Lighting up the dark in the Local Group

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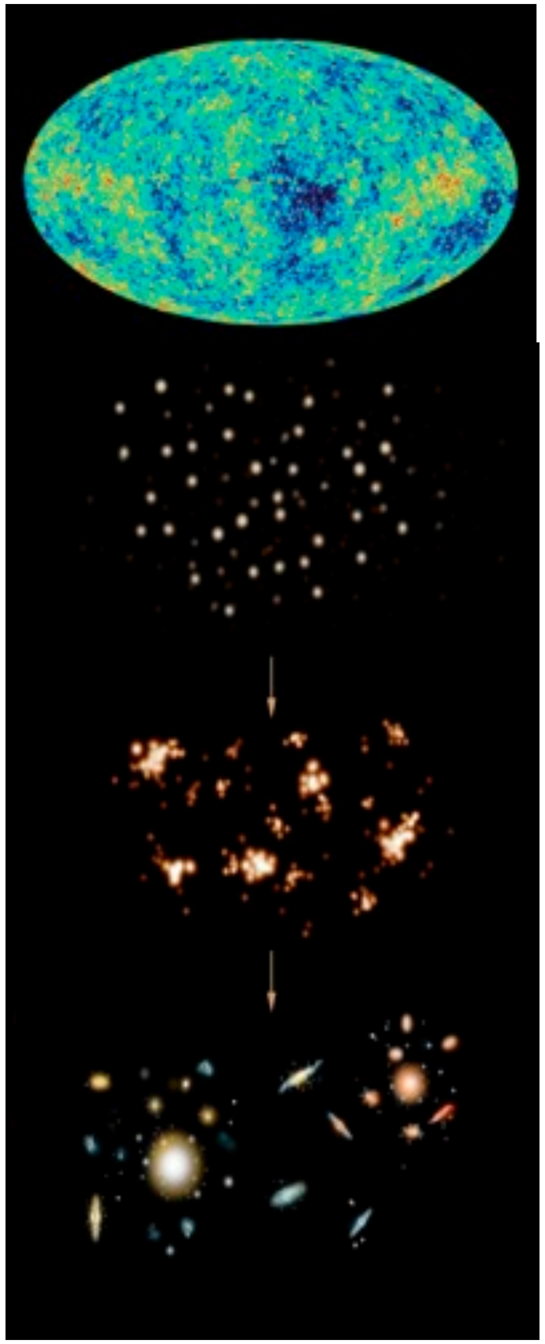
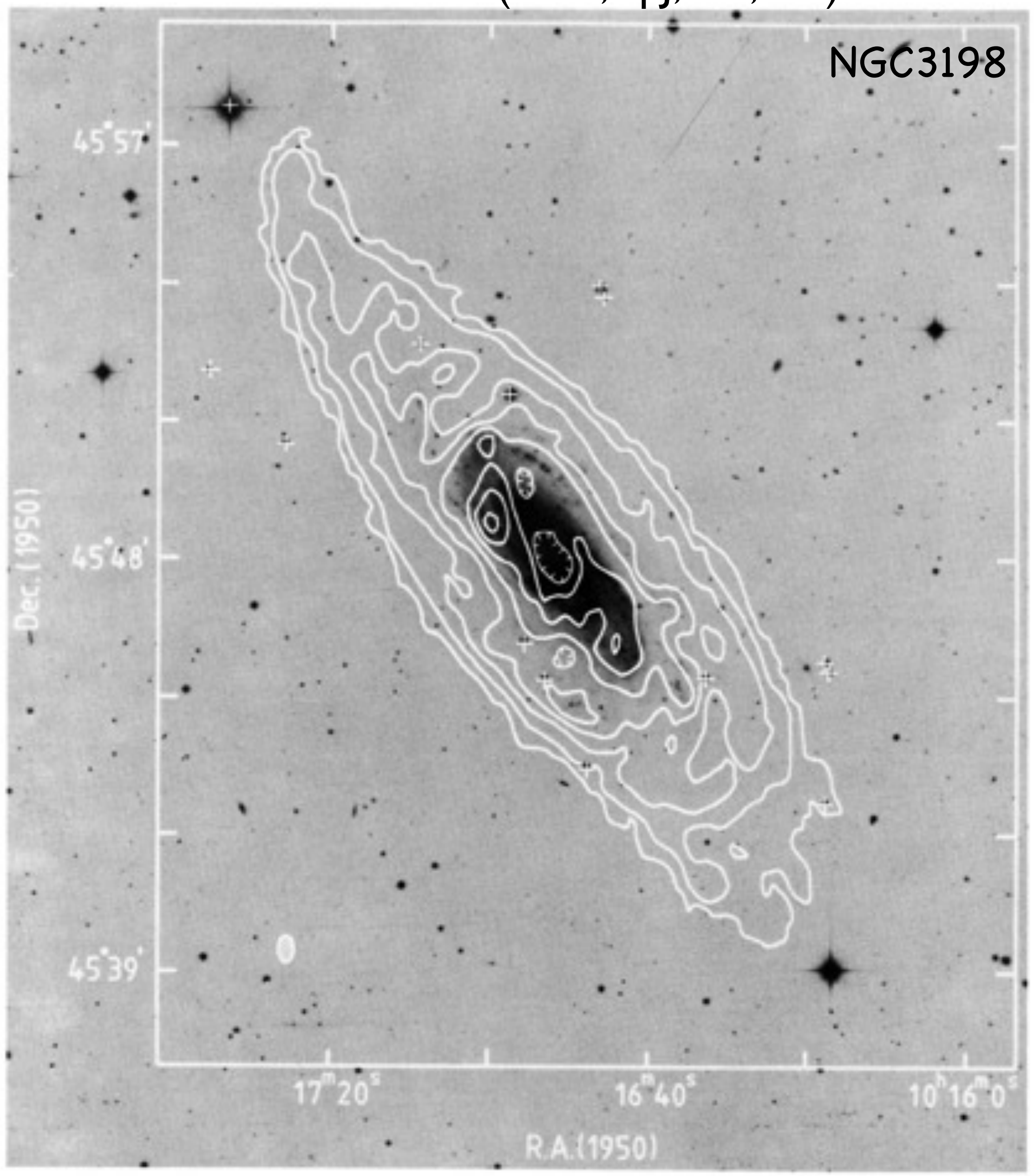
Concordance cosmology?

- ΛCDM model: flat universe + dark energy + cold dark matter
- successful on large scales, but tests inconclusive on scales of galaxies
- need dark matter, but observe light:
  - ‘adding’ baryons to dark-matter-only simulations via empirical prescription
  - ‘subtracting’ baryons from total mass distribution inferred through <u>luminous tracers</u> of the gravitational potential

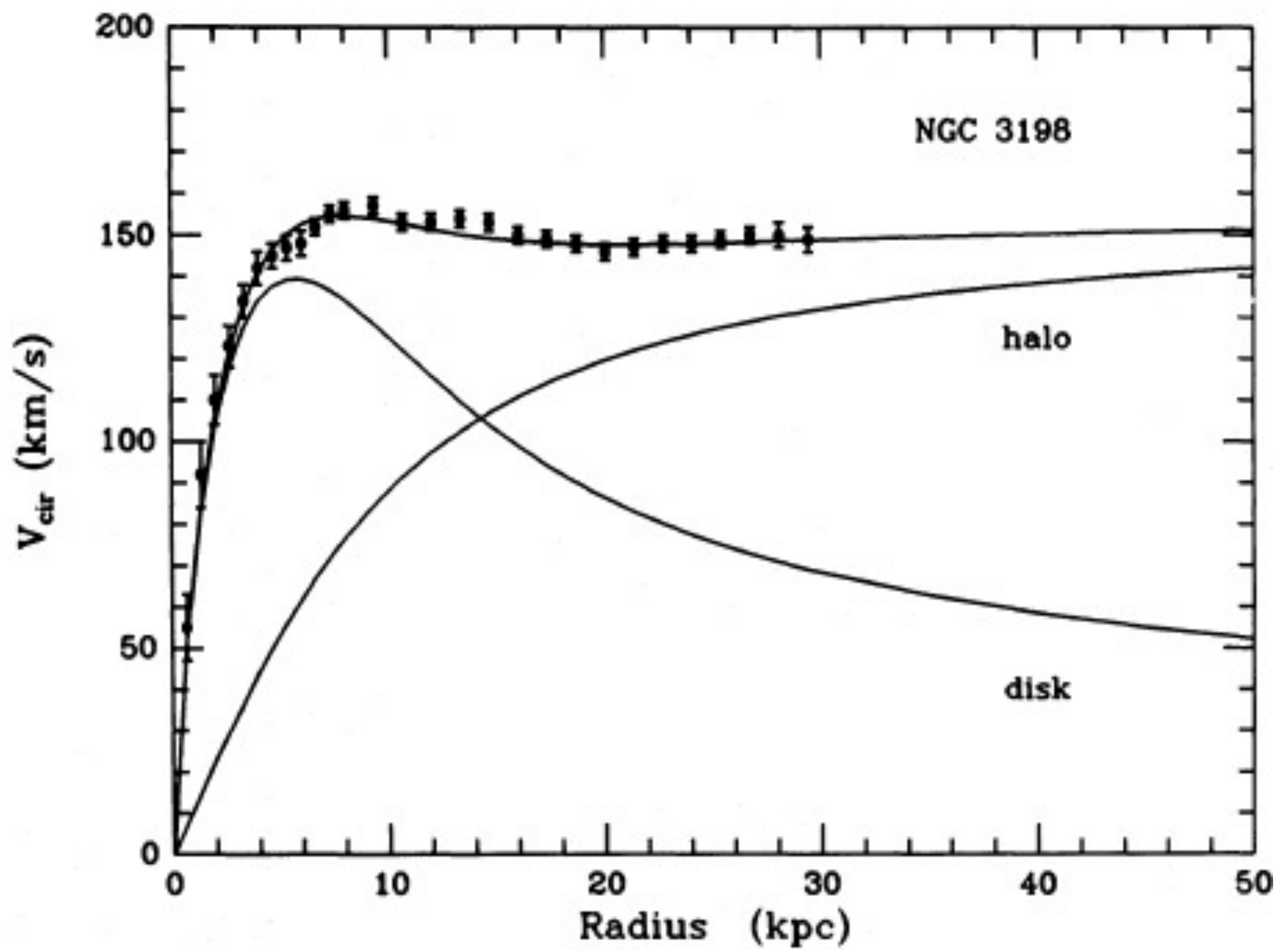


Luminous tracers: cold gas

van Albada et al. (1985,ApJ,295,305)

