Several astronomical problems solved by calibrating the distribution in projected phase space with cosmological simulations


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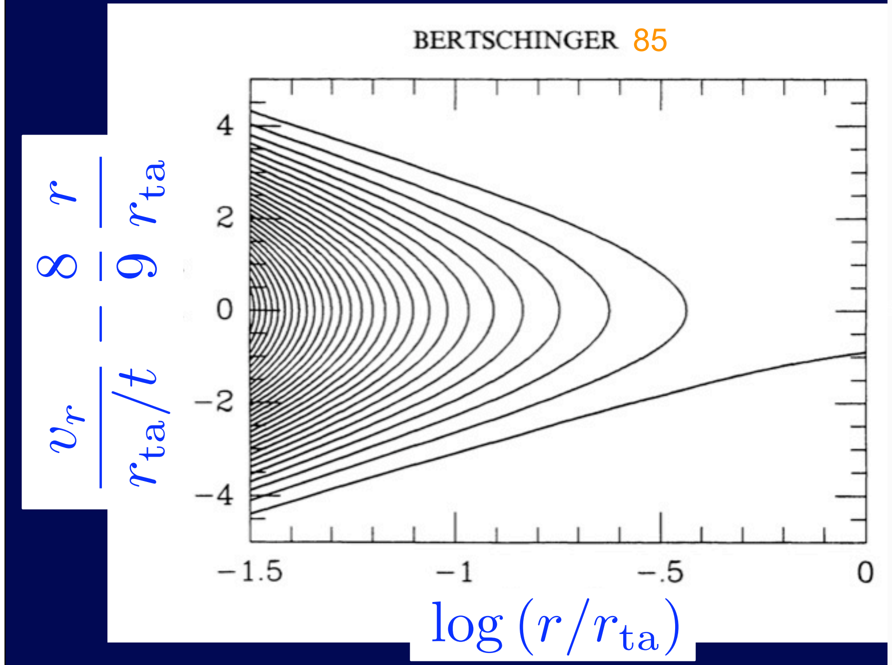
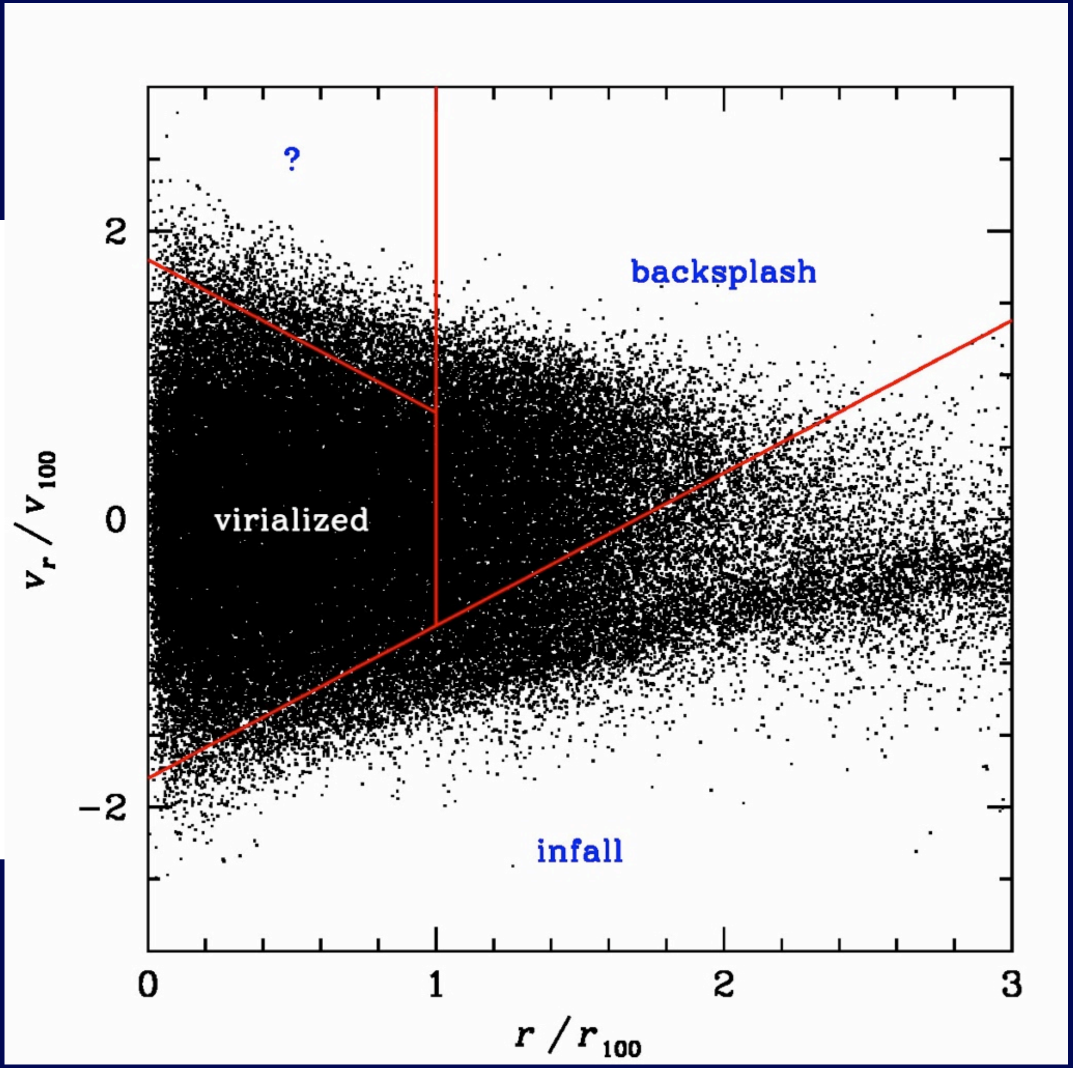
Outline

- Phase space & observers projected phase space
- Universal distribution of halo interlopers
- New mass modelling techniques see also R. Wojtak
- Applications:
  - ➡ Dark matter & orbits in quasi-spherical systems

    from galaxy clusters see also R. Wojtak *to dwarf spheroidals*
  - ➡ Neutral gas deficient spiral galaxies “in” Virgo cluster
  - ➡ Star formation history of galaxies falling into clusters

Radial phase space

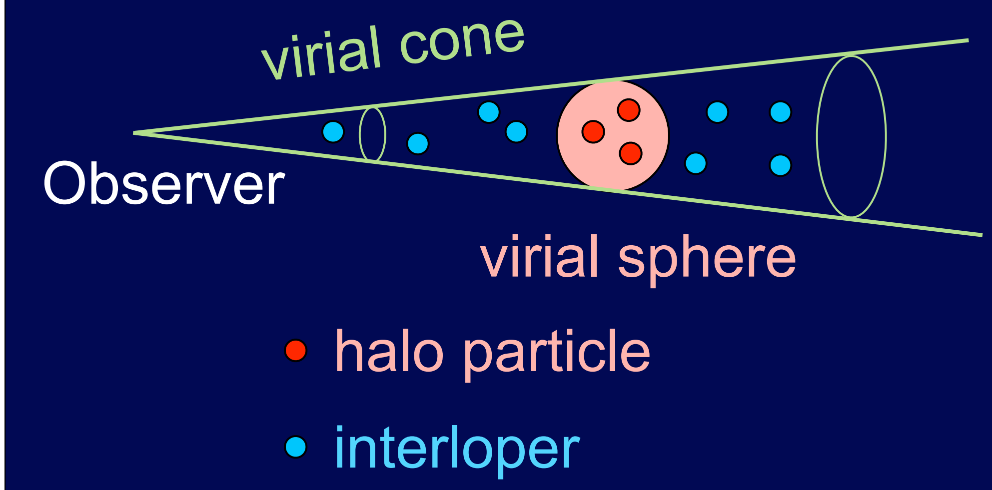


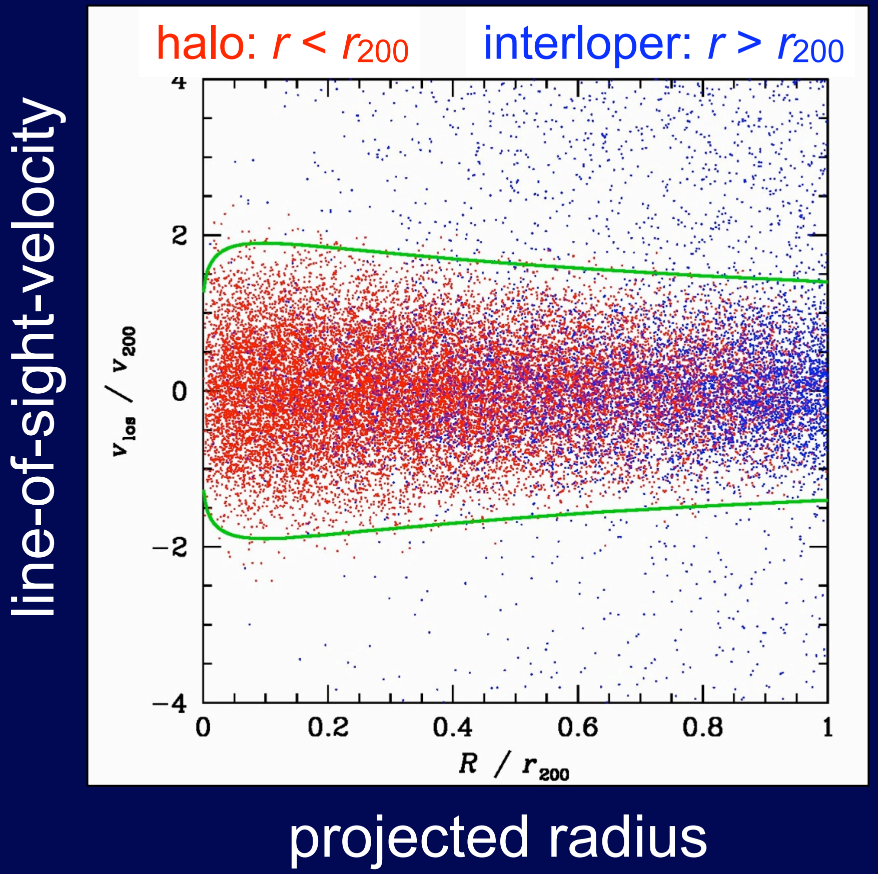


stack of 93 regular halos of dark matter particles
within hydrodynamical cosmological simulations by Borgani et al. 04

Projected phase space

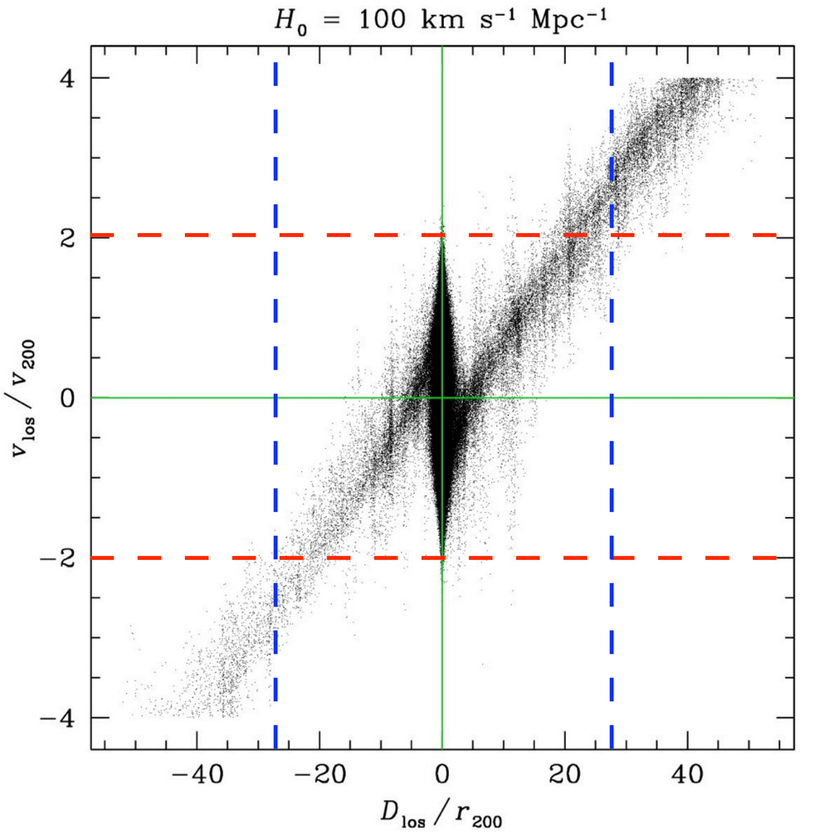
= observer’s viewpoint





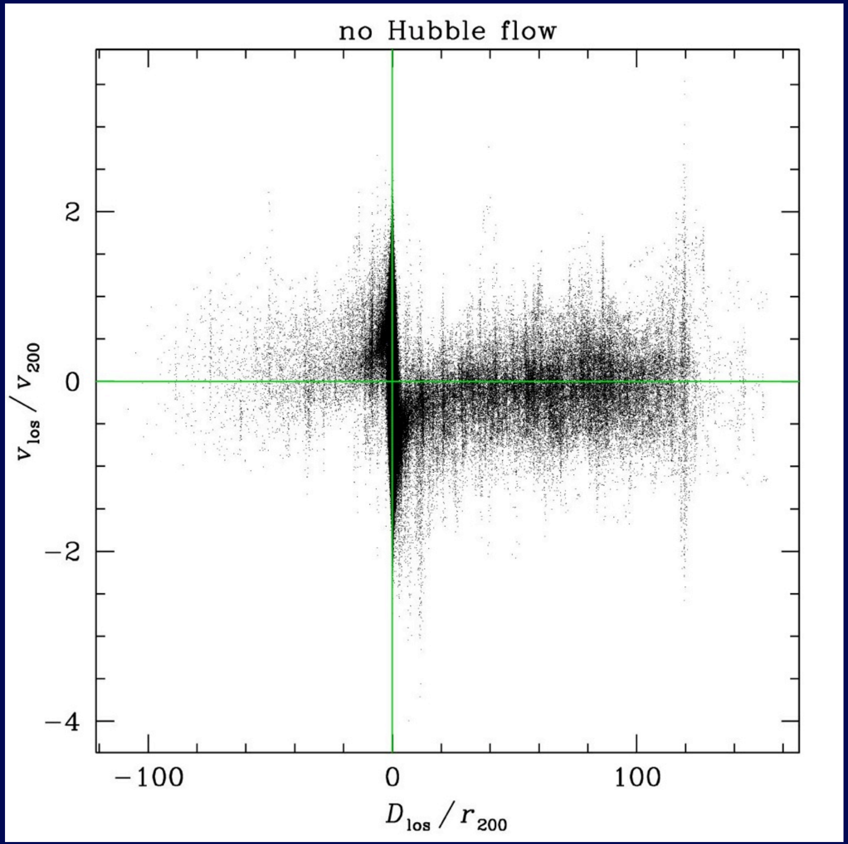
How does one learn about full phase space when limited to projected phase space view?

Hubble flow distortion



line-of-sight velocity

line-of-sight distance



line-of-sight velocity

line-of-sight distance

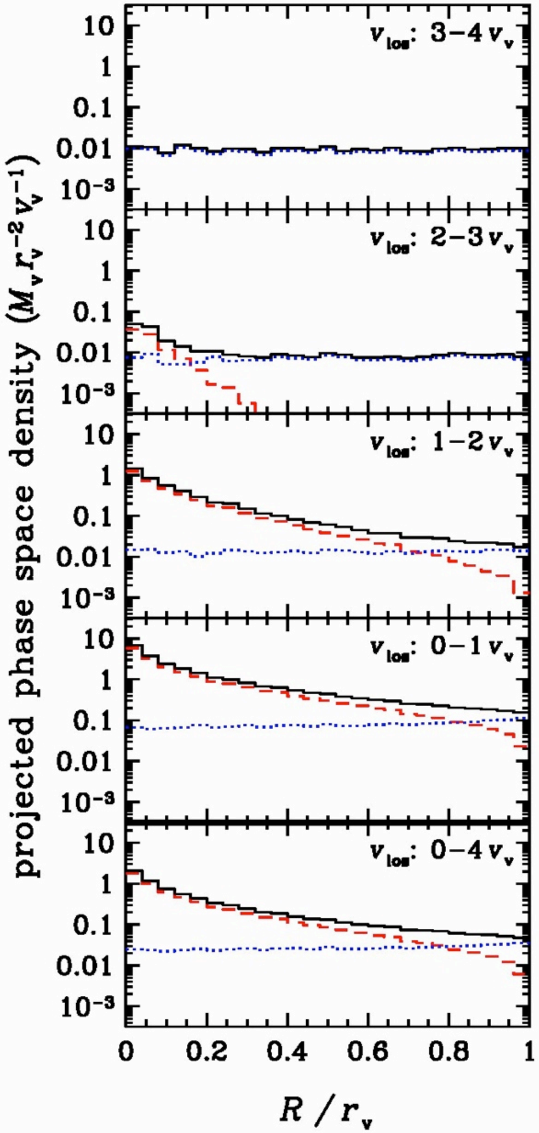
Hubble flow:

- ±3σ_v cuts ~all particles beyond ~27 r_{200}
- what effect on projected phase space?

