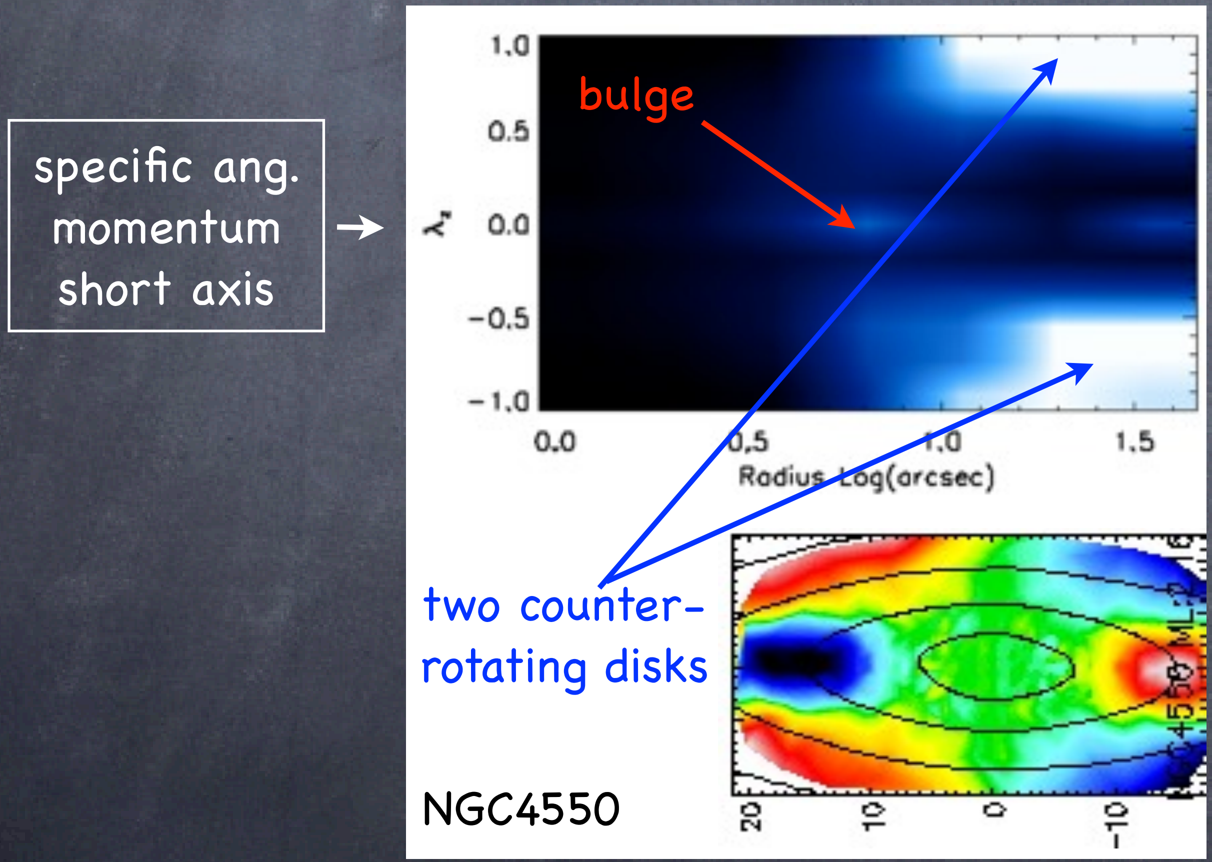
Gehardt & Thomas (2009)



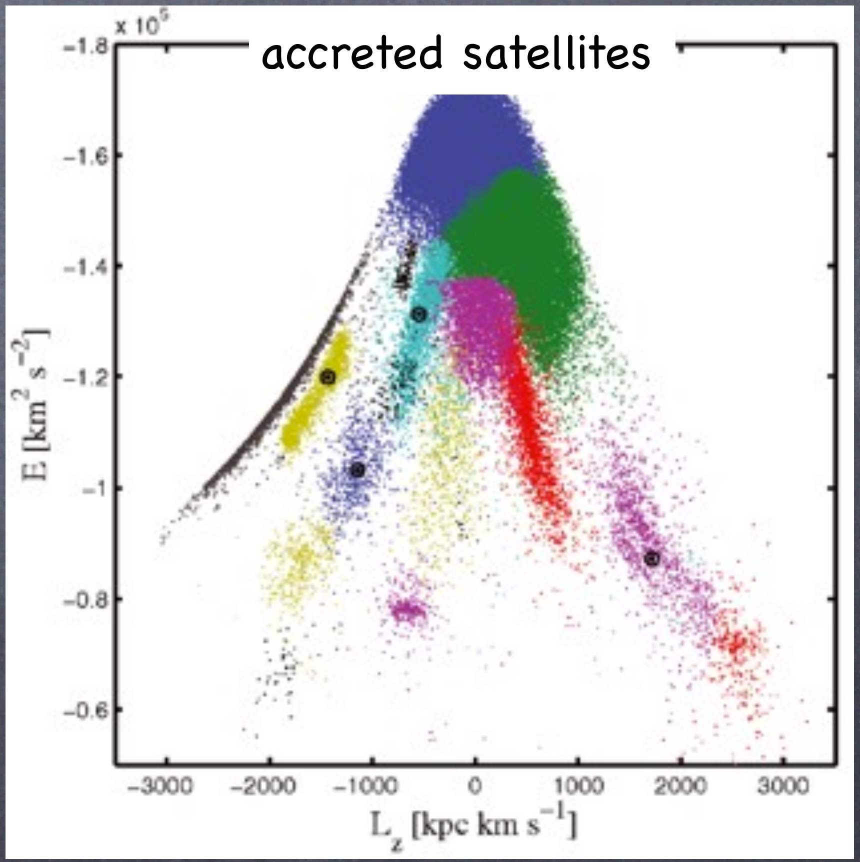
den Brok et al. (2012)

