2017/09/19-22
KIAS-YITP joint workshop
@YITP

Relativistic distortions of large-scale structure

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In collaboration with

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Plan of talk

Cosmology with large-scale structure

Redshift-space distortions (RSD) as a probe of gravity

Beyond standard RSD: relativistic distortions

Summary

Large-scale structure

Matter inhomogeneity over Giga parsec scales

= 1000 Mpc =3*10^9 light years

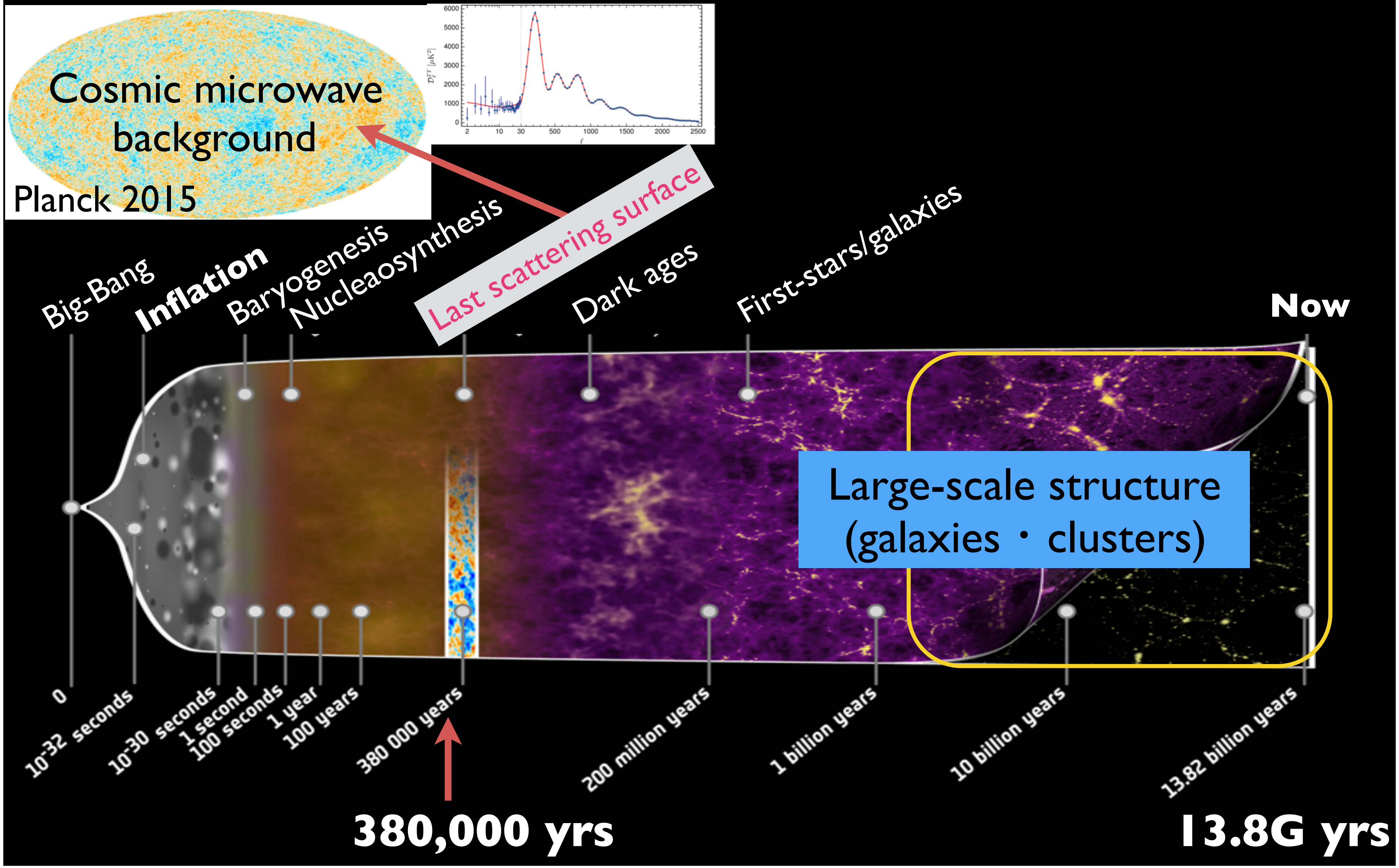
is dominated by hypothetical invisible objects (i.e., *cold dark matter*)

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, …

Timeline of the Universe



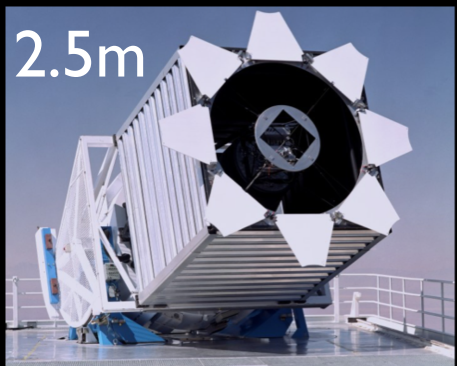
Observing large-scale structure

Intensive use of telescope is necessary

Very Large Telescope (Chile)

Subaru Telescope (Hawaii)

Canada-France-Hawaii Telescope (Hawaii)



Sloan Digital Sky Survey @ APO (New Mexico)

Blanco telescope @ CTIO (Chile)

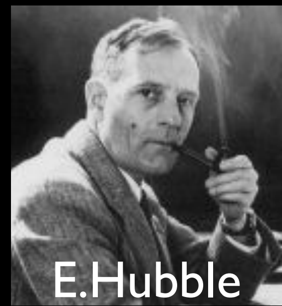
https://en.wikipedia.org/wiki/Very_Large_Telescope
http://www.sdss.org/instruments/
http://subarutelescope.org/Information/Download/DImage/index.html
http://www.cfht.hawaii.edu/en/news/CFHT30/#wallpaper
http://www.darkenergysurvey.org/DECam/index.shtml

Redshift

A key measurement to probe 3D view of large-scale structure

Distant galaxies looks *redder* than nearby galaxies due to cosmic expansion

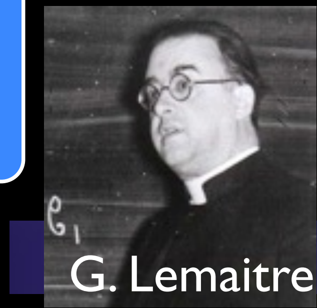
Redshift parameter $z = \Delta\lambda / \lambda$



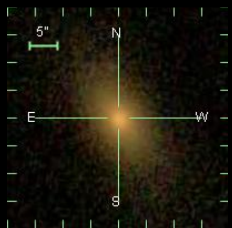
Hubble law

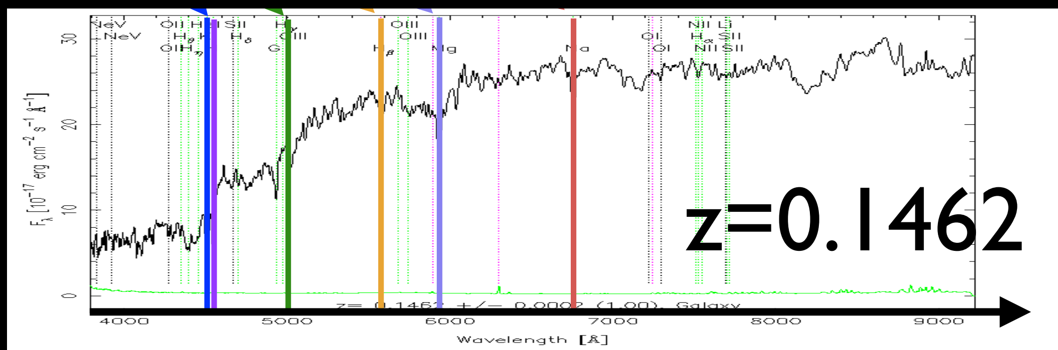
recession 'velocity' $v = H\,d$ distance to galaxy

(= *light velocity* × *redshift*) Hubble parameter



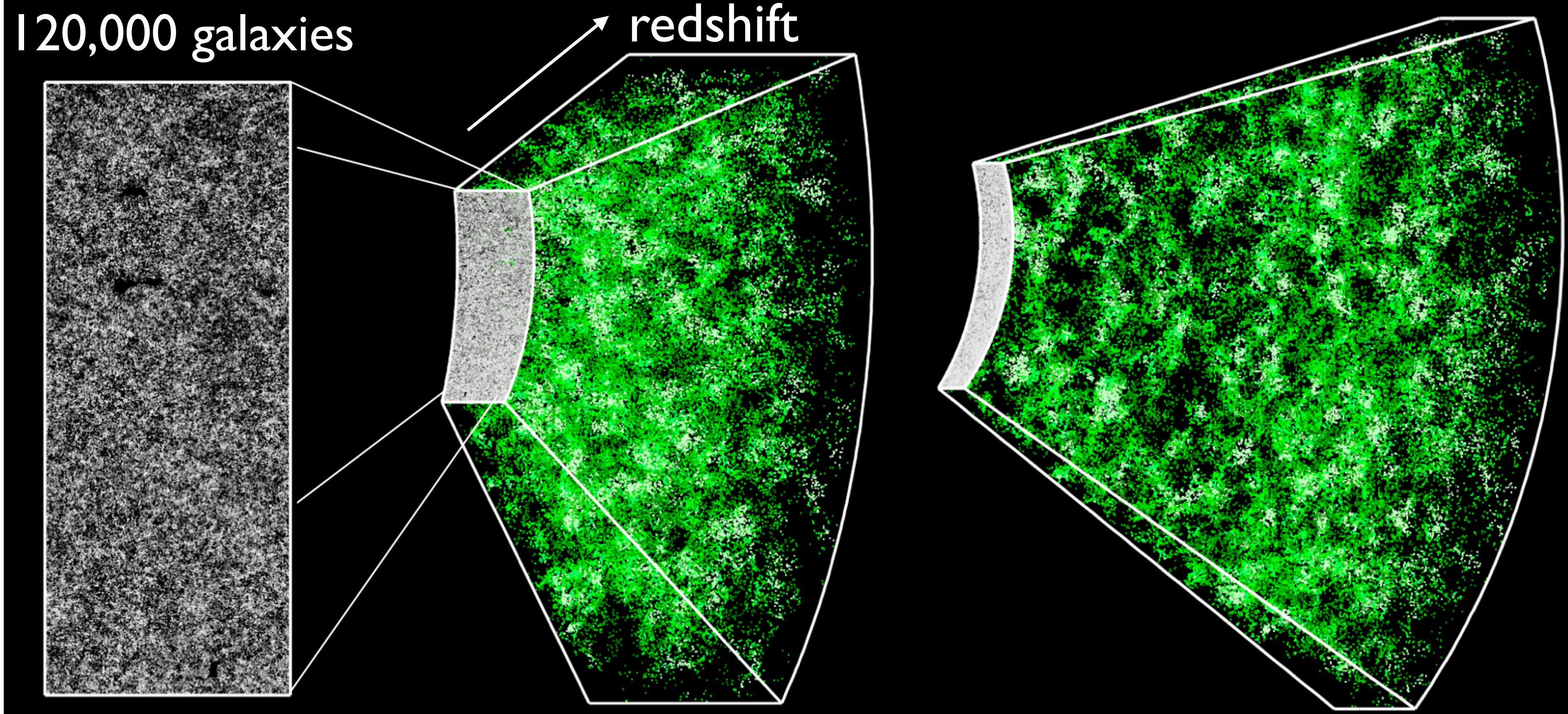
Distant galaxy





SDSS SkyServer

A section of 3D map



Sloan Digital Sky Survey (SDSS-III)
Baryon Oscillation Spectroscopic Survey

http://www.sdss.org/press-releases/astronomers-map-a-record-breaking-1-2-million-galaxies-to-study-the-properties-of-dark-energy/

