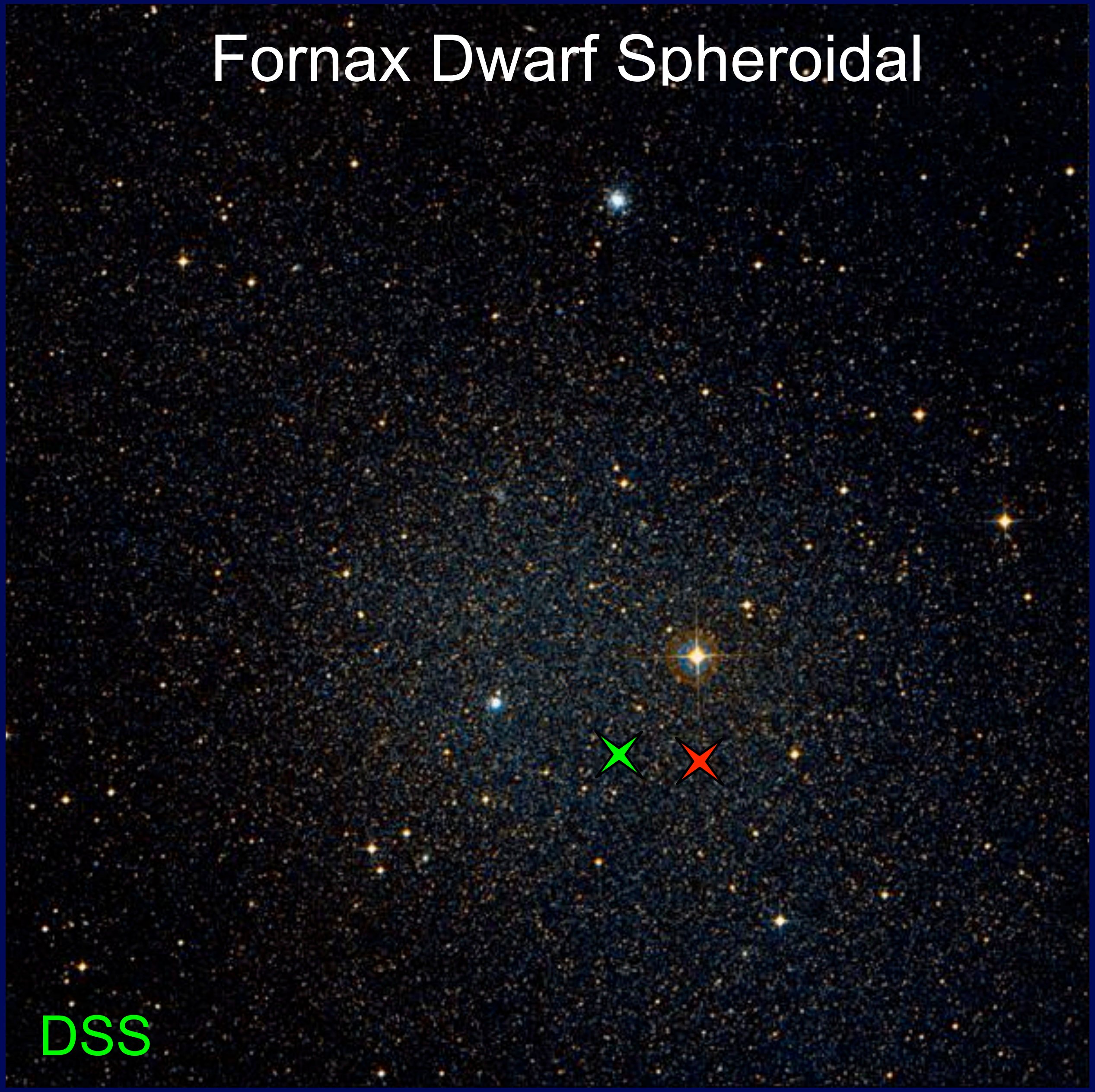
Joint mass and anisotropy modeling of the Fornax Dwarf Spheroidal



with
Chris GORDON (*Oxford*)
Andrea BIVIANO (*Trieste*)

Motivations

Large velocity data sets in Dwarf Spheroidals

Walker et al. 09

2267 member velocities in Fornax!

constraints on *Dark Matter normalization*

constraints on *Dark Matter inner slope*

constraints on *velocity anisotropy of stars*

Mass anisotropy degeneracy

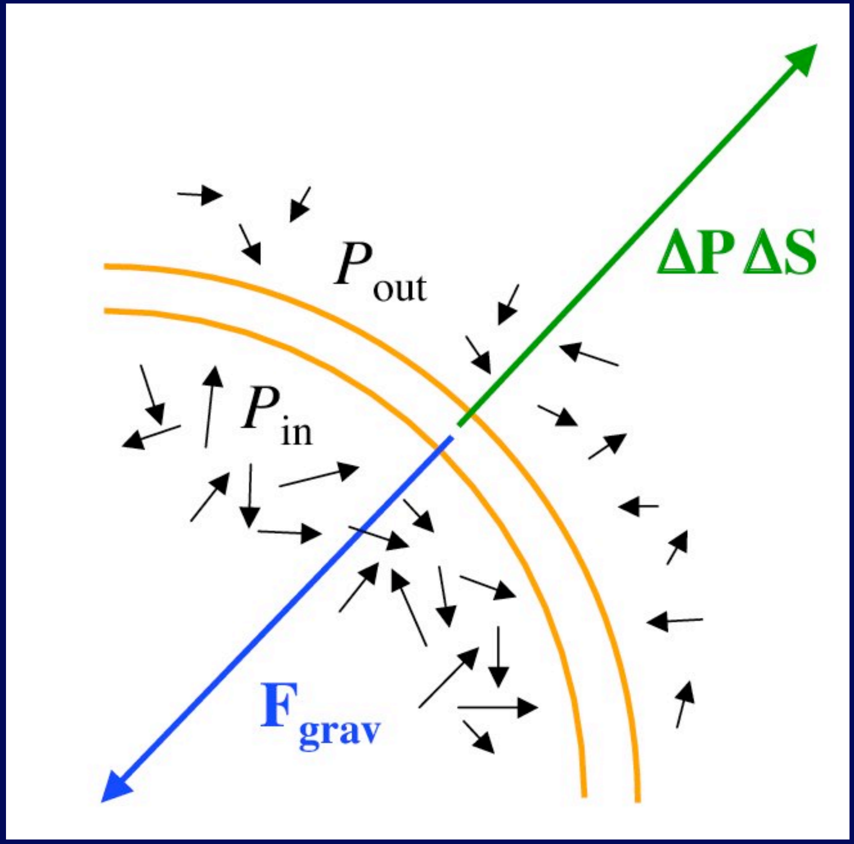
Spherical stationary Jeans equation

anisotropic dynamical pressure

tracer density

$$\frac{d\left(\nu\sigma_r^2\right)}{dr} + 2\frac{\beta(r)}{r}\,\nu\sigma_r^2 = -\nu\frac{GM(r)}{r^2}$$

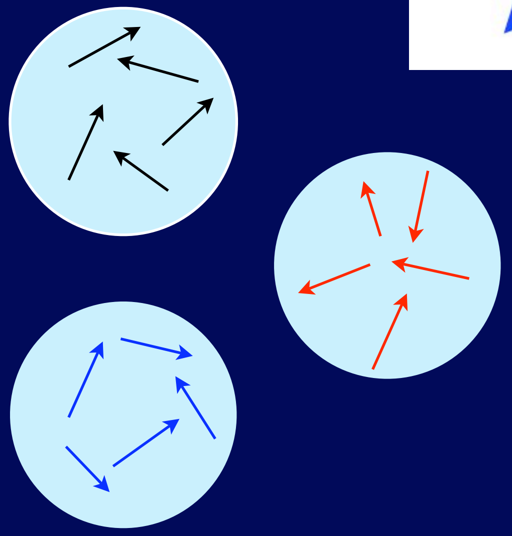
$$\beta(r) = 1 - \frac{\sigma_\theta^2(r)}{\sigma_r^2(r)}$$ = velocity anisotropy



isotropic orbits: $\beta = 0$

radial orbits: $\beta = 1$

circular orbits: $\beta \to -\infty$



Mass / Anisotropy Degeneracy *MAD*

Exploratory Mass-Anisotropy Modeling

1) Model-fitting of Line-of-Sight velocity dispersion profile

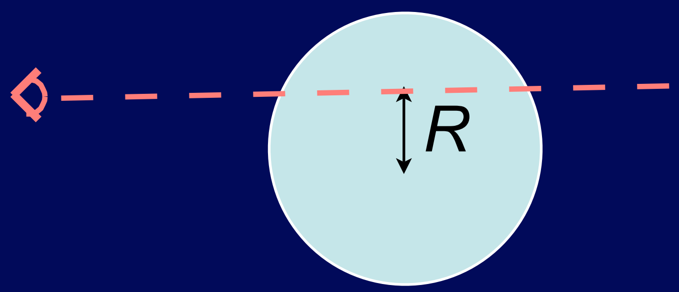
$M_{tot}(r) + \beta(r) \longrightarrow \sigma_{LOS}(R)$

1) assume both $M(r)$ & $\beta(r)$
& fit the LOS velocity dispersions

for $\beta = 0$

line-of-sight velocity dispersion

Tremaine et al. 94; Prugniel & Simien 97



$$\Sigma(R)\,\sigma_{\rm los}^2(R) = 2G \int_R^\infty \frac{\sqrt{r^2 - R^2}}{r^2}\,\nu(r)\,M(r)\,dr$$

tracer
surface density

kernels for other simple $\beta(r)$

Mamon & Łokas 05b

Exploratory Mass-Anisotropy Modeling

1) Model-fitting of Line-of-Sight velocity dispersion profile

$$M_{\mathrm{tot}}(r) + \beta(r) \longrightarrow \sigma_{\mathrm{LOS}}(R)$$

2) Anisotropy inversion

$$\left\{ \begin{array}{l} \Sigma(R) \\ \sigma_{\mathrm{LOS}}(R) \end{array} \right. + M_{\mathrm{tot}}(r) \longrightarrow \beta(r)$$

