(観測的)宇宙論は面白い(よ)！

高田昌広

(Kavli IPMU)

一昨日までスロベニアにいました

@ Summer School, 2018

Science from night sky!

@ summit of Mt. Mauna Kea (4200m), Big Island, Hawaii

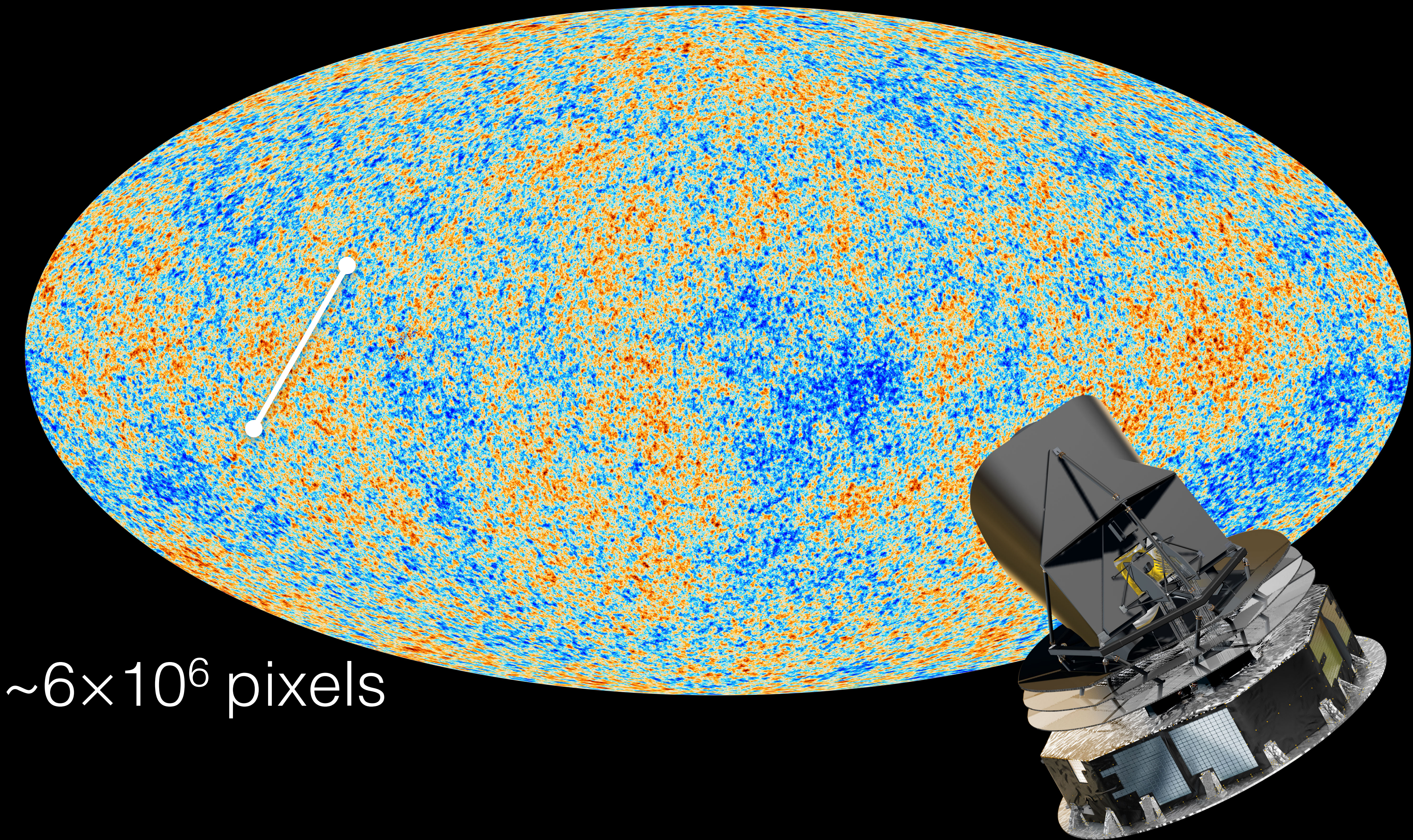
宇宙論の面白さ

- 観測と理論が直結！
- ノーベル賞級（教科書に載るような）問題、発見の可能性がある
- やるなら（研究に人生を捧げるなら）、ノーベル賞を狙いましょう！
- 勉強、経験を積みましょう！

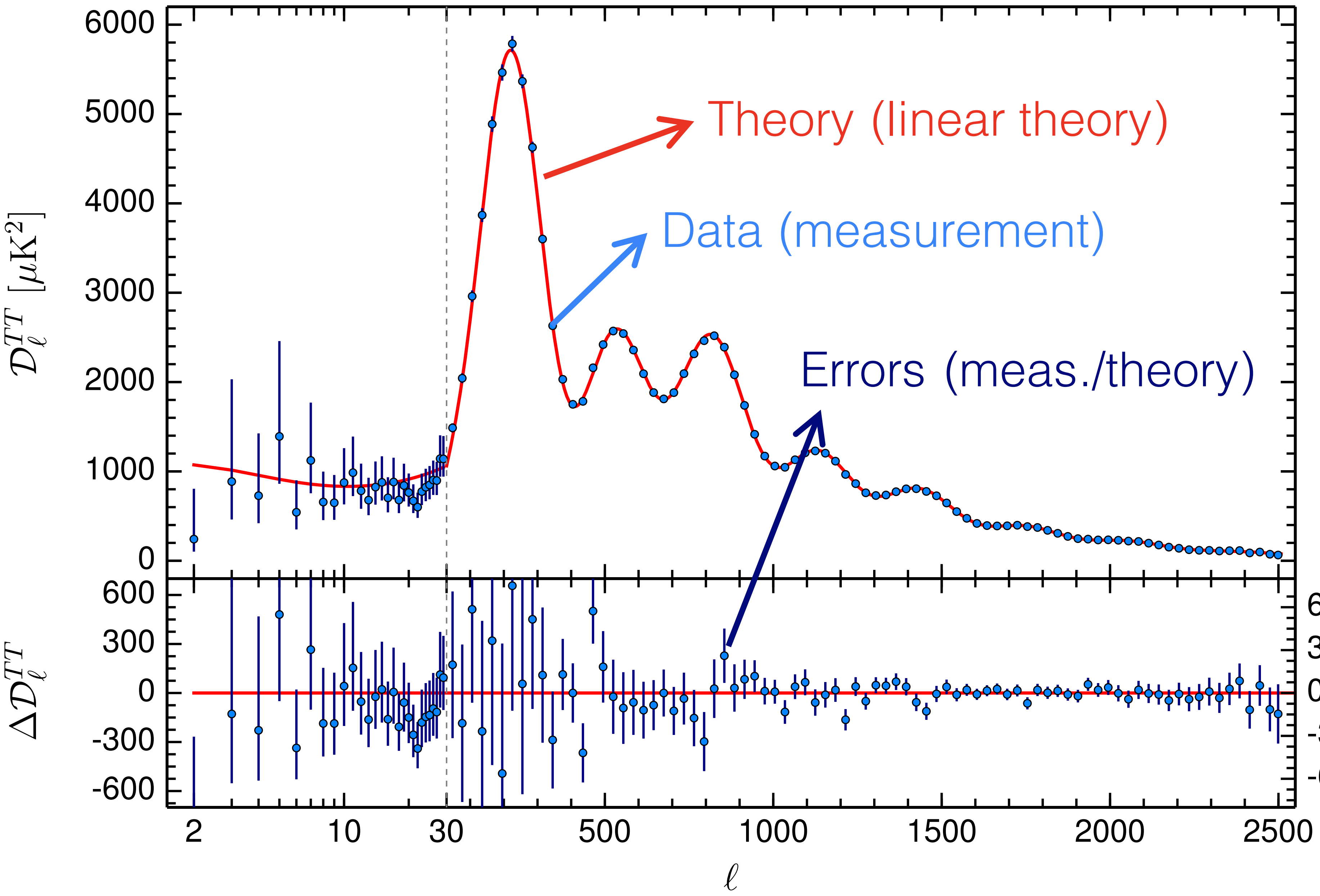
Fundamental physics with cosmology

- Dark energy or The origin of cosmic acceleration (modified gravity)
- Dark matter (e.g., discovery of primordial black hole)
- Light relics/particles (e.g., axison)
- Non-trivial properties of primordial scalar perturbations: e.g. primordial non-Gaussianity, running spectral index, features in the primordial power spectrum
- Primordial gravitational wave
- Curvature (Ω_K)
- Detection of neutrino mass
- どれか、あるいはこれらを好きになって、とことん追求してください

Cosmic microwave background (CMB)



Triumph of Physics



Linear Theory: Transfer function

- Consider scalar perturbations alone
- Different Fourier modes evolve independently
- Linearized perturbation theory: Differential equation of each fluctuation field has a form like

$$\ddot{\Theta}(\mathbf{k},\eta) + \underline{F(k,a,\dot{a},\cdots)}\dot{\Theta}(\mathbf{k},\eta) + \underline{G(k,a,\dot{a},\cdots)}\Theta(\mathbf{k},\eta) = \underline{S(k,a,\dot{a},\cdots)}O(\Psi(\mathbf{k},\eta))$$

The coefficients depend only on k and/or background quantities

- The solution is expressed in terms of "transfer function" as

$$\Theta(\mathbf{k},\eta) = \underline{T(k,\eta;\Omega_{\rm m0},\Omega_{\rm b0},\cdots)}\,\underline{\Theta(\mathbf{k},\eta_{\rm ini})} + T_{\rm iso}(k;\ldots)\Theta_{\rm iso}(\mathbf{k},\eta_{\rm ini})$$

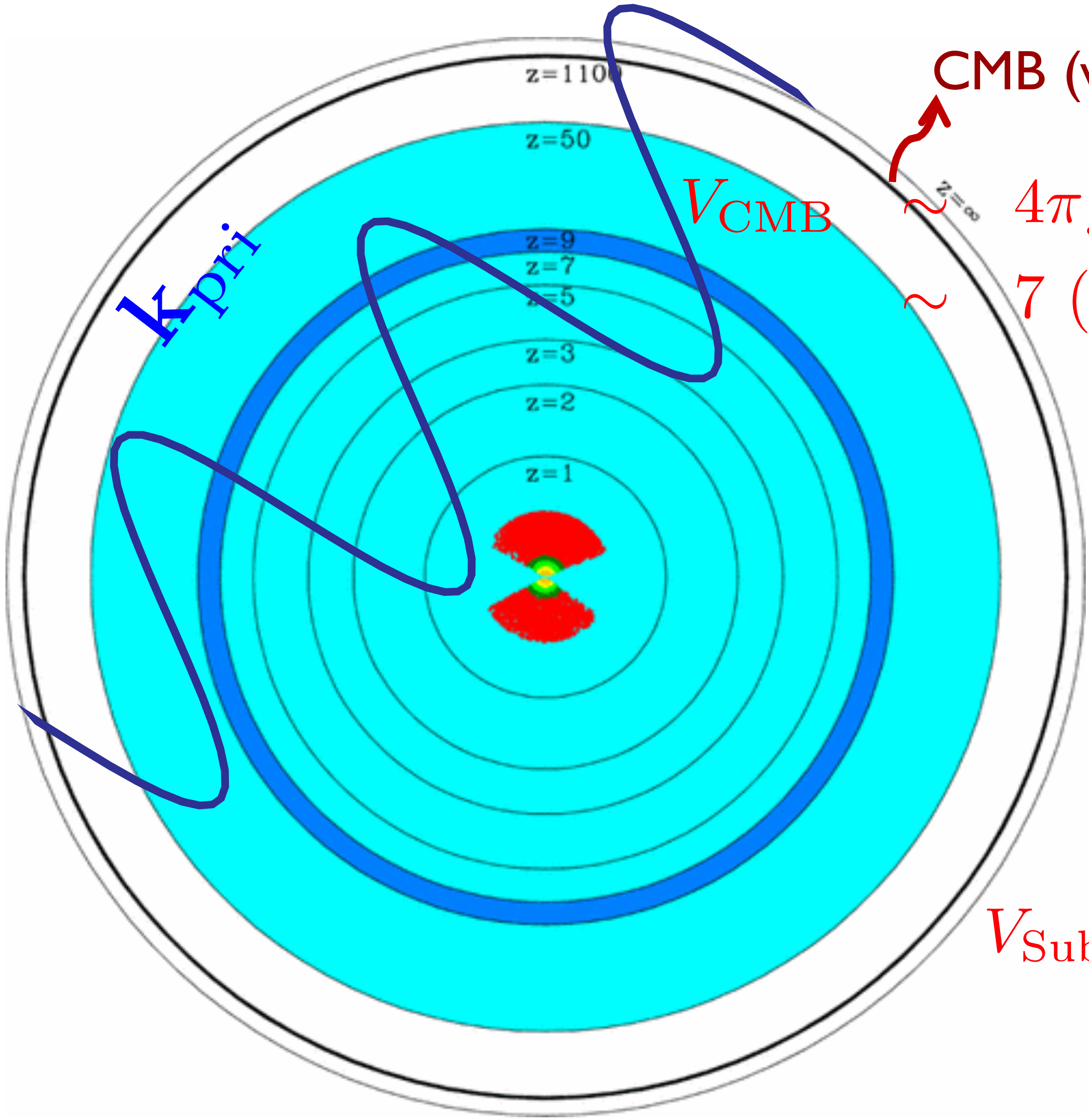
$k = |\mathbf{k}|$

Transfer function: the same for all the Fourier mode with $k = |\mathbf{k}|$

the initial condition (depends on $\mathbf{k}$)

Public codes, CMBFast, CAMB, Class, to compute the transfer functions

CMB (~2D) vs. Galaxy Surveys (3D)



Tegmark & Zaldarriaga 09

CMB (width ~ 5Mpc)

$\sim 4\pi f_{\rm sky}(14\ {\rm Gpc})^2 \times (0.005\ {\rm Gpc}$

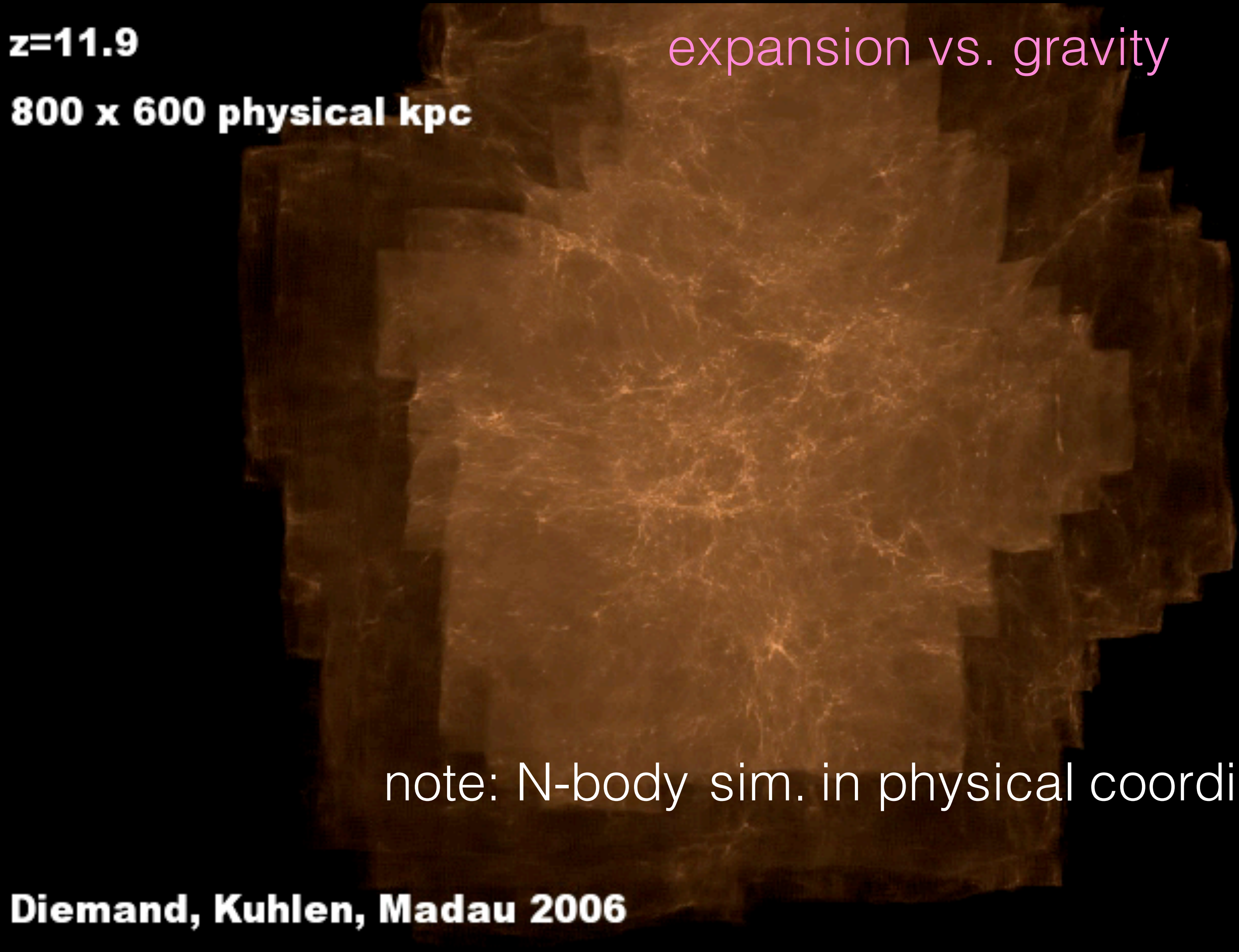
$\sim 7\ ({\rm Gpc}/h)^3$

+ time evolution btw z~1000 and z~0

$V_{\rm Subaru} \sim 9\ ({\rm Gpc}/h)^3 (f_{\rm sky}/0.04$

A huge 3D volume is still available for cosmology

Formation of cosmological hierarchical structures



expansion vs. gravity

note: N-body sim. in physical coordinates

Background and Perturbations

Decomposition of physical quantities into background (isotropy & homogeneous) and perturbations (inhomogeneities)

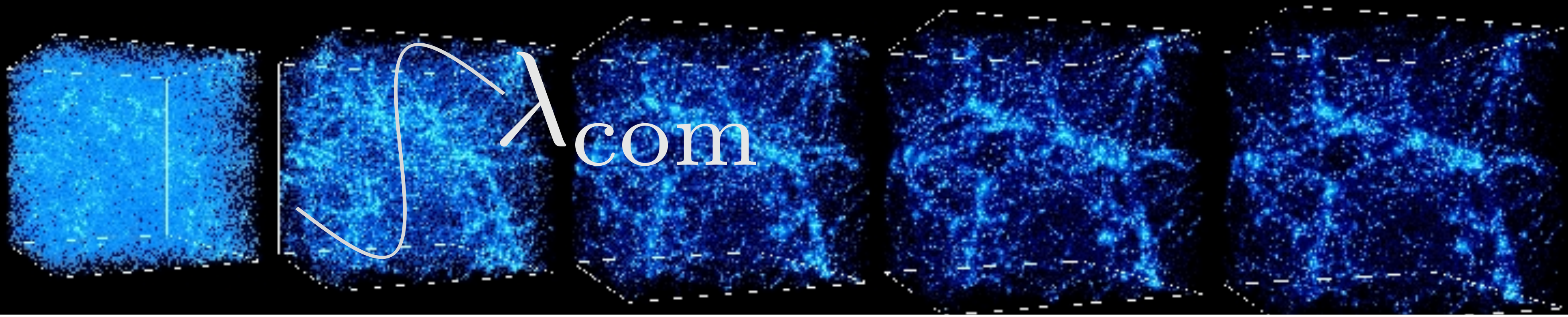
$$\mathbf{r} = a(t)\mathbf{x}$$

$$\rho(\mathbf{x}, t) = \bar{\rho}(t)\left[1 + \delta(\mathbf{x}, t)\right]$$

$$g_{\mu\nu}(\mathbf{x}, t) = a(t)^2\left[\eta_{\nu\mu} + h_{\nu\mu}(\mathbf{x}, t)\right]$$

- "Comoving" coordinates: cosmic expansion is extracted and matter stay at the same coordinates (if the universe is isotropic and homogeneous)

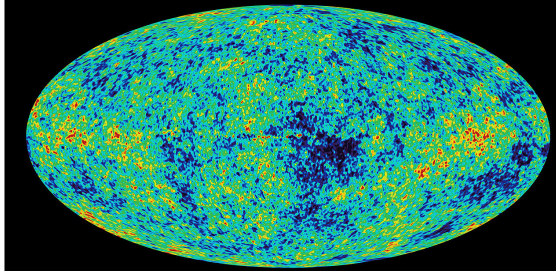
- Cosmological perturbation theory (Kodama & Sasaki 84)



