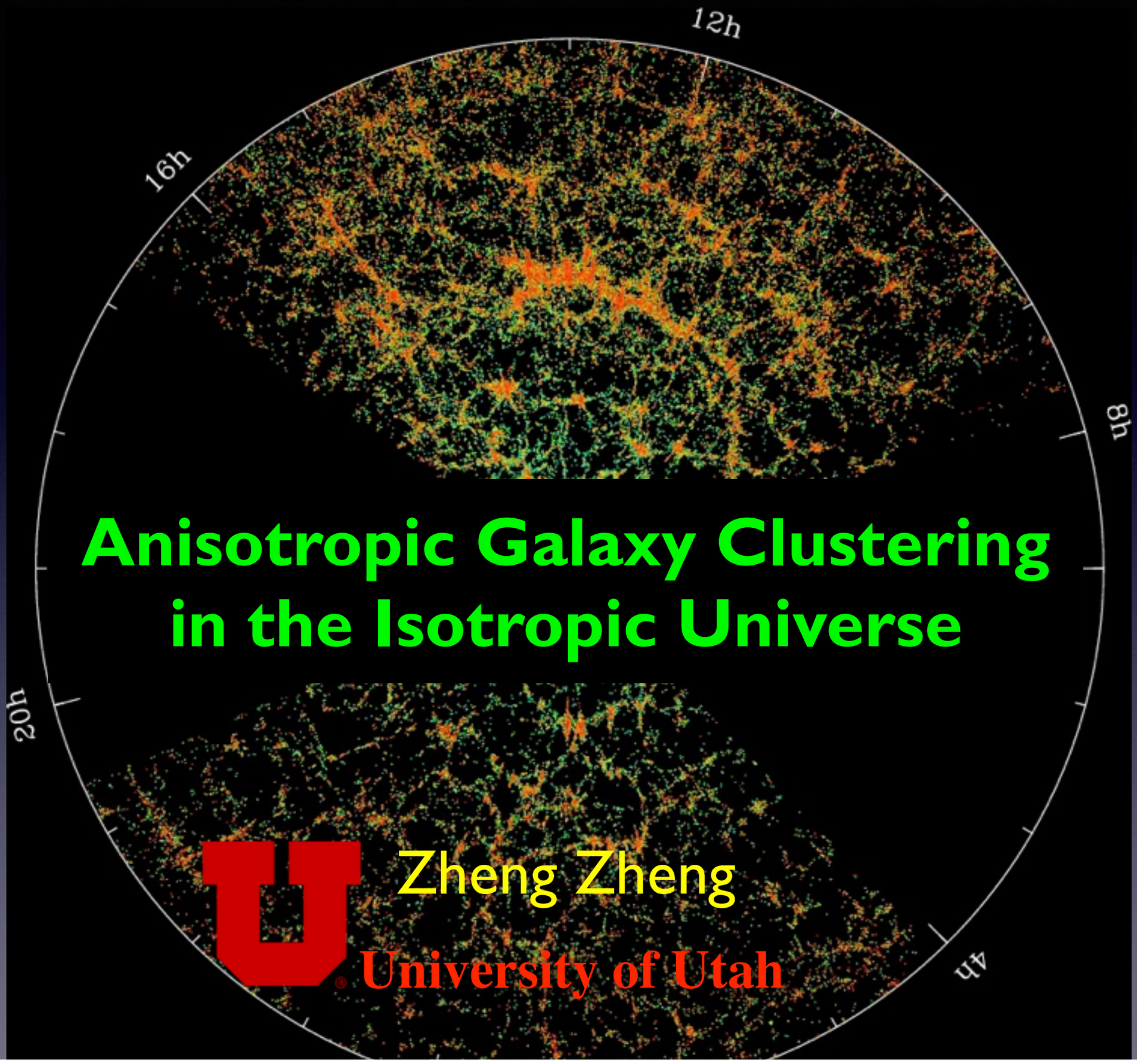


Anisotropic Galaxy Clustering in the Isotropic Universe

Zheng Zheng

University of Utah

Adam Bolton
Associate Professor
Ph.D. , MIT, 2005
structure, dynamics, and evolution of galaxies; observational cosmology; gravitational lensing; precision algorithms for astronomical spectroscopy

Kyle Dawson
Associate Professor
Ph.D. , Cornell Univ., 2004
observational cosmology; astronomical instrumentation; supernovae; large-scale structure; spectroscopic surveys

Inese Ivans
Assistant Professor
Ph.D. , Univ. of Texas at Austin, 2002
stellar spectroscopy; origins of chemical elements; stellar populations; formation and evolution of galaxies, including the Milky Way

Pearl Sandick
Assistant Professor
Ph.D. , Univ. of Minnesota, 2008
dark matter; particle astrophysics and cosmology; supersymmetry phenomenology; physics beyond the standard model

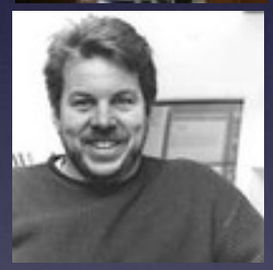
Anil Seth
Assistant Professor
Ph.D. , Univ. of Washington, 2006
observations of nearby galaxies; formation of galaxy nuclei and black holes; galaxy histories from resolved stellar populations & star clusters

Zheng Zheng
Associate Professor
Ph.D. , Ohio State University, 2004
cosmology, large-scale structure, and galaxy clustering; galaxy formation and evolution; high-redshift star forming galaxies; radiative transfer of Lyman-alpha photons and application in astrophysics

Ben Bromley
Professor
Ph.D. , Dartmouth College, 1994
planet formation; formation and evolution of black holes; galactic dynamics; large-scale structure of the universe; computational and statistical method in astrophysics

Paolo Gondolo
Professor
Ph.D. , UCLA, 1991
nature of dark matter and dark energy; high-energy cosmic neutrinos

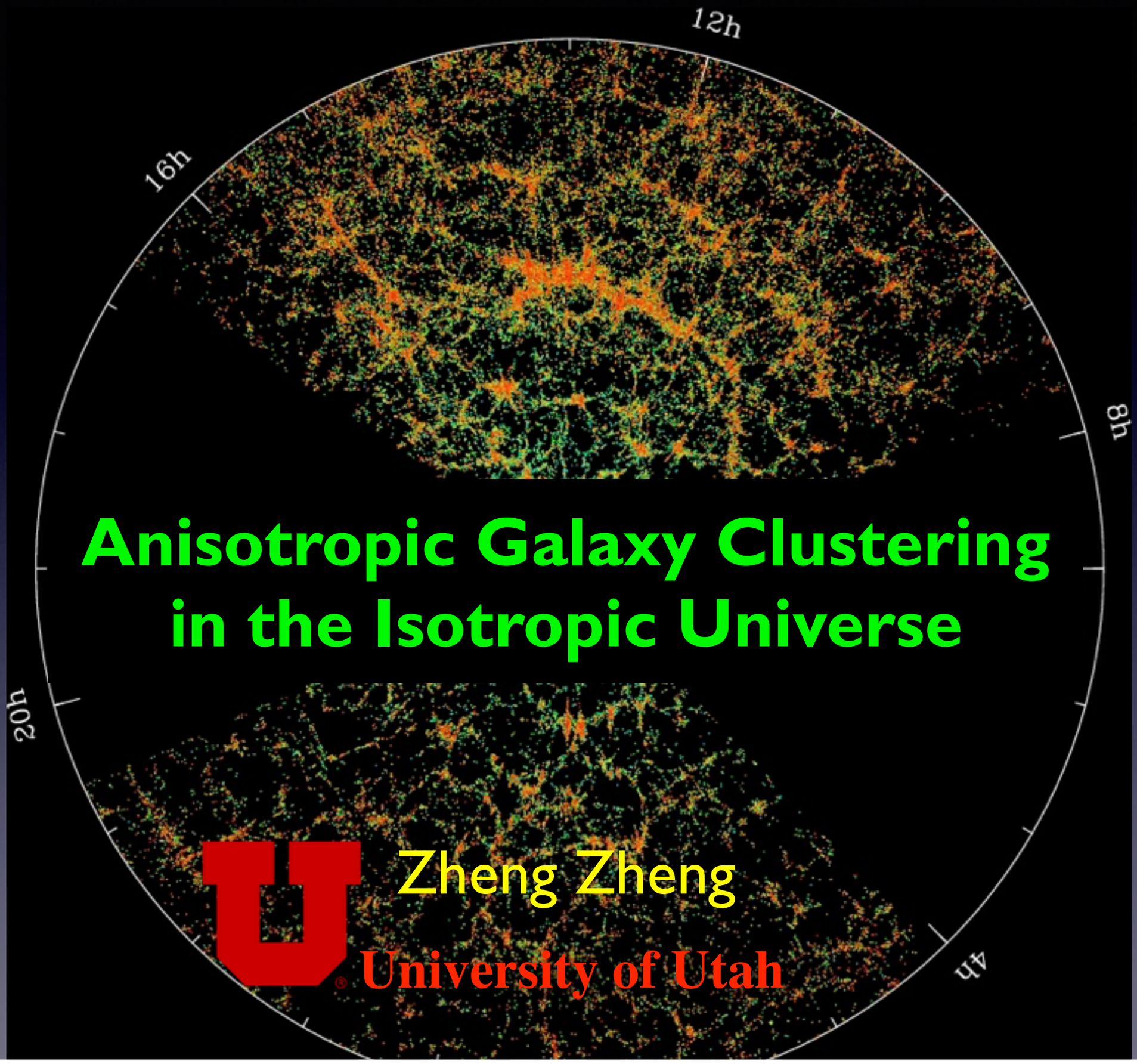
David Kieda
Professor
Ph.D. , Univ. of Pennsylvania, 1989
experimental high energy astrophysics; energetic phenomena in compact objects; gamma ray astronomy; cosmic ray physics



Wayne Springer
Associate Professor
Ph.D. , Univ. of Maryland, 1991
ultra high energy cosmic ray physics; cosmic ray detectors; astroparticle physics; observational astronomy

Institutional Member of SDSS-III/IV
Data Center for SDSS-IV

Department of Physics and Astronomy
ASTRONOMY AND ASTROPHYSICS
THE UNIVERSITY OF UTAH



Anisotropic Galaxy Clustering in the Isotropic Universe

Zheng Zheng

University of Utah

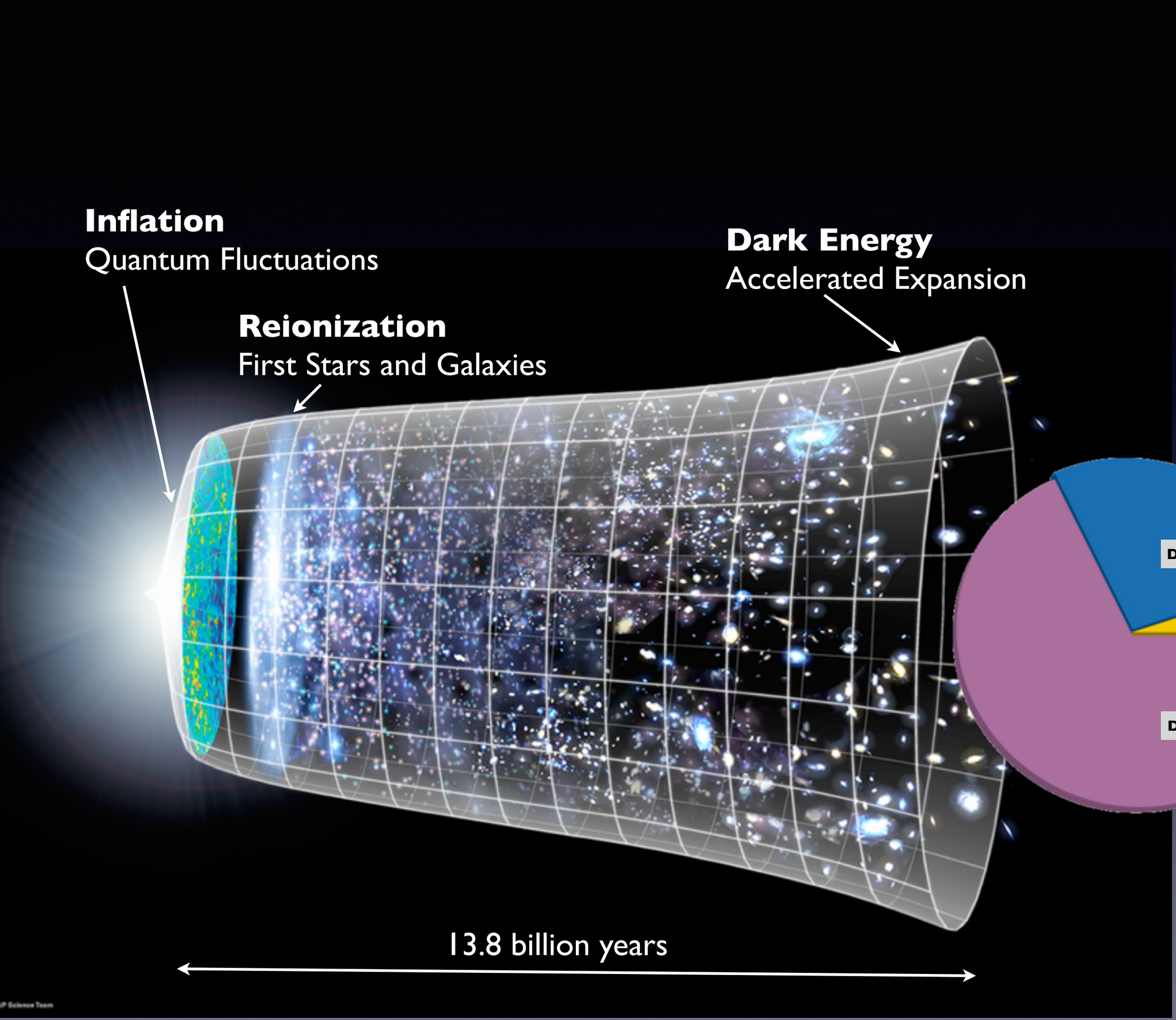
Main Collaborators

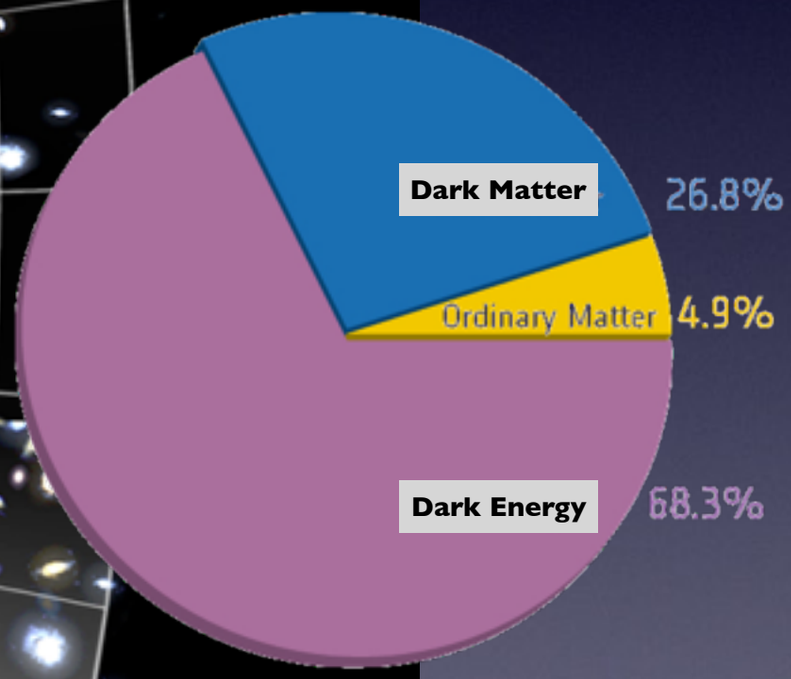
Hong Guo (Utah → SHAO)
Idit Zehavi (Case Western)
David Weinberg (Ohio State),
Renyue Cen (Princeton)
Hy Trac (Carnegie Mellon),
Jordi Miralda-Escude (U of Barcelona)
Rupert Croft (Carnegie Mellon)
Joshua Wallace (Princeton)

Inflation
Quantum Fluctuations

Reionization
First Stars and Galaxies

Dark Energy
Accelerated Expansion





13.8 billion years

Dark Matter Halo Formation

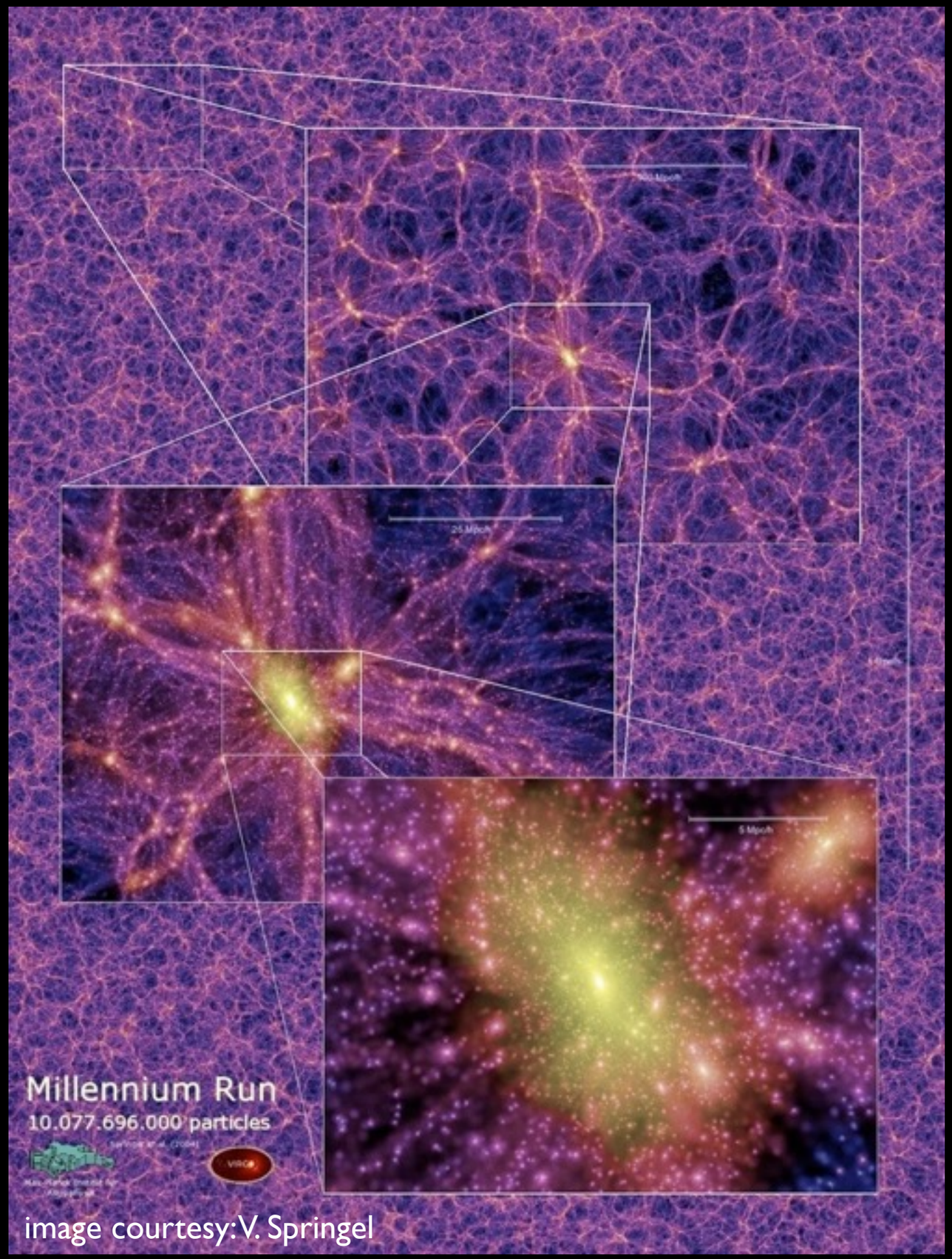
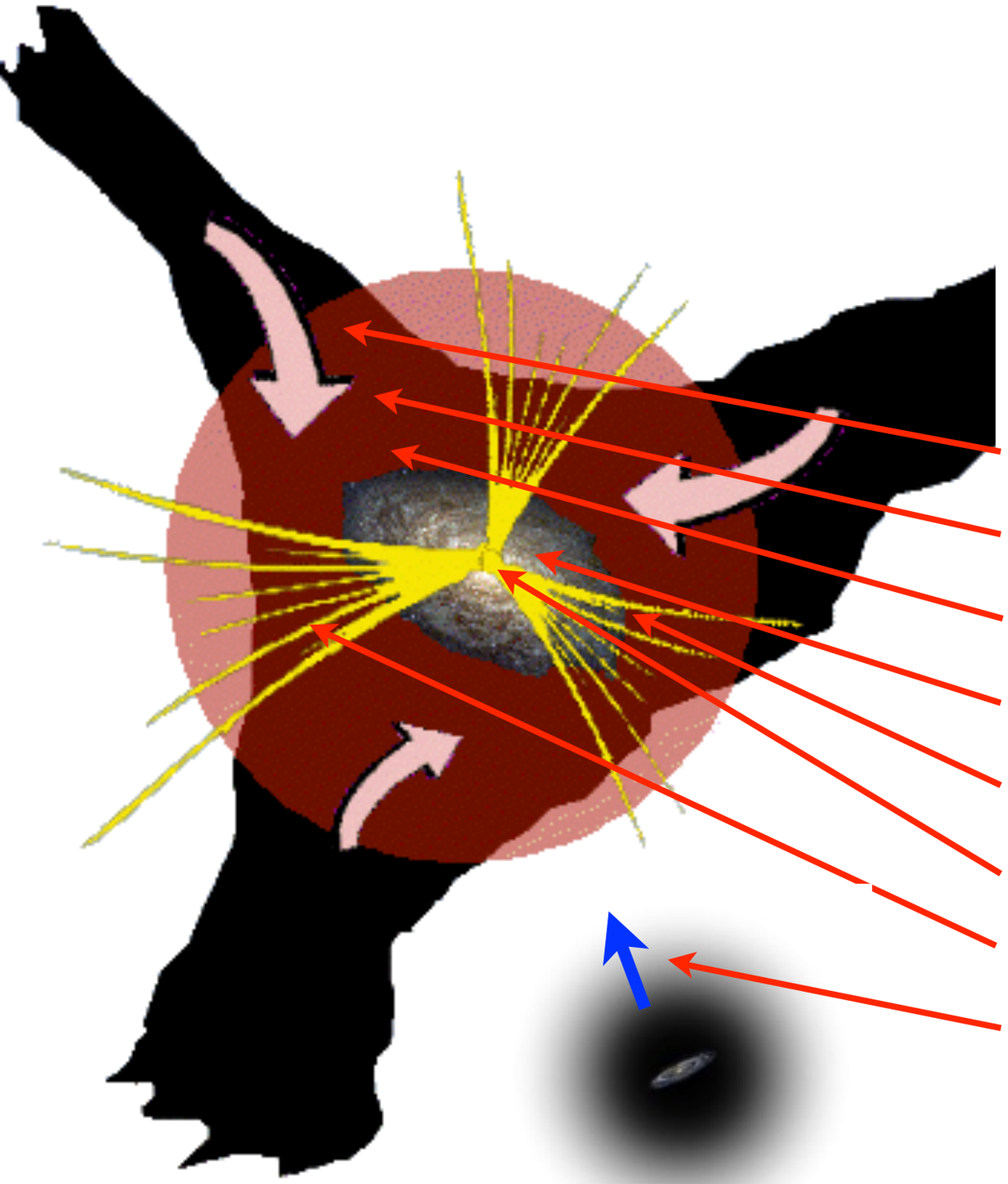


image courtesy: V. Springel

Galaxy Formation



- accretion
- heating
- cooling
- star formation
- star formation feedback
- supermassive black hole growth
- supermassive black hole feedback
- mergers
- ...

Observation: Bright Side

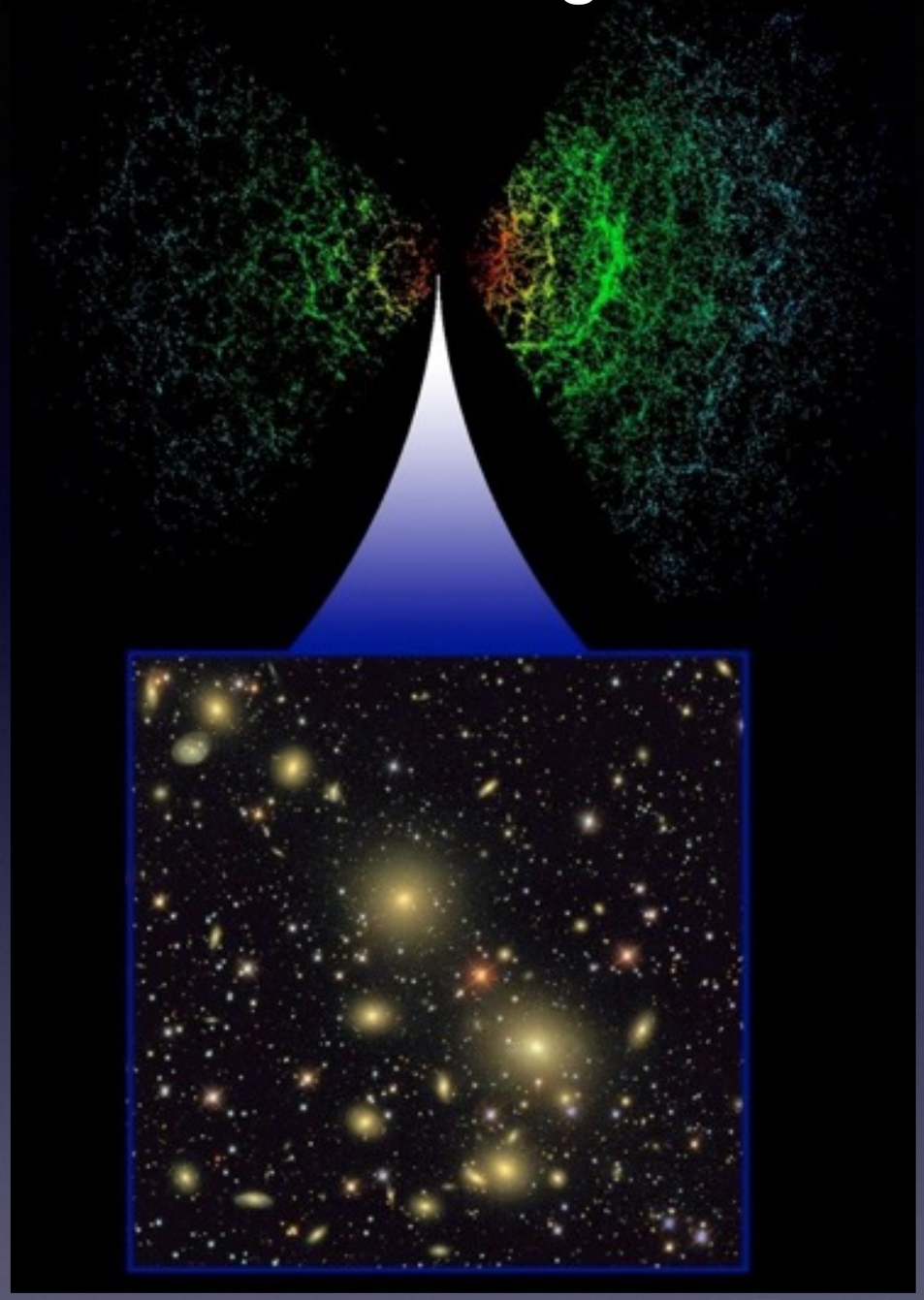


image courtesy: M. Tegmark

Theory: Dark Side

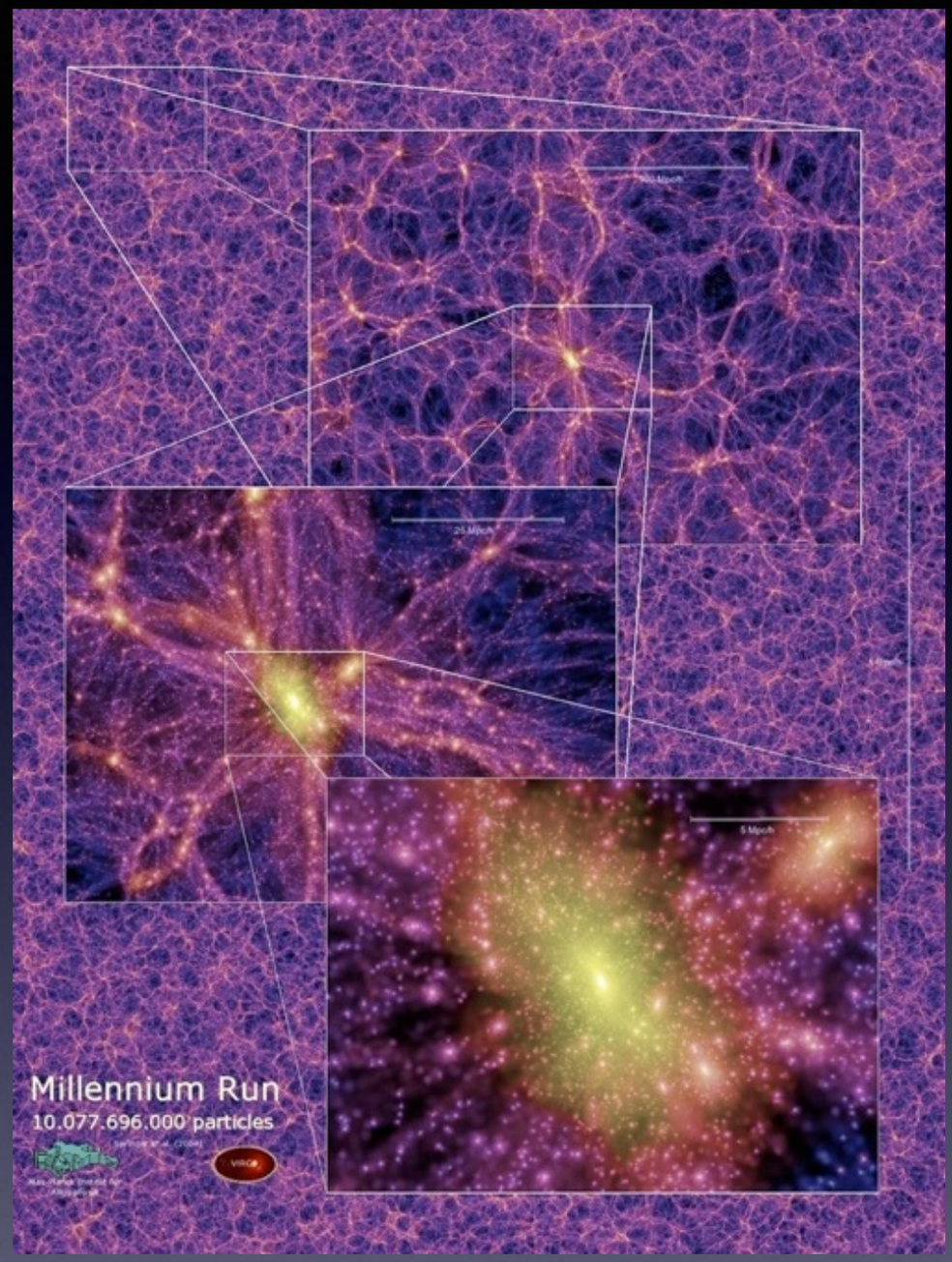


image courtesy: V. Springel

Galaxy Formation

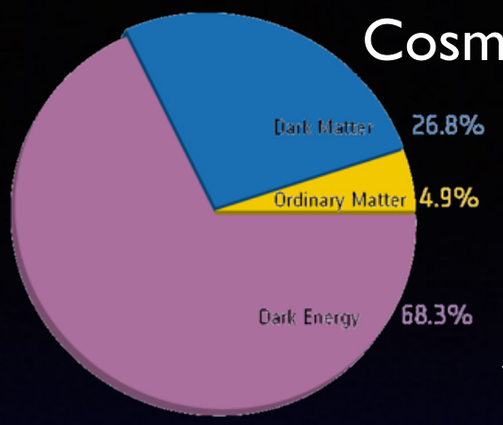
Gastrophysics

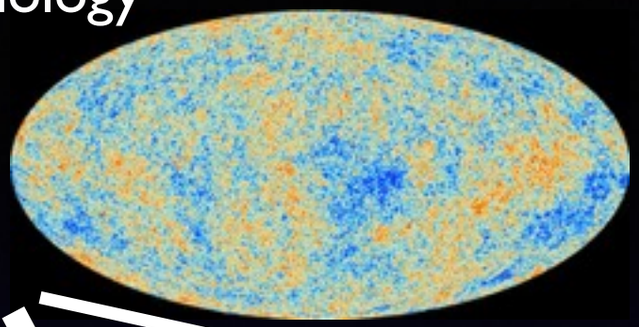
gas cooling, gas dynamics,
star formation, feedback, ...

