2017年6月27日

教室談話会@名古屋大学

宇宙の大規模構造の理論的記述：
標準宇宙モデルを超えて

Describing *observed* large-scale structure beyond standard cosmological model

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(Kyoto Univ. Yukawa Institute for Theoretical Physics)

Plan of talk

Describing *observed* large-scale structure in precision cosmology

Large-scale structure

Redshift-space distortions (RSD)

Modeling and analyzing RSD

Beyond RSD

Large-scale structure

Matter inhomogeneity over Giga parsec scales

= 1000 Mpc =3*10^9 light years

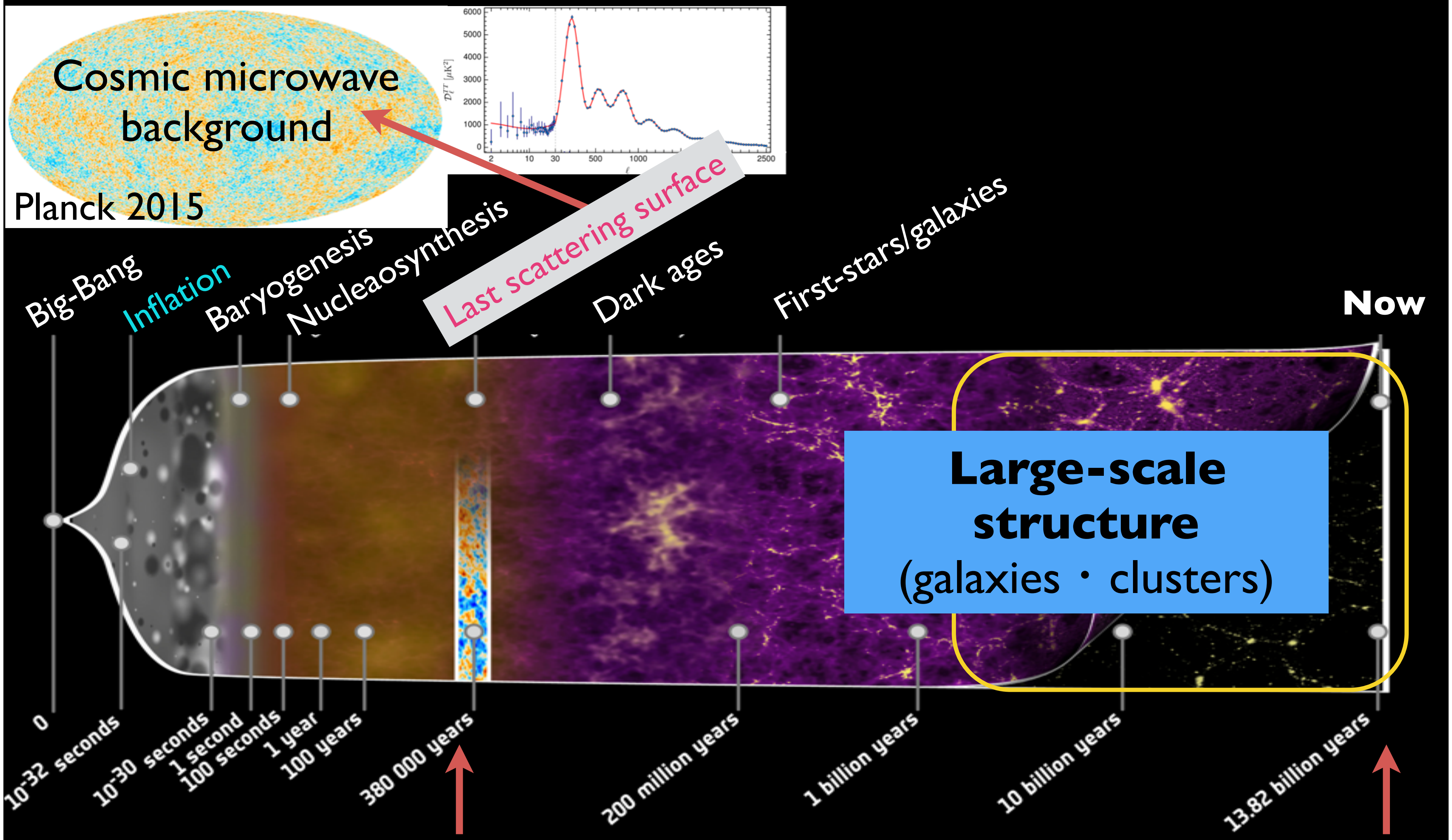
is dominated by hypothetical invisible objects (i.e., *cold dark matter*)

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



Cosmic microwave background

Planck 2015

Last scattering surface

Large-scale structure
(galaxies・clusters)

380,000 yrs

13.8G yrs

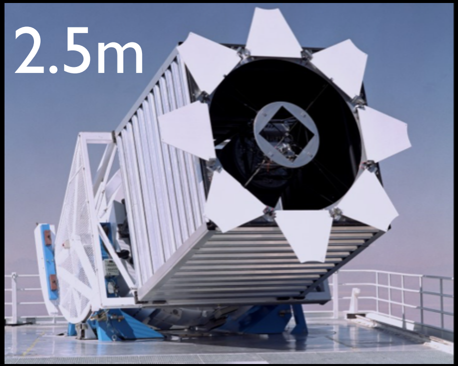
Observing large-scale structure

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

Great Debate (1920)

H. Shapley & H. Curtis

Nature of spiral nebulae (i.e., galaxies), and size of the universe

Shapley Milkyway galaxy is entirety of the known universe (e.g., Andromeda is part of our galaxy)

Curtis Andromeda and other such "nebulae" are separate galaxies, or "island universes"

M31 (Andromeda)

wikipedia

Crucial to measure

distance (indicator)

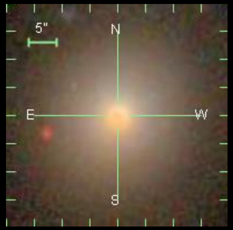
(but non-trivial issue in cosmology)

Redshift

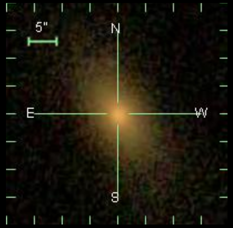
A key to probe 3D view of large-scale structure

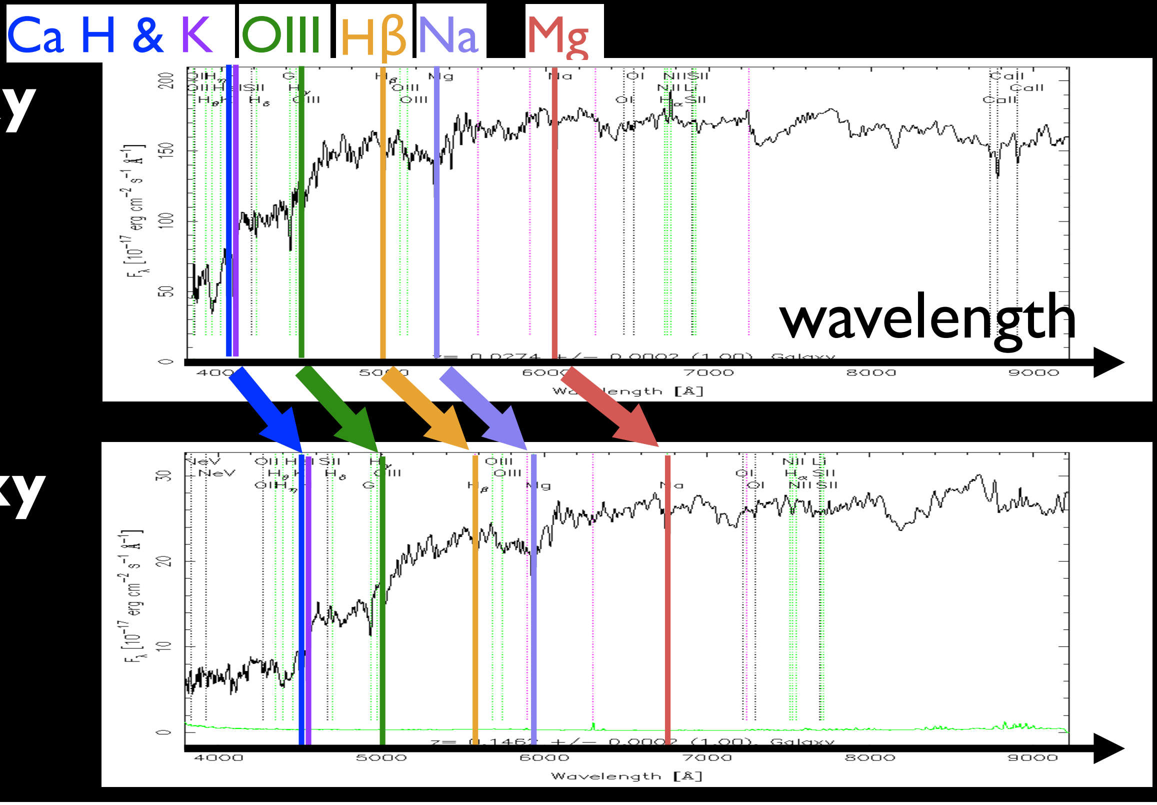
Distant galaxies looks *redder* than nearby galaxies
due to cosmic expansion

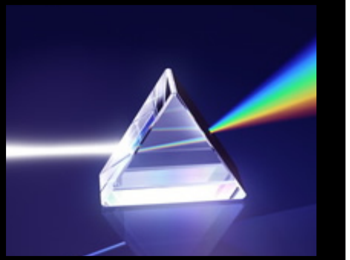
Nearby galaxy



Distant galaxy







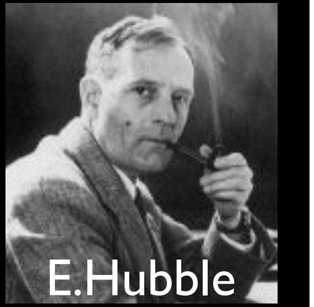
SDSS SkyServer

Redshift

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

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

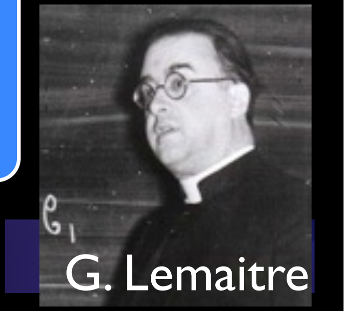
Redshift parameter $z = \Delta\lambda/\lambda$


E.Hubble

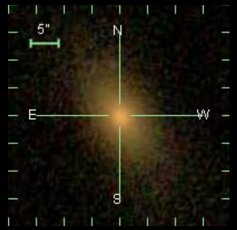
Hubble law

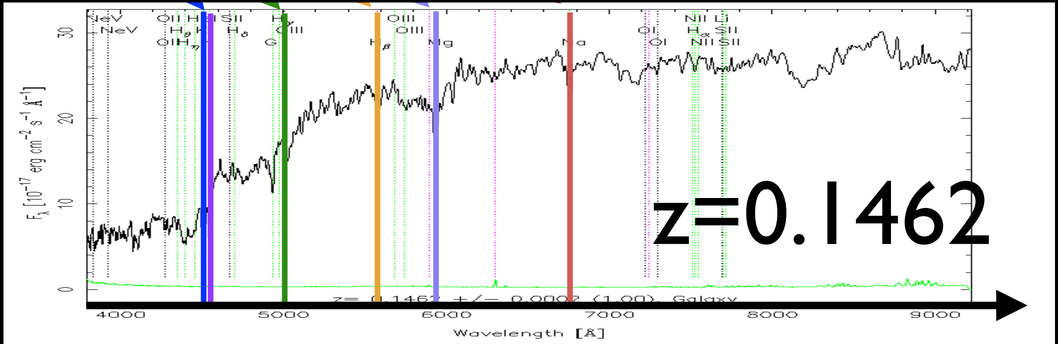
recession 'velocity' $v = \underline{\underline{H}}\, d$ distance to galaxy

(= *light velocity x redshift*) Hubble parameter


G. Lemaitre

Distant galaxy



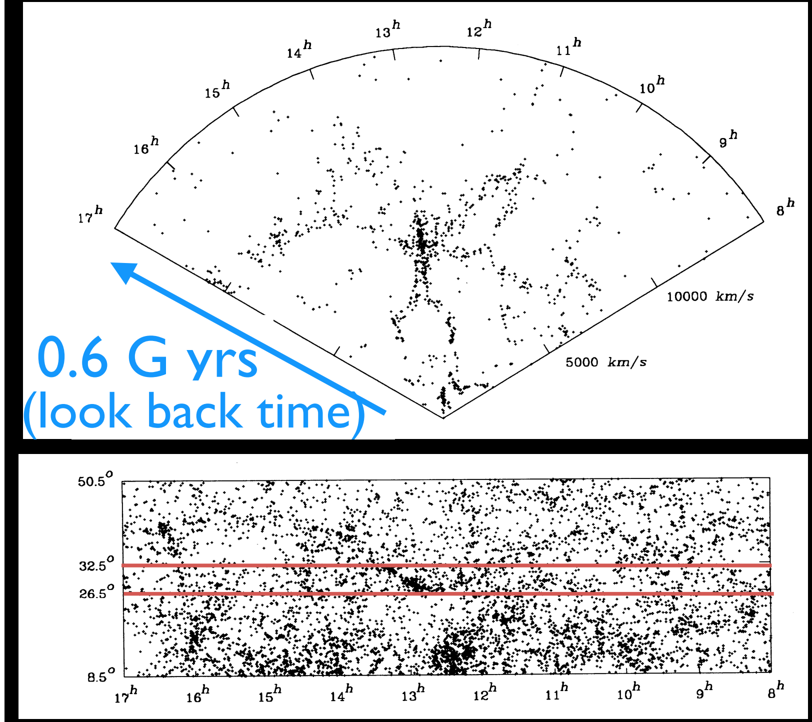


z=0.1462

SDSS SkyServer

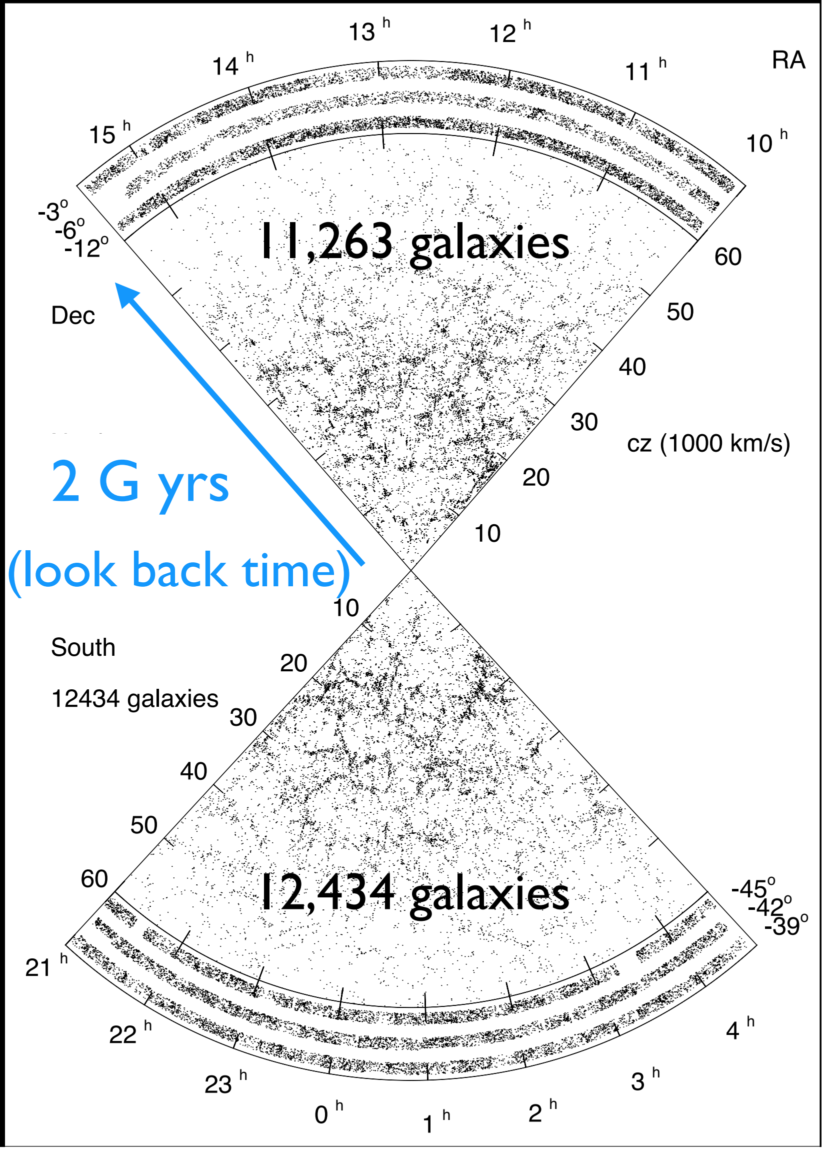
Dawn of systematic surveys

CfA galaxy redshift survey



0.6 G yrs
(look back time)

de Lapparant, Geller & Huchra ('86)



11,263 galaxies

2 G yrs

(look back time)

12,434 galaxies

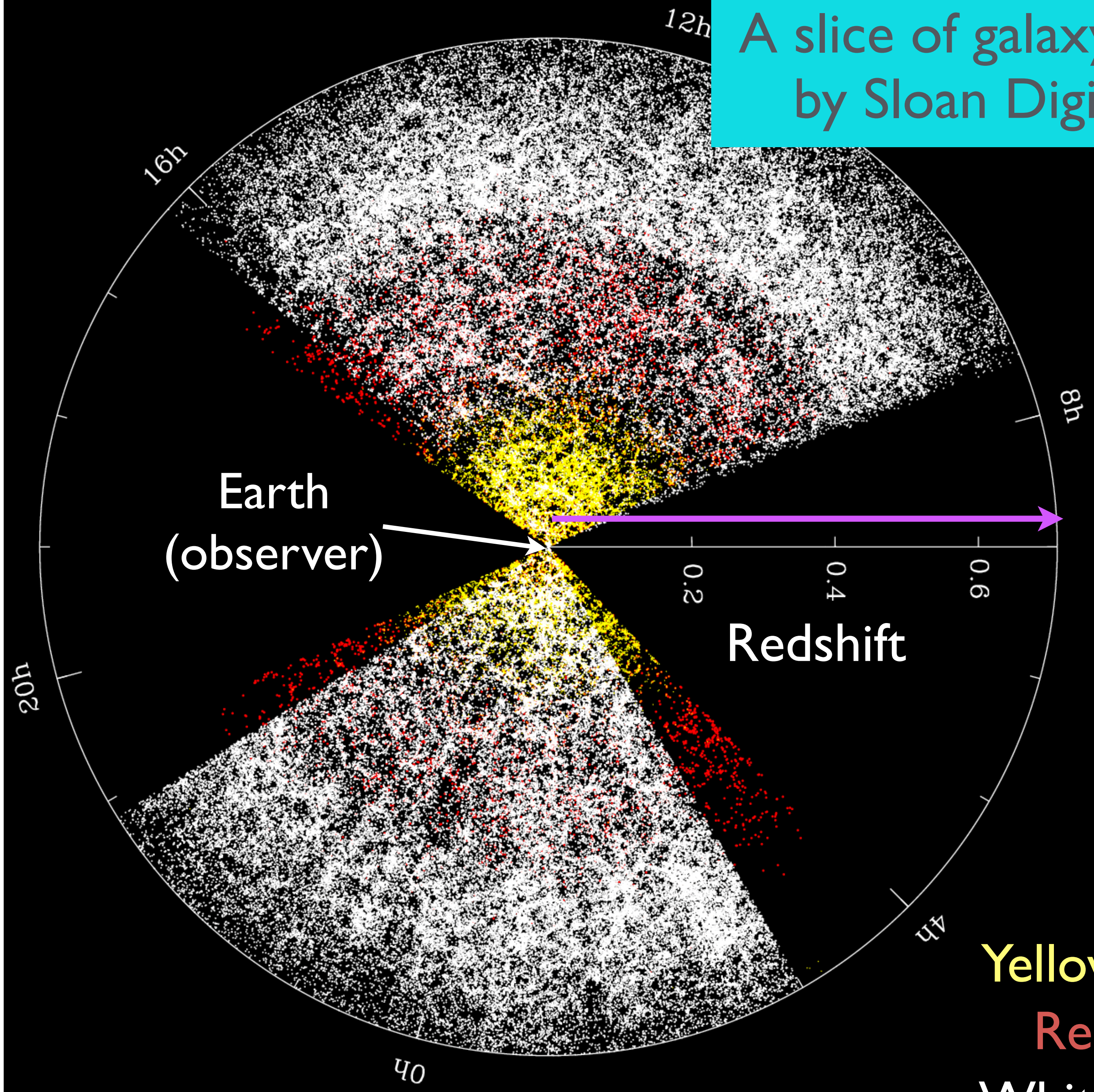
Las Campanas redshift survey

Shectmann et al. ('96)