Binney & Mamon 82
Tonry 83; Bicknell et al. 89
Solanes & Salvador-Solé 90
Dejonghe & Merritt 92

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$$\left\{ \begin{array}{l} \Sigma(R) \\ \sigma_{\rm LOS}(R) \end{array} \right. + M_{\rm tot}(r) \longrightarrow \beta(r)$$

3) Mass inversion

$$\left\{ \begin{array}{l} \Sigma(R) \\ \sigma_{\rm LOS}(R) \end{array} \right. + \beta(r) \longrightarrow M_{\rm tot}(r)$$

Mamon & Boué 10
Wolf et al. 10

3) Mass inversion

Mamon & Boué 10; Wolf et al. 10

Kinematic deprojection & mass inversion of spherical systems with known anisotropy

anisotropic kinematic projection

$$P(R) = 2\int_R^\infty \left(1-\beta\frac{R^2}{r^2}\right) p\, \frac{r\,dr}{\sqrt{r^2-R^2}}$$

$p = \rho\,\sigma_r^2$ = dynamical pressure

$P = \Sigma\,\sigma_{los}^2$ = "projected pressure"

deprojection

$$(1-\beta)\,p = \int_r^\infty K[\beta(s)] \int_s^\infty \frac{dP}{dR}\frac{R\,dR}{\sqrt{R^2-r^2}}$$

MB10: ↓→ simple $\beta(r)$

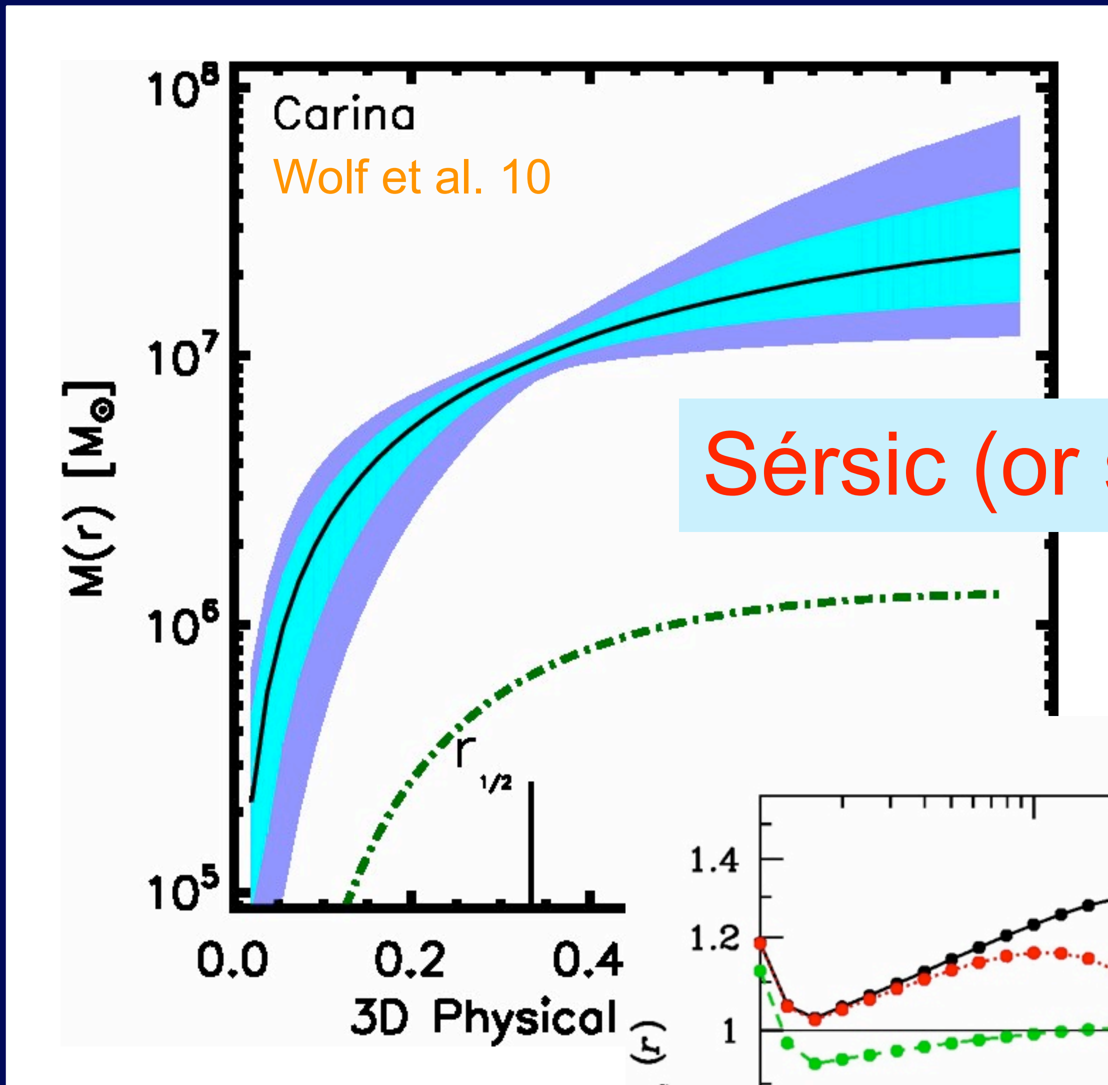
$$= \int_r^\infty L_\beta(R,r)\,\frac{\mathrm{d}P}{\mathrm{d}R}\,\mathrm{d}R$$

insert dynamical pressure into Jeans equation → mass profile

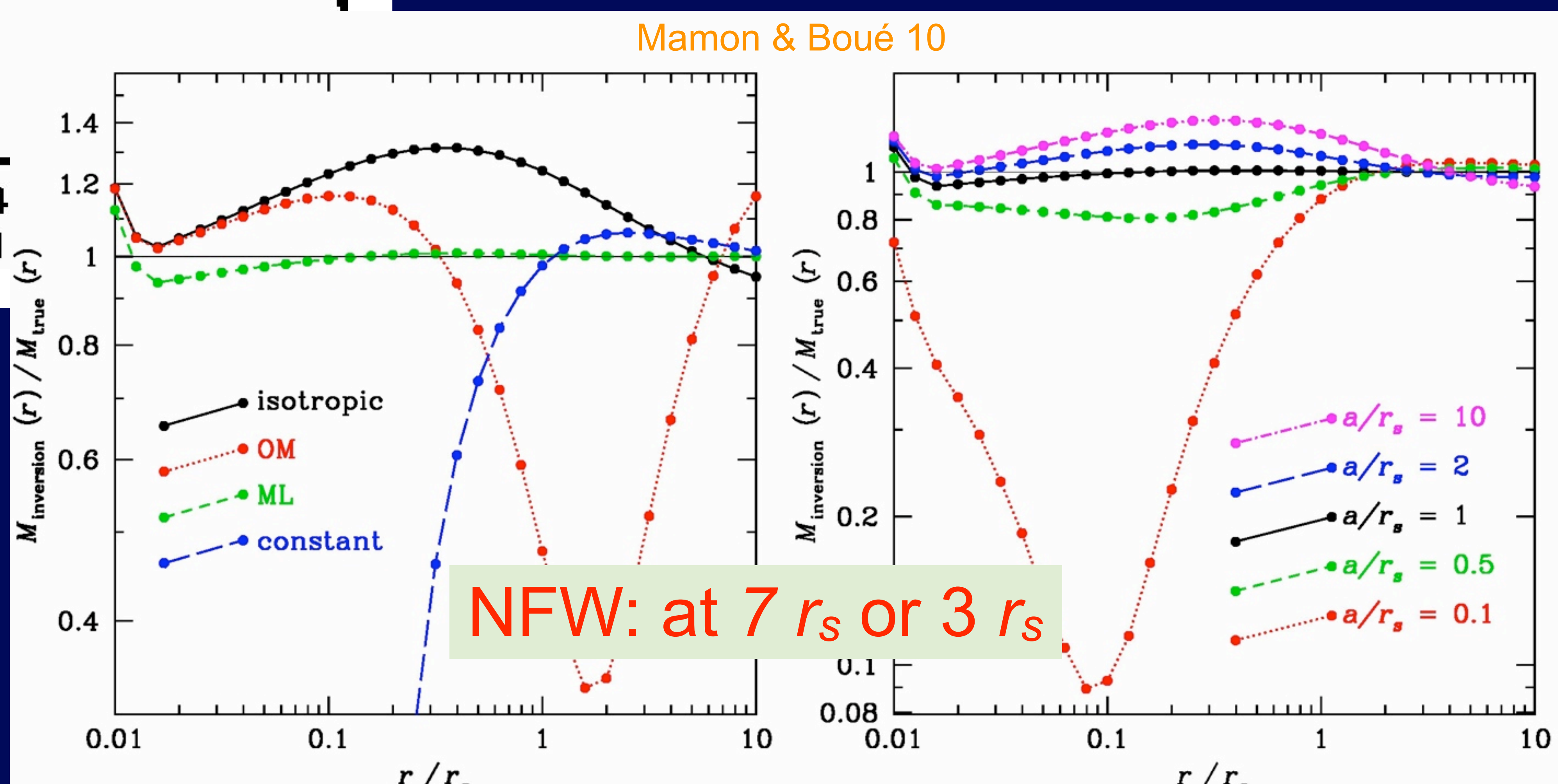
simple $\beta(r)$: single integral!

$$v_c^2(r) = \frac{1}{\pi\,[1-\beta(r)]\,\rho(r)}\int_r^\infty \left\{\frac{R}{\sqrt{R^2-r^2}}\frac{\mathrm{d}^2P}{\mathrm{d}R^2} - C_\beta(R,r)\frac{\mathrm{d}P}{\mathrm{d}R}\right\}\mathrm{d}R$$

Radius where mass is independent of anisotropy



Sérsic (or similar): at $r_{-3} \approx r_{1/2}$



NFW: at 7 r_s or 3 r_s

Exploratory Mass-Anisotropy Modeling

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$$\left\{ \begin{array}{l} \Sigma(R) \\ \sigma_{\rm LOS}(R) \end{array} \right. + M_{\rm tot}(r) \longrightarrow \beta(r)$$

