ASTRO@TS
Trieste, 25.06.2019

Dynamical Analysis of Galaxy Clusters

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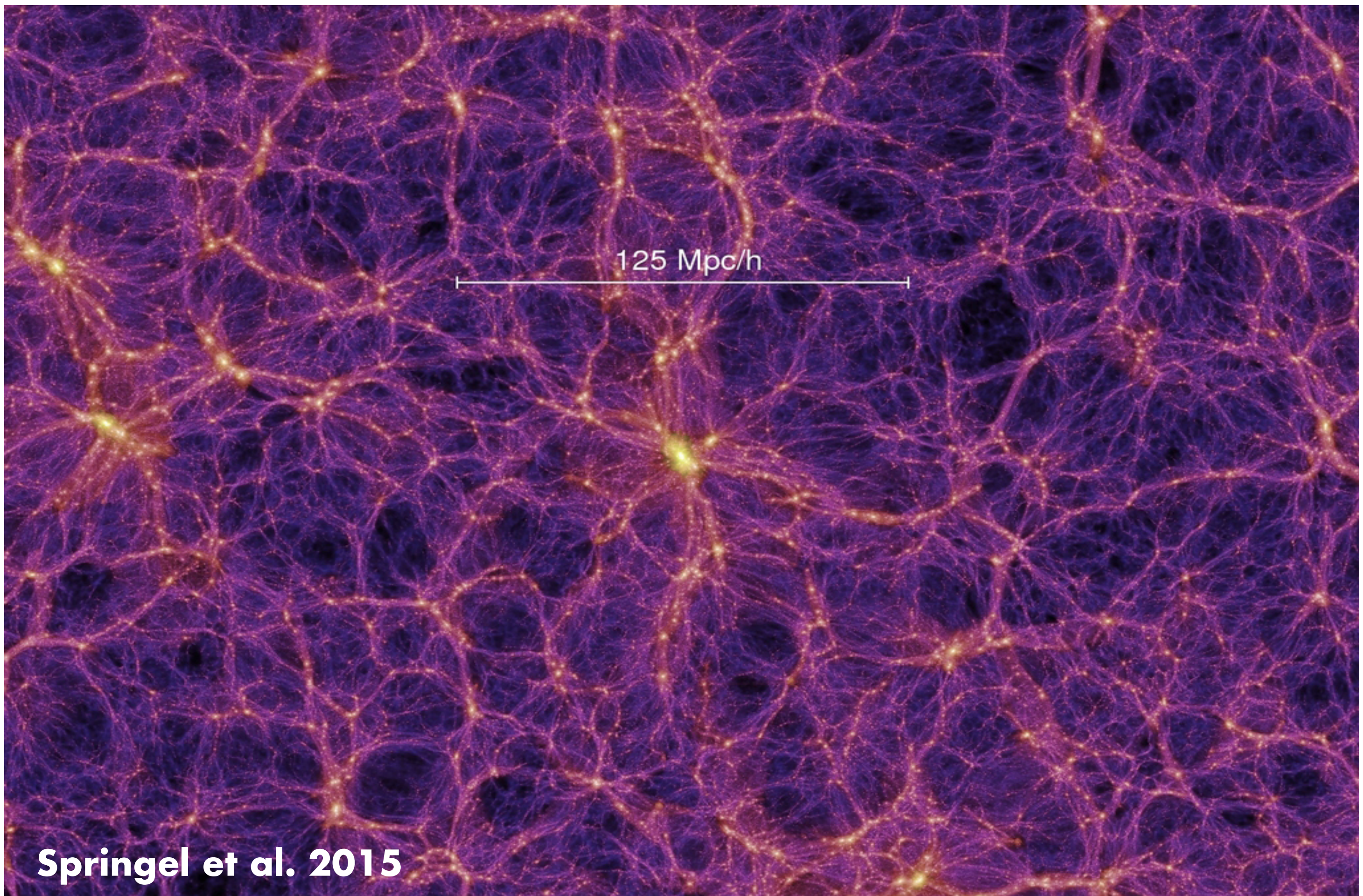
Galaxy Clusters

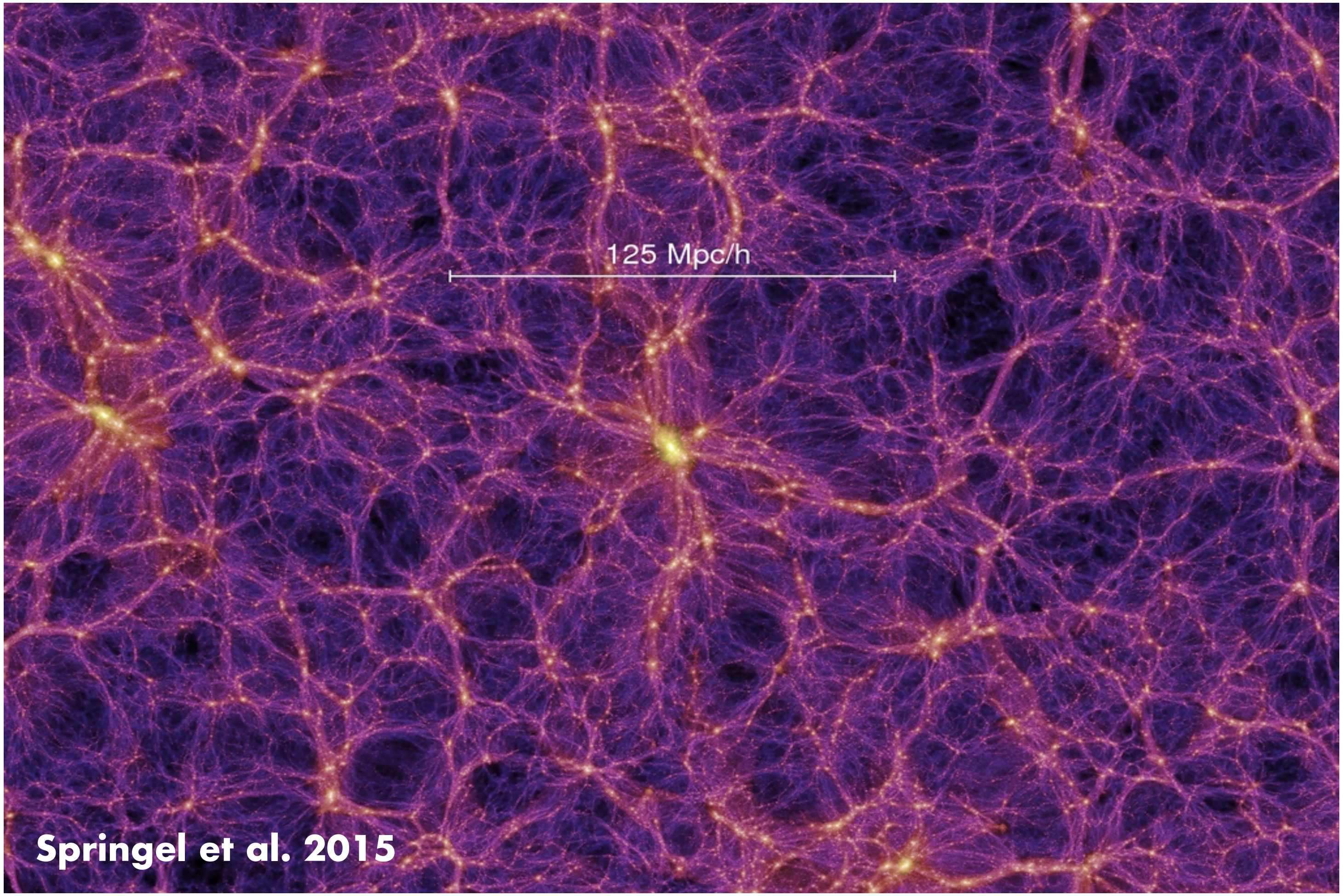
What are Galaxy Clusters?

Matter is distributed along filaments, and galaxy clusters lie at the intersections



Galaxy Clusters

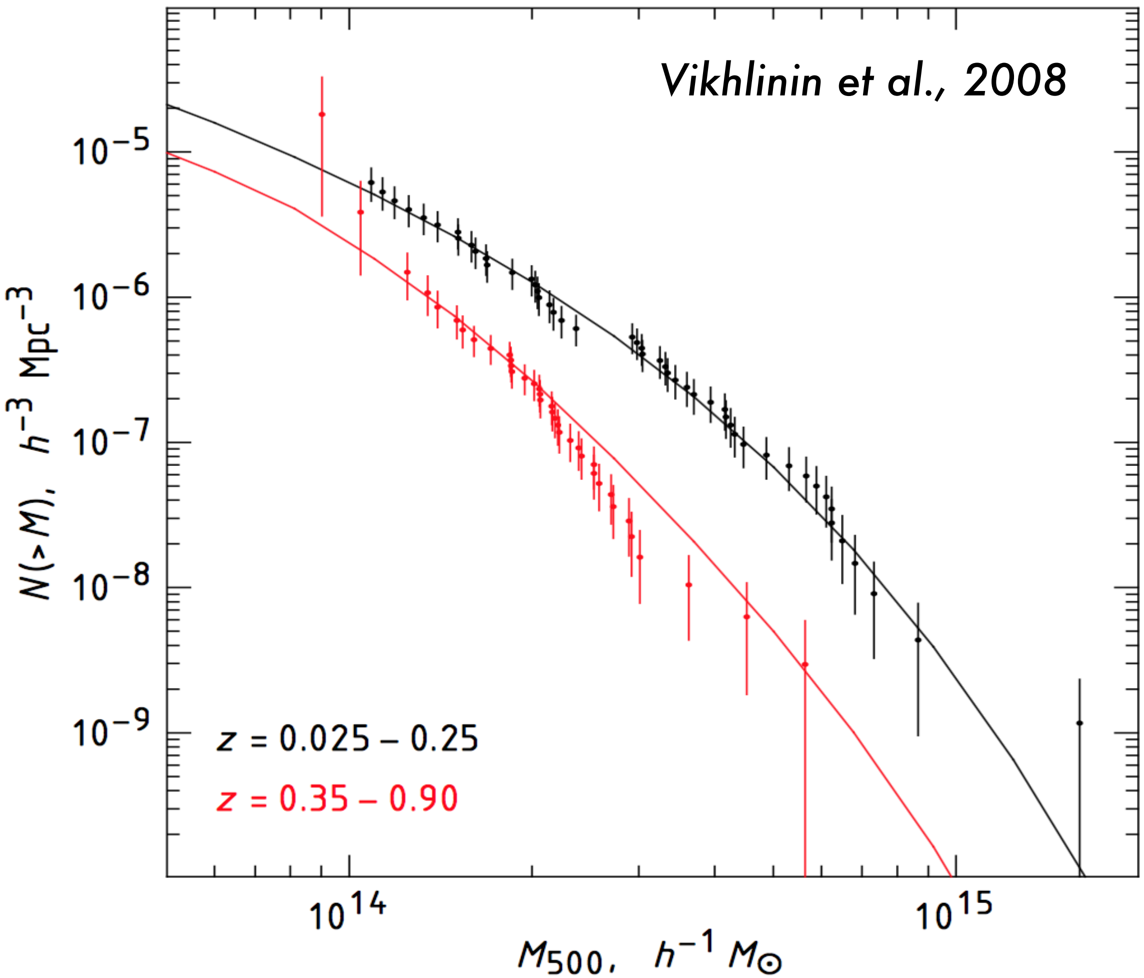
Why are they important?