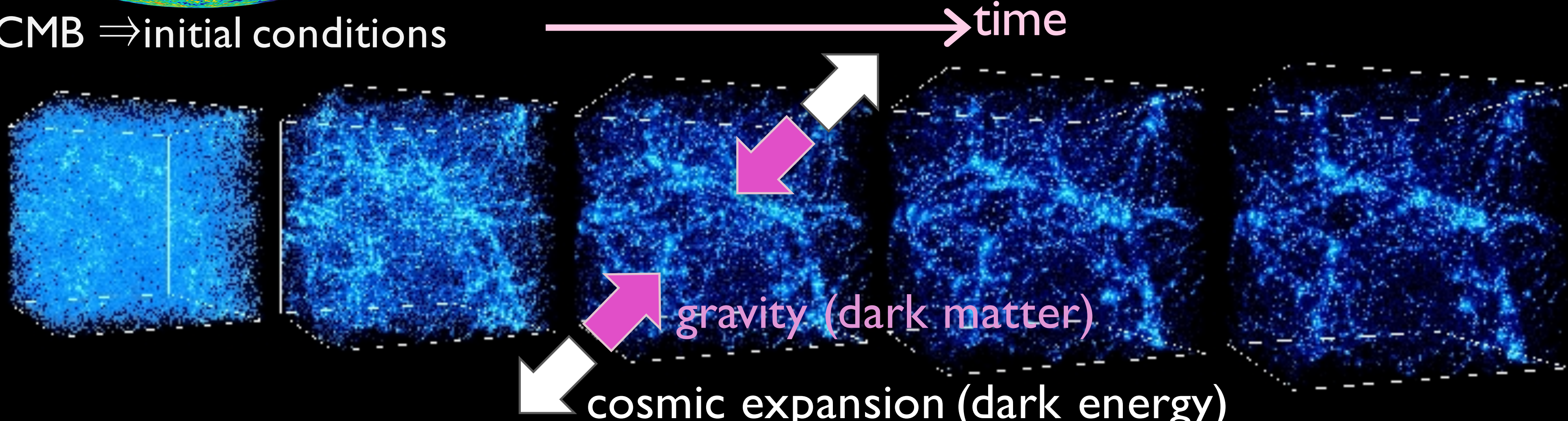
Large-scale structure formation

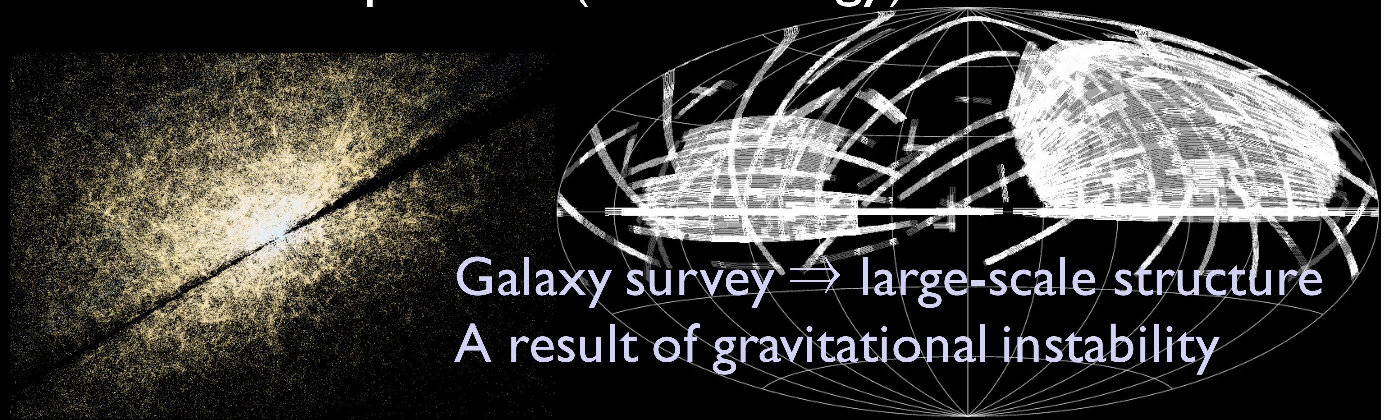
Structure formation = Time evolution of matter inhomogeneities of each scale (wavelength)

$$\ddot{\delta}_m + 2H\dot{\delta}_m - 4\pi G\bar{\rho}_m\delta_m = 0$$



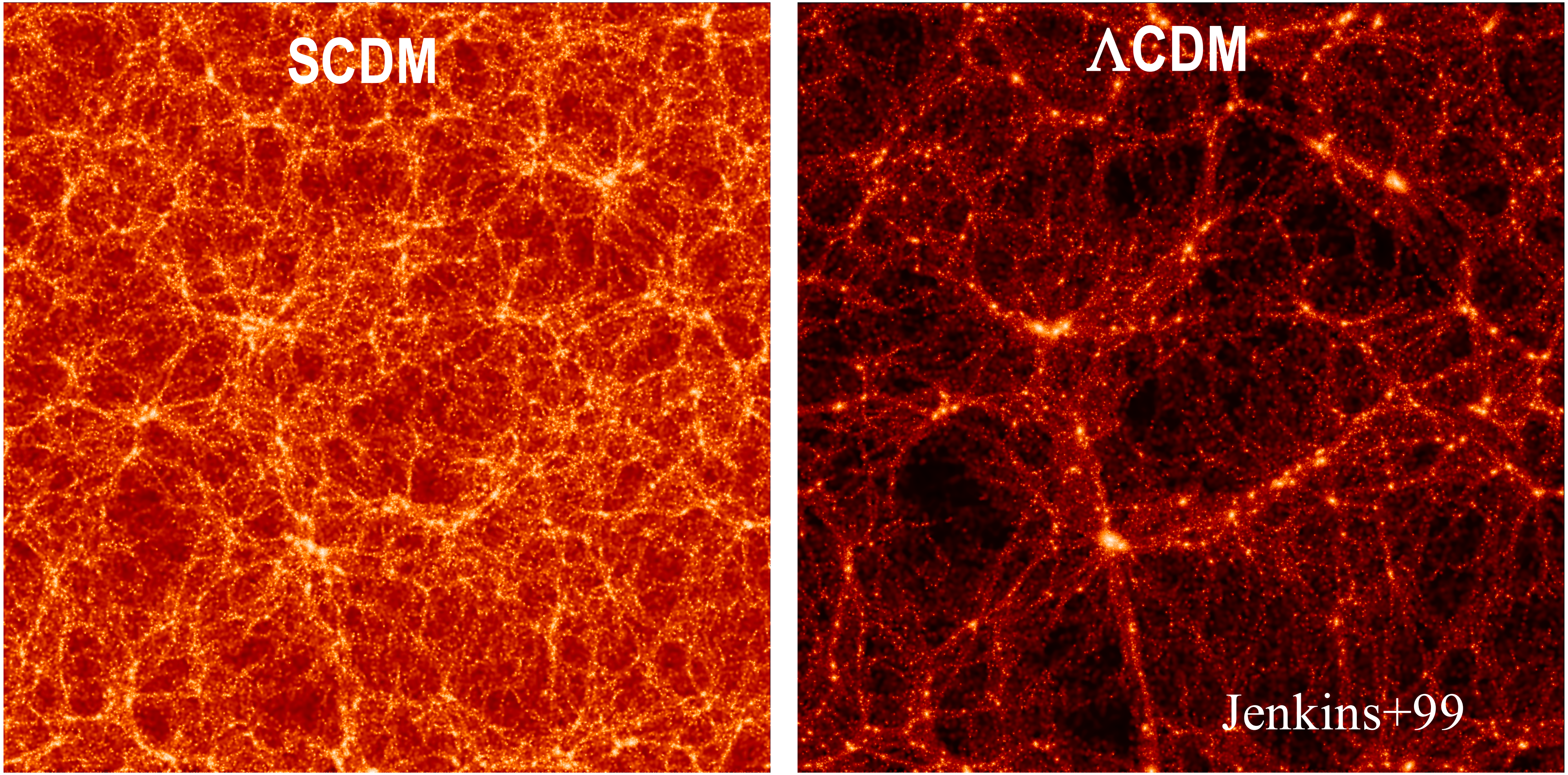
CMB ⇒initial conditions



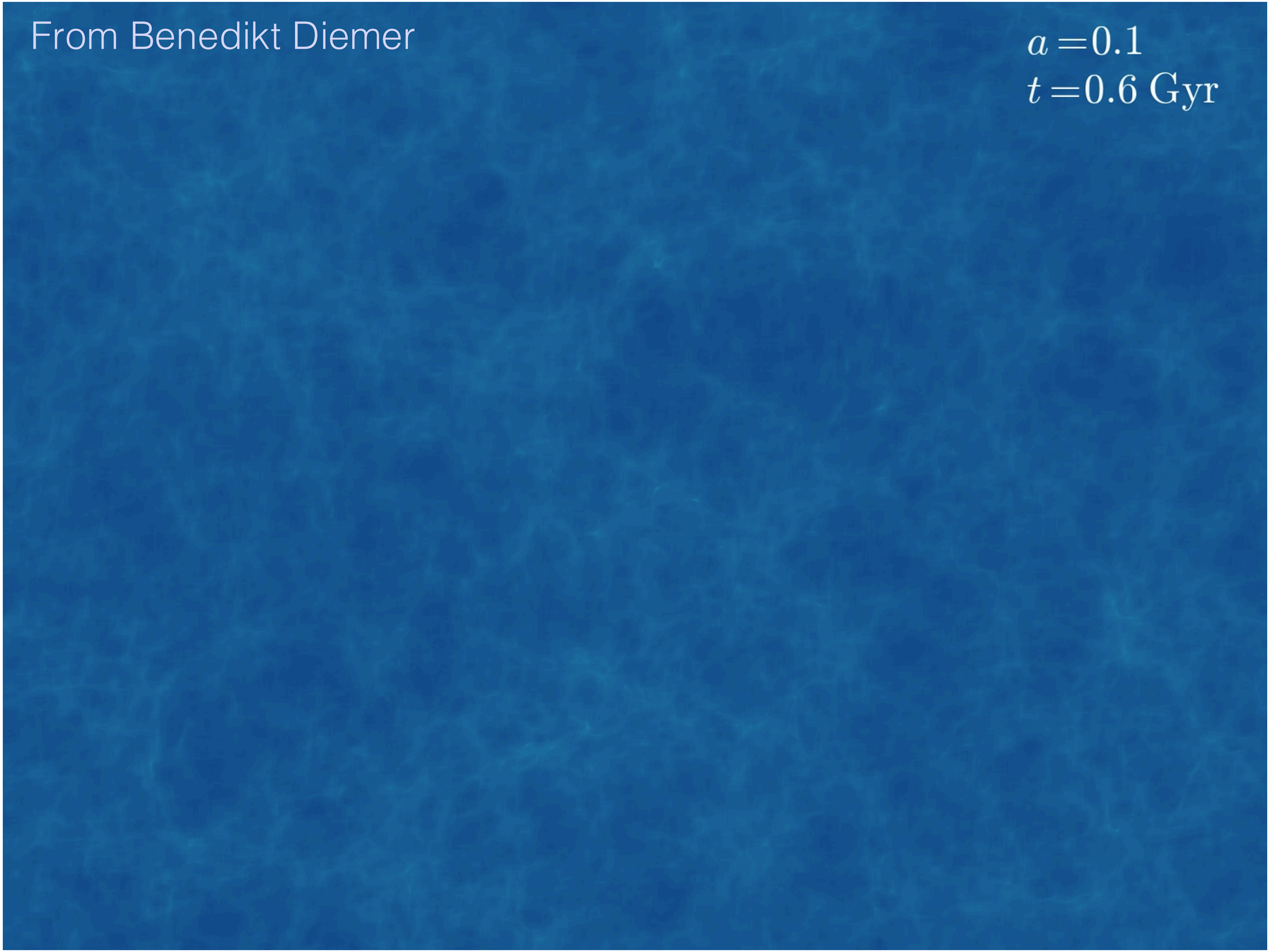


Structure formation: Expansion vs. Dark matter

w/o Λ　　　　　　with Λ



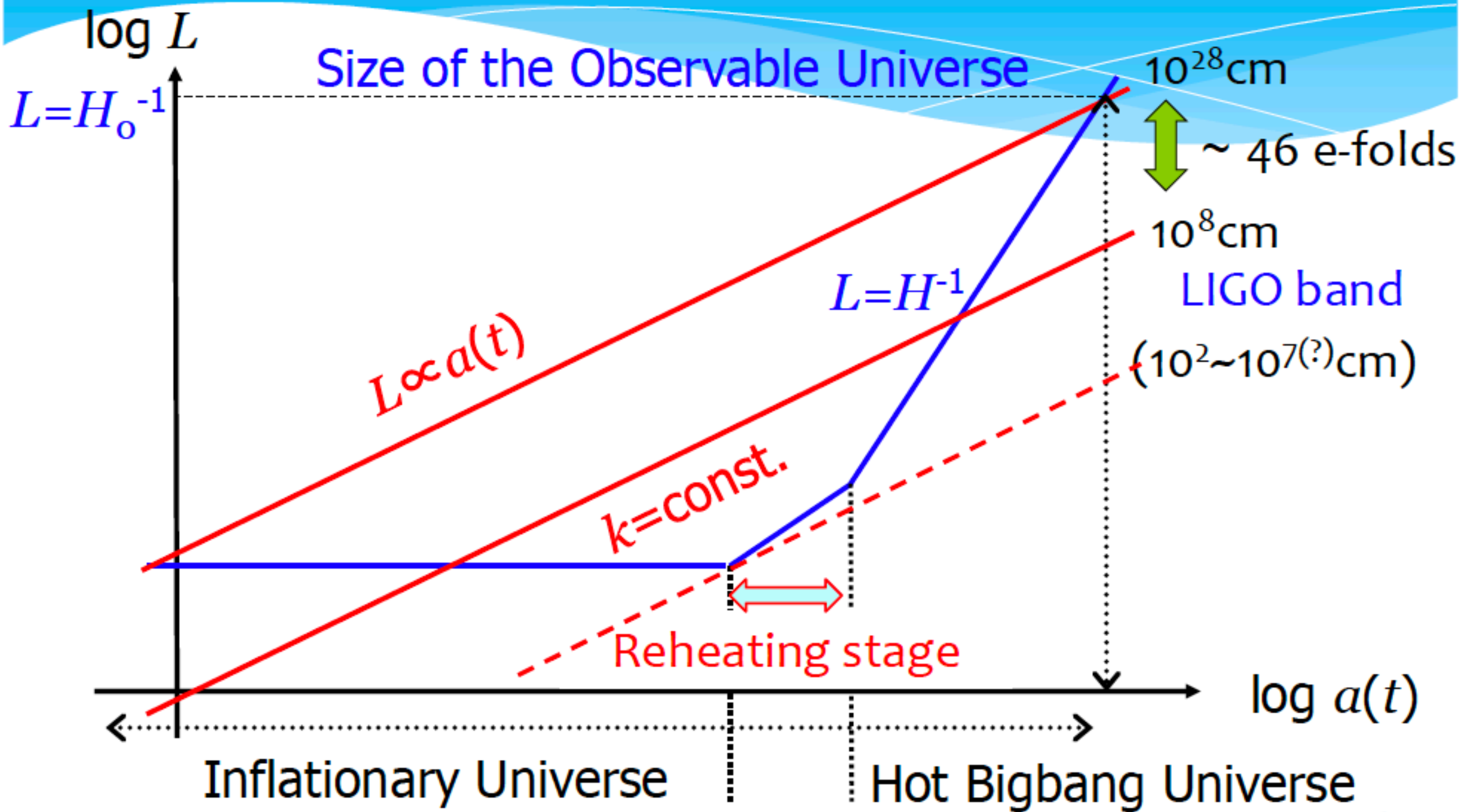
Similar CMB spectra in these two models


From Benedikt Diemer
$a = 0.1$
$t = 0.6$ Gyr

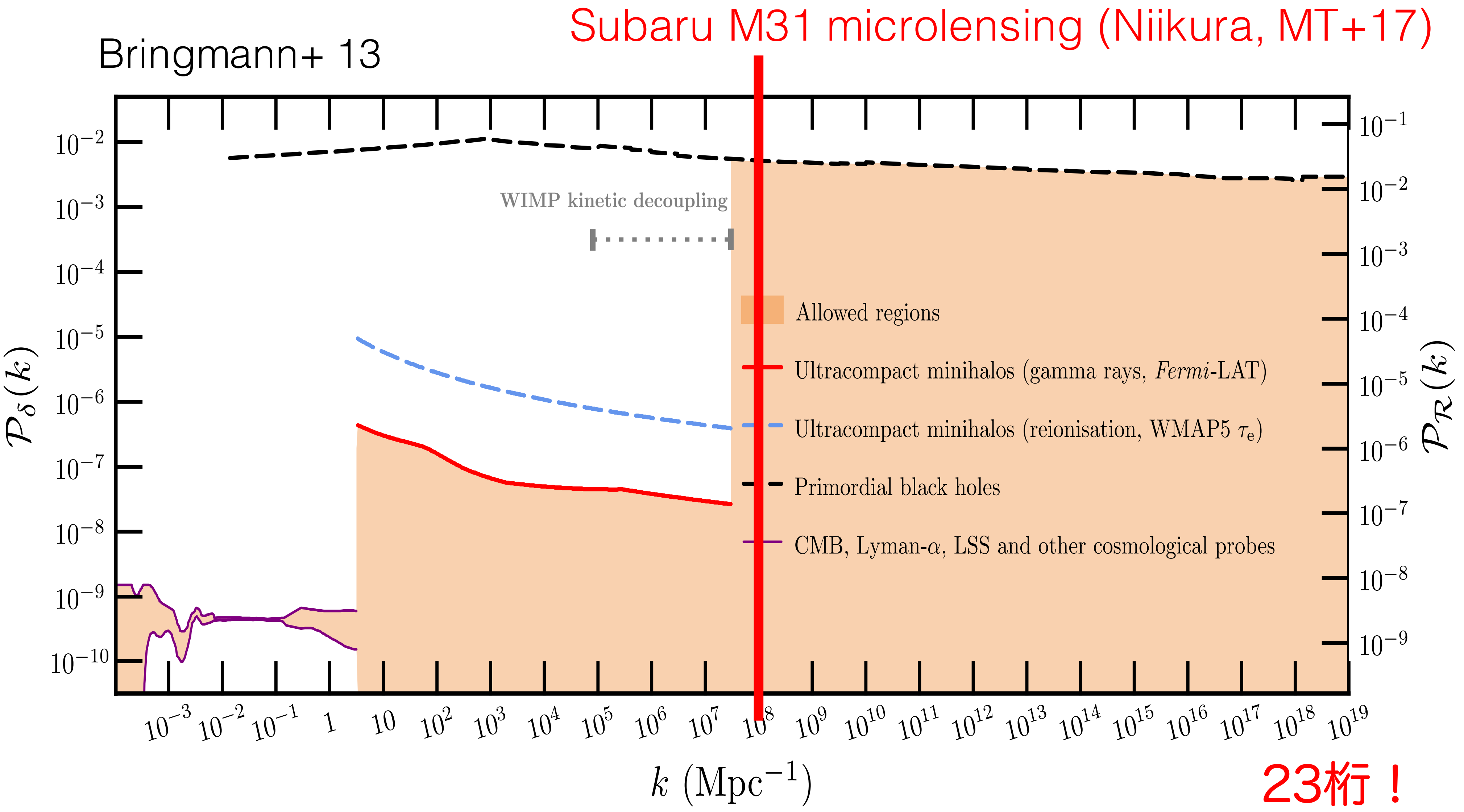
佐々木節さん（IPMU）のスライドより

length scales of the inflationary universe

⇔ targets for multi-freq GW astronomy/cosmology



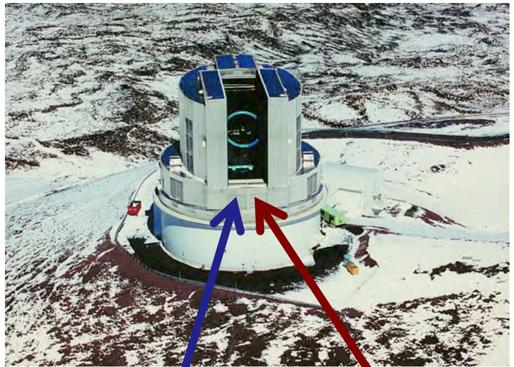
Constraining the scalar primordial perturbations over many orders of magnitude scales



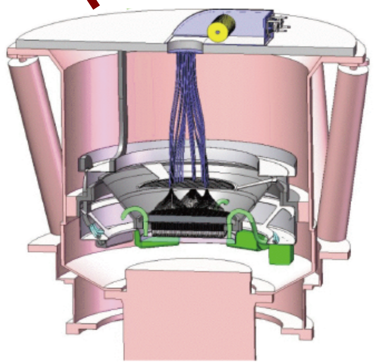
SuMIRe = Subaru Measurement of Images and Redshifts

H. Murayama (Kavli IPMU Director)

- IPMU director Hitoshi Murayama funded (~$32M) by the Cabinet in Mar 2009, as one of the stimulus package programs
- Build *wide-field* camera (Hyper Suprime-Cam; ~$55M) and *wide-field* multi-object spectrograph (Prime Focus Spectrograph; ~$80M) for the Subaru Telescope (8.2m)
- Explore the fate of our Universe: dark matter, dark energy
- Keep the Subaru Telescope a world-leading telescope in the TMT era
- Precise images of 1B galaxies
- Measure distances of ~4M galaxies
- **Do SDSS-like survey at z>1**

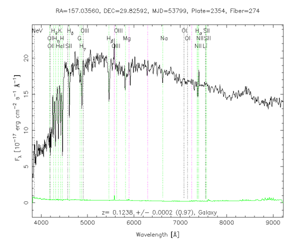


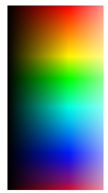
Subaru (NAOJ)