A slice of galaxy & quasar 3D map by Sloan Digital Sky Survey III

As of 2011

(finished in 2014)



Earth (observer)

Redshift

6 G yrs

(look back time)

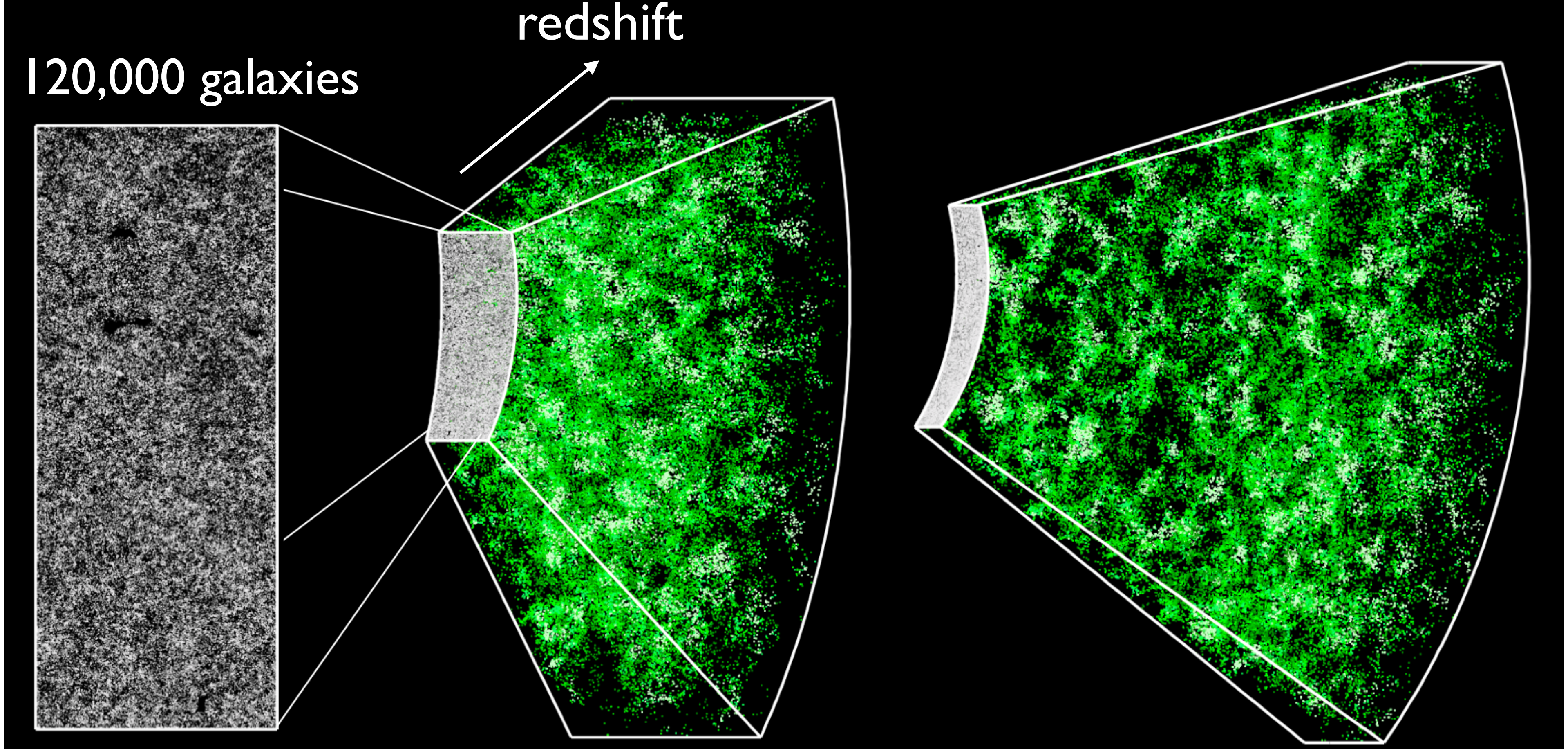
Yellow：SDSS-II main

Red：SDSS-II LRG

White：SDSS-III CMASS

http://www.mpa-garching.mpg.de/131601/hl201506

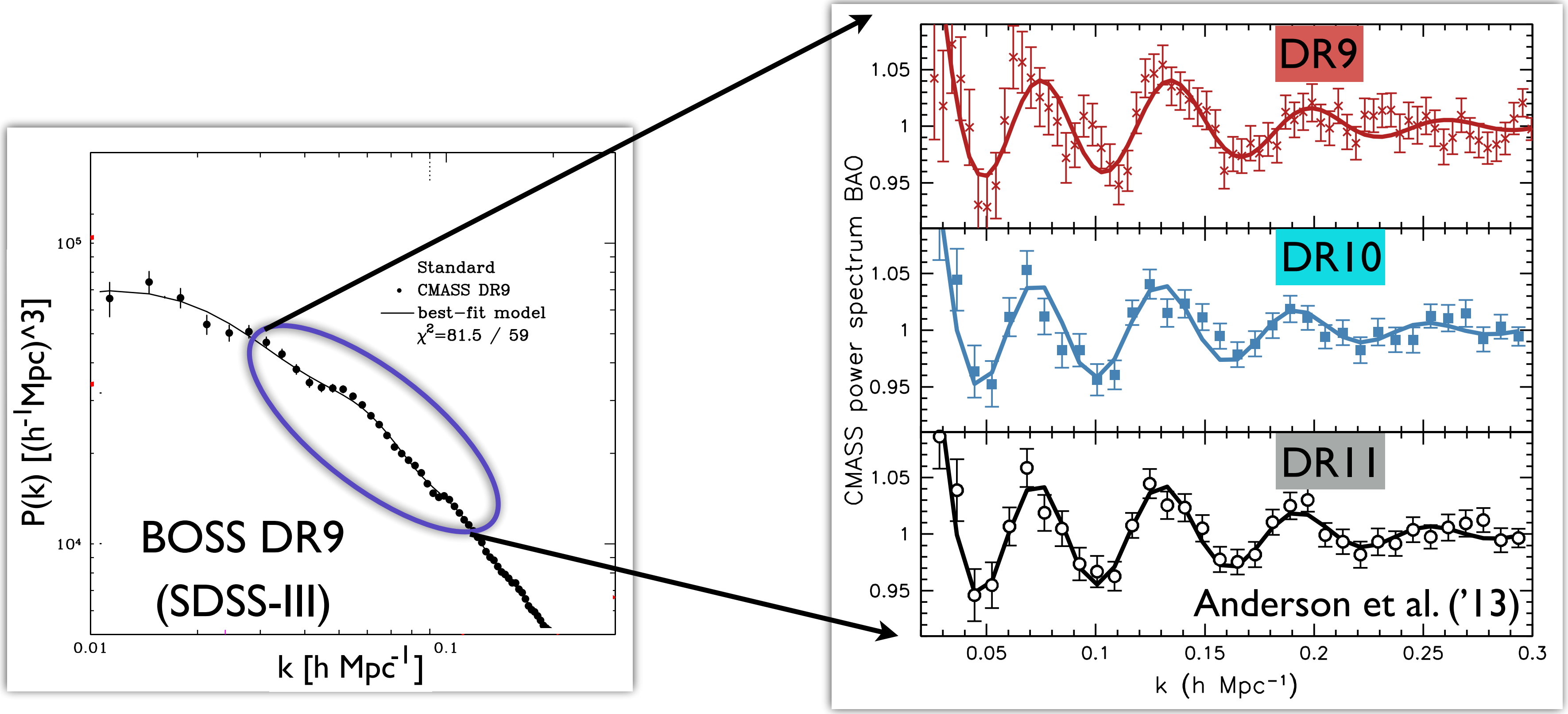
A section of 3D map



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

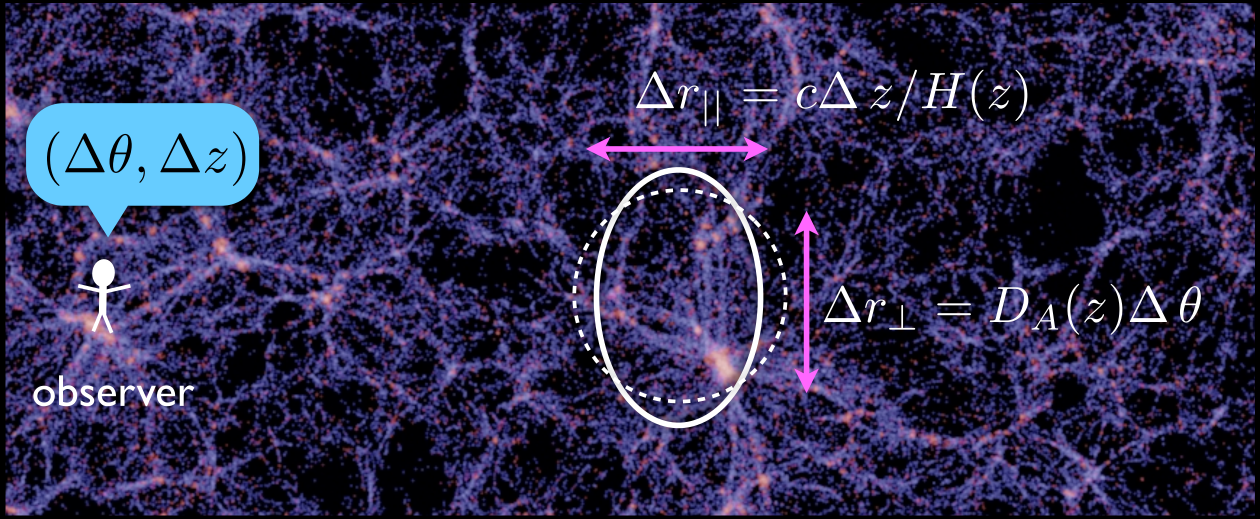


Anderson et al. ('13)

Geometric distortions

Unlocking potential power of BAO

Distortions of galaxy clustering caused by apparent mismatch of underlying cosmological models



⟶ can generate anisotropies in the galaxy clustering (higher multipole moments)

Using BAO as standard ruler,

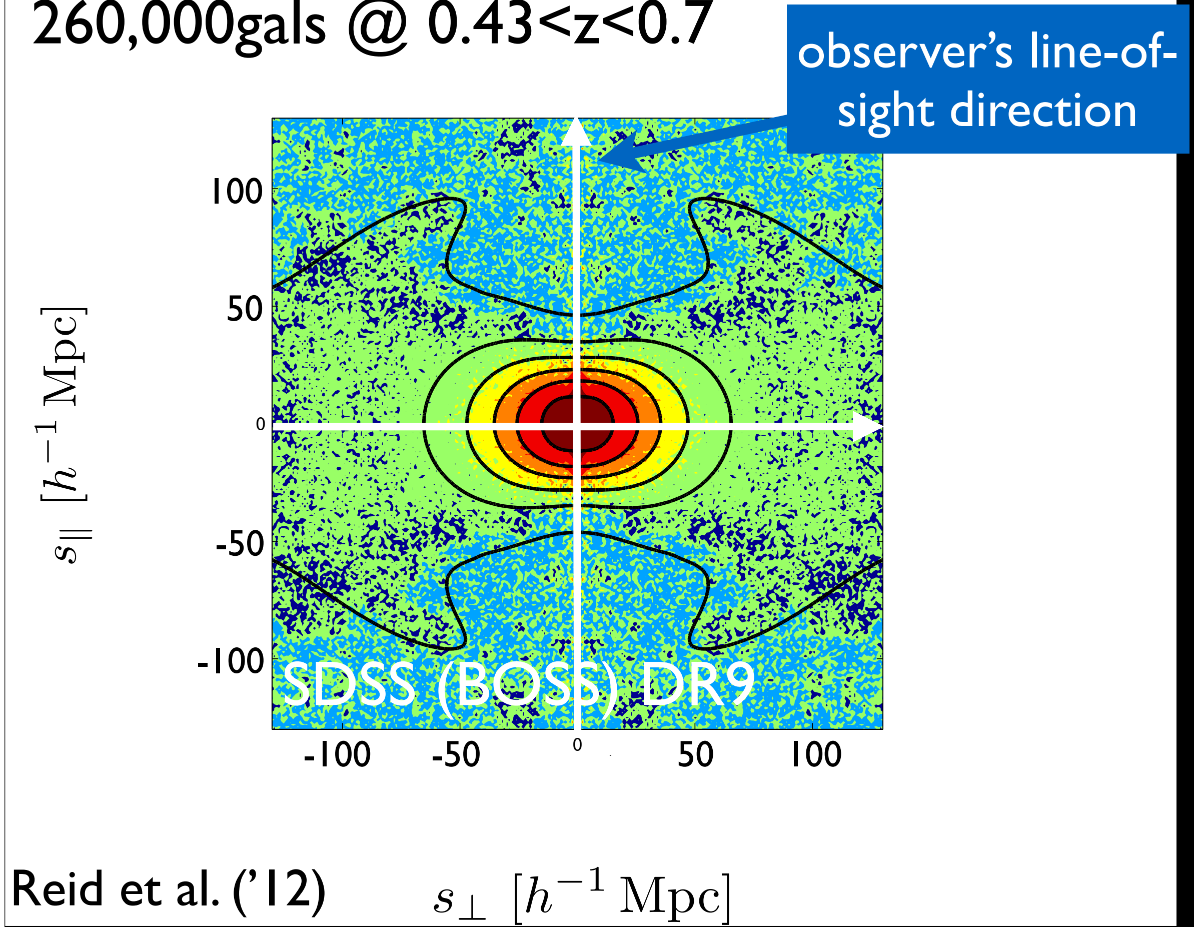
H(z) & DA(z) can be measured simultaneously

Redshift-space distortions (RSD)

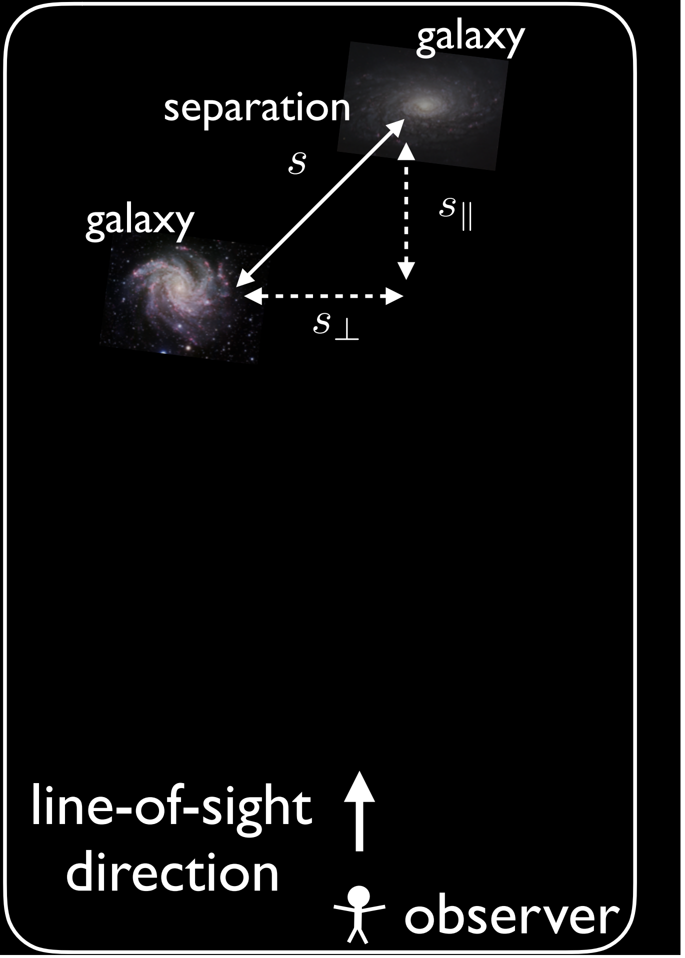
(Two-point) correlation function = counting many galaxy pairs

→ exhibit anisotropies of galaxy clustering

260,000gals @ 0.43<z<0.7



Reid et al. ('12)