Galaxy Clusters

Why are they important?

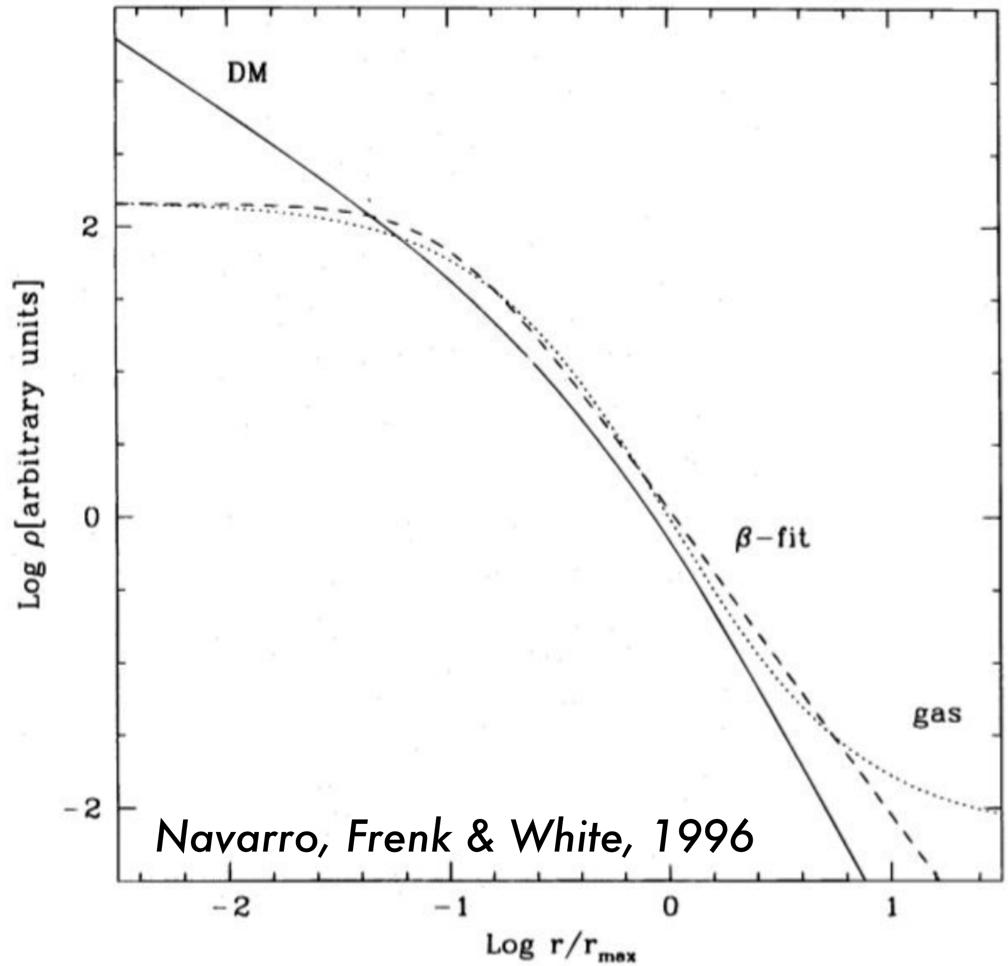
- **Evolution in the number density of galaxy clusters above a given mass, as a function of redshift (mass function) traces the growth of structure**



Galaxy Clusters

Why are they important?

- **Mapping the distribution of mass inside clusters of galaxies helps us understand:**
  - **the nature of dark matter**
  - **the way halos formed**



Navarro, Frenk & White, 1996

Galaxy Clusters

Why are they important?

- **Prevalence of red, early-type, passively-evolving galaxies in clusters**

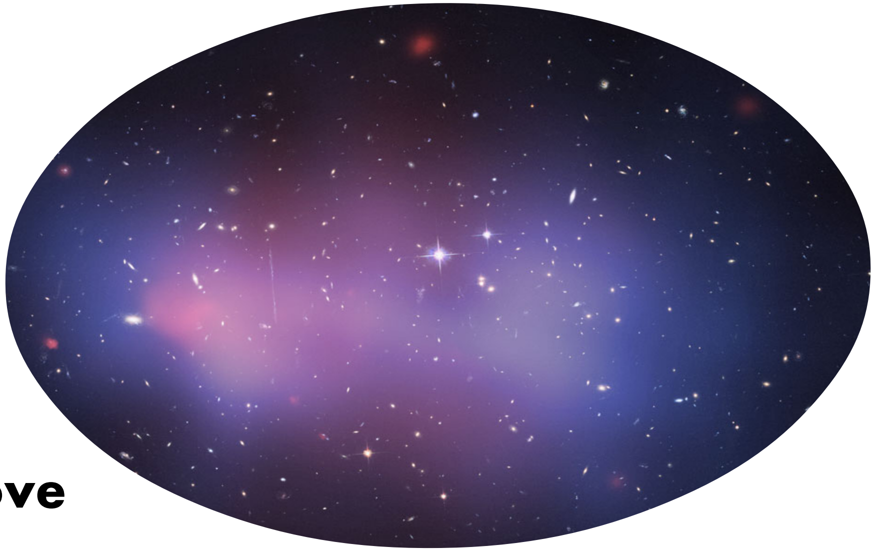
  ↓

  - **Information on cluster formation and evolution**
  - **Information on physical processes that speed up galaxy evolution by removing their gas and changing their internal structure, shaping the orbits of the galaxies**

Aim

Measurement of Dynamical Masses

- **Impact on precision of Cluster Cosmology**
- **Understanding of the nature of dark matter and halo formation**
- **Density of clusters above a given mass as a function of redshift – cosmological probe**

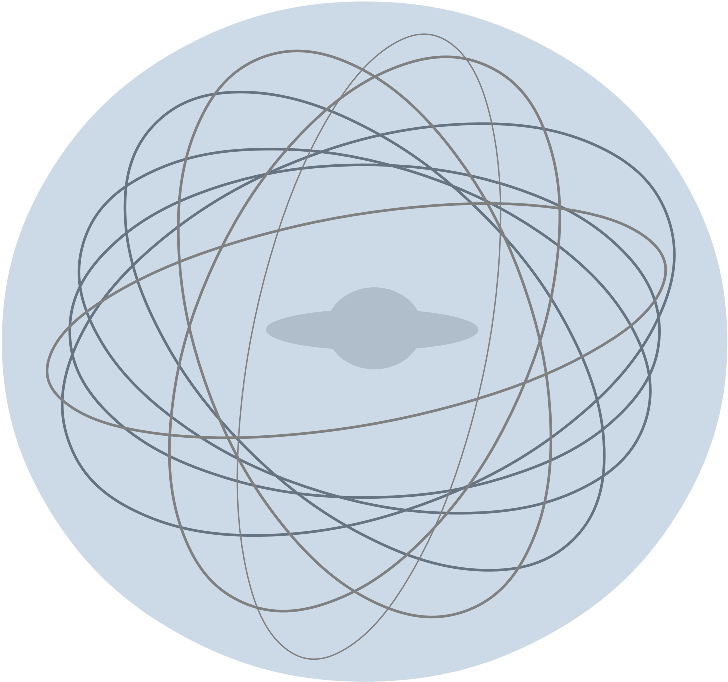


Orbital analysis

- **Information on cluster formation and evolution**
- **Processes shaping the orbits of the galaxies**

Theoretical Framework

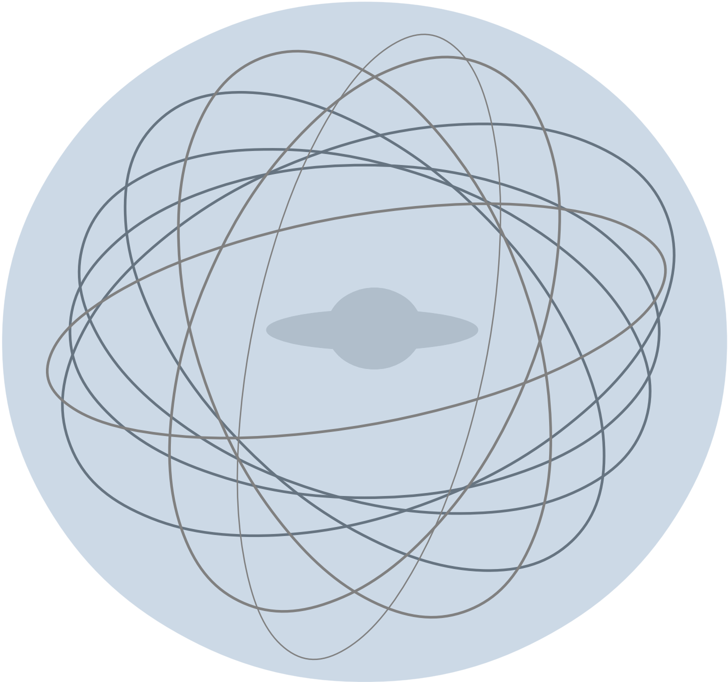
Dynamical analysis



Theoretical Framework

Dynamical analysis: the Jeans equation

$$\frac{GM(r)}{r} = -\sigma_r^2 \left(\frac{d \ln n}{d \ln r} + \frac{d \ln \sigma_r^2}{d \ln r} + 2\beta \right)$$



