Observational effects on large-scale structure observations

Redshift-space distortions

赤方偏移空間

観測者が定義する空間は‘実際’の空間とは違う

特殊相対論の最低次の効果 (*i.e.*, $v/c \ll 1$)

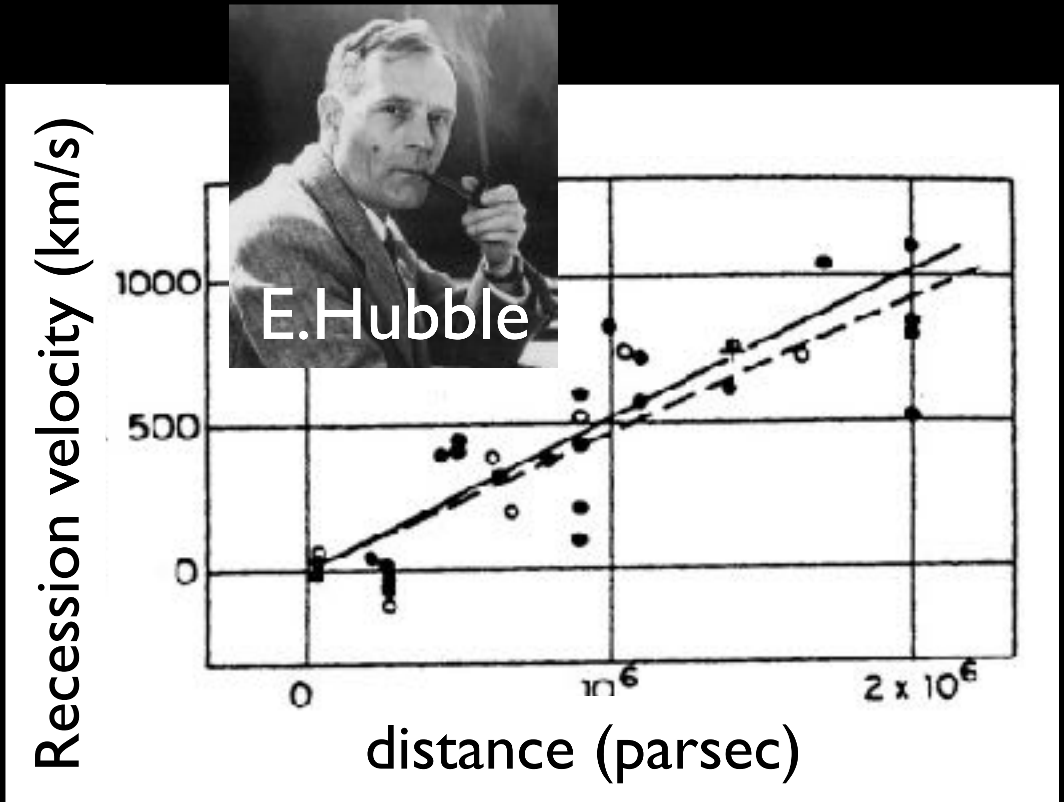
銀河の特異速度

赤方偏移空間
(共動系)

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

実空間

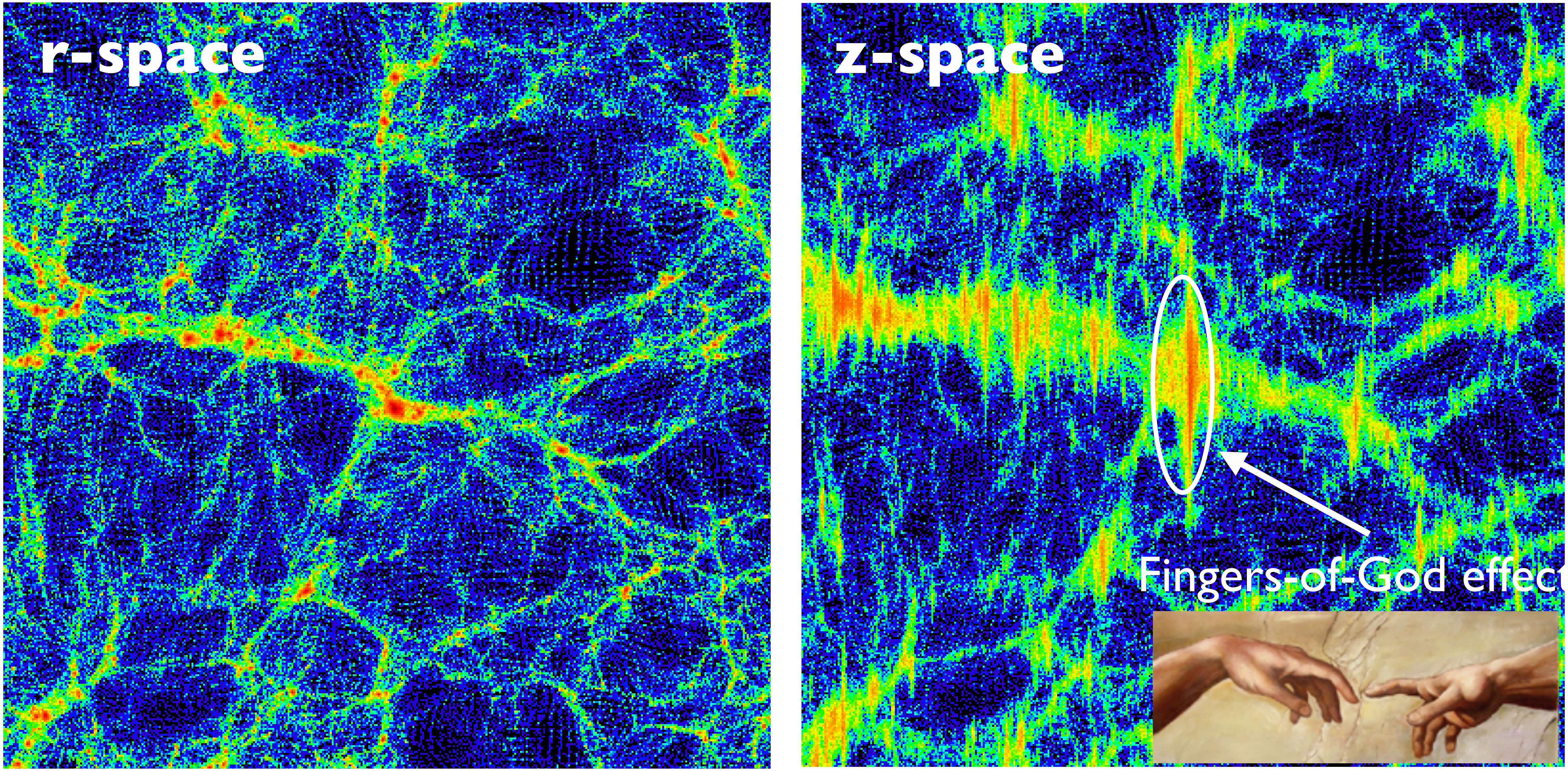
観測者の視線方向



- ハッブルダイアグラムに見られるバラツキの原因
- ２点相関関数・パワースペクトルでは系統的効果として効く

Redshift-space distortions (RSD)

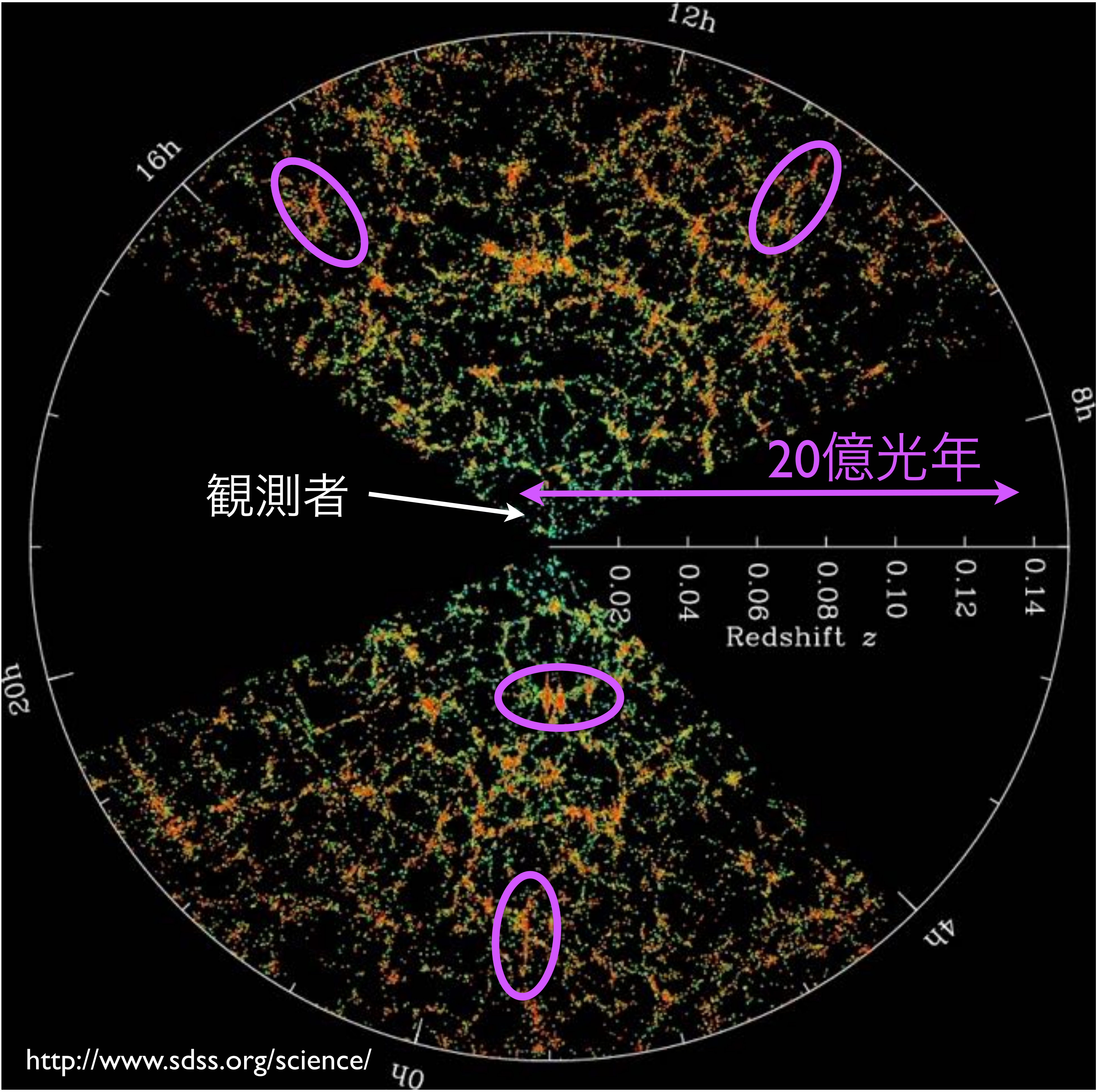
Dark matter in N-body simulations (by T. Nishimichi)



~100Mpc/h ?

↑ observer's line-of-sight direction

RSD in SDSS-II main galaxies



http://www.sdss.org/science/

色は銀河の年齢

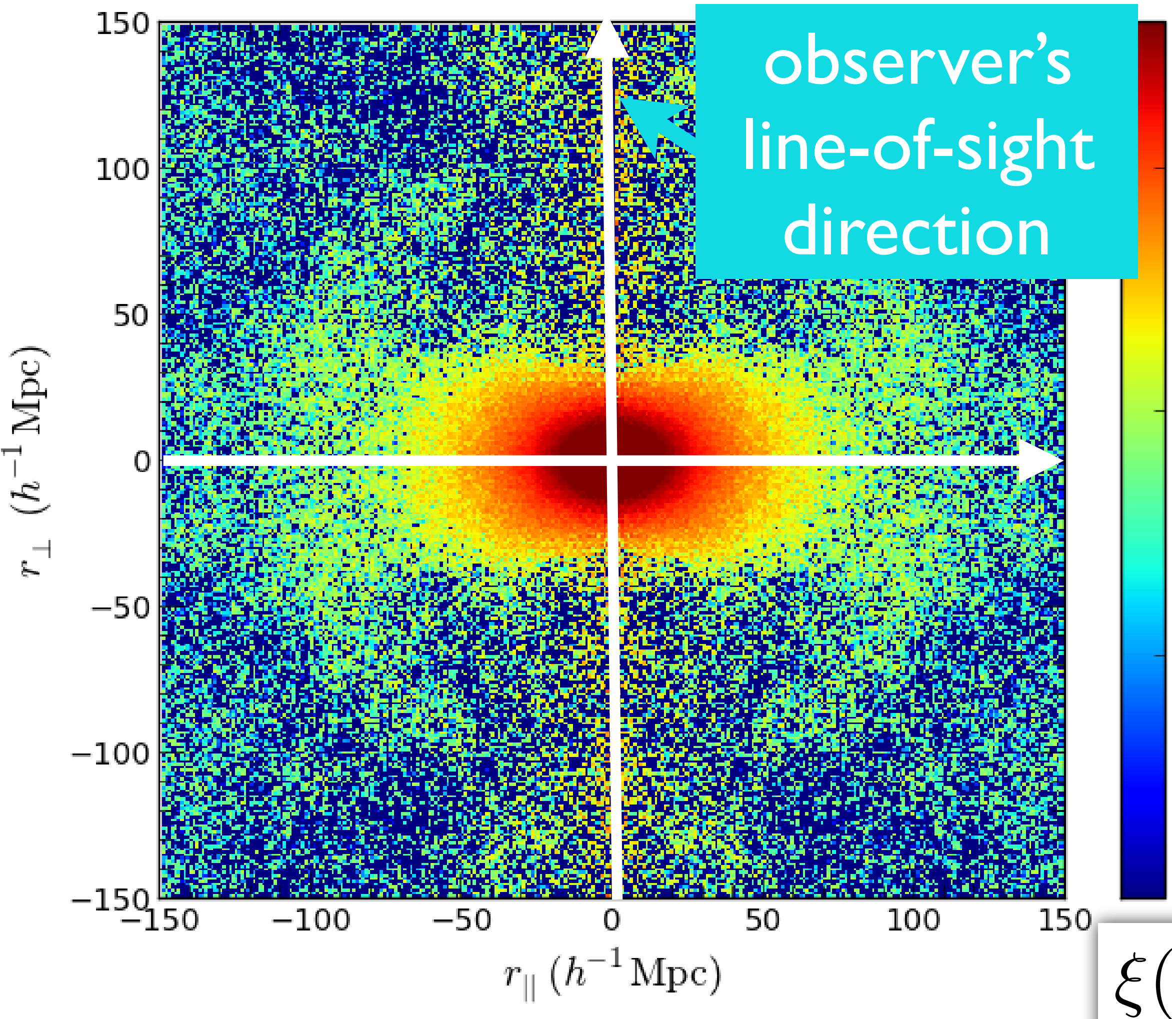
青い：若い

赤い：古い

Anisotropic correlation function

BOSS DR11, CMASS samples

700,000gals @ 0.43<z<0.7

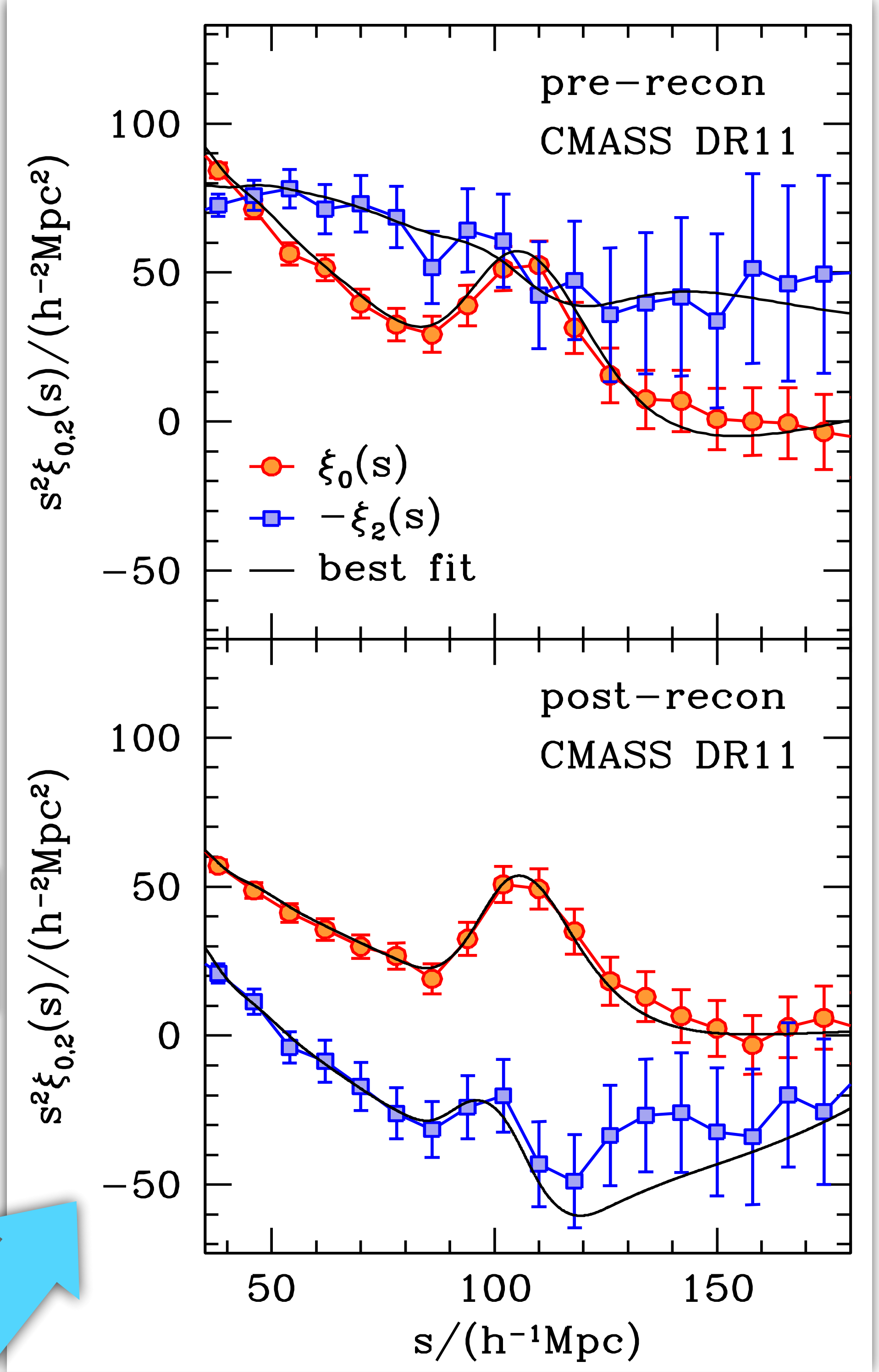


observer's line-of-sight direction

Samushia et al.('13)

