2020年代の宇宙論・構造形成 (中間報告)

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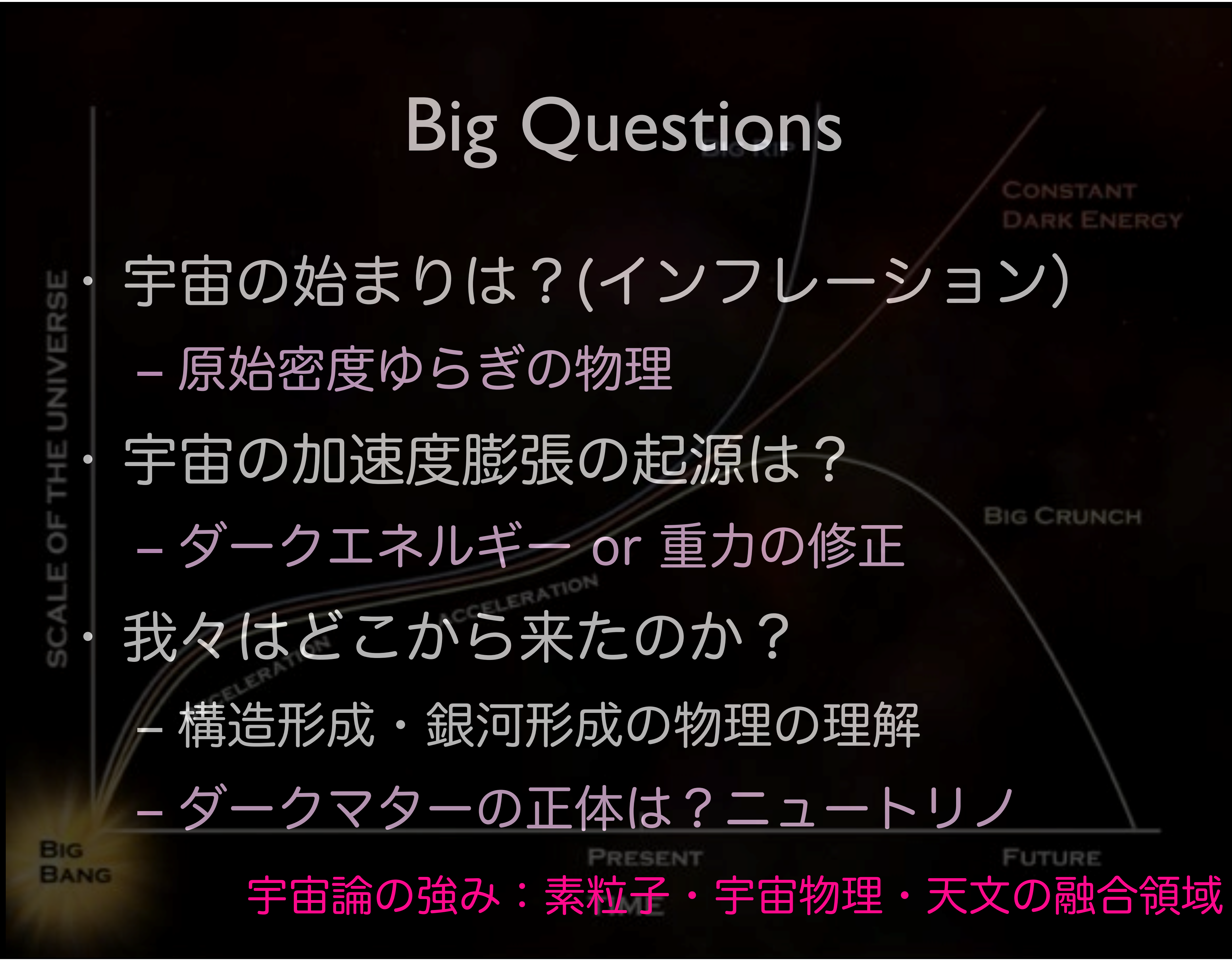
どなたでも参加してください。（特に若い方）大歓迎です！

Big Questions

- 宇宙の始まりは？(インフレーション)
  - 原始密度ゆらぎの物理
- 宇宙の加速度膨張の起源は？
  - ダークエネルギー or 重力の修正
- 我々はどこから来たのか？
  - 構造形成・銀河形成の物理の理解
  - ダークマターの正体は？ニュートリノ

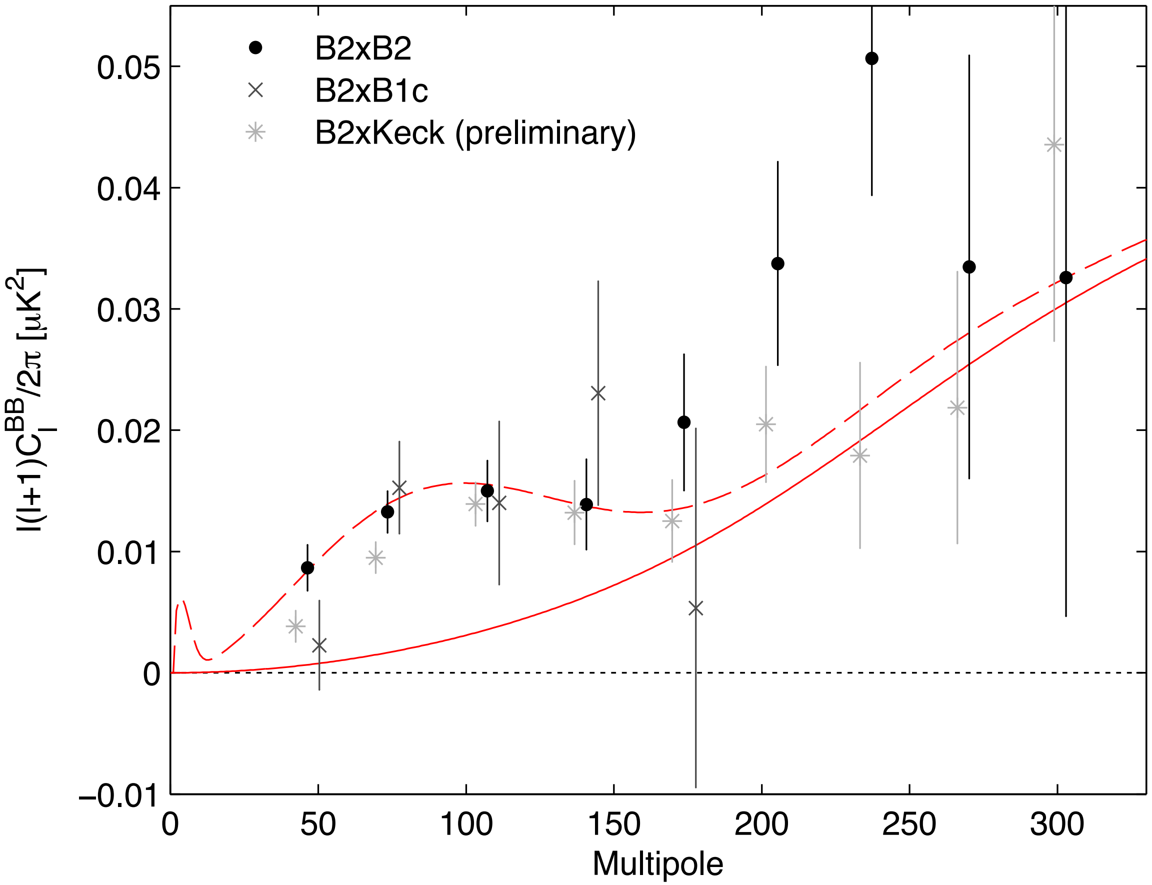
宇宙論の強み：素粒子・宇宙物理・天文の融合領域

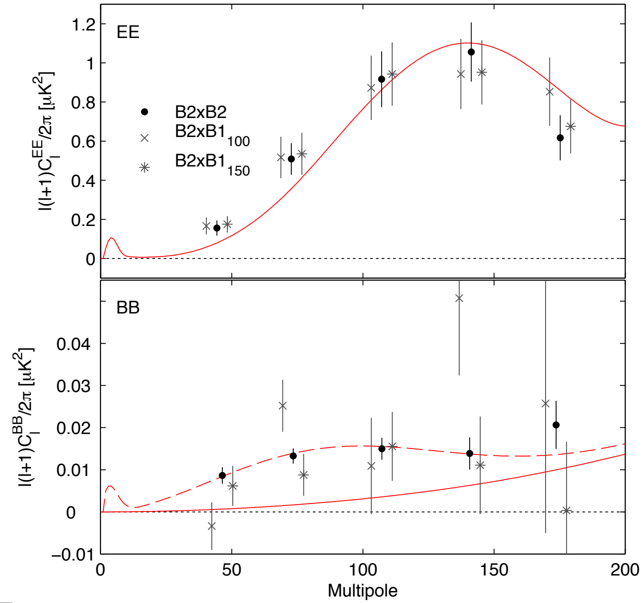


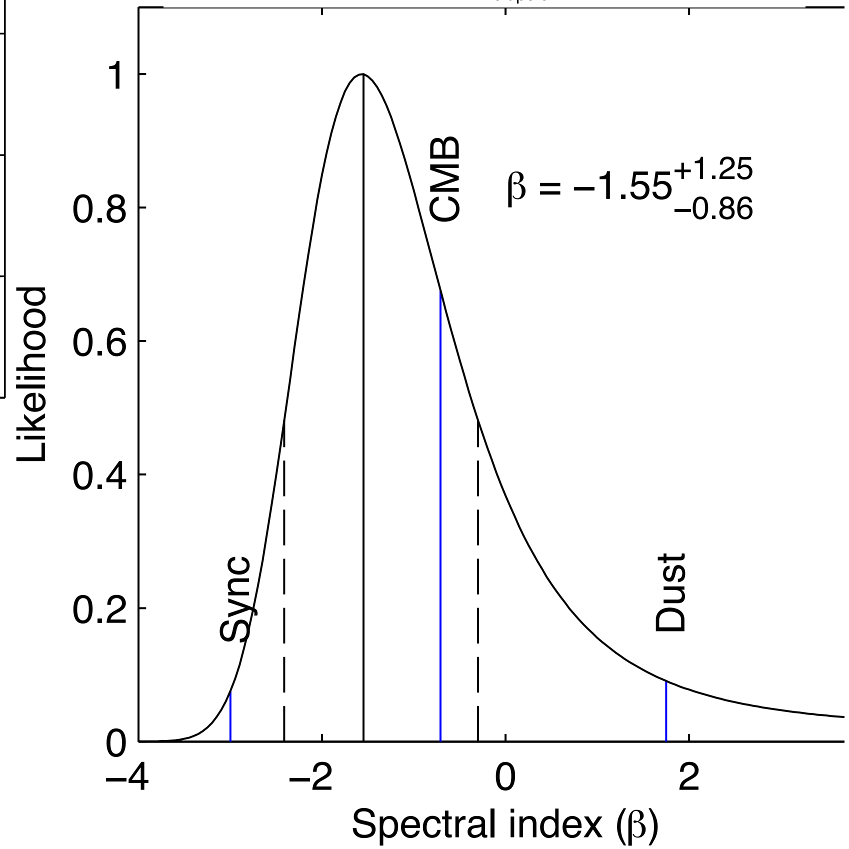
議論のポイント

- サイエンスの重要性のインパクト
- サイエンス⇒手段・手法
- 独自性：可視光・赤外の観測でしかできない計画か？
- サイエンスの発展性、他の分野との相乗効果は？
- 実現可能性は？
- 世界の情勢、世界との競争力

BICEP2 (March 17 2014)

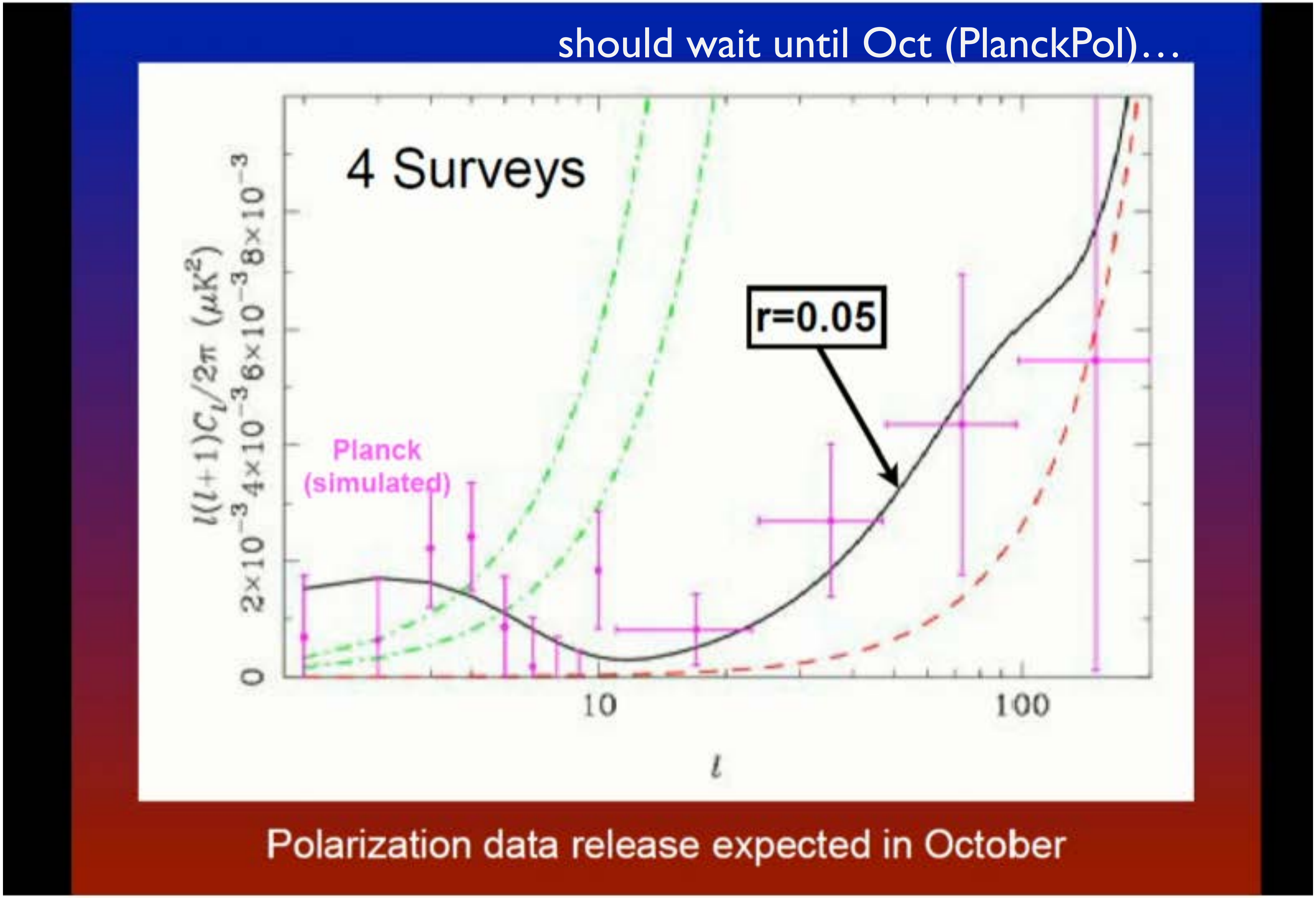






- Evidence of quantization of space-time (quantum gravity)?
- Used 100×150GHz cross to "reject" representative spectra of synchrotron and dust only at ~2 sigma

should wait until Oct (PlanckPol)…



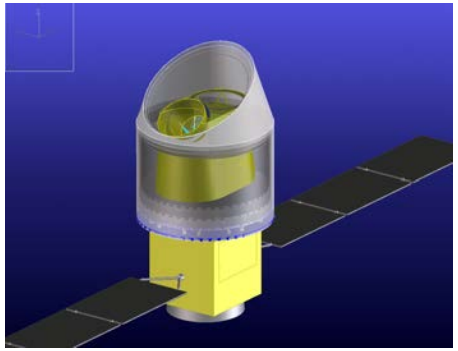
Talk by Douglas Scott@BICEP2, Perimeter Institute (April 4)

Physics of Inflation (B-mode)

High Impact!