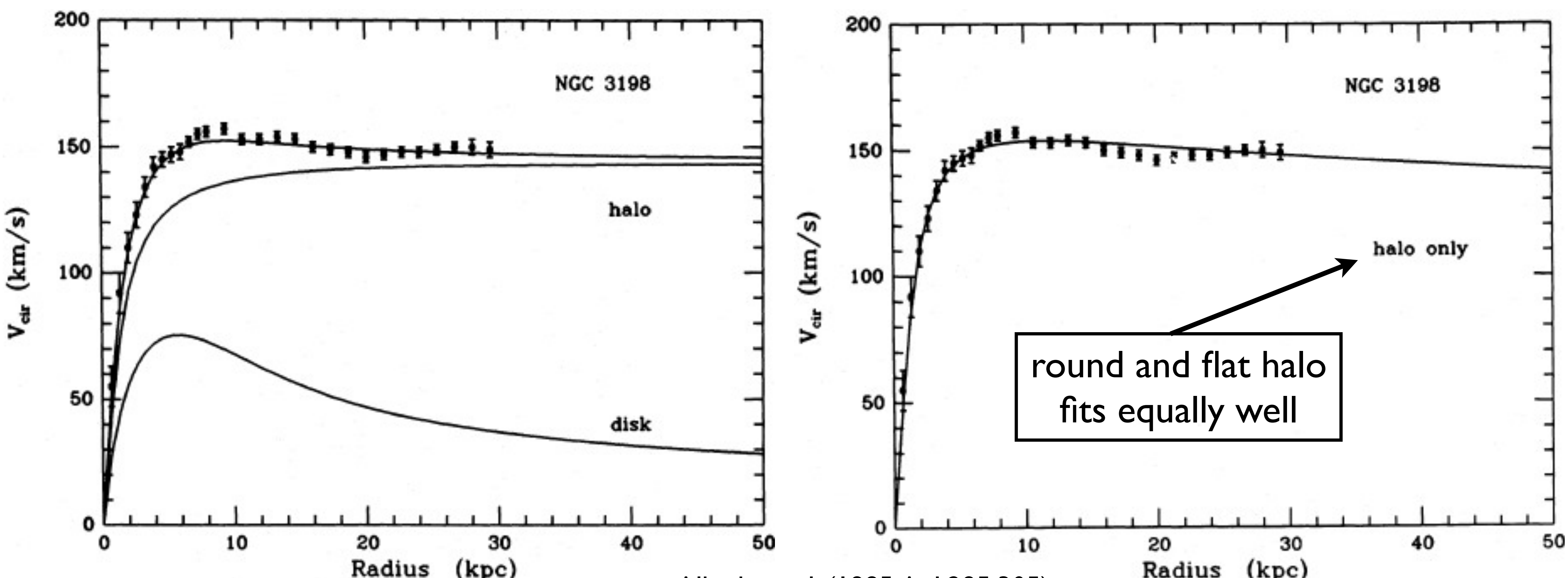


$$\frac{GM_{\rm tot}(<R)}{R} = -R\frac{\partial \Phi}{\partial R} = v_c^2(R)$$



- But requires disk stellar mass-to-light ratio and ...

Disk-halo degeneracy

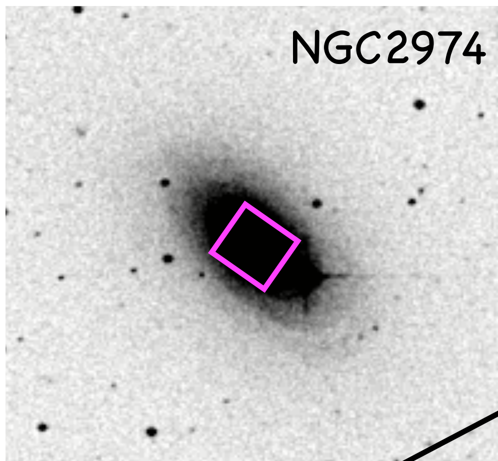


van Albada et al. (1985,ApJ,295,305)

- ... spatial resolution, correction non-circular motions, de-projection, non-spherical halo, presence of cold gas!

Luminous tracer: hot stars

tracer density

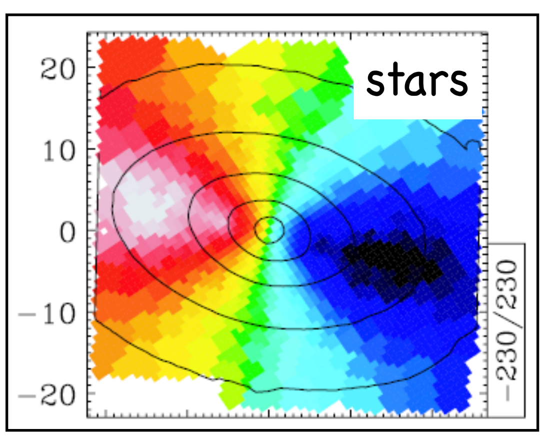


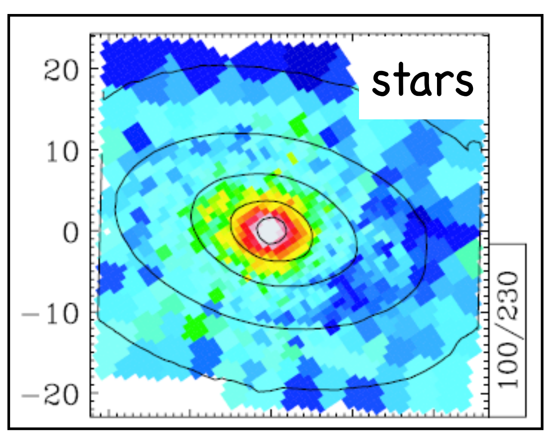
$$v_c^2(R) = \overline{v_\phi}^2 + \sigma_R^2 \left[\frac{\partial \ln \left(\nu \sigma_R^2\right)^{-1}}{\partial \ln R} + \ldots \right]$$

$\propto \sigma_R$ if $V \ll \sigma$

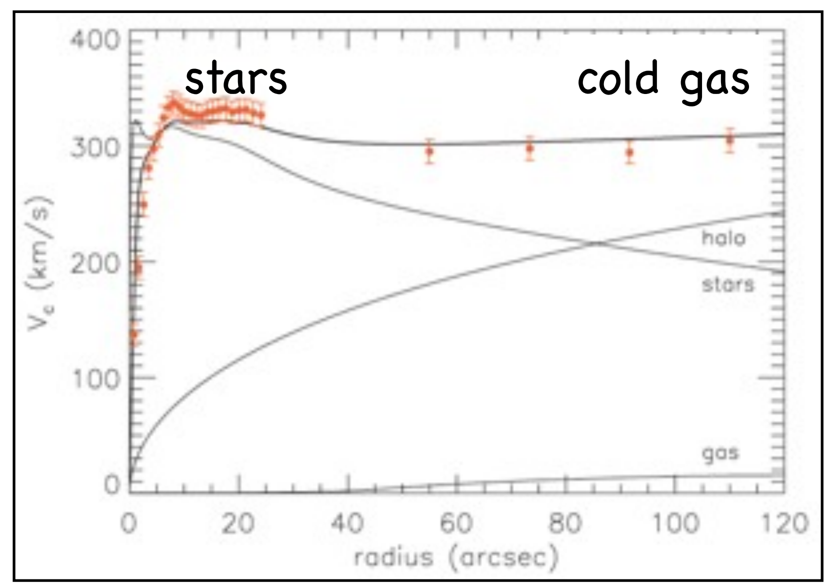
mean velocity

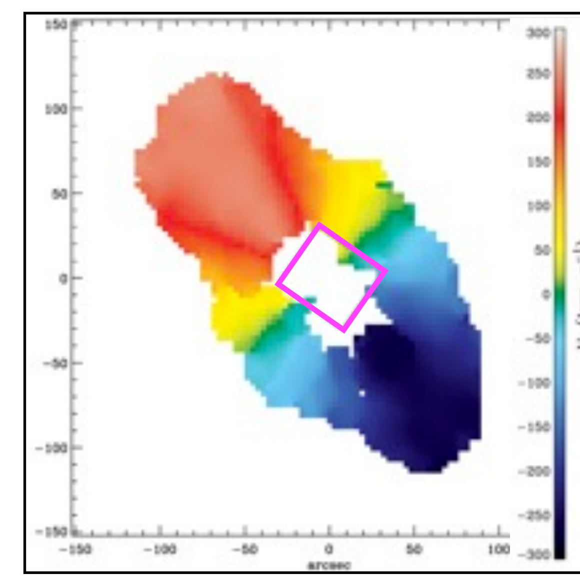
velocity dispersion





Weijmans, Krajnović, van de Ven, et al. (2008,MNRAS,383,1343)





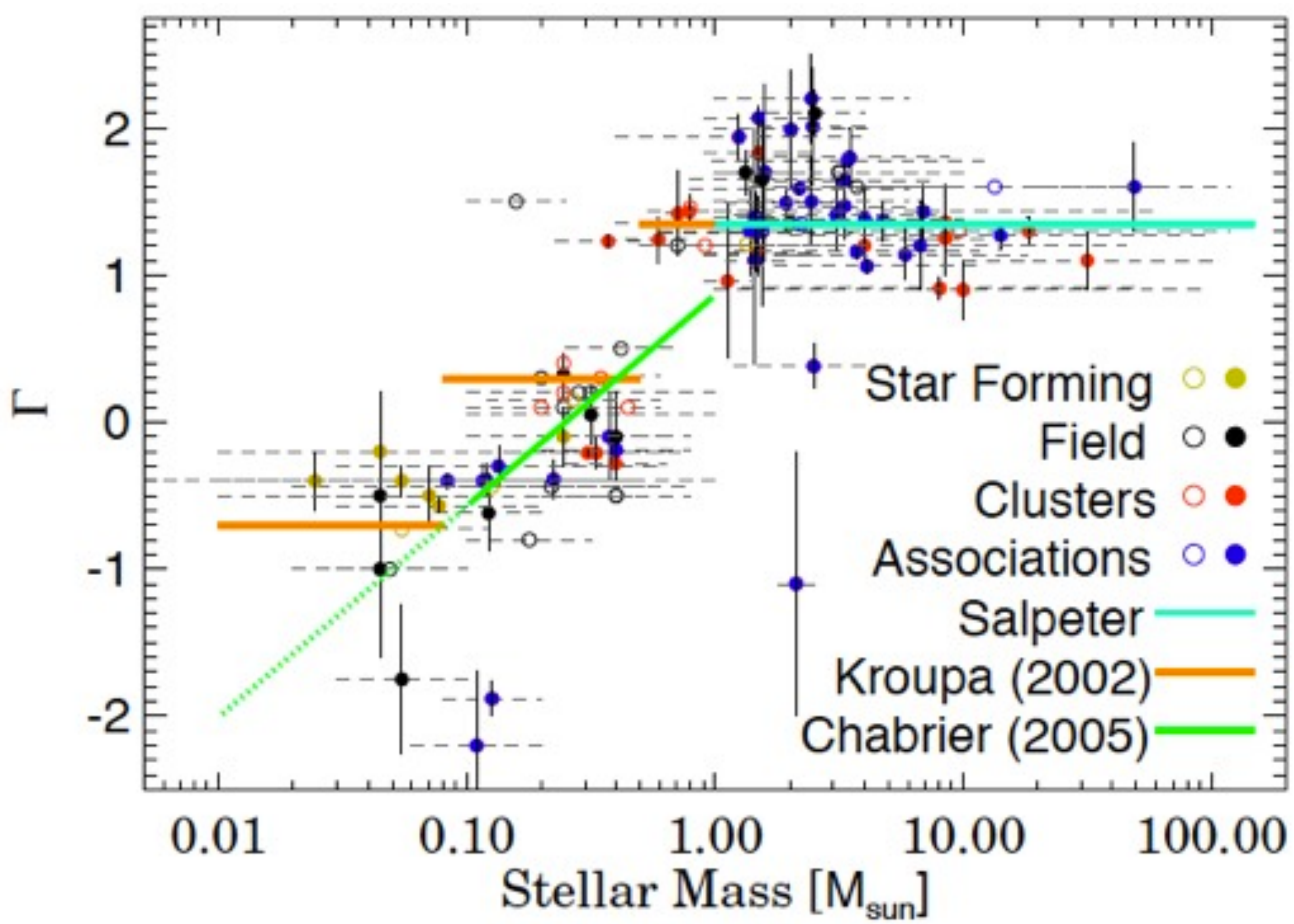
- ... but still requires stellar mass-to-light ratio and thus IMF