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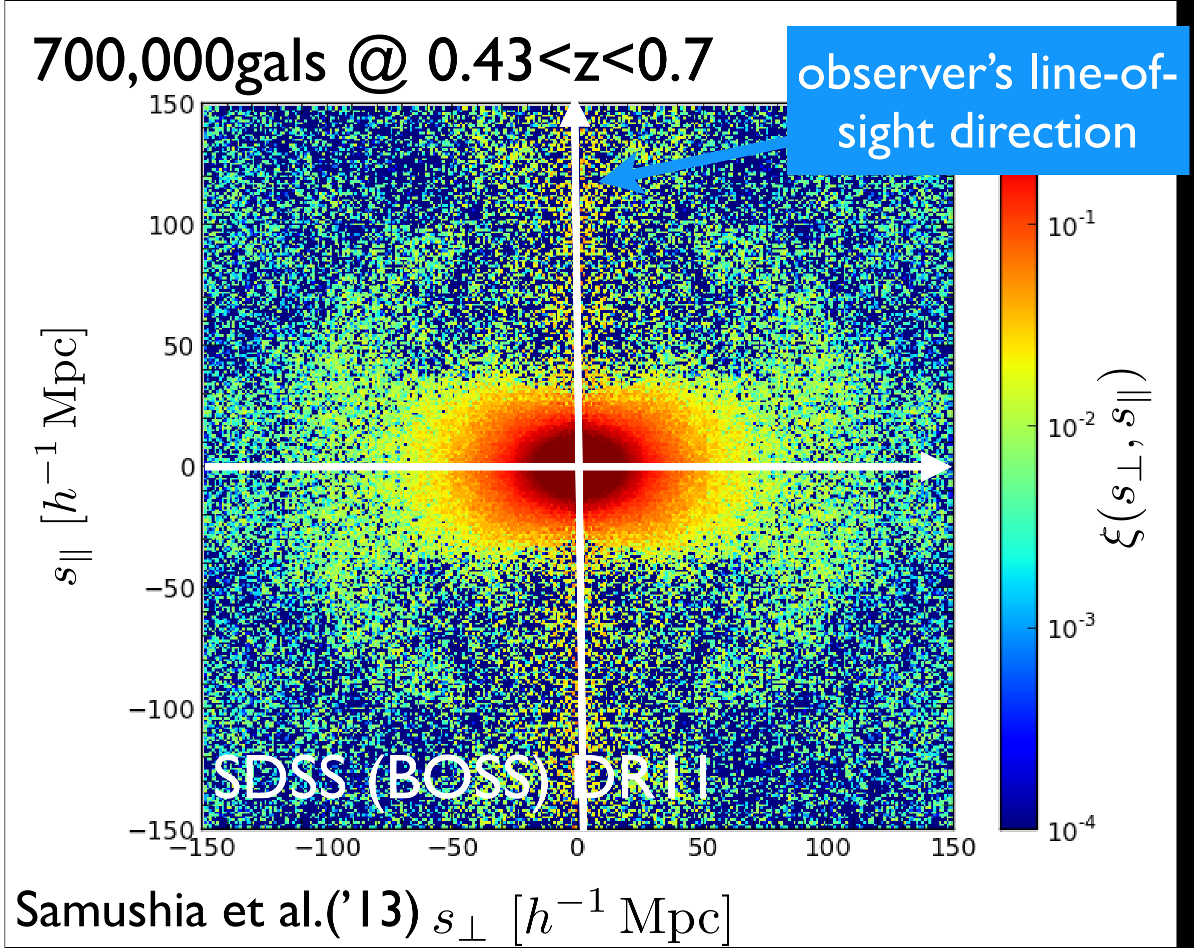
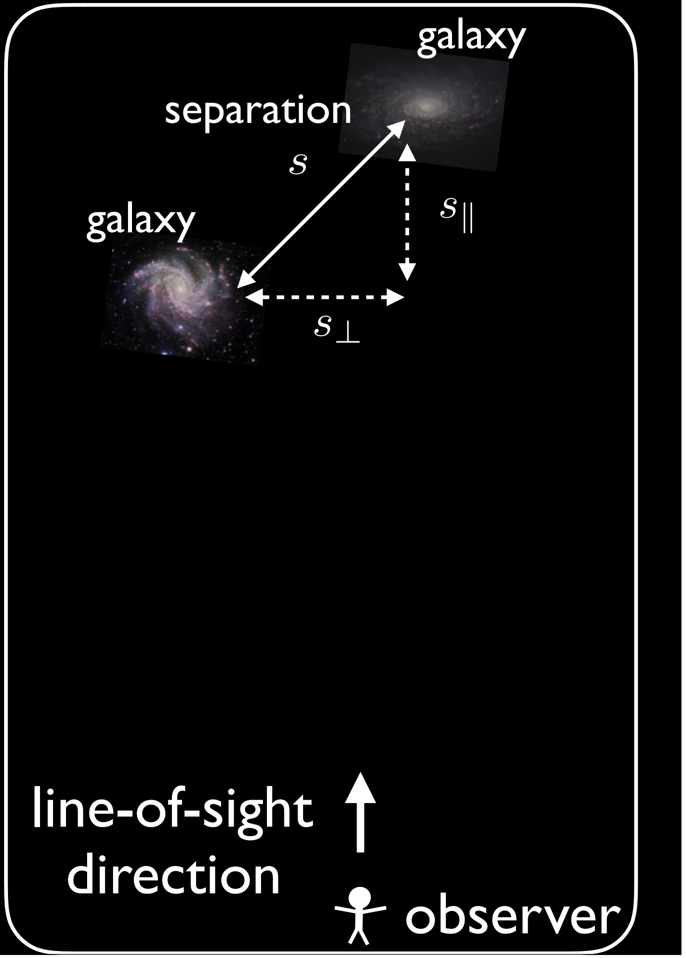


observer's line-of-sight direction

SDSS (BOSS) DR11

Samushia et al.('13)



galaxy

separation s

galaxy

$s_\parallel$

$s_\perp$

line-of-sight direction ↑

observer

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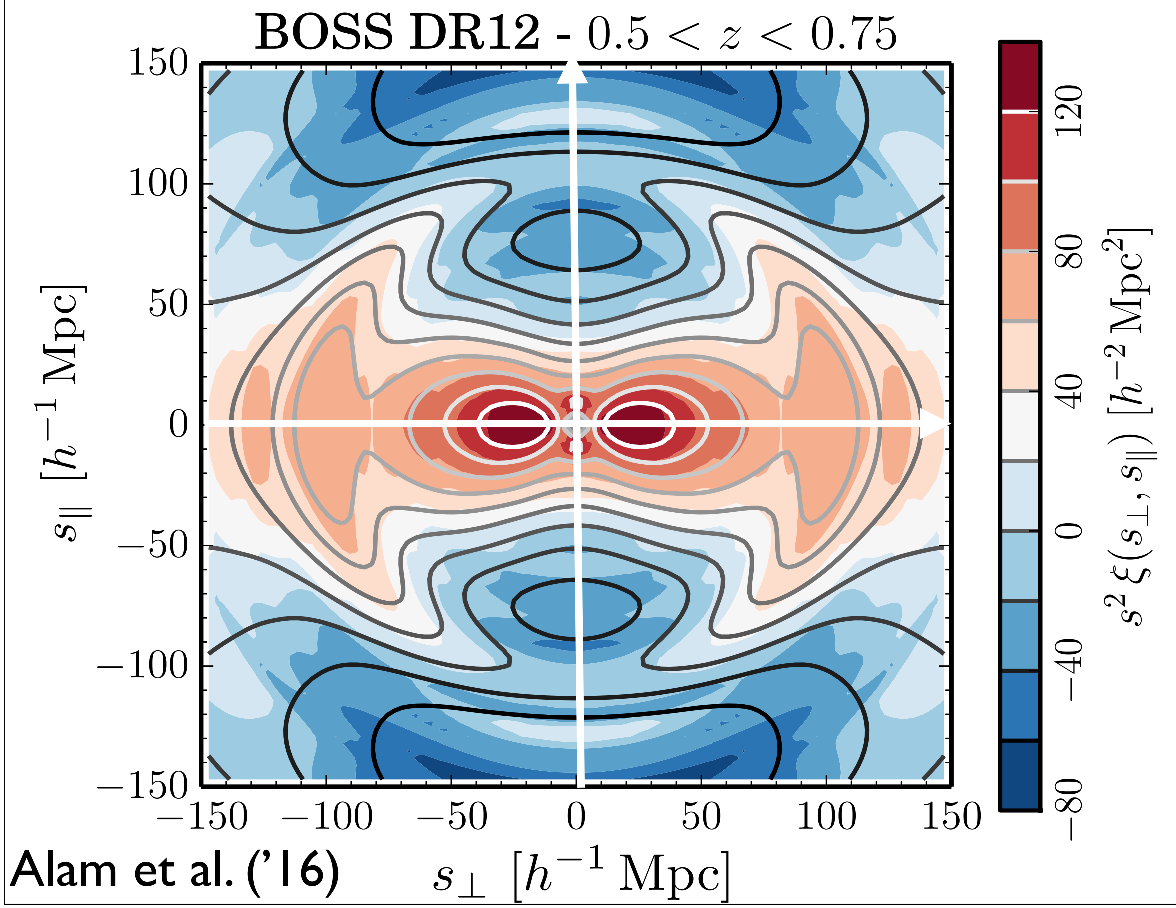
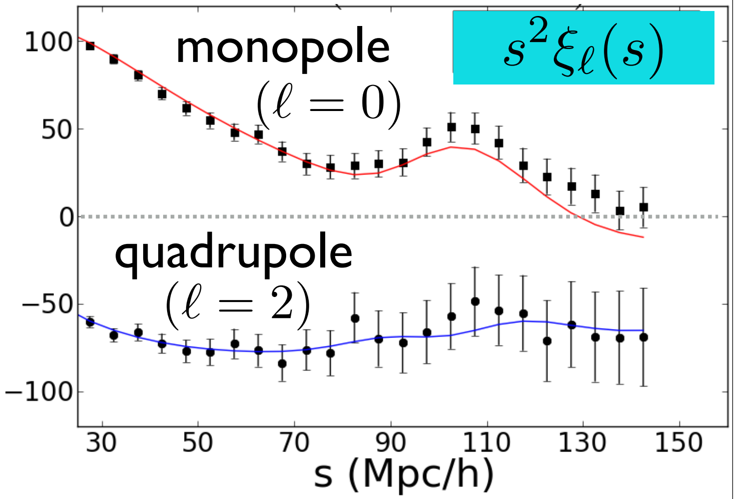


Alam et al. ('16)



Satpathy et al. ('17)

Legendre

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

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

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

Origin of anisotropies

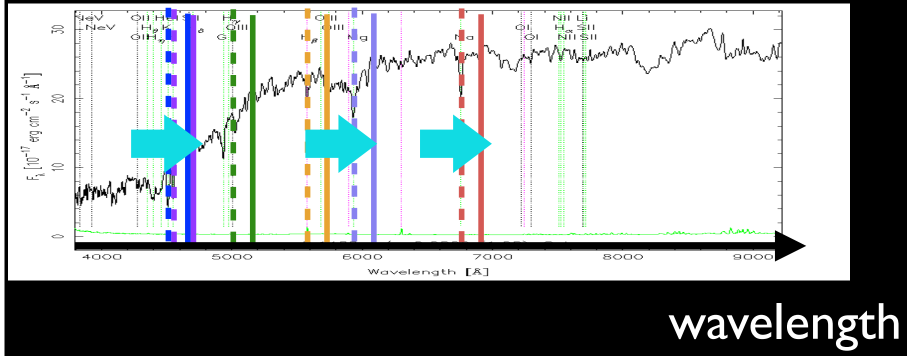
Redshift of galaxy is not a perfect distance indicator

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

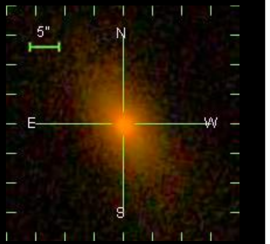
On top of cosmological redshift,

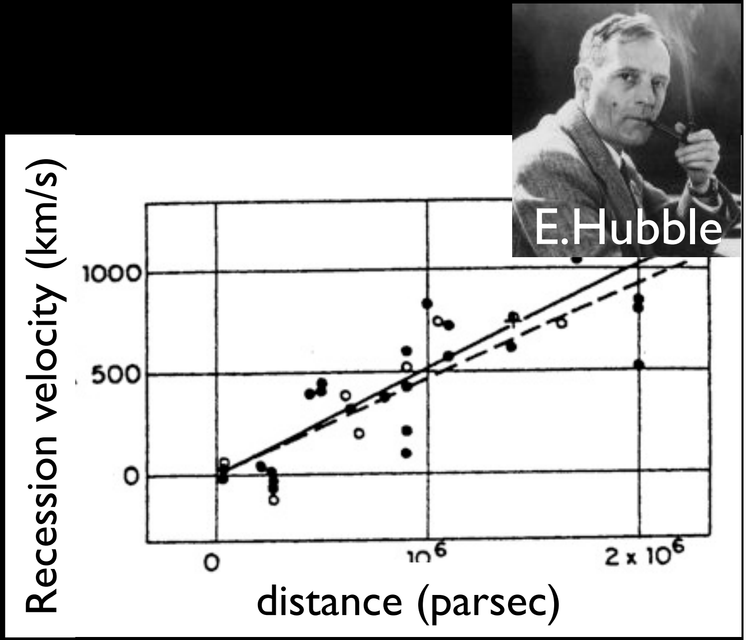
if galaxy moves toward (or away from) us

Spectrum of galaxy



Receding





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

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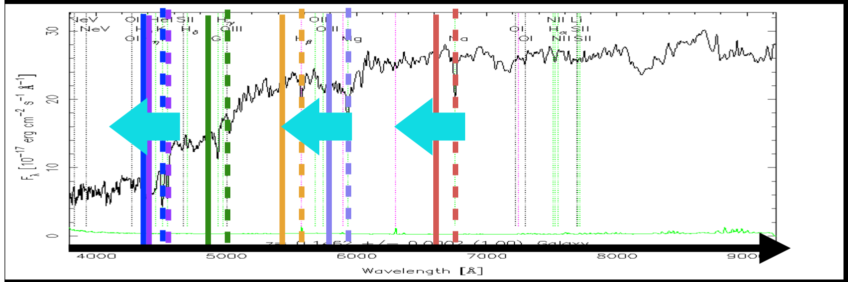
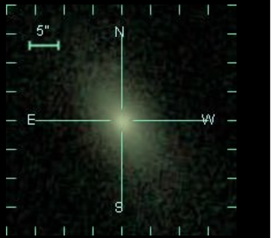
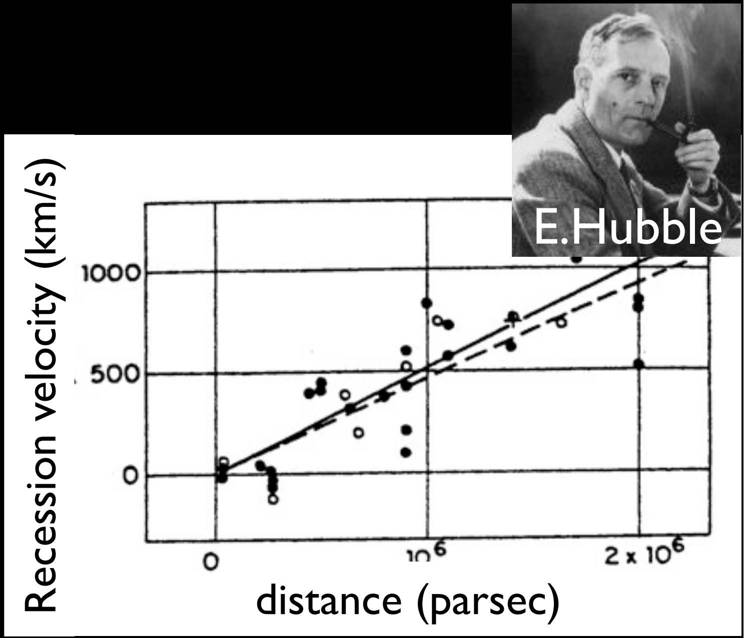


Approaching



wavelength



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

Redshift space

We may need to reconsider what is the observed space:

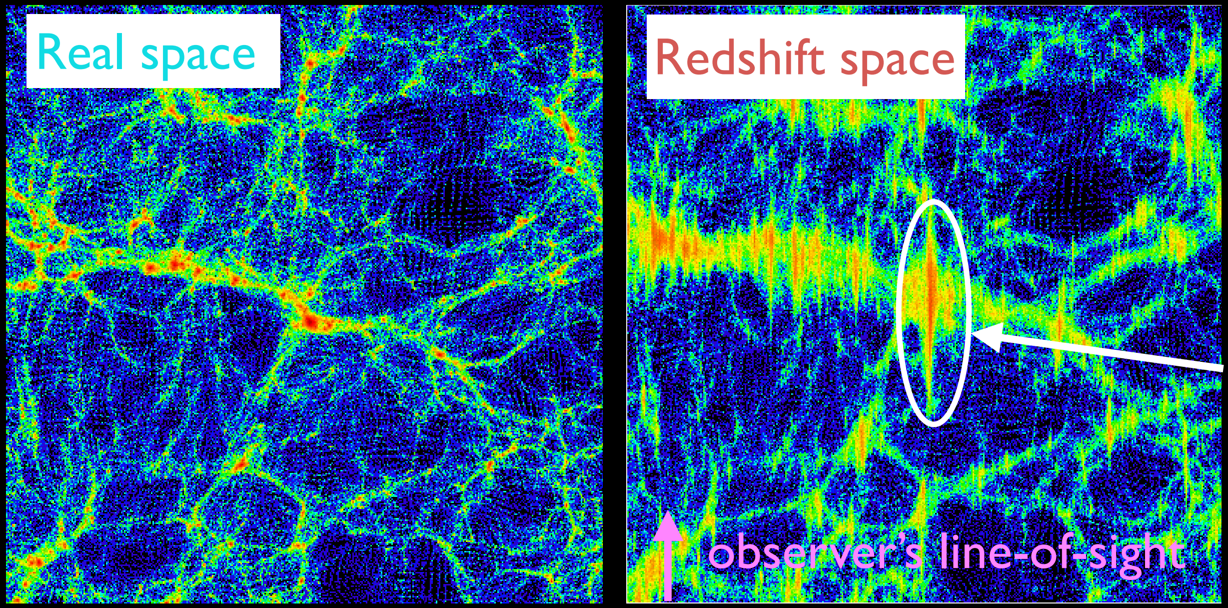
As a leading-order relativistic effect (i.e., $v/c \ll 1$*)*

Redshift space (comoving)

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

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…

Kaiser formula

Kaiser ('87)

Linear approximation $\{1+\delta^{(\mathrm{S})}(\boldsymbol{s})\}d^3\boldsymbol{s} = \{1+\delta(\boldsymbol{r})\}d^3\boldsymbol{r}$

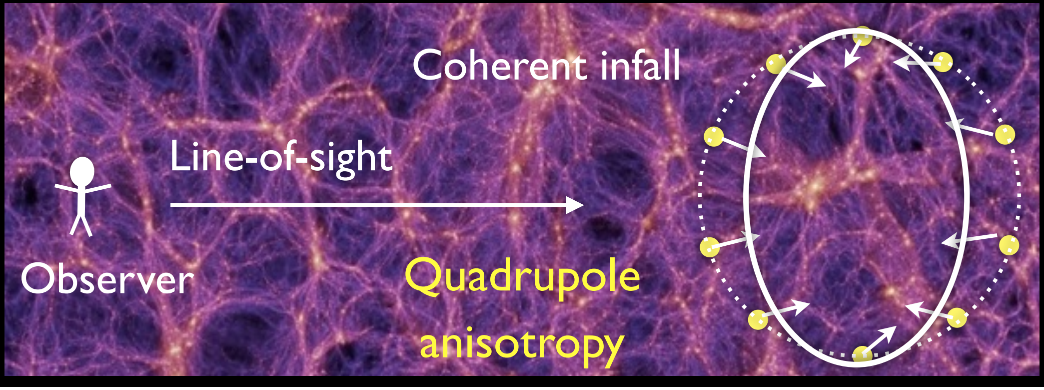
Redshift-space density field

$$\delta^{(\mathrm{S})}(\boldsymbol{s}) \simeq \delta(\boldsymbol{r}) - \frac{(1+z)}{H(z)}\partial_z v_z$$