Dark Matter Halo Formation

Gravity

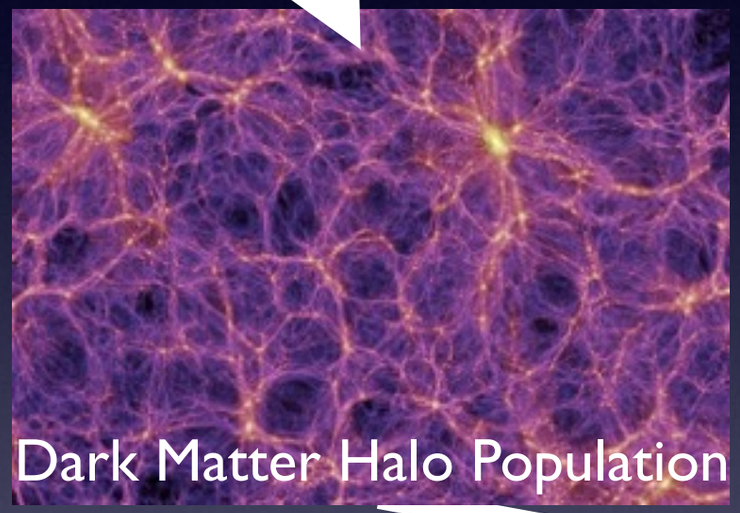
Cosmology





Galaxy Formation Physics

known unknowns
unknown unknowns



Dark Matter Halo Population

known knowns

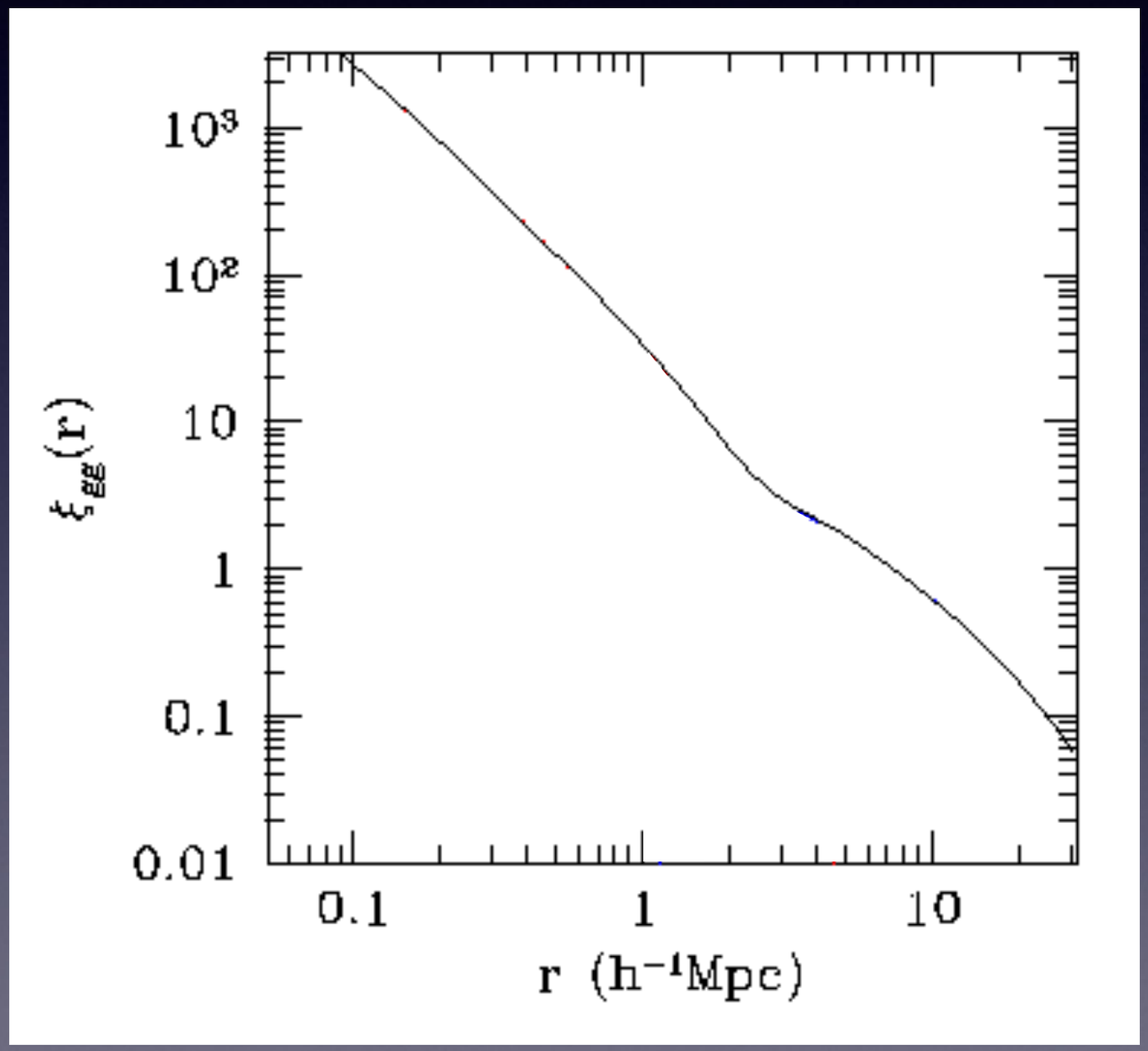
known unknowns

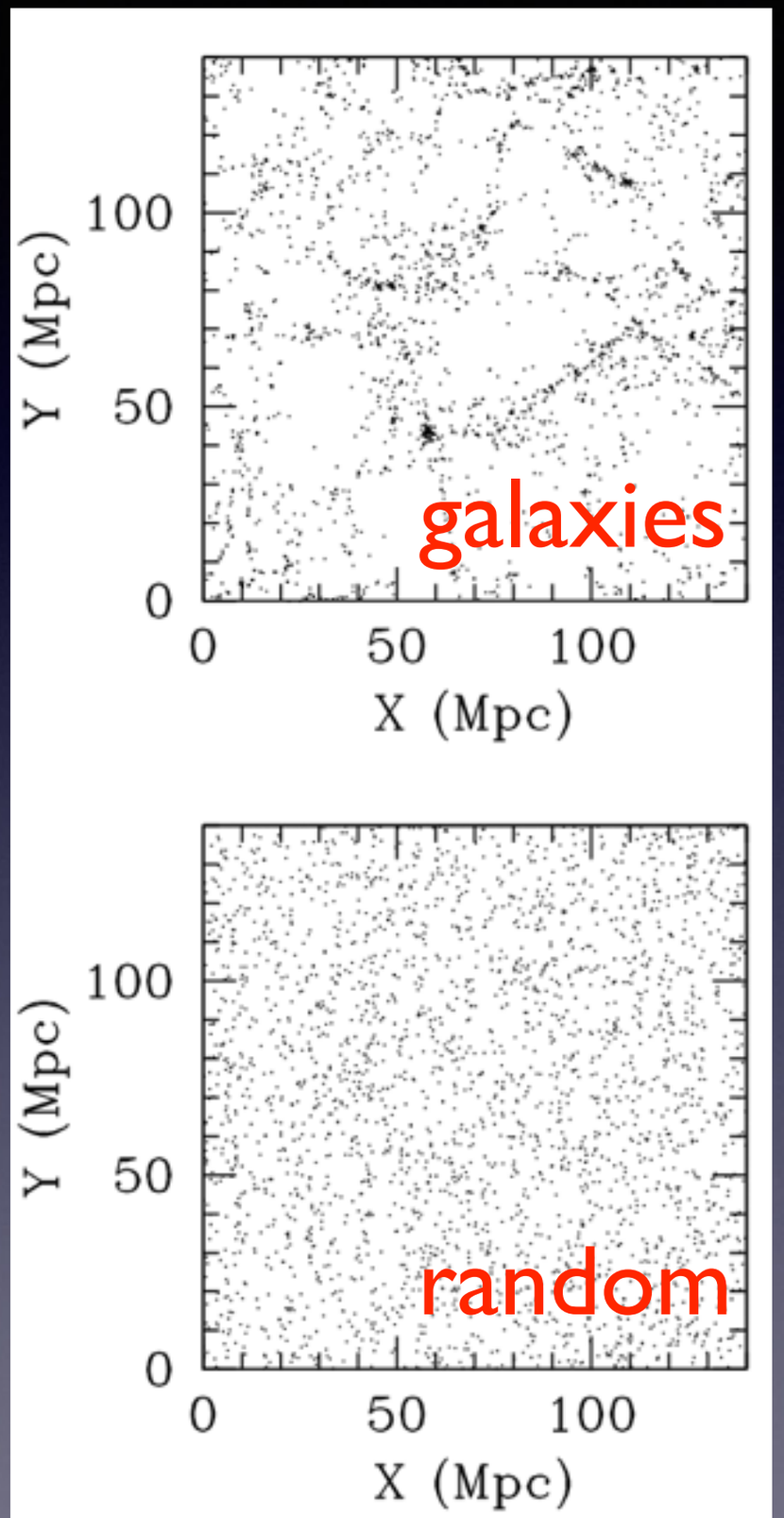
Halo Occupation Distribution
(HOD)

Galaxy Clustering

Two-point Correlation Function (2PCF) of Galaxies

Excess probability w.r.t. random distribution of finding galaxy pairs at a given separation



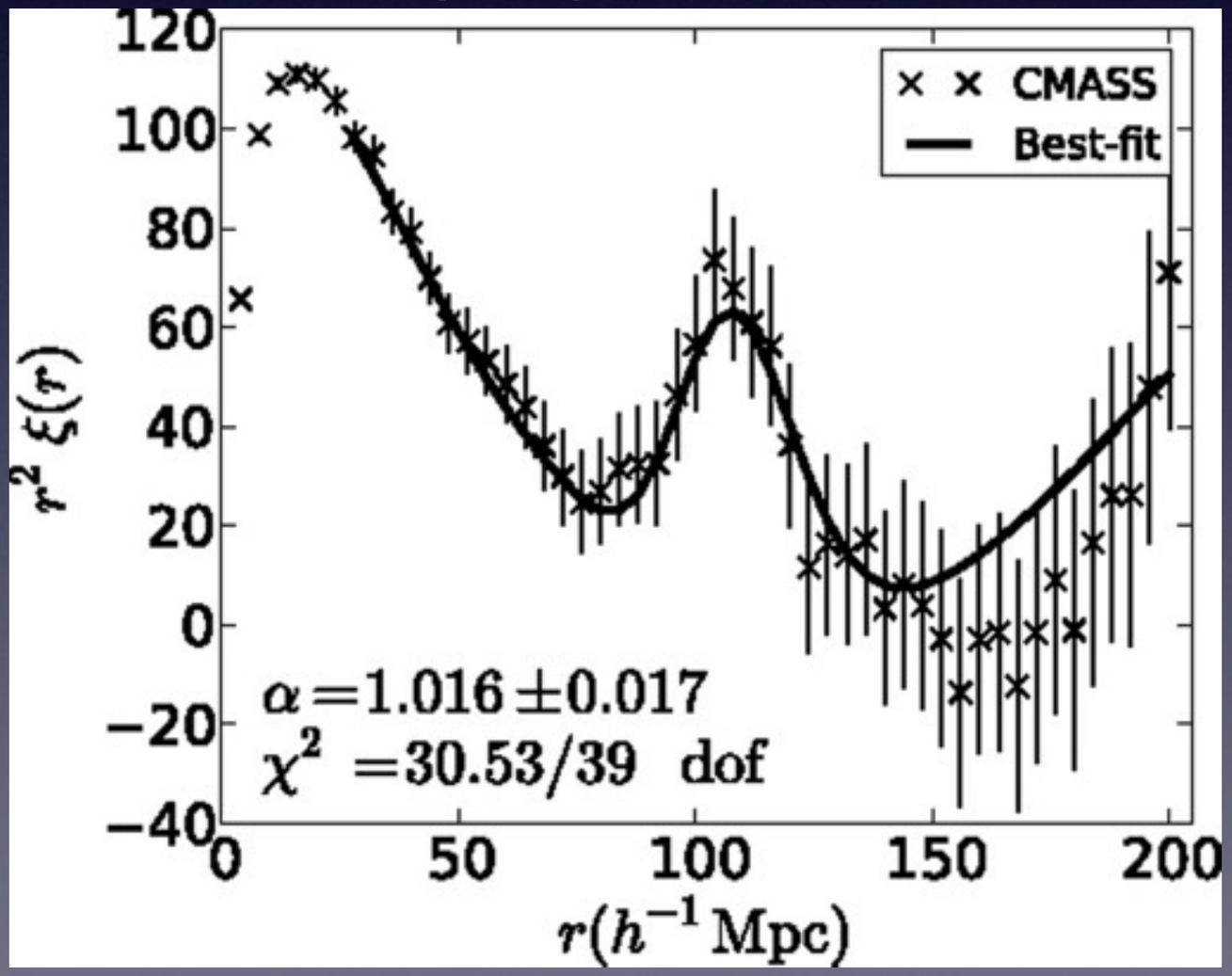


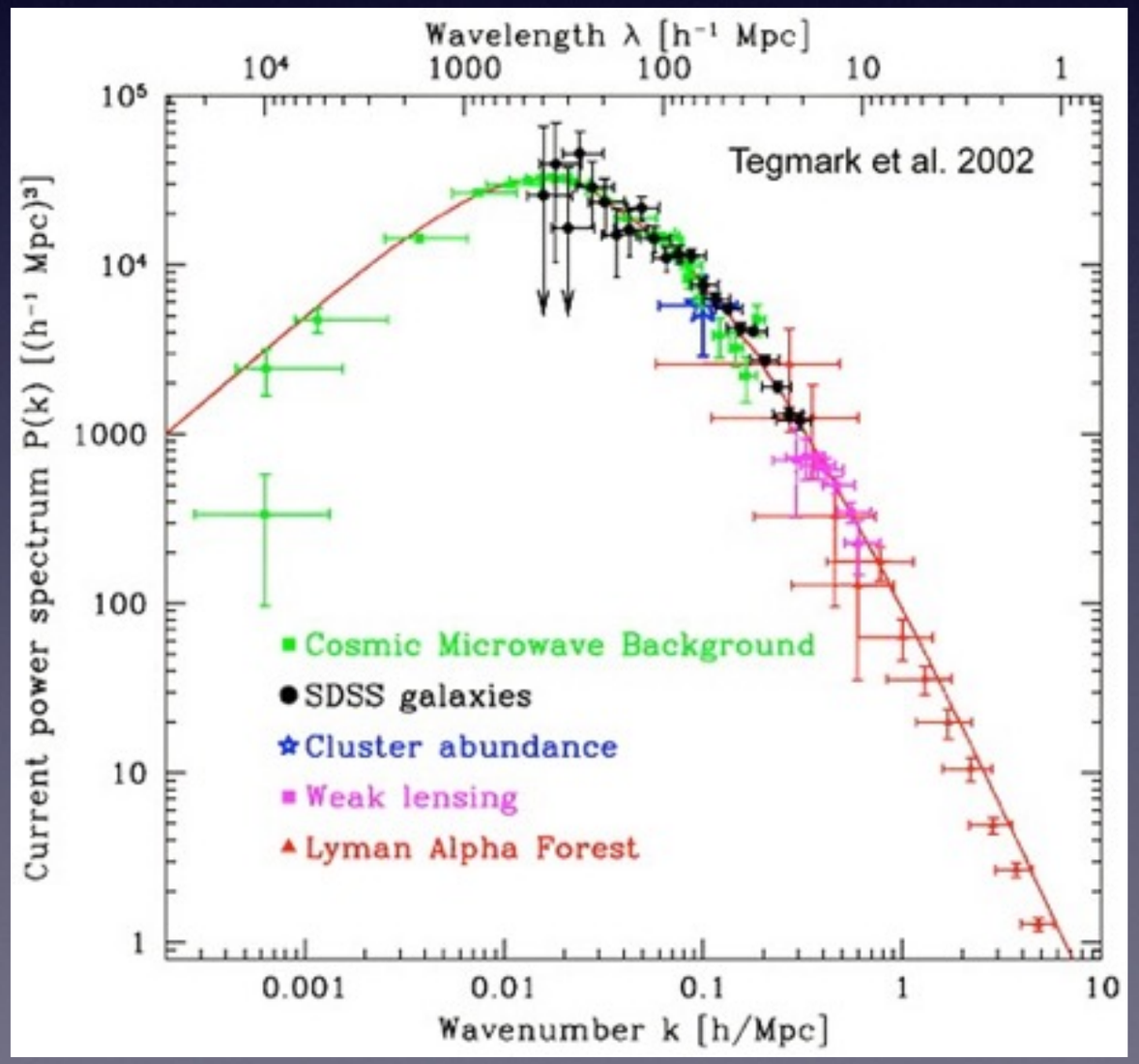
Two-point Correlation Function (2PCF) of Galaxies

Baryon Accoustic Oscillation (BAO), standard ruler
Small-scale shape, neutrino mass
Broad-band shape, cosmological parameters

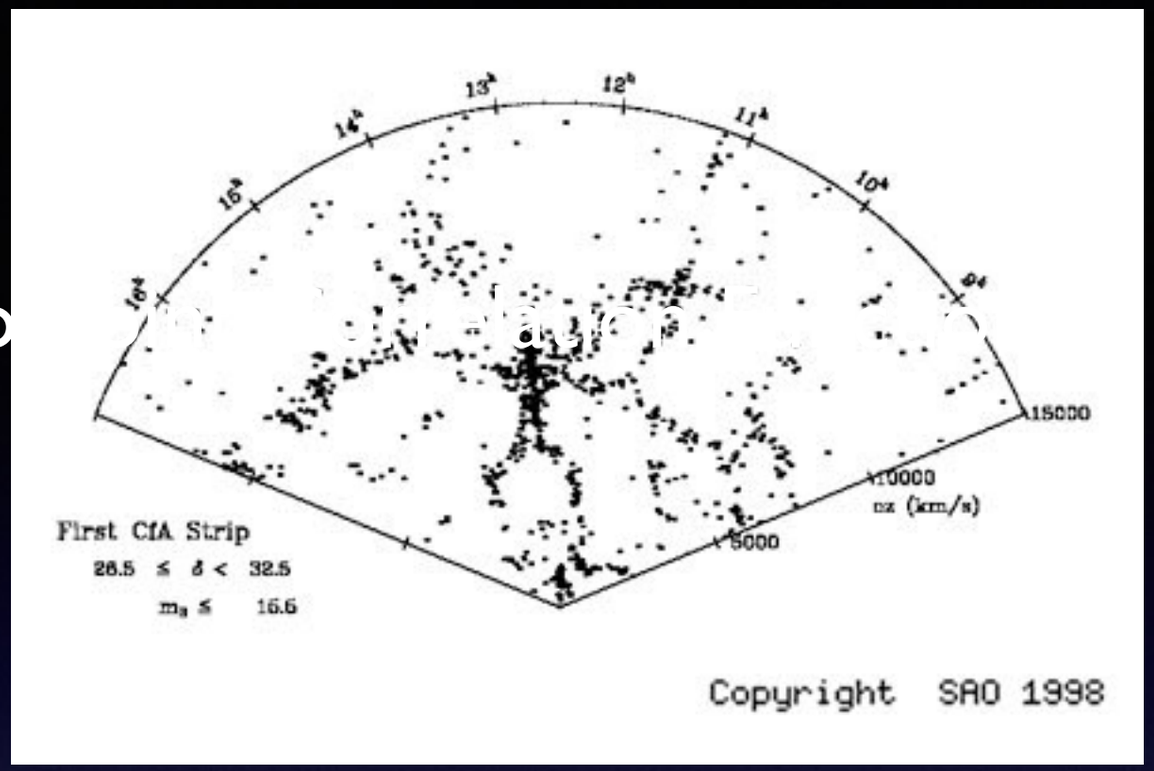
Small- and intermediate-scale shape and amplitude, galaxy-halo connection

Anderson et al. (2012)

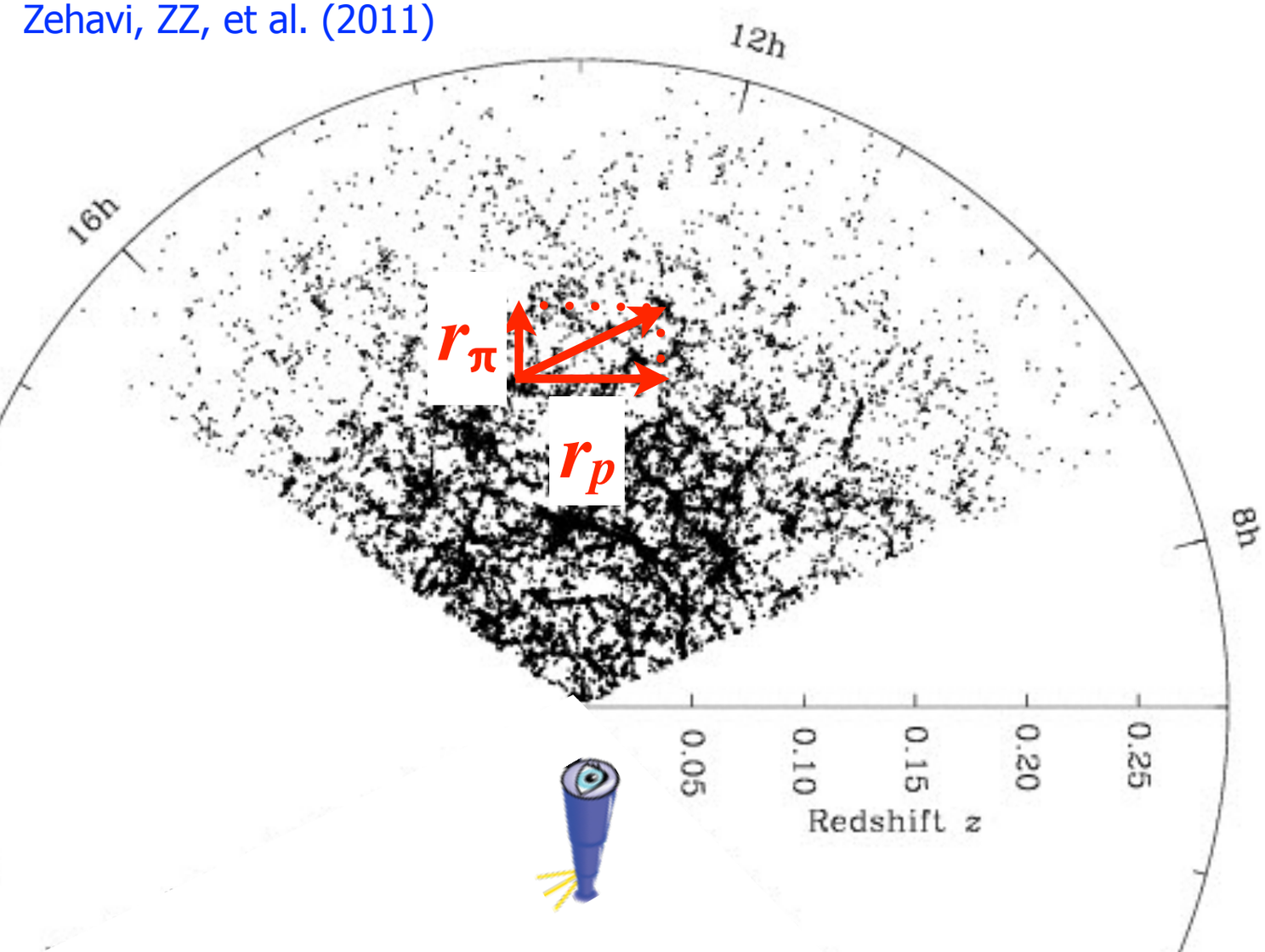




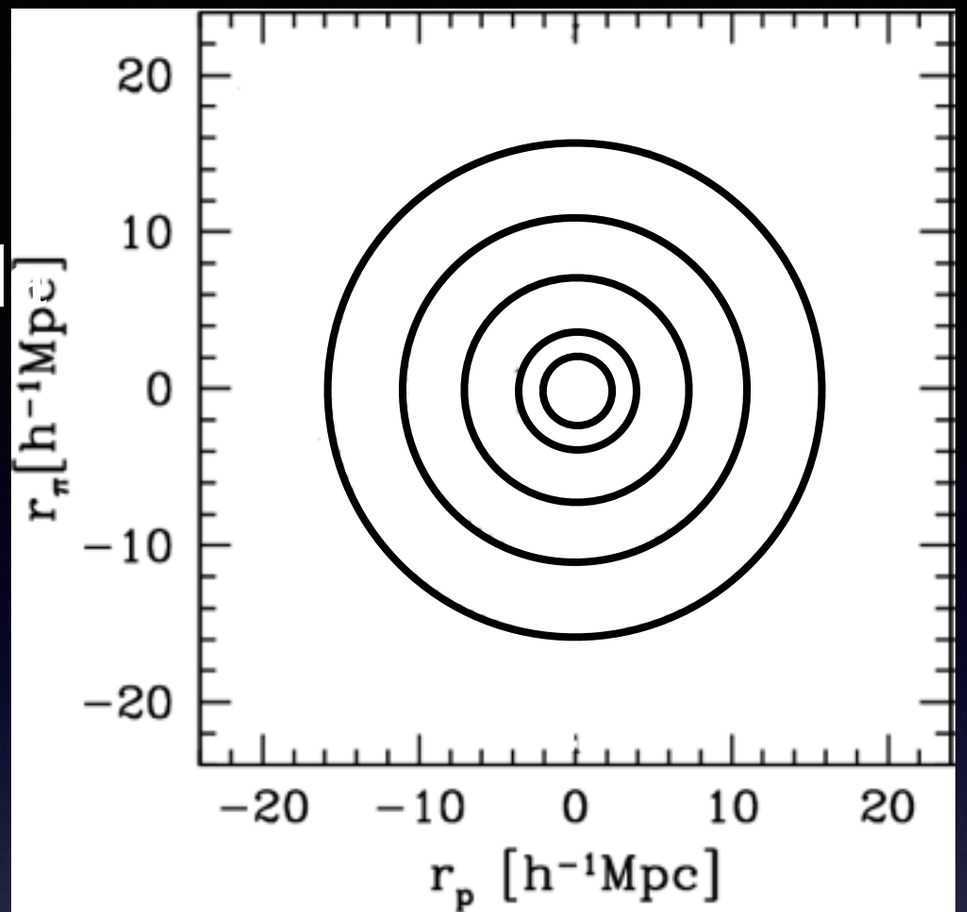
3D Two

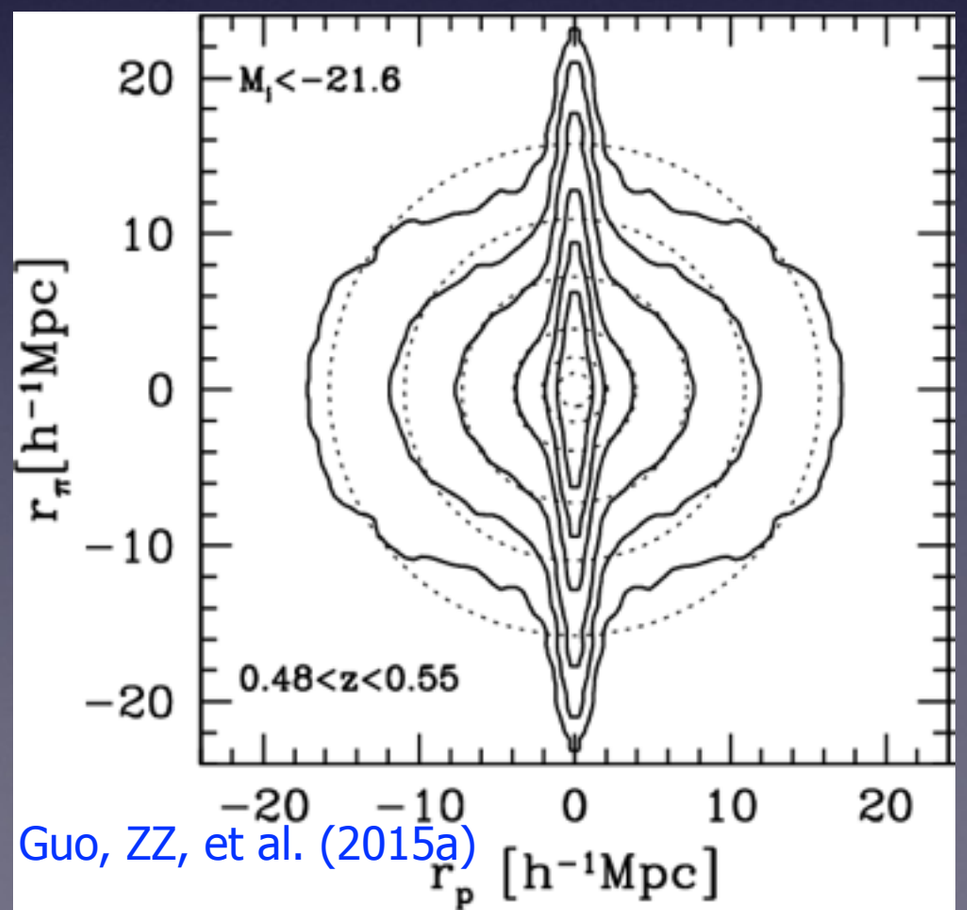


Zehavi, ZZ, et al. (2011)



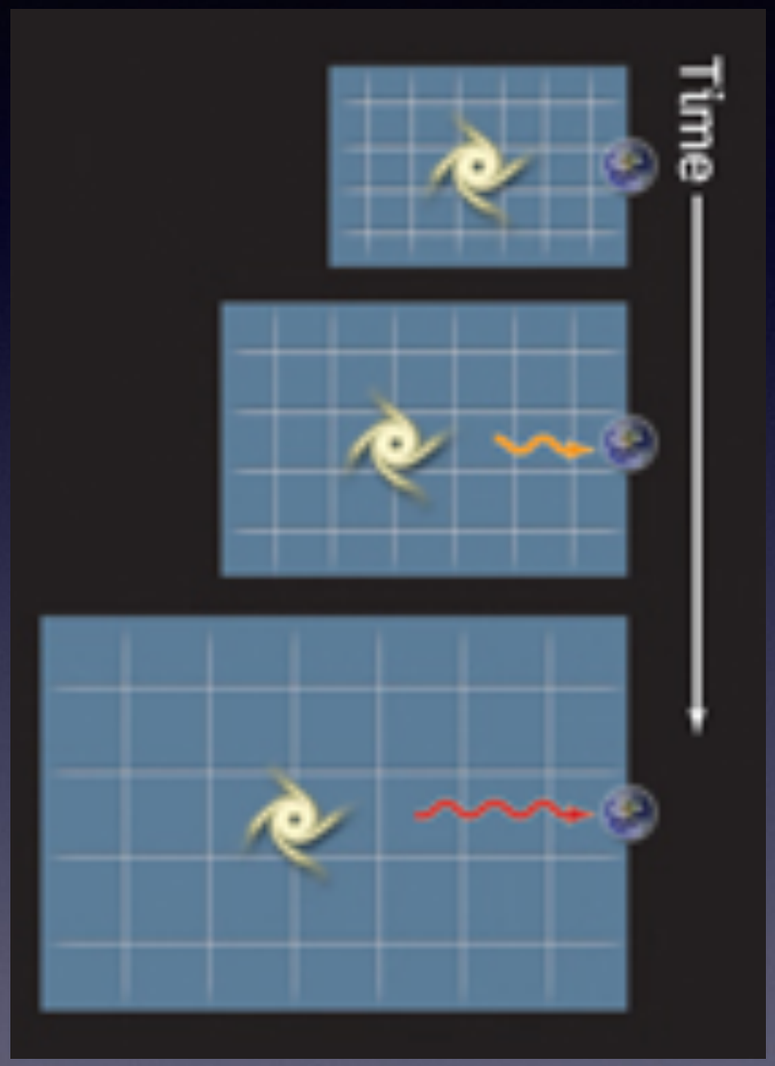
Gal





Guo, ZZ, et al. (2015a)

Galaxy comoving with the expansion
Distance ↔ Cosmological Redshift

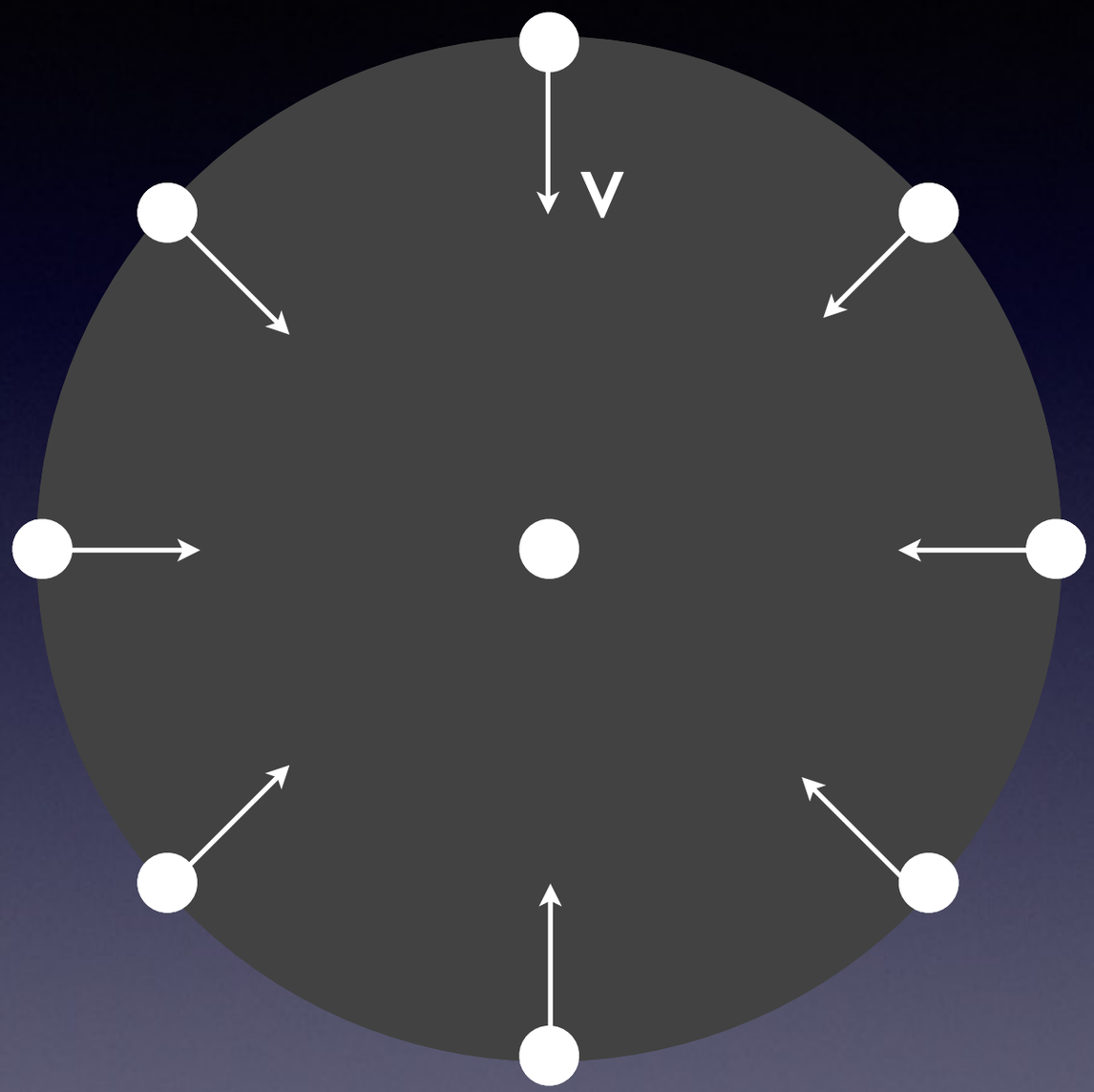


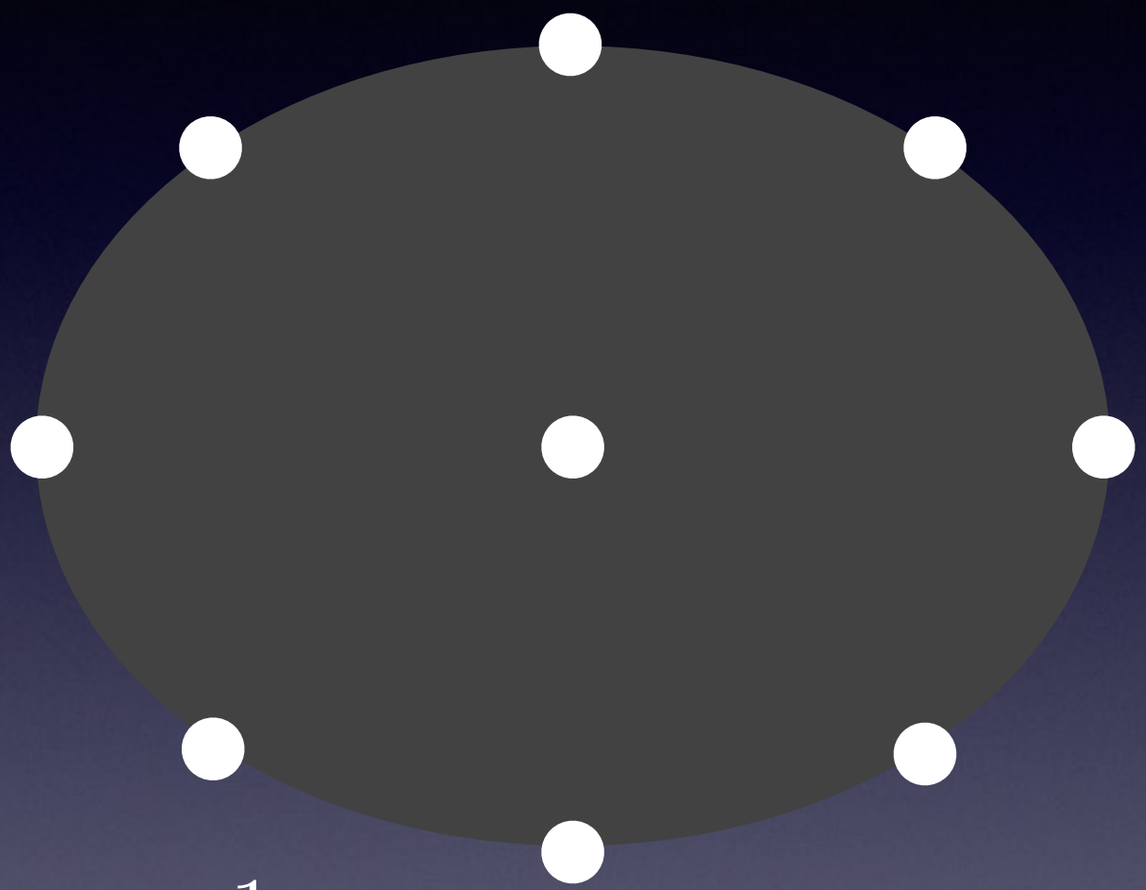
Peculiar velocity of the galaxy
velocity w.r.t. the comoving frame
=> Doppler redshift