- Inflation-induced gravitational wave

CMB B-mode determines the energy scale of inflation



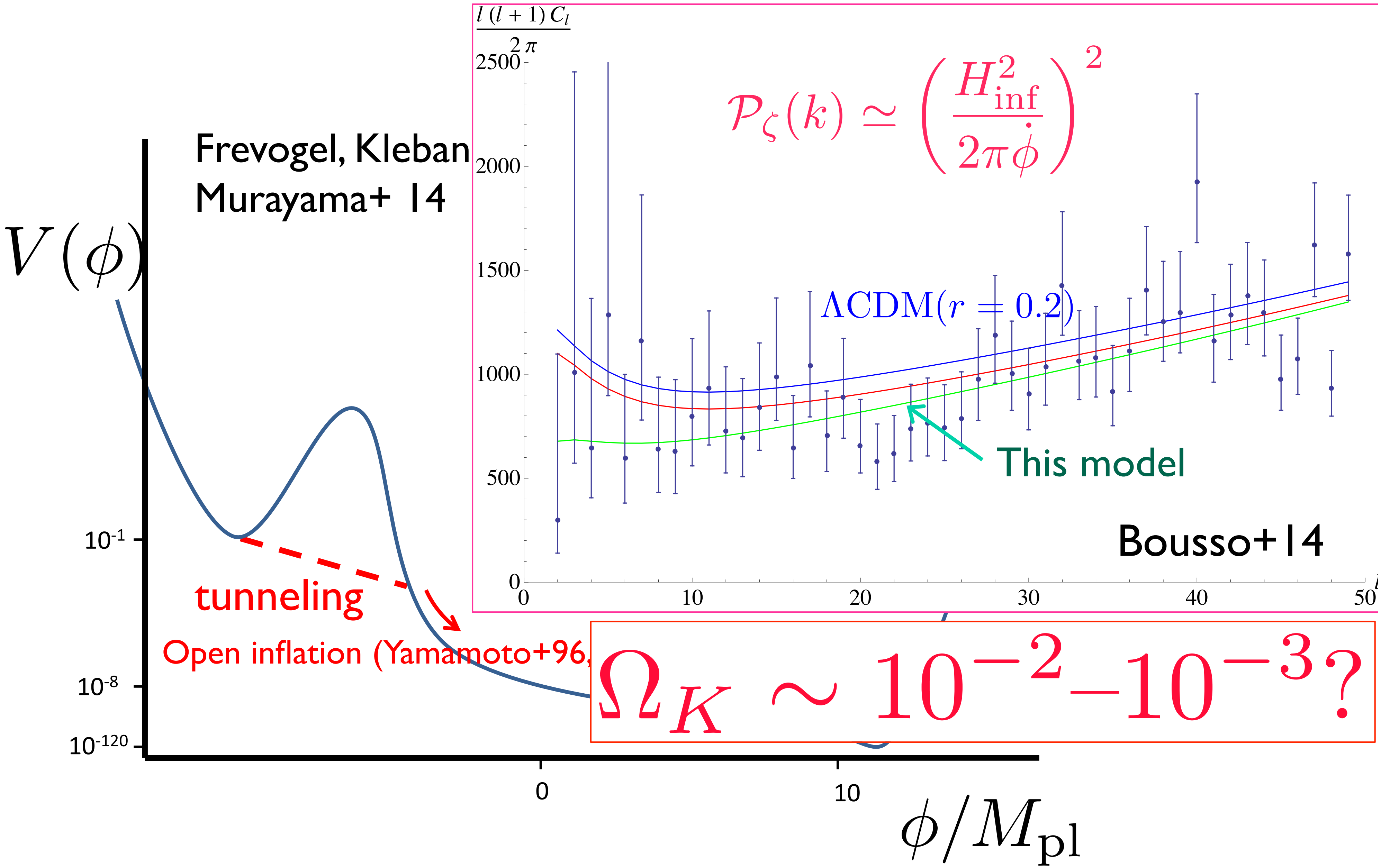
LiteBIRD

$$H_{\rm inf} \simeq 1.22 \times 10^{14}\ {\rm GeV} \left(\frac{r}{0.2}\right)^{1/2}$$

- BICEP2 implies a large field inflation (Lyth 97)

$$\frac{\Delta\phi_{\rm inf}}{M_{\rm pl}} \sim \sqrt{\frac{r}{0.01}} \longrightarrow \Delta\phi_{\rm inf} \sim {\rm a\ few}\ M_{\rm pl}$$

Landscape picture of inflation



$\Omega_K \sim 10^{-2}$–10^{-3}?

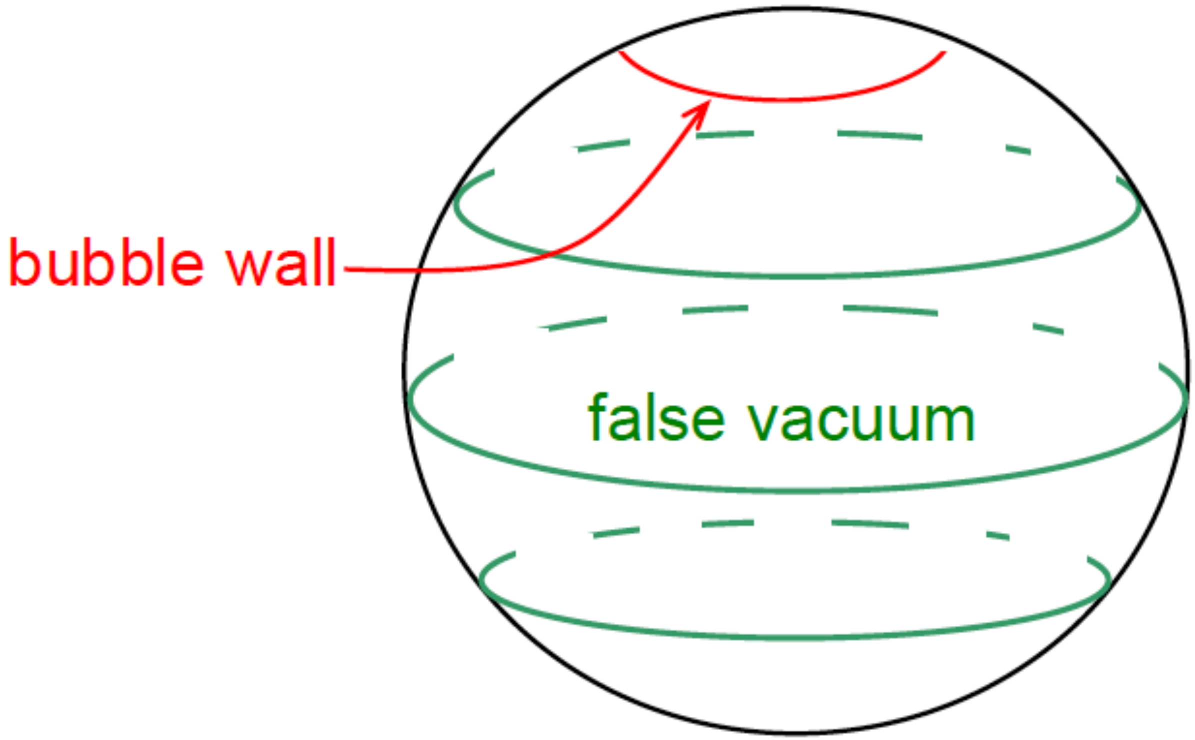
- Most plausible state of the universe before inflation is a dS vacuum with $\rho_V \sim M_P^4$. dS = O(4,1) → O(5) ~ S^4

false vacuum decay via O(4) symmetric (CDL) instanton

Coleman & De Luccia ('80)

O(4) → O(3,1)

inside bubble is an open universe



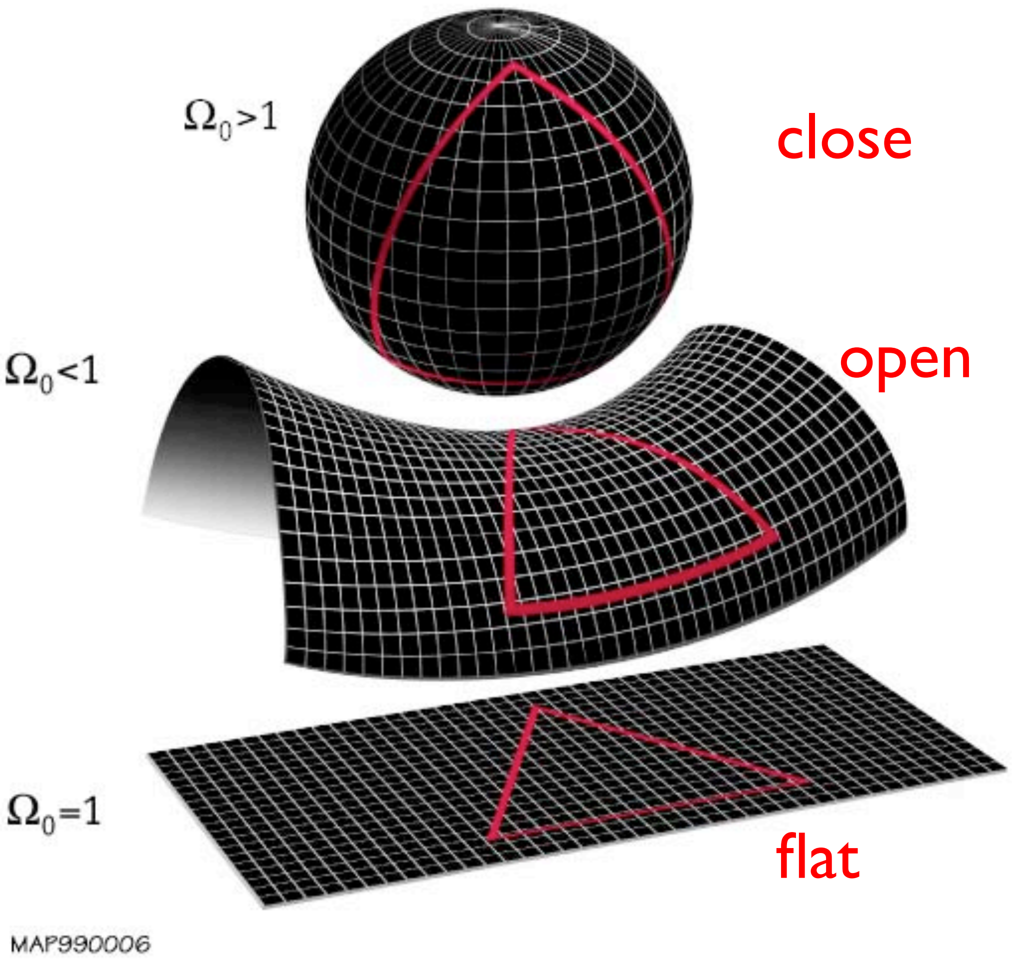
$$\tau^2 + \vec{x}^2 = R^2$$

$$\Downarrow$$

$$-t^2 + \vec{x}^2 = R^2$$

宇宙の曲率

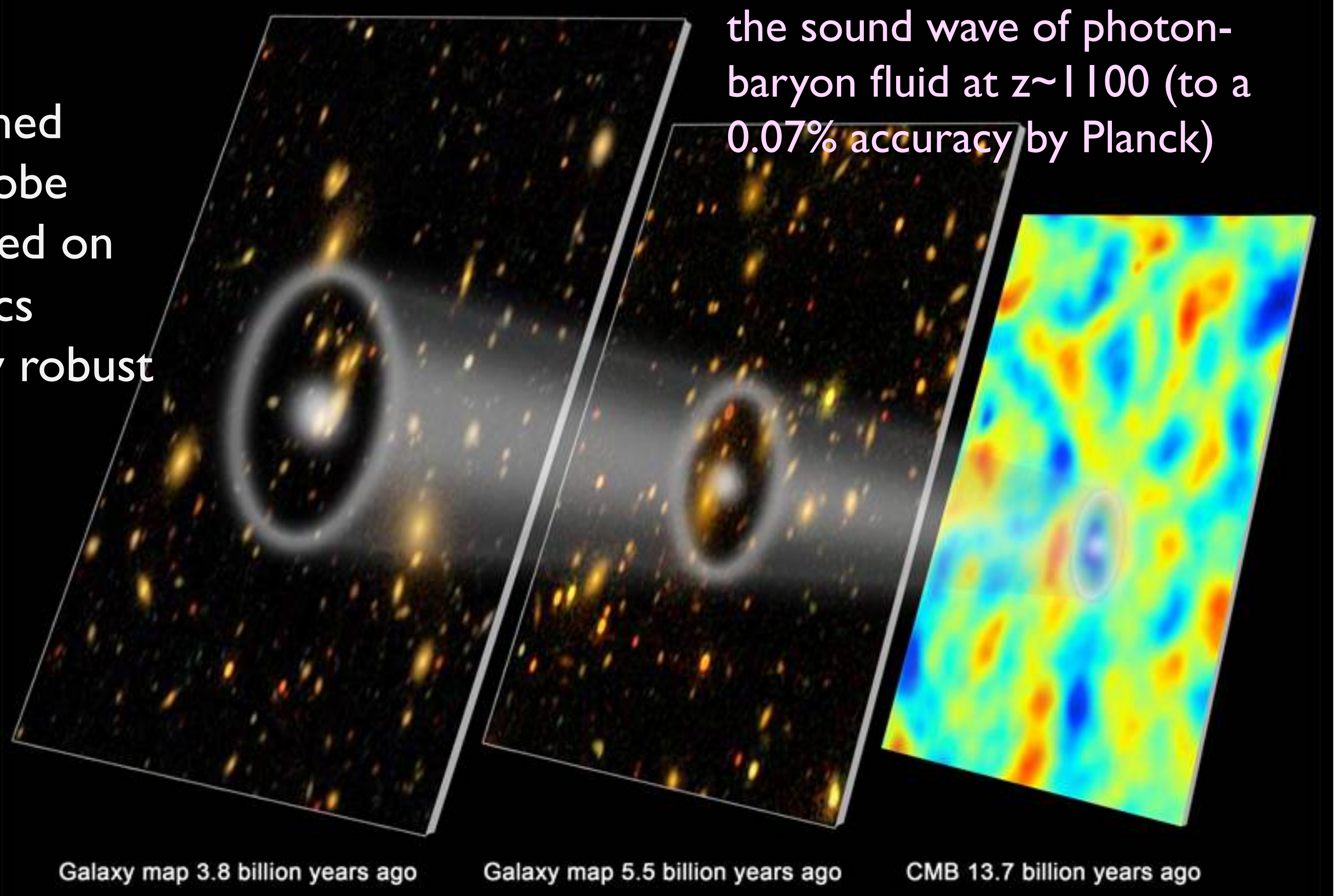
- 宇宙の大域的な構造
- 一般相対性理論の予言
- fundamental quantity
- Inflationary scenario viable in an open Universe ↔ If a close curvature is found, most of inflation models are *ruled out* (Nomura & Guth 12; Kleban & Shillo)



Baryon Acoustic Oscillation (BAO)

Newly established geometrical probe since 2005, based on the CMB physics (therefore very robust method)

The typical scale of CMB anisotropies is determined by the sound wave of photon-baryon fluid at z~1100 (to a 0.07% accuracy by Planck)



BAO (cont'd)

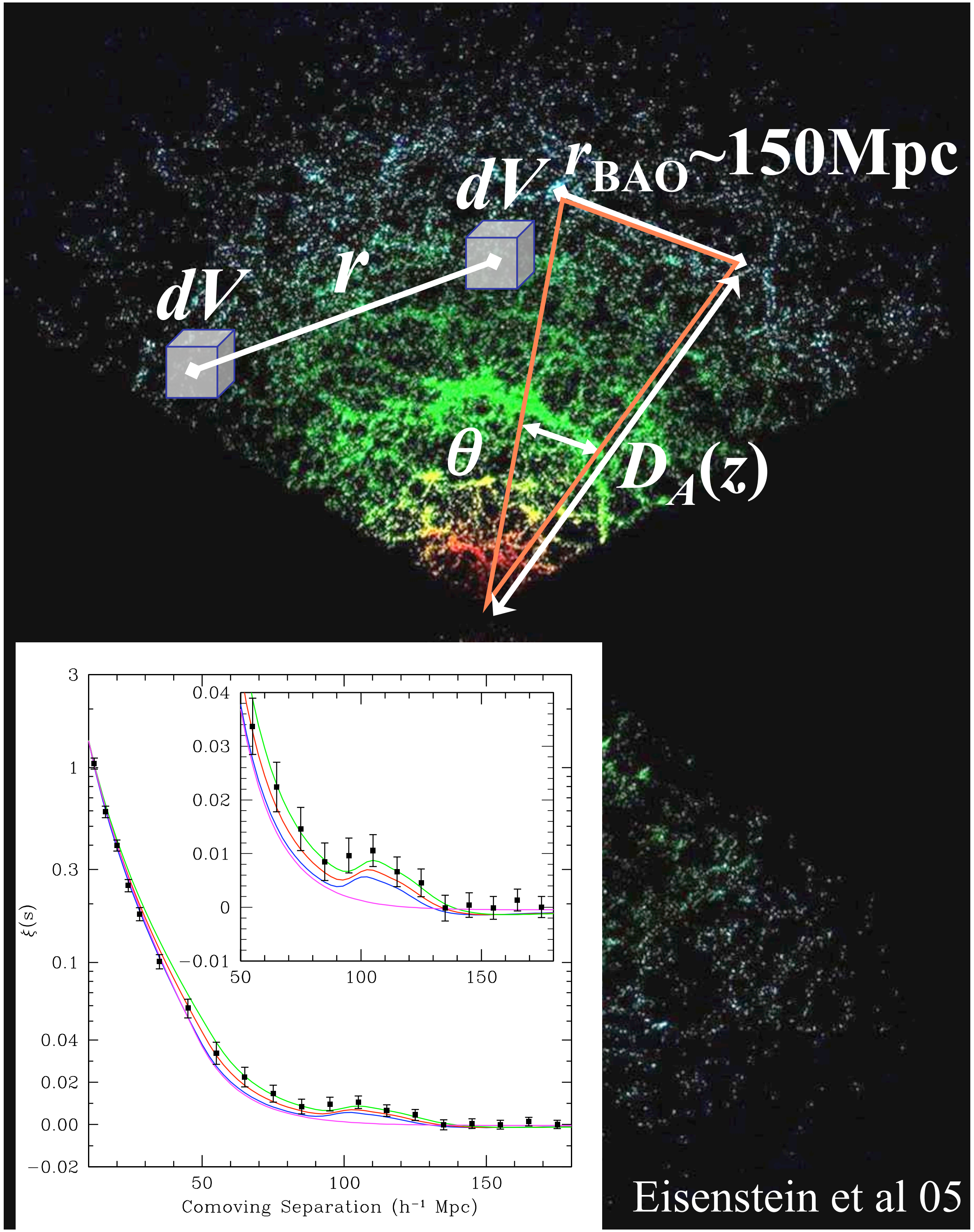
- Measure galaxy clustering strengths: 2pt correlations (or P(k))