Universal distribution of halo & interloper particles in projected phase space

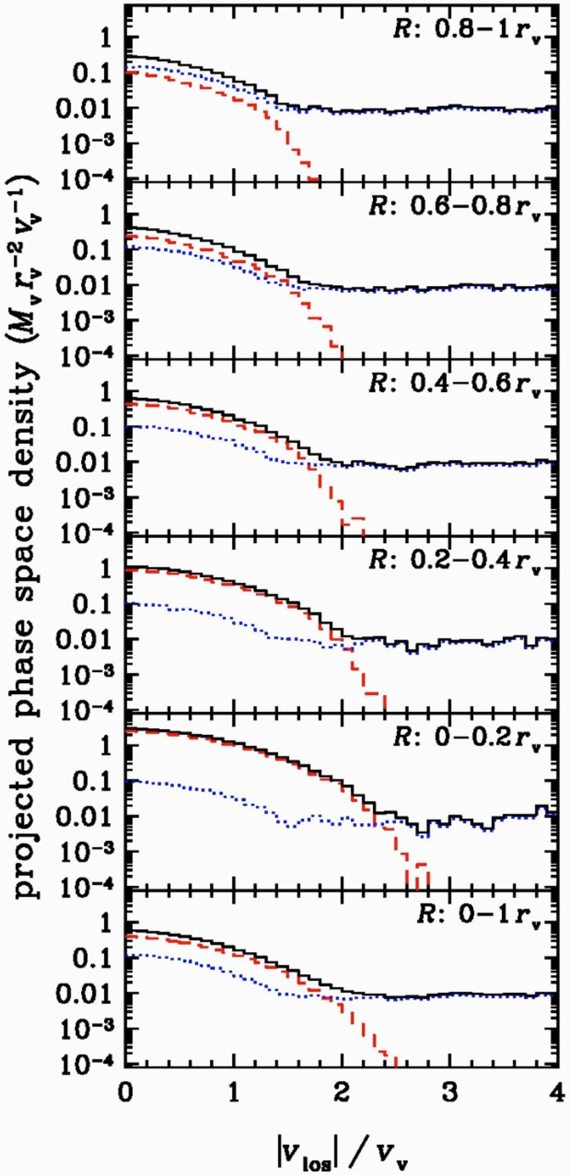
Cuts through projected phase space

Mamon, Biviano & Murante in prep.



nearly constant surface density

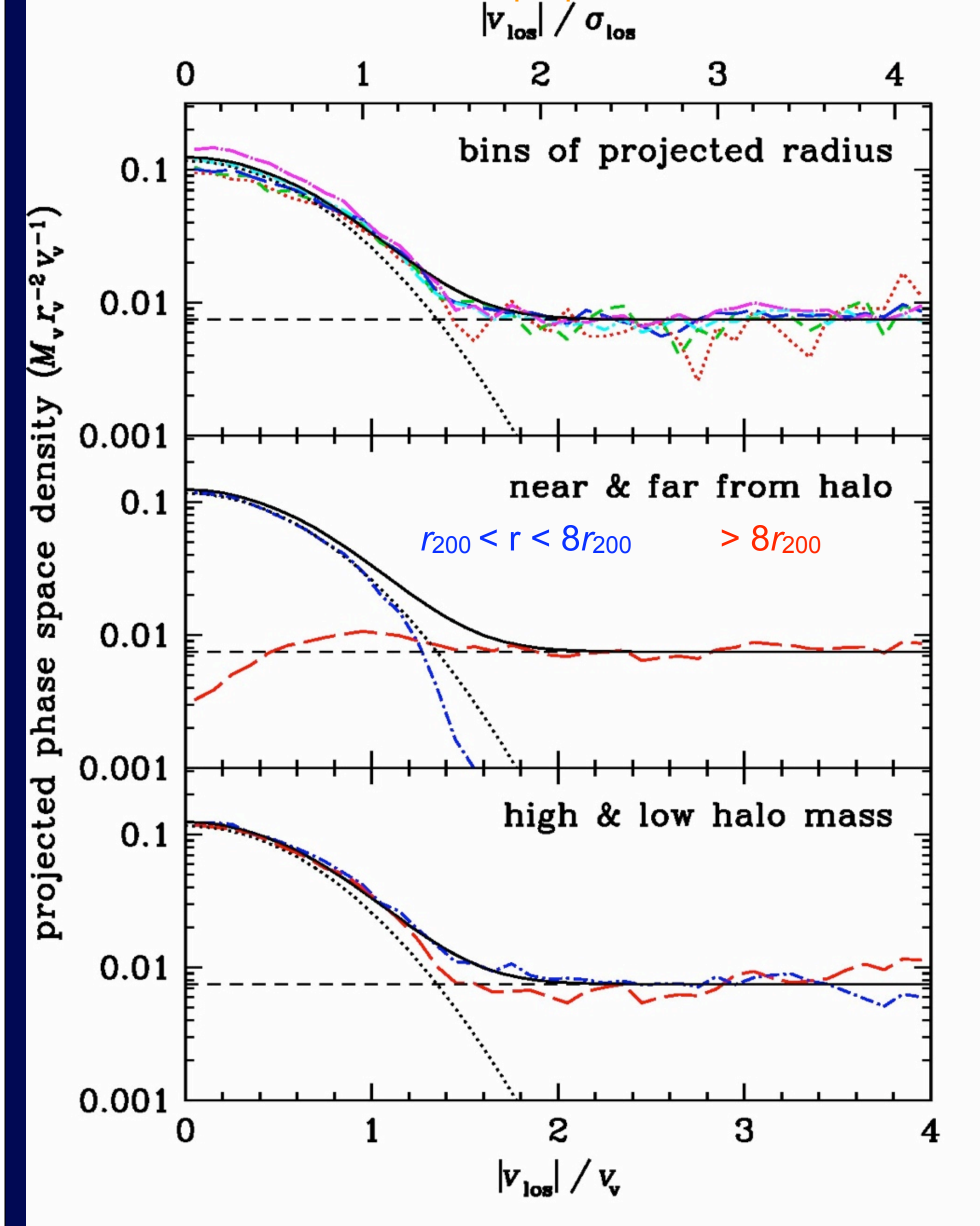
Mamon, Biviano & Murante in prep.



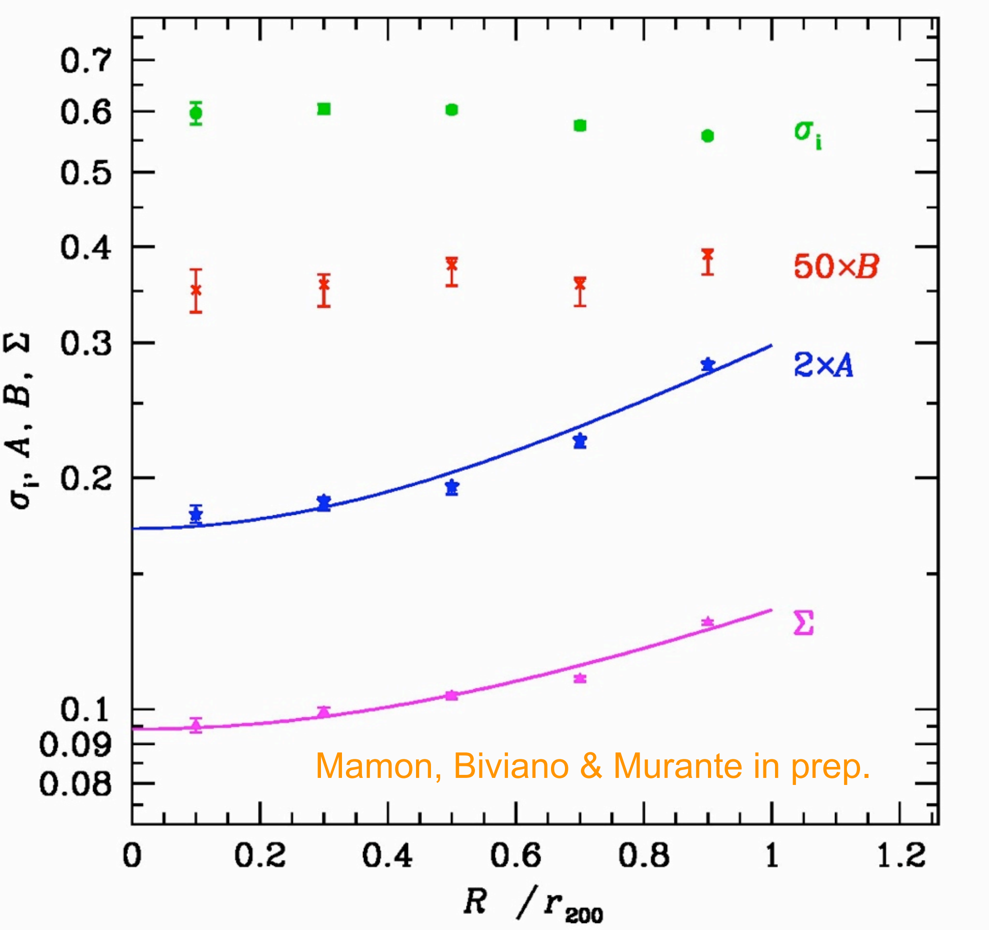
gaussian + constant velocity distribution

Universality

Mamon, Biviano & Murante in prep.



$$g\left(R, |v_{\rm los}|\right) = A \exp\left[-\frac{1}{2}\left(\frac{|v_{\rm los}|}{\sigma_i}\right)^2\right] + B$$



Mamon, Biviano & Murante in prep.

Old & New Mass Modeling Techniques using internal motions

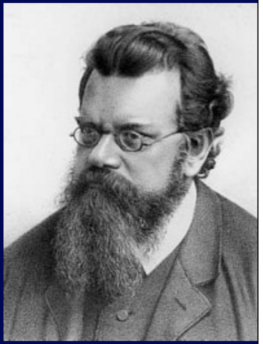
From phase space to local space

$f = f(r,v) \equiv$ distribution function=6D phase space density

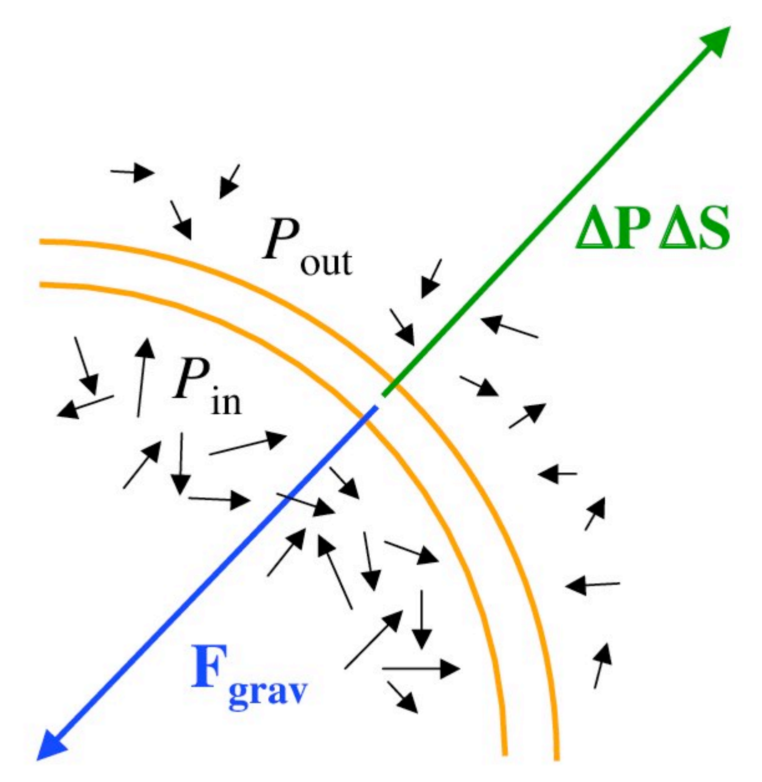
Collisionless Boltzmann Equation

$$\frac{\partial f}{\partial t} + \mathbf{v} \cdot \nabla f - \nabla \Phi \cdot \frac{\partial f}{\partial \mathbf{v}} = 0$$

test particles in potential
= incompressible 6D fluid



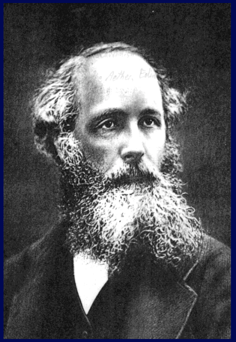
$$\int v_j \, \mathrm{CBE} \, d^3\mathbf{v}$$



$$\nabla \bullet P = -\nu \nabla \Phi$$

Jeans Equation

tracer density



Maxwell

Jeans

2 classes of
mass & anisotropy modelling

- Jeans analysis
- Fitting the projected phase space distribution

Spherical stationary Jeans equation

tracer density

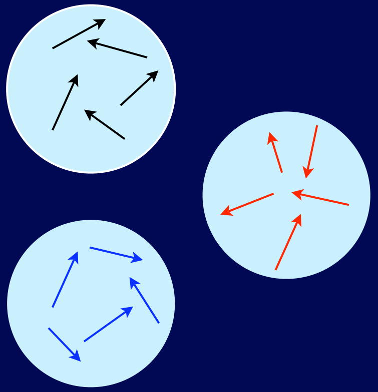
anisotropic dynamical pressure

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

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

= velocity anisotropy

isotropic orbits: $\beta = 0$
radial orbits: $\beta = 1$
circular orbits: $\beta \to -\infty$



⇨ mass / anisotropy degeneracy

MAD

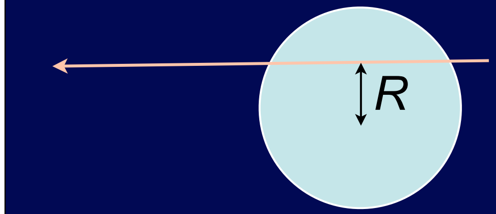
Jeans 1) assume both $M(r)$ & $\beta(r)$ & fit the projected velocity dispersions

for $\beta = 0$

line-of-sight velocity dispersion

Tremaine et al. 94; Prugniel & Simien 97

surface density



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

kernels for other simple $\beta(r)$

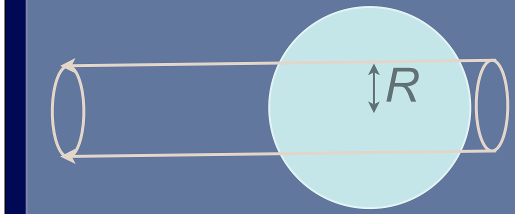
Mamon & Łokas 05b

axisymmetric models

Cappellari 08

aperture velocity dispersion

Mamon & Łokas 05a



$$\frac{3}{4\pi G}M_2(R)\,\sigma_{\rm ap}^2(R) = \int_0^\infty r\,\nu\,M\,dr - \int_R^\infty \frac{\left(r^2-R^2\right)^{3/2}}{r^2}\nu\,M\,dr$$

Jeans 2) assume either $M(r)$ or $\beta(r)$

given projected observations:

surface density $\Sigma(R)$

line of sight velocity dispersion $\sigma_{\rm los}(R)$

2a) Anisotropy inversion

assume $M(r) \to \beta(r)$

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

Jeans 2b) Mass inversion

Mamon & Boué 09, MNRAS in press
Wolf et al. 09, MNRAS submitted

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

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

anisotropic kinematic projection

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

anisotropic kinematic deprojection

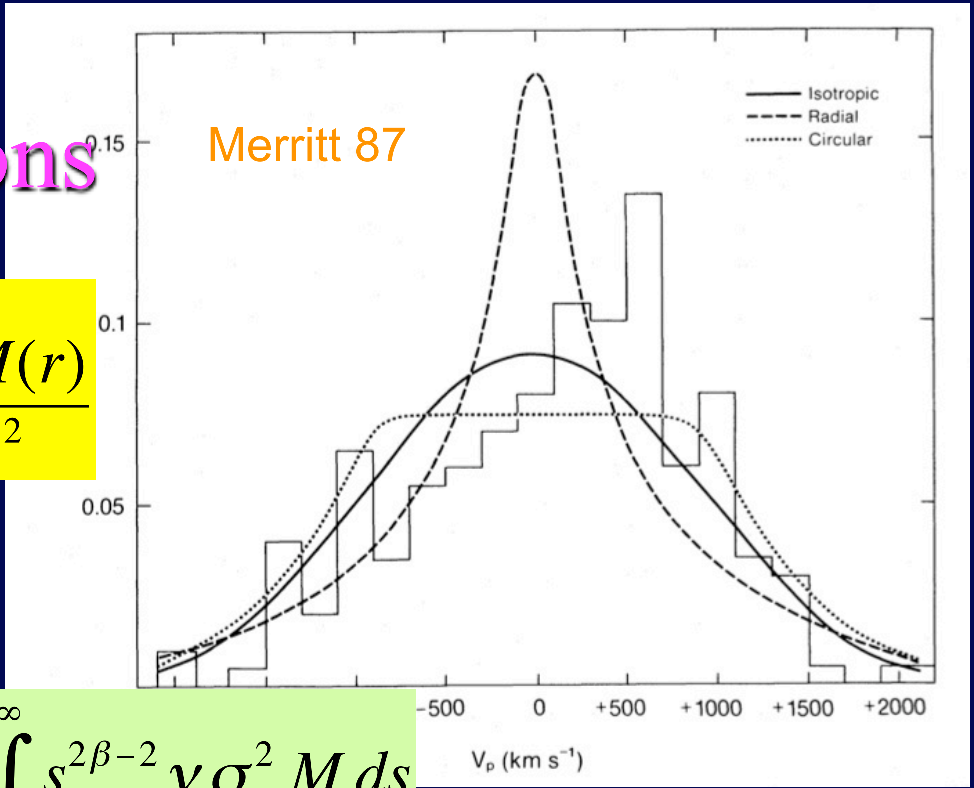
$$(1-\beta)\,p(r) = \int_r^\infty K_\beta(R,r)\,\frac{dP}{dR}\,dR$$

$$\rho v_c^2 = -p' - 2\,\frac{\beta}{r}\,p$$

insert dynamical pressure into Jeans equation → mass profile

Jeans 3) combine dispersion & kurtosis assuming cst β

$4^{\rm th}$ moment Jeans equations


Merritt 87

$$\frac{d\left(\nu\,\overline{v_r^4}\right)}{dr} + 2\,\frac{\beta}{r}\left(\nu\,\overline{v_r^4}\right) = -3\,\nu\,\sigma_r^2\,\frac{GM(r)}{r^2}$$

Łokas 02; Łokas & Mamon 03

if β = cst

⇨

$$\overline{v_r^4}(r) = \frac{3\,G\,r^{-2\beta}}{\nu(r)}\int_r^\infty s^{2\beta-2}\,\nu\,\sigma_r^2\,M\,ds$$

line of sight kurtosis

$$\kappa_{\rm los}(R) = \frac{\overline{v_{\rm los}^4}(R)}{\sigma_{\rm los}^4(R)} - 3$$

fit to distribution in projected phase space

- Clean method:
  projected phase space from distribution function and potential

$$g(R, v_z) = 2\int_R^\infty \frac{r dr}{\sqrt{r^2 - R^2}} \int_{-\infty}^\infty dv_R \int_{-\infty}^\infty dv_\theta\, f\left[1/2v^2 + \Phi(r), J\right]$$

Dejonghe & Merritt 92

which $f(E,J)$?