3) Mass inversion

$$\left\{ \begin{array}{l} \Sigma(R) \\ \sigma_{\rm LOS}(R) \end{array} \right. + \beta(r) \longrightarrow M_{\rm tot}(r)$$

4) Fitting stars in Projected Phase Space MAMPOSSt

Mamon, Biviano & Boué 11, to be subm

$$\nu(r) + M_{\rm tot}(r) + \beta(r) + \{v\}(r) \longrightarrow g(R, v_{\rm LOS})$$

Other popular modeling methods

gaussian $\{v_{\rm LOS}(R)\}$ lose info on β

$v(r) + M_{\rm tot}(r) + \beta[r] + \{v_{\rm LOS}\}(R) \longrightarrow g(R, v_{\rm LOS})$

dispersion-kurtosis Łokas 02; see Łokas, Mamon & Prada 05

$M_{\rm tot}(r) + \beta \longrightarrow \sigma_{\rm LOS}(R) + \kappa_{\rm LOS}(R)$

must assume β = cst

distribution function modeling Dejonghe & Merritt 92; Merritt & Saha 93

$M_{\rm tot}(\mathbf{r}) + f(E,J)$ or $\{f_i(E,J)\} \longrightarrow g(R, v_{\rm LOS})$

don't know $f(E,J)$; not sure that $\{f_i(E,J)\}$ = basis set

orbit modeling Schwarzschild 79; de Lorenzi et al. 09

$M_{\rm tot}(\mathbf{r}) + \{orbits\} \longrightarrow g(R, v_{\rm LOS})$

too slow for MCMC investigation of parameter space

Mass modeling of
the Fornax dwarf spheroidal

Fornax data

2633 velocities
2278 Fornax members

$L_V = 1.9 \times 10^7\ L_{sun}$
Irwin & Hatzimiditriou 95

$L_V = 0.9 \times 10^7\ L_{sun}$
Walcher et al. 03

m = 0.7 Sersic distribution
Walcher et al. 03;
Battaglia et al. 06

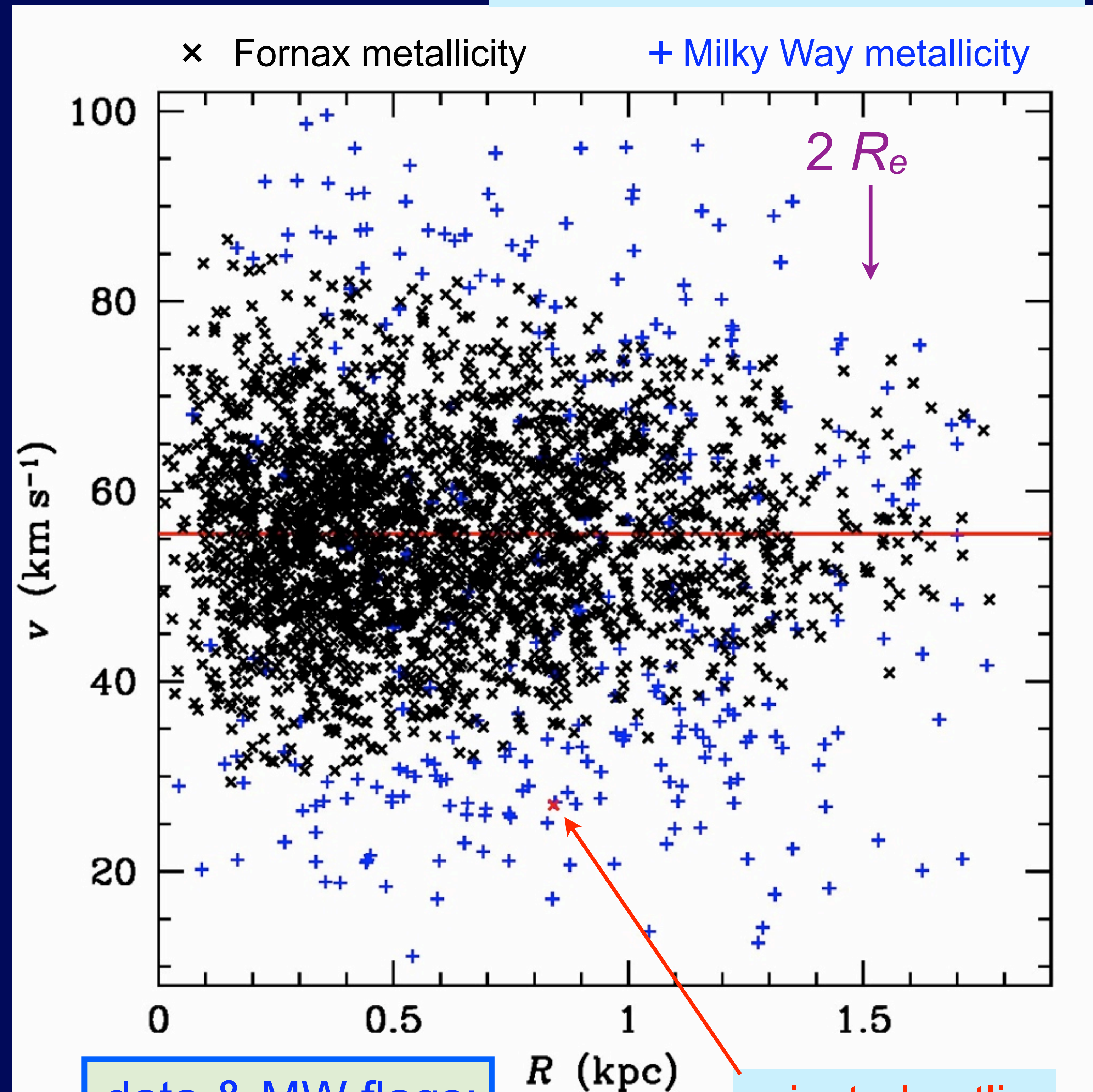
ellipticity: 0.21 → 0.36
Battaglia et al. 06