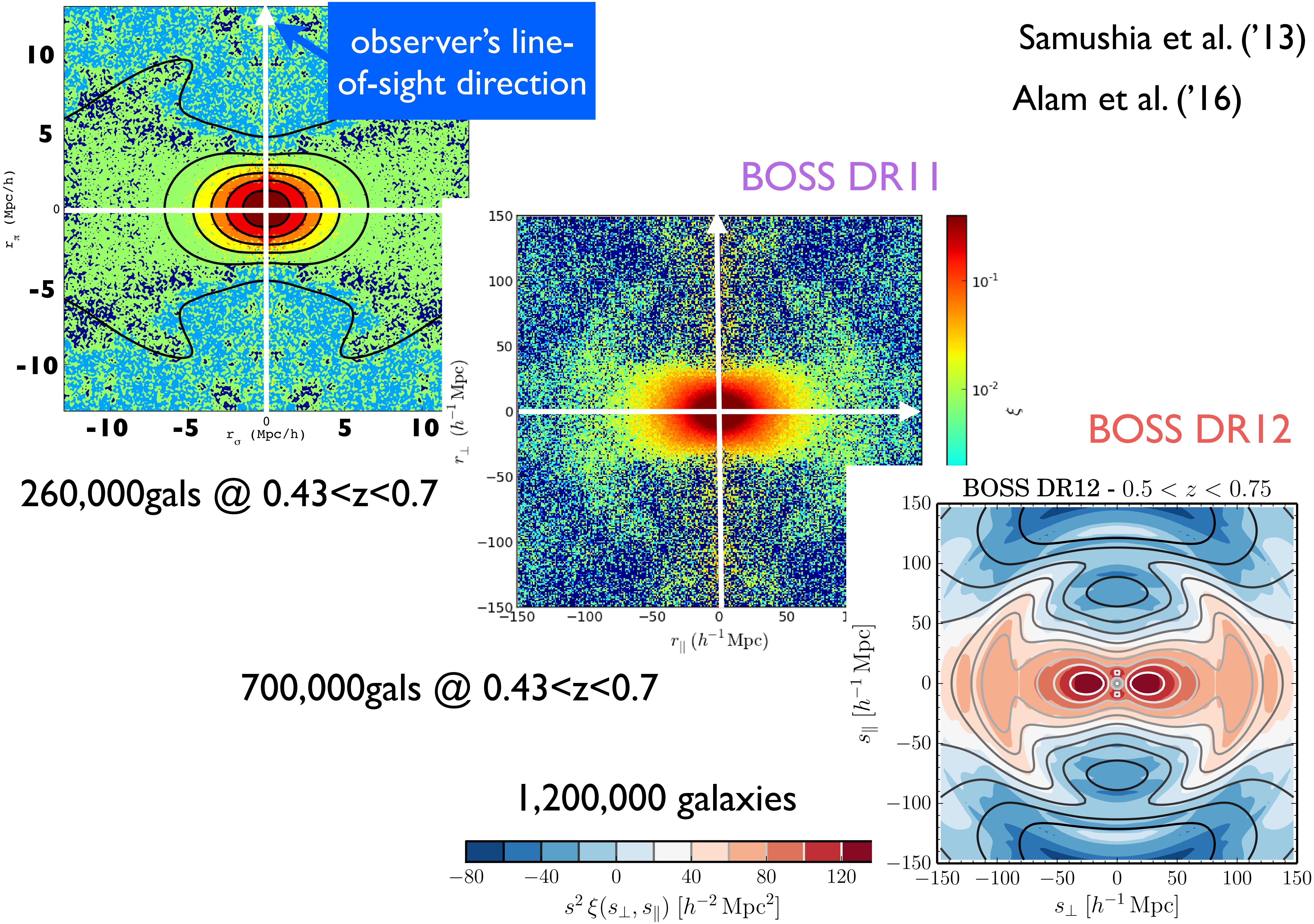
$\xi(r_\perp, r_\parallel)$

Anderson et al.('13)



Multipole expansion

$$\xi(r_\perp, r_\parallel) = \sum_{\ell:\mathrm{even}} \xi_\ell(s)\,\mathcal{L}_\ell(r_\parallel/s)\ ;\ \ s = (r_\perp^2 + r_\parallel^2)^{1/2}$$



BOSS DR9

260,000gals @ 0.43<z<0.7

BOSS DR11

700,000gals @ 0.43<z<0.7

BOSS DR12

1,200,000 galaxies

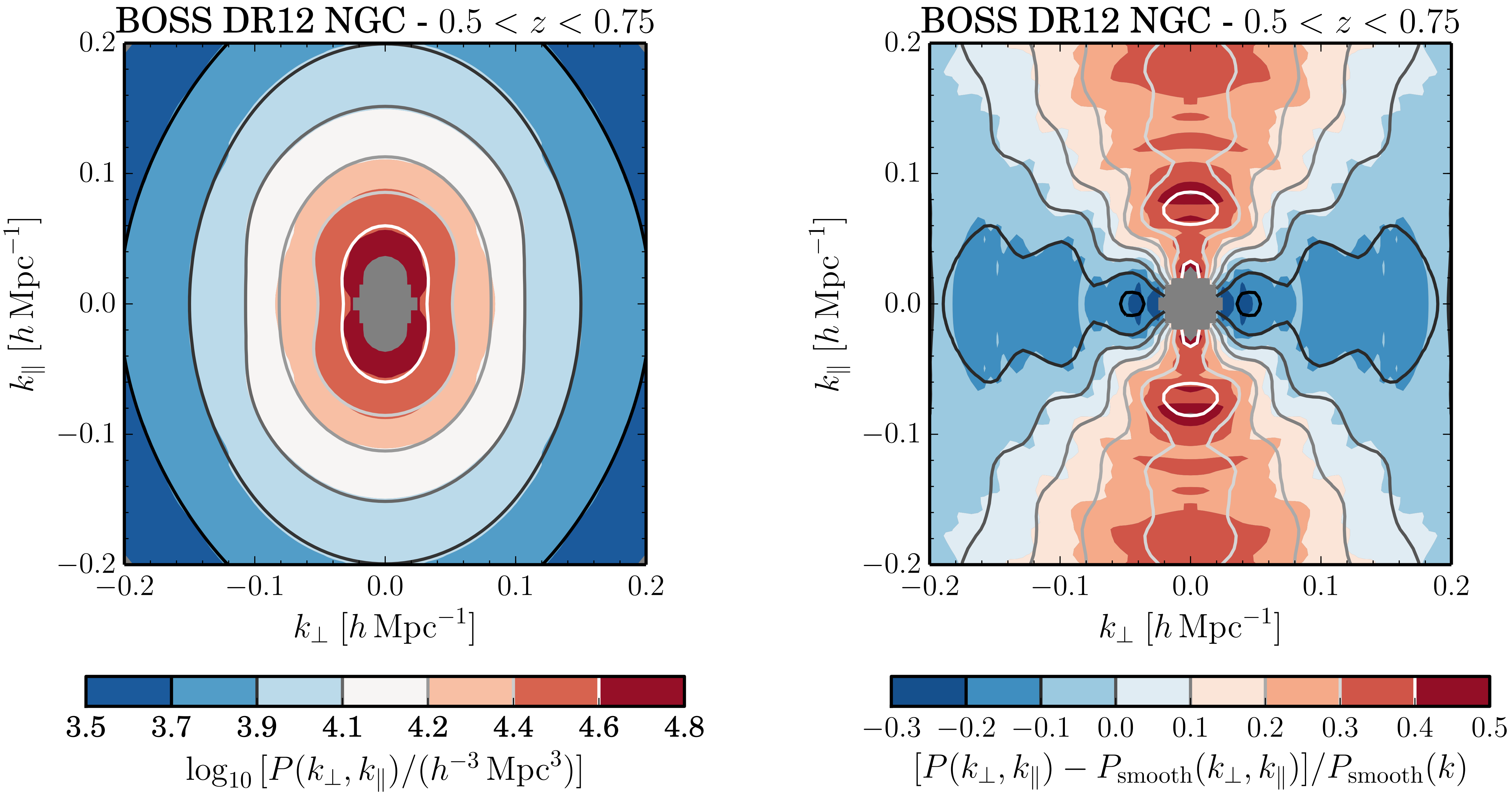
Reid et al. ('12)

Samushia et al. ('13)

Alam et al. ('16)

Anisotropic power spectrum

BOSS DR12

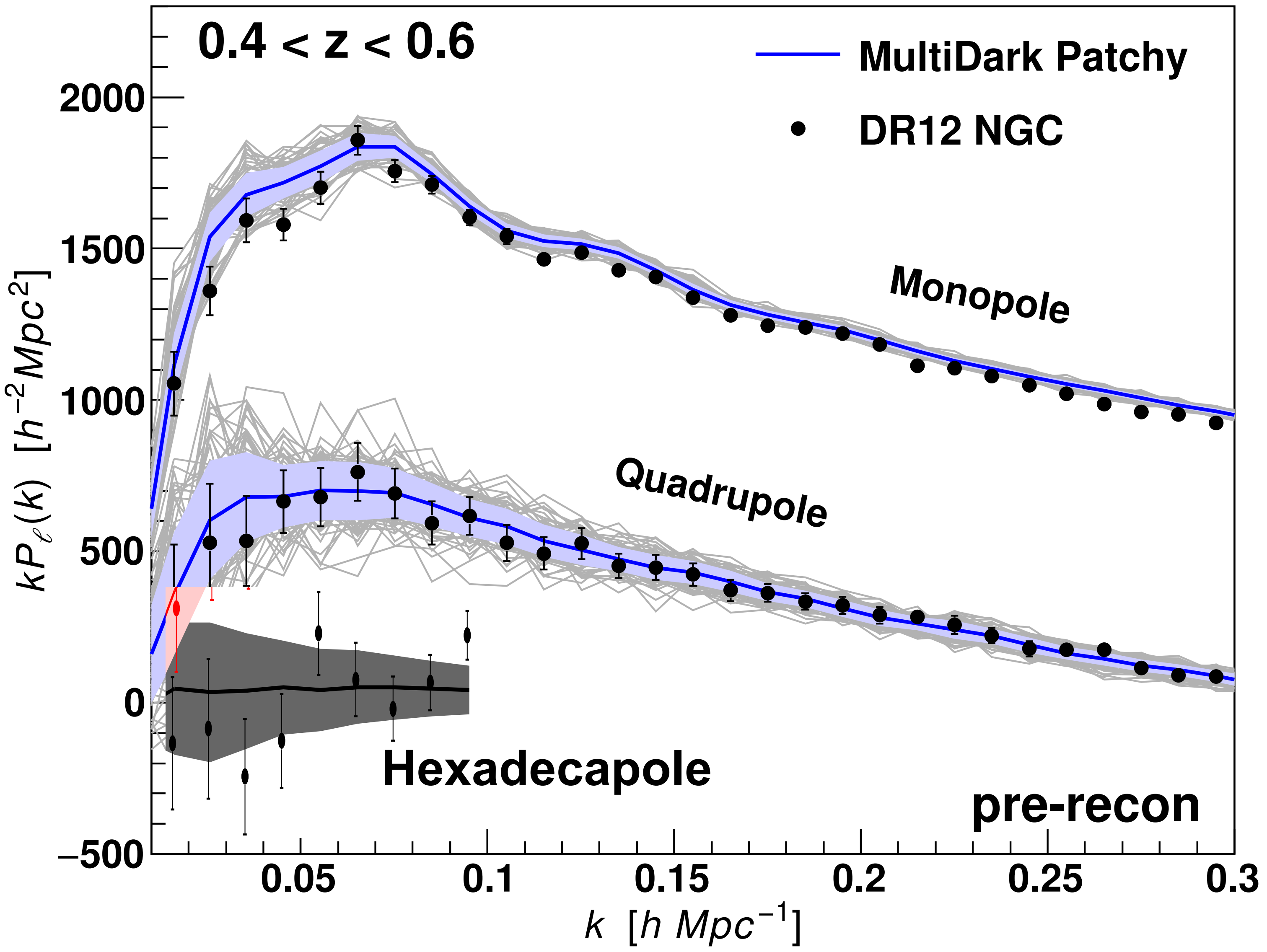


Alam et al. ('16)

Anisotropic power spectrum

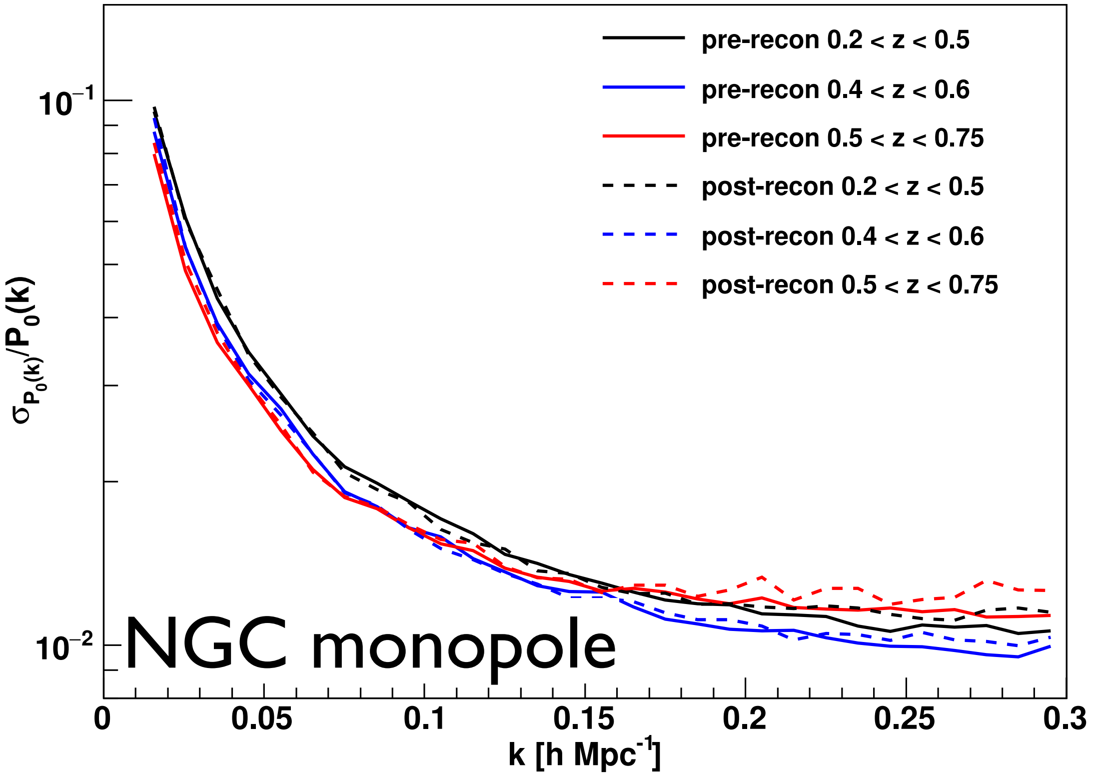
BOSS DR12

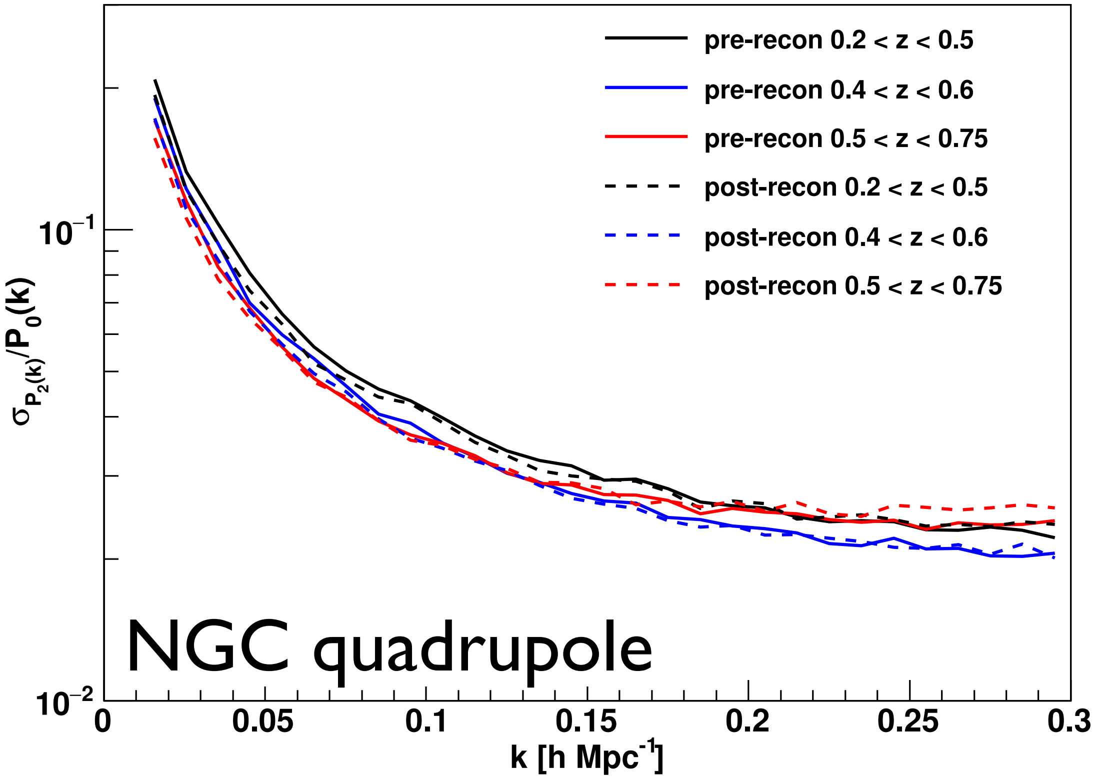
Beutler et al. ('16)



$$P(k_\parallel, k_\perp) = \sum_{\ell:\ \mathrm{even}} P_\ell(k)\, \mathcal{P}_\ell(k_\parallel/k)$$

$$;\ k = (k_\parallel^2 + k_\perp^2)^{1/2}$$





カイザー公式

Kaiser (‘87)

赤方偏移空間の密度場

$$\delta^{(\mathrm{S})}(\boldsymbol{s}) = \left|\frac{\partial \boldsymbol{s}}{\partial \boldsymbol{x}}\right|^{-1}\{1+\delta(\boldsymbol{s})\}-1$$

