2017/09/7-8
The 3rd CINY workshop
@YITP

Relativistic distortions of large-scale structure

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In collaboration with

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Plan of talk

Observed redshift space in precision cosmology

Simulating relativistic effects on large-scale structure

Preliminary results

Summary

Large-scale structure

Matter inhomogeneity over Giga parsec scales

=

1000 Mpc =3*10^9 light years

is dominated by hypothetical invisible objects (i.e., *cold dark matter*)

has evolved from tiny fluctuations (most likely seeded by inflation) under influence of cosmic expansion and gravity

- Provide a wealth of cosmological information
- Is key observations in post-Planck precision cosmology

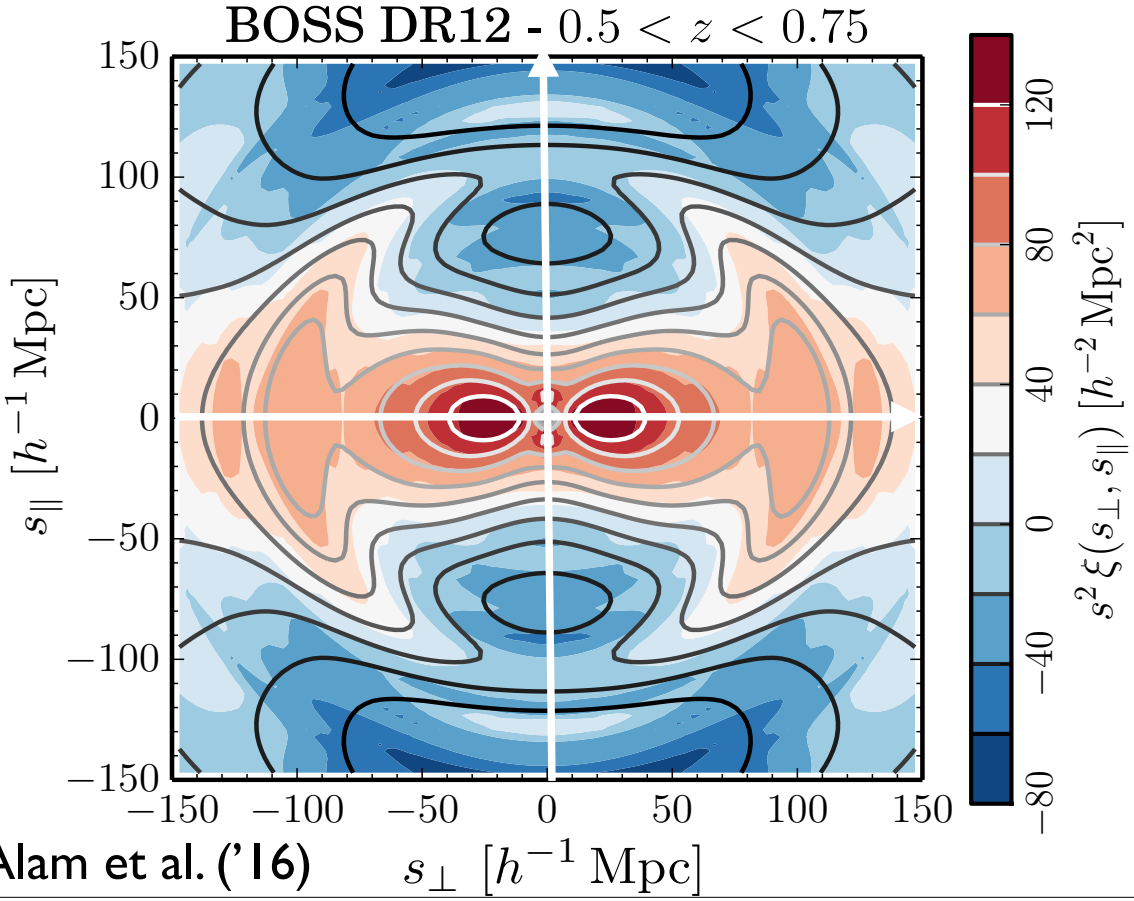
Origin of cosmic acceleration, nature of dark sectors, …

Anisotropic galaxy clustering

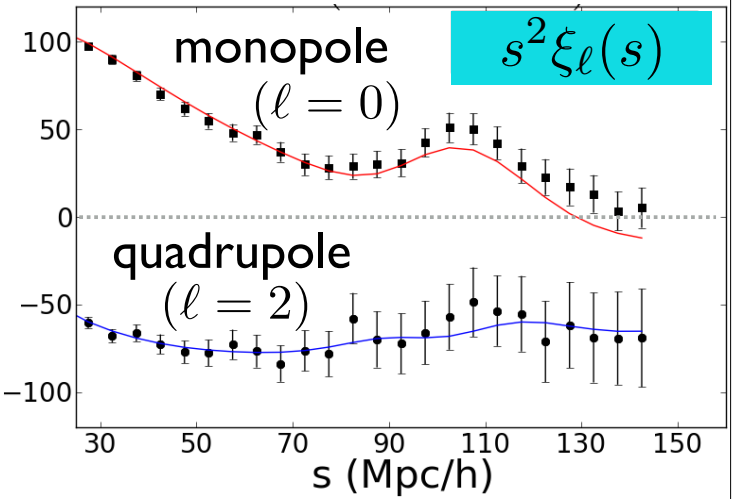
(Two-point) correlation function = counting many galaxy pairs

→ exhibit anisotropies of galaxy clustering

clue to cosmology



Alam et al. ('16)



Satpathy et al. ('17)

Legendre

$$\xi_\ell(s) = \frac{2\ell+1}{2}\int_{-1}^{1} d\mu\, \xi(s_\perp, s_\parallel)\, \mathcal{P}_\ell(\mu)$$

$$\mu = s_\parallel / s$$

$$s = (s_\perp^2 + s_\parallel^2)^{1/2}$$

Redshift space

Our observed space intrinsically violates statistical isotropy

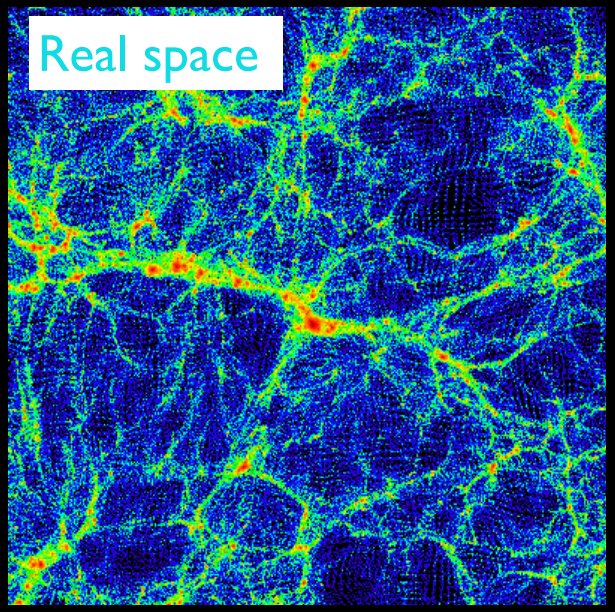
As a leading-order relativistic effect (i.e., $v/c \ll 1$*)*

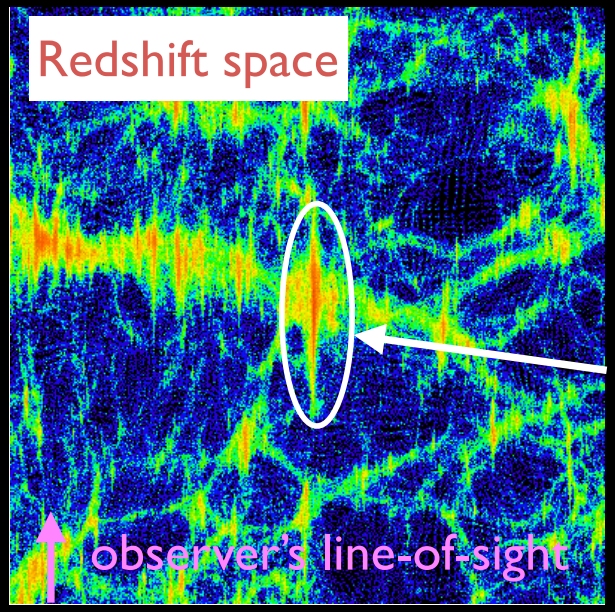
Redshift space (comoving)

$$\vec{s} = \vec{r} + \frac{1+z}{H(z)}(\vec{v}\cdot\hat{z})\hat{z}$$

Real space

observer's line-of-sight





N-body simulation (by T.Nishimichi)