Why dynamical modeling? -- DF

- distribution function of (sub-)populations
- dynamical decomposition: bulge, disk, halo
- stellar merger/accretion conserved in phase-space
- chemical tagging: growth of disk and bulge



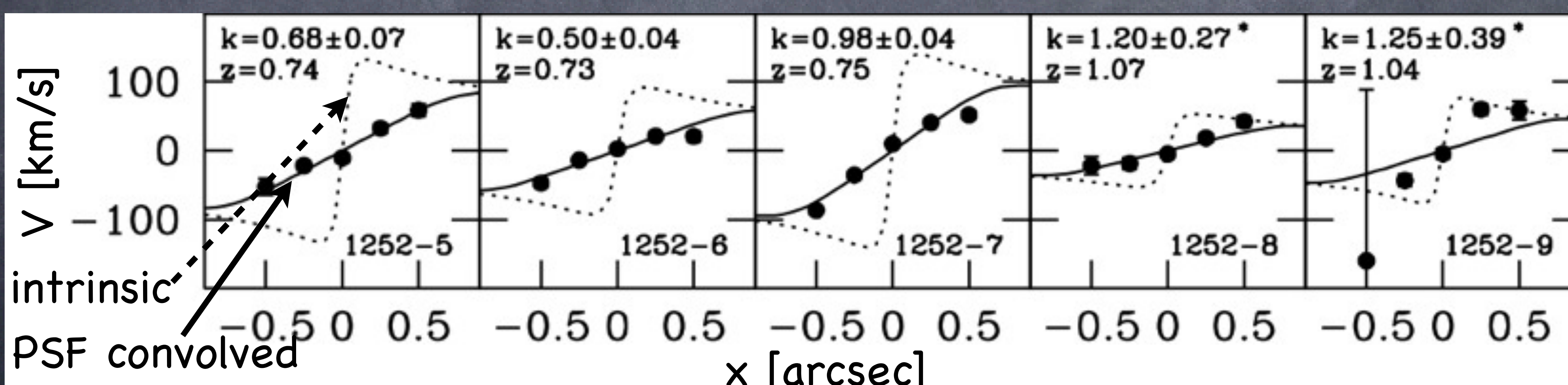
van den Bosch et al. (2012)



Gomez et al. (2010)

Kinematic tracers: integrated spectra

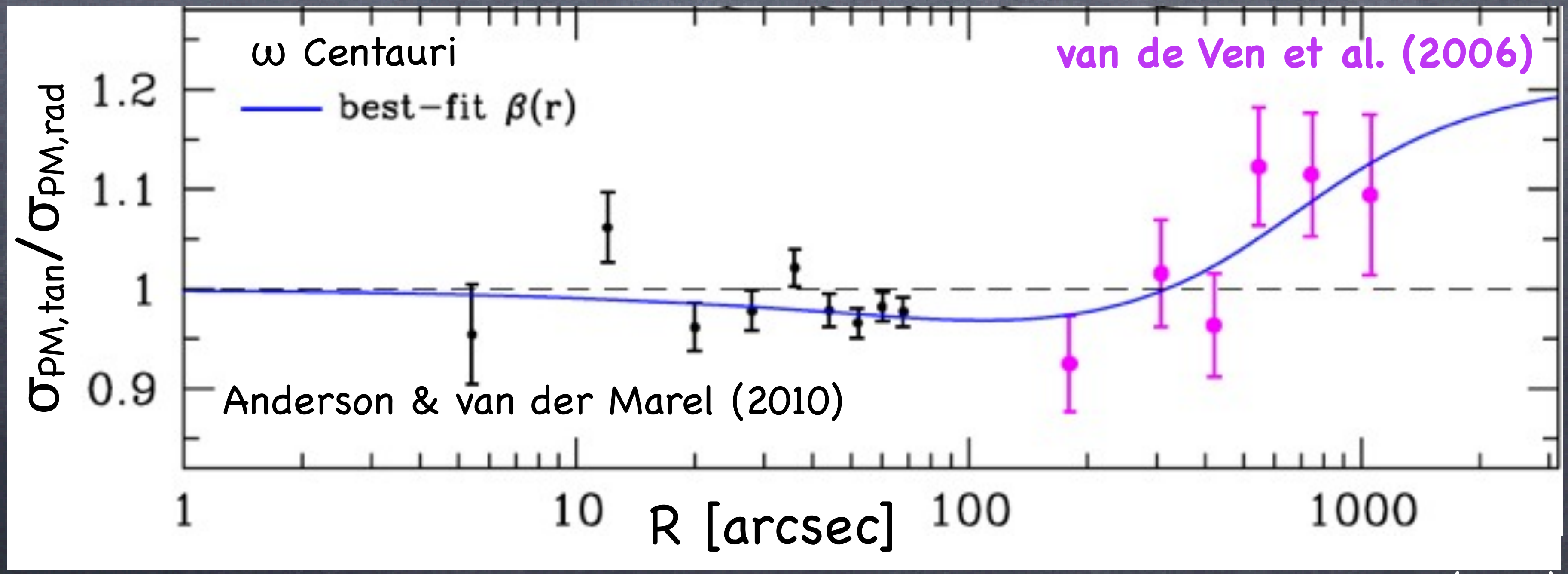
- inner parts external galaxies & distant universe; random errors mostly limited by exposure time
- observed spectrum = stellar spectra ⊗ LOSVD
  line-of-sight velocity distr. moments: V, σ, h_3, h_4, ...
  - aperture: single value; physical size depends on z
  - long-slit: radial profile; multiplexing at high(er) z
  - integral-field spectroscopy: maps; uncover kinematical substructures, better constraints mass and DF