PFS

HSC





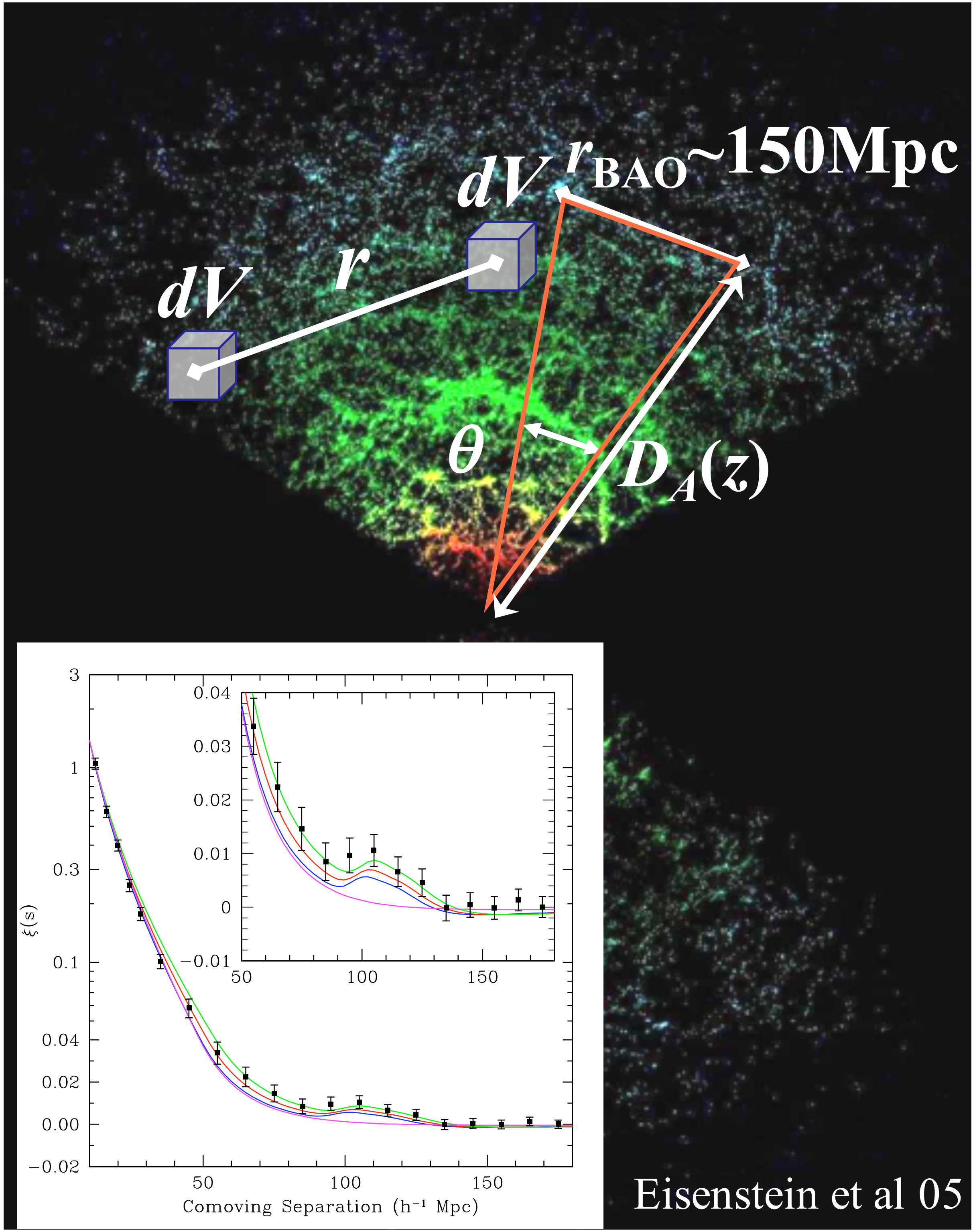
BAO

- Measure galaxy clustering strengths: 2pt correlations (or P(k))

$$dP = \bar{n}_g^2\left[1+\xi_g(r)\right]dV^2$$

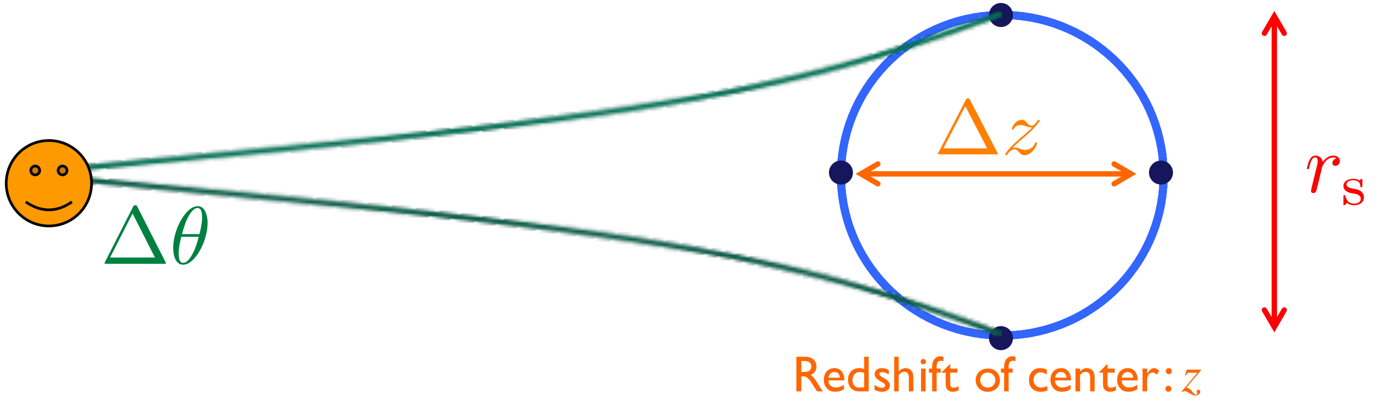
- Find a tiny excess in the galaxy pairs at BAO scale (a priori known from CMB to be ~150Mpc)

$$r_{\mathrm{BAO}} = D_A(z)\theta_{\mathrm{obs}}$$



BAO=Cosmological geometrical test

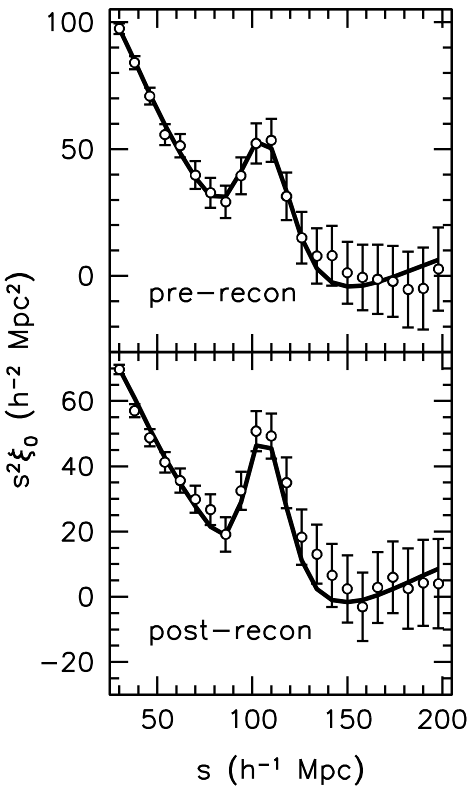
- Suppose that you have an object whose size or length scale you *a priori* know – standard ruler

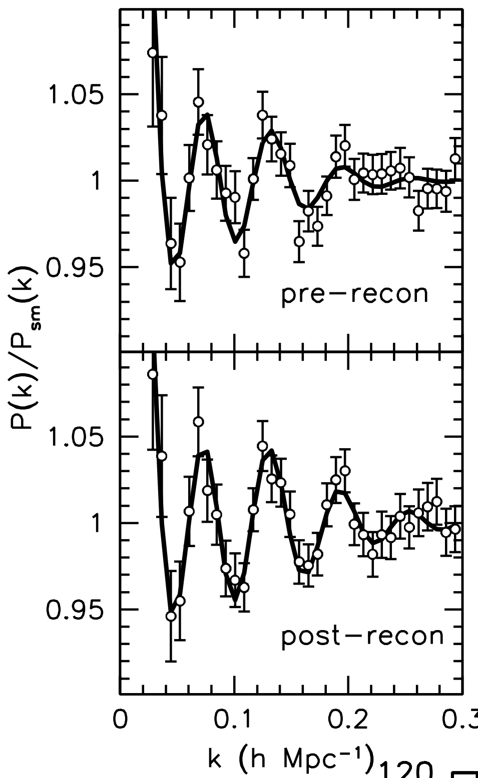


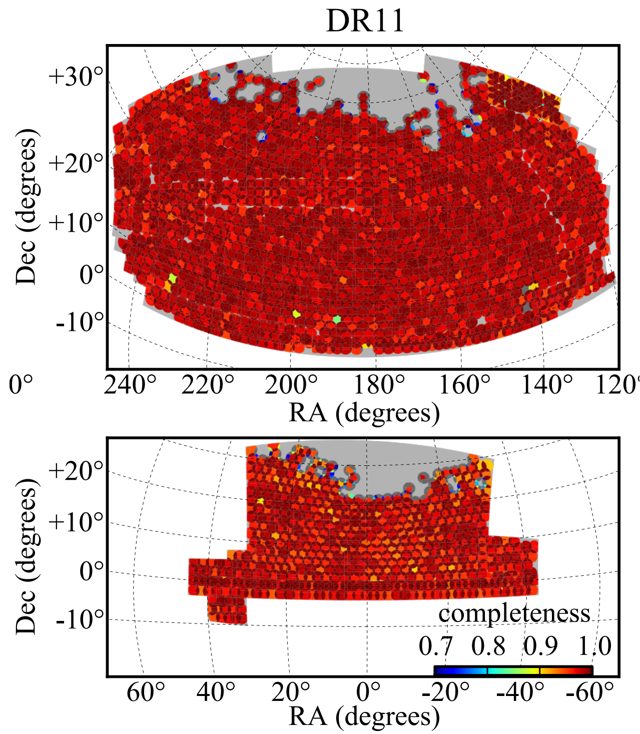
- The standard ruler allows us to infer the radial and angular diameter distances, from the redshift and angular extents

$$r_s = \Delta\chi = \frac{\Delta z}{H(z)}, \quad r_s = d_A^{\rm com}(z)\Delta\theta$$

SDSS Baryon Oscillation Spectroscopic Survey (BOSS)



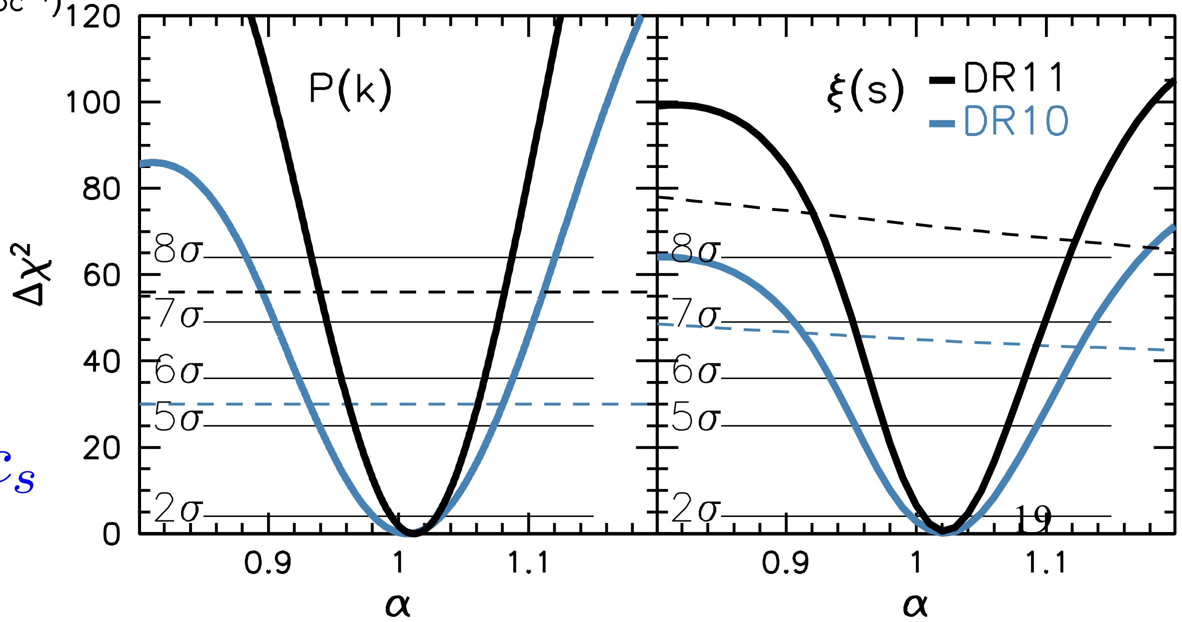




Shun Saito (MPA)

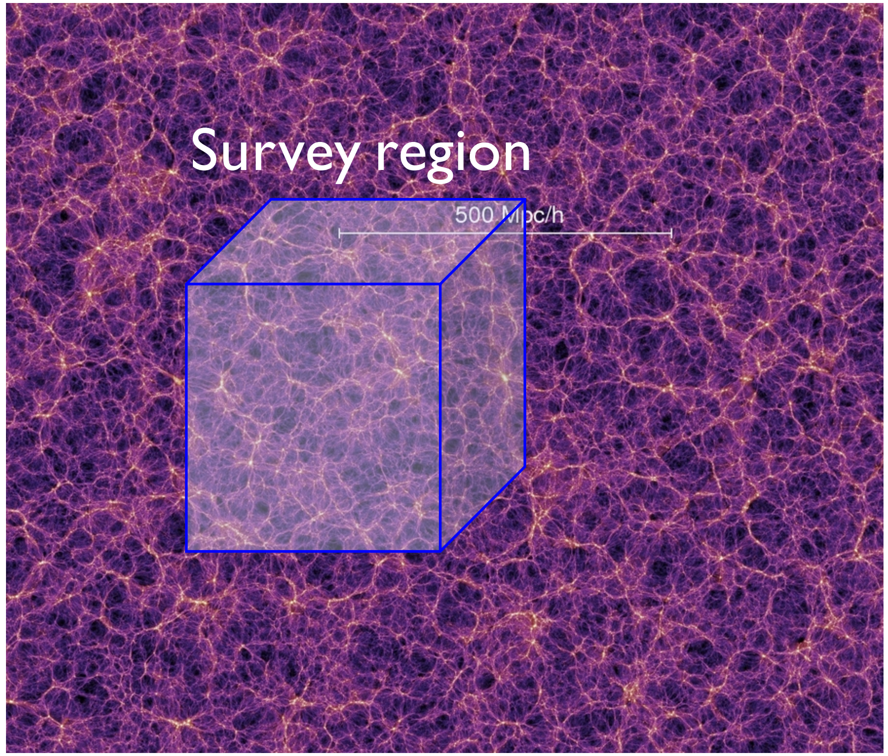
- *~8σ significance for the BAO detection*

$$\Theta_\gamma \sim \cos(ks), s \equiv \int \mathrm{d}\eta \, c_s$$

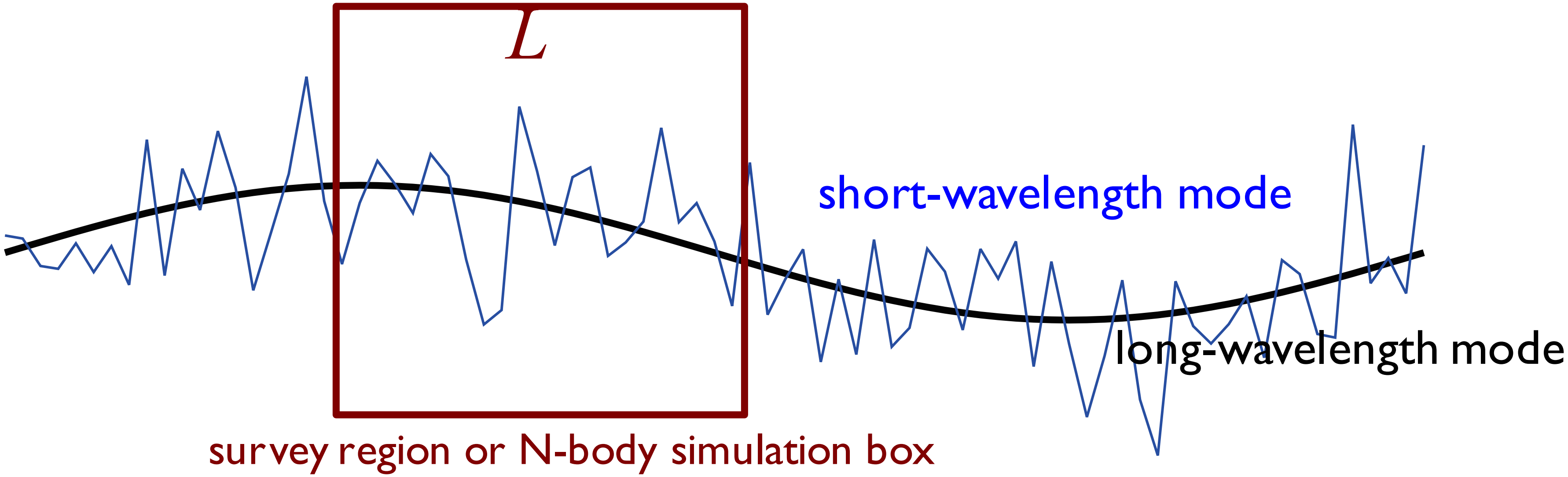


“Super” survey mode (soft mode)

- Inflation predicts all-scale perturbations
- Any cosmological survey probes a finite volume in the universe
- Nonlinear mode coupling (coupling btw different Fourier modes)
- N-body simulation is done with a finite volume (with periodic boundary conditions)
- In the late-time universe, three might be additional perturbations (e.g. dark energy) that can’t be seen in CMB



Super-survey modes



Long-wavelength modes can be expanded around the survey region

$$\Phi_L(\mathbf{x}) \simeq \bar{\Phi}_L + \nabla_i \Phi_L(\mathbf{x}) L_i + \frac{1}{2}\nabla_i \nabla_j \Phi_L L_i L_j + \cdots$$

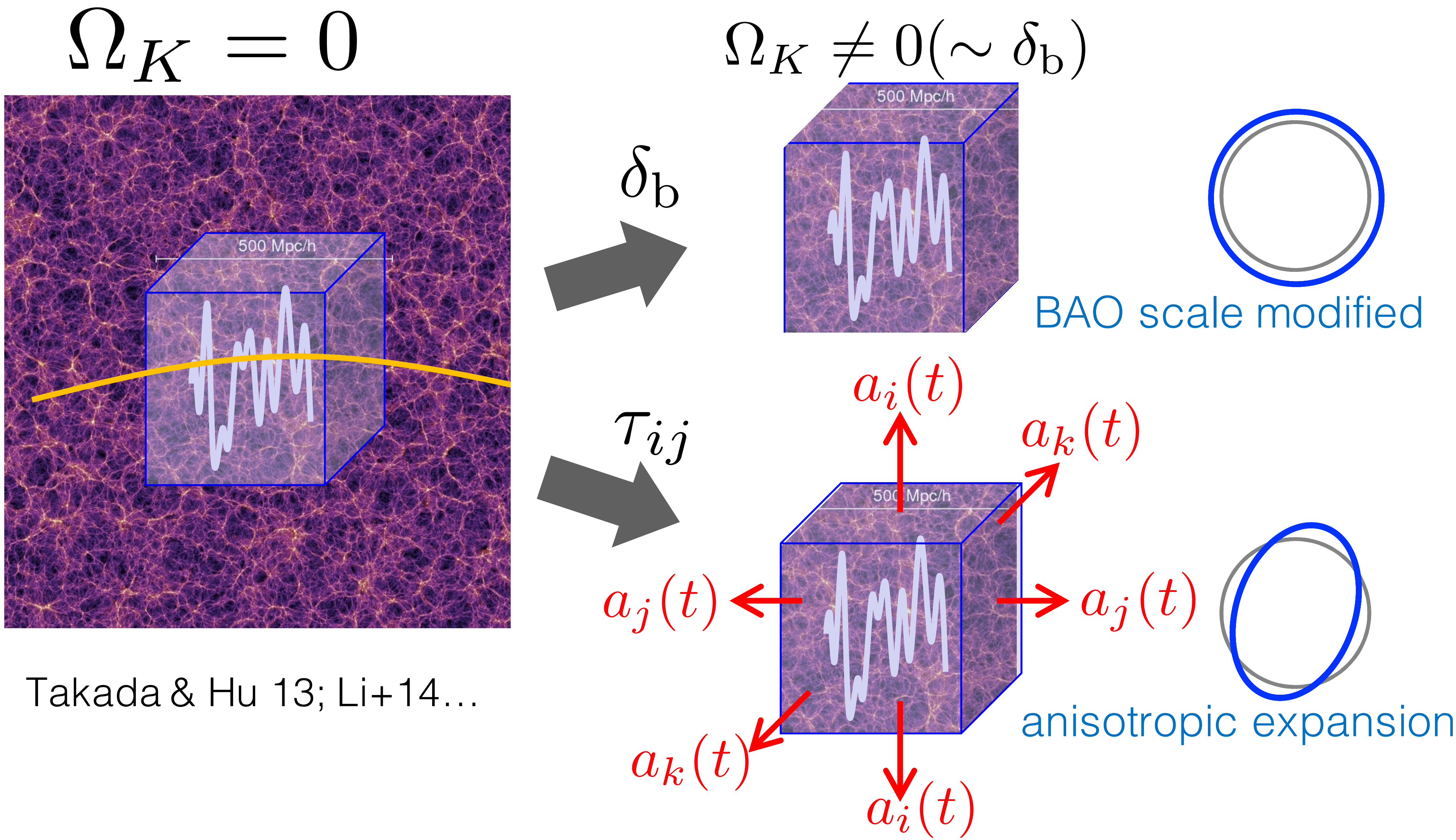
$$= \bar{\Phi}_L + \frac{1}{2}(\Delta \Phi_L)\frac{1}{3}L^2 + \nabla_i \Phi_L(\mathbf{x}) L_i + \frac{1}{2}\tau_{ij} L_i L_j + \cdots$$

$$= \bar{\Phi}_L + 2\pi G \bar{\rho} \bar{\delta}_b \frac{1}{3} L^2 + \nabla_i \Phi_L(\mathbf{x}) L_i + \frac{1}{2}\tau_{ij} L_i L_j + \cdots$$

mean density modulation — gradient field — tidal field

Separate universe picture

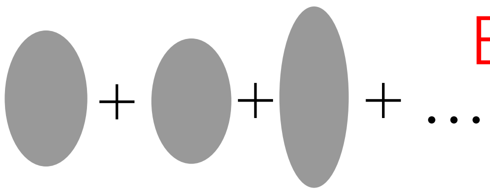
The effect of large scale mode can be absorbed by a change in the background expansion of **local** universe



