Learning Precise Relationships between Dark Matter and Galaxies by Imposing Exact Physical Symmetries

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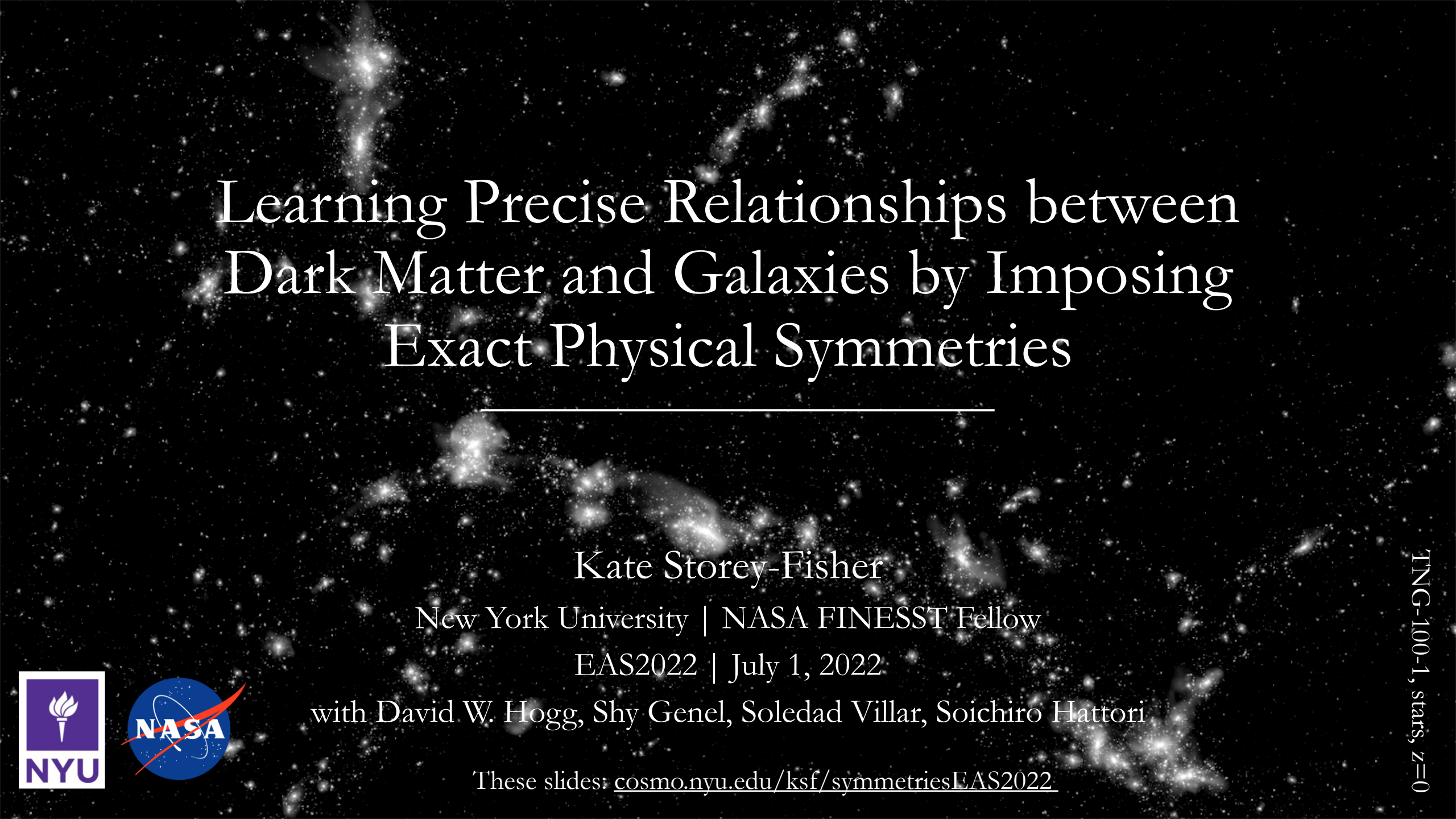
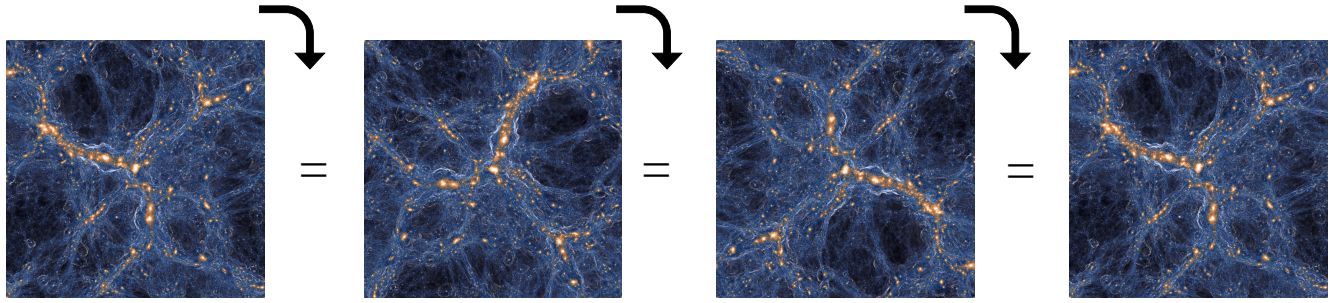
with David W. Hogg, Shy Genel, Soledad Villar, Soichiro Hattori