Observed Redshift: Cosmological Redshift + Doppler Redshift

Distance inference: distorted by the Doppler redshift from galaxy peculiar motion

Large-Scale Linear Redshift-Space Distortion (Kaiser 1987)





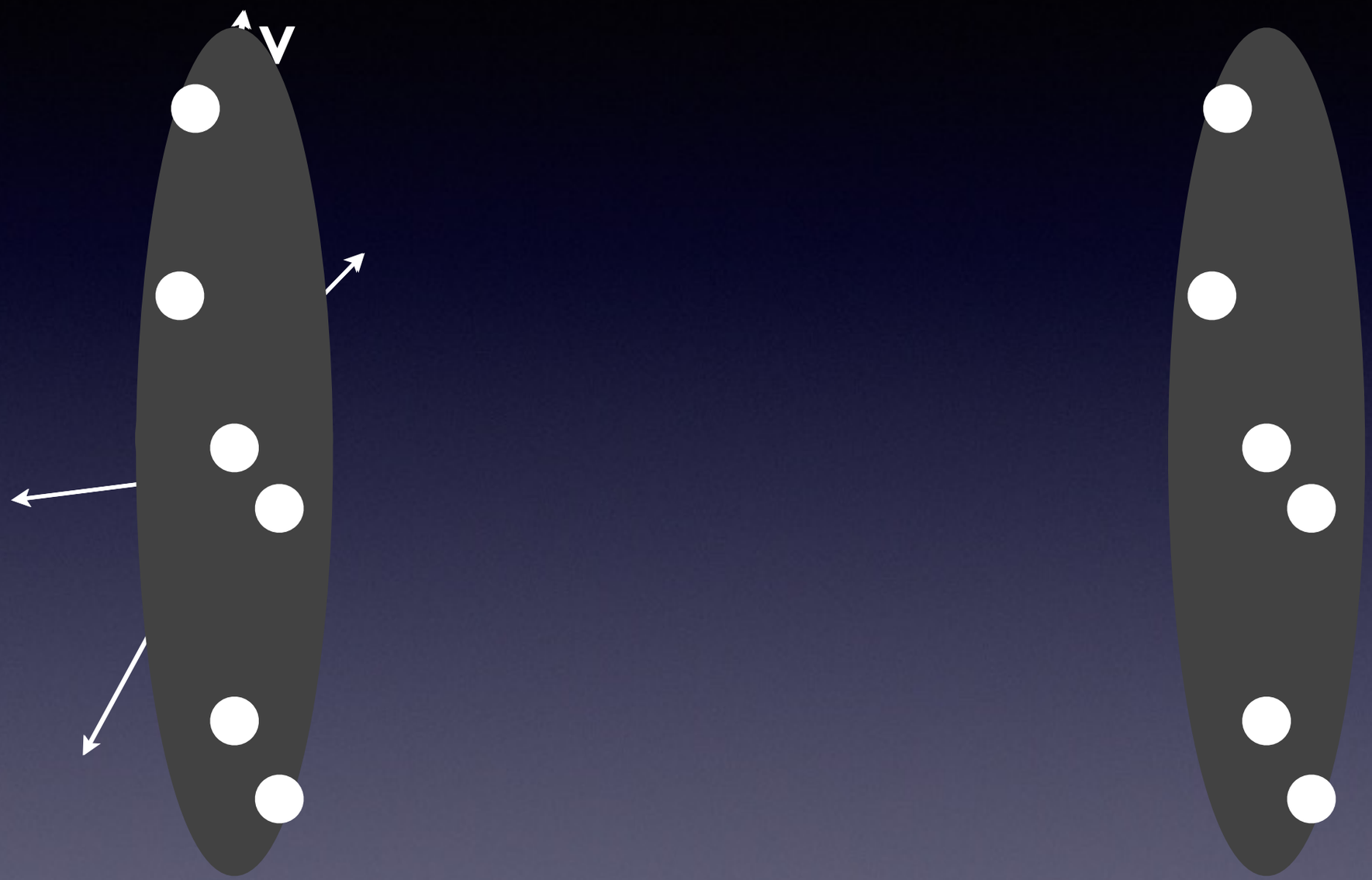
$$\dot{\delta} + \frac{1}{a}\nabla \cdot \mathbf{v} = 0 \quad \text{(continuity)}$$

Probe combination of structure growth rate and fluctuation amplitude (gravity, dark energy)

Real Space

Redshift Space

Small-Scale Nonlinear Redshift-Space Distortion (Finger-of-God Effect)

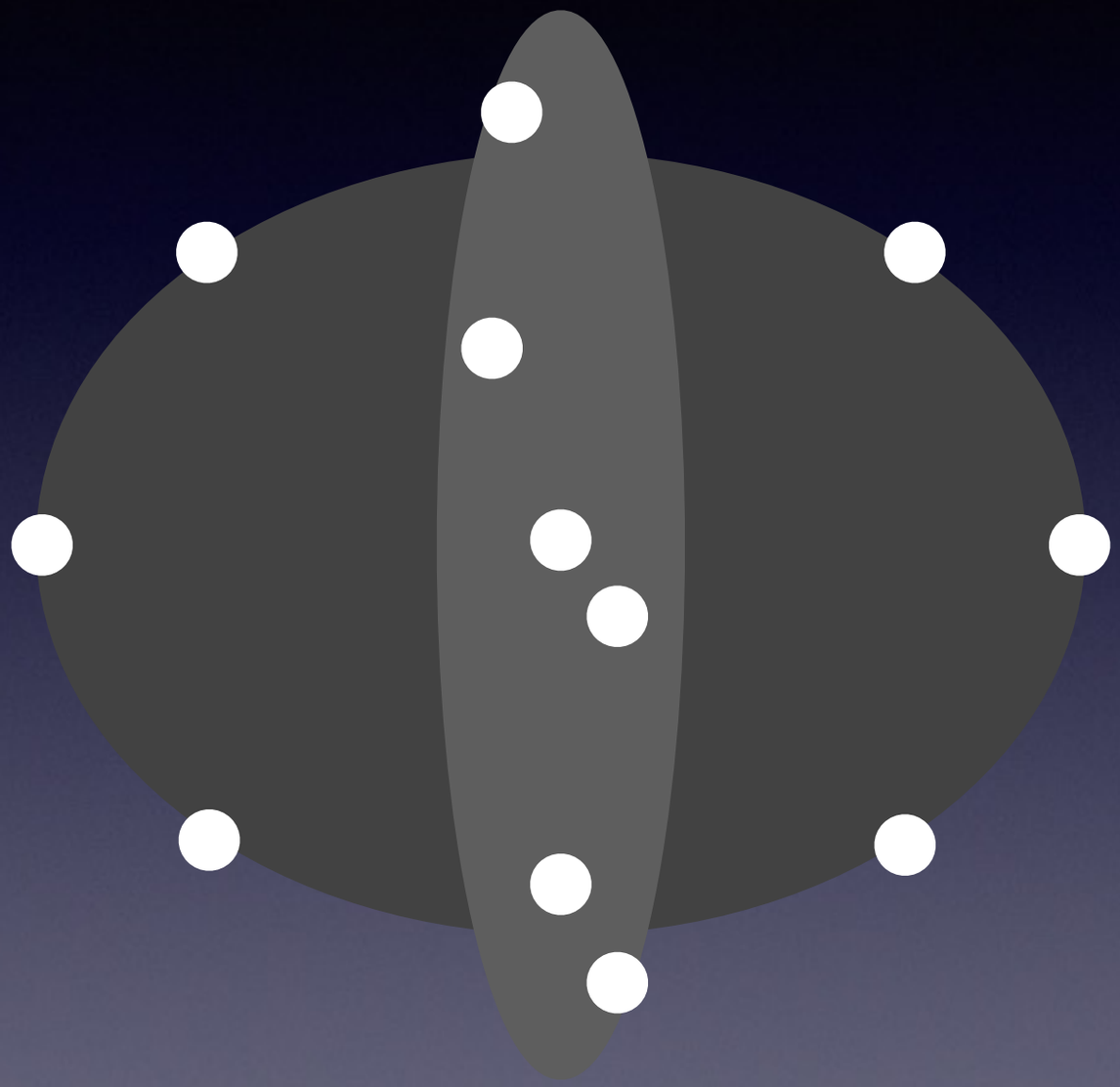


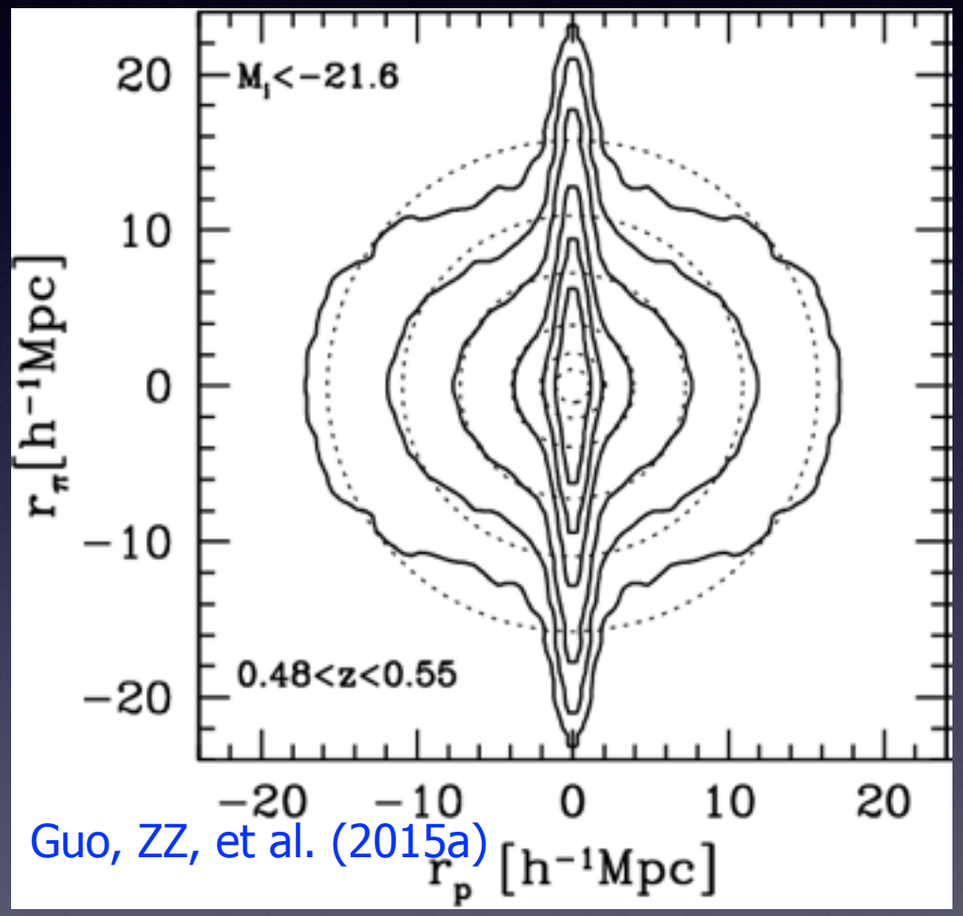
Probe galaxy kinematics inside dark matter halos (galaxy formation and evolution)

Real Space

Redshift Space

Redshift-Space Distortion (Gravitational Distortion)





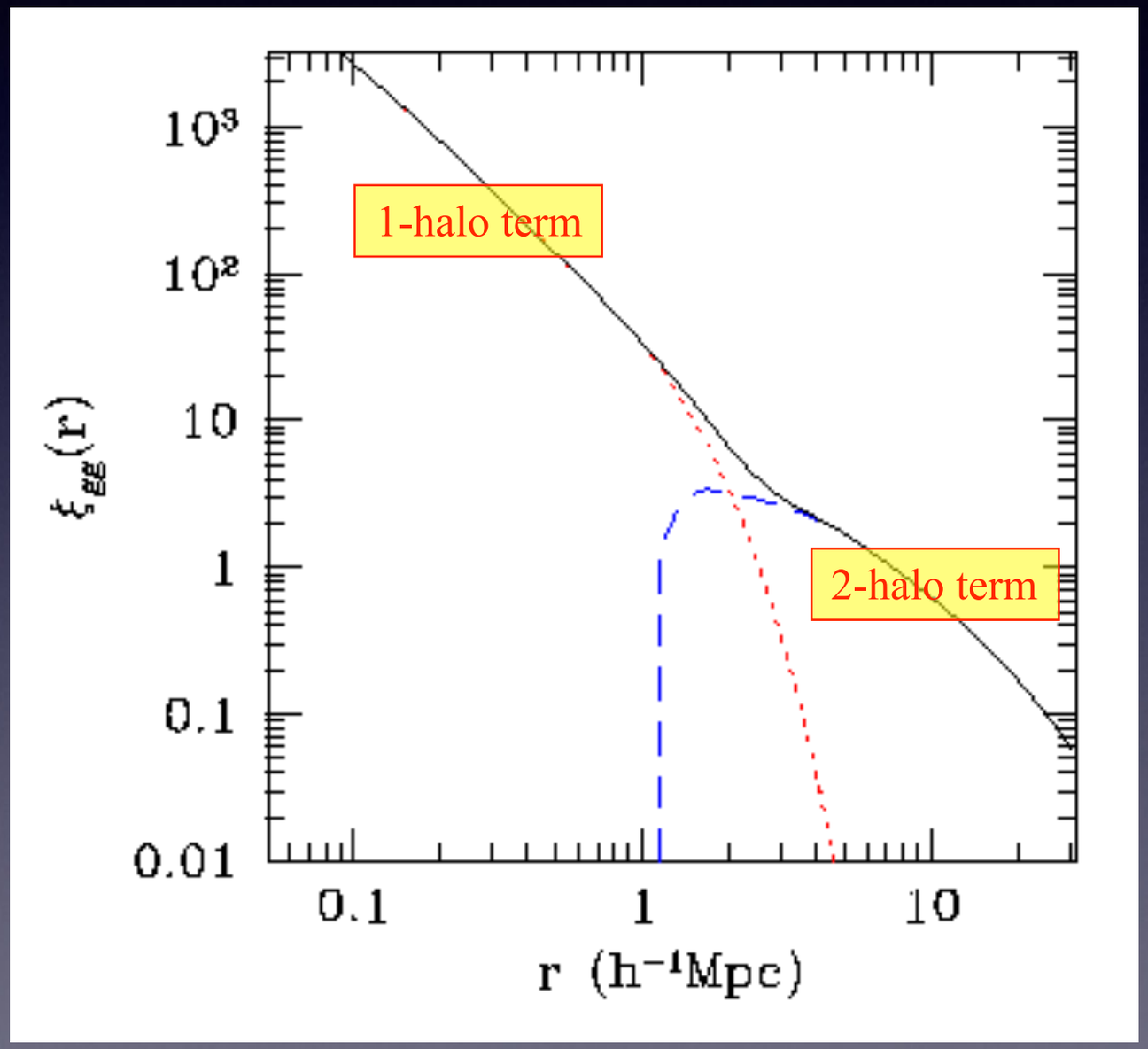
Guo, ZZ, et al. (2015a)

Galaxy Formation and evolution: kinematics of galaxies inside halos

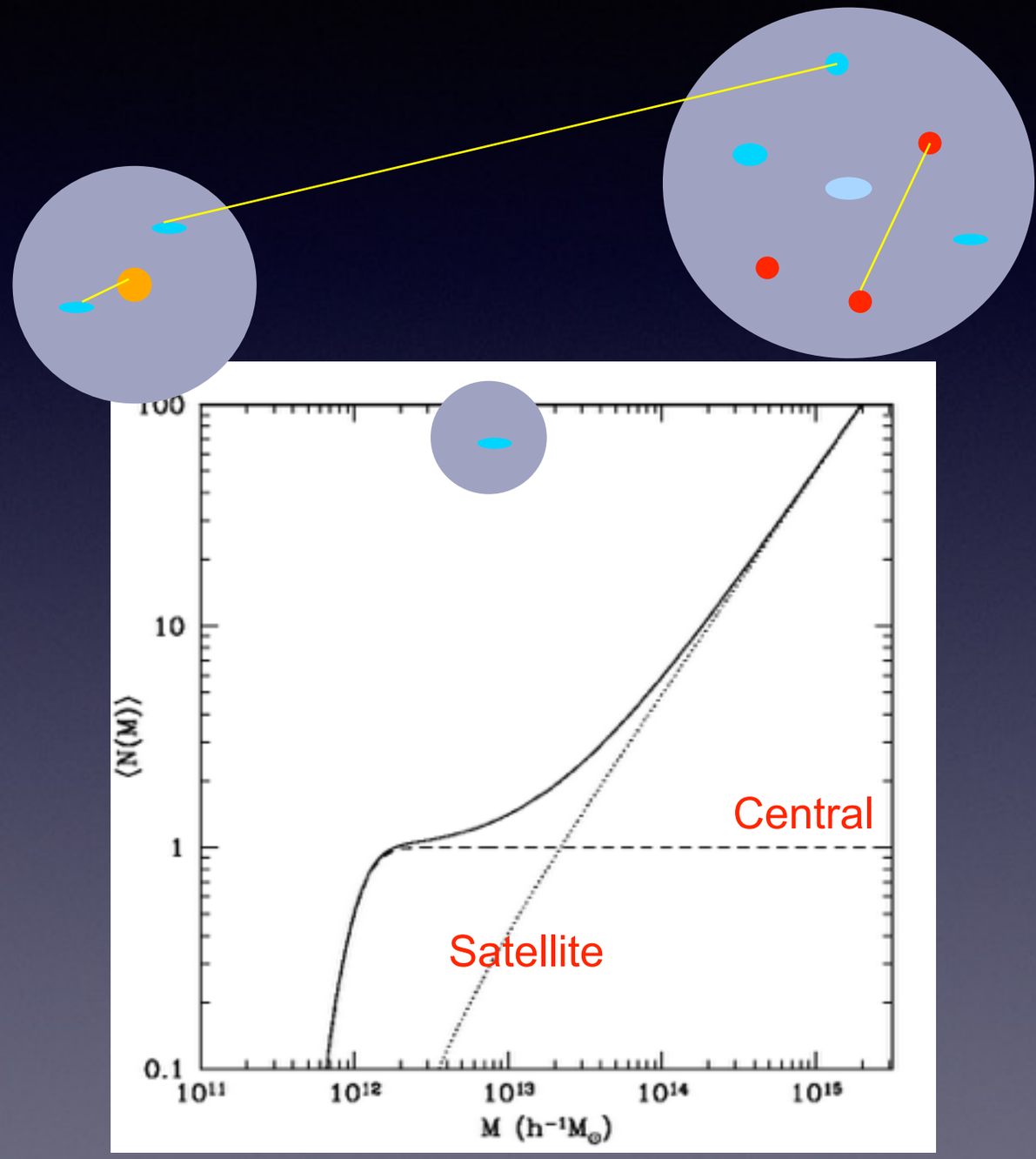
Cosmology: amplitude and growth rate of matter density fluctuation

Projected Two-point Correlation Function of Galaxies

redshift-space distortion effect removed
essentially the real-space clustering



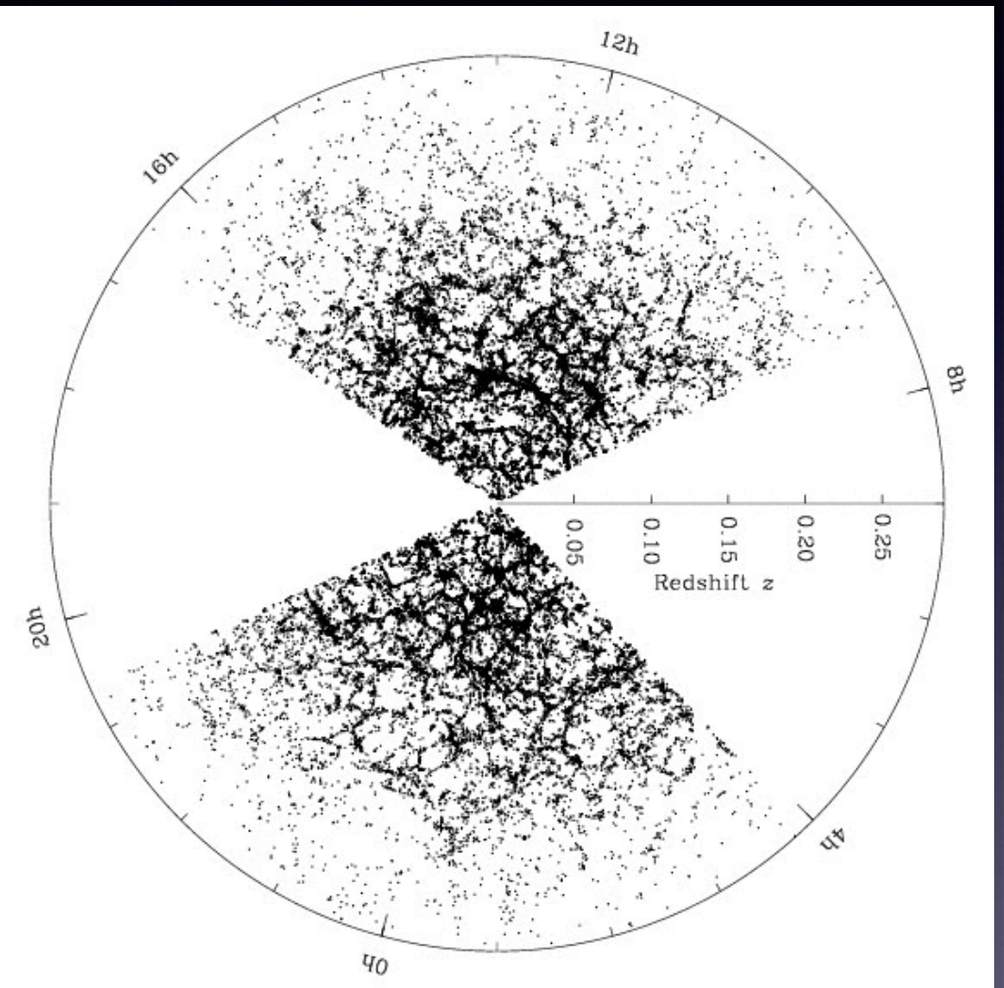
Galaxy Pair Counts



HOD (Galaxy-Halo Relation)

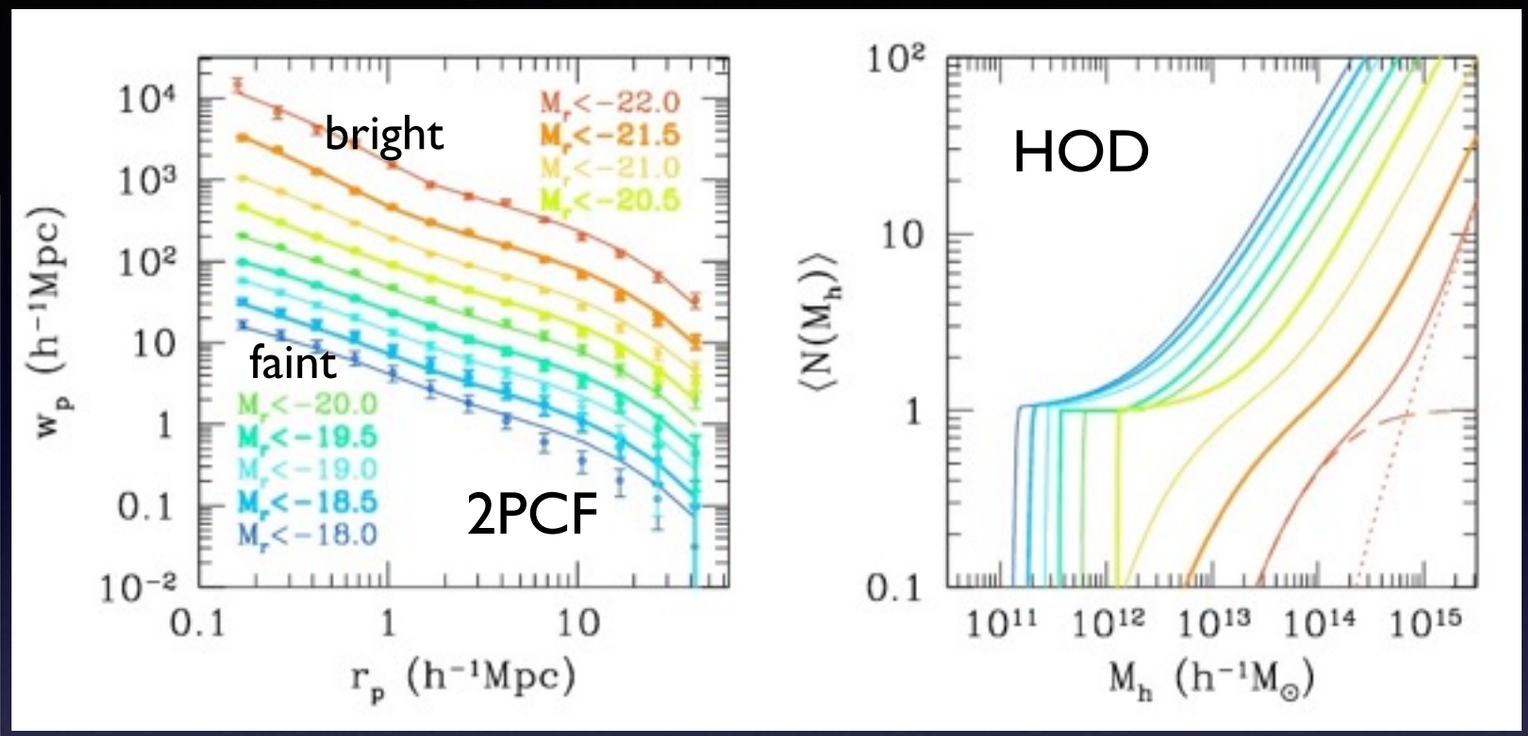
HOD Modeling of the SDSS Galaxy Clustering

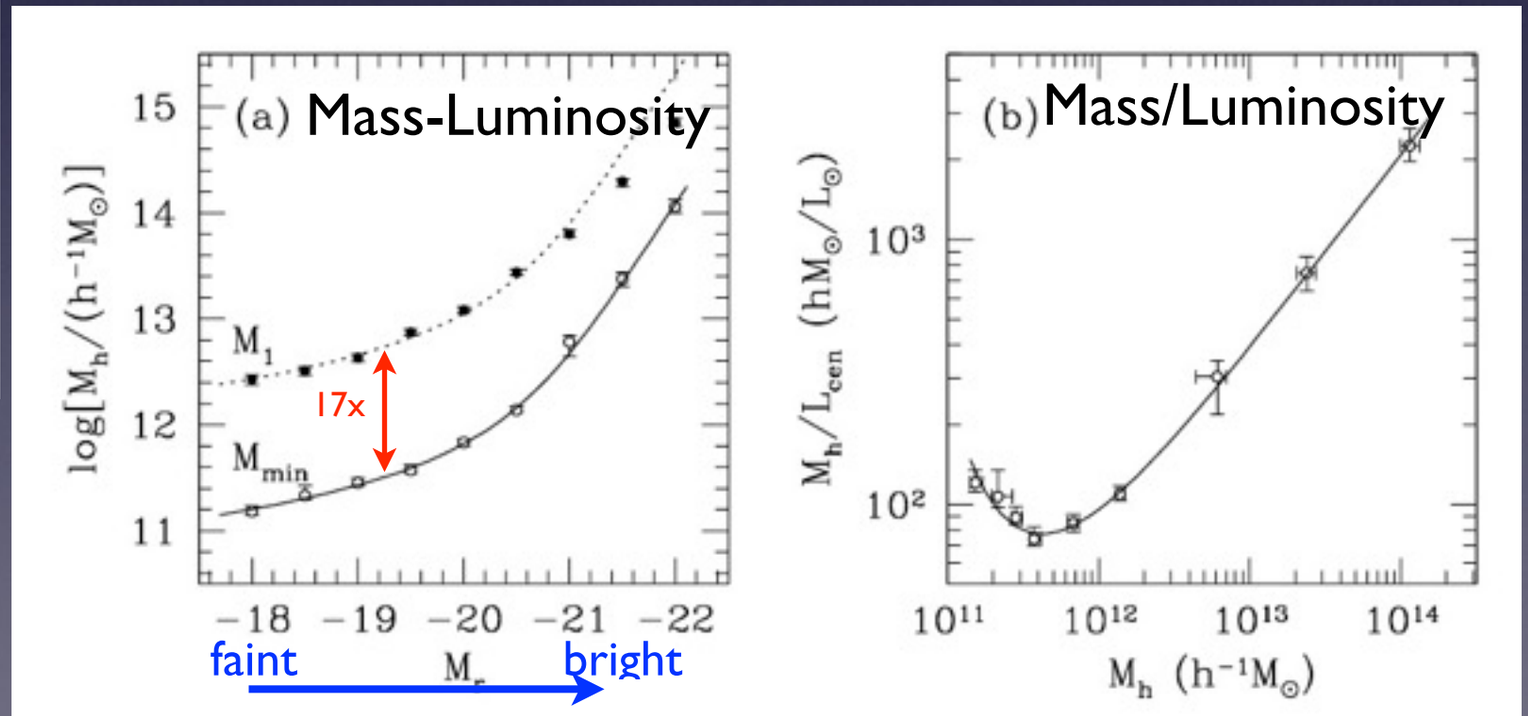
z~0.1



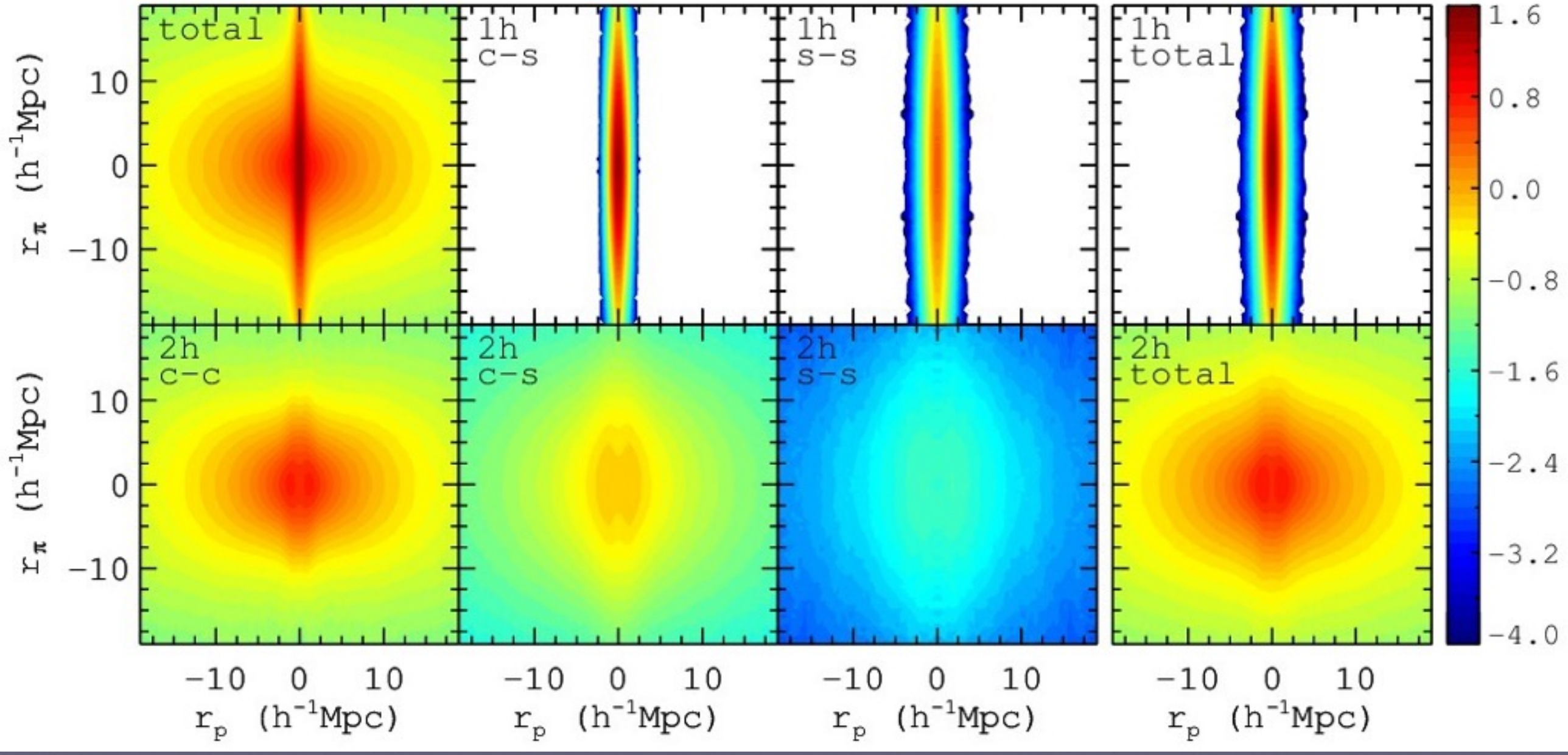
Zehavi, ZZ, et al. (2011)