Initial Mass Function

- Number of stars formed per unit mass

$$dN/d\log m \propto m^{-\Gamma}, \qquad dN/dm \propto m^{-\alpha}, \qquad \alpha = \Gamma + 1$$

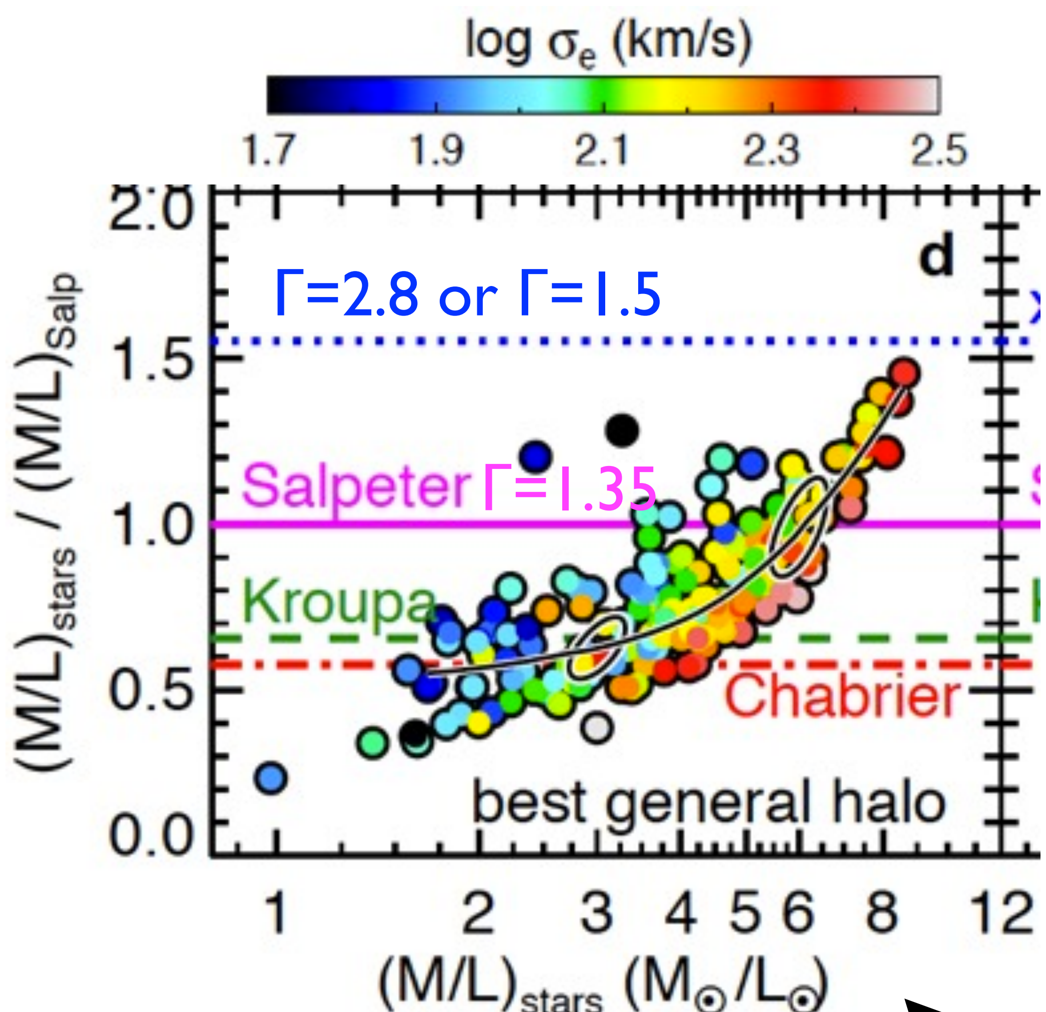
- Salpeter (1955) single power-law with Γ=1.35
  Kroupa (2001) broken power-law below 0.5 M_{sun}
  Charbrier (2003) log-normal below 1.0 M_{sun}



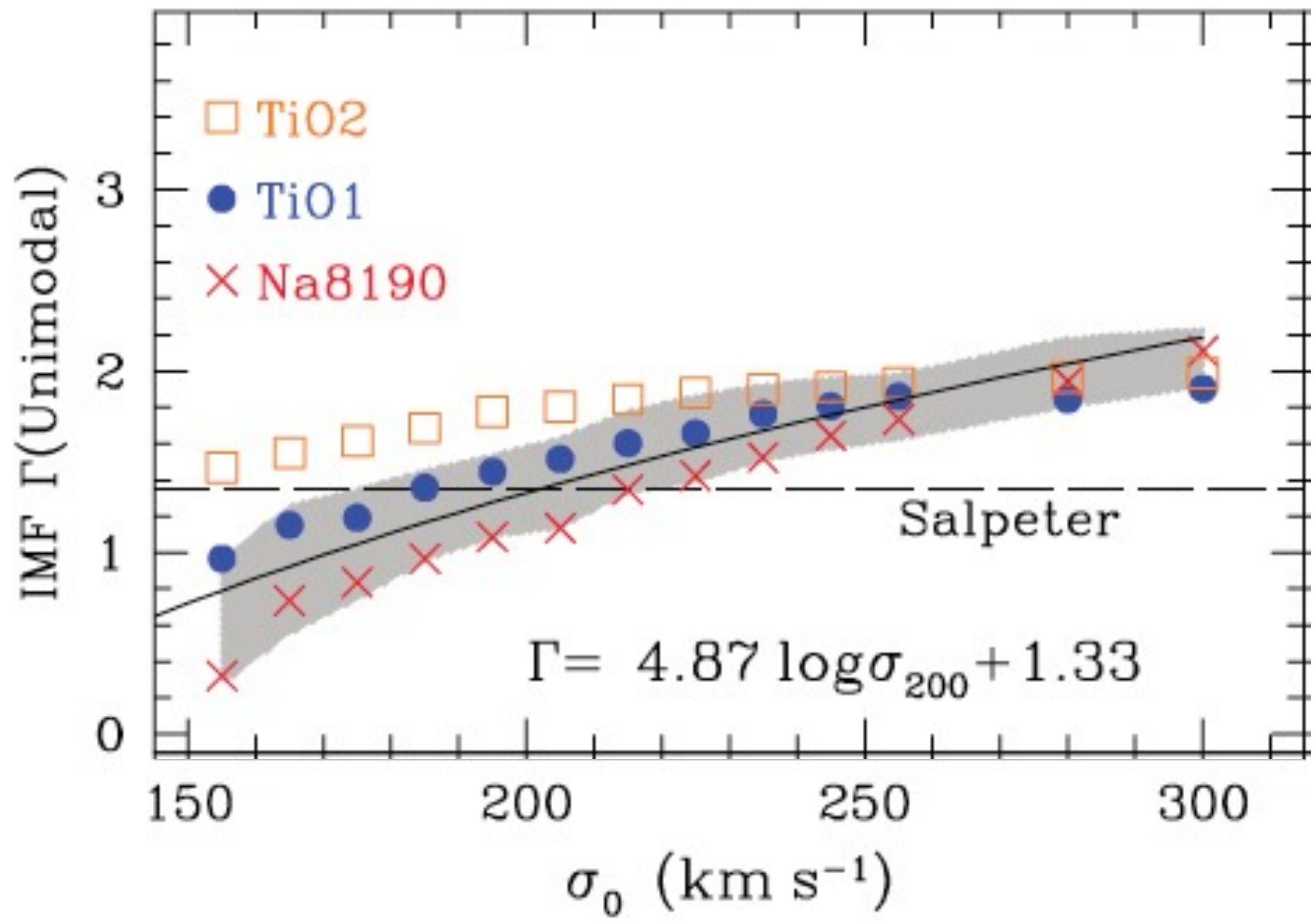
Bastian et al. (2010, ARA&A,48,339)

Non-universal IMF?

Cappellari et al. (2012,Nature,484,485)



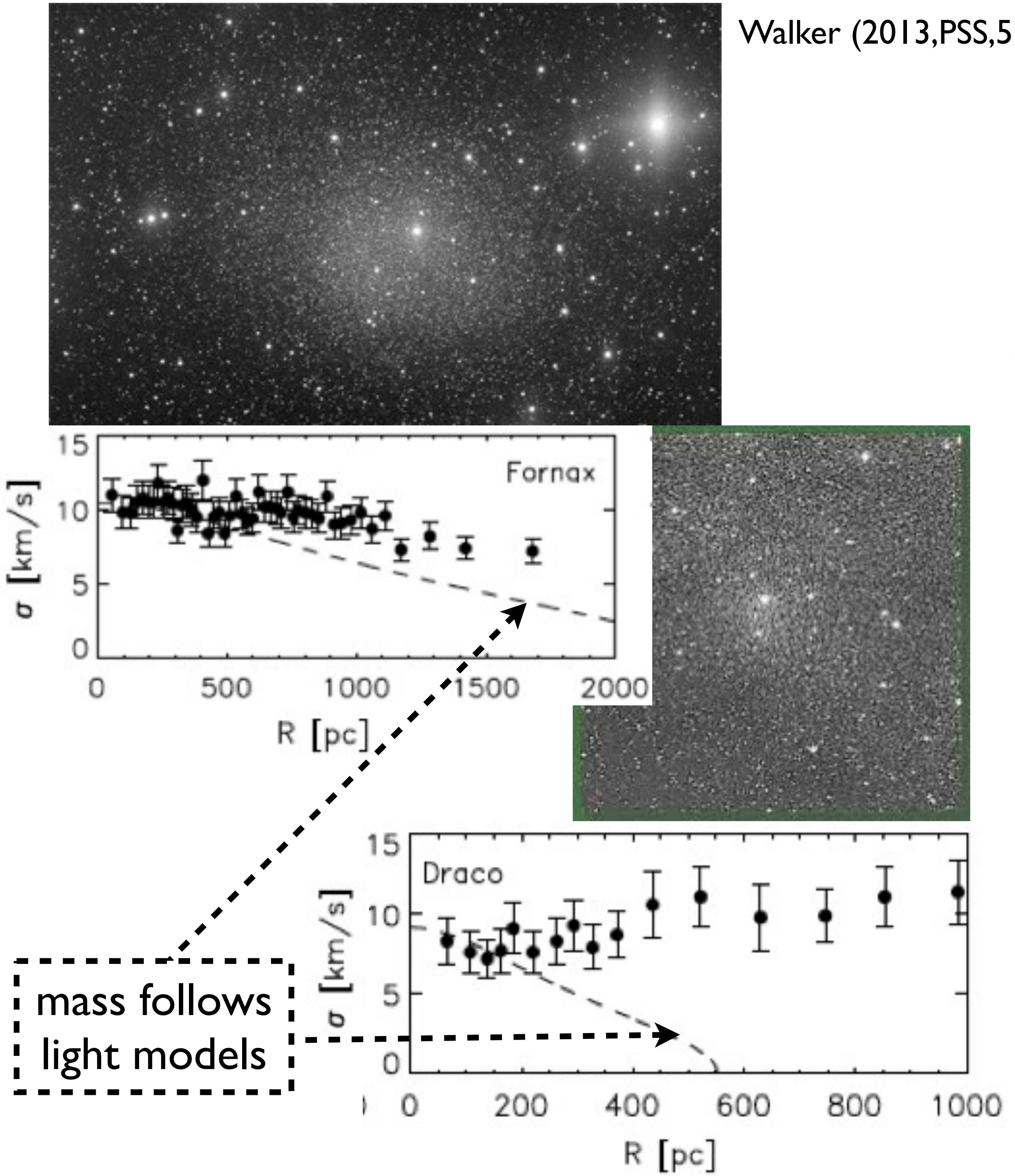
Ferreras et al. (2013,MNRAS,429,15)