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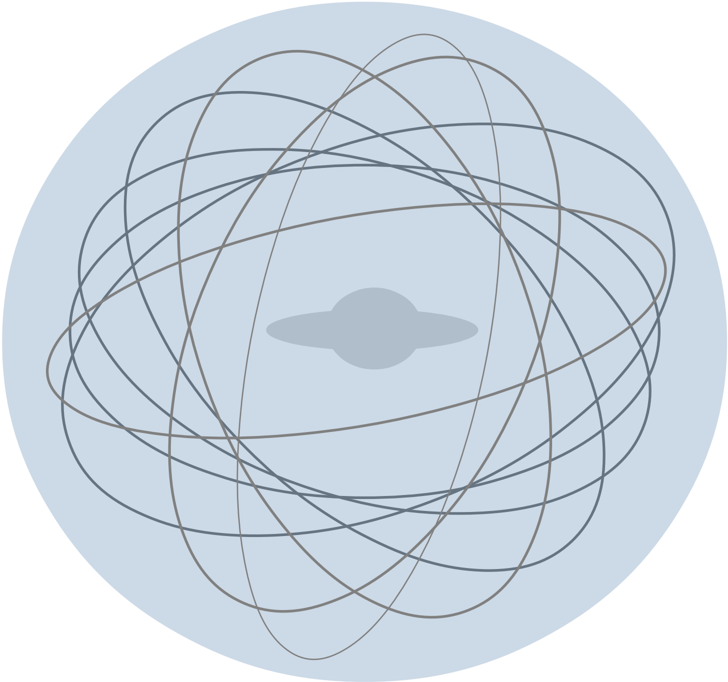

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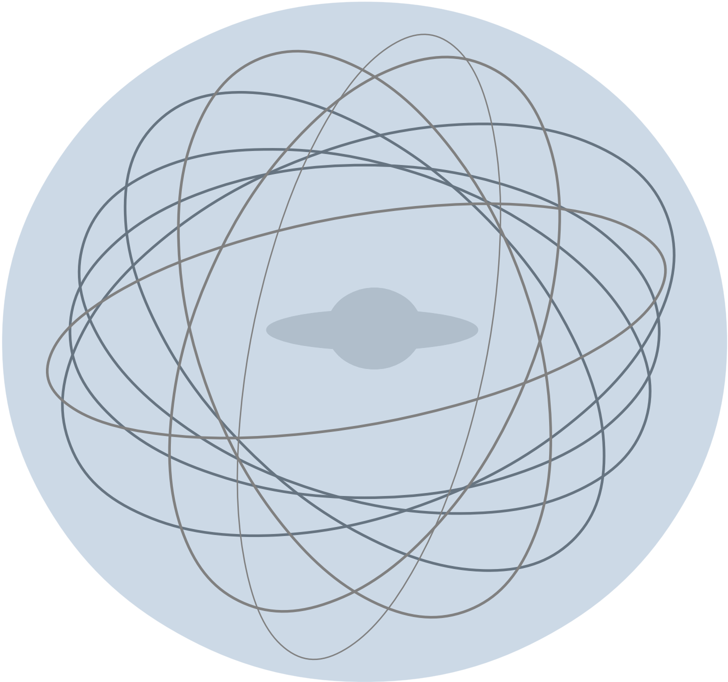

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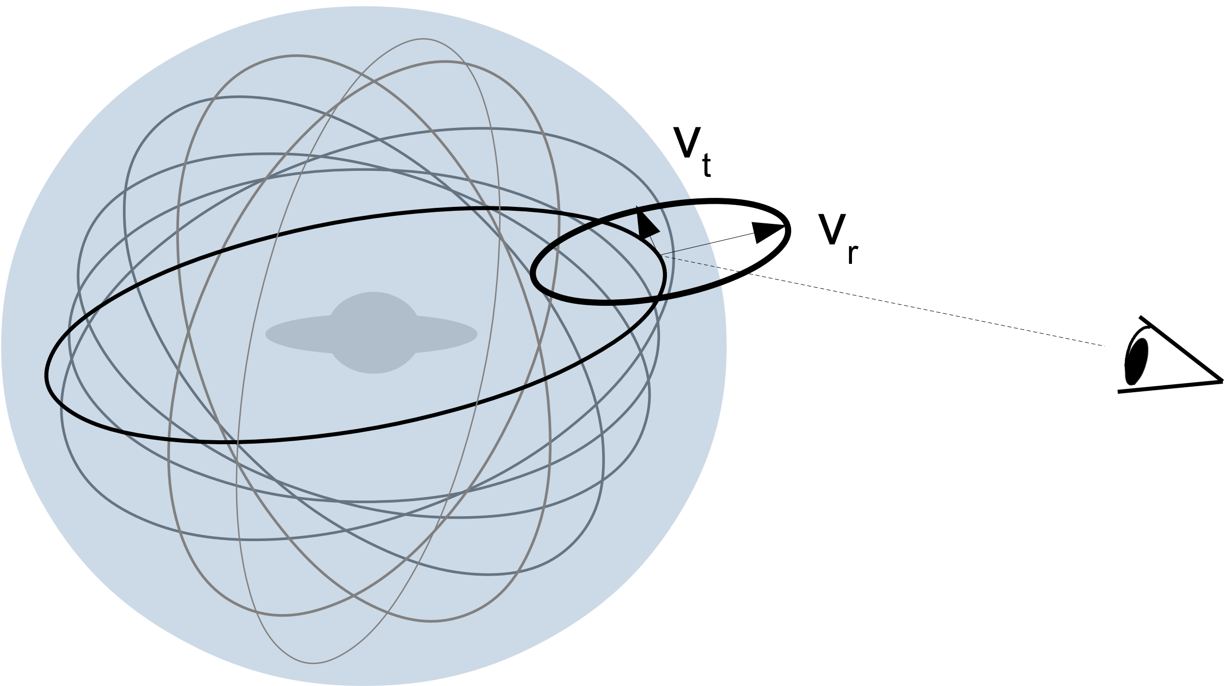

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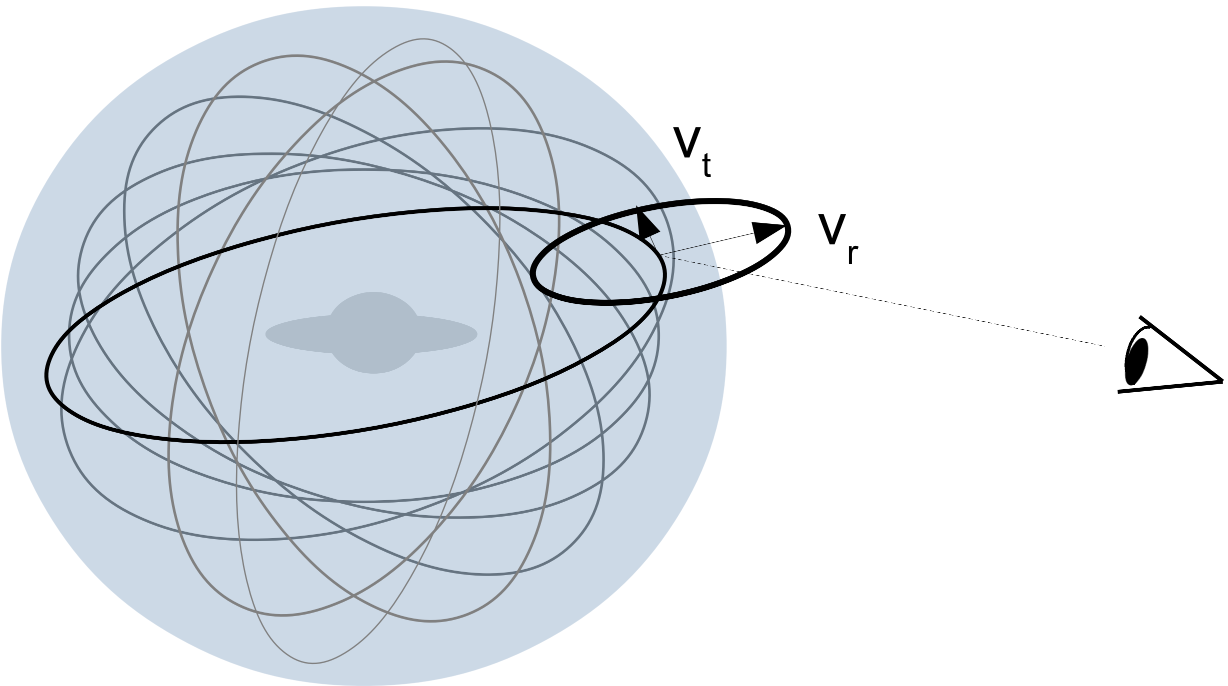
- **Mass – orbit degeneracy**



Theoretical Framework

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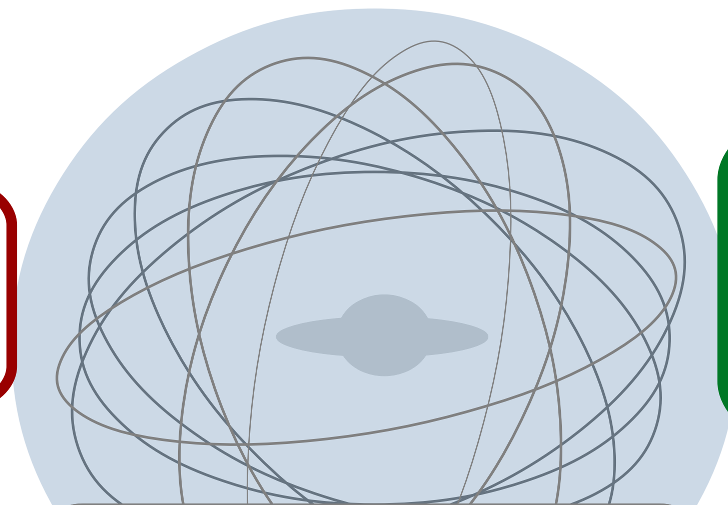
MASS PROFILE

M(R)



