The orbits of galaxies in clusters

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Outline of this seminar:

1) Motivation:
why studying the orbits of galaxies in clusters?

2) Methods:
how to determine these orbits?

3) Results:
what do we know about them?

4) Interpretation:
what do they tell us about the evolution of clusters and cluster galaxies

5) Prospects:
what next?

Motivation:

why studying the orbits of galaxies in clusters?

Why studying the orbits of galaxies in clusters?

1. Understanding the evolution of galaxy clusters
2. Understanding the evolution of galaxies
3. Estimating the mass of clusters of galaxies

Why studying the orbits of galaxies in clusters?

1. Understanding the evolution of galaxy clusters

Theory predicts two evolutionary phases:

1. early, fast collapse
2. late, slow accretion

the orbits of galaxies inside the cluster are shaped by the way the cluster achieves its dynamical equilibrium, i.e. via collective collisions ("violent relaxation") and/or slow inside-out growth (mass accretion from the surrounding field)

the shape of the orbits as a function of distance from the cluster center measures the clumpiness of the collisions by which the cluster grows its mass with time

(Lapi & Cavaliere 2011)

Why studying the orbits of galaxies in clusters?

2. Understanding the evolution of galaxies

The population of cluster galaxies ≠
the population of galaxies in the general field,

being mostly red, E/S0, low-star formation, low-gas content

What causes this difference?
Maybe some physical processes related to the high density of dark and baryonic (galaxies + gas) matter inside clusters

The density of dark and baryonic matter inside clusters decreases with distance from the cluster centers

↓

galaxies on different orbits pass different amount of times in regions of different densities, hence they are more or less affected by density-related evolutionary processes

Why studying the orbits of galaxies in clusters?

3. Estimating the mass of clusters of galaxies

The mass of a cluster, M,
is related to its velocity dispersion, σ_v,
measured from the motions of its galaxies
(e.g. the Dark Matter discovery by Zwicky 1933):
a larger M is needed to keep the galaxies bound
to the system if their velocities are higher

We only observe the line-of-sight component of σ_v,
i.e. σ_p, from the galaxies spectral redshifts,

↓

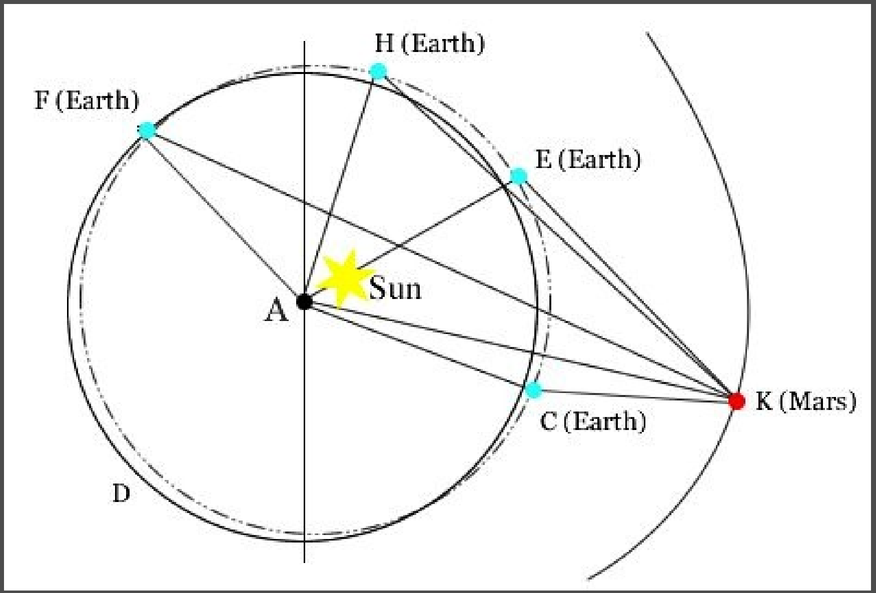
the scaling relation M vs. σ_p depends on the orbital
distribution of galaxies inside the cluster

Methods:

how to determine the orbits of galaxies in clusters?

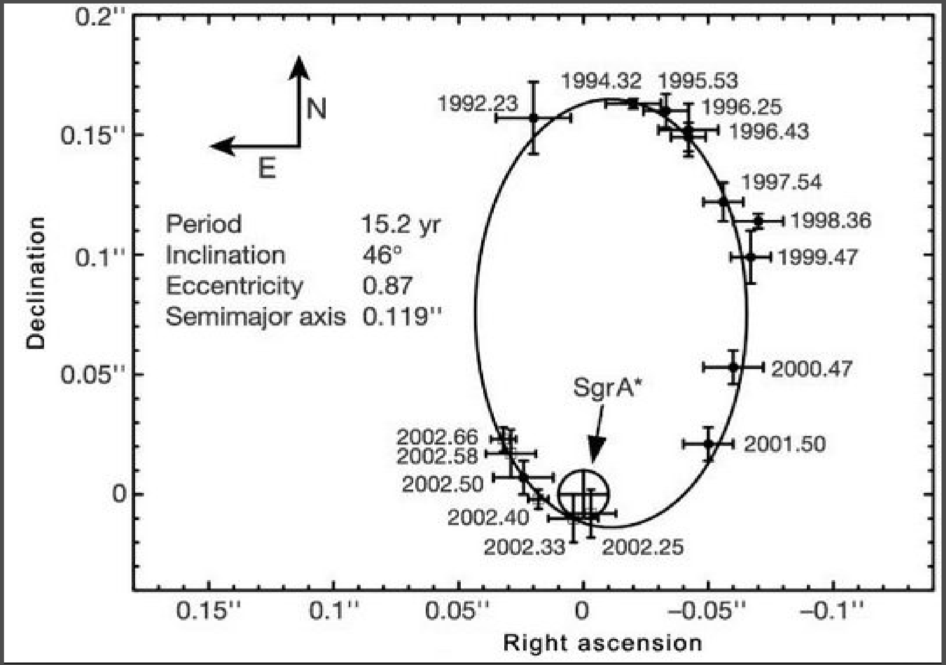
How to determine the orbits of cluster galaxies?

Ideally one would use the positions of galaxies in the cluster at different times



e.g. Johannes Kepler and the determination of the orbit of planet Mars, 1609

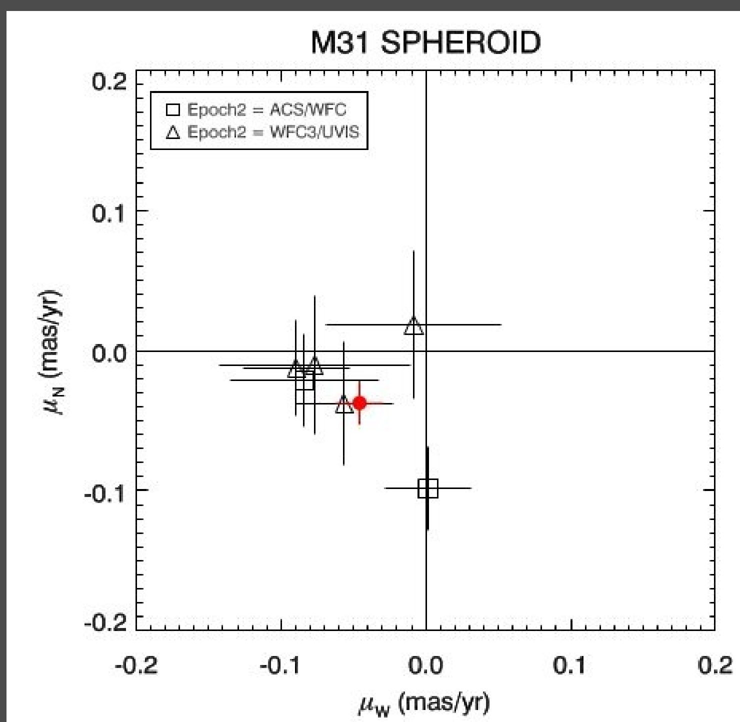
e.g. Reinhardt Genzel and the motion of a star around the central black hole of our Milky Way, 2008



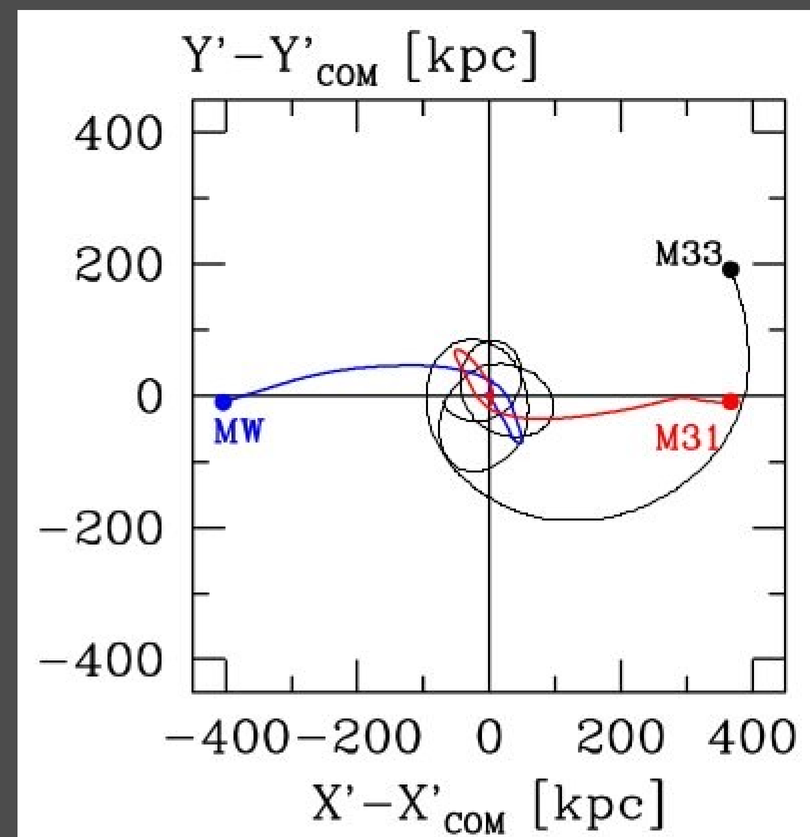
How to determine the orbits of cluster galaxies?

Unfortunately cluster galaxies are too far away to detect a change in their positions within their cluster

This is possible for galaxies in our Local Group (Sohn+12; van der Marel+12)



proper motion of M31 measured using HST observations of thousands of M31 stars and hundreds of compact background galaxies



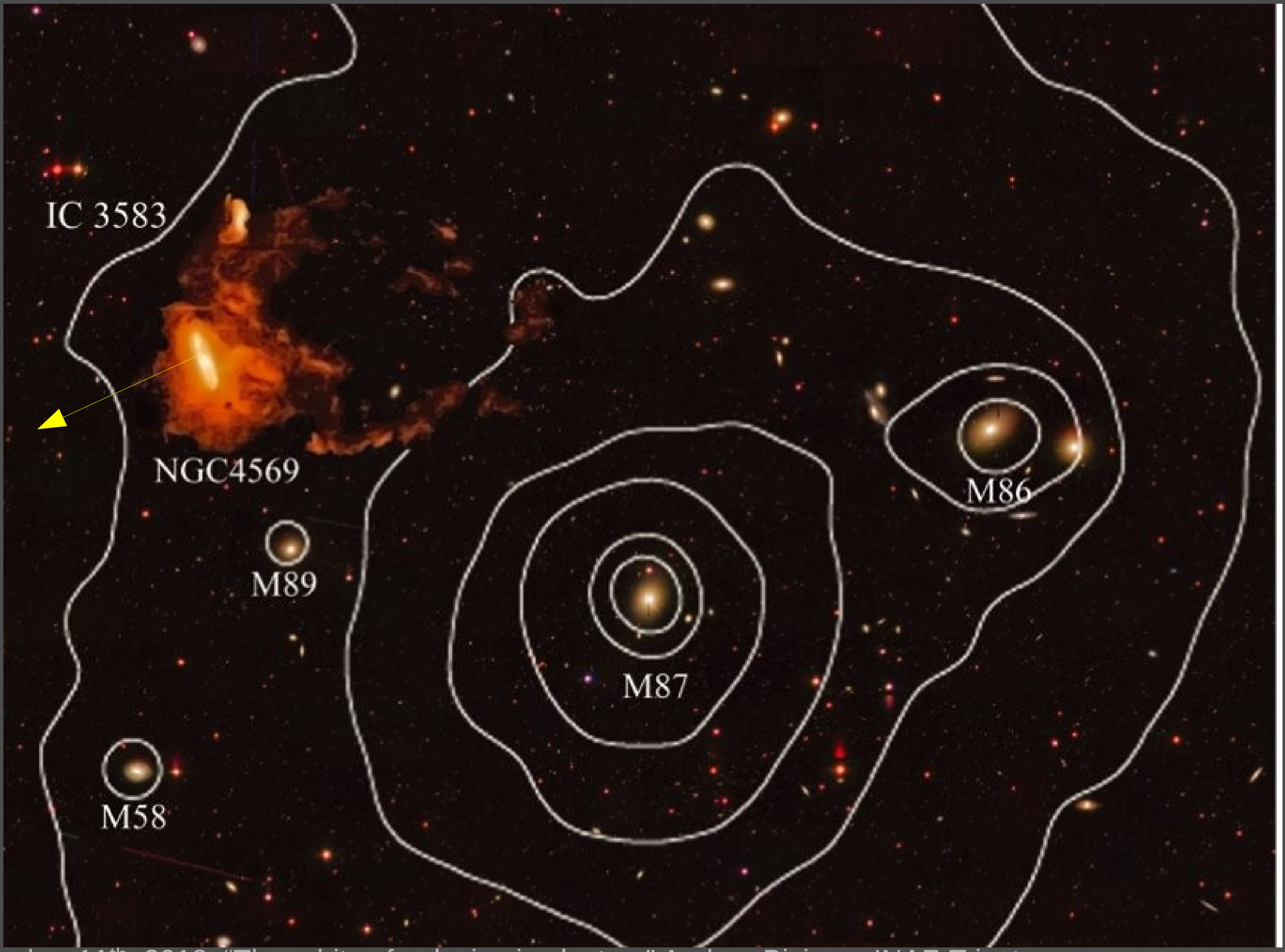
predicted orbits (10 Gyr) for the 3 main galaxies of our Local Group, based on semi-analytic integration

How to determine the orbits of cluster galaxies?

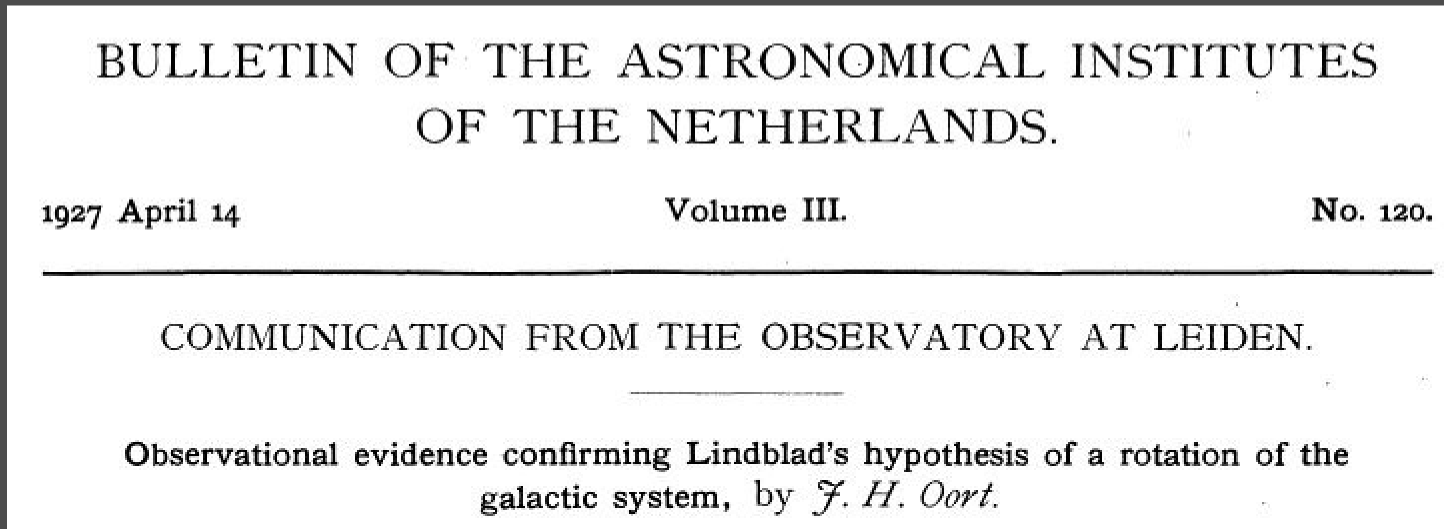
For some cluster galaxies we can infer their orbits by their gas trails (Boselli+16; but these detections are rare)

Ionized gas Hα+[NII] trailing from the galaxy NGC4569 in the nearby Virgo cluster, centered around M87.

The size of NGC4569 is exaggerated by a factor 6 to illustrate the trailing direction



How to determine the orbits of cluster galaxies?



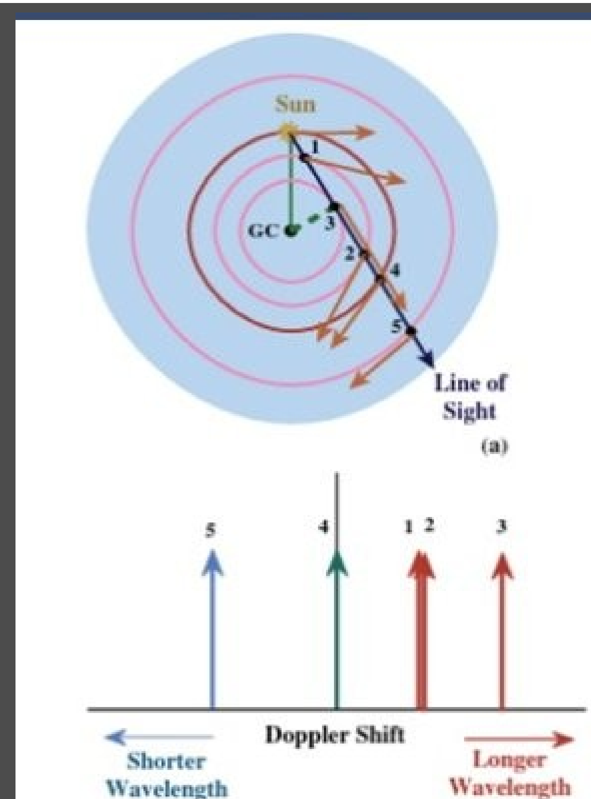
BULLETIN OF THE ASTRONOMICAL INSTITUTES
OF THE NETHERLANDS.

1927 April 14 Volume III. No. 120.

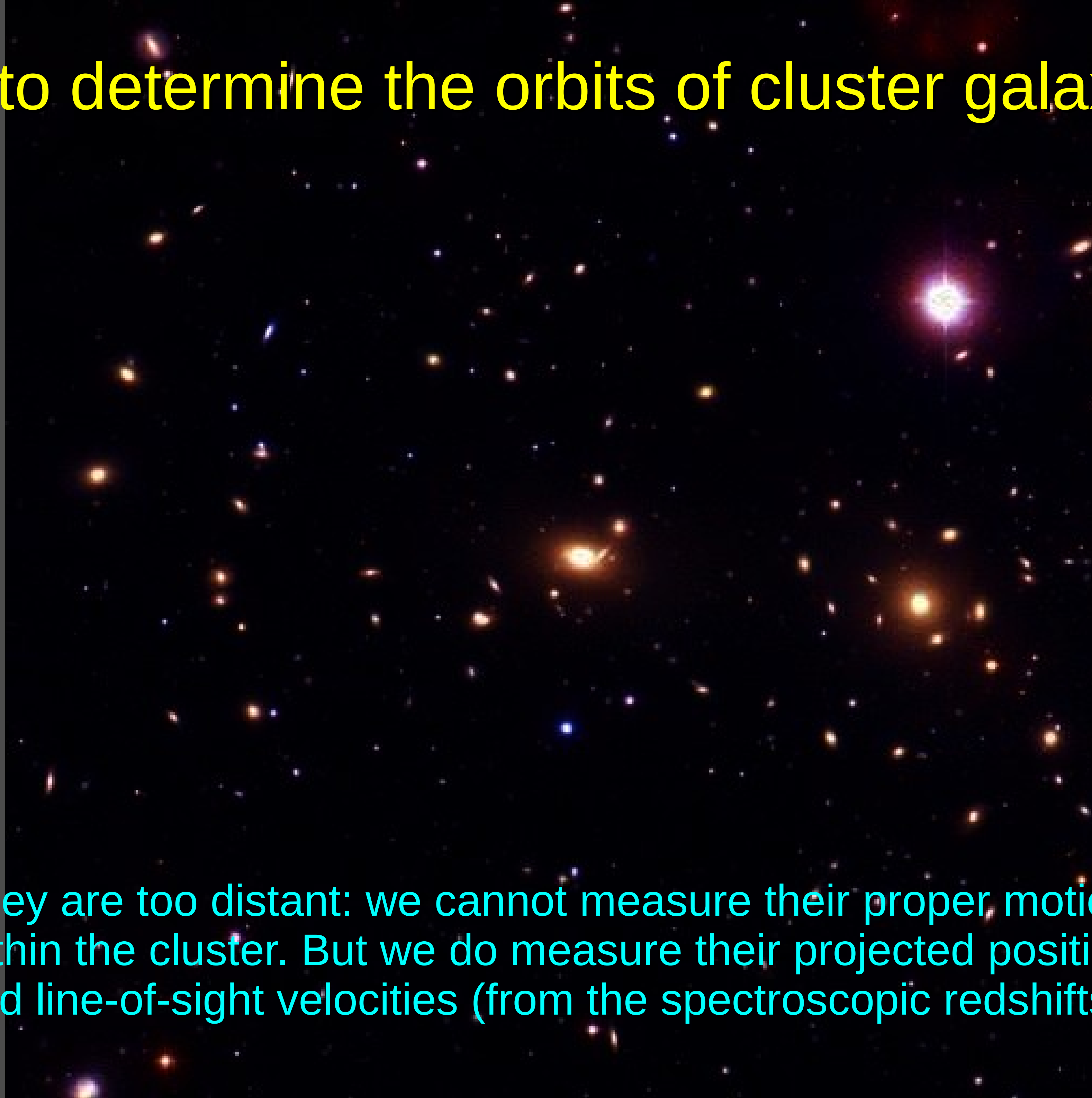
COMMUNICATION FROM THE OBSERVATORY AT LEIDEN.