van der Wel & van der Marel (2008)

Kinematic tracers: discrete velocities

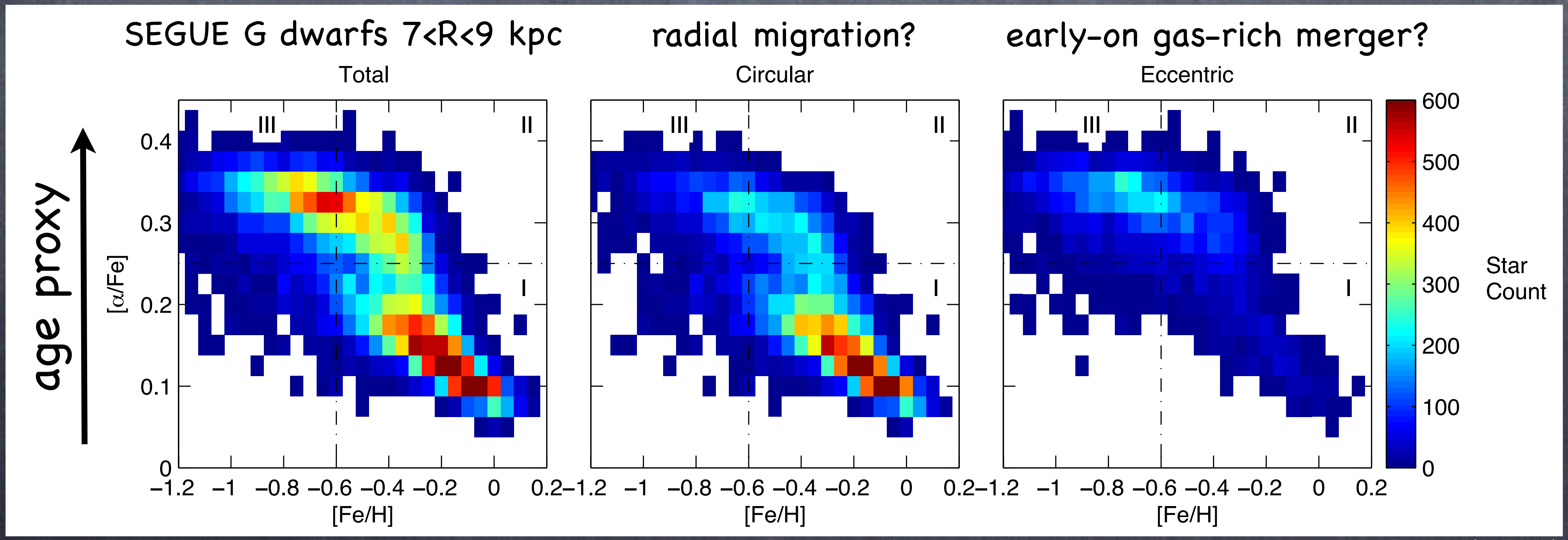
- outer parts external galaxies / groups & Local Group; random errors mostly limited by numbers [$d\sigma/\sigma=(2N)^{-1/2}$]
- observed spectrum of single, resolved object:
  - line-of-sight velocities (v_{los}): satellites, PNe, GCs, resolved stars
  - proper motions (μ_α&μ_δ): Galactic GCs, dSph galaxies?
    direct measure of velocity anisotropy $\beta = 1 - \sigma_{tan}^2/\sigma_{rad}^2$
  - plus distance ($\alpha,\delta,D,\mu_\alpha,\mu_\delta,v_{los}$): Milky Way stars



van der Marel & Anderson (2010)

