Cosmological Implication of Redshift distortions

May 19th 2014
IAS Workshop
on New Perspectives on Cosmology

Yong-Seon Song
(CosKASI: Cosmology Group at Korea Astronomy and Space Science Institute)

Dark energy study prospects

- Precision measurements of distance, growth, and curvature: it is desirable for future surveys to provide results of the distance and growth of structure, so that different theoretical models can be discernible.

- Is dark energy a cosmological constant? : w=-1 even with generalized parameterization of all possibilities, e.g. variation of w, screening effect, induced anisotropy etc.

- Is dark energy isotropic and homogeneous? : we need examine the distribution, mean, and rms value of w over all the pixels to see.

- Is acceleration caused by modified gravity instead? : we need at least two different probes, WL and coherent motions.

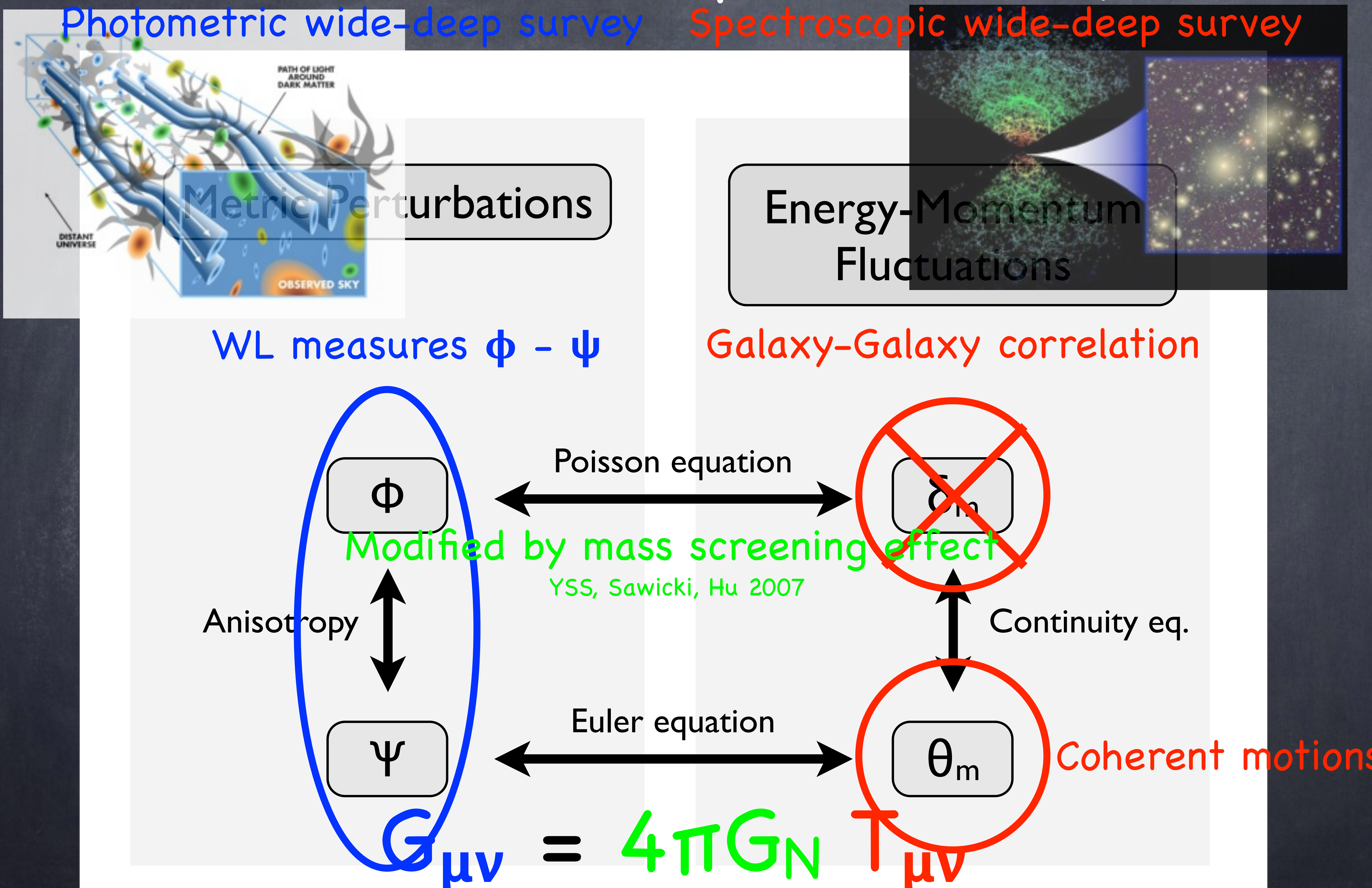
Beyond Standard Models

- With the level of precision available in these surveys, what they tell us about fundamental physics? : whether we can test GR cosmologically, whether we can constrain beyond Standard Model of particle physics.

- What can a wide deep survey tell us about the basic assumptions behind the standard cosmology? : test cosmological principle (isotropy and homogeneity), and Gaussianity.

- What are the technical challenges to making these future surveys productive ?