Observational evidence confirming Lindblad's hypothesis of a rotation of the galactic system, by *J. H. Oort.*

Learn from
Oort (1927):
the non-uniform
rotation of the
Milky Way
is inferred from
the **projected positions and radial velocities**
of its stars



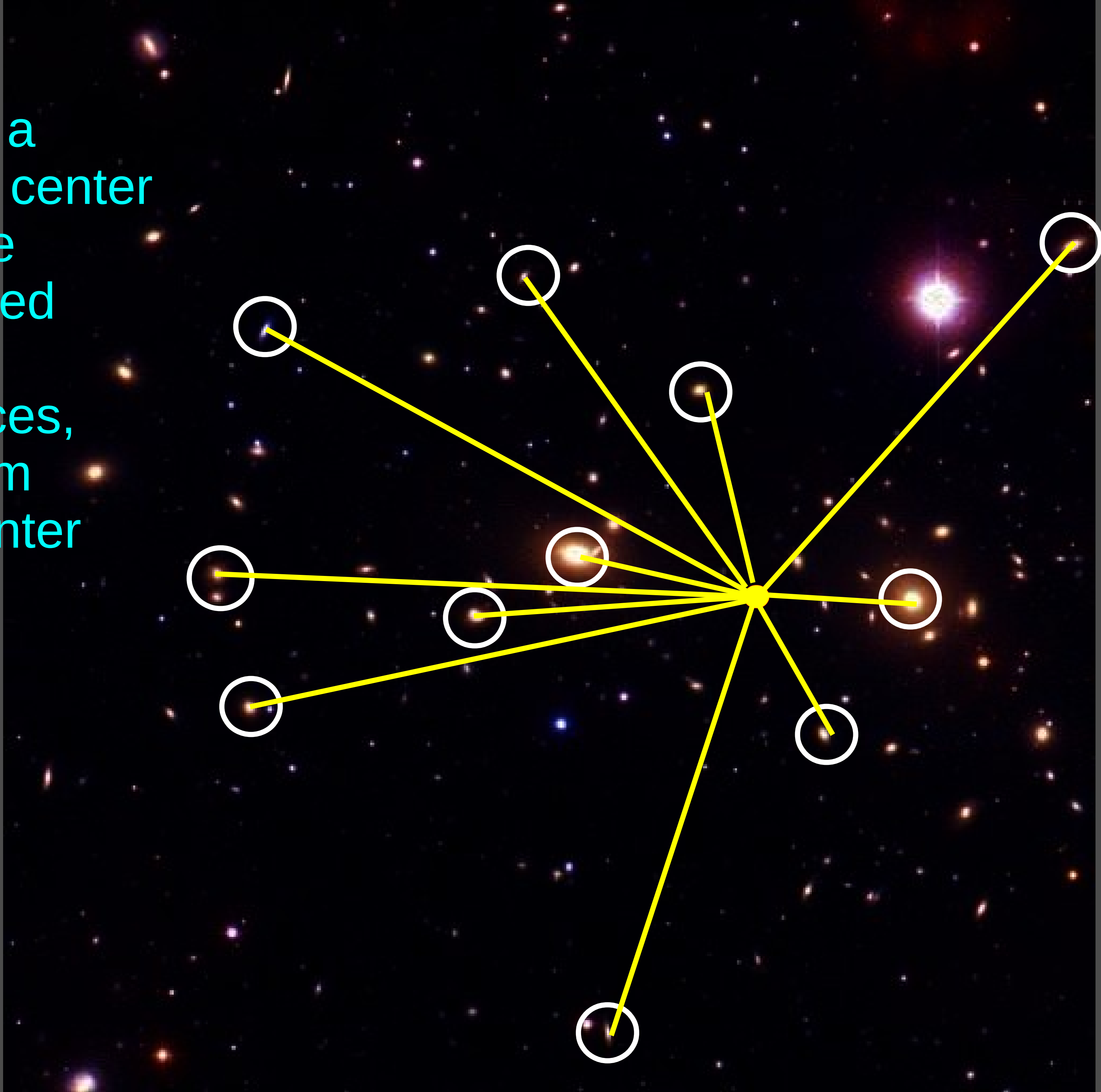
How to determine the orbits of cluster galaxies?



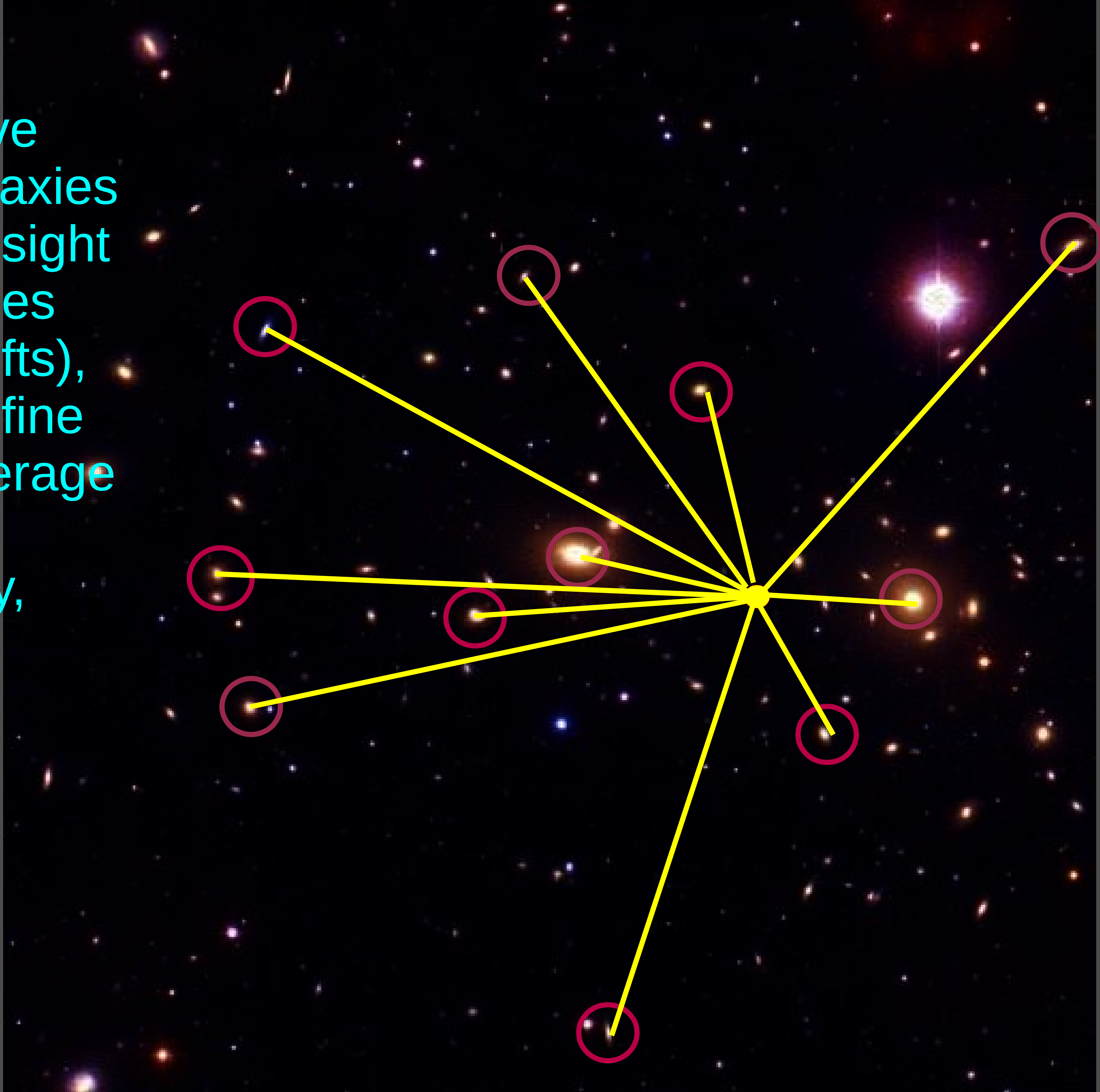
They are too distant: we cannot measure their proper motions within the cluster. But we do measure their projected positions and line-of-sight velocities (from the spectroscopic redshifts)

Observe the projected positions of the cluster galaxies

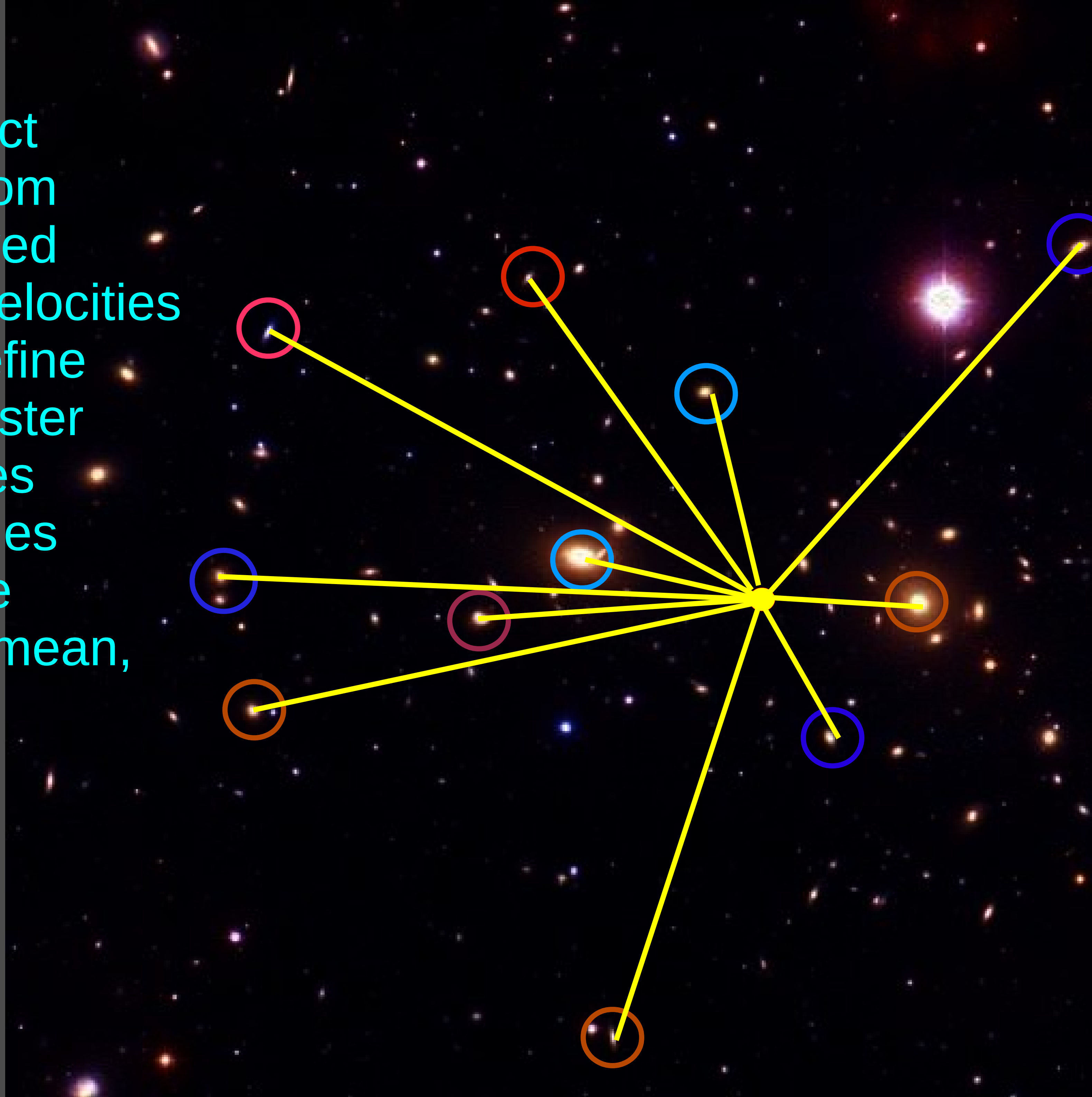
Define a cluster center and the projected galaxy distances, 'R', from this center



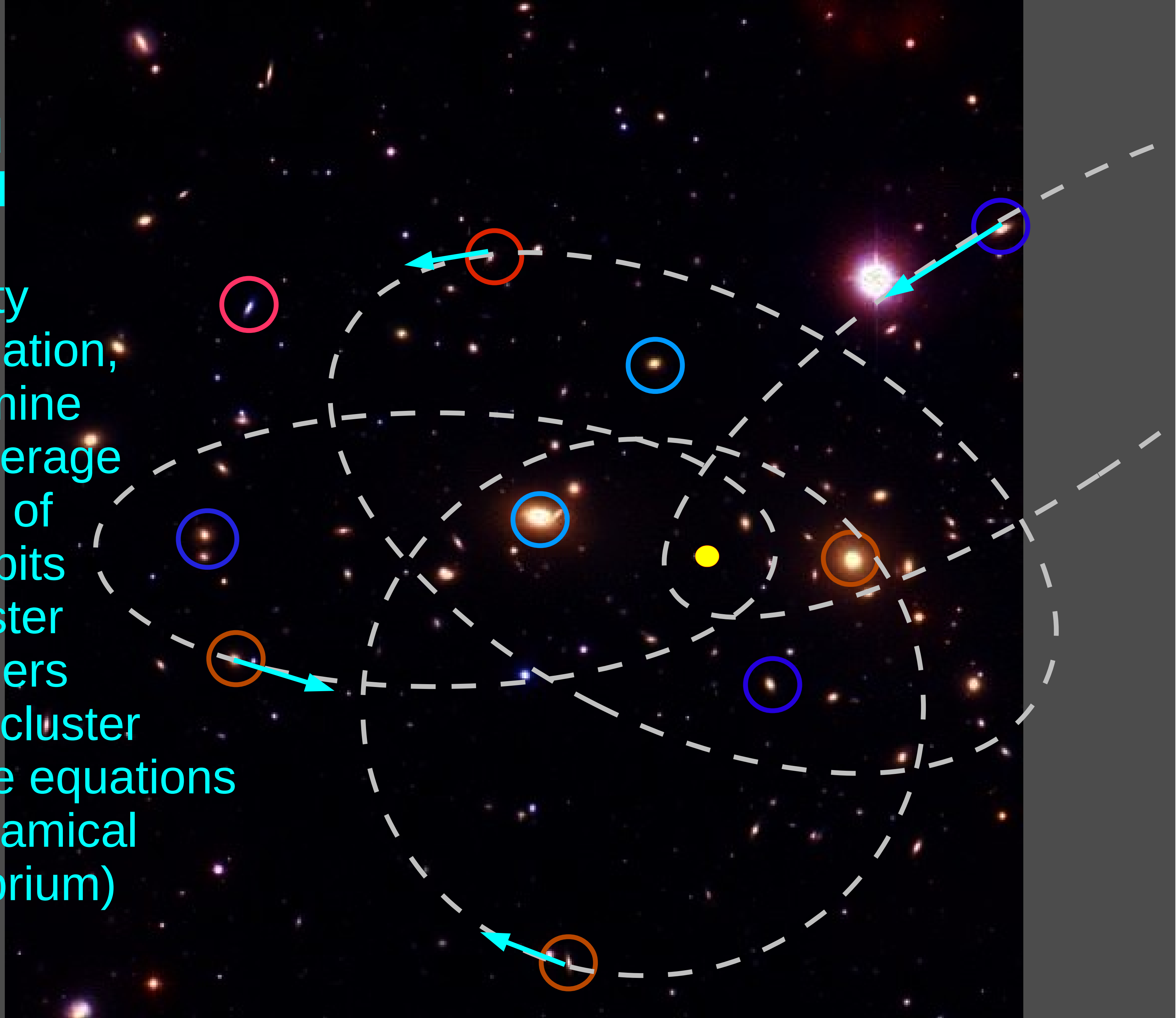
Observe the galaxies line-of-sight velocities (redshifts), and define the average cluster velocity, <V>



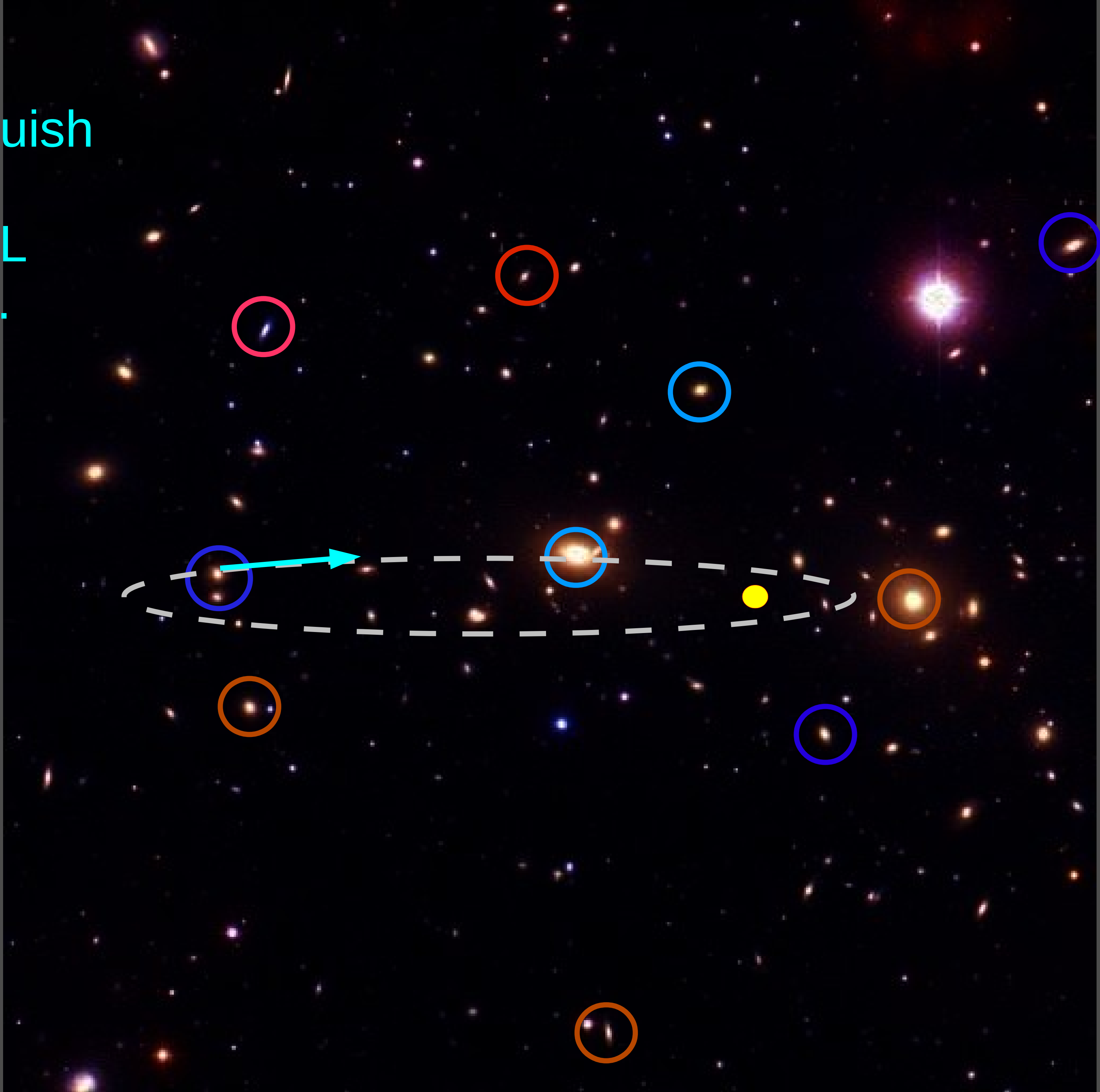
Subtract <V> from observed l.o.s. velocities and define the cluster galaxies velocities relative to the mean, 'v'