Fingers-of-God effect

This complicates the interpretation of galaxy clustering data, however,

RSD as a probe of gravity

Kaiser formula

$$\delta^{(\mathrm{S})}(\boldsymbol{k}) = (1 + f\,\mu_k^2)\,\delta(\boldsymbol{k}) \;; \qquad f \equiv \frac{d\ln D_+}{d\ln a}$$

Linear growth factor

scale factor

This parameter tells us

how the nature of gravity affects the growth of structure

Importantly,

This Kaiser formula holds <u>irrespective of gravity theory</u>

➡ probe of gravity (general relativity) on cosmological scales

- Untested hypothesis in ΛCDM model
- Hint for cosmic acceleration

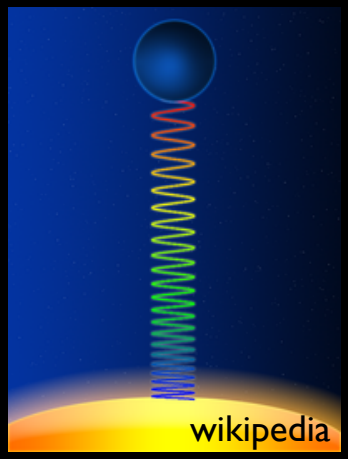
Linder ('08); Guzzo et al. ('08); Yamamoto et al. ('08); Percival & White ('09); White, Song & Percival ('09); Song & Percival ('09)

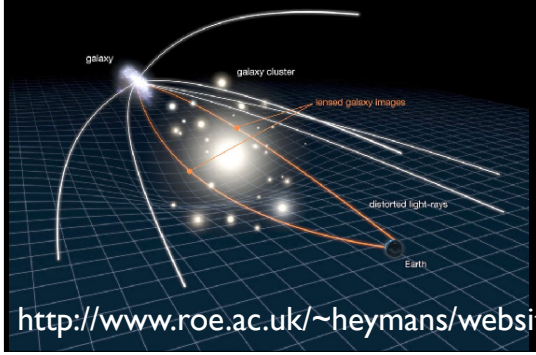
Beyond redshift-space distortions

An improved statistical precision of gigantic galaxy survey,

will open up a new window to detect *relativistic effects*

On top of redshift-space distortions,





http://www.roe.ac.uk/~heymans/website_images/Gravitational-lensing-galaxyApril12_2010-1024x768.jpg

Transverse Doppler effect

Gravitational redshift

(Integrated) Sachs-Wolfe effect

Weak gravitational lensing effect

Light-cone effect

Yoo, Fitzpatrick & Zaldarriaga ('09); McDonald ('09); Yoo ('10), Challinor & Lewis ('11); Bonvin & Durrer ('11)

Relativistic corrections to observed large-scale structure

Angular position

distortion of photon path caused by (weak) gravitational lensing

Redshift

energy shift of photon along photon path

(Observed) Redshift

(Observed) angular position

$$z_O = \frac{a_O}{a_S}\left(1 + \frac{\vec{v_S}.\vec{n}}{c} - \frac{\phi_S - \phi_O}{c^2} + \frac{v_S^2}{2c^2} - 2\int_{\eta_S}^{\eta_O} \frac{\dot{\phi}}{c^2} d\eta\right) - 1$$

$$\vec{\beta} = \vec{\theta} - \vec{\alpha}$$

HOMOGENEOUS

RSD

GRAVITATIONAL REDSHIFT

TRANSVERSE DOPPLER

INTEGRATED TERMS: ISW & LENSING

(from Y. Rasera)

Observed density field: linear theory

Relativistic linear perturbation

e.g., Bonvin & Durrer ('11)

(standard) Kaiser term

magnification bias ignored

$$\Delta^{\text{obs}}(\mathbf{n}, z) = b\,\delta - 2\Phi + \Psi - \frac{1}{\mathcal{H}}\partial_r(\mathbf{n}\cdot\mathbf{v}) - \left(\frac{2}{r\mathcal{H}} + \frac{\dot{\mathcal{H}}}{\mathcal{H}^2}\right)\mathbf{n}\cdot\mathbf{v} + \frac{\dot{\Phi}}{\mathcal{H}} + \frac{1}{\mathcal{H}}\left(\partial_r\Psi + \mathcal{H}\,\mathbf{n}\cdot\mathbf{v} + \mathbf{n}\cdot\dot{\mathbf{v}}\right)$$
$$+ \frac{1}{r}\int_0^r dr'\left[2 - \frac{r-r'}{r'}\Delta_\Omega\right](\Phi+\Psi) + \left(\frac{2}{r\mathcal{H}} + \frac{\dot{\mathcal{H}}}{\mathcal{H}^2}\right)\left(\Psi + \int_0^r (\dot{\Psi}+\dot{\Phi})dr'\right).$$

δ : density contrast in comoving gauge

Dipole anisotropies

n : (wide-angle) line-of-sight

$(\dot{})$: conformal time derivative

A part of

dipole anisotropies can be regarded as relativistic contribution (i.e., gravitational redshift)

Relativistic contribution to dipole

Bonvin, Hui & Gaztañaga ('14)

Cross correlation between different galaxy samples gives you non-vanishing dipole moment :

Assuming Euler eq. for pressureless fluid

$\left(\dot{\boldsymbol{V}} \cdot \hat{\boldsymbol{n}} + \mathcal{H}\, \boldsymbol{V} \cdot \hat{\boldsymbol{n}} + \partial_r \Psi = 0 \right)$

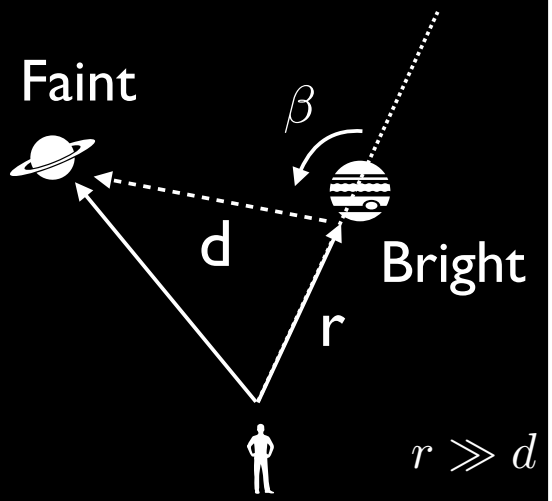
$$\Delta^{\text{obs}}_{\text{rel}}(z, \hat{\boldsymbol{n}}) = - \left[\frac{\dot{\mathcal{H}}}{\mathcal{H}^2} + \frac{2}{r\,\mathcal{H}} \right] \boldsymbol{V} \cdot \hat{\boldsymbol{n}}$$

$$\xi^{\text{BF}}(z, z', \theta) = \langle \Delta_{\text{B}}(z, \hat{\mathbf{n}}) \Delta_{\text{F}}(z', \hat{\mathbf{n}}') \rangle$$

Correction of $\mathcal{O}\left(\frac{d}{r}\right)$

$$\xi^{\text{BF}}_{\text{dipole}}(r(z), d) \simeq (b_{\text{B}} - b_{\text{F}}) \left(\frac{\dot{\mathcal{H}}}{\mathcal{H}^2} + \frac{2}{r\mathcal{H}} \right) \times \frac{\mathcal{H}}{\mathcal{H}_0} \frac{f}{2\pi^2} \int dk k \mathcal{H}_0 P(k, \bar{z}) j_1(kd)$$