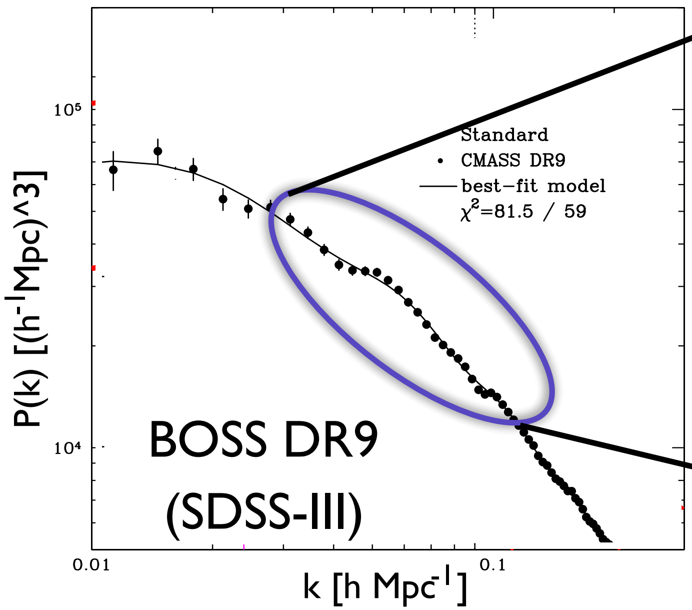
Baryon acoustic oscillations (BAO)

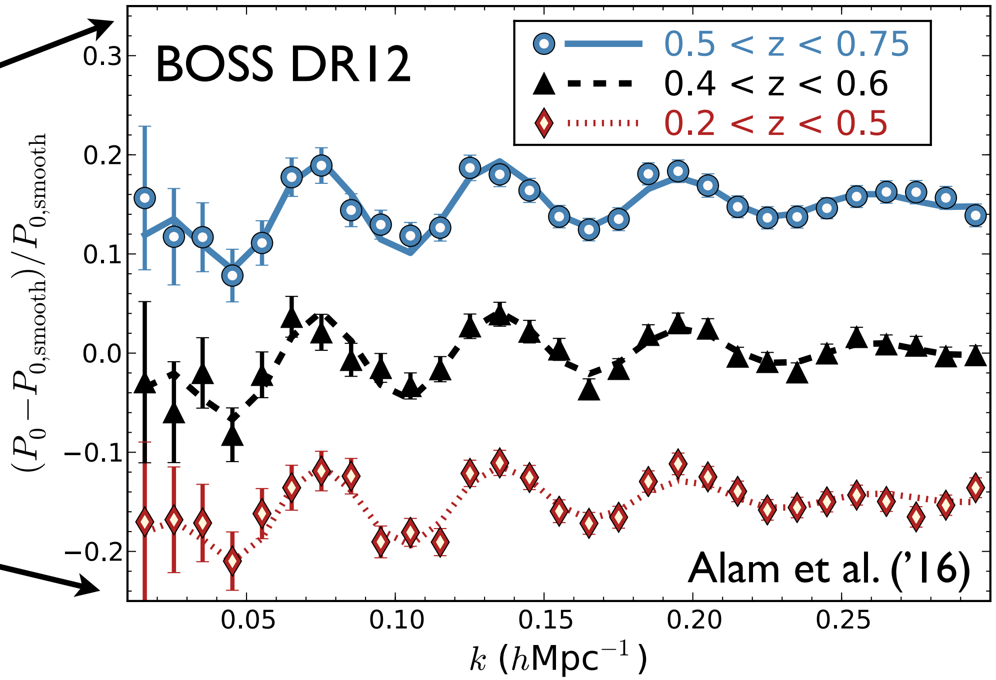
- Characteristic scale of primeval baryon-photon fluid (~150Mpc)
  (⇔ acoustic signal in CMB anisotropies)
- Can be used as standard ruler to measure distance at high-z
  (theoretical prior) →probe of cosmic expansion

power spectrum

$$P(k) = \frac{1}{N_k} \sum_{|\vec{k}|=k} |\delta(\vec{k})|^2$$

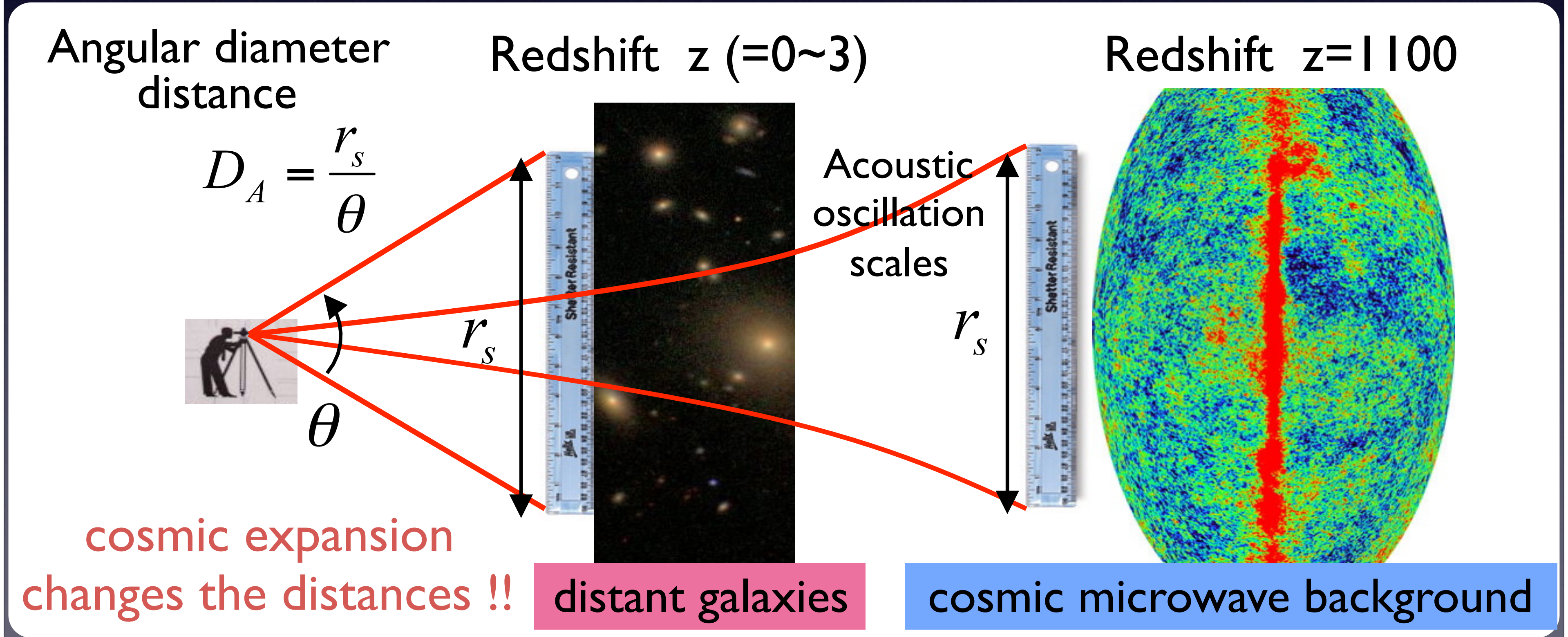
density fluc





Baryon acoustic oscillations (BAO)

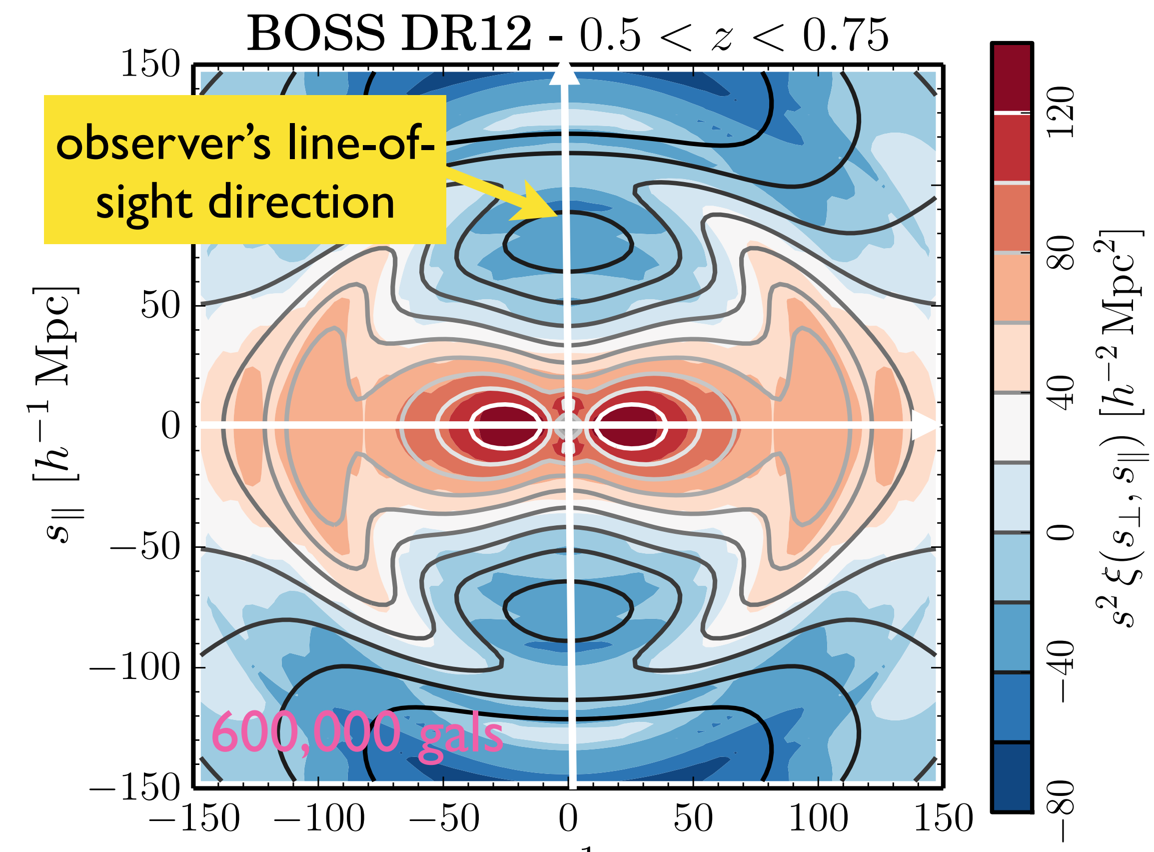
- Characteristic scale of primeval baryon-photon fluid (~150Mpc)
  (⇔ acoustic signal in CMB anisotropies)
- Can be used as <u>standard ruler</u> to measure cosmic expansion
  (theoretical prior)