main starburst: age = 5.4 Gyr
Saviane et al. 00

⬇

$M_{stars}/L_V = 4.8$
Walcher et al. 03

(uncertain) center:
Battaglia et al. 06

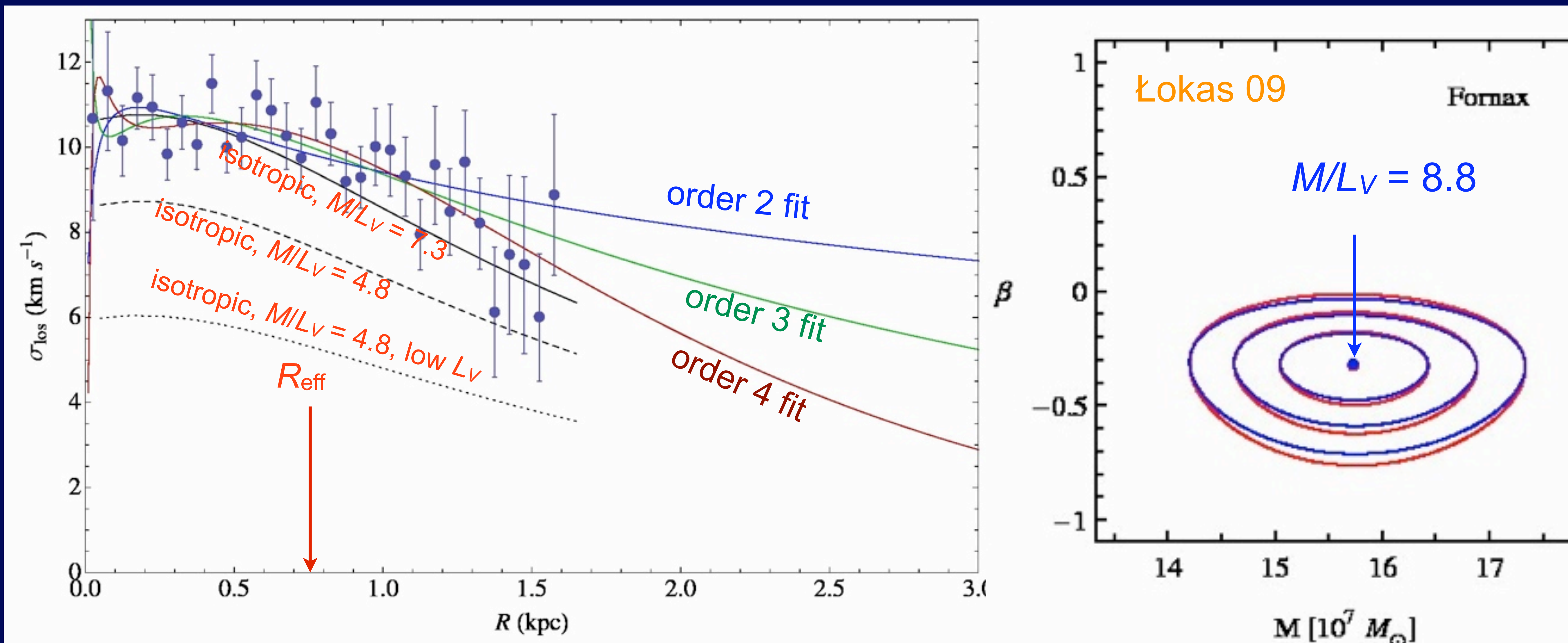


rejected outlier

data & MW flags:
Walker et al. 09
Magellan/MMFS

Fornax: velocity dispersion profile

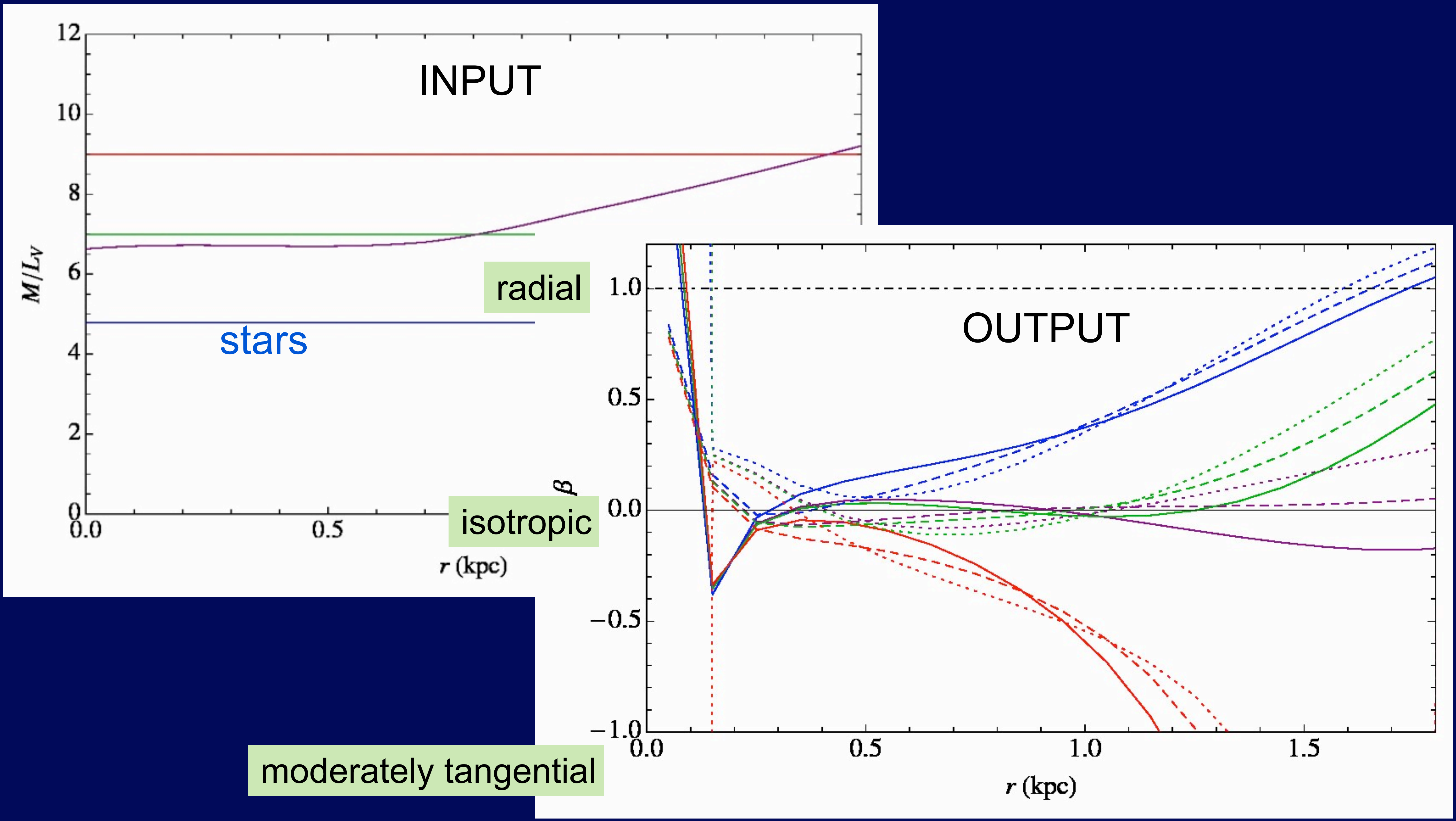
out to 2 $R_{\rm eff}$



1/3 fraction of dark matter in inner regions? OR L_V underestimated by 40%?

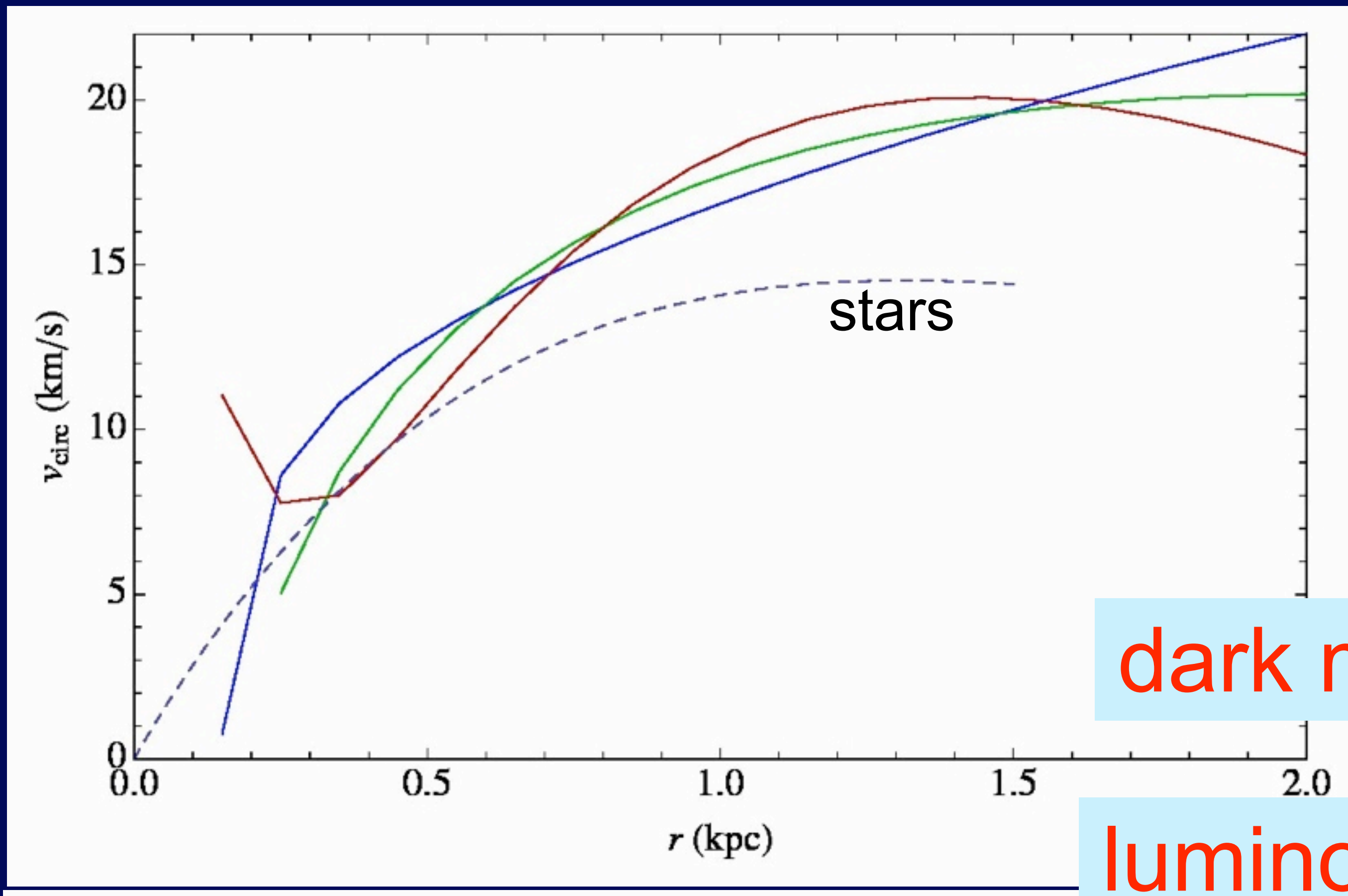
M/*L* increases outwards? OR tangential outer orbits?

Fornax: *anisotropy inversion*



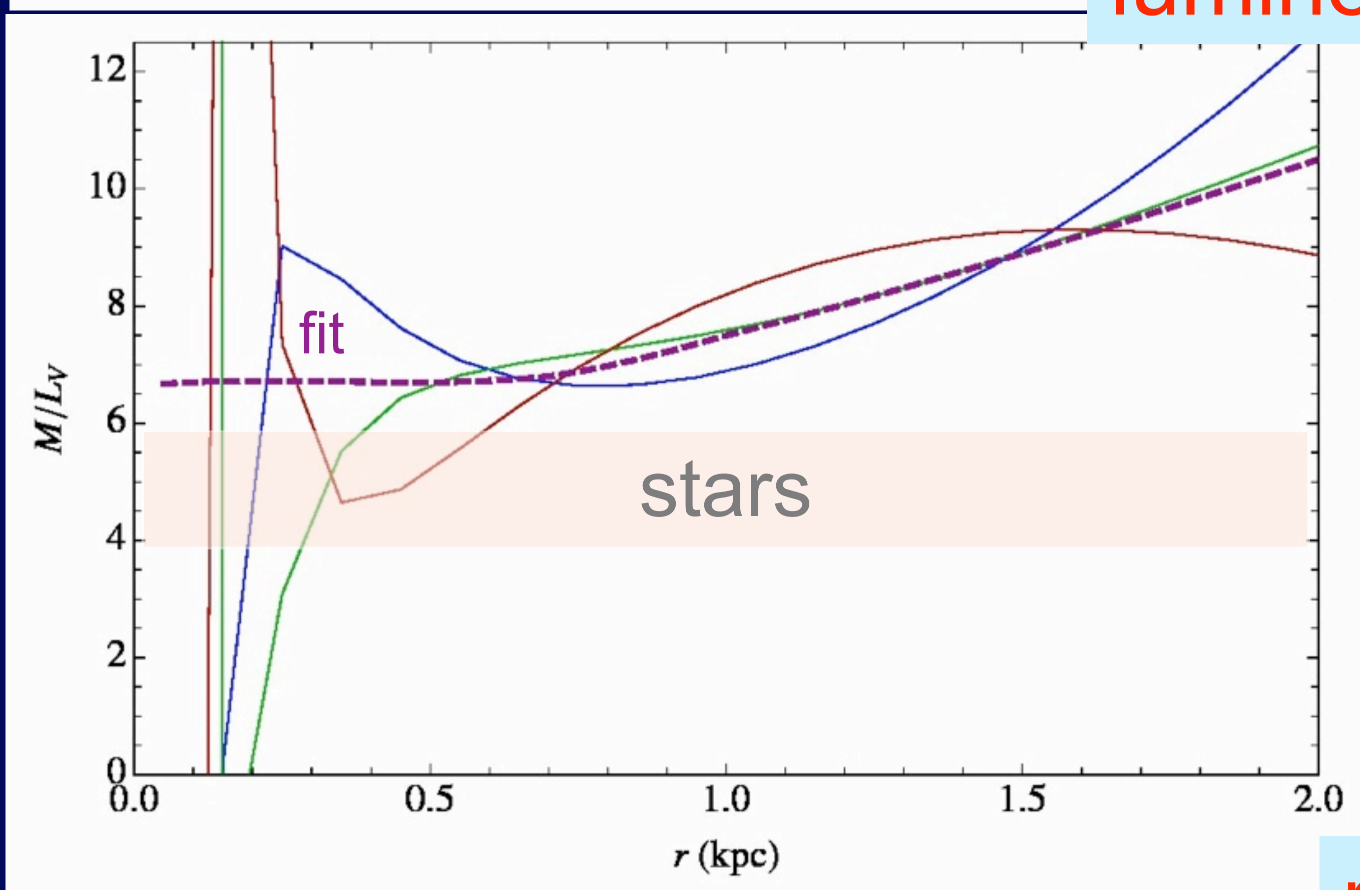
cst *M*/*L* → radial (low *M*/*L*) or tangential (high *M*/*L*) orbits