Kinematic tracers + chemical tags

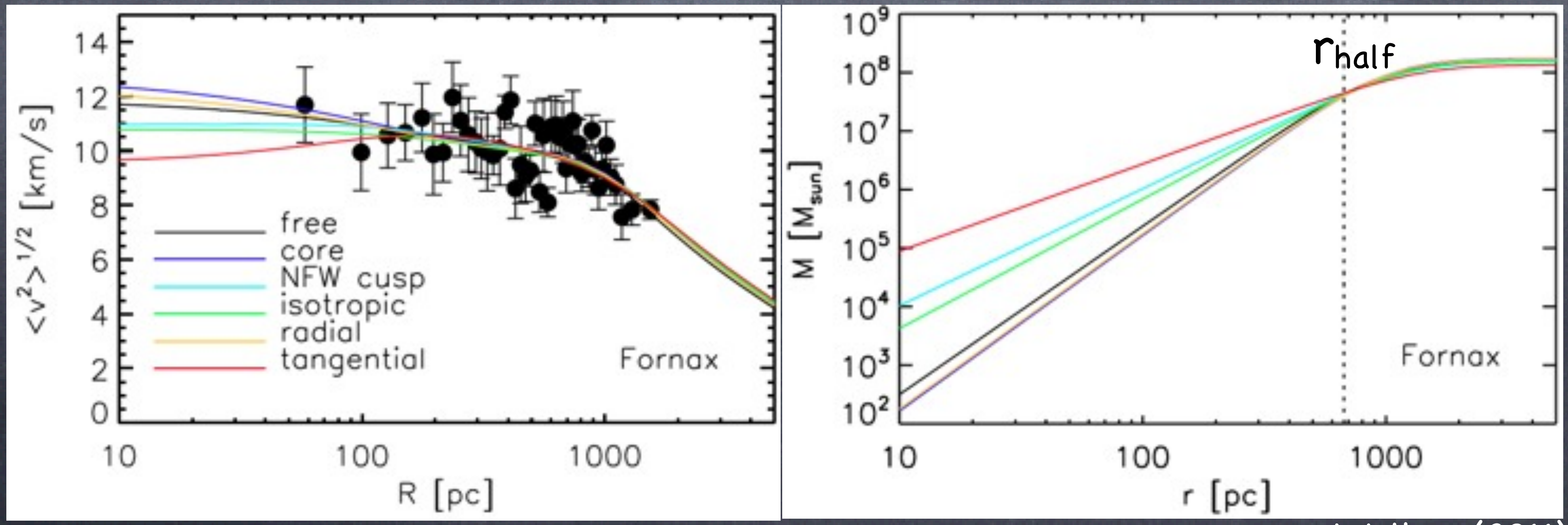
- chemical tags are true integrals of motion
- integrated spectra: break degeneracy multiple stellar populations; additional info from UV & FIR?
- resolved stars photometry: (rough) estimate [Fe/H]
- resolved stars spectra: [Fe/H], [a/Fe] age proxy; beyond requires expensive high spectral resolution



Liu & van de Ven (2012)

Modeling methods: virial mass

- Scalar virial theorem: $M = v_{RMS}^2 \, r_g / G$
  Virial mass estimate: $M = \kappa \, \sigma_{los}^2 \, r_h / G$, $\kappa \neq$ constant:
  - r_g/r_h depends on surface brightness distribution, mass-to-light ratio profile (incl. dark halo), viewing direction
  - v_{RMS}/σ_{los} depends velocity anisotropy, (model beyond) radial extend kinematic tracers, viewing direction
- still works due to insensitivity beyond $\sim r_h$, but dynamical modeling needed to go beyond single mass value



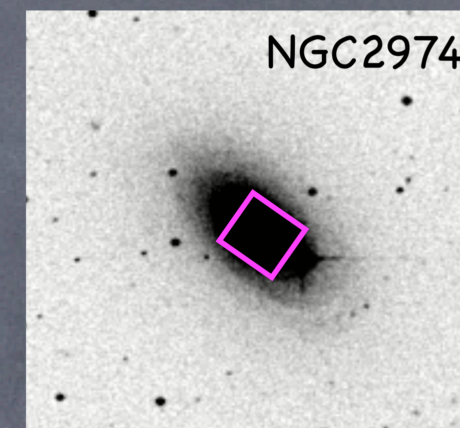
Walker (2011)

Modeling methods: Jeans equations

$$\frac{GM_{tot}(<R)}{R} = -R\frac{d\Phi}{dR} = V_c^2(R)$$

$$V_c^2(R) = V_\phi^2 + \sigma_R^2 \left[\frac{\partial \ln\left(\nu\sigma_R^2\right)^{-1}}{\partial \ln R} + \ldots \right]$$