Takada & Hu 13; Li+14…

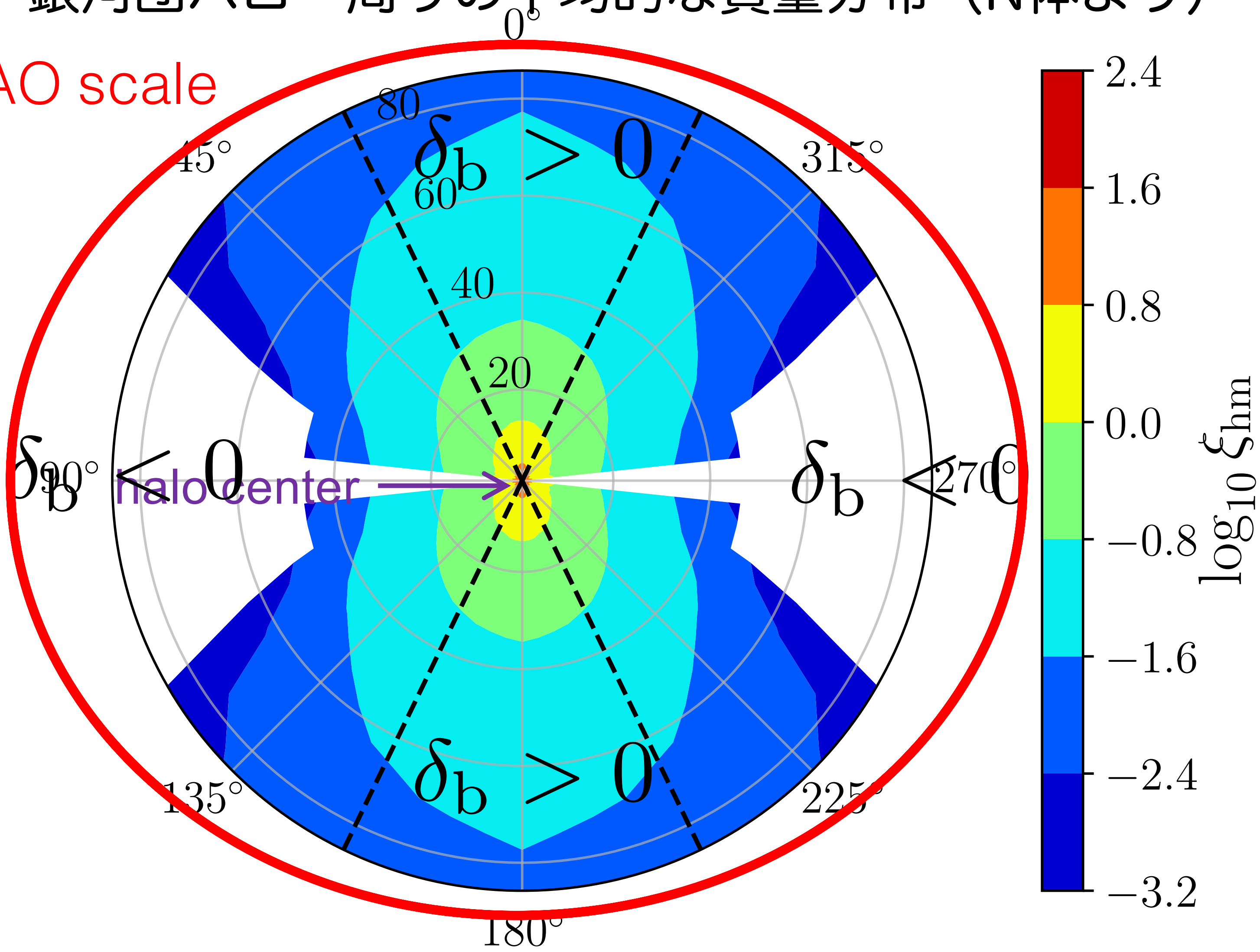
Alignment btw halo shapes and surrounding tidal field

Osato +18

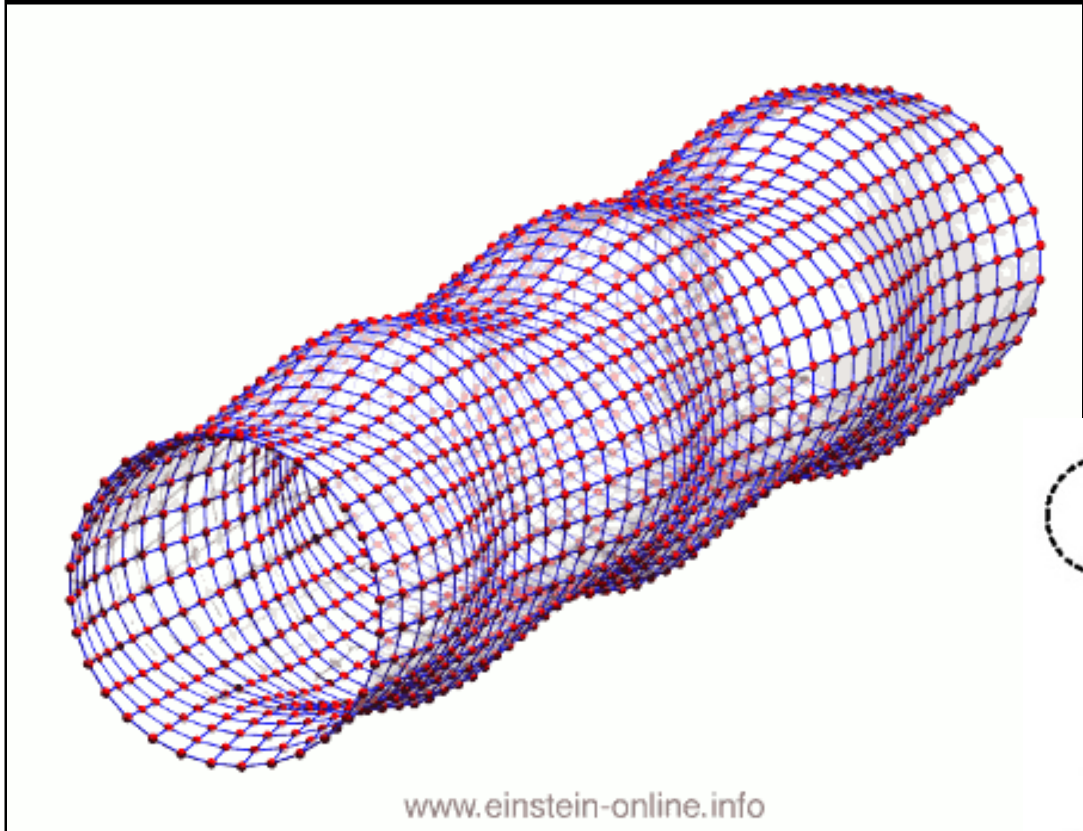


Align the principal axis of each cluster-scale halo to the z-axis direction, and then stack the surrounding mass distribution

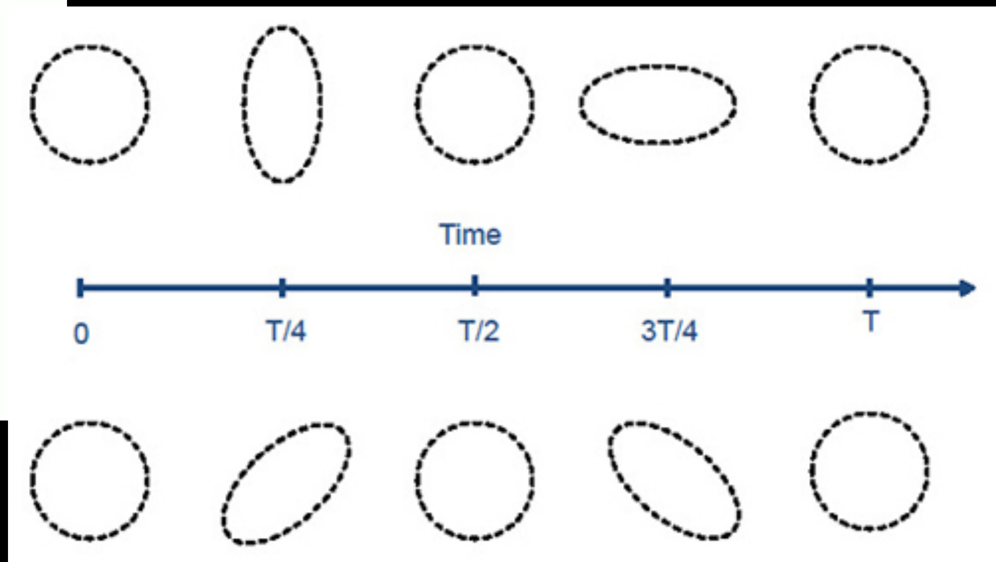
銀河団ハロー周りの平均的な質量分布（N体より）



Gravitational wave (stretch of space time)

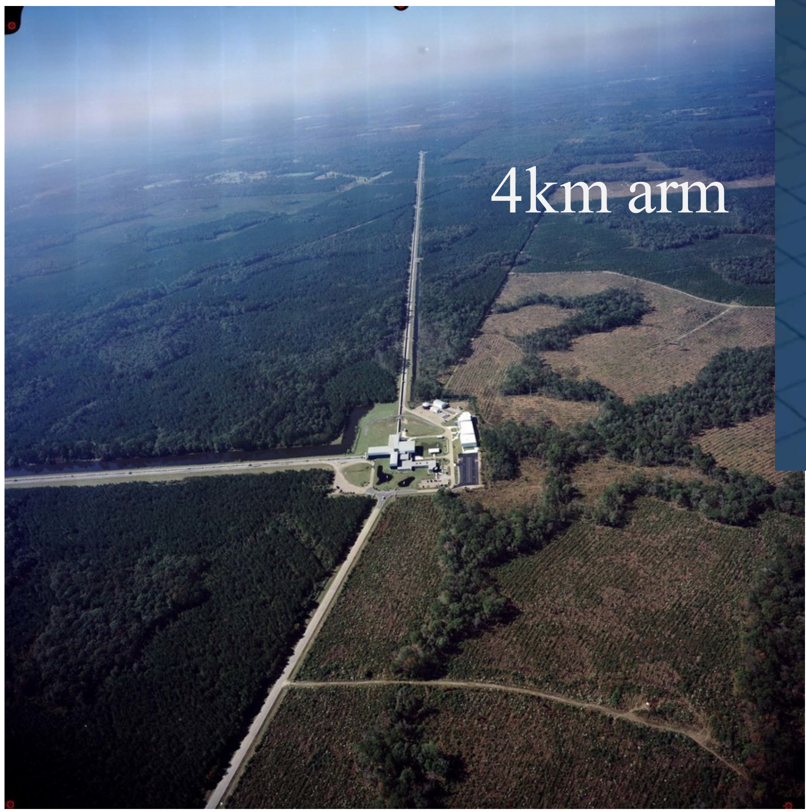


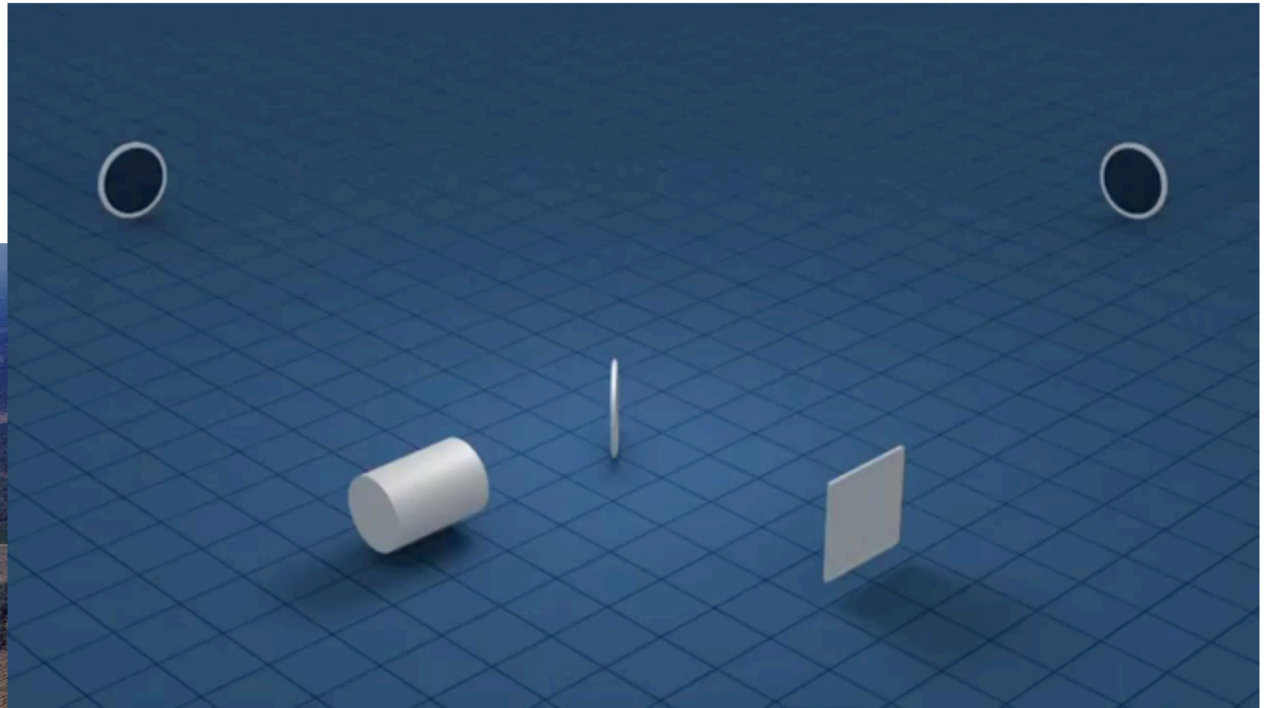
transverse and quadrupole



レーザー干渉計重力波天文台 LIGO (米国)

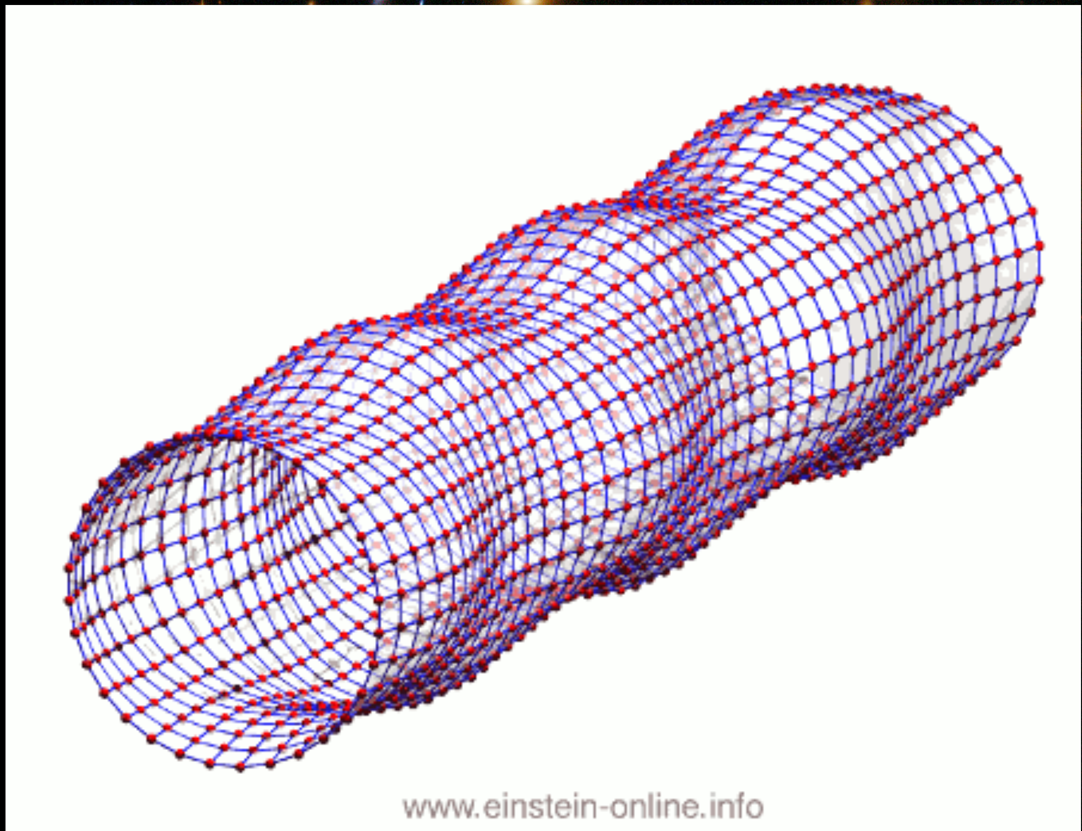
LIGO Livingston

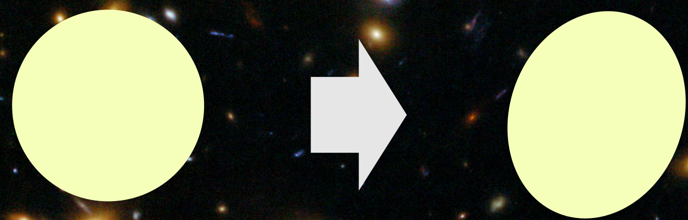




LIGO Hanford

Primordial GW affects galaxy shapes?