Luminosity Dependence

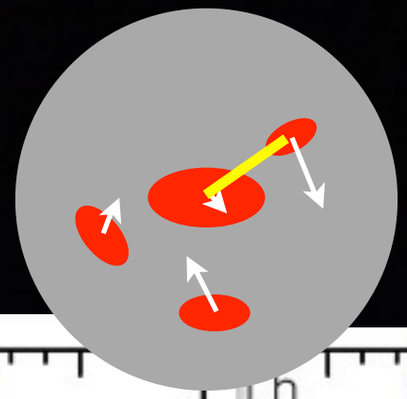


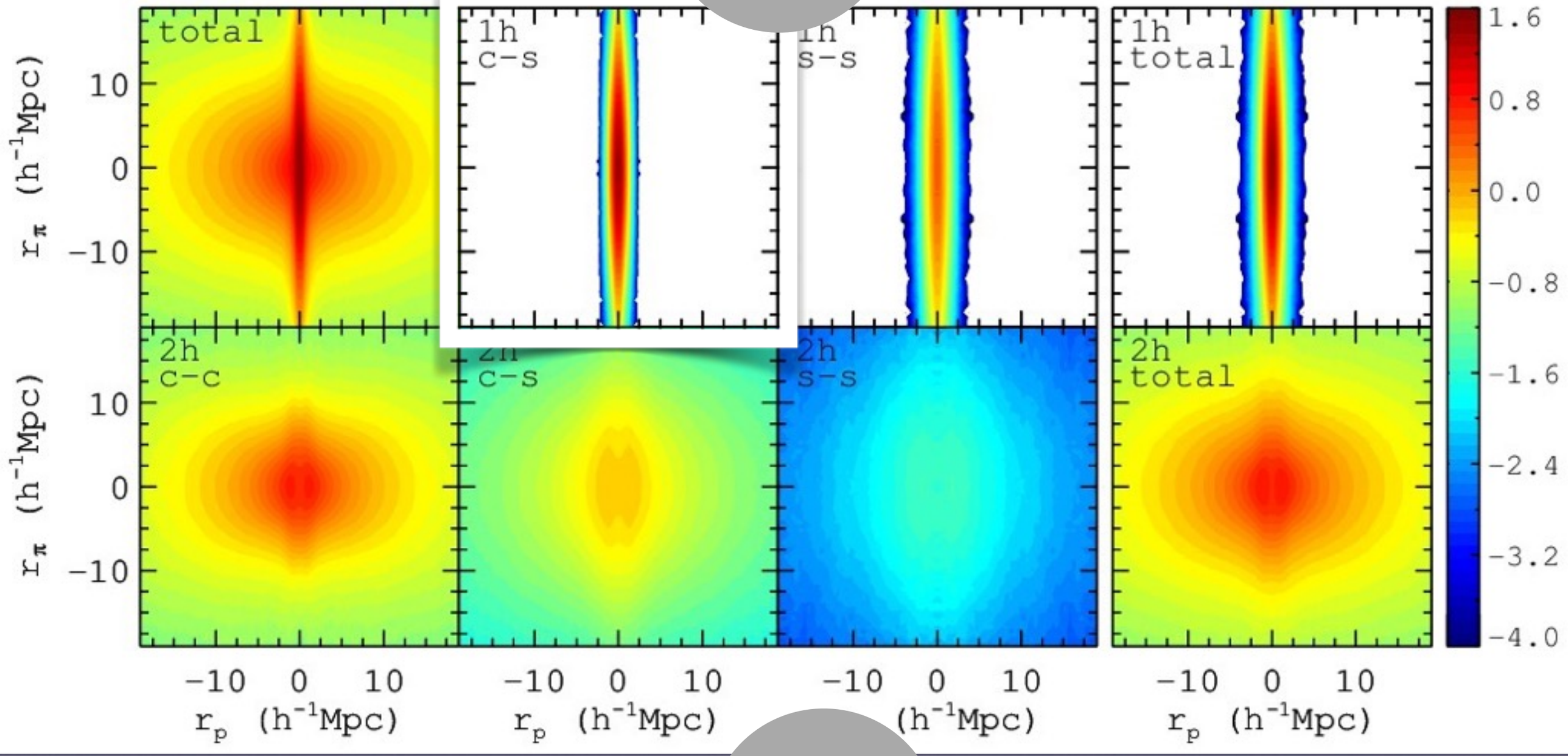


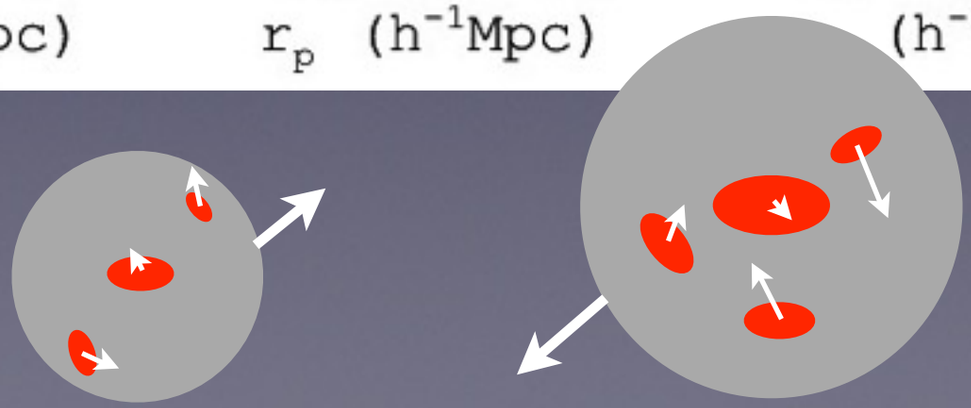
An Accurate and Efficient Simulation-based Model for Redshift-Space Galaxy Two-Point Correlation Function



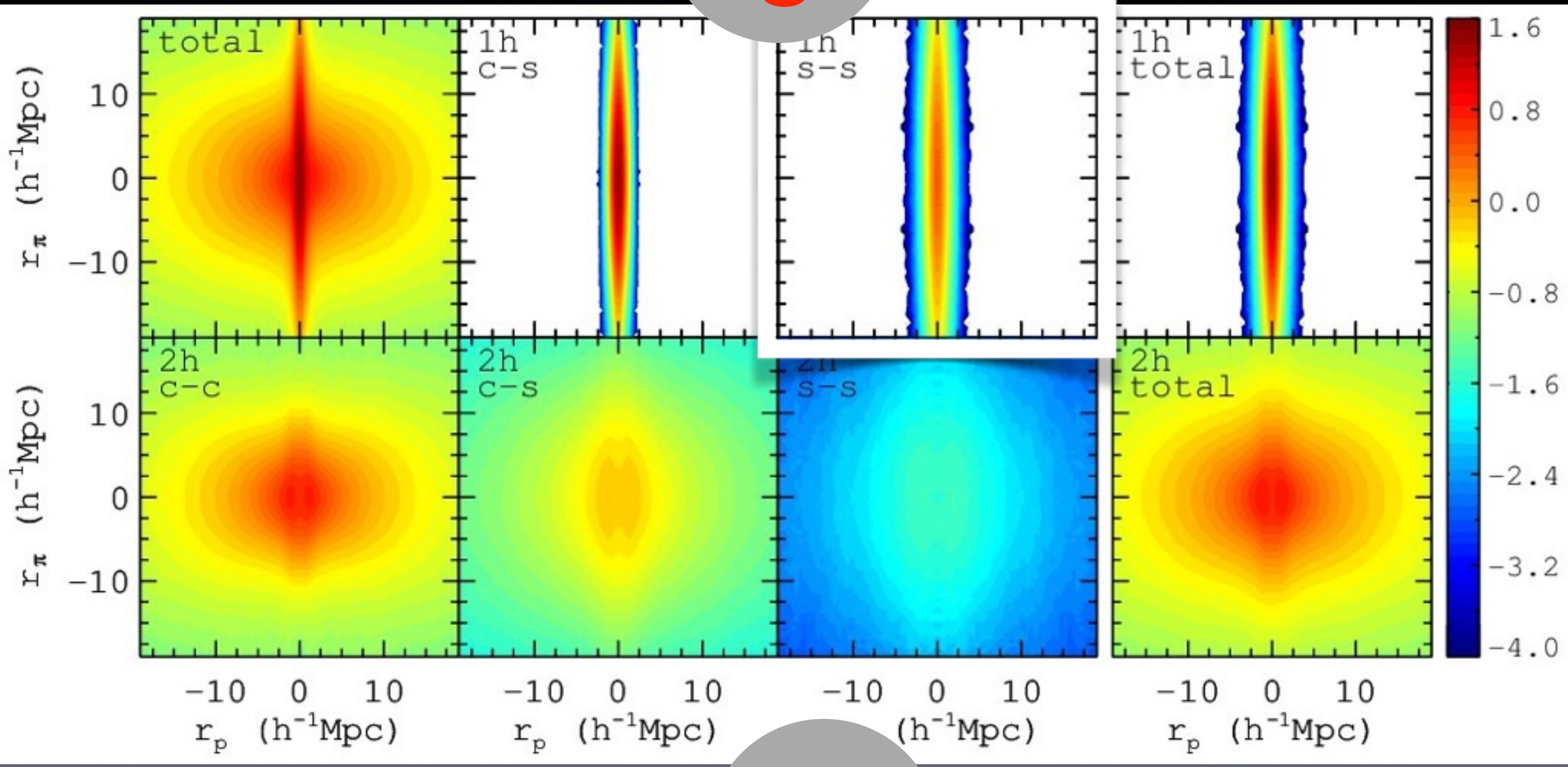
ZZ & Guo (1506.07523)



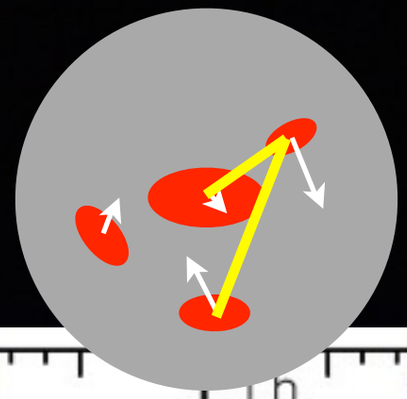




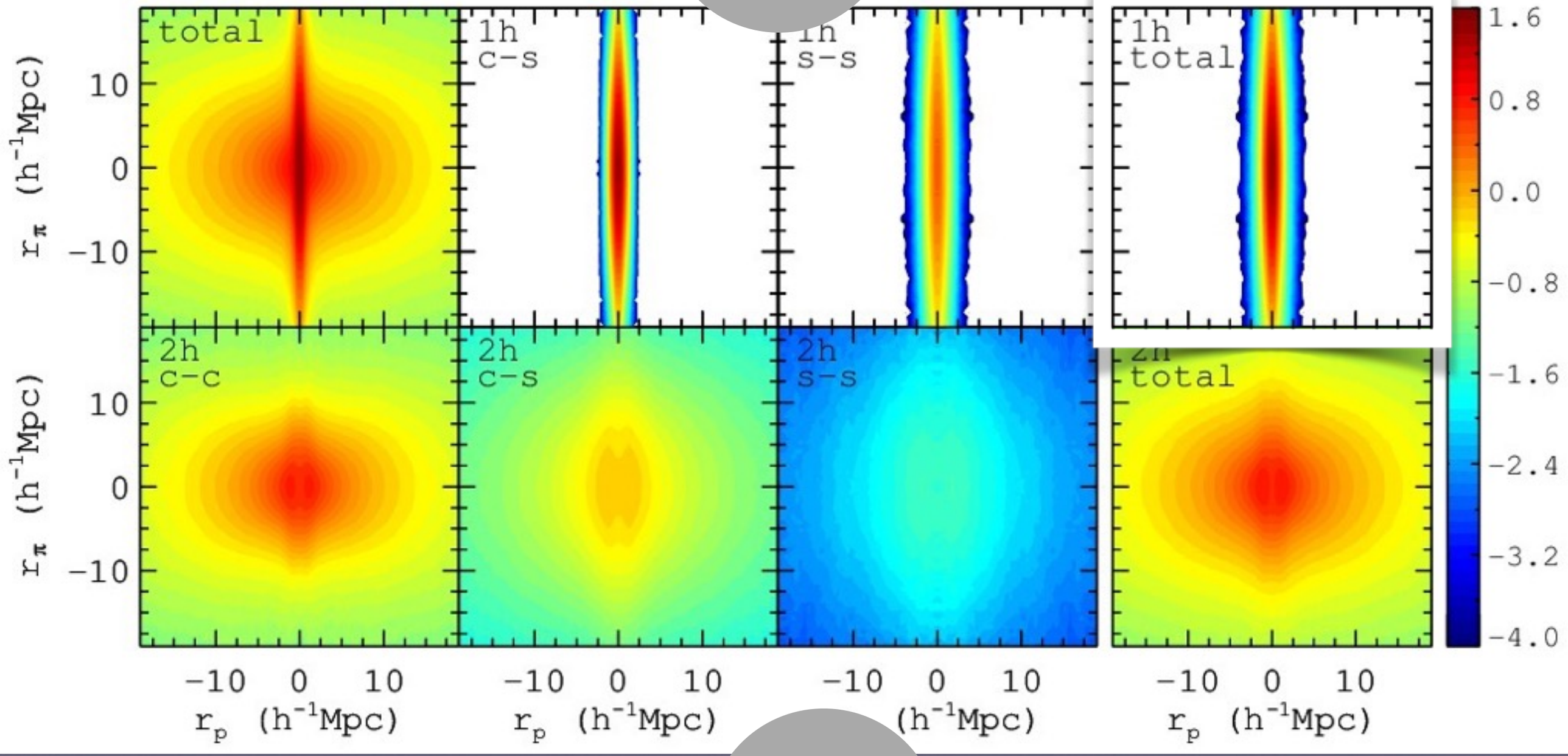
ZZ & Guo (1506.07523)

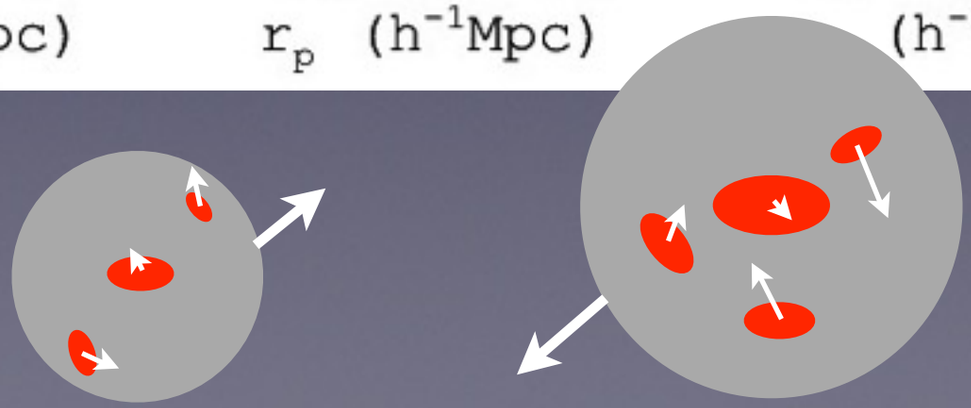


ZZ & Guo (1506.07523)

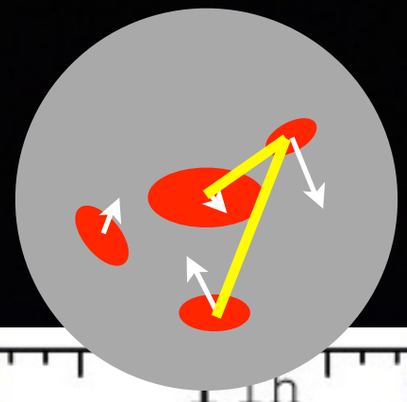


one-halo total

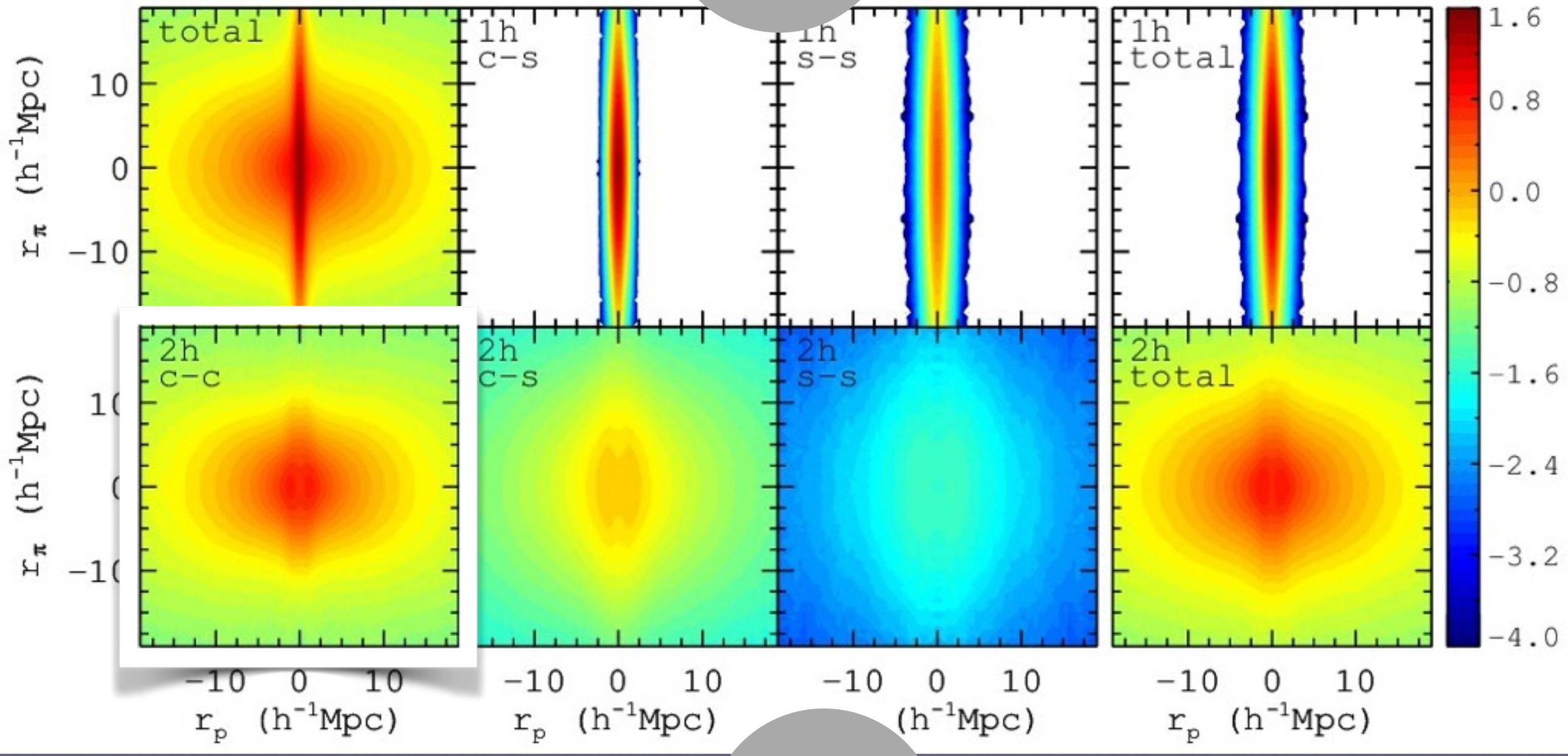


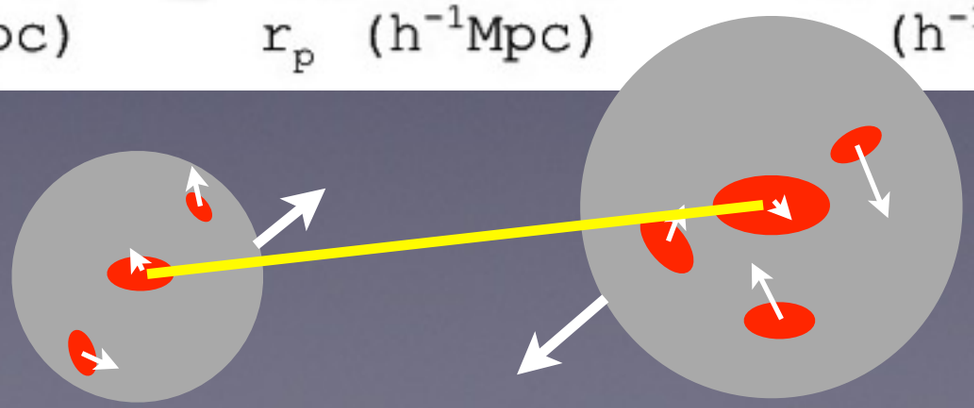


ZZ & Guo (1506.07523)



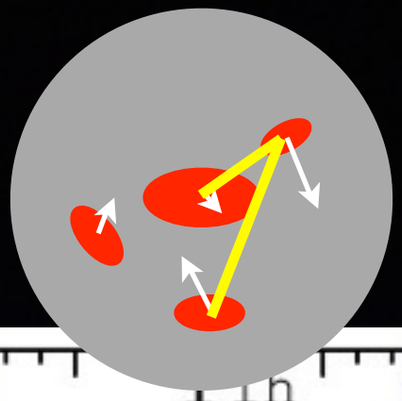
one-halo total

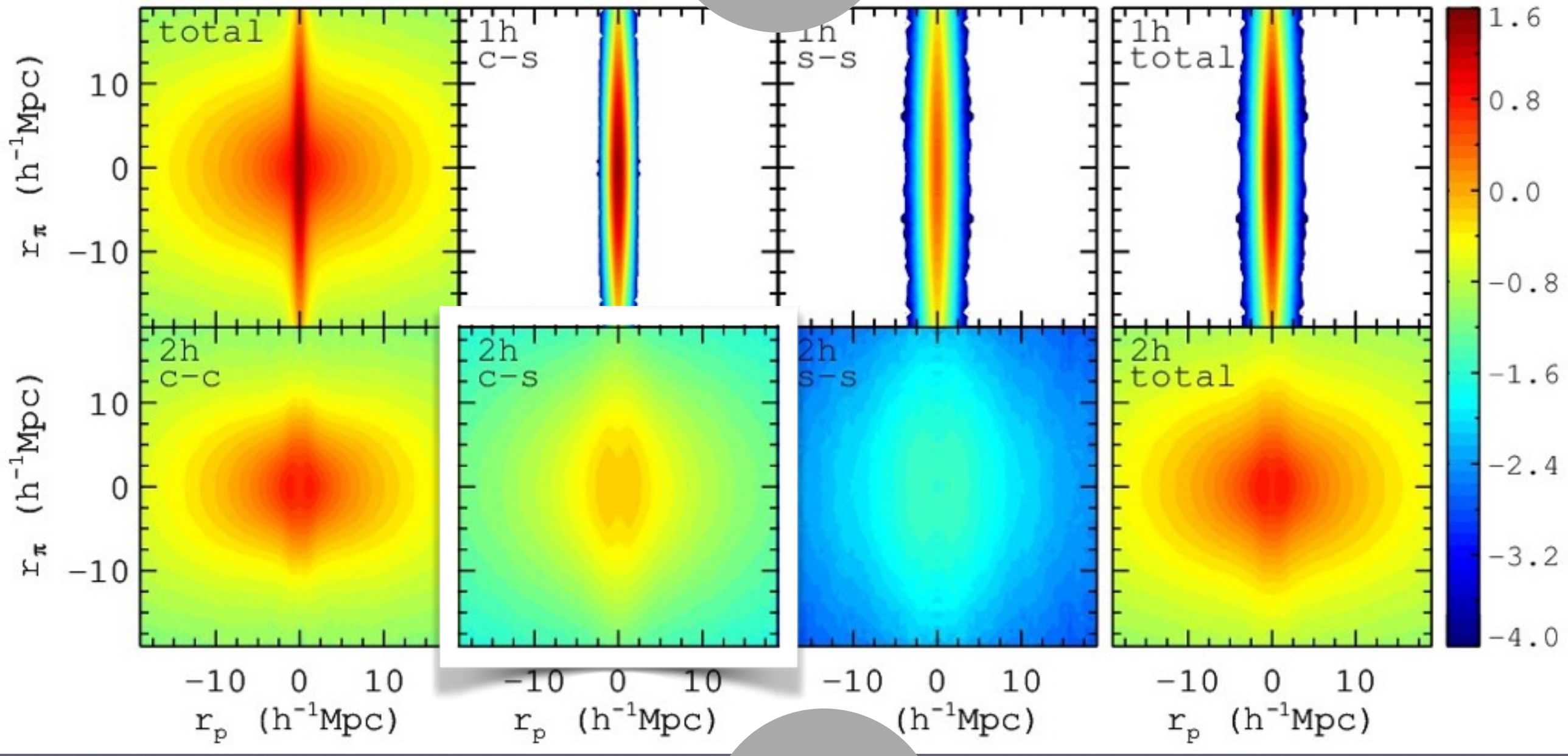


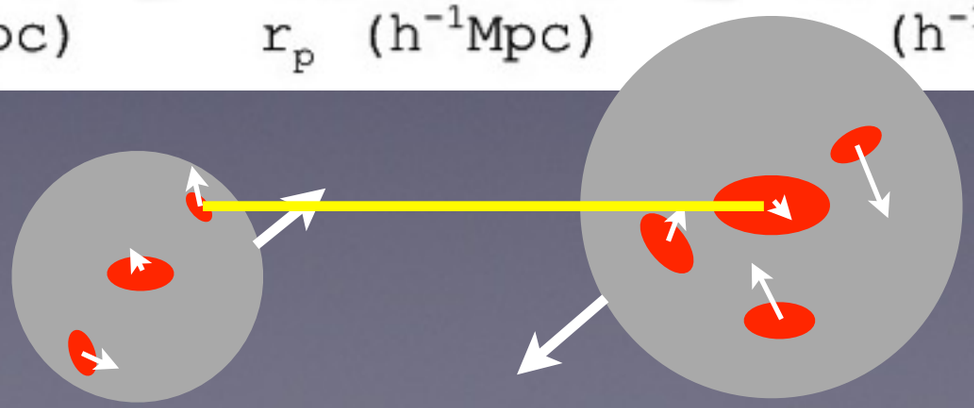


ZZ & Guo (1506.07523)

one-halo total







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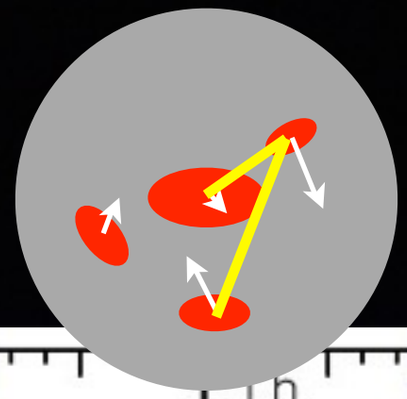
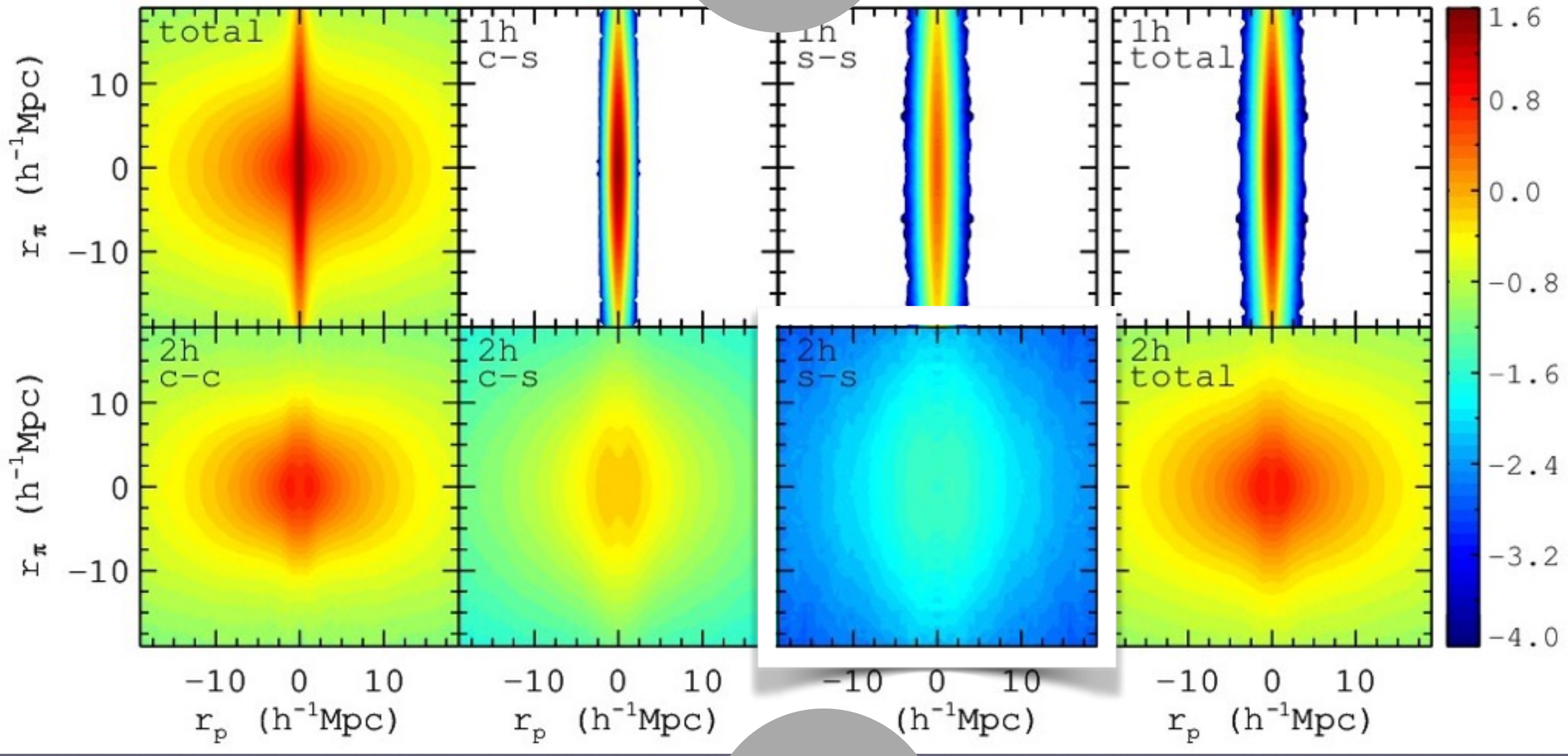
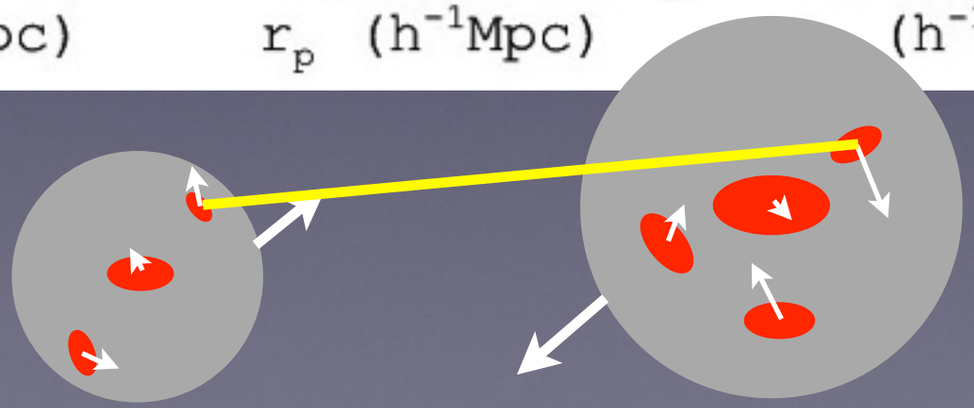


one-halo total





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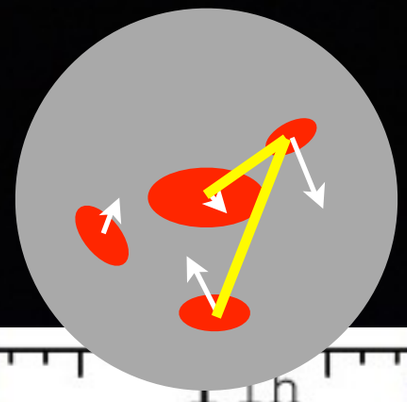
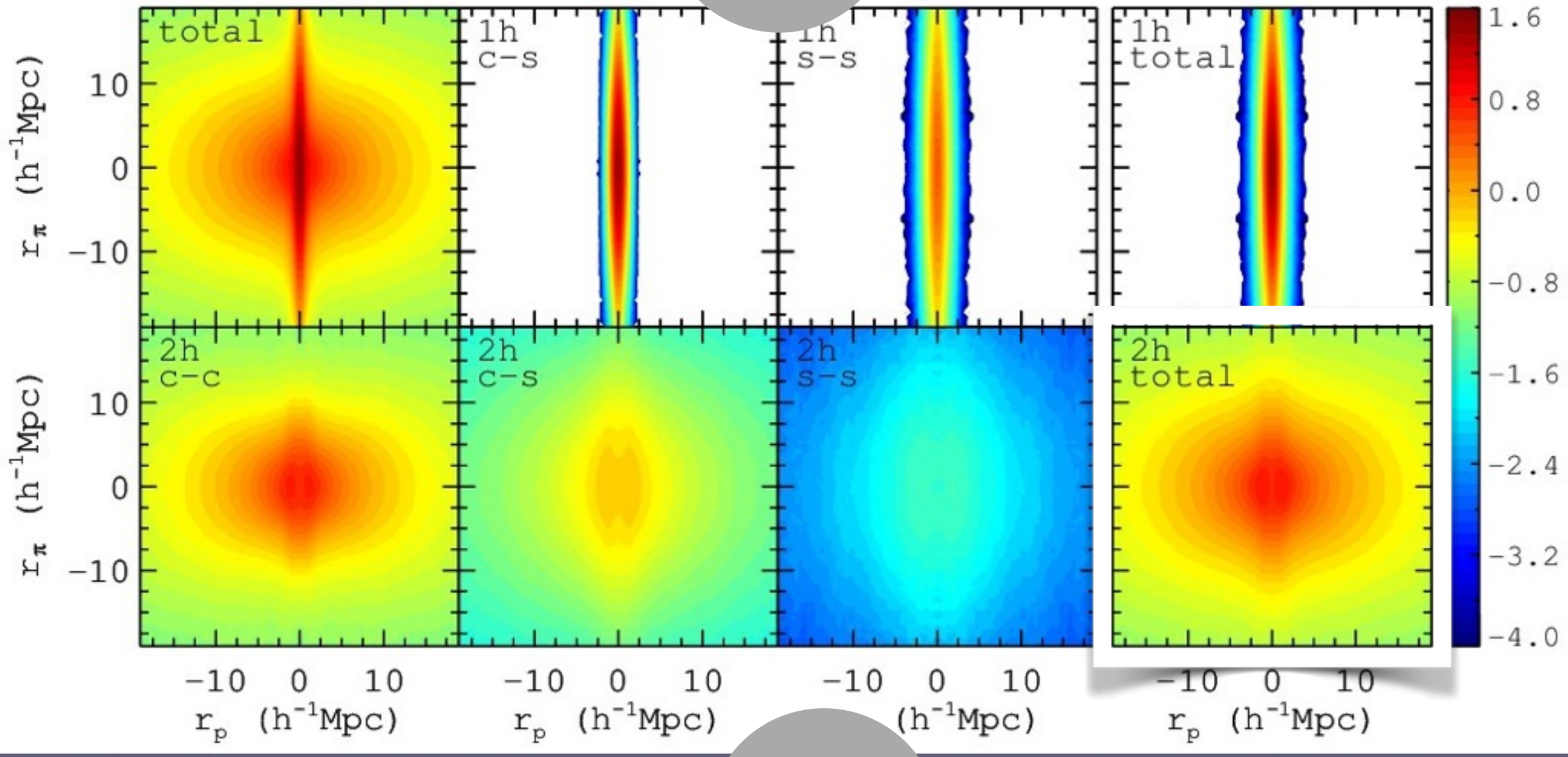
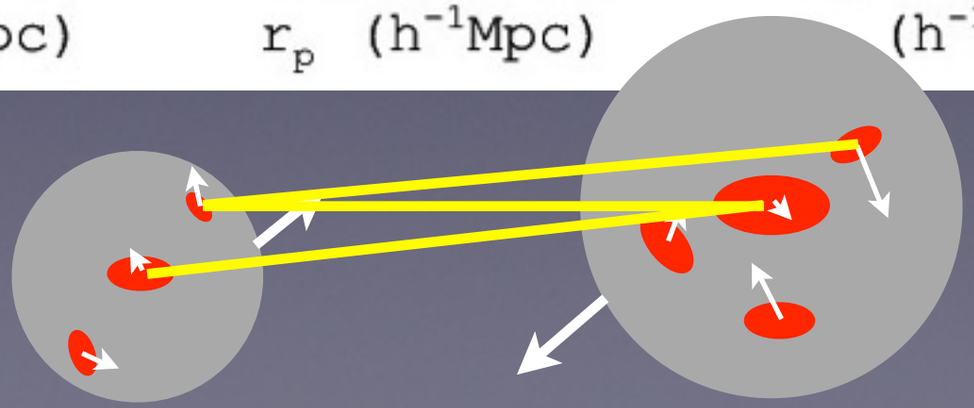