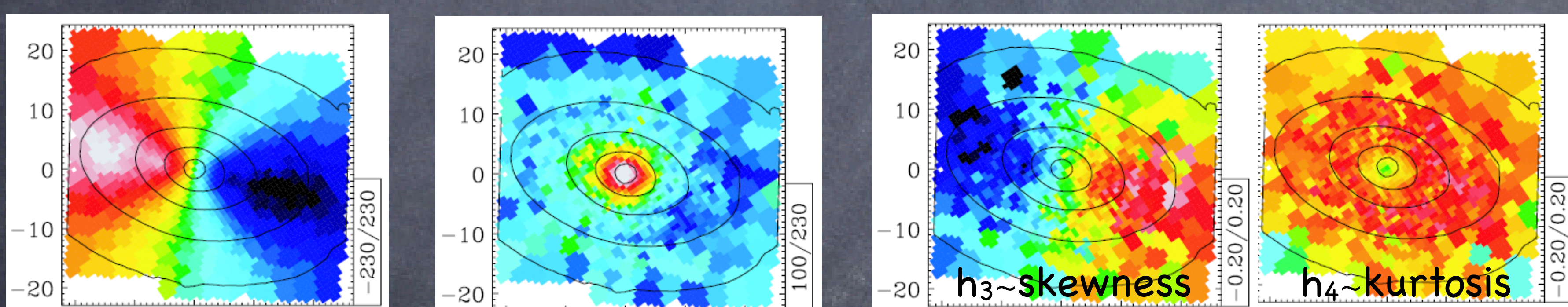
tracer density



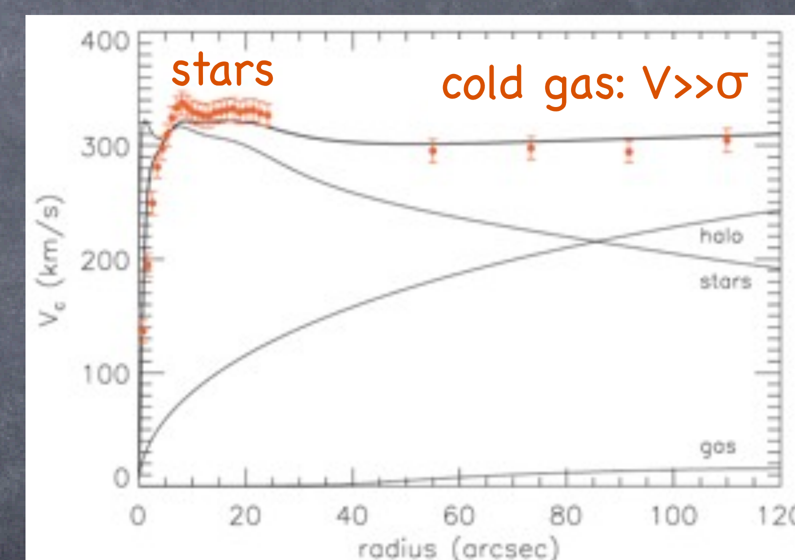
mean velocity

velocity dispersion

velocity anisotropy



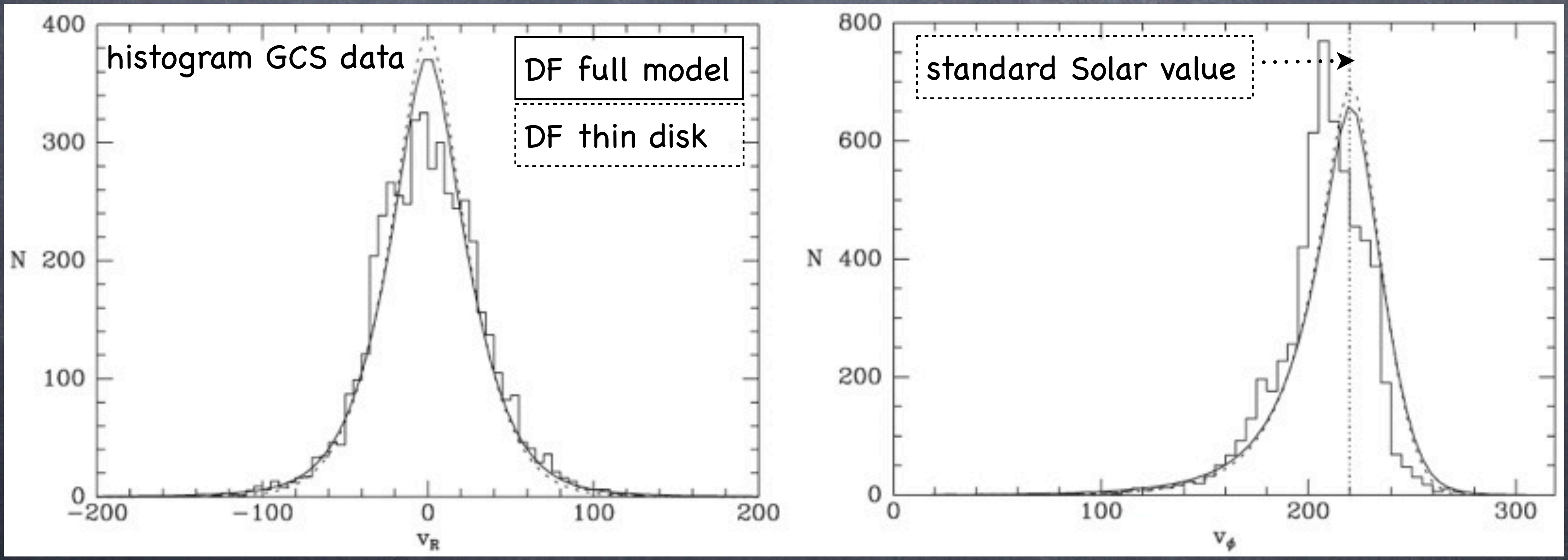
Weijmans et al. (2008)



Velocity anisotropy? Axial symmetry? DF non-negative?