Future wide deep field survey

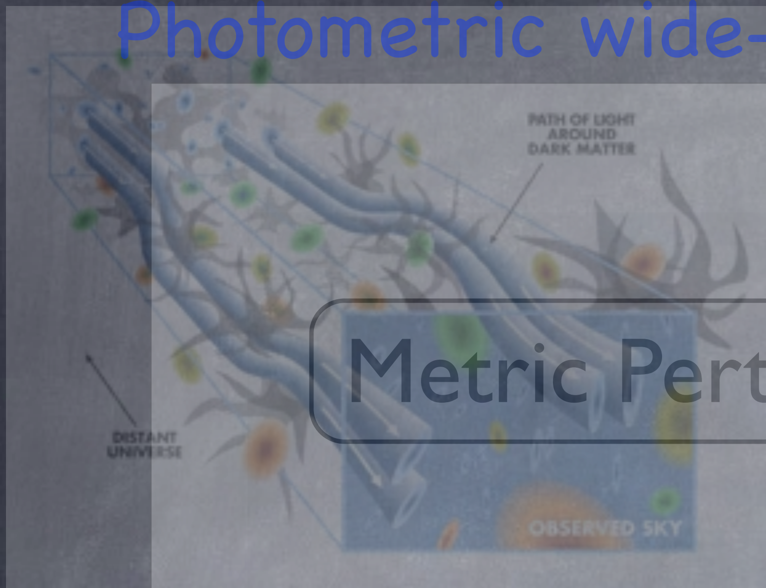


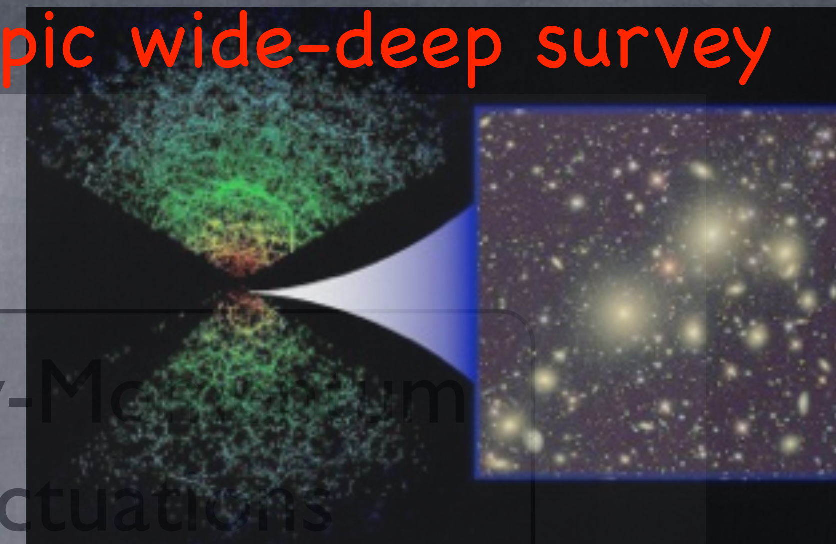
YSS 2006, YSS, Kazuya 2009

Future wide deep field survey

Photometric wide-deep survey

Spectroscopic wide-deep survey



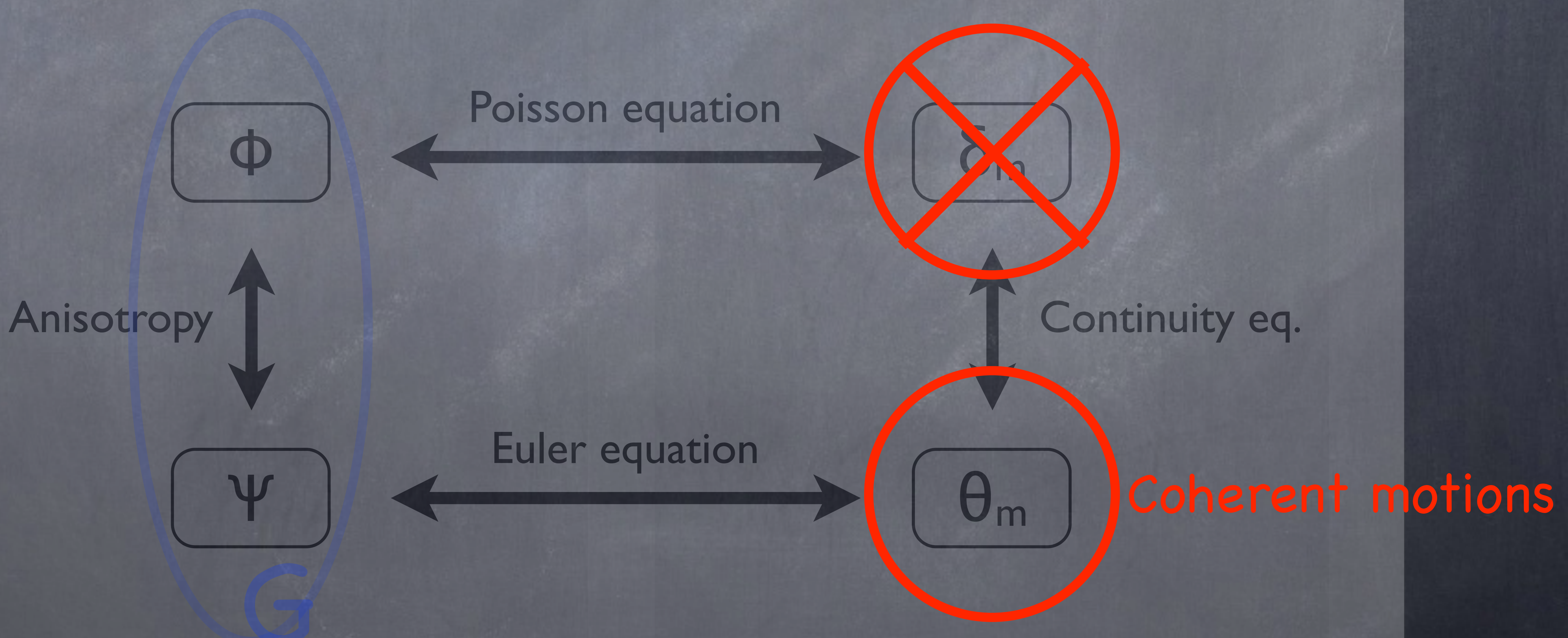


Metric Perturbations

Energy-Momentum Fluctuations

WL measures

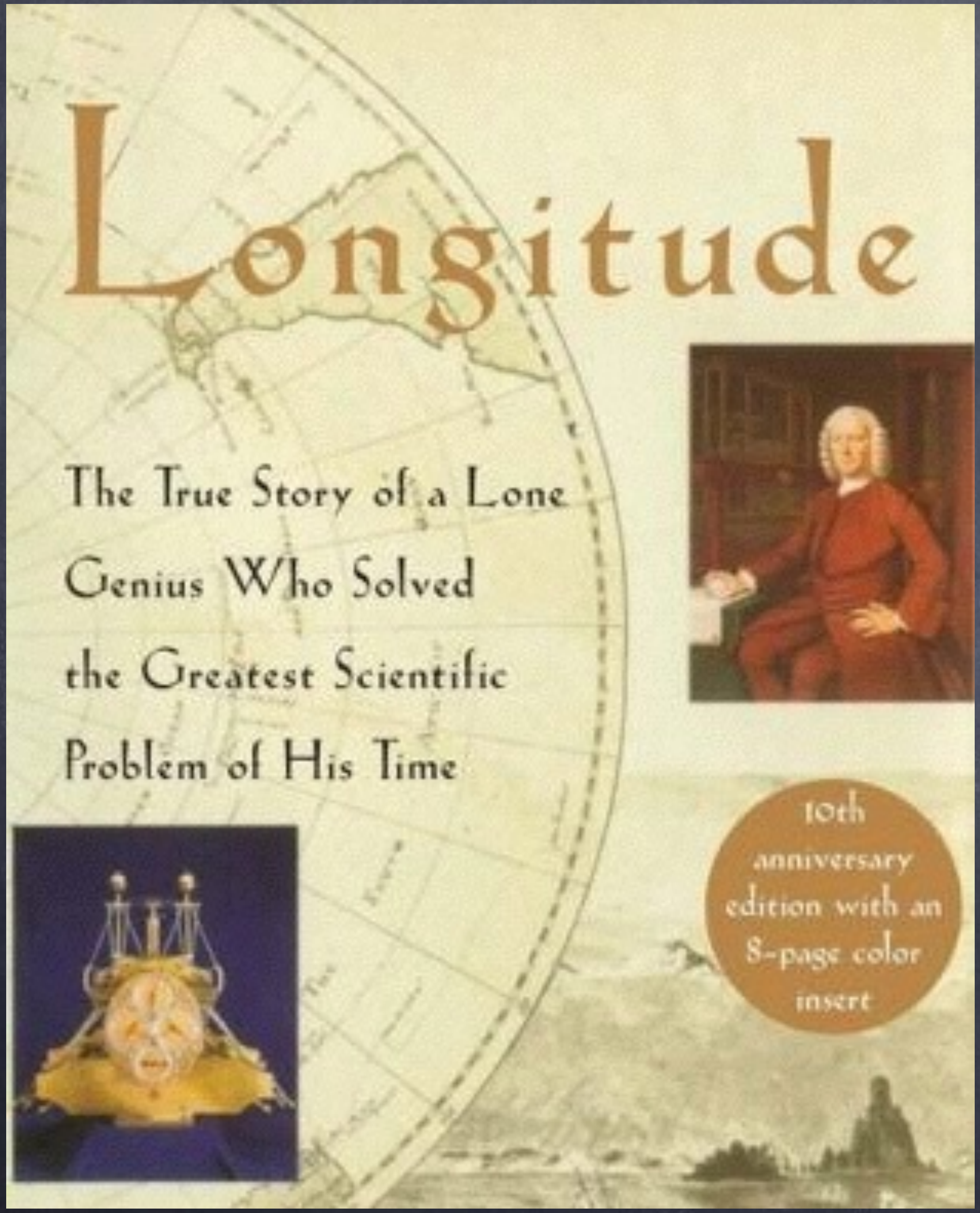
Galaxy-Galaxy correlation

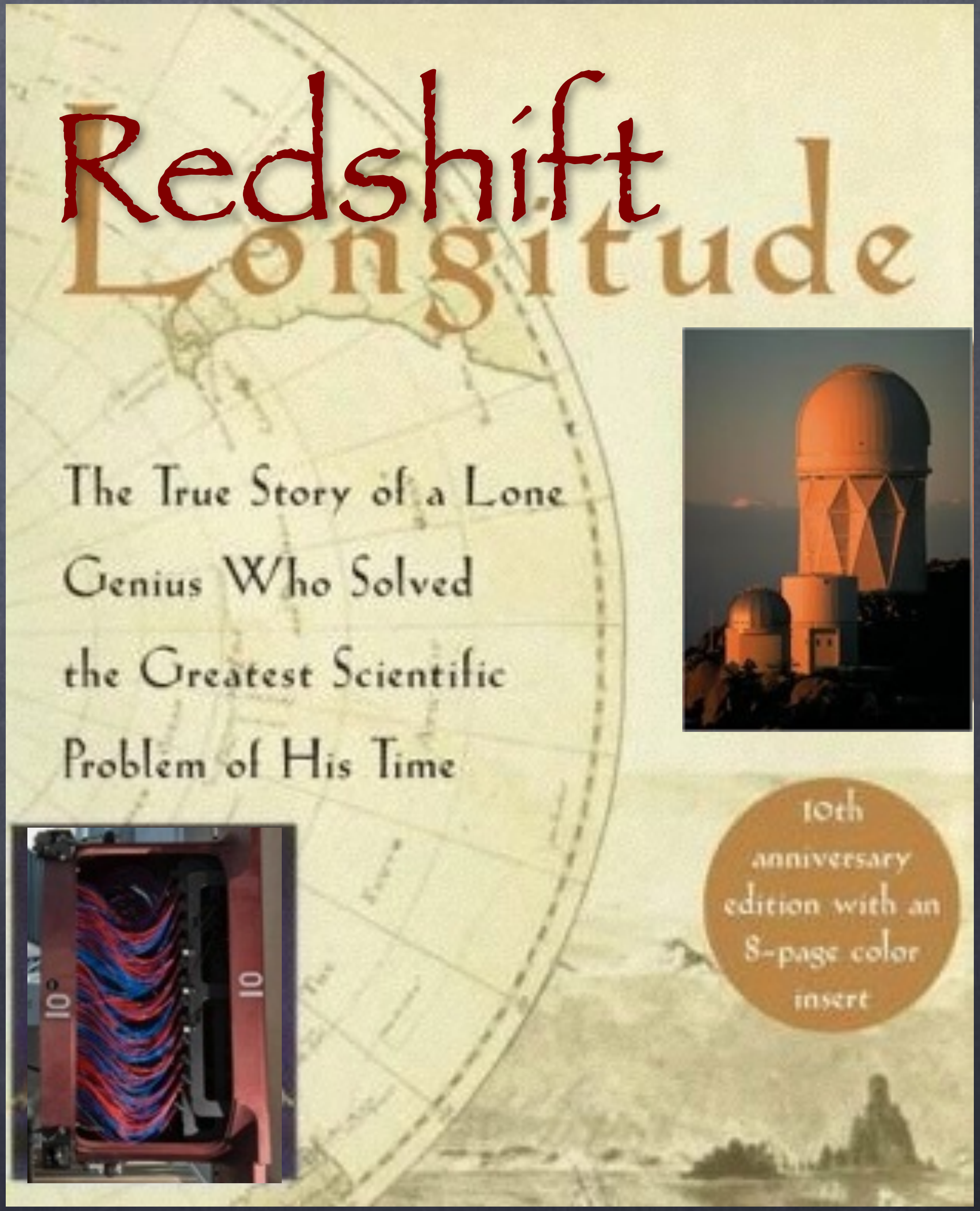


YSS 2006, YSS, Kazuya 2009

Longitude problem in 21st century

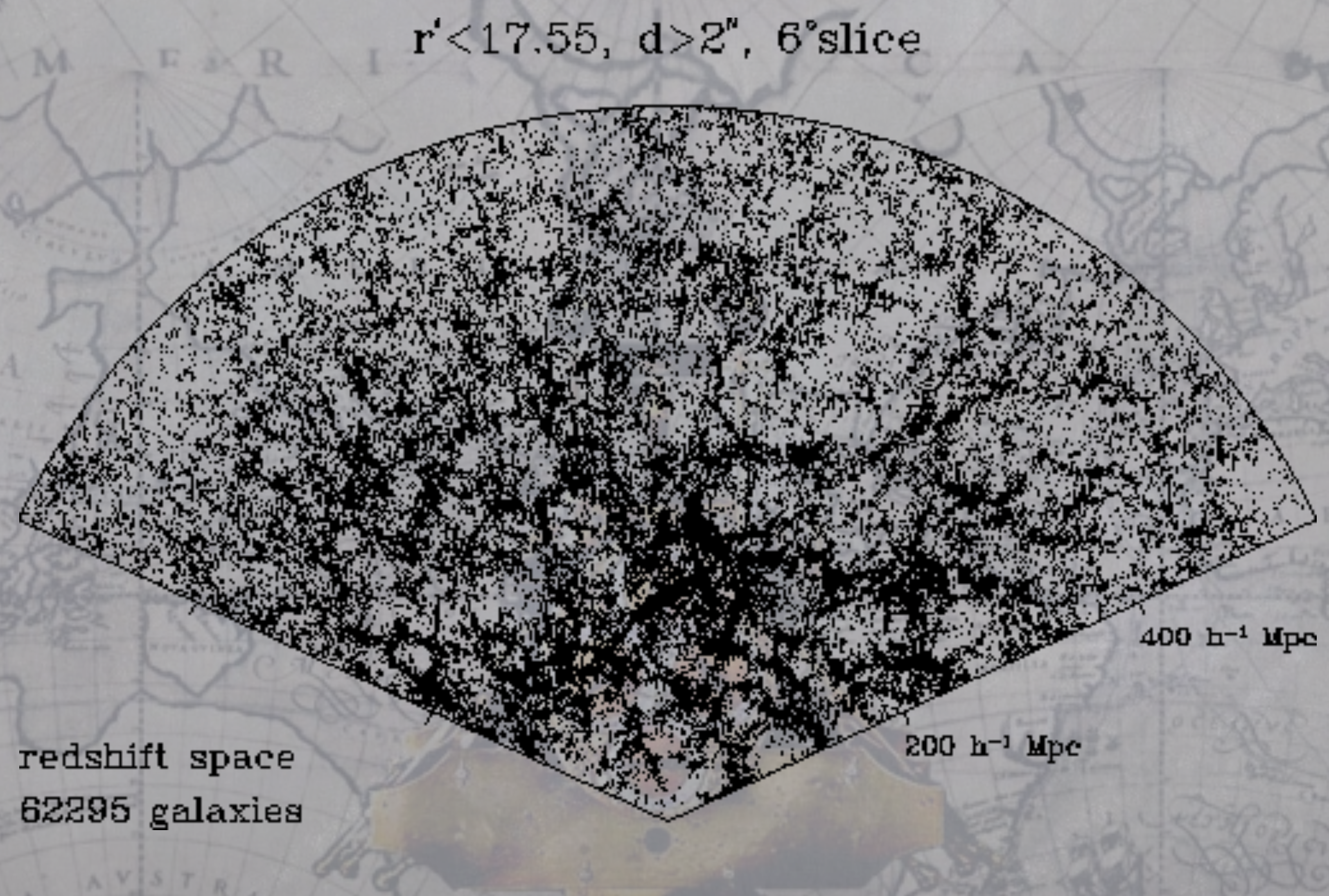
Measuring the redshift of the universe





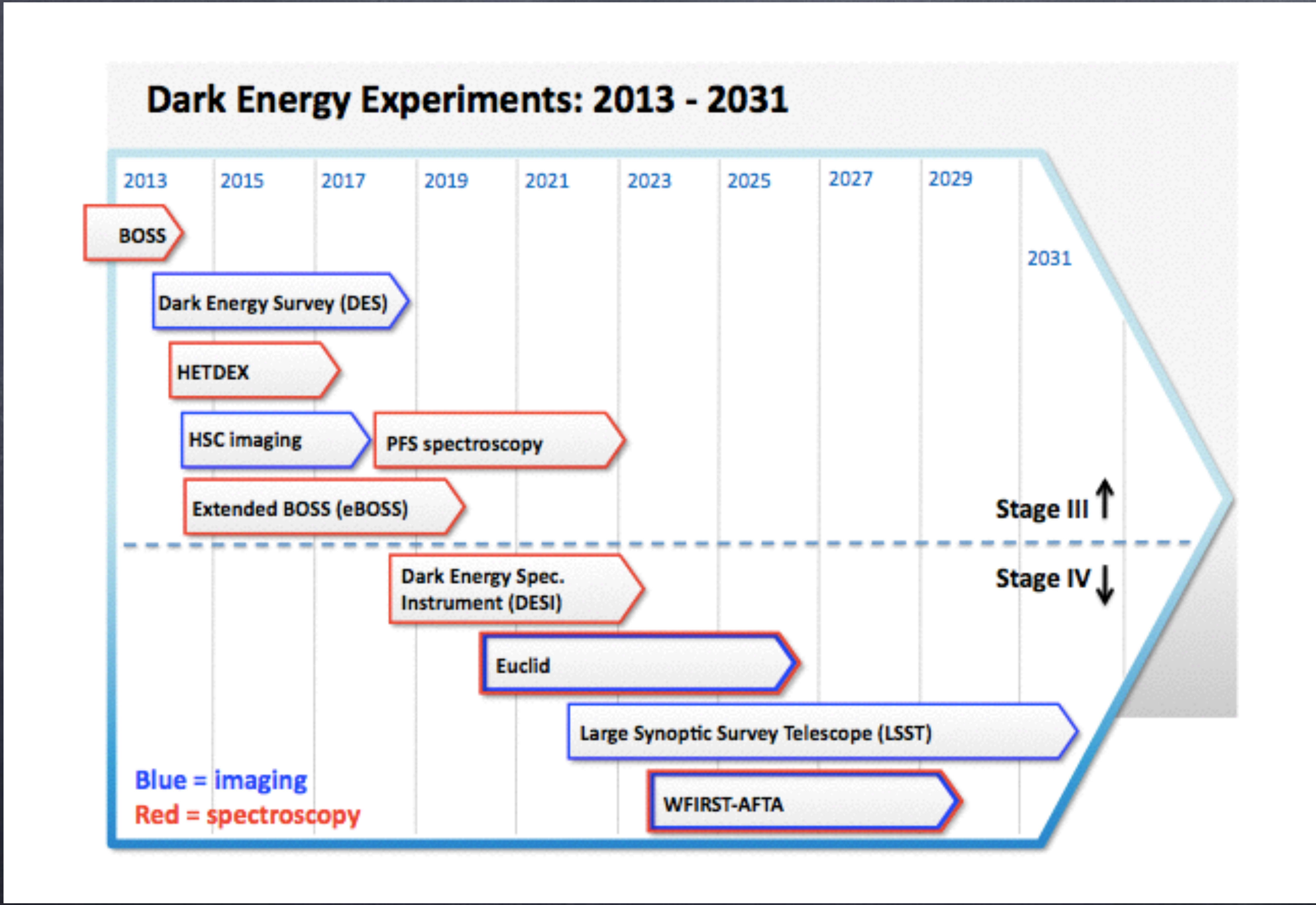
Longitude problem in 21st century

Measuring the redshift of the universe



2dF scanned the first evidence of cosmic web of the universe. New spectroscopy technology allows us to locate the radial distance.