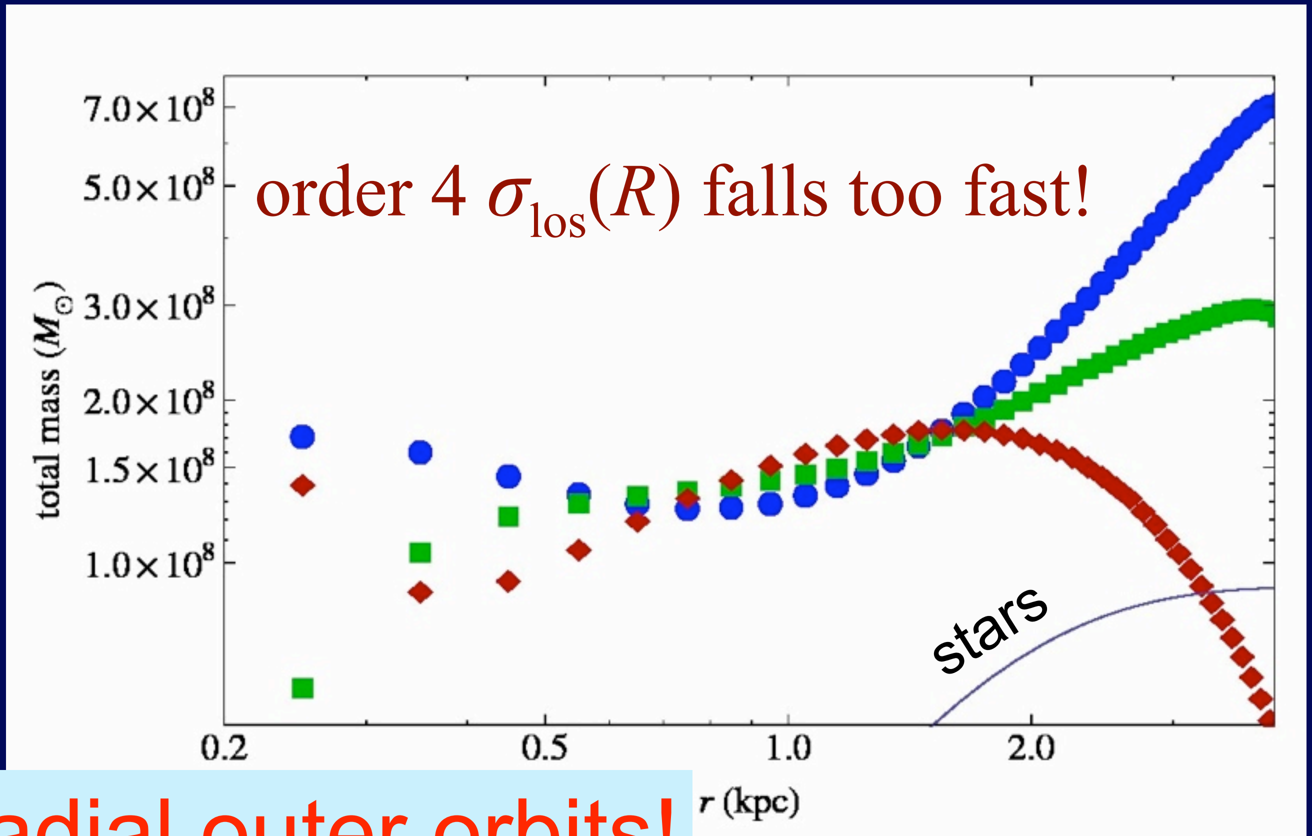
Fornax: *isotropic mass inversion*



dark matter, even in inner regions?

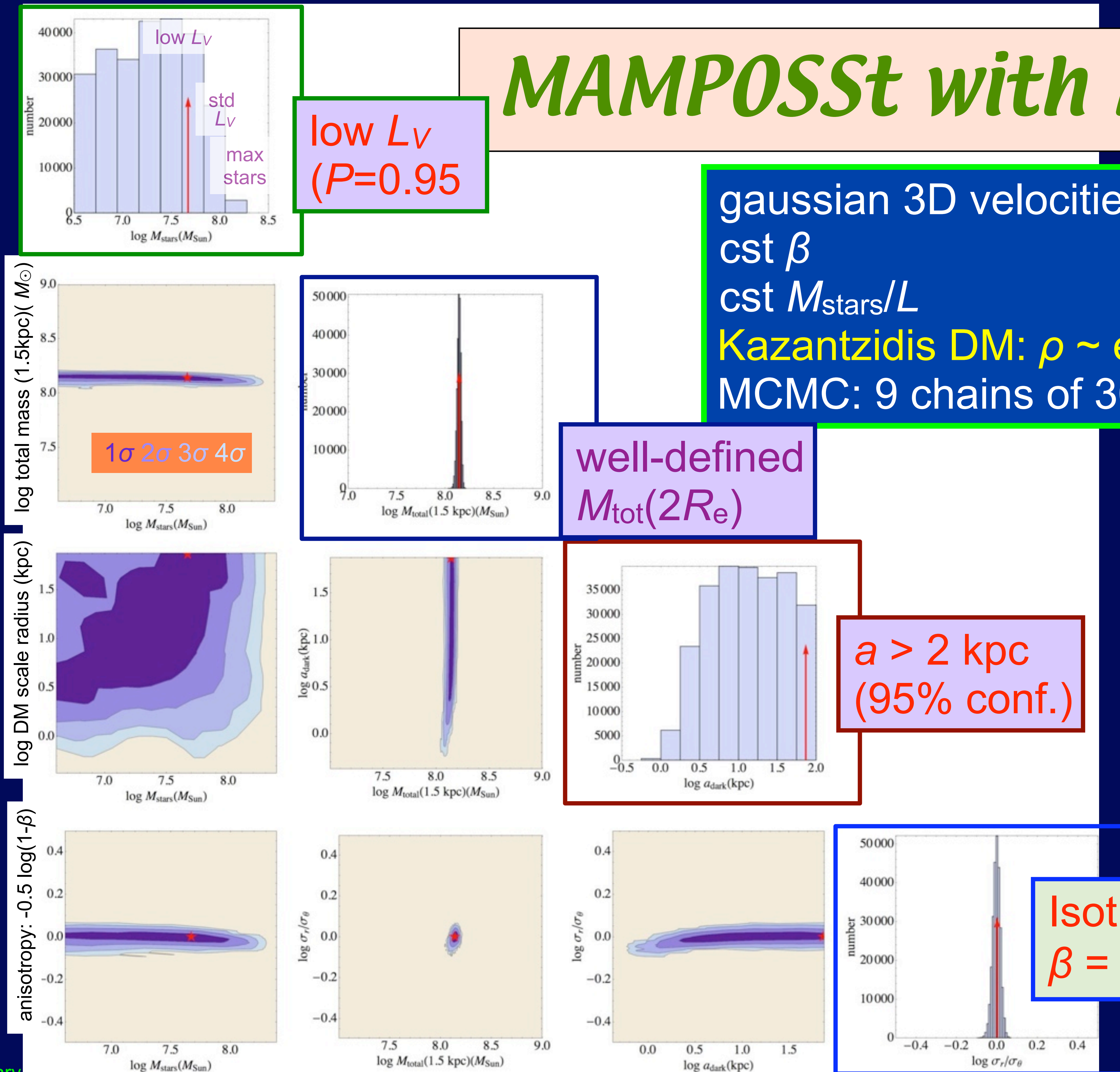
luminosity and/or M_{stars}/L too low?





radial outer orbits!

MAMPOSSt with MCMC



low L_V (P=0.95

- gaussian 3D velocities
- cst β
- cst M_{stars}/L
- Kazantzidis DM: $\rho \sim \exp(-r/a) / r$
- MCMC: 9 chains of 30 000