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

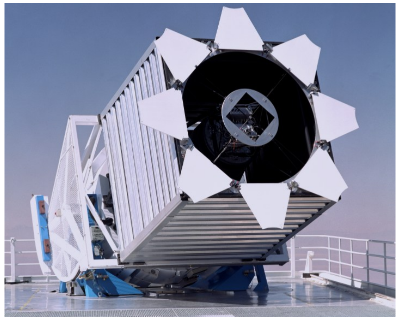
- Find a tiny excess in the galaxy pairs at BAO scale (a priori known from CMB to be ~150Mpc)

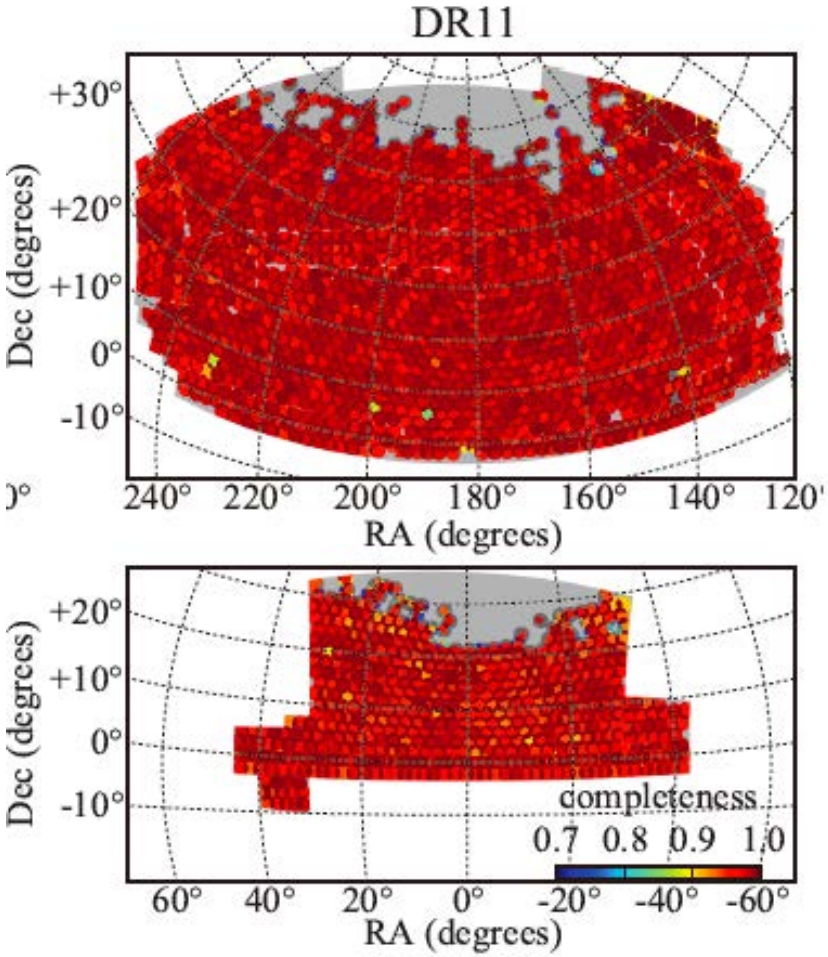
$$r_{\rm BAO} = D_A(z)\theta_{\rm obs}$$

$$r_{\rm BAO} = \frac{\Delta z}{H(z)}$$



Baryon Oscillation Spectroscopic Survey (BOSS: 1999-)

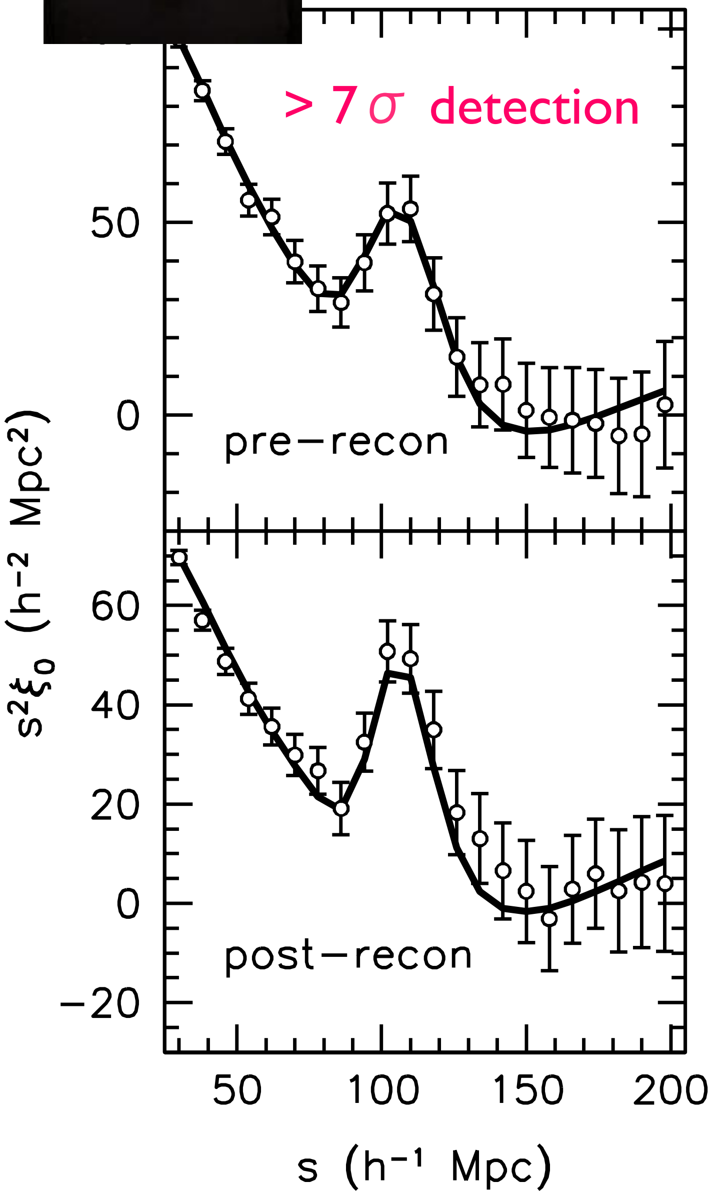




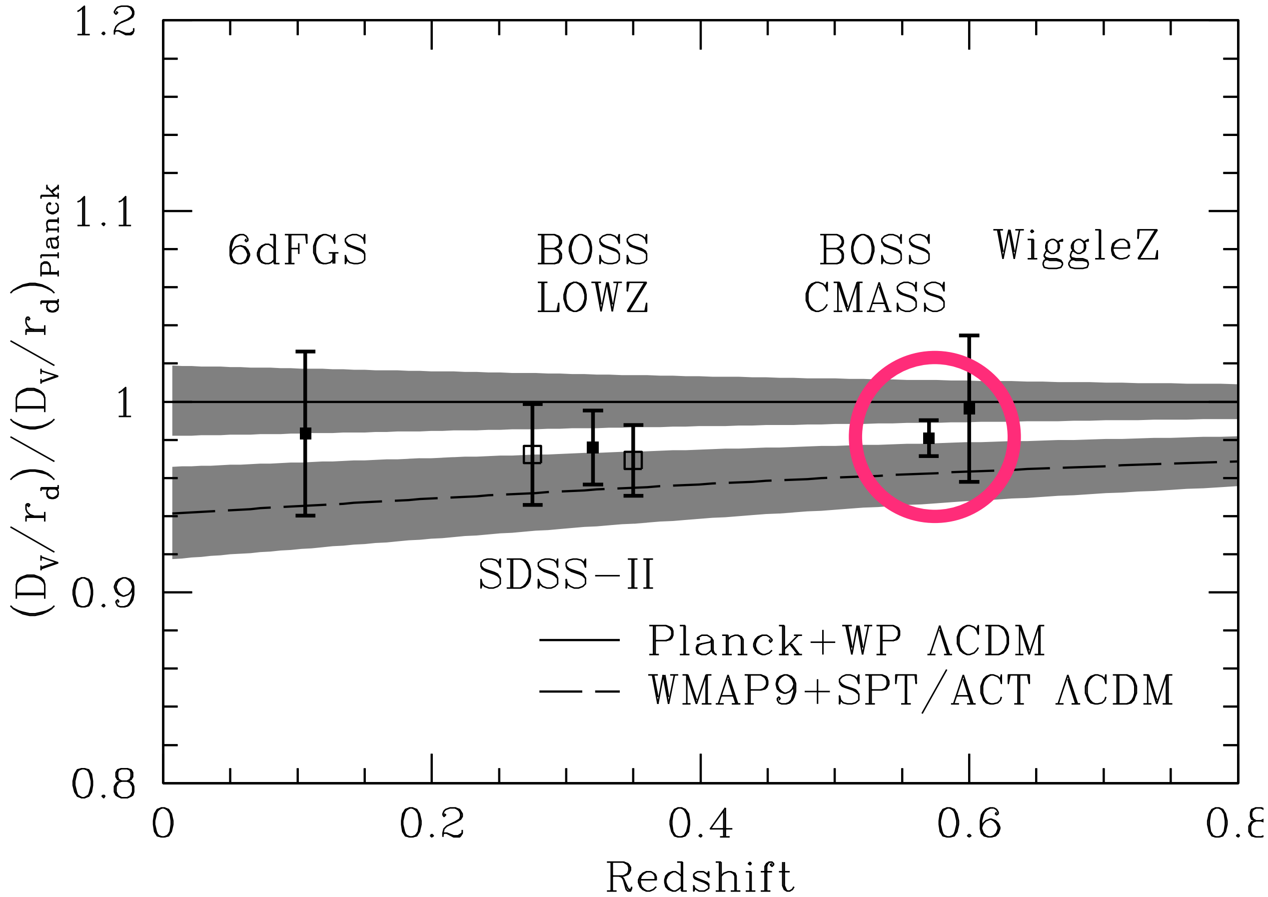
- The BAO-dedicated spectroscopic survey, a part of the 3rd generation of SDSS (SDSS-III), using the dedicated 2.5m telescope in NM, USA
- U. Tokyo is the participation institute (anyone at U. Tokyo has access to the data)
- The new BAO result using the Data Release 11 (DR11) just announced (Dec 18, 2013)

BOSS DR11 BAO (Anderson+13)

Shun Saito (IPMU)



$D_V(z=0.57) = (2056 \pm 20 \text{ Mpc})(r_{\text{BAO}}/r_{\text{BAO,fid}})$



A 2σ-level tension between BAO and CMB constraints; we should wait for the 2nd-yaer Planck result, coming around Sep 2014)

Model-independent reconstruction of curvature

Comoving radial distance

$$D_C(z) = \int_0^z \frac{dz'}{\underline{H(z')}}$$

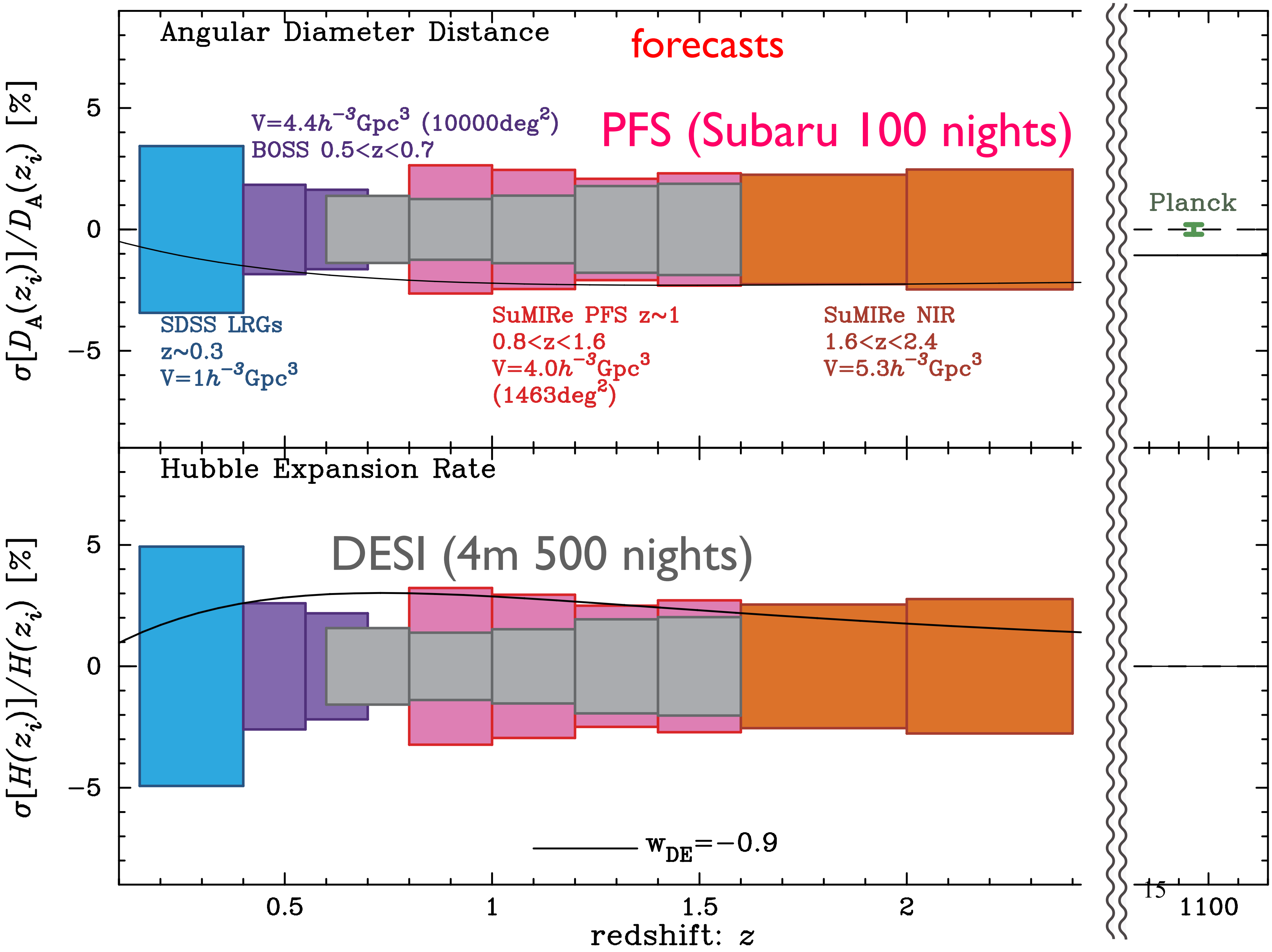
BAO

Comoving angular distance

$$\begin{aligned} \underline{D_A(z)} &= \frac{1}{\sqrt{-K}} \sinh \sqrt{-K} D_C(z) \\ &\simeq D_C(z) \left[1 - \frac{1}{6} K D_C(z)^2 \right] \end{aligned}$$

BAO

- By combining measurements of $H(z)$ and $D_A(z)$ via BAO, we can constrain the curvature in a *model-independent* way (only assumed metric theory and light propagation)



Angular Diameter Distance
forecasts
PFS (Subaru 100 nights)
V=4.4h^-3Gpc^3 (10000deg^2)
BOSS 0.5<z<0.7
SDSS LRGs
z~0.3
V=1h^-3Gpc^3
SuMIRe PFS z~1
0.8<z<1.6
V=4.0h^-3Gpc^3
(1463deg^2)
SuMIRe NIR
1.6<z<2.4
V=5.3h^-3Gpc^3
Planck
σ[D_A(z_i)]/D_A(z_i) [%]
Hubble Expansion Rate
DESI (4m 500 nights)
σ[H(z_i)]/H(z_i) [%]
w_DE=−0.9
redshift: z
0.5
1
1.5
2
1100
5
0
−5

Curvature parameter (cont'd)

$\sigma(\Omega_K) \sim 10^{-3}$ (Preliminary)

(cosmic variance limited survey up to $z = 5$)