- fit from combination of orbits Schwazschild 79; Syer & Tremaine 94
  De Lorenzi, Gerhard et al. 07
- fit from combination of elementary $f_i(E,J)$ Merritt & Saha 93; Gerhard et al. 98
- fit from non-parametric $f(E,J)$ Wu & Tremaine 06
- simple $f(E,J)$ from ΛCDM halos Wojtak, Lokas, Mamon, Gottlöber & Klypin 08

fit to distribution in projected phase space

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Dejonghe & Merritt 92

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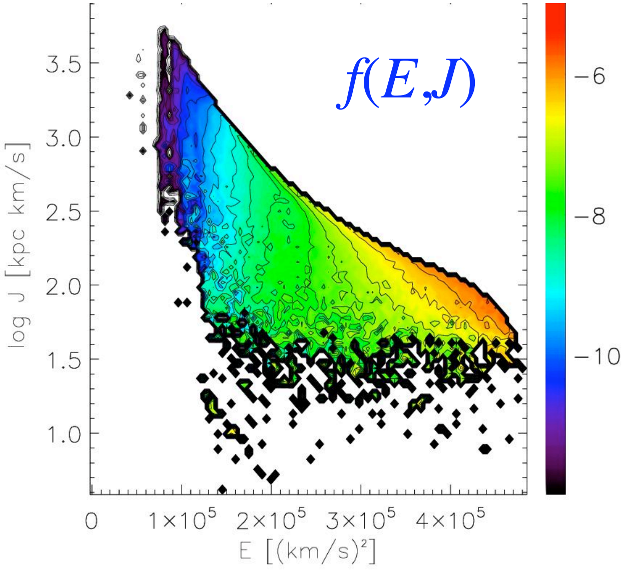
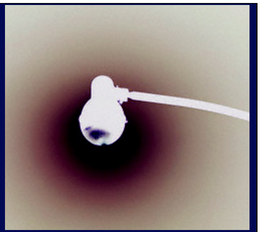
- fit from non-parametric $f(E,J)$ Wu & Tremai
- simple $f(E,J)$ from ΛCDM halos Wojtak, Lo 08
- dissipative mergers?



Kotera & Mamon, unpublished

fit to distribution in projected phase space (2)



- Quick method: *MAMPOSSt*

  projected phase space from velocity distribution, anisotropy & potential

  Mamon, Biviano & Boué, to be submitted soon

assume radial profiles: $M_{\rm tot}(r), \beta(r), \{v\}(r)$

gaussian $\{v\}(r)$

$$p(v_z|R) = \frac{\sqrt{2/\pi}}{\Sigma(R)} \int_R^\infty \frac{r\,\nu}{\sqrt{r^2-R^2}} \frac{(1-\beta R^2/r^2)^{-1/2}}{\sigma_r} \exp\left[-\frac{v_z^2}{2(1-\beta R^2/r^2)\,\sigma_r^2}\right] dr$$

$$\sigma_z^2(R,r) = \left[1-\beta\left(\frac{R}{r}\right)^2\right] \sigma_r^2(r)$$

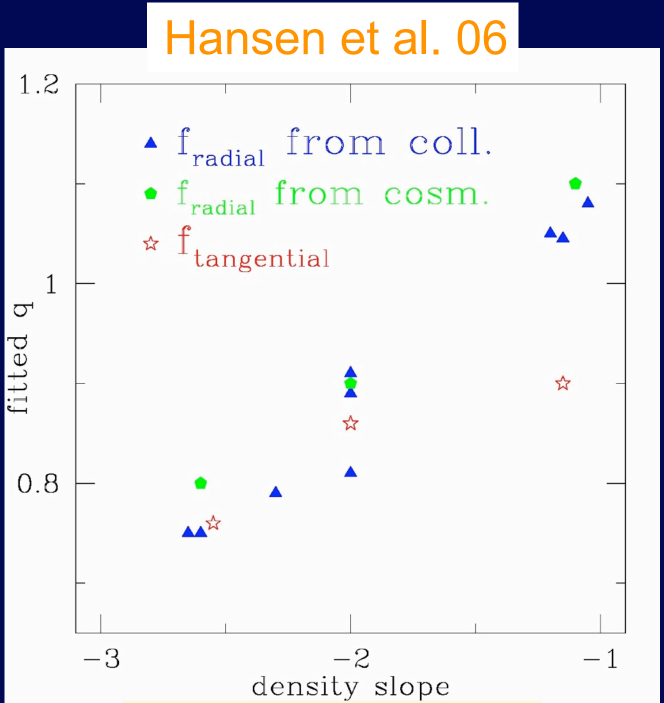
for academic case of β=cst, gaussian-*MAMPOSSt* predicts*:*

correct l.o.s. velocity dispersion profile

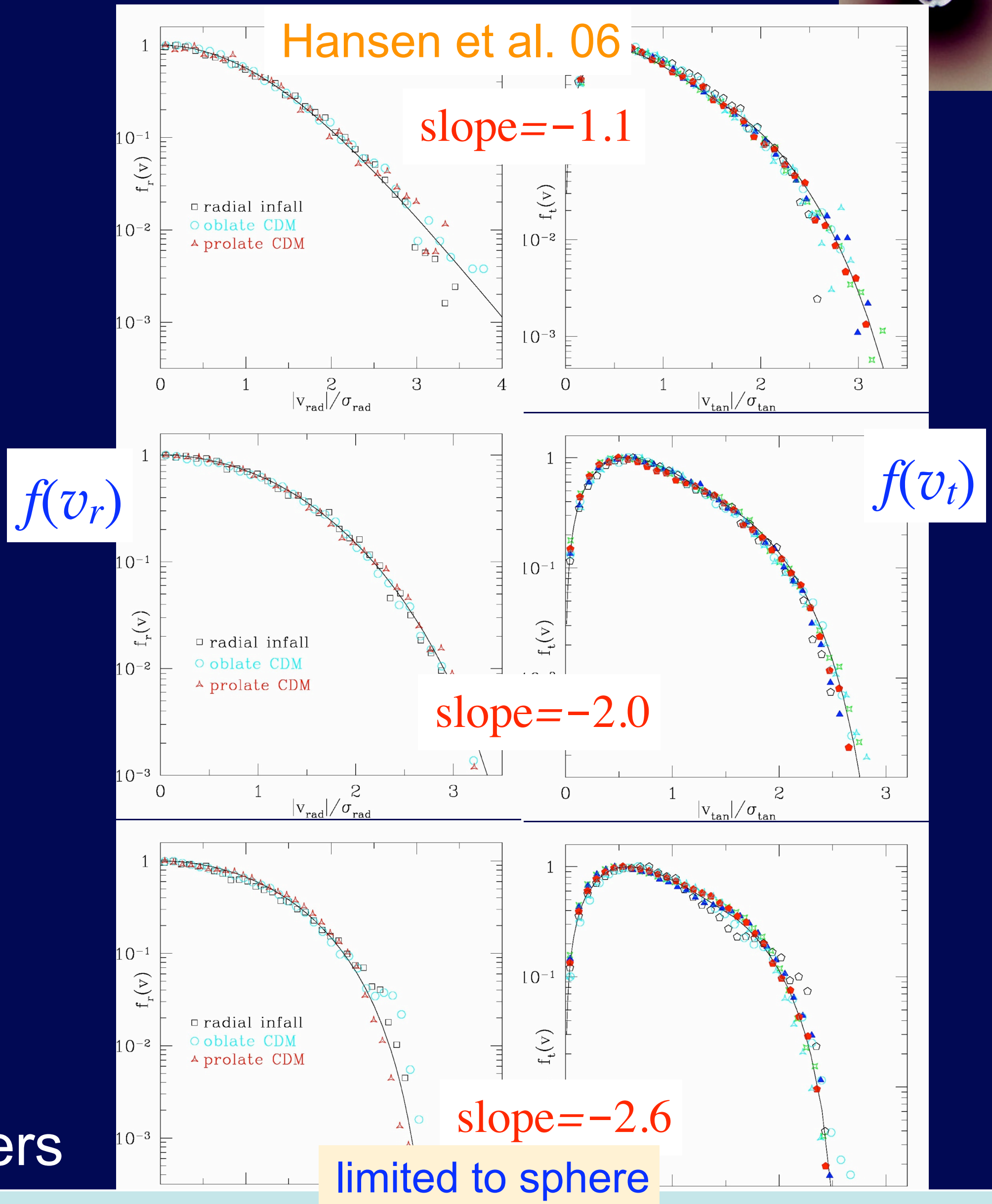
but incorrect l.o.s. velocity kurtosis profile

Possible improvements to MAMPOSSt

- More realistic velocity profiles: variable-index Tsallis



q = *a* + *b* slope



limited to sphere

- Universal distribution of interlopers in projected phase space

$$p(v\ |R) = \frac{g(R,v\ )}{\Sigma(R)} = \frac{g_{\rm halo}(R,v\ ) + g_{\rm interlopers}(R,v\ )}{\Sigma(R)}$$

kinematical effects of:

- *non-sphericity*
- *projected infalling filaments*
- *substructure*
- *streaming motions (infall, rebound)*

test with halos from cosmological *N*-body simulations:

measure in 3D & reestimate in 2D

mass follows number, β=cst

dispersion-kurtosis

Sanchis, Łokas & Mamon 04

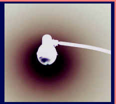
10 halos × 3 projections (400 pts / halo)

$$\Delta \log M_{100} = -0.07 \pm 0.10$$

$$\Delta \log c = 0.08 \pm 0.24$$

$$\Delta \log \left(\frac{\sigma_r}{\sigma_\theta} \right) = -0.04 \pm 0.11$$

MAMPOSSt



Mamon, Biviano & Boué in prep.

11 halos × 3 projections (500 pts / halo)

$$\Delta \log M_{200} = 0.01 \pm 0.09$$

$$\Delta \log c = 0.07 \pm 0.20$$

$$\Delta \log \left(\frac{\sigma_r}{\sigma_\theta} \right) = -0.03 \pm 0.08$$

dispersion-kurtosis: very uncertain concentration

MAMPOSSt: somewhat better!

Comparison with orbit modeling

- requires systems not far from spherical symmetry
- rotation, substructure not incorporated

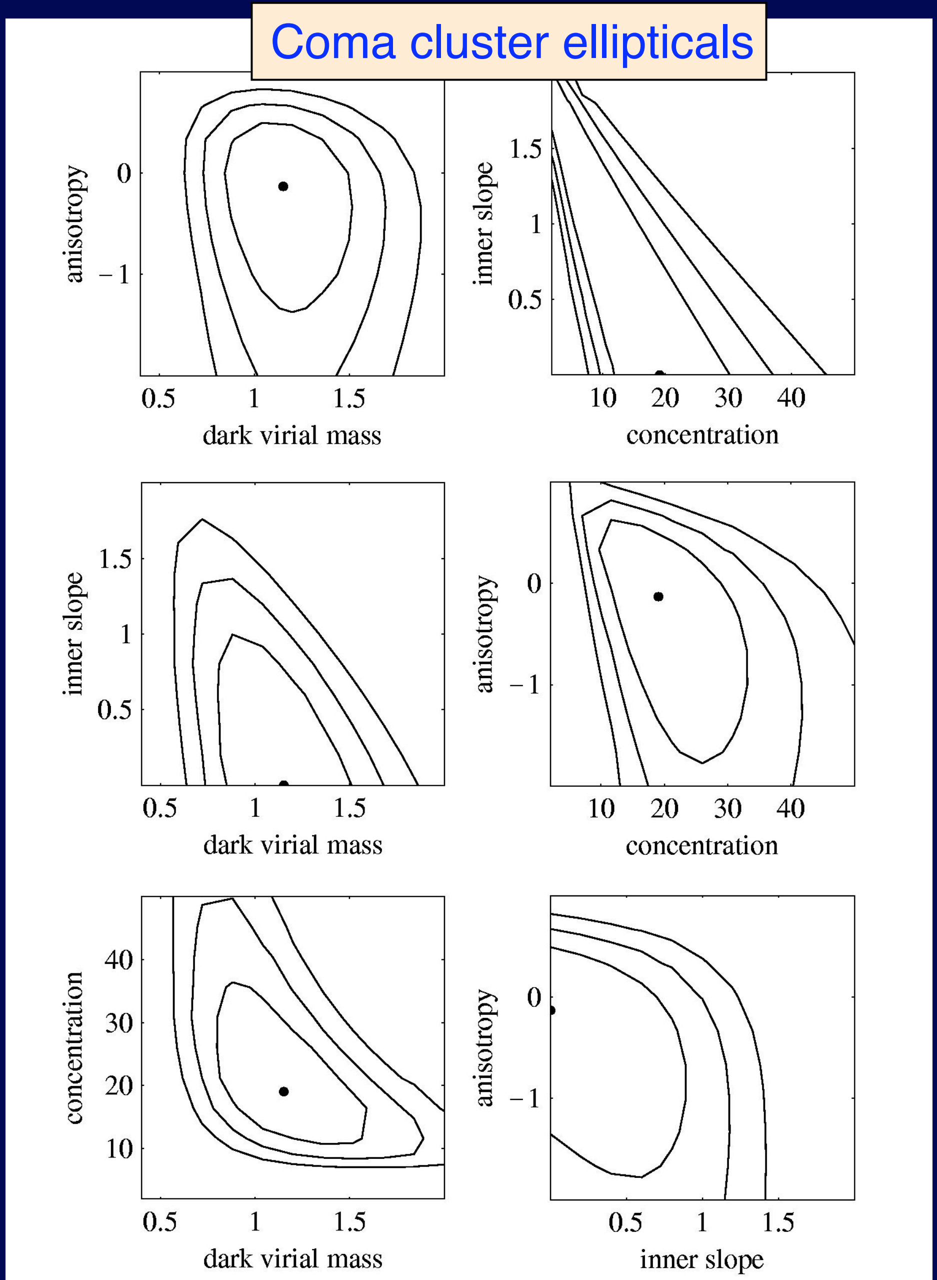
BUT

- dispersion-kurtosis, *MAMPOSSt* & Wojtak method tested on cosmological halos
- mass & anisotropy inversions: non-parametric
- less a black box and more intuition
- fast enough to probe set of solutions (MCMC)

Applications of new mass & anisotropy modelling techniques

Mass & anisotropy modeling of Clusters of galaxies

Partially lifting the anisotropy / mass degeneracy: joint fits to velocity dispersion & kurtosis profiles



Coma cluster ellipticals

Łokas & Mamon 03

isotropic fits best!

cusp and core
both agree with data

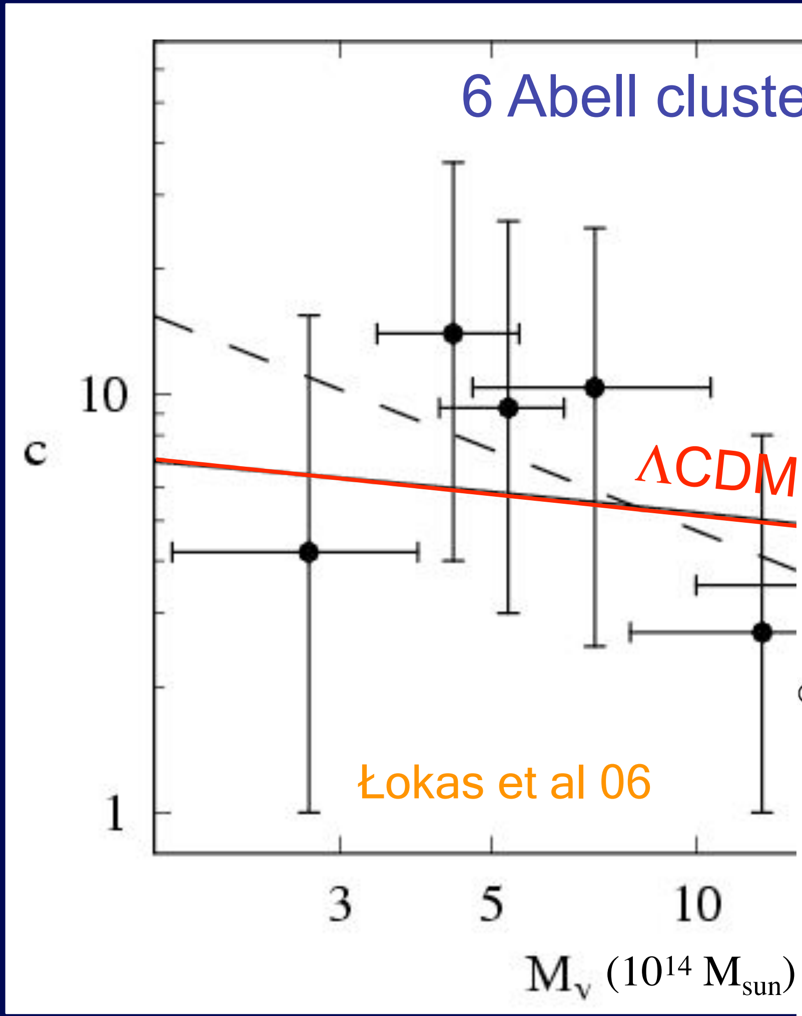
NFW: $c = \dfrac{r_{100}}{r_s} \approx 9.4$

vs.