Modeling methods: distribution function

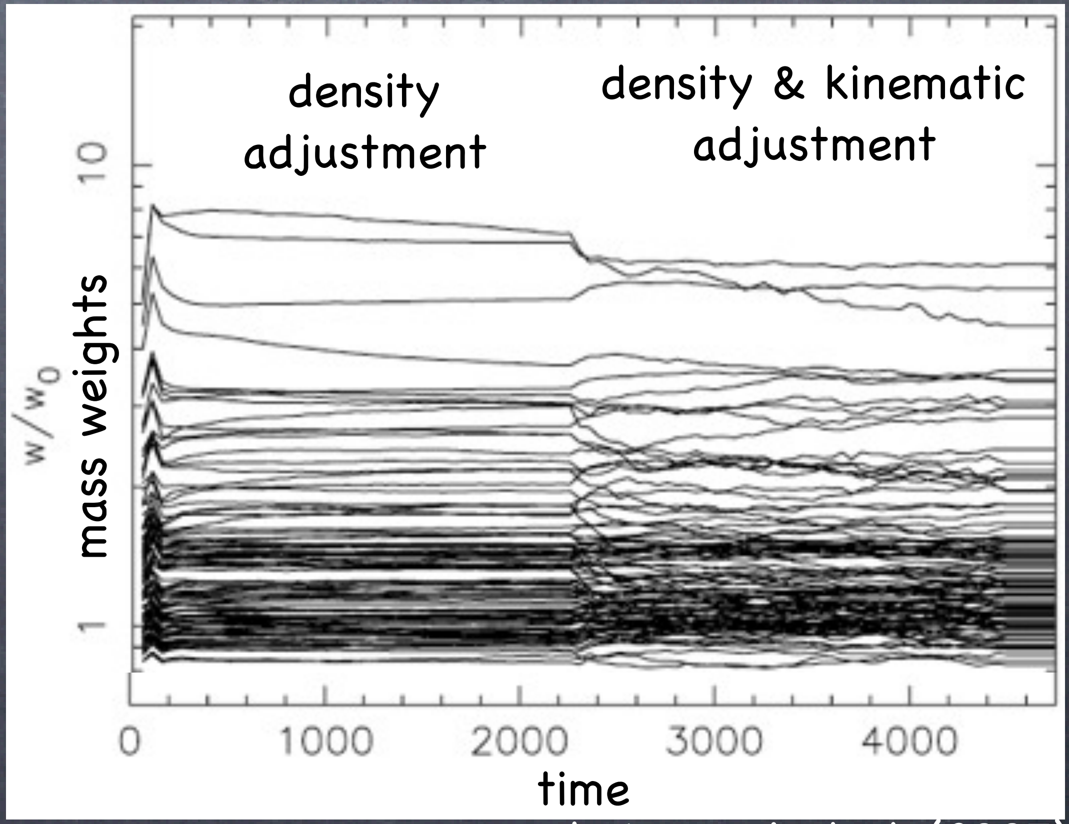
- Steady-state equilibrium: DF depends on 3 integrals of motion: energy E, second I2 = {L,Lz,Lx,...}, third I3 = ?
- Analytical DFs in literature, but specific forms assumed and I3 unknown (exception separable Stäckel potentials)
- Numerical DFs via mass weighted superposition of orbits (Schwarzschild's method) or tori fitted to obs. kinematics



Binney (2010), McMillan & Binney (2010)

Modeling methods: particles

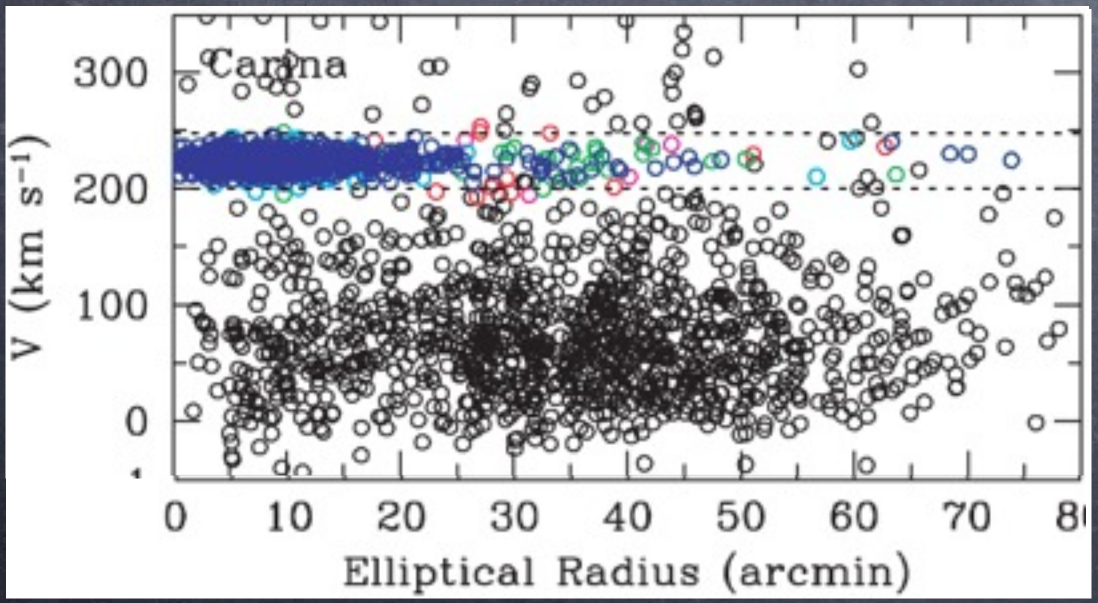
- evolving, non-equilibrium systems with particle models:
  - asymmetric mass distribution: warps, lopsided, mergers
  - rotating components: bars and spiral arms
  - evolution particles and gravitational potential & stability
- but computationally expensive and unknown initial conditions
- Made-to-Measure N-body: vary particle masses to converge toward observations (Syer & Tremaine 1996)