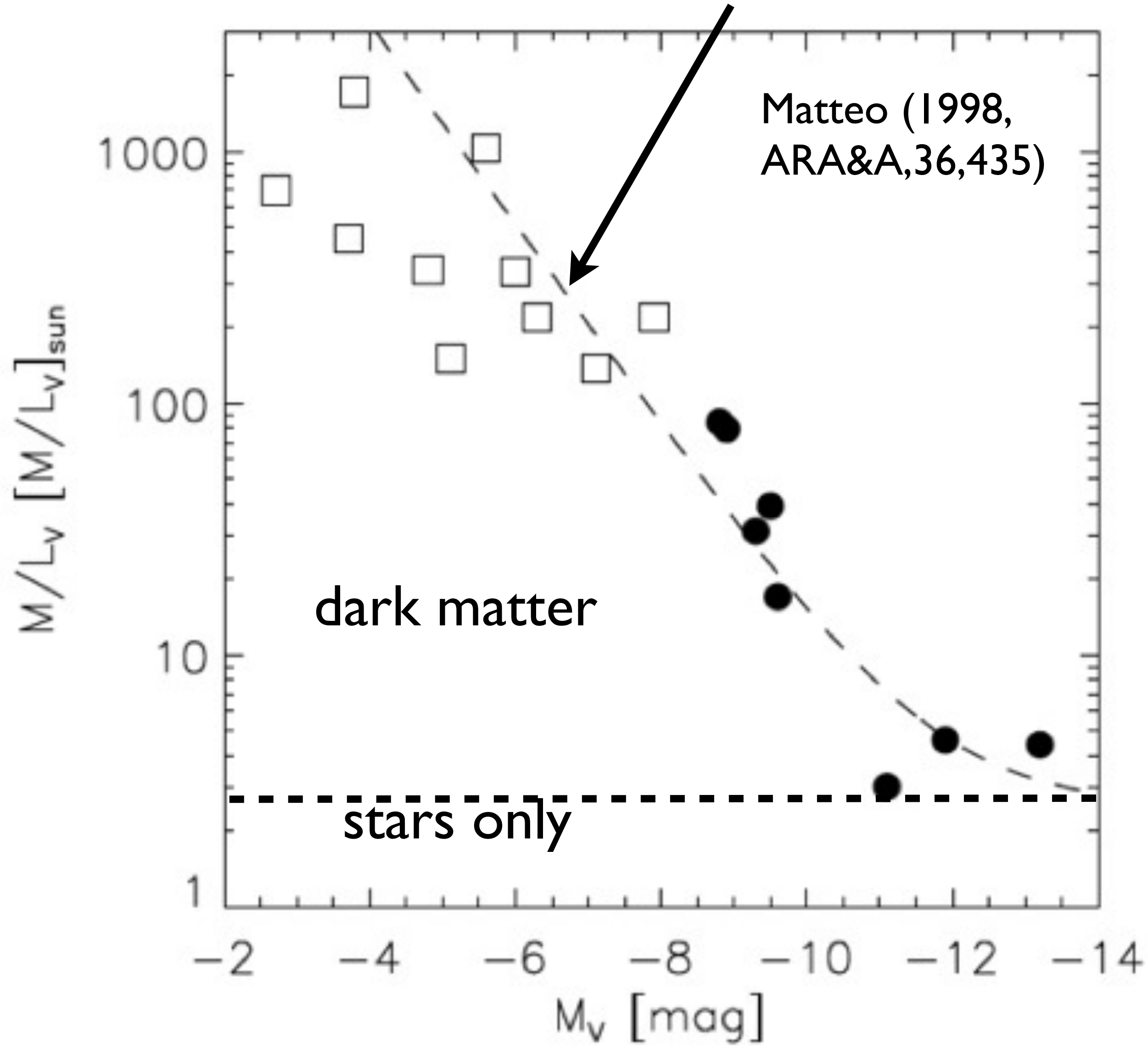
- ... combine stellar dynamical and populations models to constrain IMF shape and hence stellar mass-to-light ratio (e.g., Läsker, van den Bosch, van de Ven, et al., 2013,MNRAS,in print)

Dark-matter dominated

Walker (2013,PSS,51039)



$$[M/L_V/[M/L_V]_\odot] = 2.5 + 10^7/(L/L_{V,\odot})$$

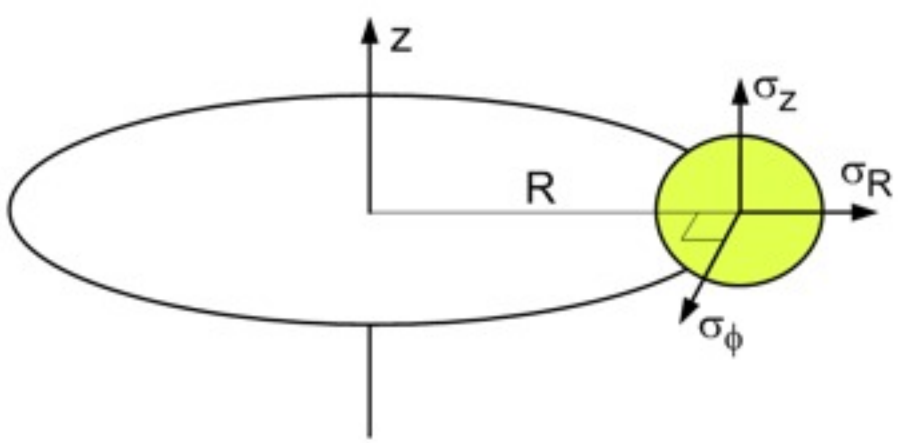


- ... but non-spherical halo and velocity anistropy?

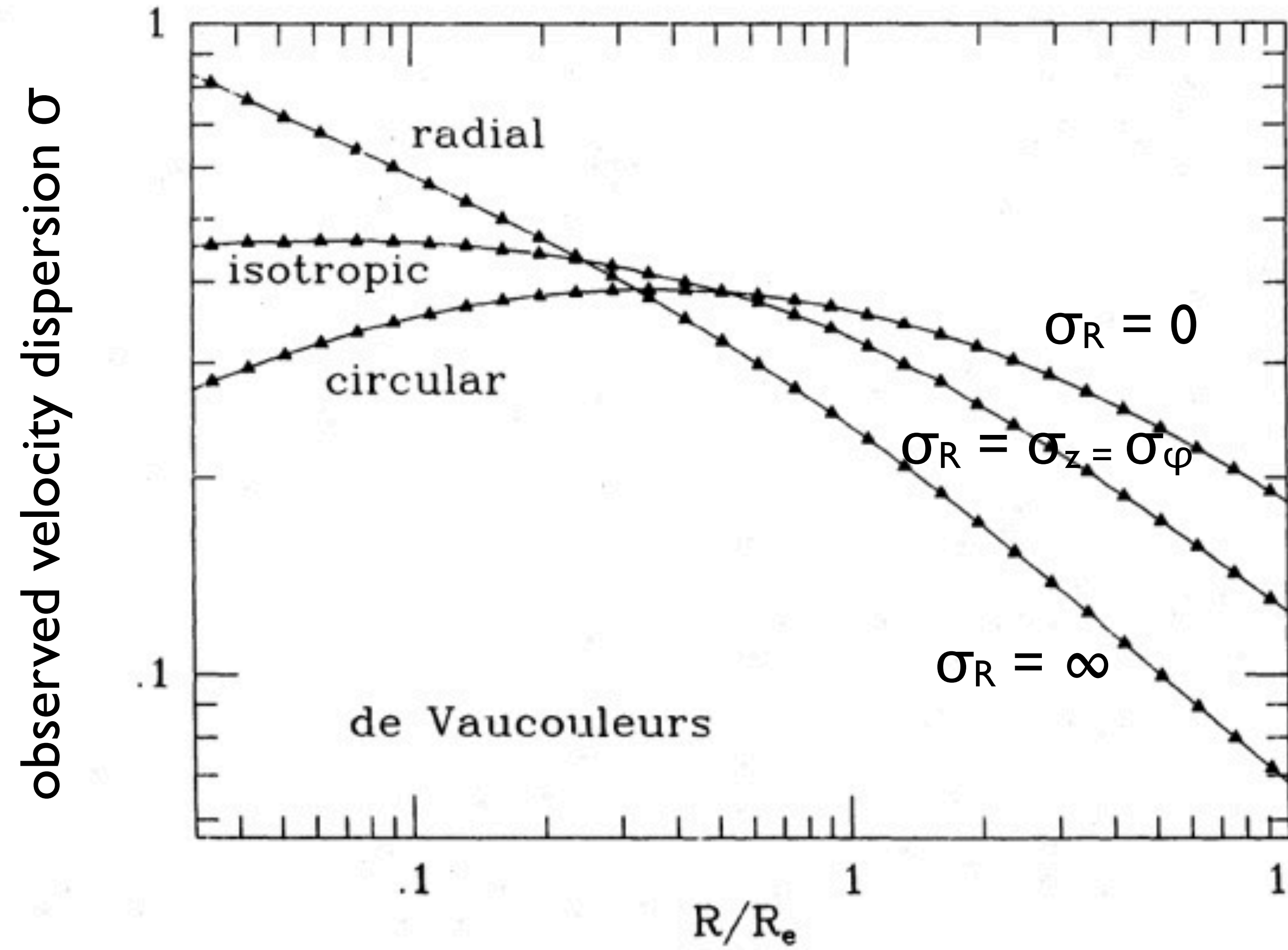
Mass-anisotropy degeneracy

$$v_c^2(R) = \overline{v_\phi}^2 + \sigma_R^2 \left[\frac{\partial \ln \left(\nu \sigma_R^2\right)^{-1}}{\partial \ln R} + \dots \right]$$

velocity anisotropy:
σ_φ/σ_R, σ_z/σ_R, ...?