Fourier transform

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

$$\delta^{(\mathrm{S})}(\boldsymbol{k}) = \left(1 + \mu_k^2 \underbrace{\frac{d}{d\ln a}}_{>0}\right)\delta(\boldsymbol{k}) \;; \quad \mu_k \equiv \hat{\boldsymbol{k}}\cdot\hat{z}$$



Apparent enhancement along line-of-sight

RSD as a probe of gravity

Kaiser formula

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

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

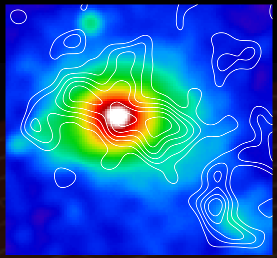
e.g., Linder ('08); Guzzo et al. ('08); Yamamoto et al. ('08); Percival & White ('09)

Gravity on cosmological scales

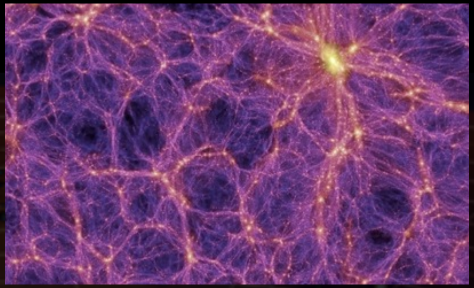
galaxy

High density

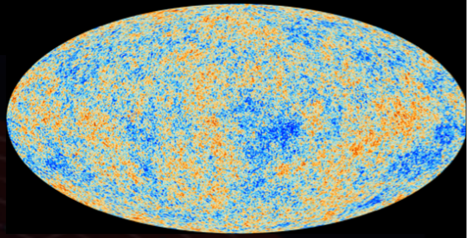
cluster



galaxy clustering



CMB



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

recover GR
(by screening mechanism)

fifth force mediated
by new scalar d.o.f

➡ cosmic acceleration

Framework to describe modified gravity is well (too) developed :

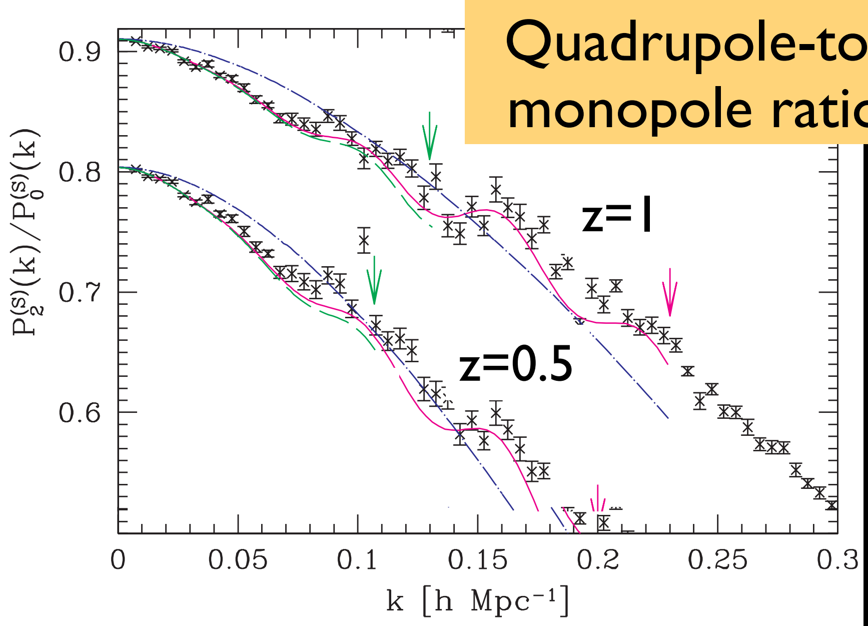
f(R) gravity, DGP, Horndeski, GLPV theory, EFT approach,…

Beyond Kaiser formula

Testing gravity with RSD needs a further investigation

- Limitation of linear Kaiser formula

Due to nonlinear nature of mapping from real to redshift spaces, applicable range of linear theory is severely limited



Quadrupole-to-monopole ratio

Kaiser formula predicts constant value, but …

AT, Nishimichi & Saito ('10)

Beyond Kaiser formula

Testing gravity with RSD needs a further improvement & renovation

- Limitation of linear Kaiser formula

  Due to nonlinear nature of mapping from real to redshift spaces, applicable range of linear theory is severely limited

- Difficulty in model-independent test of gravity

  Beyond linear regime, nonlinear fifth force comes to play in a wide class of modified models

Poisson eq.

$$\frac{1}{a^2}\nabla^2\psi = 4\pi\, G\,\overline{\rho}_m\,\delta \boxed{-\frac{1}{2a^2}\nabla^2\varphi}$$

Fifth force mediated by new scalar d.o.f

Newton potential

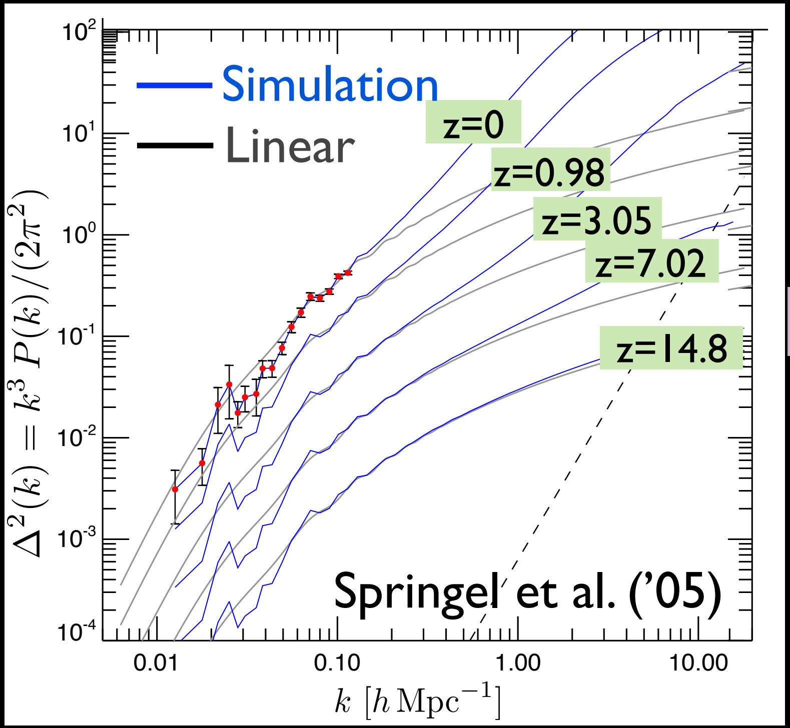
Density field

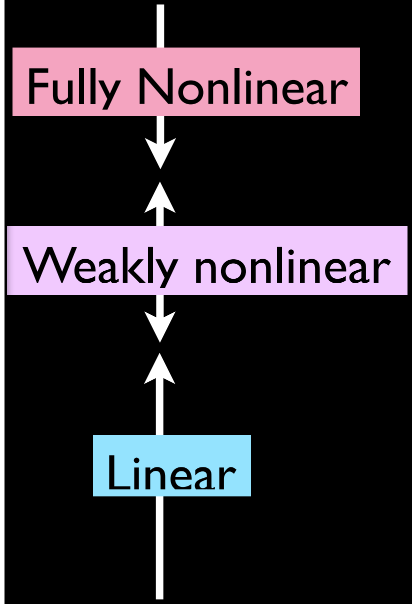
⟶ *coupled to model-dependent nonlinear field equation*

Perturbation theory: reloaded

On-going (upcoming) galaxy surveys (will) uncover gigantic volume

Regime of our interest k<0.2–0.3 h/Mpc at z~0.5~1.5 *weakly nonlinear regime*





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$k<0.2$–0.3 h/Mpc at $z\sim0.5\sim1.5$

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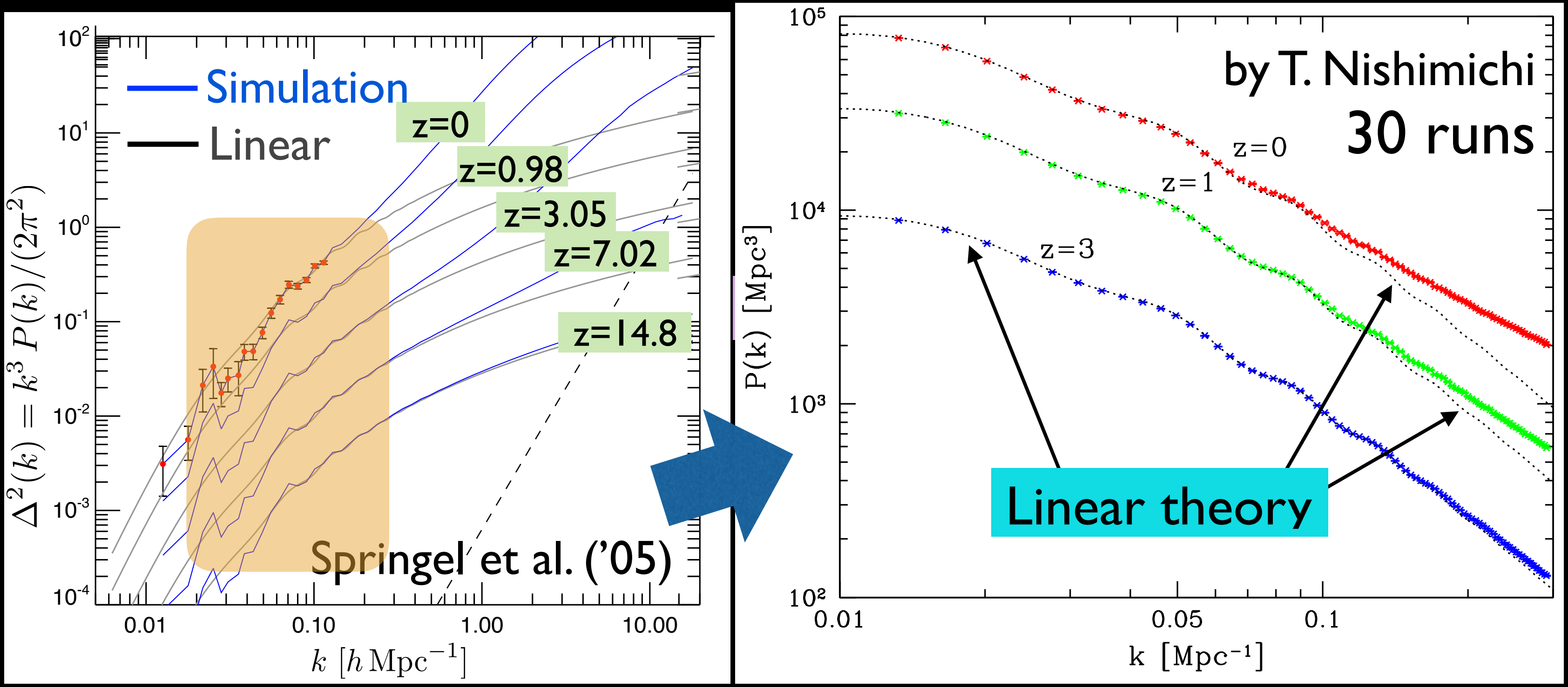

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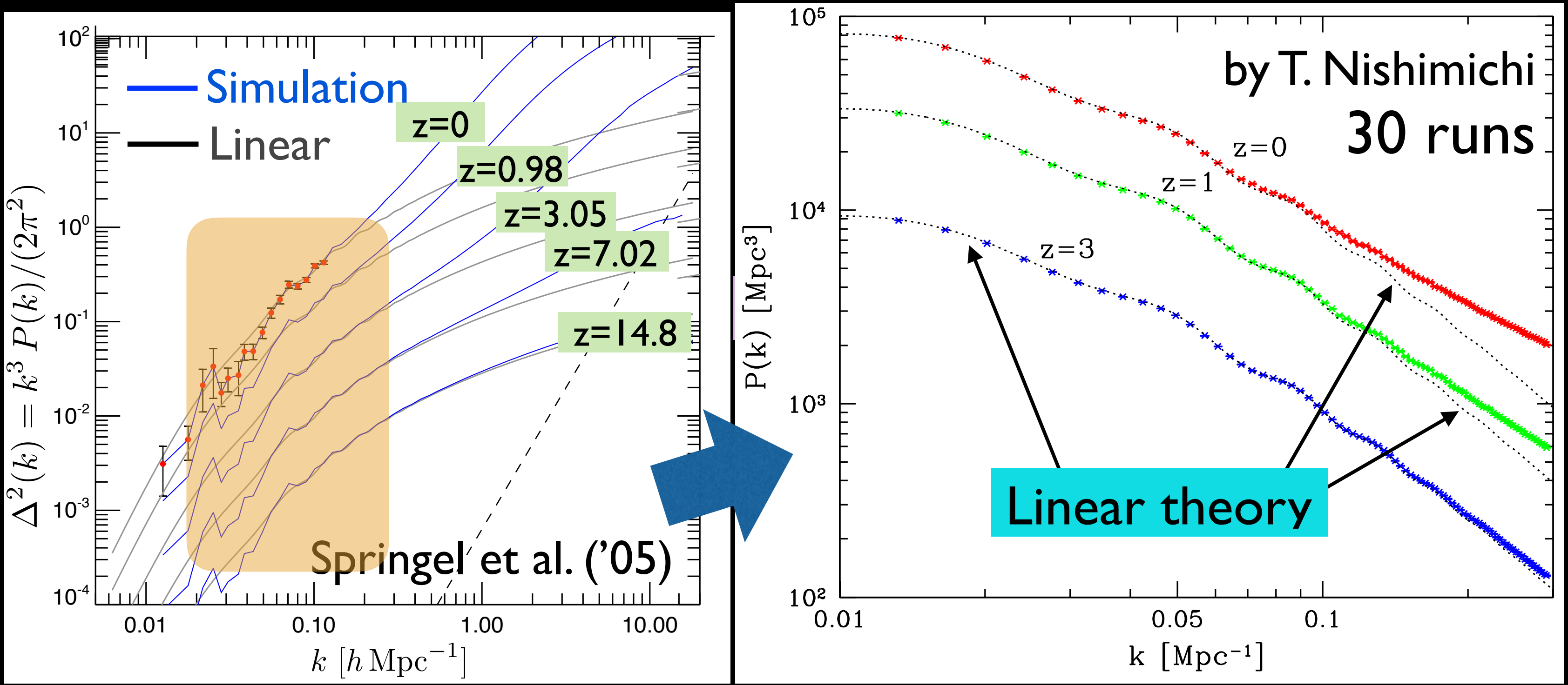


Perturbative approach ($\delta = \delta_1 + \delta_2 + \delta_3 + \cdots$) is supposed to work well

New formula for RSD

AT, Nishimichi & Saito ('10)

Exact expression

$$P^{(\mathrm{S})}(\mathbf{k}) = \int d^3\mathbf{x}\, e^{i\mathbf{k}\cdot\mathbf{x}} \left\langle e^{-ik\mu\,\Delta u_z} \{\delta(\mathbf{r}) + f\nabla_z u_z(\mathbf{r})\} \{\delta(\mathbf{r}') + f\nabla_z u_z(\mathbf{r}')\} \right\rangle$$

$$\boldsymbol{x} = \boldsymbol{r} - \boldsymbol{r}'$$

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

Rewriting it in terms of cumulants, and applying low-k expansion, while keeping non-perturbative factor

Perturbation theory formula

θ : velocity-divergence field $(\sim\ \delta)$

$$P^{(\mathrm{S})}(k,\mu) = e^{-(k\mu f\sigma_{\mathrm{v}})^2} \Big[P_{\delta\delta}(k) + 2f\mu^2 P_{\delta\theta}(k) + f^2\mu^4 P_{\theta\theta}(k) + A(k,\mu) + B(k,\mu) \Big]$$

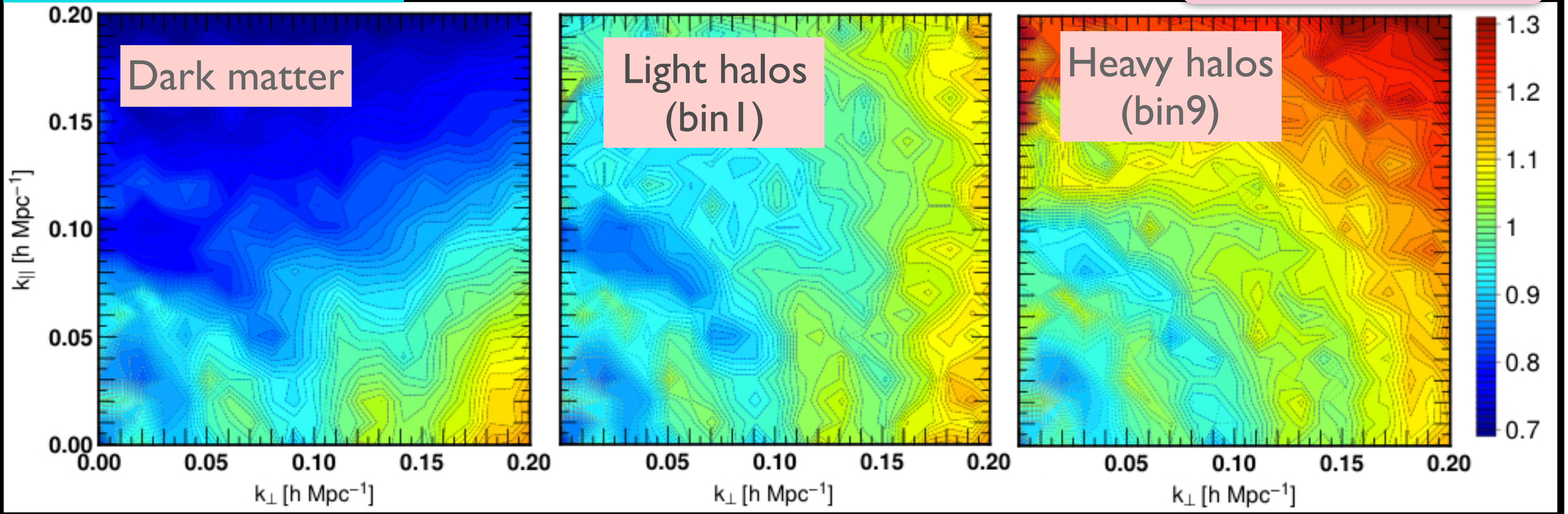
Next-to-leading order corrections (bispectrum & power spec. squared)

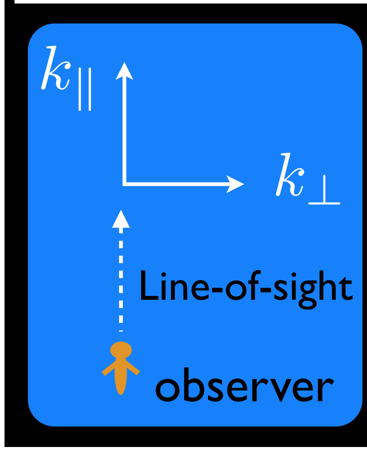
(c.f.) Linear Kaiser formula: $P^{(\mathrm{S})}(k,\mu) = (1 + f\,\mu^2)^2 P_{\delta\delta}(k)$