These slides: cosmo.nyu.edu/ksf/symmetriesEAS2022



Cosmological simulations obey *symmetries*.

- Rotation (*rotating* the box)
- Translation (*shifting* the particle positions)
- Permutation (*reordering* the particles)
- Units (*rescaling* to different units)

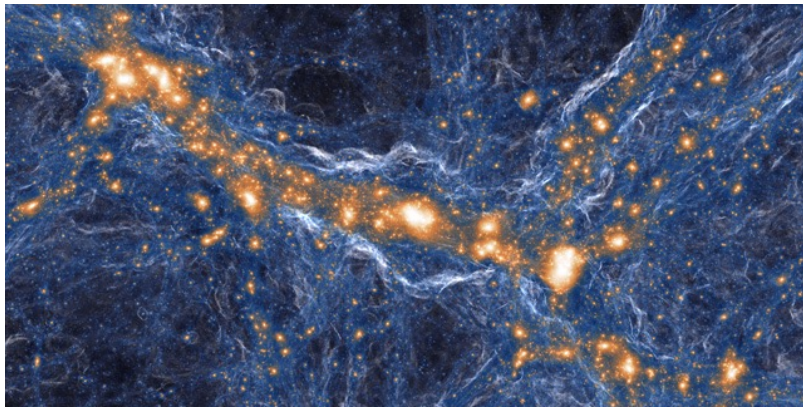


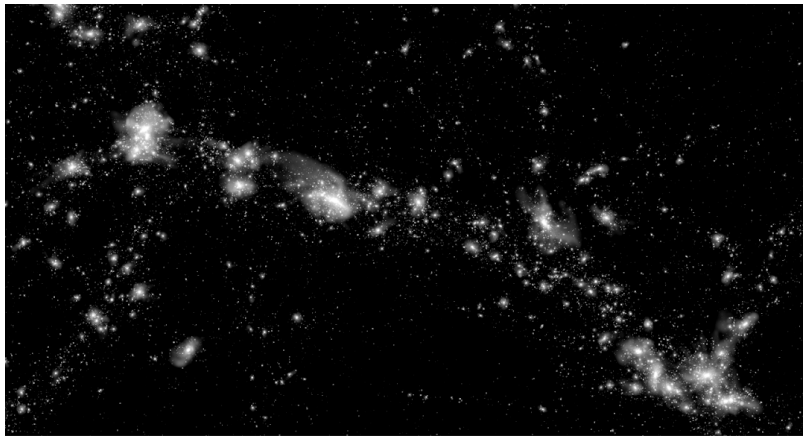
→ { same *scalar* outputs (*invariance*) ; appropriately transformed *vector* outputs (*equivariance*) }

Our operations on the simulations should preserve these symmetries – as should the real universe!