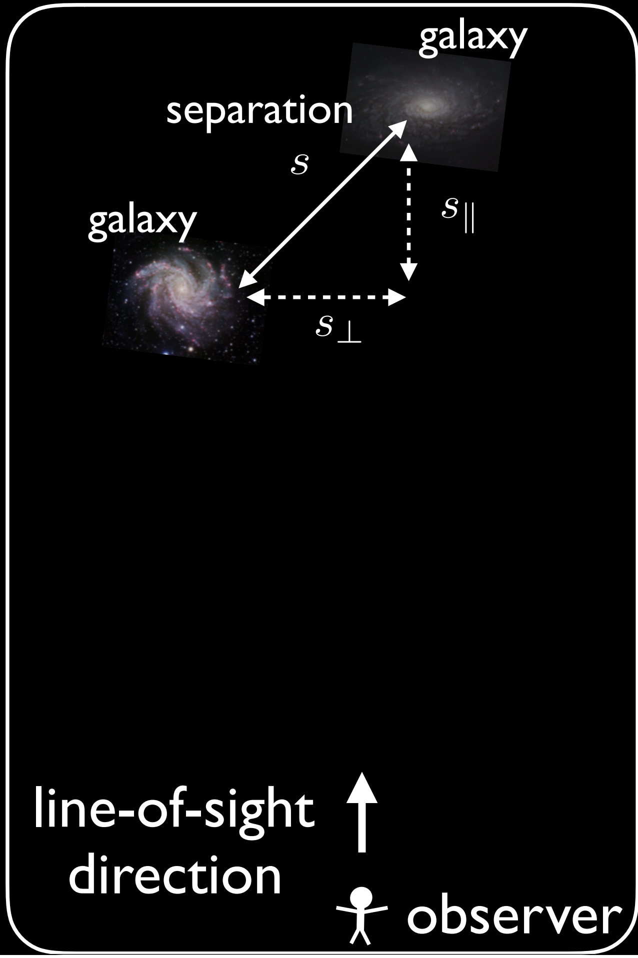
Redshift-space distortions (RSD)

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

→ exhibit anisotropies of galaxy clustering (also for power spectrum)



Alam et al. ('16)



Origin of anisotropies

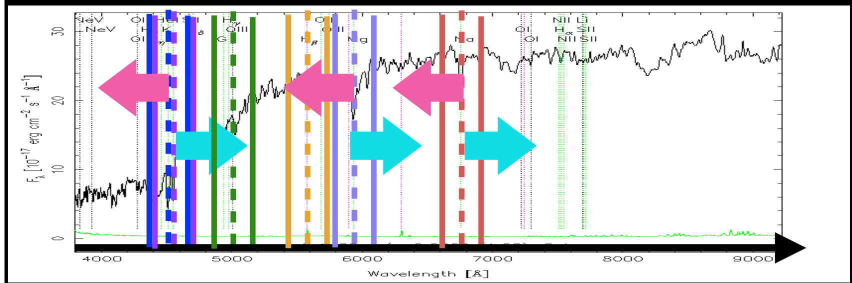
Redshift of galaxy is not a perfect distance indicator

→ distorted by peculiar motion of galaxies through Doppler effect (*along line-of-sight*)

On top of cosmological redshift,

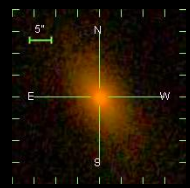
if galaxy moves toward (or away from) us

Spectrum of galaxy

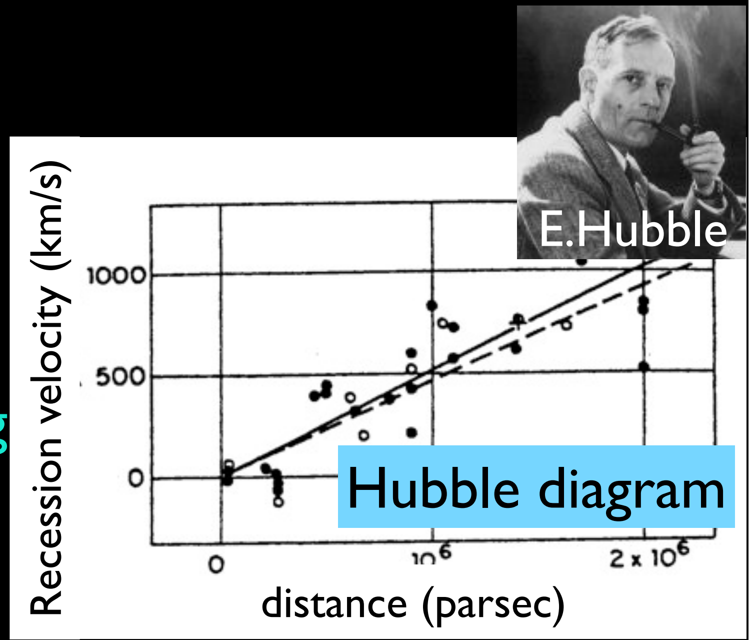


wavelength

Receding



Approaching



This is indeed manifest in the scatter of Hubble diagram, but it appears as systematic effect in ξ(s) & power spectrum

Redshift space

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

Redshift space (comoving)

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

Real space ($\vec{r}$)

observer's line-of-sight ($\hat{z}$)

Linear approx.

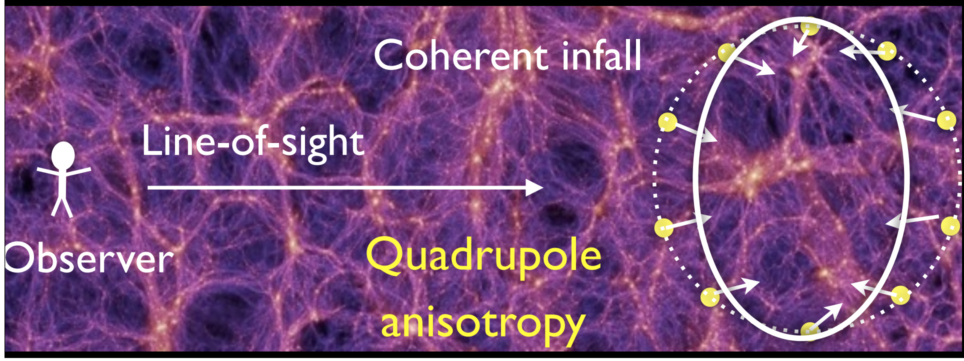
$$\delta^{(\mathrm{S})}(\boldsymbol{s}) = \left|\frac{\partial \boldsymbol{s}}{\partial \boldsymbol{r}}\right|^{-1}\{1+\delta(\boldsymbol{r})\} - 1 \;\simeq \delta(\boldsymbol{r}) - \frac{1}{a\,H}\partial_z v_z$$

Fourier transform

Eq. of continuity : $\dot{\delta} + \dfrac{1}{a}\nabla\cdot\boldsymbol{v} \simeq 0$

$$\delta^{(\mathrm{S})}(\boldsymbol{k}) = \left(1 + \mu_k^2\,\frac{d}{d\ln a}\right)\delta(\boldsymbol{k}) \quad ; \quad \mu_k \equiv \hat{\boldsymbol{k}}\cdot\hat{z}$$

$\frac{d}{d\ln a}$ >0



Apparent enhancement along line-of-sight

RSD as a probe of gravity

Kaiser formula (Kaiser '87)

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

D_+: Linear growth factor; a: 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

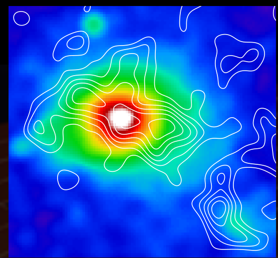
- Untested hypothesis in ΛCDM model
- Hint for cosmic acceleration

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

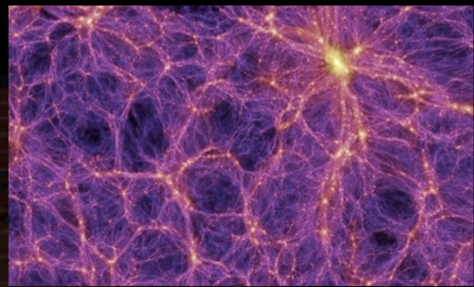
Gravity on cosmological scales

galaxy

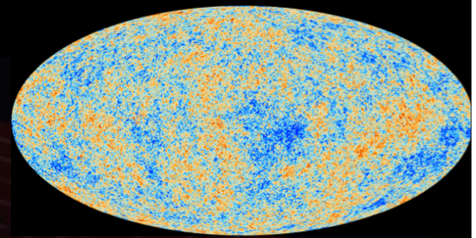
cluster



galaxy clustering



CMB



High density

Small scale (~kpc) ← structure formation modified → Large scale (~Gpc)

recover GR
(by screening mechanism)

5th force mediated by new scalar d.o.f
➡ cosmic acceleration

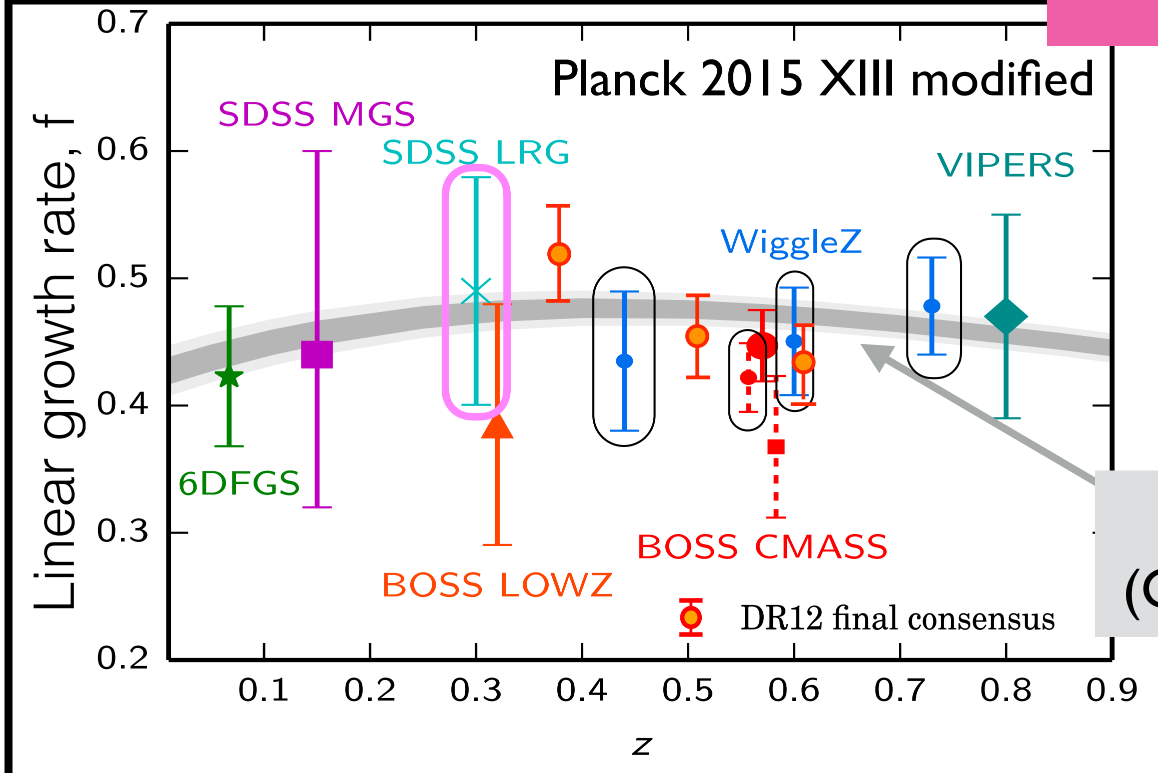
Framework to describe modified gravity is well (too) developed :
f(R) gravity, DGP, (beyond-)Horndeski, EFT approach,…