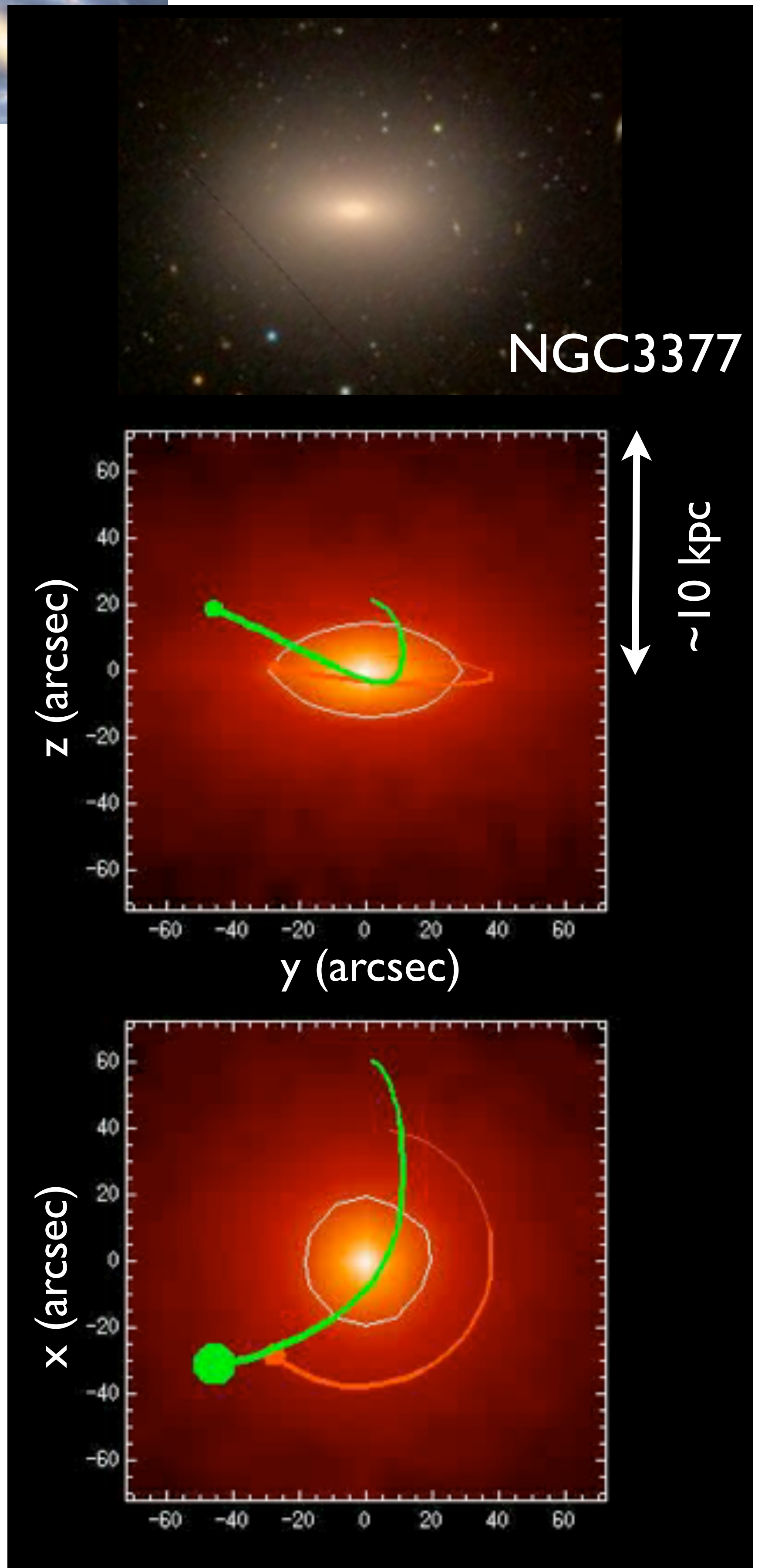


Richstone & Tremaine (1984,ApJ,286,27)



- Adopt (ad-hoc) assumptions velocity anisotropy, otherwise data *and* models beyond *V* and σ ...

Stellar orbits

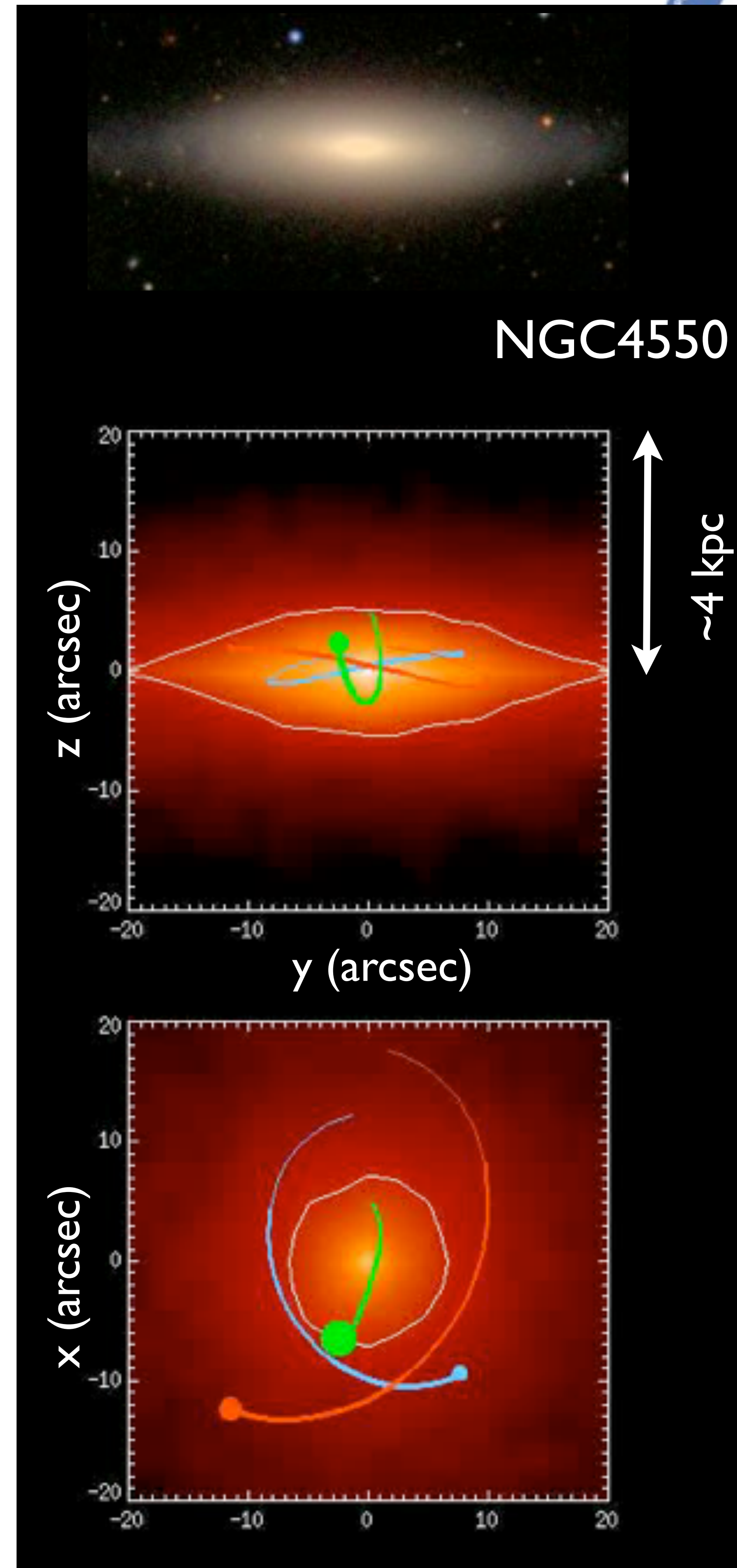


disk-like orbits

bulge-like orbits

retrograde disk-like orbits

van den Bosch,
van de Ven,
et al. (in prep.)



Luminous tracers

- *Cold gas*: directly circular velocity, but restricted to disk plane and sensitive to perturbations, needs IMF unless dark-matter dominated
- *Hot stars*: everywhere, but data and model beyond *V* and σ to break mass-shape-anisotropy degeneracy, needs IMF unless dark-matter dominated
- *Local Group*: stars are resolved, positions and distances, line-of-sight velocities and proper motions, chemical properties and even (proxies for) ages ...

Axisymmetric Jeans eqs.

- ‘Radial’ Jeans equation yields ‘rotation curve’:

$$\frac{\partial(R\nu\overline{v_R^2})}{\partial R} + R\frac{\partial(\nu\overline{v_R v_z})}{\partial z} - \nu\overline{v_\phi^2} + R\nu\frac{\partial\Phi}{\partial R} = 0$$

$$\Rightarrow \quad -R\frac{\partial\Phi(R,z)}{\partial R}\bigg|_{z=0} = v_c(R)^2 = \overline{v_\phi}^2 + \sigma_R^2\left[\frac{\partial\ln\left(\nu\sigma_R^2\right)^{-1}}{\partial\ln R} + \dots\right]$$

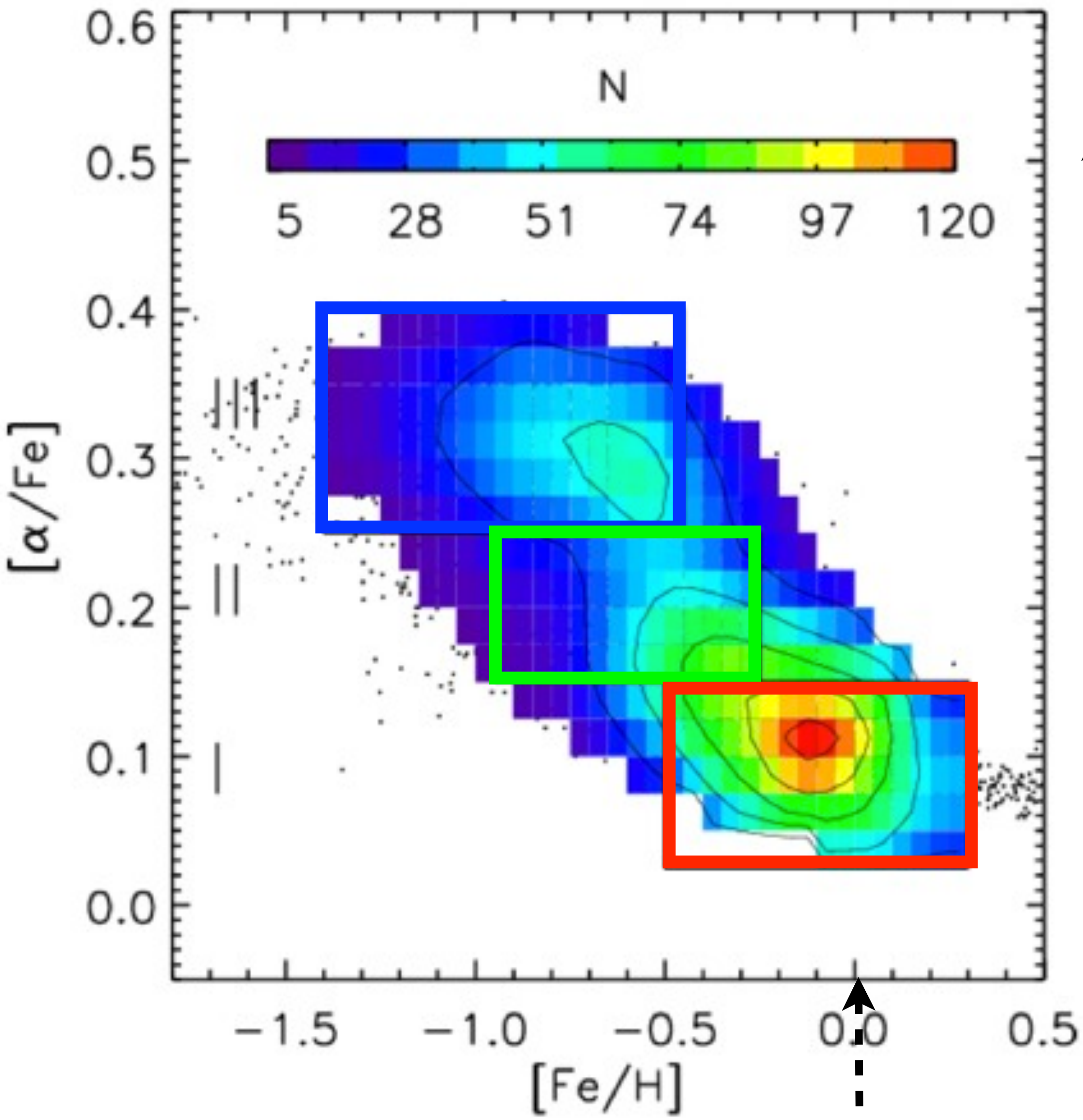
- ‘Vertical’ Jeans equation with *R* and *z* decoupled:

$$\cancel{\frac{\partial(R\nu\overline{v_R v_z})}{\partial R}} + R\frac{\partial(\nu\overline{v_z^2})}{\partial z} + R\nu\frac{\partial\Phi}{\partial z} = 0$$

$$\Rightarrow \quad -\frac{\partial\Phi(R,z)_\odot}{\partial z}\bigg|_{R=R_0} = K_z(z) = \frac{1}{\nu}\frac{\mathrm{d}}{\mathrm{d}z}\left(\nu\sigma_z^2\right)$$