- $c = 6$ (cosmo sims) Bullock et al. 01
- $c = 5.5$ (stacked 2dFGRS) Biviano & Girardi 03
- $c = 4$ (stacked ENACS) Katgert, Biviano & Mazure 04

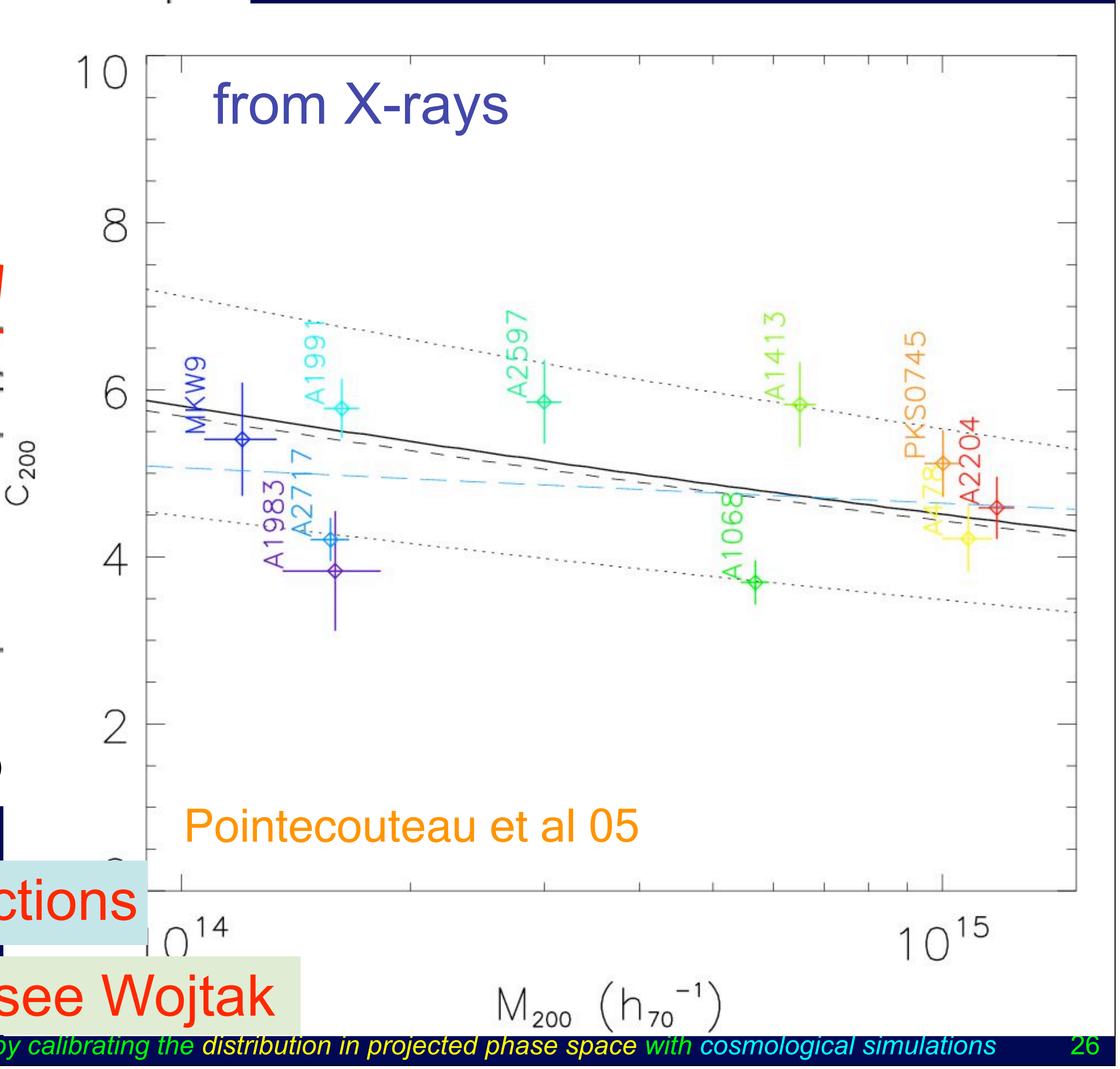
Cluster concentration vs. mass

$= r_{200}/r_{-2}$



6 Abell clusters

Łokas et al 06



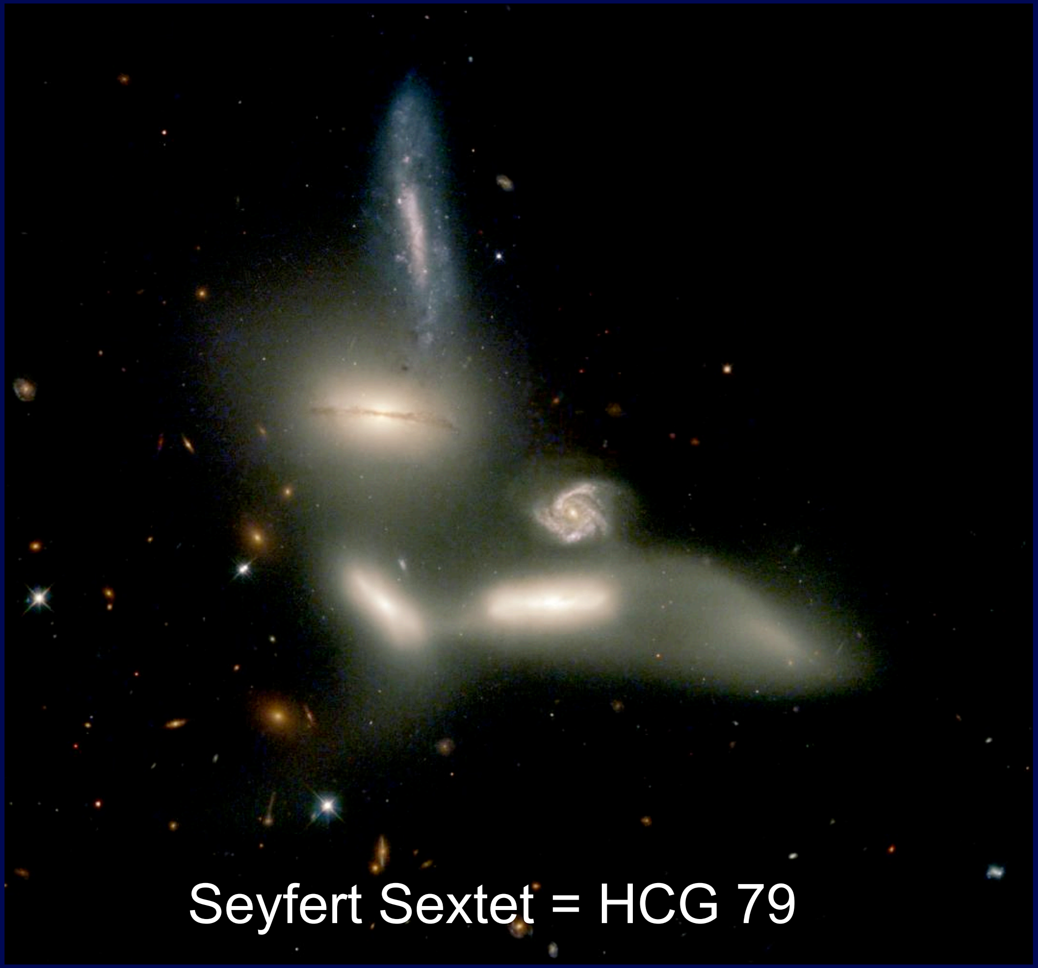
from X-rays

Pointecouteau et al 05

consistent with ΛCDM predictions

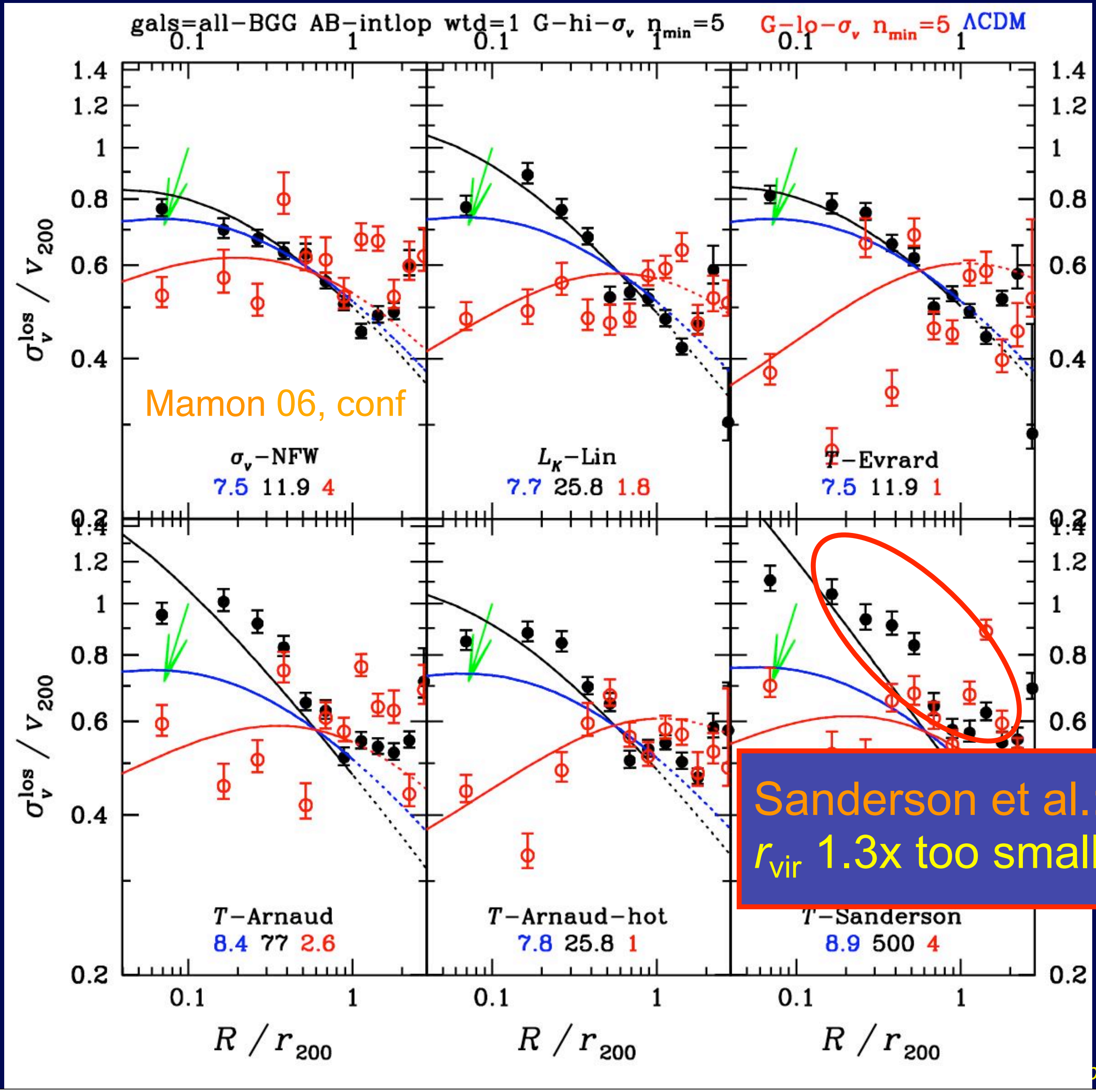
X-rays: less scatter, but see Wojtak

Mass & anisotropy modelling of Groups of Galaxies



Seyfert Sextet = HCG 79

Line-of-sight velocity dispersion profiles of groups: effect of global velocity dispersion



Mamon 06, conf

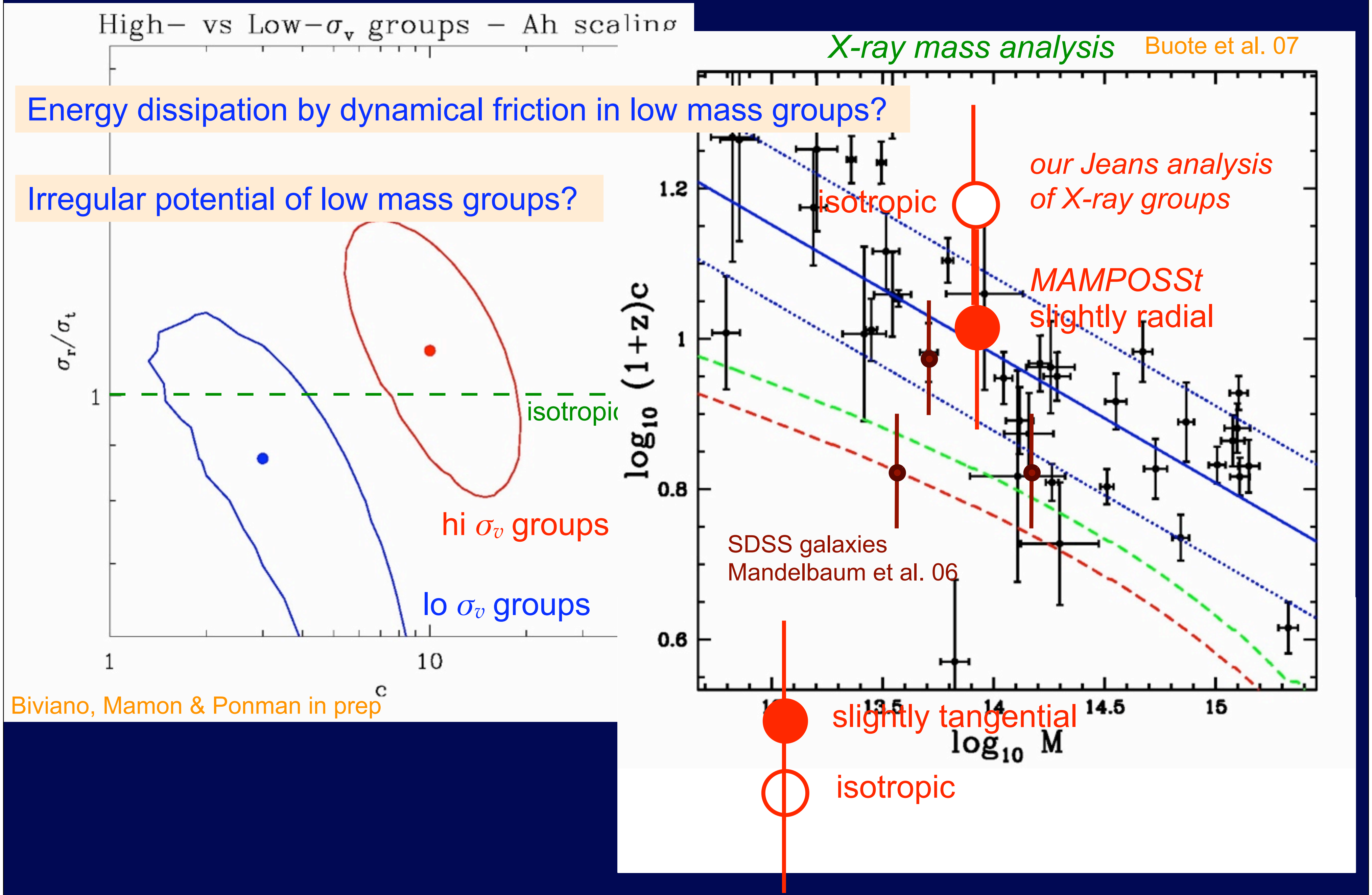
low σ_v (< 300 km/s) groups:
shallower $\rho(r)$
OR
tangential orbits

Sanderson et al.:
r_{vir} 1.3x too small ⇒ M_{vir} 2x too small

Concentration vs. Mass

Energy dissipation by dynamical friction in low mass groups?

Irregular potential of low mass groups?



hi σ_v groups

lo σ_v groups

Biviano, Mamon & Ponman in prep

Buote et al. 07

isotropic

our Jeans analysis of X-ray groups

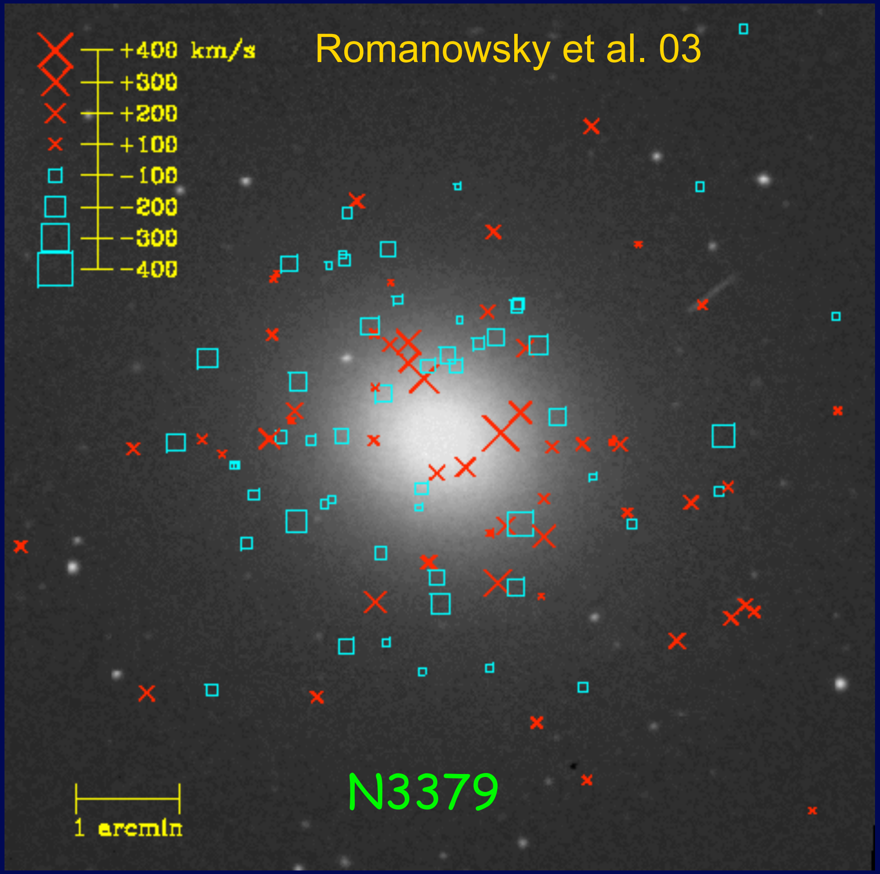
MAMPOSSt slightly radial

SDSS galaxies
Mandelbaum et al. 06

slightly tangential

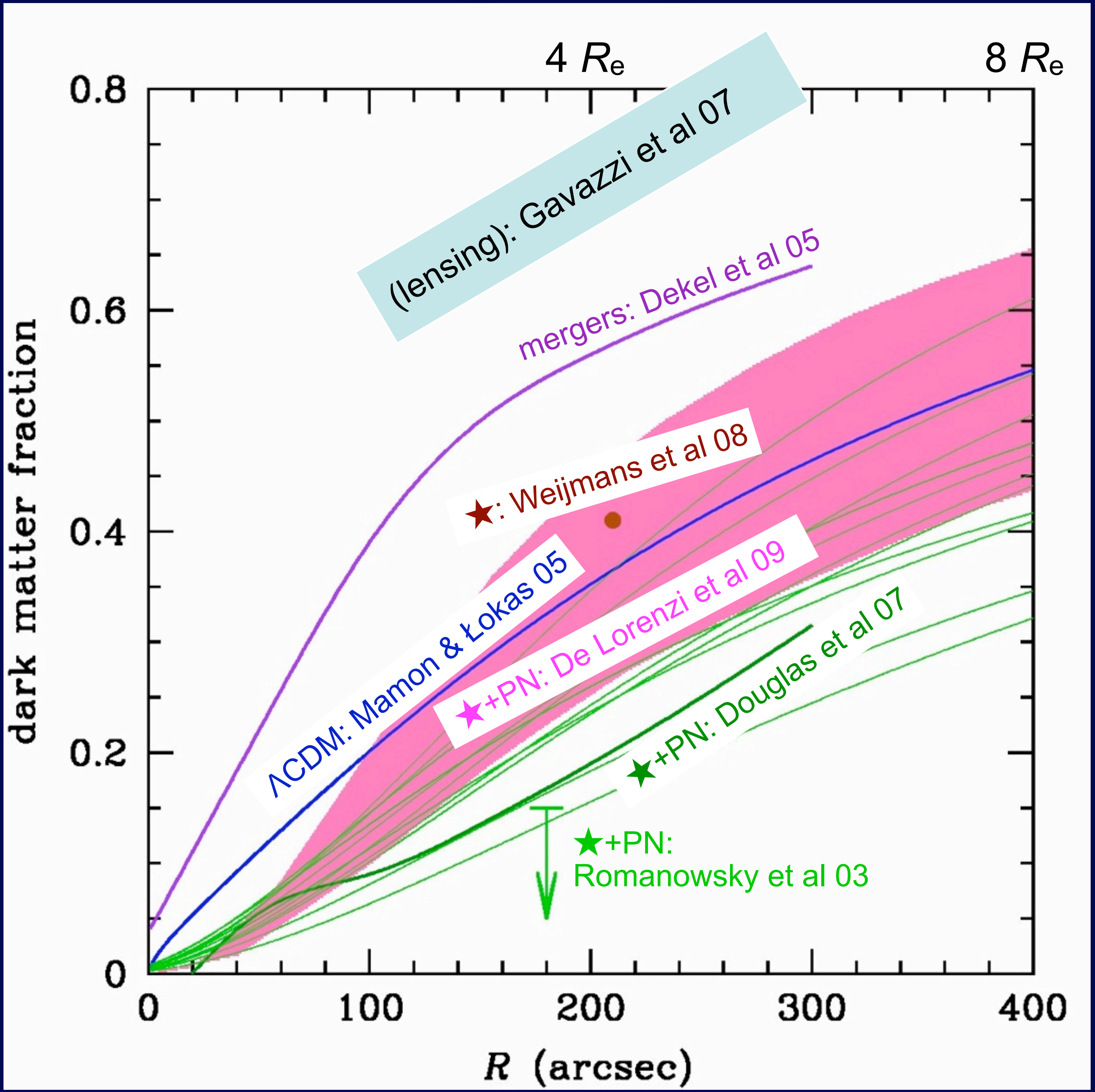
isotropic

Mass & anisotropy modeling of Elliptical galaxies



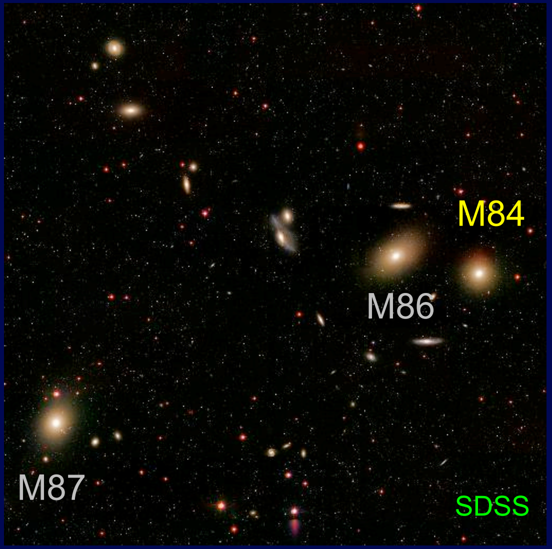
A dearth of dark matter
in ordinary elliptical galaxies
Romanowsky et al. 03, Science