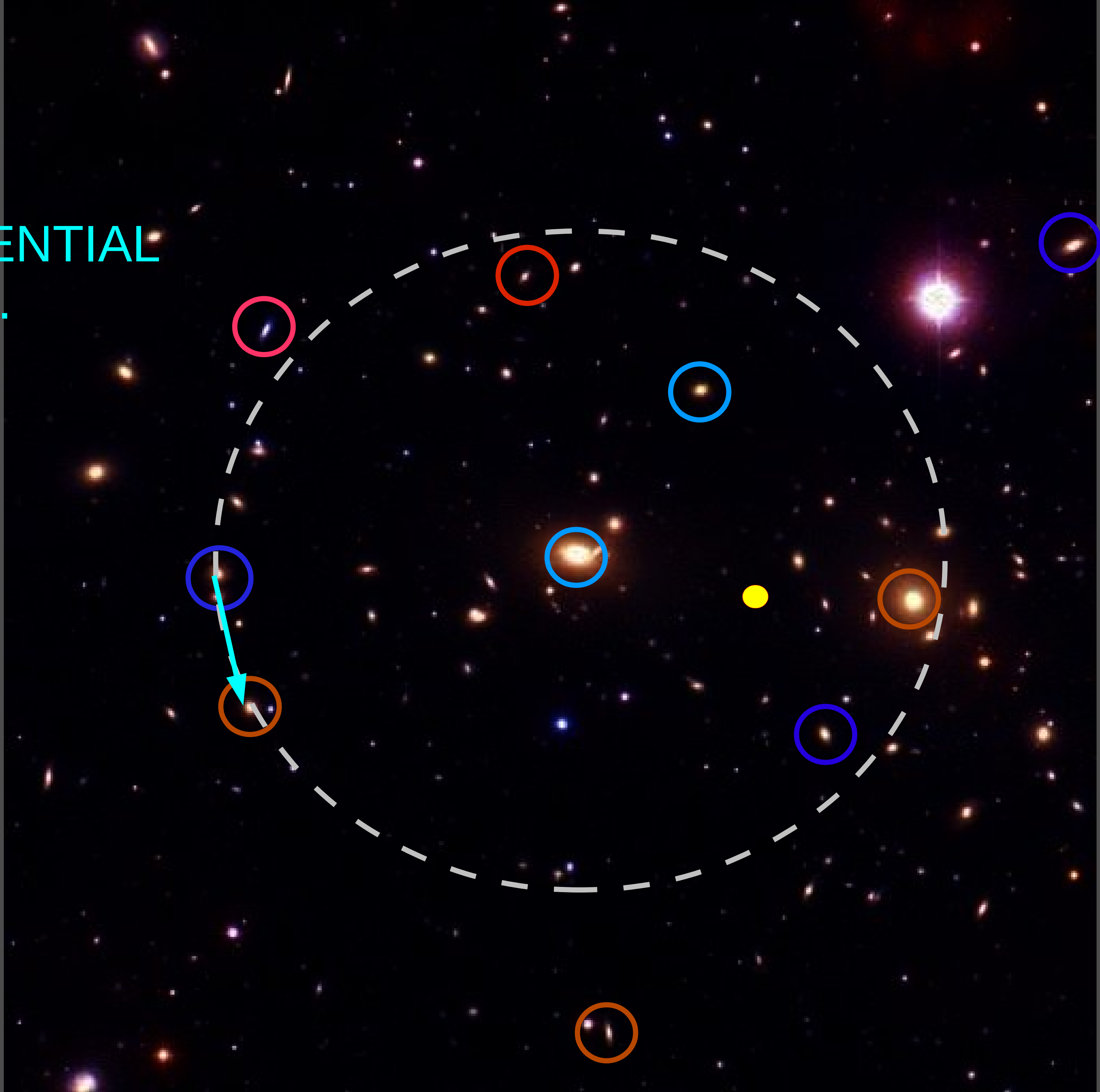
Using 2d+1d spatial and velocity information, determine the average shape of the orbits of cluster members in the cluster (by the equations of dynamical equilibrium)



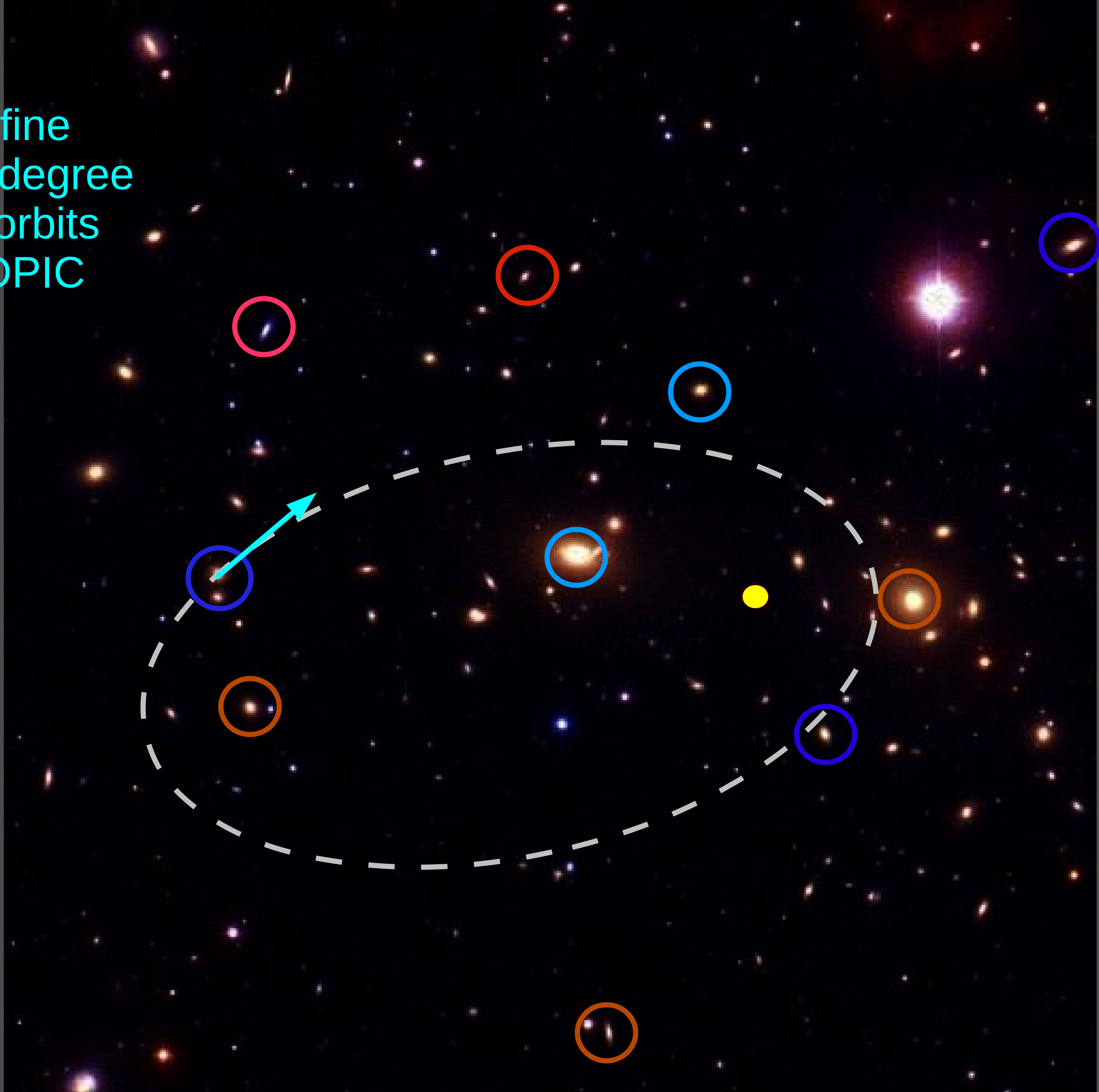
Distinguish mostly RADIAL orbits...



...from mostly TANGENTIAL orbits...



...i.e. define
to what degree
are the orbits
ISOTROPIC



The equation of dynamical equilibrium

$$M(<r) = -\frac{r\sigma_r^2}{G}\left(\frac{d\ln\nu}{d\ln r} + \frac{d\ln\sigma_r^2}{d\ln r} + 2\beta\right)$$

$\beta=1-(\sigma_t/\sigma_r)^2$

M = total mass profile
σ_r = velocity dispersion profile along the radial direction
σ_t = velocity disp. profile along the tangential direction
ν = number density profile of the tracer (galaxies)
β = velocity anisotropy profile of the tracer

β(r) is related to the orbital distribution of galaxies:

- <0: orbits are more tangential
- >0: orbits are more radial
- =0: orbits are isotropic (no preference for radial vs. tangential)

The equation of dynamical equilibrium

$$M(<r) = -\frac{r\sigma_r^2}{G}\left(\frac{d\ln\nu}{d\ln r} + \frac{d\ln\sigma_r^2}{d\ln r} + 2\beta\right)$$

M = total mass profile

$\beta = 1 - (\sigma_t/\sigma_r)^2$

σ_r = velocity dispersion profile along the radial direction

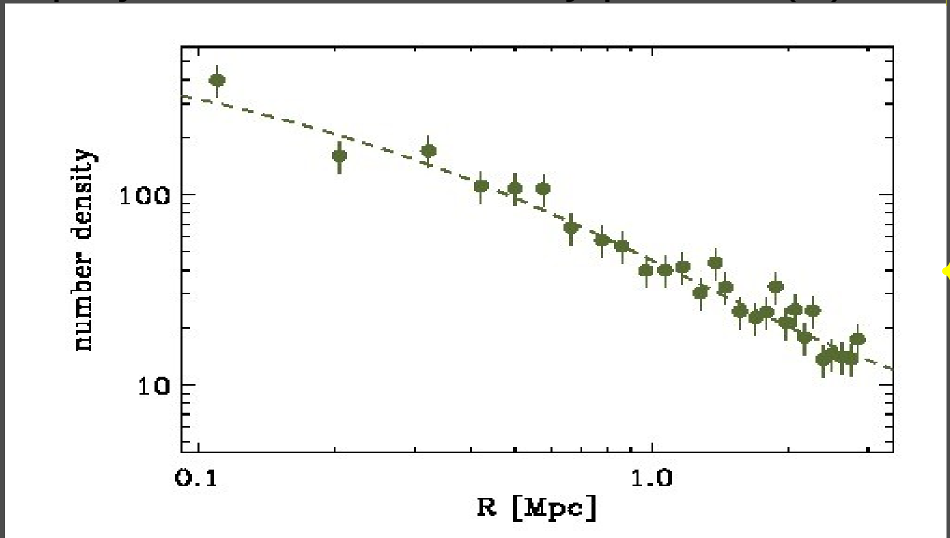
σ_t = velocity disp. profile along the tangential direction

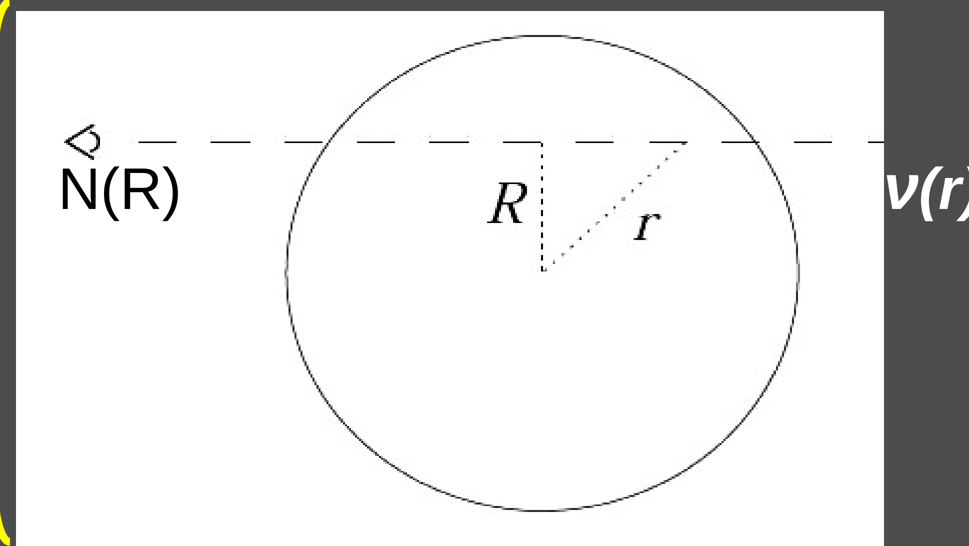
ν = number density profile of the tracer (galaxies)

β = velocity anisotropy profile of the tracer

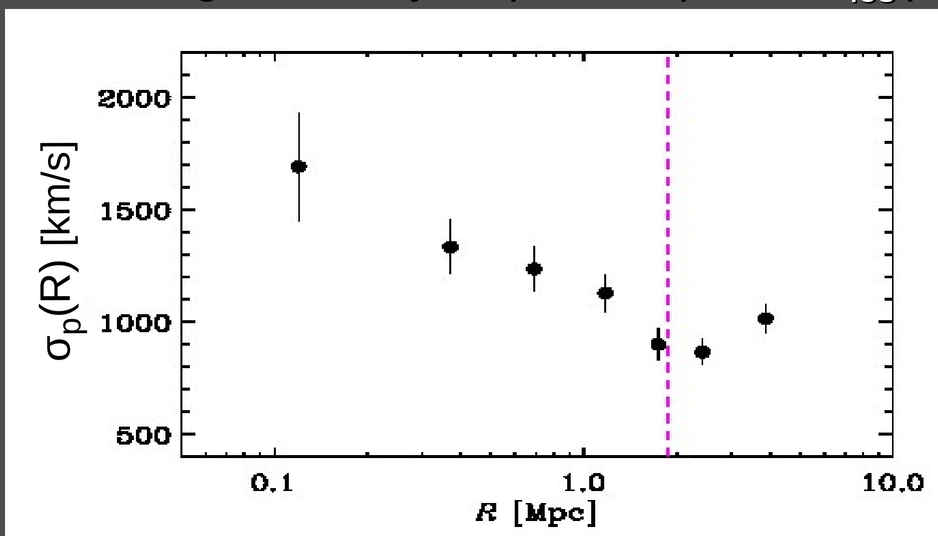
But how do we get $\nu(r)$, $\sigma_r(r)$, $\beta(r)$ from the observables, the projected spatial and line-of-sight velocity distributions?

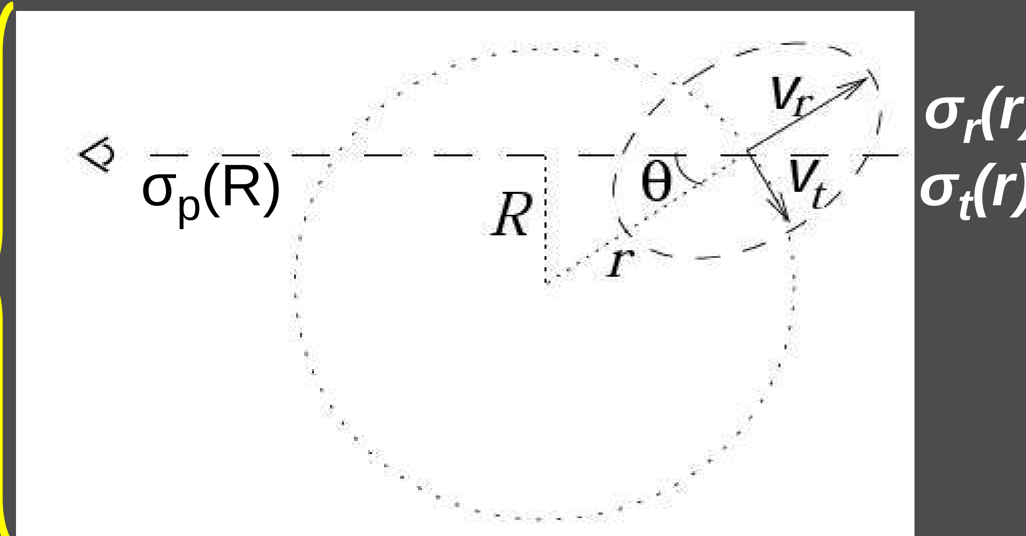
projected number density profile N(R)





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

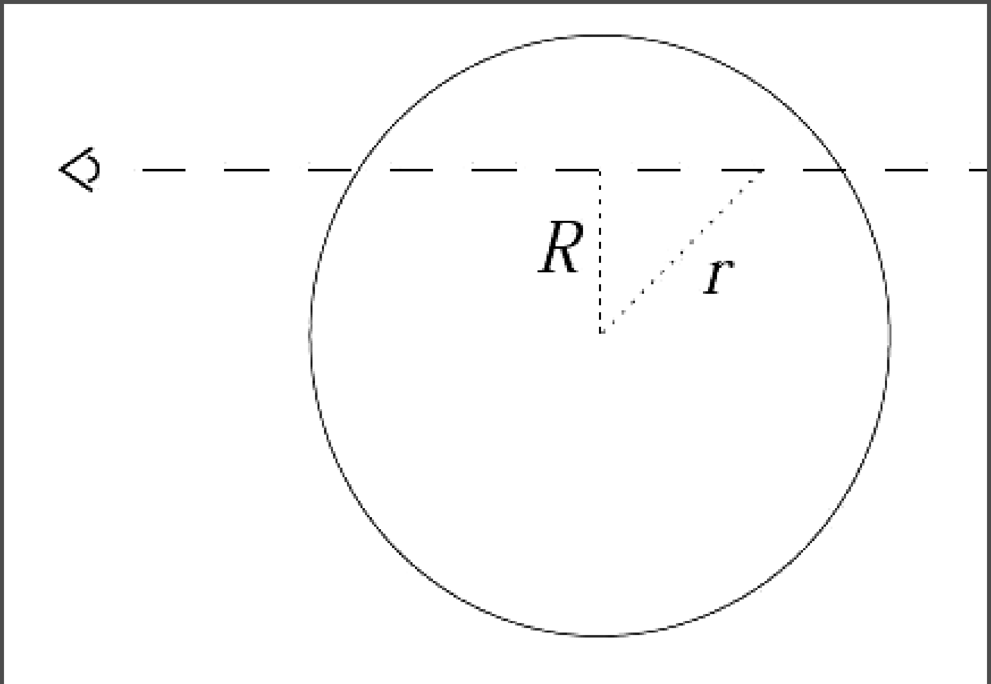




$$M(<r) = -\frac{r\sigma_r^2}{G}\left(\frac{d\ln\nu}{d\ln r} + \frac{d\ln\sigma_r^2}{d\ln r} + 2\beta\right)$$

$\beta = 1 - (\sigma_t/\sigma_r)^2$

The 3-d number density profile, ν(r), can be recovered with no degeneracy from the 2-d projected profile, N(R), assuming spherical symmetry and using the Abel inversion equation:

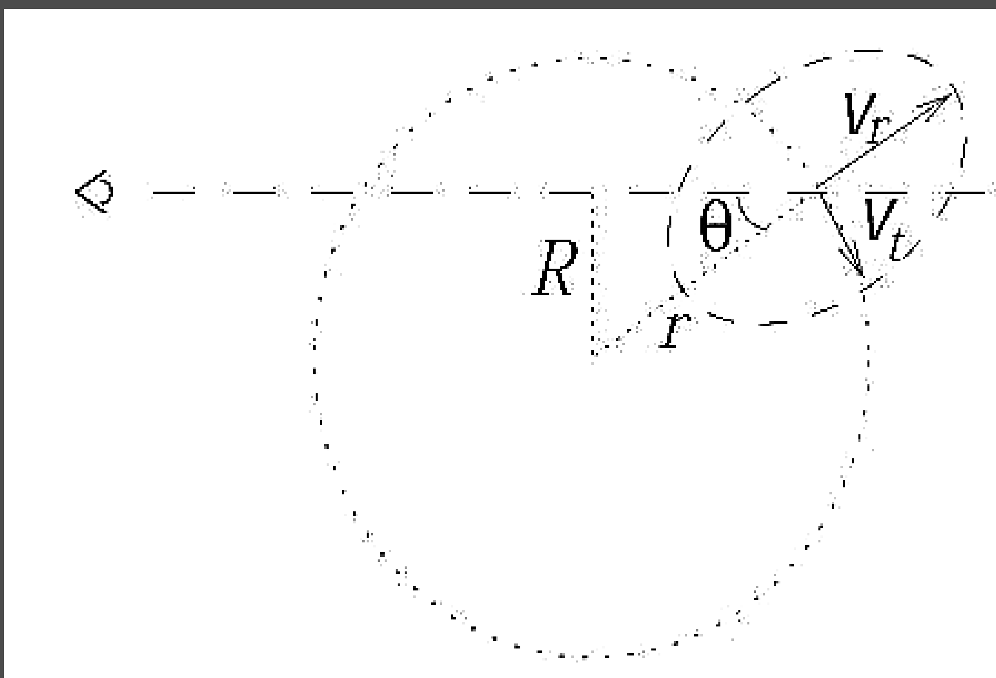


$$N(R) = 2\int_R^\infty \frac{\nu\, r\, dr}{\sqrt{r^2 - R^2}}$$

$$\updownarrow$$

$$\nu(r) = -\frac{1}{\pi}\int_r^\infty \frac{dN}{dR}\frac{dR}{\sqrt{R^2 - r^2}}$$

Knowledge of β(r) is needed to determine all the components of the 3-d velocity dispersion profile, $\sigma_r(r)$ and $\sigma_t(r)$, from the observed vel.disp. along the line-of-sight, $\sigma_p(R)$; assuming spherical symmetry is not sufficient.