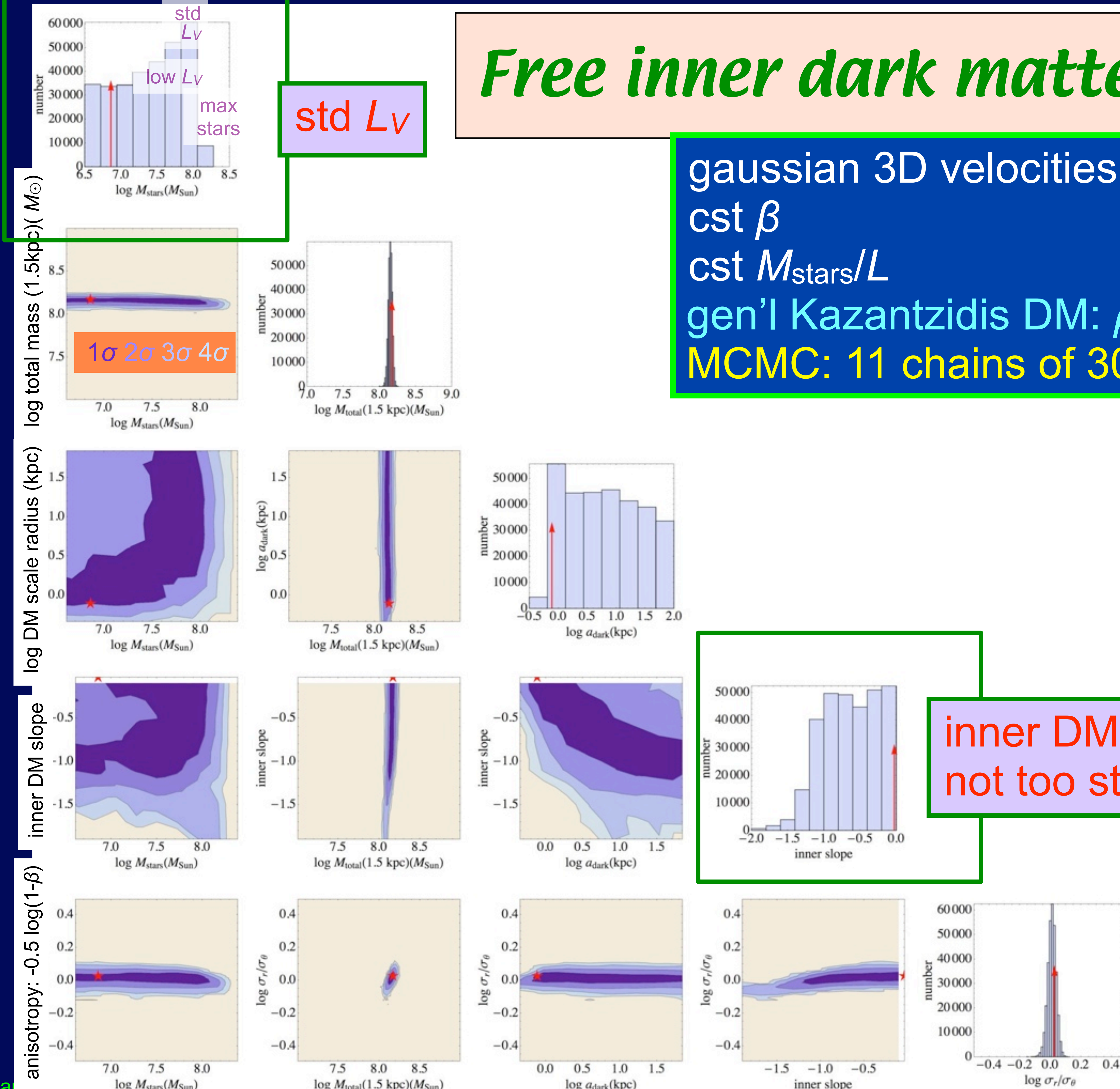
well-defined $M_{tot}(2R_e)$

a > 2 kpc (95% conf.)

Isotropic orbits! $\beta = -0.03 \pm 0.09$

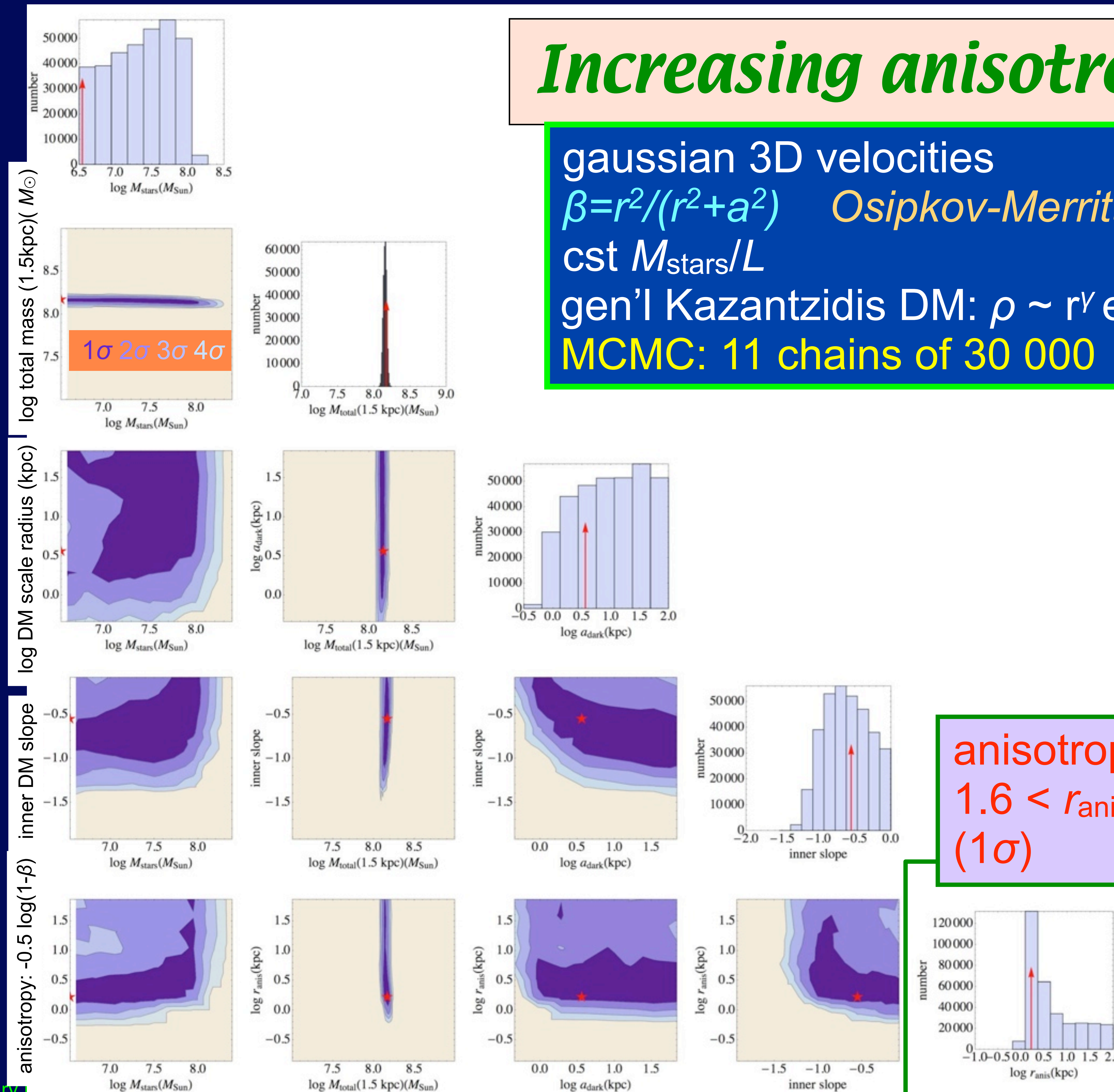
Free inner dark matter slope…

gaussian 3D velocities
cst β
cst M_{stars}/L
gen'l Kazantzidis DM: $\rho \sim r^{\gamma} \exp(-r/a)$
MCMC: 11 chains of 30 000



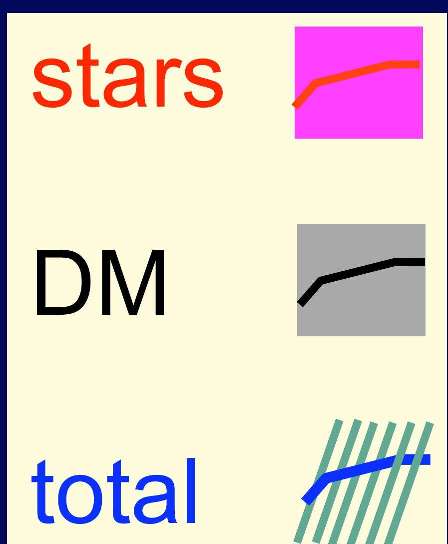
Increasing anisotropy…

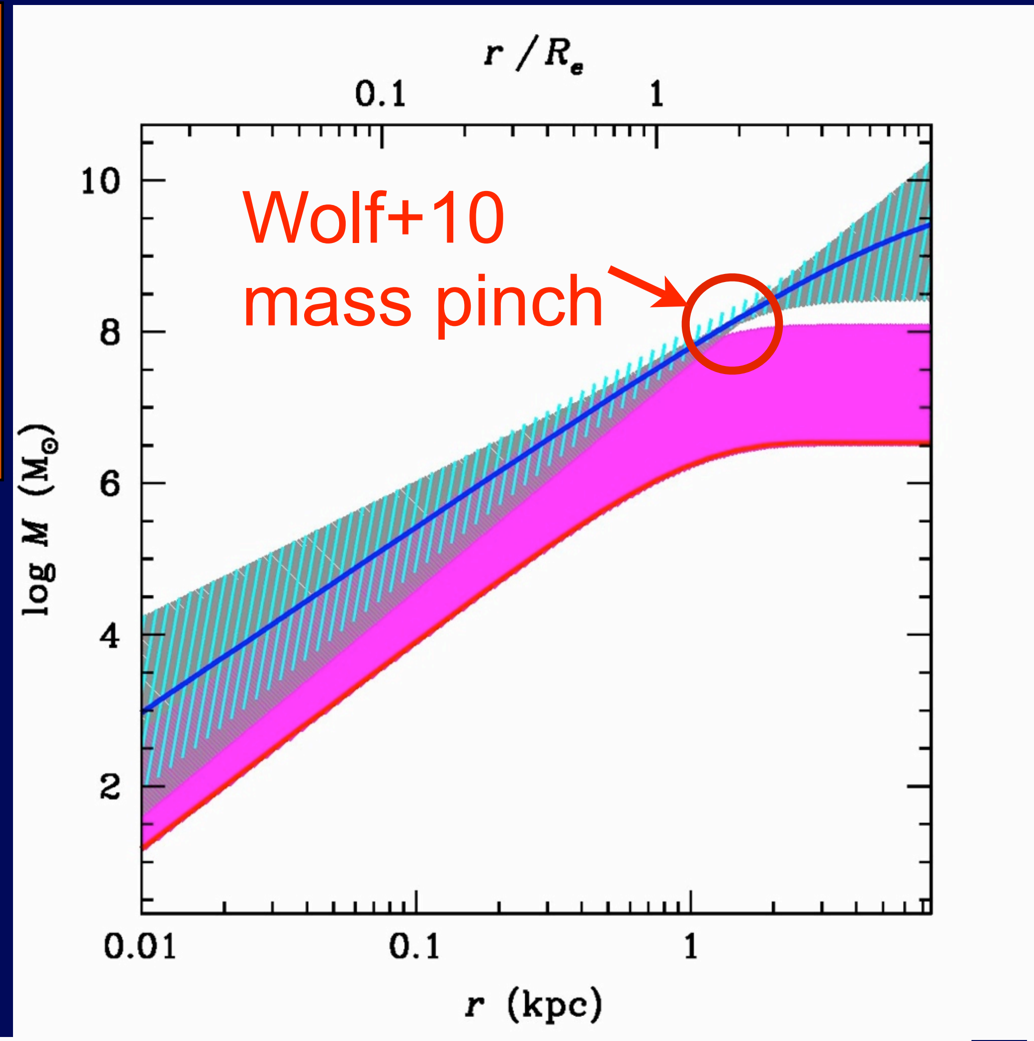
gaussian 3D velocities
$\beta = r^2/(r^2+a^2)$ Osipkov-Merritt
cst $M_{\rm stars}/L$
gen'l Kazantzidis DM: $\rho \sim r^{\gamma} \exp(-r/a)$
MCMC: 11 chains of 30 000