Recent analyses of NGC 3379

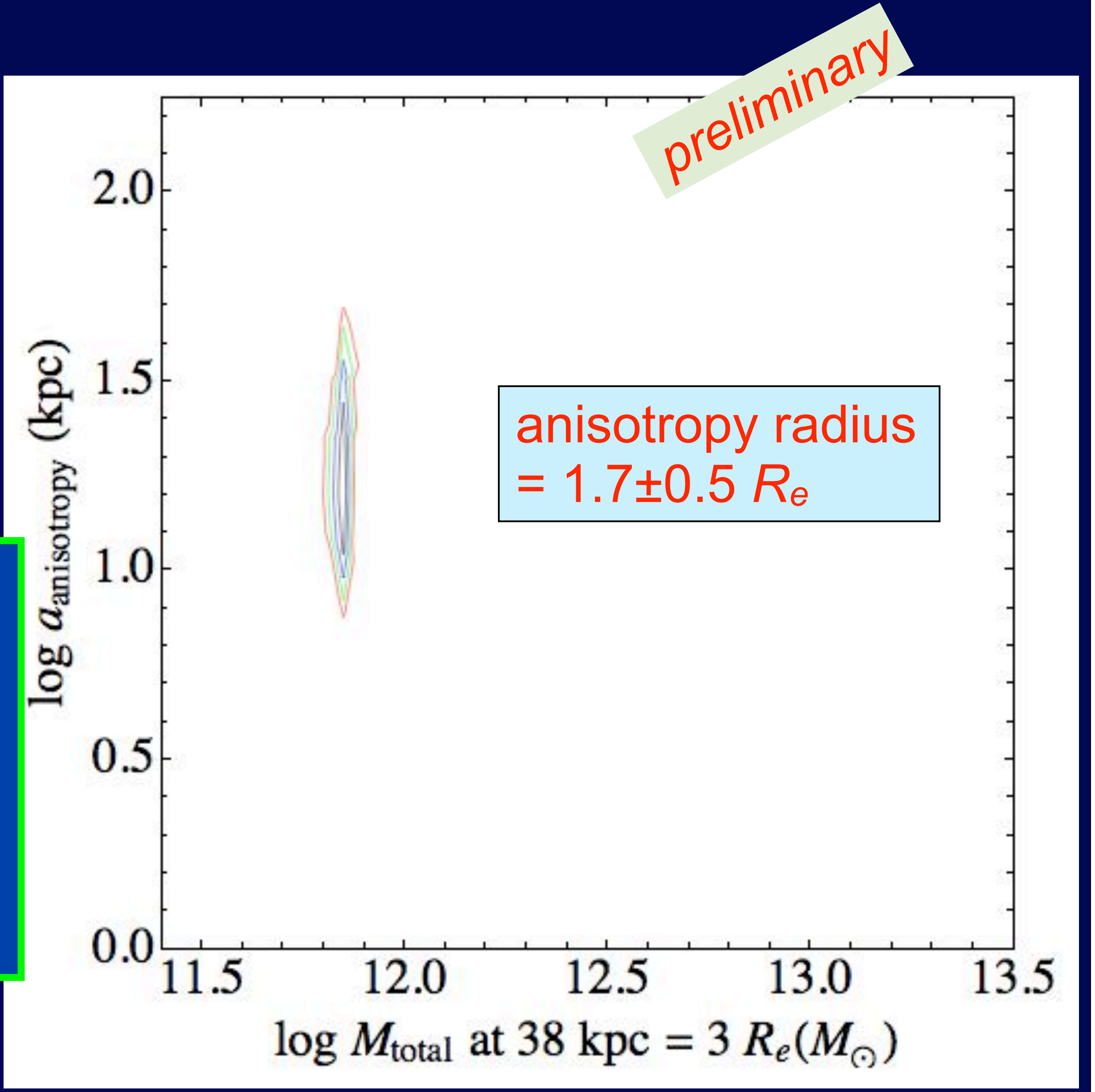


dark matter content @ 4 R_e still very uncertain!

anisotropy vs. mass in M84



M84 with MAMPOSSt
452 PN velocities (PN.S)
gaussian 3D velocities
$\beta = r^2/(r^2+a^2)$ Osipkov-Merritt
cst M_{stars}/L
Einasto dark matter
$c = c_{\Lambda\mathrm{CDM}}(M_{\mathrm{vir}})$



anisotropy radius
= 1.7±0.5 R_e

Mass & anisotropy modelling of the Fornax dwarf spheroidal

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

Fornax data

2633 velocities
2278 Fornax members

L_V = 1.9 x 10^7 L_{sun}
Irwin & Hatzimiditriou 95

L_V = 0.9 x 10^7 L_{sun}
Walcher et al. 03

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

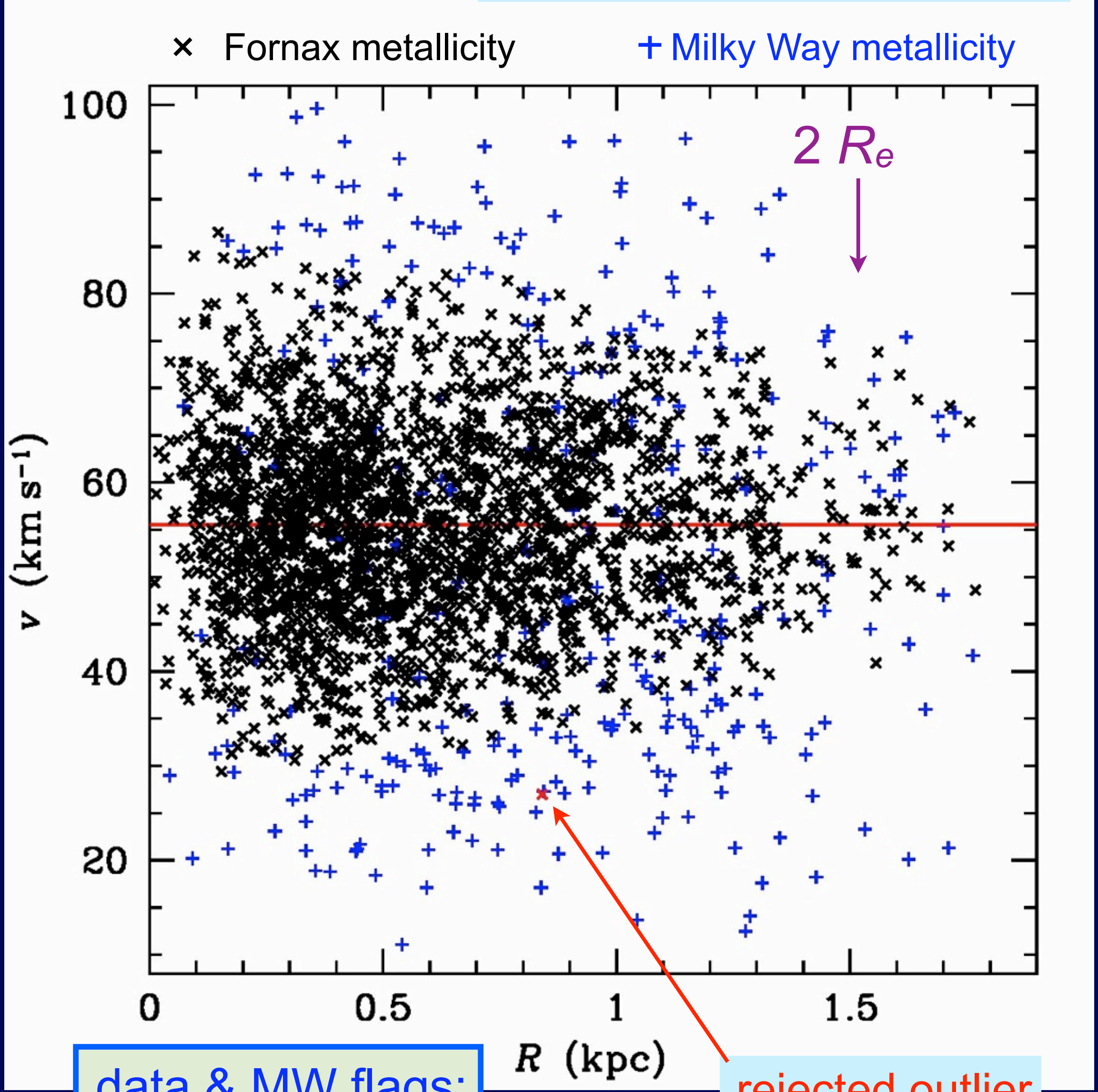
ellipticity: 0.21 → 0.36
Battaglia et al. 06

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



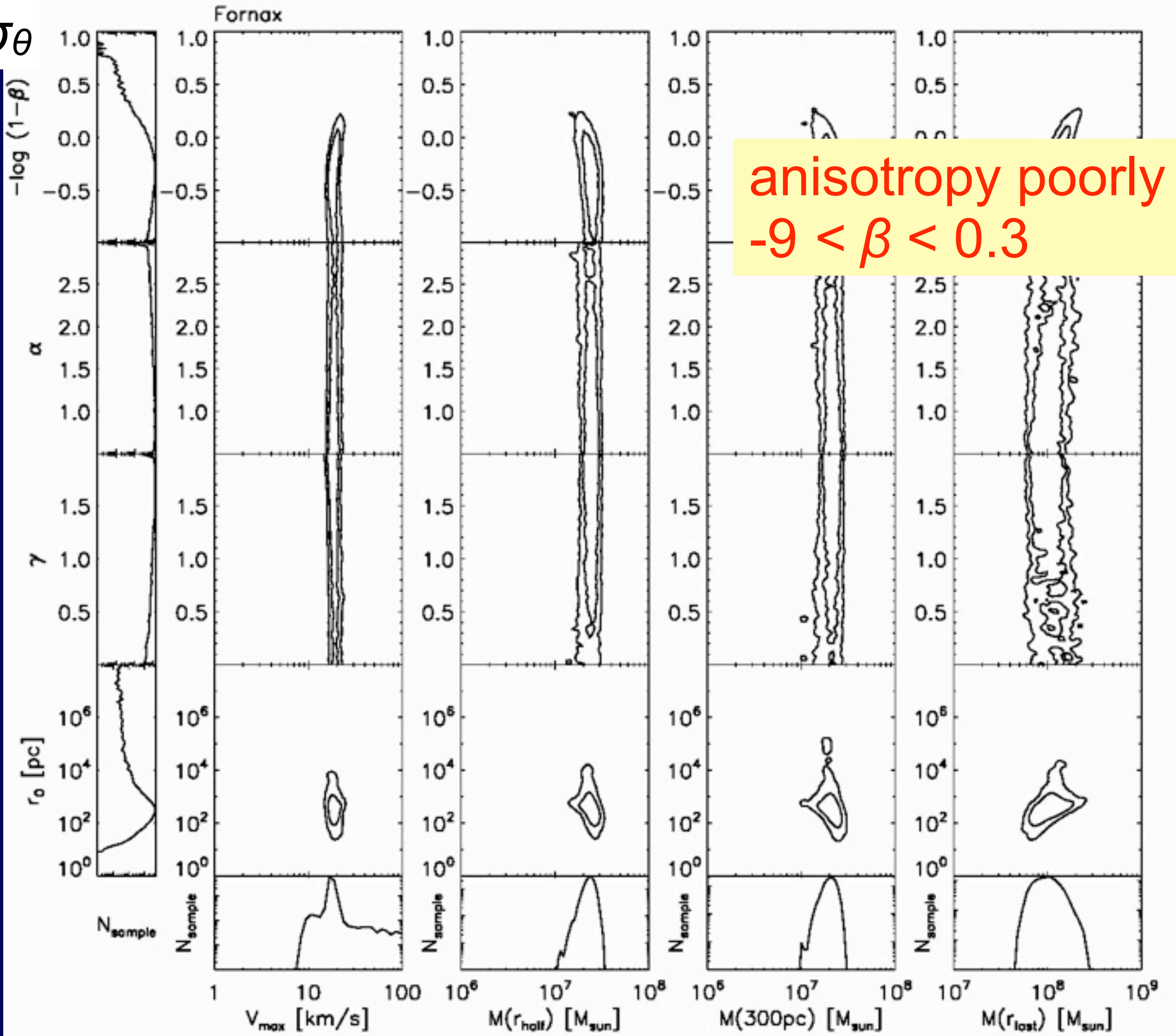
data & MW flags:
Walker et al. 09
Magellan/MMFS

rejected outlier

Fitting velocity dispersion only

Walker et al. 09

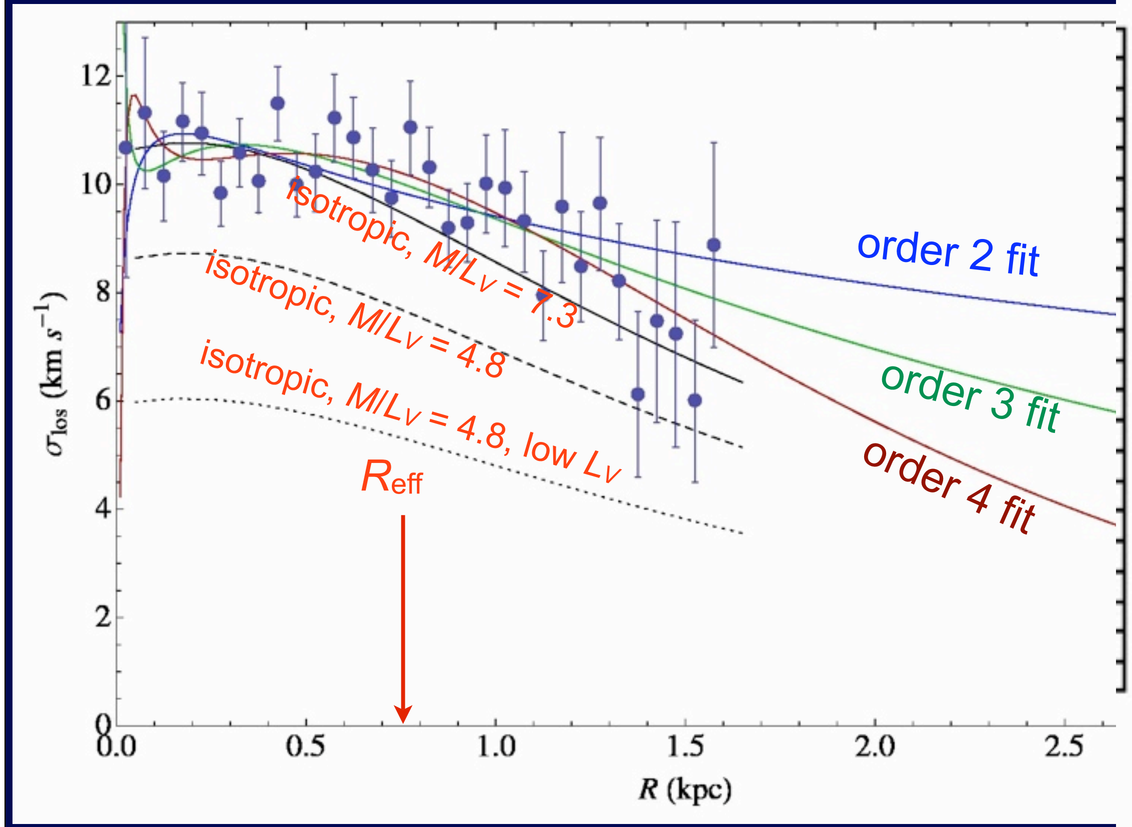
log σ_r/σ_θ



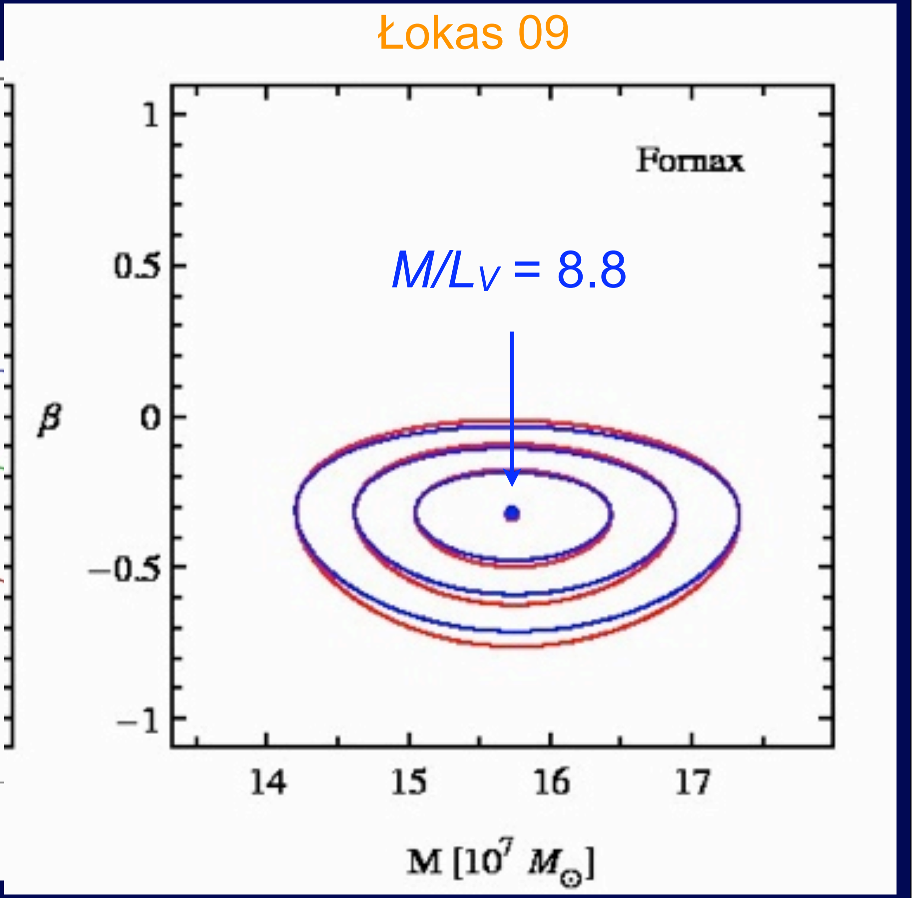
anisotropy poorly constrained:
$-9 < \beta < 0.3$