Consistency test of GR

In practice

Testing gravity needs a nonlinear RSD model assuming underlying theory of gravity

A blind fit of growth rate based on GR-based template



Based on perturbation theory template

Oka, Saito, Nishimichi, AT & Yamamoto ('14)

Planck ΛCDM (General relativity)

No strong evidence of deviation from GR

(See also Beutler, Seo, Saito et al. '16 for latest BOSS DR12)

Beyond consistency test of gravity

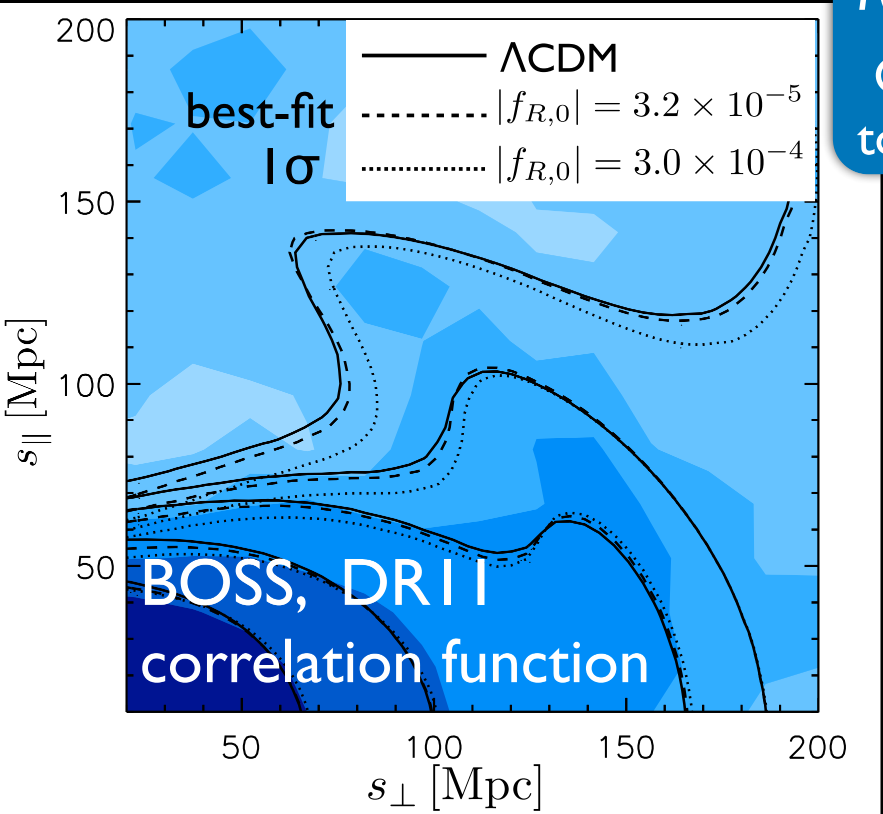
Y-S.Song, AT, Linder, Koyama et al. ('15)

Taking a proper account of nonlinear modification of gravity、

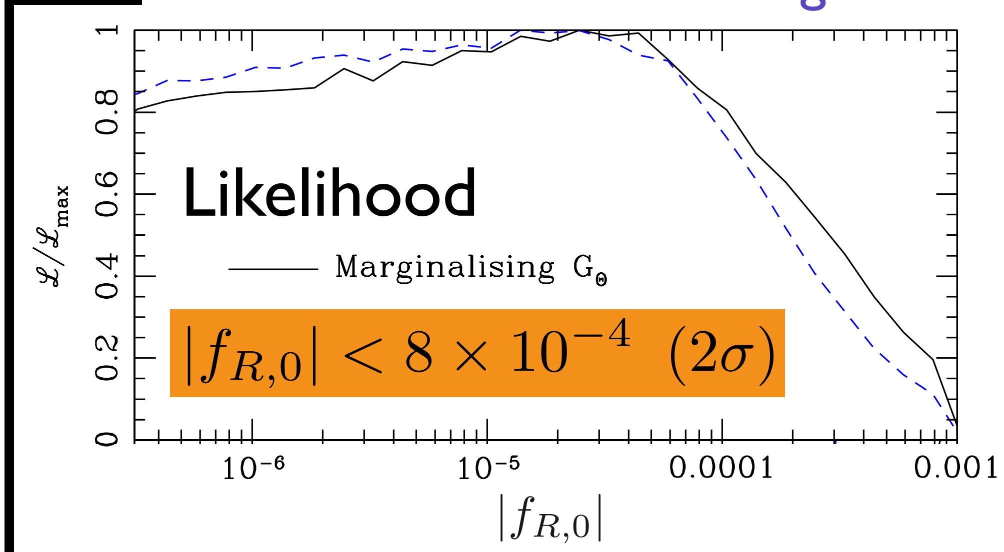
test of gravity has been made for a specific gravity model

f(R) gravity (Starobinsky '07; Hu & Sawicki '07)

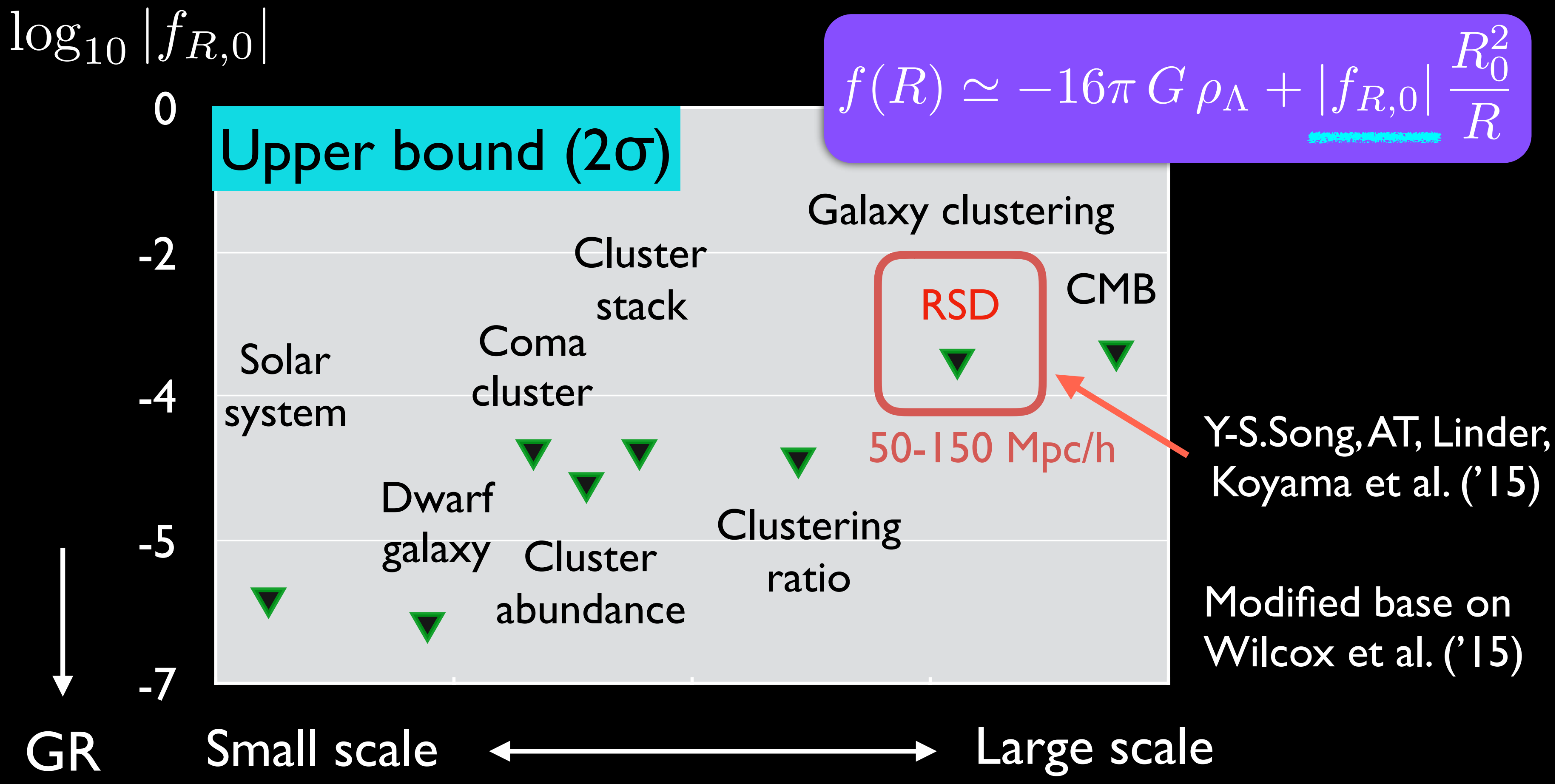
Correction to EH action $f(R) \simeq -16\pi\, G\, \rho_\Lambda + |f_{R,0}|\, \frac{R_0^2}{R}$



Geometric distortions marginalized



Comparison with other obs.



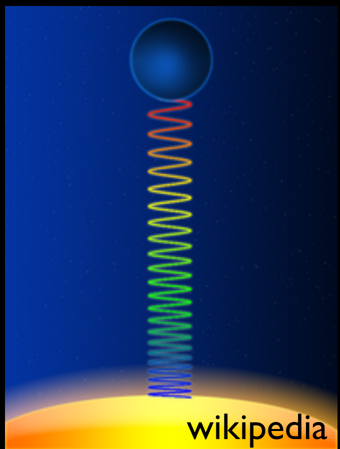
Next-generation galaxy surveys will further improve the constraint at large scales (>50Mpc). Stay tuned !