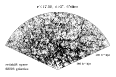
Timetable of present and future generation



DESI: Dark Energy Spectroscopy Instrument

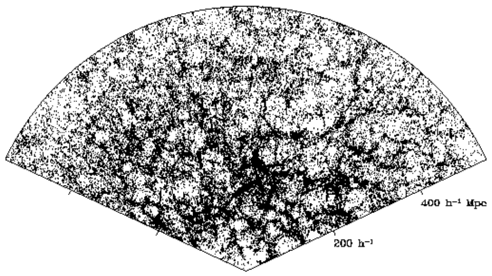
Collaboration started in 2014
First light expected in 2017

Past, Present and Future



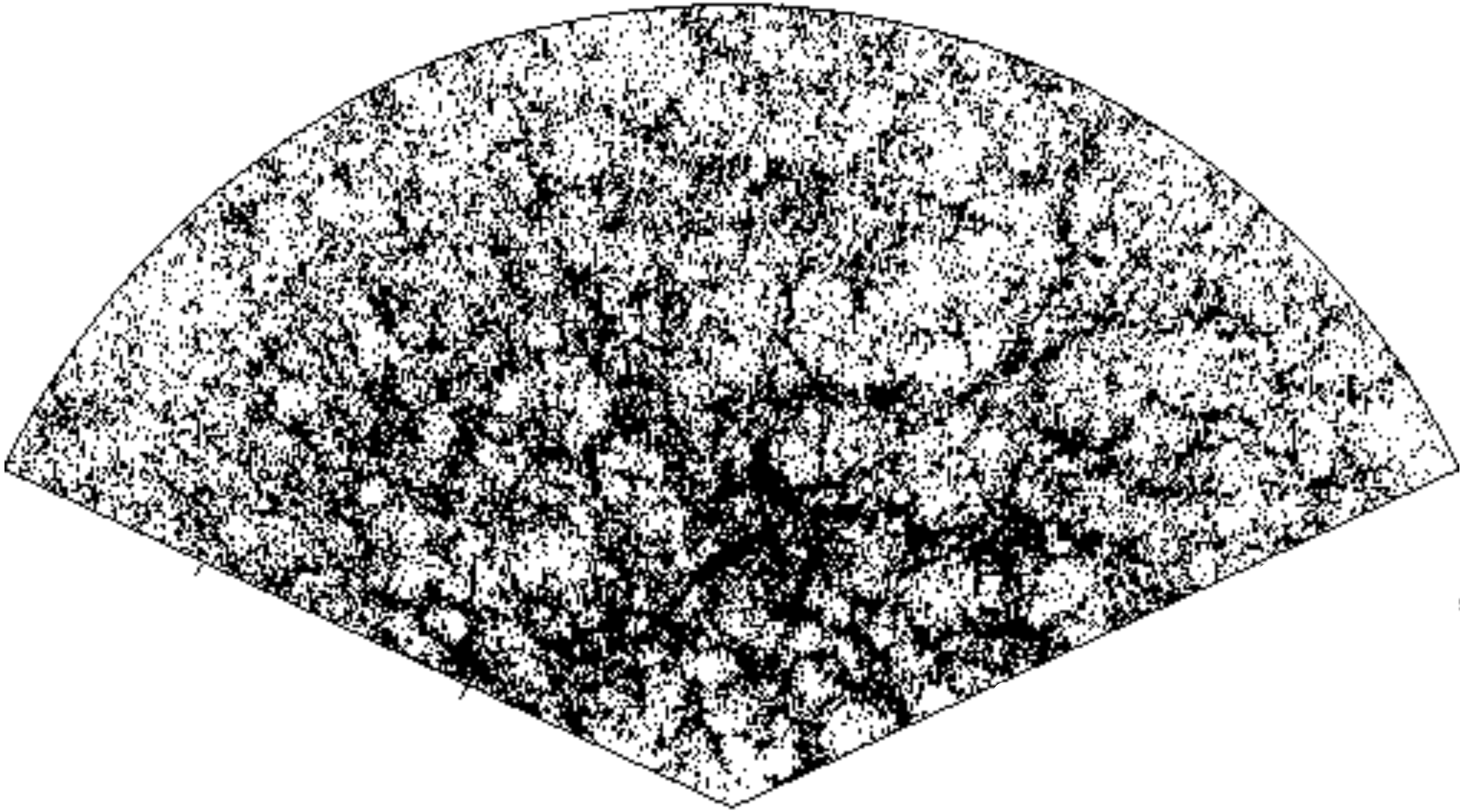
Past, Present and Future

Stage III



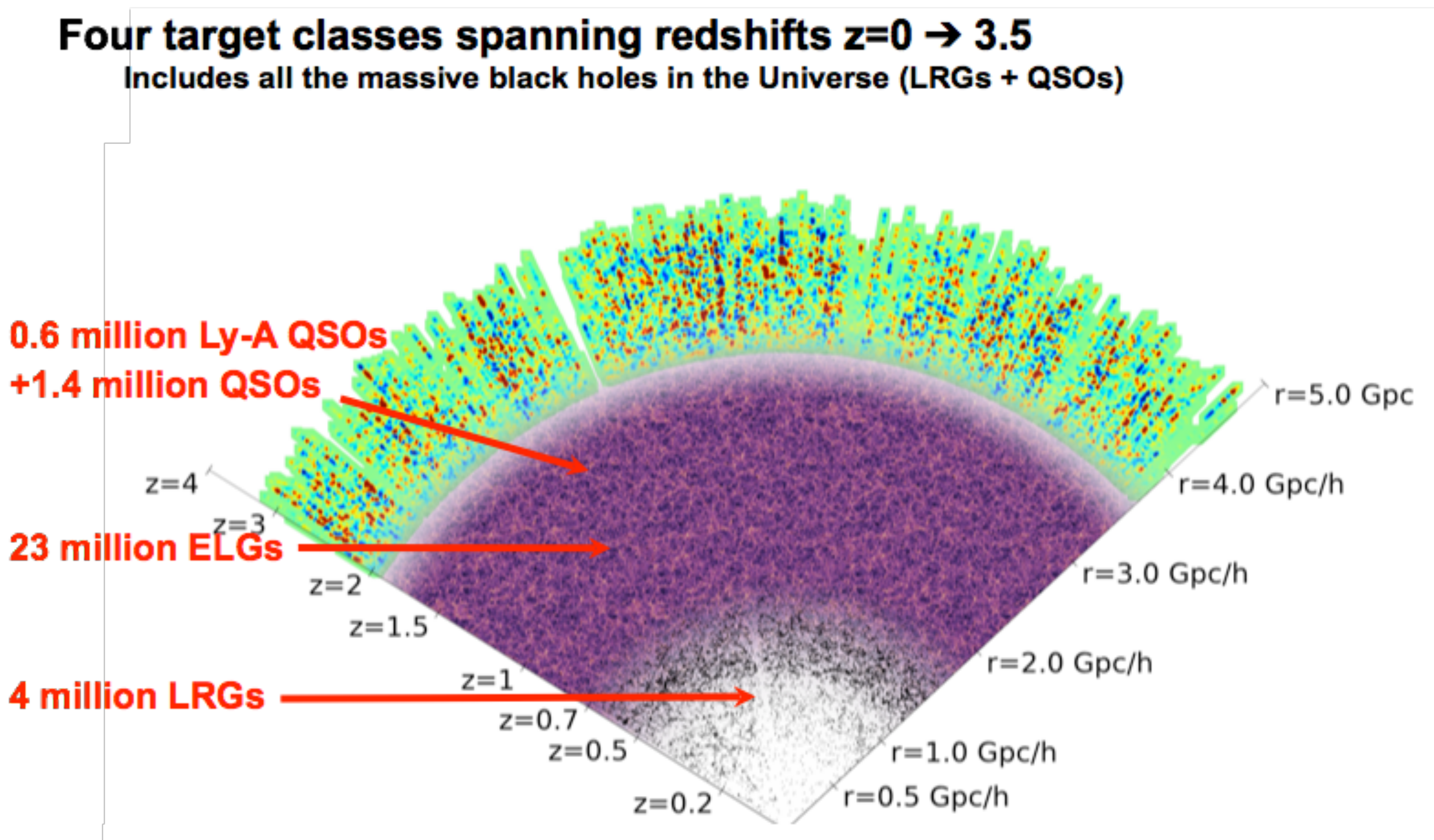
Past, Present and Future

Stage IV

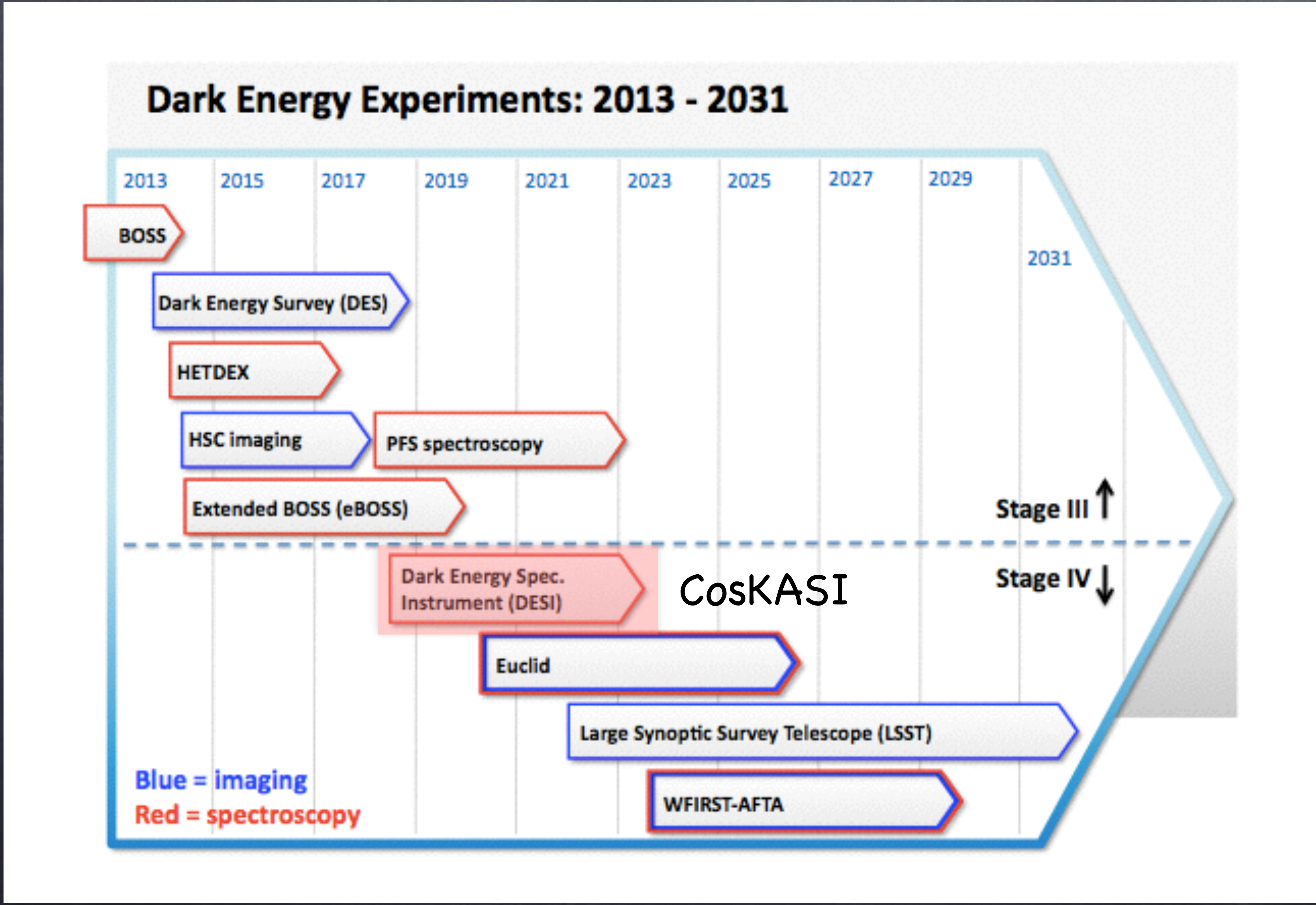


Past, Present and Future

DESI



The participation of CosKASI



Key observables in cosmological science

Angular diameter distance D_A: Exploiting BAO as standard rulers which measure the angular diameter distance and expansion rate as a function of redshift.

Radial distance H^{-1}: Exploiting redshift distortions as intrinsic anisotropy to decompose the radial distance represented by the inverse of Hubble rate as a function of redshift.

Coherent motion G_θ: The coherent motion, or flow, of galaxies can be statistically estimated from their effect on the clustering measurements of large redshift surveys, or through the measurement of redshift space distortions.

Transverse and radial distances

Angular diameter distance D_A: Exploiting BAO as standard rulers which measure the angular diameter distance and expansion rate as a function of redshift.