質量密度の保存

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

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

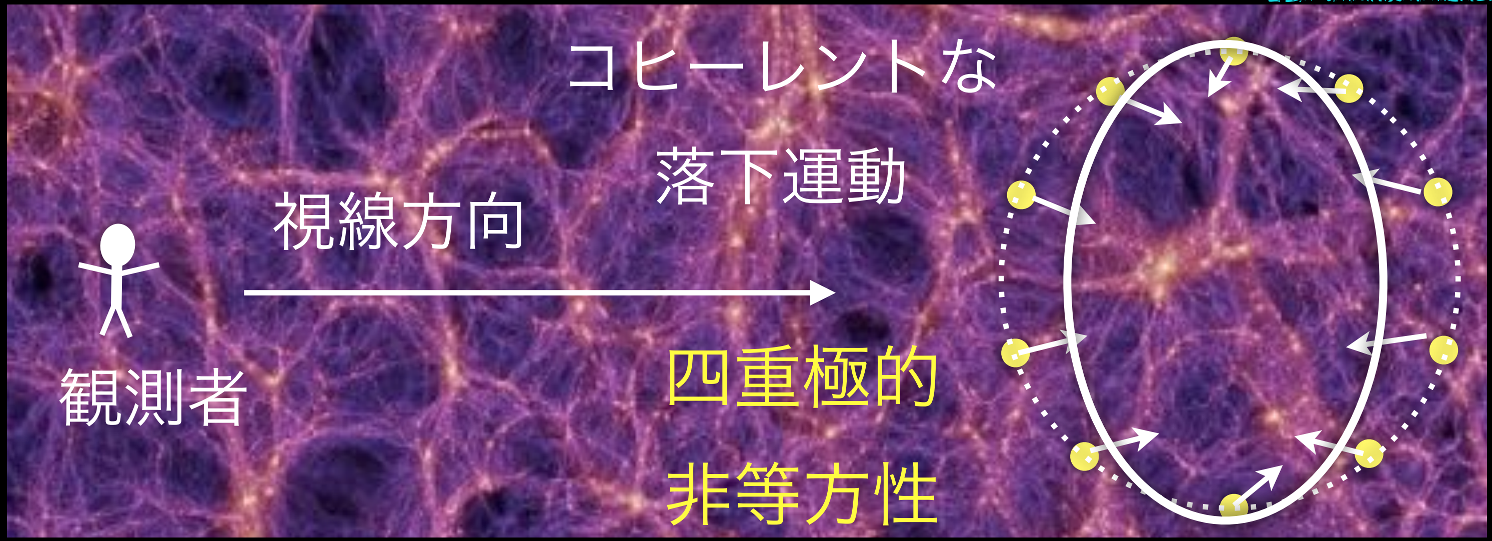
（線形近似）

フーリエ変換

連続の式：$\dot{\delta} + \frac{1}{a}\nabla\cdot\boldsymbol{v} \simeq 0$

（渦なし）

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



視線方向に沿って密度場の振幅超過

重力のプローブ

カイザー公式

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

線形成長因子

スケール因子

構造の成長率は重力の性質によって変わりうる

しかも

カイザー公式は重力理論とは無関係に成り立つ

➡ 宇宙論的大スケールで重力理論（相対論）を検証する手段

- ΛCDMモデルの中で未だ検証されていない仮定
- 加速膨張の起源に迫る手がかり

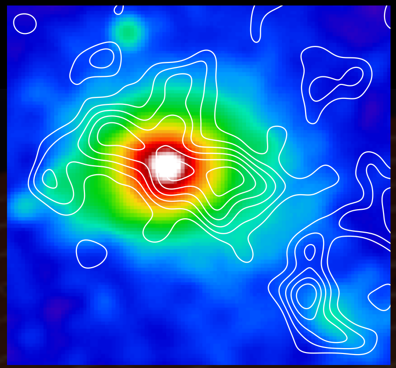
e.g., Linder ('08); Guzzo et al. ('08); Yamamoto et al. ('08); Percival & White ('09)

宇宙論的大スケールにおける重力

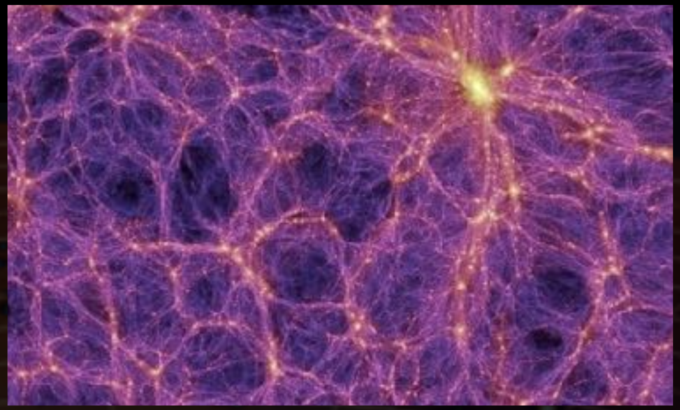
銀河

高密度

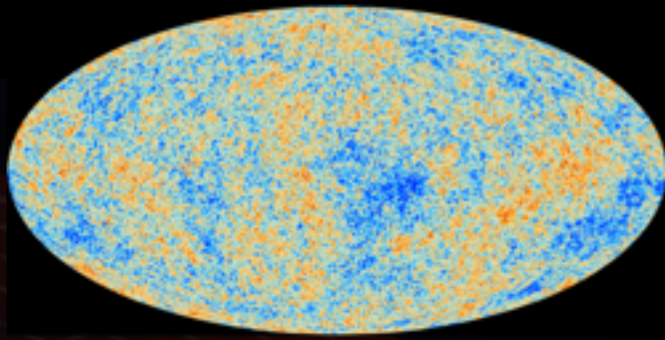
銀河団



銀河のクラスタリング



CMB



小スケール
(~kpc)

構造形成の修正

大スケール
(~Gpc)

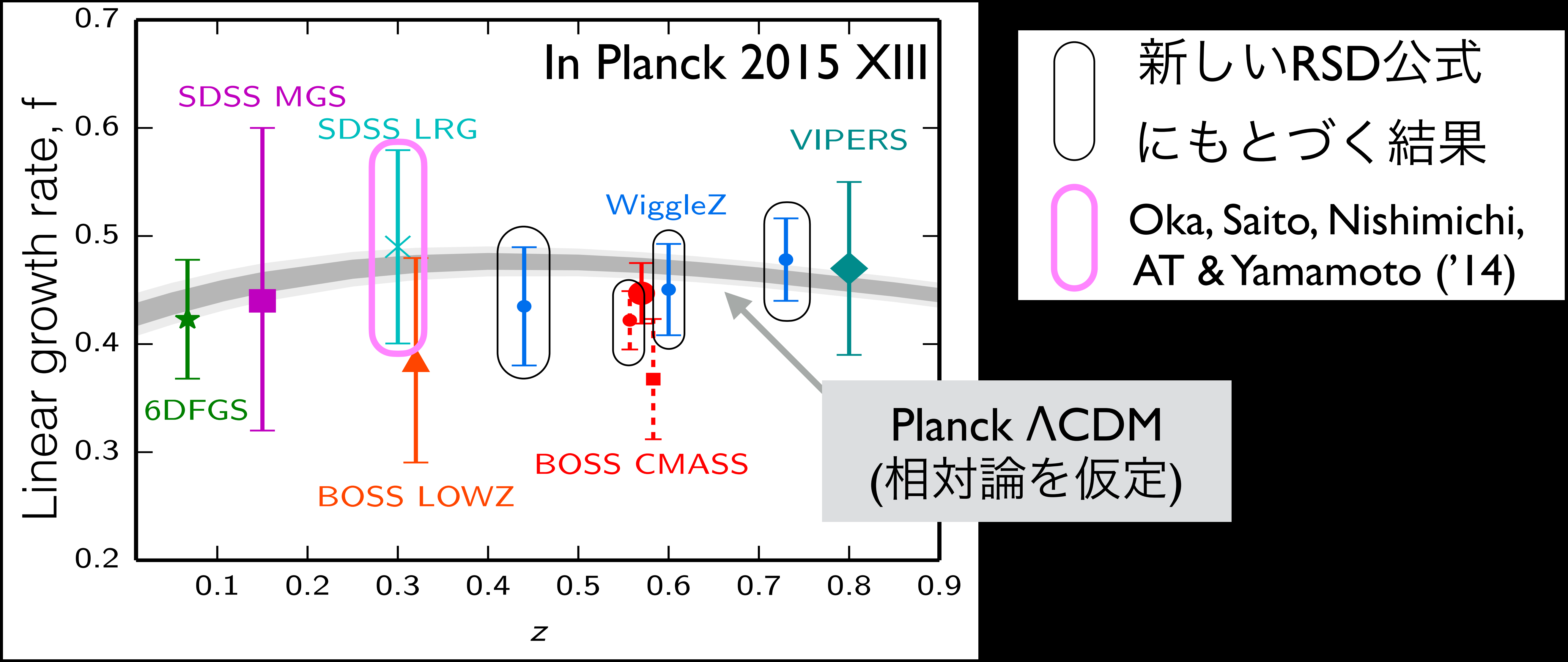
一般相対論を再現
(重力スクリーニング)

スカラー自由度による
第５の力の発現
➡ 加速膨張

修正重力を記述する理論的枠組みは十分すぎるほど発展した:
f(R)重力、DGP、ホルンデスキー、ビヨンドホルンデスキー…

相対論のテスト

相対論（ΛCDM）が正しいと仮定して構築した理論テンプレートを観測データと比較して、正しく成長率が求まるか？



新しいRSD公式にもとづく結果

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

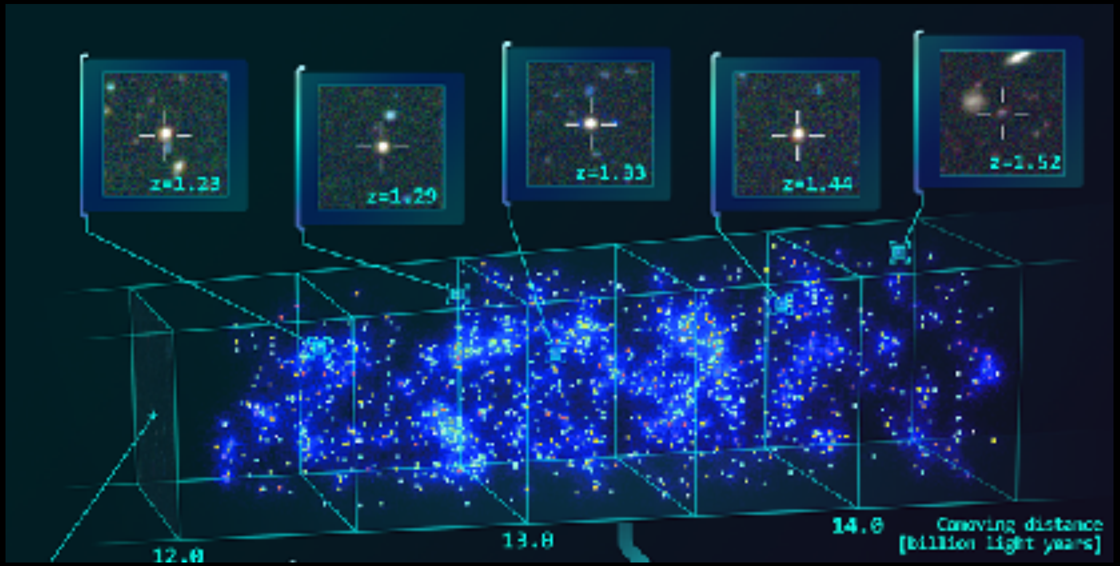
Planck ΛCDM
(相対論を仮定)

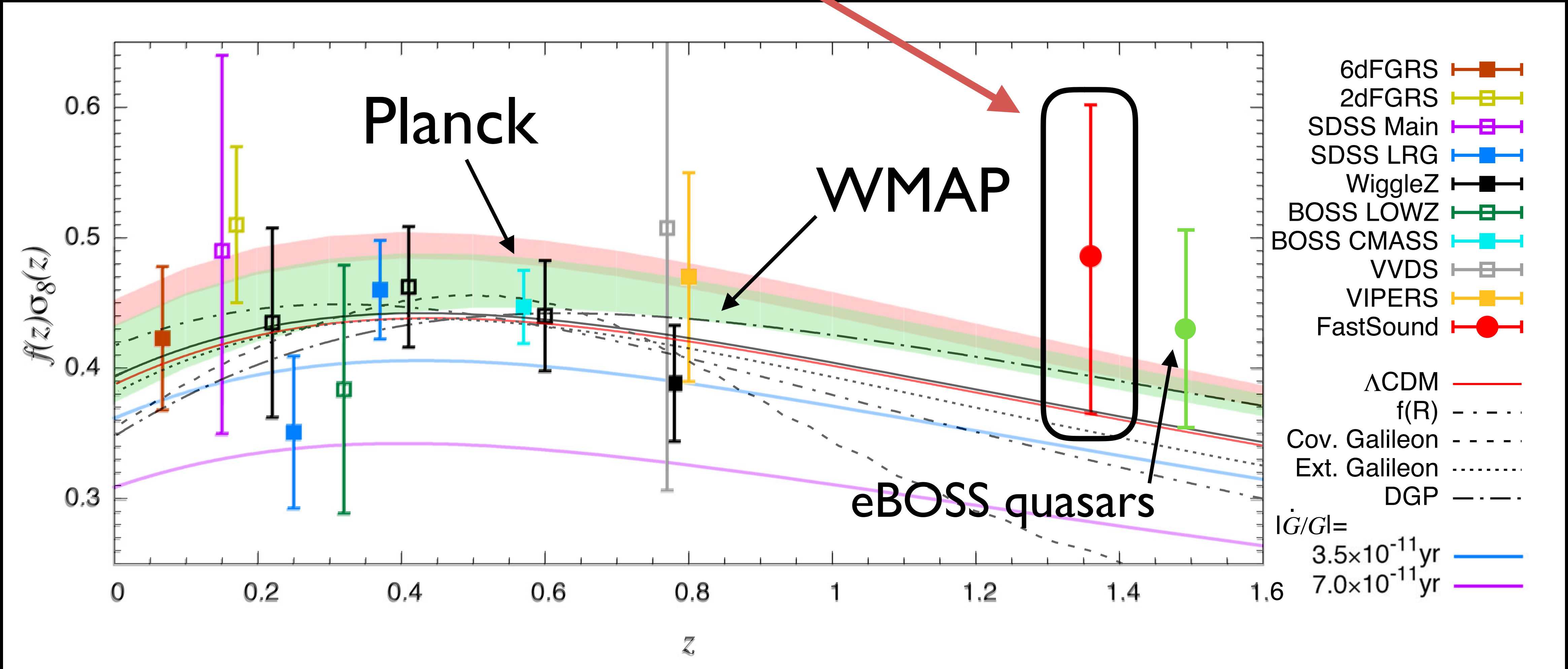
最近のデータ（BOSS DR12）でも新しいRSD公式が使われたが、相対論からの有意なずれは見つかっていない　(Beutler, Seo, Saito et al. '16)

高赤方偏移での制限

z~1.4 で2800個の輝線銀河を用いた

RSD観測　（線形理論でよくフィット）





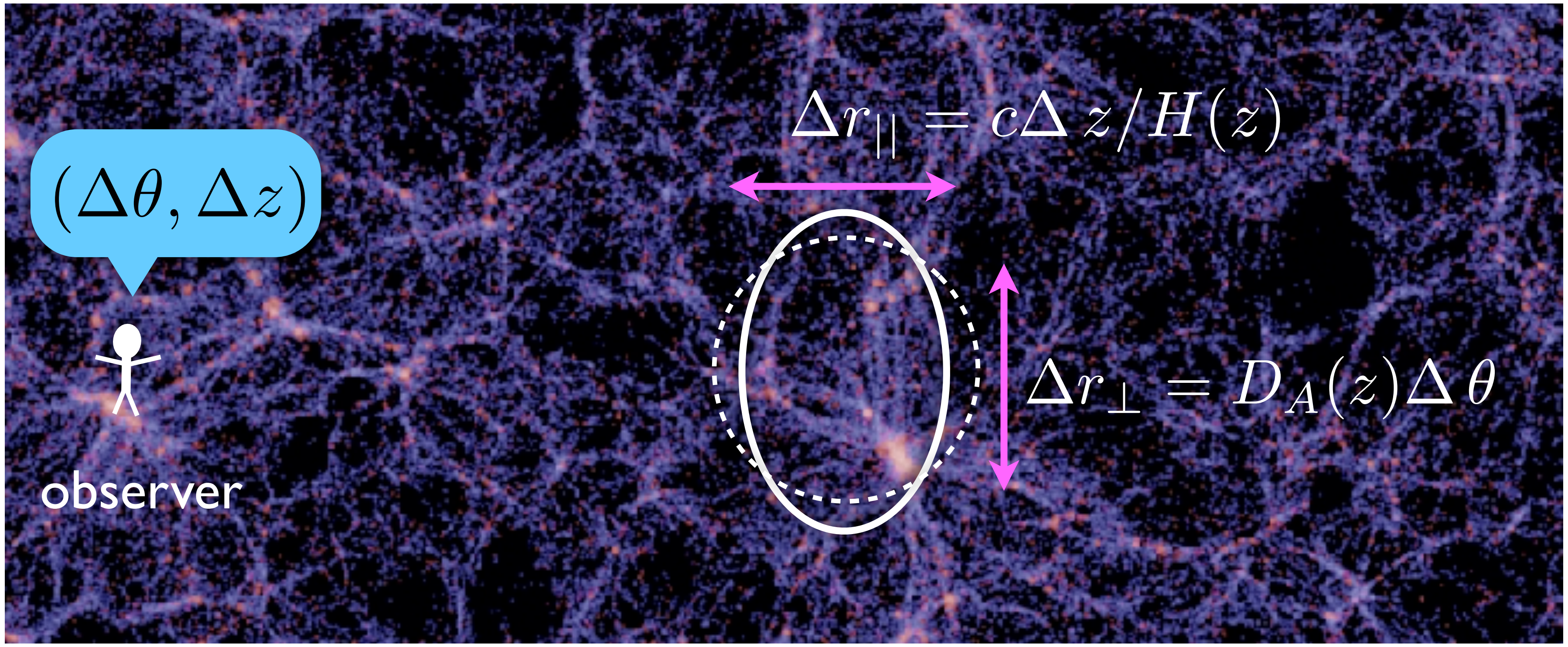
Okumura et al. ('16)

Geometric distortions (Alcock-Paczynski effect)

Geometric distortions

(Alcock-Paczynski effect)

Cosmological distortions caused by apparent mismatch of underlying cosmological models