VELOCITY ANISOTROPY PROFILE

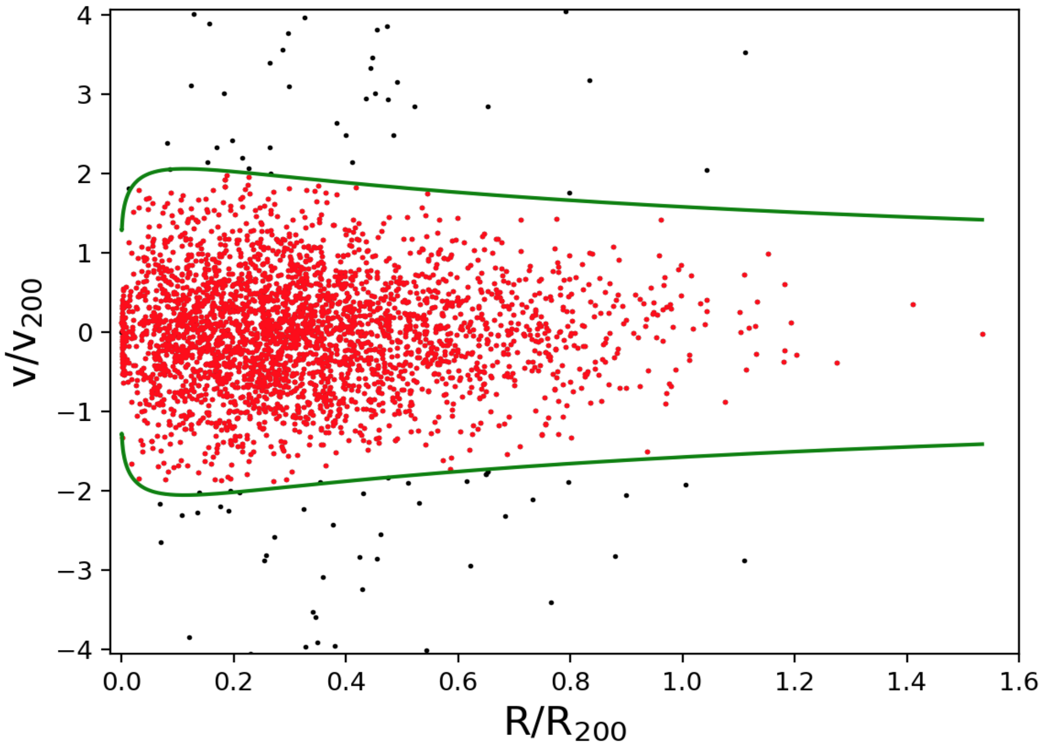
β(R)

Find combination of Mass and Orbital Profiles that make observed data plausible

SPT-SZ Cluster Sample

- Clusters observed with the South Pole Telescope (SPT), selected through their Sunyaev Zel'dovich Effect (SZE) signature
- Spectroscopic follow-up of the clusters from Gemini, Magellan and VLT (Ruel+14, Bayliss+16)
- 110 clusters up to z ~ 1.3
- ~ 4700 spectra; ~ 3500 members; ~ 3000 nELG

SPT-SZ Cluster Sample



Capasso+19 (MNRAS, 482, 1043)

- **Use the full stacked phase-space to solve for the Jeans equation**
- **Adopt parametric models for the 3D mass distribution and 3D velocity anisotropy profile** β
- **Likelihood evaluation of the parameters with Modelling Anisotropy and Mass Profiles Of Spherical Systems (Mamon, Biviano & Boué, 2013)**

Method

- **Mass profile: NFW, well justified from theory**
- **β profile: much less studied in terms of universality; adopt 5 different models:**

1) **β constant**
2) **Tiret et al. (2007):** $\beta_T(r) = \beta_\infty \frac{r}{r + r_{-2}}$,
3) **Opposite:** $\beta_O(r) = \beta_\infty \frac{r - r_{-2}}{r + r_{-2}}$.
4) **Mamon & Łokas (2005):** $\beta_{MŁ} = 0.5 \frac{r}{r + r_\beta}$
5) **Osipkov (1979) & Merritt (1985):** $\beta_{OM} = \frac{r^2}{r^2 + r_\beta^2}$.

Use full bayesian framework (model averaging) to combine models

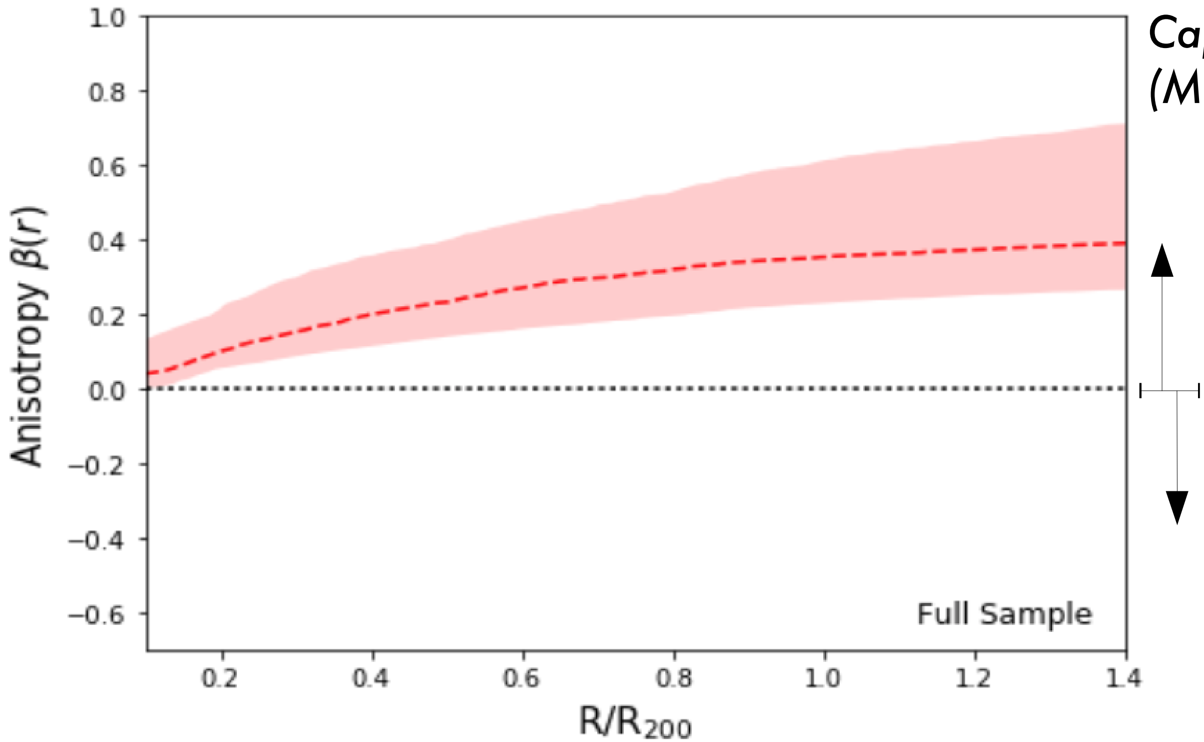
$$p(\boldsymbol{\theta}|\, D, M) = \frac{L(D|\,\boldsymbol{\theta}, M)}{E(D|\, M)} p(\boldsymbol{\theta})$$

$$E(D \mid M) = \int L(D \mid \theta, M) p(\theta) d\theta$$

- **Use MAMPOSSt to evaluate** $\mathcal{L}_{\rm tot} = \prod_{i \in {\rm gal}} \mathcal{L}(R^i, v^i_{\rm los} \mid r_{200}, r_s, \theta_\beta)$

Orbital anisotropy profile

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



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- **Isotropic orbits in the center, increasingly radial**

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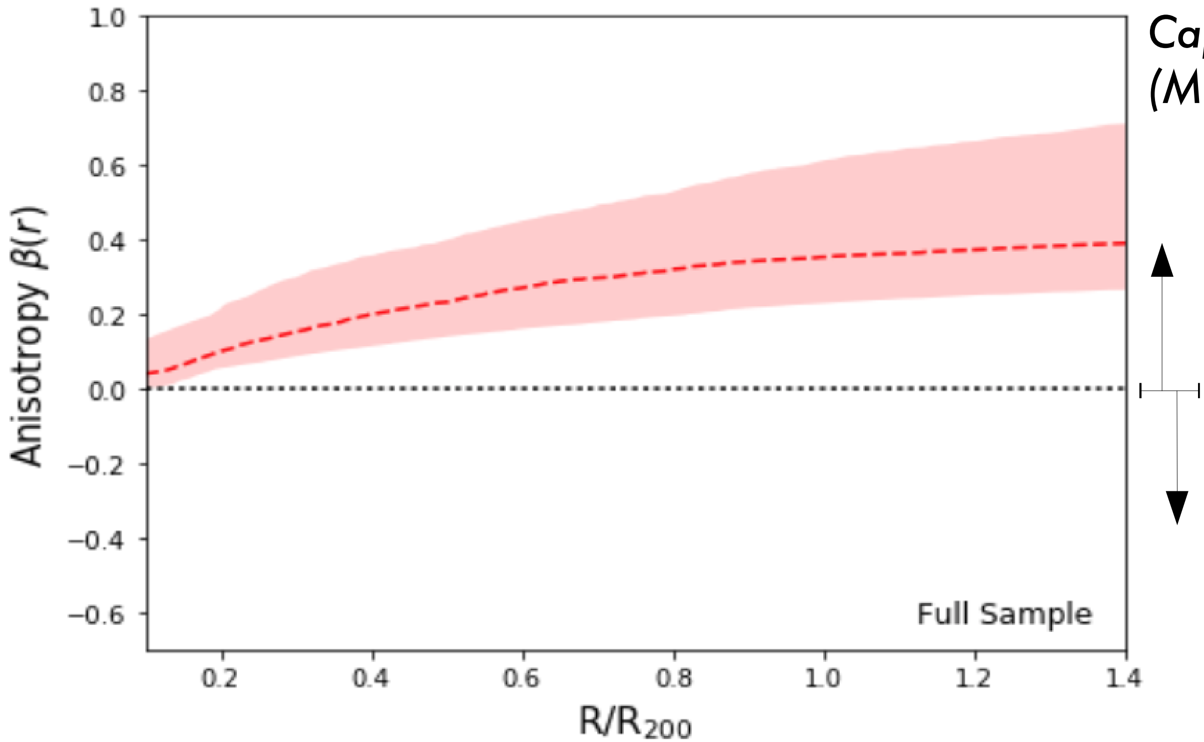