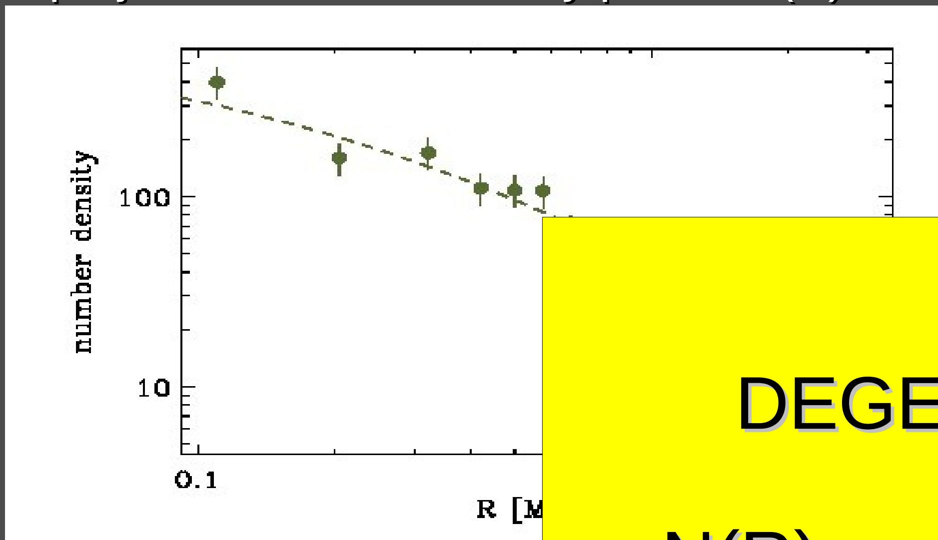
$$N(R)\sigma_p^2(R) = 2\int_R^{\infty}\left(1-\beta\frac{R^2}{r^2}\right)\frac{\nu\,\sigma_r^2(r)\,r\,dr}{\sqrt{r^2-R^2}}$$

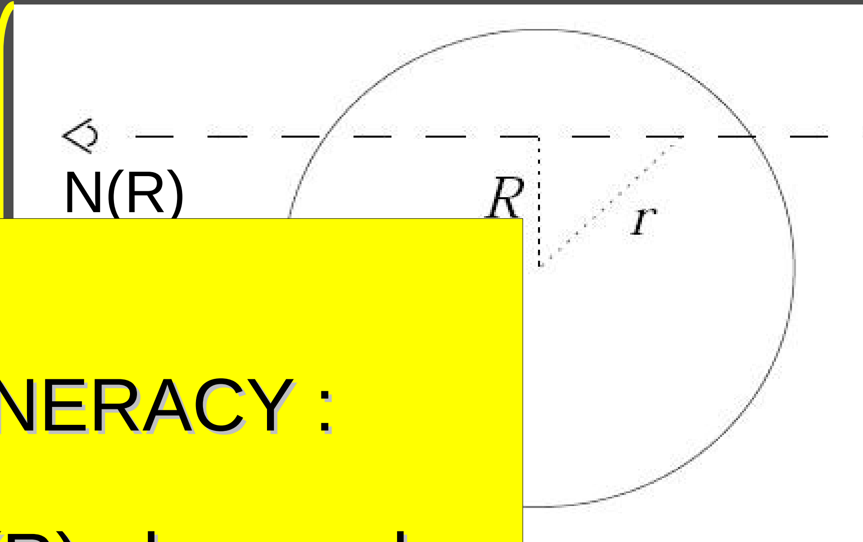
Only if β=0

$$\sigma_r^2 = -\frac{1}{\pi\nu(r)}\int_r^{\infty}\frac{d[N\times\sigma_p^2]}{dR}\frac{dR}{\sqrt{R^2-r^2}}$$

$\beta=1-(\sigma_t/\sigma_r)^2$

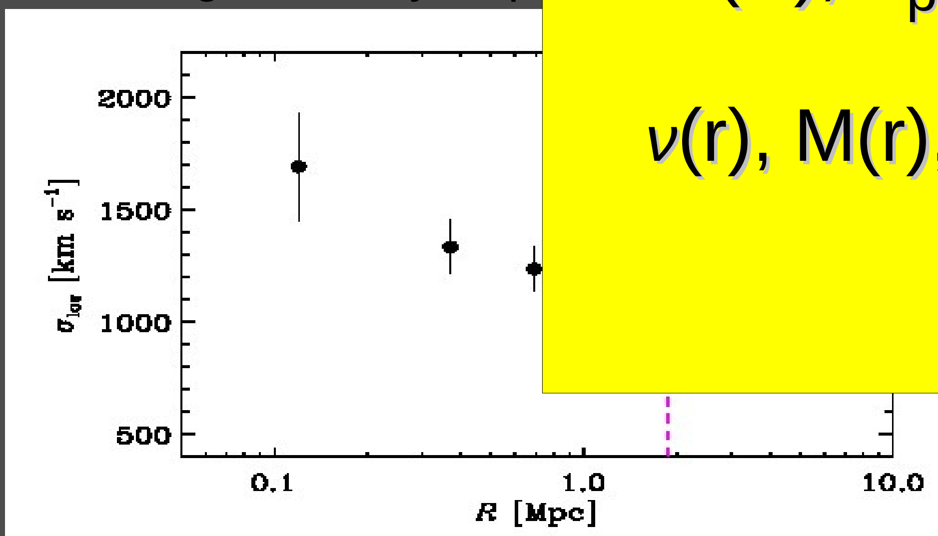
projected number density profile N(R)

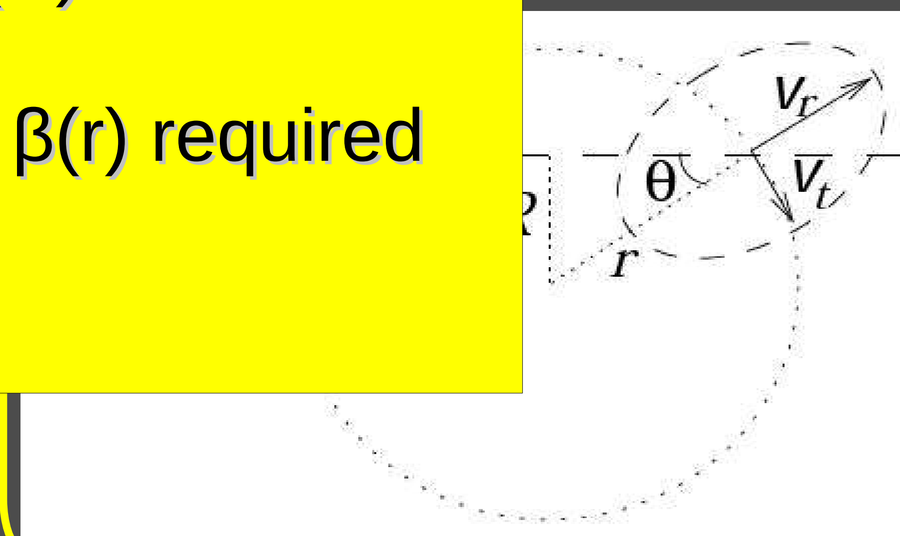




$\nu(r)$

line-of-sight velocity dispe





$\sigma_r(r)$

$\sigma_t(r)$

DEGENERACY :

N(R), σ_p(R) observed

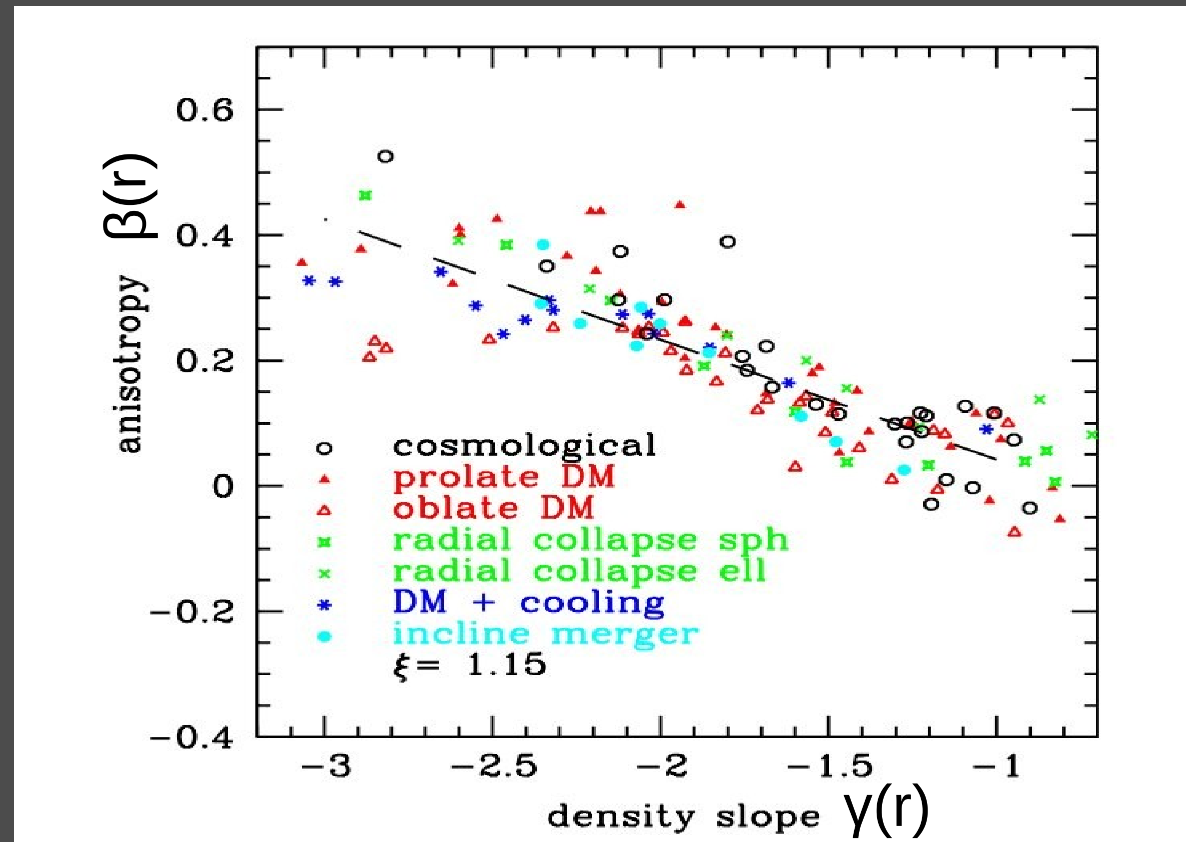
ν(r), M(r), β(r) required

$$M(<r) = -\frac{r\sigma_r^2}{G}\left(\frac{d\ln\nu}{d\ln r} + \frac{d\ln\sigma_r^2}{d\ln r} + 2\beta\right)$$

$\beta = 1-(\sigma_t/\sigma_r)^2$

How to solve the Jeans equation:

Numerical simulations indicate the existence of a linear relation between β(r) and γ(r), the slope of the mass density profile $\gamma(r) = d \log \rho / d \log r$, with $M(r) = 4\pi \int x^2 \rho(x)\, dx$ *(Hansen+Moore 03)*



Assume the β-γ relation is valid in real clusters:

Observables
N(R), $\sigma_p(R)$

Abel+Jeans → M(r) & β(r)

How to solve the Jeans equation:

Assume “mass follows light”: $M(r) = 4\pi \int x^2 \rho(x)\, dx$,
mass density profile: $\rho(r) \propto \nu(r)$ and $\nu(r)$ is obtained from N(R)
(Mahdavi+Geller 99)

Observables
N(R), $\sigma_p(R)$

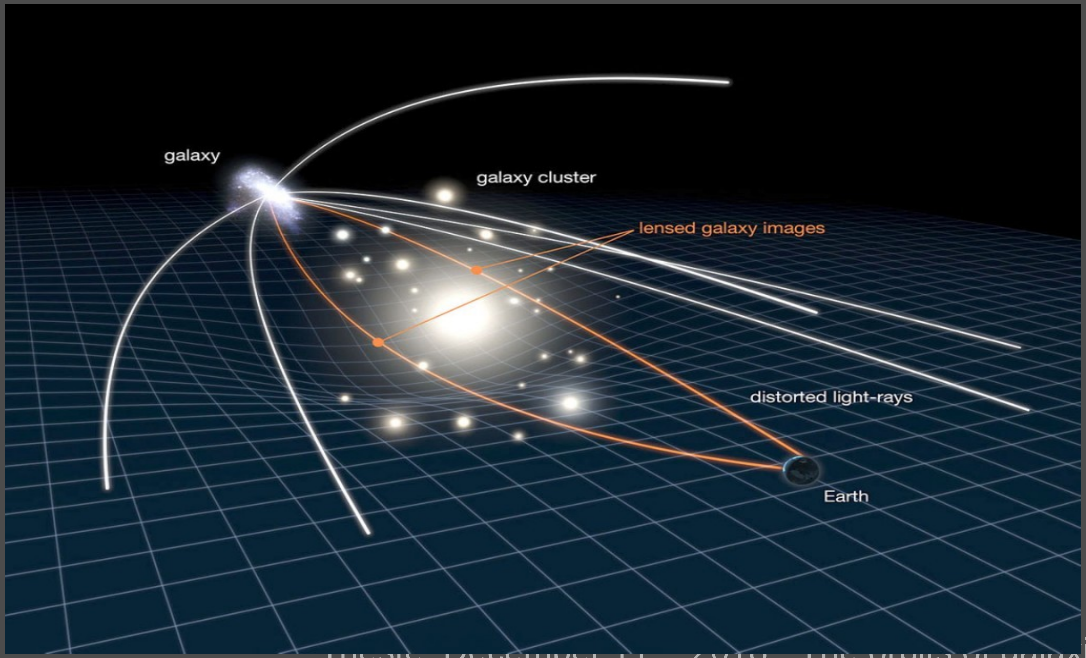
+M(r) → **Abel+Jeans** → $\beta(r)$

How to solve the Jeans equation:

Estimate M(r) not from the cluster kinematics but using other probes, e.g. gravitational lensing (Natarajan+Kneib 96)

Observables
N(R), σ_p(R)

+M(r) **Abel+Jeans** → β(r)



How to solve the Jeans equation:

Use two populations of tracers of the same gravitational potential: M(r) is unique, β(r) does not need to be identical for the two populations (AB+Poggianti 09)

Observables1
N(R), $\sigma_p(R)$

≠

Observables2
N(R), $\sigma_p(R)$

tracer 1

snaeJ+lebA

tracer 2

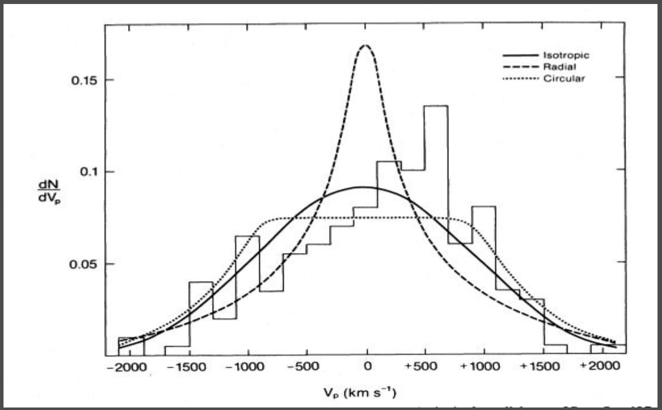
M(r)+ { $\beta_1(r)$, $\beta_2(r)$ }

How to solve the Jeans equation:

There is more information in the projected spatial distribution than just the number density profile N(R) and in the line-of-sight velocity distribution than just the velocity dispersion profile $\sigma_p(R)$.

The shape of the velocity distribution depends on the orbital distribution β(r) (Merritt 87)

Parametrize the velocity distribution by its 2nd and 4th moments (the *"Dispersion+Kurtosis"* technique, Łokas+Mamon 03)
or by the Gauss-Hermite moments (van der Marel + 00)



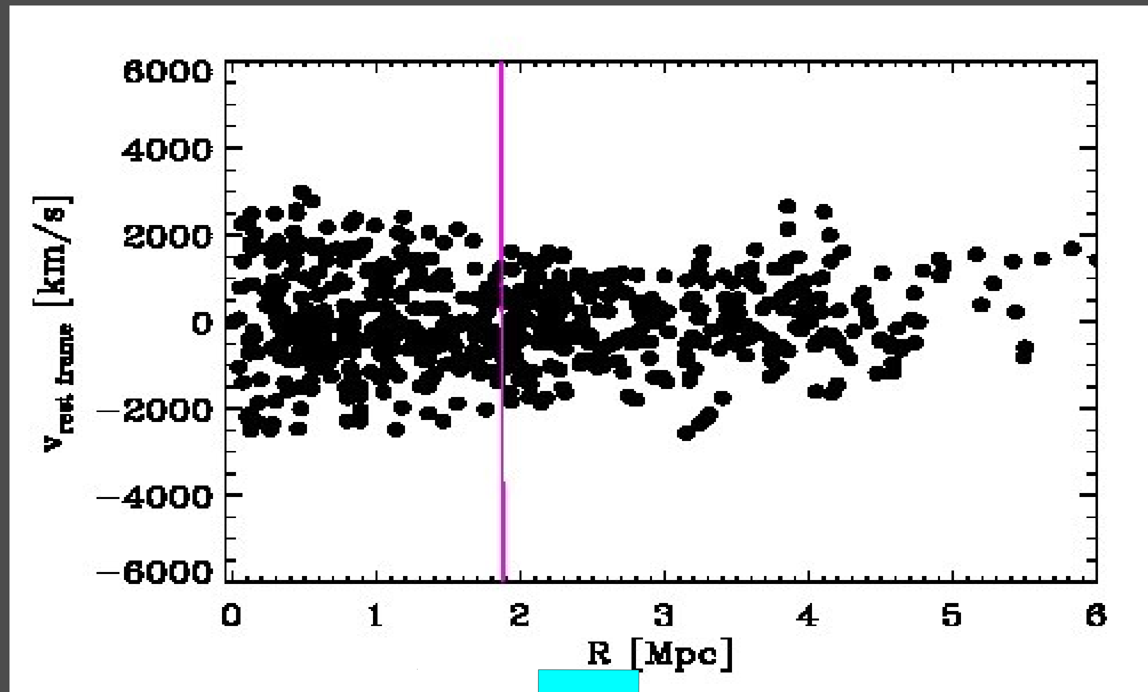
Observed distribution of velocities for Coma cluster galaxies and predicted distributions for β=1,0,-∞