Performance of new formula

Simulation

$$\frac{P_{\rm halo}(k_{||},k_{\perp})}{(b^2+f\,\mu^2)^2 P_{\rm lin,no\text{-}wiggle}(k)}$$





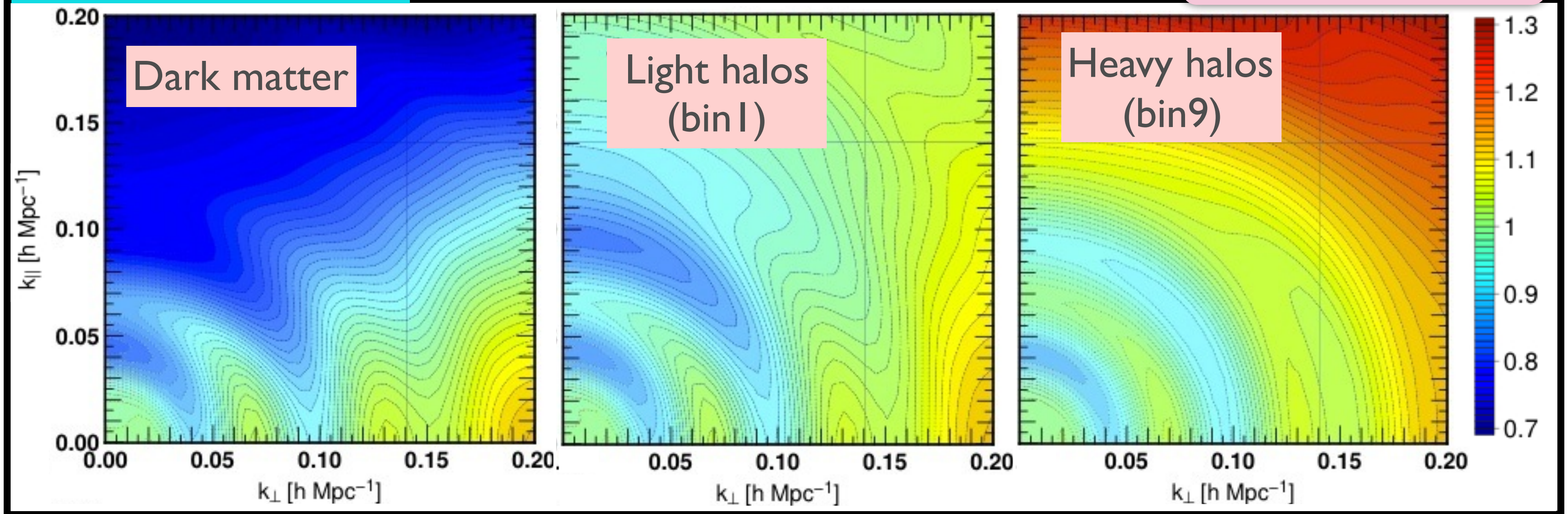
Predictions based on resummed PT

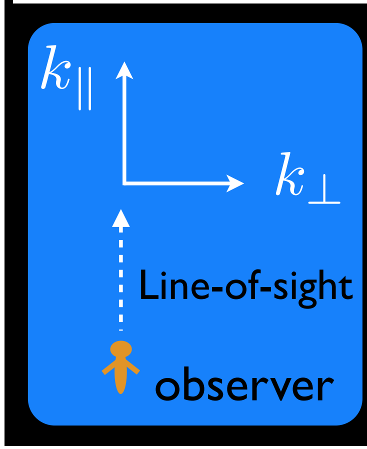
Nishimichi & AT ('11)

Performance of new formula

PT-based formula

$$\frac{P_{\rm halo}(k_{||},k_{\perp})}{(b^2+f\,\mu^2)^2P_{\rm lin,no\text{-}wiggle}(k)}$$





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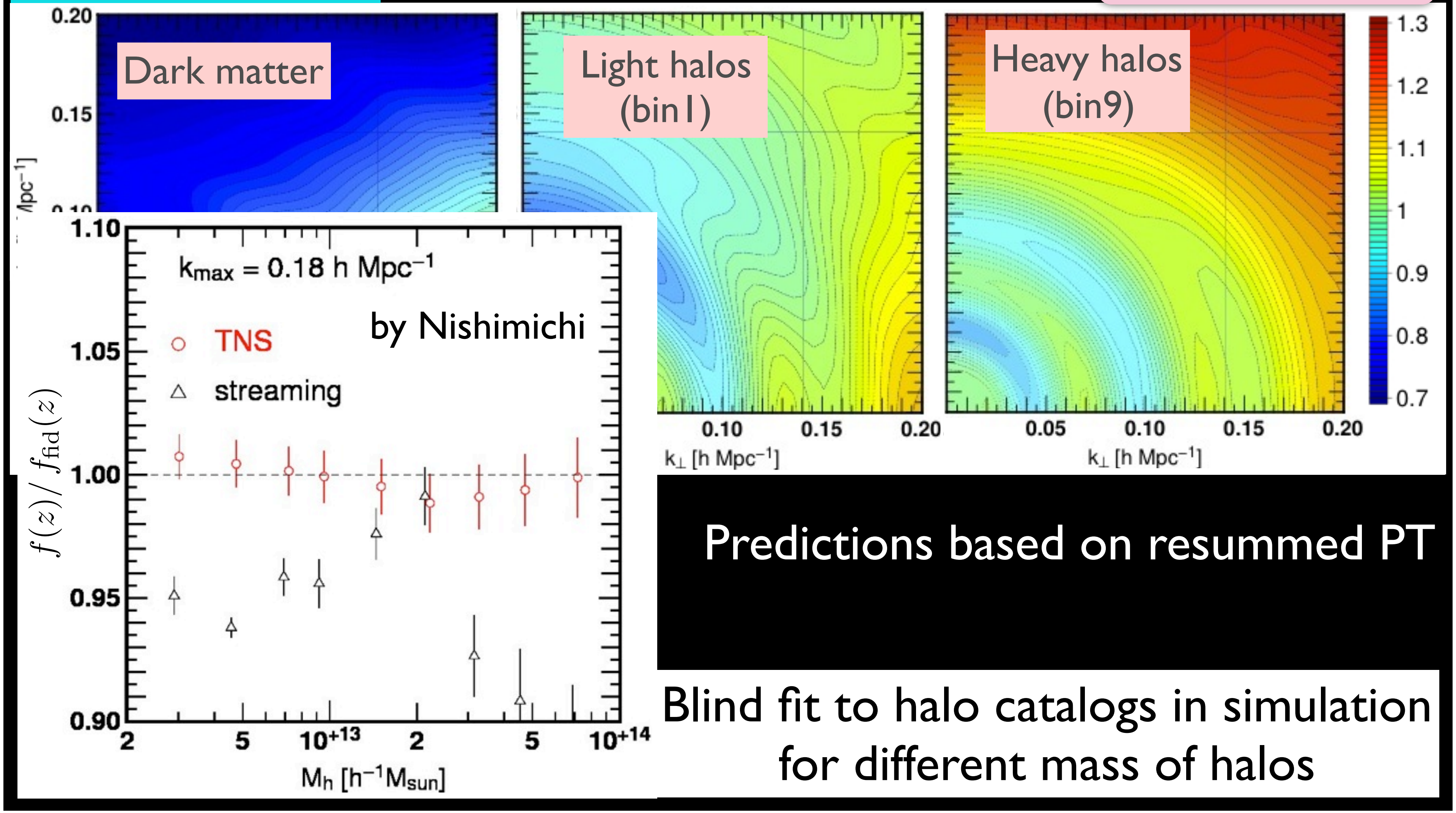
Nishimichi & AT ('11)

Performance of new formula

PT-based formula

$$\frac{P_{\rm halo}(k_{||},k_\perp)}{(b^2+f\,\mu^2)^2 P_{\rm lin,no\text{-}wiggle}(k)}$$

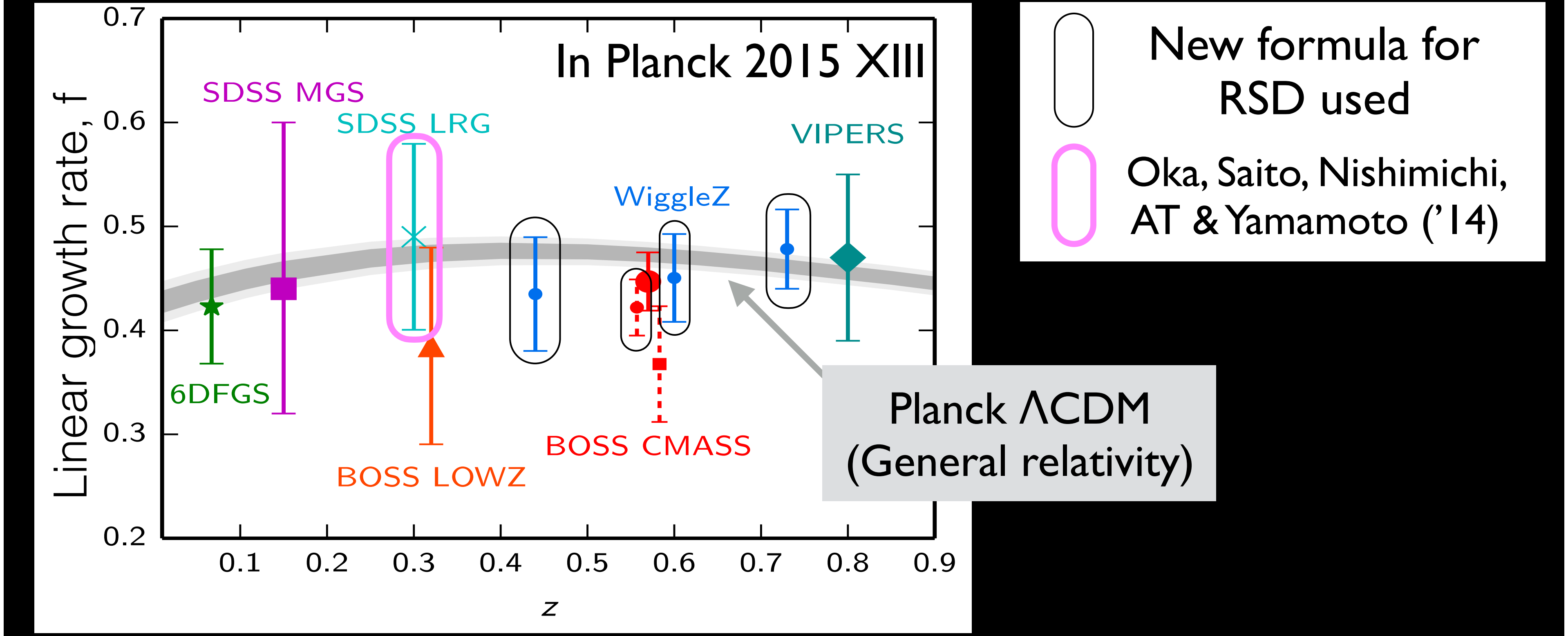


Predictions based on resummed PT

Blind fit to halo catalogs in simulation
for different mass of halos

Consistency test of GR

Assuming underlying theory of gravity is GR, PT-based template is compared with observations



New formula for RSD used

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

Planck ΛCDM (General relativity)

Formula has been also used for latest BOSS data (DR12), and no strong evidence for deviation from GR has been found (Beutler, Seo, Saito et al. '16)

PT in modified gravity models

Koyama, AT & Hiramatsu ('09)

- Matter sector : (Standard) fluid system
- Gravity sector: Theory looks like Brans-Dicke (BD) gravity on sub-horizon scales

Continuity eq.

$$\frac{\partial\delta}{\partial t}+\frac{1}{a}\nabla\cdot[(1+\delta)\,\boldsymbol{v}]=0$$

Euler eq.

$$\frac{\partial\boldsymbol{v}}{\partial t}+H\boldsymbol{v}+\frac{1}{a}(\boldsymbol{v}\cdot\nabla)\boldsymbol{v}=-\frac{1}{a}\nabla\psi$$

Poisson eq.

$$\frac{1}{a^2}\nabla^2\psi=4\pi\,G\,\bar{\rho}_m\,\delta-\frac{1}{2a^2}\nabla^2\varphi$$

BD scalar

E.O.M for BD scalar

$$(3+2\omega_{\rm BD})\frac{1}{a^2}\nabla^2\varphi=8\pi\,G\,\bar{\rho}_m\,\delta-\mathcal{I}(\varphi)$$

Model-dependent nonlinear potential

$$M_1\varphi+M_2\varphi\cdot\varphi+\cdots$$

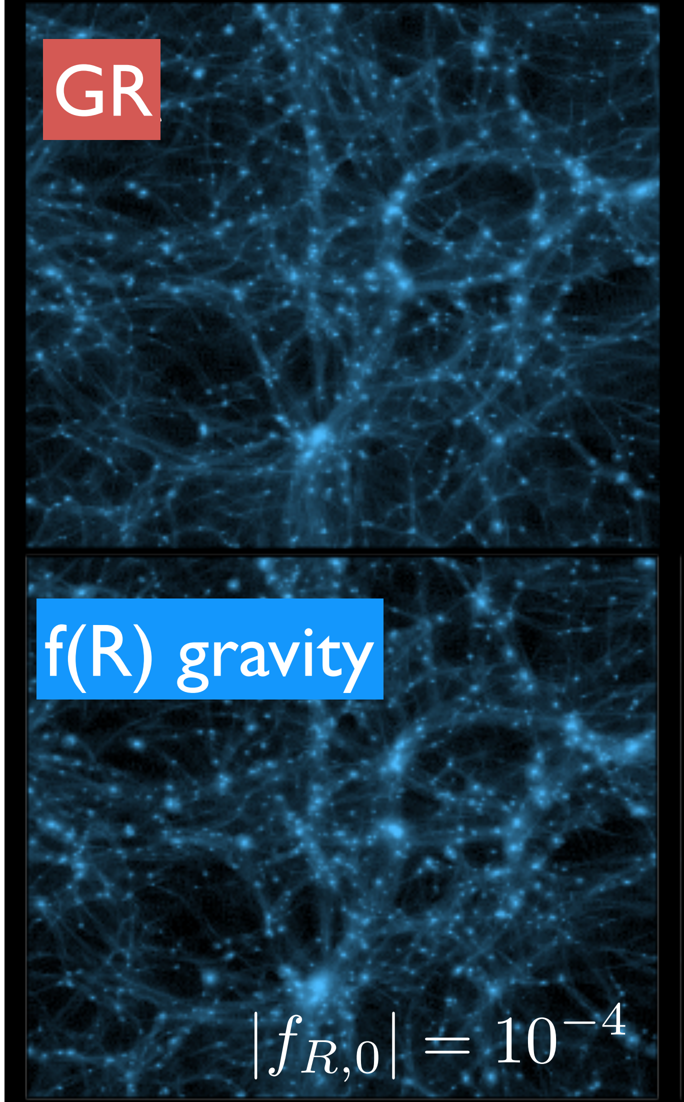
In f(R) gravity,

$$\omega_{\rm BD}=0$$

$$\varphi=\delta f_R\;;\,f_R\equiv\frac{d\,f(R)}{dR}$$

$$\Psi_a\equiv\begin{pmatrix}\delta\\ \theta\end{pmatrix}=\Psi_a^{(1)}+\Psi_a^{(2)}+\Psi_a^{(3)}+\cdots\;\Rightarrow\;\langle\Psi_a(\boldsymbol{k})\Psi_b(\boldsymbol{k}')\rangle=(2\pi)^3\delta_D(\boldsymbol{k}+\boldsymbol{k}')\,P_{ab}(k)$$