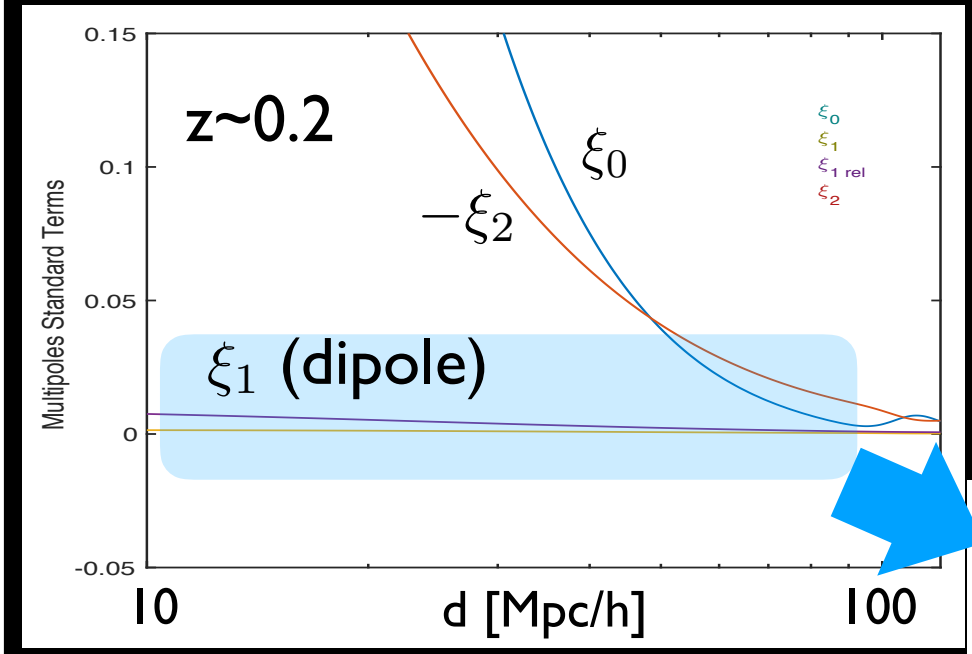
linear galaxy bias

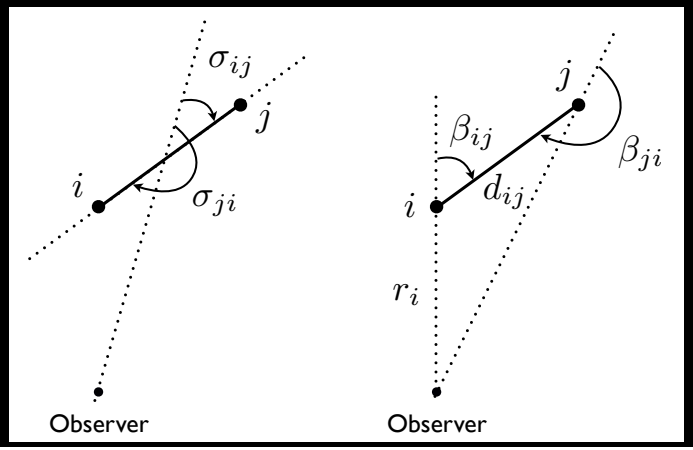


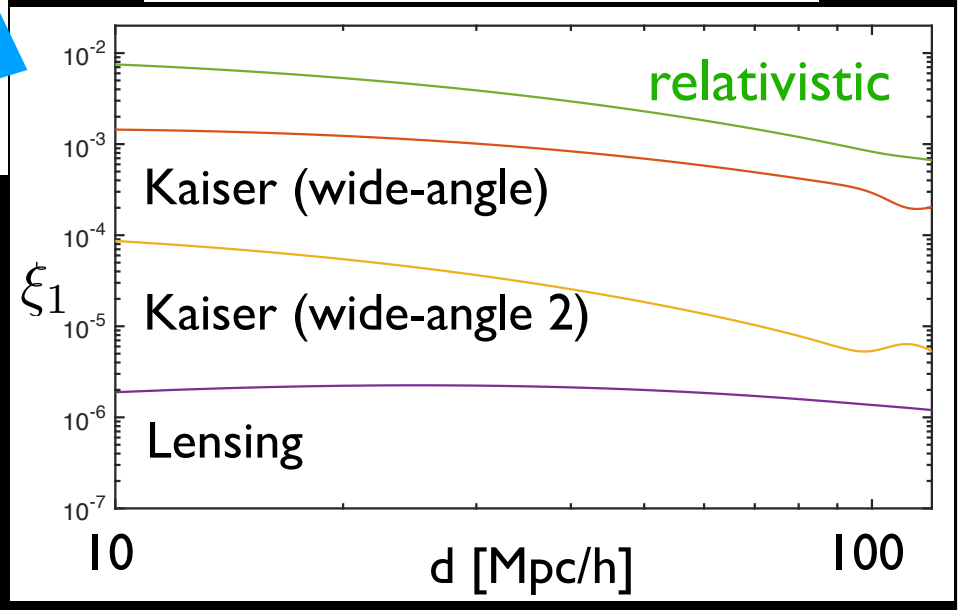
$$\xi_{\text{dipole}}(r, d) = \frac{3}{2} \int_{-1}^{1} d\cos(\beta)\, \xi(r, d, \beta)\, \cos(\beta)$$

Linear theory prediction

Bonvin, Hui & Gaztañaga ('14)
Internship report by Osmin







Detectability

~2.4σ for SDSS main

~7.4σ for DESI

Bonvin, Hui & Gaztañaga ('16)

Simulating relativistic effects

Michel-Andrès Breton & Yann Rasera

Using standard N-body code (RAMSES)

➡ Dark matter/halo distributions at many redshifts (Light-cone data)

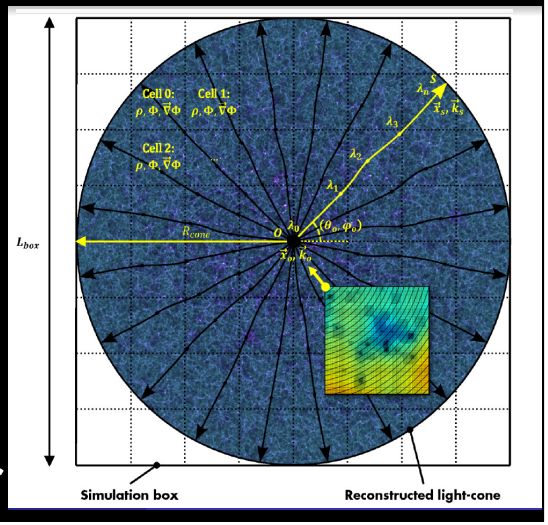
- Storing potential data on light cone
- Tracing back the light ray to the source by direct integration of geodesic equation (assuming $\Phi = \Psi$)

⟶ distorted angular position & redshift:

$$1 + z = \frac{(g_{\mu\nu} k^\mu u^\nu)_\mathrm{s}}{(g_{\mu\nu} k^\mu u^\nu)_\mathrm{o}}$$