Fornax: velocity dispersion profile

out to 2 $R_{\rm eff}$



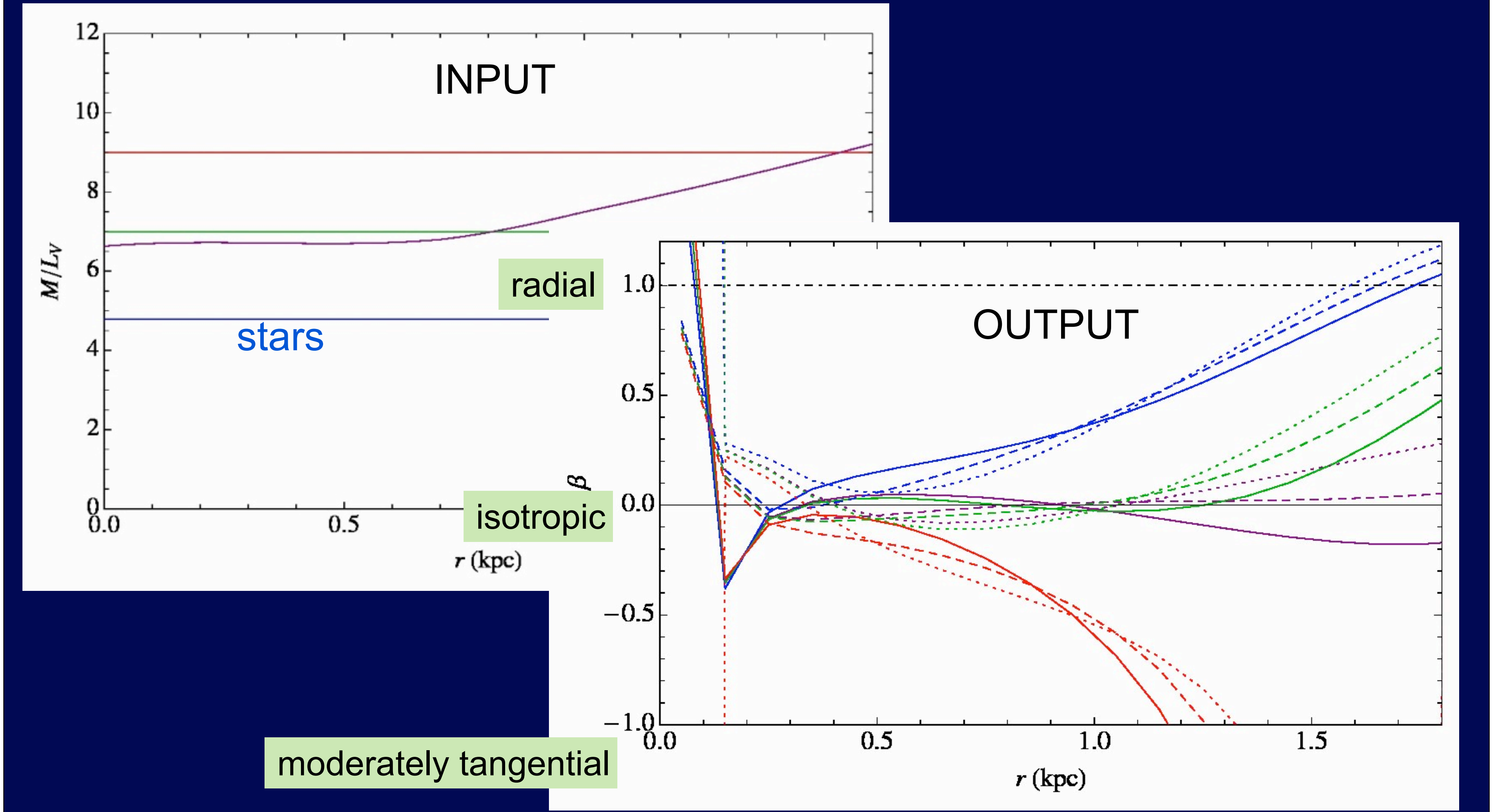
Łokas 09



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

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

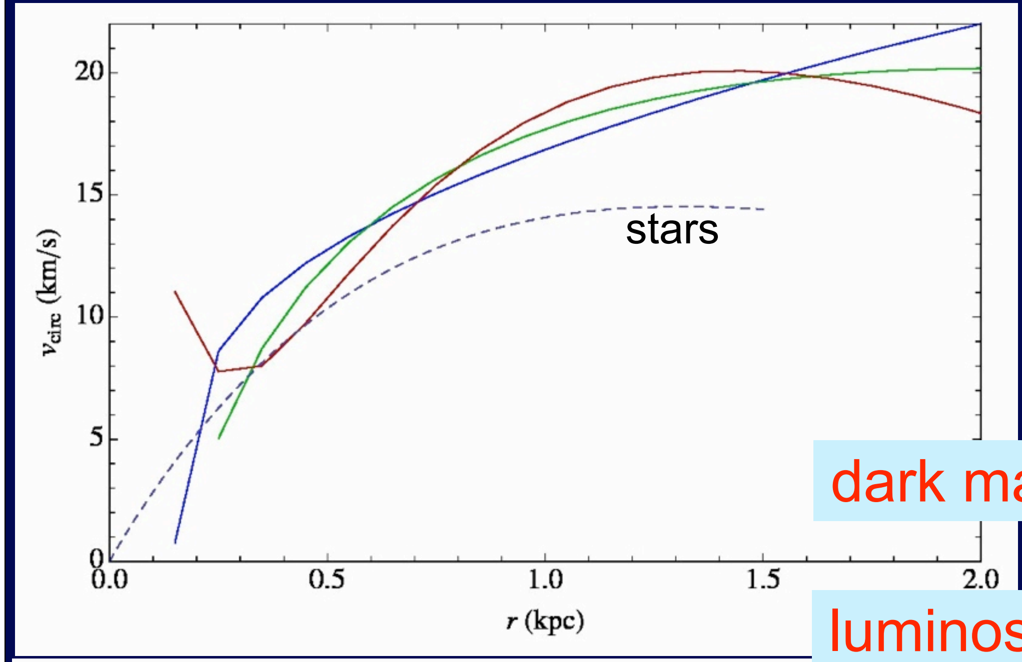
Fornax: anisotropy inversion



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

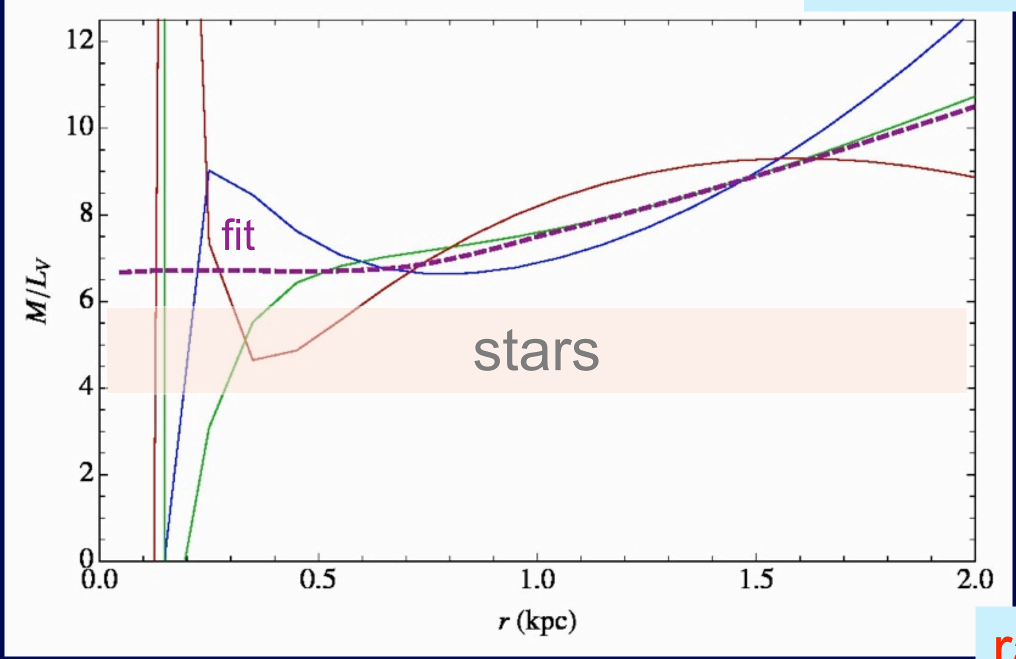
no dark matter solution fails at large radius

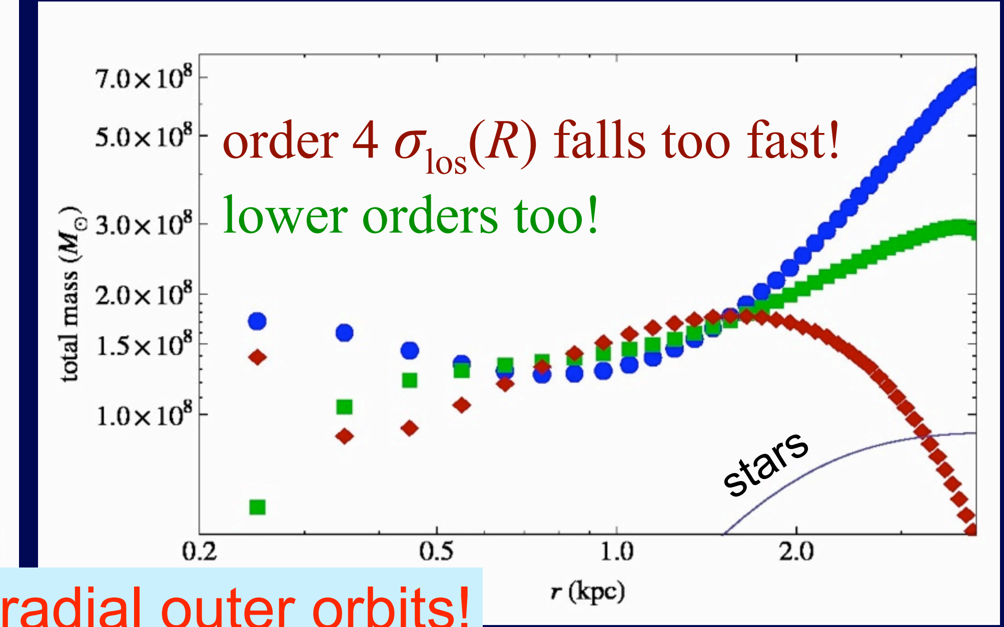
Fornax: isotropic mass inversion



dark matter, even in inner regions?

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





order 4 $\sigma_{\rm los}(R)$ falls too fast!

lower orders too!

radial outer orbits!

Mamon, Gordon & Biviano in prep.

Fornax with MAMPOSSt

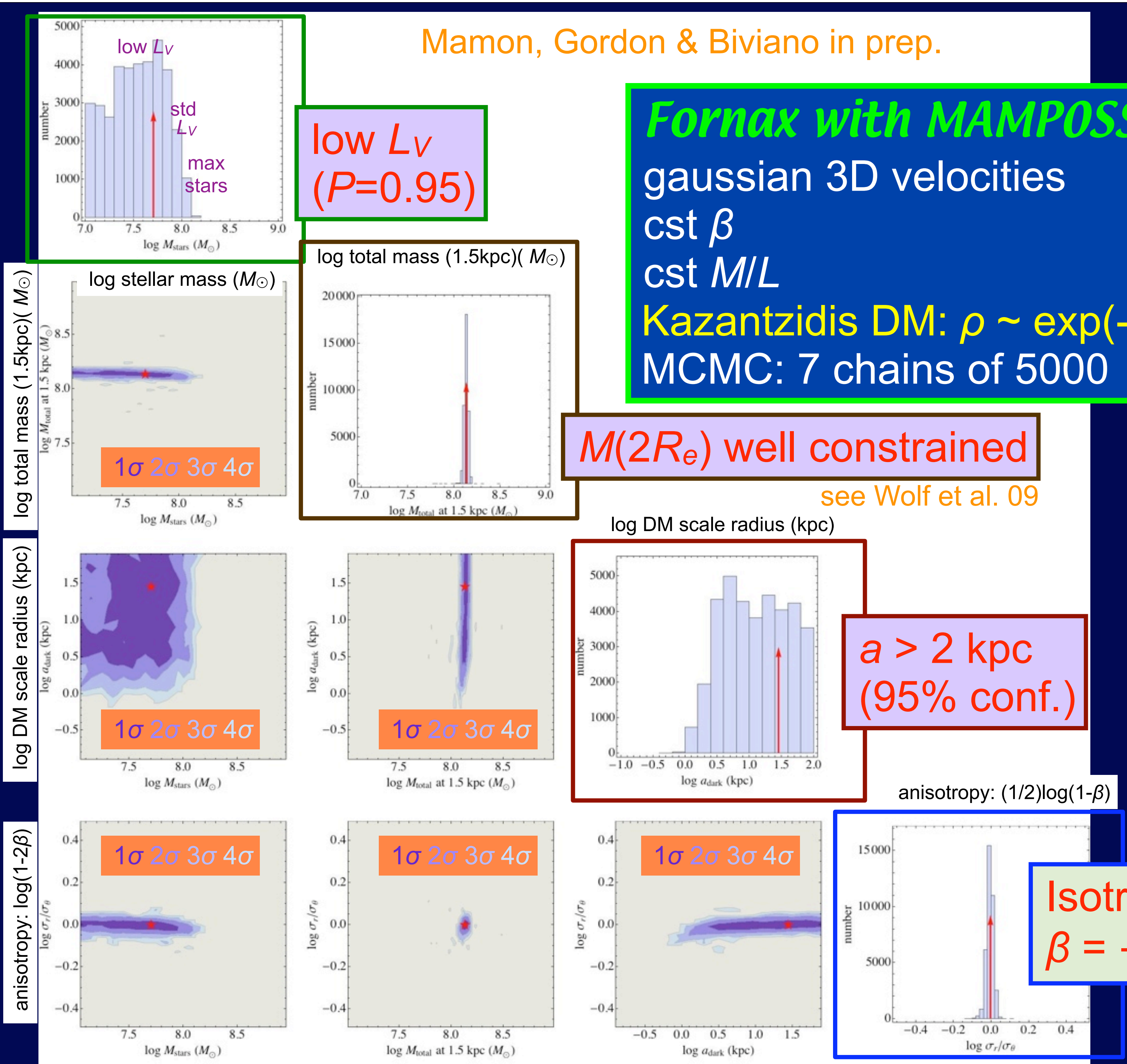
gaussian 3D velocities

cst β

cst M/L

Kazantzidis DM: $\rho \sim \exp(-r/a)\,/\,r$

MCMC: 7 chains of 5000



low L_V (P=0.95)

$M(2R_e)$ well constrained

see Wolf et al. 09

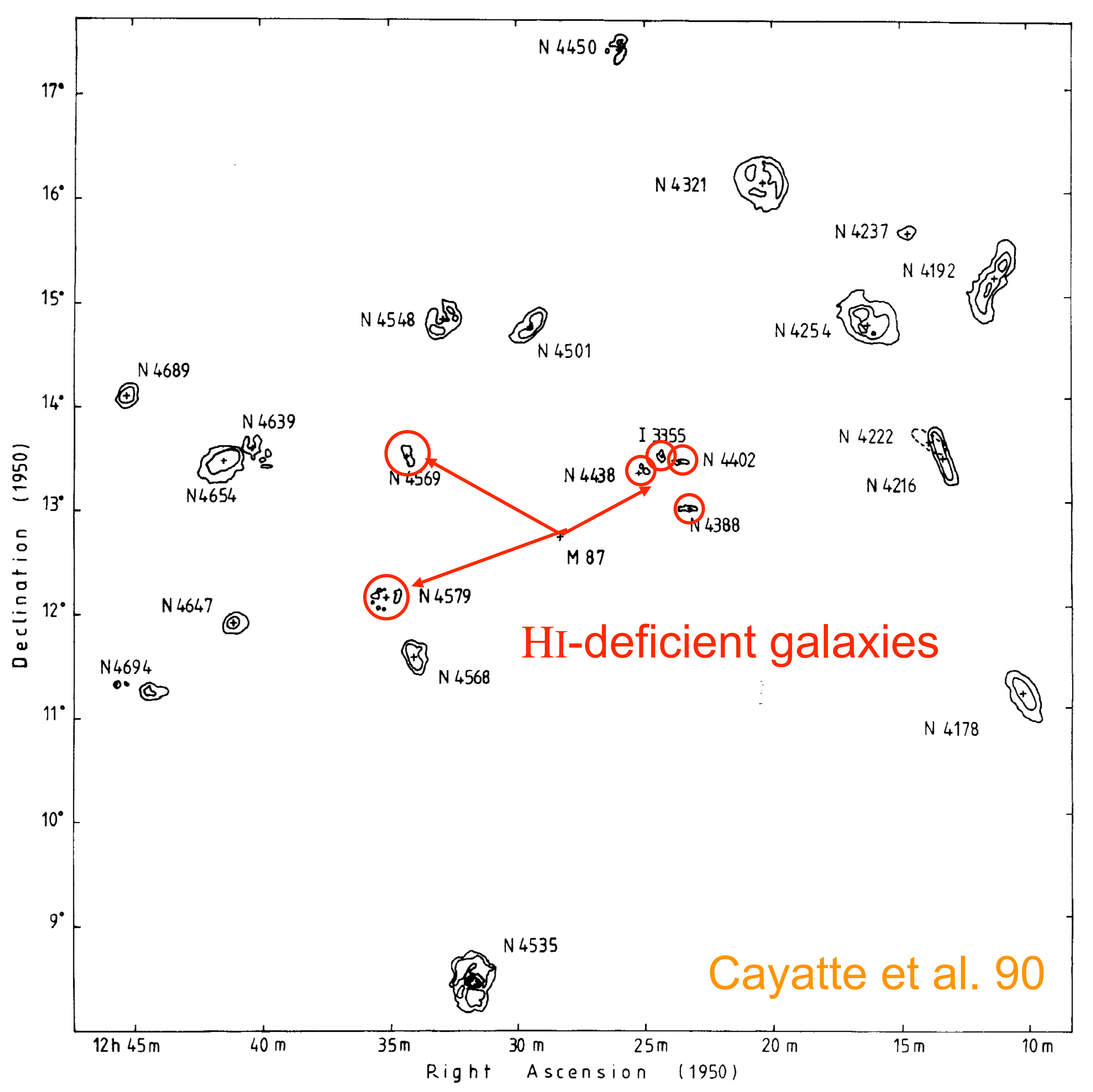
a > 2 kpc (95% conf.)