Solar Neighborhood

Zhang, Rix, van de Ven et al. (2013,arXiv:1209.0256)



α-old

α-young

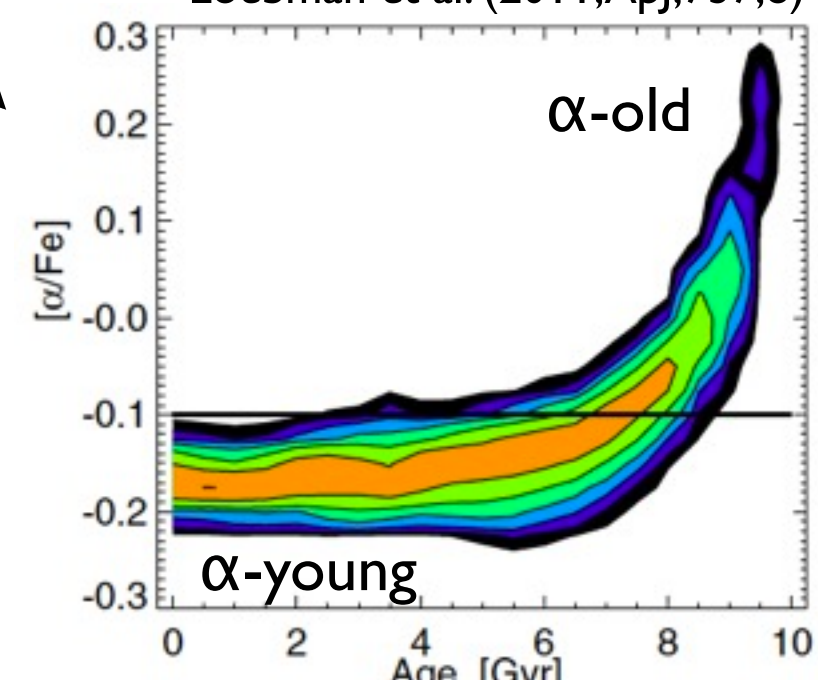
metal-poor

metal-rich

Sun

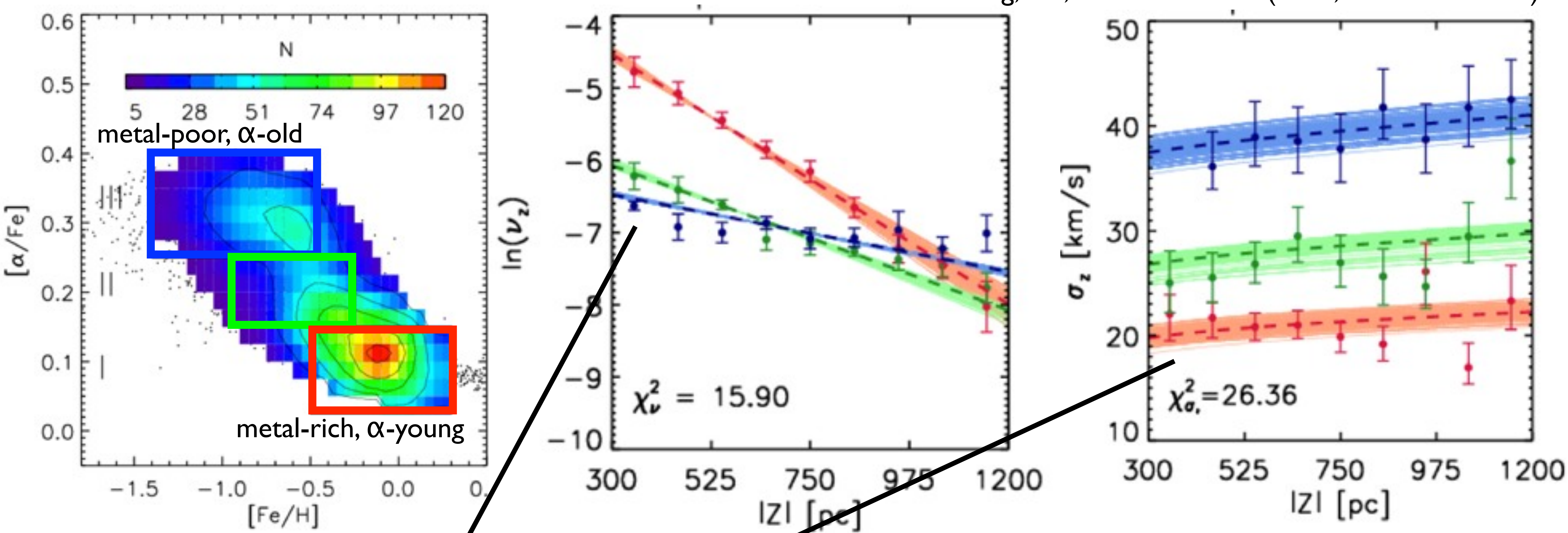
- 9,000 SDSS/SEGUE K-dwarfs
- $|(R-R_{sun})| < 0.4$ kpc
  $0.3 \text{ kpc} < |z| < 1.2$ kpc
- $\alpha, \delta, D, v_{los}, \mu_\alpha, \mu_\delta$ (=6D)
  [Fe/H], [α/Fe] & errors

Loebman et al. (2011,ApJ,737,8)



Vertical Jeans equation

Zhang, Rix, van de Ven et al. (2013,arXiv:1209.0256)



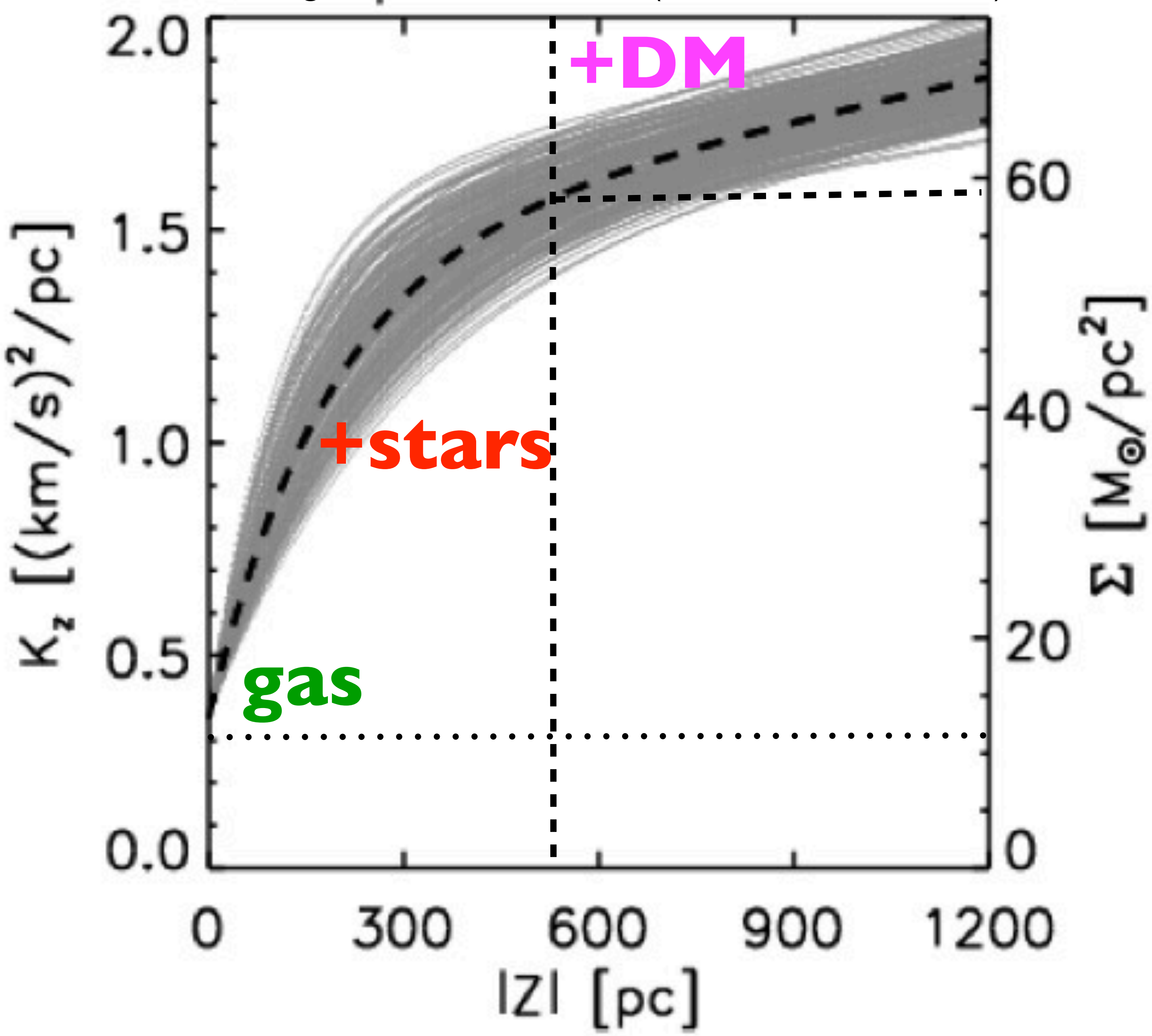
$$K_z(z) = \frac{1}{\nu}\frac{\mathrm{d}}{\mathrm{d}z}\left(\nu\sigma_z^2\right)$$

Poisson's eq.

$$\rho_{tot} = \rho_{gas} + \rho_{stars} + \rho_{DM}$$

Disentangling stars and DM

Zhang, Rix, van de Ven et al. (2013,arXiv:1209.0256)