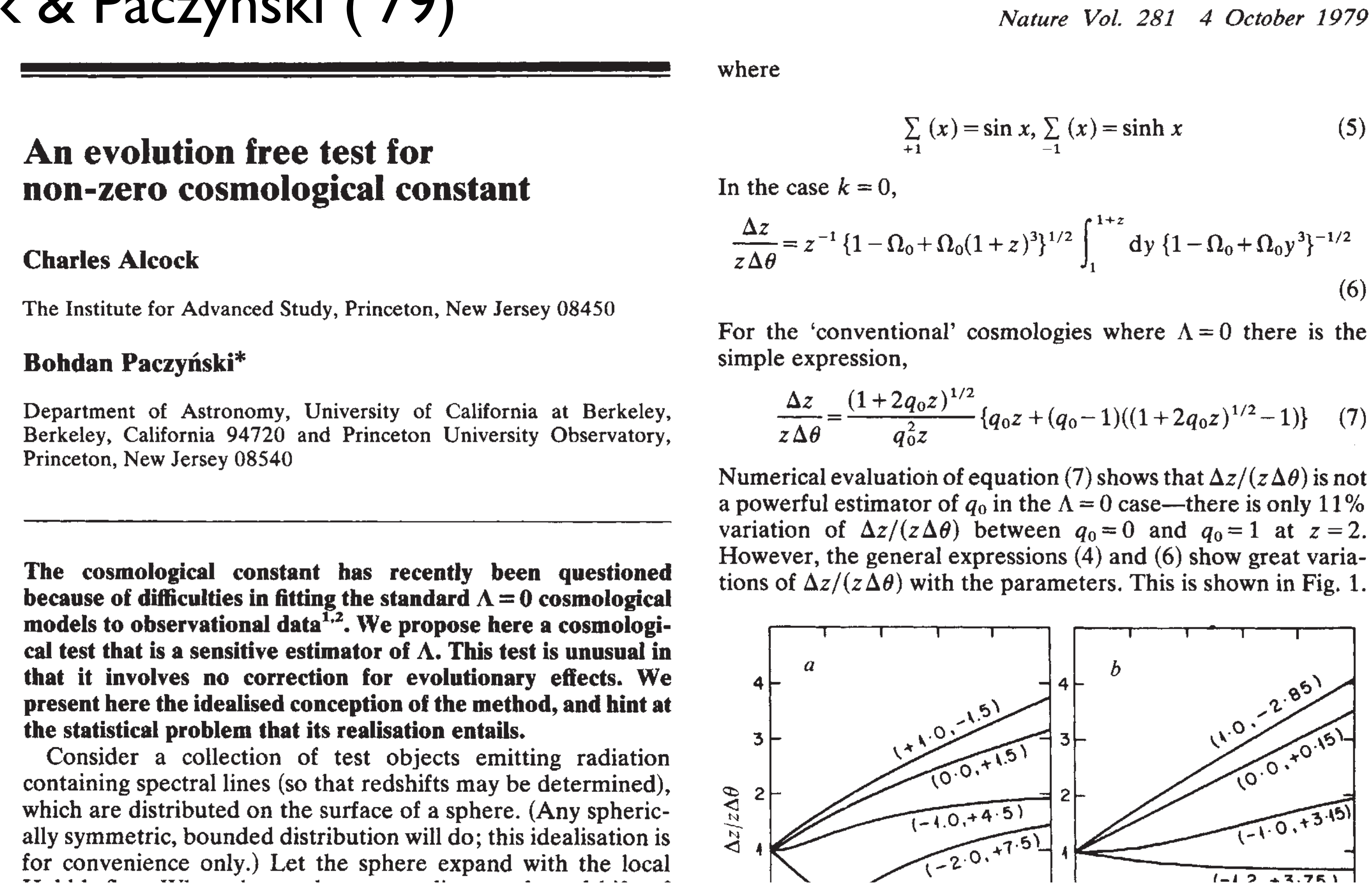


⟶ can generate higher multipole moments of anisotropies

Using the standard ruler,

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

Alcock & Paczynski ('79)



Nature Vol. 281 4 October 1979

An evolution free test for non-zero cosmological constant

Charles Alcock

The Institute for Advanced Study, Princeton, New Jersey 08450

Bohdan Paczyński*

Department of Astronomy, University of California at Berkeley, Berkeley, California 94720 and Princeton University Observatory, Princeton, New Jersey 08540

The cosmological constant has recently been questioned because of difficulties in fitting the standard $\Lambda = 0$ cosmological models to observational data[1,2]. We propose here a cosmological test that is a sensitive estimator of Λ. This test is unusual in that it involves no correction for evolutionary effects. We present here the idealised conception of the method, and hint at the statistical problem that its realisation entails.

Consider a collection of test objects emitting radiation containing spectral lines (so that redshifts may be determined), which are distributed on the surface of a sphere. (Any spherically symmetric, bounded distribution will do; this idealisation is for convenience only.) Let the sphere expand with the local

where

$$\sum_{+1}(x) = \sin x,\ \sum_{-1}(x) = \sinh x \qquad (5)$$

In the case $k = 0$,

$$\frac{\Delta z}{z\Delta\theta} = z^{-1}\{1-\Omega_0+\Omega_0(1+z)^3\}^{1/2}\int_1^{1+z} \mathrm{d}y\,\{1-\Omega_0+\Omega_0 y^3\}^{-1/2} \qquad (6)$$

For the 'conventional' cosmologies where $\Lambda = 0$ there is the simple expression,

$$\frac{\Delta z}{z\Delta\theta} = \frac{(1+2q_0z)^{1/2}}{q_0^2 z}\{q_0z+(q_0-1)((1+2q_0z)^{1/2}-1)\} \qquad (7)$$

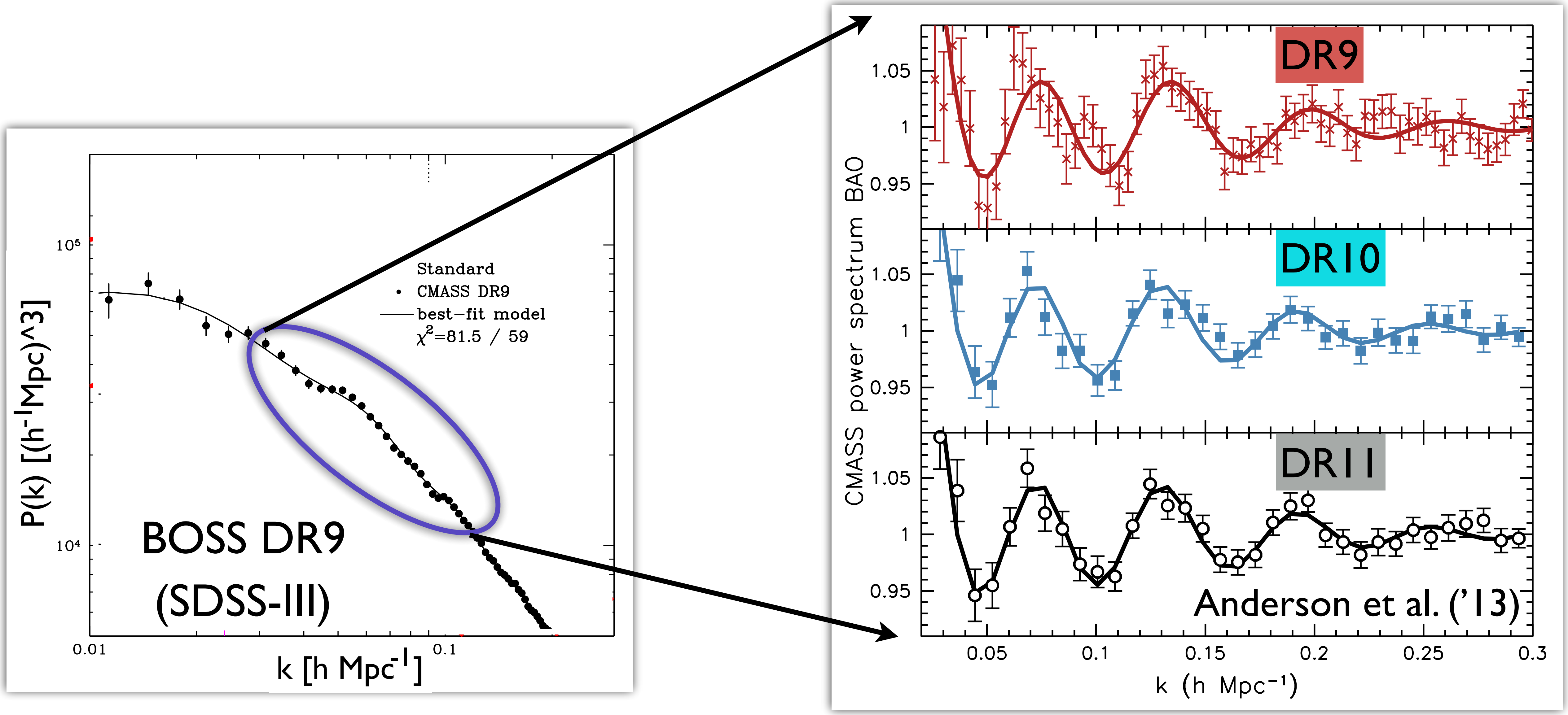
Numerical evaluation of equation (7) shows that $\Delta z/(z\Delta\theta)$ is not a powerful estimator of q_0 in the $\Lambda = 0$ case—there is only 11% variation of $\Delta z/(z\Delta\theta)$ between $q_0 = 0$ and $q_0 = 1$ at $z = 2$. However, the general expressions (4) and (6) show great variations of $\Delta z/(z\Delta\theta)$ with the parameters. This is shown in Fig. 1.

Early studies before detection of BAOs :

- Ryden ('95) --------- shape of void
- Ballinger, Peacock & Heavens ('96)
- Matsubara & Suto ('96); Magira, Jing & Suto ('98) --------- global shape of P(k) or ξ(r)

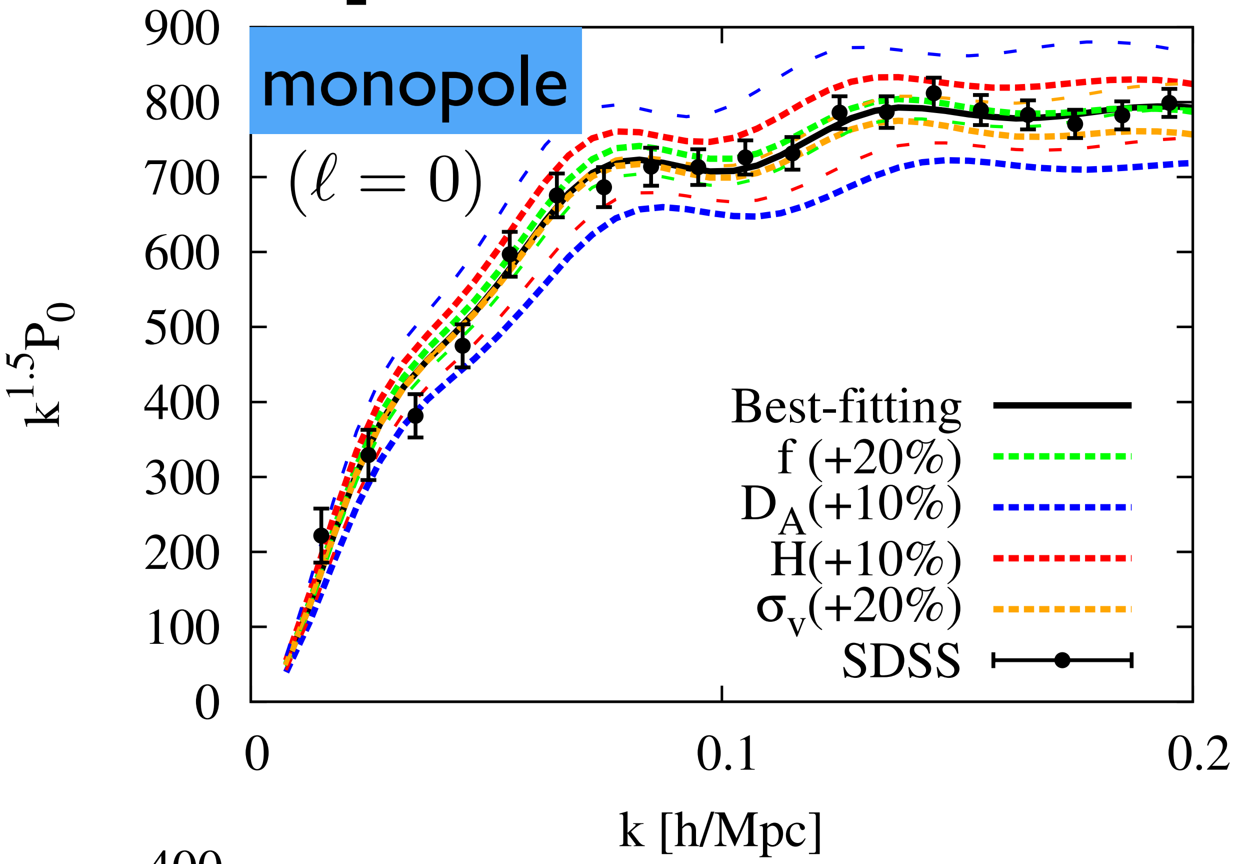
Baryon acoustic oscillations

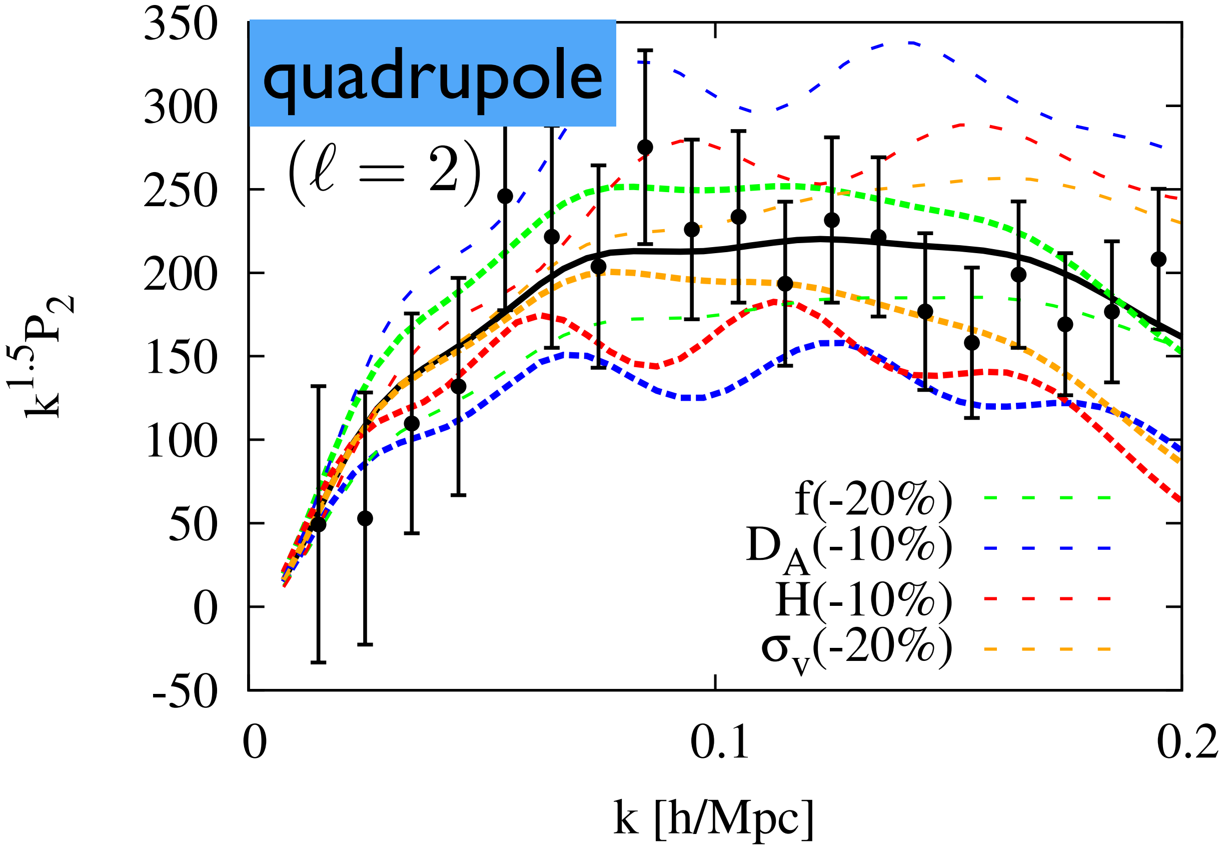
- Characteristic scale of primeval baryon-photon fluid (~150Mpc) imprinted on P(k) or ξ(r)
- Can be used as standard ruler to estimate distance to galaxies

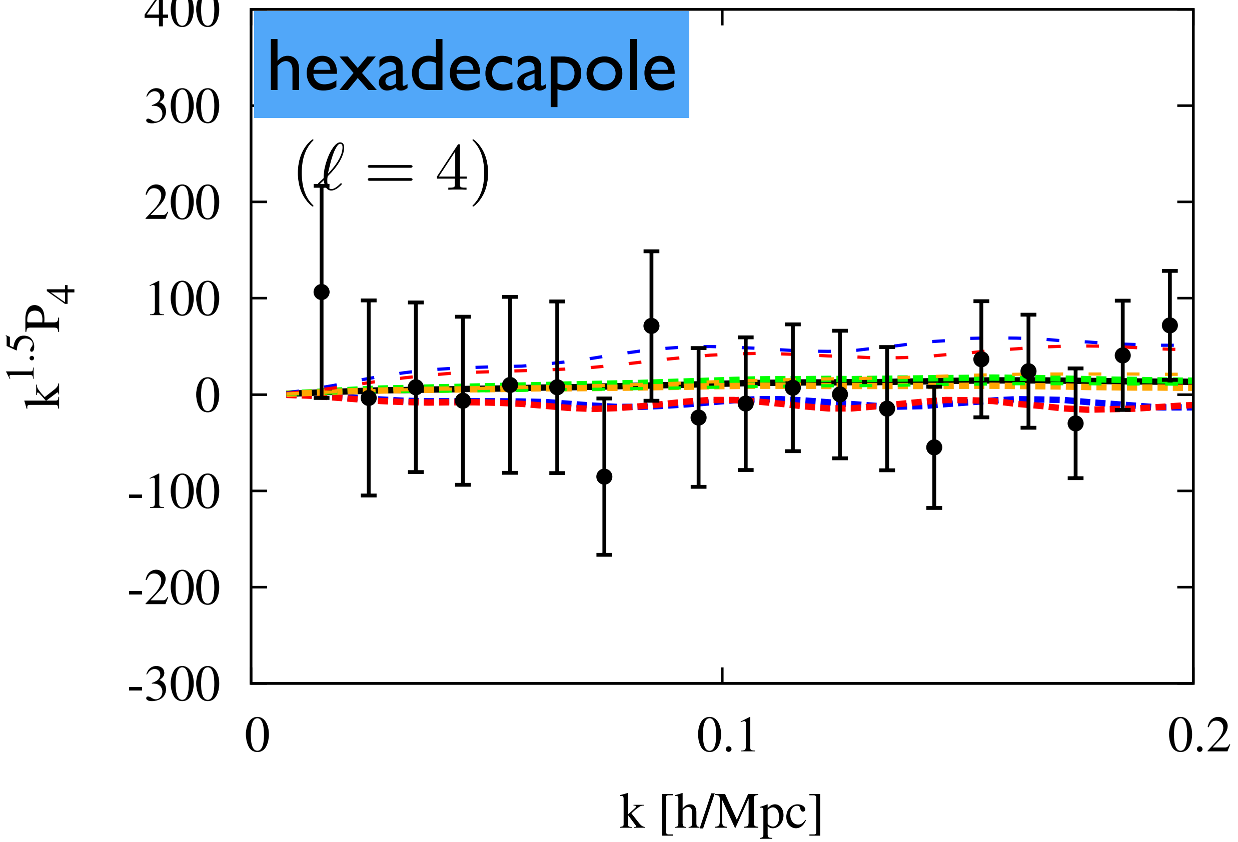


Anderson et al. ('13)