Weak lensing, RSD, ISW, transverse Doppler, gravitational redshift, …

k^μ :null 4-vector u^μ :observer's or source's 4-vector



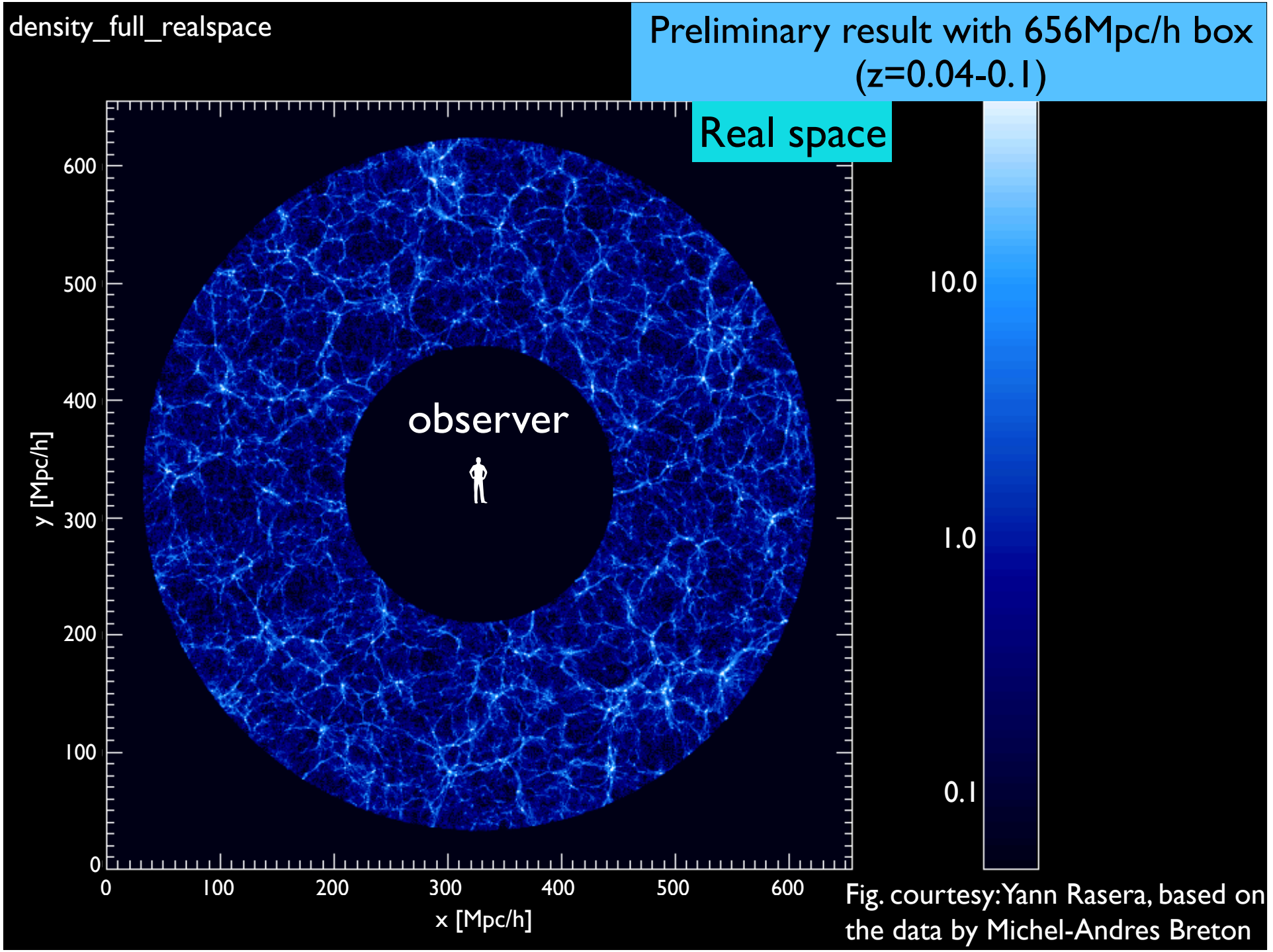
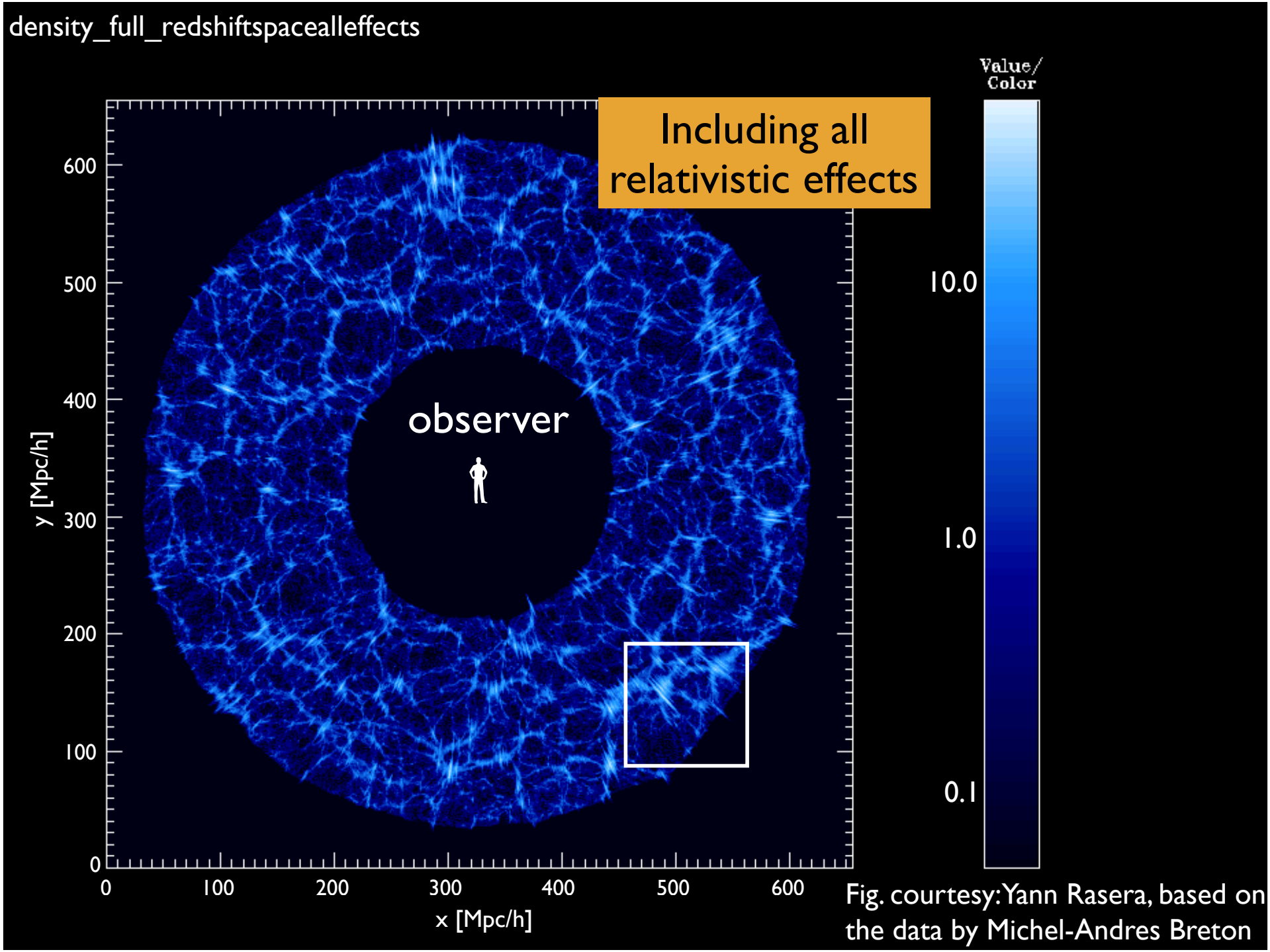