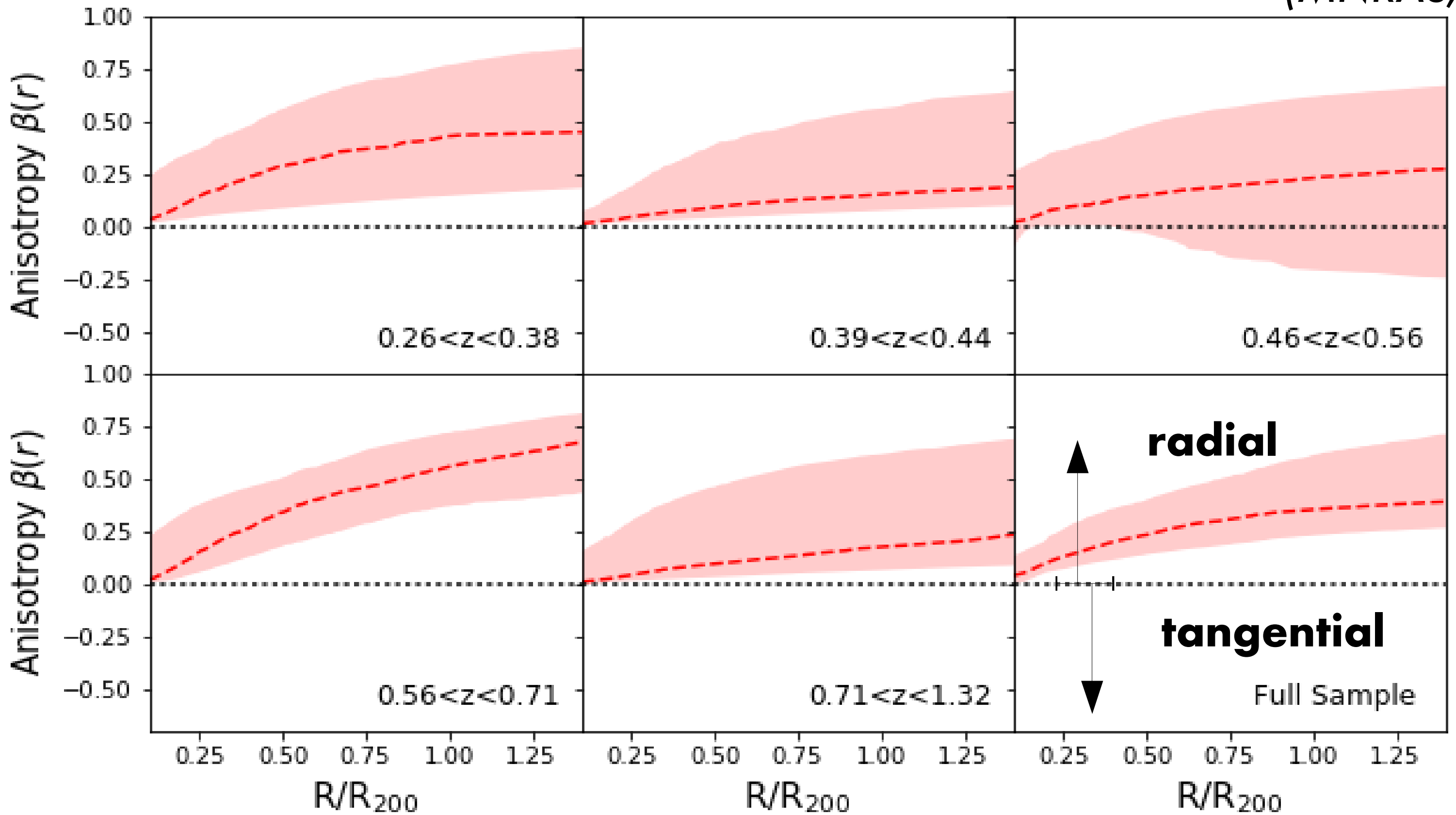
Capasso+19 (MNRAS, 482, 1043)

- **Isotropic orbits in the center, increasingly radial**
- **Possible processes: violent relaxation followed by smooth accretion (Lapi&Cavaliere, 2009)**
  - **Growth of structures undergoes two phases: 1) early, fast accretion (major mergers – violent relaxation), 2) calmer stage (minor mergers, smooth accretion)**

Orbital anisotropy profile

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

Capasso+19 (MNRAS, 482, 1043)

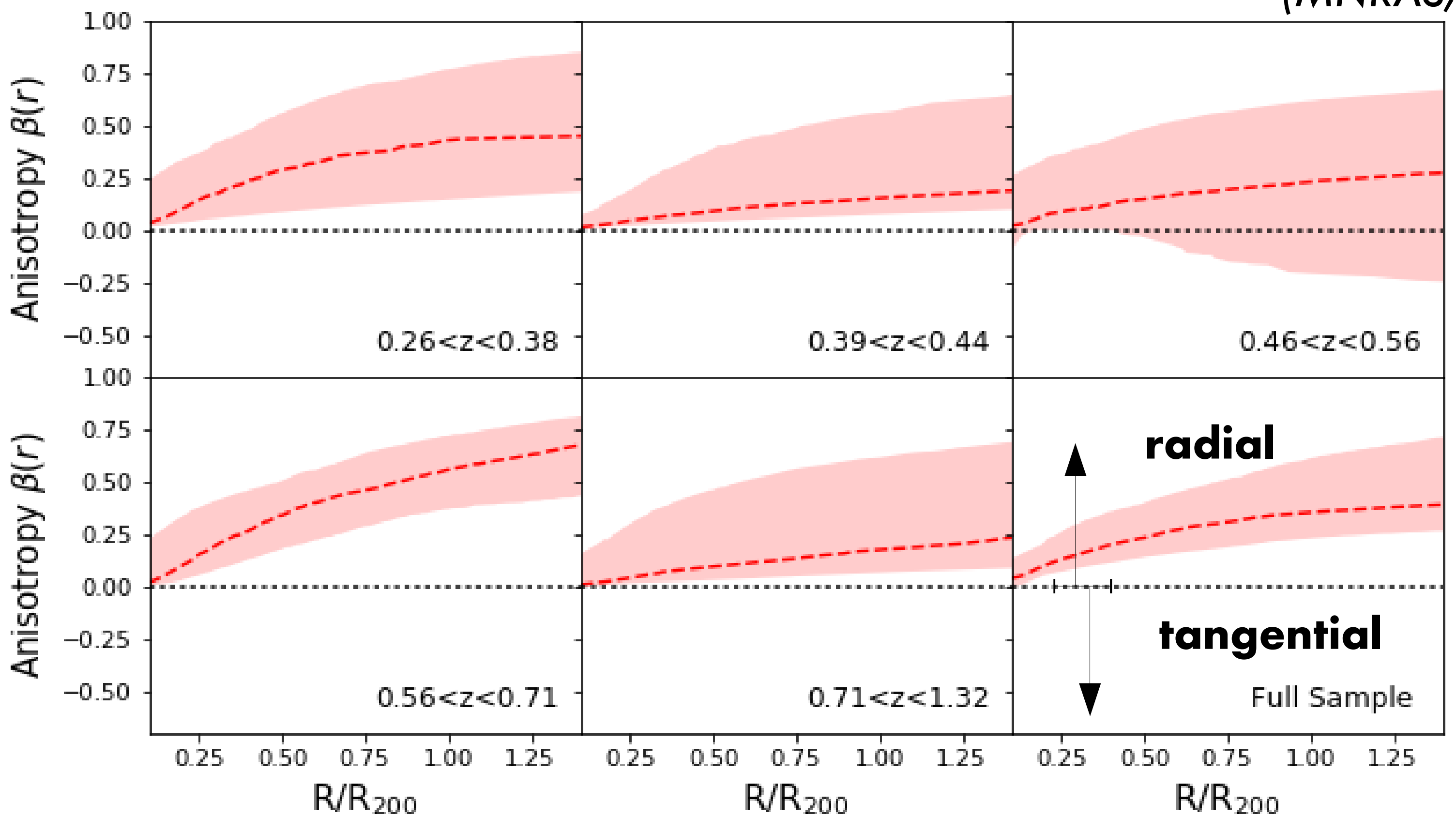


- **No evidence of redshift trends within the uncertainties**

Orbital anisotropy profile

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

Capasso+19 (MNRAS, 482, 1043)



- **No evidence of redshift trends within the uncertainties**
  - **Merging and relaxation processes responsible for the β profiles underway at all cosmic epochs probed**

Mass comparisons

$$N^{\exp}(\xi) = \int \underbrace{n(M)}_{\text{cosmo}} \underbrace{P(\xi \mid M)}_{\text{mass-obs relation}} dM$$