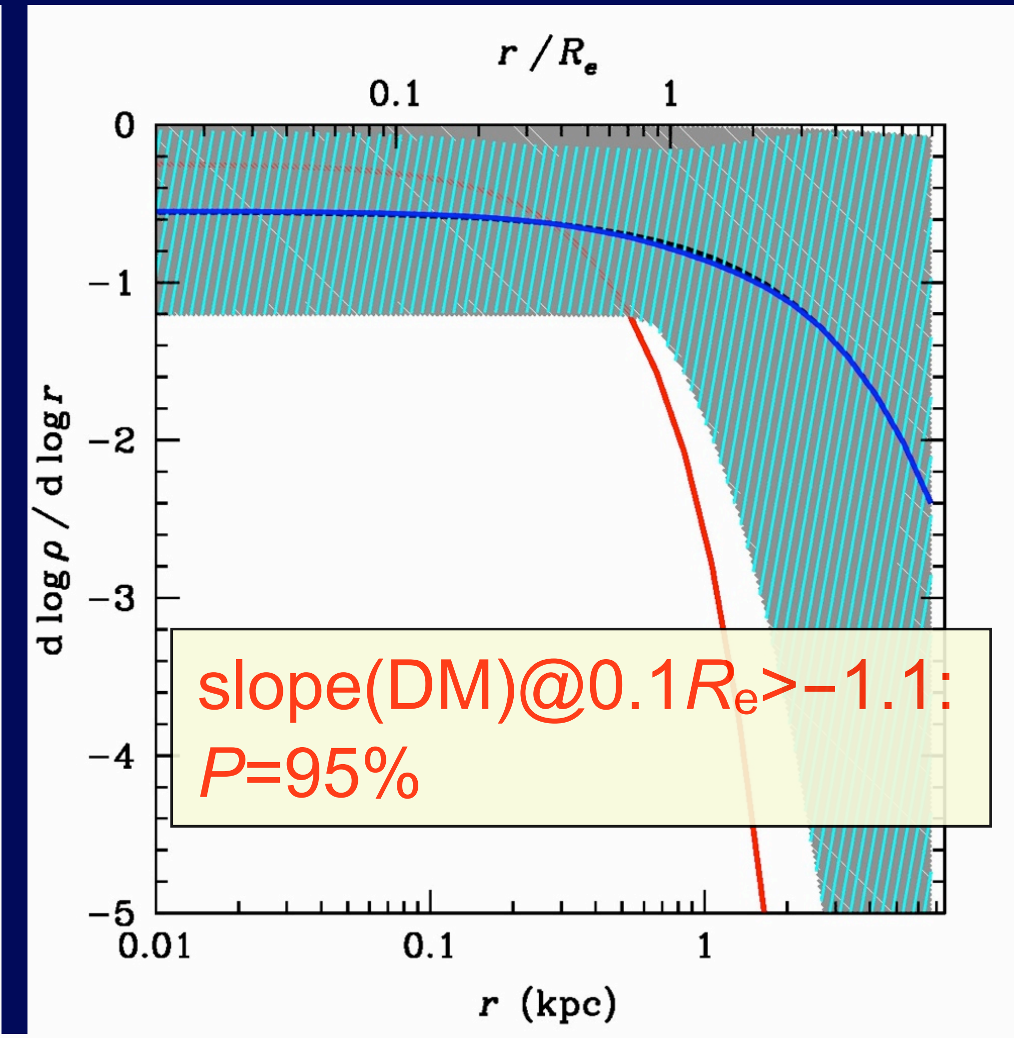


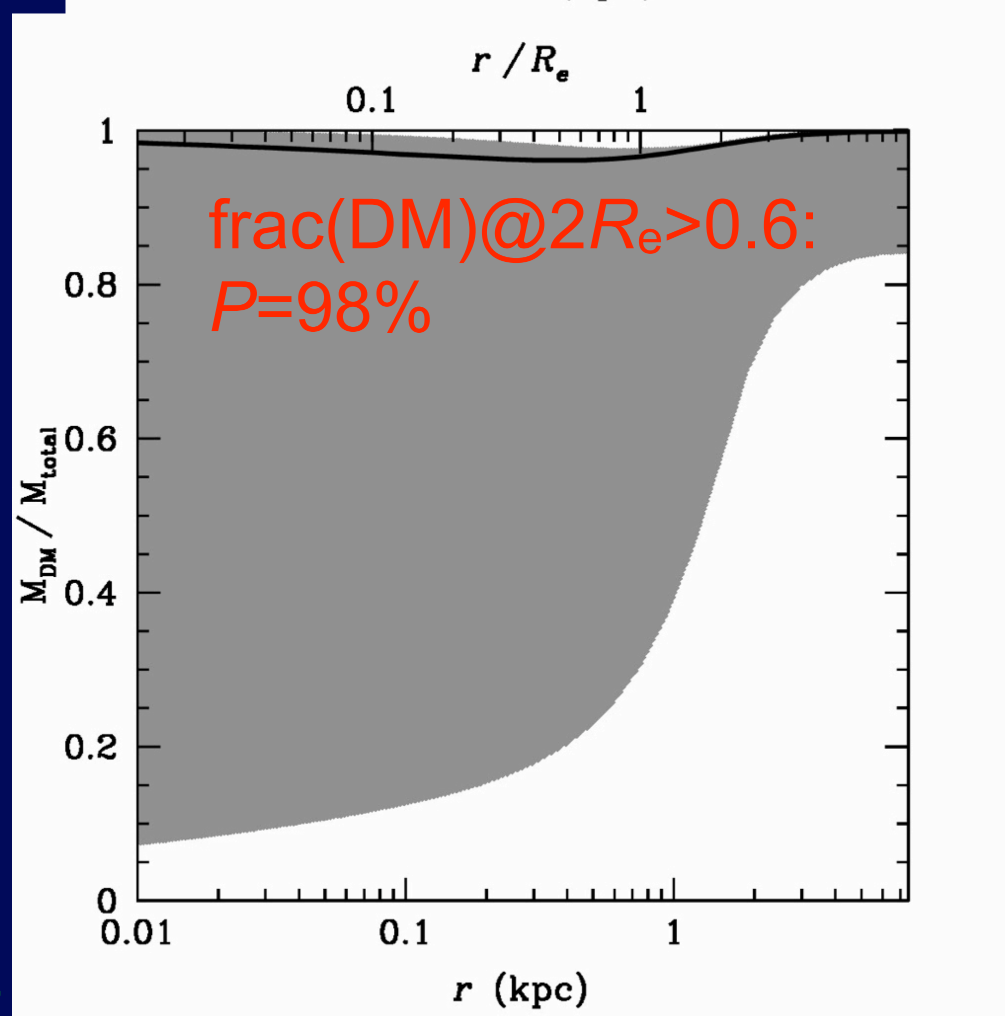
anisotropy radius:
$1.6 < r_{\rm anis} < 25$ kpc
(1σ)