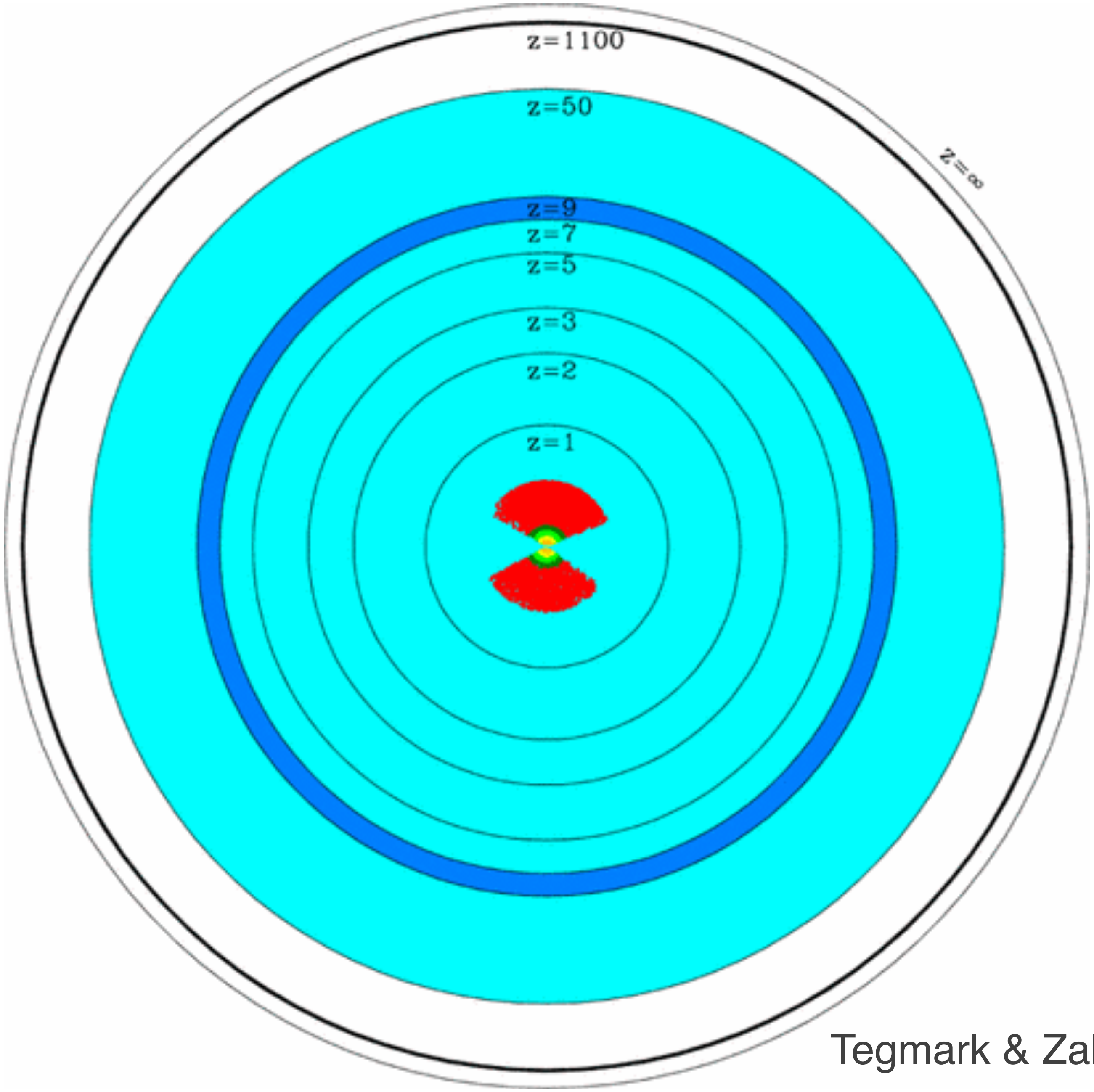
Constraining the curvature with BAO experiments

Masahiro Takada[1], Christopher Hirata[2] and Olivier Doré[3]
[1]*Kavli Institute for the Physics and Mathematics of the Universe (Kavli IPMU), The University of Tokyo, Chiba 277-8583, Japan*
[2]*Caltech M/C 350-17, Pasadena, CA 91125, USA*
[3]*Jet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove Drive, Pasadena, California, U.S.A.*

The radial and angular cosmological distances, measured via the two-dimensional BAO experiment, can be used to determine the curvature without assuming any models of the cosmic expansion history including the nature of dark energy. We discuss almost all-sky BAO experiment can determine the curvature parameter to the accuracy **MT:** $\sigma(K/H_0^2)$ =**XXX**%. In particular, we show that BAO experiments covering to higher redshift as well as without gap in the redshift coverage are very important to achieve the high-precision measurement of the curvature. ....

PACS numbers:

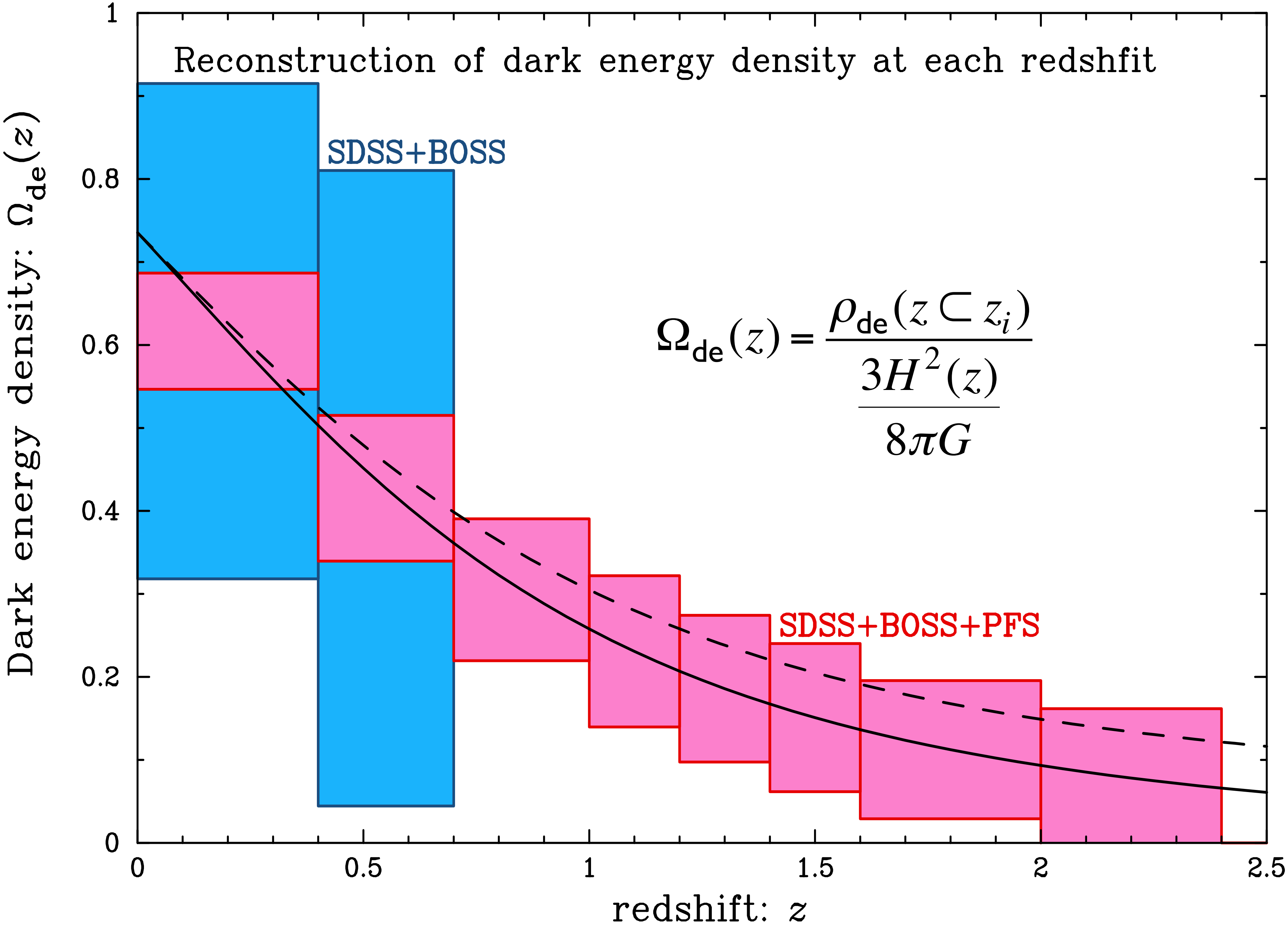
Observable universe with galaxies



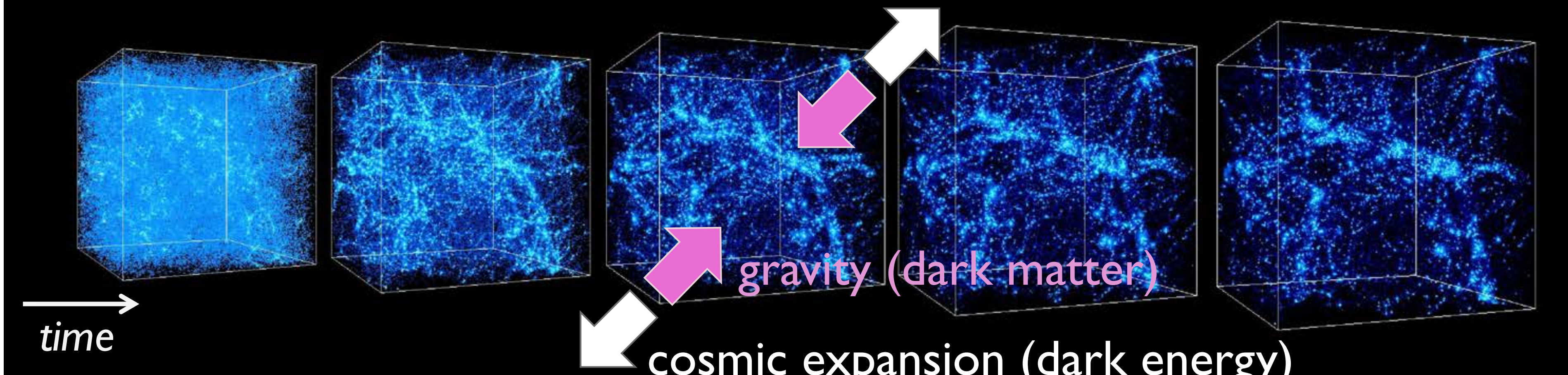
Tegmark & Zaldarriaga 09

- SDSS-I – IV (red galaxies, emission-line galaxies), z<0.7
- PFS (OII-emitters): 0.8<z<2.4
- Other emission lines, OII, Lyman-alpha (potentially up to z~6?)
- QSO & Lyman-alpha forests (z<4-5)
- Eventually 21cm

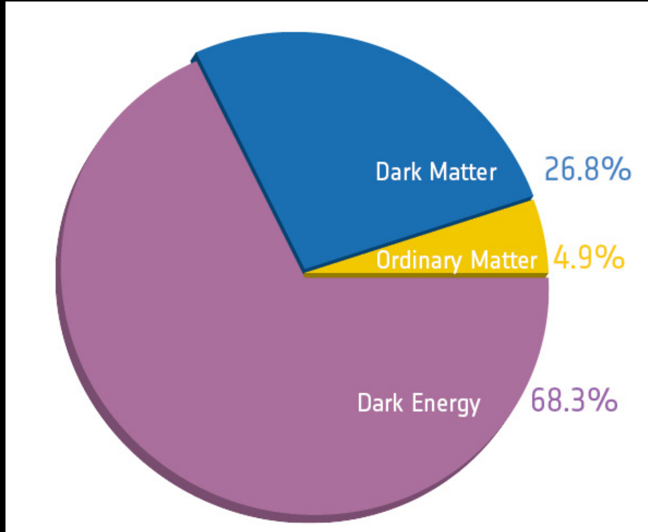
DE reconstruction



Cosmic structure formation



- The present-day large-scale structure arises from a gravitational amplification of the tiny perturbations in the early universe
- Assume Cold Dark Matter (CDM) for unknown source of gravity – cold, massive & collision-less
- LCDM = current standard model
- Gravity (DM) vs. Cosmic expansion (DE)



Planck collaboration

宇宙の加速膨張問題：
ダークエネルギー or 重力の破綻？

- *観測事実は宇宙の加速膨張*

$$R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R + \Lambda g_{\mu\nu} = 8\pi G T_{\mu\nu}$$

$$\text{or} \quad R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R = 8\pi G \left(T_{\mu\nu} - \frac{\Lambda}{8\pi G} g_{\mu\nu} \right)$$

- ΛCDMモデル：アインシュタイン重力(GR)に基づく、宇宙膨張、構造形成のモデル（>6パラメータ: Ω_m, Ω_b, n_s, ⋯, **+Λ**）
- GRは ~1mm – 10Gpc (29桁)にわたり正しいのか？
- ２つのシナリオの区別は？：膨張則の測定（BAO, SN）と構造形成史の測定（WL, galaxy clustering, 銀河団）が組み合わせることが必要

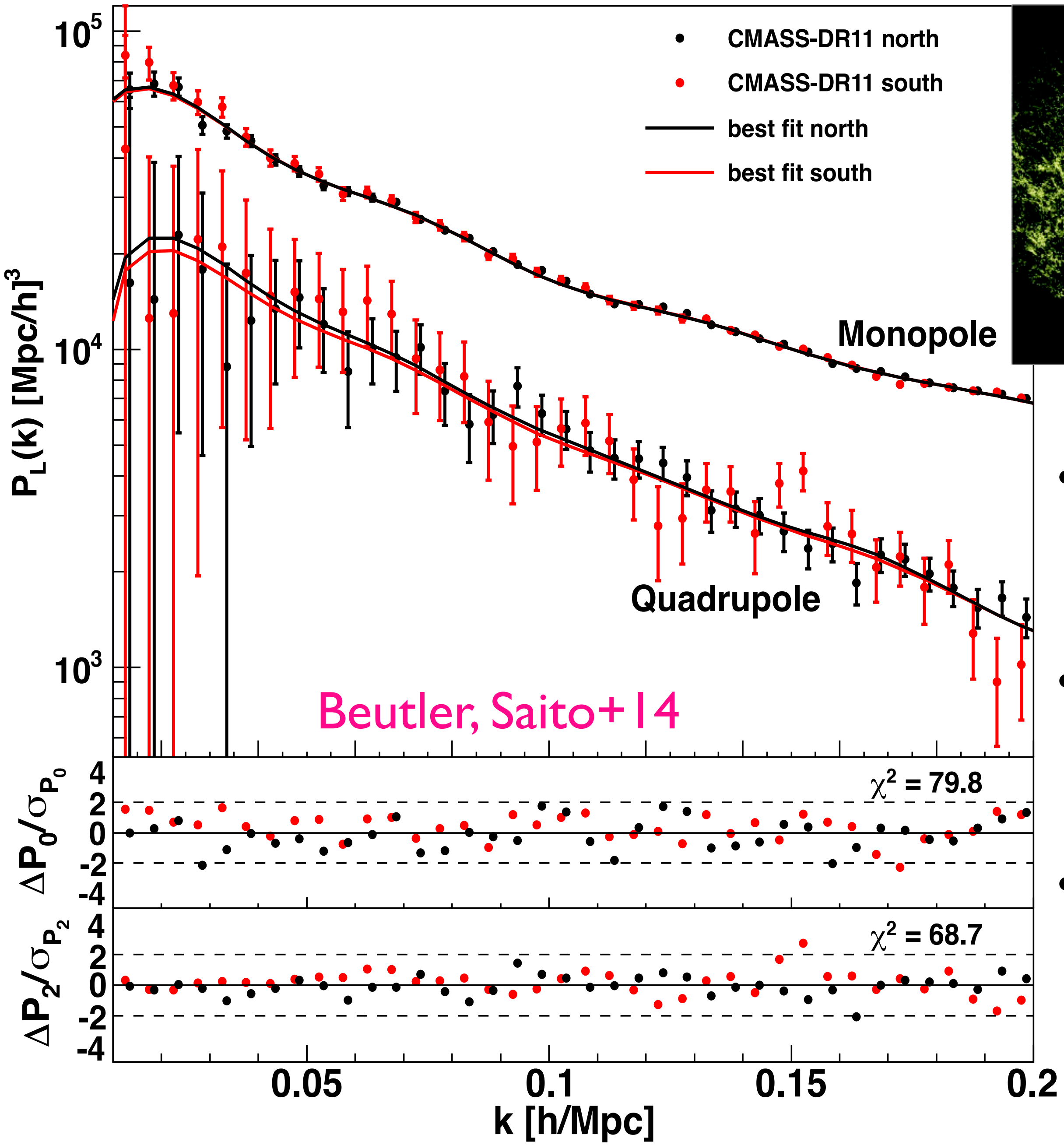
Dark Energy vs. Modified Gravity

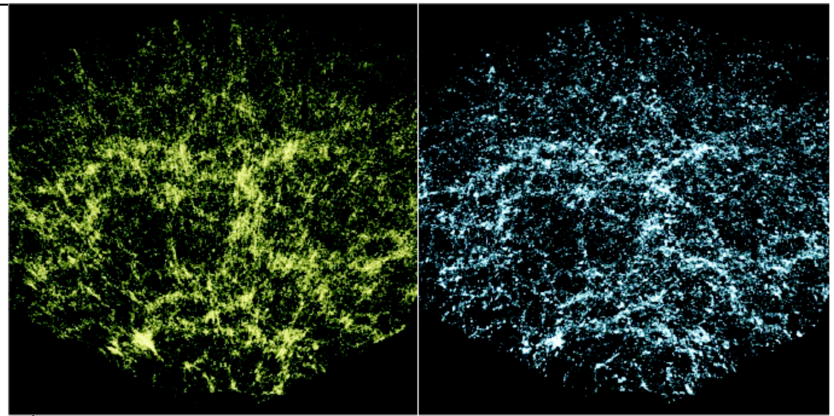
A most general from of metric in matter-dominated era

$$ds^2 = a(t)^2 \left[-(1+2\Phi)d\eta^2 + (1-2\Psi)d\vec{x}^2\right]$$

- LCDM: $\Phi = \Psi$
- Gravitational lensing: $\alpha \sim \nabla(\Phi + \Psi)$
- Peculiar velocities of galaxies (redshift-space distortion): $\vec{v} \sim \nabla\Phi$
- Lensing + RSD allows a model-independent test of gravity at cosmological scales