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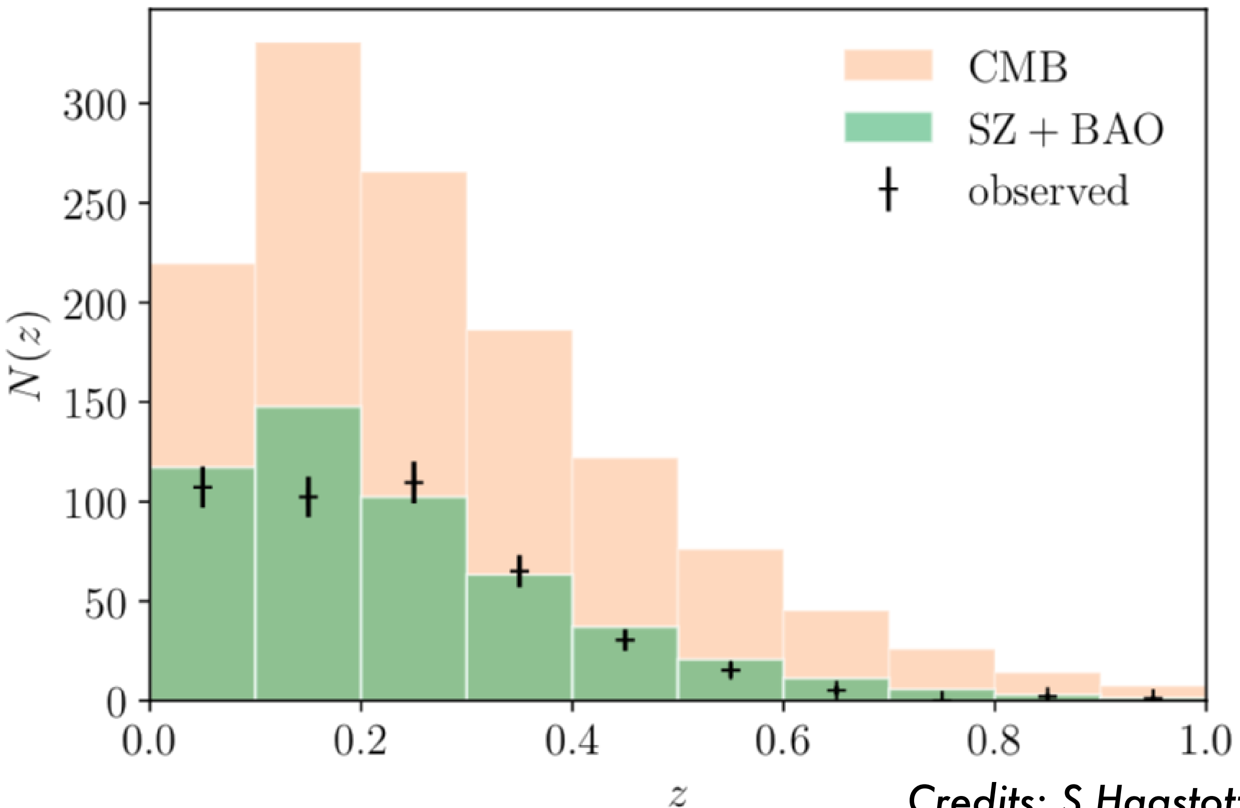
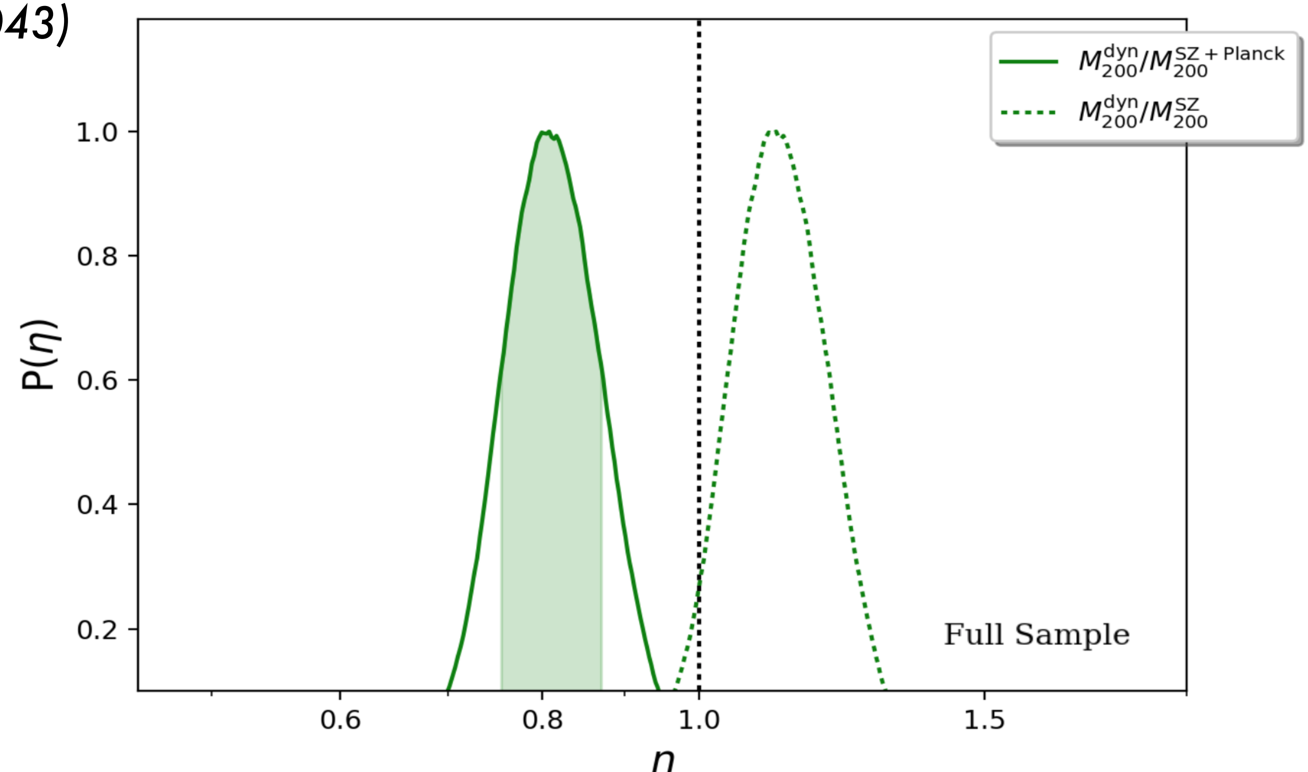


Credits: S.Hagstotz

Mass comparisons

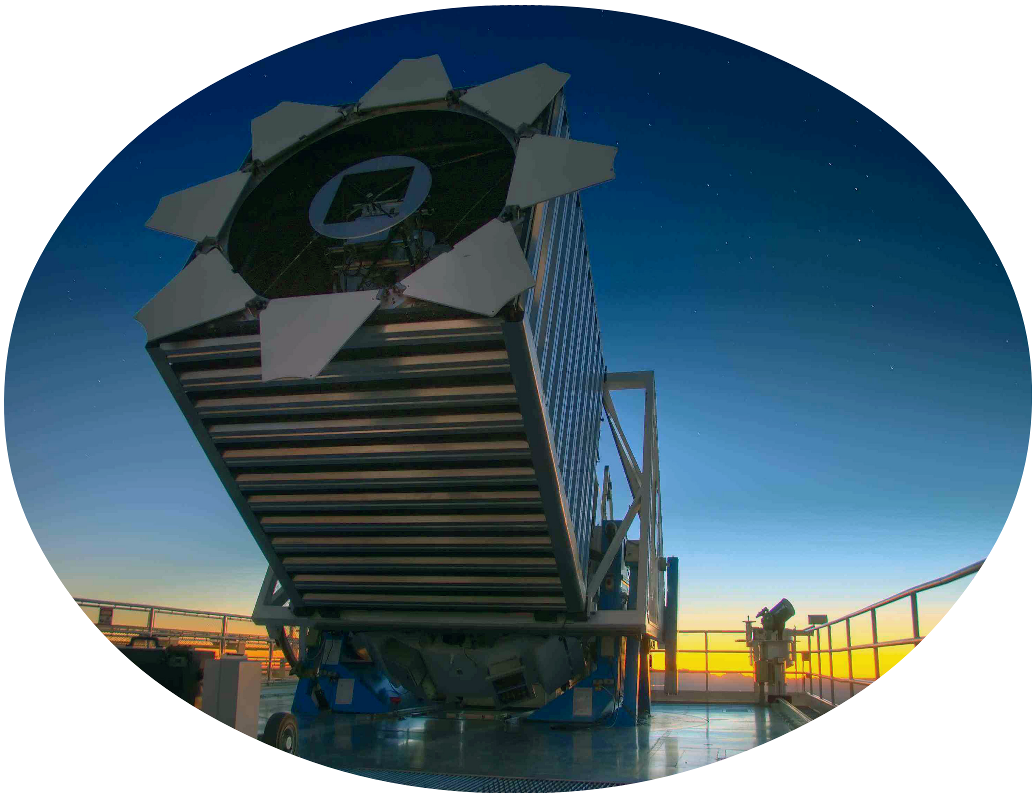
Capasso+19
(MNRAS, 482, 1043)



- **Comparison with masses derived from SPT cluster counts + external cosmological constraints from the Planck CMB anisotropy**
- **Cosmology from Planck CMB anisotropy suggests higher masses than the observed dynamical ones**
- **2.6σ tension**

Mass-Observable Relations

The SPectroscopic IDentification of eROSITA Sources (SPIDERS) programm

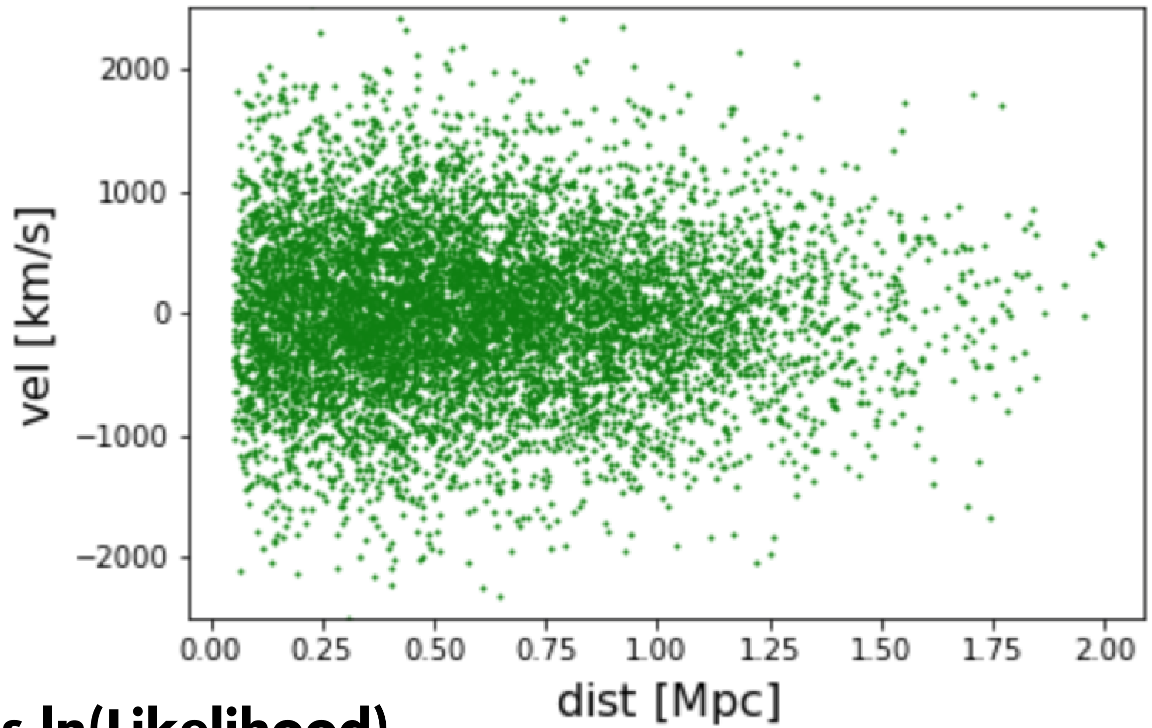


- Prior to eROSITA: spectroscopic follow-up of the CODEX sample
  - CODEX → galaxy clusters discovered in RASS (ROSAT All-Sky Survey) → X-ray luminosity Lx in the [0.1-2.4] KeV rest-frame band
  - RedMaPPer → red-sequence galaxies identified in SDSS-IV → Richness λ
  - SPIDERS → Spectroscopic redshifts