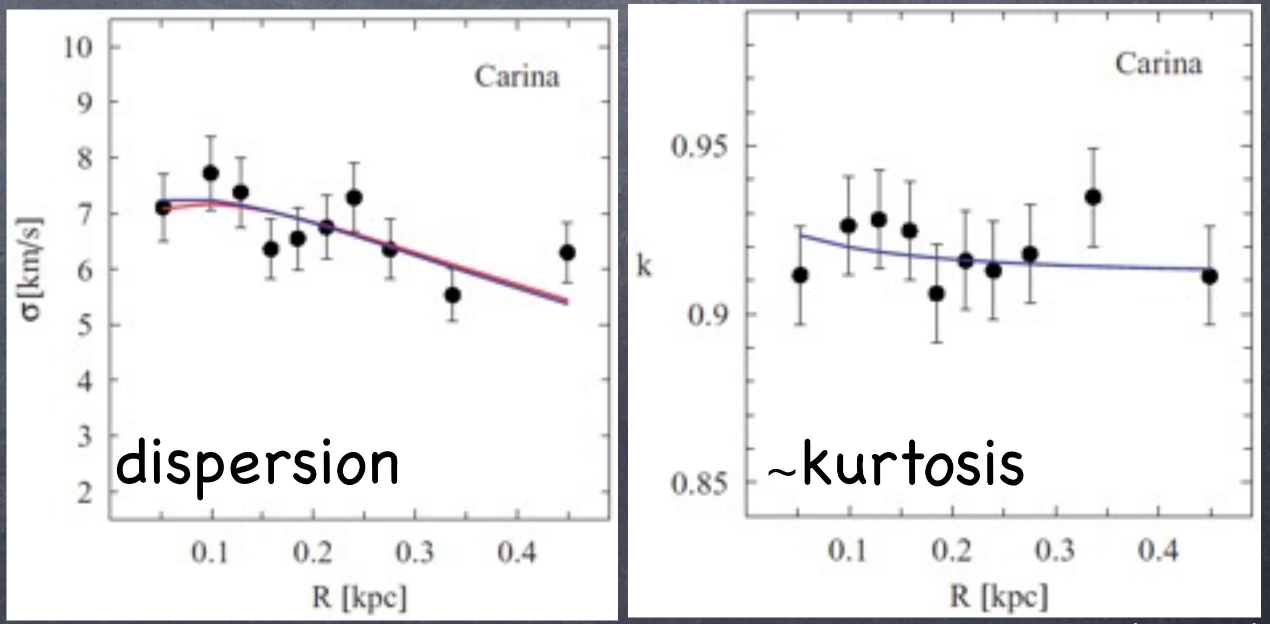
de Lorenzi et al. (2007)

Inference: velocity moments

- integrated spectra:
  - now fit extracted moments or histogram LOSVD
  - fit spectra directly using observed/model stellar templates?
- discrete velocities:
  - better cleaning for non-members also removes more members
  - more spatial binning to extract higher-order velocity moments
  - tracer density from photometry, but often challenging corrections for incompleteness and selection biases