RSD measurement



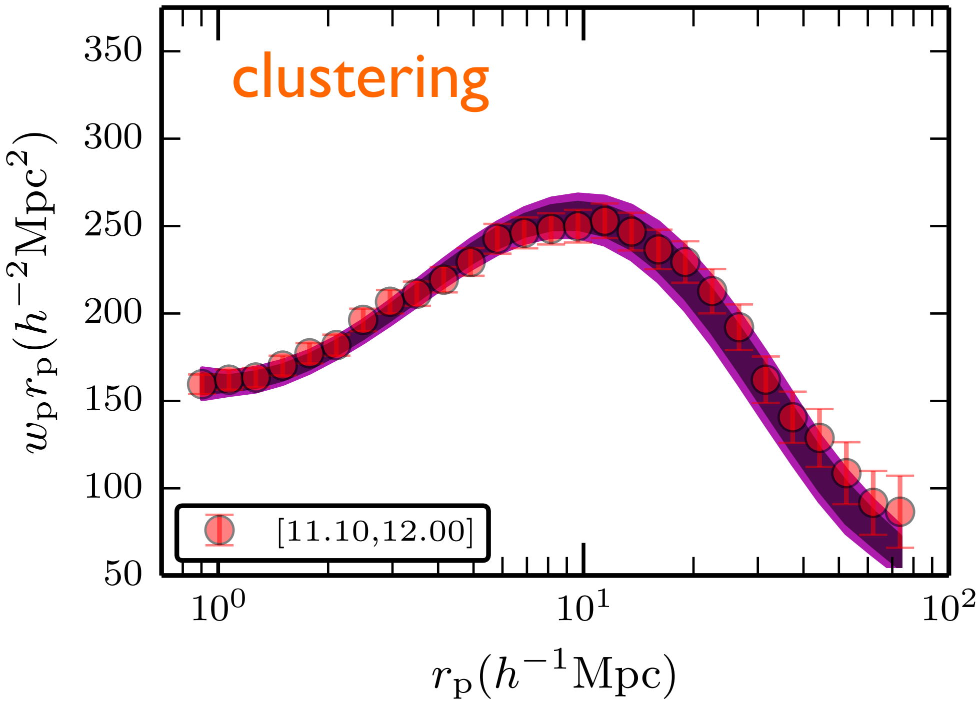


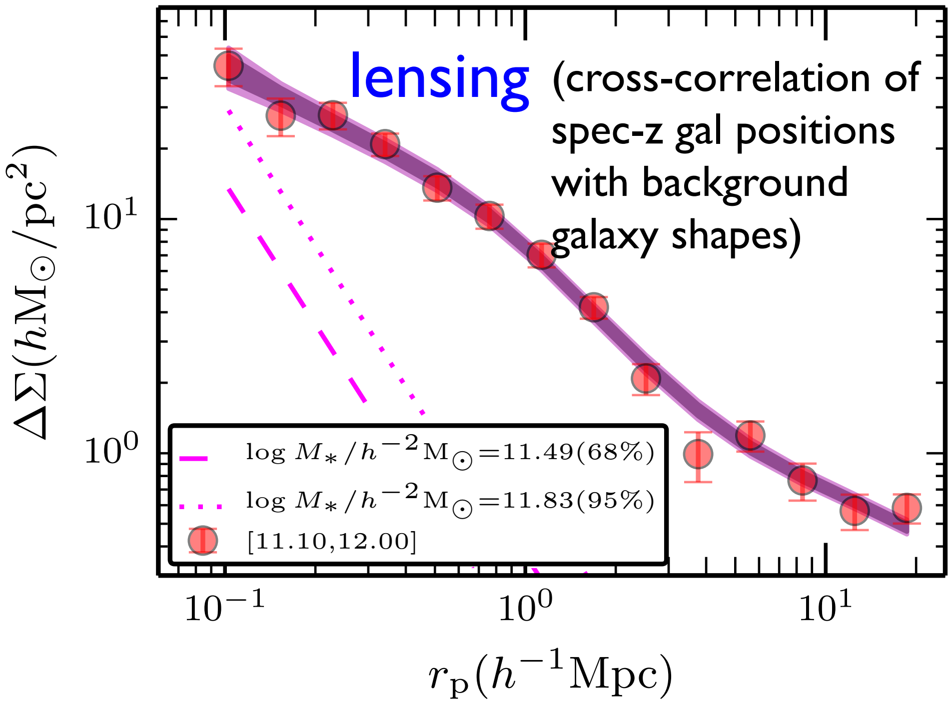
- The state-of-art measurement by BOSS (z~0.5)
- So far the measurement is consistent with Einstein gravity
- Biggest uncertainty: *galaxy bias*

Combined probes:
Lensing (imaging) + Clustering (spec-z)

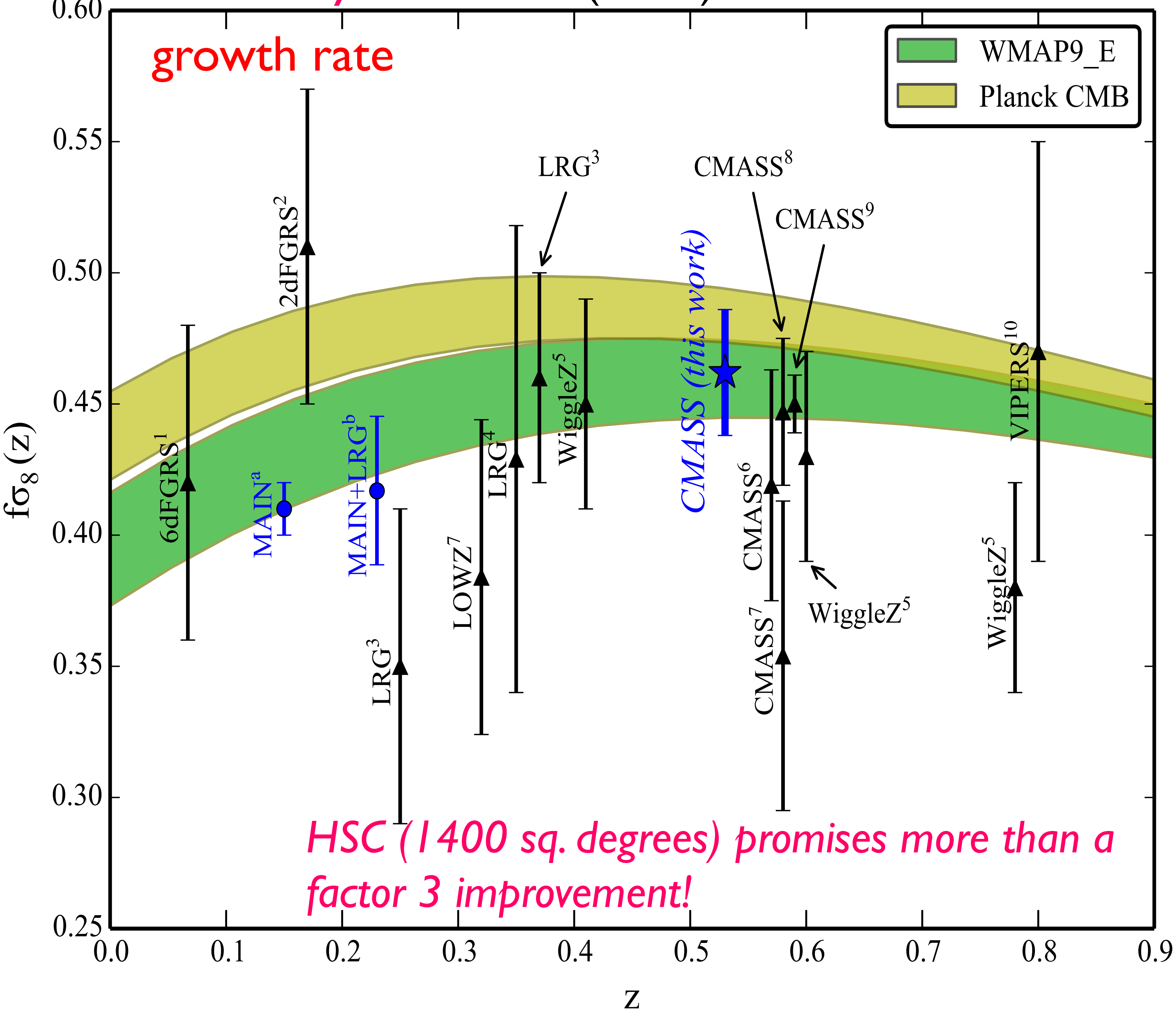
S. More

- Lensing: directly measure the DM distribution, but projected
- Clustering: 3D mapping of galaxy distribution; a much higher S/N, but galaxy bias uncertainty
- More, Miyatake, Mandelbaum, MT, Spergel, et al. (2014): CFHTLenS (3.6m imaging, *only ~120 sq. deg*) + BOSS (2.5m spec-z, 10000 sq. deg)





More, Miyatake et al. (2014)



RSD
[1] Beutler et al. (2012)
[2] Percival et al. (2004)
[3] Samushia et al. (2012)
[4] Chuang & Wang (2013)
[5] Blake et al. (2011)
[6] Beutler et al. (2013)
[7] Chuang et al. (2013)
[8] Samushia et al. (2014)
[9] Reid et al. (2014)
[10] de la Torre et al. (2013)

Clustering+Lensing
[a] Cacciato et al. (2013)
[b] Mandelbaum et al. (2013)

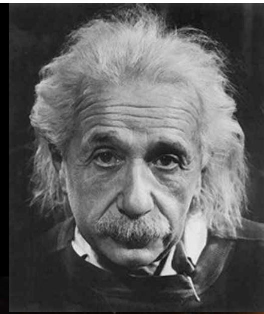
A journey through the “*observed*” galaxy distribution (1.5M gals)

Sloan Digital Sky Survey (1999-) with the dedicated 2.5m telescope

可視光の強み！

A journey through simulated universe (Millennium Simulation)

Nature of Dark Matter



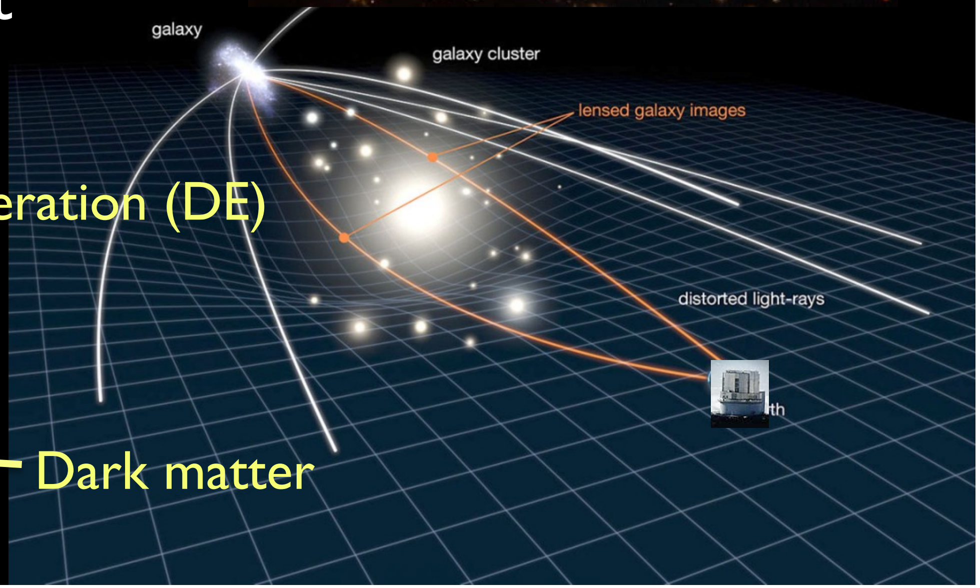
Gravitational lensing

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

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

The *curved* space-time bends "light path"

The lensing distorts images of distant galaxies



Lensing strength =

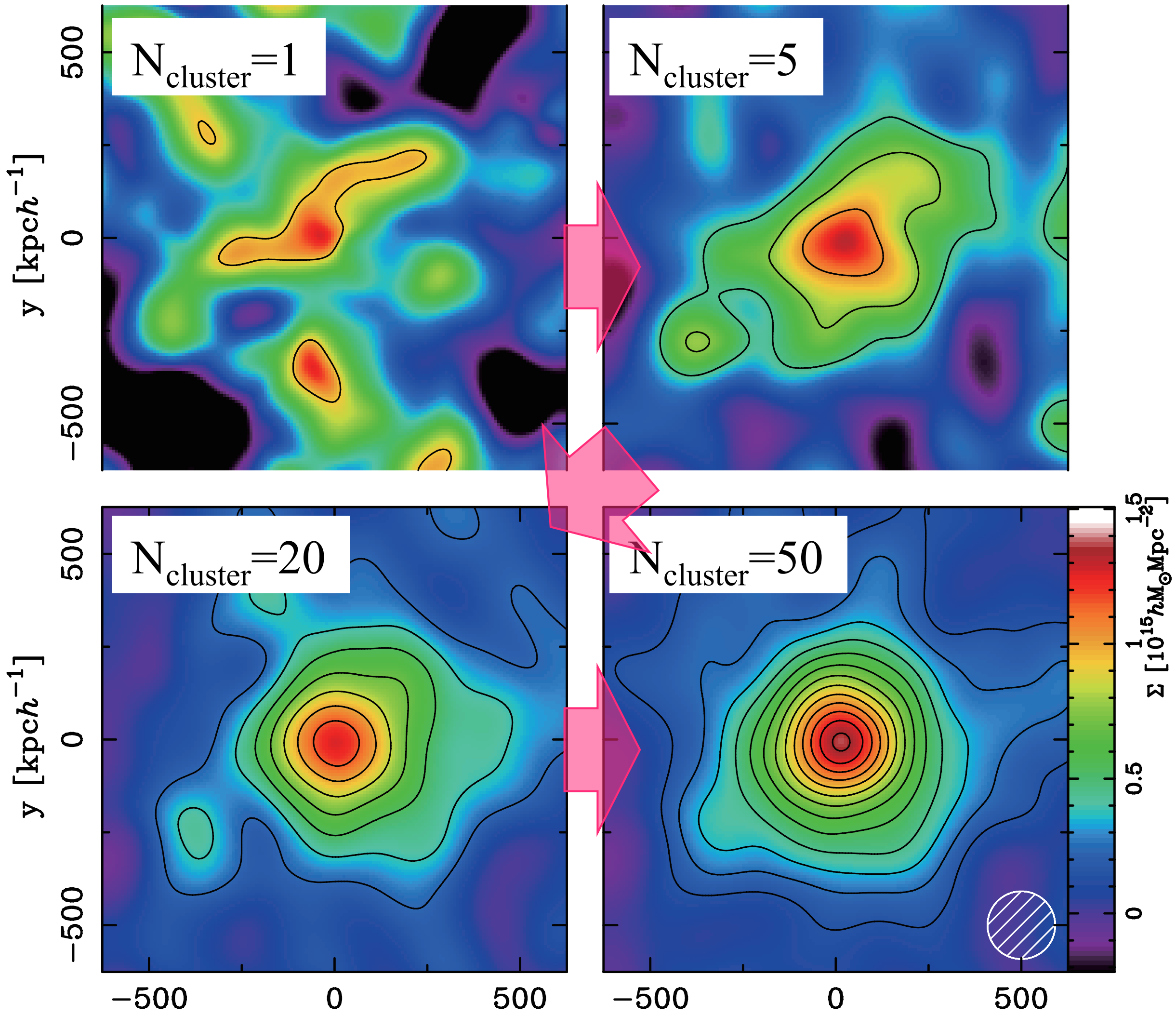
(geometry of the universe) ← Cosmic acceleration (DE)

× (total matter of lens(es)) ← Dark matter

DM distribution of galaxy clusters

- Collected Subaru data of 50 clusters, *all* the most X-ray luminous clusters accessible from Subaru (about 15 Subaru nights; 5 yrs)
- The averaged DM distribution from the combined WL data