Fig. courtesy: Yann Rasera, based on the data by Michel-Andres Breton



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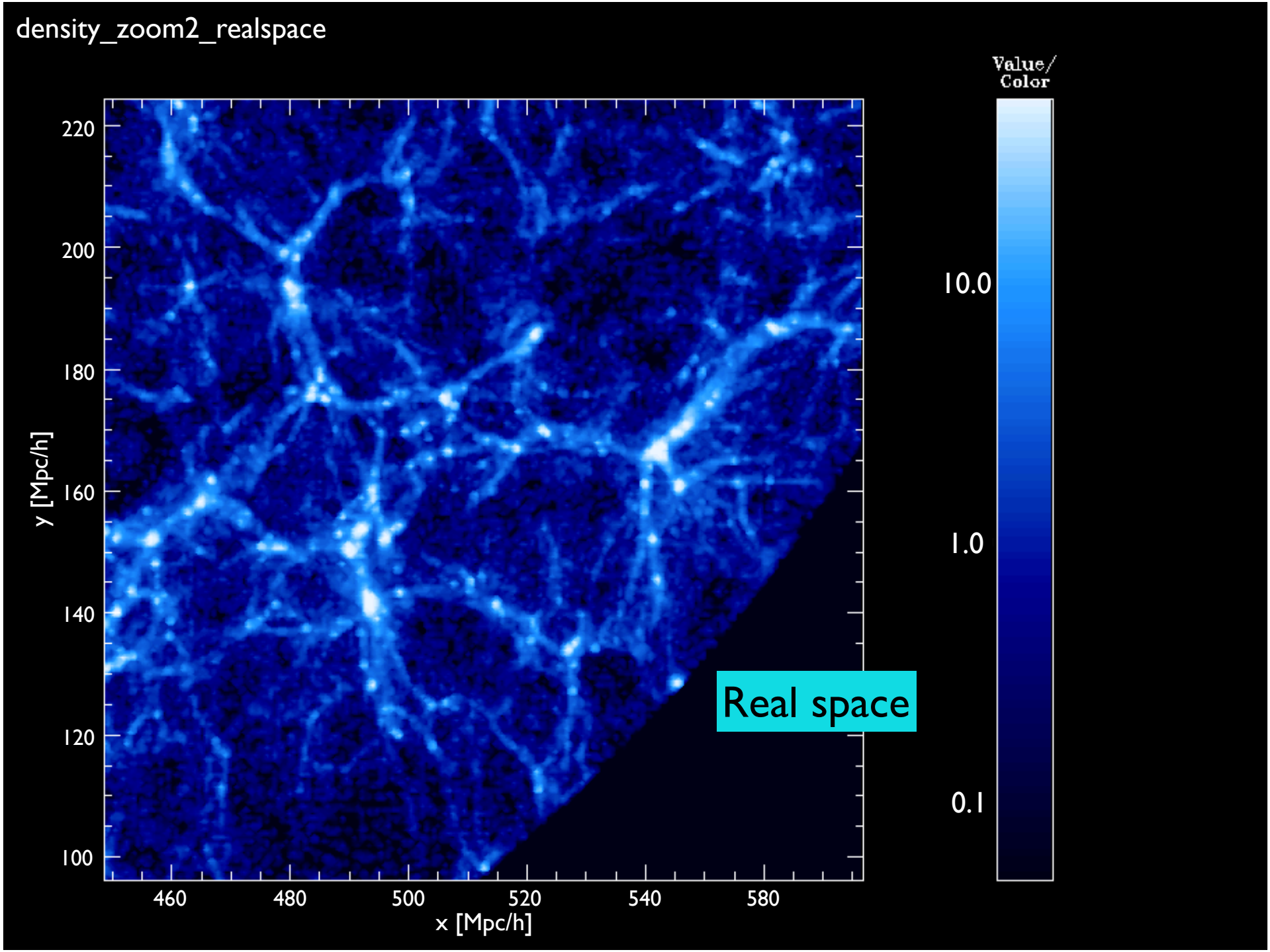
density_zoom2_realspace
Value/
Color
10.0
1.0
0.1
220
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y [Mpc/h]
460
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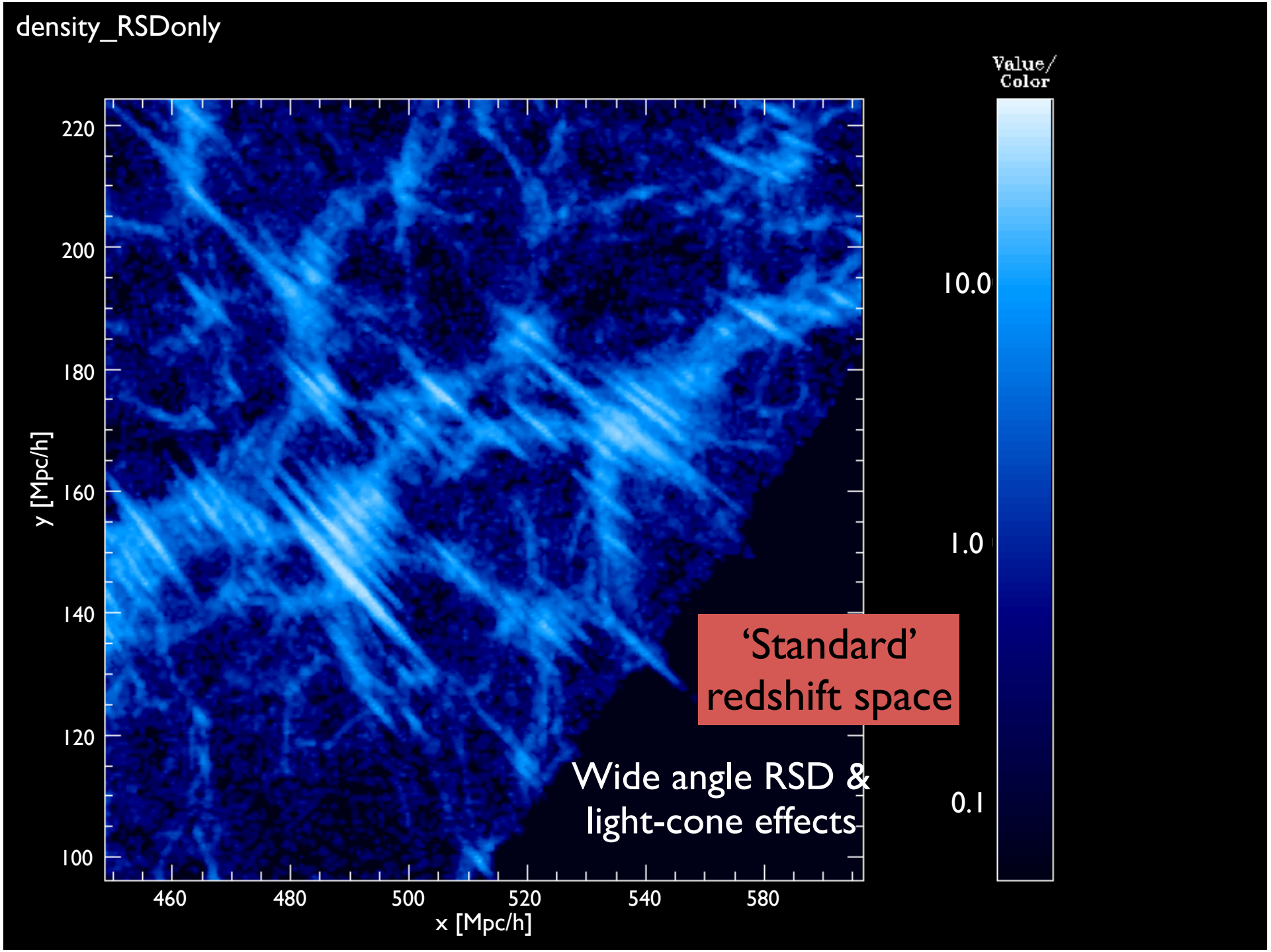
x [Mpc/h]