Impact of RSD & A-P effects







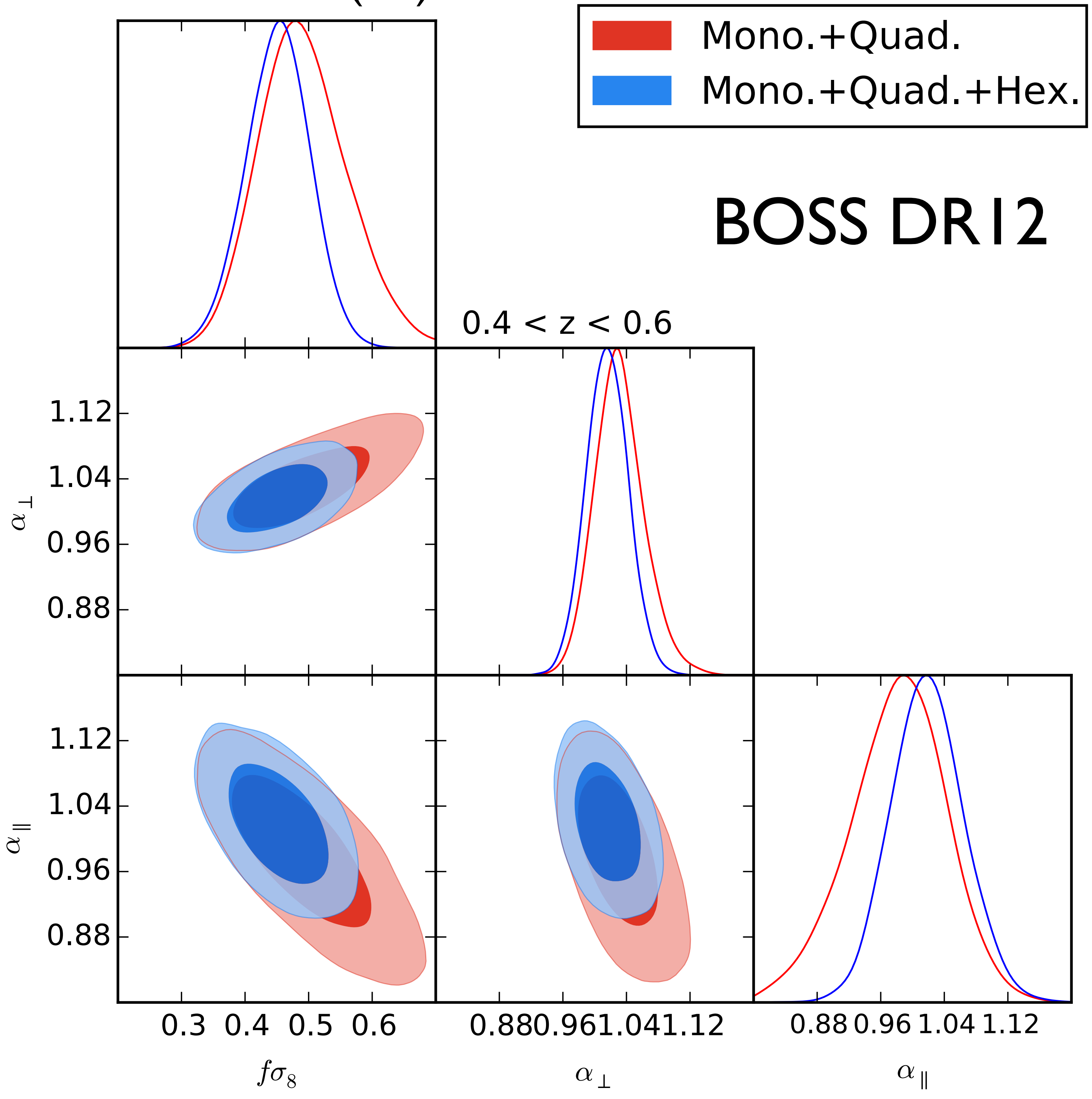
Sensitivity of clustering anisotropies to DA, H & f

Obs. data: SDSS-II DR7 LRG

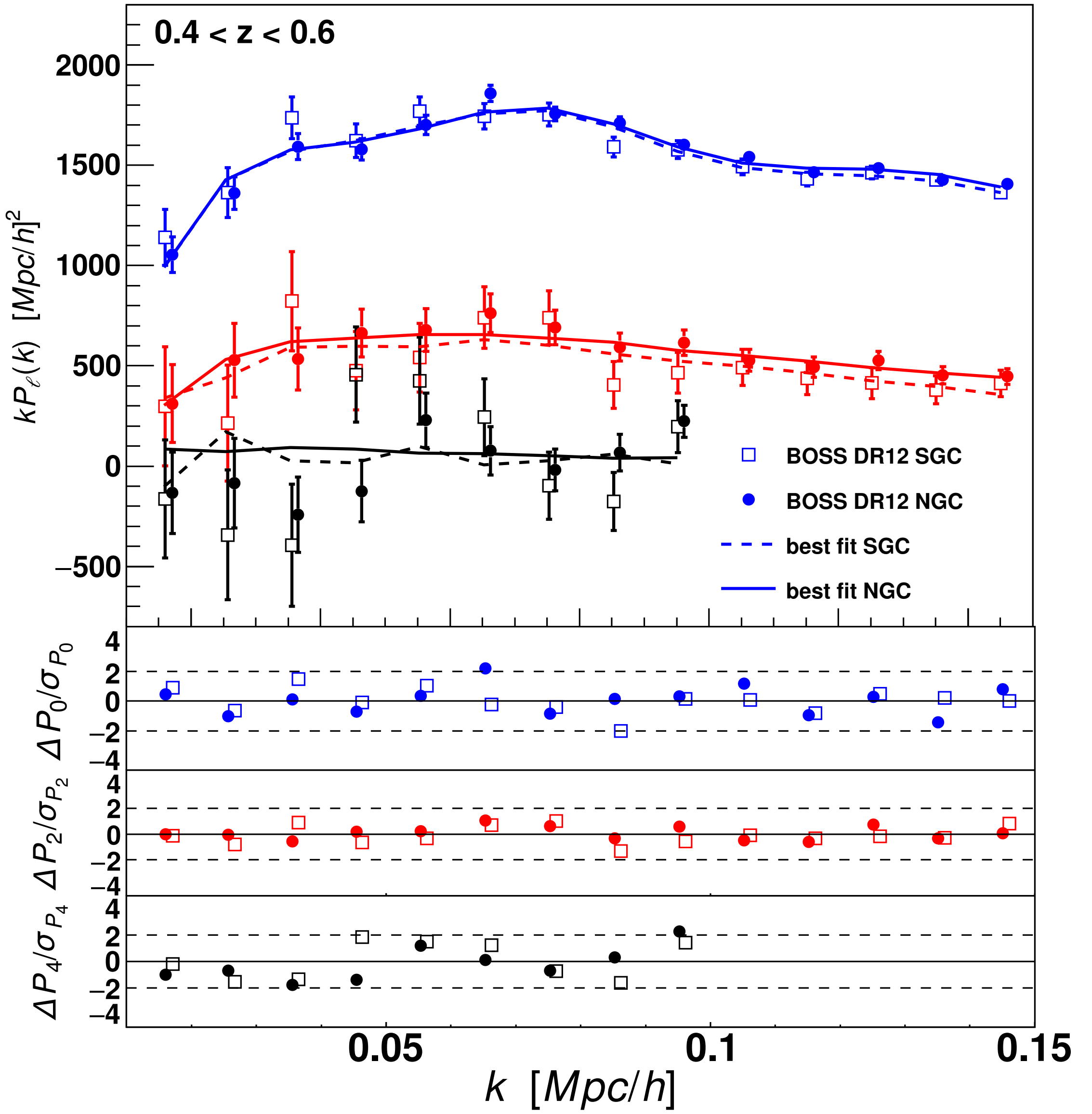
Oka et al.('13) modified

Cosmological constraints

Beutler et al. (16)



BOSS DR12



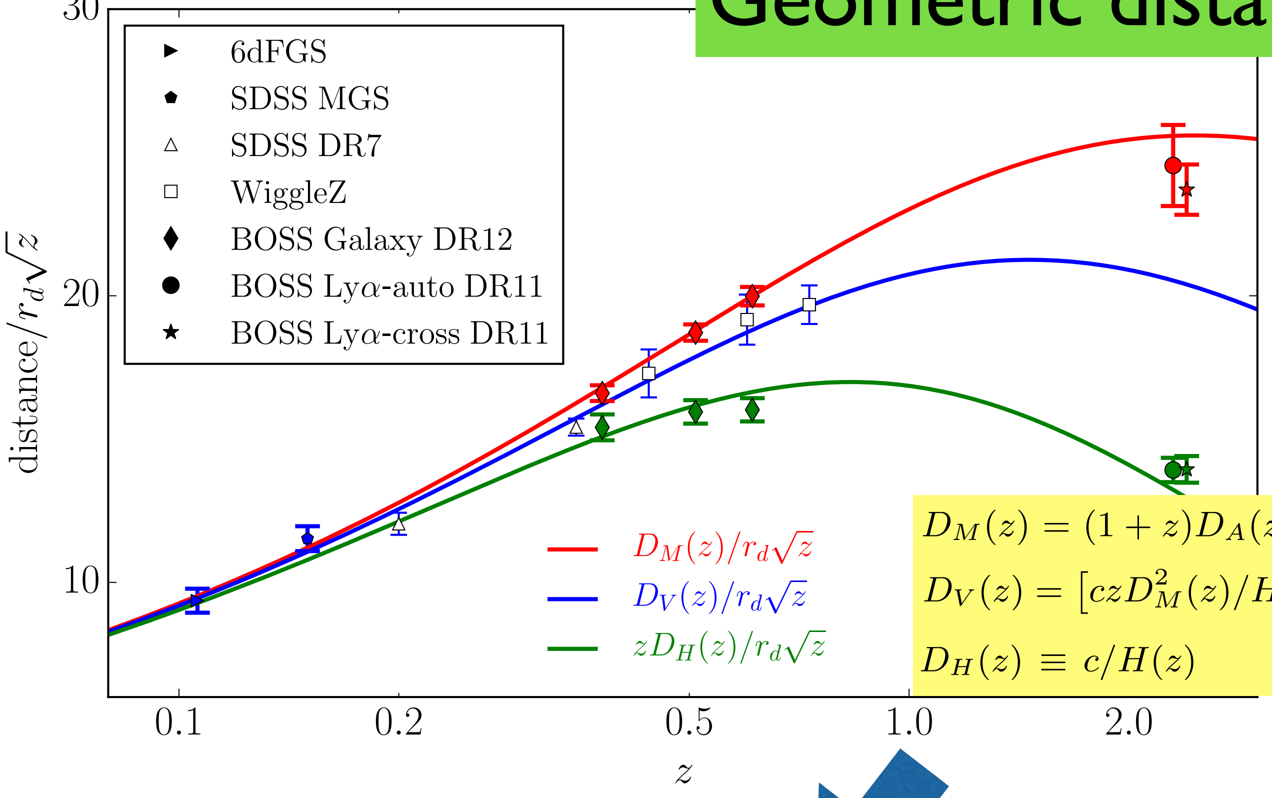
$$\alpha_\parallel = \frac{H^{\text{fid}}(z) r_s^{\text{fid}}(z_d)}{H(z) r_s(z_d)}$$

$$\alpha_\perp = \frac{D_A(z) r_s^{\text{fid}}(z_d)}{D_A^{\text{fid}}(z) r_s(z_d)}$$

Cosmological constraints

Alam et al. ('16)