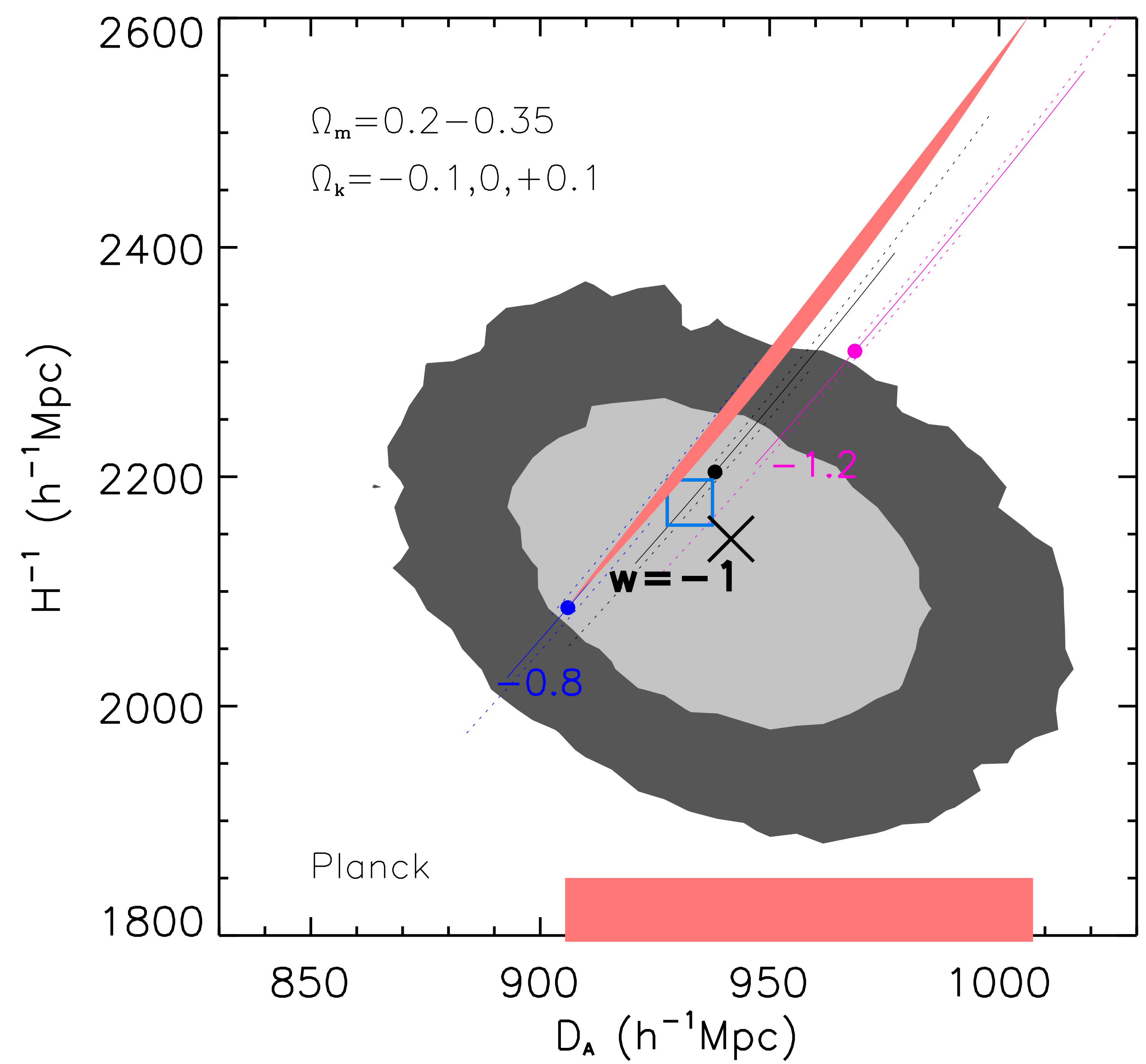
Radial distance H^{-1}: Exploiting redshift distortions as intrinsic anisotropy to decompose the radial distance represented by the inverse of Hubble rate as a function of redshift.

Coherent motion G

can be statistically estimated from their effect on the clustering measurements of large redshift surveys, or through the measurement of redshift space distortions.

Transverse and radial distances

The given theoretical models span the narrow range in the transverse and radial coordinate plane



Transverse and radial distances

Angular diameter distance D_A: Exploiting BAO as standard rulers which measure the angular diameter distance and expansion rate as a function of redshift.

Radial distance H^{-1}: Exploiting redshift distortions as intrinsic anisotropy to decompose the radial distance represented by the inverse of Hubble rate as a function of redshift.

Those are essential observables to test theoretical models explaining cosmic acceleration;

1) ΛCDM universe

2) Dynamical dark energy

Coherent motions

Angular diameter distance D
which measure the angular diameter distance and expansion rate as a function of redshift.

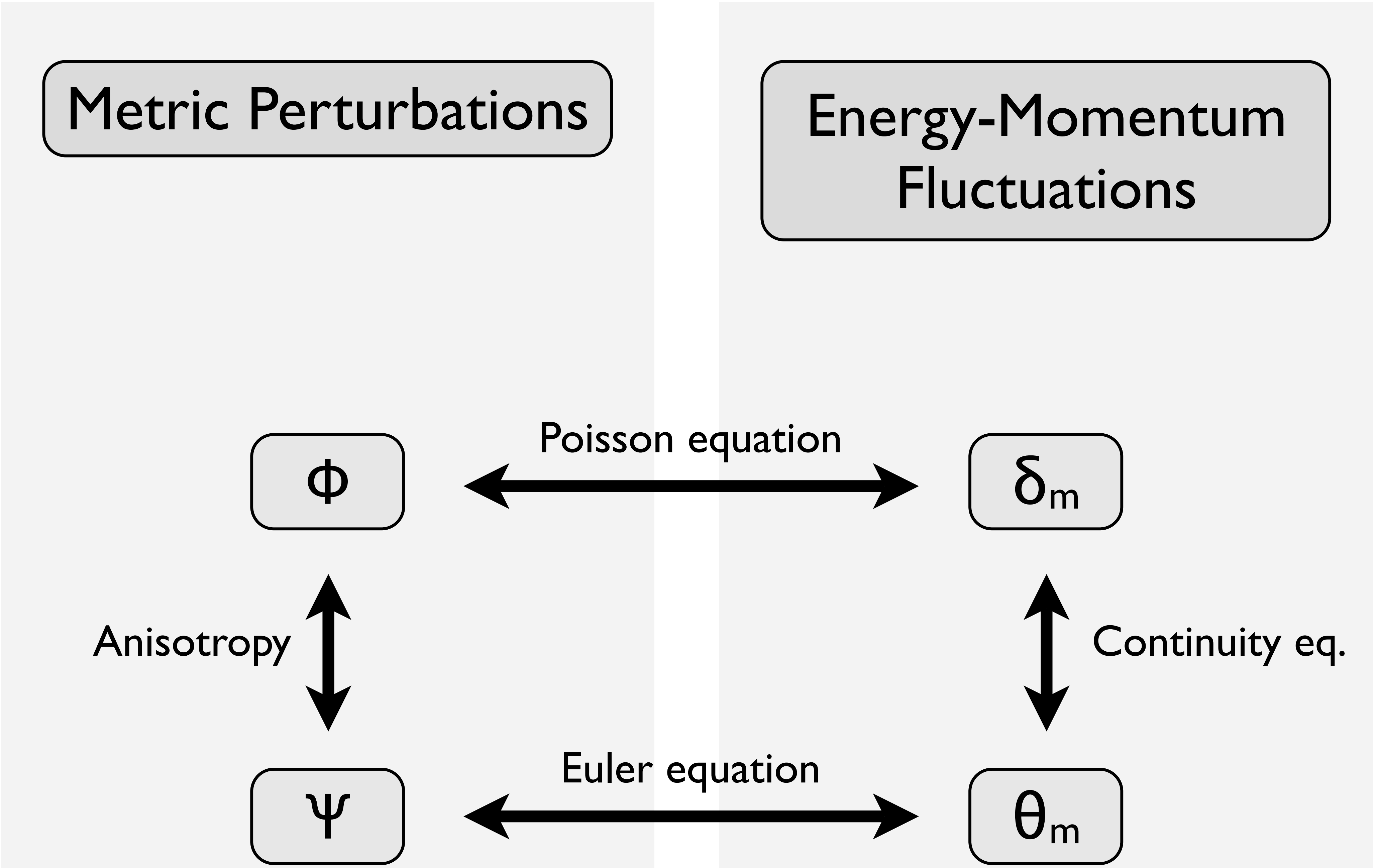
Radial distance H
anisotropy to decompose the radial distance represented by the inverse of Hubble rate as a function of redshift.

Coherent motion G_θ: The coherent motion, or flow, of galaxies can be statistically estimated from their effect on the clustering measurements of large redshift surveys, or through the measurement of redshift space distortions.

Implication of cosmic acceleration

- Breaking down our knowledge of particle physics: we have limited knowledge of particle physics bounded by testable high energy, and our efforts to explain the cosmic acceleration turn out in vain.
    - Alternative mechanism to generate fine tuned vacuum energy
    - New unknown energy component
    - Unification or coupling between dark sectors
- Breaking down our knowledge of gravitational physics: gravitational physics has been tested in solar system scales, and it is yet confirmed at horizon size,
    - Presence of extra dimension
    - Non-linear interaction to Einstein equation
- Failure of standard cosmology model: our understanding of the universe is still standing on assumptions:
    - Inhomogeneous models: LTB, back reaction