Predicting galaxy properties from dark-matter only simulations

dark-matter only (DM density)

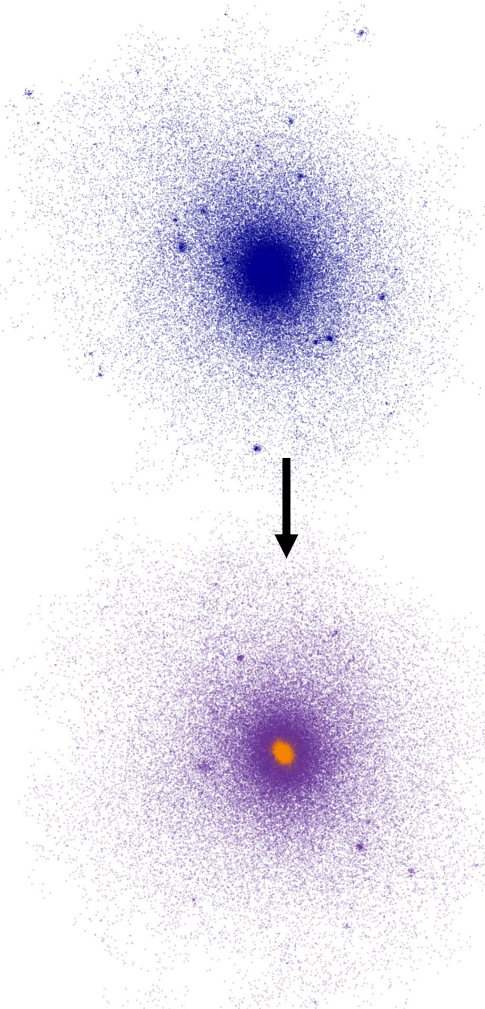




+ hydrodynamics (stellar density)

TNG100-1

Weinberger+2017 (1607.03486), Pillepich+2018 (1703.02970)



Input: DM halo in DM-only simulation

This prediction should preserve physical symmetries.

Output: properties of central galaxy hosted by that halo in matched hydro sim

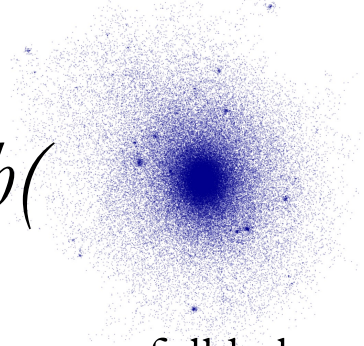
The *scalars* approach

A function *invariant* to a certain symmetry can be expressed in terms of a collection of *scalars*.

(This generalizes to *equivariant* vector functions as well.)

New approach by Villar+2021(incl **KSF**) (2106.06610)

$$\{m_*, R_*, SFR, \mathit{etc}\} = h\Big(\quad\Big) = f(s_0, s_1, s_2, \dots)$$



scalar galaxy properties

some invariant function

full halo description

set of scalars describing halo

So to predict scalar galaxy properties from DM halos and preserve cosmological symmetries, we need to describe the halos with *invariant scalars*.