Geometric distances

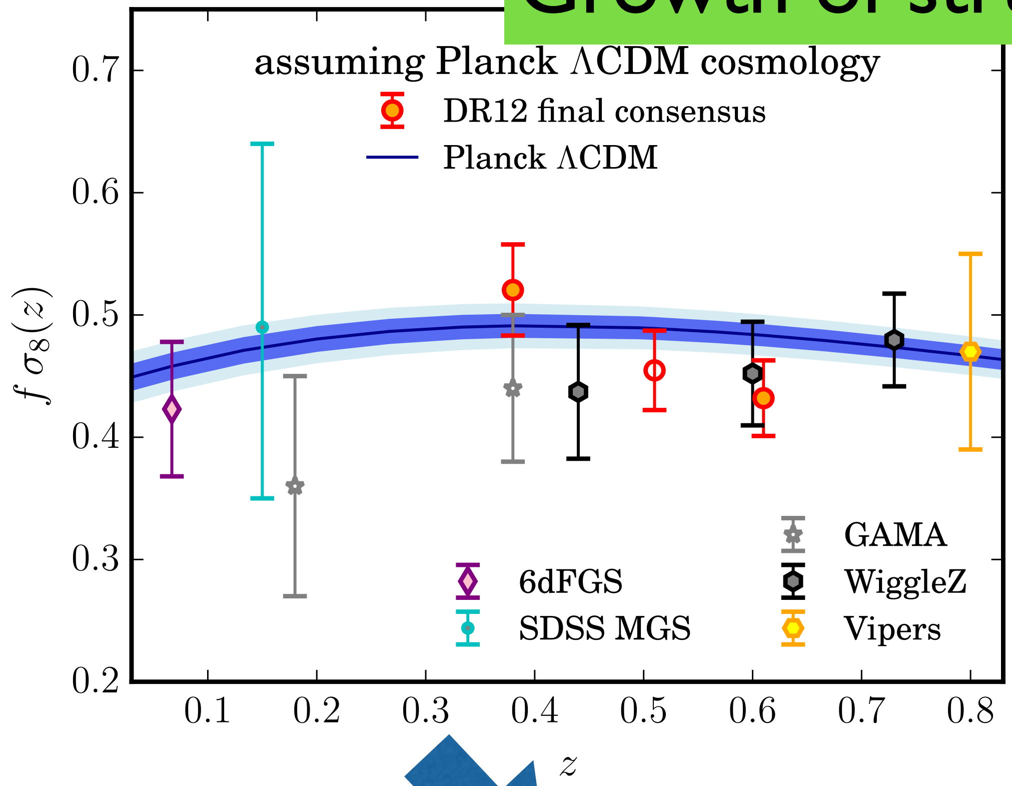


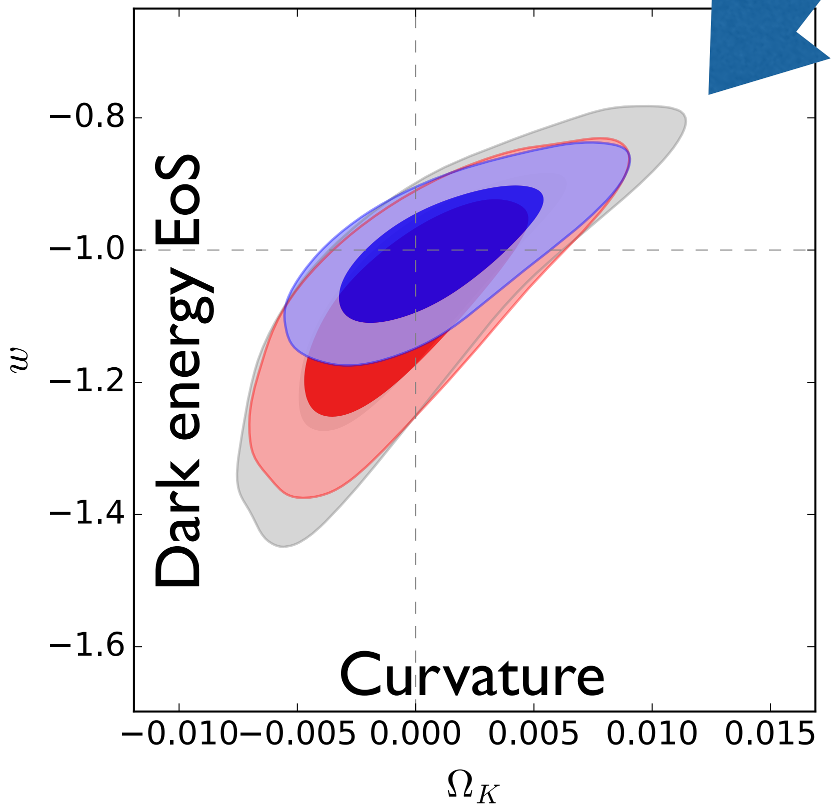
$$D_M(z) = (1+z)D_A(z)$$

$$D_V(z) = \left[czD_M^2(z)/H(z)\right]^{1/3}$$

$$D_H(z) \equiv c/H(z)$$

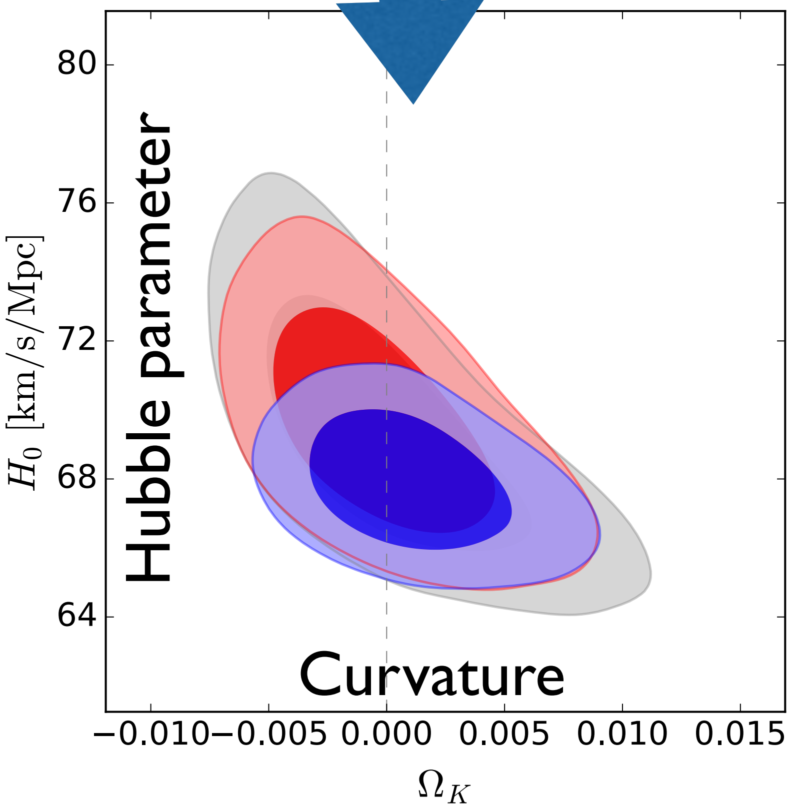
Growth of structure





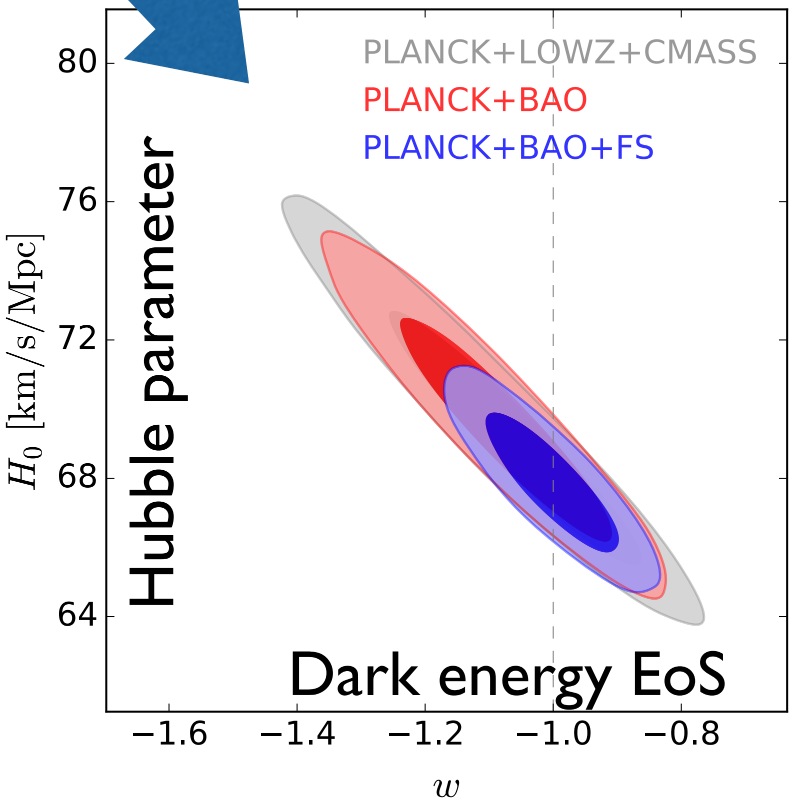
Dark energy EoS

Curvature



Hubble parameter

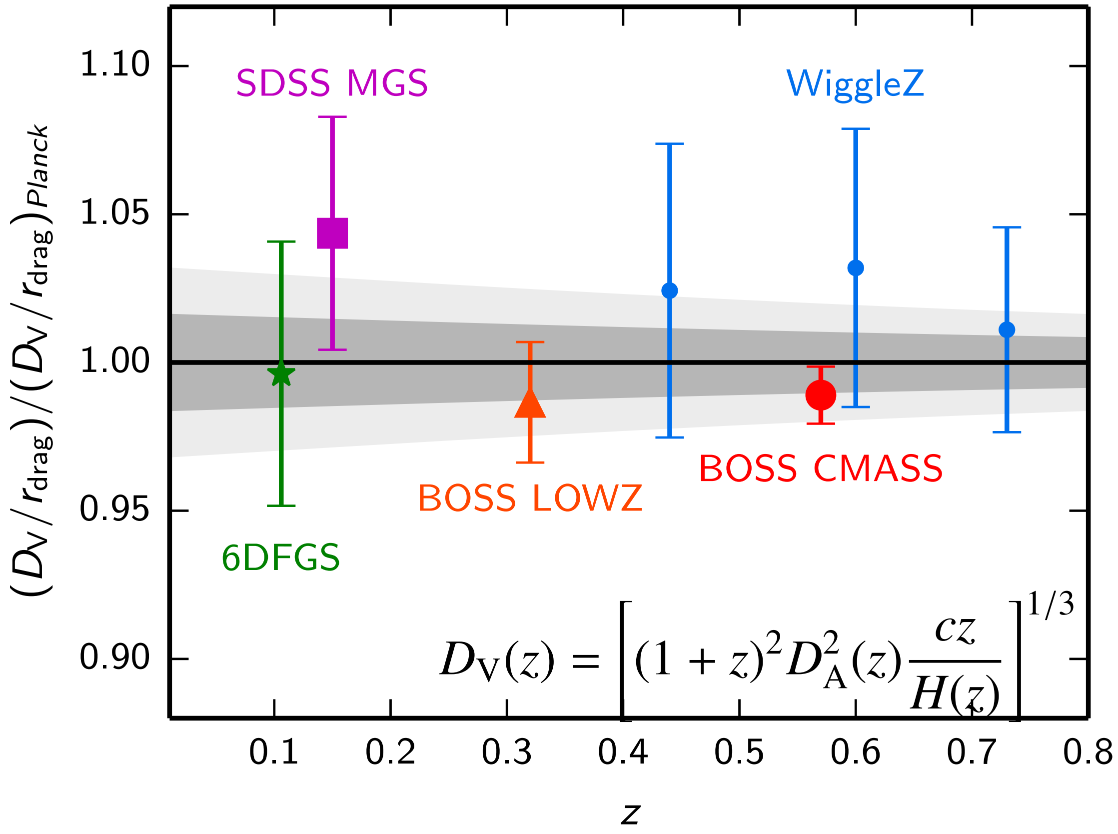
Curvature

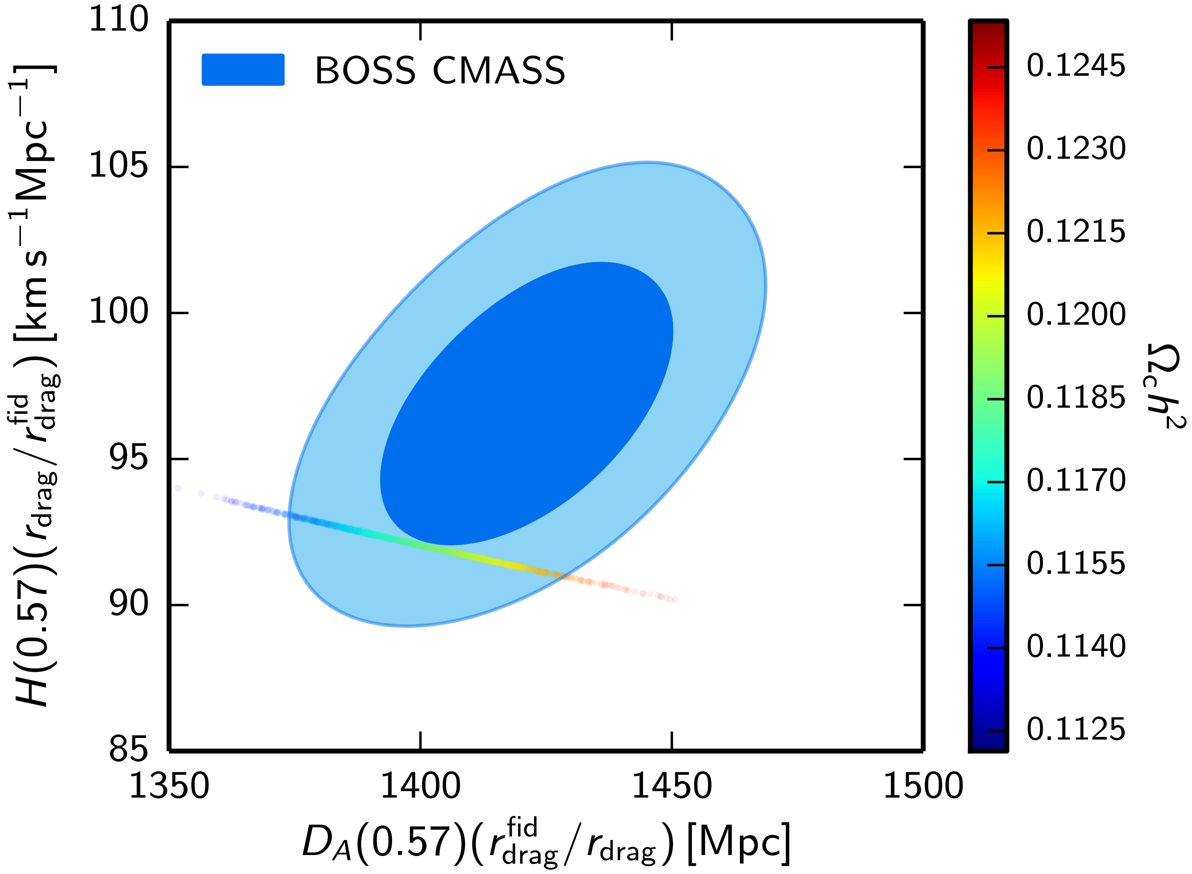


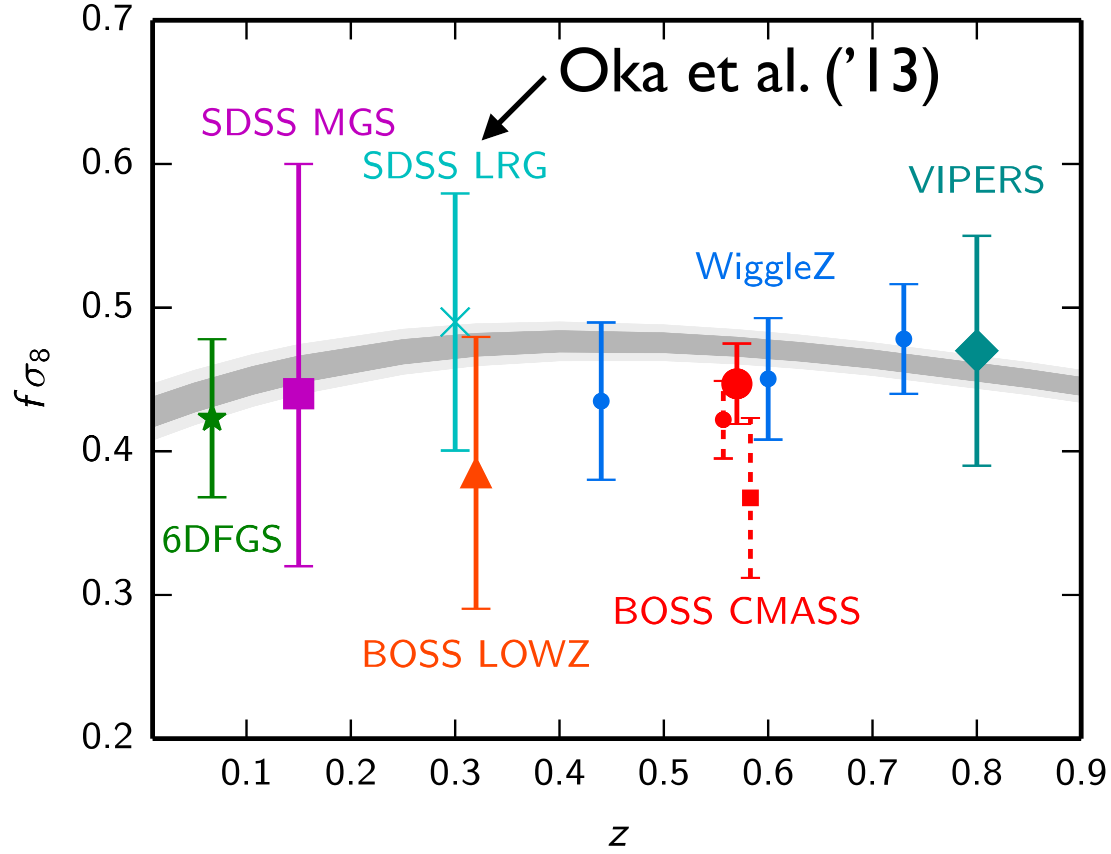
Hubble parameter

Dark energy EoS

Compilation of other observations





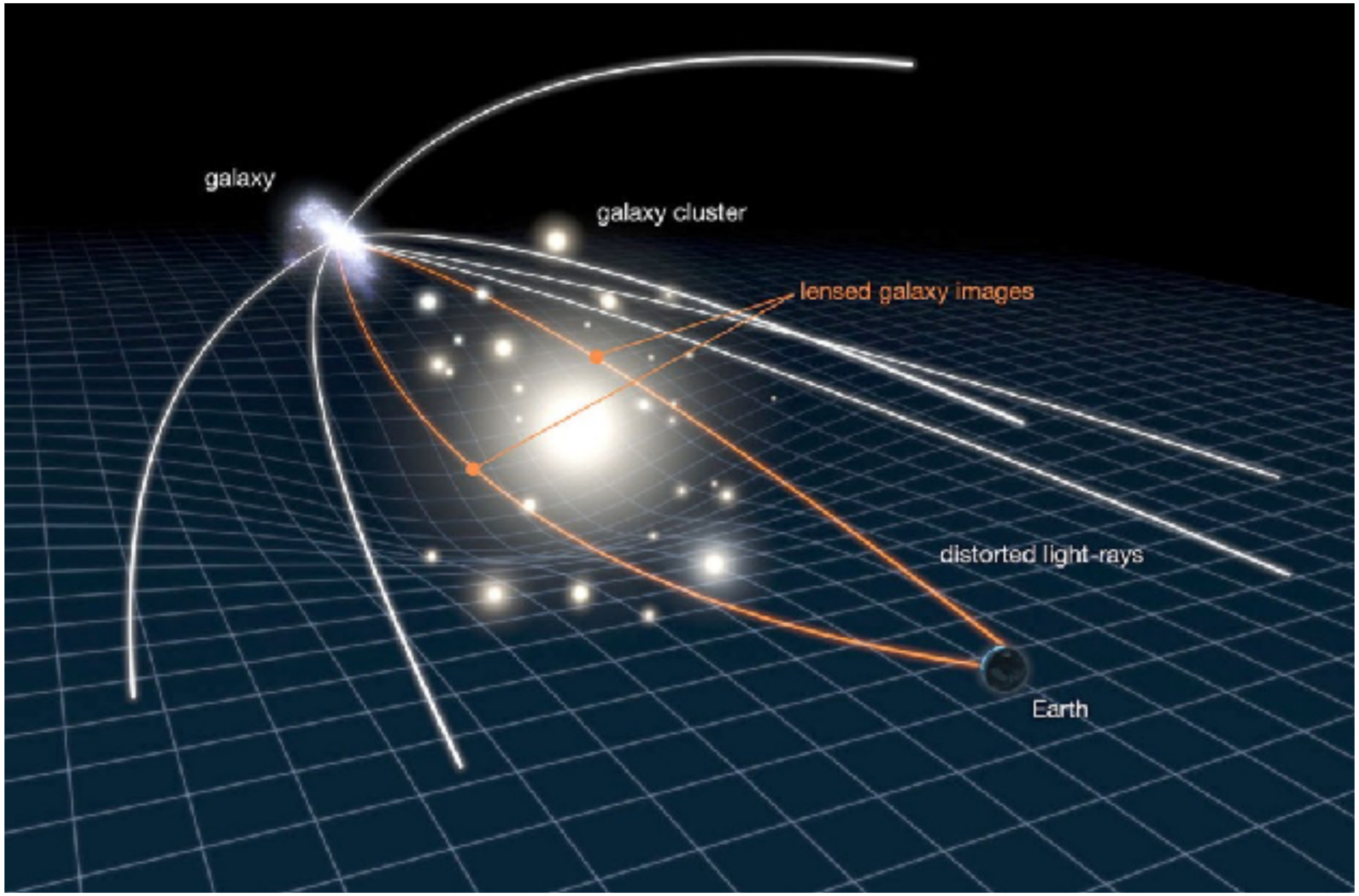

Oka et al. ('13)