Observables: N(R), $\sigma_p(R)$, and higher moments of the velocity distribution

snaeJ+lebA

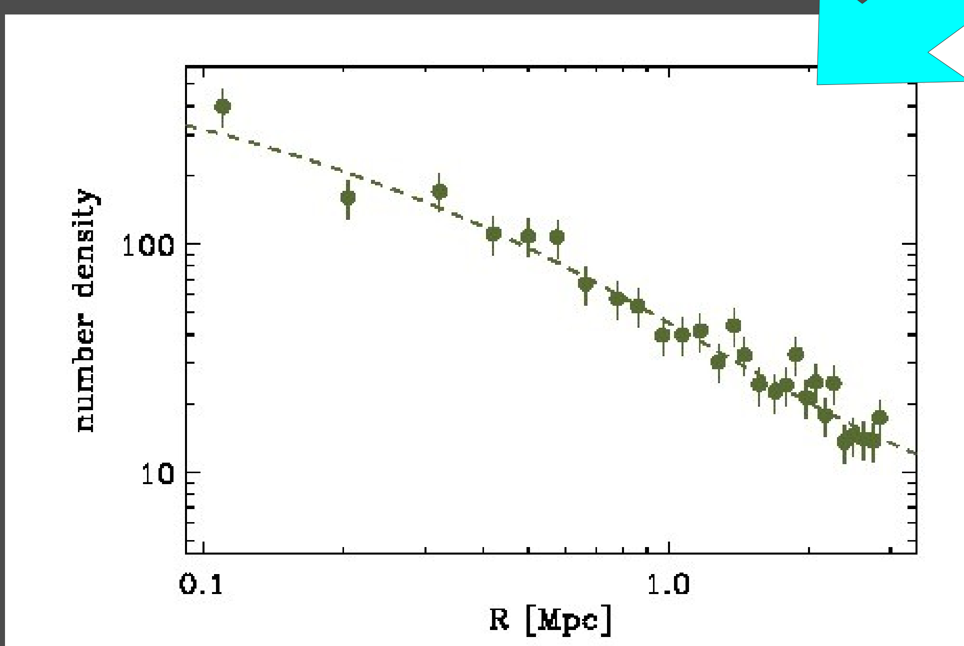
M(r)+β(r)

Phase-space distribution of cluster member galaxies in projection *(rest-frame velocities vs. distances from the cluster center)*

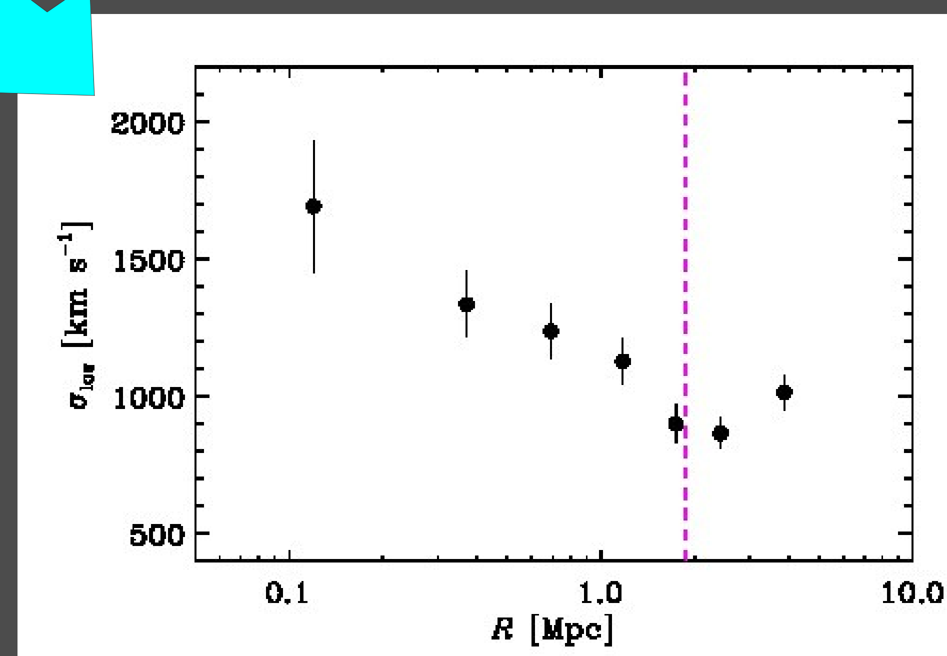


CLASH-VLT cluster MACS1206

projected number density profile N(R)



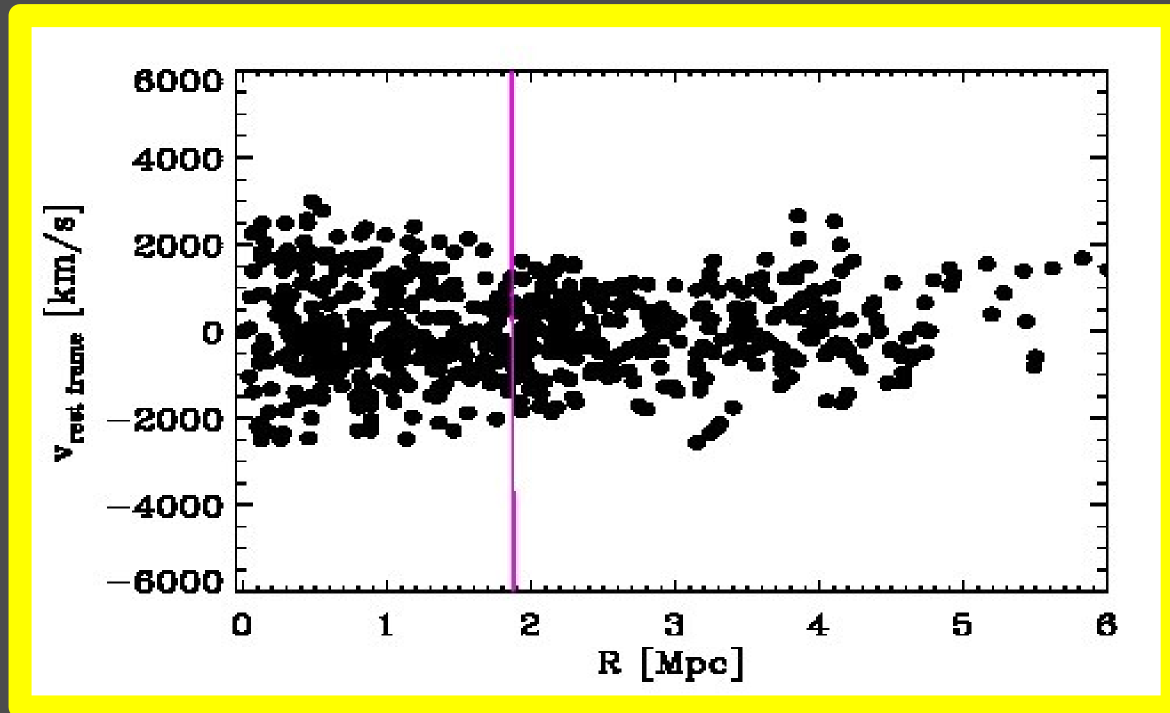
l.o.s. velocity dispersion profile $\sigma_p(R)$



MAMPOSSt

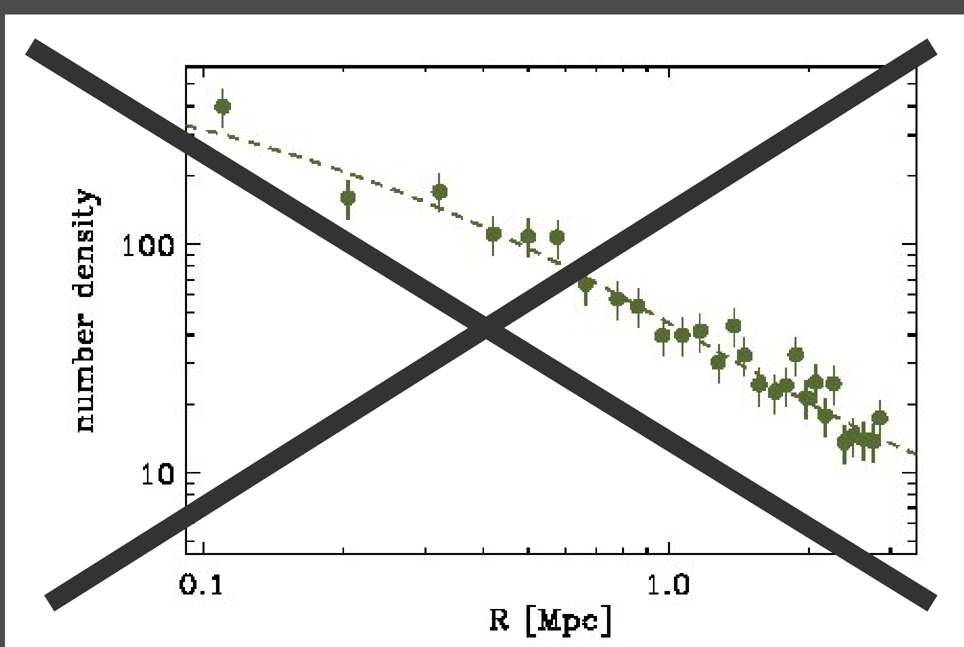
(Mamon, AB, Boué 13)

direct maximum likelihood fit to the phase-space distribution of cluster galaxies in projection

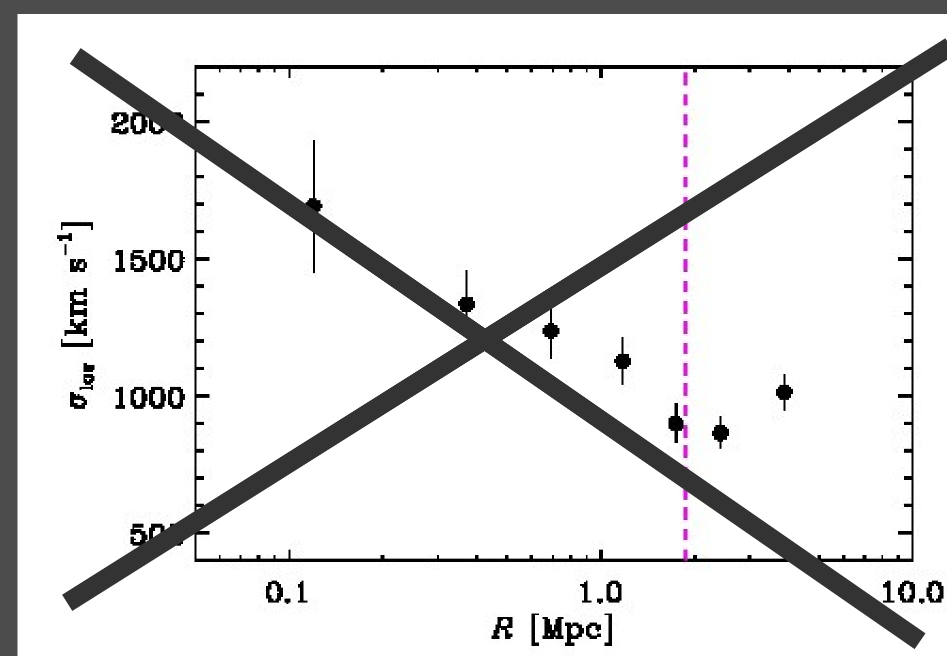


Modelling
Anisotropy and
Mass
Profiles of
Observed
Spherical
Sys**t**ems

projected number density profile N(R)



l.o.s. velocity dispersion profile $\sigma_p(R)$



The surface density of observed objects in projected phase space is:

MAMPOSSt:
(Mamon, AB, Boué 13)

direct maximum likelihood fit to the phase-space distribution of cluster galaxies in projection

$$g(R, v_z) = \Sigma(R)\ \langle h(v_z|R,r)\rangle_{\rm LOS}$$
$$= 2\int_R^\infty \frac{r\,\nu(r)}{\sqrt{r^2-R^2}}\,h(v_z|R,r)\,{\rm d}r\ , \quad (4)$$
$$= 2\int_R^\infty \frac{r\,{\rm d}r}{\sqrt{r^2-R^2}}\int_{-\infty}^{+\infty}{\rm d}v_\perp\int_{-\infty}^{+\infty} f(r, v_z, v_\perp, v_\phi)\,{\rm d}v_\phi, \quad (5)$$

Hence, the probability density of observing an object at position (R,v_z) is:

$$q(R, v_z) = \frac{2\pi\,R\,g(R,v_z)}{\Delta N_{\rm p}}$$
$$= \frac{4\pi\,R}{\Delta N_{\rm p}}\int_R^\infty \frac{r\,\nu(r)}{\sqrt{r^2-R^2}}\,h(v_z|R,r)\,{\rm d}r$$

Can be solved by assuming a distribution for 3D galaxy velocities (e.g. Gaussian):

$$h(v_z|R,r) = \frac{1}{\sqrt{2\pi\sigma_z^2(R,r)}}\ \exp\left[-\frac{v_z^2}{2\,\sigma_z^2(R,r)}\right]$$

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

where $\sigma_r^2(r)$ is obtained from the Jeans equation, given M(r) and β(r)

$$\sigma_r^2(r) = \frac{1}{\nu(r)}\int_r^\infty \exp\left[2\int_r^s \beta(t)\frac{{\rm d}t}{t}\right]\ \nu(s)\frac{G\,M(s)}{s^2}{\rm d}s$$

How to solve the Jeans equation:

MAMPOSSt
(Mamon, AB, Boué 13)

Observables:
projected
phase-space
distribution of
cluster galaxies,
R, $v_{rest\text{-}frame}$

snaeJ+lebA

M(r)+β(r)

How to solve the Jeans equation:

Distribution Function methods
(modeling the binding energy E
 and angular momentum L of the
 system; Wojtak+09)

$$f_{\rm L}(L) = \left(1 + \frac{L^2}{2L_0^2}\right)^{-\beta_\infty+\beta_0} L^{-2\beta_0}$$

$$\rho(r) = \iiint f_{\rm E}(E)\left(1 + \frac{L^2}{2L_0^2}\right)^{-\beta_\infty+\beta_0} L^{-2\beta_0}\,{\rm d}^3 v$$

Observables:
projected
phase-space
distribution of
cluster galaxies,
R, $v_{\text{rest-frame}}$

snaeJ+lebA

$f_E + f_L$

How to solve the Jeans equation:

Observables +β(r) → **Abel+Jeans** → M(r)

Constructing a constrained model of β(r) for cluster galaxies as a function of redshift, it will reduce the systematics in the determination of cluster masses from kinematics

How to solve the Jeans equation: summary of the methods

β-γ

Observables
N(R), $\sigma_p(R)$

Abel+Jeans → M(r) & $\beta(r)$

mass~light / ext-M(r)

Observables
N(R), $\sigma_p(R)$ +M(r)

Abel+Jeans → $\beta(r)$

2 tracers

Observables1
N(R), $\sigma_p(R)$

Observables2
N(R), $\sigma_p(R)$

tracer 1

tracer 2

← snaeJ+lebA M(r)+ { $\beta_1(r)$, $\beta_2(r)$ }

v-moments

Observables:
N(R), $\sigma_p(R)$, and higher moments of the velocity distribution

← snaeJ+lebA M(r)+$\beta(r)$

MAMPOSSt

Observables:
projected phase-space distribution of cluster galaxies, R, $v_{rest\text{-}frame}$

← snaeJ+lebA M(r)+$\beta(r)$

E+L

Observables:
projected phase-space distribution of cluster galaxies, R, $v_{rest\text{-}frame}$

← snaeJ+lebA f_E+f_L

Results:

what do we know about
the orbits of galaxies in clusters?

$\beta(r)$ for low-redshift clusters ($z<0.2$)

$\beta(r) \approx 0$ near the center (isotropic orbits)

$\beta(r)$ increases with distance from the center (radial orbits)

$\beta(r) \approx 0$ at all radii for early-type/passive/red galaxies

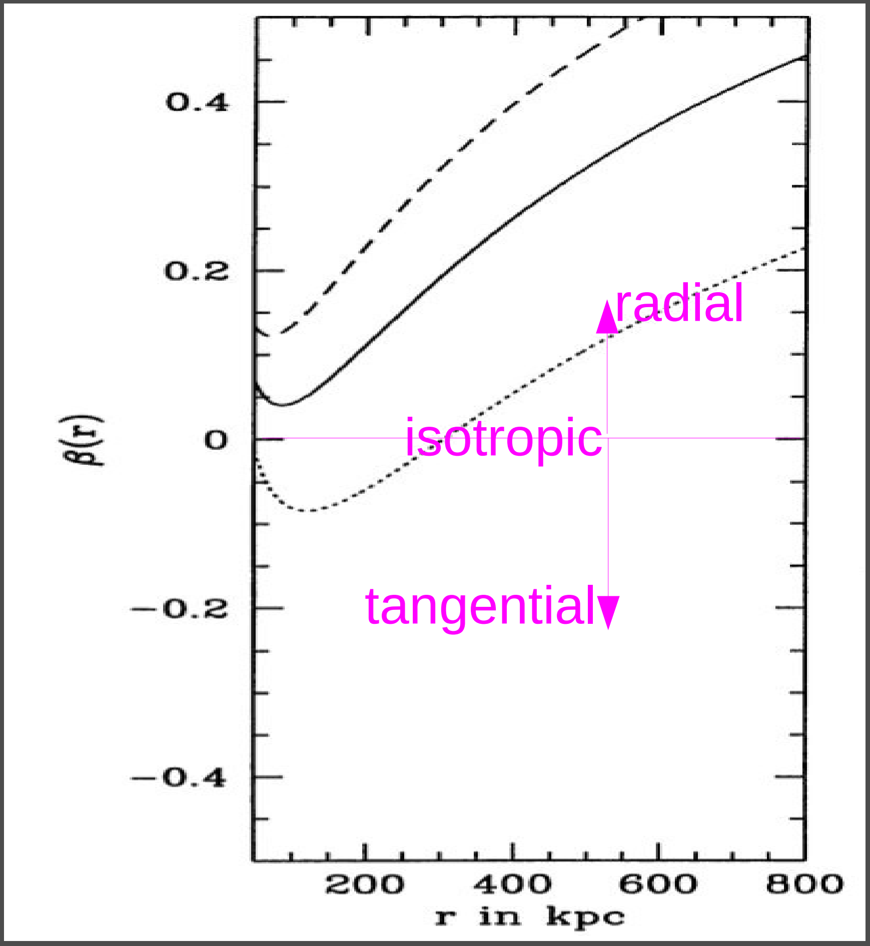
$\beta(r)_{\text{early-type/passive/red}} < \beta(r)_{\text{late-type/star-forming/blue}}$

$\beta(r)_{\text{early-type dwarfs}} > 0$ near the center (radial orbits)

β(r) for low-redshift clusters (z<0.2)

β(r) ≈ 0 near the center (isotropic orbits)

β(r) increases with distance from the center (radial orbits)



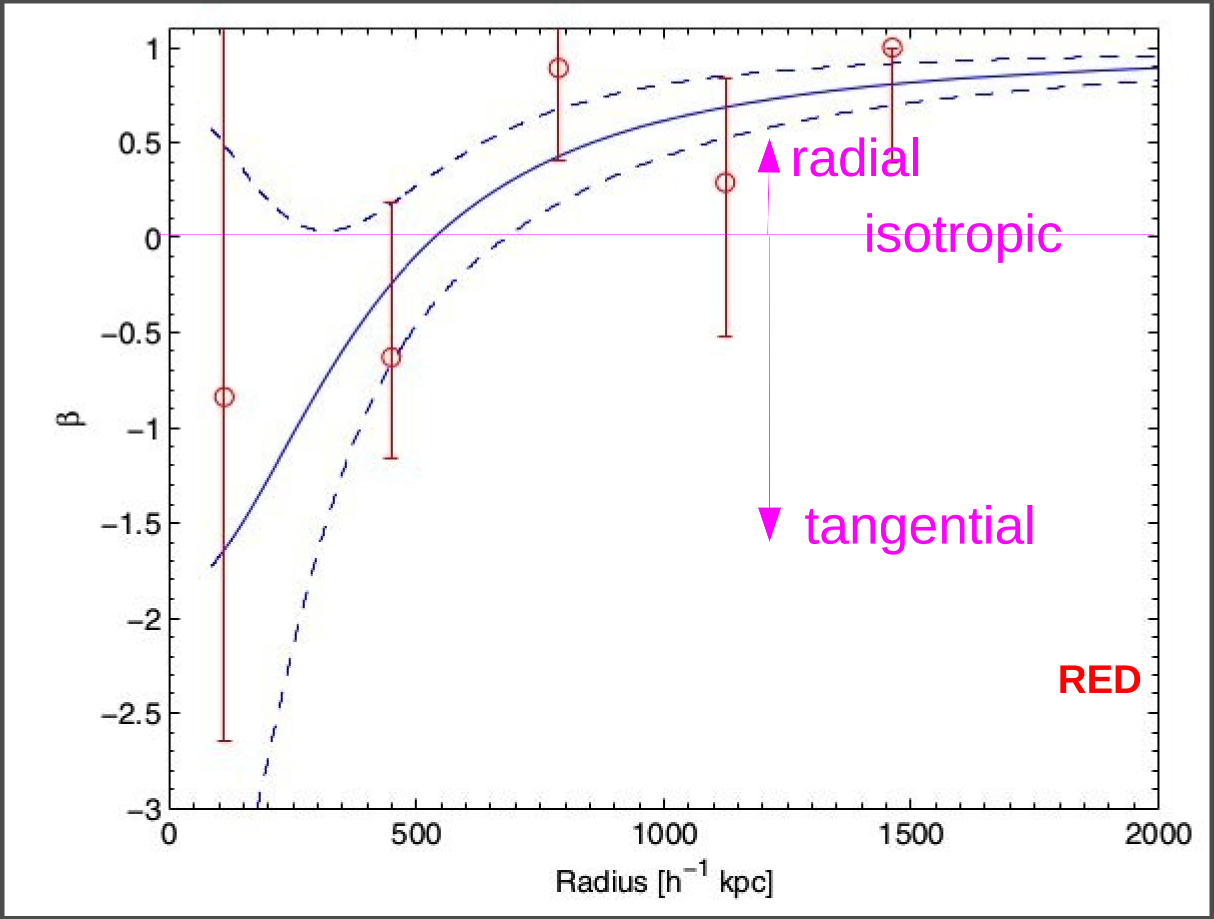
Natarajan+Kneib 96:

method: ext-M(r) from lensing

56 galaxies in one cluster (A2218)