Isotropic orbits!

β = −0.03±0.09

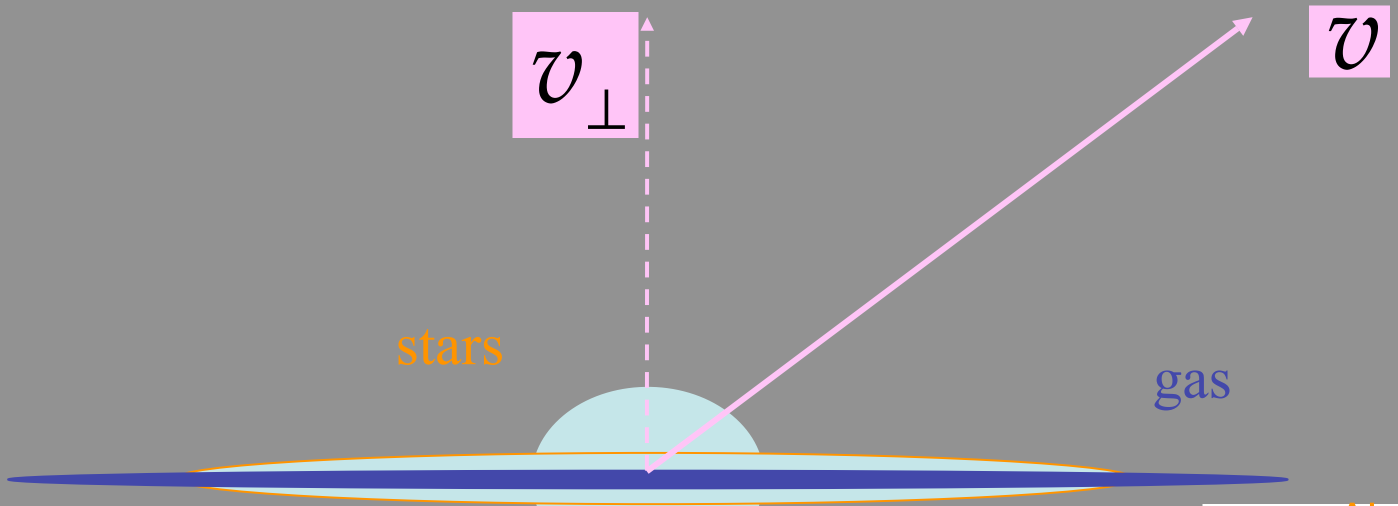
Neutral gas deficient spiral galaxies towards the Virgo cluster

Neutral gas (HI) maps in Virgo cluster



Ram pressure stripping

Gunn & Gott 72

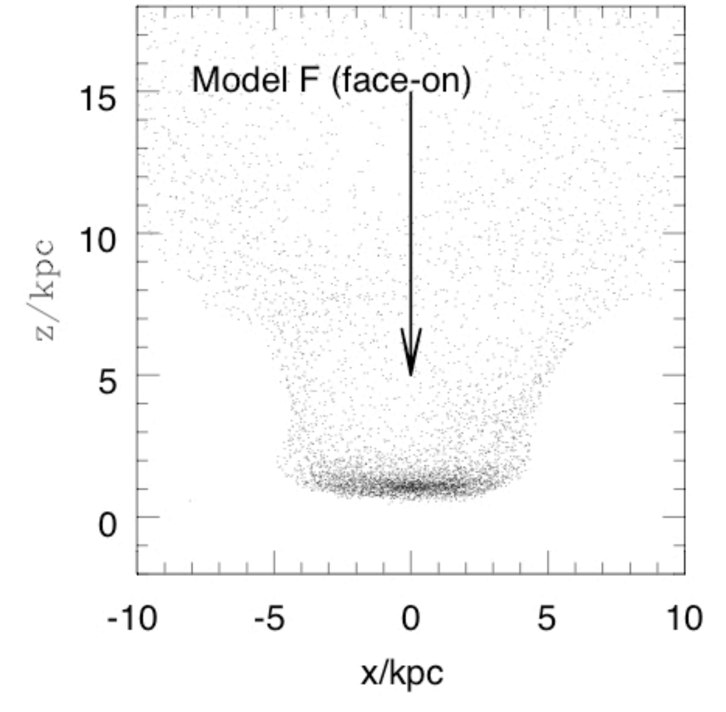


$$\rho_{\mathrm{gas}}^{\mathrm{ICM}} v^2 \cos\theta > 2\pi G \Sigma_* \Sigma_{\mathrm{gas}}$$

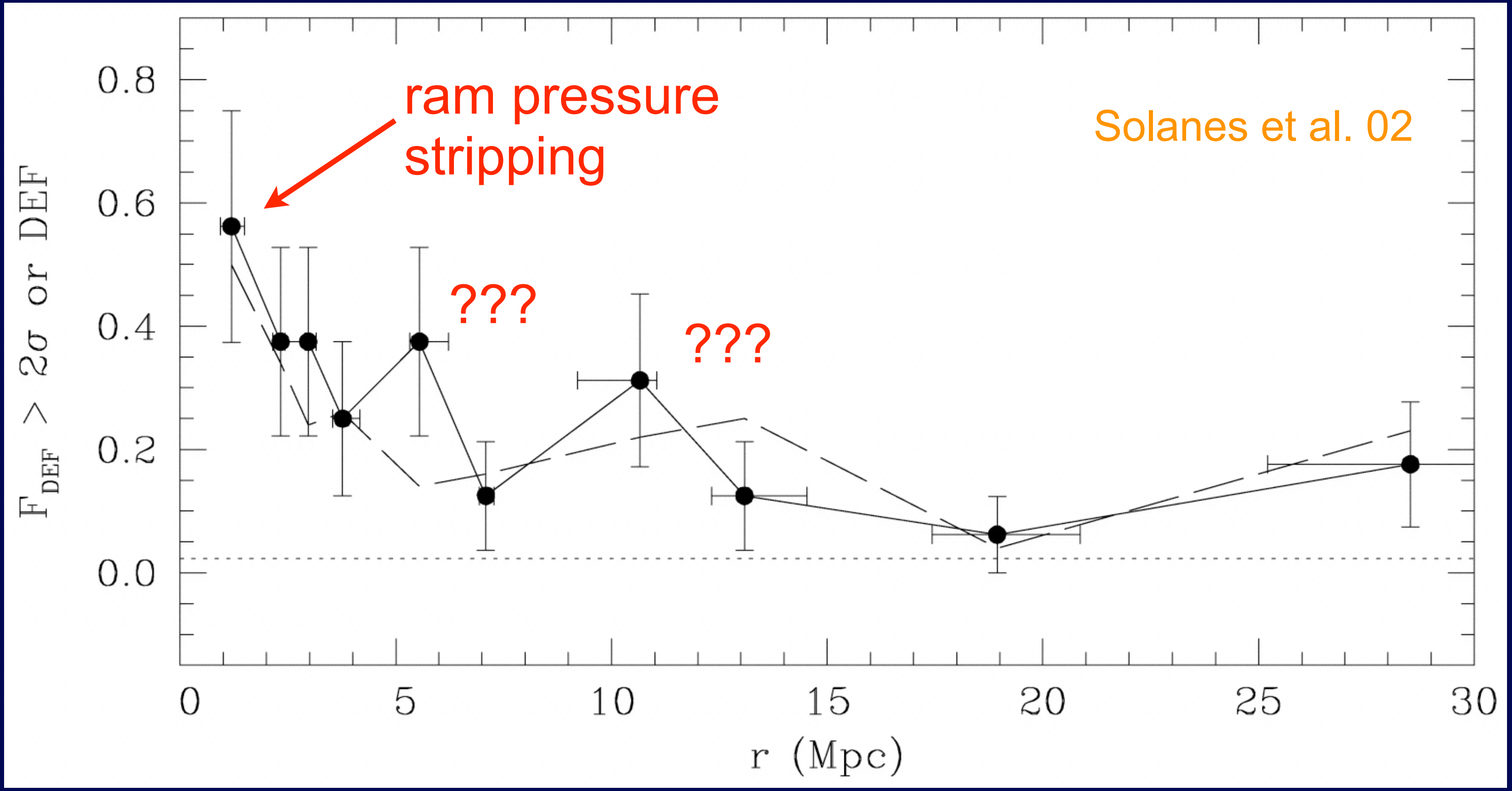
explains pattern of HI-deficiency in Virgo

Chamaraux, Balkowski & Gérard 80

Abadi , Moore & Bower 99

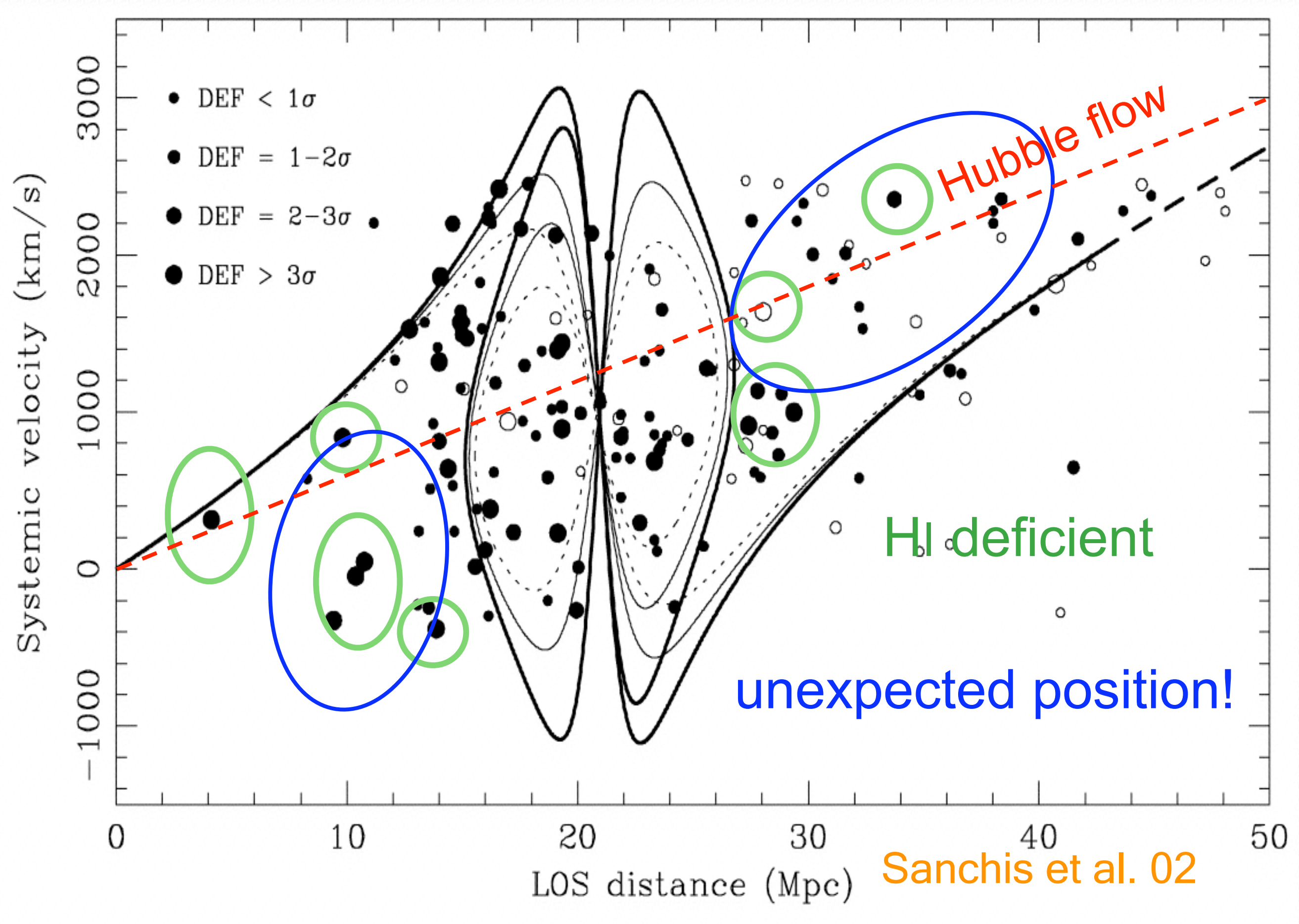


HI deficiency vs. line-of-sight distance



What causes HI-deficiency in distant galaxies?

HI-deficient galaxies on the outskirts of the Virgo cluster!



Sanchis et al. 02

Could distant HI-deficient spirals have passed through cluster & been stripped?

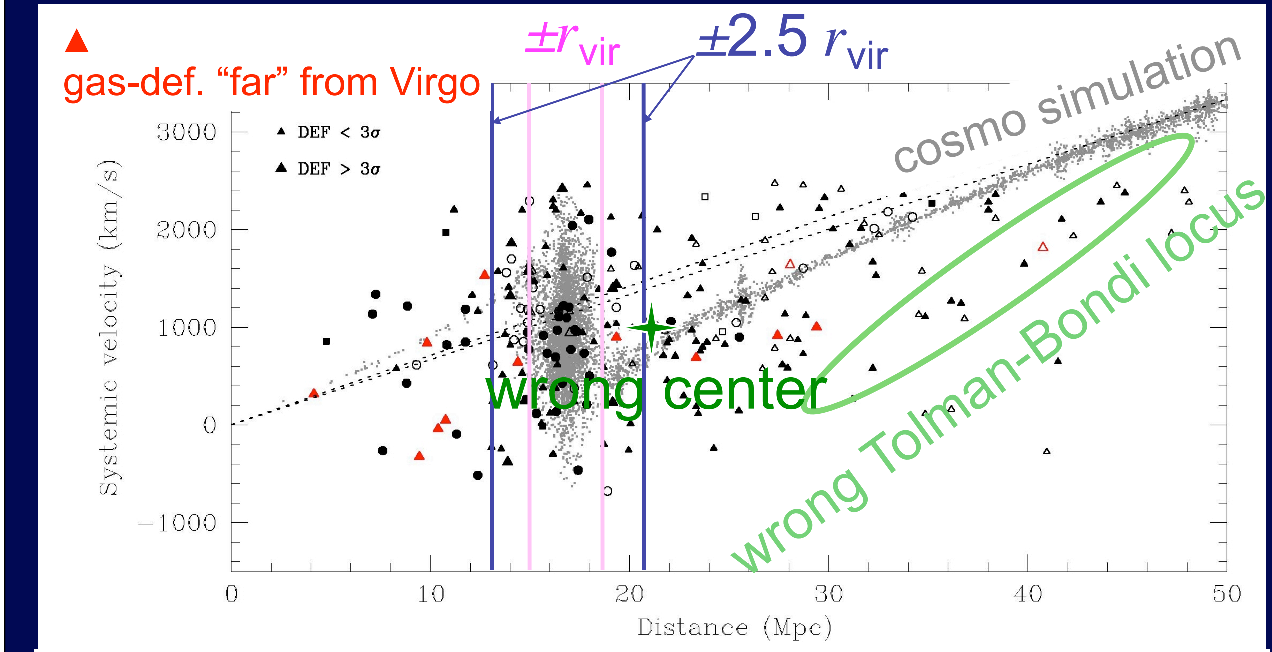
How far can galaxies bounce out of clusters?