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 *standard* redshift-space distortions,



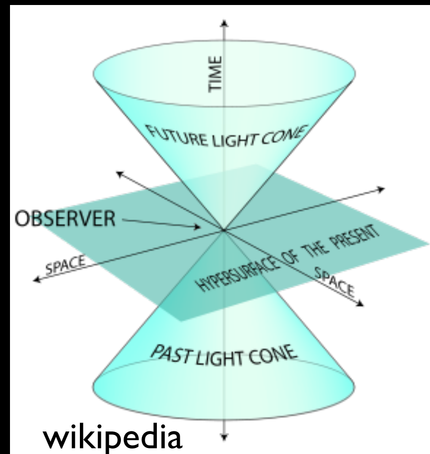
Transverse Doppler effect

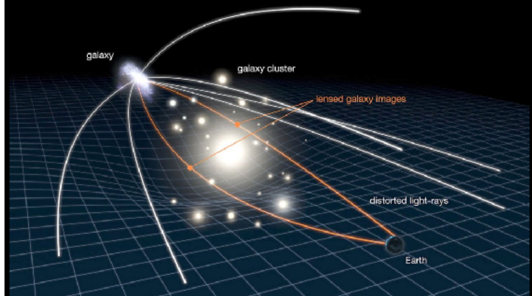
Gravitational redshift

(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)

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

Relativistic distortions

Do we really understand what we measure ?

Consider the photon path in the perturbed Friedmann universe:

$$ds^2 = \left[-(1+2\Psi/c^2)(c\,dt)^2 + a^2(t)(1-2\Phi/c^2)\delta_{ij}dx^i dx^j\right]$$

Distortion of photon path by gravitational lensing

Sky position

$$\vec{\theta}_{\rm O} = \vec{\theta}_{\rm S} + \vec{\alpha}\ ;$$

deflection angle

$$\vec{\alpha} = -\frac{1}{c^2}\int_0^{\chi_{\rm S}} d\chi' \frac{\chi_{\rm S}-\chi'}{\chi_{\rm S}} \nabla_\perp(\Psi+\Phi)$$

Energy shift of photon by special & general relativistic effects

Redshift

$$z_{\rm O} = \frac{a_{\rm O}}{a_{\rm S}}\left[1 + \frac{\boldsymbol{v}_{\rm S}\cdot\boldsymbol{n}}{c} - \frac{\Psi_{\rm S}-\Psi_{\rm O}}{c^2} + \frac{v_{\rm S}^2}{c^2} + \frac{1}{c^2}\int_{t_{\rm O}}^{t_{\rm S}} dt'(\dot{\Phi}+\dot{\Psi}) + \cdots\right] - 1$$

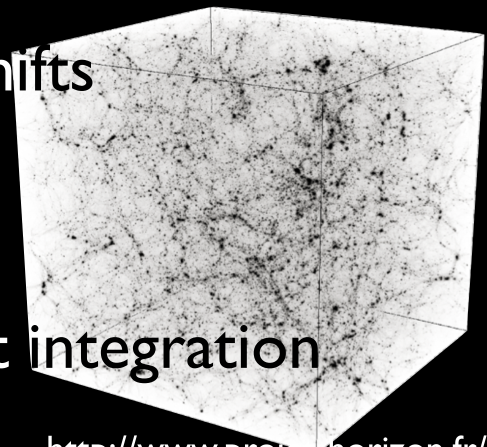
standard RSD (Doppler) | gravitational redshift | transverse Doppler | integrated Sachs-Wolfe

Simulating relativistic distortions

With Michel-Andrès Breton
& Yann Rasera

Using standard N-body code (RAMSES)

➡ Dark matter/halo distributions at many redshifts



http://www.projet-horizon.fr/

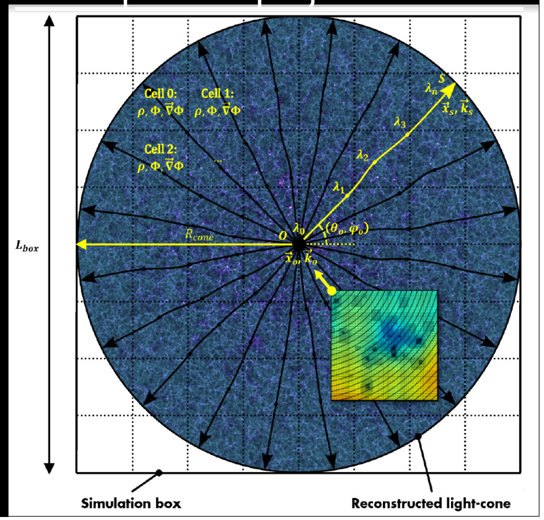
- Storing potential data on light cone
- Tracing back the light ray to the source by direct integration of geodesic equation (assuming $\Phi = \Psi$)

⟶ distorted angular position & redshift:

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

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

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



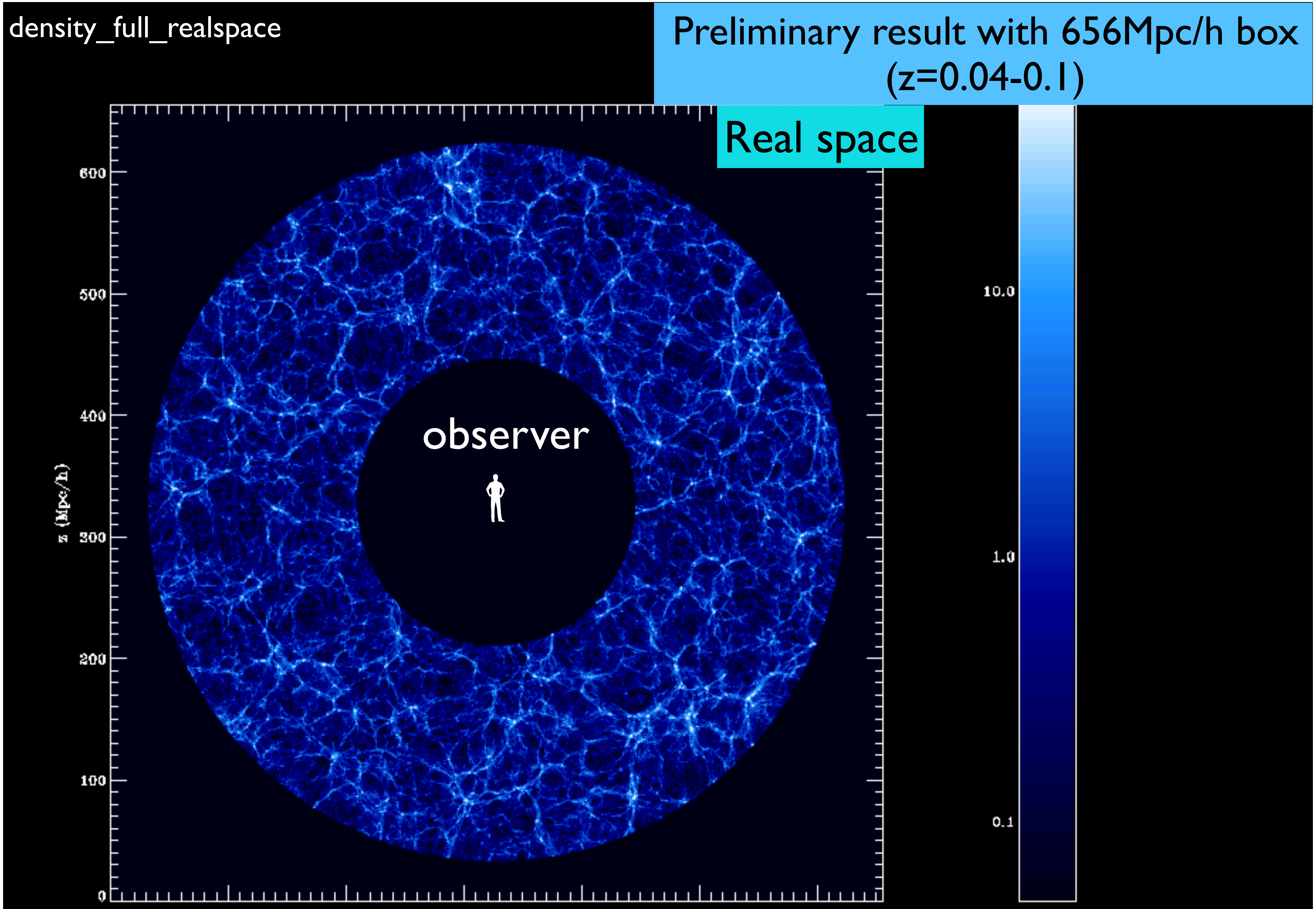


Fig. courtesy: Yann Rasera, based on the data by Michel-Andres Breton density_full_redshiftspacealleffects