Real space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y [Mpc/h]
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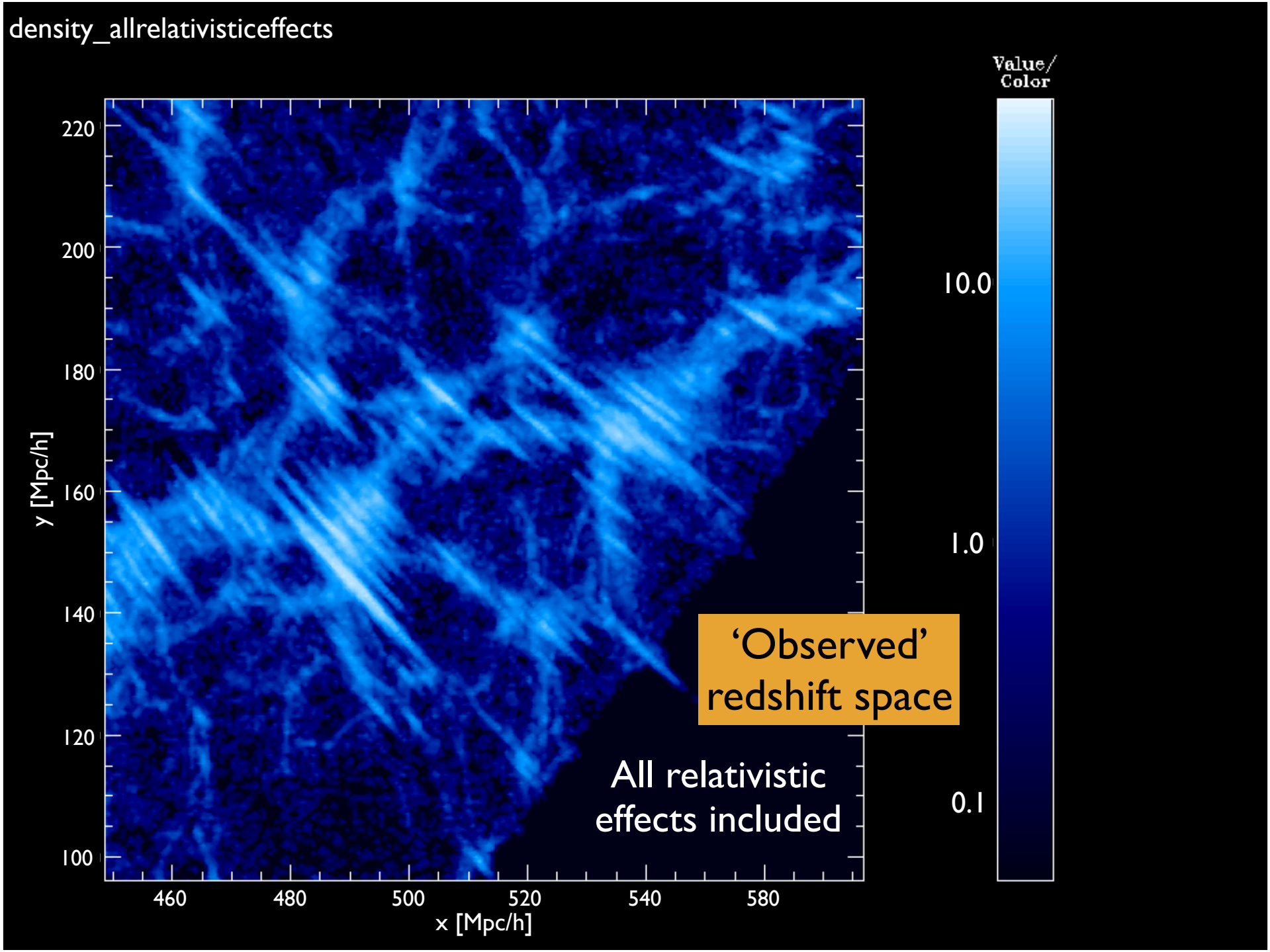
x [Mpc/h]
'Standard'
redshift space
Wide angle RSD &
light-cone effects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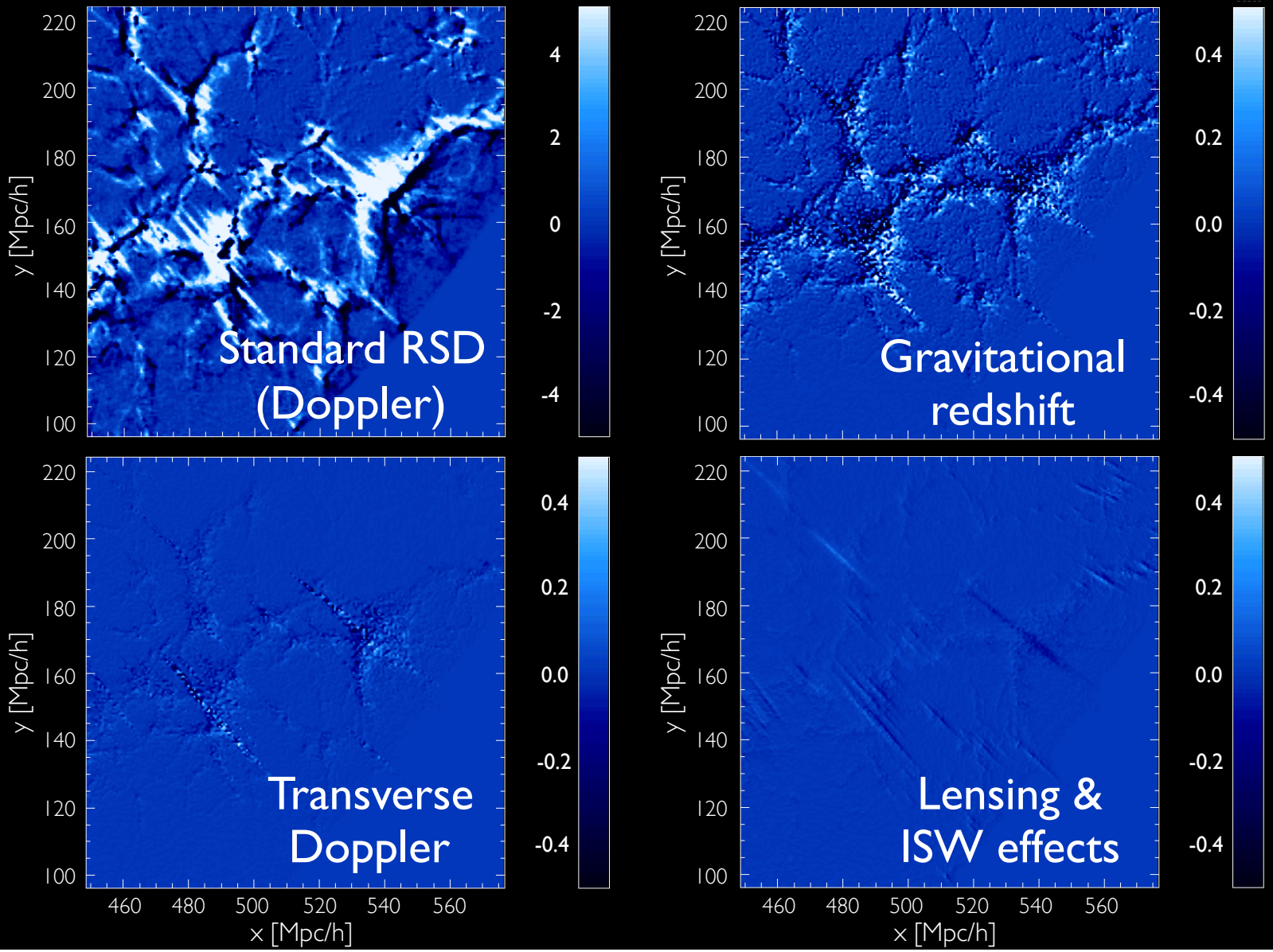
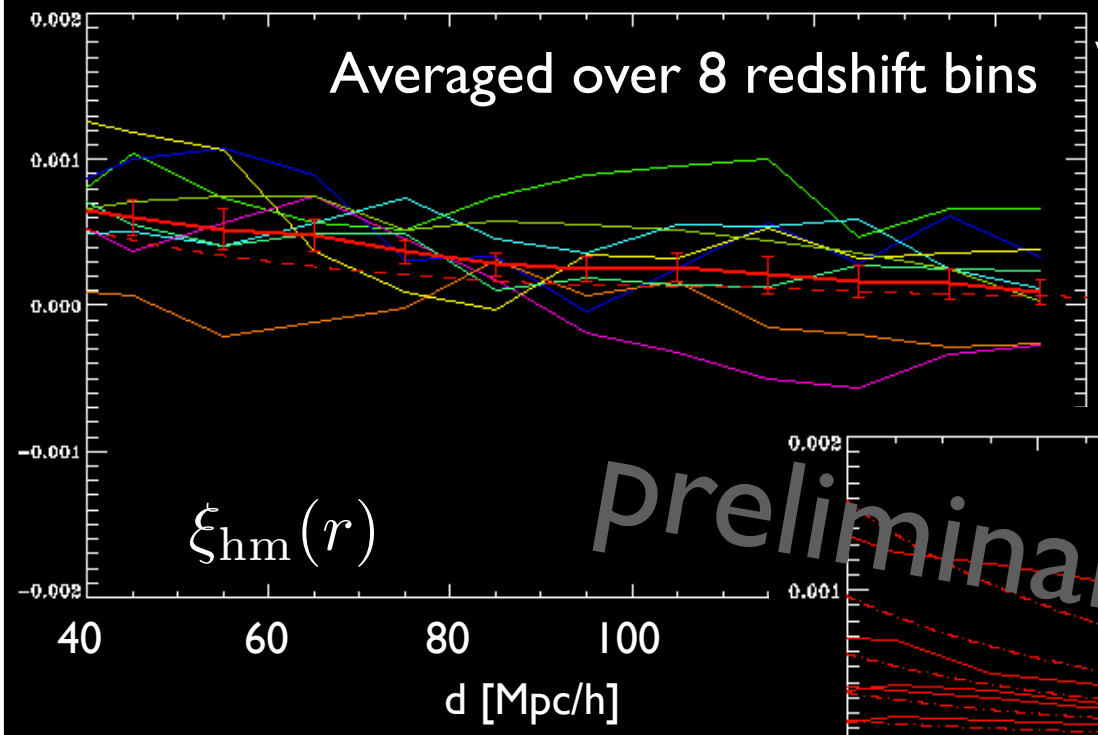
x [Mpc/h]
'Observed'
redshift space
All relativistic
effects included