Mamon et al. 04

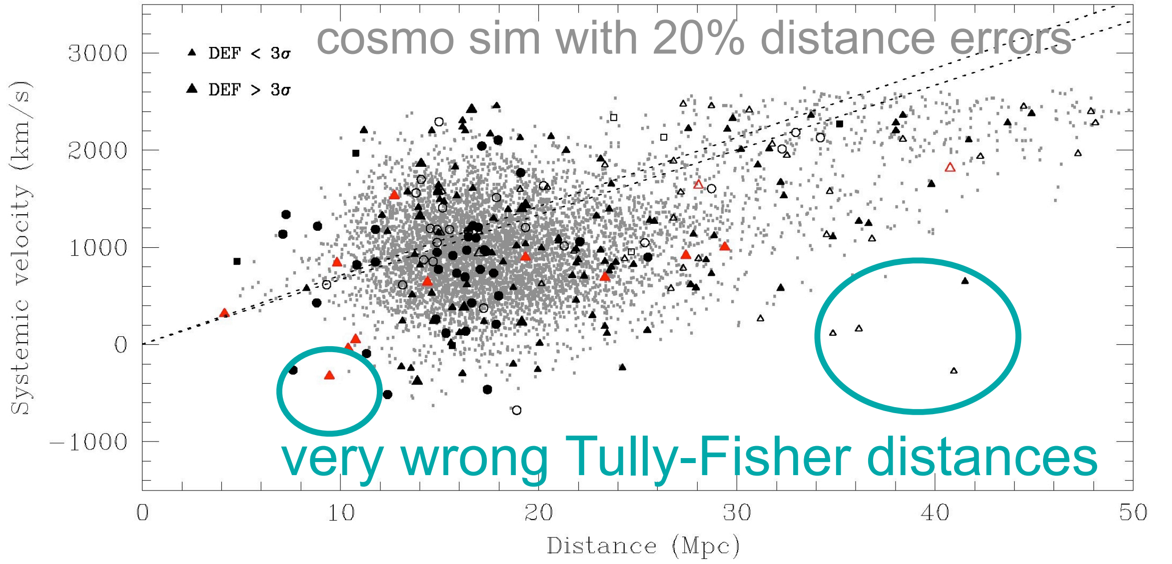
- hand-waving → $r_{\rm rebound} = r_{\rm vir}$
- phase-space at z = 0 → $r_{\rm rebound} = 1.7\ r_{\rm vir}$
- particle turnaround & rebound times & radii
  - toy models → $r_{\rm rebound} = 1 \text{ to } 2.5\ r_{\rm vir}$
  - in simulations → $r_{\rm rebound} = 0.5 \text{ to } 1.3\ r_{\rm vir}$
- Summary → $r_{\rm rebound} = 1 \text{ to } 2.5\ r_{\rm vir}$
- direct following of orbits in simulations → $r_{\rm rebound} = 2.5\ r_{\rm vir}$

Gill et al. 05

Comparison with cosmological simulations



Sanchis, Mamon, Salvador-Solé & Solanes 04, A&A

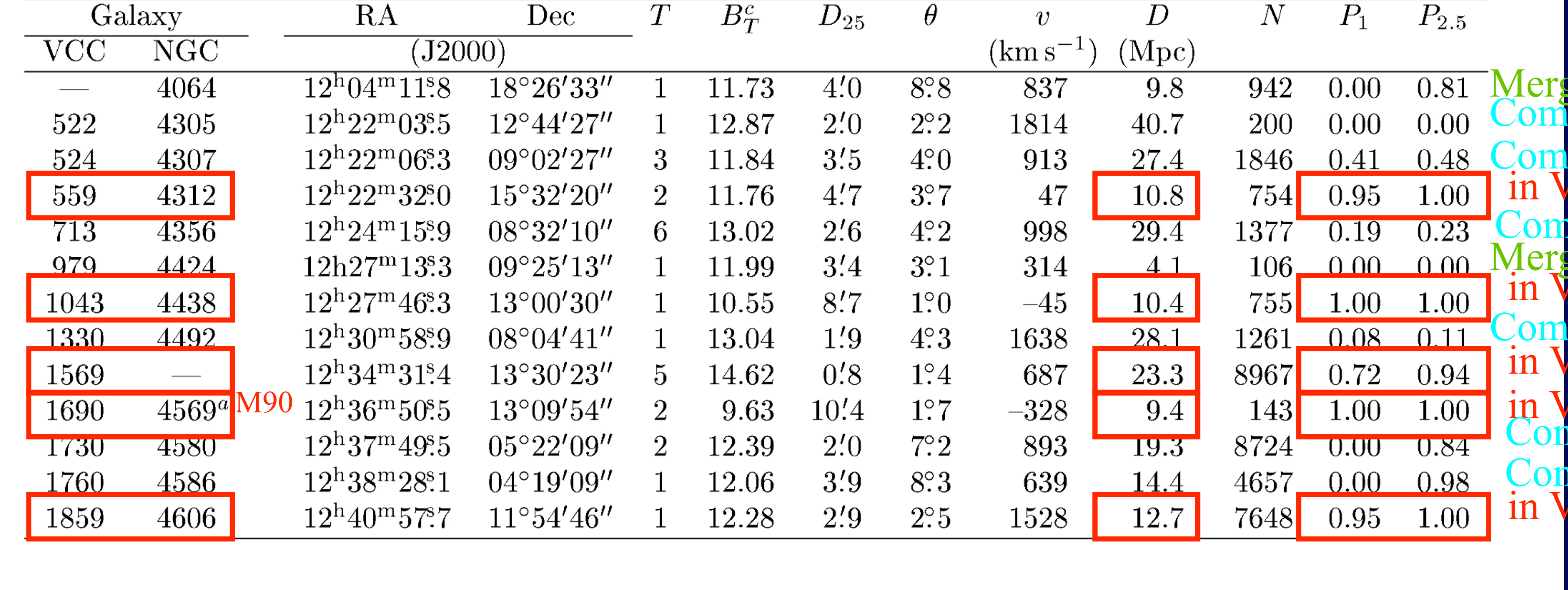


including ellipticals

13 HI-deficient outliers

neighboring particles in $\{D_{\rm los},R,v_{\rm los}\}$ space (w errors):

what fraction in Virgo before including the distance errors?



Galaxy		RA	Dec	T	B_T^c	D_{25}	θ	v	D	N	P_1	$P_{2.5}$
VCC	NGC	(J2000)						(km s^{-1})	(Mpc)			
—	4064	$12^{\rm h}04^{\rm m}11^{\rm s}.8$	$18^\circ26'33''$	1	11.73	$4'.0$	$8^\circ.8$	837	9.8	942	0.00	0.81
522	4305	$12^{\rm h}22^{\rm m}03^{\rm s}.5$	$12^\circ44'27''$	1	12.87	$2'.0$	$2^\circ.2$	1814	40.7	200	0.00	0.00
524	4307	$12^{\rm h}22^{\rm m}06^{\rm s}.3$	$09^\circ02'27''$	3	11.84	$3'.5$	$4^\circ.0$	913	27.4	1846	0.41	0.48
559	4312	$12^{\rm h}22^{\rm m}32^{\rm s}.0$	$15^\circ32'20''$	2	11.76	$4'.7$	$3^\circ.7$	47	10.8	754	0.95	1.00
713	4356	$12^{\rm h}24^{\rm m}15^{\rm s}.9$	$08^\circ32'10''$	6	13.02	$2'.6$	$4^\circ.2$	998	29.4	1377	0.19	0.23
979	4424	$12{\rm h}27^{\rm m}13^{\rm s}.3$	$09^\circ25'13''$	1	11.99	$3'.4$	$3^\circ.1$	314	4.1	106	0.00	0.00
1043	4438	$12^{\rm h}27^{\rm m}46^{\rm s}.3$	$13^\circ00'30''$	1	10.55	$8'.7$	$1^\circ.0$	−45	10.4	755	1.00	1.00
1330	4492	$12^{\rm h}30^{\rm m}58^{\rm s}.9$	$08^\circ04'41''$	1	13.04	$1'.9$	$4^\circ.3$	1638	28.1	1261	0.08	0.11
1569	—	$12^{\rm h}34^{\rm m}31^{\rm s}.4$	$13^\circ30'23''$	5	14.62	$0'.8$	$1^\circ.4$	687	23.3	8967	0.72	0.94
1690	4569^a	$12^{\rm h}36^{\rm m}50^{\rm s}.5$	$13^\circ09'54''$	2	9.63	$10'.4$	$1^\circ.7$	−328	9.4	143	1.00	1.00
1730	4580	$12^{\rm h}37^{\rm m}49^{\rm s}.5$	$05^\circ22'09''$	2	12.39	$2'.0$	$7^\circ.2$	893	19.3	8724	0.00	0.84
1760	4586	$12^{\rm h}38^{\rm m}28^{\rm s}.1$	$04^\circ19'09''$	1	12.06	$3'.9$	$8^\circ.3$	639	14.4	4657	0.00	0.98
1859	4606	$12^{\rm h}40^{\rm m}57^{\rm s}.7$	$11^\circ54'46''$	1	12.28	$2'.9$	$2^\circ.5$	1528	12.7	7648	0.95	1.00

M90

Merger
Companion
Companion
in Virgo
Companion
Merger
in Virgo
Companion
in Virgo
in Virgo
Companion
Companion
in Virgo

at least 5 out of 13 must be in Virgo: suffered ram pressure stripping

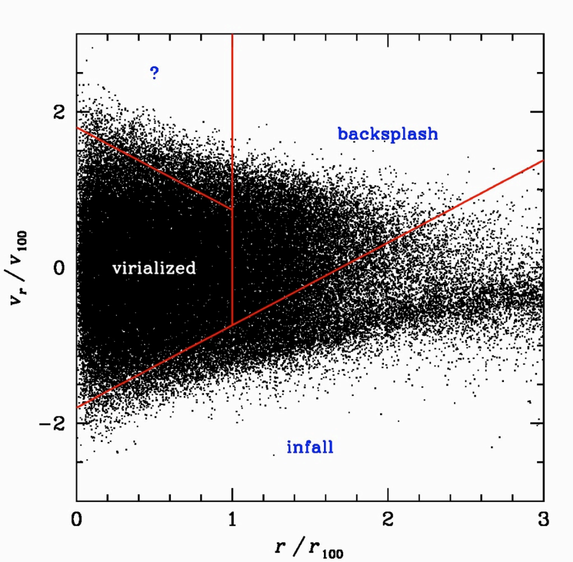
6/13 have companions: induce *tidal* stripping of outer gas

2/13: minor mergers heat up & ionize neutral Hydrogen

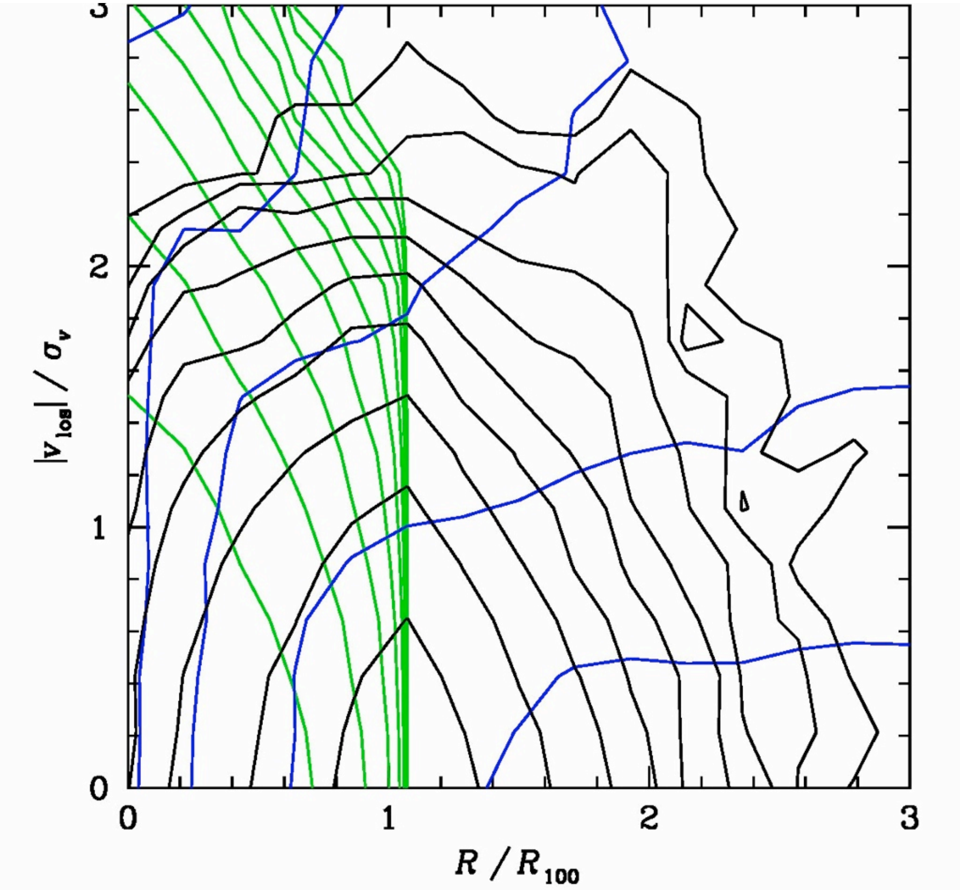
Star formation history of galaxies falling in clusters

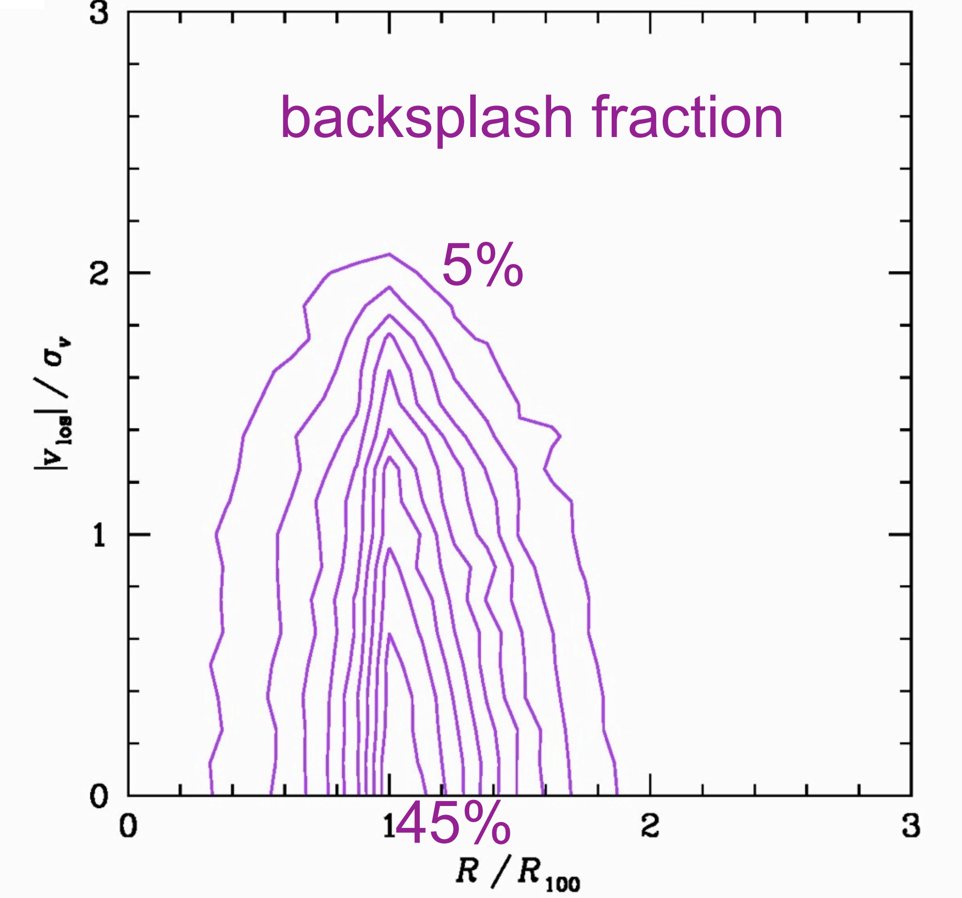
with Smriti MAHAJAN & Somak RAYCHAUDHURY

Virialized, infalling & backsplash galaxies



densities of virialized, infall & backsplash

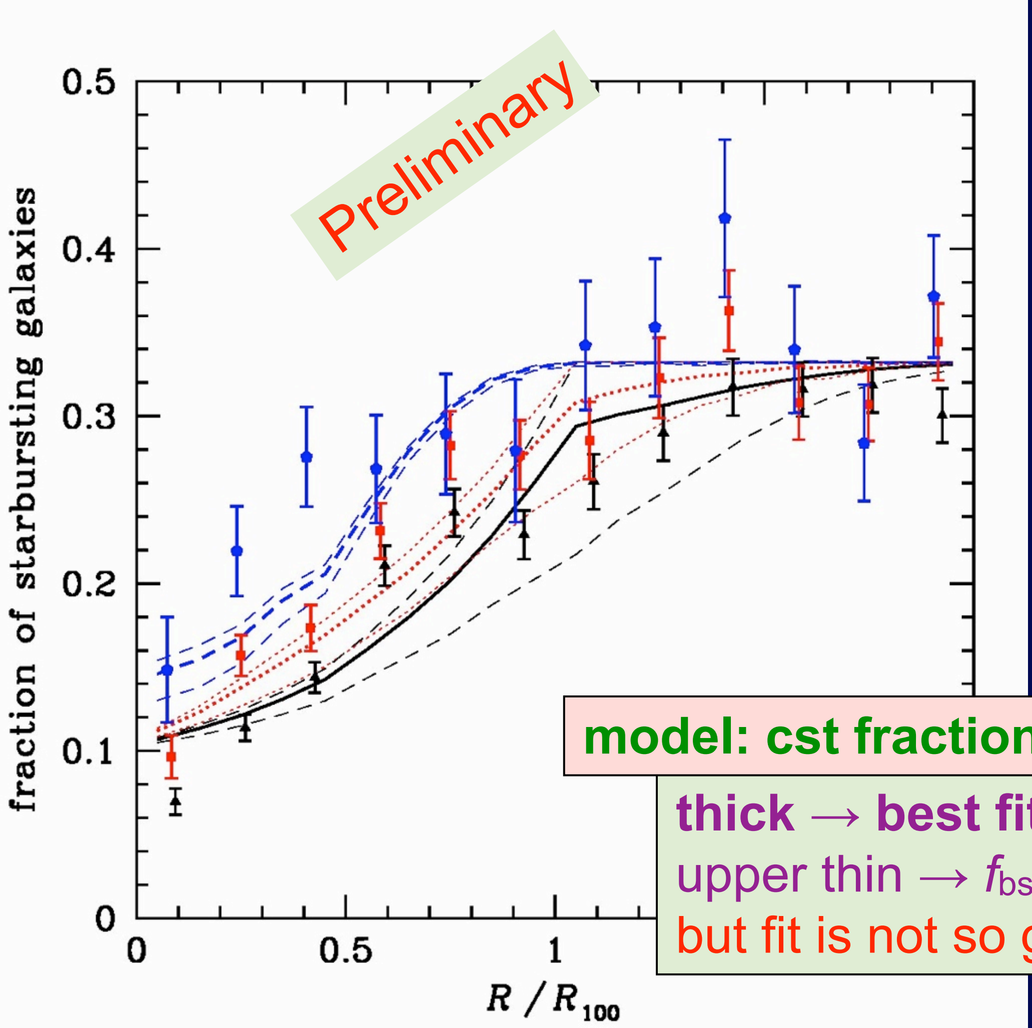




Fraction of starburst galaxies vs. projected radius & line-of-sight velocity

SDSS data: galaxies more luminous than $M_r = -20.5$ around $M > 10^{14}\, M_\odot$ clusters Yang et al. 07

efficient recent star formation: $\mathrm{EW}(\mathrm{H}\delta) > 2\text{Å}$ & $\mathrm{D}_n4000 < 1.5$



$2 < |v|/\sigma_{\rm cluster} < 3$

$1 < |v|/\sigma_{\rm cluster} < 2$

$0 < |v|/\sigma_{\rm cluster} < 1$

model: cst fraction of star forming galaxies per class

thick → best fit: $f_{\rm vir}$=10±1%, $f_{\rm inf}$=33±1%, $f_{\rm bsp}$=26±4%

upper thin → $f_{\rm bsp}=f_{\rm inf}$ lower thin → $f_{\rm bsp}=f_{\rm vir}$

but fit is not so good...

Conclusions

Mass modelling = *exploratory data analysis*:
try ≠ methods: * mass & β inversions
* dispersion-kurtosis
* *MAMPOSSt or* Wojtak+09

Coma cluster
- E/S0s on isotropic orbits

X-ray groups
- very low concentration of low mass ones:
  ➪ irregular potential or energy dissipation

M84
- Strong radial anisotropy beyond 1.5 R_e
- Dark matter dominates at 4 R_e

Fornax
- Isotropic inner orbits, ≈ radial outer orbits
- Dark matter present:
  - likely > 50% at all radii

seen in simulations: Klimentowski+07

Conclusions (2)

- Universal distribution of interlopers in projected phase space

  → incorporate in mass & anisotropy modelling

- Half of neutral gas deficient spirals behind Virgo are in Virgo!

- Single passage through cluster decreases fraction of recent starbursts by only < 20%