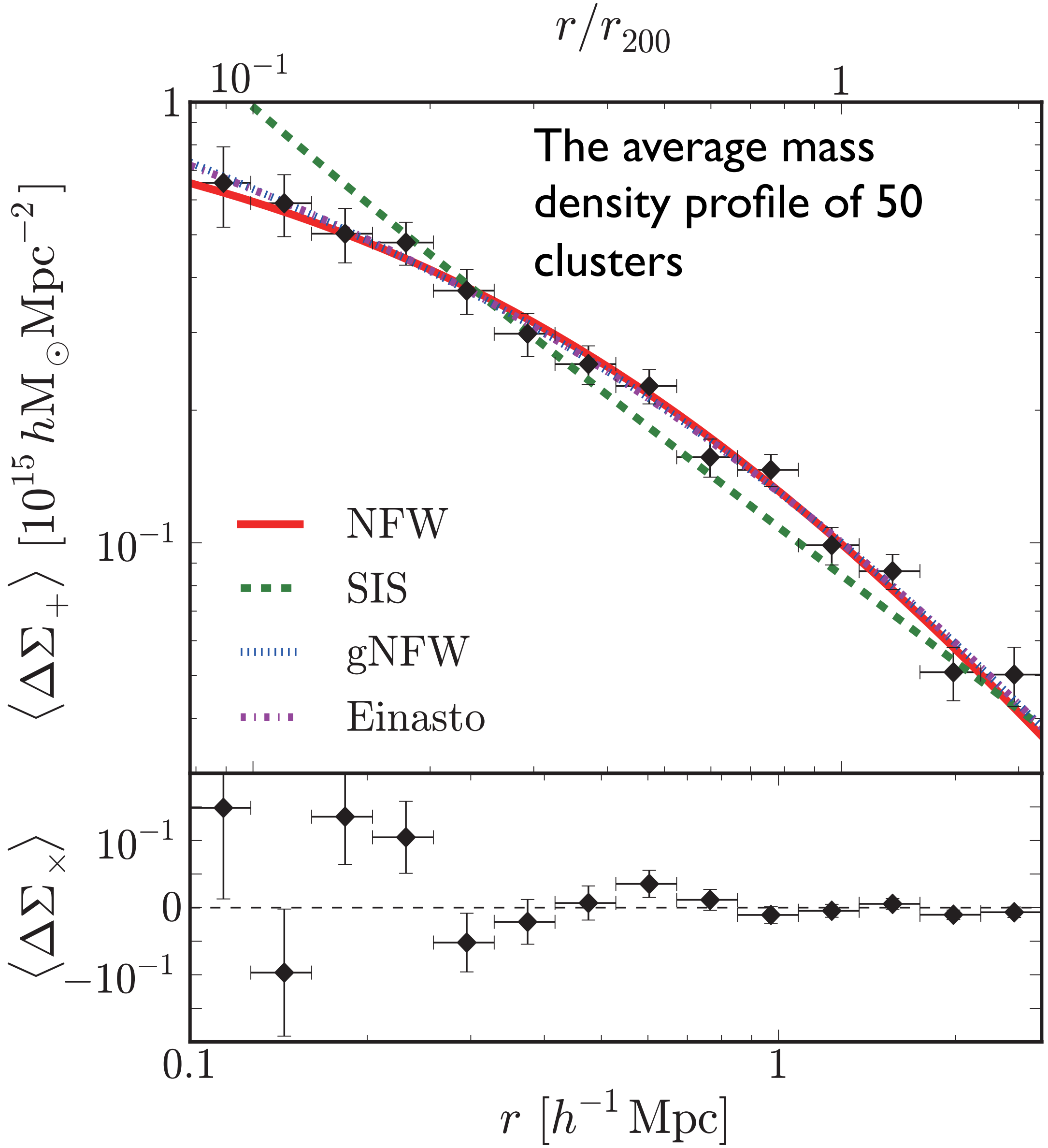
Nobuhiro Okabe

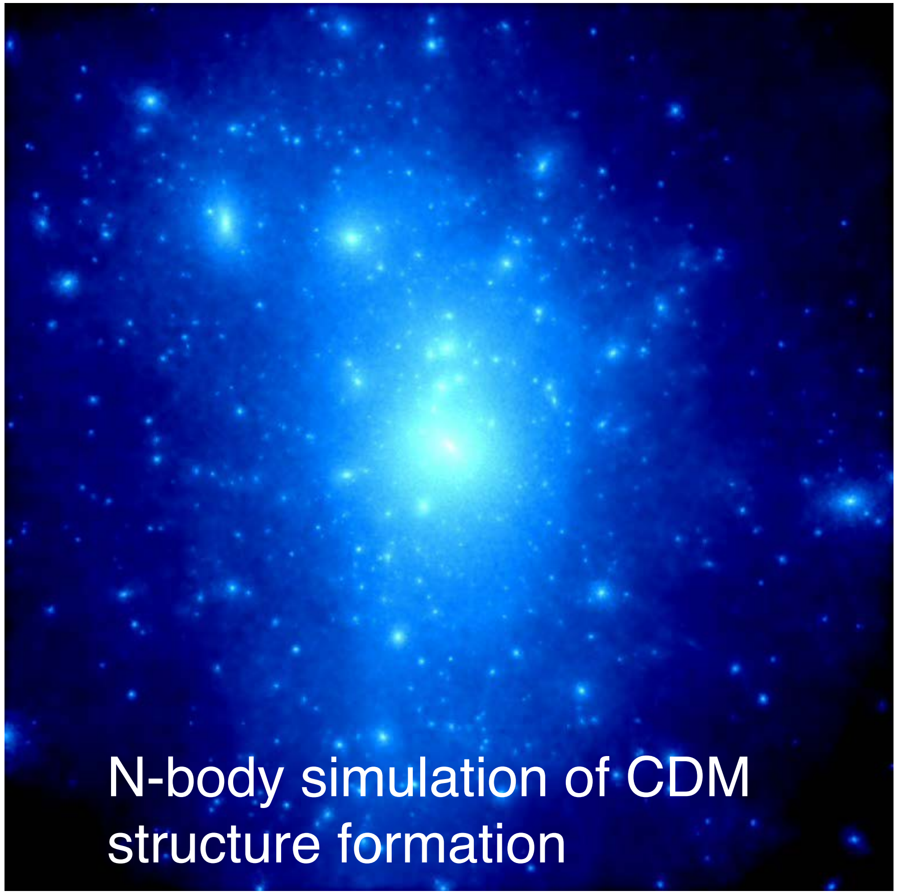


Signal-to-Noise ratio *(S/N)*~5 for one cluster ⇒ *S/N*~30 when 50 clusters combined

Okabe et al. 13, ApJ Letters
Okabe, MT+ 10,PASJ

DM distribution of galaxy clusters (cont'd)

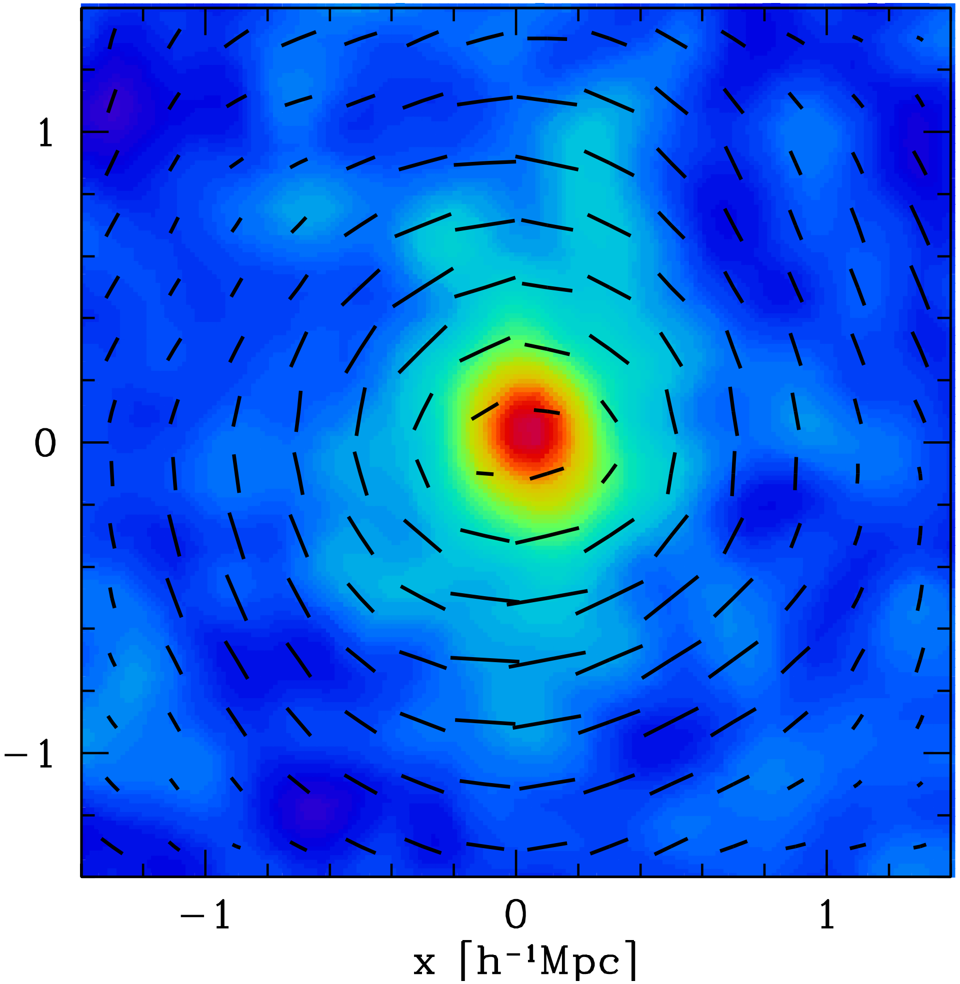




- Subaru WL result shows a perfect agreement with the CDM model prediction
- ~5% accuracy of the cluster mass determination

Shape of dark matter halo

Oguri+12: a detection of dark matter halo shape with WL+strong lensing for Subaru cluster data (also see Oguri+10)

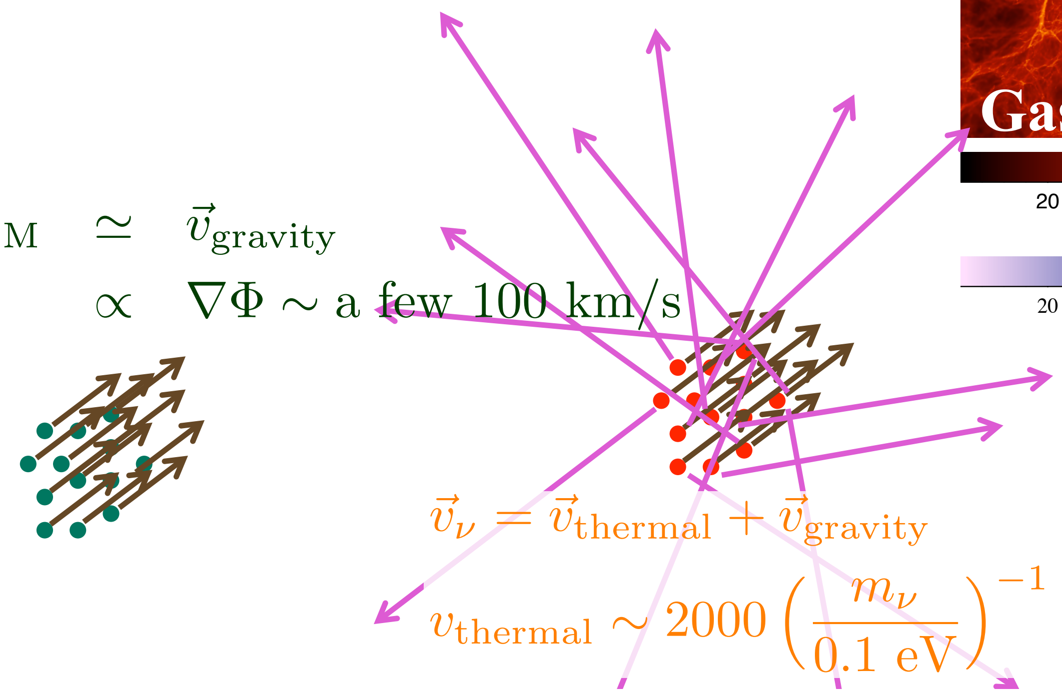


- Collision-less nature of DM predicts that a shape of halo should be aspherical
- CDM predictions seem consistent with WL measurements on clusters
- What about small scales? (galactic scales and smaller scales)
  - More sensitive to the nature of dark matter: warm (~keV) vs. cold
  - Baryonic physics is also significant
  - Strong lensing?

Neutrino Mass

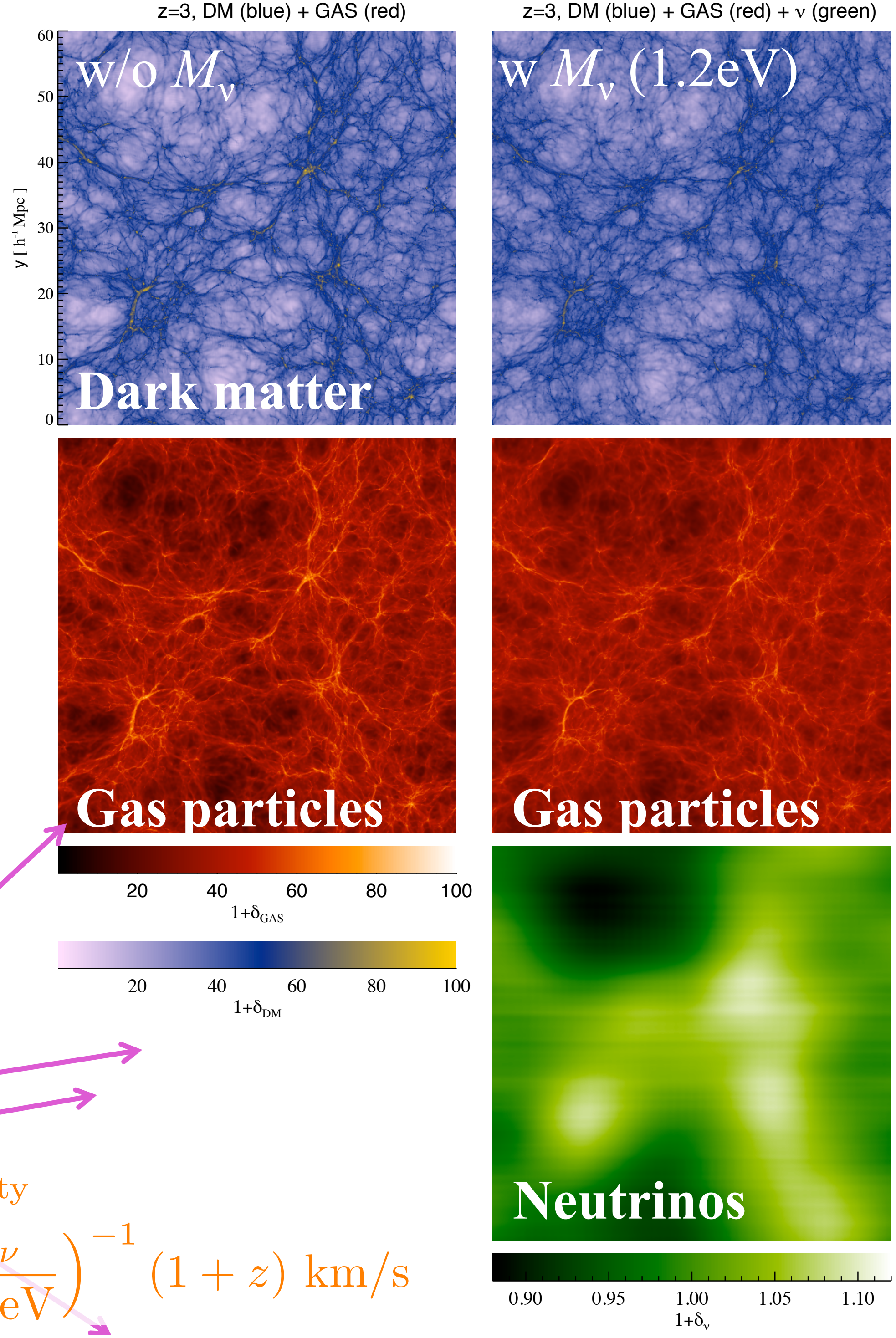
- We know *neutrinos are massive (Kamiokande; SuperK)*
- The absolute mass scale *unknown*
- Partly contribute to *dark matter*
- *Suppress* the growth of large-scale structure at small scales

$$\vec{v}_{\rm CDM} \simeq \vec{v}_{\rm gravity} \propto \nabla\Phi \sim \text{a few 100 km/s}$$



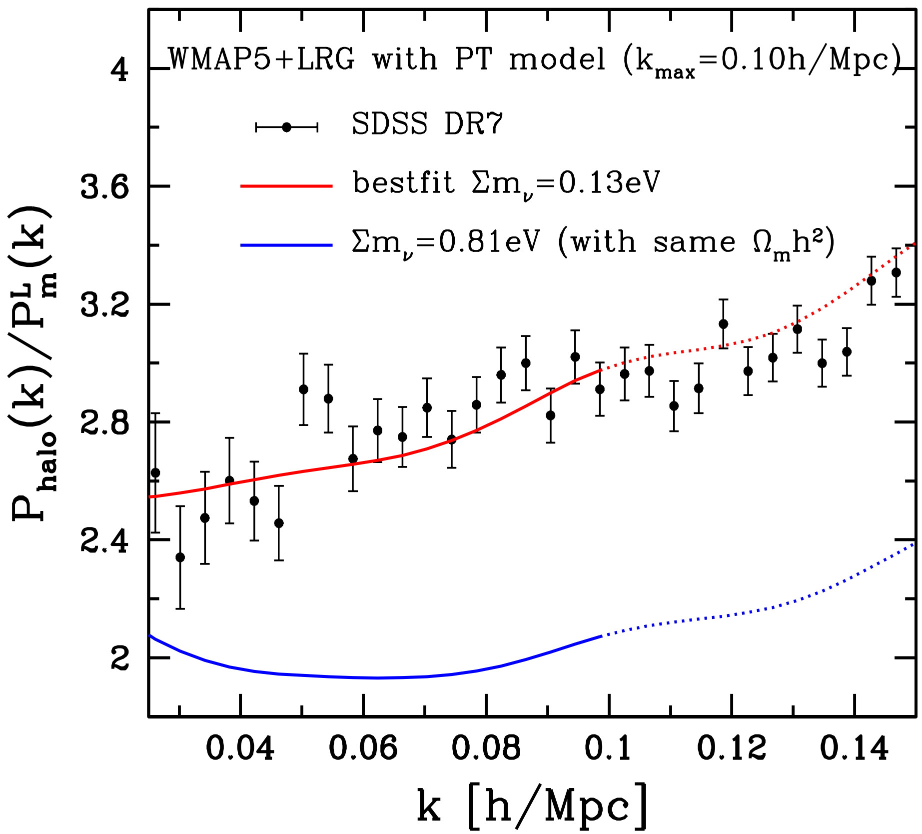
$$\vec{v}_\nu = \vec{v}_{\rm thermal} + \vec{v}_{\rm gravity}$$