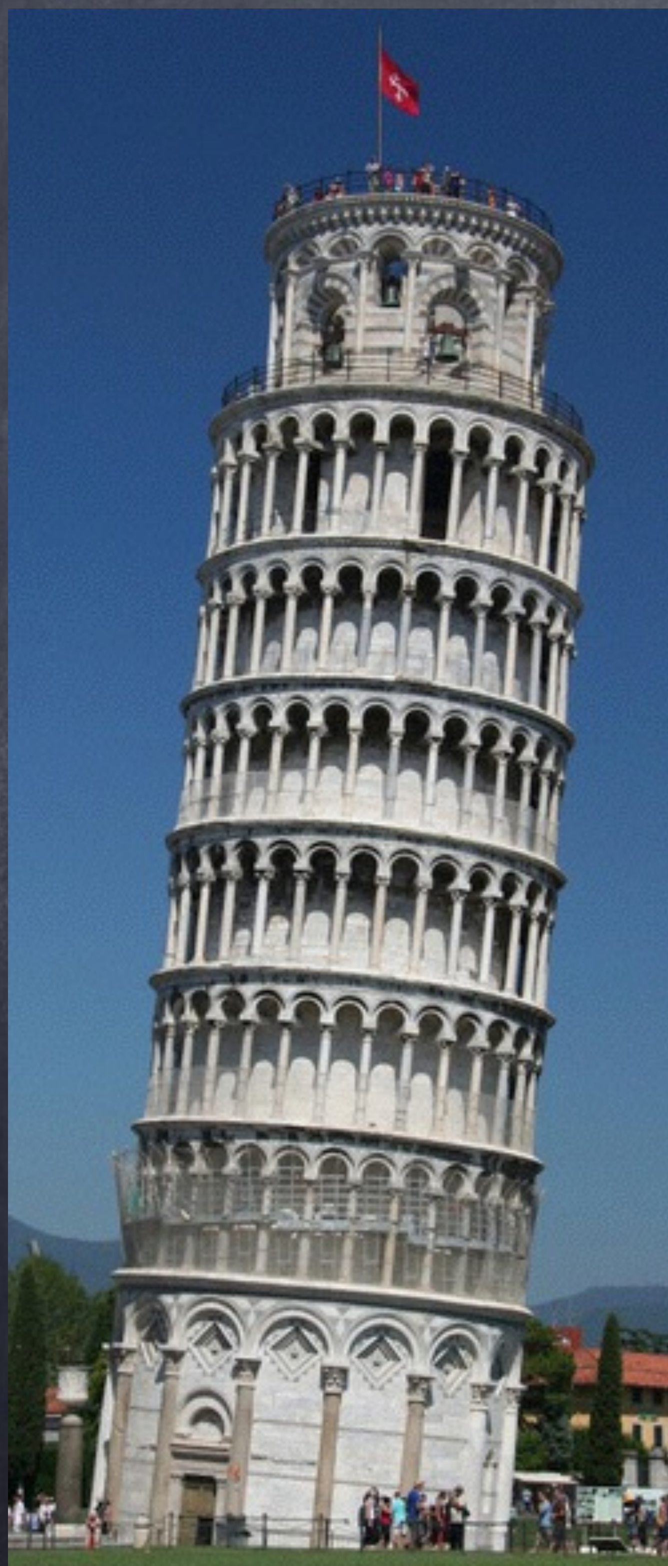
Future wide deep field survey



$$G_{\mu\nu} = 4\pi G_N \, T_{\mu\nu}$$

YSS 2006, YSS, Kazuya 2009

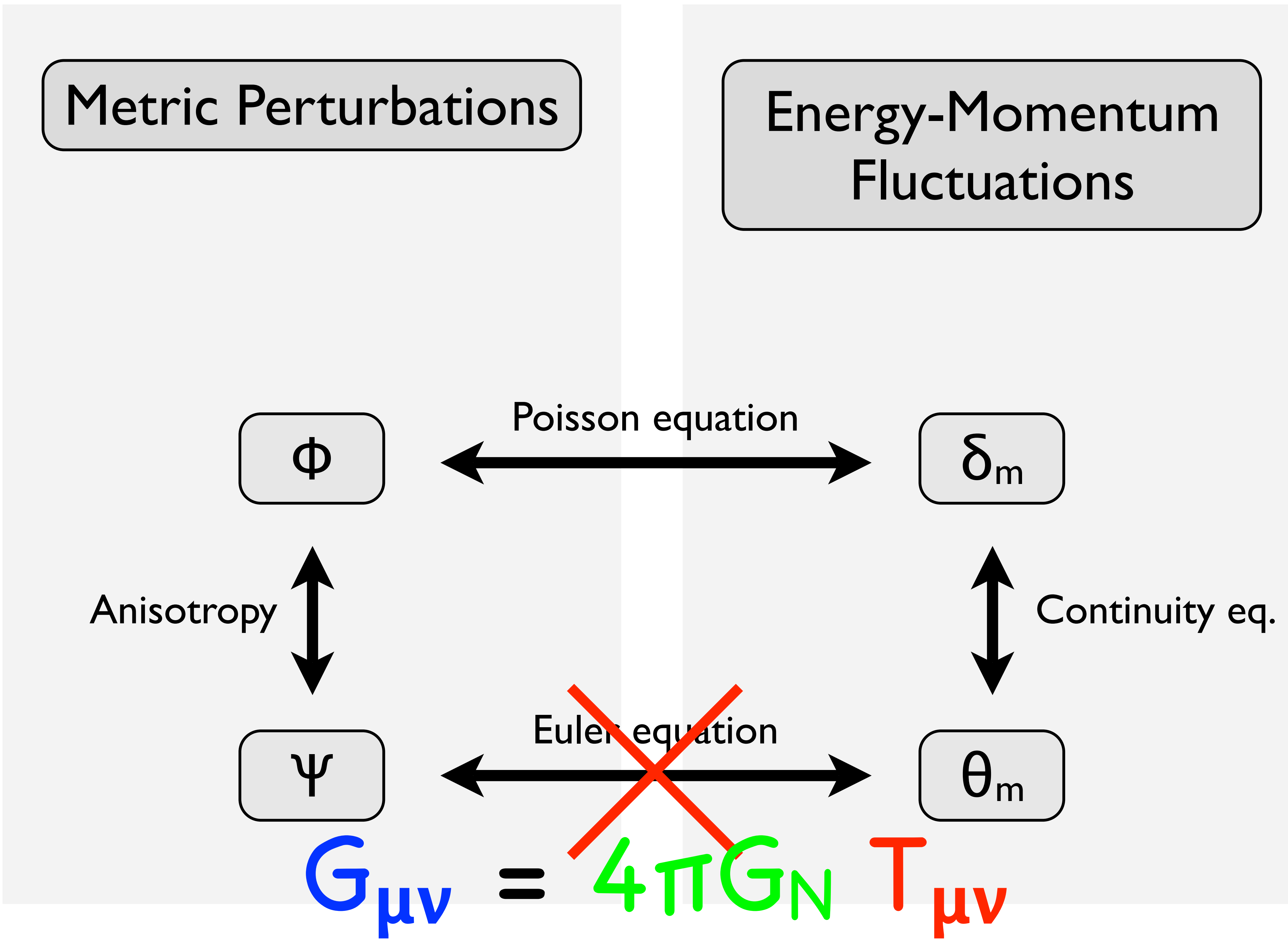
Coupling between dark sectors



$$Q_c^\mu = -\alpha \rho_c \nabla^\mu \varphi \,,$$

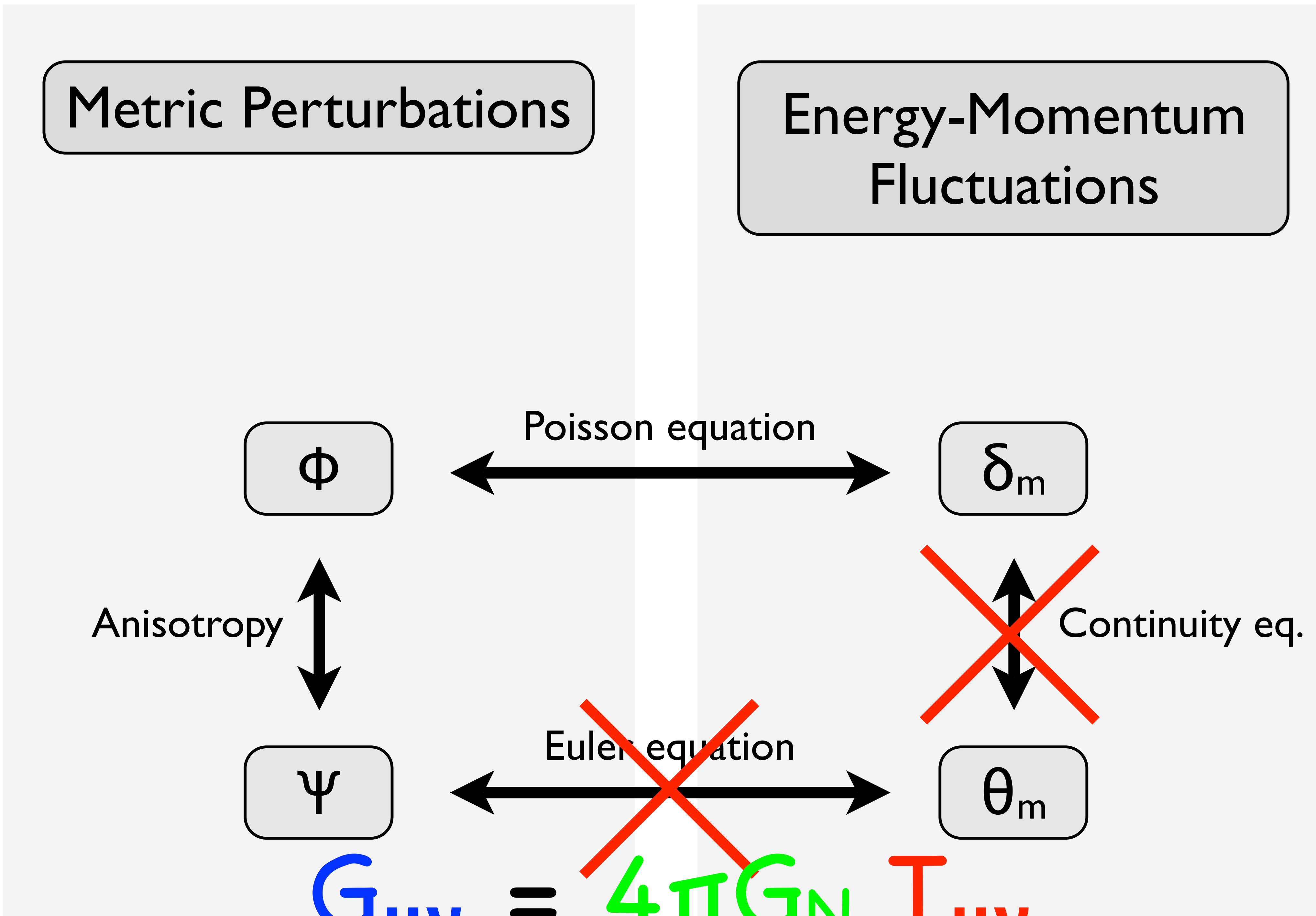
If the coupling term is proportional to scalar field, then Euler equation is broken, i.e. the universality of free falling between baryon and dark matter is violated.

Future wide deep field survey



YSS 2006, YSS, Kazuya 2009

Future wide deep field survey



$$G_{\mu\nu} = 4\pi G_N T_{\mu\nu}$$

YSS 2006, YSS, Kazuya 2009

Brane world model (DGP)

In DGP, gravity alone propagates in the bulk, and 5D gravitational theory is complemented by an induced 4D Ricci scalar restricted to the brane.

$$S=\int d^5x\sqrt{-g}\left[R^{(5)}/2\mu^{(5)}+\delta(\varkappa)\left(R^{(4)}/2\mu^{(4)}+L_M\right)\right]$$

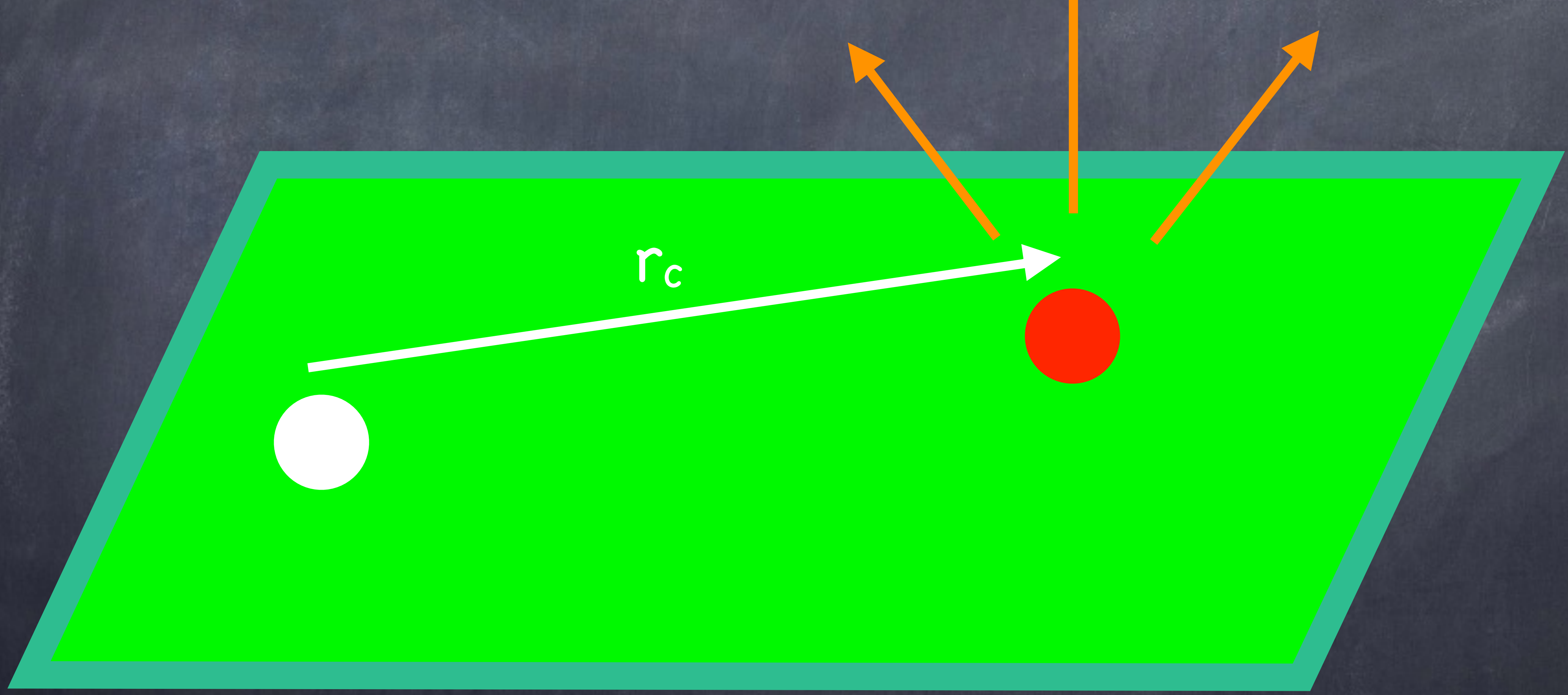
The ratio of the two scales defines a cross-over radius beyond which the four dimensional gravitational theory transition into a five dimensional regime,

$$r_c = \mu^{(5)}/2\mu^{(4)}$$

Dvali, Gabadadze, Porrati (2000)

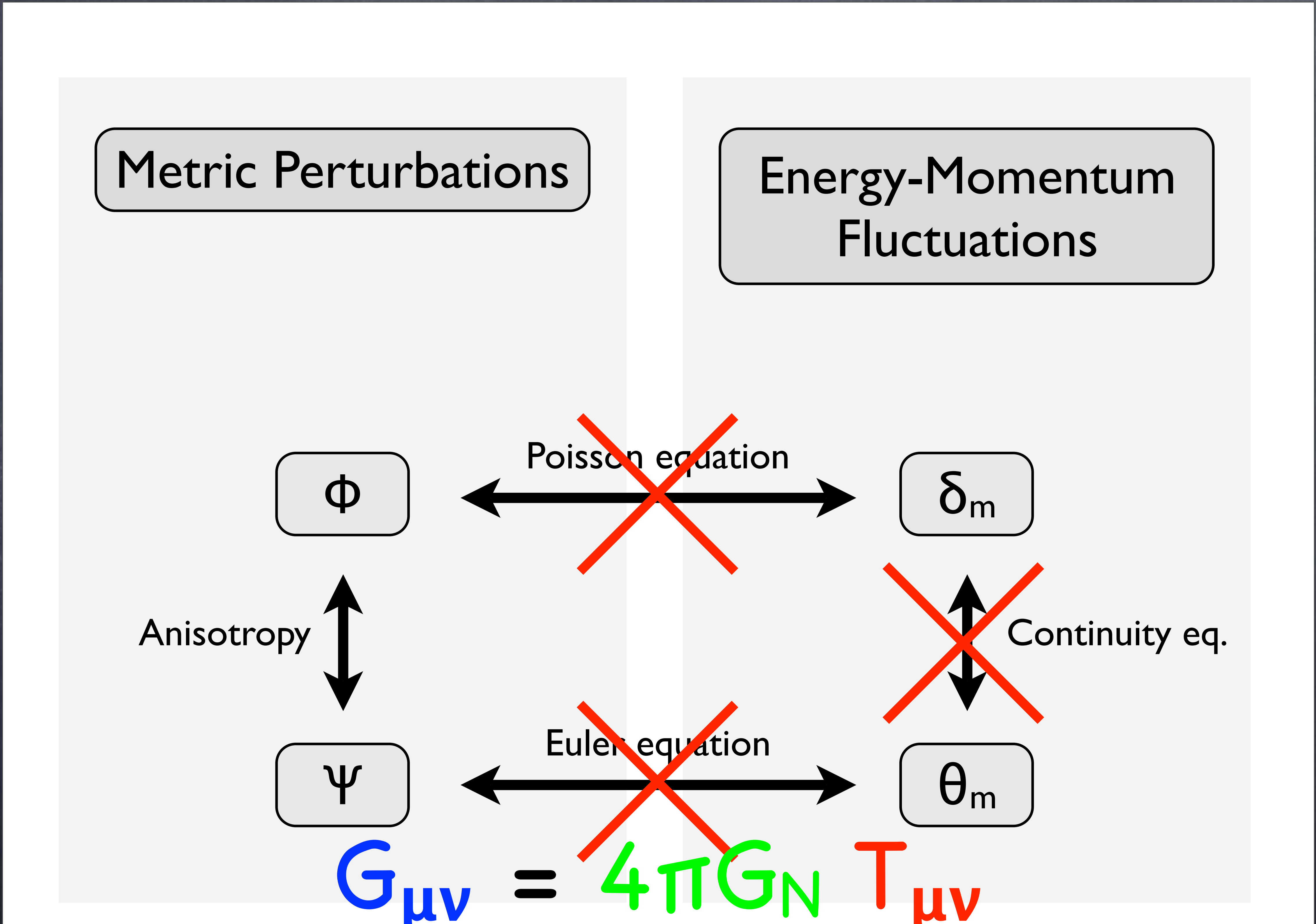
Brane world model (DGP)

Sound wave propagate through air (leaving) table, and system on the table loses energy at $r>r_c$.