β(r) for low-redshift clusters (z<0.2)

β(r) increases with distance from the center (radial orbits)



Lemze+ 09:

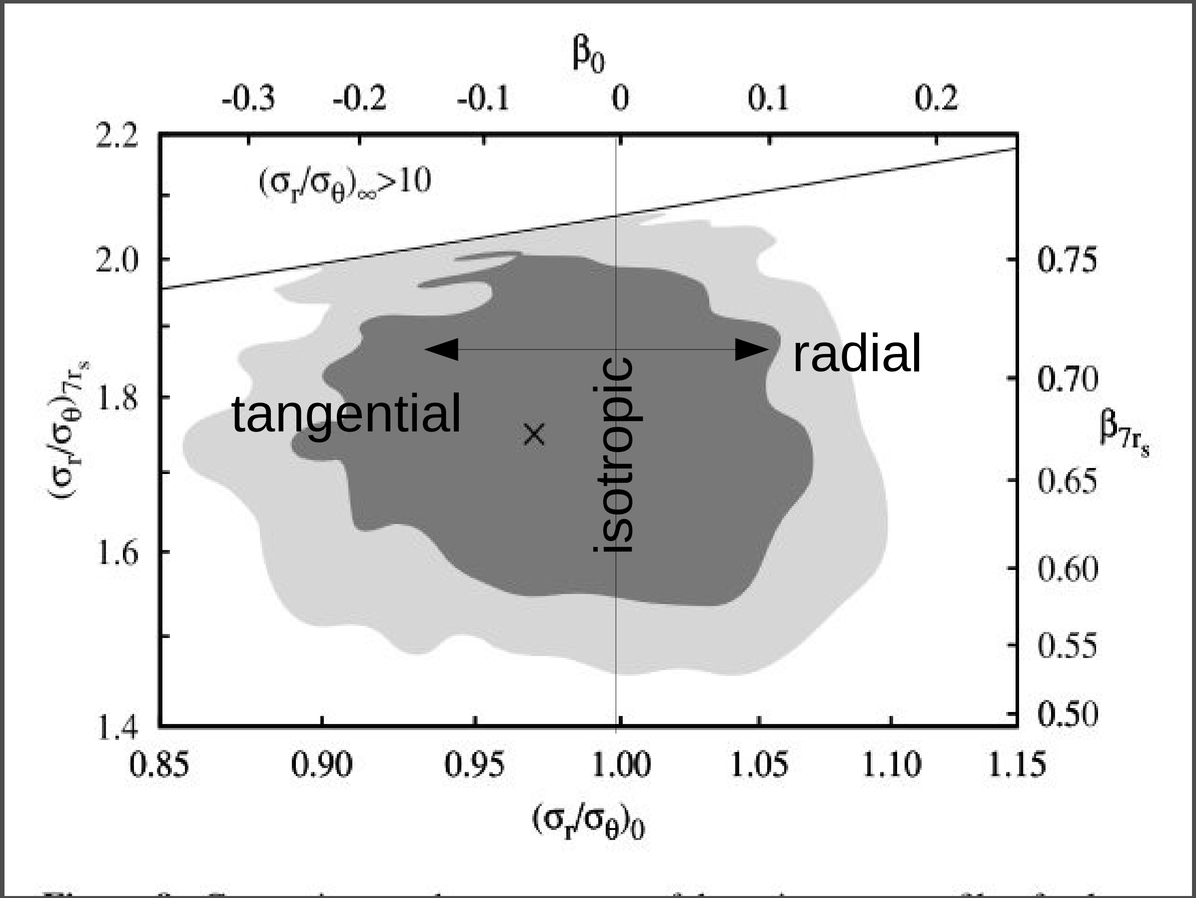
method: ext-M(r) from X-ray & lensing;

~500 galaxies in the cluster A1689

β(r) for low-redshift clusters (z<0.2)

β(r) ≈ 0 near the center (isotropic orbits)

β(r) increases with distance from the center (radial orbits)



Wojtak+Łokas 10:

method: E+L

from 66 to 365 members in each of 41 clusters:

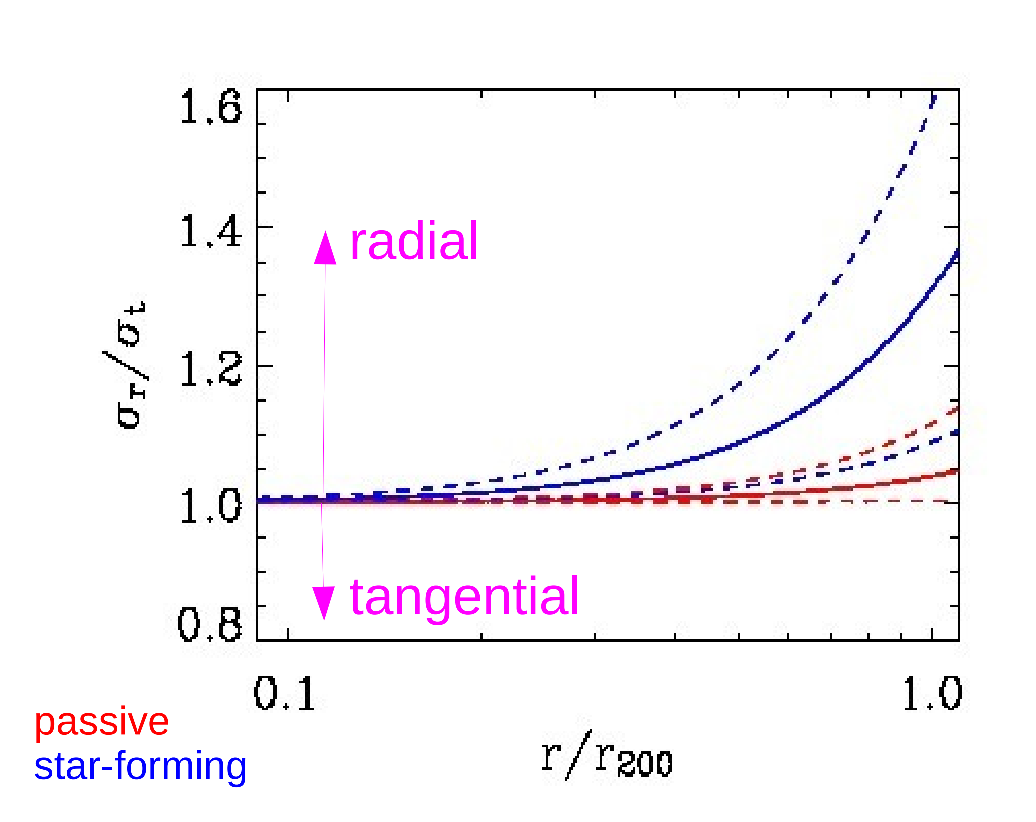
β(virial radius) vs. β(0)

β(r) for low-redshift clusters (z<0.2)

β(r) increases with distance from the center (radial orbits)

β(r) ≈ 0 at all radii for early-type/passive/red galaxies

$\beta(r)_{\text{early-type/passive/red}} < \beta(r)_{\text{late-type/star-forming/blue}}$



AB + Poggianti 09:

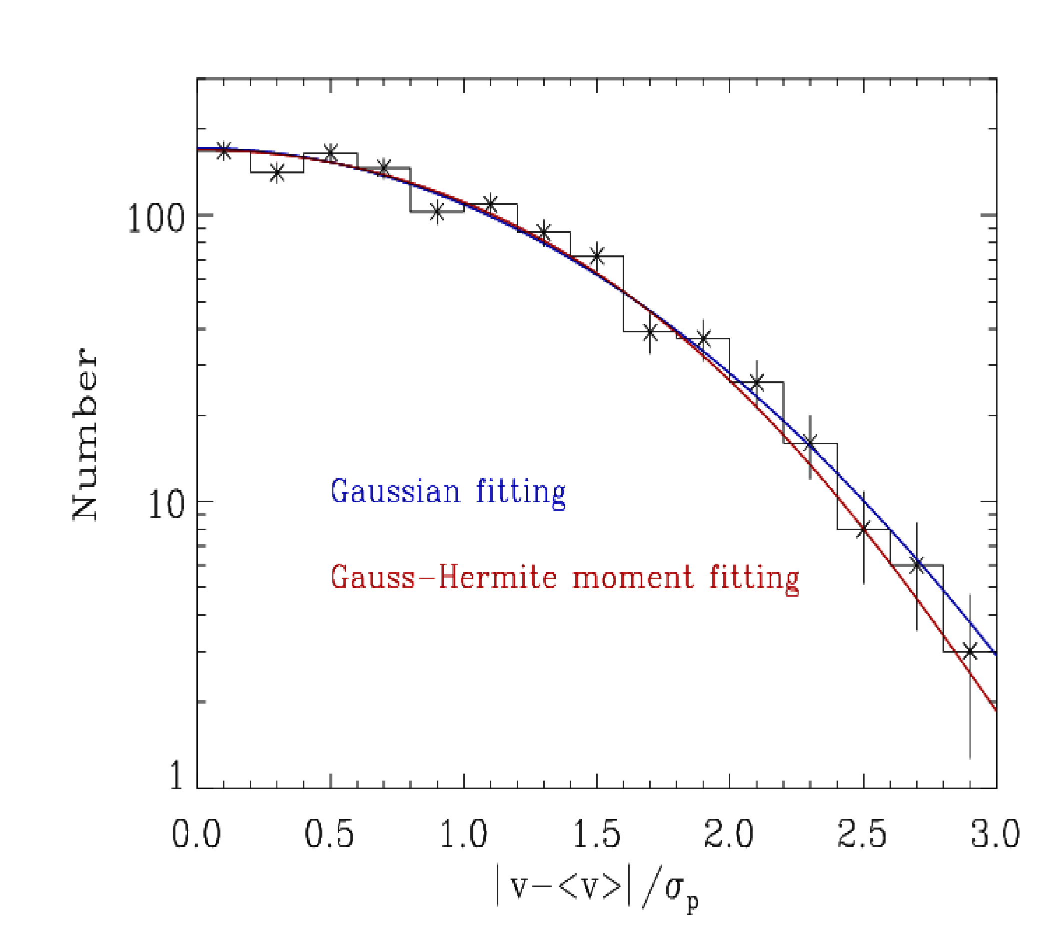
method: 2 tracers

~2600 galaxies in 59 clusters:
2200 passive, 400 star-forming
(ENACS)

$\beta = 1 - (\sigma_t/\sigma_r)^2$

β(r) for low-redshift clusters (z<0.2)

β(r) ≈ 0 at all radii for early-type/passive/red galaxies



Katgert, AB, Mazure 04:

method: v-moments

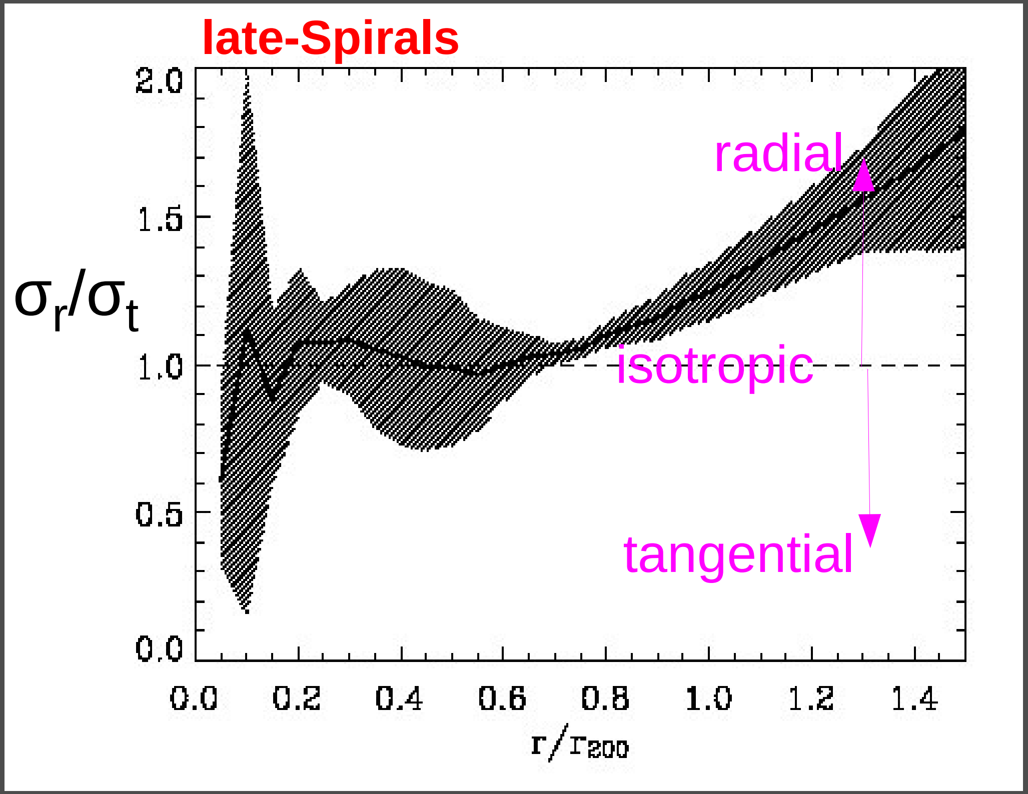
~2200 early-type galaxies in 59 clusters (ENACS)

$-0.6 \leq \beta \leq 0.1$

β(r) for low-redshift clusters (z<0.2)

$\beta(r)_{\text{early-type/passive/red}} < \beta(r)_{\text{late-type/star-forming/blue}}$

β(r) increases with distance from the center (radial orbits)



AB + Katgert 04:

method: ext-M(r) from kinematics

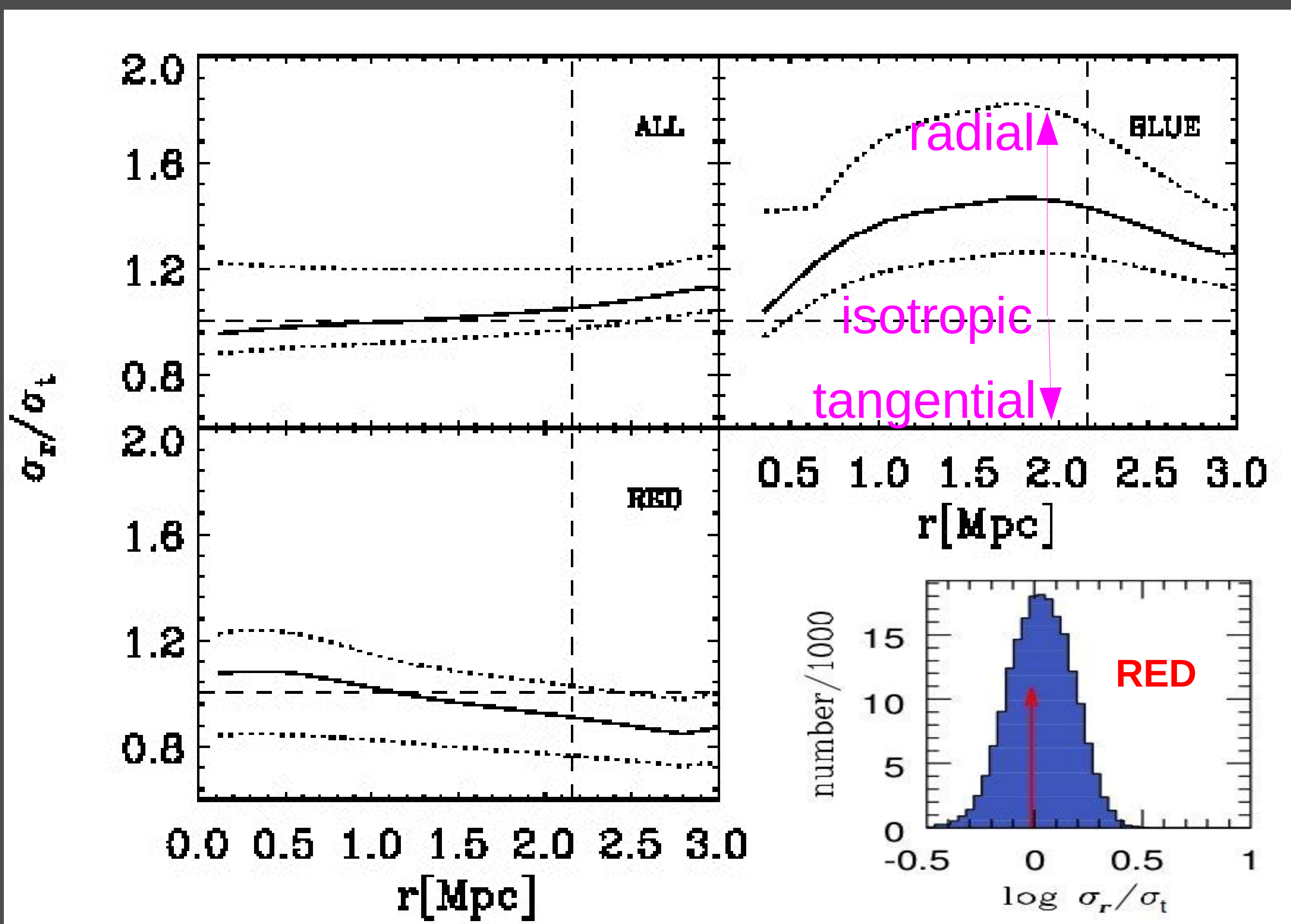
~300 Sc, Sd, Irr galaxies
in 59 clusters (ENACS)

$\beta = 1 - (\sigma_t/\sigma_r)^2$

$\beta(r)$ for low-redshift clusters (z<0.2)

$\beta(r) \approx 0$ at all radii for early-type/passive/red galaxies

$\beta(r)_{\text{early-type/passive/red}} < \beta(r)_{\text{late-type/star-forming/blue}}$



Munari, AB, Mamon 14:

methods:
1) ext-M(r) from
X-ray & lensing;
2) MAMPOSSt

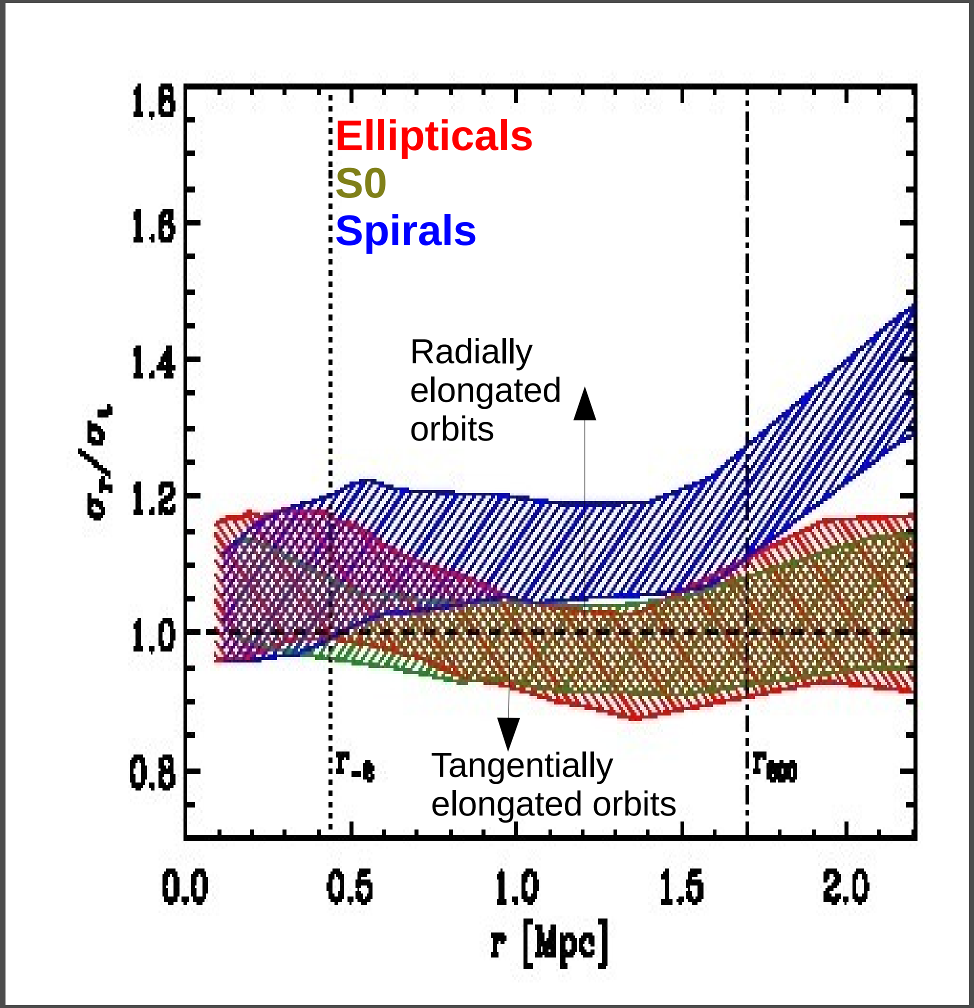
~1000 galaxies
in the cluster A2142
(~600 red, ~300 blue)

$\beta = 1 - (\sigma_t/\sigma_r)^2$

β(r) for low-redshift clusters (z<0.2)

$\beta(r) \approx 0$ at all radii for early-type (E, S0) galaxies

$\beta(r)_{\text{early-type}} < \beta(r)_{\text{late-type (S)}}$



Mamon, Cava, AB et al. (2019, in prep.)