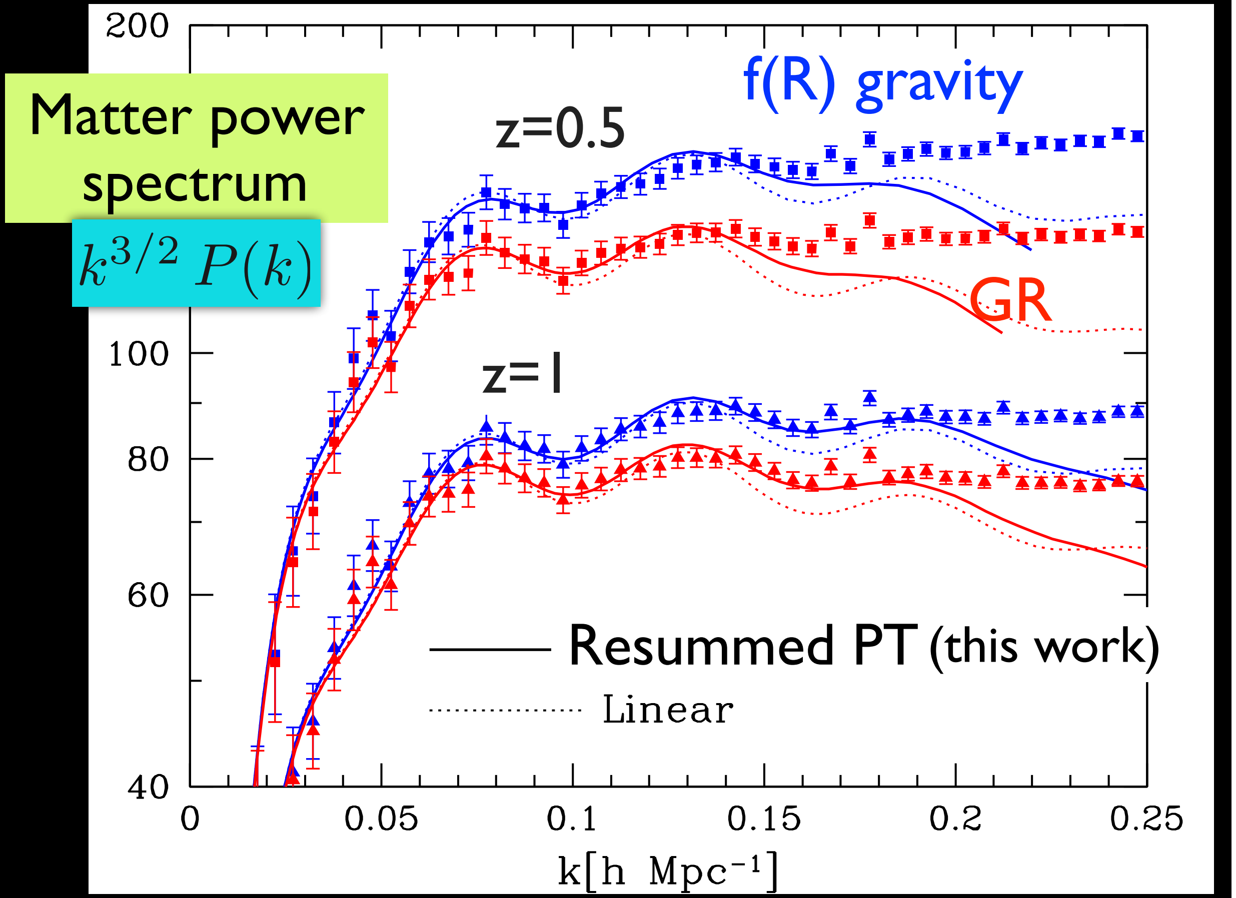
Performance of PT template



http://icosmology.info/Nbody_Simulation.html

f(R) gravity model

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

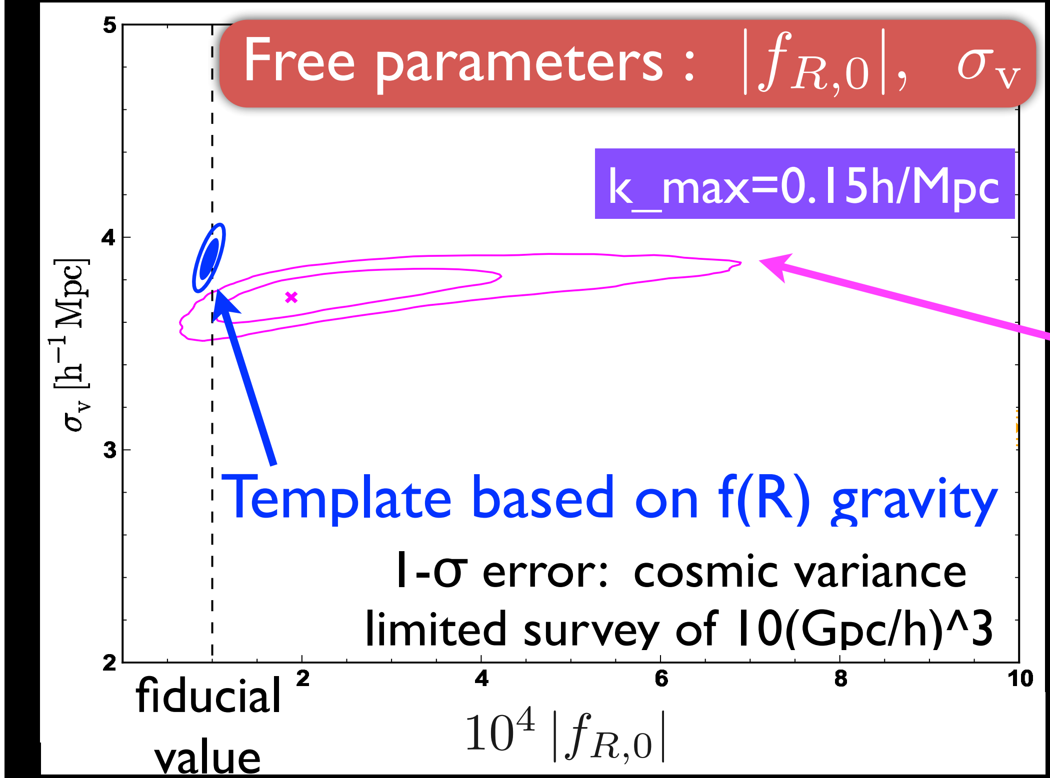


AT, Nishimichi, Bernardeau et al. ('15); AT ('16)

Test against mock simulations

Combining PT template with new formula of RSD,

how well one can constrain the parameter, $|f_{R,0}|$, in N-body data ?



Free parameters : $|f_{R,0}|,\ \sigma_\mathrm{v}$

k_max=0.15h/Mpc

Template based on f(R) gravity

1-σ error: cosmic variance limited survey of 10(Gpc/h)^3

fiducial value

GR-based template through scale-dept. linear growth rate in f(R) gravity

$$P_\ell^{(\mathrm{GR})}(k;f)$$

Consistently incorporating the modified gravity effects into theoretical template greatly improves the parameter constraints

Consistent modified gravity analysis

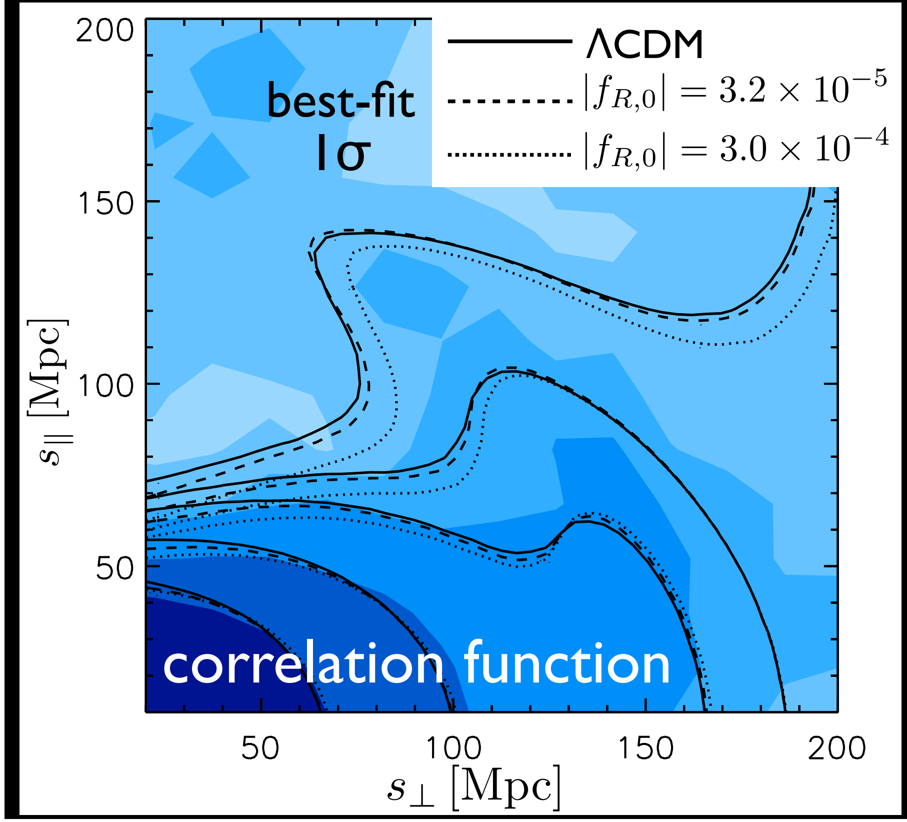
Y-S.Song, AT, Linder, Koyama et al. ('15)

Application of PT template to observations:

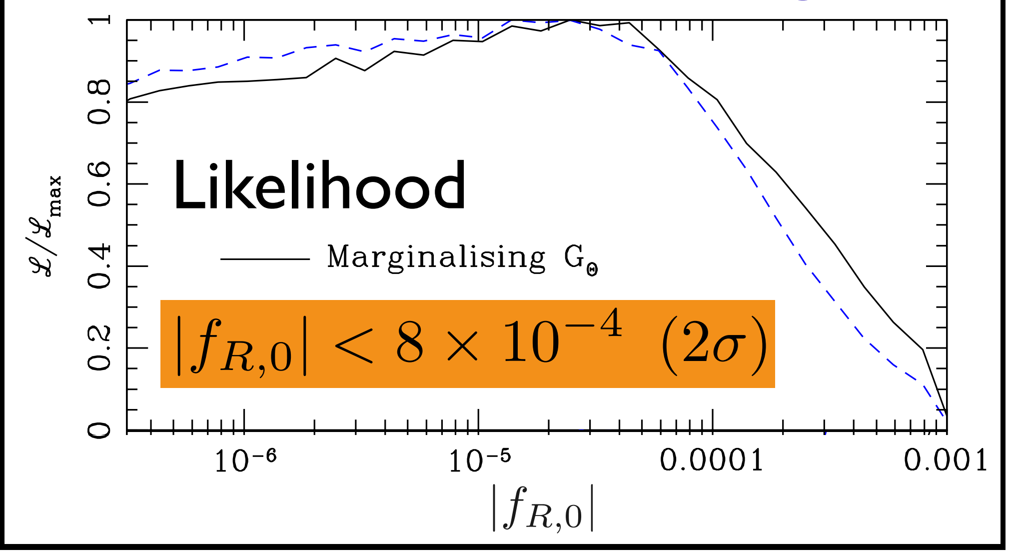
Baryon Oscillation Spectroscopic Survey (BOSS), DR11

(690,000 galaxies @ z=0.57)

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



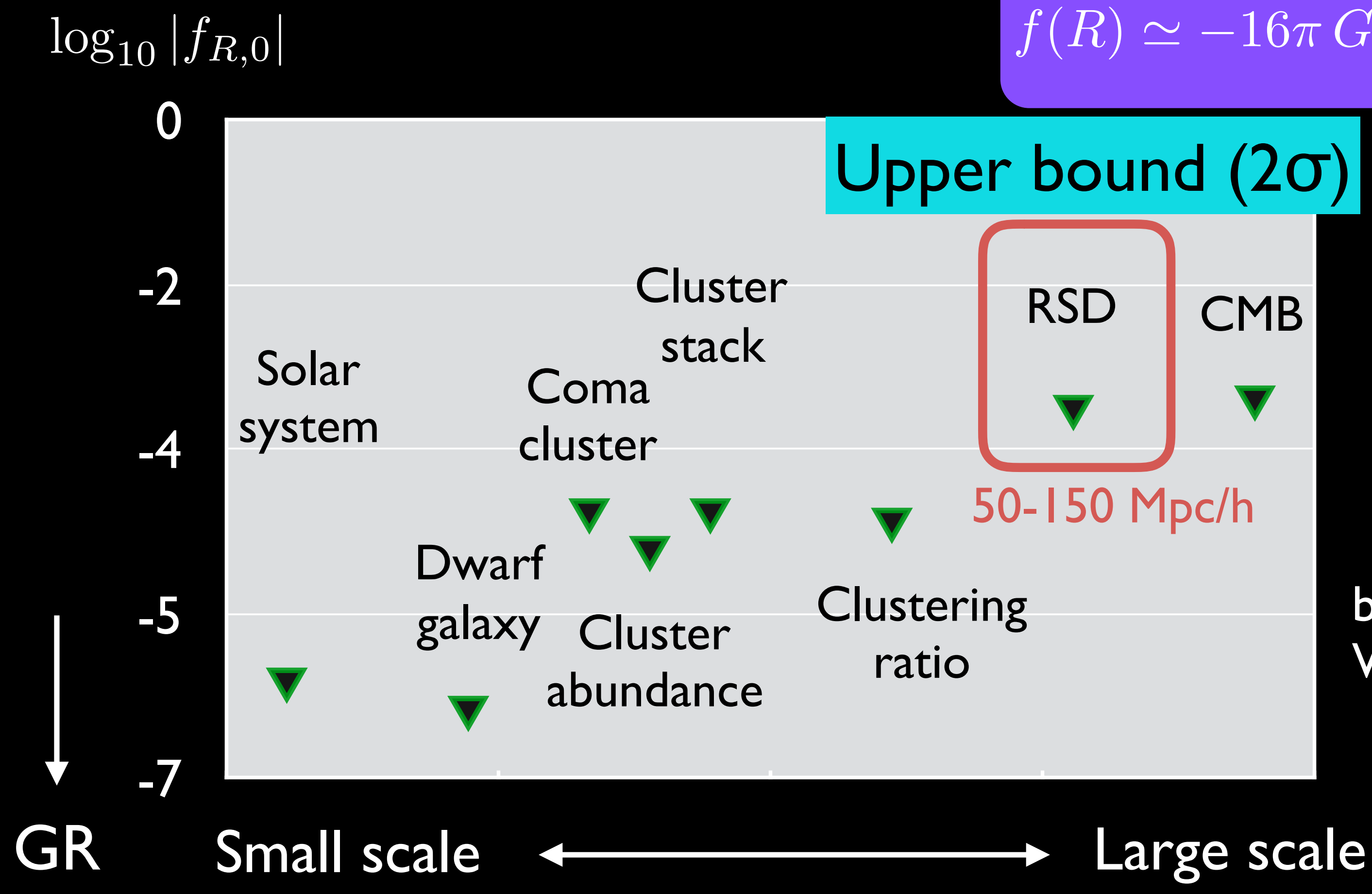
Geometric distortions marginalized



$$|f_{R,0}| < 8 \times 10^{-4} \quad (2\sigma)$$

Comparison with other obs.

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



base on
Wilcox et al. ('15)

A broad parameter range is still allowed at large scales (>50Mpc)

Short summary

RSD effect of large-scale structure can be used to probe gravity on cosmological scales, and test has been made with development of analytical tools

So far, consistent with

General relativity

(Lambda CDM model)

But,

- constraint on gravity is still weak at large scales
- measured '*f*' is systematically smaller than ΛCDM predictions

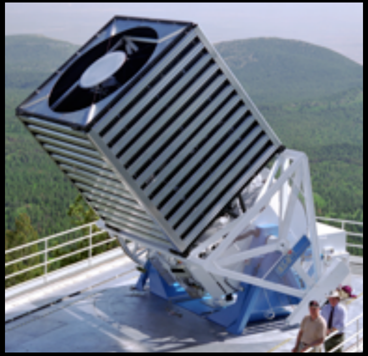
hint of modified gravity ? → future obs.

Upcoming/on-going projects

Multi-purpose ground- & space-based experiments

DES (2013~)

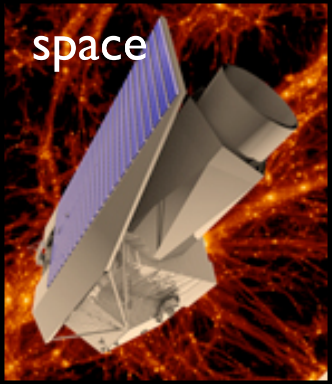
HETDEX (2016+)

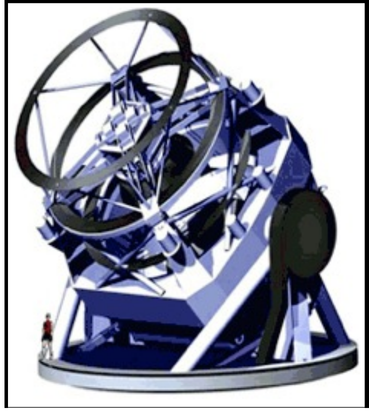


eBOSS (2014~)

DESI
(2018+)

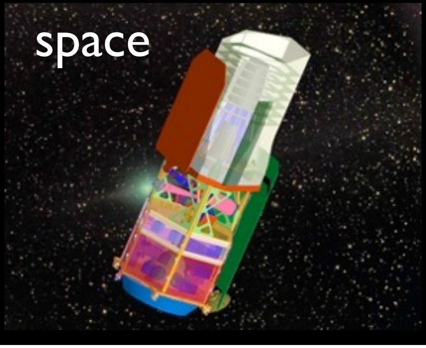
WFIRST
(2024++)



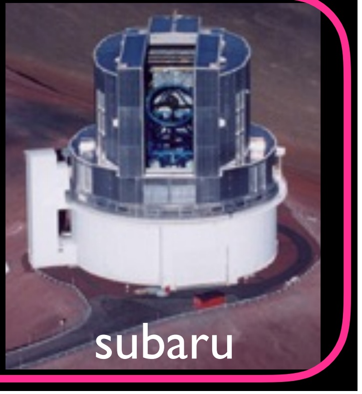


LSST
(2022++)

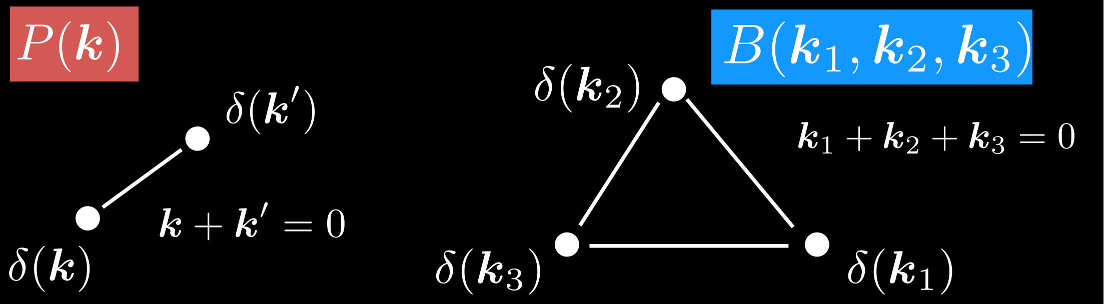
Euclid (2020)



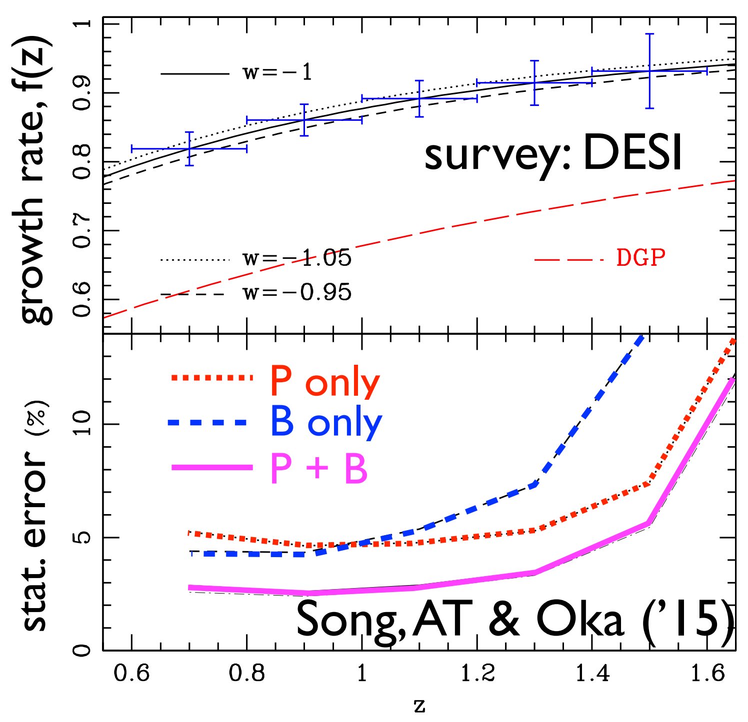
SuMIRe
(2014~)