$\rho_{gas}+\rho_{stars}+\rho_{DM}$

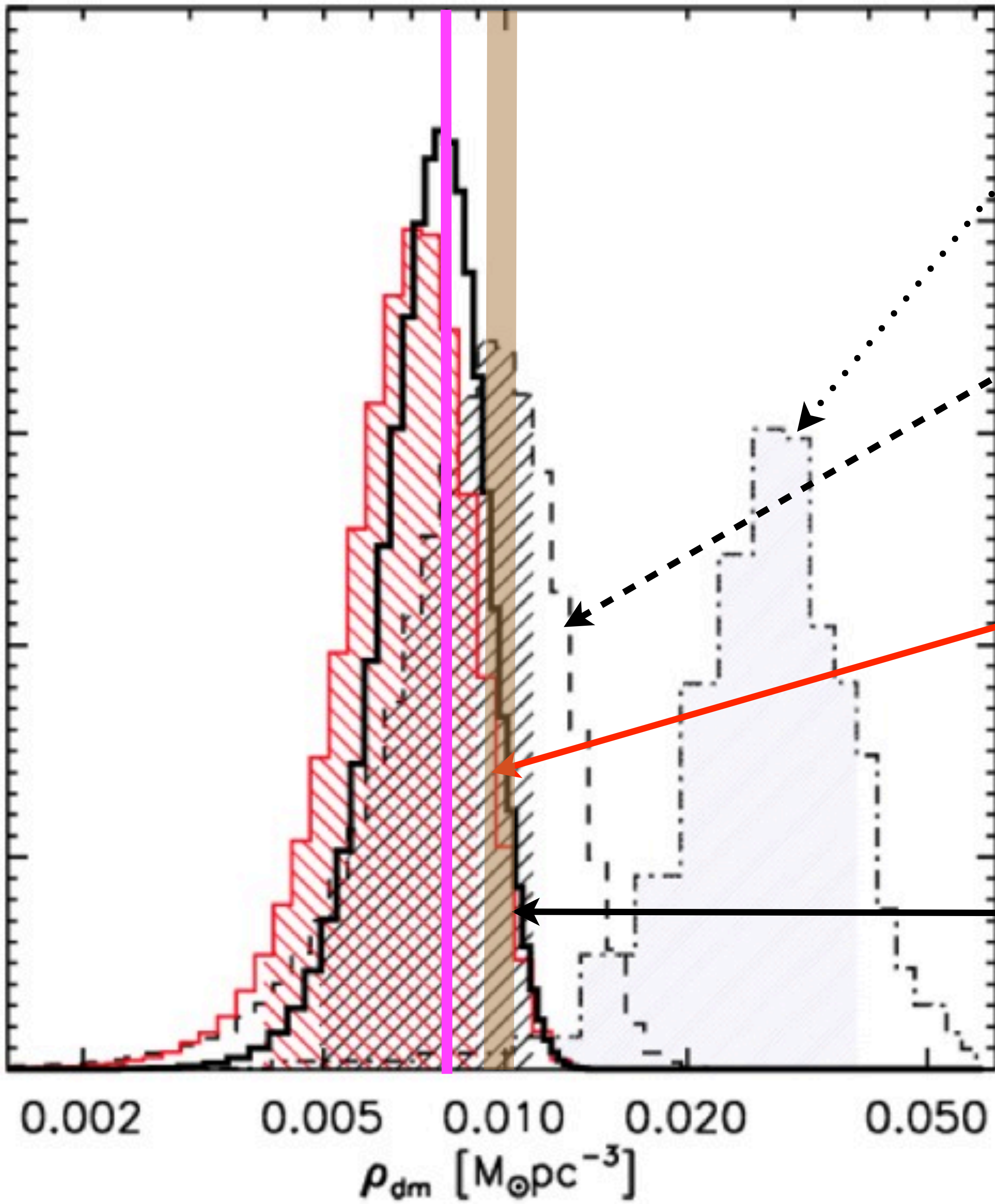
$\sim\rho_{gas}+\rho_{stars}$

$\sim\rho_{gas}$

Local DM density

Standard Halo Model

Catena & Ullio (2010,JCAP,8,4):



Garbari et al. (2012,MNRAS,425,1445)
~2,000 K-type dwarfs

Bovy & Tremaine (2012,ApJ,756,89)
~400 giant stars
(from Moni Bidin et al. 2012,,ApJ,751,30
but corrected for d<V_{φ}>/dR≠0)

Zhang et al. (2013,arXiv:1209.0256)
~9,000 K-type dwarfs

Joint probability:

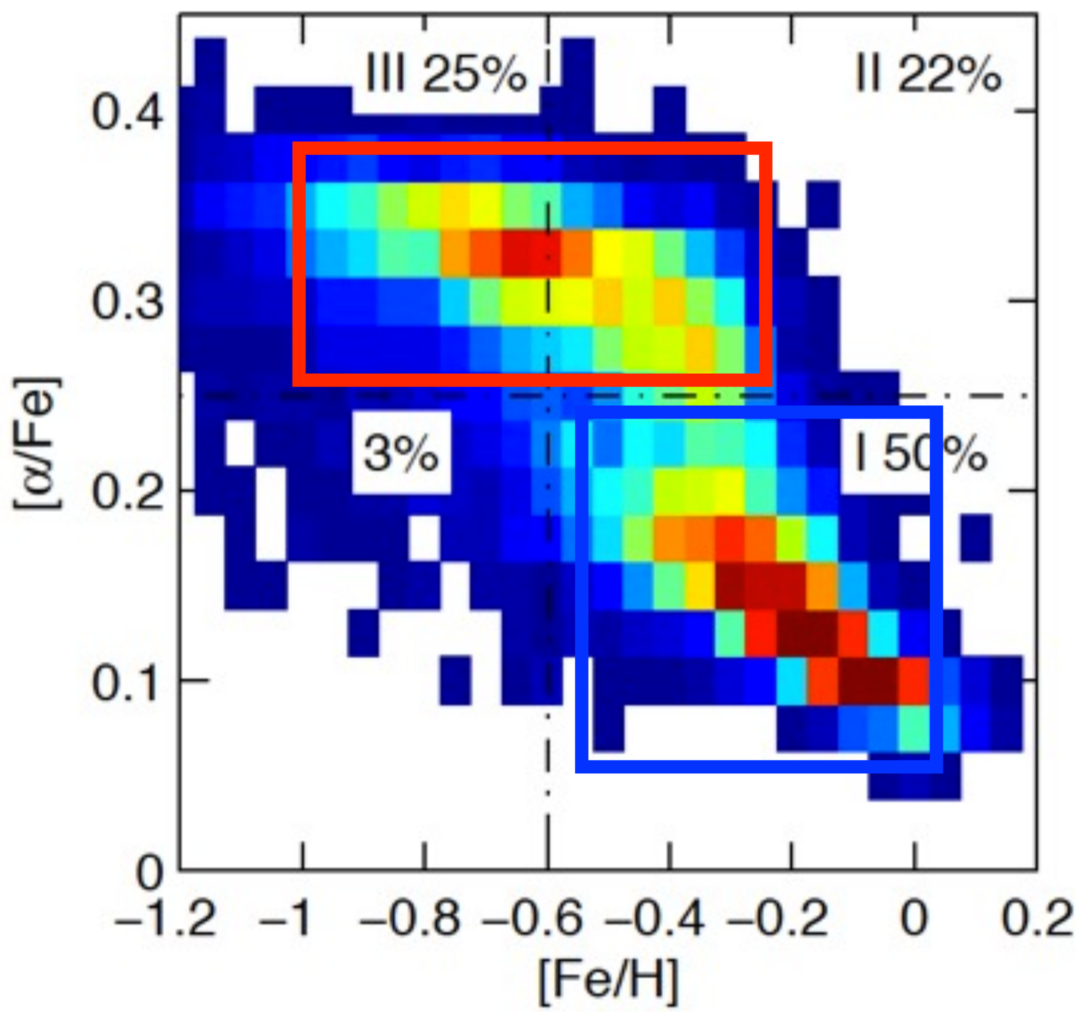
$$0.0075 \pm 0.0021 \ M_{\odot}\,\mathrm{pc}^{-3}$$

$$(0.28 \pm 0.08 \ \mathrm{GeV\,cm}^{-3})$$

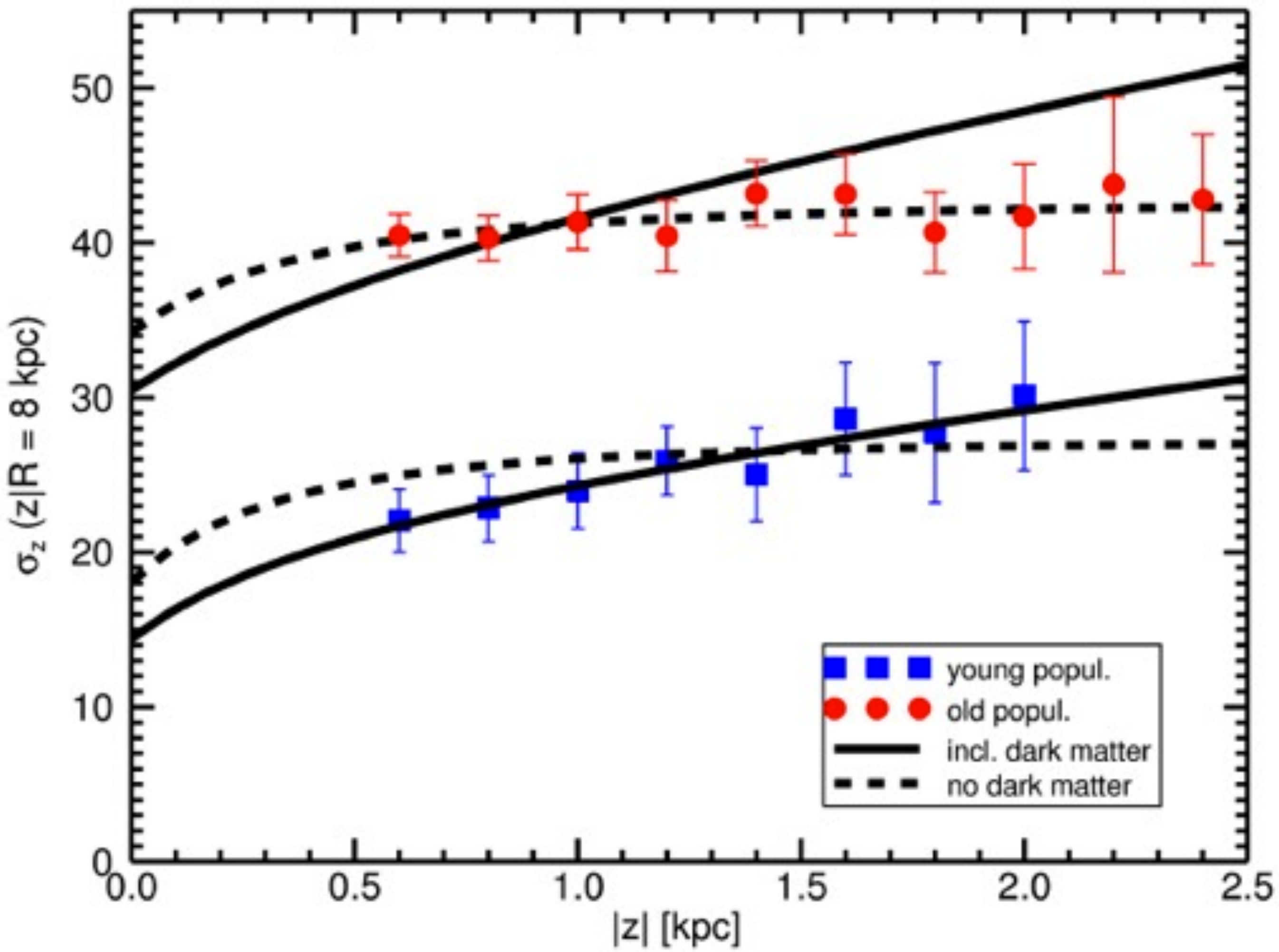
Zhang, Rix, van de Ven et al. (2013,arXiv:1209.0256)

Beyond vertical Jeans

Liu & van de Ven (2012,MNRAS,425,2144)



Büdenbender, van de Ven & Watkins (in prep.)