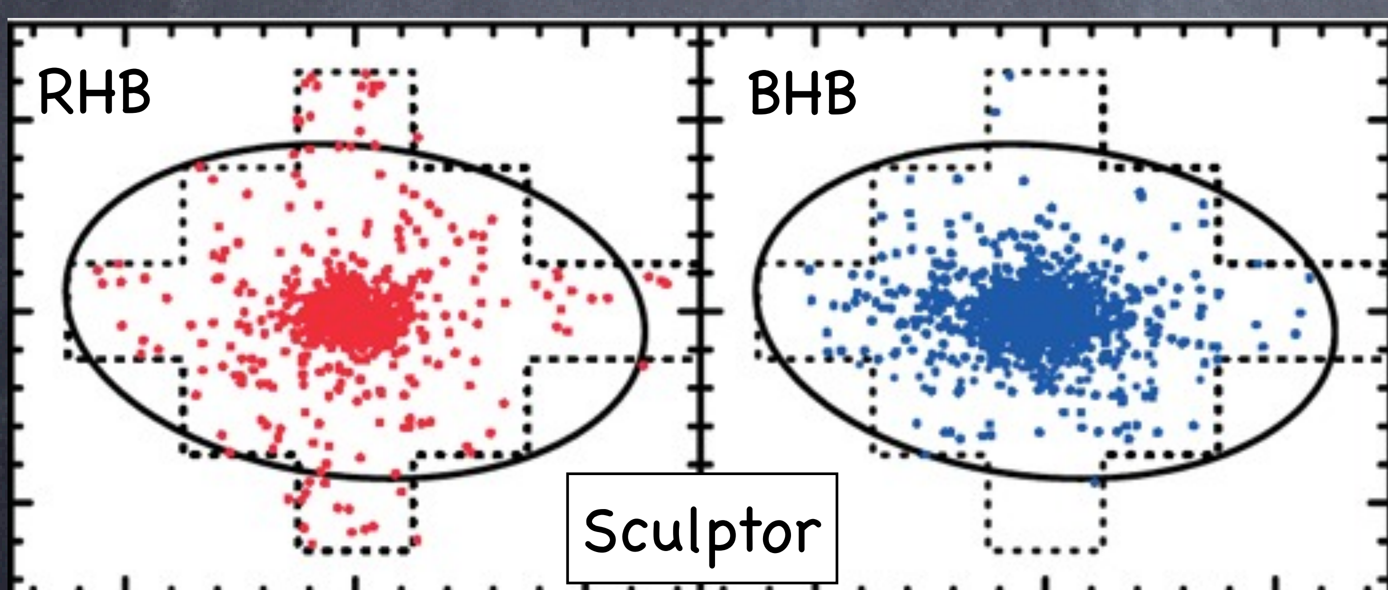
Walker et al. (2009)



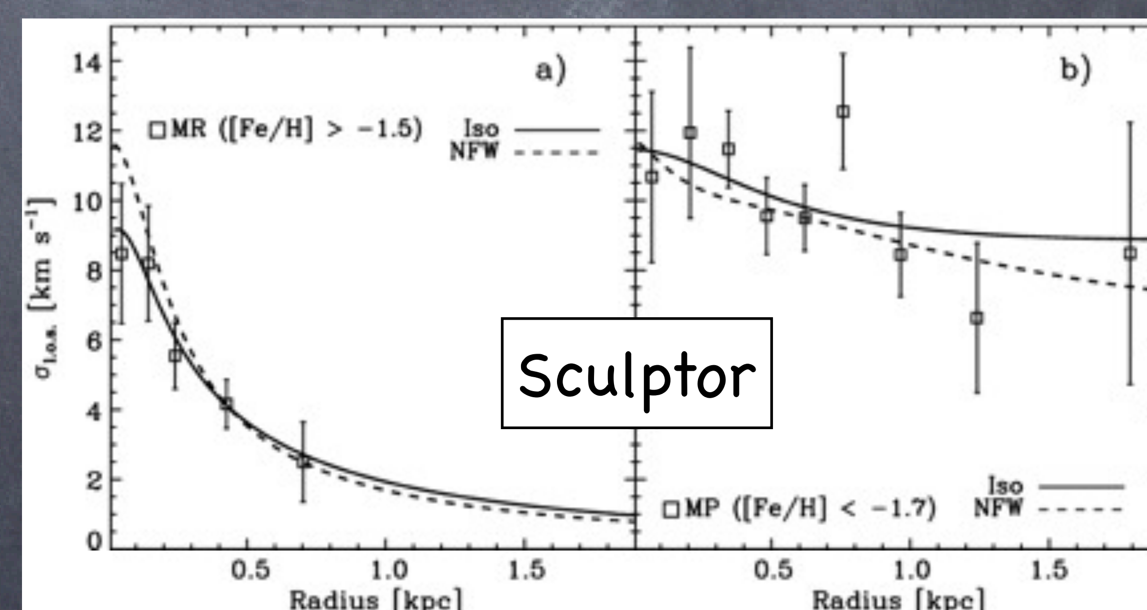
Łokas (2009)

Inference: discrete likelihood

- likelihood fitting discrete velocities
  - better spatial resolution; improve constraint (IM)BH?
  - non-members via background model in likelihood
  - computationally expensive; first constrain parameter range with simpler, faster (Jeans) models
- chemical tags
  - velocity moments: "hard cut" in e.g. [Fe/H]
  - discrete: additional chemical model in likelihood



Tolstoy et al. (2004)



Battaglia et al. (2008)

This workshop:
Dynamics meets kinematic tracers

- Kinematic tracers:
  Session 1 - Hans-Walter Rix: What data can do for you
  Session 2 - Discrete Data: incompleteness and selection effects
- Modeling methods:
  Session 1 - James Binney: What models can do for you
  Session 3 - Modeling approaches: speed versus accuracy
- Session 4 - Inference: the challenges of fitting models to data
- Session 5 - Results 1: versatile dynamics
  Session 6 - Results 2: cores or cusps?
- Session 7: Next steps