one-halo total

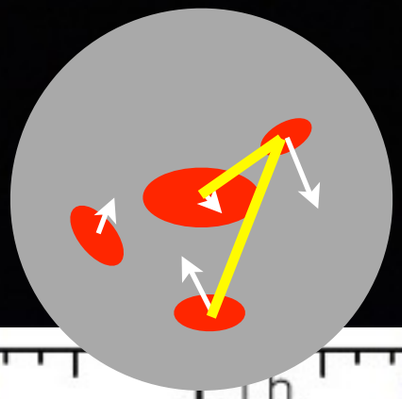




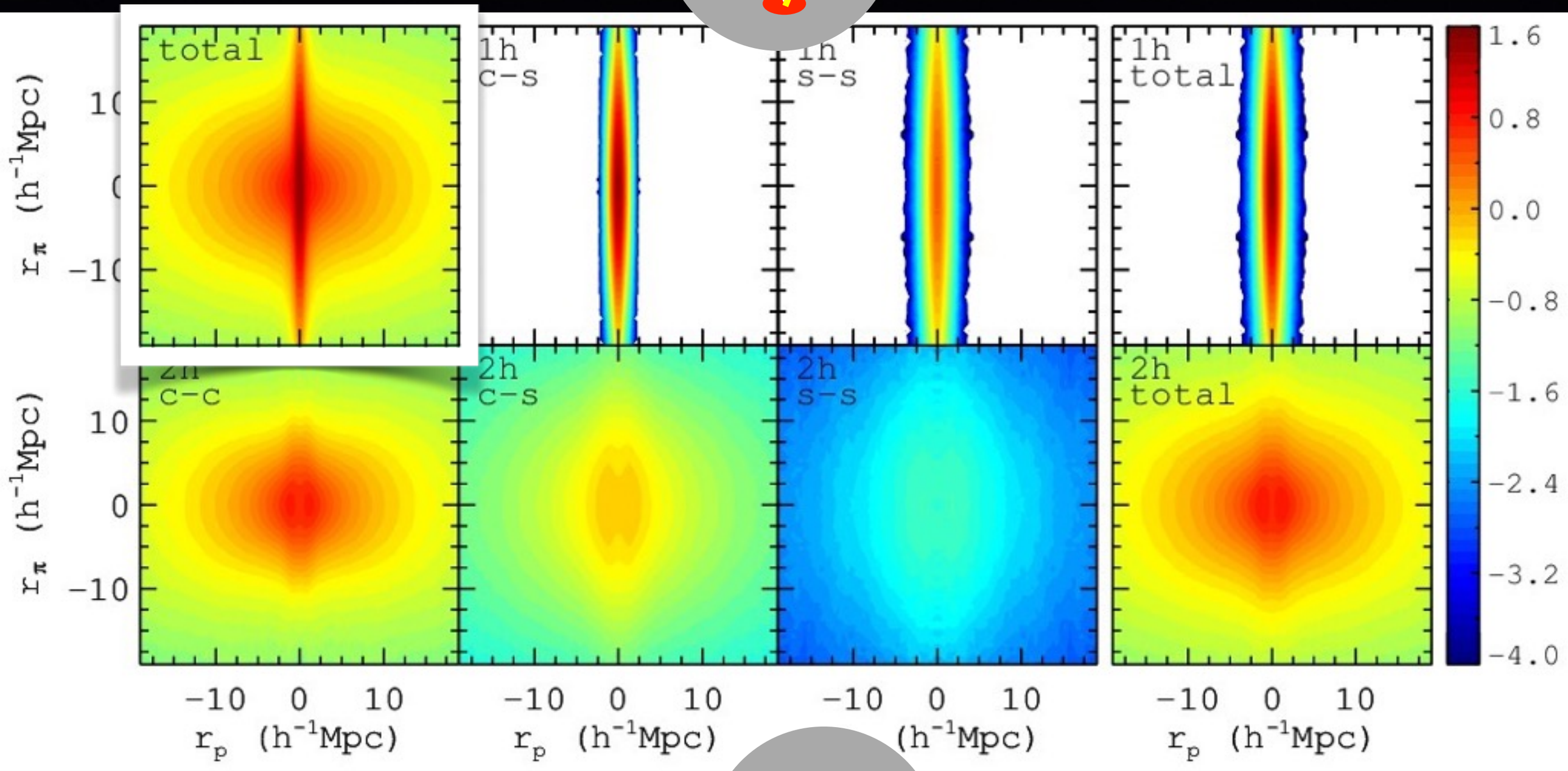
two-halo total

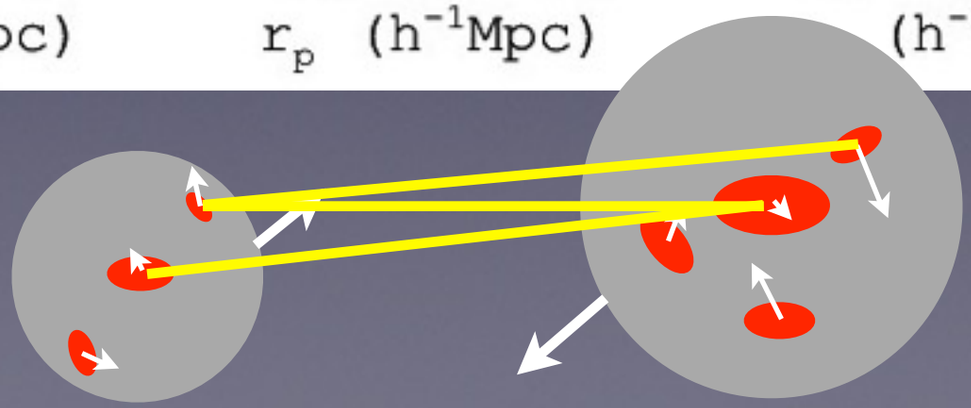
ZZ & Guo (1506.07523)

total



one-halo total

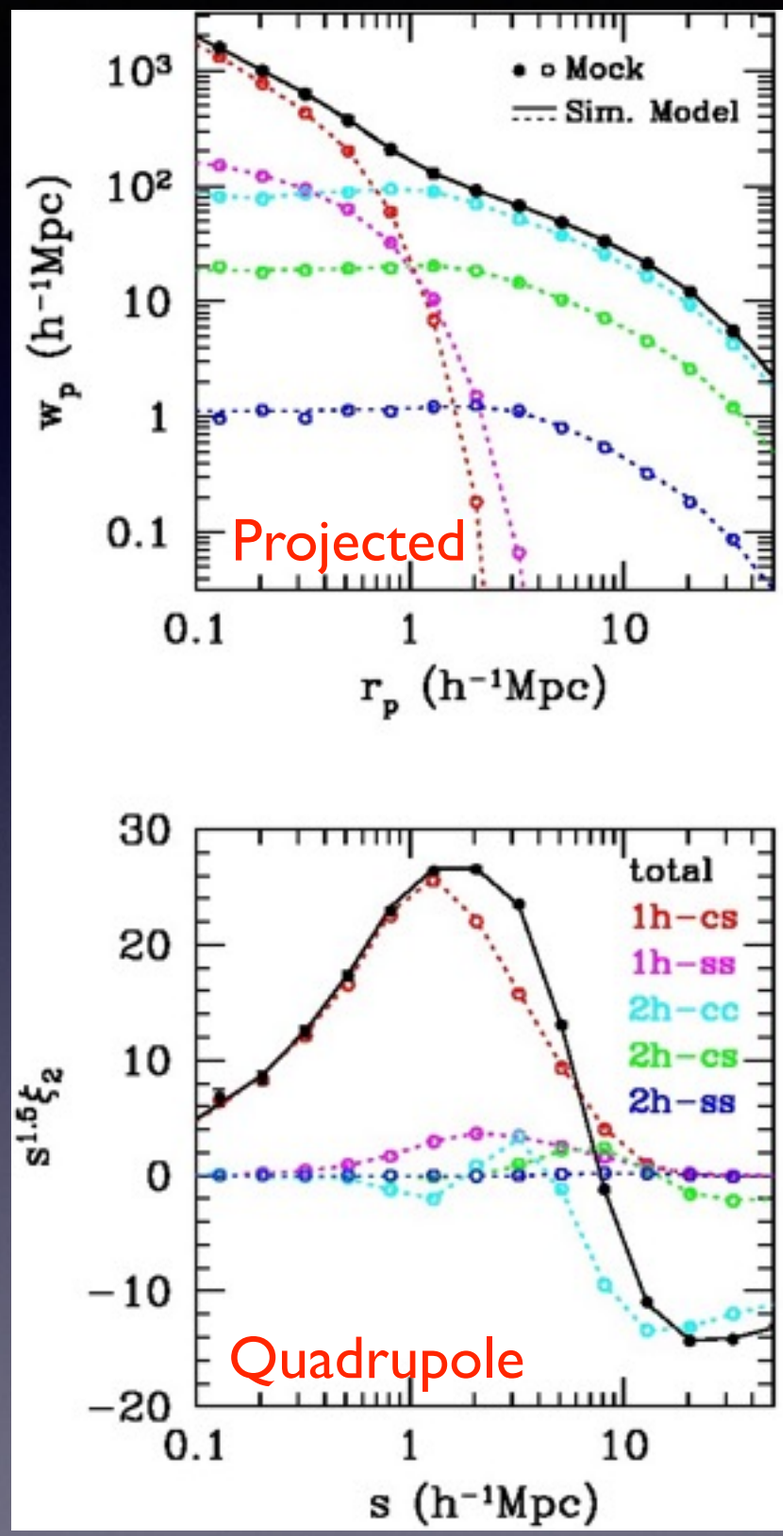


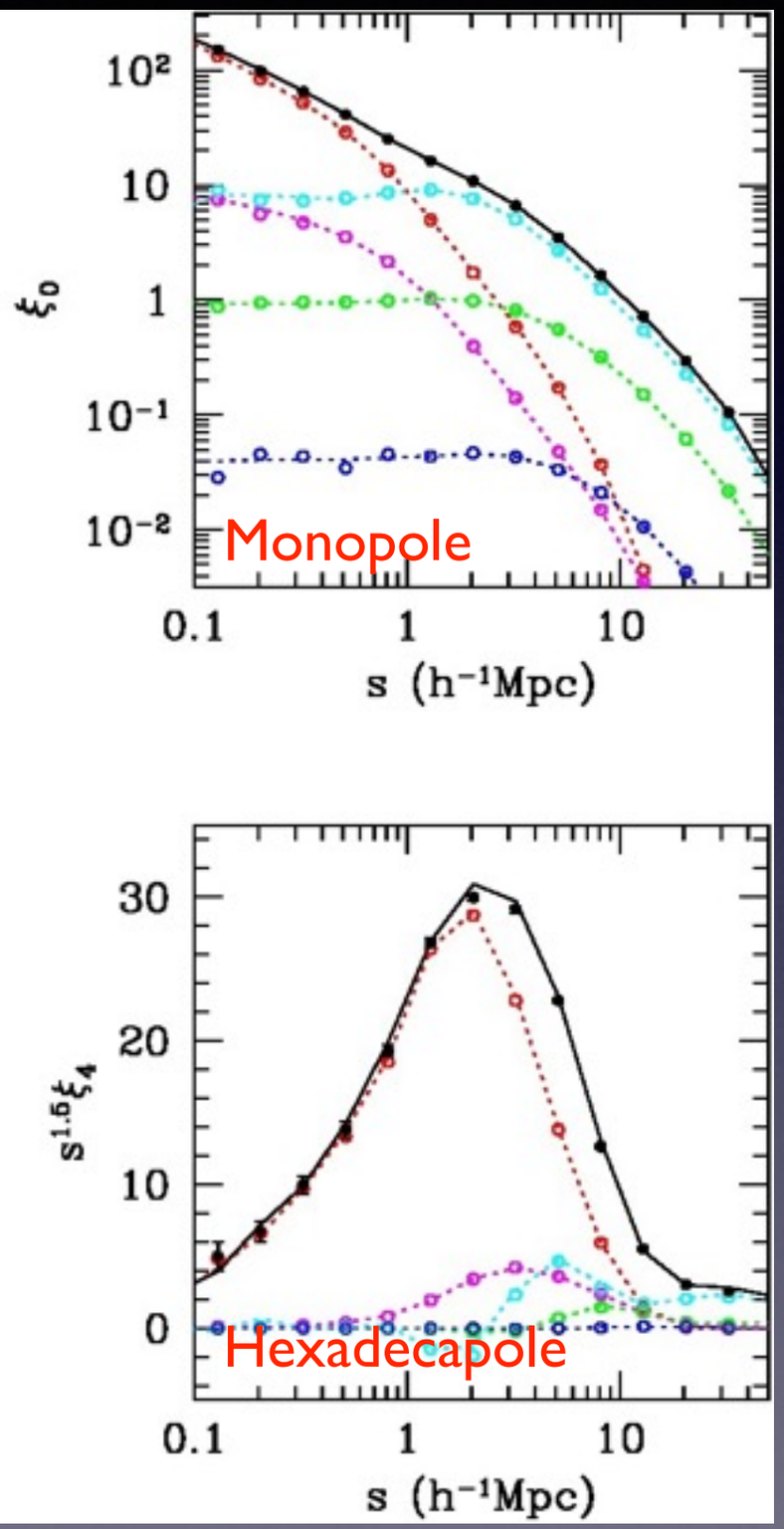


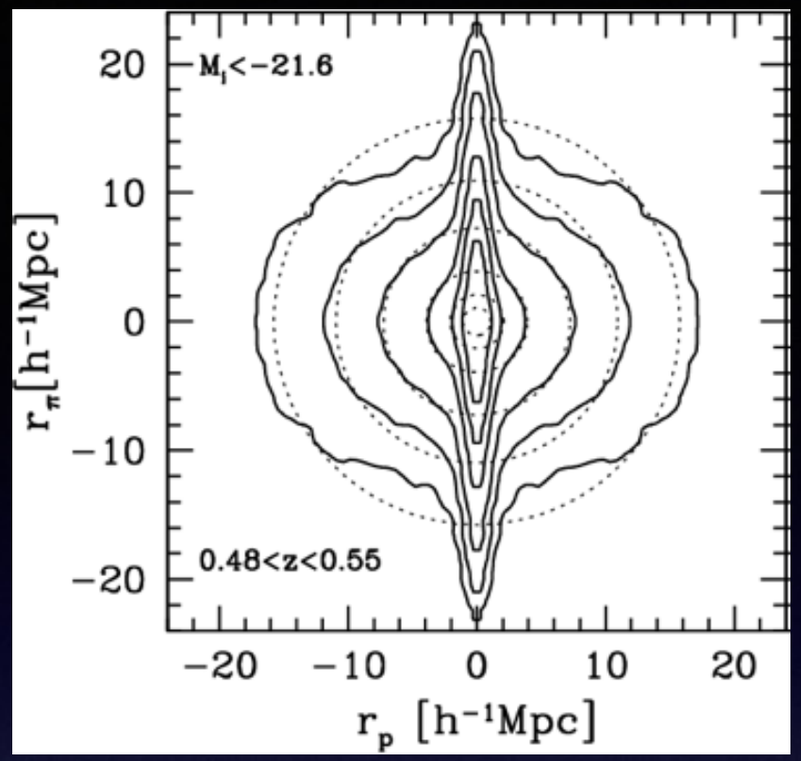
two-halo total

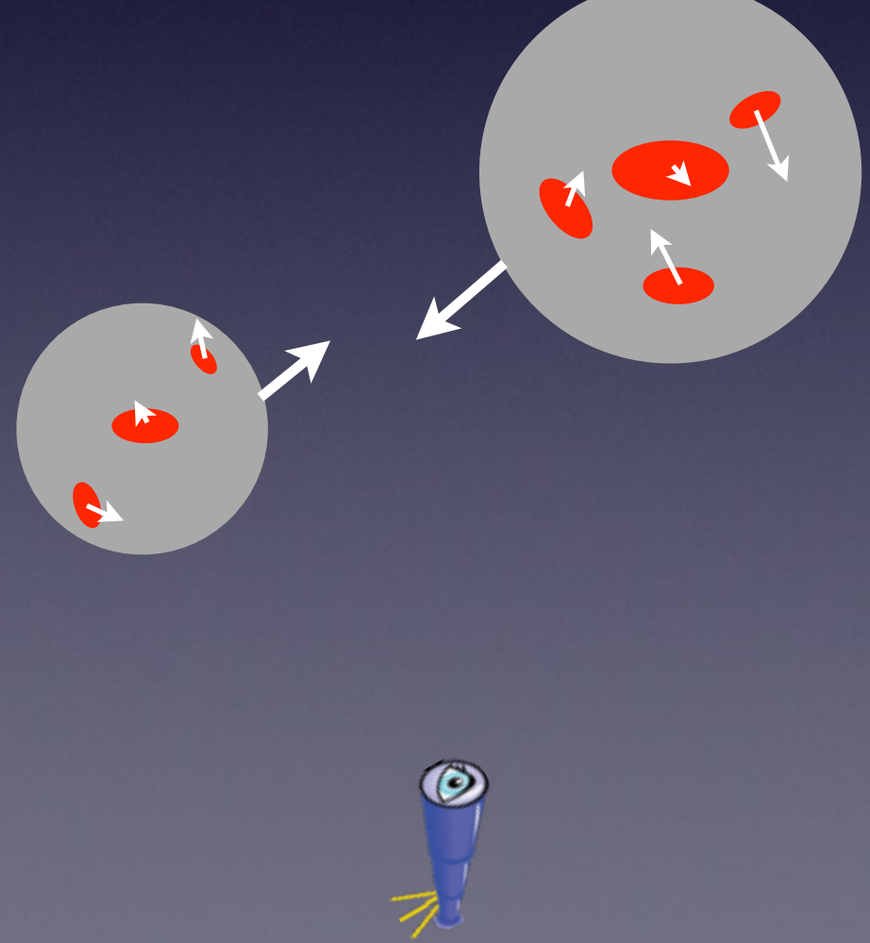
ZZ & Guo (1506.07523)

An Accurate and Efficient Simulation-based Model for Redshift-Space Galaxy Two-Point Correlation Function









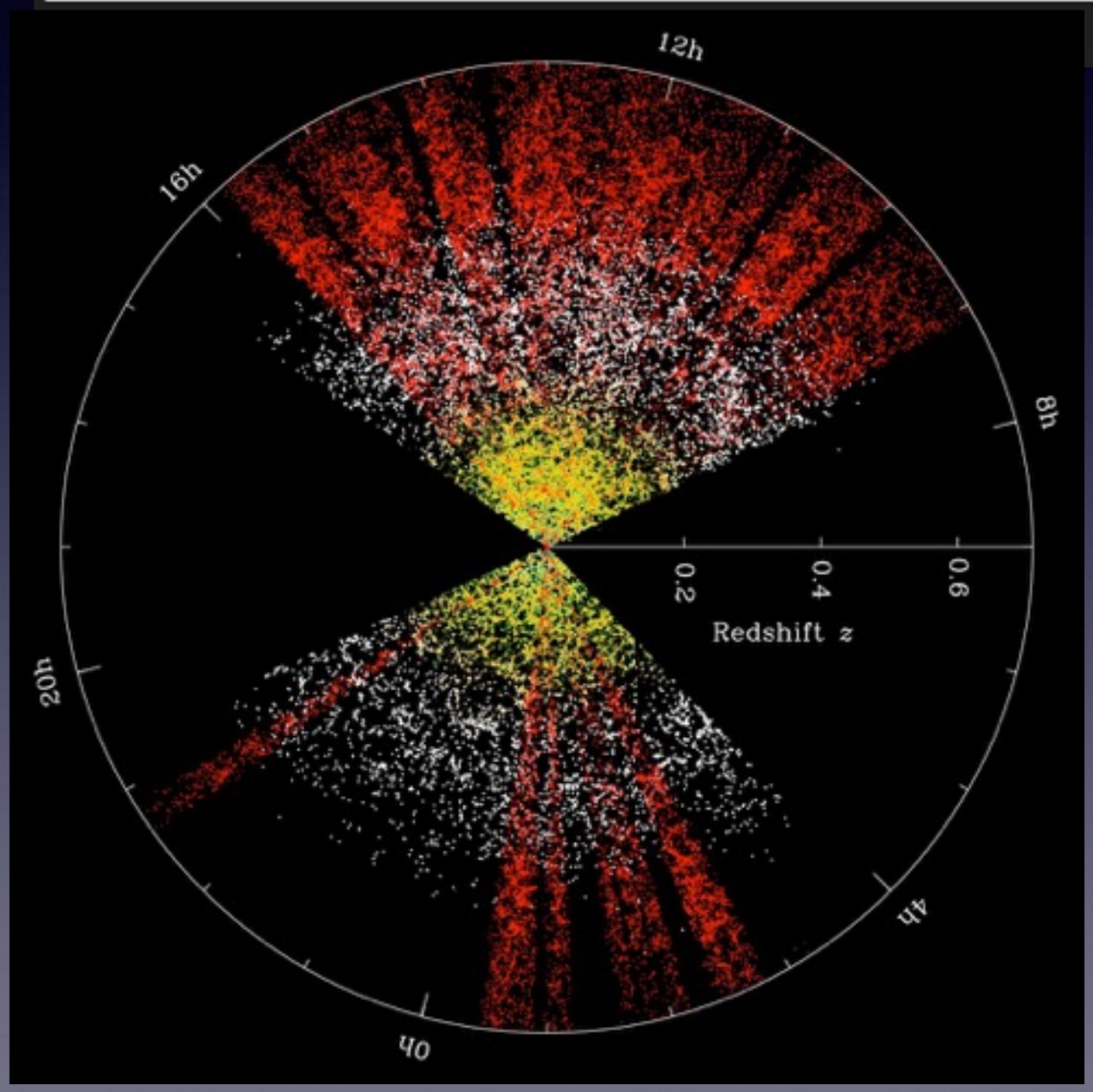
ZZ & Guo (1506.07523)

SDSS-III

Massive Spectroscopic Surveys of the Distant Universe, the Milky Way Galaxy and Extrasolar Planetary Systems

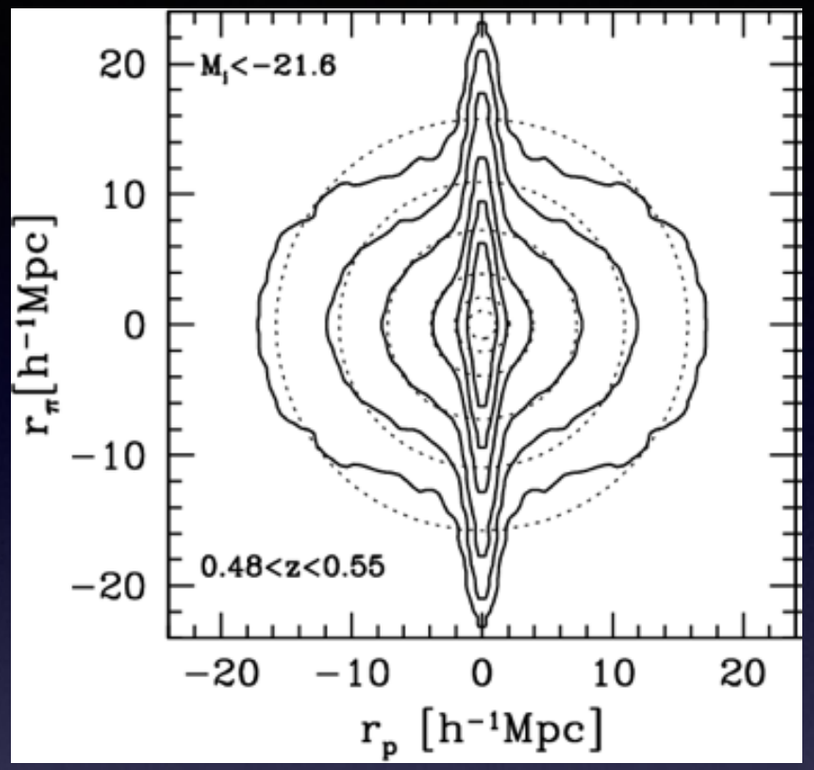
www.sdss3.org

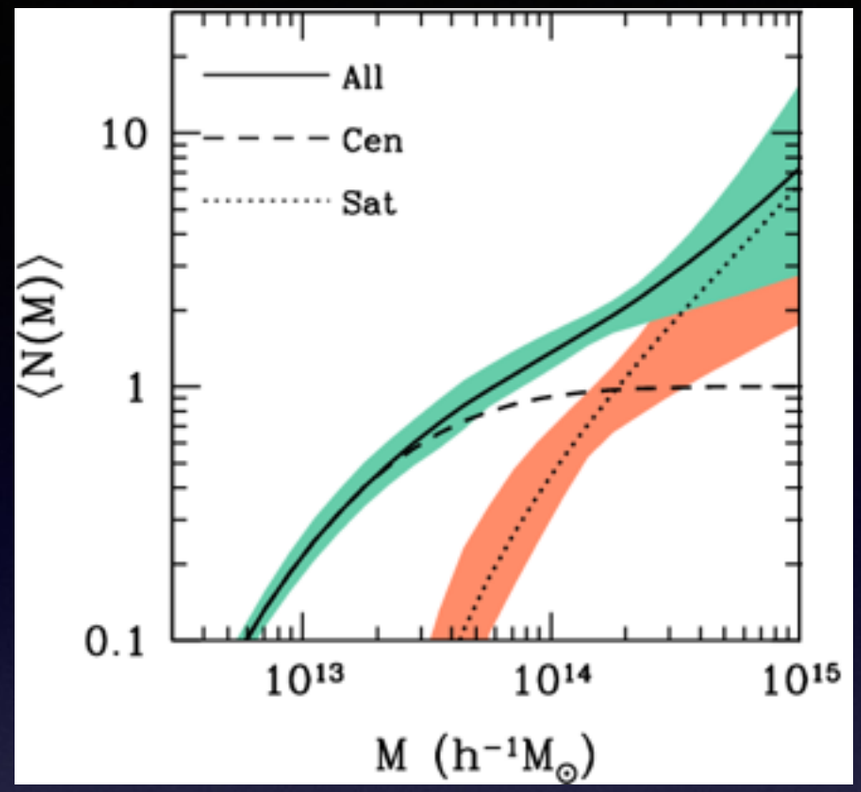
SDSS-III BOSS SEGUE-2 APOGEE MARVELS



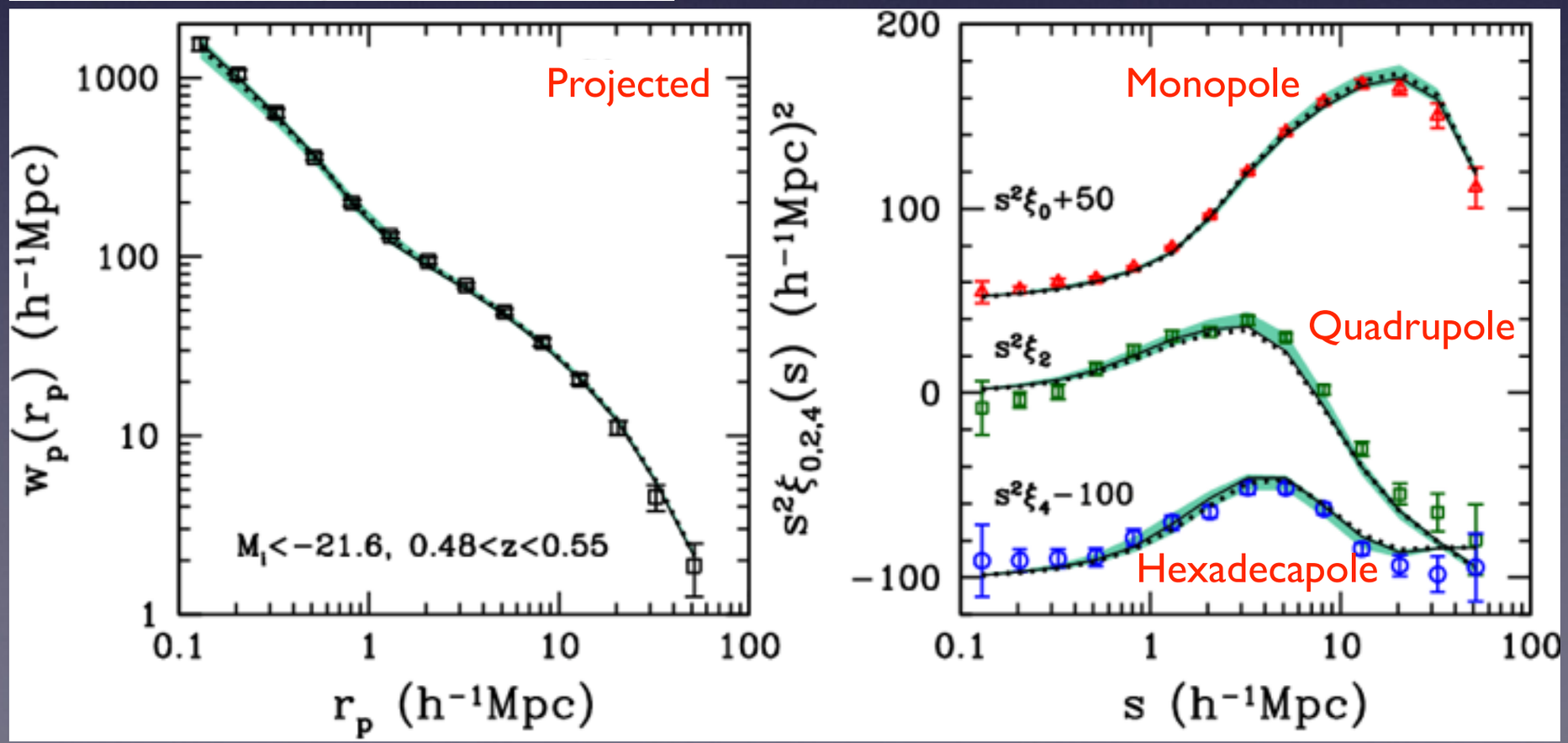
BOSS (Baryon Oscillation Spectroscopic Survey)
z~0.5 massive galaxies

Measuring and Modeling the Redshift-Space Galaxy Clustering

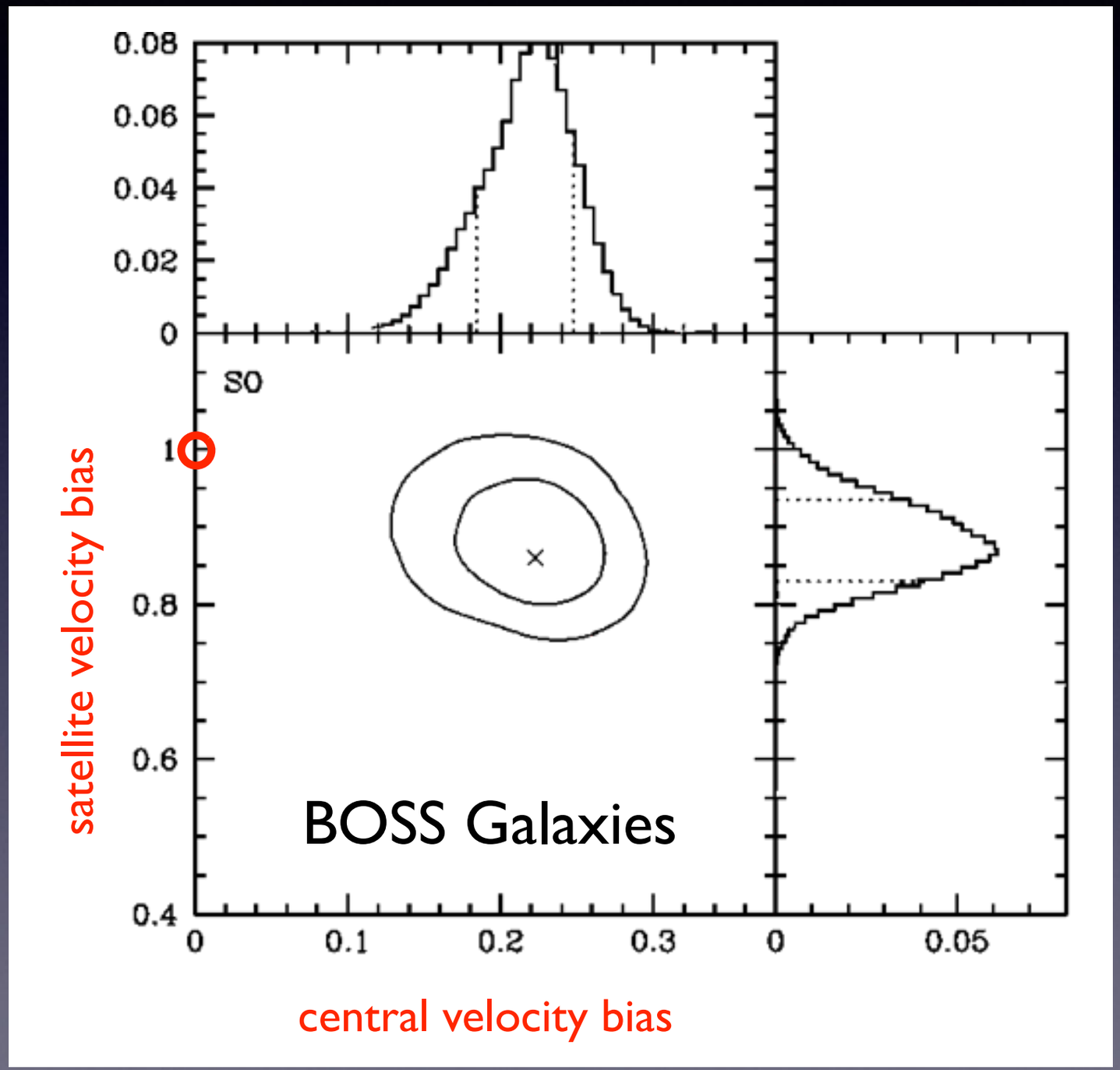


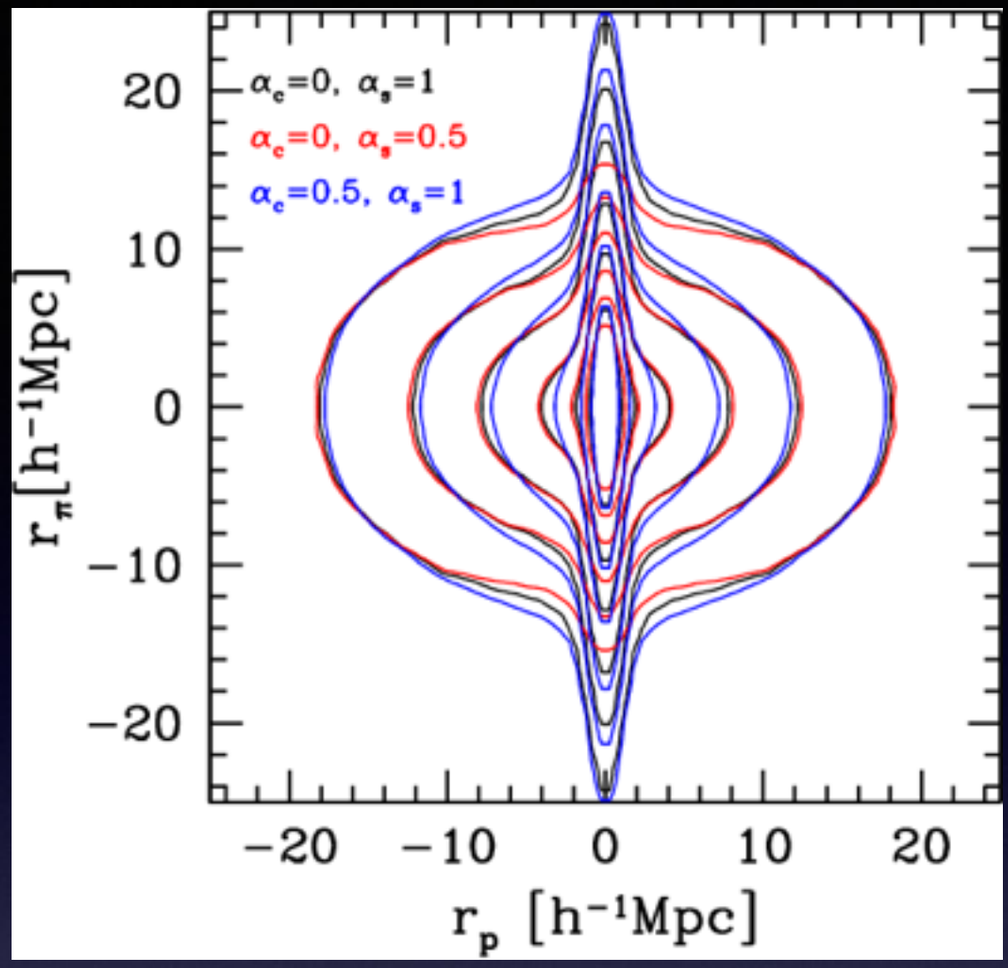


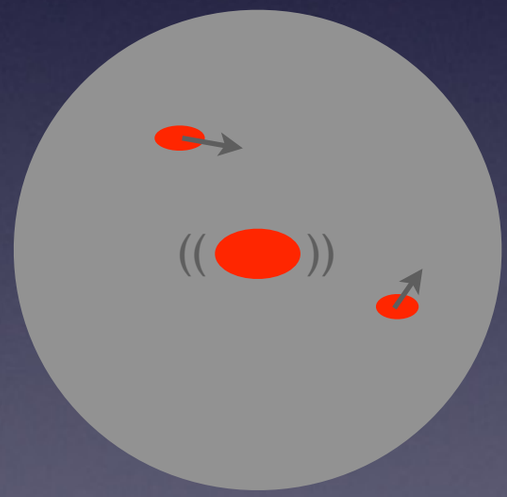
Guo, ZZ, et al. (2015a)