>13,000 G-type dwarfs
7 < R/kpc < 9
0.5 < |z|/kpc < 2.5

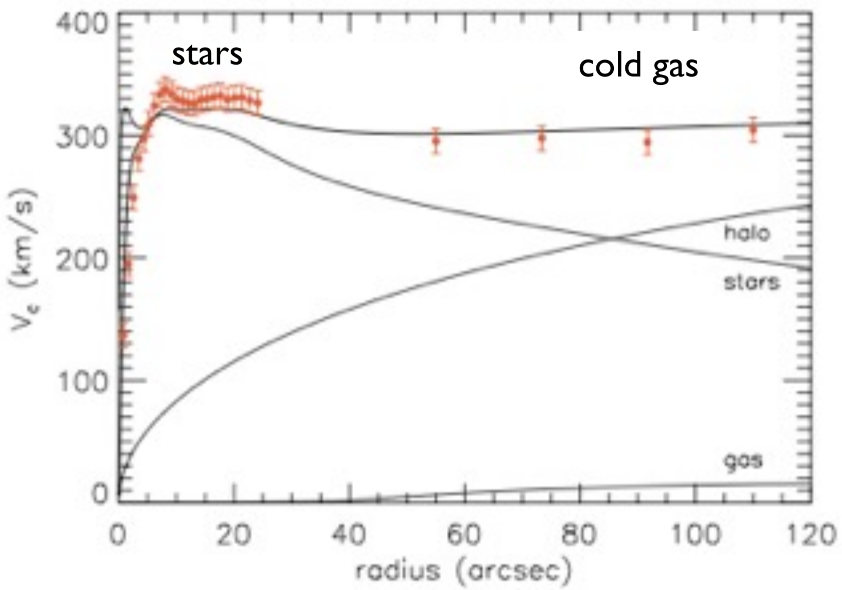
Extending modeling to include:
- *R* and z coupling (non-zero tilt)
- discrete fitting + contamination

Next steps

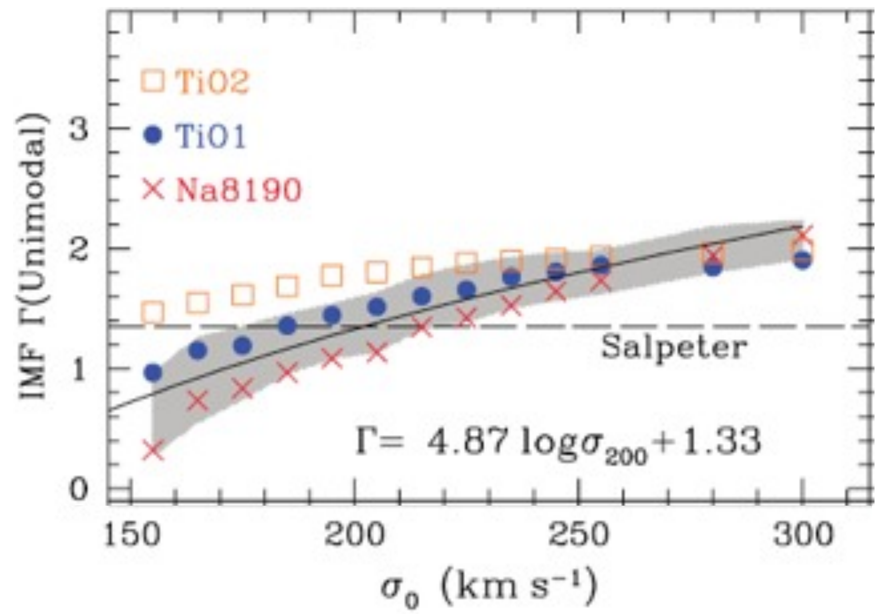
- High quantity and quality discrete (chemo-) kinematic data (SDSS/APOGEE, Gaia/ESO, ...)
- Beyond Jeans through orbit and/or distribution-function based (chemo-)dynamical models
  (e.g., Ting et al. 2013, arXiv:1212.0006)
- Avoid binning and hard cuts via discrete fitting including contaminants in Bayesian framework
  (e.g., Watkins, van de Ven, et al. 2013)
- ... improved robust constraints on dark matter amount and *distribution* in the Local Group

Summary in Figures

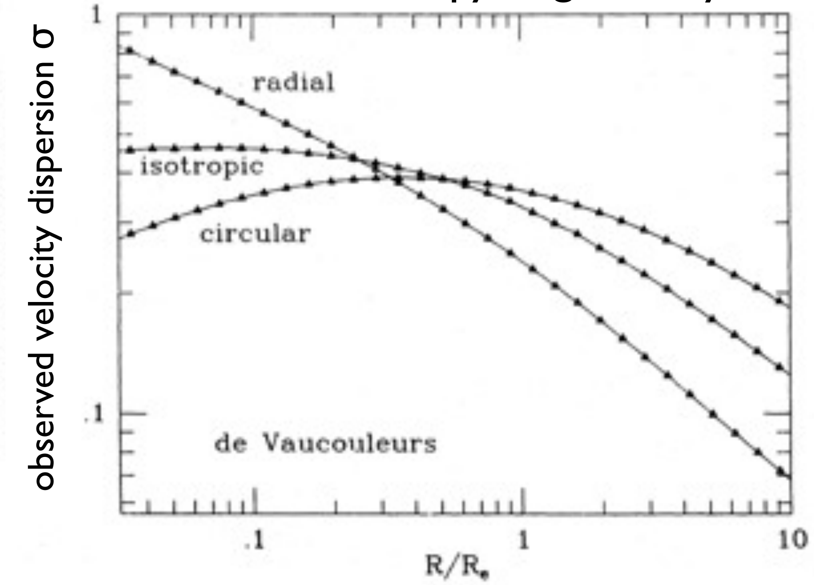
disk/bulge-halo degeneracy



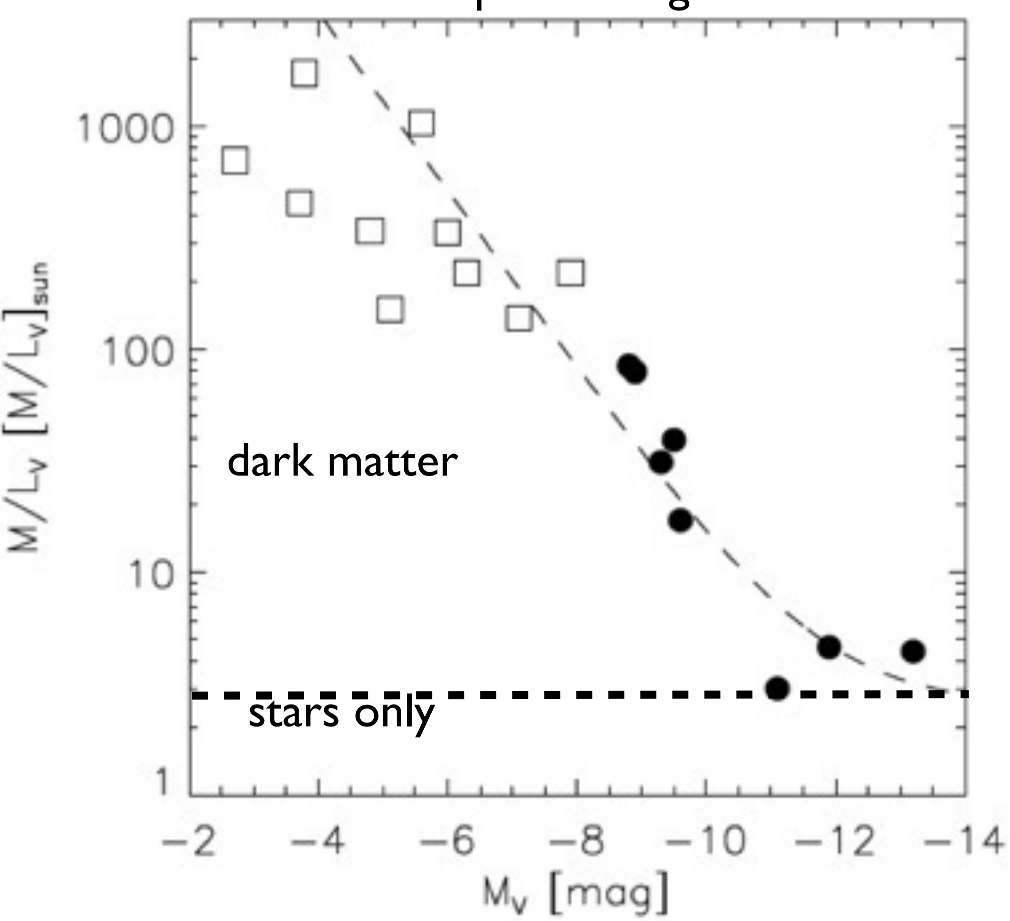
non-universal initial mass function



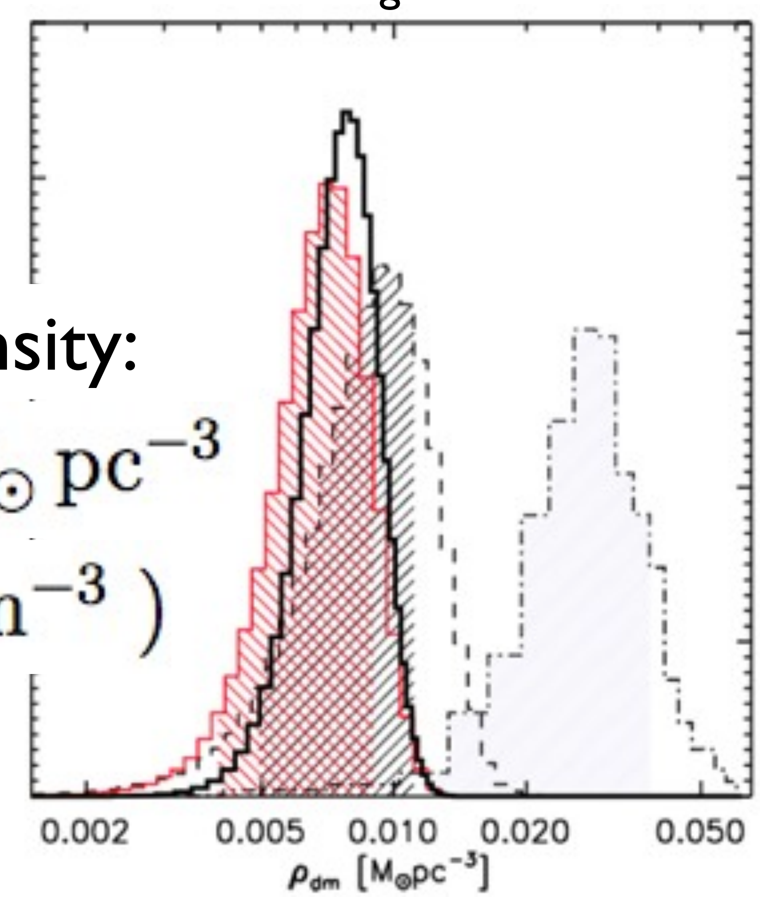
mass-anisotropy degeneracy



dwarf spheroidal galaxies



Solar Neighborhood



Local dark matter density:

$$0.0075 \pm 0.0021\ M_\odot\,\mathrm{pc}^{-3}$$

$$(0.28 \pm 0.08\ \mathrm{GeV\,cm}^{-3})$$