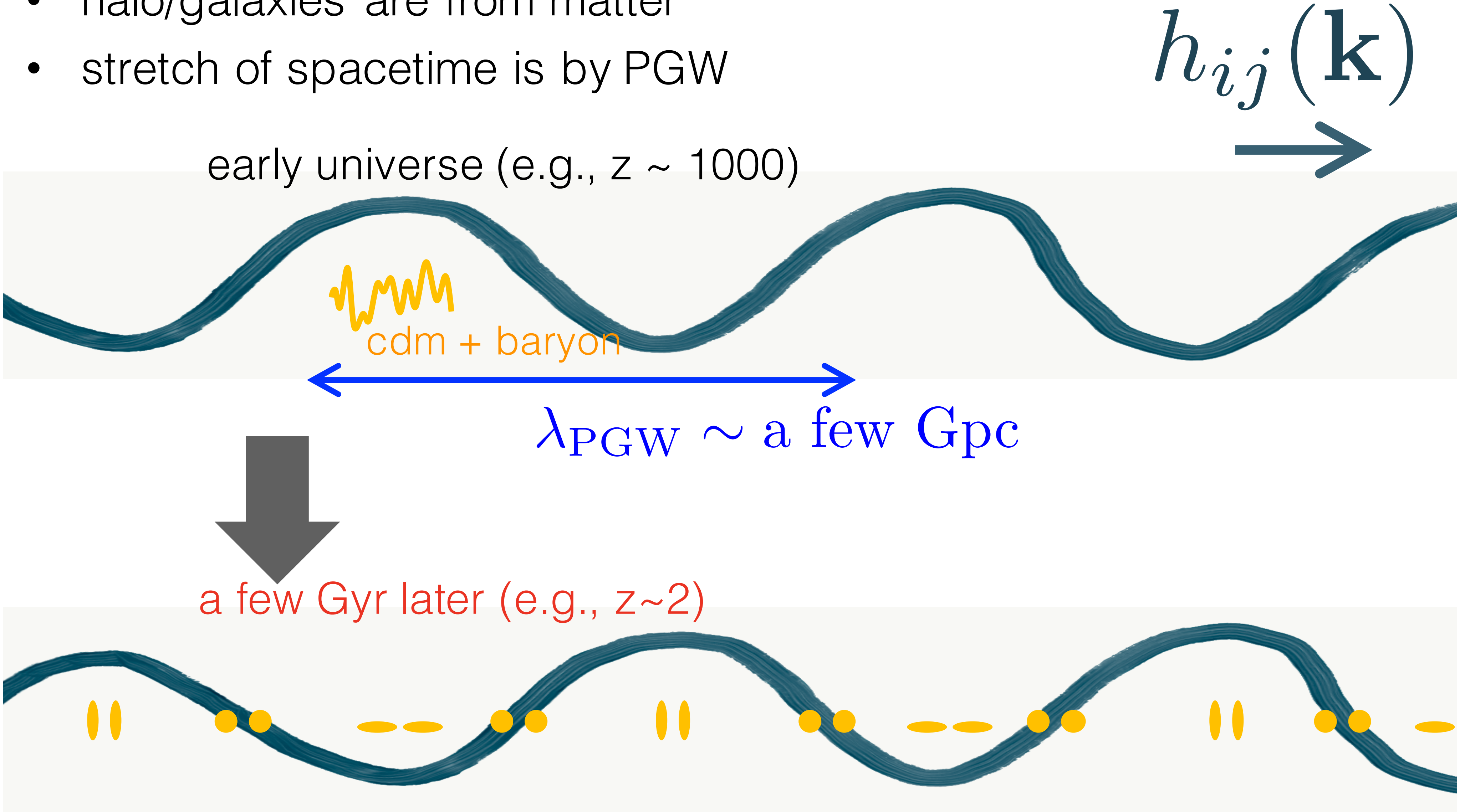




$$ds^2 = -dt^2 + a(t)^2 \left[\delta_{ij} + h_{ij}(\mathbf{x}, t)\right] dx^i dx^j$$

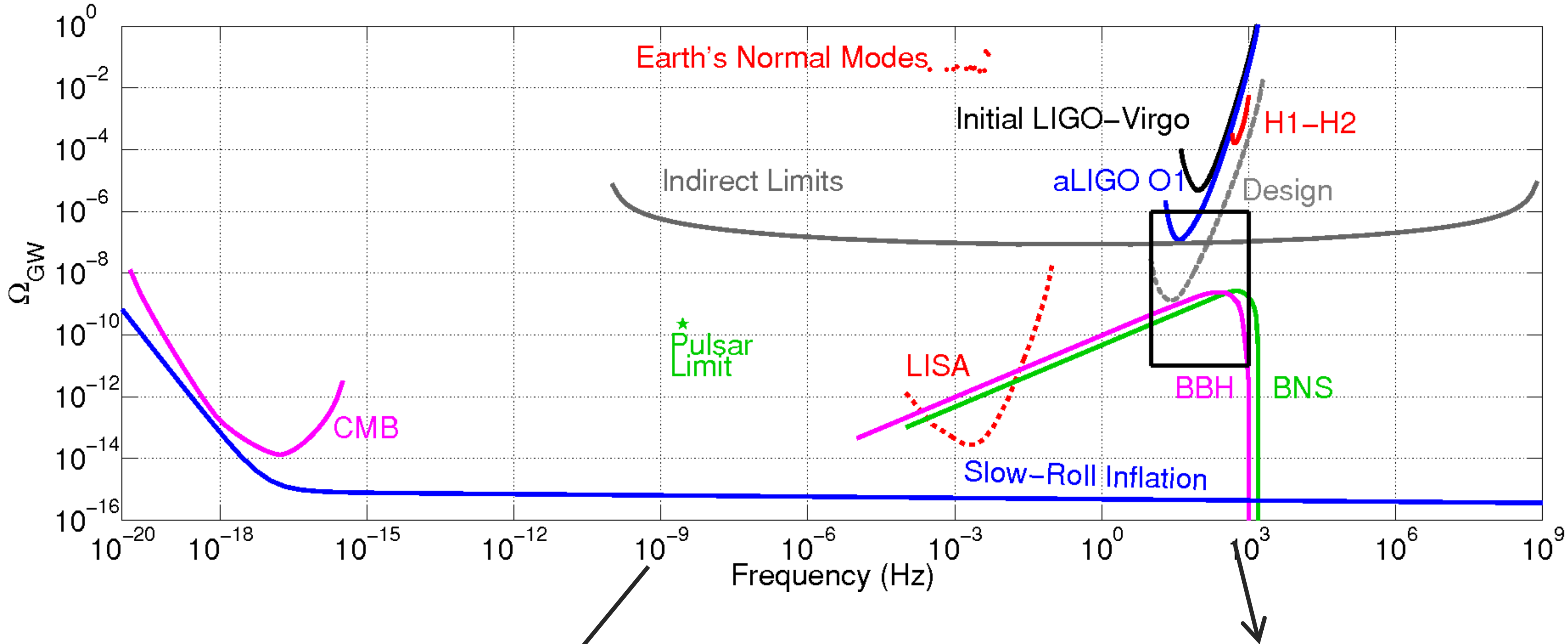
Schmidt + 15

- halo/galaxies are from matter
- stretch of spacetime is by PGW



intrinsic shapes can be induced by large-scale GW

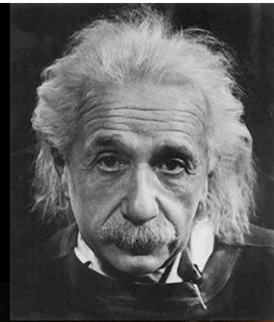
Constraints on stochastic (primordial) GW background



$$\lambda_{\rm stoch.\ GW} \simeq \text{a few} \times 10^3\ \text{km}$$

$$\lambda_{\rm stoch.\ GW} \simeq c f^{-1} \sim 3 \times 10^{10}\ [\text{cm/s}] \times 10^9\ [\text{s}] \sim 10\ \text{pc}$$

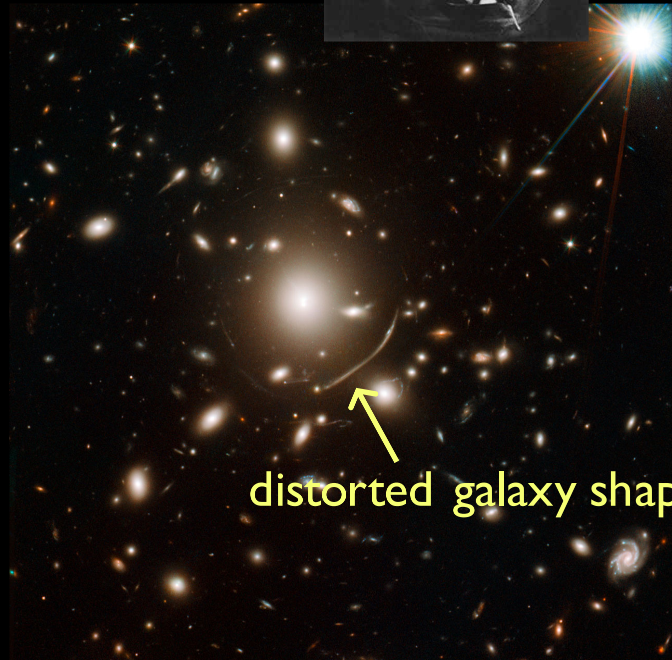
Gravitational lensing = GR prediction



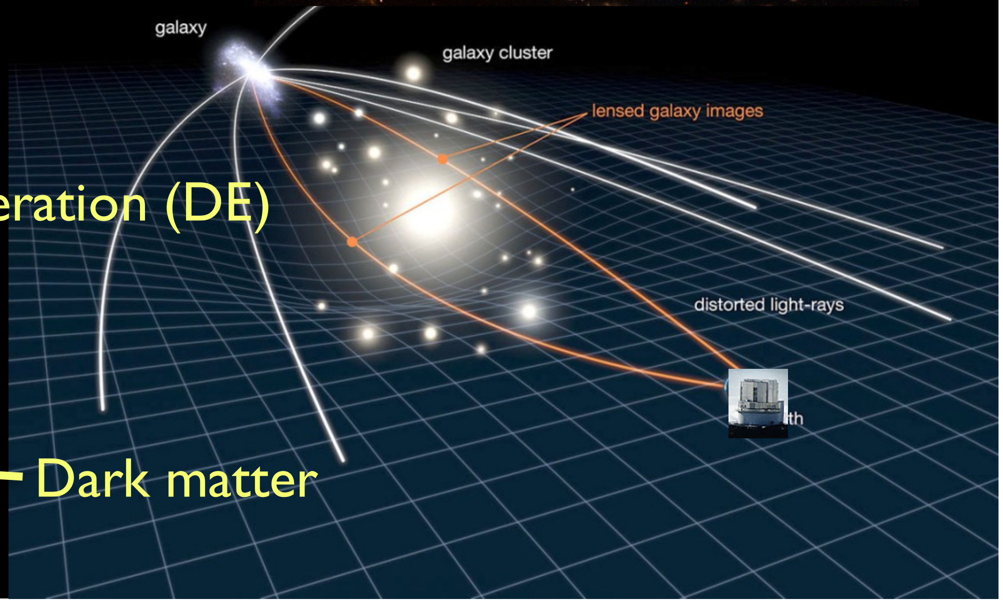
$$G_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}$$

$$\Rightarrow \ \text{light path: } \boldsymbol{x} = \boldsymbol{x}[z; g_{\mu\nu}]$$

Light-ray path, emitted from a distant galaxy, is bent by the foreground matter distribution



It causes a distortion in galaxy image

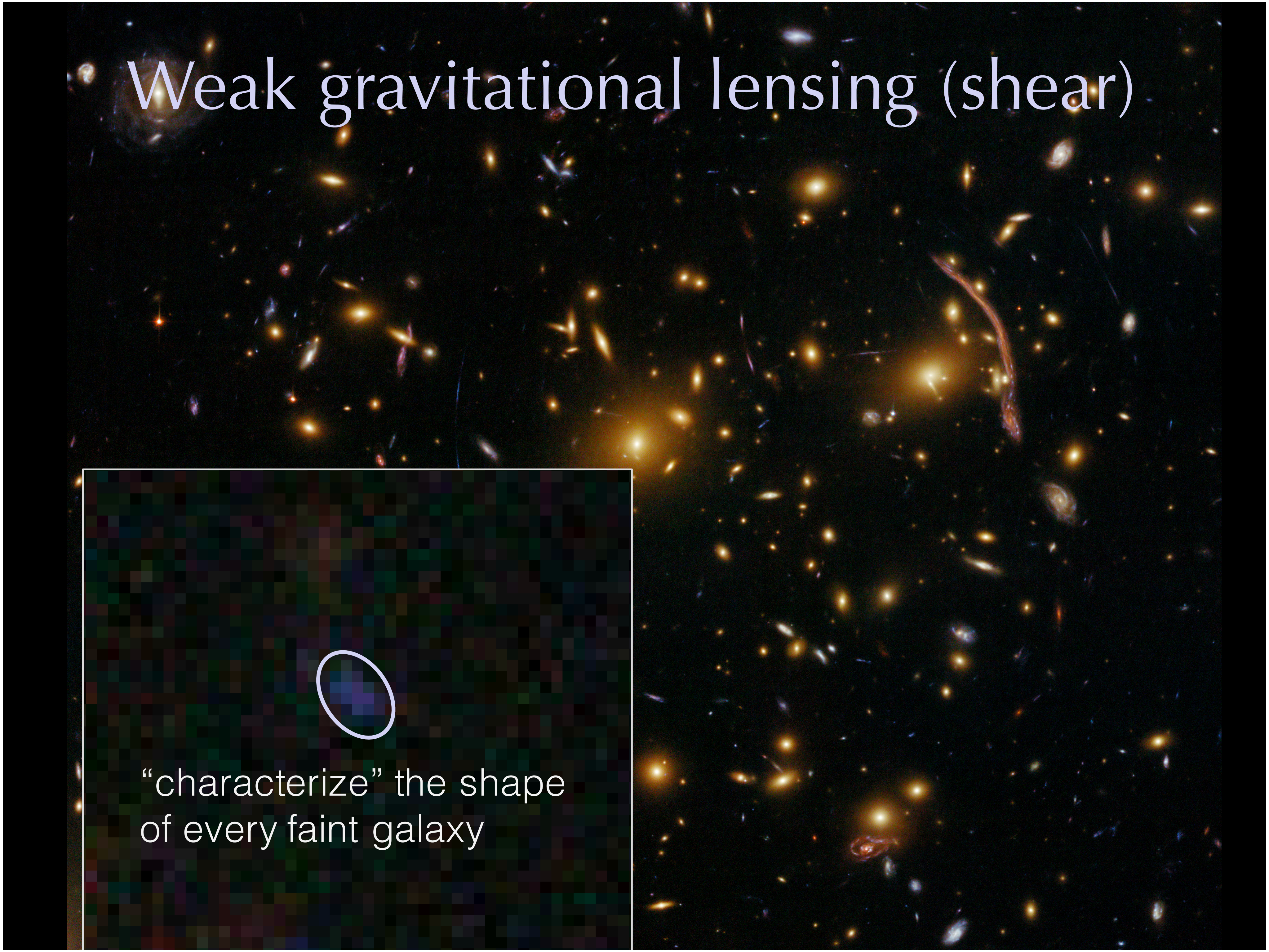


Lensing strength = (geometry of the universe) × (total matter of lens(es))

Cosmic acceleration (DE) → (geometry of the universe)

Dark matter → (total matter of lens(es))

Weak gravitational lensing (shear)



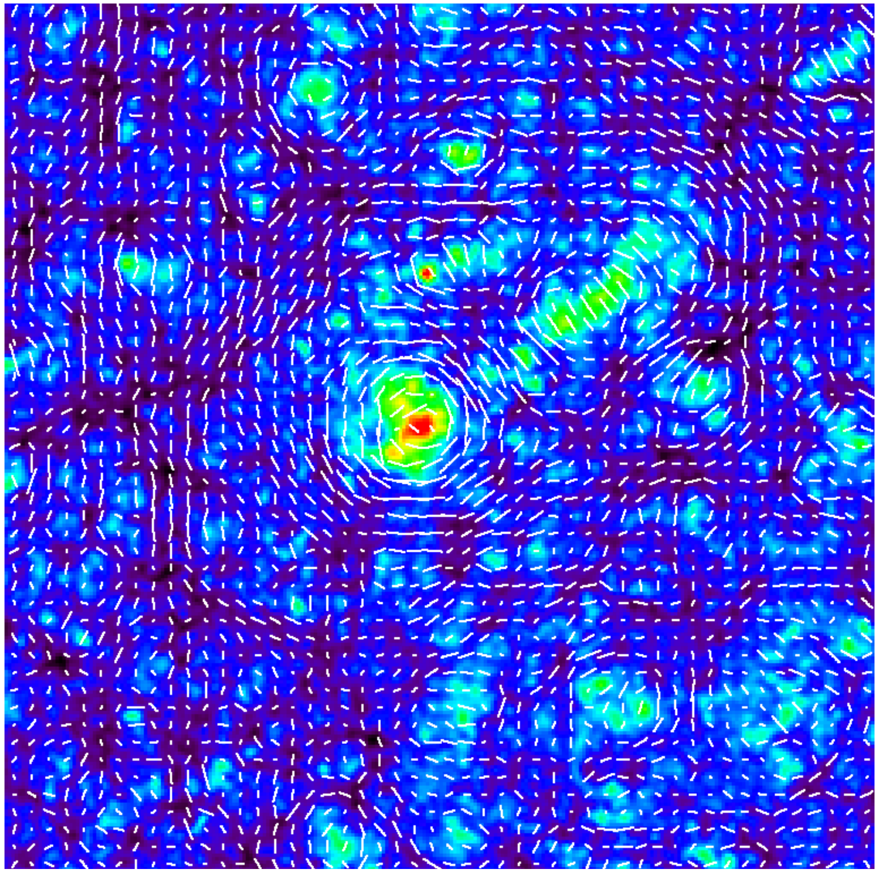
Weak lensing

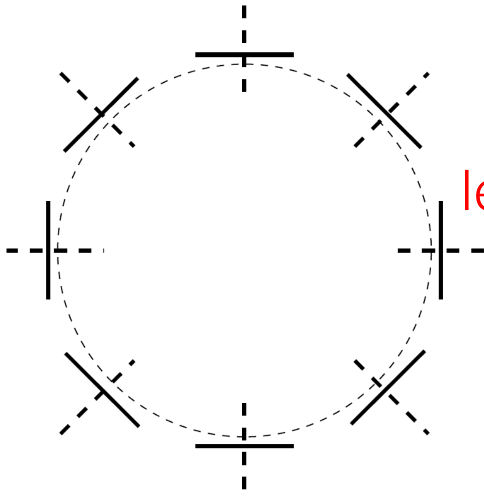
The signal is tiny: allows for a **direct reconstruction** of gravitational potential due to nonlinear matter distribution in the universe

shear $$\gamma_{ij} \sim \int_0^{z_s} \mathrm{d}z_l \; W(z_s, z_l) \nabla_{\perp i} \nabla_{\perp j} \Phi[\mathbf{x}_{\rm photon\ path}(t)]$$

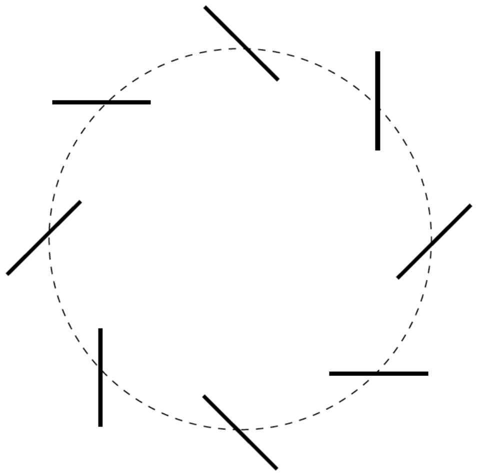
$$\nabla^2 \Phi(\mathbf{x}, t) = 4\pi G \bar{\rho}_m a^2 \delta_m(\mathbf{x}, t)$$

Simulated lensing map (color = 2D DM map, stick=shear)



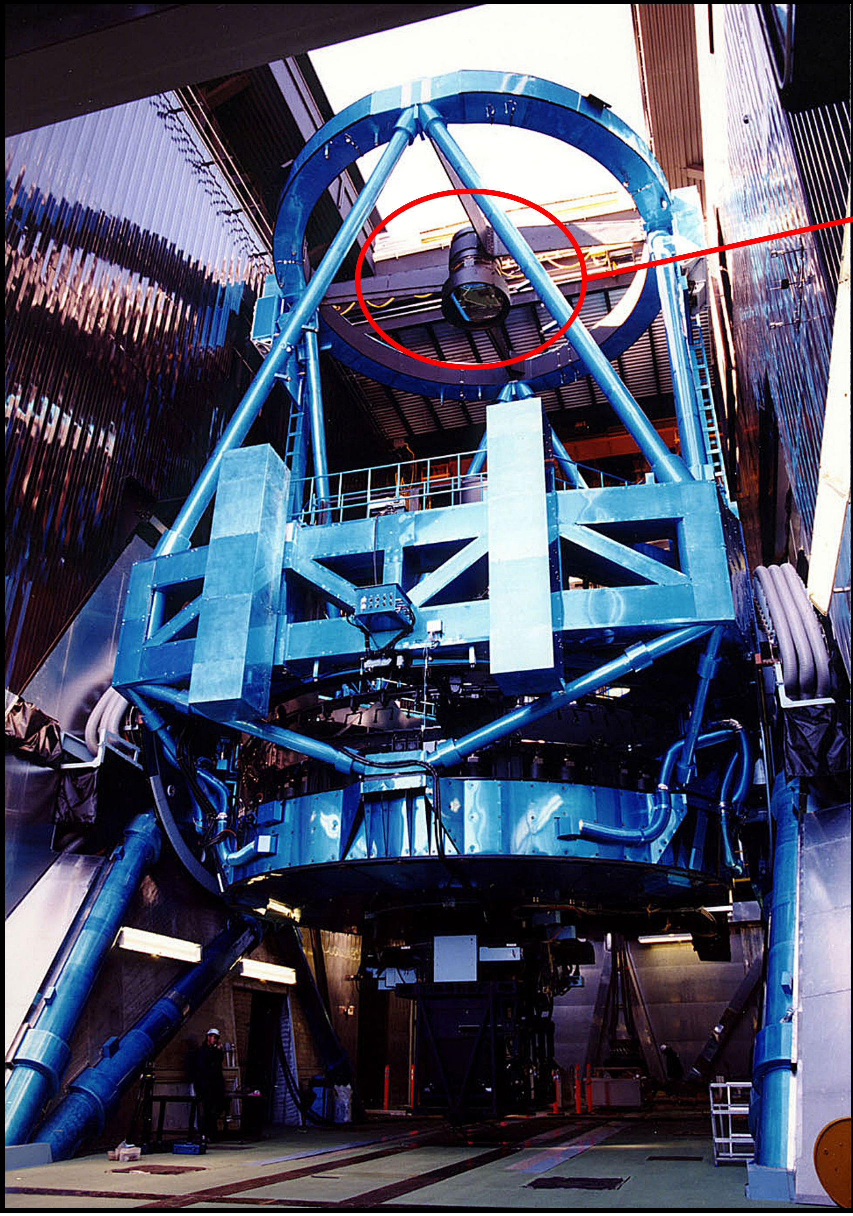


lensing mode (E mode)