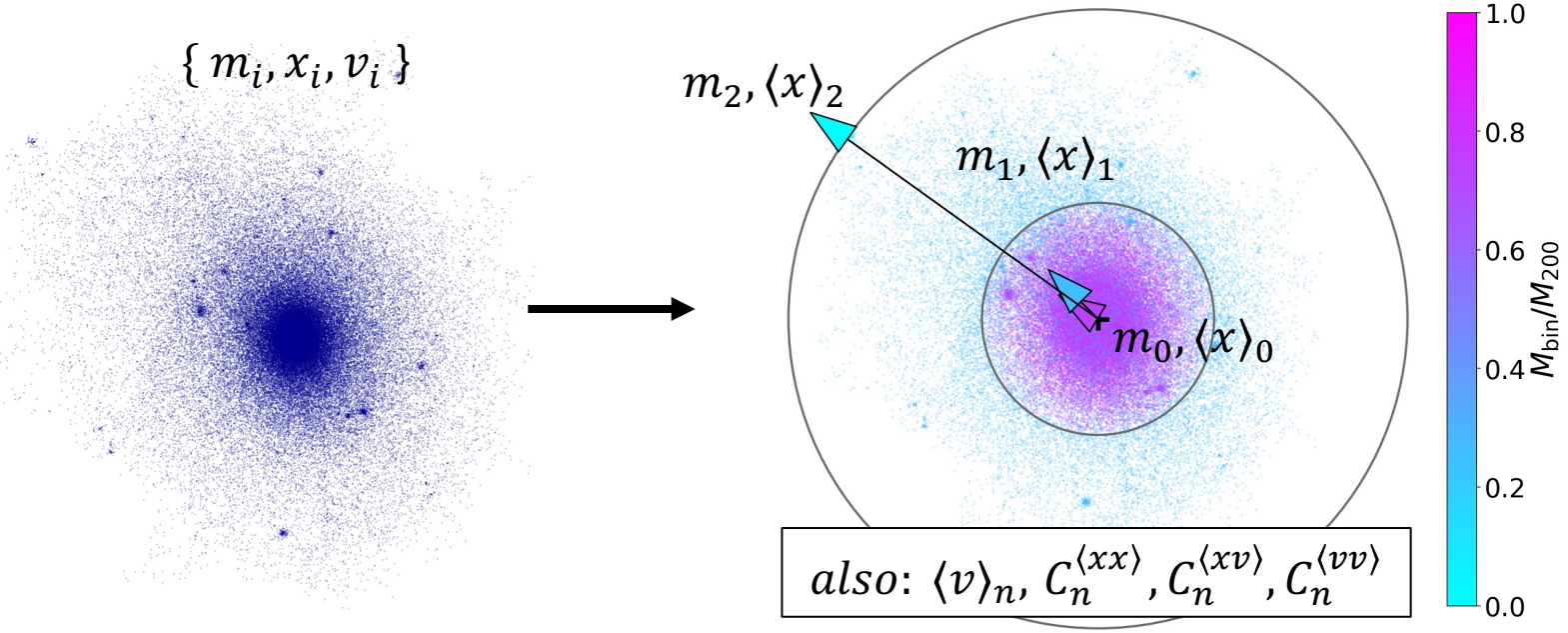
Describing a DM halo with scalars

particle masses, positions, and velocities of DM-only sim halo

geometric features: multipole expansion

$$g_{lpn} = \frac{1}{M}\frac{1}{R^l}\frac{1}{V^p} \times \sum_i m_i \, W_n(|x_i|) \; x_i^{\otimes l} \otimes v_i^{\otimes p}$$

scalar features: scalar contractions of the geometric features



e.g.

$m_0 m_1$

$[\langle x \rangle_0]_j [\langle x \rangle_2]_j$

eigenvalues of $C_1^{\langle xx \rangle}$

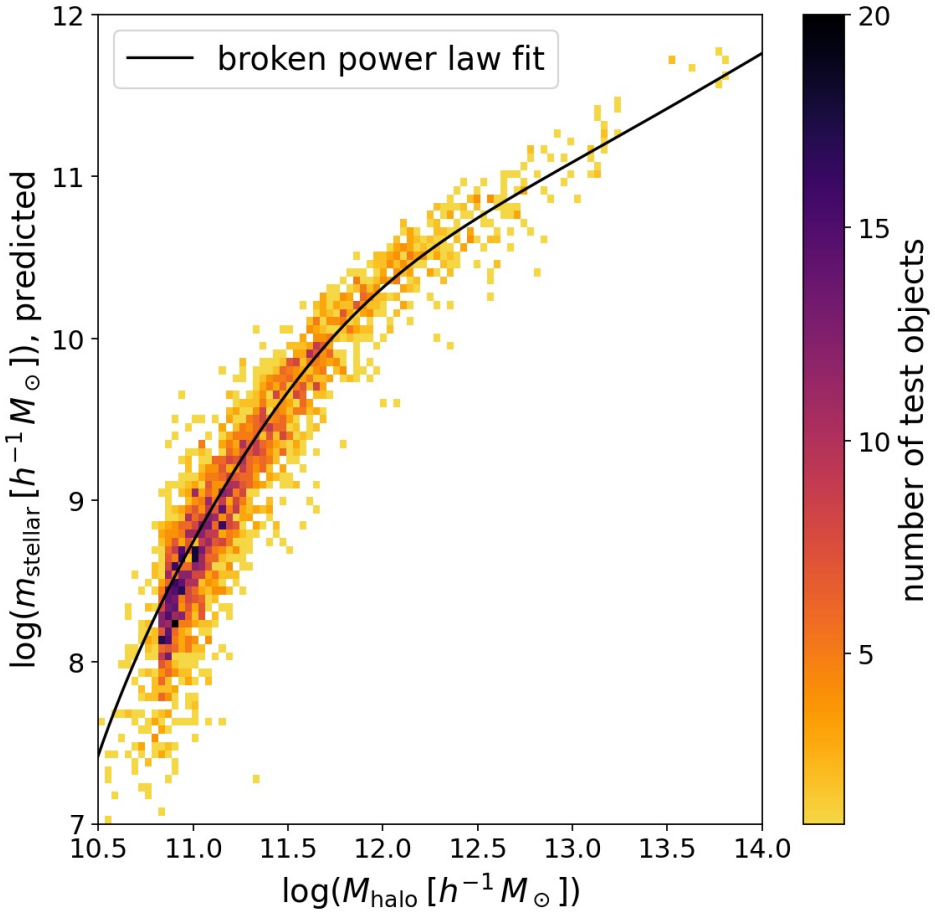
$[C_1^{\langle xv \rangle}]_{jk}$ $[C_1^{\langle vv \rangle}]_{jk}$