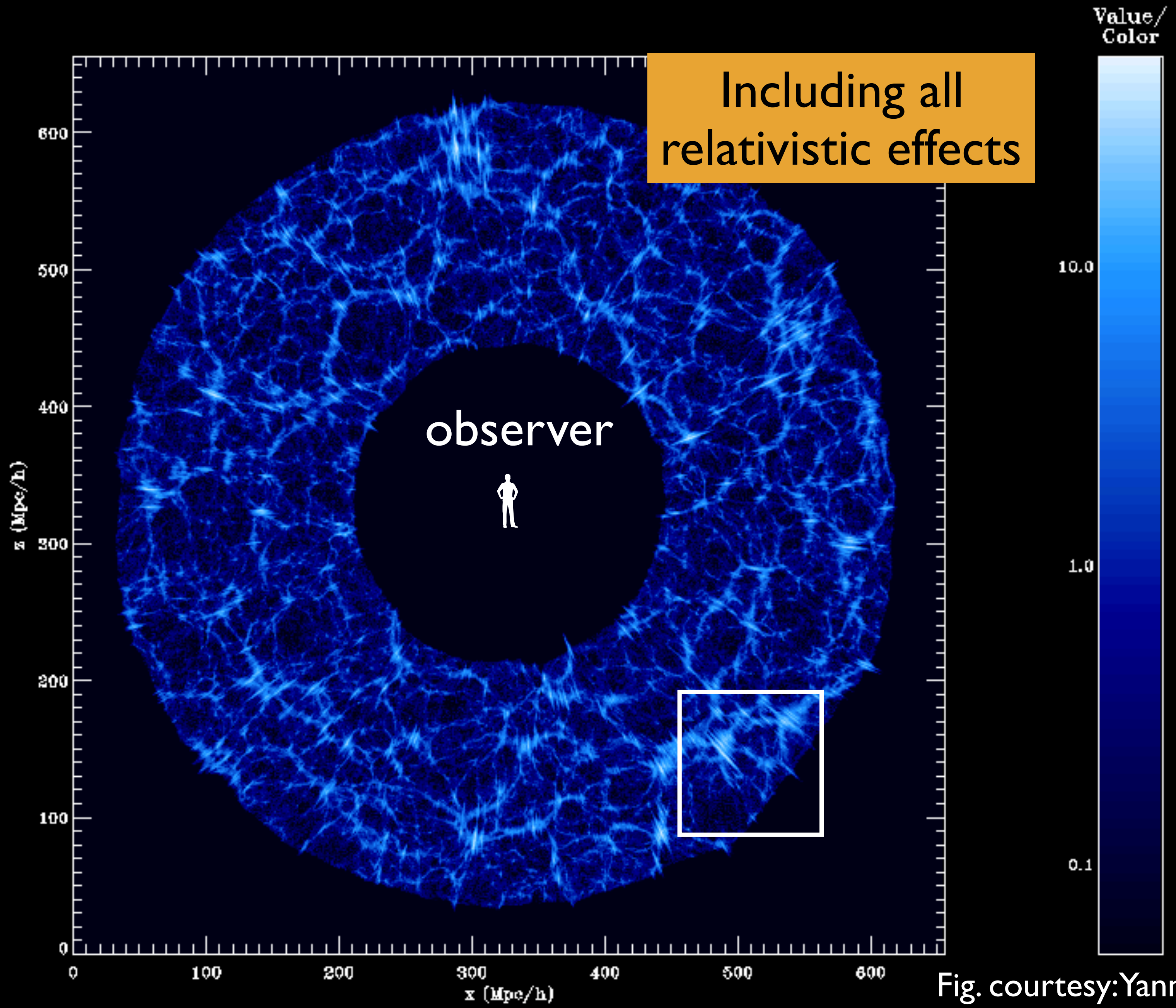
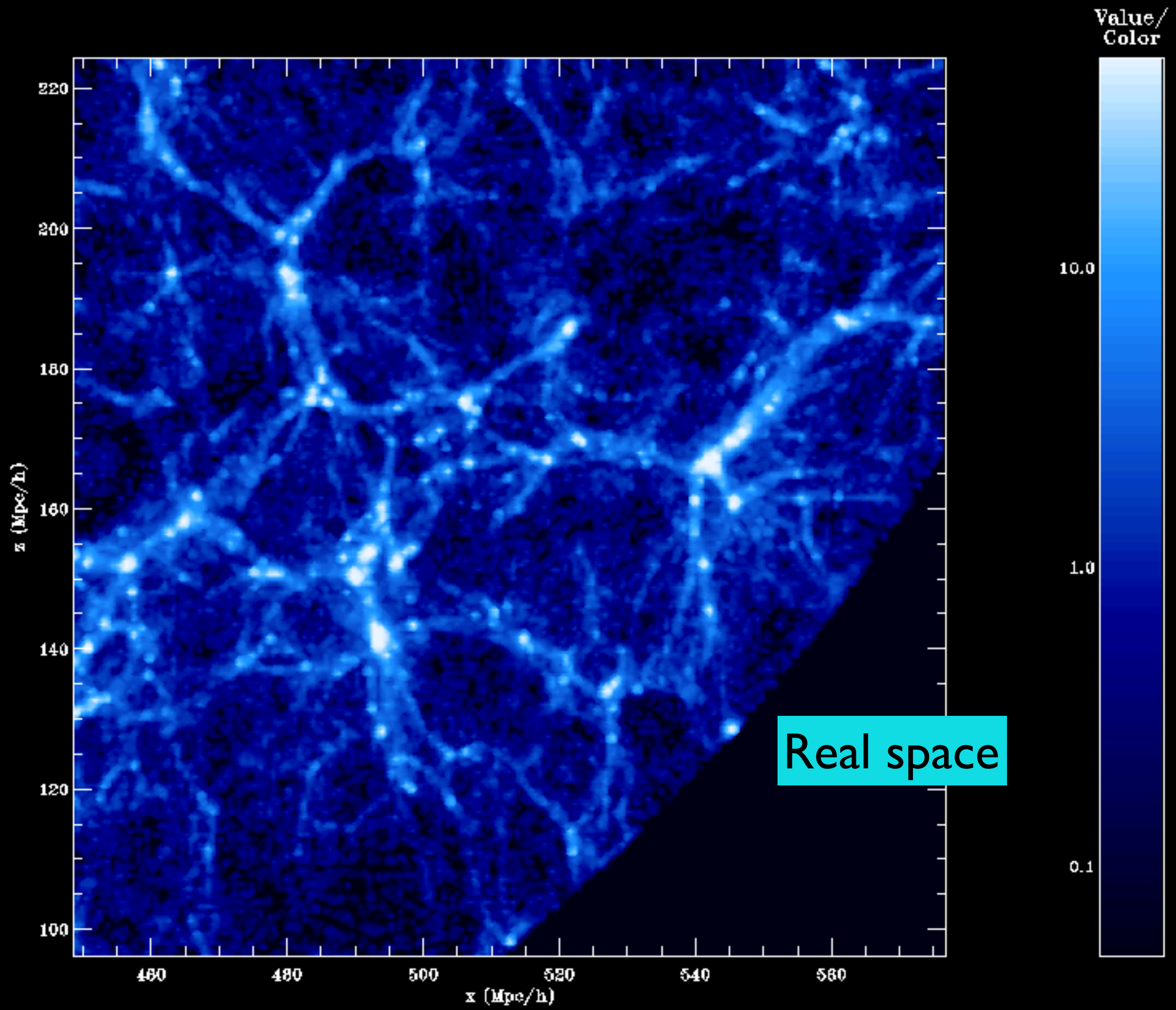
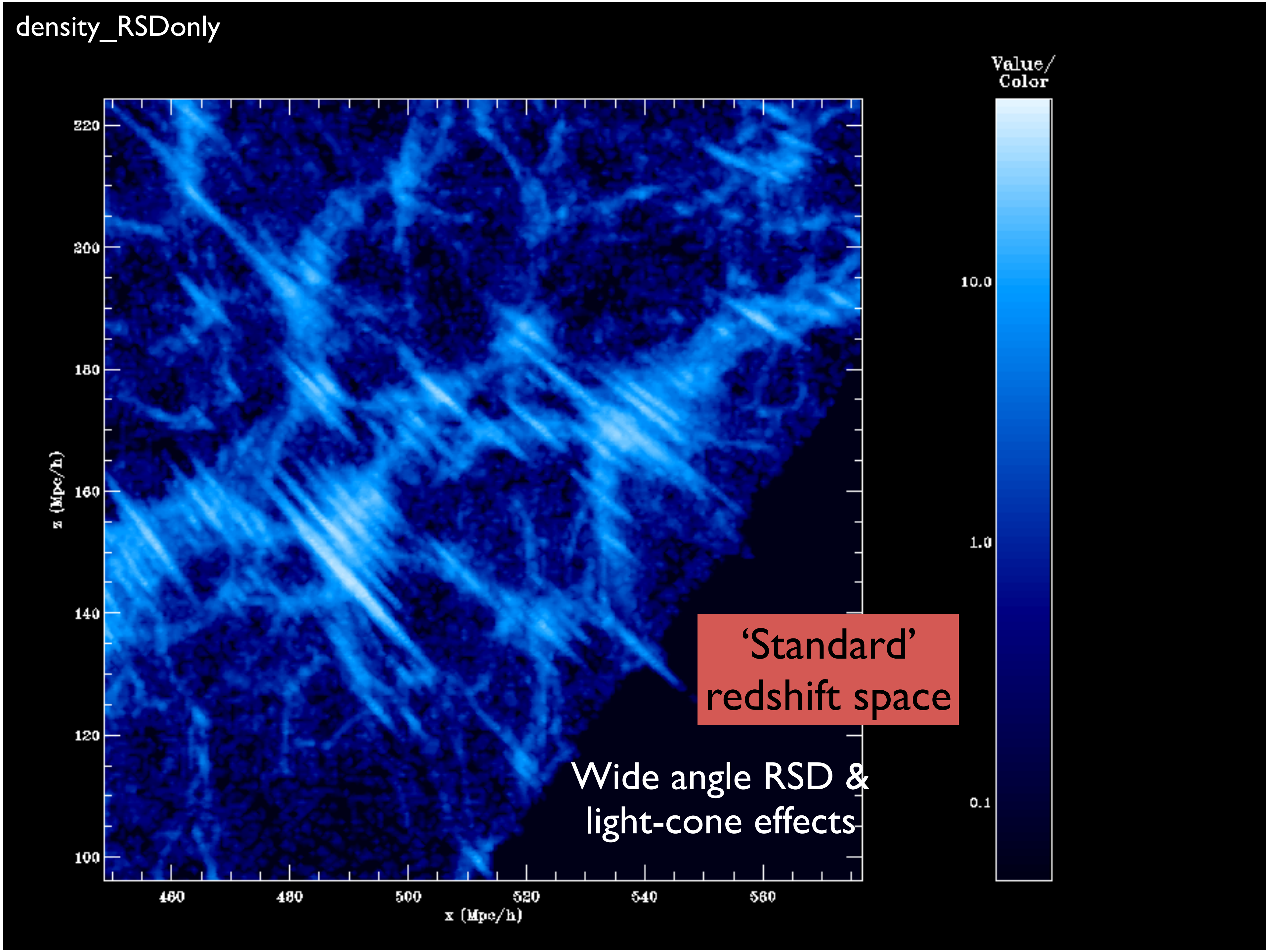
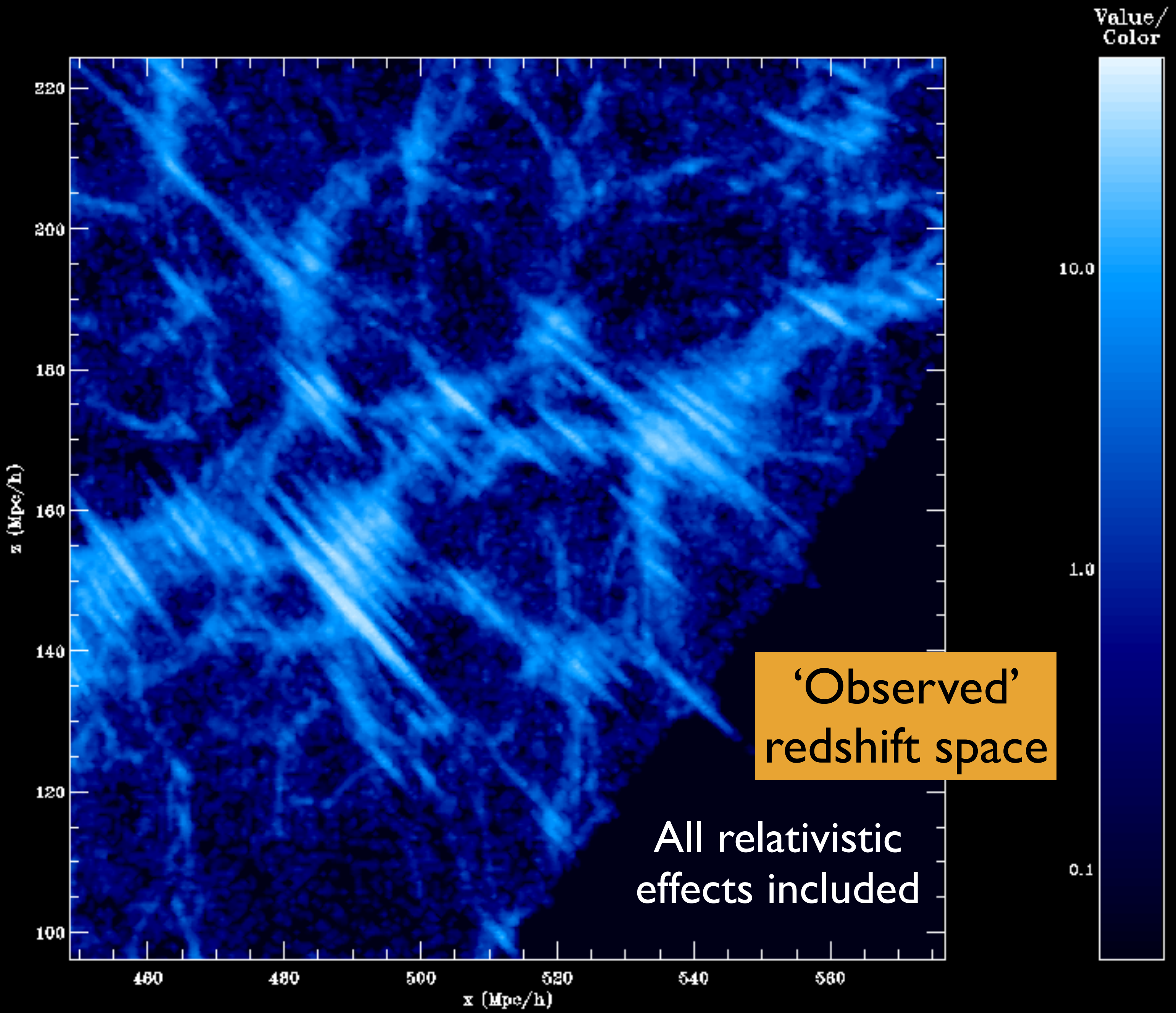