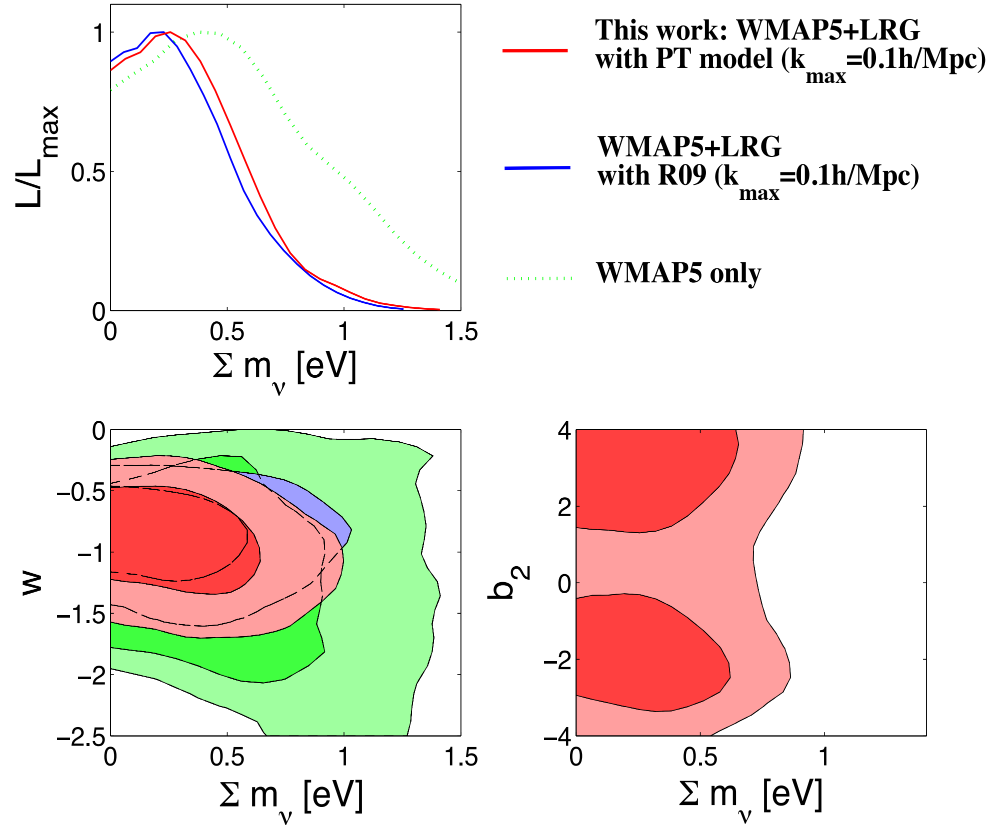
$$v_{\rm thermal} \sim 2000 \left(\frac{m_\nu}{0.1\ {\rm eV}}\right)^{-1} (1+z)\ {\rm km/s}$$



Large-scale structure for a CDM+ν model (cont'd)

Saito, MT & Taruya 08 PRL; 09, 11 PRD; also Ichiki, MT & Takahashi 09 PRD; Ichiki & MT 12 PRD

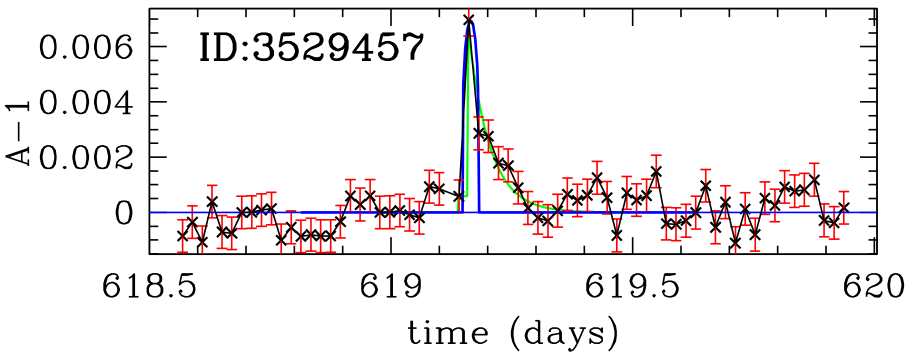


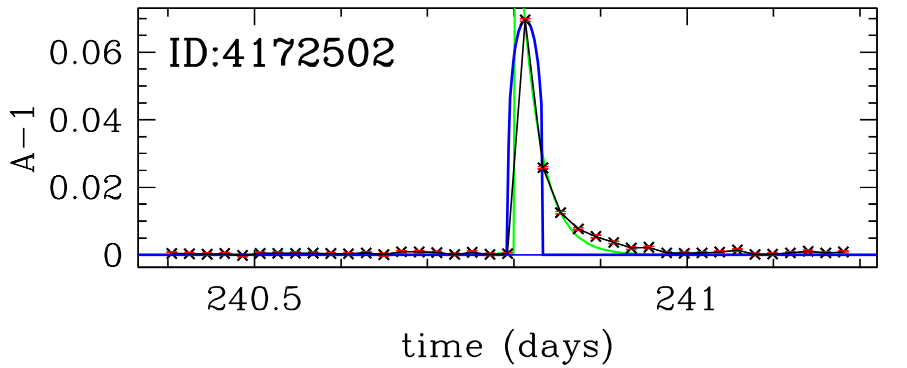


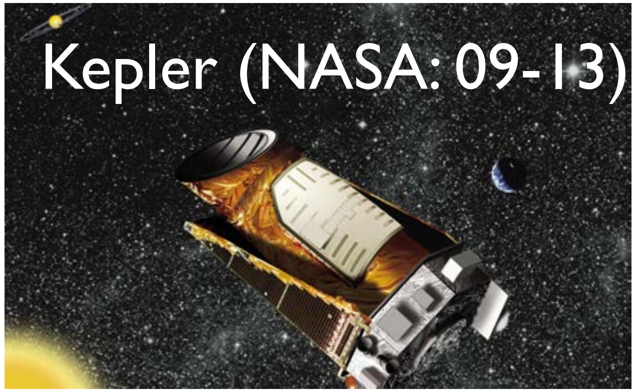
- Applied the model to SDSS LRG power spectrum measurement
- Included effects of *nonlinear clustering*, *nonlinear bias*, and *dark energy*
- Obtained a robust constraint on neutrino mass: $M_{\nu,\mathrm{tot}} < 0.80$ eV (95%C.L.)
- *Goal for SuMIRe:* $\sigma(M_{\nu,\mathrm{tot}}) = 0.05$ eV Fukugita & Yanagida (86)

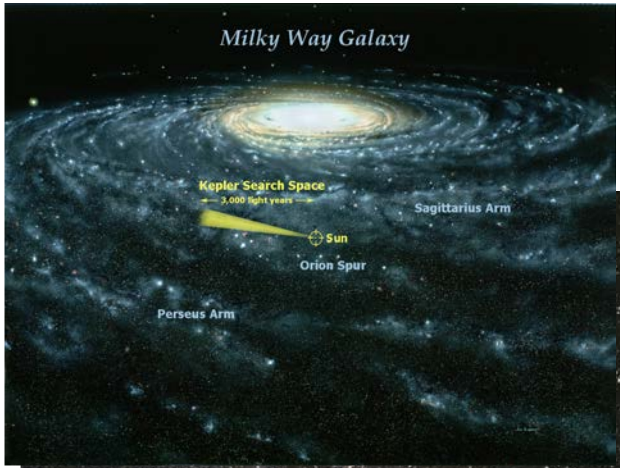
PBH

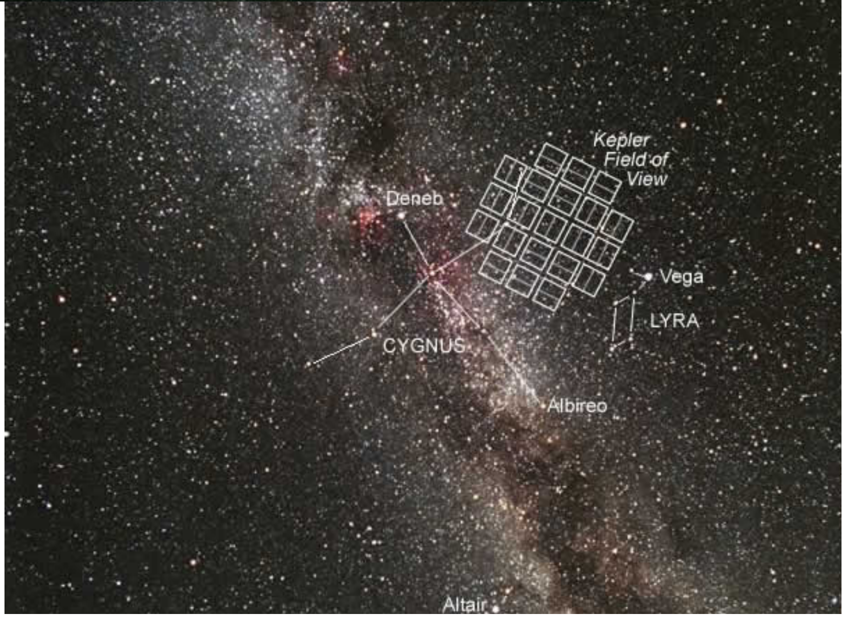
- Kepler: satellite mission for exoplanet search (~3000 planets reported)
- Griest et al. proposed to use the Kepler data to search for microlensing events by PBHs
- No strong candidate





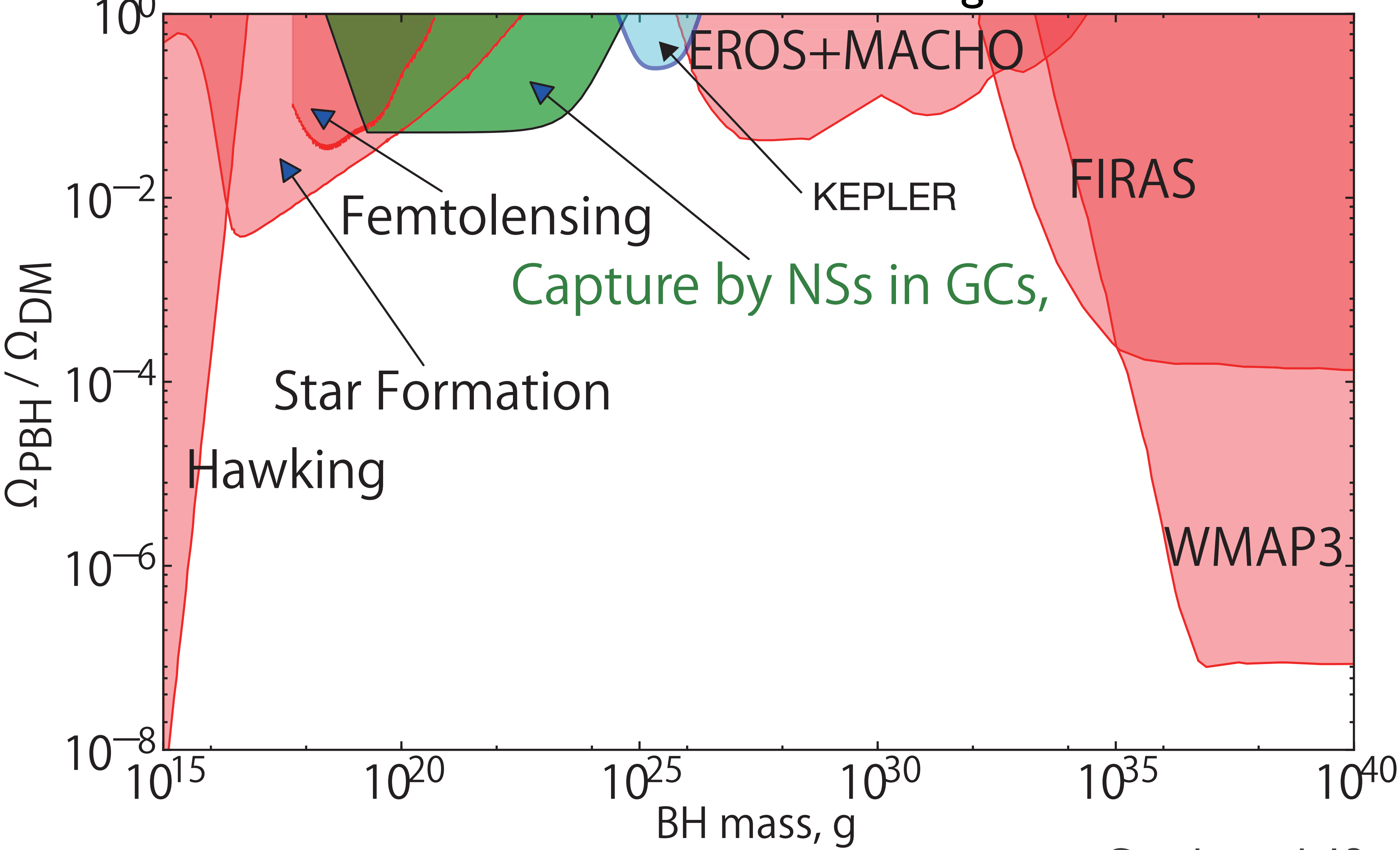






New constraints on PBH

Now no window in the PBH mass range

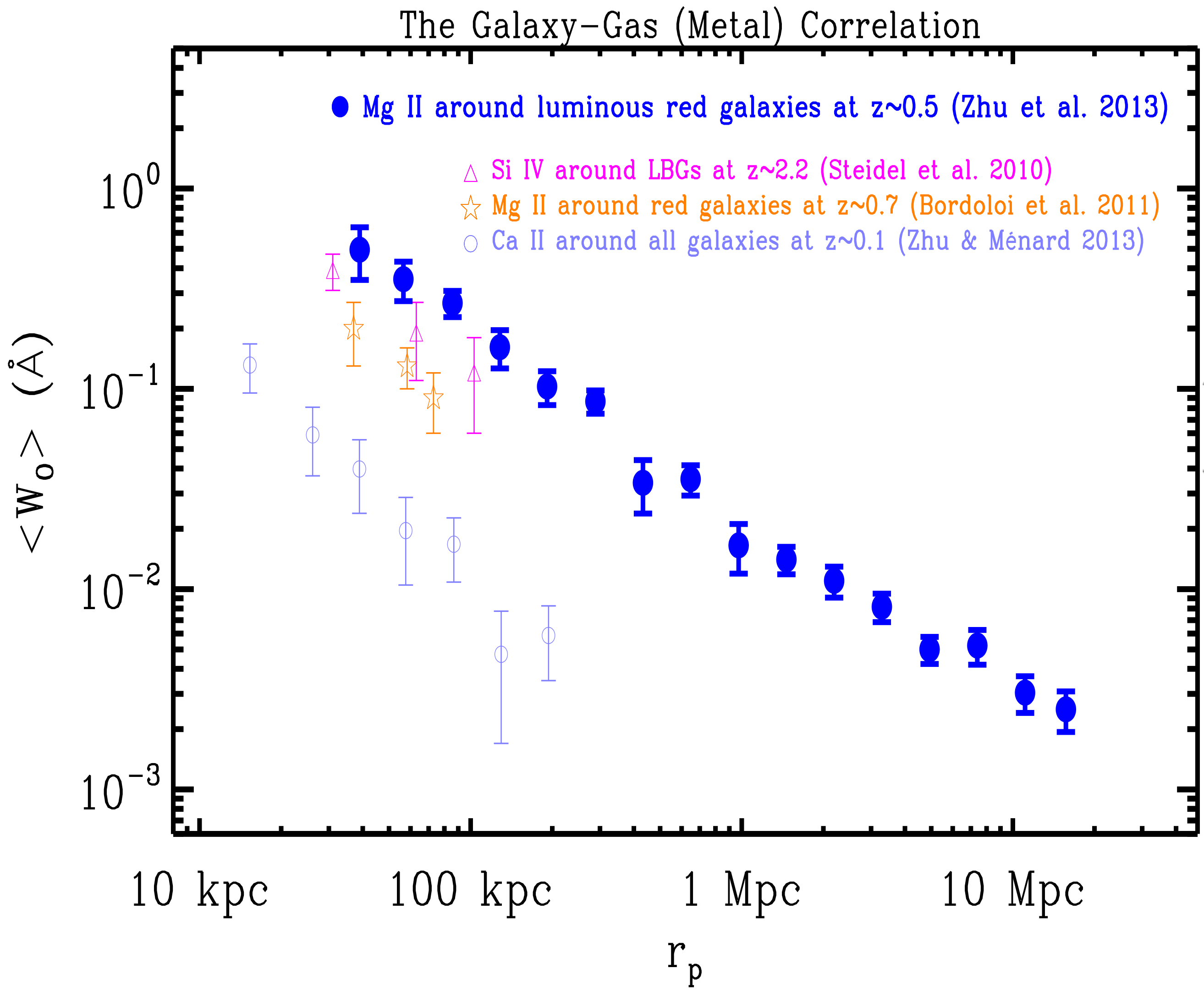


Capela et al. 13

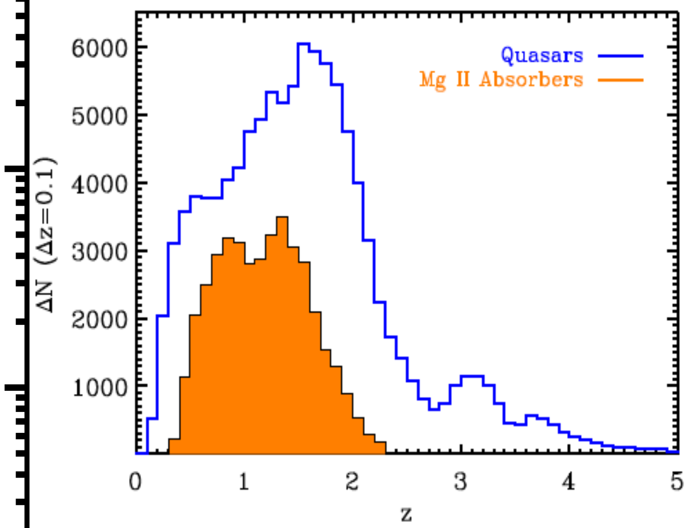
Cross-correlation of galaxies and IGM gas