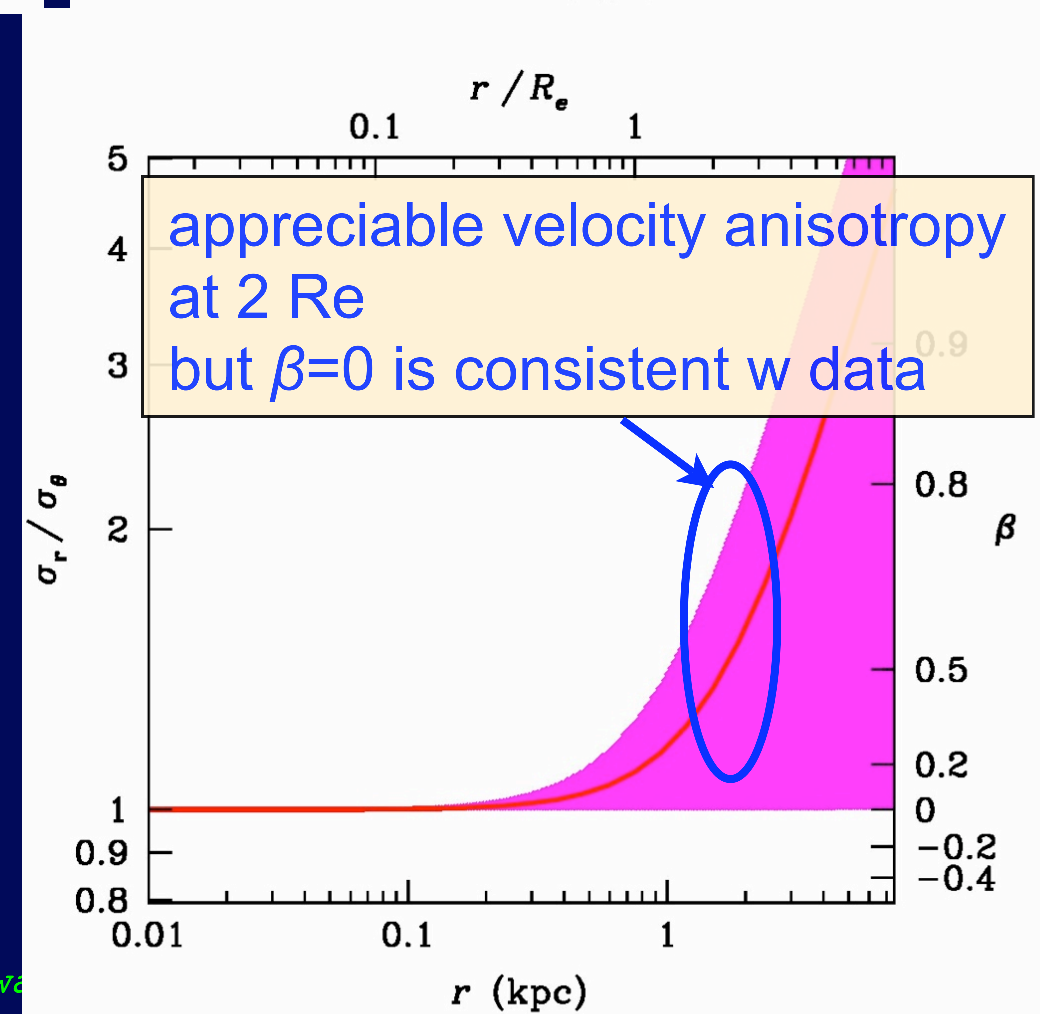
Radial variations



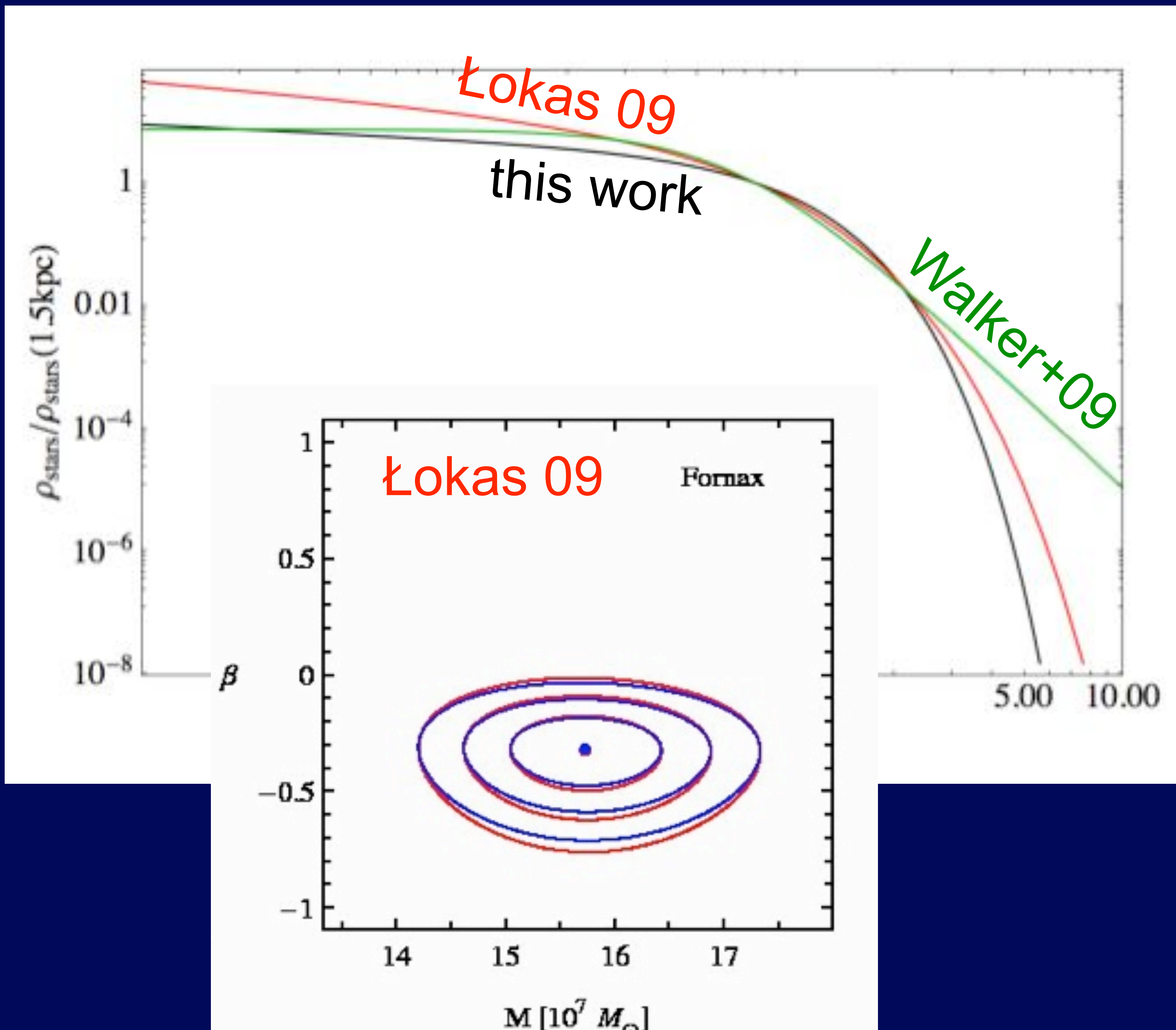


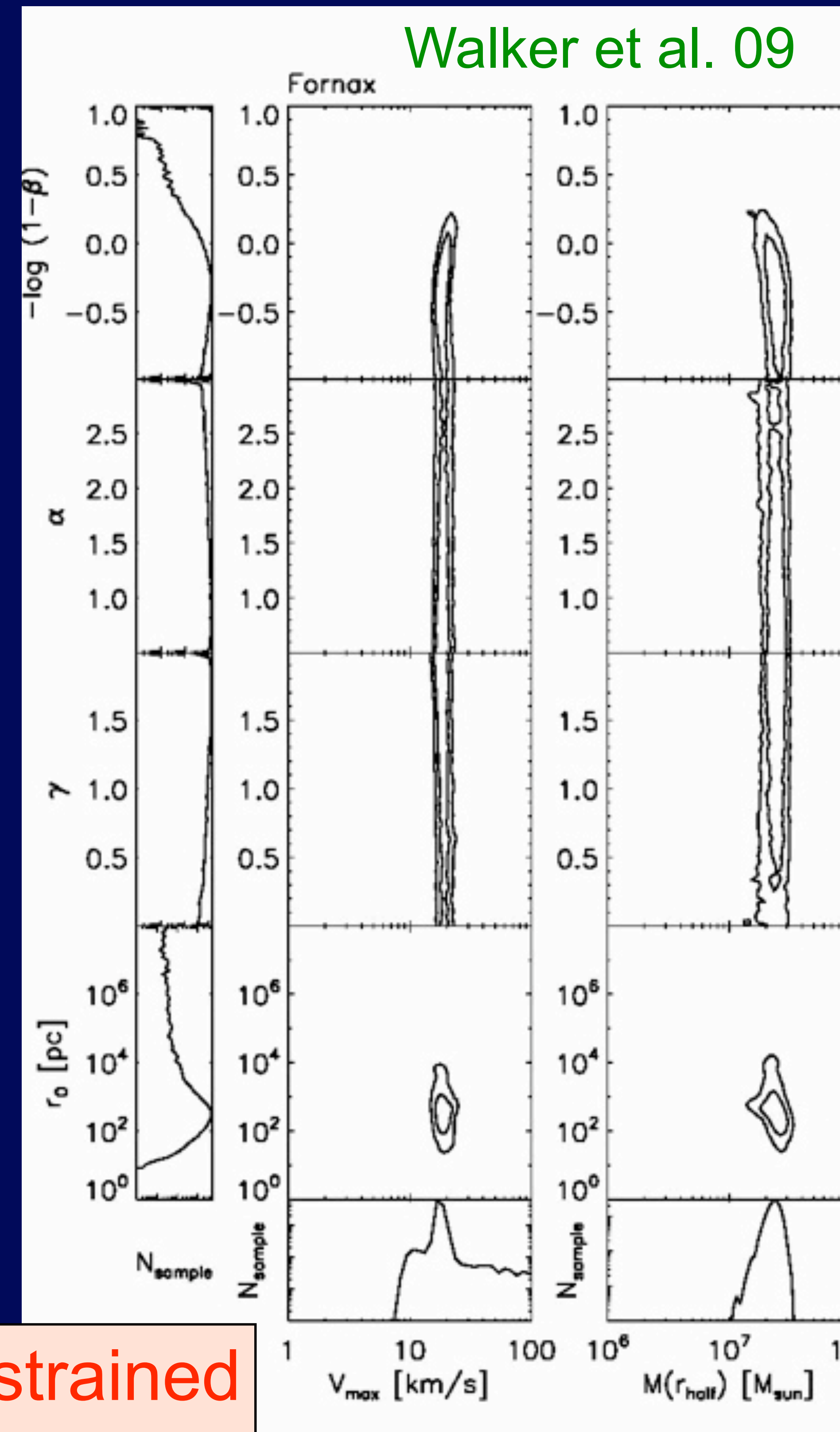






Comparison with previous work





anisotropy poorly constrained:

$-0.42 < \beta < -0.18$

$\beta < 0.17$

vs. $-0.05 < \beta < 0.13$

1σ limits

inner slope not constrained

$\gamma < -0.3$ vs. $\gamma > -1.0$

Conclusions

Mass modelling = *exploratory data analysis*:
try ≠ methods: mass & β inversions, & MAMPOSSt

Fornax

- MAMPOSSt → stronger constraints
- Isotropic inner orbits, ≈ radial outer orbits
- Dark matter present:
  - likely > 50% at all radii
    seen in simulations: Klimentowski+07; Lokas+10
- Dark matter inner slope shallower than −1.1
  see Pennarubia for tidal effects on GCs

Perspectives

- MAMPOSSt with non-gaussian 3D velocity distributions
- model rotation & metallicity effects Battaglia+06 in Fornax
- higher-parameter MCMC fits