Relative contributions



Measurement of dipole



With new large catalog of

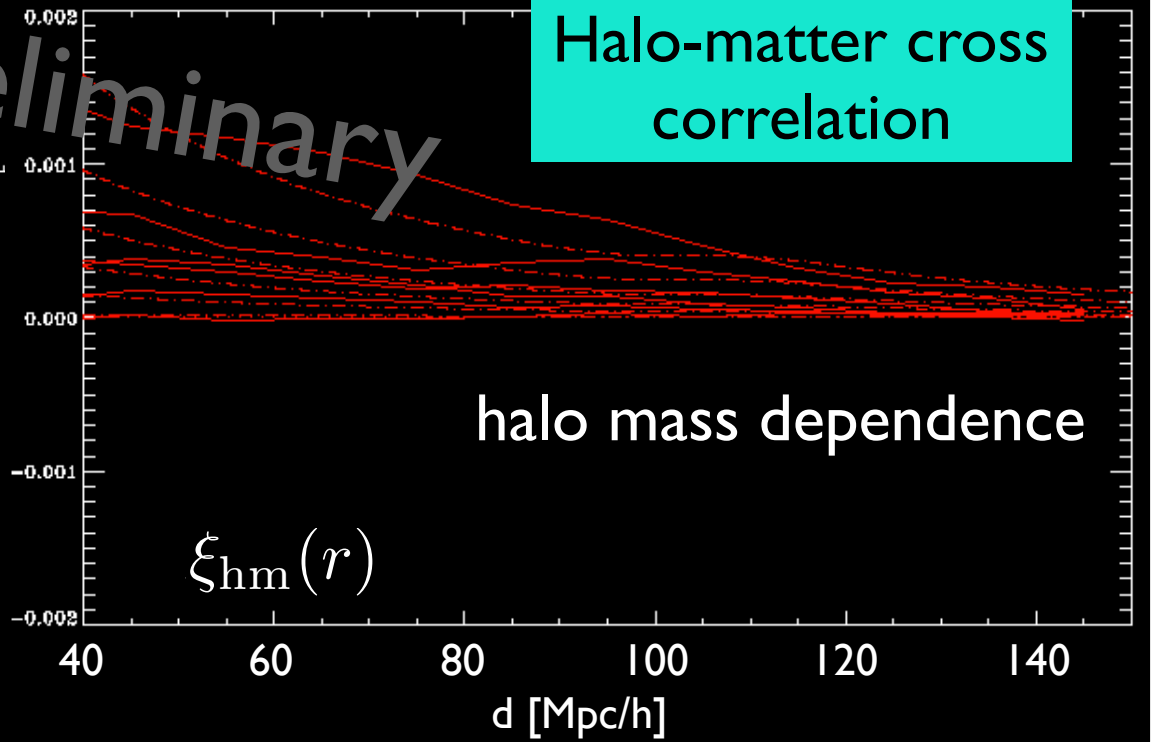
4096^3 particles, 2.5Gpc/h box

RayGalGroupSims

(will be available soon)

Preliminary

Halo-matter cross correlation



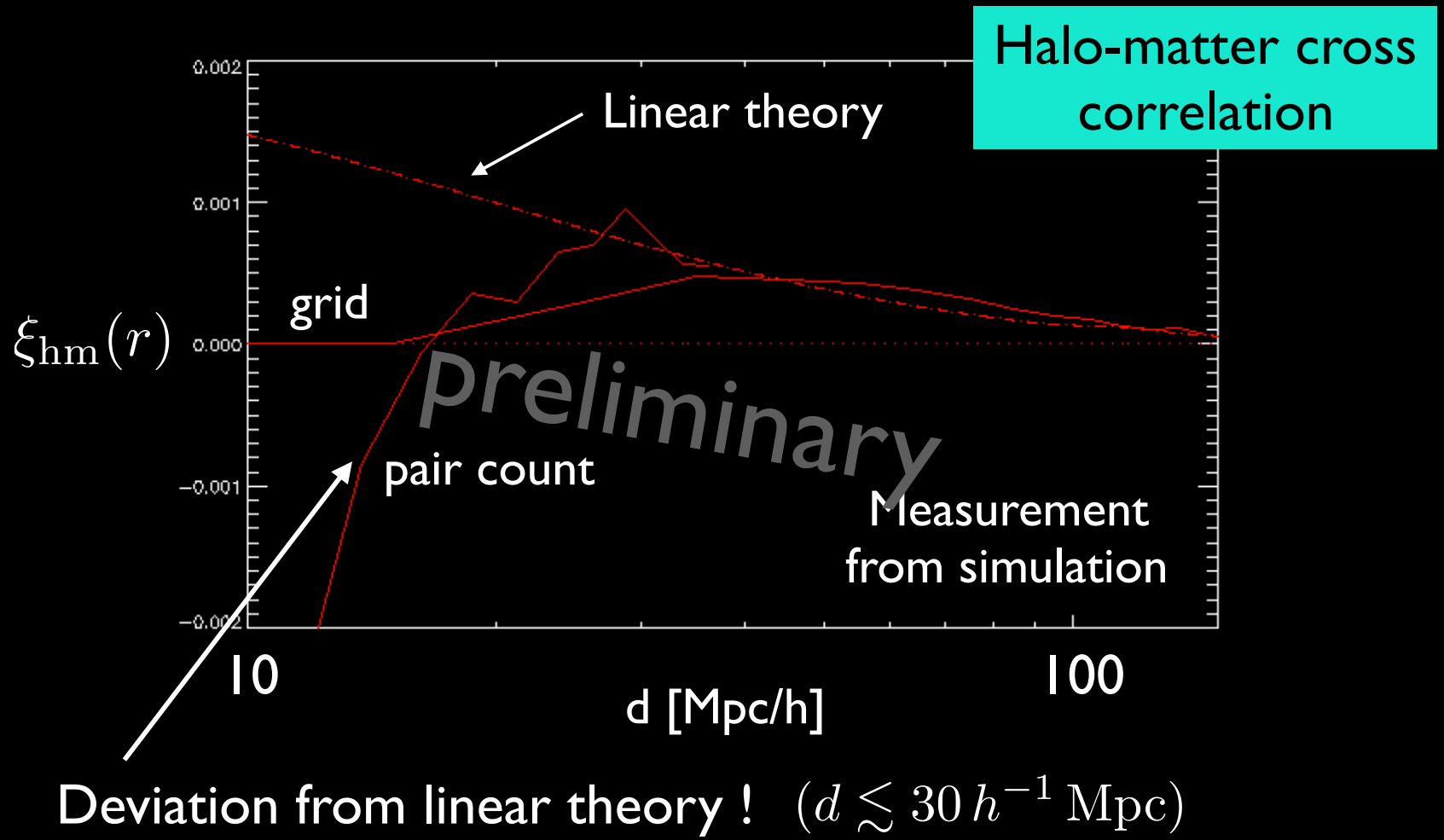
halo mass dependence

Red solid: measurement

Red dashed: linear theory

(using measured linear bias parameter)