Mass-Observable Relations

Capasso+19b (MNRAS, 486, 1594)

- **λ > 20, L_X > 4.5·10[42] , redshift up to ~0.65**
- **428 clusters, ~7800 nELG after interloper rejection**

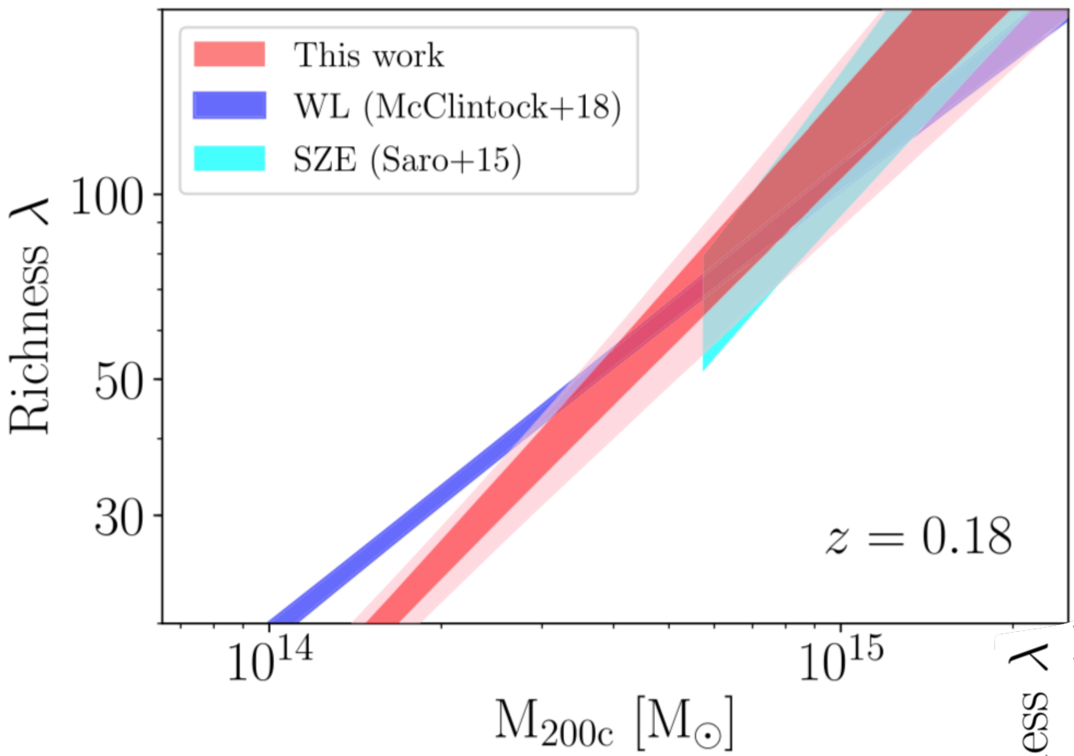


- **Sum of individual clusters ln(Likelihood)**

$$\mathrm{Obs} = A \left(\frac{M_{200}}{M_{piv}}\right)^{B} \left(\frac{1+z}{1+z_{piv}}\right)^{\gamma}$$

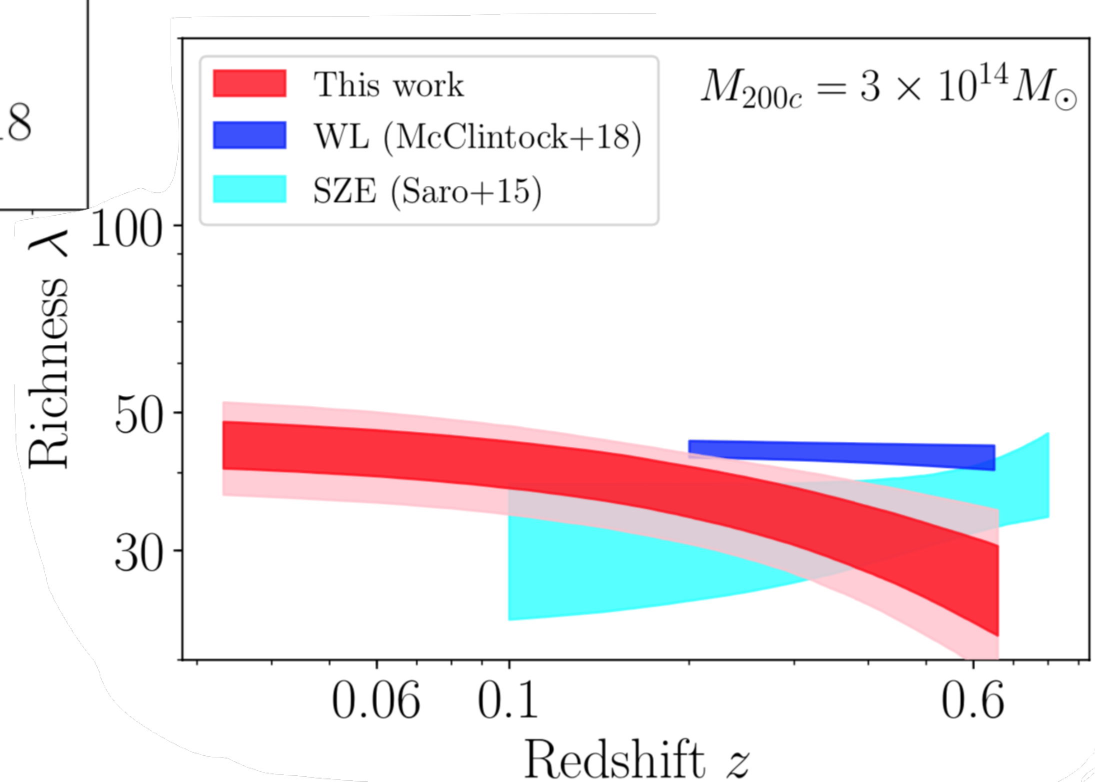
$$\mathcal{L}_j = \prod_{j \in \mathrm{gal}} \mathcal{L}(R^i, v^i_{\mathrm{los}}, \lambda_j, z_j \mid A, B, \gamma, \theta_\beta) \longrightarrow \mathcal{L}_{\mathrm{tot}} = \prod_{j \in \mathrm{clus}} \mathcal{L}_j$$

Mass-richness relation



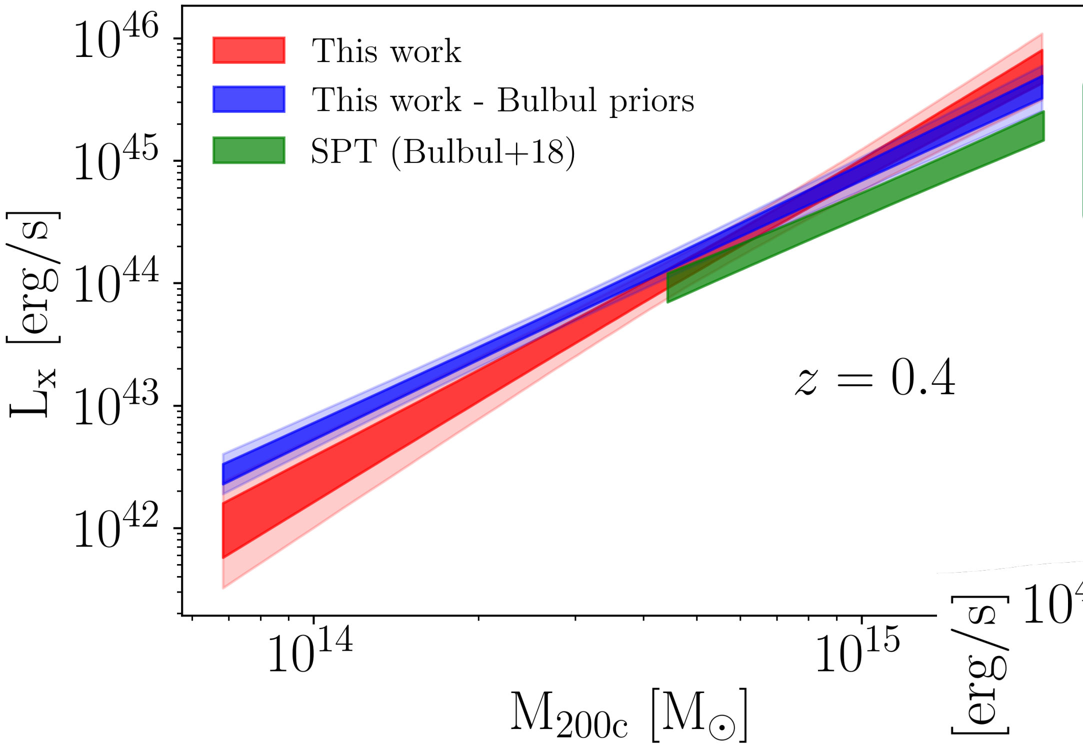
Capasso+19b (MNRAS, 486, 1594)

$$\lambda = A_\lambda \left(\frac{M_{200c}}{M_{piv}}\right)^{B_\lambda} \left(\frac{1+z}{1+z_{piv}}\right)^{\gamma_\lambda}$$