Galaxy Kinematics inside Halos



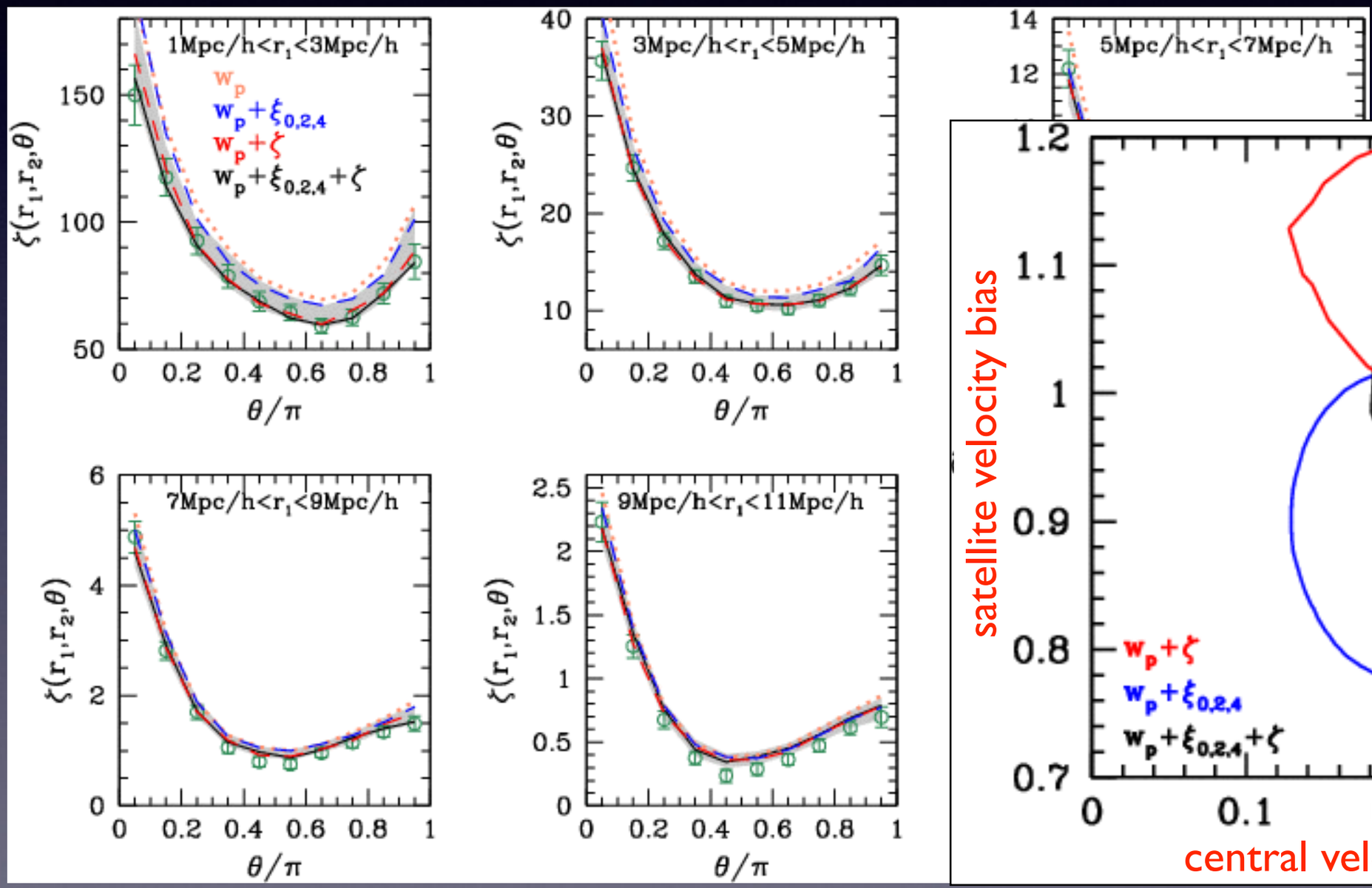


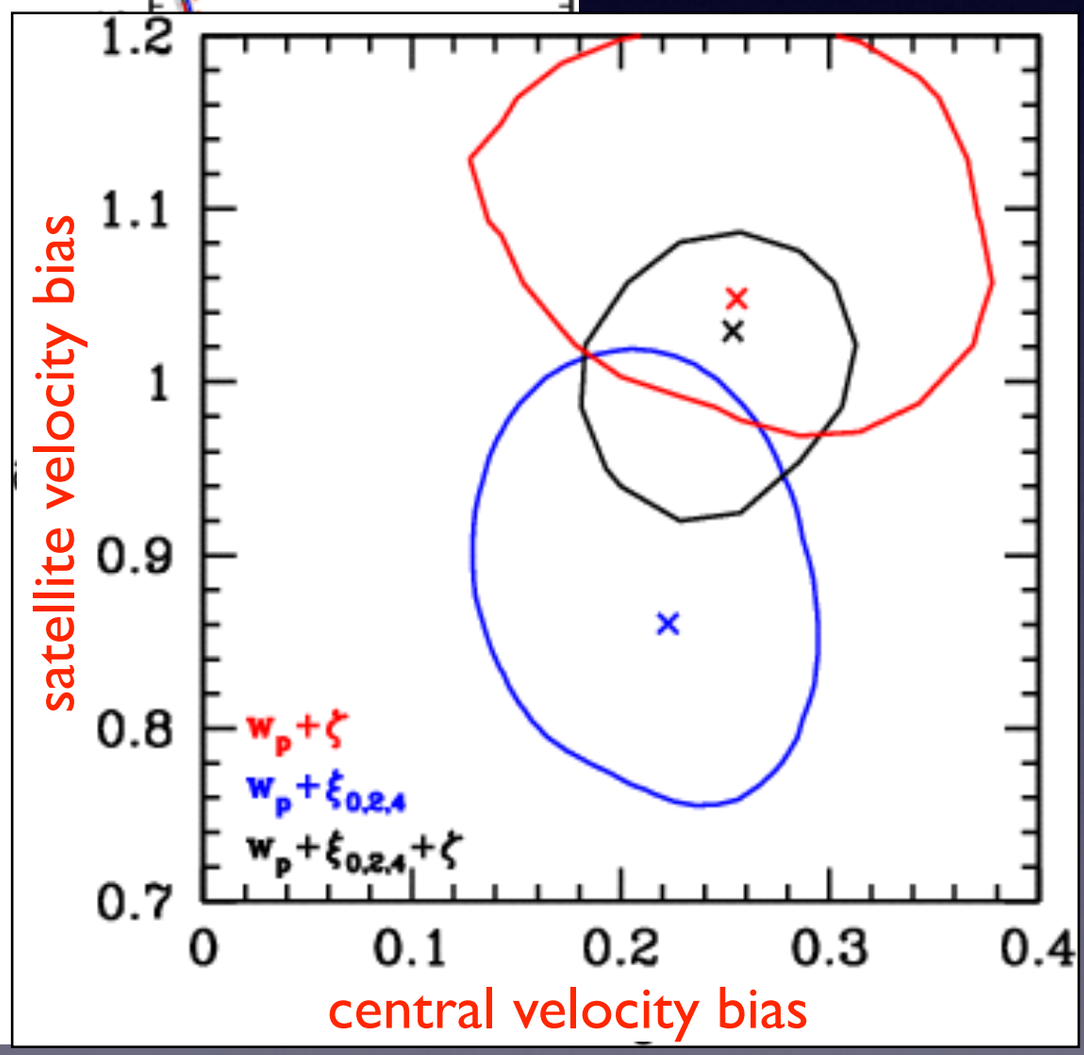


The central galaxy in a halo is not at rest w.r.t. the halo.

Guo, ZZ, et al. (2015a)

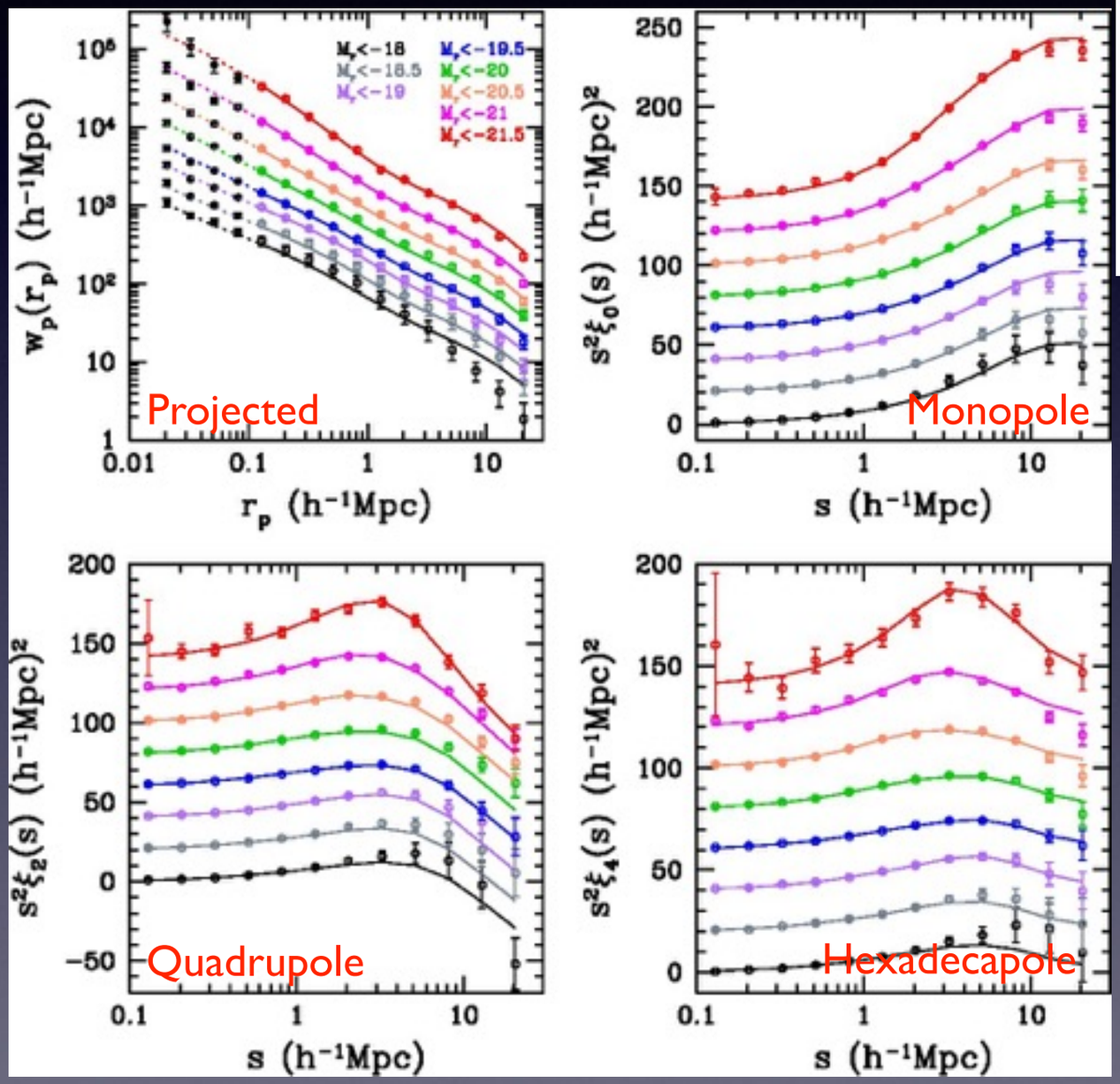
Similar Results of Galaxy Motion from Redshift-Space 3-point Correlation Functions

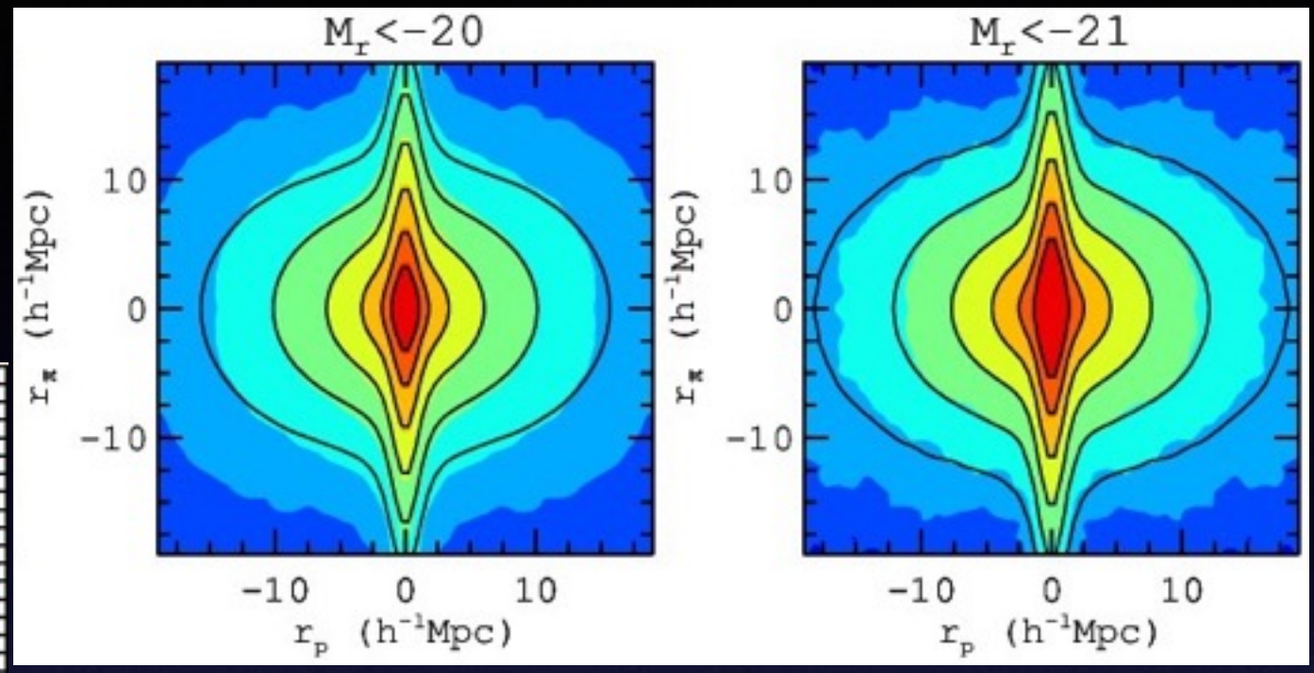


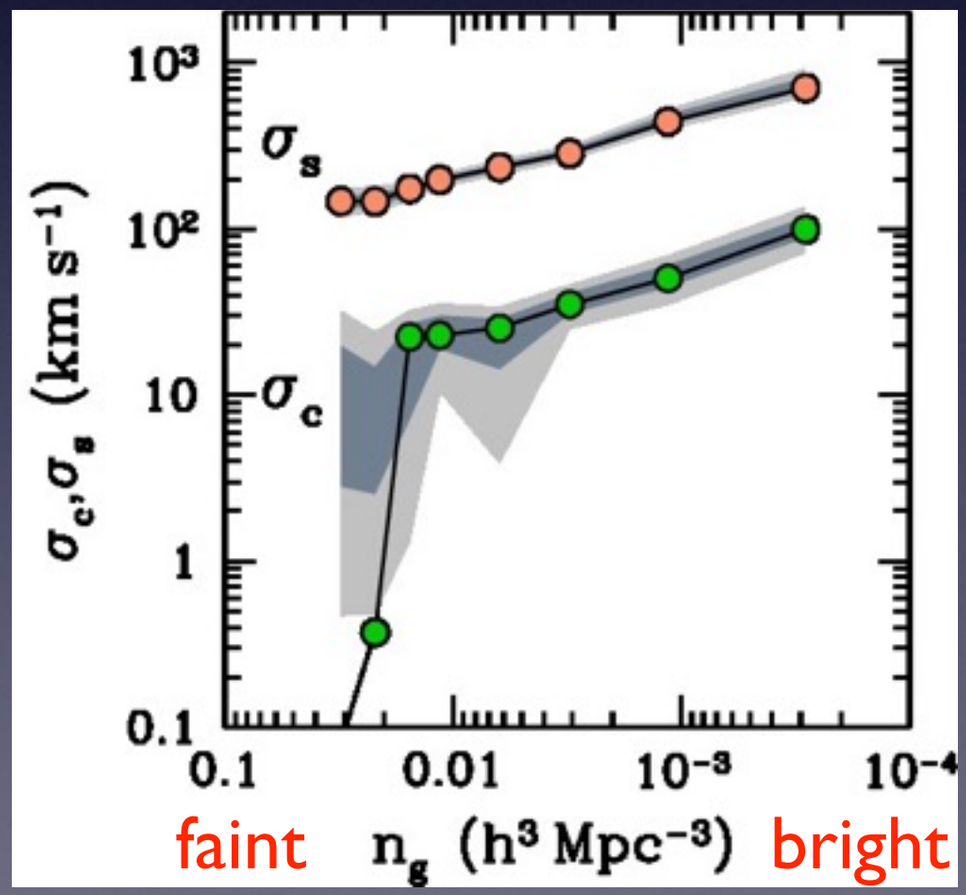


Guo, ZZ, et al. (2015b)

SDSS Main Galaxy Sample (z~0)

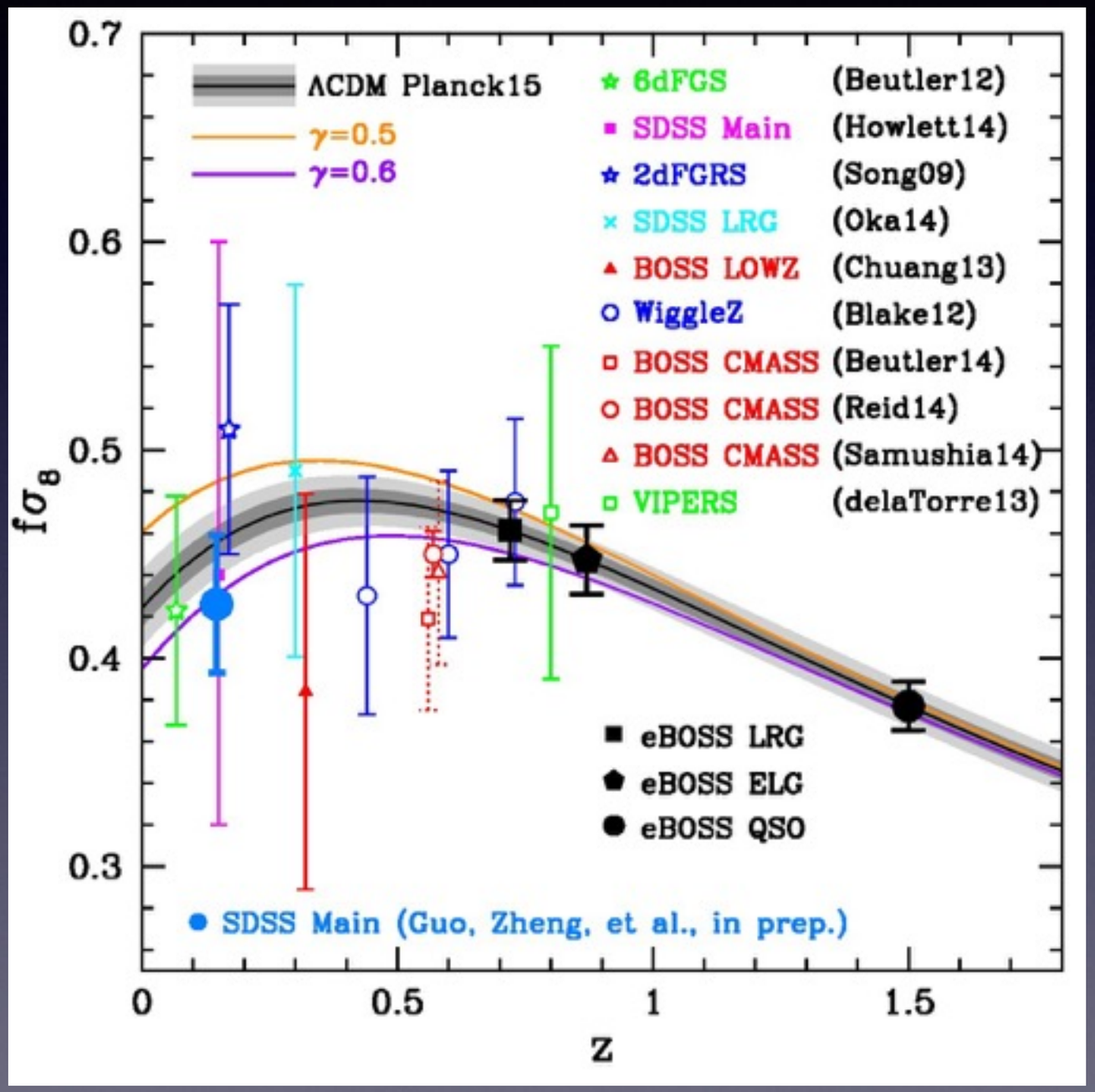






Guo, ZZ, et al. (2015c)

Small- and intermediate-scale redshift-space distortions help tighten cosmological constraints.



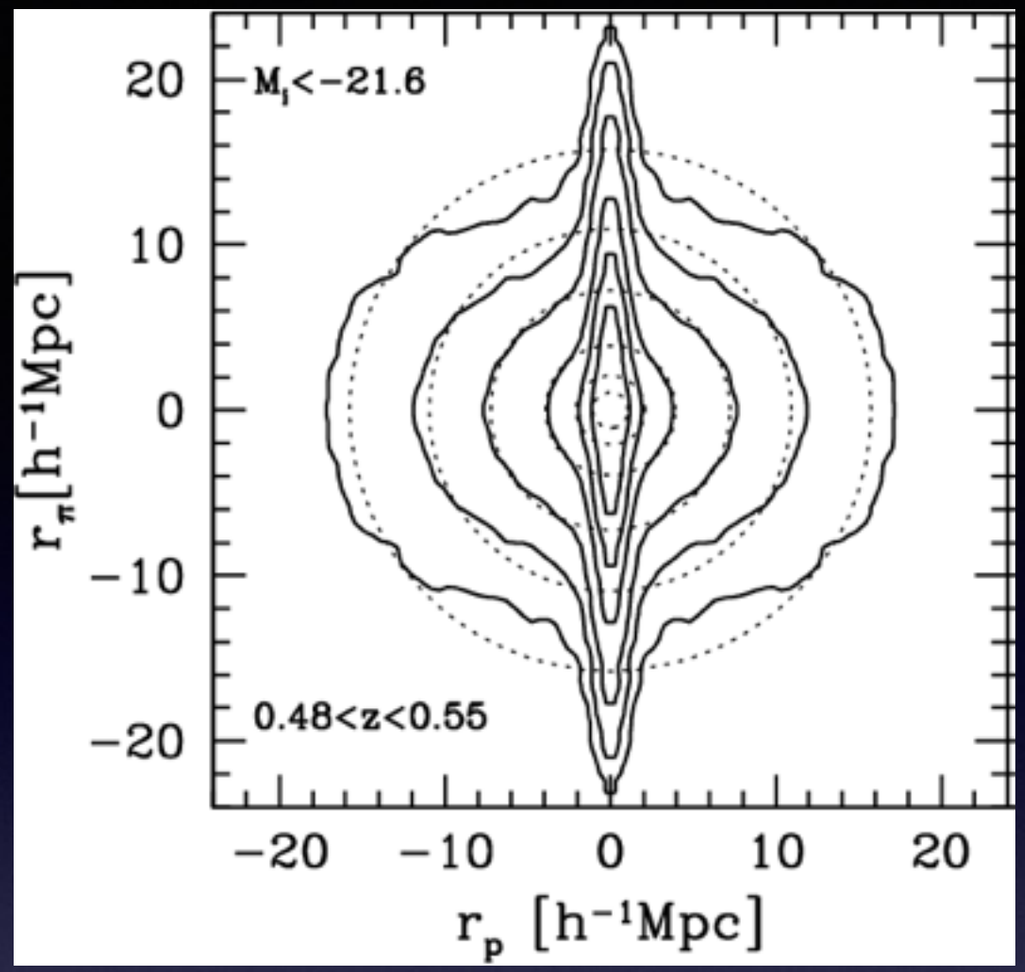
$$\dot{\delta} + \frac{1}{a}\nabla \cdot \mathbf{v} = 0 \quad \text{(continuity)}$$

- Probe structure growth rate
- Test theories of gravity
- Constrain dark energy

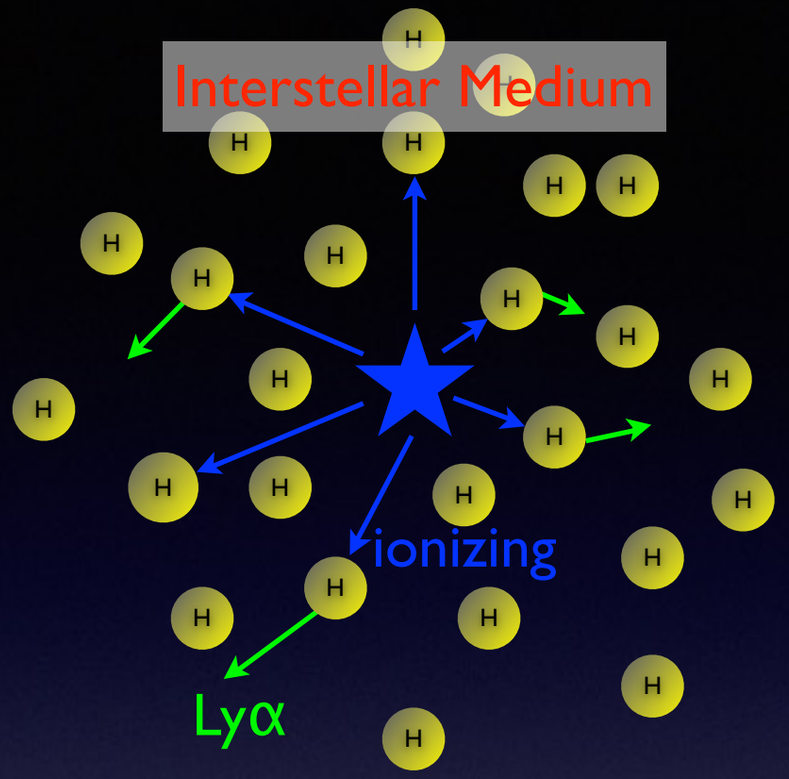
Dawson, et al. (2015)

Redshift-Space Anisotropic Galaxy Clustering

Gravitational Distortion



- Constraints on the phase-space distribution of galaxies inside halos
- Relative relaxation between central galaxies and halos
  (offsets, external shear in gravitational lensing modeling)
- Dynamical friction effect on satellite galaxies
- Merging and dynamical evolution of galaxies
- Tests of galaxy formation models
- Tightening cosmological constraints (theories of gravity, dark energy)

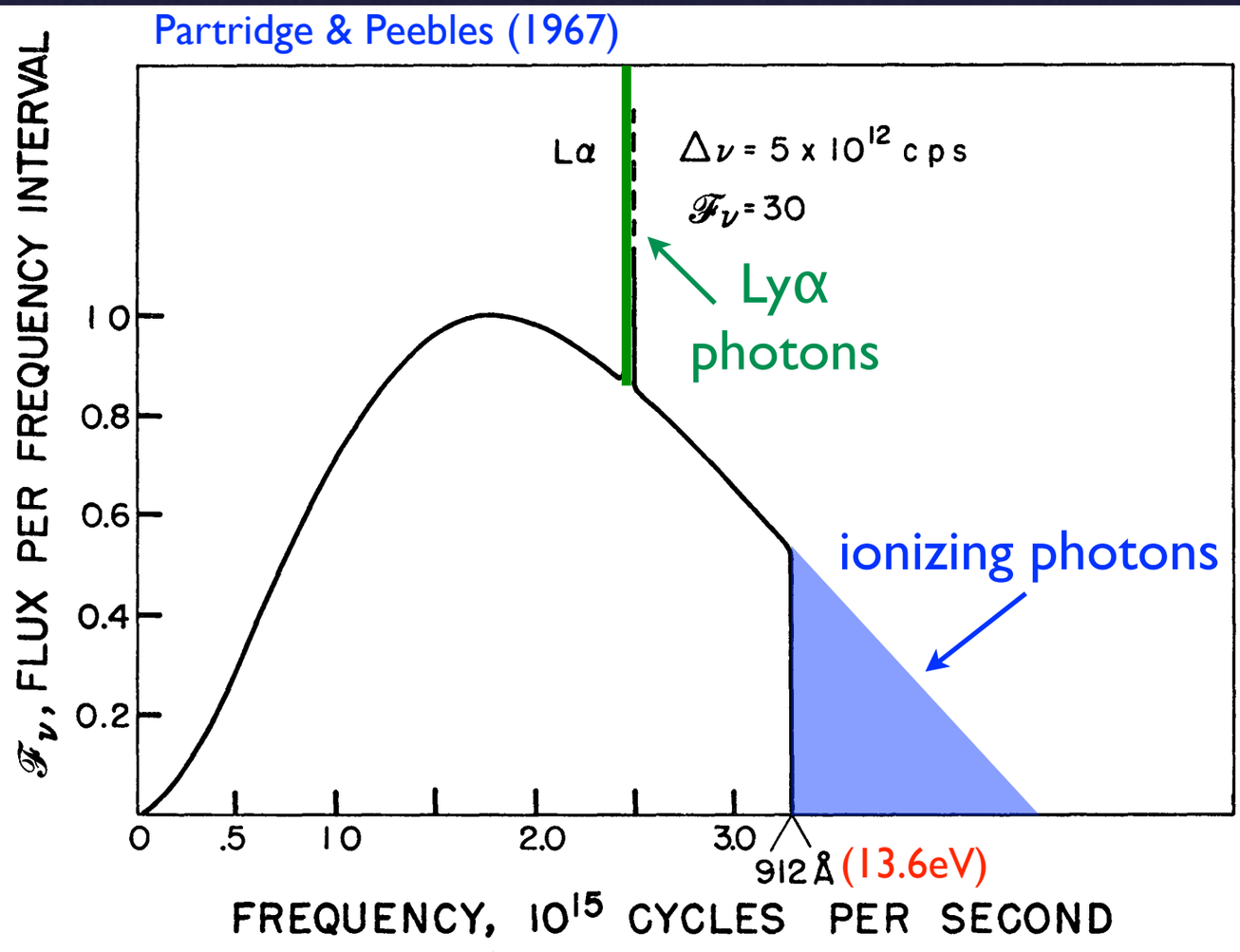


Lyα Emitting Galaxies / Lyα Emitters (LAEs)

- studying young star-forming galaxies
- probing circum-galactic and intergalactic gas
- constraining the end of dark ages - reionization (the cosmic dawn)
- constraining cosmology