Fig. courtesy: Yann Rasera, based on the data by Michel-Andres Breton density_zoom2_realspace

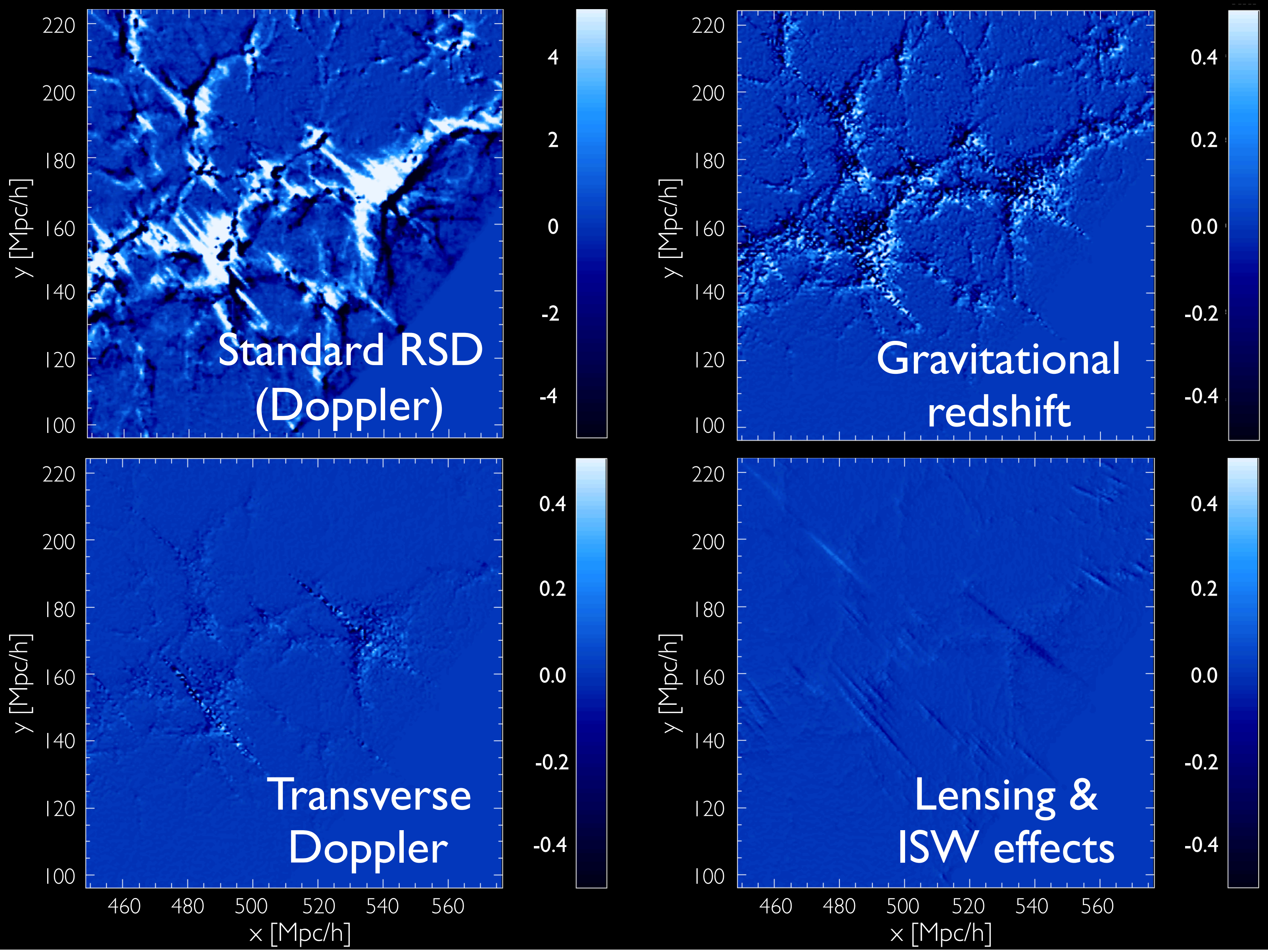



density_RSDonly
Value/
Color
10.0
1.0
0.1
220
200
180
160
140
120
100
z (Mpc/h)
460
480
500
520
540
560
x (Mpc/h)
'Standard'
redshift space
Wide angle RSD &
light-cone effects

density_allrelativisticeffects



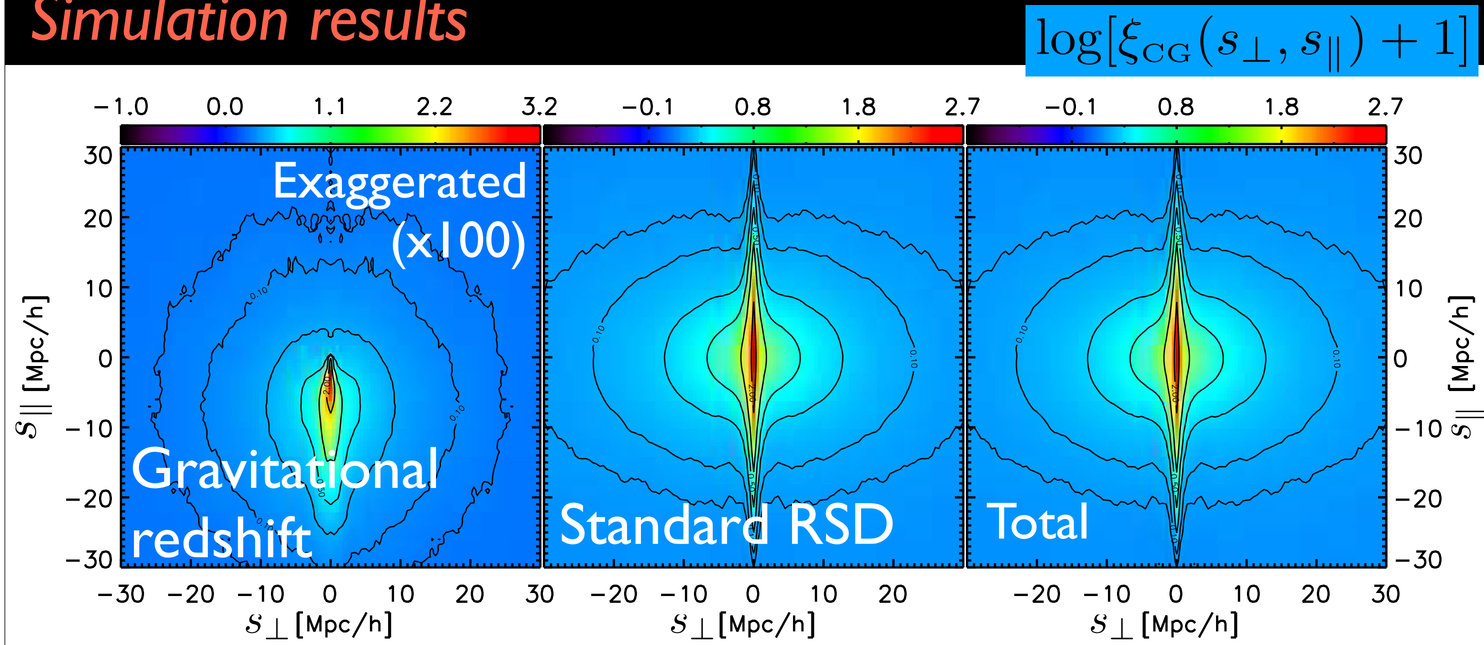
Relative contributions

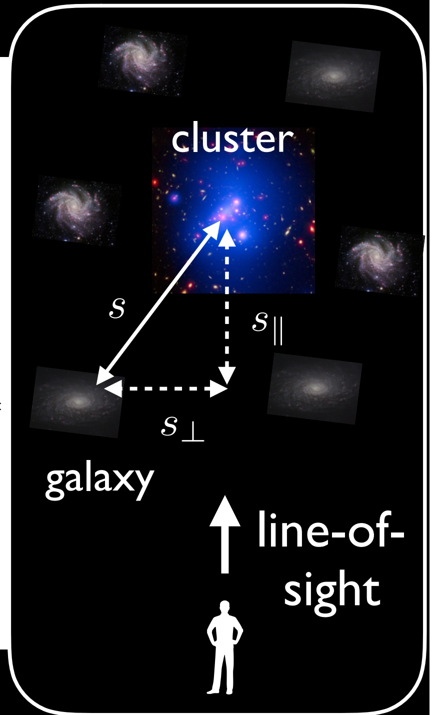


Signature of new relativistic effect

Relativistic contributions induces *dipole anisotropies* in cluster-galaxy *cross-correlation* function

Simulation results





Cai, Kaiser, Cole & Frenk ('17)

Dipole correlation may be used for

New test of gravity

(Still open issue on what is the best statistics)