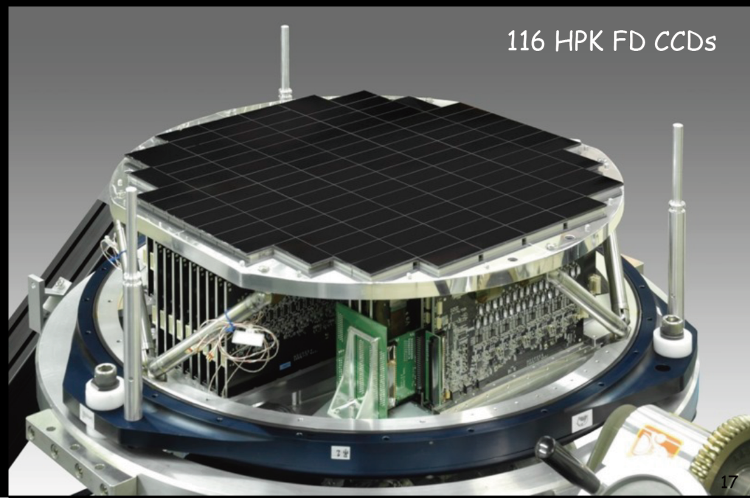


non-lensing mode (e.g., systematics) (B mode)

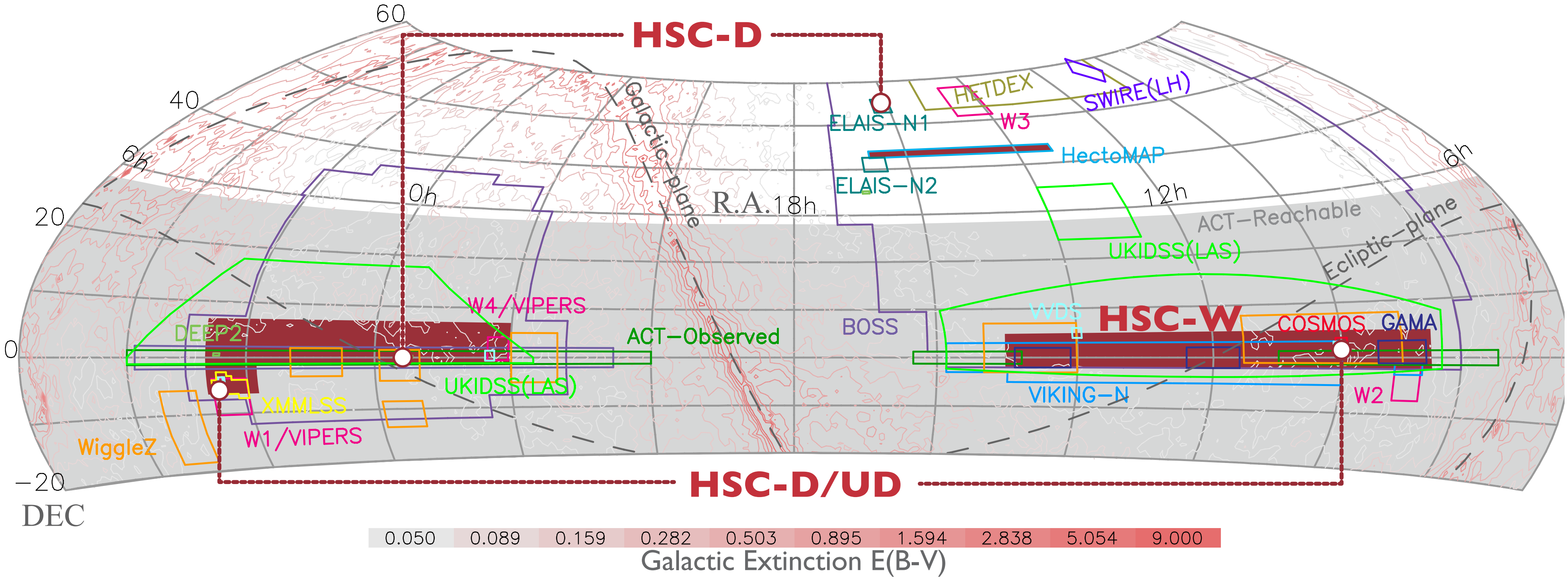
Hyper Suprime-Cam



- largest camera
- 3m high
- weigh 3 ton
- 104 CCDs (~0.9B pixels)



Subaru HSC Survey

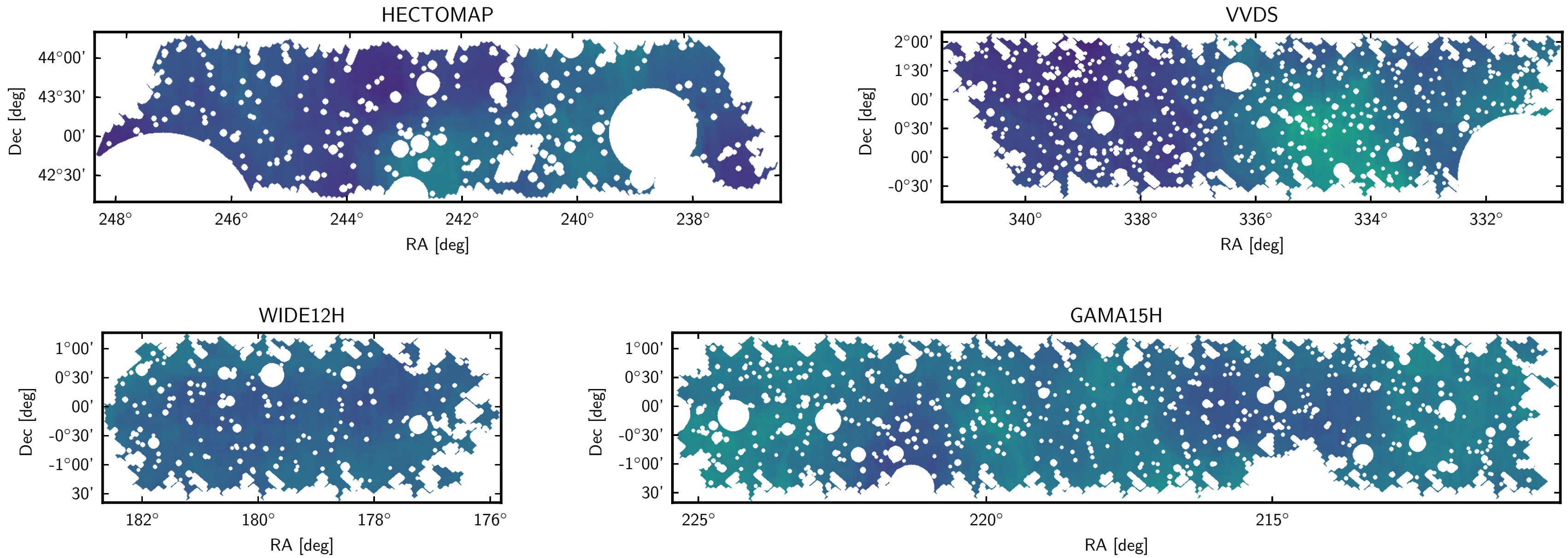


- **Subaru 300 nights** granted (2014 – 19)
- HSC Survey Fields selected based on
  - Overlap with SDSS regions and other interesting, external datasets (ACT CMB, NIR, spectroscopic surveys, …); Low dust extinction; Spread in RA
- The main scientific objectives are
  - Wide: Cosmology, Deep: galaxy evolution, UD: cosmic reionization

Subaru HSC = superb image quality

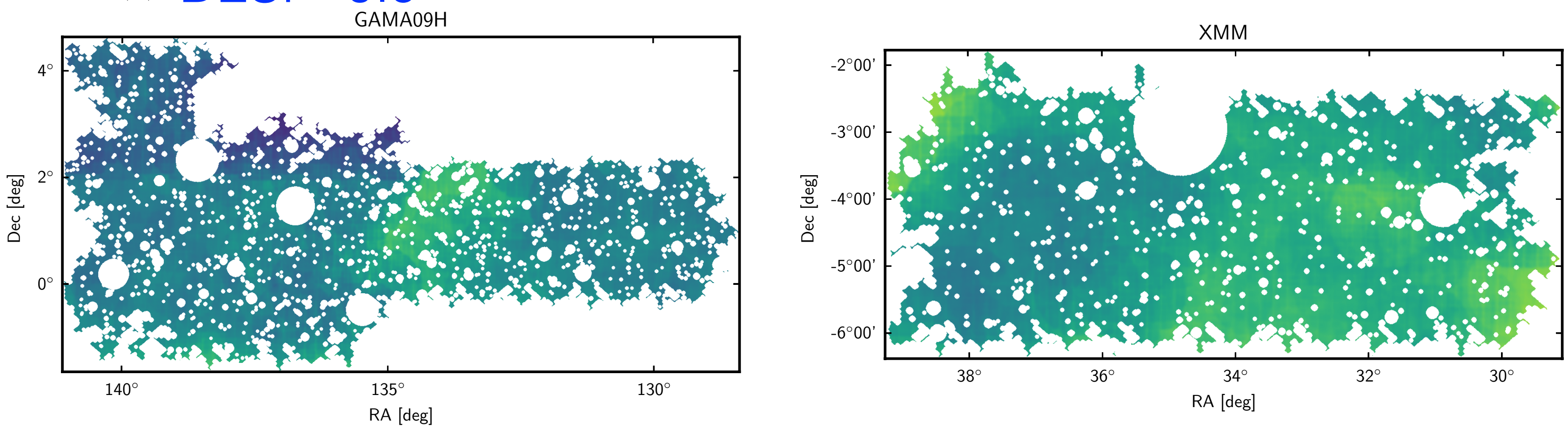
6 fields (~140 sq. deg. in total)

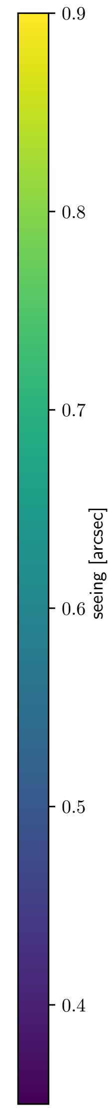
$n_{\rm eff} \simeq 22\ {\rm arcmin}^{-2}$



Subaru HSC typically **0.6" seeing** FWHM (spatial resolution)

⇔ DES: ~0.9"





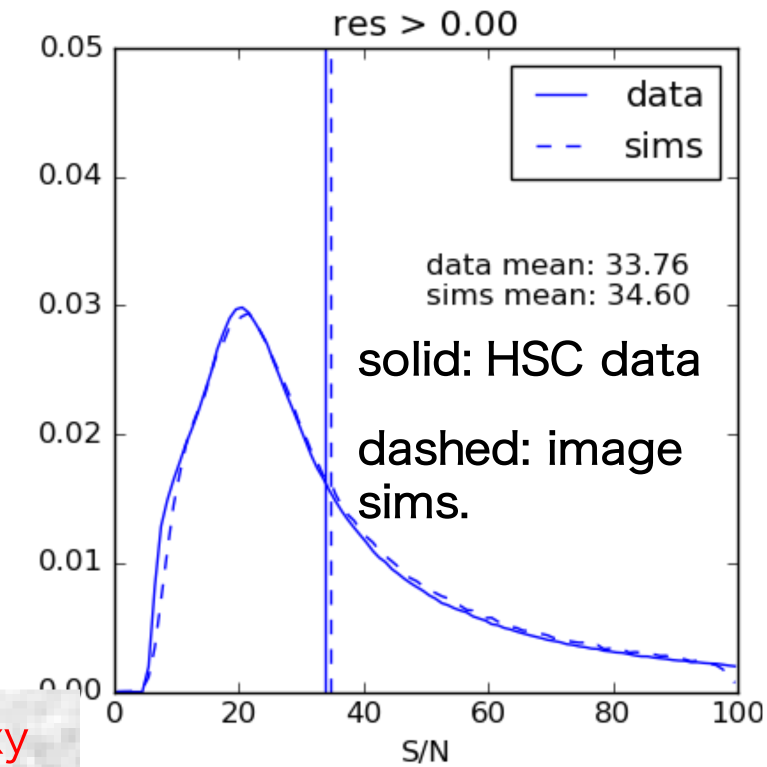
Mandelbaum, Miyatake+, PASJ 2018

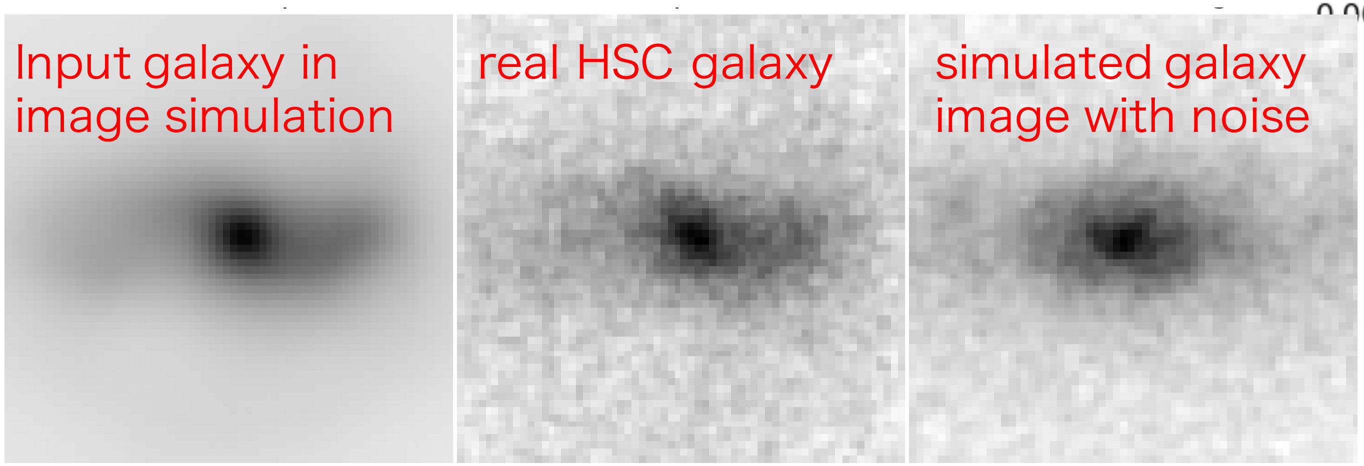
HSC galaxy shape catalog


R. Mandelbaum (CMU)

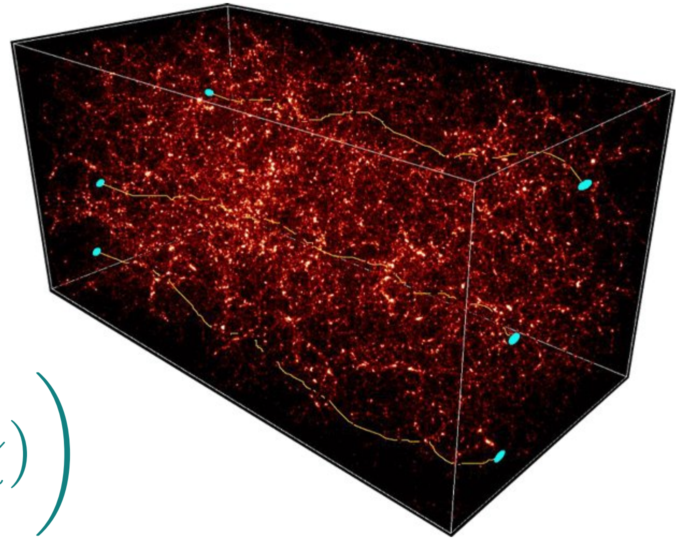

Hironao Miyatake (Nagoya/IPMU)

- Developed the pipeline for galaxy shape measurement
- Tested/validated the galaxy shape catalog with sophisticated image simulations
- **~10M galaxies (~20 gals/sq. arcmin., ~140 sq. deg.)**
- Ready to use for weak lensing science





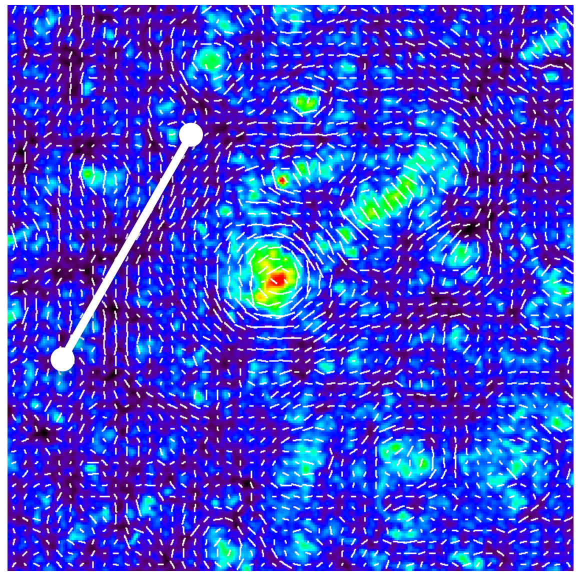
Cosmic shear cosmology



- Pros
  - Can measure "total" matter power clustering

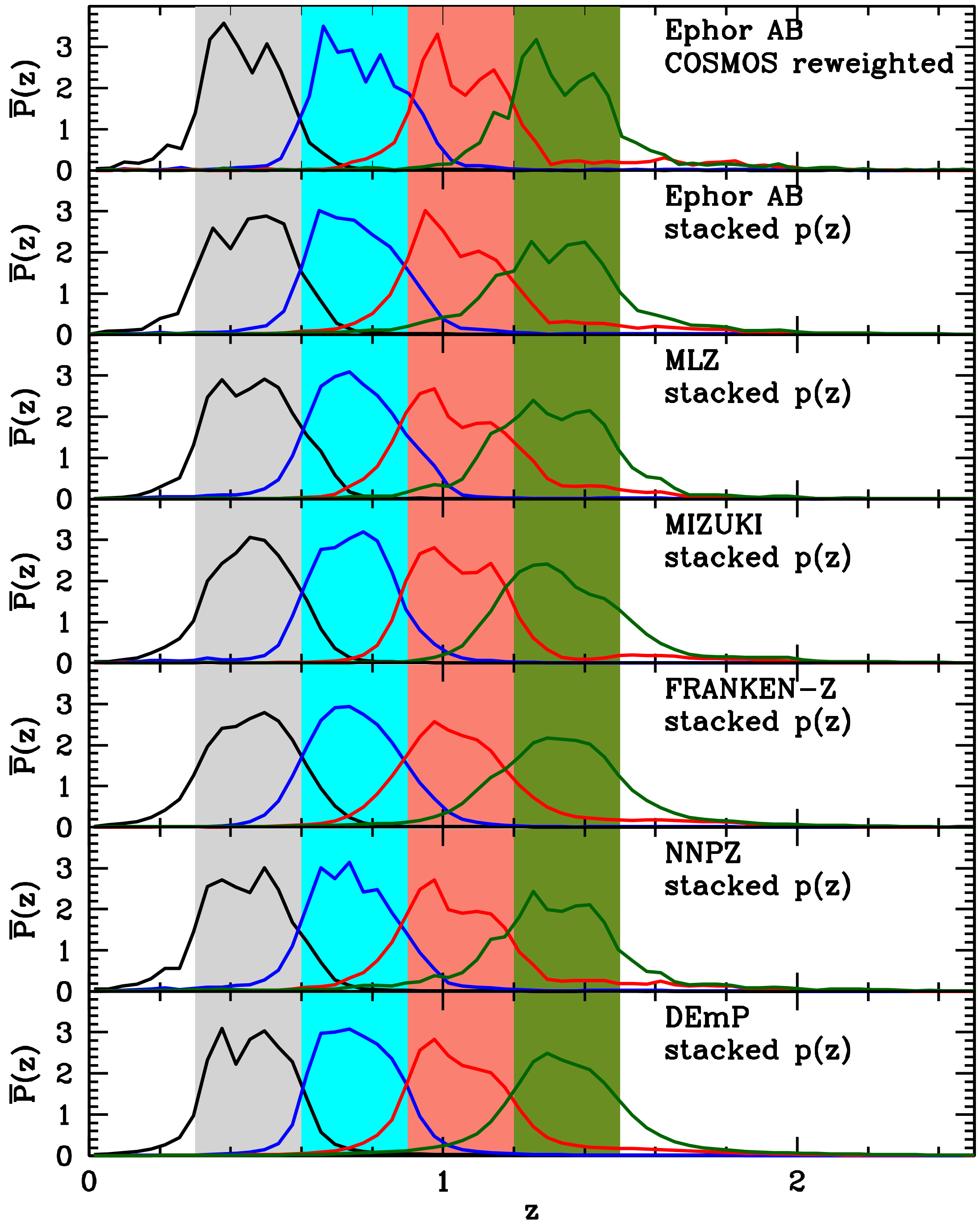
$$C_\ell = \int d\chi \, W_{\rm GL}(\chi)^2 \chi^{-2} P_{\rm m}^{\rm NL}\left(k = \frac{\ell}{\chi}; z(\chi)\right)$$

- Cons
  - All the systematic errors additively contribute the measurements (⇔ g-g lensing)
  - Challenges: Photo-z errors and baryonic physics
  - HSC data are very deep compared to DES: precursor of LSST