Lyman-alpha Emission from Star-forming Galaxies

~2/3 ionizing photons are converted to Lyα photons



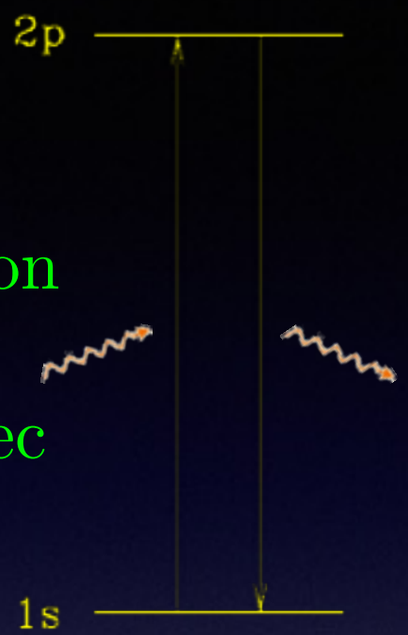
Lyα Radiative Transfer

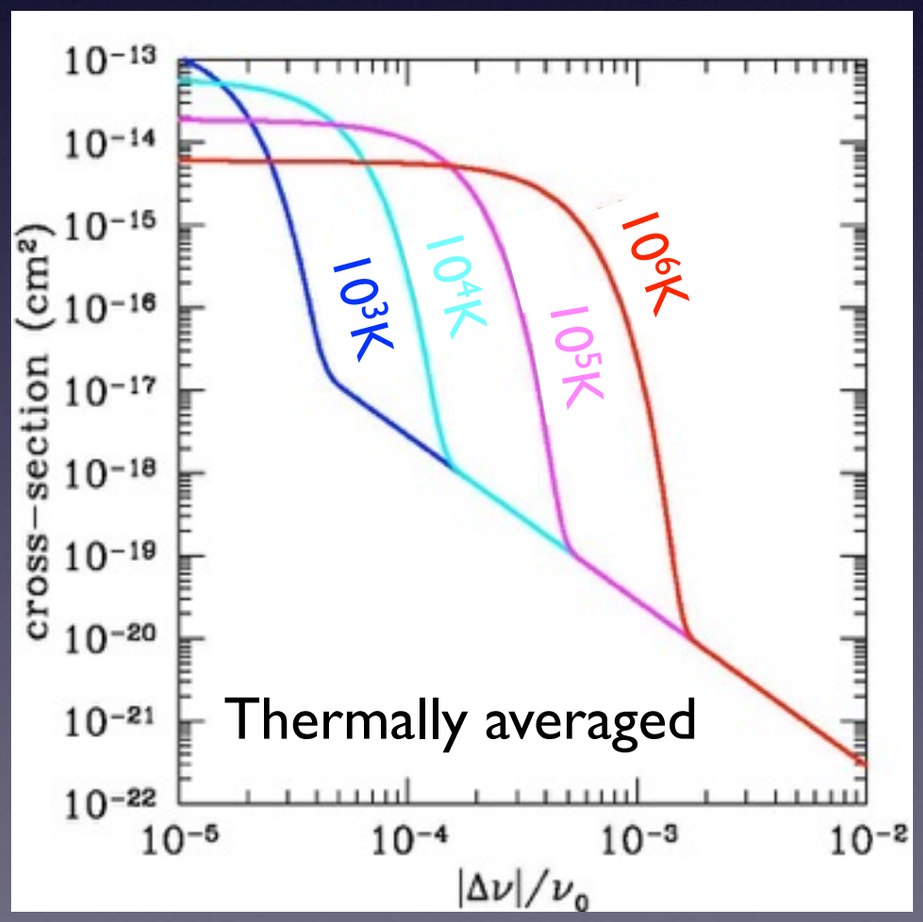
Lyα line

$1s - 2p$ transition

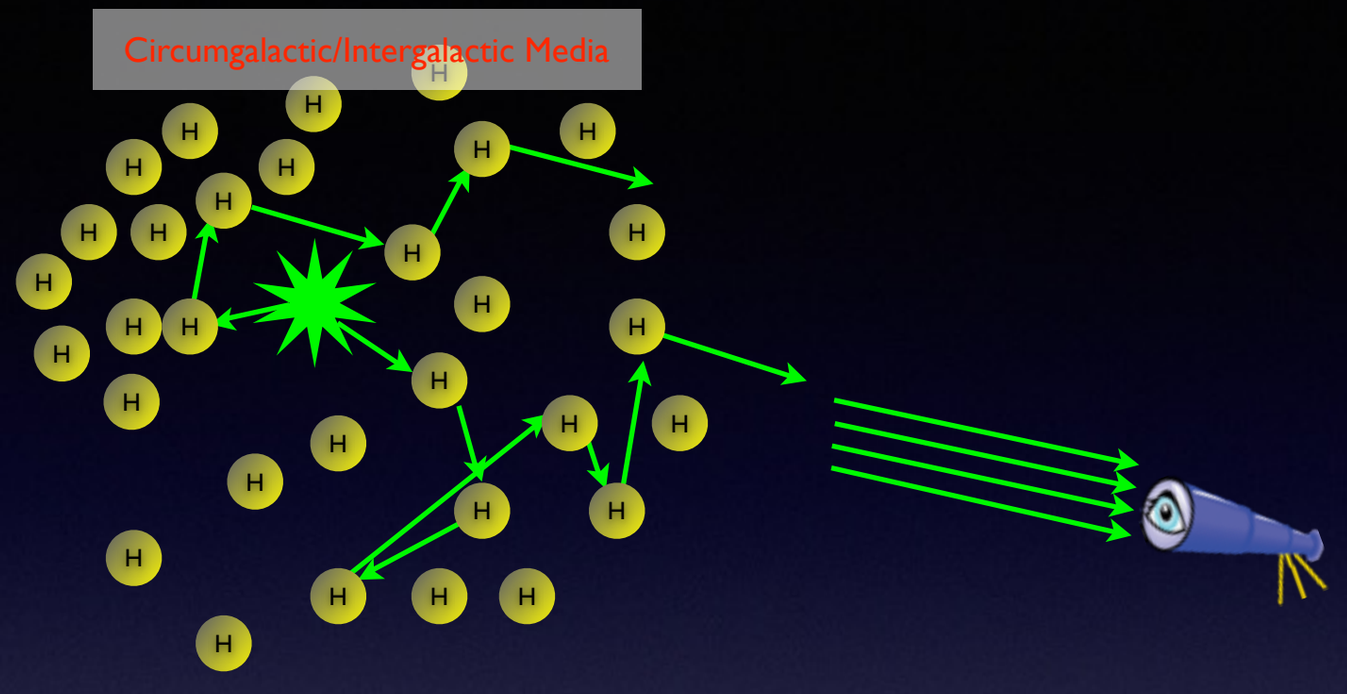
$\lambda_0 = 1216\mathring{A}$

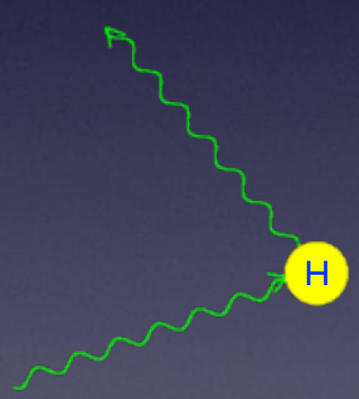
lifetime $\sim 10^{-8}$sec



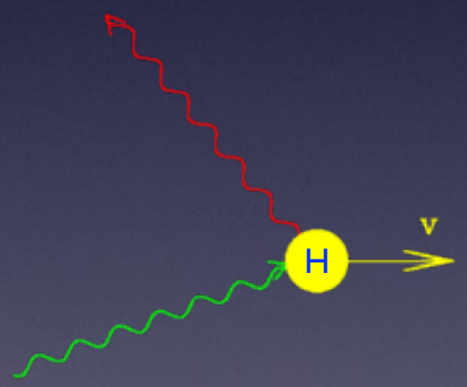


scattering cross-section: large at line center
small at line wings





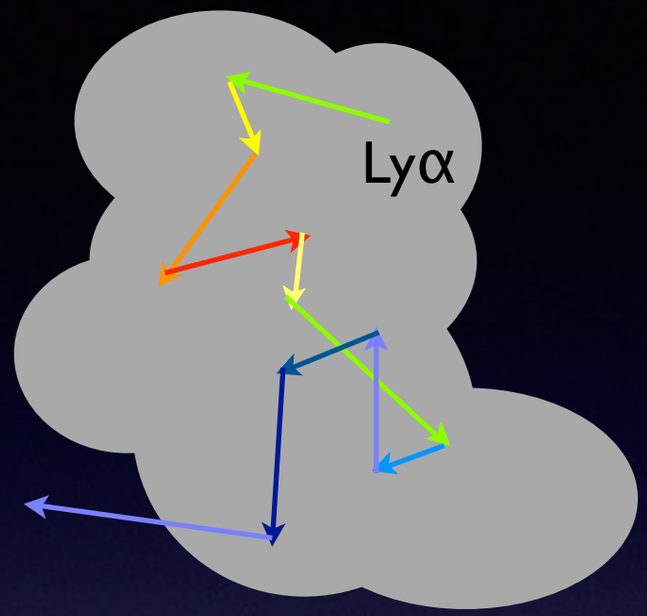
atom rest frame



laboratory frame

- a large number of scatterings
- position/direction change from scattering
- frequency change after each scattering

Calculating the Lyα Radiative Transfer



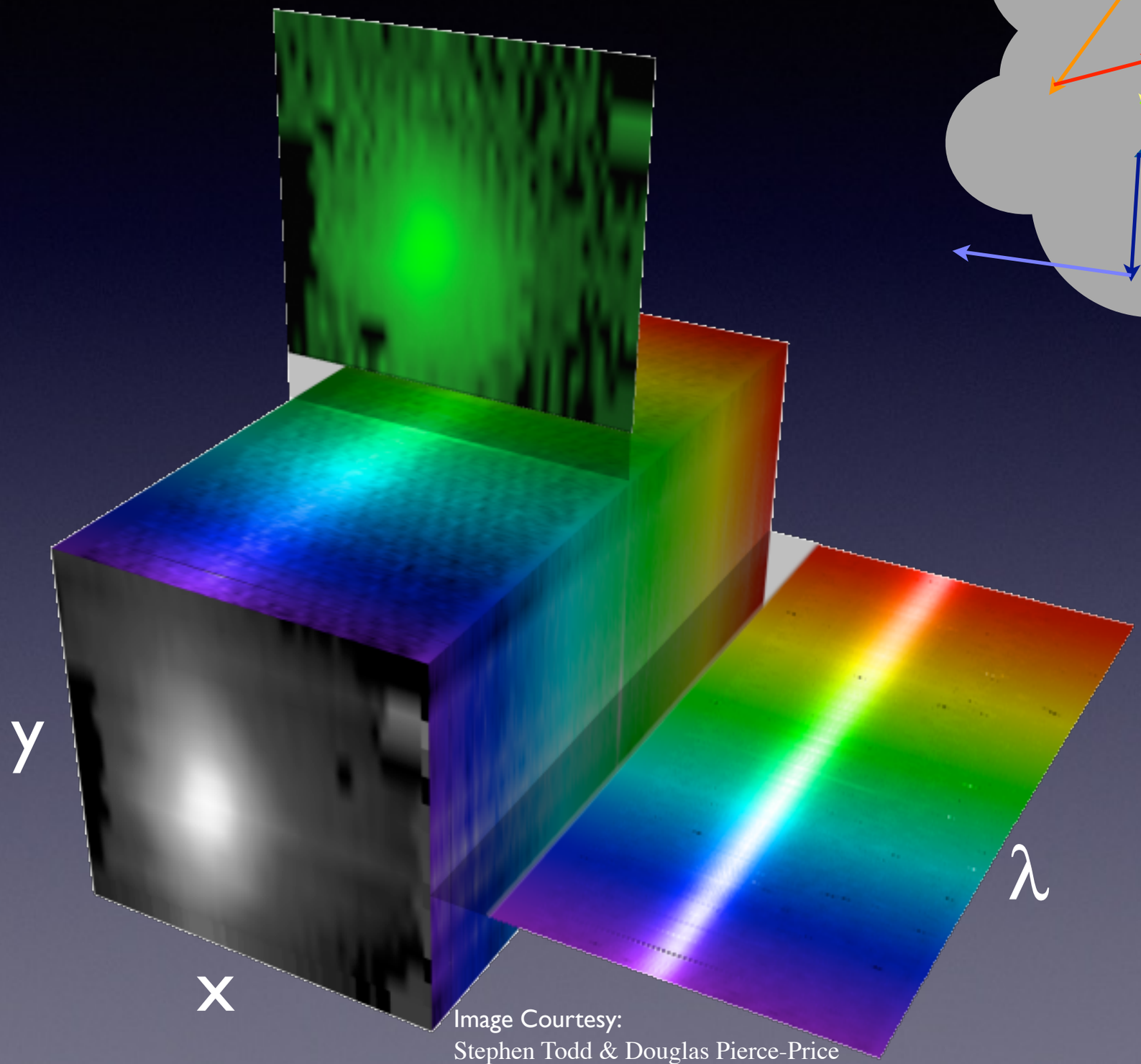
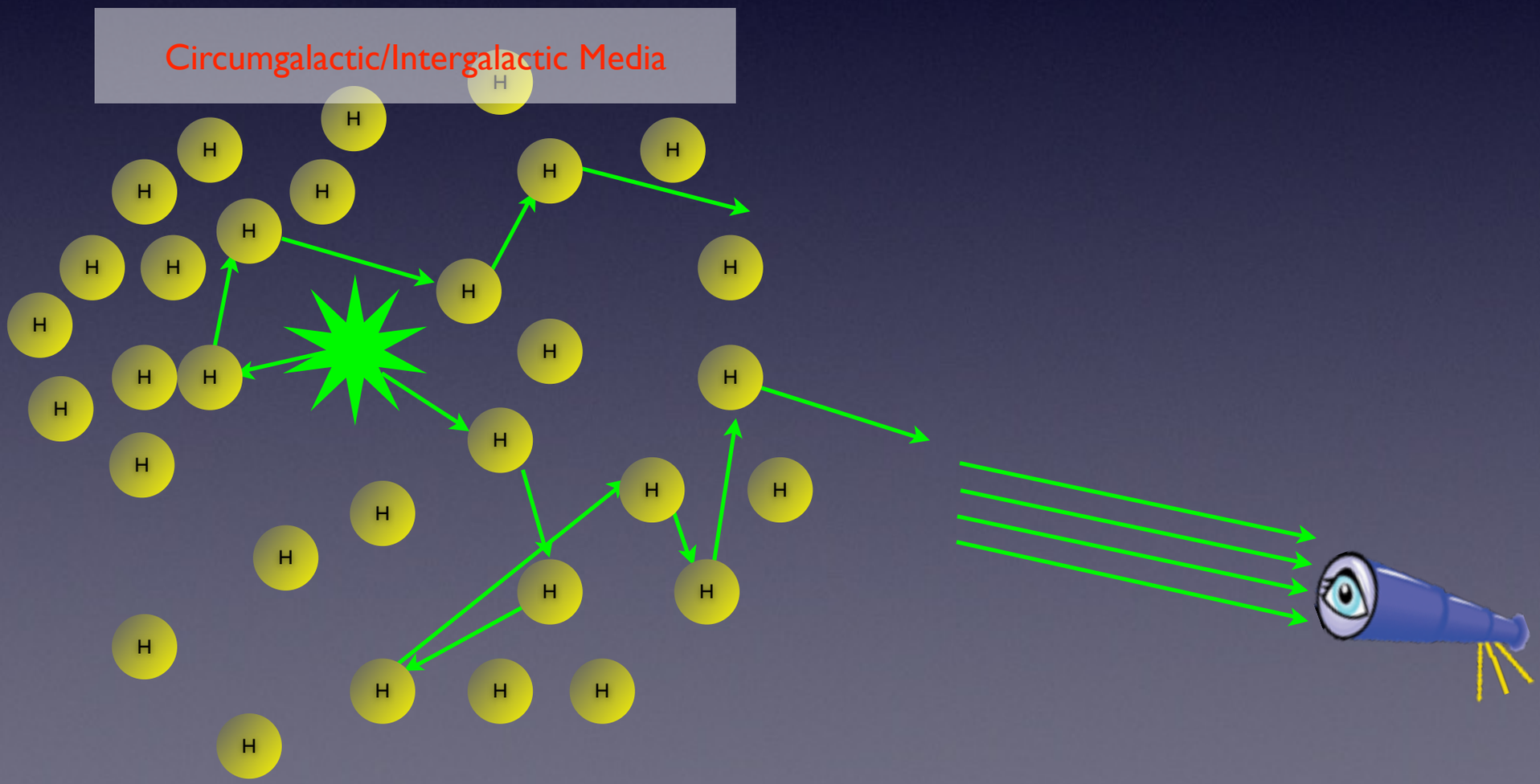


Image Courtesy:
Stephen Todd & Douglas Pierce-Price

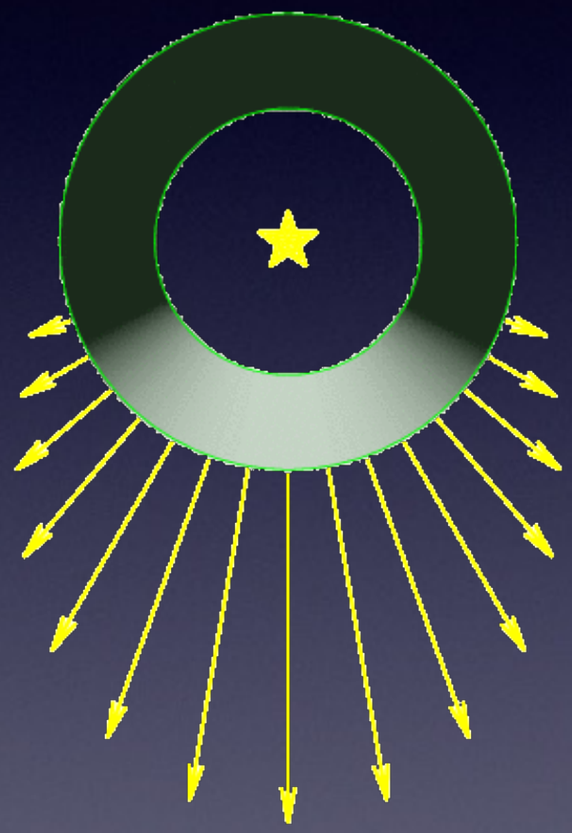
A Key Result from Radiative Transfer Modeling of LAEs

Coupling between observed Lyman-alpha emission properties and circumgalactic and intergalactic environments



spatial and frequency diffusion

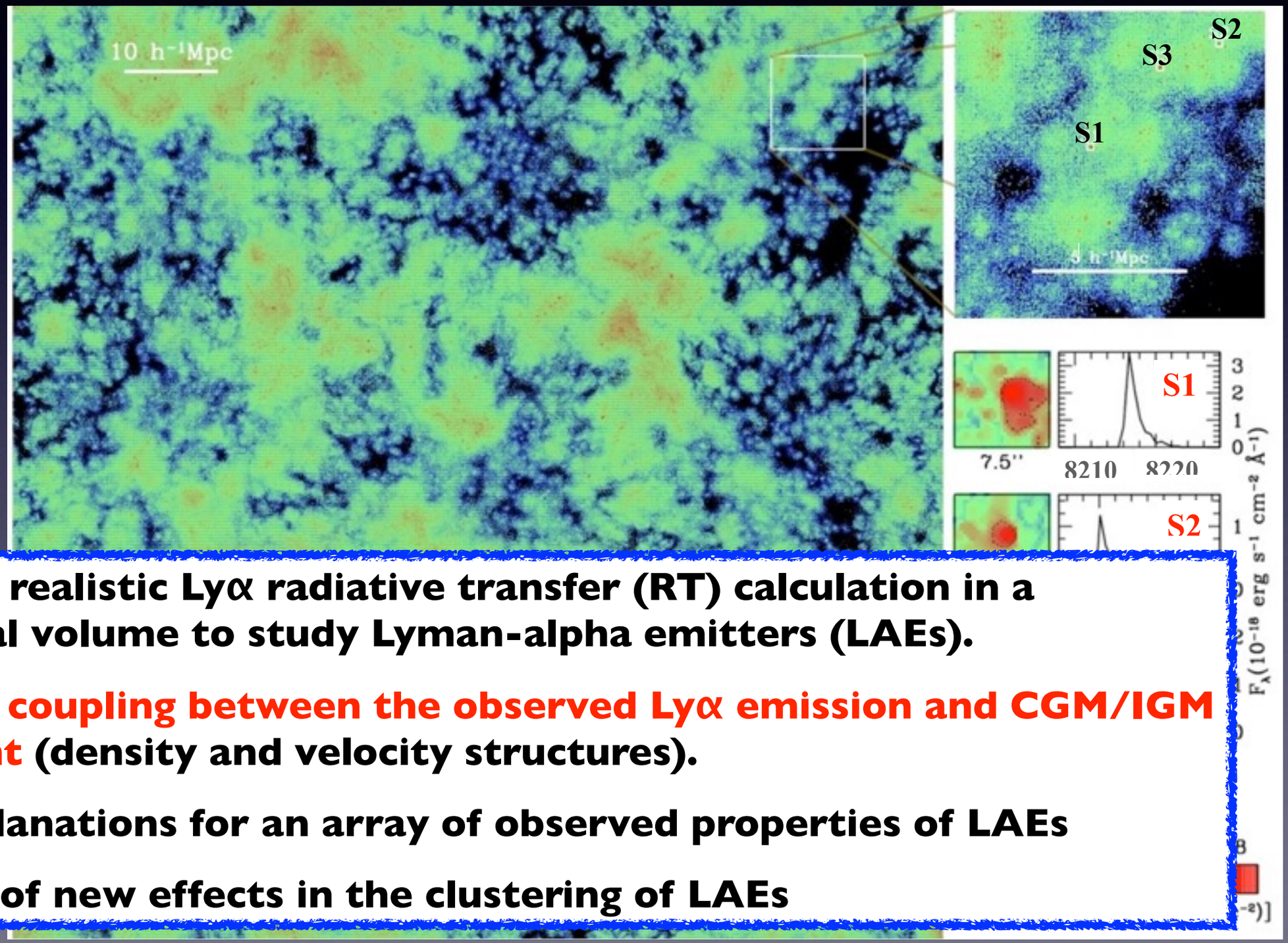
Anisotropic density and velocity distribution of circumgalactic and intergalactic gas leads to anisotropic Lyman-alpha escape.



ZZ et al. (2010)
ZZ & Wallace (2014)

Radiative Transfer Modeling of LAEs in a Large Cosmological Simulation

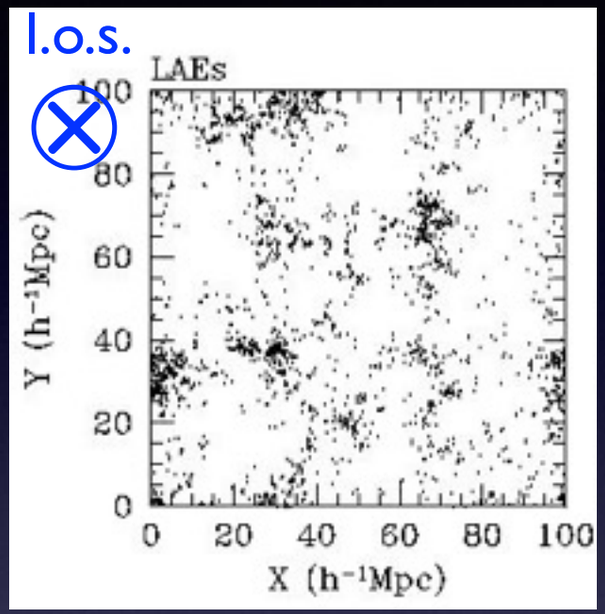
z=5.7 ZZ et al. (2010, 2011a, 2011b)

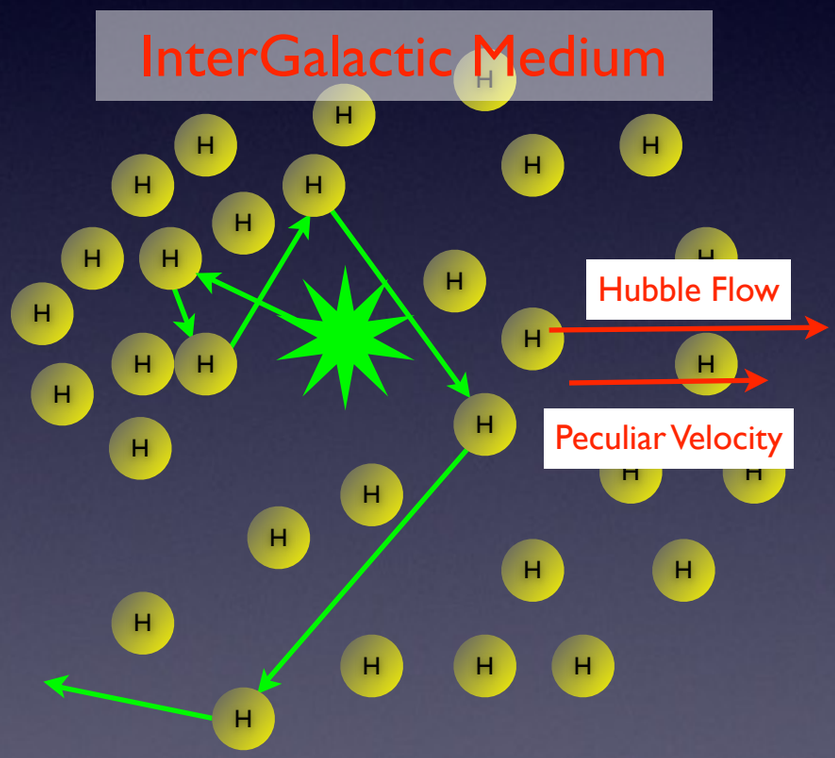


- **first time, a realistic Lyα radiative transfer (RT) calculation in a cosmological volume to study Lyman-alpha emitters (LAEs).**
- **RT-induced coupling between the observed Lyα emission and CGM/IGM environment (density and velocity structures).**
- **natural explanations for an array of observed properties of LAEs**
- **predictions of new effects in the clustering of LAEs**

Clustering of LAEs: Model Prediction

selection effect caused by environment dependent Lya RT

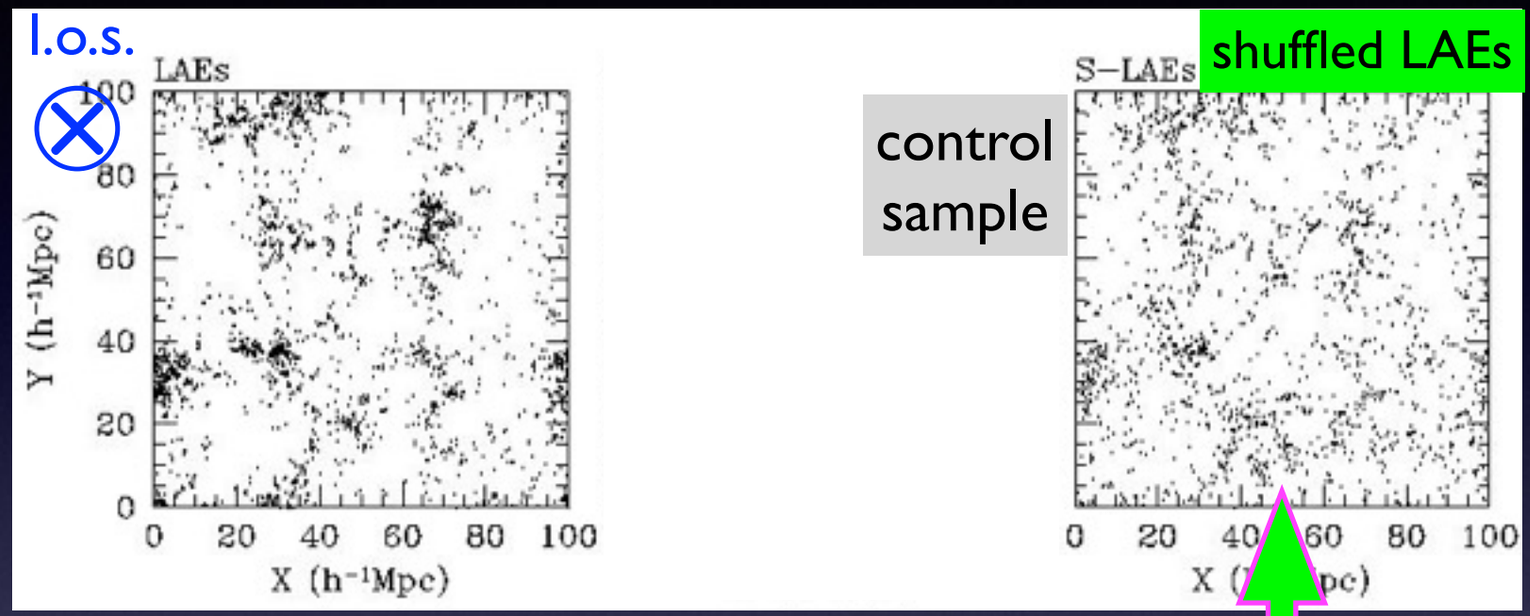




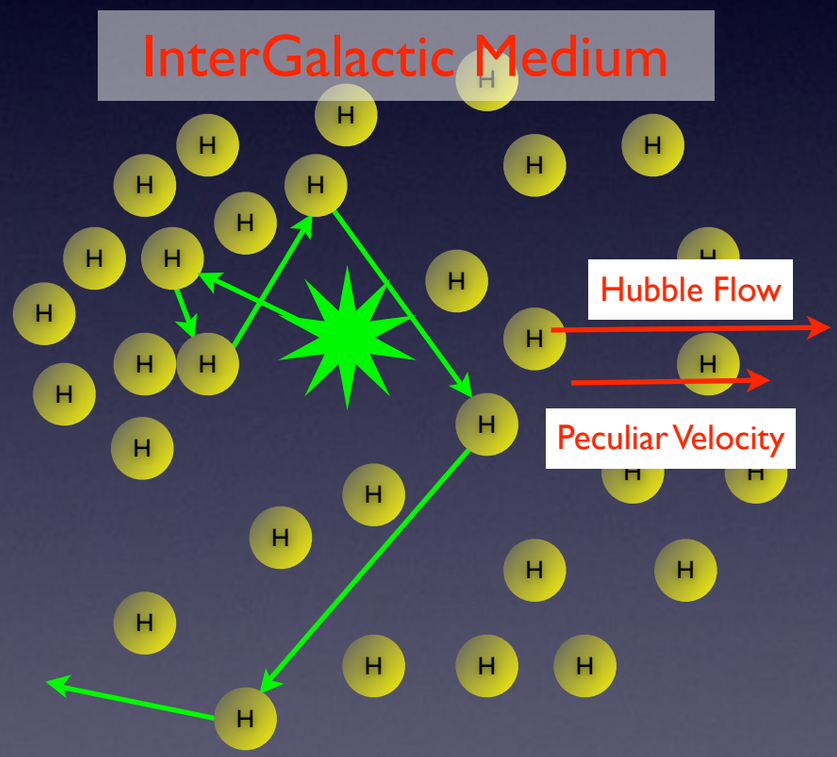
Clustering of LAEs: Model Prediction

enhancement in the transverse fluctuation

selection effect caused by environment dependent Lya RT



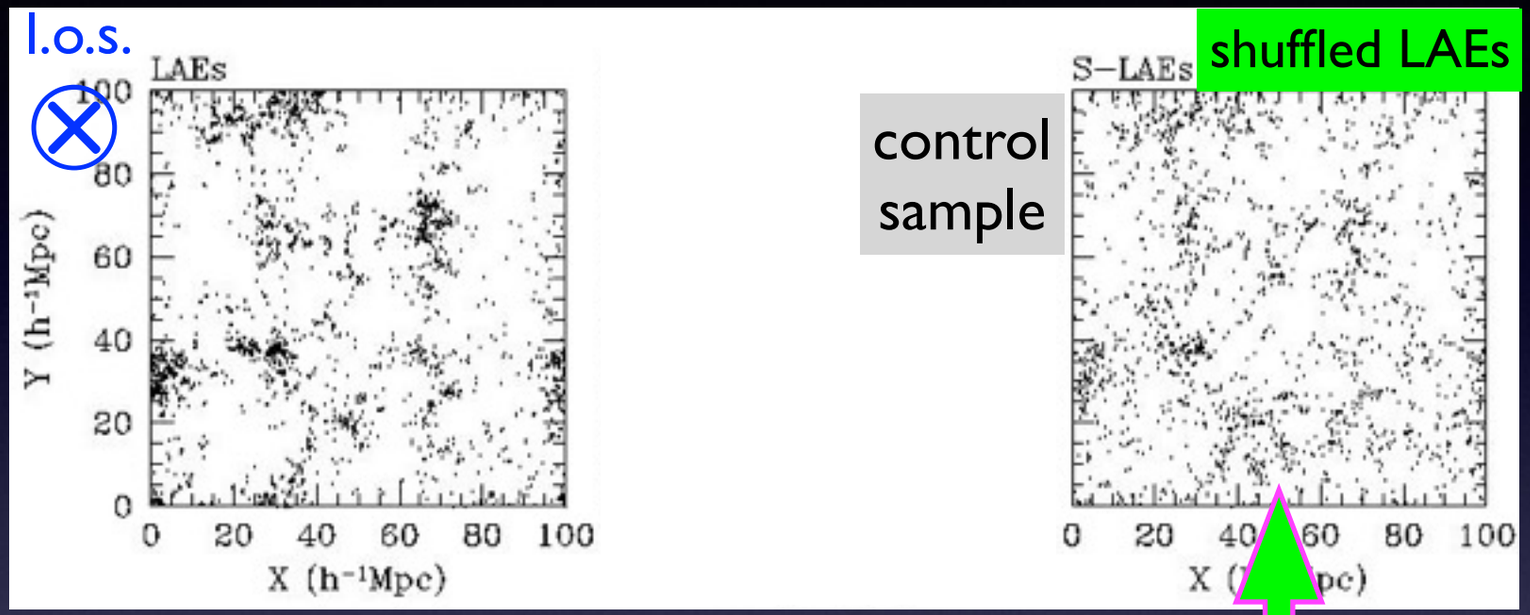
if the environment dependence of radiative transfer were eliminated