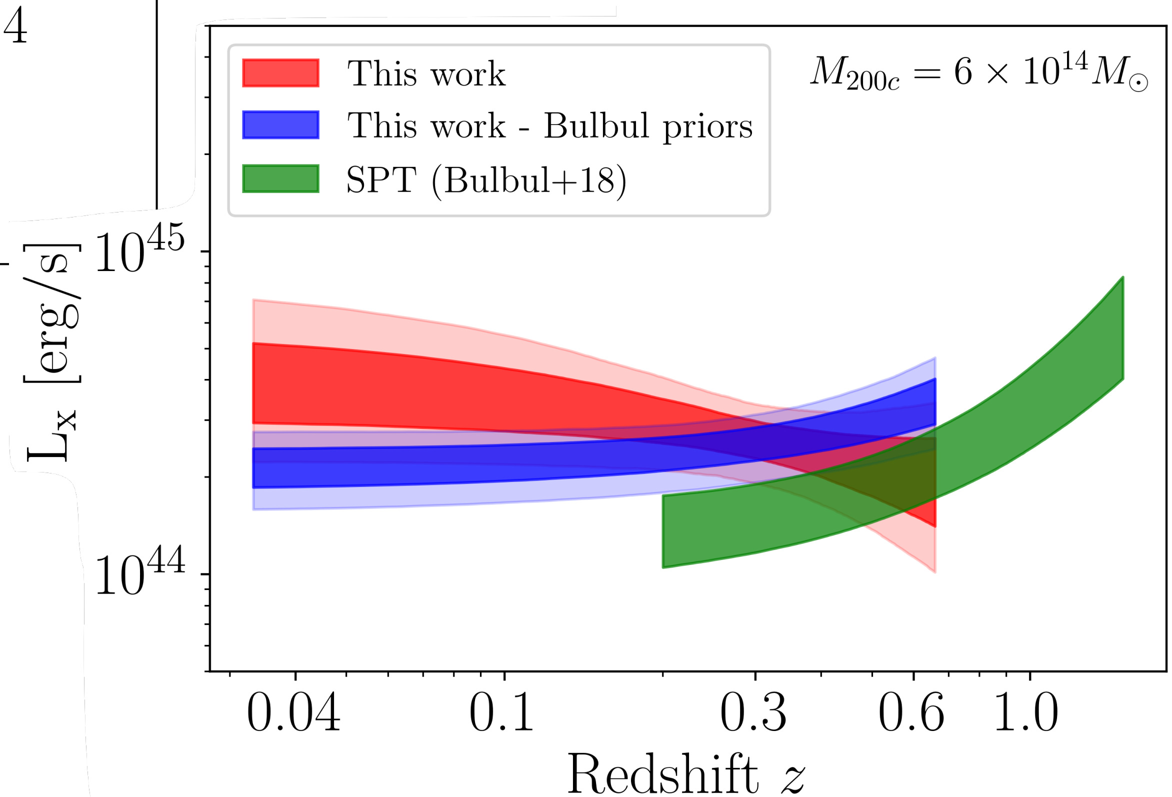
- $M_{piv} = 3 \times 10^{14} M_\odot$
- $z_{piv} = 0.18$

Mass-L_x relation



Capasso+19c, in prep.

$$\frac{L_X}{(10^{44}\mathrm{erg\,s^{-1}})} = A_X \left(\frac{M_{200c}}{M_{piv}}\right)^{B_X} \left(\frac{E(z)}{E(z_{piv})}\right)^2 \left(\frac{1+z}{1+z_{piv}}\right)^{\gamma_X}$$



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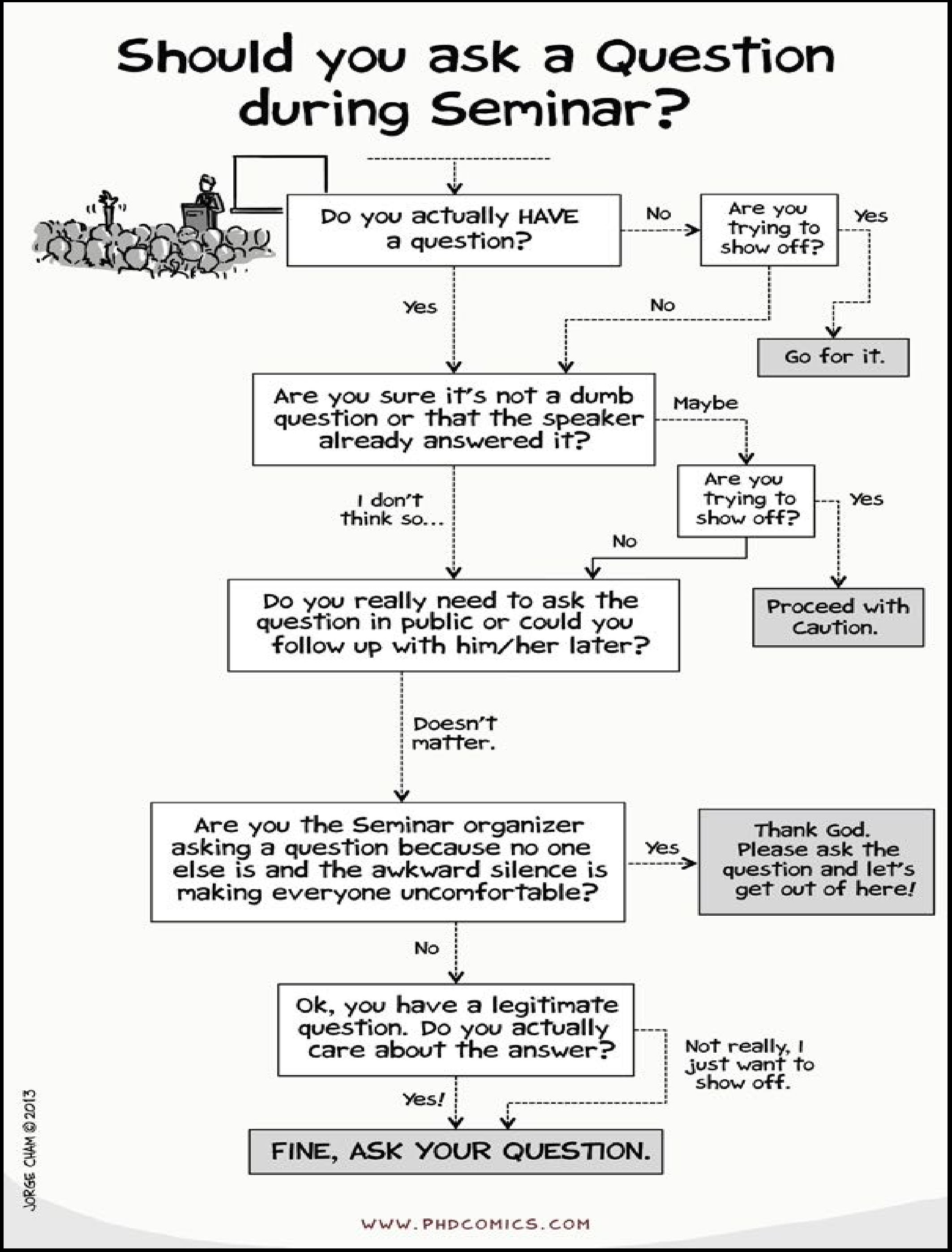
Summary

Jeans analysis of cluster member galaxies

- Constraints on velocity anisotropy profile β and its redshift trend
- Info on formation and evolution of clusters
- Mass comparisons and inventigation of cosmological tensions
- Calibration of competitive mass-observable relations

→ dynamical analysis is ideal for mass calibrations even with a small number of member galaxies

Questions?


Should you ask a Question during Seminar?
Do you actually HAVE a question?
No
Are you trying to show off?
Yes
Go for it.
No
Yes
Are you sure it's not a dumb question or that the speaker already answered it?
Maybe
Are you trying to show off?
Yes
Proceed with Caution.
No
I don't think so...
Do you really need to ask the question in public or could you follow up with him/her later?
Doesn't matter.
Are you the Seminar organizer asking a question because no one else is and the awkward silence is making everyone uncomfortable?
Yes
Thank God. Please ask the question and let's get out of here!
No
Ok, you have a legitimate question. Do you actually care about the answer?
Not really, I just want to show off.
Yes!
FINE, ASK YOUR QUESTION.
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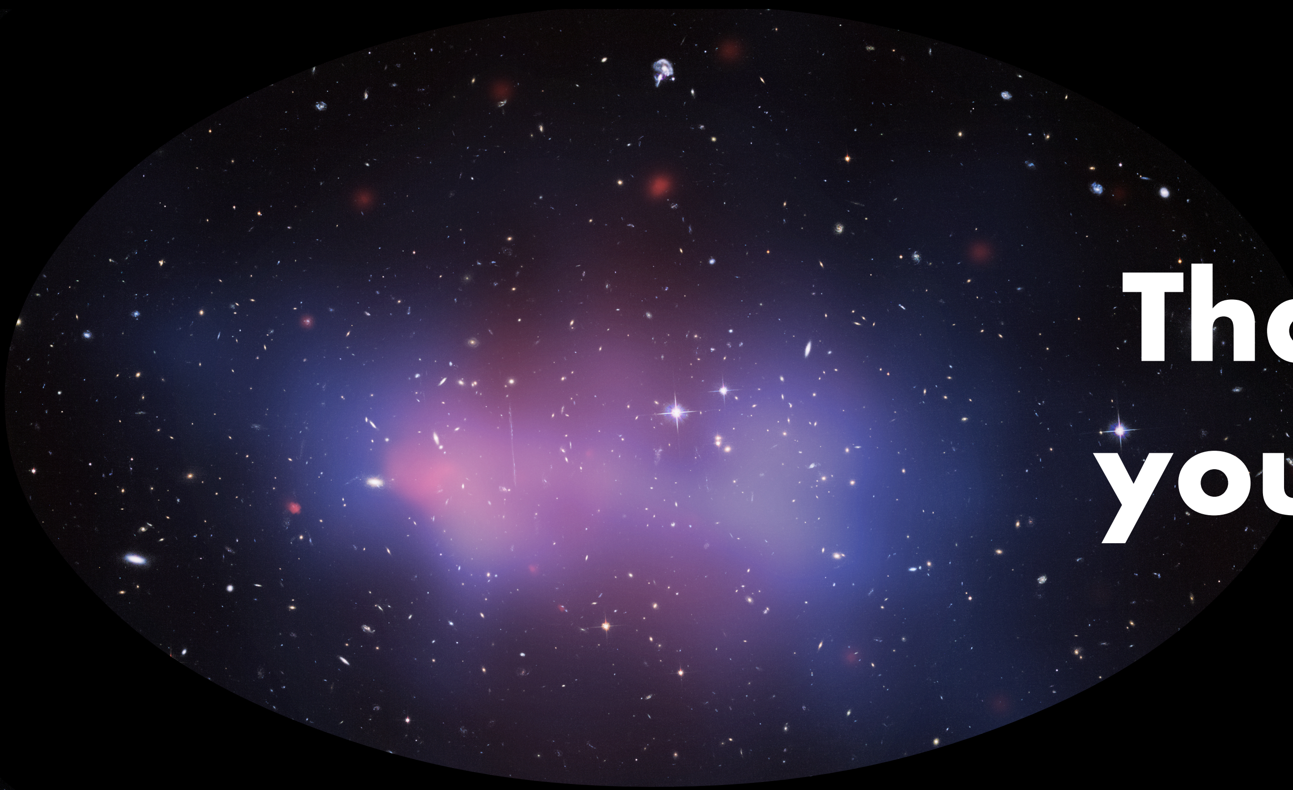

Thank you for your attention!

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