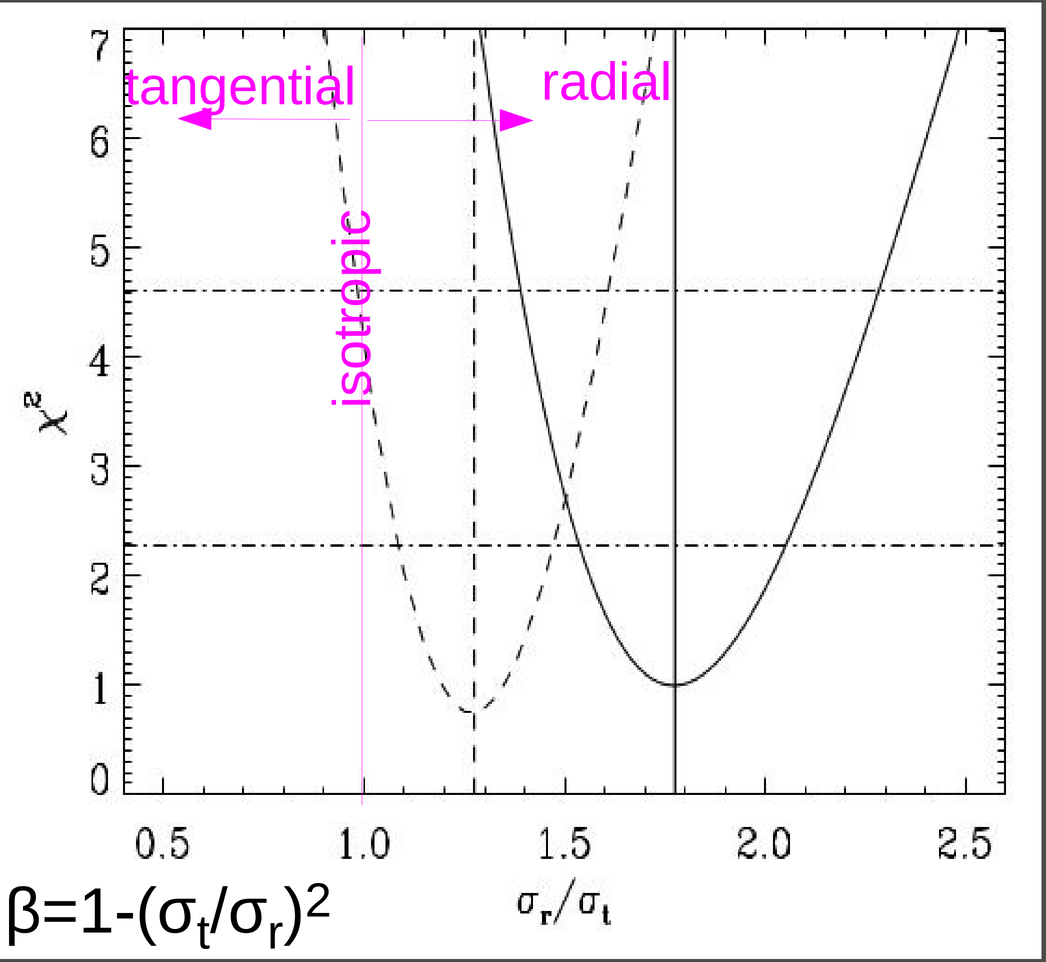
method:
1) MAMPOSSt
2) ext-M(r) from kinematics

~5000 galaxies
in a stack of 54 clusters
(3 types: E, S0, S)

$\beta = 1 - (\sigma_t/\sigma_r)^2$

β(r) for low-redshift clusters (z<0.2)

$\beta(r)_{\text{early-type dwarfs}} > 0$ near the center (radial orbits)



Adami+ 09:

method: ext-M(r) from kinematics

64 $21<m_R<23$ early-tpye dwarfs in the Coma cluster central region

$\beta(r)$ for medium-redshift clusters (0.2<z<0.8)

$\beta(r) > 0$ (radial orbits), not always ≈ 0 at $r \rightarrow 0$ *≠ from low-z!*

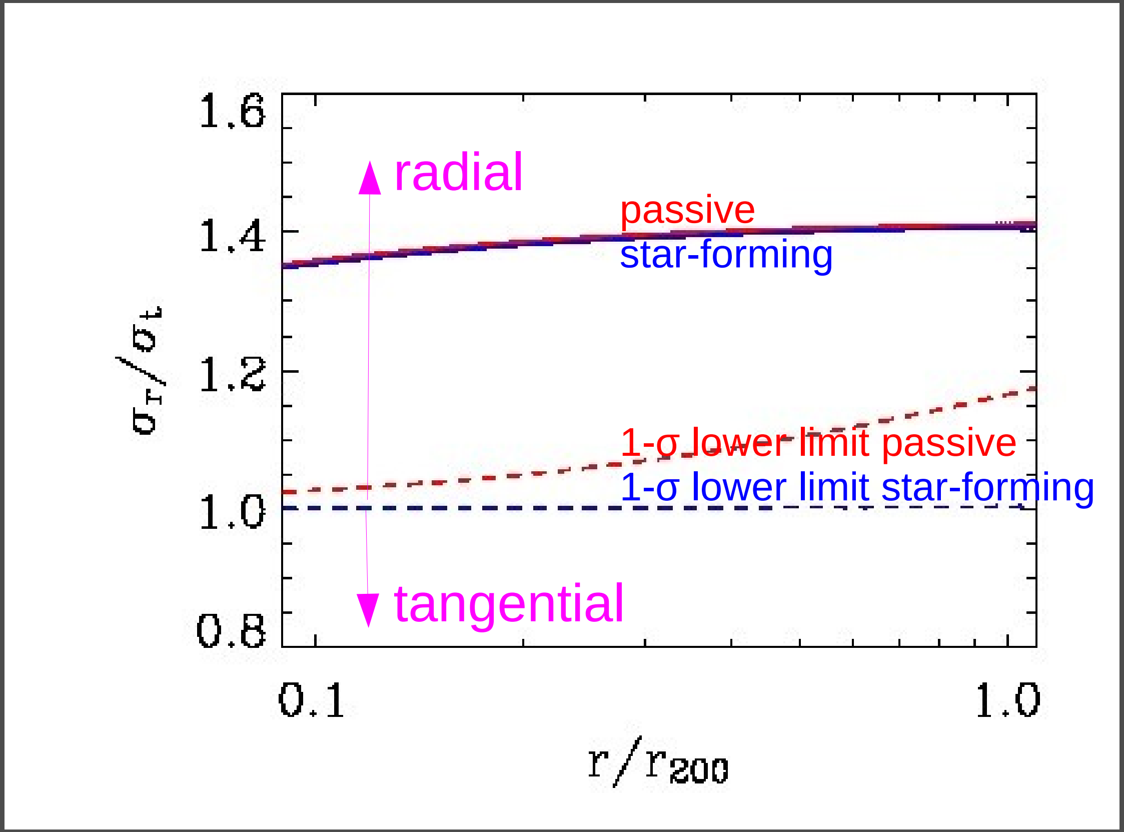
$\beta(r)_{\text{early-type/passive/red}} \approx \beta(r)_{\text{late-type/star-forming/blue}}$ *≠ from low-z!*

$\beta(r \rightarrow 0)_{\text{low-mass passive}} < 0 < \beta(r \rightarrow 0)_{\text{high-mass passive}}$ *≠ from low-z!*

β(r) for medium-redshift clusters (0.2<z<0.8)

$\beta(r) > 0$ (radial orbits), not always ≈ 0 at $r \rightarrow 0$

$\beta(r)_{\text{early-type/passive/red}} \approx \beta(r)_{\text{late-type/star-forming/blue}}$



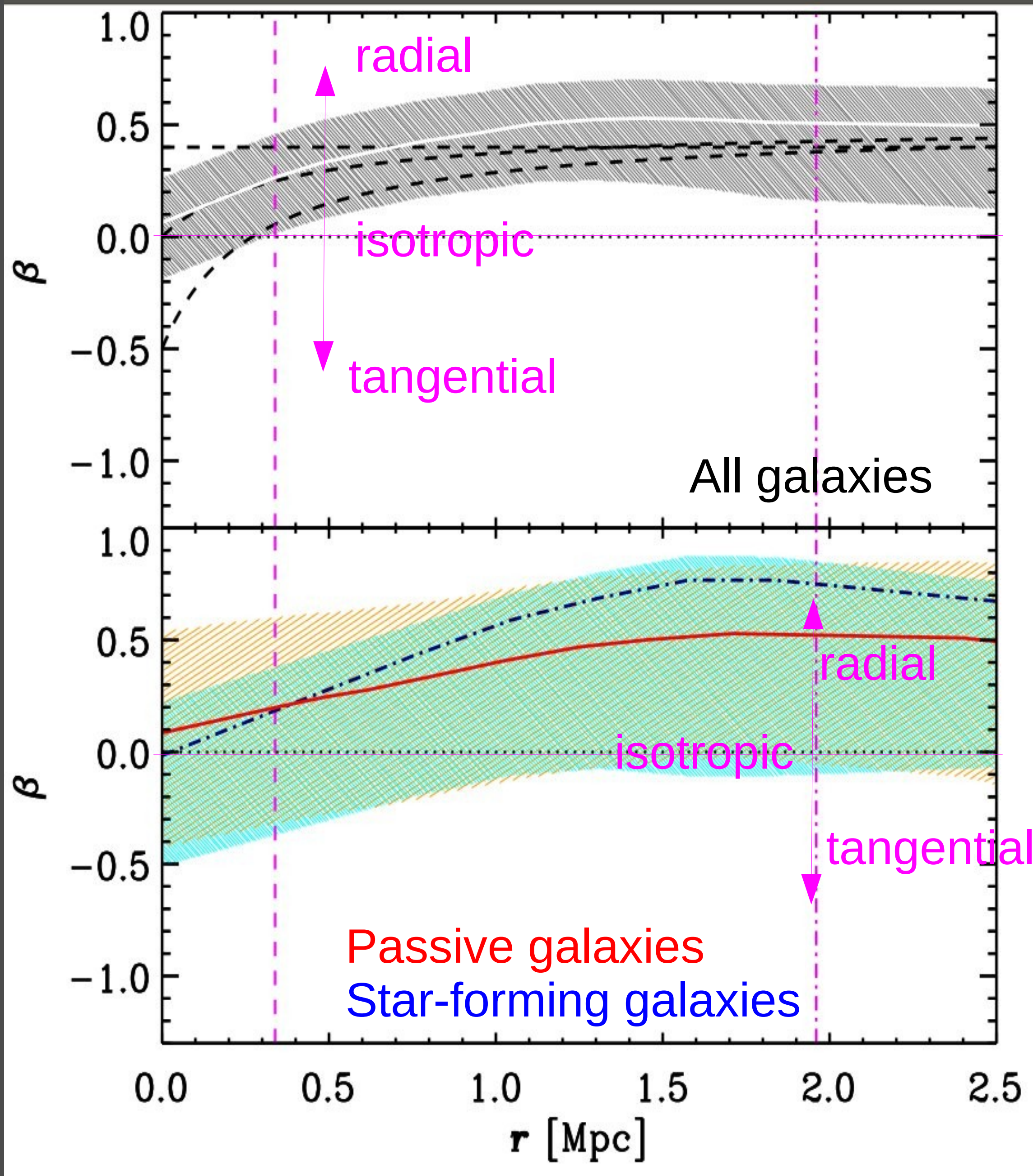
AB + Poggianti 09:

method: 2 tracers

~600 galaxies in 19 clusters
at 0.39<z<0.79 (EDisCS):
~350 passive, ~250 star-forming

$\beta = 1 - (\sigma_t/\sigma_r)^2$

β(r) for medium-redshift clusters (0.2<z<0.8)



$\beta(r) > 0$ (radial orbits)

$\beta(r)_{\text{early-type/passive/red}} \approx \beta(r)_{\text{late-type/star-forming/blue}}$

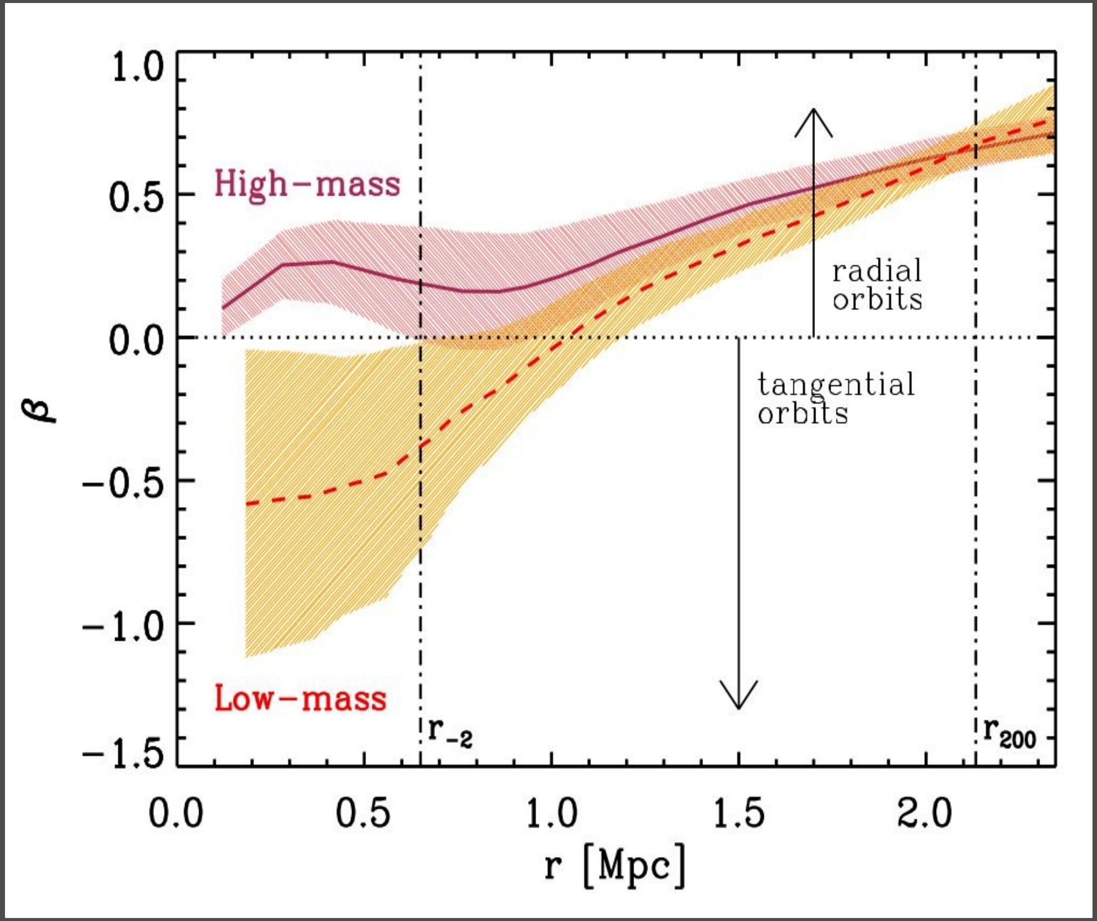
AB+14:

methods:
1) MAMPOSSt
2) ext-M(r) from lensing

~600 galaxies in the cluster MACS1206 at z=0.44 (CLASH-VLT):
~400 passive,
~200 star-forming

β(r) for medium-redshift clusters (0.2<z<0.8)

$$\beta(r \to 0)_{\text{low-mass passive}} < 0 < \beta(r \to 0)_{\text{high-mass passive}}$$



Annunziatella+15:

method: ext-M(r) from Lensing

~1000 galaxies in the cluster A209 at z=0.21 (CLASH-VLT):

~500 with stellar mass $<10^{10}$ $M_\odot$

~500 with stellar mass $>10^{10}$ $M_\odot$

$\beta(r)$ for high-redshift clusters (0.8<z<1.2)

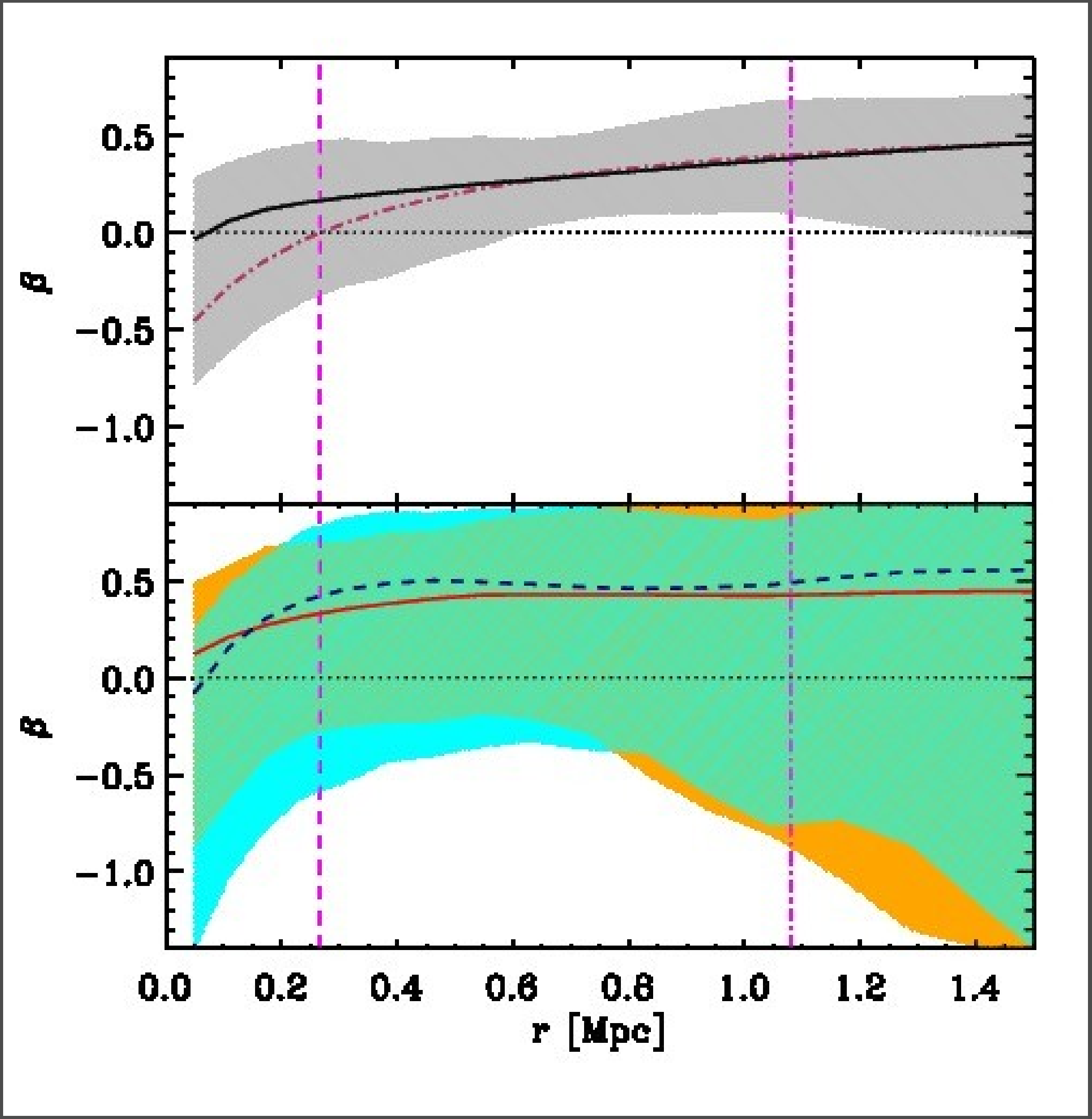
$\beta(r) \approx 0$ near the center (isotropic orbits) *= low-z*