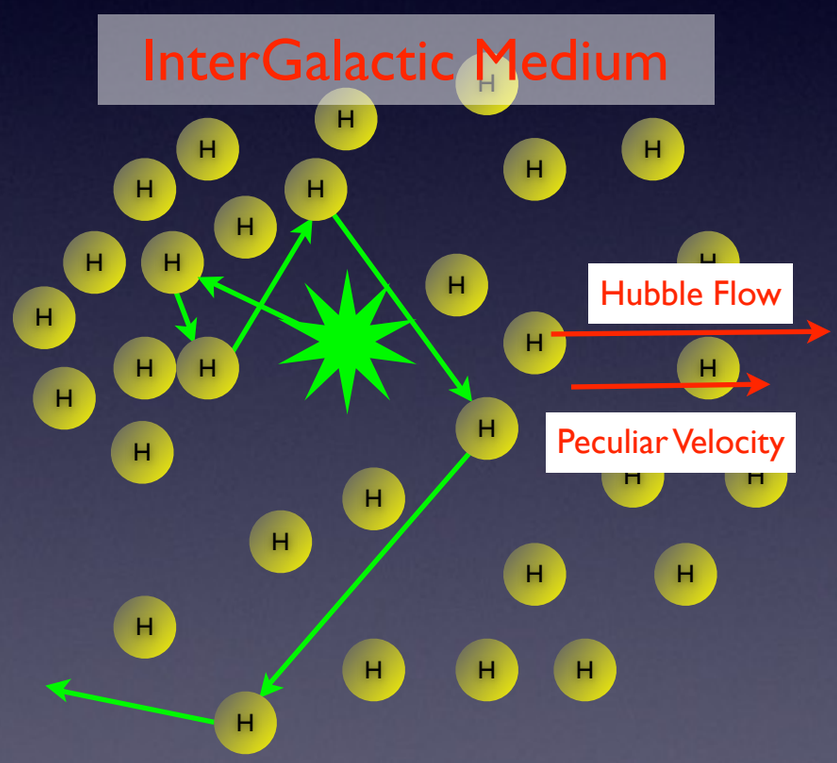


Clustering of LAEs: Model Prediction

enhancement in the transverse fluctuation

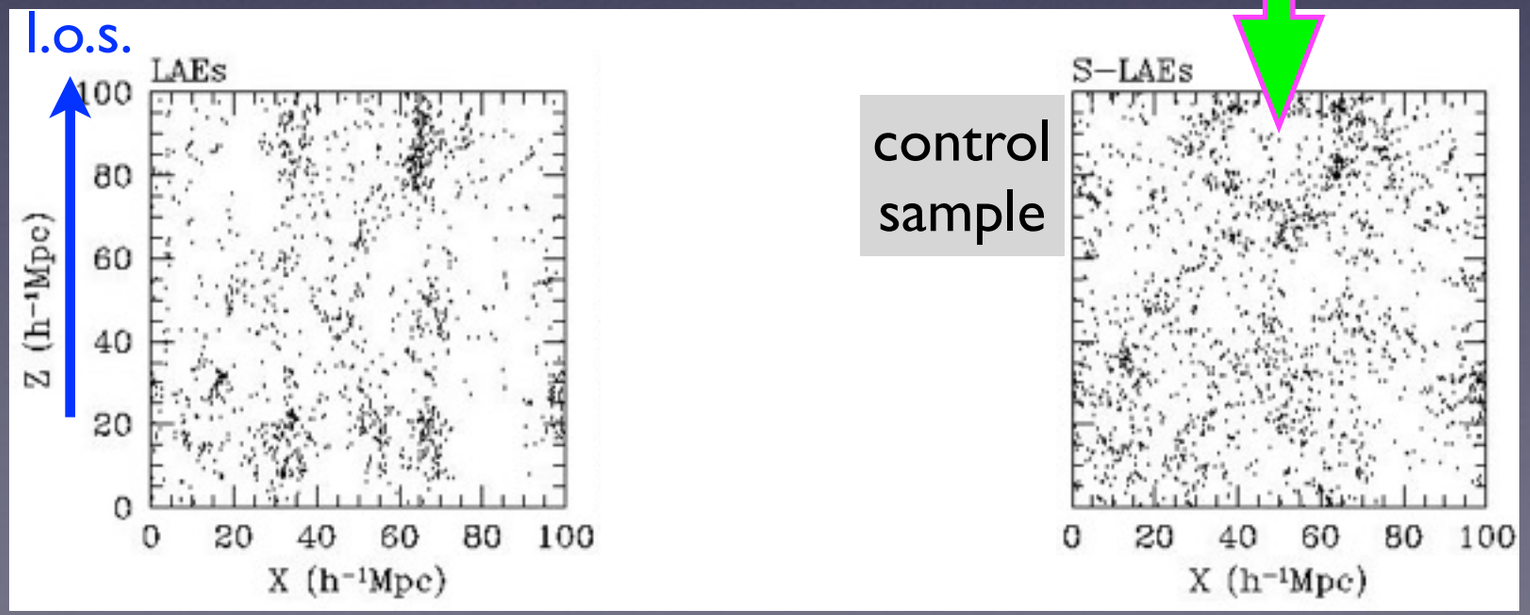
selection effect caused by environment dependent Lya RT





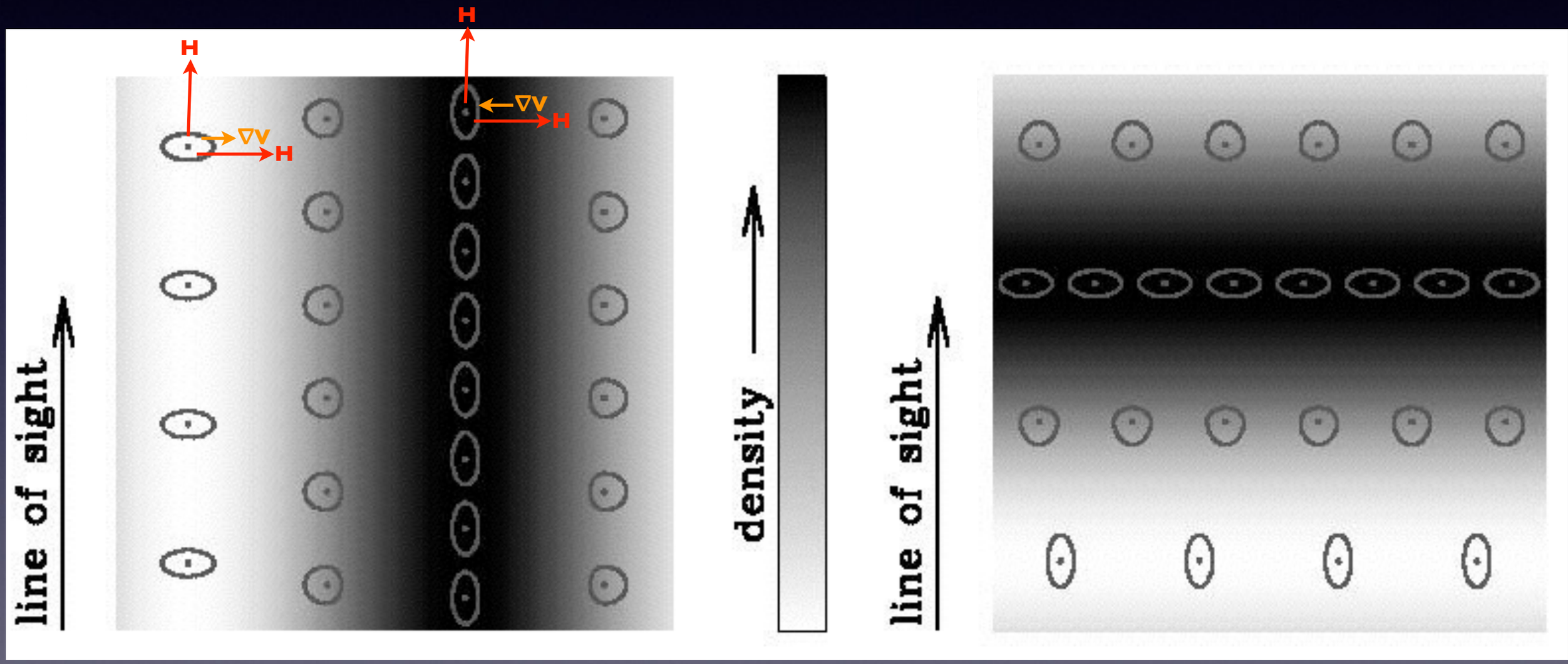
if the environment dependence of radiative transfer were eliminated

suppression in the line-of-sight fluctuation



Clustering of LAEs: Model Prediction

An intuitive picture

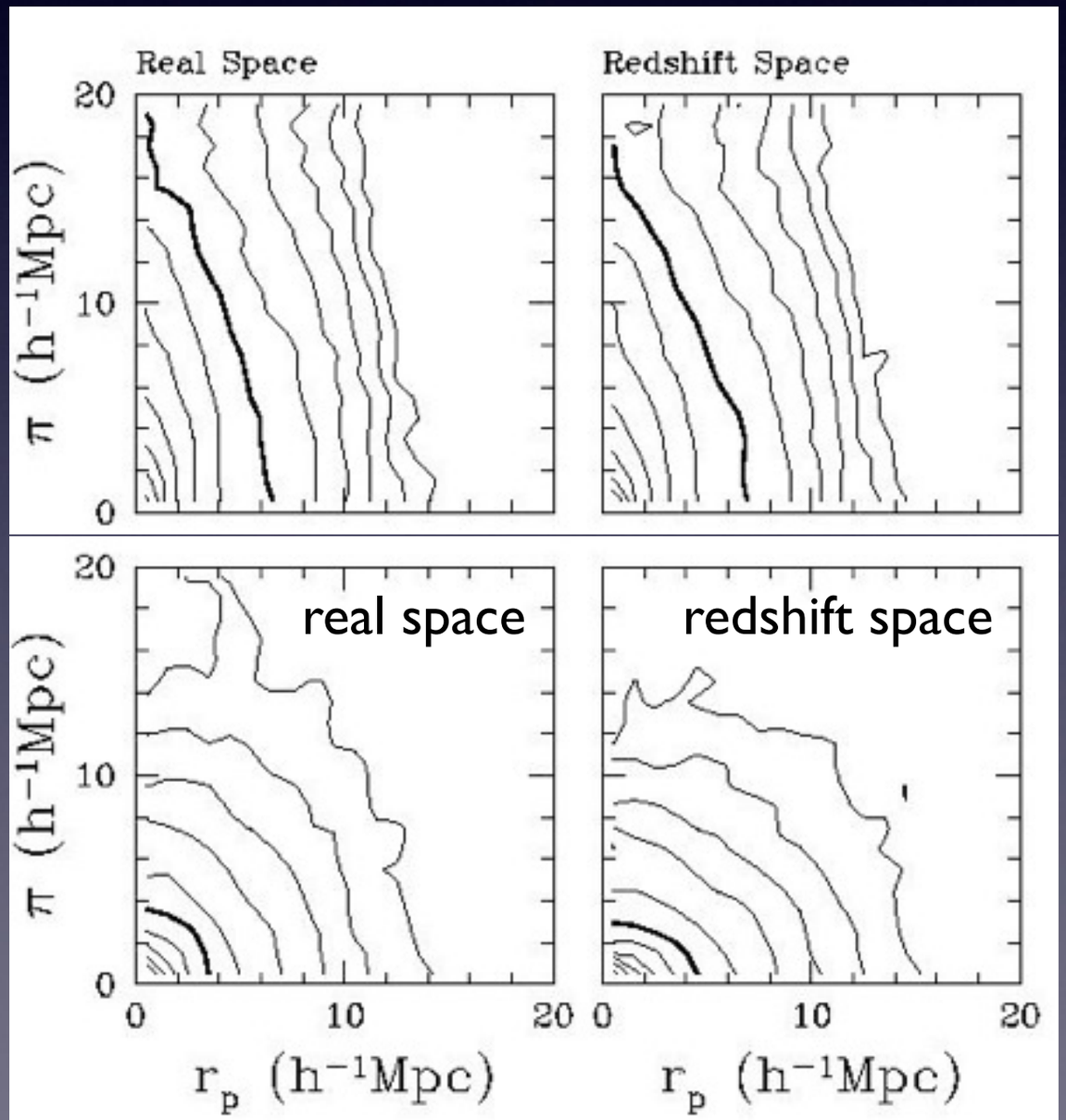


Clustering of LAEs: 3D Clustering

Anisotropic 3D two-point correlation function of LAEs

Zheng, et al. (2011a)

Radiative Transfer Effect



LAEs

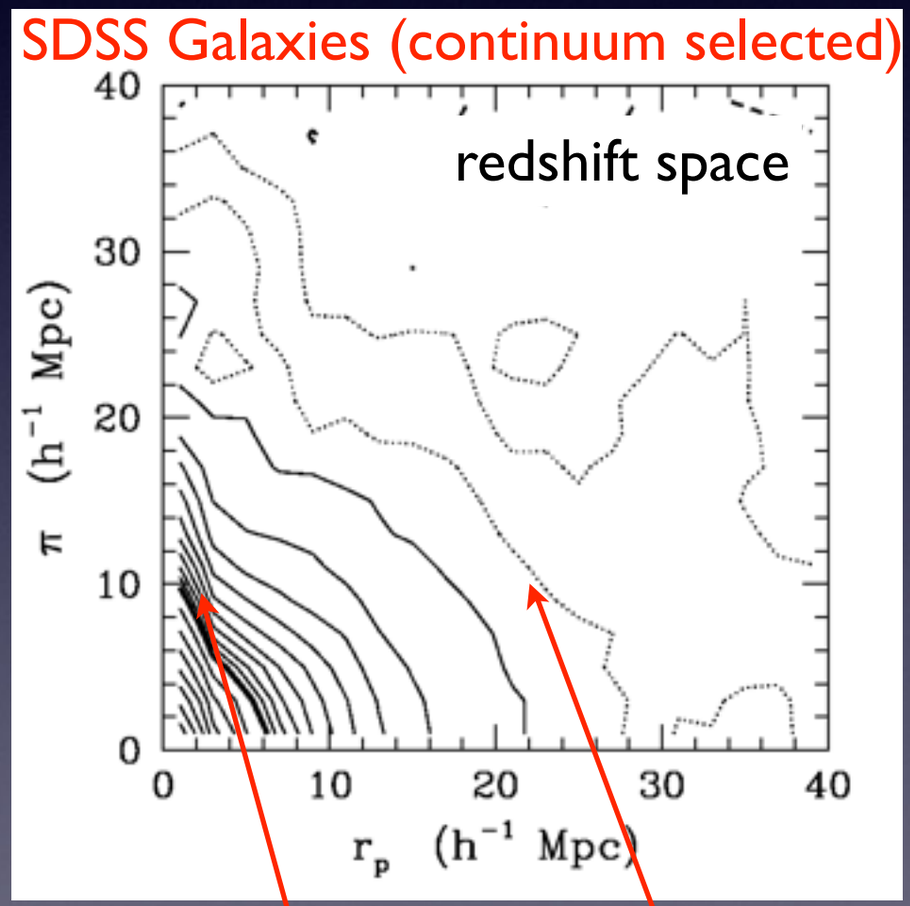
Shuffled LAEs

environment dependence of radiative transfer

Eliminated

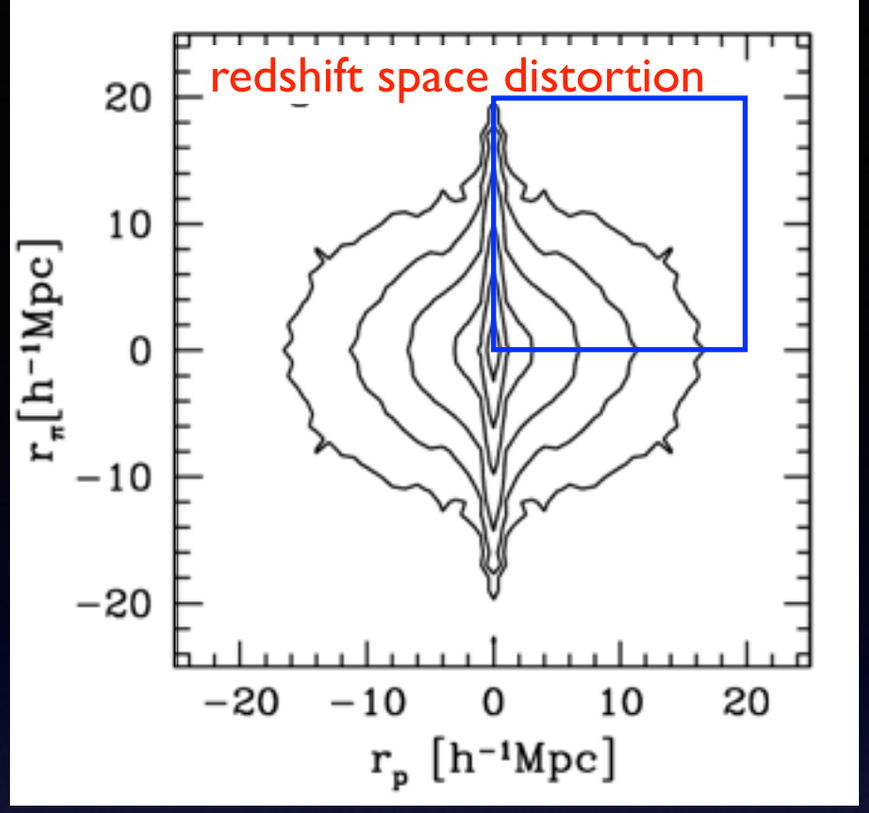
Zehavi, Zheng, et al. (2011)

SDSS Galaxies (continuum selected)



Finger-of-God Effect
nonlinear redshift distortion

Kaiser Effect
linear redshift distortion



New Effect in Galaxy Clustering
(induced by environment-dependent
Lyα radiative transfer)

Non-gravitational Distortion

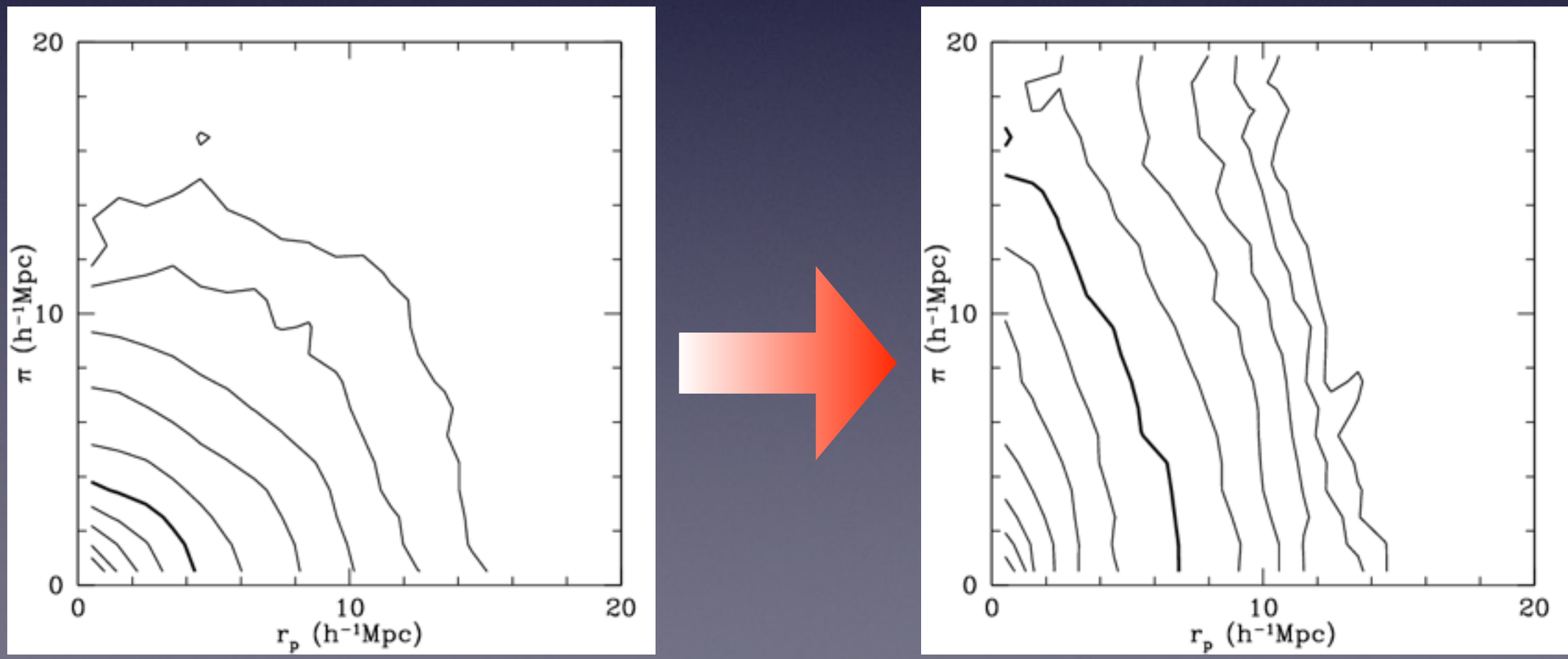
new window to probe the physical
conditions in galaxies and surrounding gas

No Coupling

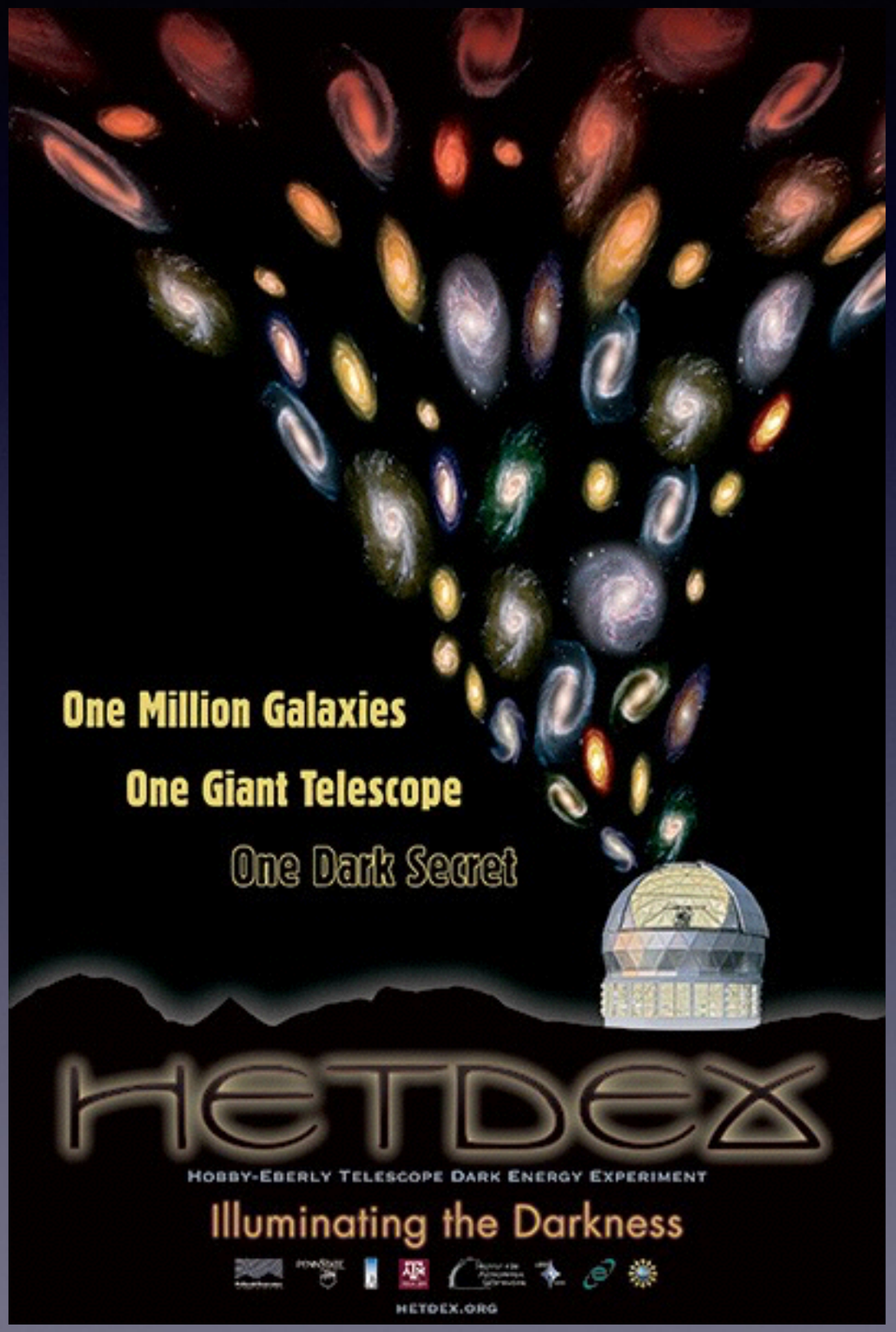
Kaiser effect dominated

Strong Coupling

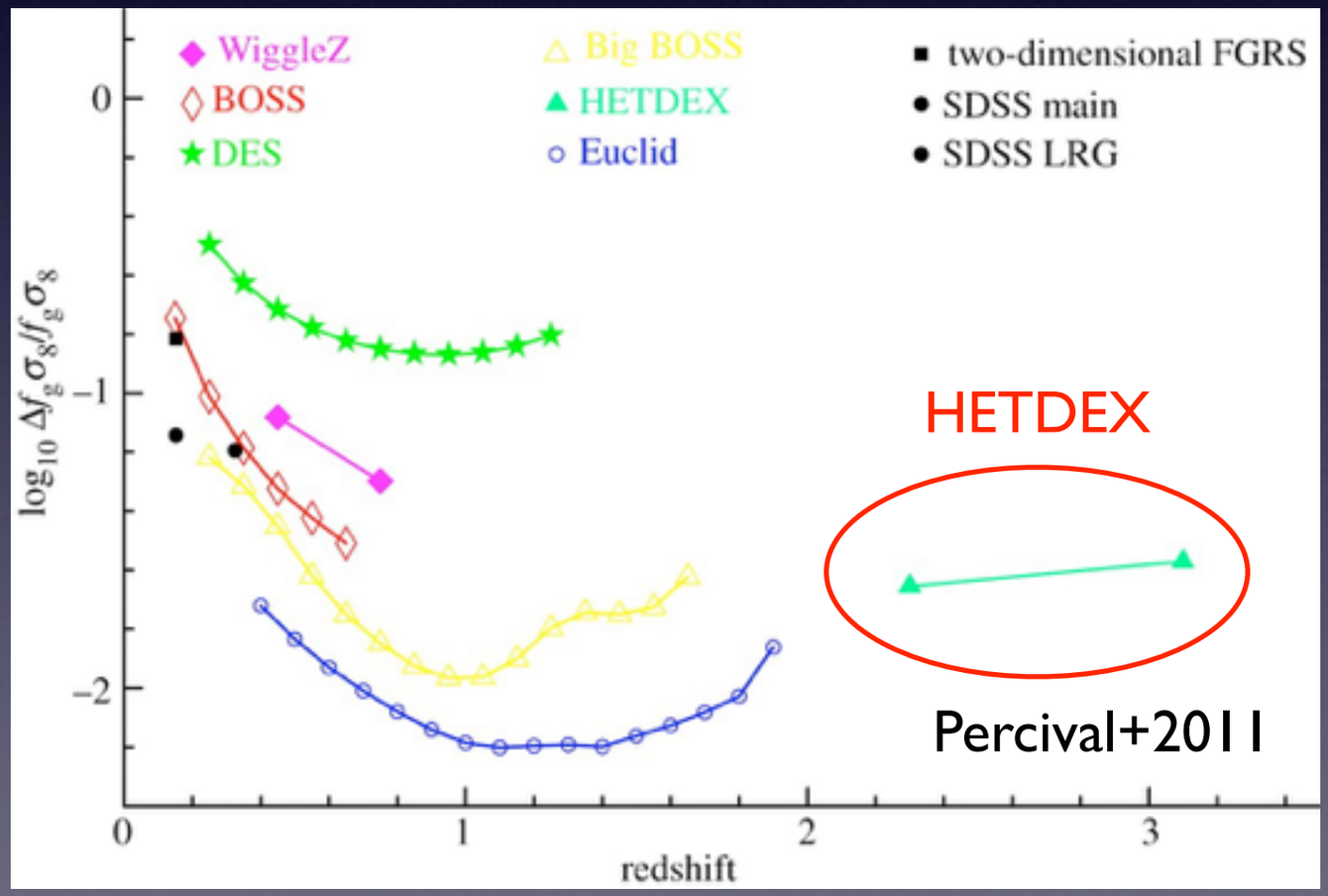
RT effect dominated



Large Redshift Surveys of LAEs for Cosmological Study from Galaxy Clustering

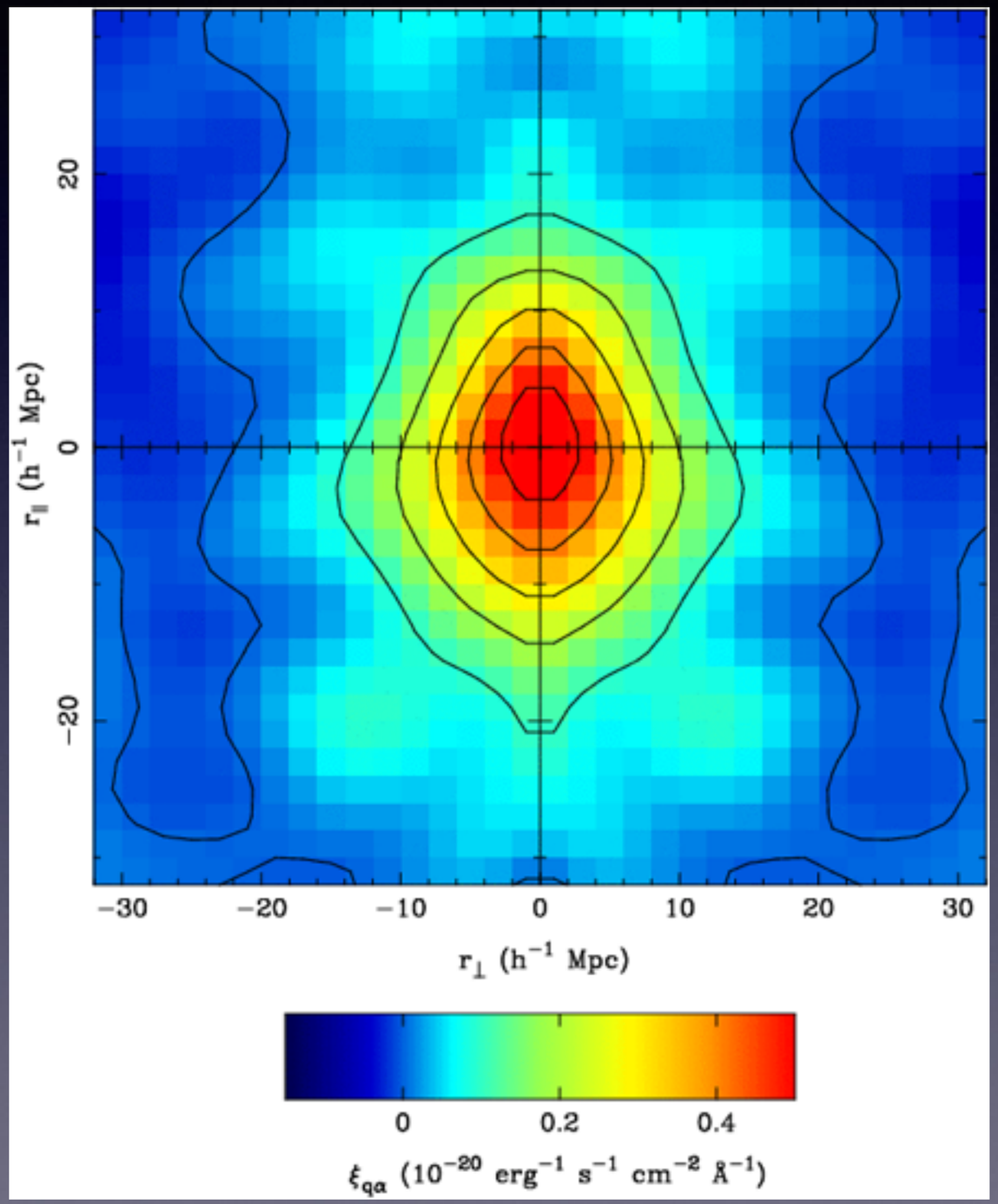


unique data points from high redshifts
accurate distance scales, growth rate, ...
constraints on dark energy evolution
constraints on gravity theory



important to understand the clustering of LAEs

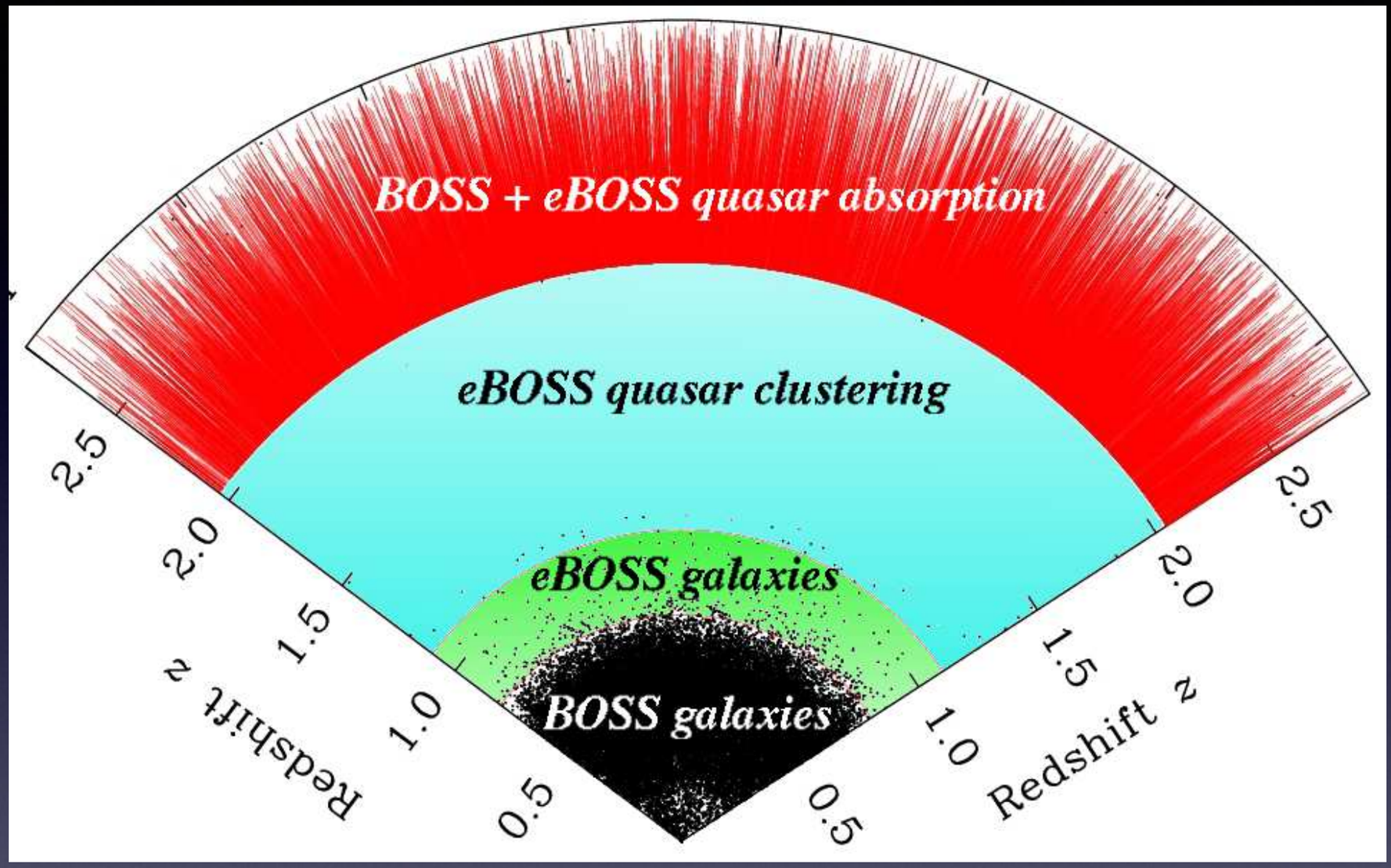
A Tentative Observational Case from SDSS-III BOSS Quasar-LAE Cross-Correlation



Croft, Miralda-Escude, ZZ, et al. (1504.04088)

Future Work

SDSS-IV
(2014-2020)



Luminous Red Galaxies (LRGs)
Emission Line Galaxies (ELGs)
Quasars / Quasar Absorption Systems

Redshift-Space Distortion Modeling
Cosmological Constraints with Redshift-Space Distortion

Future Work

Lyman-alpha Emitting Galaxies

HETDEX
(Hobby-Erberly Telescope Dark Energy Experiment)

~10^6 Lyman-alpha Emitting Galaxies at 2<z<4

LAE properties, Clustering, CGM/IGM probe

Subaru HyperSuprimeCam Survey
(Wide - 30 deg^2; Deep - a few deg^2)

~10,000 Lyman-alpha Emitting Galaxies at z>6

Reionization study

Summary

- Redshift-space distortion (gravitational distortion) in galaxy clustering is powerful to constrain the galaxy-halo connection, the phase-space distribution of galaxies inside halos, and the cosmic structure growth rate and fluctuation amplitude.

- Lyman-alpha radiative transfer induces nongravitational distortion in star-forming galaxy clustering - a new window to learn about physical conditions in galaxies and their surrounding gas, a potential probe for cosmic reionization, an important factor to be included for cosmological applications.