Dipole at small scales



Beyond linear theory prediction

Mapping from real space to 'observed' redshift space is, in nature, nonlinear

In the distant-observer limit

redshift space

$$\boldsymbol{s} = \boldsymbol{r} - \Big\{ f\, u_z(\boldsymbol{r}) + \epsilon(\boldsymbol{r}) \Big\} \hat{z} \;;$$

real space

relativistic corrections

$$\epsilon = \frac{1}{aH} \left[\Psi + \int_{\eta_S}^{\eta_O} d\eta' (\Phi' + \Psi') + \cdots \right]$$

Cross power spectrum

$$P^{(S)}(\boldsymbol{k}) = \int d^3\boldsymbol{x}\, e^{i\boldsymbol{k}\cdot\boldsymbol{x}} \Big\langle e^{-i\,k\mu\,(f\Delta u_z + \Delta\epsilon)} \times \Big[\delta_B(\boldsymbol{r}) + \nabla_z \{ f u_z(\boldsymbol{r}) + \epsilon(\boldsymbol{r}) \} \Big] \Big[\delta_F(\boldsymbol{r}') + \nabla_z \{ f u_z(\boldsymbol{r}') + \epsilon(\boldsymbol{r}') \} \Big] \Big\rangle$$

$$\Delta u_z \equiv u_z(\boldsymbol{r}) - u_z(\boldsymbol{r}')$$

$$\Delta\epsilon \equiv \epsilon(\boldsymbol{r}) - \epsilon(\boldsymbol{r}')$$

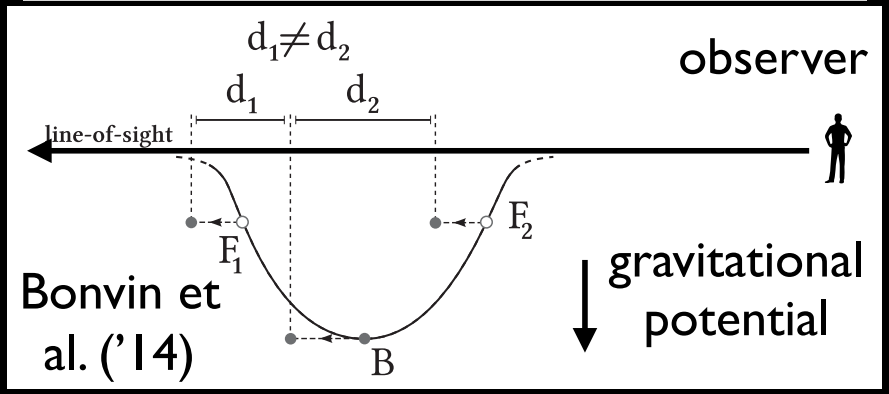
Nonlinear cross talk between velocity (standard RSD) and relativistic corrections ⇒ need a proper treatment with perturbation theory

(work in progress)

Detection of gravitational redshift

Shell estimator Croft ('13)

$$z_{\rm g}^{\rm shell}(r') = \frac{\int_{r'}^{r'+\Delta r'} H r_\parallel [1+\xi(r_\perp, r_\parallel)] r^2 {\rm d}r}{\int_{r'}^{r'+\Delta r'} [1+\xi(r_\perp, r_\parallel)] r^2 {\rm d}r}$$

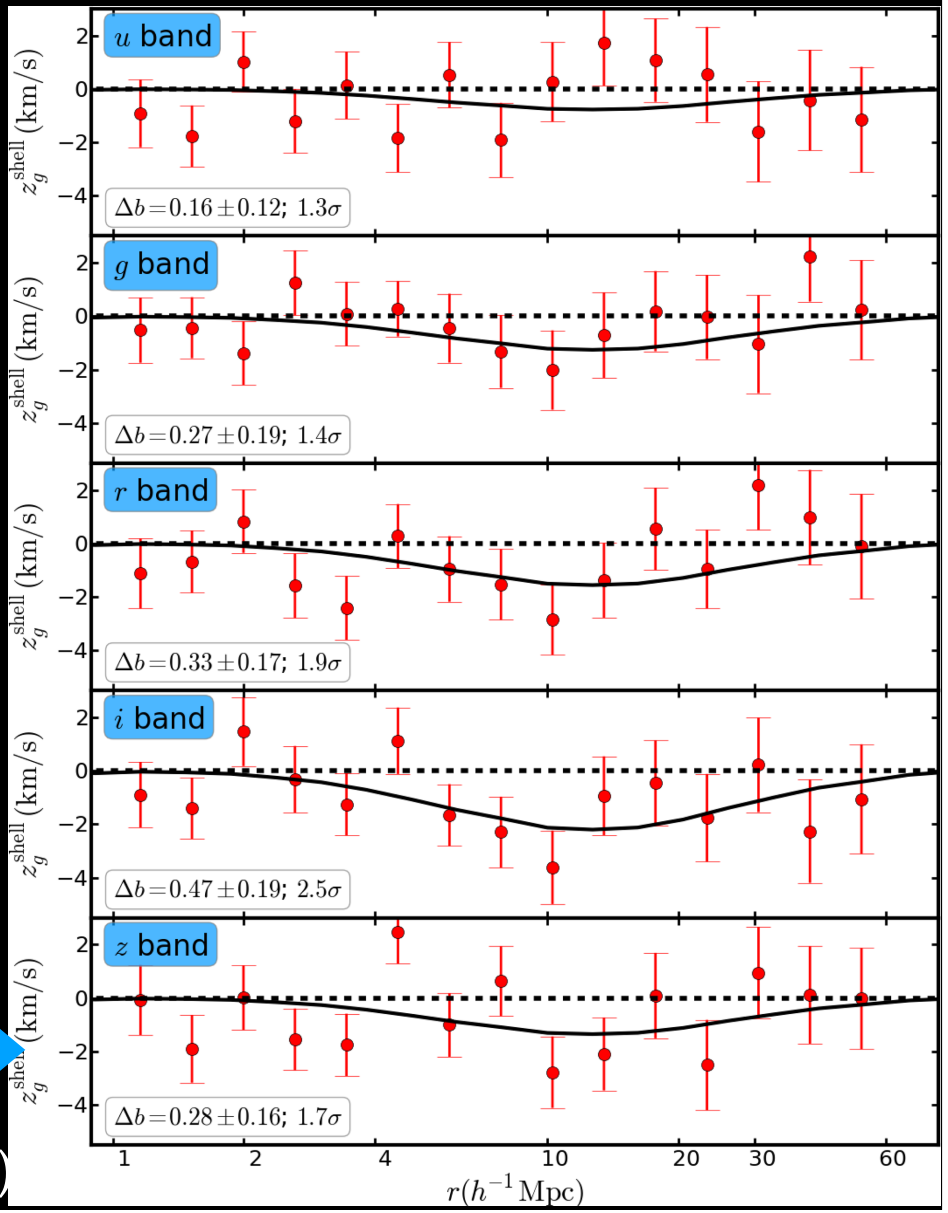


SDSS-III BOSS CMASS samples
765,000 gals @ 0.4<z<0.7

⟶ two color bins

All combinations give a detection at 2.7σ level (Alam et al.'17)

(For cluster samples, see e.g., Wojtak et al.'11)



Summary

Future observations will be able to not only demonstrate a precision test of gravity, but also open a new window

Relativistic effects imprinted in large-scale structure observations

⟶ Asymmetric cross correlation function

Simulating relativistic effects of large-scale structure :

Large scales linear theory prediction is good

Small scales deviation from linear theory is found → perturbation theory prediction needs to be developed (in progress)

Detection of relativistic effects (gravitational redshifts) is really fun, and it can give new cosmological information