$\{$ *568 scalars* $\}$

Taking this to the (theoretical) limit would include *every possible dimensionless scalar measure* of halo shape.

Prediction of the galaxy stellar mass, m_*

true stellar-to-halo mass relation (SHMR)



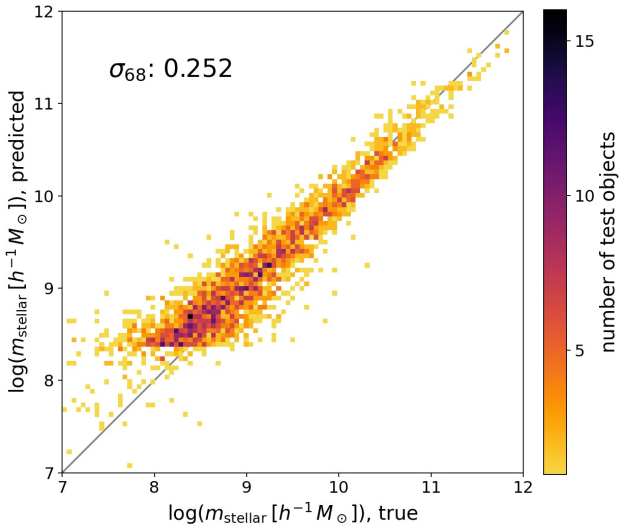
KSF+ (in prep.)

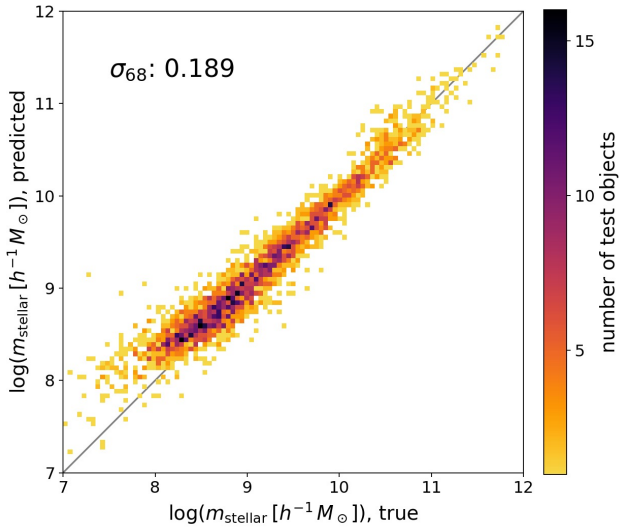
Method:

- Fit broken power law (BPL) to training set
- Include intrinsic uncertainties on m_*
- Perform linear regression with BPL and scalar features