Although balls do not leave, energy loss due to leaking sound wane above table.

Future wide deep field survey



YSS 2006, YSS, Kazuya 2009

f(R) gravity

Corrections are introduced in the Einstein-Hilbert Lagrangian to modify the general relativity, which gets influential only low curvature, e.g. late time & not dense region. The corrections can be adjusted to generate the cosmic acceleration, Carroll, Duvvuri, Trodden, Turner (2004:CDTT)

$$S = \int d^4x \sqrt{-g}\left[\frac{R + f(R)}{2\mu^2} + \mathcal{L}_{\rm m}\right]$$

cosmic acceleration was discovered with $f(R) = -a/R$. Ruled out

Two distinct branches of f(R) gravity was found depending on the sign of second order derivative of f(R) in terms of R,

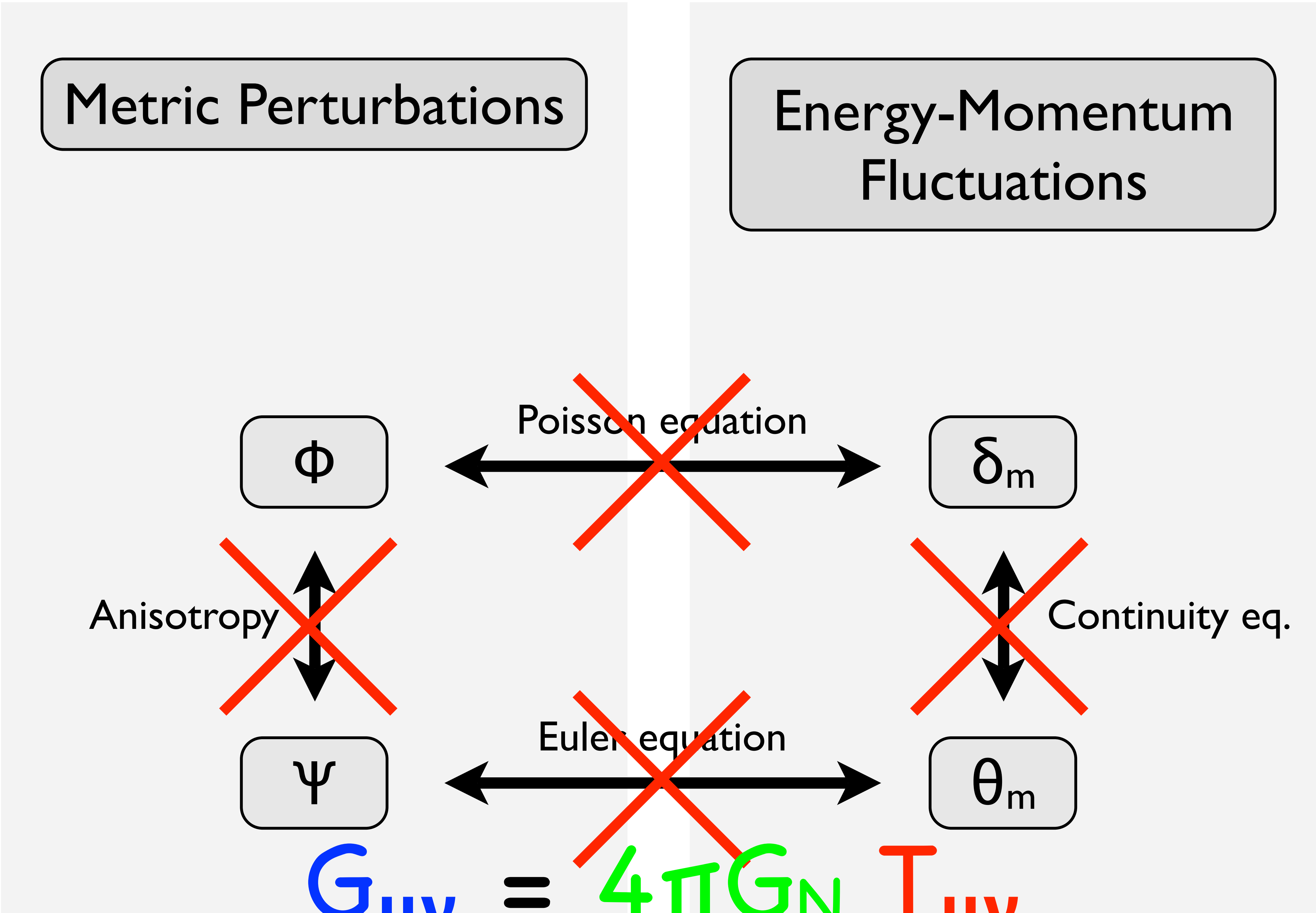
$f_{RR} = d^2f/dR^2 < 0$ Unstable

$f_{RR} = d^2f/dR^2 > 0$ Stable

The original proposal of CDTT is ruled out due to instability.

YSS, Hu, Sawicki (2007)

Future wide deep field survey



$$G_{\mu\nu} = 4\pi G_N T_{\mu\nu}$$

YSS 2006, YSS, Kazuya 2009

Investigation using Brans-Dicke models

Dynamic equations of perturbations of Brans-Dicke models

$$d\delta_m/dt + \theta_m/a = 0$$

$$d\theta_m/dt + H\theta_m = k^2\psi/a$$

$$k^2\Phi = 3/2\, H_0^2\Omega_m\, \delta_m/a + k^2\varphi$$

$$\Phi + \psi = \varphi$$

$$(1+3\omega_{BD})\, k^2\varphi\omega = -3H_0^2\Omega_m\, \delta_m/a - M^2\varphi$$

The large distance modification of gravitation, which is necessary to explain cosmic acceleration, generally modifies gravity even on sub-horizon scales due to the new scalar degree of freedom. This modification of gravity due to scalar mode is described by Brans-Dicke (BD) models.

YSS, Hollenstein, Cabral, Koyama (2011)

Investigation using Brans-Dicke models

Dynamic equations of perturbations of Brans-Dicke models

$$d\delta_m/dt + \theta_m/a = 0$$

$$d\theta_m/dt + H\theta_m = k^2\psi/a$$

$$k^2\Phi = 3/2\, H_0{}^2\Omega_m\, \delta_m/a + k^2\varphi$$

$$\Phi + \psi = \varphi$$

$$(1+3\omega_{BD})\, k^2\varphi\omega = -3H_0{}^2\Omega_m\, \delta_m/a - M^2\varphi$$

Correspondence to DGP at quasi-static scales;

$$\omega_{BD} = 3/2\,(\beta-1),\ M=0$$

Correspondence to f(R) gravity at quasi-static scales;

$$\omega_{BD} = 0$$

YSS, Hollenstein, Cabral, Koyama (2011)

Investigation using Brans-Dicke models

Dynamic equations of perturbations of Brans-Dicke models

$$d\delta_m/dt + \theta_m/a = 0$$

$$d\theta_m/dt + H\theta_m = k^2\psi/a$$

$$k^2\Phi = 3/2\, H_0^2\Omega_m\, \delta_m/a + k^2\varphi$$

$$\Phi + \psi = \varphi$$

$$(1+3\omega_{BD})\, k^2\varphi\omega = -3H_0^2\Omega_m\, \delta_m/a - M^2\varphi$$

If we impose coherent growth function condition (M=0), then

No modification on photon trajectory;

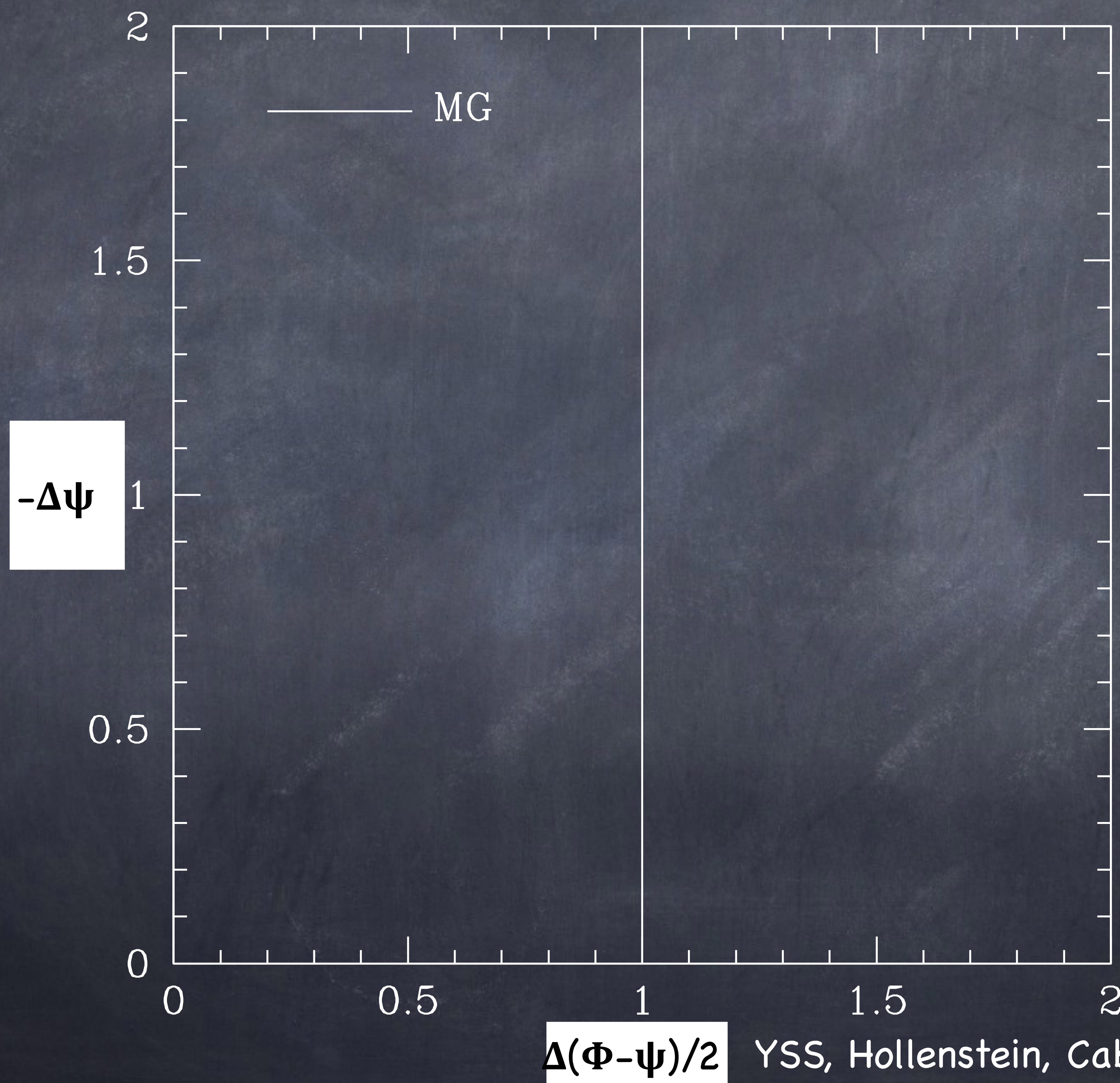
$$\Phi_{MG} - \psi_{MG} = \Phi_{GR} - \psi_{GR}$$