Cosmic shear tomography

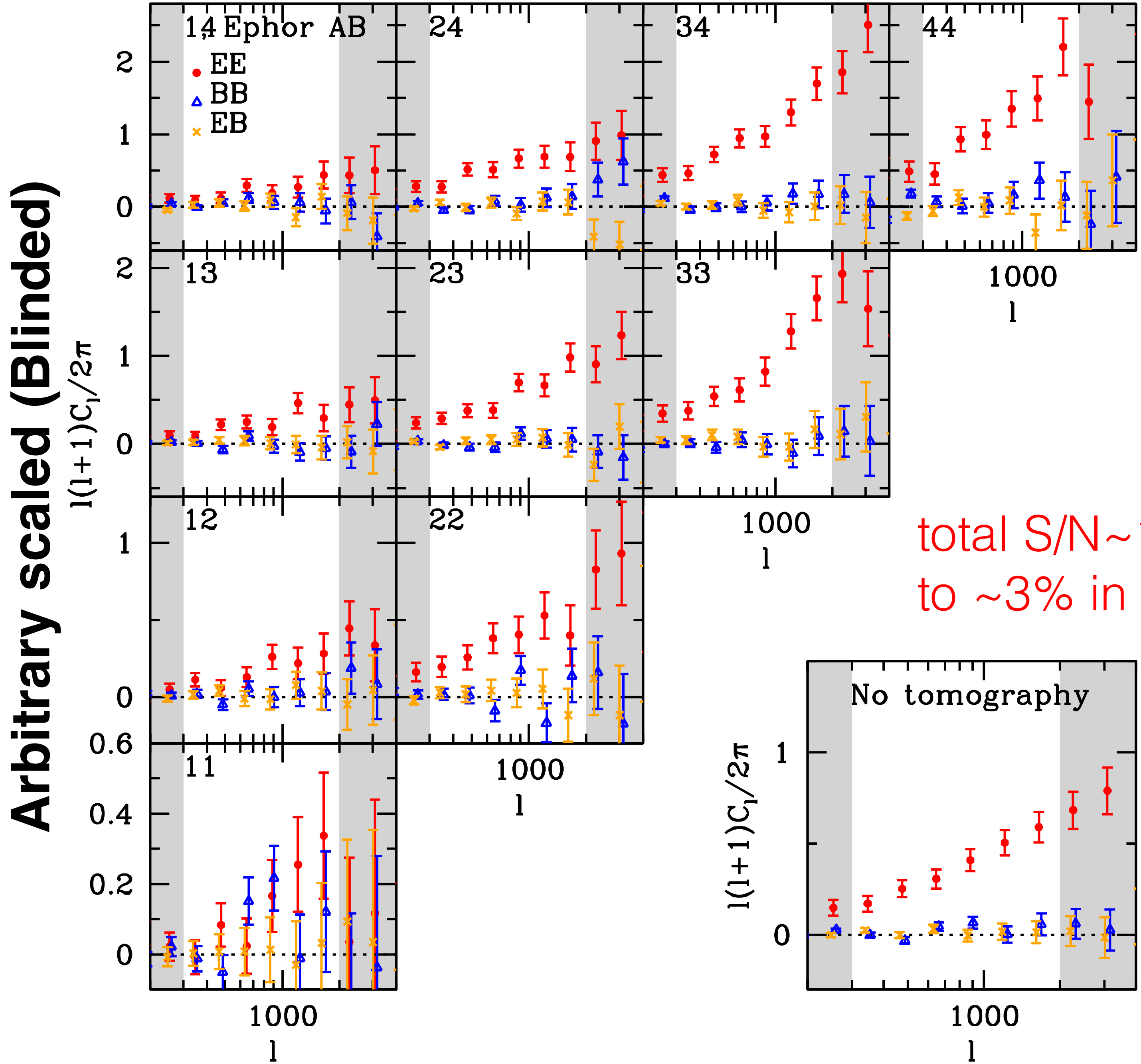
- Used photo-z's of each galaxy to have **4 tomographic bins**
- Used the **HSC-Wide depth data of COSMOS field** for galaxies after the WL cut to calibrate the photo-z errors
- Test the results against the different photo-z catalogs



Pseudo-power spectrum estimator
(Hikage, MT, Hamana, Spergel 11)

$$\tilde{E}_{\ell m} \pm i\tilde{B}_{\ell m} = \int \mathrm{d}^2\mathbf{n}\; w(\mathbf{n}) \left[\gamma_1(\mathbf{n}) \pm i\gamma_2(\mathbf{n})\right] Y_{\ell m}(\mathbf{n})$$

$$\hat{C}_l^{EE} = \mathbf{M}_{ll'}^{-1} \left[C_{l'}^{EE} - N_{l'}\right]$$

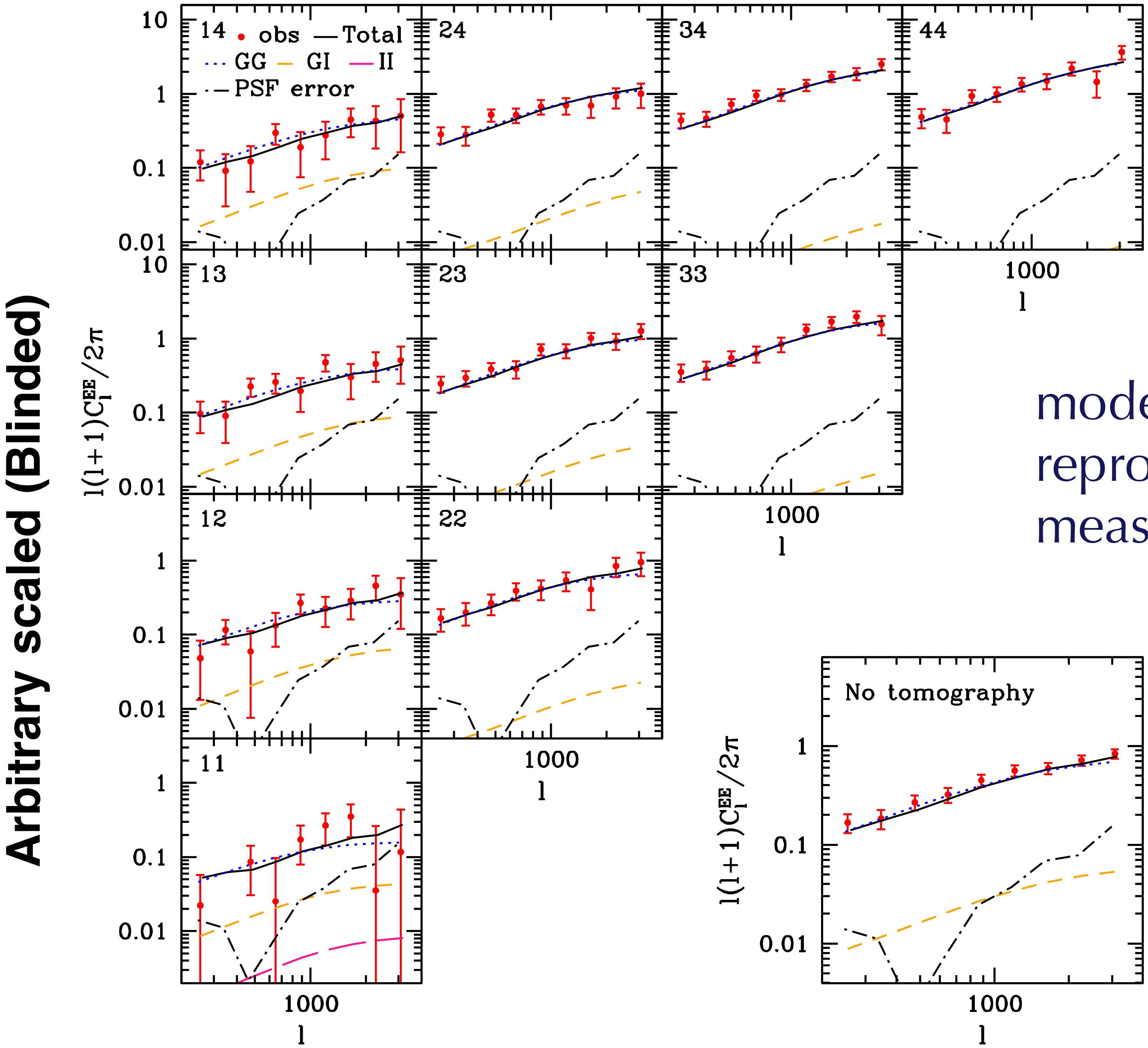


137 sq. deg.
0.3<z<1.5
300<ell<1900
n_eff~16.5 arcmin^{-2}

total S/N~16, corresponding to ~3% in S_8

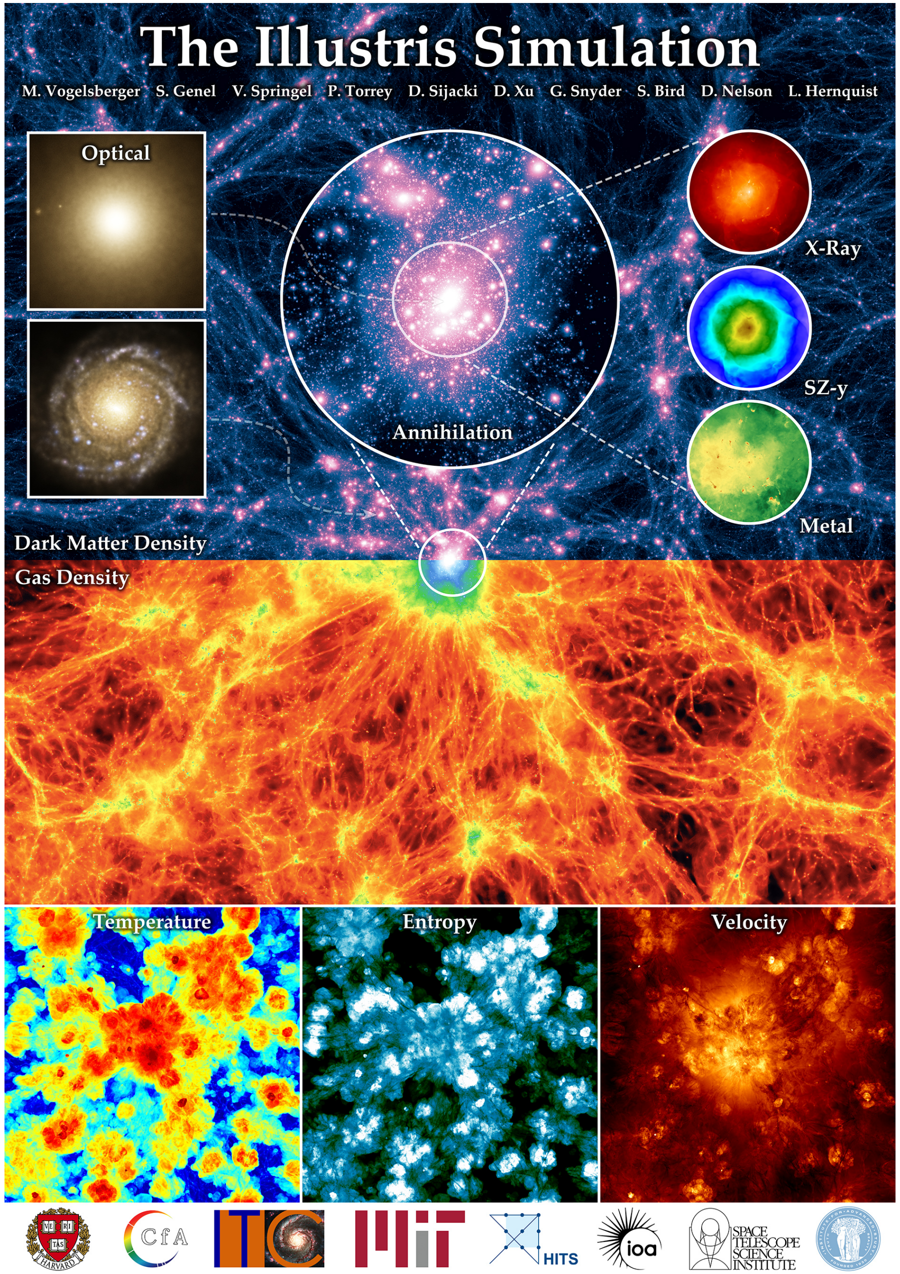
HSC collaboration (HSC WLWG)
ブライド解析

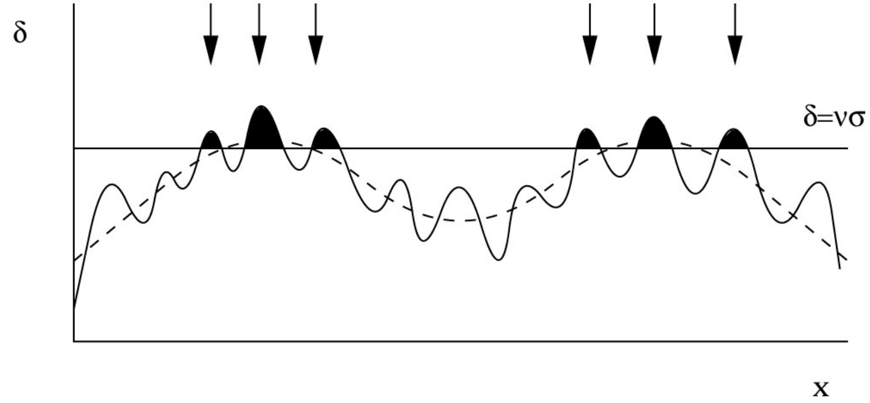
We (HSC WLWG) unblinded the cosmological results (catalog and analysis levels) at the telecon of *26 June, 2018*



model can reproduce the measurements!

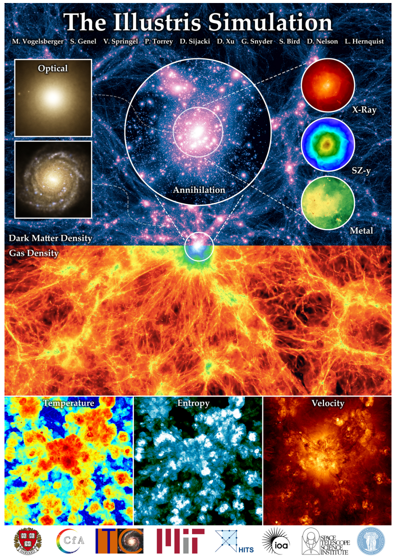
Challenges: Nonlinear, nonlinear, nonlinear…





- Cosmology with galaxy surveys is more complicated than CMB (LHC ⇔ electron/positron colliders)
- Complications: Galaxy bias, nonlinear clustering, baryon …
- However, we should keep in mind which observables are clean or dirty; we have conservations (mass and momentum)
- E.g., halo bias is little affected by baryonic physics

Towards precision cosmology: Modeling LSS observables



- **Hydrodynamical simulations**
  - unique way to model galaxy formation
  - still too expensive
- **Perturbation theory** Makino, Sasaki & Suto 92; Matsubara+; Taruya+
  - very accurate. The effective field theory approach for galaxy bias (rigorous due to symmetry). The theory errors are under control
  - however, breaks down at k>k_NL
- **Halo-based approach**
  - easy to model (at least in N-body sims.)
  - use halos and their statistics for cosmology
  - need parameters or ways to connect halos in simulations and galaxies (observables) in a survey
- Reconstruction of initial conditions (fields)

Perturbation theory or Effective field theory of LSS

- Effective field of theory

$$\delta = \delta_{(1)} + \delta_{(2)} + \delta_{(3)} + \delta_{(4)} + \delta_{(5)} + \cdots$$

$$\partial_\tau \delta + \partial_i[(1+\delta)v^i] = \partial_i u^i \ ,$$

$$\partial_\tau v^i + \mathcal{H} v^i + \partial^i \phi + v^j \partial_j v^i = \underline{-\frac{1}{a\rho}\partial_j \tau^{ij}}$$

$$\triangle \phi = \frac{3}{2}\mathcal{H}^2 \Omega_{\rm m} \delta \ .$$

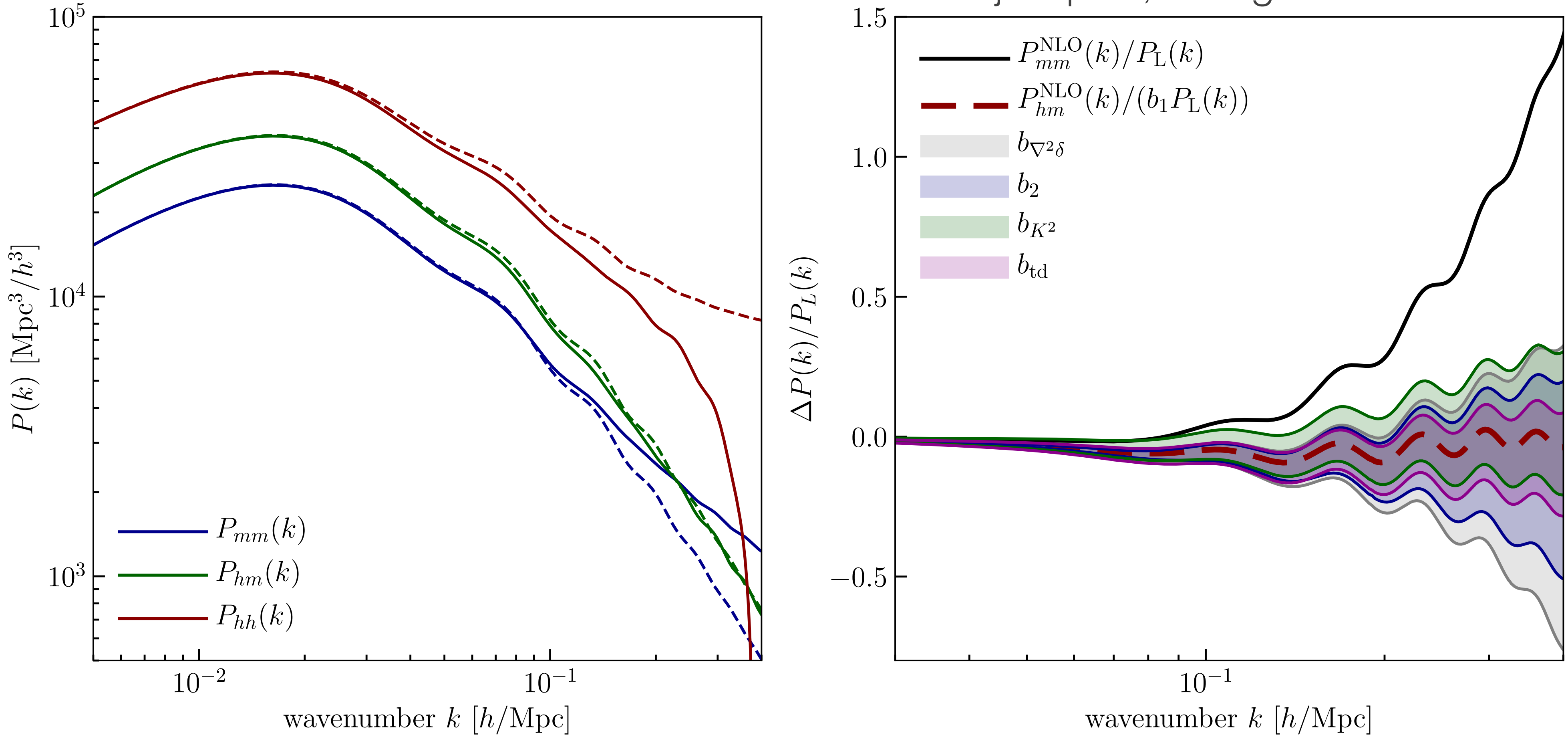
- Goal

$$\delta_{\rm h}(\mathbf{k}) = F(k; \Omega_{\rm m}, n_s, ..., \mathbf{p}_{\rm astrophys}, M, ...; \delta^{\rm L}(\mathbf{q}) + \epsilon(\mathbf{q})$$

$$\begin{aligned}\delta_{\rm h}(\boldsymbol{x}) = {} & b_1\left(\delta^{(1)}(\boldsymbol{x}) + \delta^{(2)}(\boldsymbol{x}) + \delta^{(3)}(\boldsymbol{x})\right) + \frac{b_2}{2!}\left(\delta^2(\boldsymbol{x}) - \sigma^2\right) \\ & + b_2\left(\delta^{(1)}\delta^{(2)}(\boldsymbol{x}) - \frac{68}{21}\sigma^2\delta(\boldsymbol{x})\right) + b_{s^2}\left(s^2(\boldsymbol{x}) - \frac{2}{3}\sigma^2\right) \\ & + 2b_{s^2}\left(s^{(3)}(\boldsymbol{x}) - \frac{136}{63}\delta(\boldsymbol{x})\sigma^2\right) + b_{\delta^3}\left(\delta^3(\boldsymbol{x}) - 3\delta(\boldsymbol{x})\sigma^2\right) \\ & + b_{\mathcal{G}_3}\mathcal{G}_3(\boldsymbol{x}) + b_{\mathcal{G}_2\delta}\left(\mathcal{G}_2\delta(\boldsymbol{x}) + 4\delta(\boldsymbol{x})\sigma^2\right) + b_{\Gamma_3}\left(\Gamma_3(\boldsymbol{x}) + \frac{32}{35}\delta(\boldsymbol{x})\sigma^2\right) \\ & + b_{\nabla^2\delta}\nabla^2\delta(\boldsymbol{x}) + \ldots\end{aligned}$$