Planck 2015 results. XIII

Gravitational lensing effect

重力レンズ効果

星や銀河・銀河団などの重い天体の重力場によって光が曲げられる現象　→ 強い重力レンズ、弱い重力レンズに大別



強い重力レンズ：多重像、増光（減光）がみえる
弱い重力レンズ：像の歪みがみえる

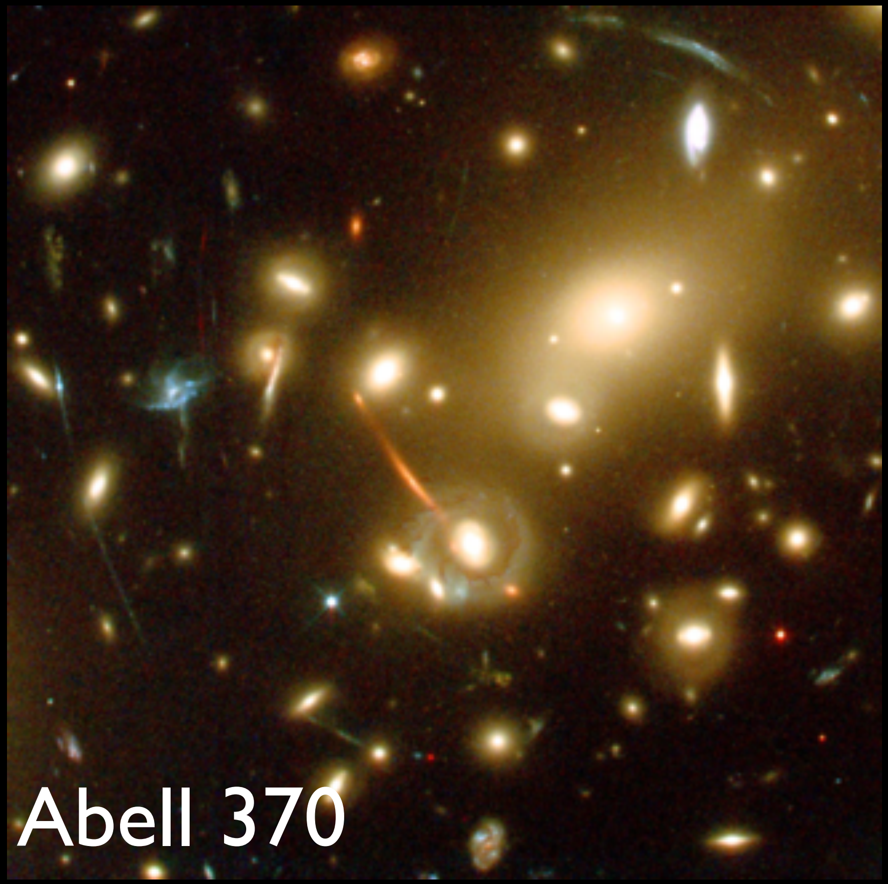
（強い）重力レンズ効果


LRG 3-757


アインシュタイン
の十字架


"スマイリー"
SDSS J1038+4849

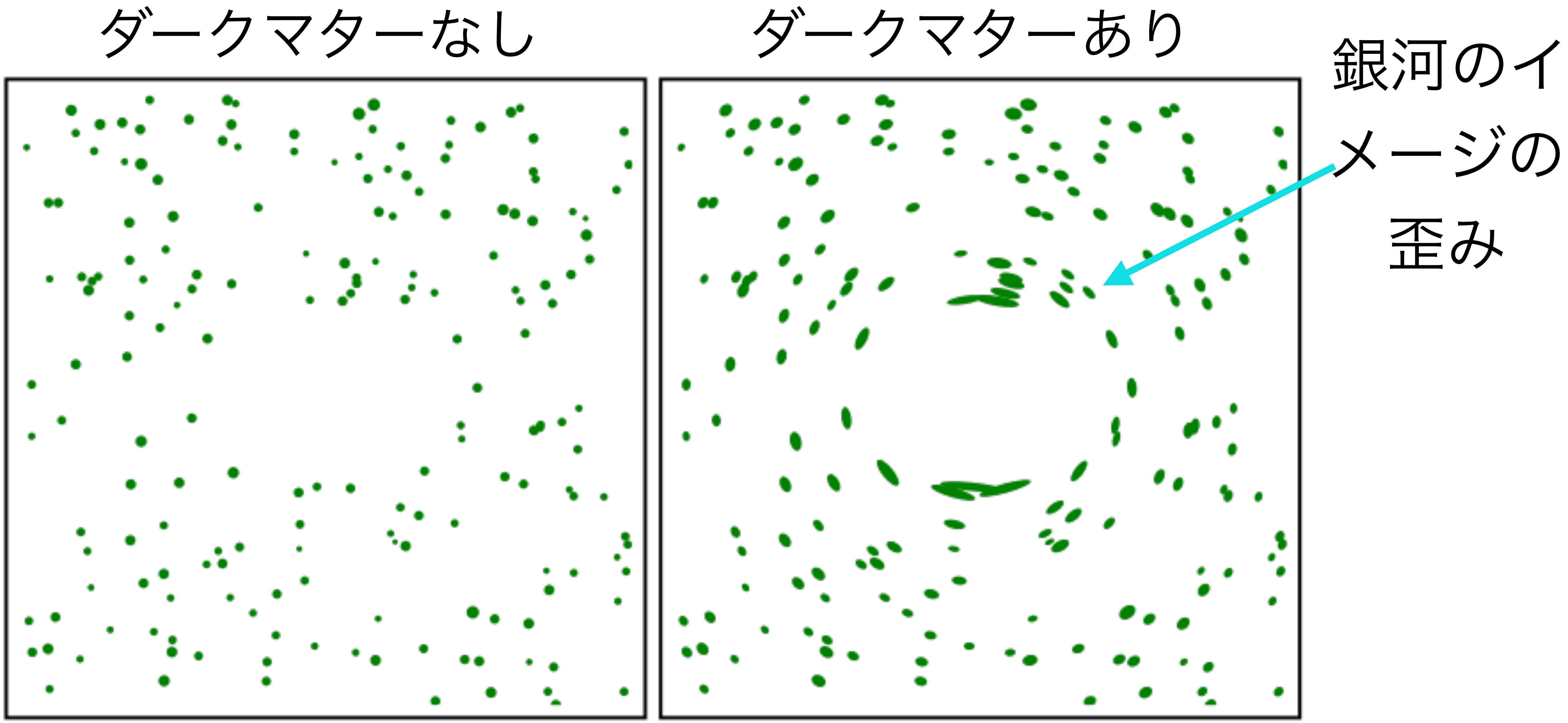

Abell 1689


Abell 370

wikipedia
http://hubblesite.org/gallery/album/exotic/gravitational_lens/

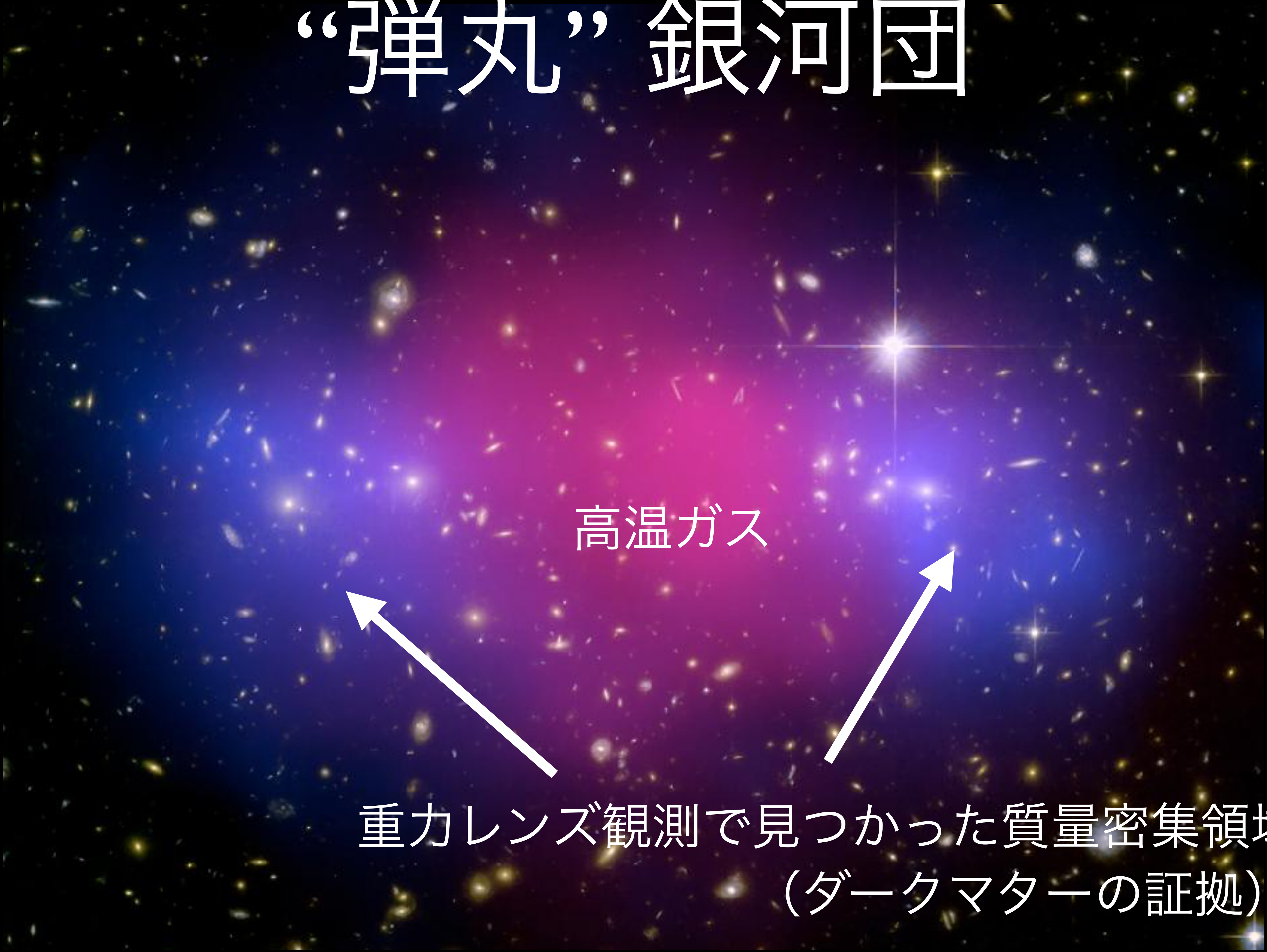
弱い重力レンズ効果

背景銀河の歪みから手前の見えない天体（ダークマターハロー）の性質を探ることができる



https://en.m.wikipedia.org/wiki/Weak_gravitational_lensing

“弾丸” 銀河団



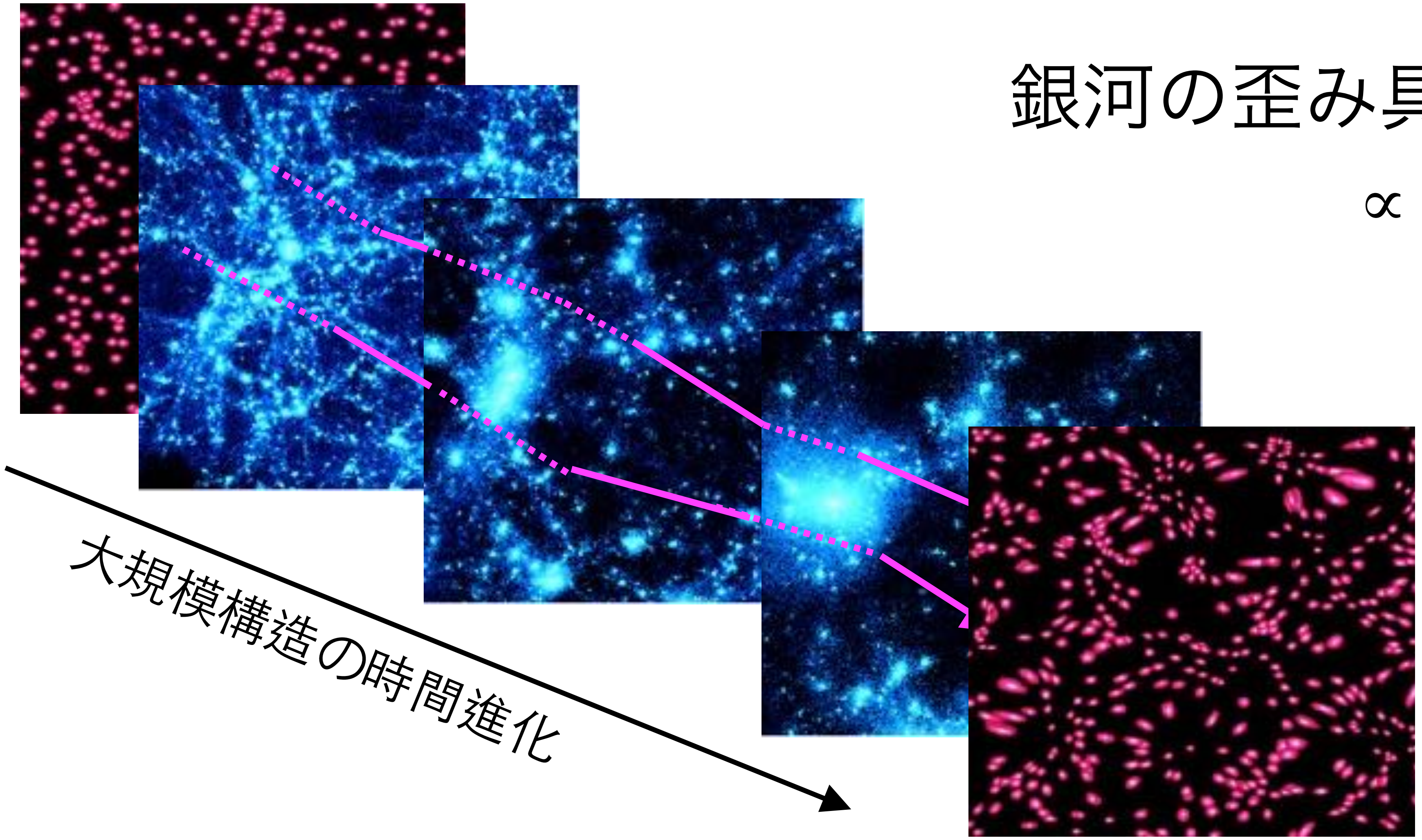
高温ガス

重力レンズ観測で見つかった質量密集領域
（ダークマターの証拠）

http://www.nasa.gov/multimedia/imagegallery/image_feature_1163.html

コスミック シア（Cosmic shear）

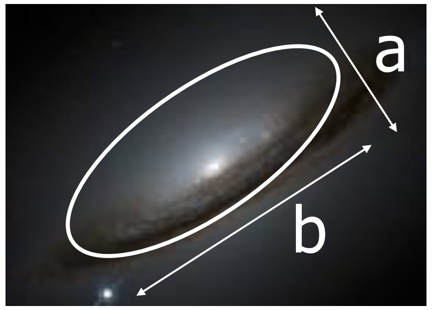
手前に存在する宇宙大規模構造が作る（弱い）重力レンズ効果により、遠方の背景銀河のイメージが歪む現象



銀河の歪み具合（楕円率）

∝ 幾何学的重み

×密度ゆらぎの振幅



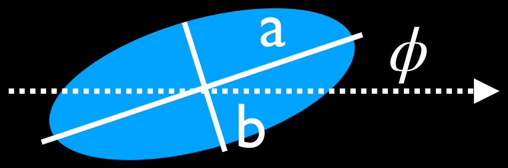
$$\gamma = \frac{a - b}{a + b}$$

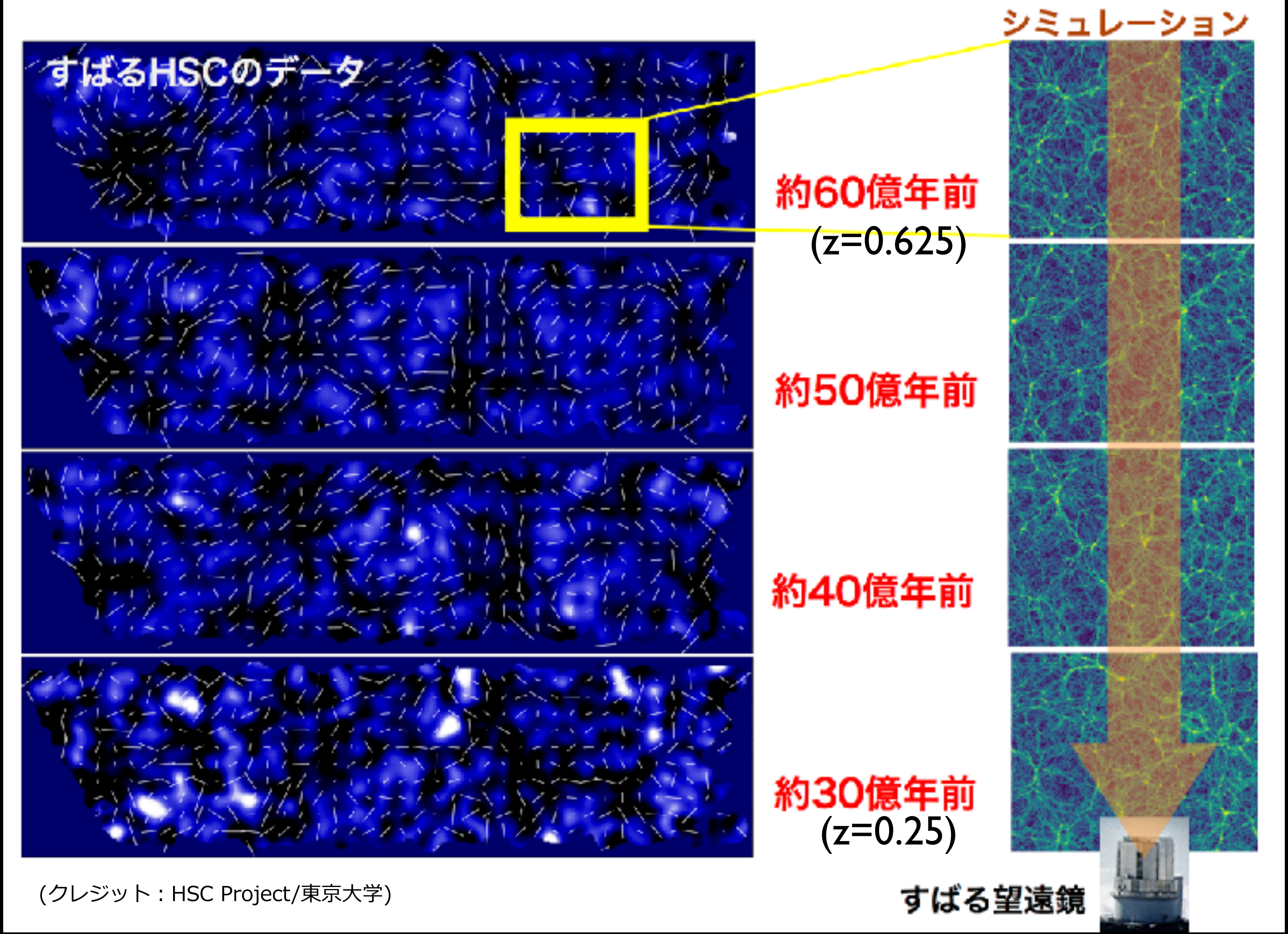
イメージの歪みの空間相関から、宇宙大規模構造のもつ宇宙論的情報を引き出せる → 精密宇宙論の基本観測量

Subaru HSC 1year result

Ellipticity of each object :

$$\boldsymbol{e} = (e_1, e_2) = \frac{1-(b/a)^2}{1+(b/a)^2}(\cos 2\phi, \sin 2\phi)$$





(クレジット：HSC Project/東京大学)

https://www.subarutelescope.org/Pressrelease/2018/09/25/j_index.html

Cosmic shear statistics : theory

“Convergence field”（or Eモード）　（平坦宇宙の場合）

$$\kappa(\vec{\theta}) = \frac{3}{2}\Omega_{\rm m}\frac{H_0^2}{c^2}\int_0^{\chi_\infty} d\chi_s \boxed{n(\chi_s)} \int_0^{\chi_s} d\chi \boxed{\frac{\chi(\chi_s-\chi)}{\chi_s}} \frac{\delta(\vec{\theta},\chi)}{a(\chi)}$$