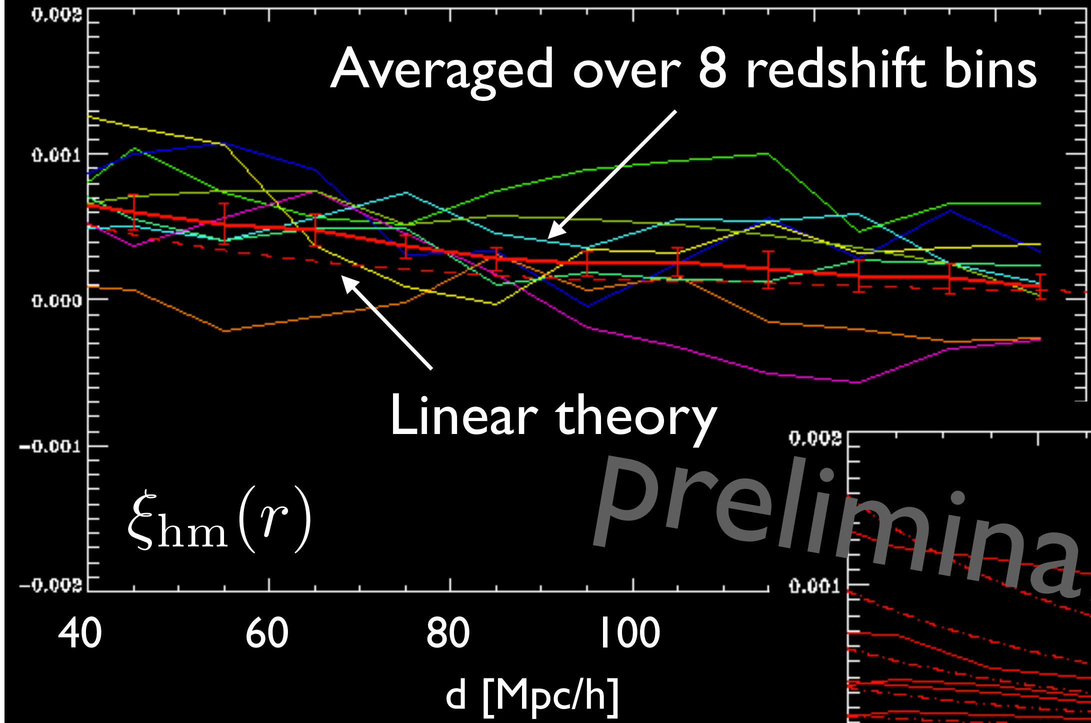
Measurement of dipole

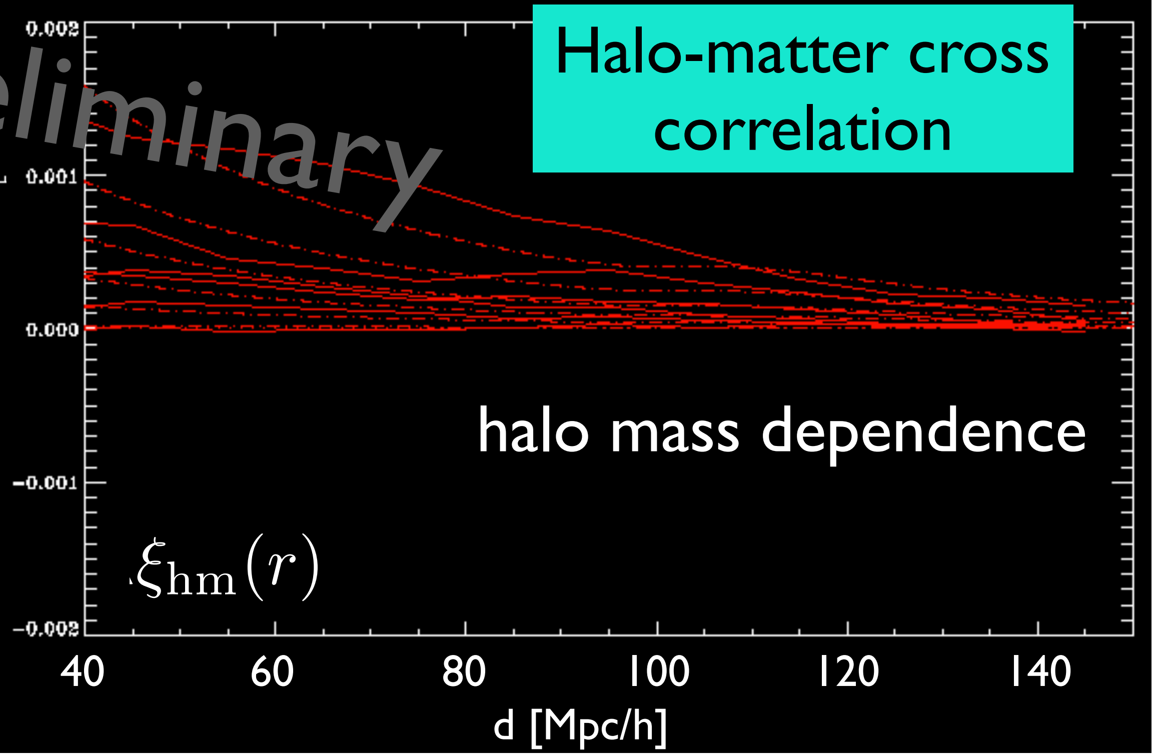
With new large catalog of

4096^3 particles, 2.5Gpc/h box

RayGalGroupSims

(will be public soon)





Red solid: measurement

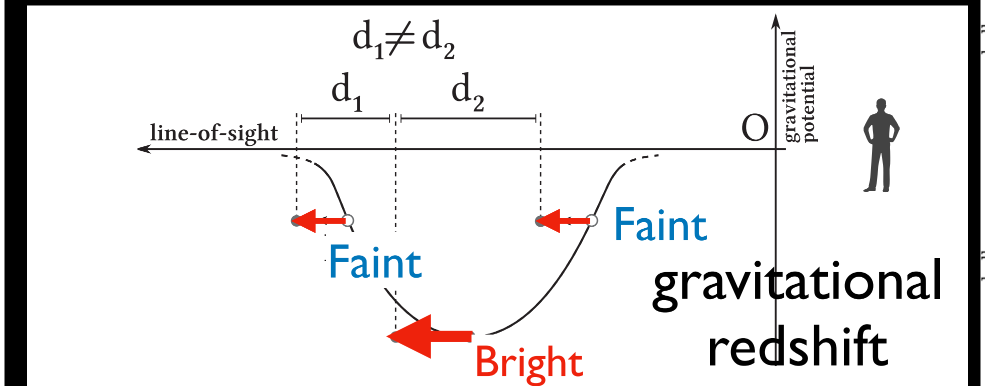
Red dashed: linear theory

(using measured linear bias parameter)

Gravitational redshift detected ?

Shell estimator Croft ('13)

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

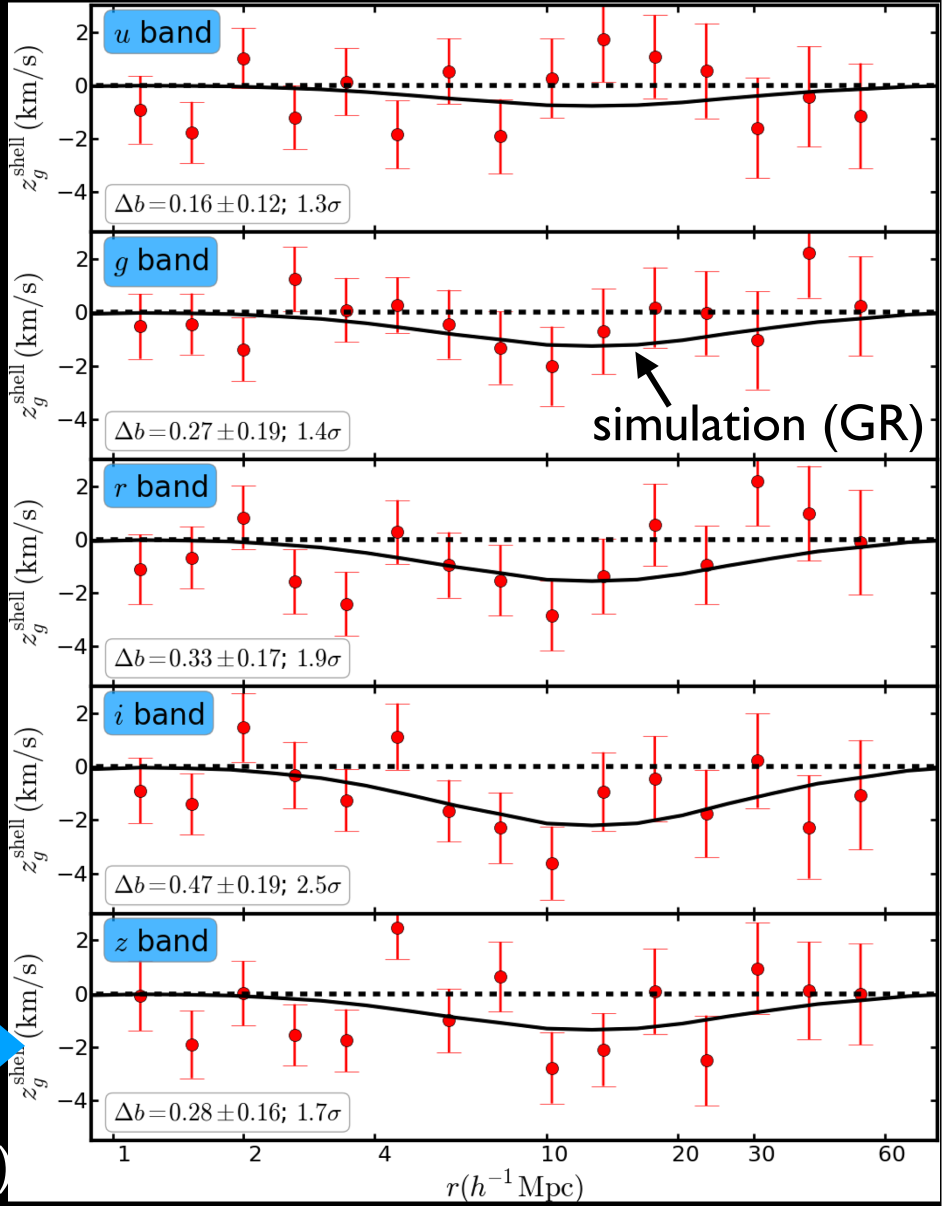


SDSS-III BOSS CMASS samples
765,000 gals @ 0.4<z<0.7

⟶ 2 color bins (brighter & fainter)

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 large-scale structure observations will be able to not only demonstrate a precision test of gravity, but also open a new window

Redshift-space distortions caused by Doppler effect of galaxies can be used to probe growth of structure :

- consistency test of general relativity
- constraint on modified gravity models

Relativistic distortions as yet another effect caused by relativistic contributions will be detected and used for new test of gravity

- Simulating relativistic distortions of large-scale structure
- Asymmetric cross-correlation function

More fun for precision cosmology !