Narrowing constraints in future

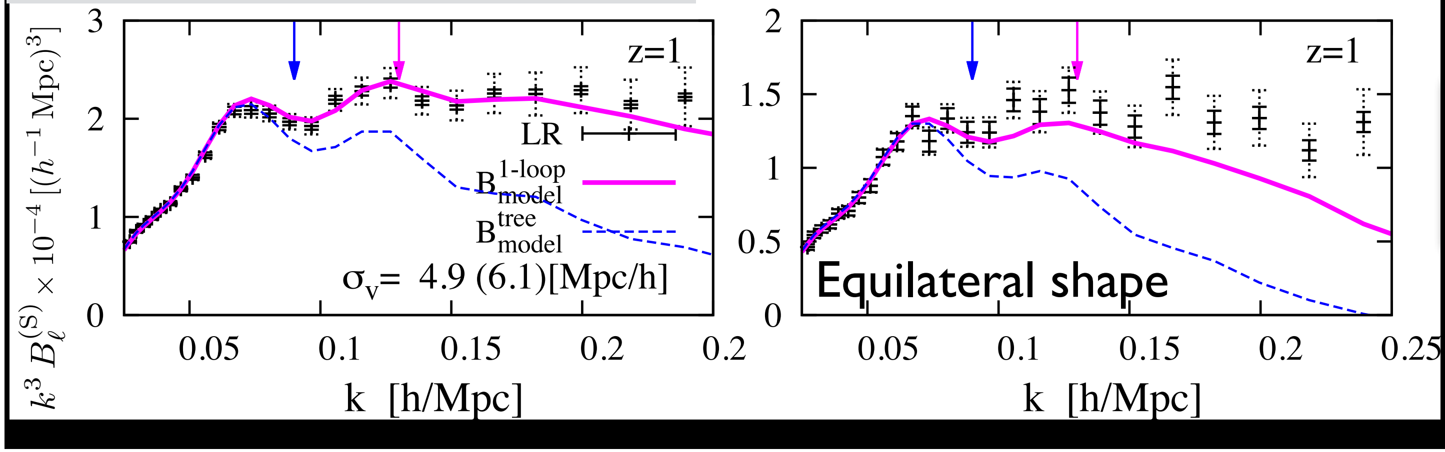


Combination of bispectrum will tighten the constraint or improve the test (by more than factor of two)



Song, AT & Oka ('15)

PT prediction of bispectrum



Standard PT tree

New 1-loop

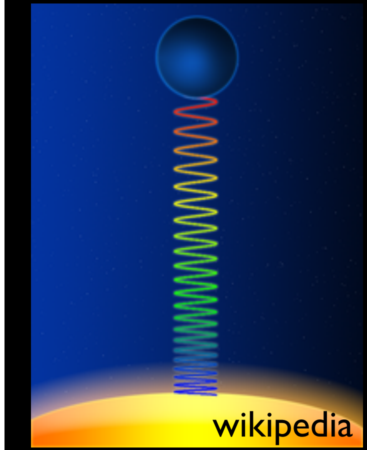
Hashimoto, Rasera & AT ('17)

Beyond redshift-space distortions

An improved statistical precision of gigantic galaxy survey,

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

On top of redshift-space distortions,


wikipedia

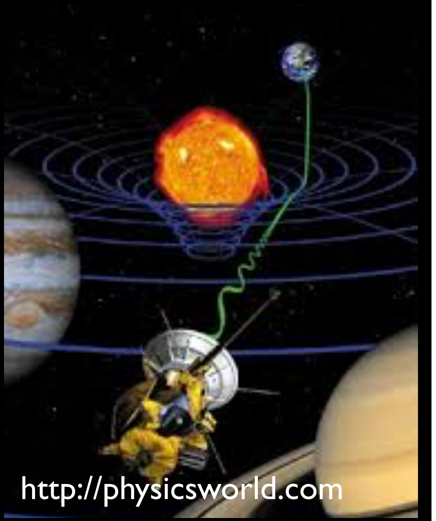
Gravitational redshift

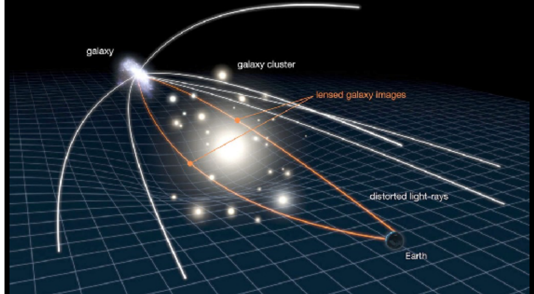
Shapiro time-delay

(Integrated) Sachs-Wolfe effect

Weak gravitational lensing effect

Light-cone effect


http://physicsworld.com



Yoo, Fitzpatrick & Zaldarriaga ('09)
Yoo ('10), Bonvin & Durrer ('11)

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

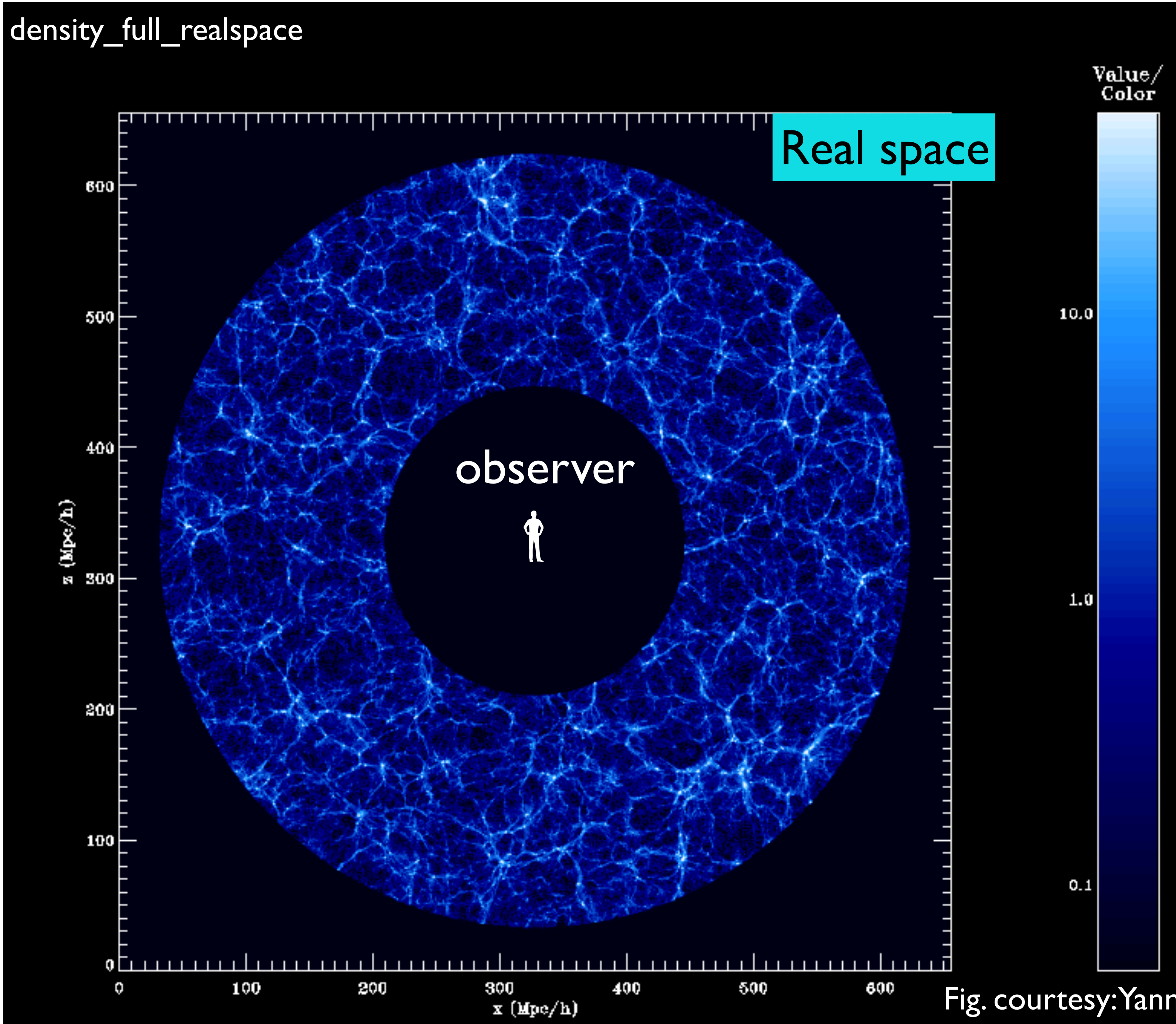
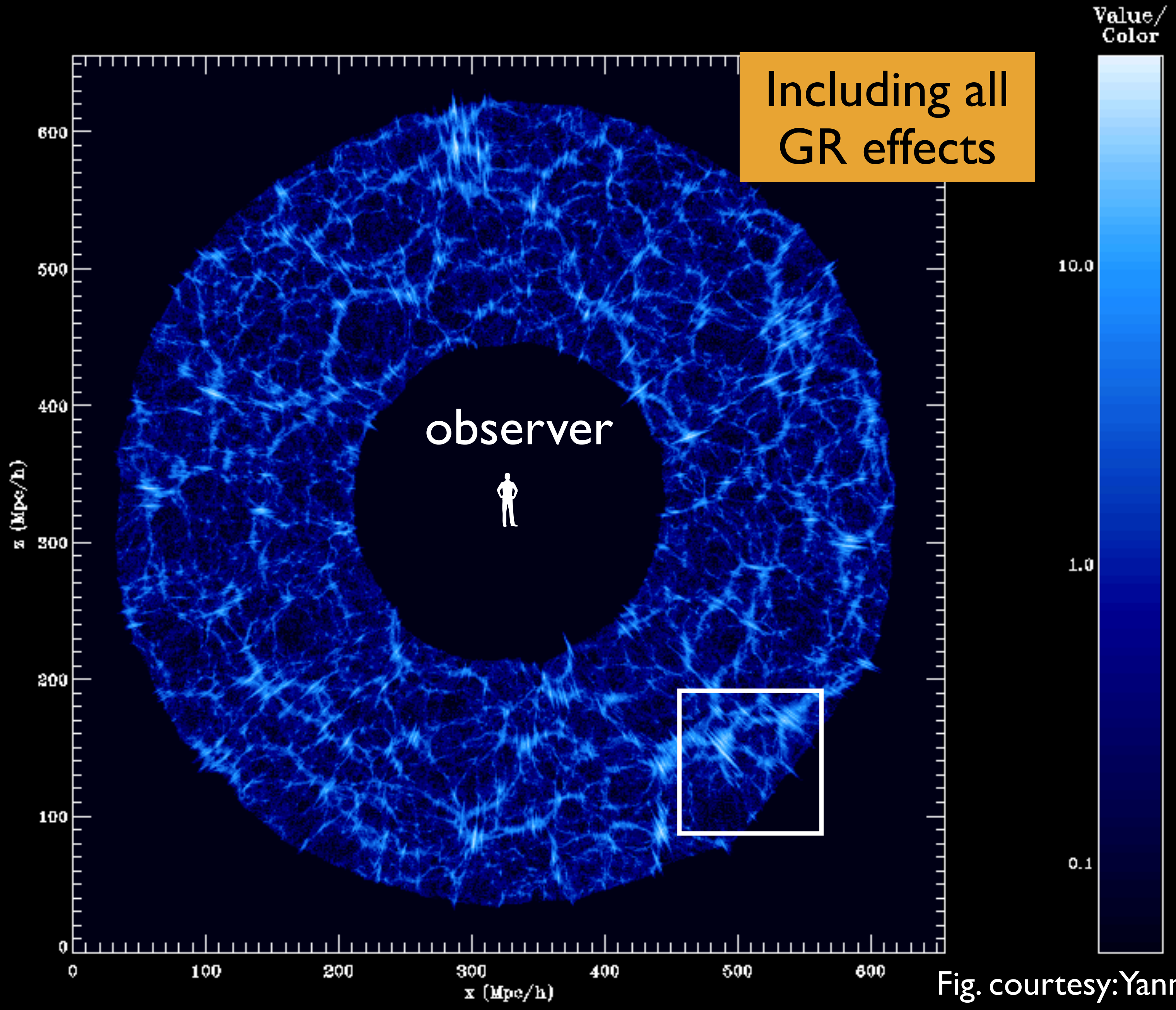


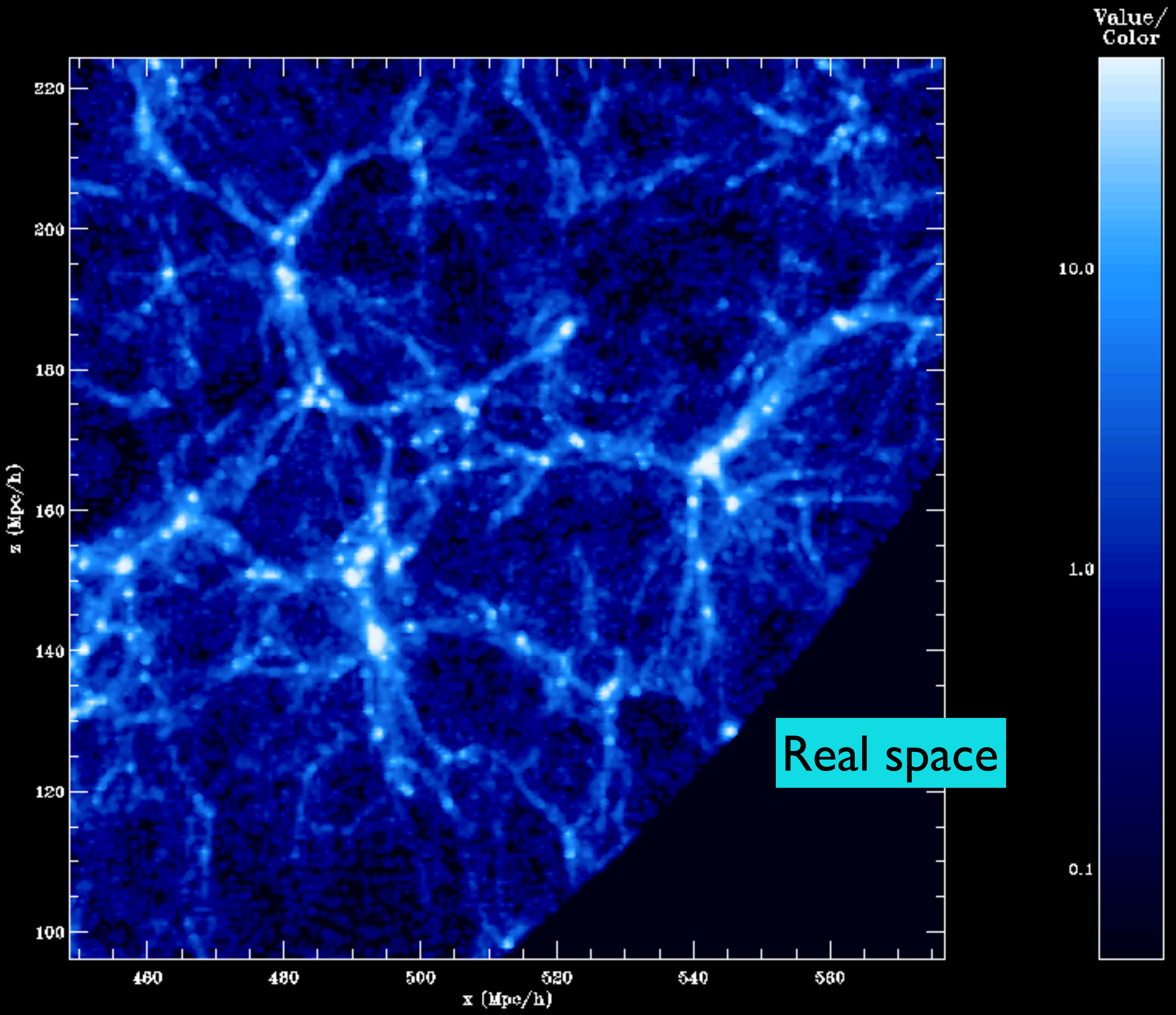
Fig. courtesy: Yann Rasera, based on the data by Michel-Andres Breton density_full_redshiftspacealleffects