Prediction of the galaxy stellar mass, m_*

mass only: broken power law + M_{200}



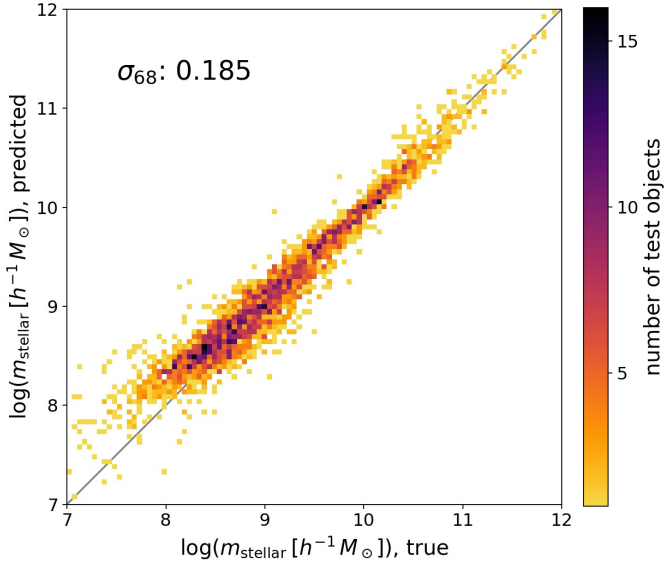


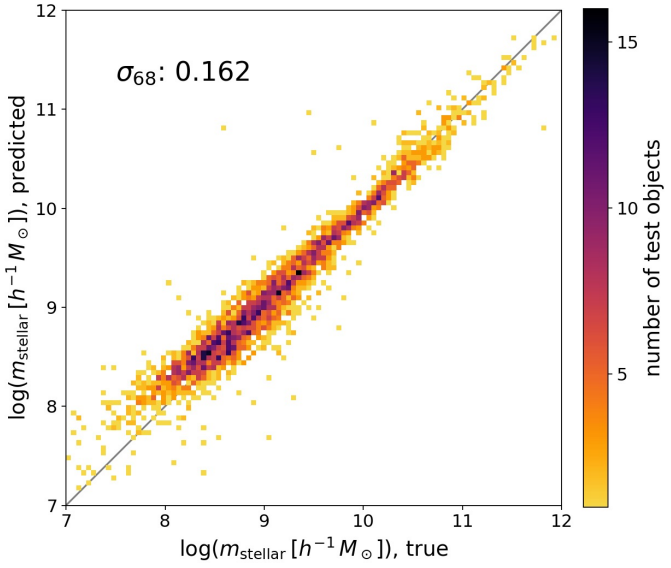
global halo properties:

$M_{c200}, c_{c200}, a_{\rm form}$

geometric feature components (+ broken power law, $M_{200}, R_{200}, V_{200}$)

not invariant!





scalar features (+ broken power law, $M_{200}, R_{200}, V_{200}$)

invariant!

KSF+ (in prep.)