Modification on Newtonian force depending on sign of $3+2\omega_{BD}$

$$\psi_{MG} = \psi_{GR}\,\frac{2(1+\omega_{BD})}{3+2\omega_{BD}}$$

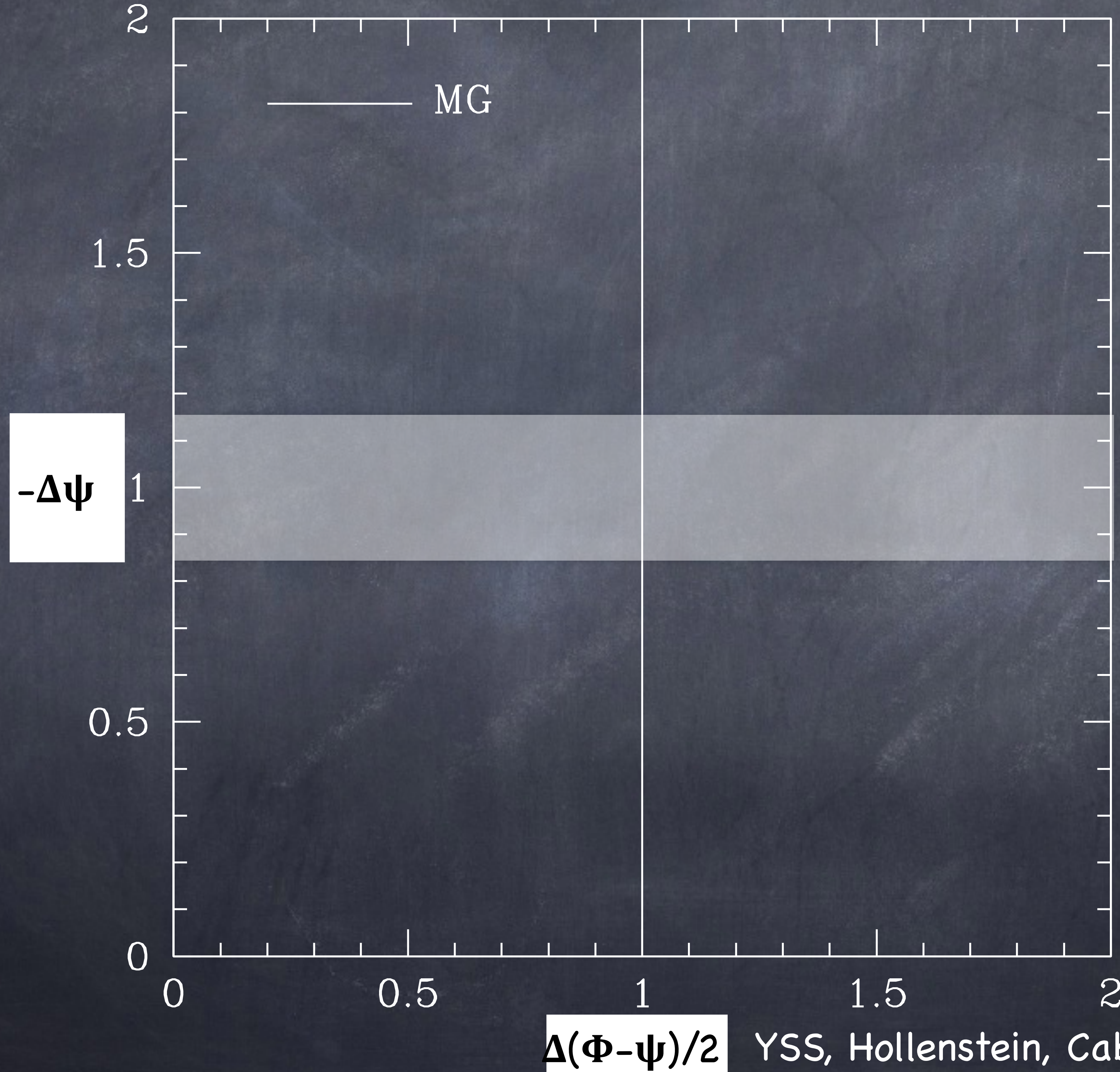
YSS, Hollenstein, Cabral, Koyama (2011)

Degrees of freedom of departure



YSS, Hollenstein, Cabral, Koyama (2011)

Degrees of freedom of departure



YSS, Hollenstein, Cabral, Koyama (2011)

Coherent motions

Angular diameter distance D

which measure the angular diameter distance and expansion rate as a function of redshift.

Radial distance H

anisotropy to decompose the radial distance represented by the inverse of Hubble rate as a function of redshift.

Measured coherent motions help us to test Einstein's gravity at cosmological scale

Coherent motion G_θ: The coherent motion, or flow, of galaxies can be statistically estimated from their effect on the clustering measurements of large redshift surveys, or through the measurement of redshift space distortions.

Targets using redshift distortions

Angular diameter distance D_A: Exploiting BAO as standard rulers which measure the angular diameter distance and expansion rate as a function of redshift.

Radial distance H^{-1}: Exploiting redshift distortions as intrinsic anisotropy to decompose the radial distance represented by the inverse of Hubble rate as a function of redshift.

Coherent motion G_θ: The coherent motion, or flow, of galaxies can be statistically estimated from their effect on the clustering measurements of large redshift surveys, or through the measurement of redshift space distortions.

Targets using redshift distortions

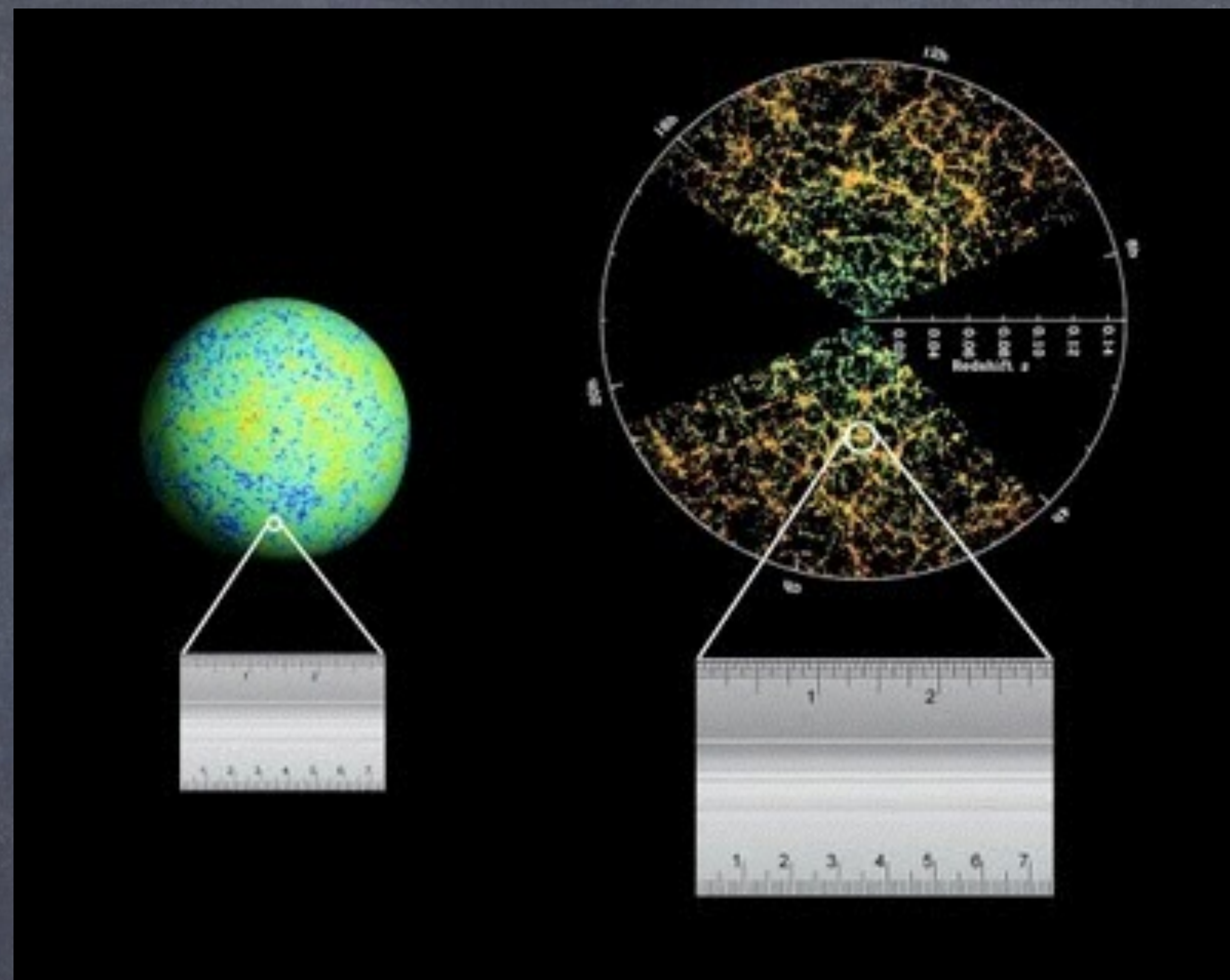
Angular diameter distance D_A: Exploiting BAO as standard rulers which measure the angular diameter distance and expansion rate as a function of redshift.

Radial distance H^{-1}: Exploiting redshift distortions as intrinsic anisotropy to decompose the radial distance represented by the inverse of Hubble rate as a function of redshift.

Coherent motion G

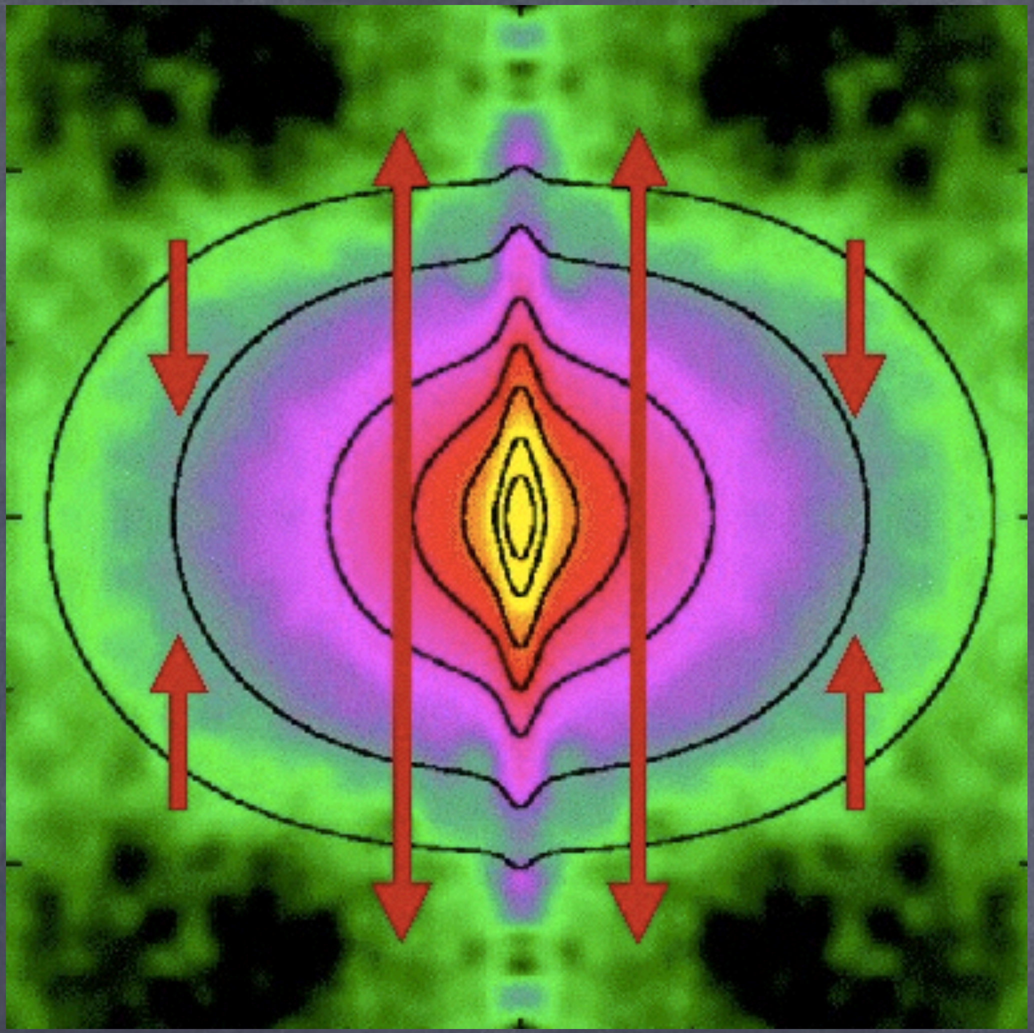
can be statistically estimated from their effect on the clustering measurements of large redshift surveys, or through the measurement of redshift space distortions.

Measurements using large scale structure



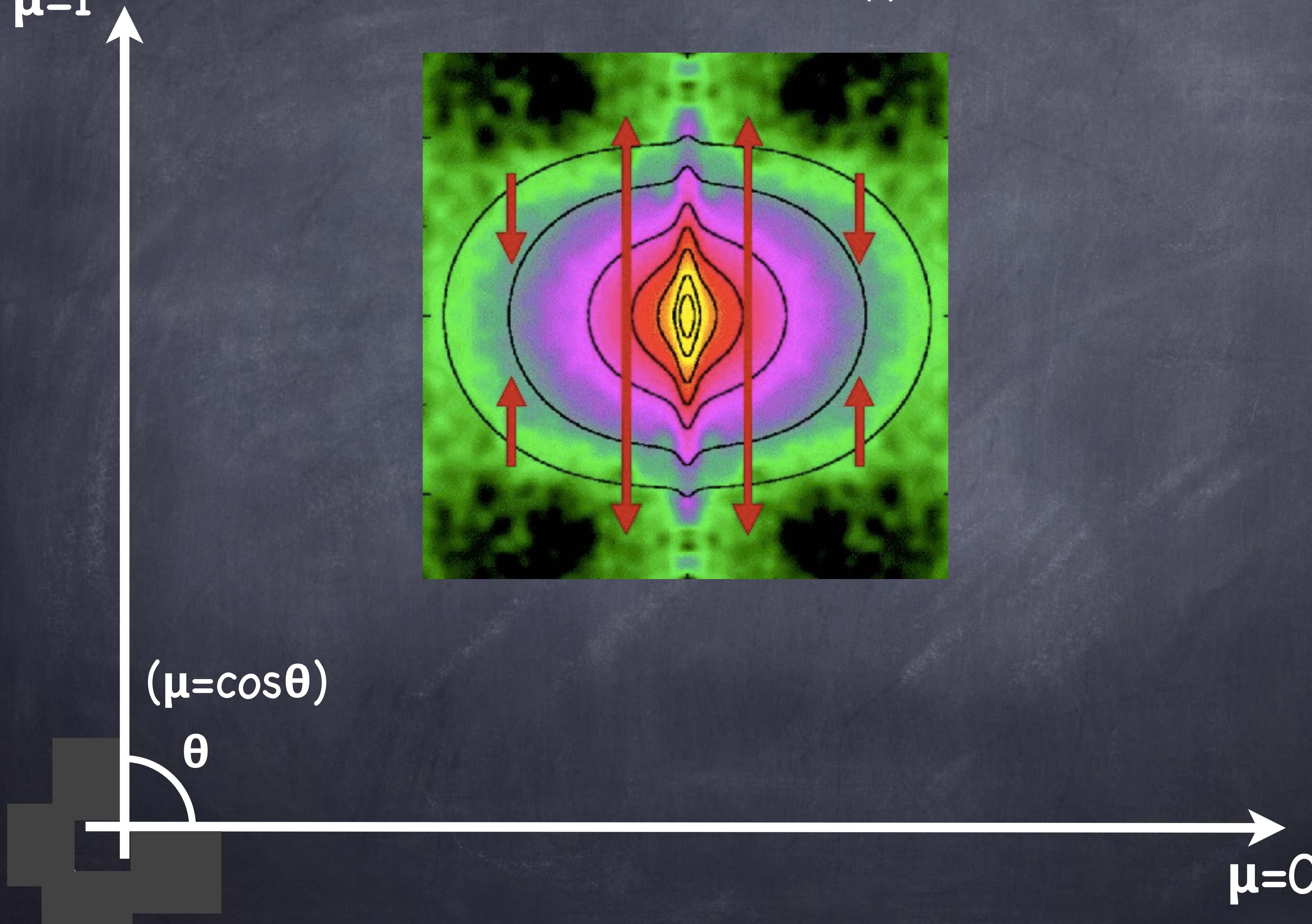
The full history of cosmic expansion can be reconstructed using galaxy redshift surveys. An anisotropy arises because of galaxy recession velocities include components from both the Hubble flow and peculiar velocities, which allows constraints to be placed on the rate of clustering growth and Hubble flow.