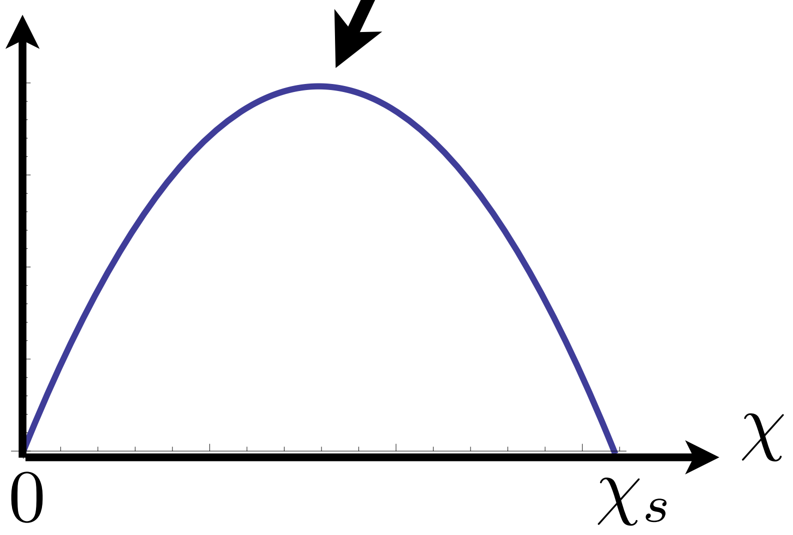
背景銀河の分布

レンズカーネル

質量分布（大規模構造）

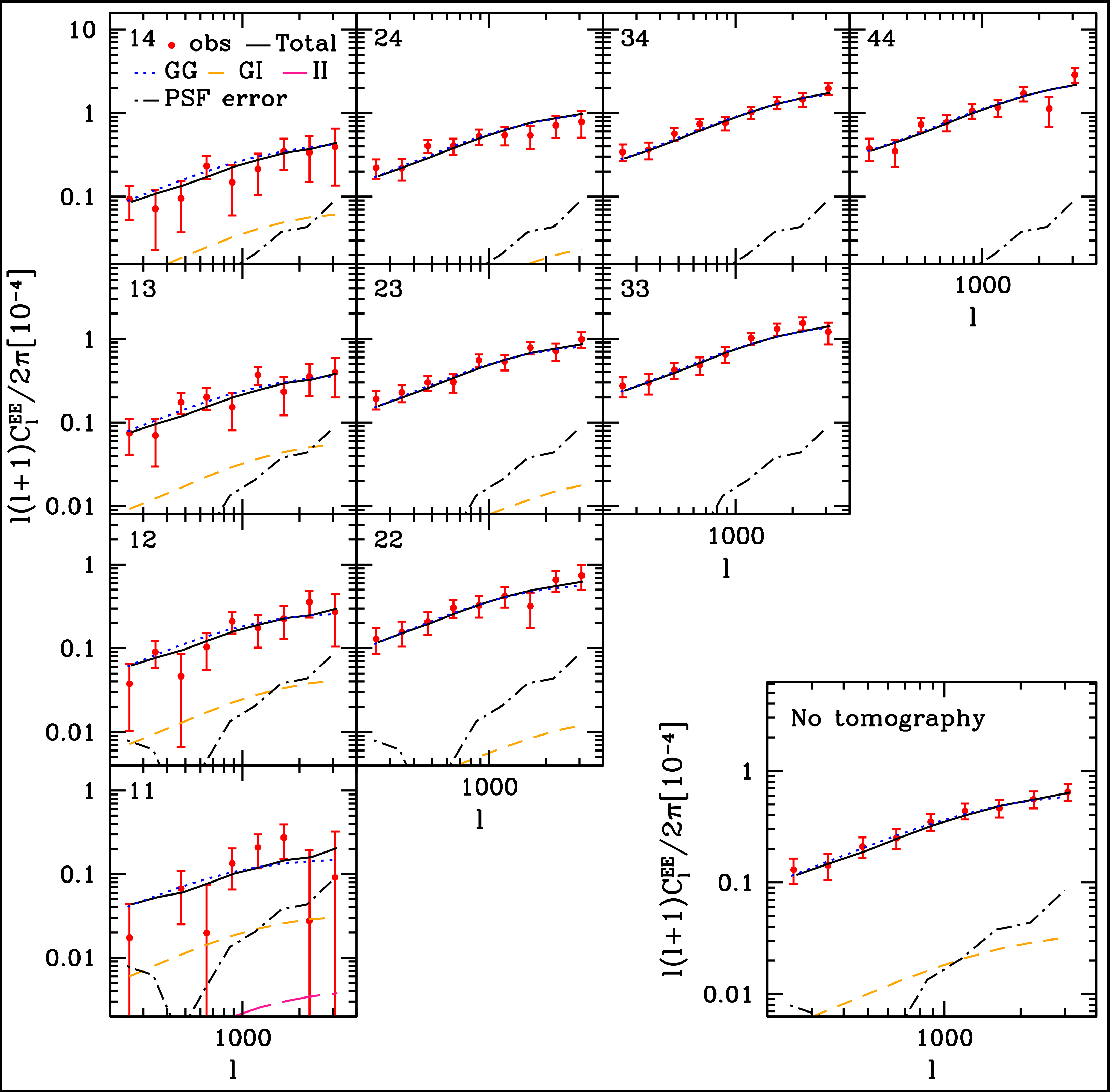
（共動）動径距離：

$$\chi(z) = \int_0^z \frac{c\,dz}{H(z)}$$



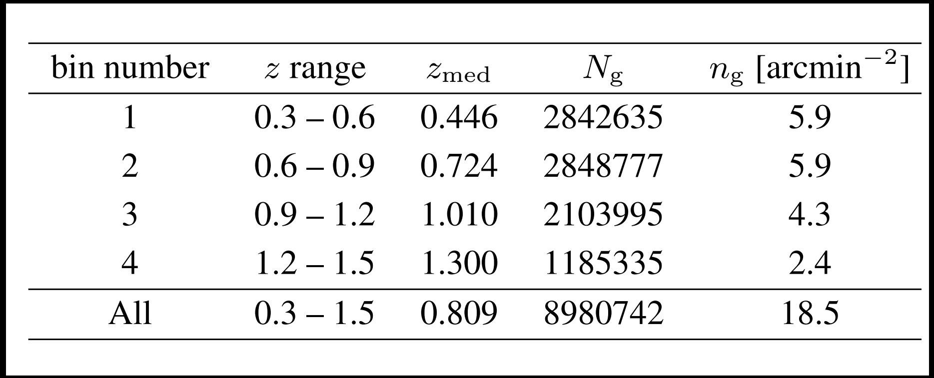
いろんな赤方偏移からの寄与が混じる (projection effect)

Cosmic shear power spectrum



Multipole $(\ell \sim \pi/\theta)$

Multipole



bin number	z range	$z_{\rm med}$	$N_{\rm g}$	$n_{\rm g}$ [arcmin^{-2}]
1	0.3 – 0.6	0.446	2842635	5.9
2	0.6 – 0.9	0.724	2848777	5.9
3	0.9 – 1.2	1.010	2103995	4.3
4	1.2 – 1.5	1.300	1185335	2.4
All	0.3 – 1.5	0.809	8980742	18.5

Auto- & cross power spectrum between multiple photo-z bins

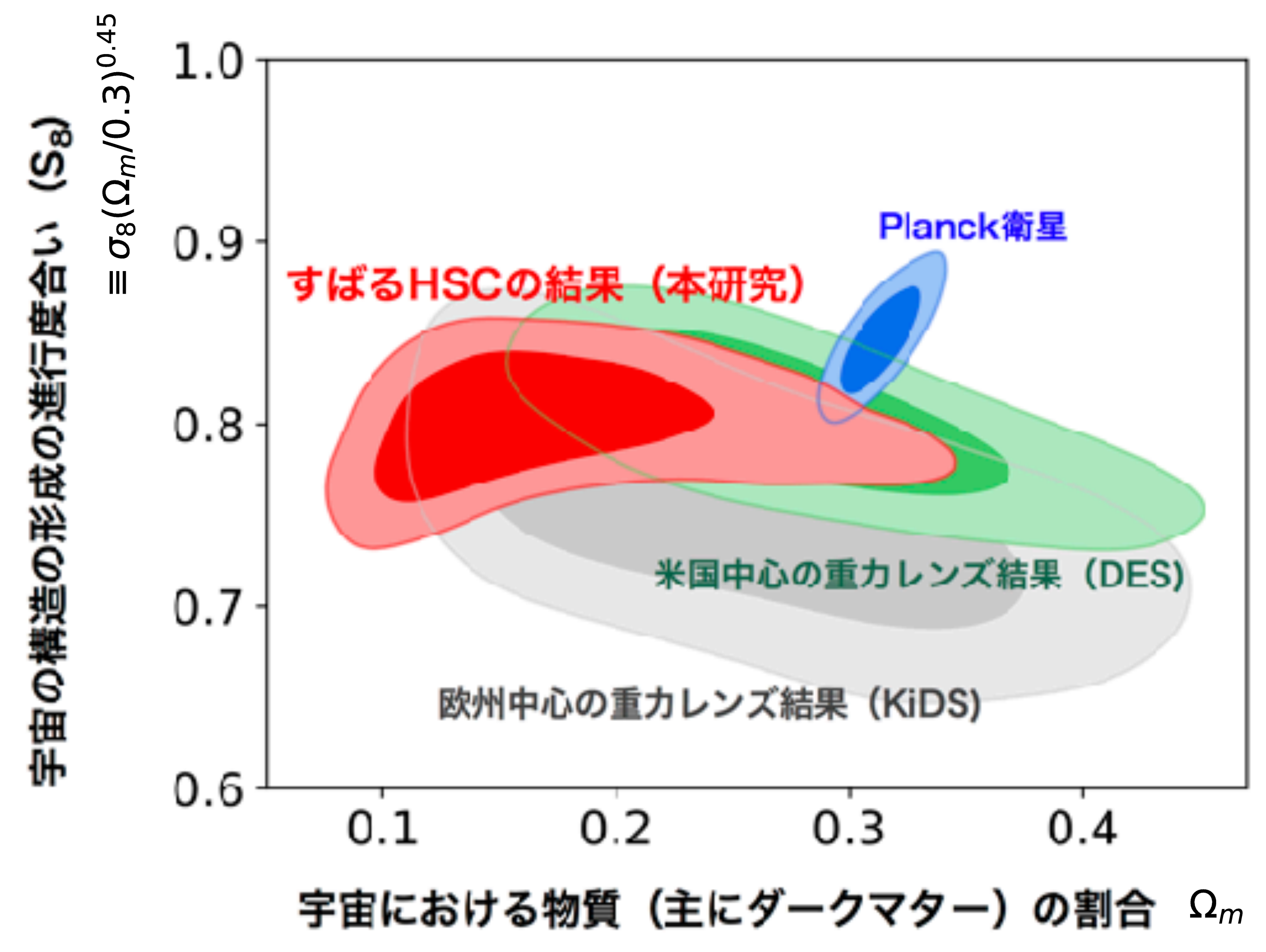
(lensing tomography)

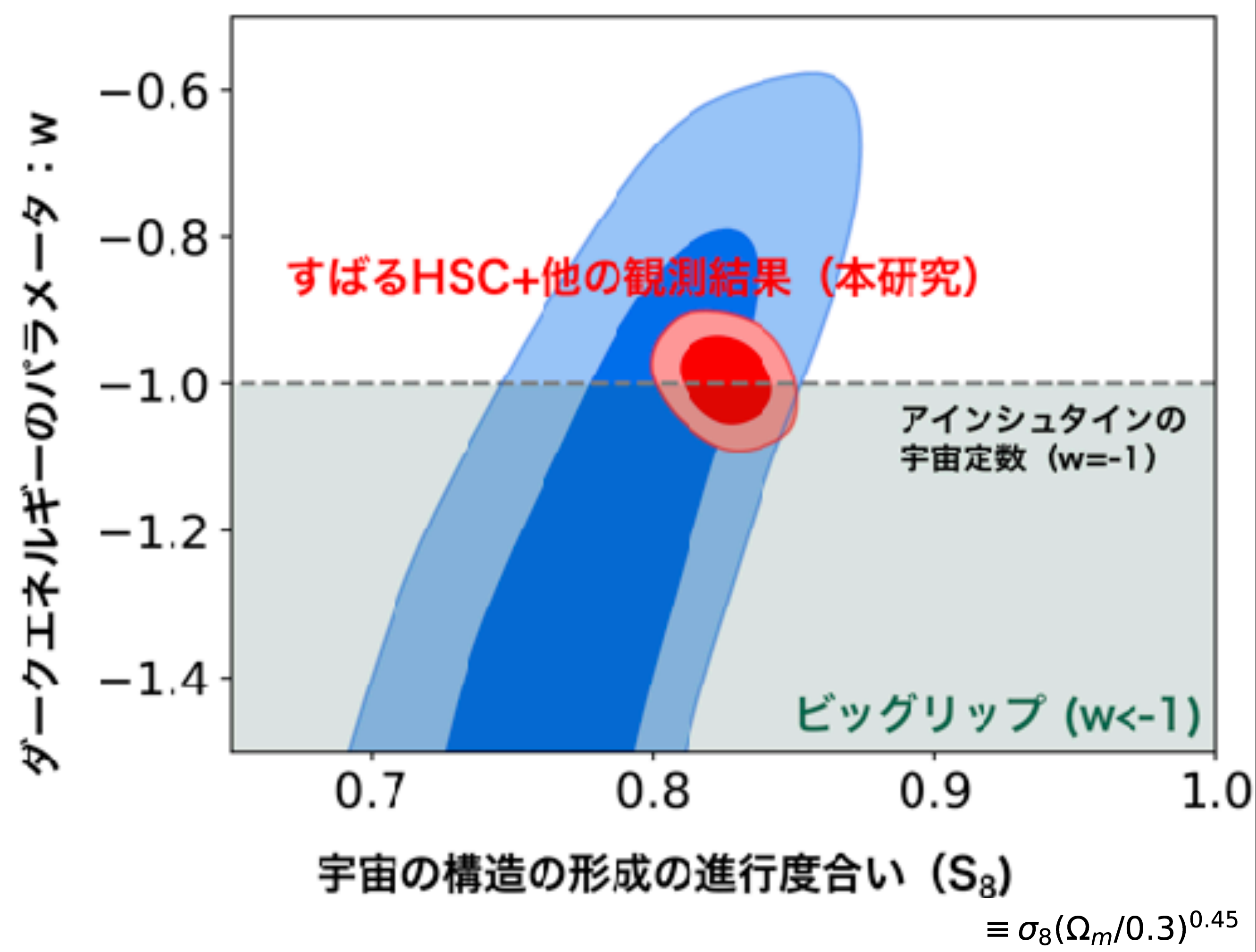
$$C_\ell = \frac{1}{2\ell+1}\sum_{m=-\ell}^{\ell} |e_{\ell m}|^2$$

$$\left(e(\vec{\theta}) = \sum_{\ell,m} e_{\ell m} Y_{\ell m}(\vec{\theta}) \right)$$

Hikage et al. (arXiv:1809.09148)

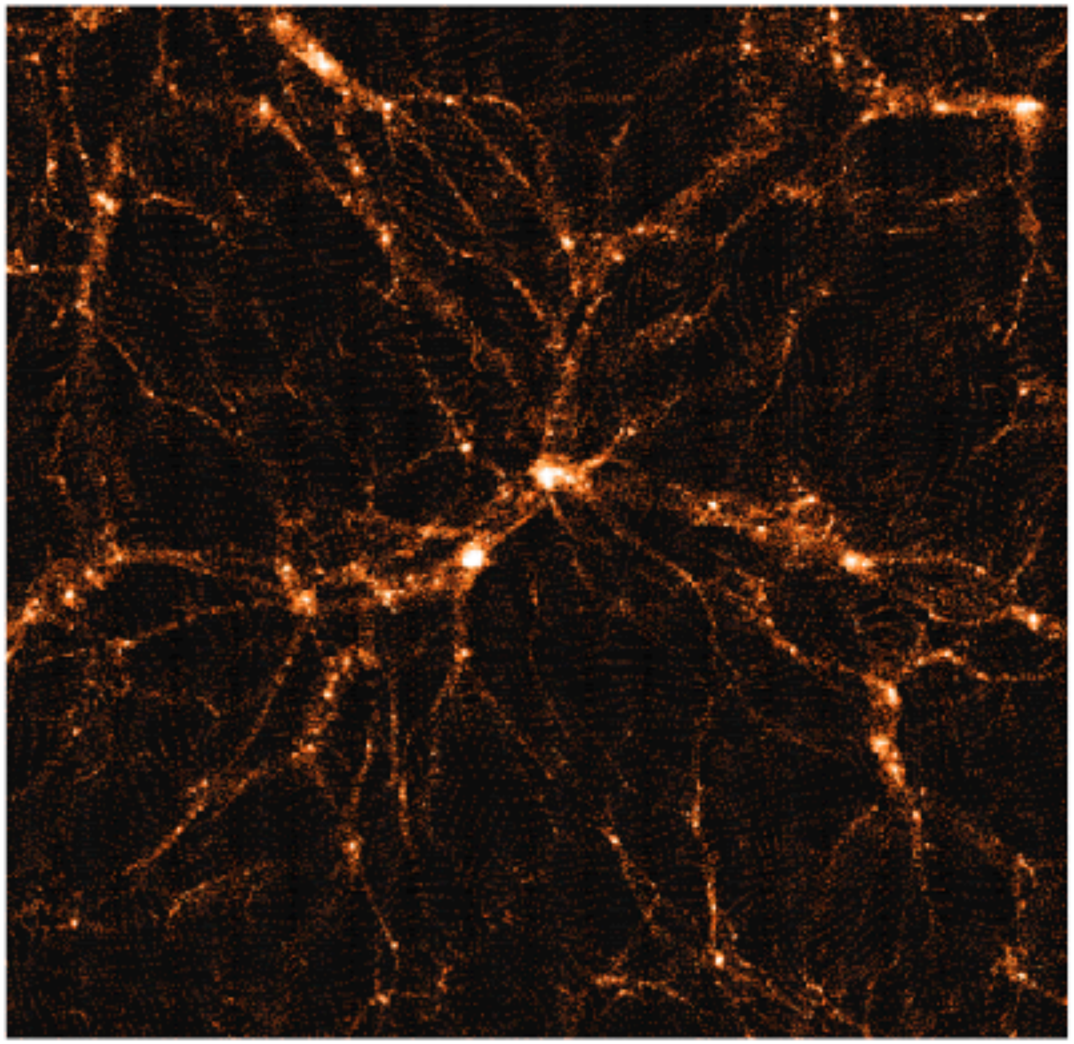
Cosmological constraint



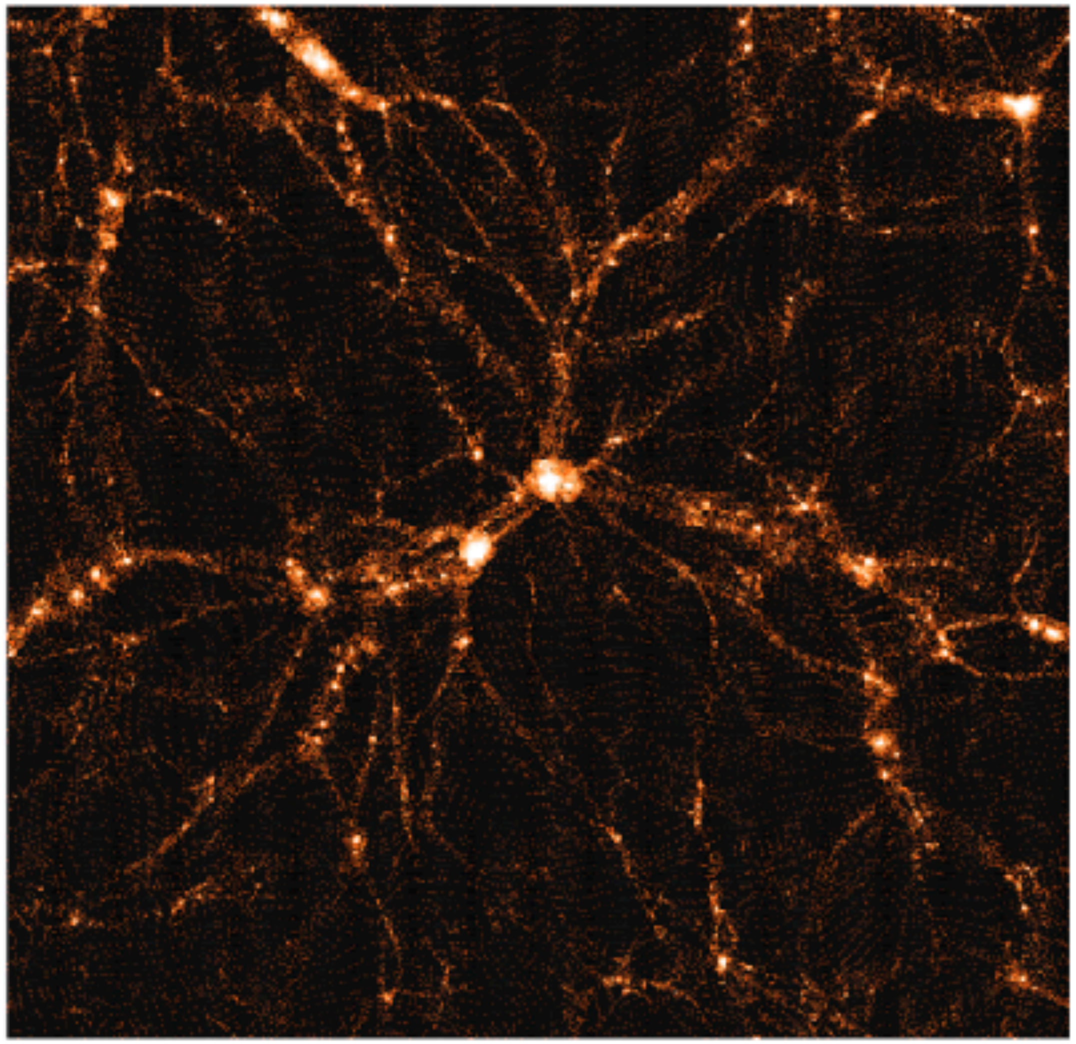


Hikage et al. (arXiv:1809.09148)

HSCデータが支持する宇宙
（シミュレーション）



プランク衛星が支持する宇宙



クレジット：東京大学、Kavli IPMU 西道啓博特任助教提供)