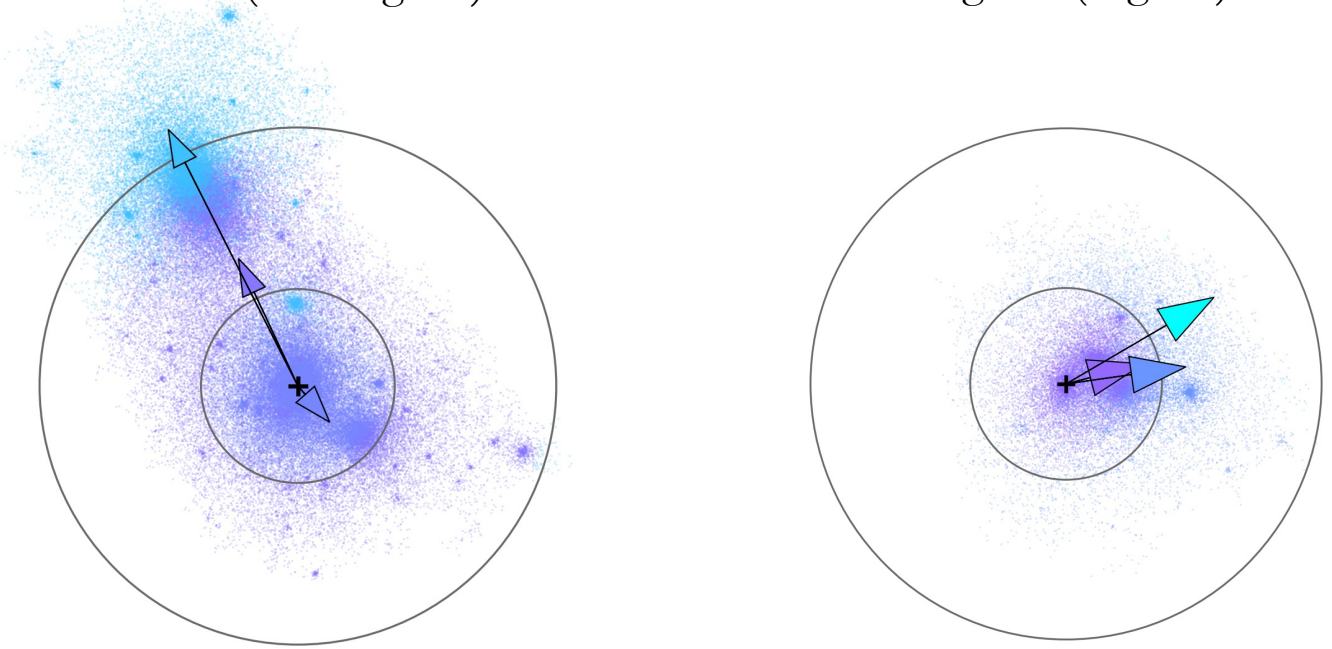
We can use the scalar features to understand the information content in phase-space structure.

About 12 features contain ~90% of the information for m_* as all 568 features.

One of the most important features: $[\langle x \rangle_0]_j [\langle x \rangle_1]_j$,
the alignment of the center of mass of the inner and outer halo

lowest (anti-aligned)

highest (aligned)



Summary

- We can describe the shape of dark matter halos in terms of scalar features that preserve the known physical symmetries.
- Using this approach, we successfully predict the stellar mass of central galaxies in the TNG100 cosmological hydro simulation from a DM-only simulation.
- We can use these features to understand the information content in the halo phase-space structure.

Ongoing Work

- Predict other galaxy properties, including vector and tensor properties (spin!)
- Compare to output of semi-analytic models (not limited to single set of cosmological & astrophysical parameters)

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Also talk to me about…

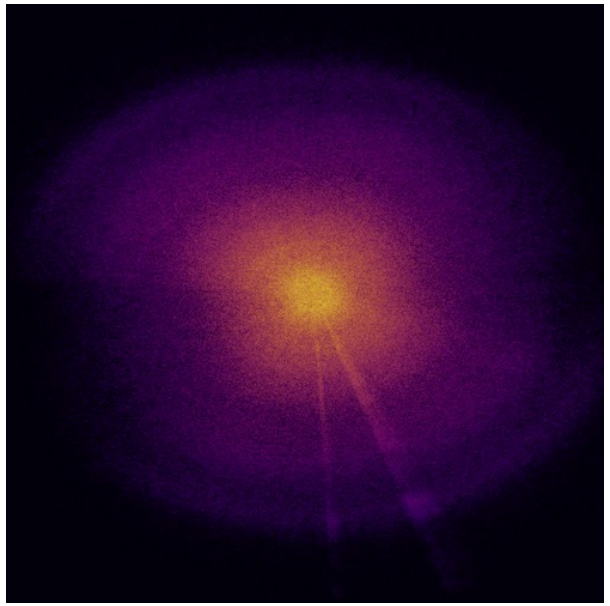
large-scale structure!

galaxies!

statistics & machine learning!

- Emulation of clustering statistics for cosmological inference (cosmo.nyu.edu/ksf/aemulusEAS2022)
- A generalized correlation function estimator & measuring inhomogeneity (2105.02434)
- Anomaly detection in galaxy images with generative models (2105.02434)
- The Gaia quasar sample for large-scale structure cosmology
- Postdoc opportunities :)

→ *EAS talk on The Aemulus Project at 12:30pm today in S2 (Room 2)*



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