$\beta(r)$ increases with distance from the center (radial orbits) *= low-z*

$\beta(r)_{\text{early-type/passive/red}} \approx \beta(r)_{\text{late-type/star-forming/blue}}$ *≠ from low-z!*

= medium-z

β(r) for high-redshift clusters (0.8<z<1.2)



AB+ 16:

methods:
1) MAMPOSSt
2) ext-M(r) from kinematics

~400 galaxies in
10 clusters at 0.8<z<1.2
(GCLASS):
~270 passive
~120 star-forming

Interpretation:

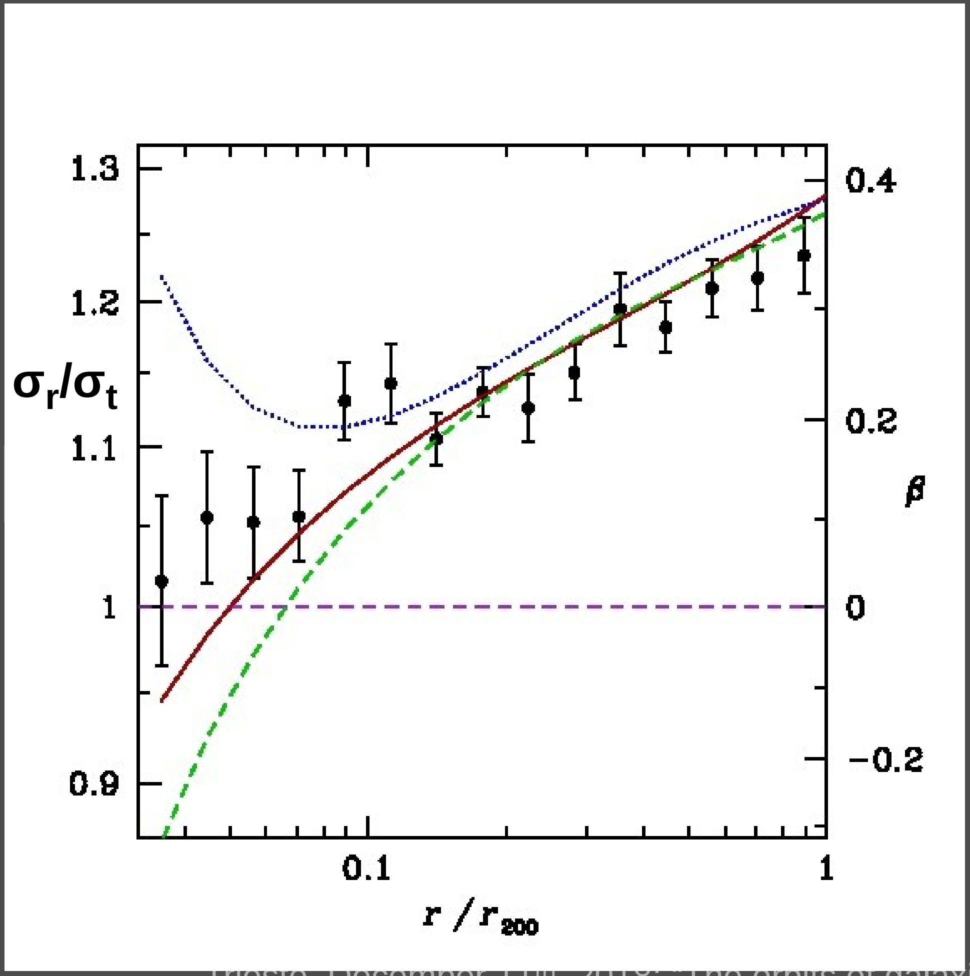
what do the orbits of galaxies in clusters tell us about the evolution of clusters and clusters of galaxies?

Theoretical interpretation

The average shape of clusters β(r)

seen at all z

On the average β(r→0)≈0 and increasing outwards (radial orbits):



Same shape for DM particles: its origin must be in collisionless dynamics.

Average β(r)
for 93 simulated halos at low-z
(Mamon, AB, Murante 2010)

Theoretical interpretation

The origin of the shape of β(r)

β(r) ≈ 0 near the center (isotropic orbits)
β(r) increases with distance from the center (radial orbits)

Galaxies near the cluster center enter the cluster before the last epoch of violent relaxation, so their orbits have become isotropic due to collective collisions *(Lapi+Cavaliere 11)*

In the following phase of slow-accretion, clusters grow inside-out (van der Burg+15) and the external galaxies retain memory of their infalling, mostly radial, orbits *(Lapi+Cavaliere 11)*

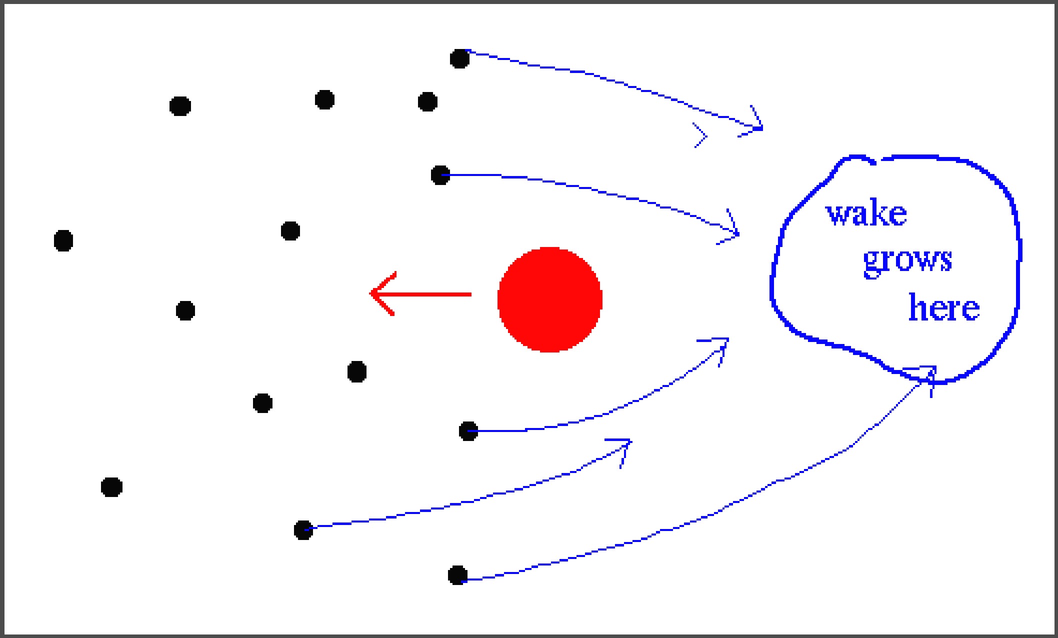
Theoretical interpretation

The evolution of $\beta(r)$ for early-type galaxies

z<0.2: $\beta(r)_{\text{early-type/passive/red}} < \beta(r)_{\text{late-type/star-forming/blue}}$

0.2<z<1.2: $\beta(r)_{\text{early-type/passive/red}} \approx \beta(r)_{\text{late-type/star-forming/blue}}$

Galaxies become passive before their orbits in the external regions become isotropic. Dynamical friction might explain the long timescale



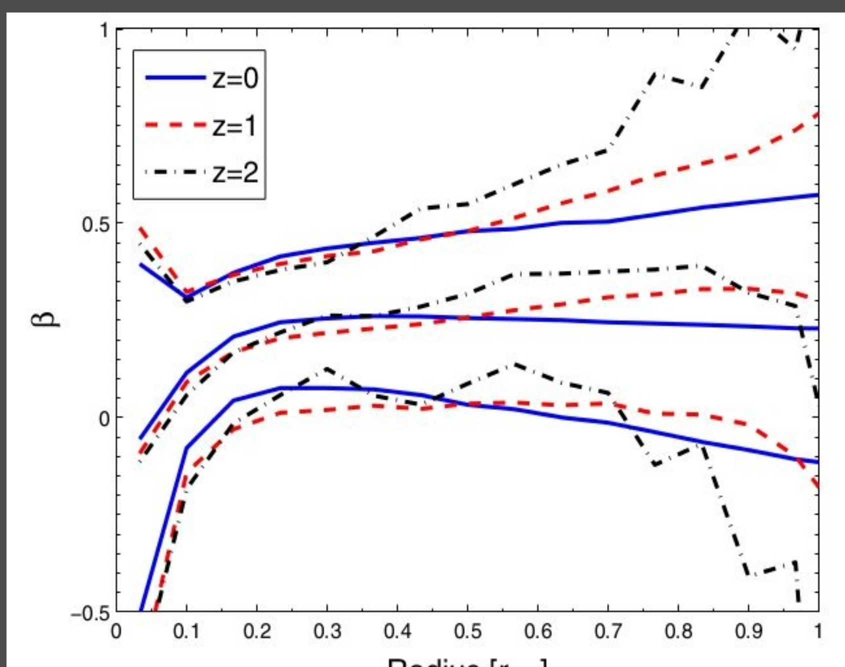
Theoretical interpretation

The global evolution of β(r) with z

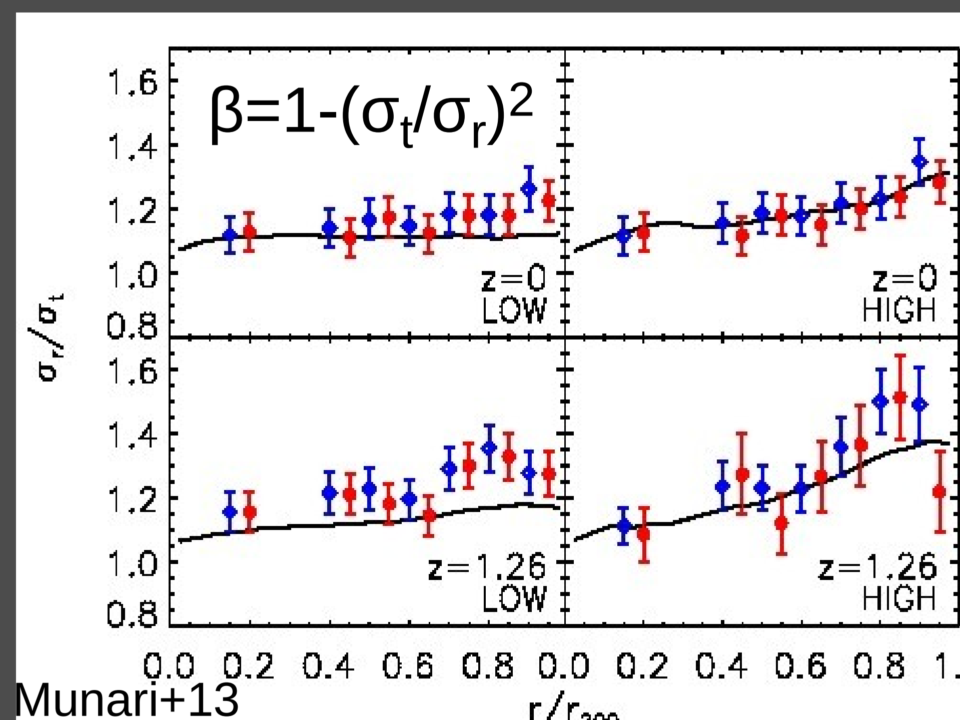
z<0.2: $\beta(r)_{\text{early-type/passive/red}} < \beta(r)_{\text{late-type/star-forming/blue}}$

0.2<z<1.2: $\beta(r)_{\text{early-type/passive/red}} \approx \beta(r)_{\text{late-type/star-forming/blue}}$

This implies an overall β decrease with time for the full population of cluster galaxies (early+late, red+blue, passive+star-forming) qualitatively consistent with cosmological simulation results



Lemze+12



Munari+13

Theoretical interpretation

The different $\beta(r)$ for low-mass and dwarf early-types

z=0.21: $\beta(r \rightarrow 0)_{\text{low-mass passive}} < 0 < \beta(r \rightarrow 0)_{\text{high-mass passive}}$

Low-z: $\beta(r)_{\text{early-type dwarfs}} > 0$ near the center

Not in contradiction!

z=0.21 low-mass early-type galaxies have $\log M_*/M_\odot \gtrsim 9.0$

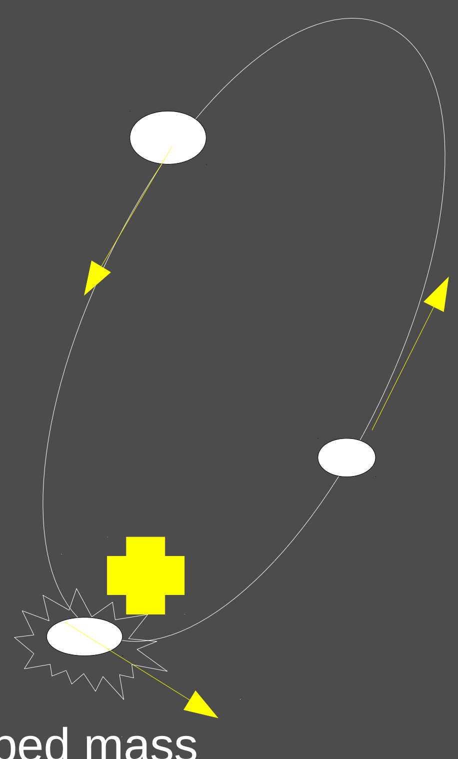
low-z dwarf early-type galaxies have $\log M_*/M_\odot \lesssim 9.0$

Theoretical interpretation

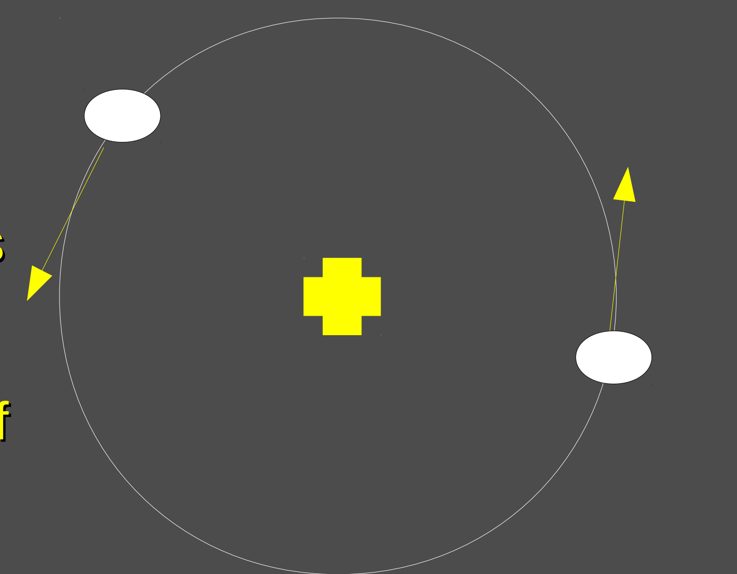
The different $\beta(r)$ for low-mass and dwarf early-types

$z=0.21$: $\beta(r\rightarrow 0)_{\text{low-mass passive}} < 0 < \beta(r\rightarrow 0)_{\text{high-mass passive}}$

Low-z: $\beta(r)_{\text{early-type dwarfs}} > 0$ near the center



Low-mass galaxy on radial orbit suffers tidal stripping by the cluster gravitational field. Part of its mass is lost to the Intra-Cluster Light. It emerges as a dwarf galaxy still on radial orbit.



Low-mass galaxies on tangential orbits do not lose mass and pass the mass-selection

Prospects:

what next?

Will allow determination of β(r) for ~12 medium-z clusters with ~500 members each

CLASH-VLT: A VIMOS Large Programme to Map the Dark Matter Mass Distribution in Galaxy Clusters and Probe Distant Lensed Galaxies

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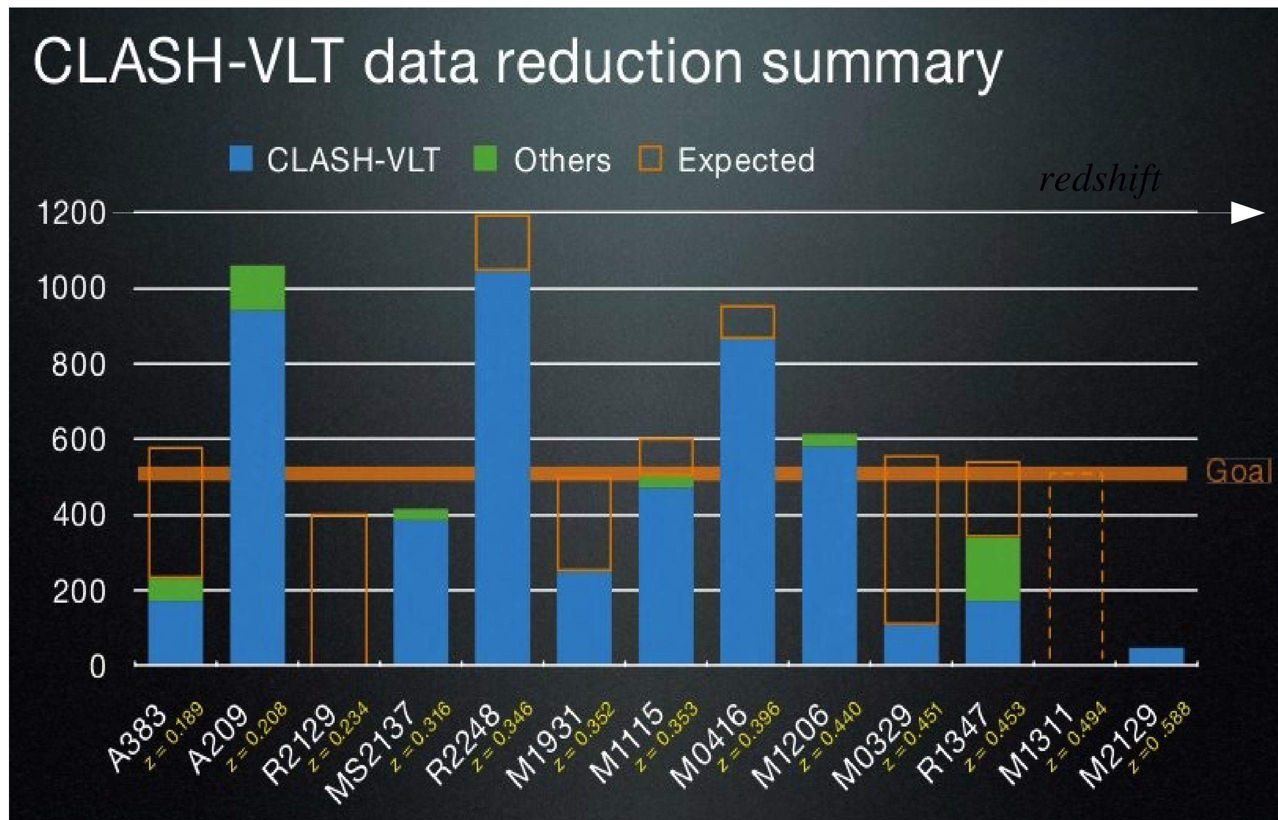

Rosati et al. 2014, The Messenger 158, 48

GOGREEN

Gemini Observations of Galaxies in Rich Early Environments

Project Description

GOGREEN will use the upgraded GMOS detectors on Gemini North and South to obtain multiobject spectroscopy of galaxies in 21 clusters and groups in the redshift range $1<z<1.5$. Targets are selected primarily from deep imaging at 3.6 micron from IRAC (exisiting) and in z-band, either from existing data or obtained as part of GOGREEN itself.

Each cluster will be observed either with 3 masks of 5 hours each, or 5 masks of 3 hours each. The faintest objects may be assigned to all masks, ensuring a maximum of 15h exposure. The masks for a given cluster will generally be spread over several semesters, so that slits can be reassigned after some set of criteria (TBD) have been achieved. The choice of 3x5 versus 5x3 is determined by the expected number of new members. Poor groups, and clusters with existing spectroscopy, will generally only need 3 masks. More information on the Survey strategy is available here.

Spectroscopy is planned for the R150 grating and a red blocking filter, allowing up to two tiers per mask. Imaging will generally be done in queue mode, while spectroscopy will be done as much as possible in Priority Visitor mode. Spectroscopy on the North will have to wait for the detector upgrade. In the meantime, deep imaging will be obtained from the South where possible, with perhaps shorter exposures (for good mask design) obtained from the North once the detectors are in place.

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Will allow determination of $\beta(r)$ for stack of ~500 galaxies in ~21 clusters/groups at $1<z<1.5$