PT looks appealing… though

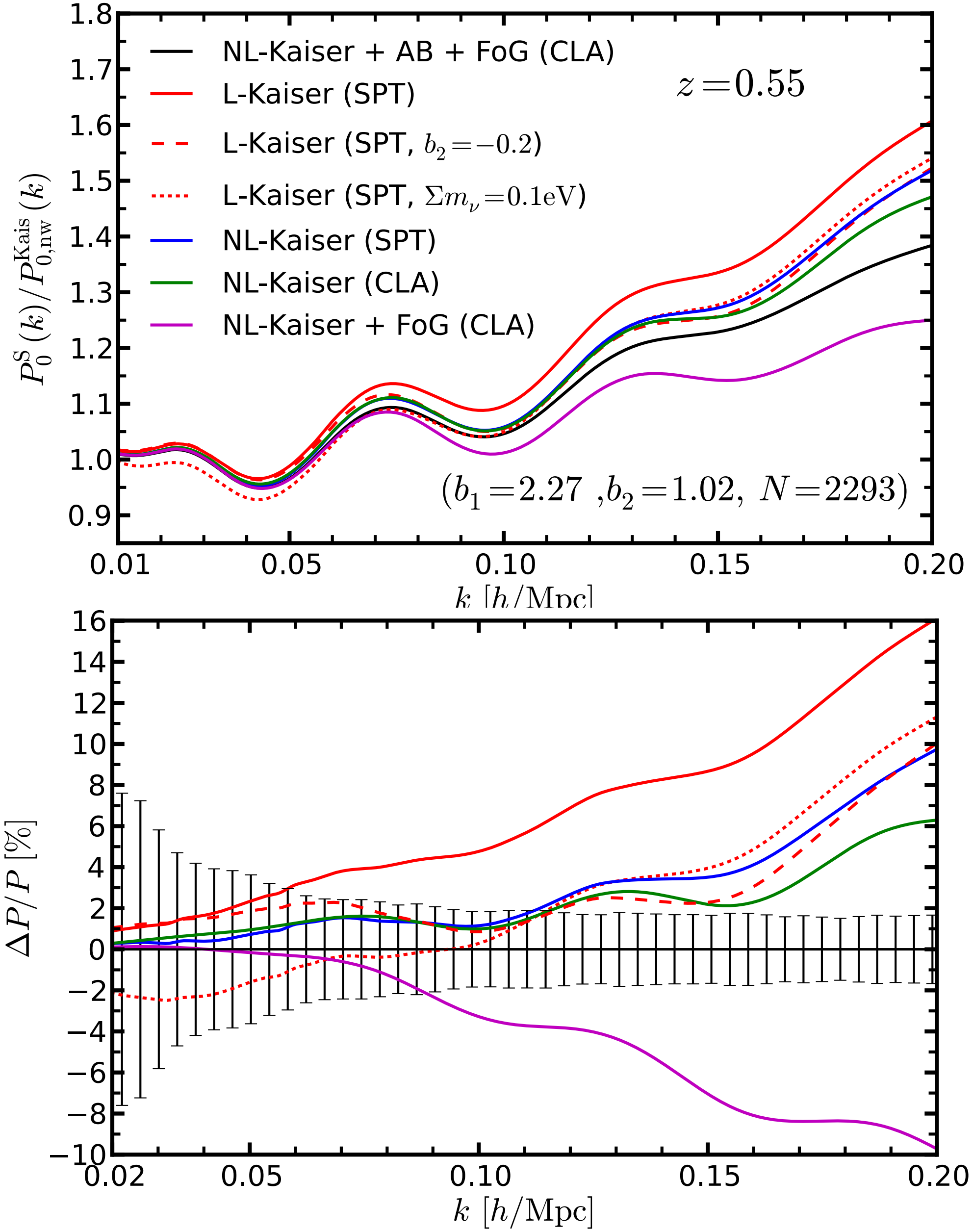
Desjacques, Jeong & Schmidt PRR



- Well defined and rigorous. The theory error well controlled
- Need to introduce **many** nuisance parameters (>7 parameters) (nonlinearities, primordial peak shapes, halo exclusion effect, etc.)
- PT for "matter" clustering anyway **breaks down** at k≳0.15 h/Mpc (also see Nishizawa, Nishimichi & MT 15)

Any useful information in nonlinear regime?

Zhao, Saito, Percival+ 12: The work with BOSS data

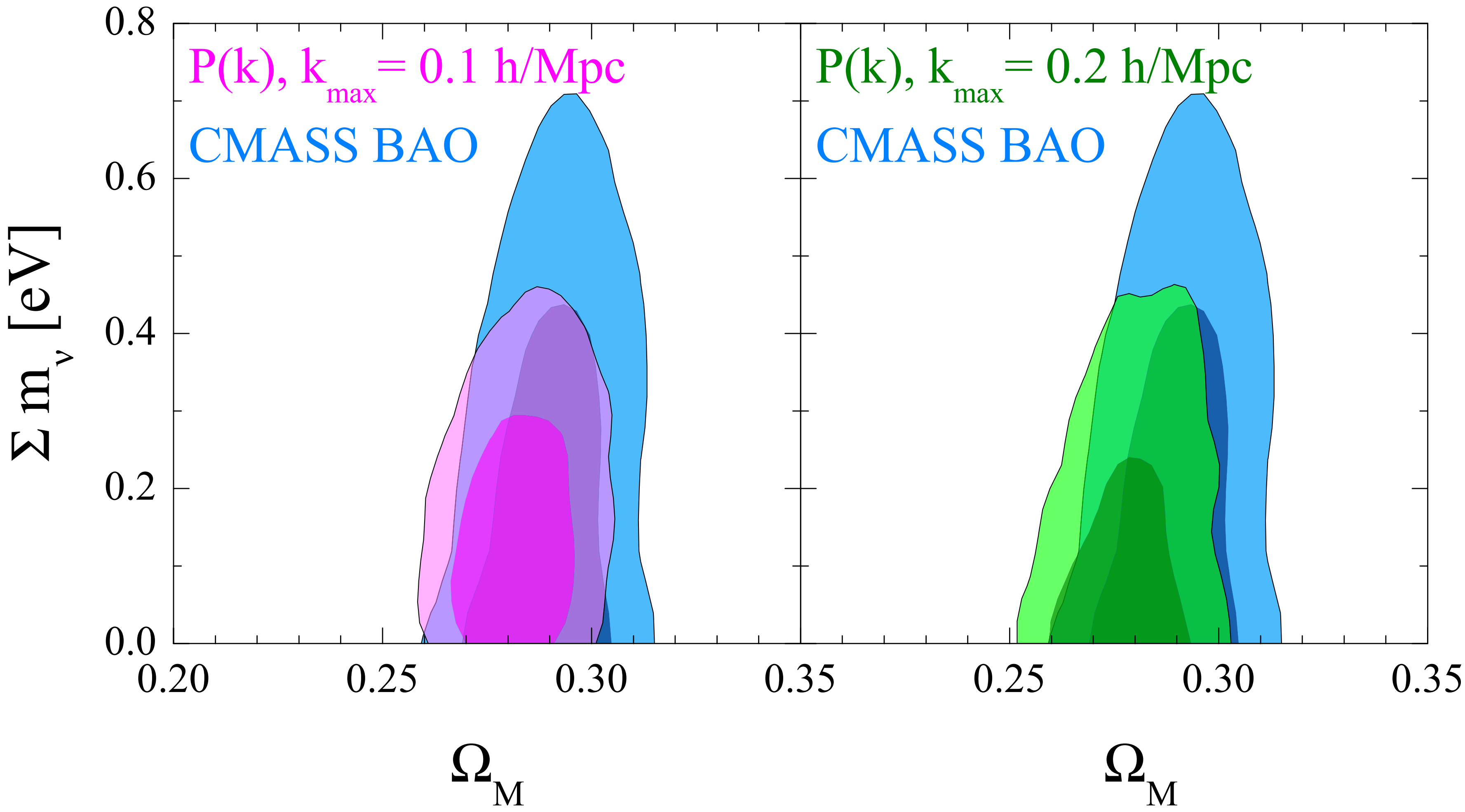


- Various model predictions for nonlinear galaxy redshift-space power spectrum
- Nonlinear effects become significant at **k>0.1 h/Mpc**
- Some models introduce nuisance parameters to model unknown effects such as galaxy bias

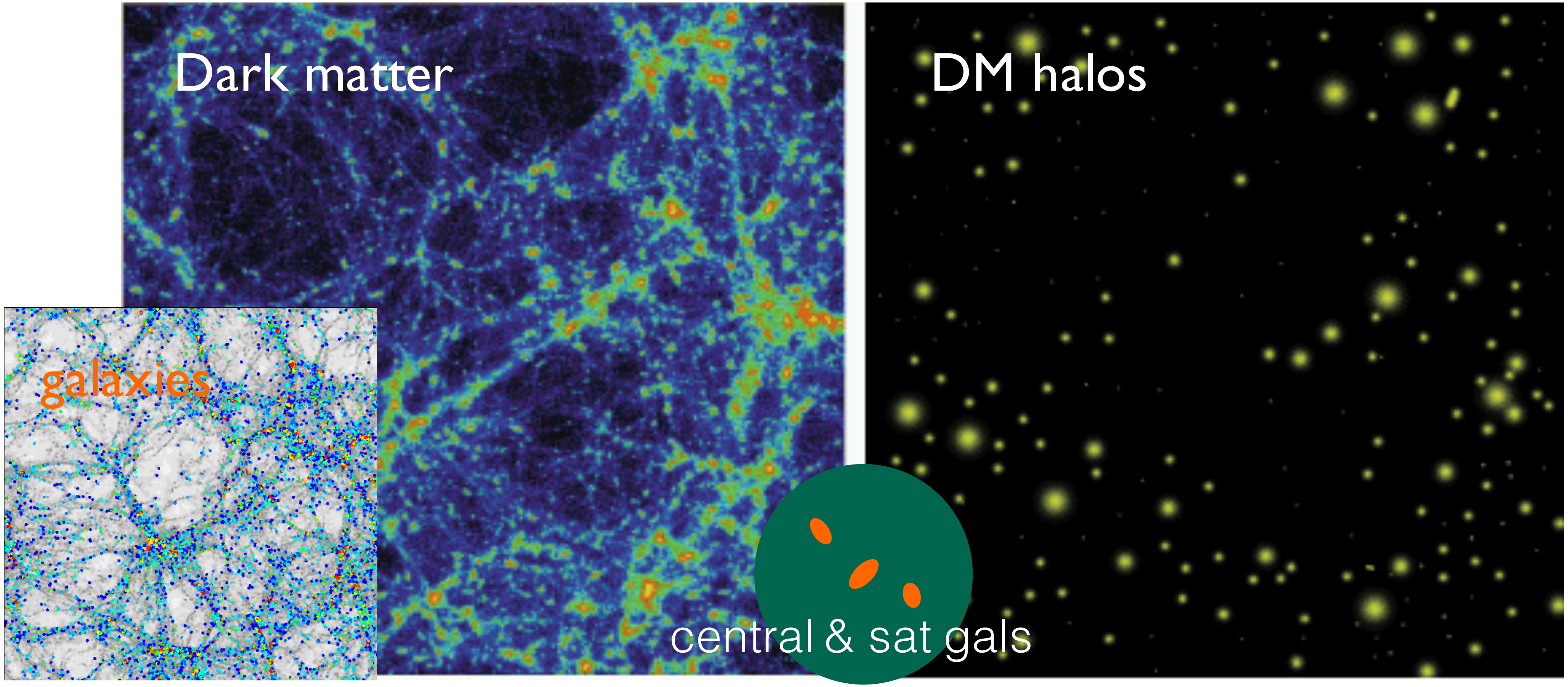
Any useful information in nonlinear regime?

Zhao, Saito, Percival+ 12: The work with BOSS data

No improvement in cosmo paras by adding the information of k=[0.1,0.2], regardless of a factor 8 more information content in P(k)



Halo model: DM halos ⇔ Galaxies



- Galaxies (central and satellite gals) reside in dark matter halos
- Clustering of dark matter halos are relatively easy to model based on simulations and/or analytical models

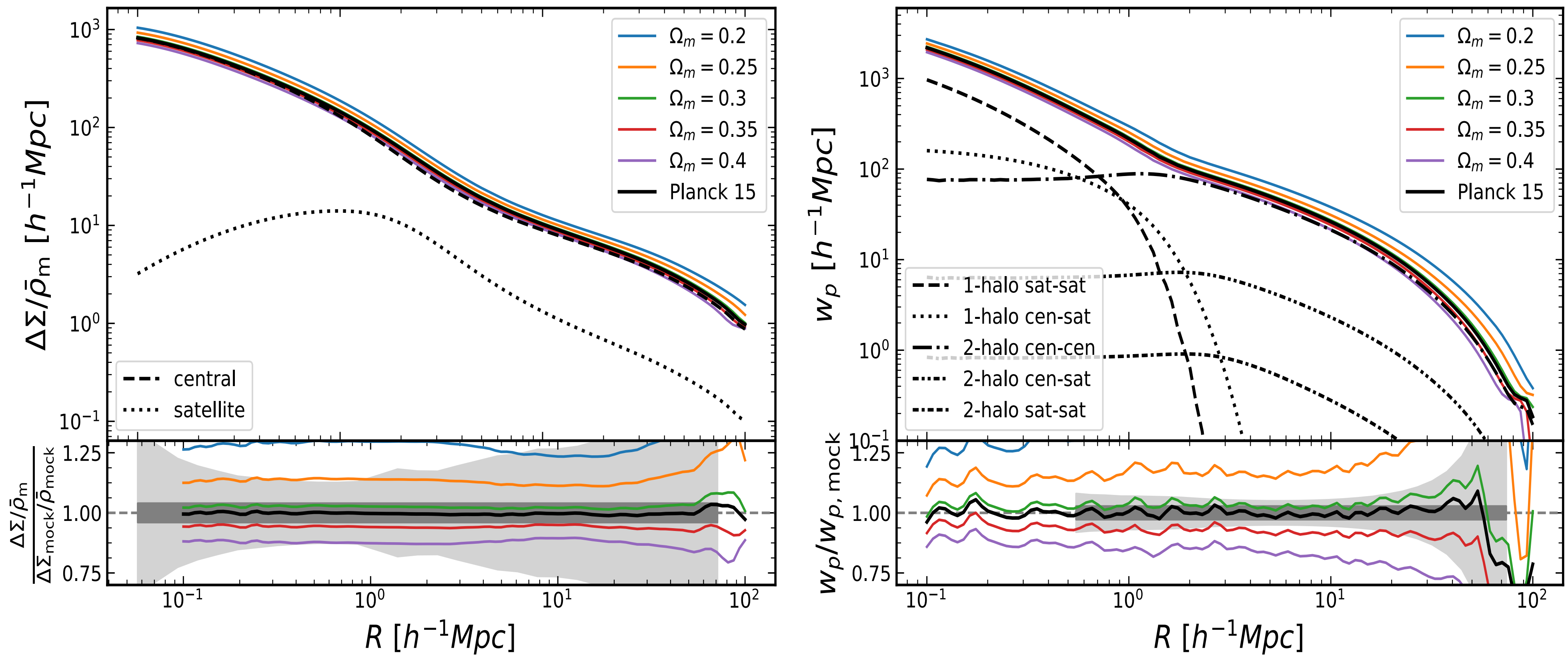
Cosmology with HSC and BOSS

Nishimichi, MT in prep.

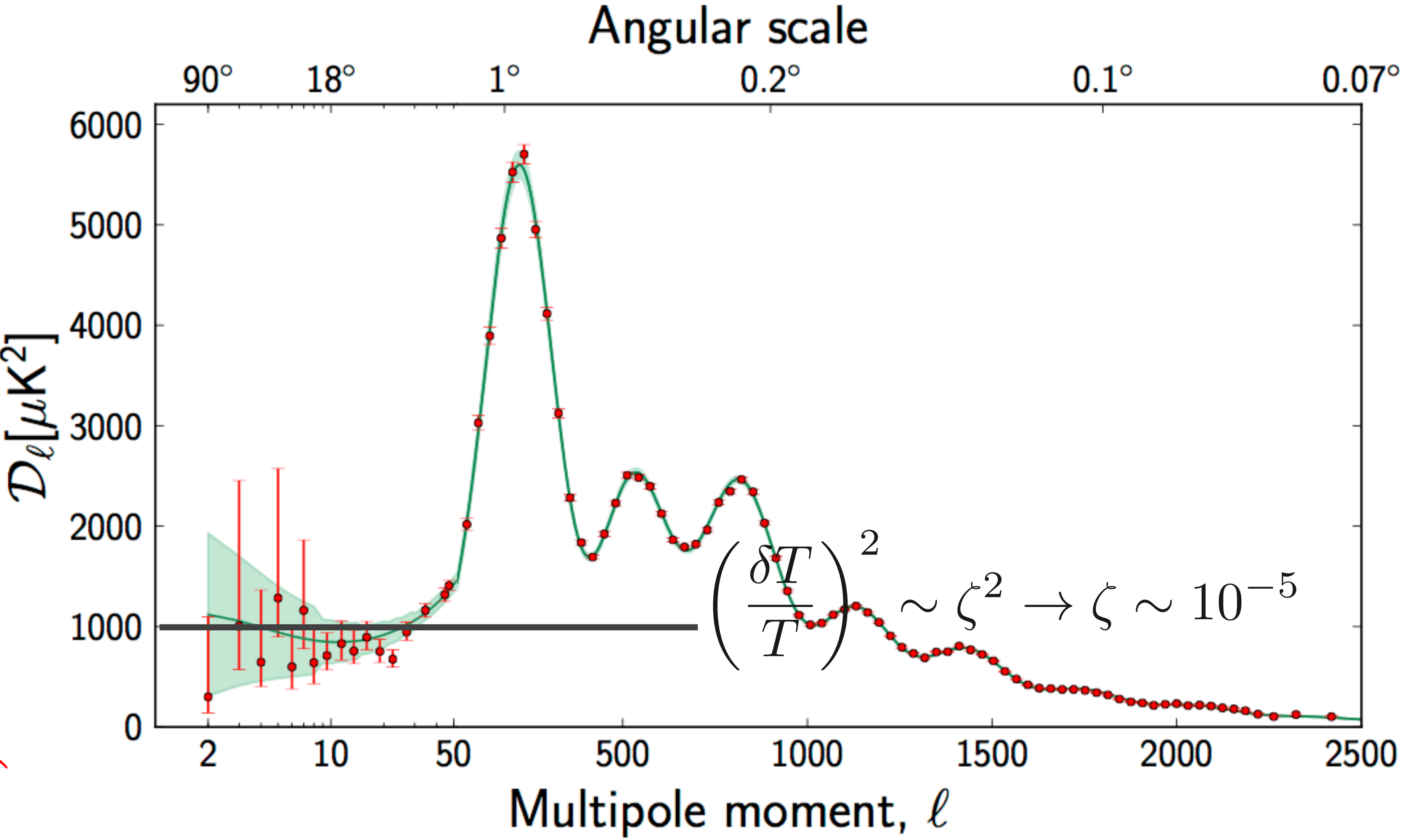
$$P_{\rm gm}(k) = \underline{P^{\rm 2h}_{\rm gm}(k)} + \underline{P^{\rm 1h}_{\rm gm}(k)}$$

from Halo Emulator (Takahiro's talk)

many nuisance parameters (~10) to connect galaxies and halos



クイズ



$$\left(\frac{\delta T}{T}\right)^2 \sim D_\ell^2 / T_{\rm CMB}^2 = \ell(\ell+1) C_\ell / 2\pi$$

$$\left(\frac{\delta T}{T}\right)^2 \sim \zeta^2 \to \zeta \sim 10^{-5}$$

なぜhigh-multipoleの温度ゆらぎは増幅されているの？

最近の素朴な疑問

- 晴れ上がり前には陽子、電子、ヘリウムはなぜ一緒に運動するのかな？
- 晴れ上がり後は残存電子、水素、ヘリウムは一緒に運動するのかな？
- 1億年後、100億年後のCMBの空はどのようにに見えるのかな？（今のCMBマップと違う？）
- ニュートリノ背景放射の角度異方性スペクトルはどんな形？
- 陽子-電子散乱、電子-陽電子散乱、電子-電子散乱の電磁放射は違うのかな？
- 重力波が伝播しても物差しも一緒に伸びるから、息子の身長は同じように見えるのかな？
- 原始重力波をどうやって測れるかな、、、、

研究スタイル

- 理論研究
  - 地道に未解決問題を調べる（答えがでるとは限らない）
  - 基本的にうまくいかない
  - 発見、新しい物理的効果が見つかれば、影響は大
  - 観測的に検証できることを調べたほうが良いのでは？
- 観測的研究 or 観測データ
  - 世界最高データにアクセスがあれば、最初から優位
  - 過去の測定結果の改善。（簡単に研究ができる）
  - インパクトは大。ただし、新しい観測結果が出るとそれ以降は忘れられる
- ハイブリット研究
  - 観測にも関心を持ちつつ、理論研究にも通じている
  - どちらにも拘らず、興味の赴くままに研究

皆さん、宇宙論をたくさん勉強して、宇宙の神秘、精巧さを学んでください。そして、存分に楽しみましょう！

機会があれば、一緒に研究しましょう！