Including all GR effects

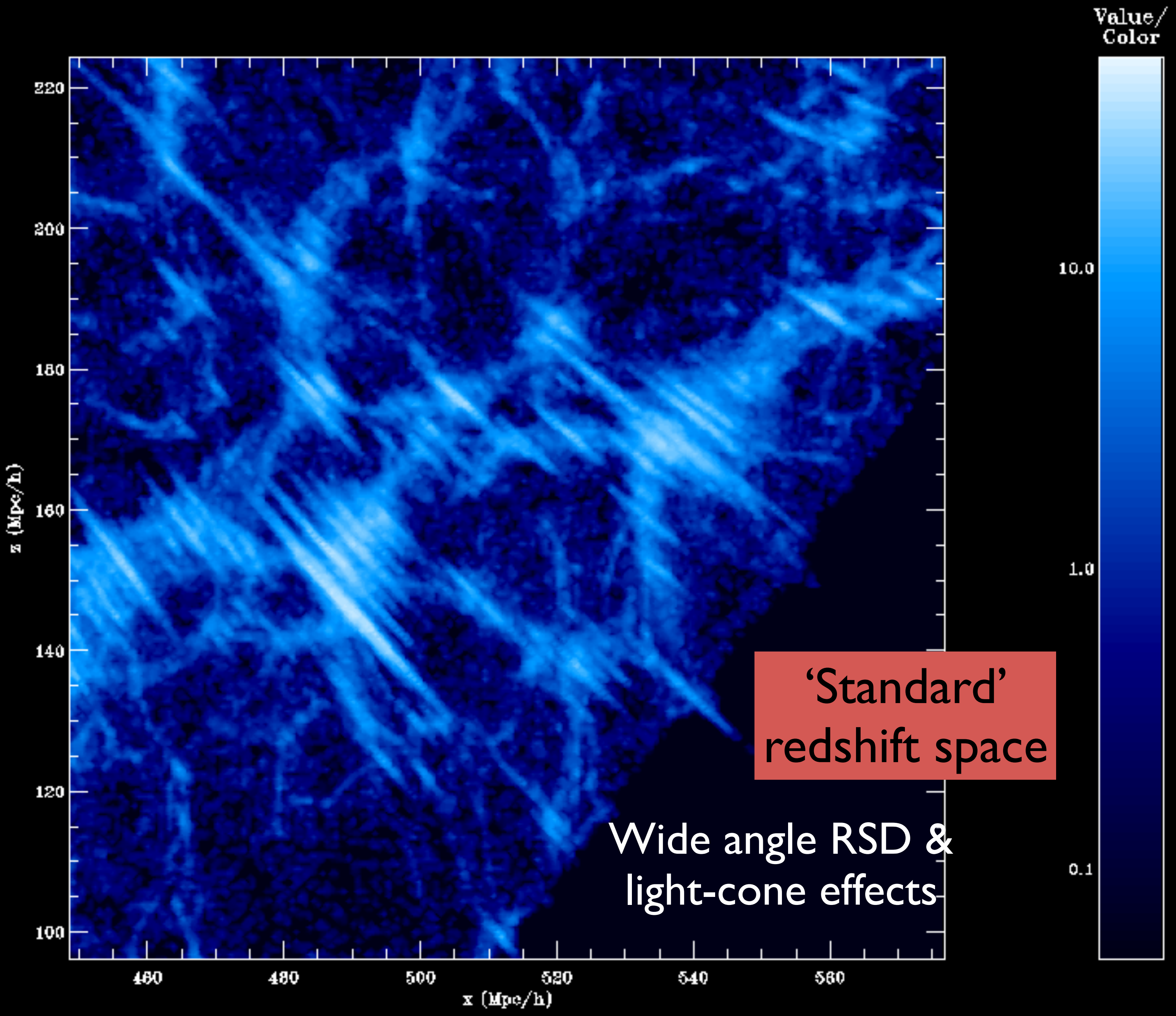
observer

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



Real space

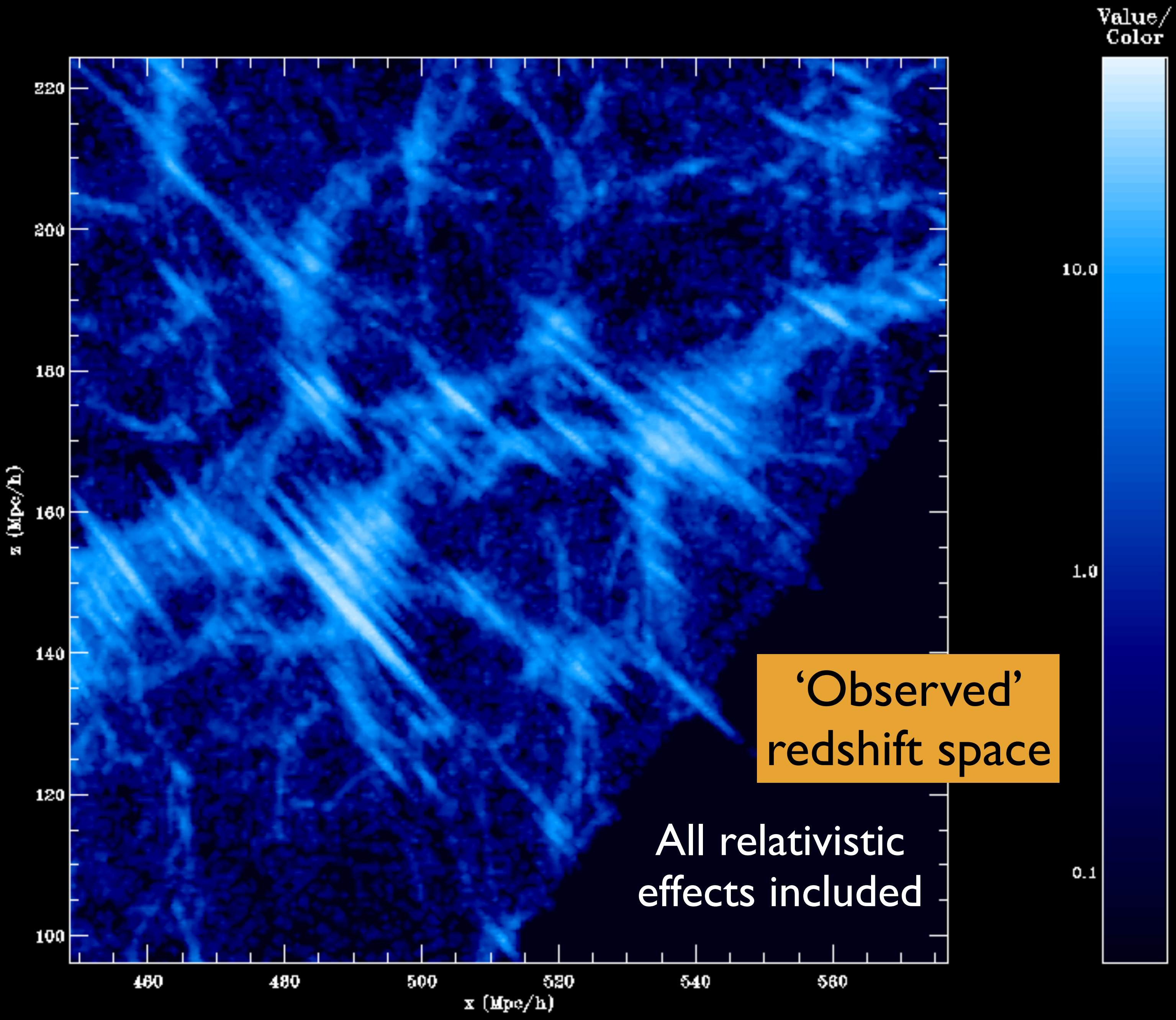
density_RSDonly



'Standard' redshift space

Wide angle RSD & light-cone effects

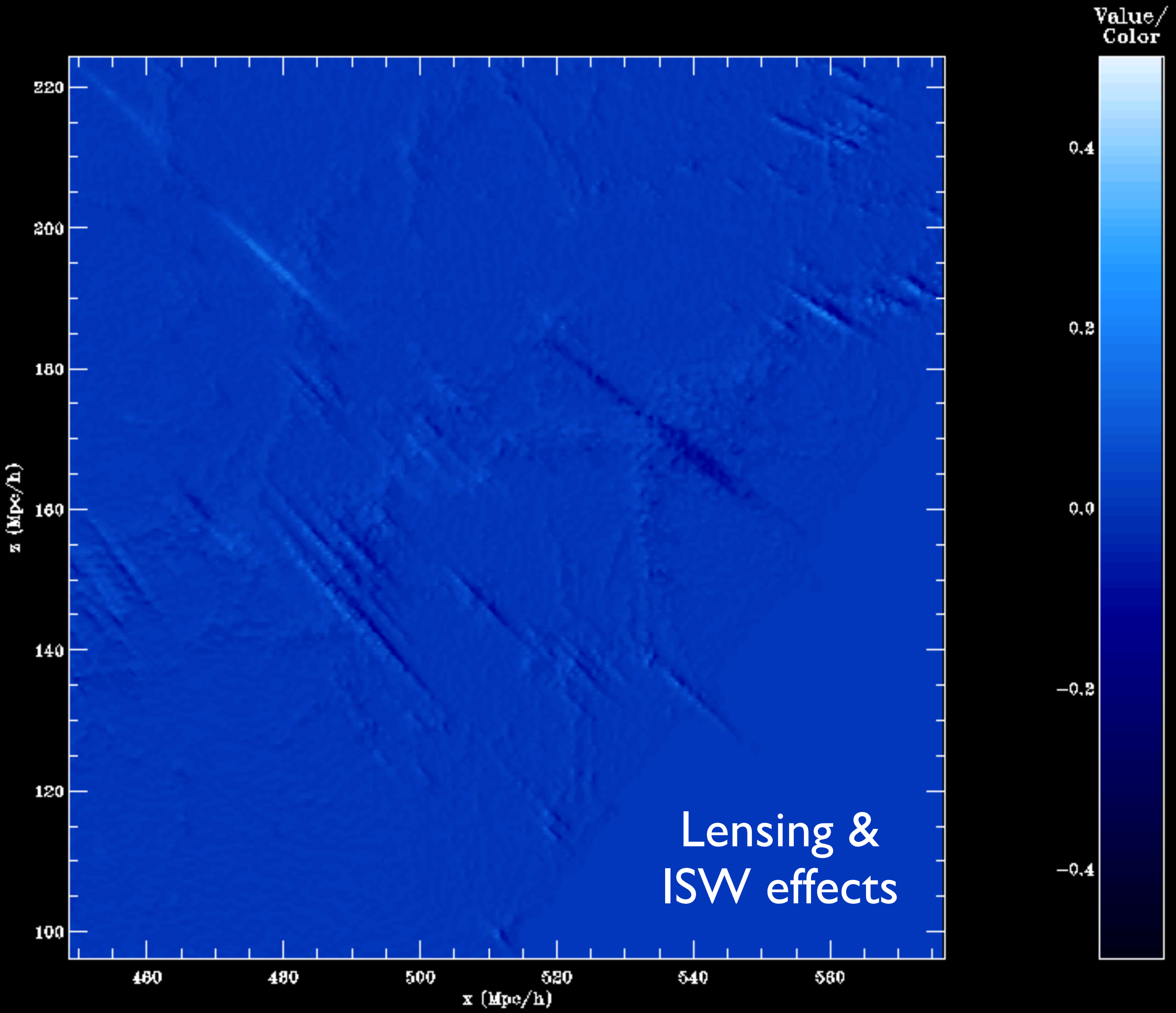
density_allrelativisticeffects



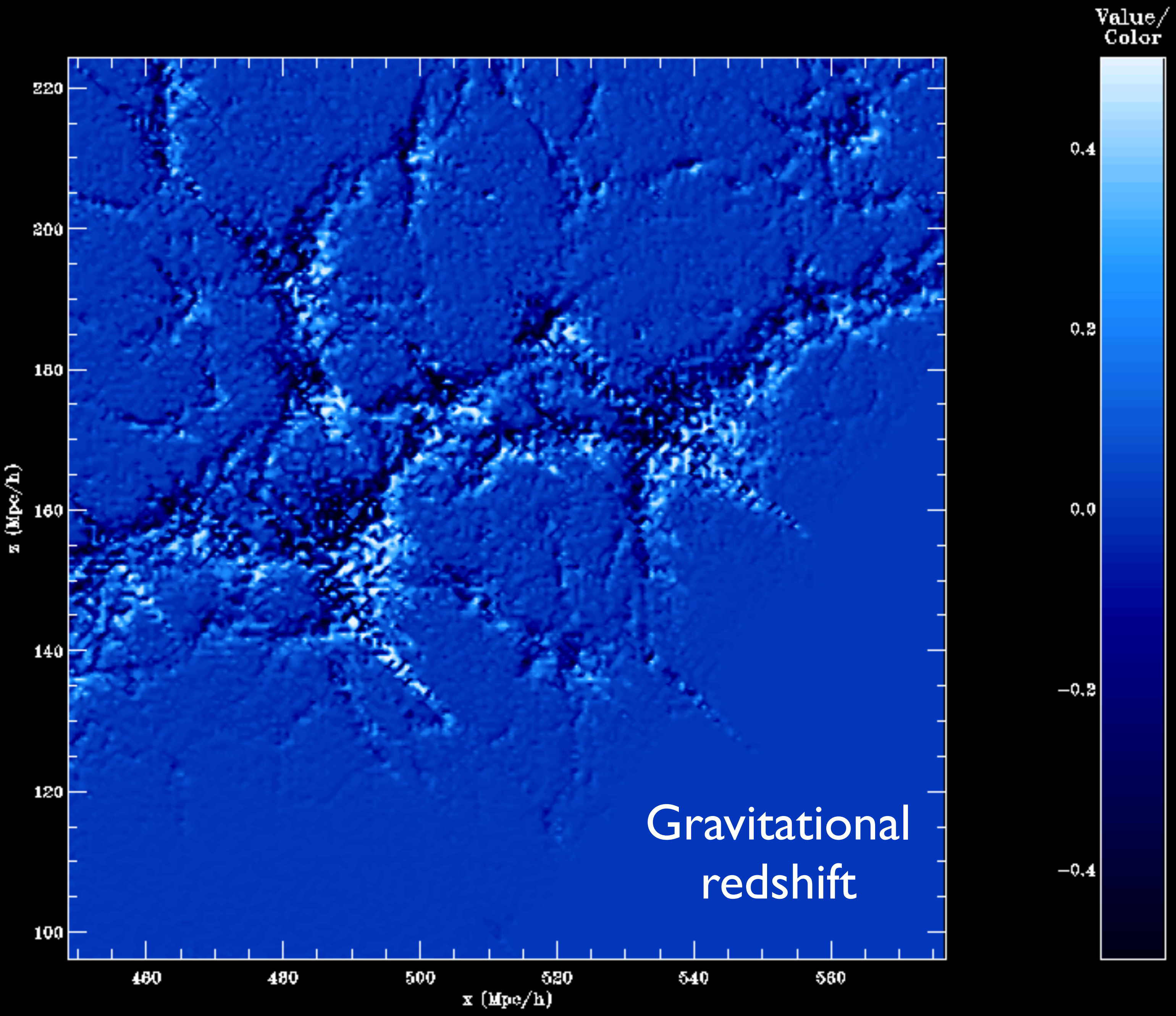
‘Observed’
redshift space

All relativistic
effects included

density_zoom2_integrated_contrib

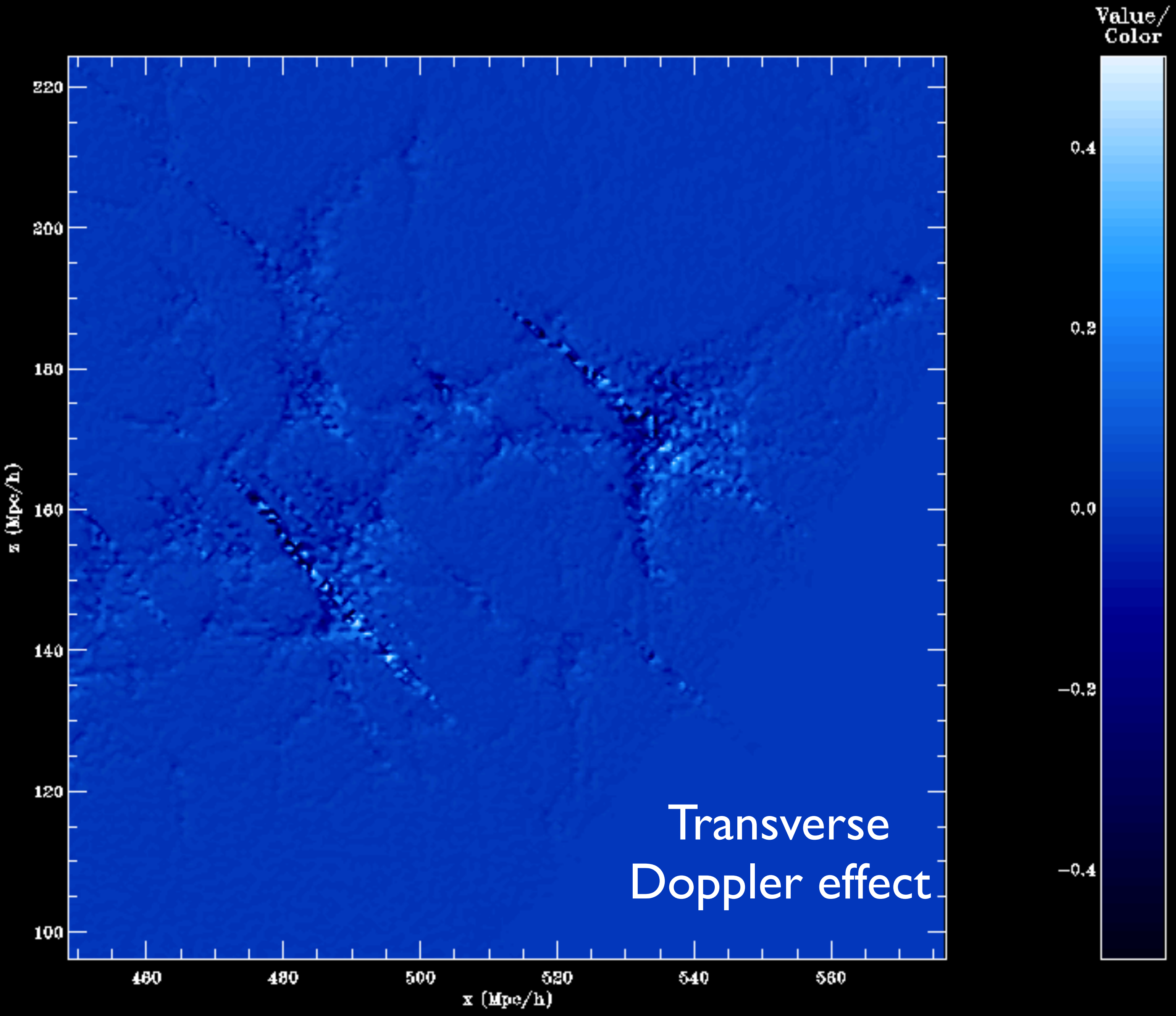


density_zoom2_potential_contrib



Gravitational redshift

density_zoom2_transversedoppler_contrib

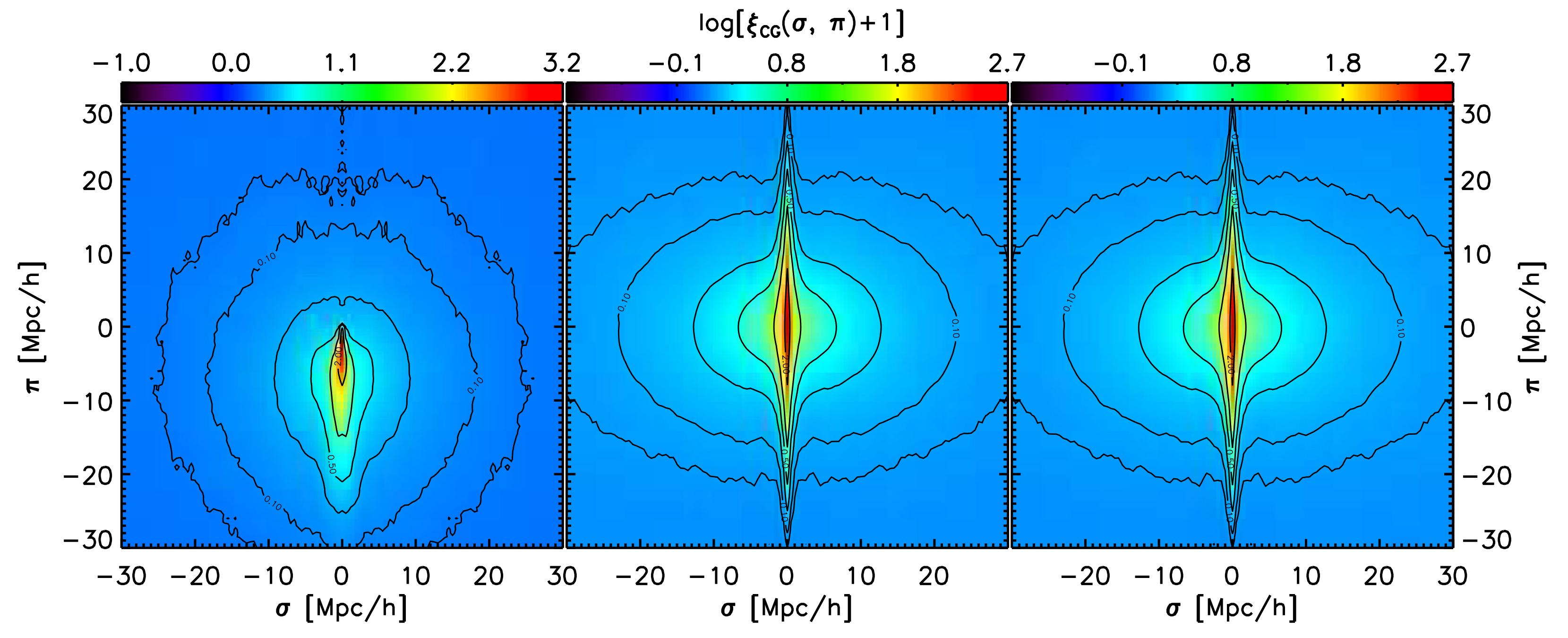


Transverse
Doppler effect

Signature of new relativistic effect

Gravitational redshift induces *dipole anisotropies* in cluster-mass cross-correlation function

Gravitational redshift RSD Total



Cai, Kaiser, Cole & Frenk ('17)

Summary

Describing observed large-scale structure in precision cosmology
redshift-space distortions and beyond

Redshift-space distortions as a probe of gravity

Modeling RSD from perturbation theory

⟶ Testing and constraining gravity from SDSS data

General relativistic effects on large-scale structure

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

More fun for precision cosmology !