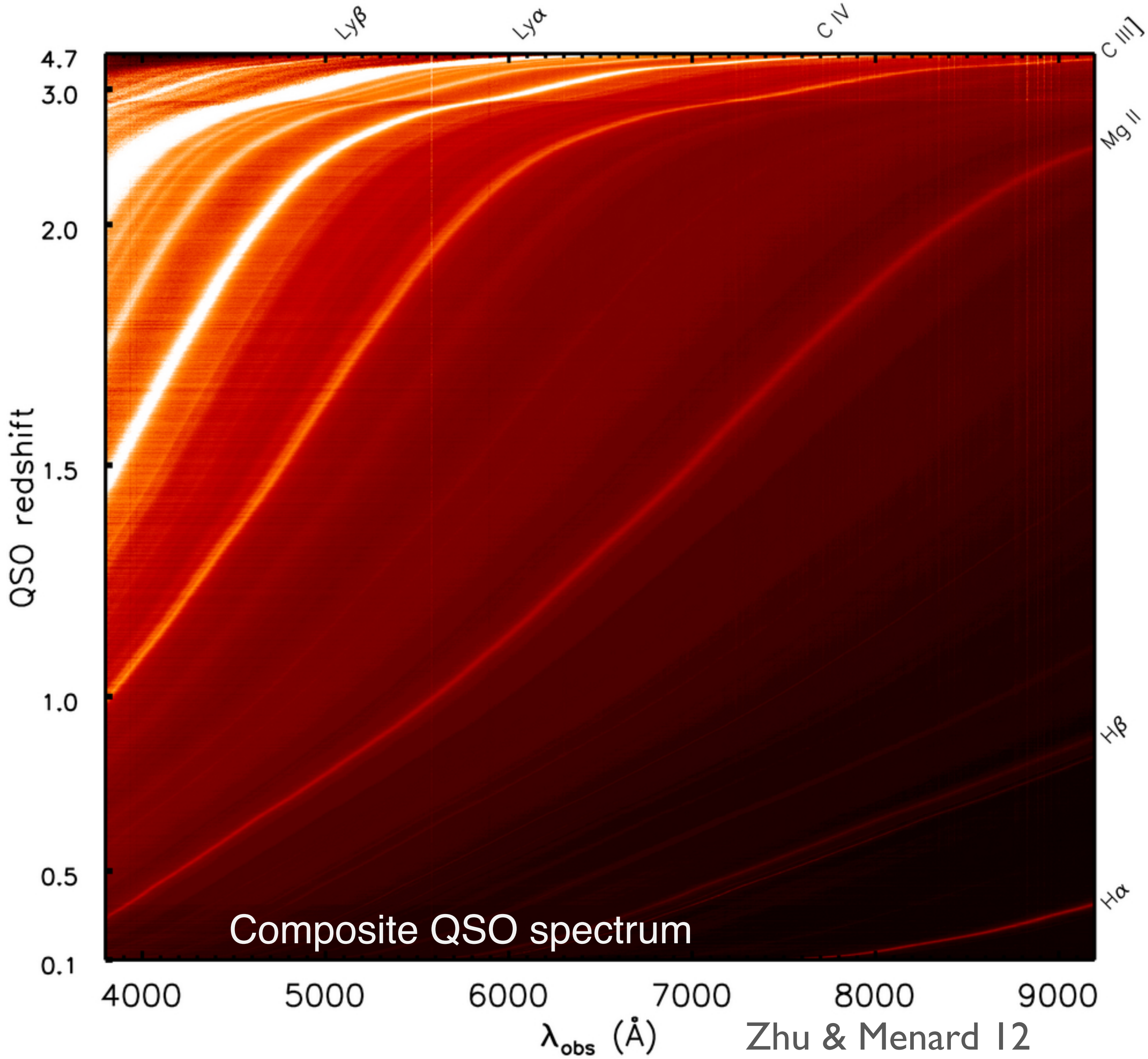
- A series of amazing works by Brice Menard (JHU/IPMU)

$$\langle \delta_{gas} \delta_{galaxy} \rangle$$ (one tracers have spec-z)



dN/dz



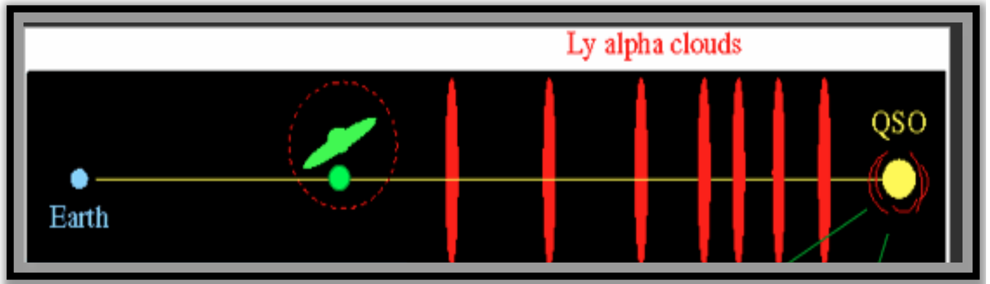


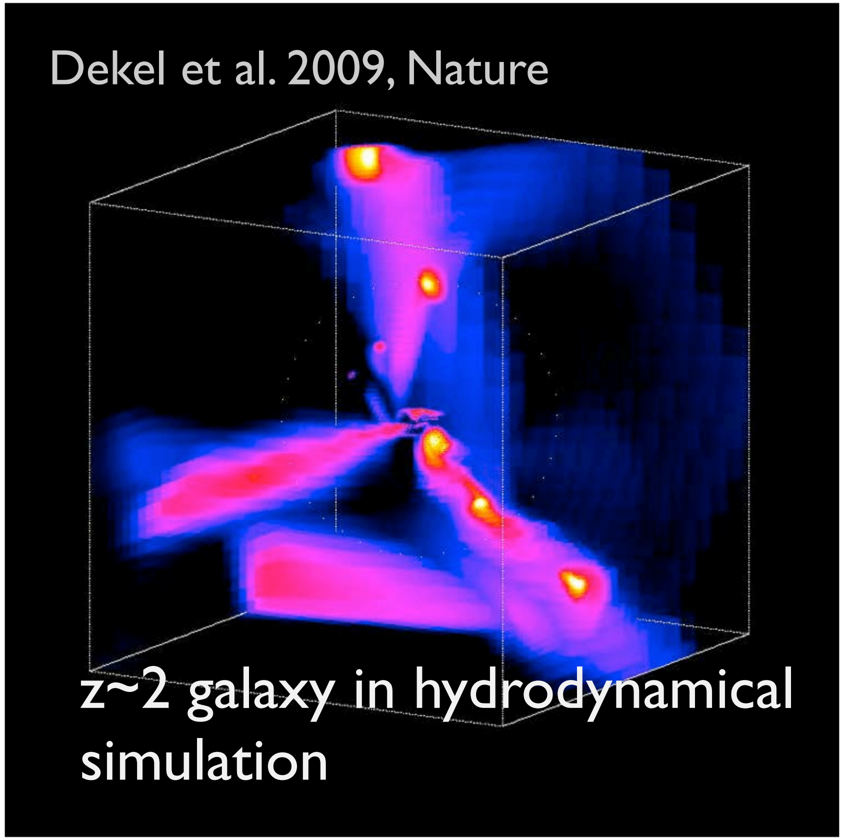
Zhu & Menard 12

銀河形成の激動期(z~2-3)：暗黒物質、星形成、ガス

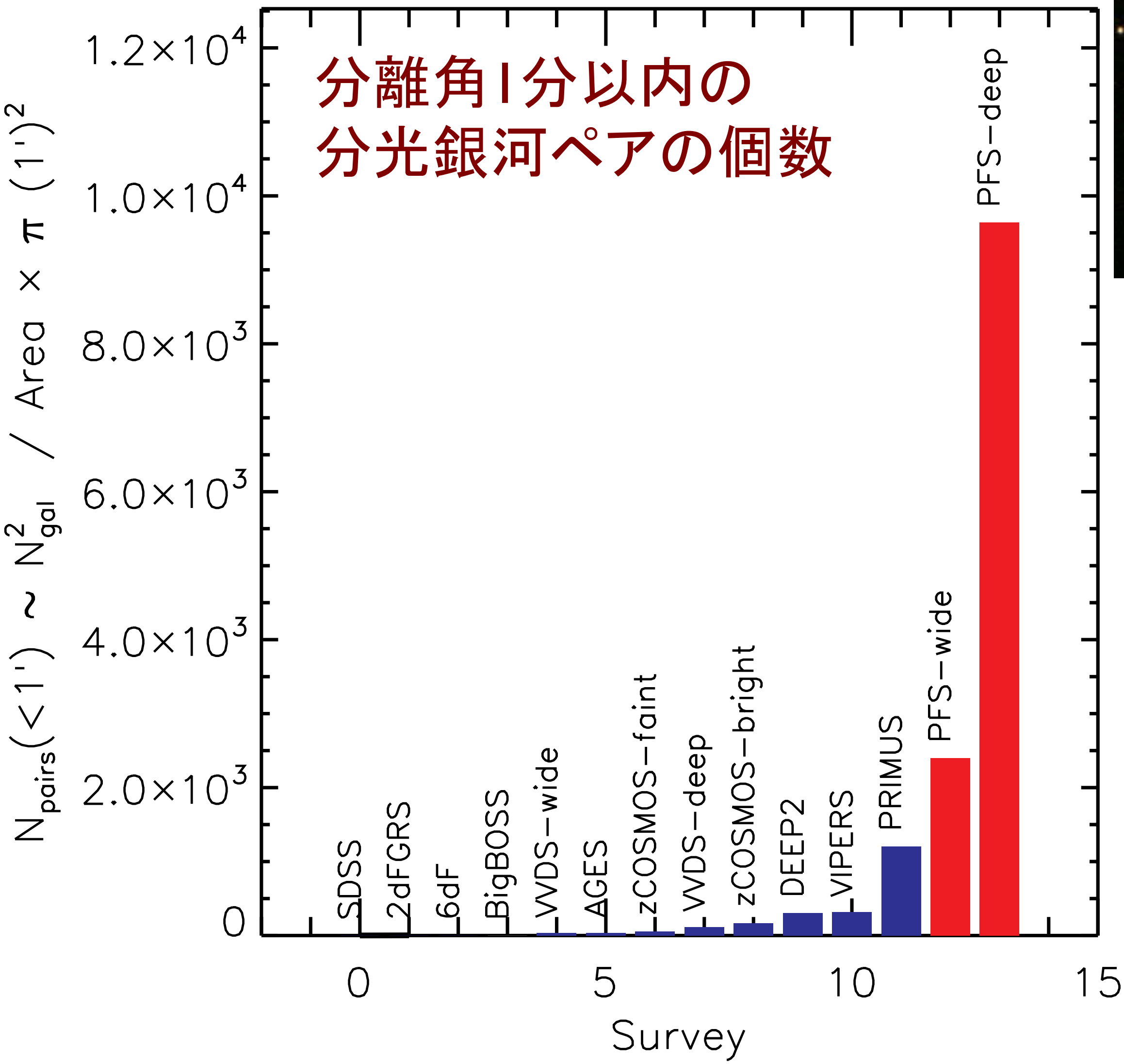
- 「統計的」重力レンズ → 銀河まわりの暗黒物質分布 (z<1.5)
- 背景光源（QSOと究極的には銀河）と前景銀河の相相関 → 銀河ハロー内のcold ダスト (z<3.5)
- 背景光源スペクトルと前景銀河の相相関（例、HSC-SDSS/BOSS) → 銀河ハロー内の矮小銀河 (z<1)
- 赤外線: warm ダスト (z~3)
- 重力レンズで増光された遠方銀河の２次元面分光（例、HSC-TMT） → 銀河の回転曲線の進化 (z<5)

階層的構造形成シナリオにおける銀河形成「物理」の系統的な理解



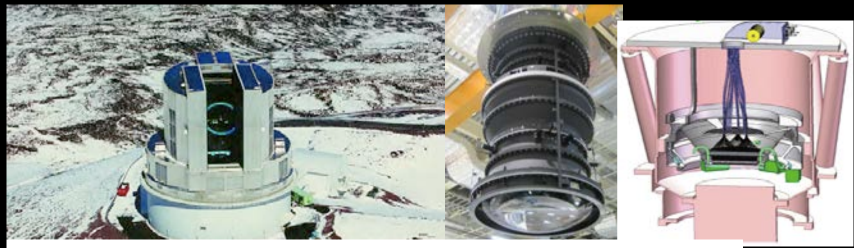


宇宙論的銀河形成研究：多角的視点、多波長、理論＋観測…

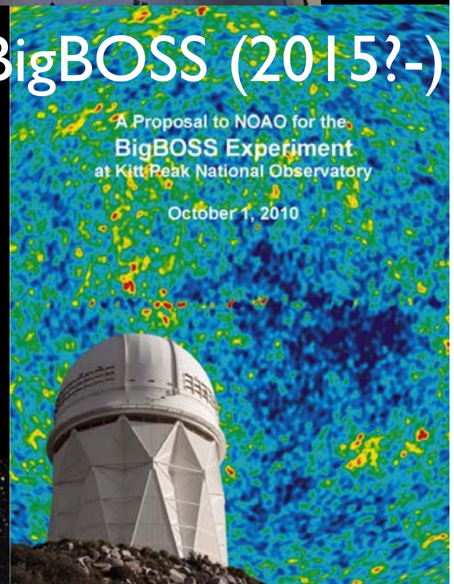


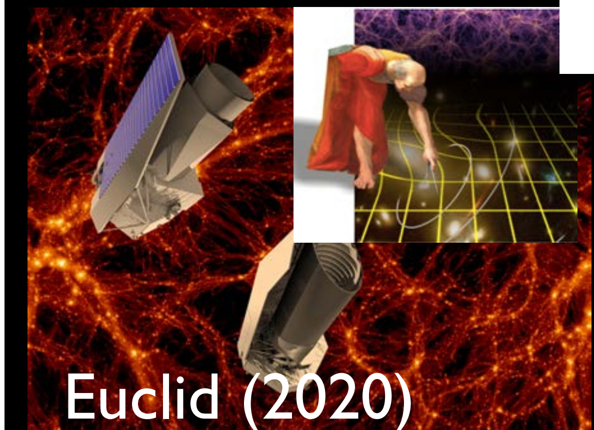
- HSC – SDSS/BOSS QSOs/Galaxies
- HSC/SDSS – Subaru AO
- HSC – PFS
- HSC/PFS – TMT
- HSC/PFS – ALMA
- 宇宙論シュミレーション

The world situation



Subaru SuMIRe (2013-)





NSF funding ($27.5M) in FY2014 for LSST construction now started
LSST survey (2022-2032 if everything goes well)

AURA — ASSOCIATION OF UNIVERSITIES FOR RESEARCH IN ASTRONOMY

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NEWS

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AURA Awarded Support by the National Science Foundation To Begin Constructing LSST

August 4, 2014

The National Science Foundation (NSF) agreed on Friday to support the Association of Universities for Research in Astronomy (AURA) to manage the construction of the Large Synoptic Survey Telescope (LSST). This marks the official federal start of the LSST project, the top-ranked major ground-based facility recommended by the National Research Council's Astronomy and Astrophysics decadal survey committee in its 2010 report, New Worlds, New Horizons. It is being carried out as an NSF and Department of Energy (DOE) partnership, with NSF responsible for the telescope and site, education & outreach, and the data management system, and DOE providing the camera and related instrumentation. Both agencies expect to support post-construction operation of the observatory.

The NSF construction budget for LSST is not to exceed $473M. The DOE Camera fabrication budget will be baselined later this year, but is estimated to be $165M. Operations costs will be around $40M per year for the ten-year survey. With the approved start occurring now, LSST will see first light in 2019 and begin full science operations in 2022. Today's action culminates over ten years of developing, planning and reviewing of the LSST concept.

LSST Project Manager, Victor Krabbendam, was delighted to receive the welcome news from NSF: "This agreement is a tribute to the hard work of an exceptional team of highly skilled individuals, many of whom have dedicated more than a decade to bringing LSST to this point. After a rigorous design and development phase, the project team is ready to get down and dirty and actually build this amazing facility."

LSST Director, Steven Kahn of Stanford University, commented on the unique contributions LSST will make to astronomy and fundamental physics: "The broad range of science enabled by the LSST survey will change our understanding of the dynamic Universe on timescales ranging from its earliest moments after the Big Bang to the motions of asteroids in the solar system today. The open nature of our data products means that the public will have the opportunity to share in this exciting adventure along with the scientific community. The most exciting discoveries will probably be those we haven't yet even envisioned!"

その他のトピック

- 原始密度ゆらぎの復元（構造形成の非線形性の物理的理解）
- ダークマターハローと銀河の関係
- 超新星サーベイ
- QSO吸収線宇宙論
- 物理定数の時間進化
- TMTによる宇宙膨張の直接測定(超高分解能分光)
- 全天偏光サーベイ（CMB前景放射の補正）

宇宙論に必要な銀河サーベイの方向性

- Imaging and spec. survey for the *same* region of the sky
  - *Wider* area (wider FoV + high multiplexity)
  - Up to *higher* redshift without any gap in redshift (wider wavelength coverage; ground vs. space)
  - Denser sampling of galaxies in imaging and redshift
  - HSC + PFS very powerful
- Cosmology = Statistics
  - Various cross-correlation: imaging – spec-z galaxies, CMB 2nd effects, cold gas in IGM, warm gas in galaxies (via infrared such as SPICA)
  - Time-domain survey: microlensing, supernovae
  - A follow-up detailed observation of interesting objects with TMT
- 銀河形成・バリオン物理の理解の重要性
  - 銀河、AGN班との連携
  - シミュレーション？