Measurements using large scale structure

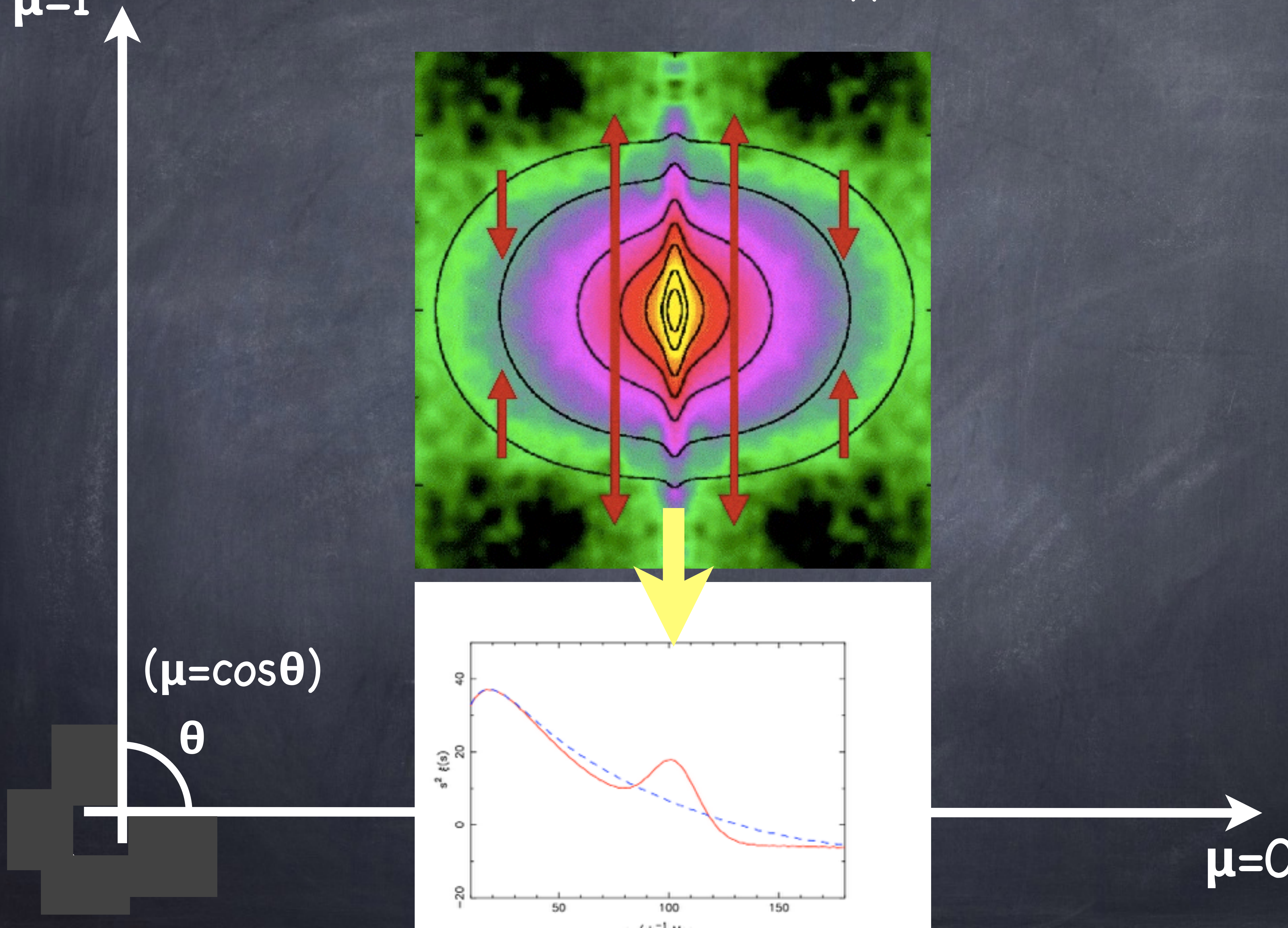


The full history of cosmic expansion can be reconstructed using galaxy redshift surveys. An anisotropy arises because of galaxy recession velocities include components from both the Hubble flow and peculiar velocities, which allows constraints to be placed on the rate of clustering growth and Hubble flow.

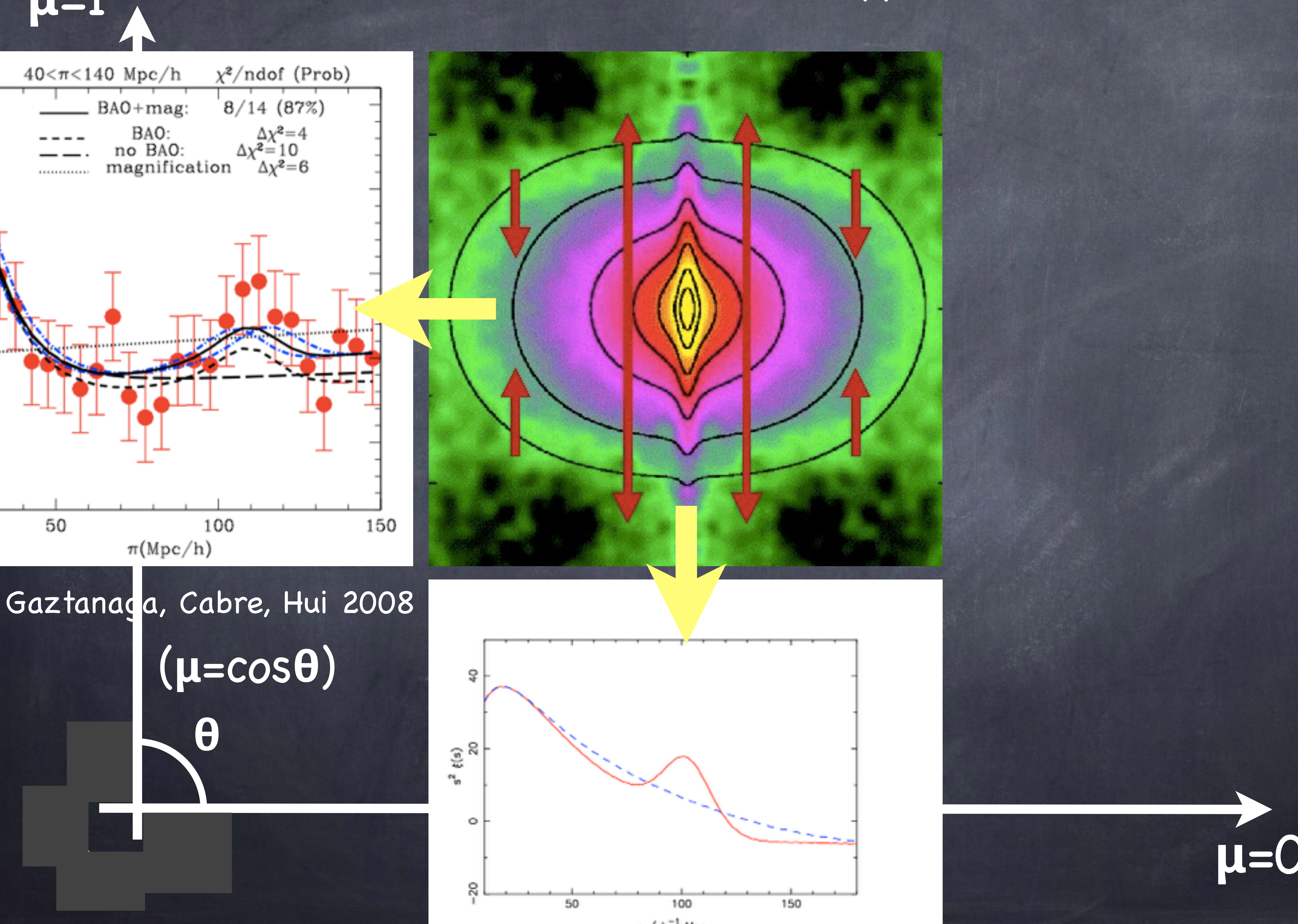
Standard rulers of D_A and H^{-1}



Standard rulers of D_A and H^{-1}

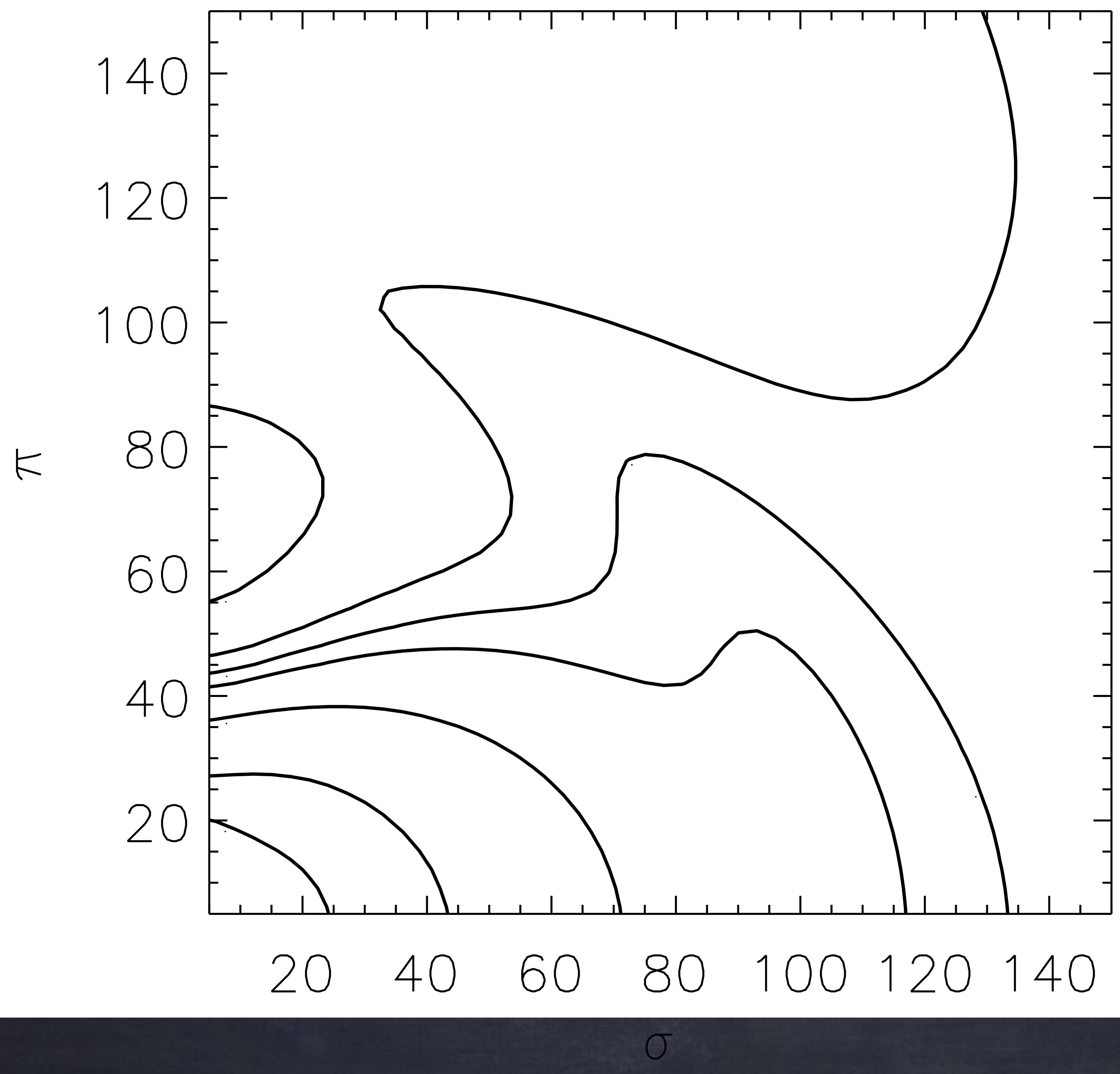


Standard rulers of D_A and H^{-1}



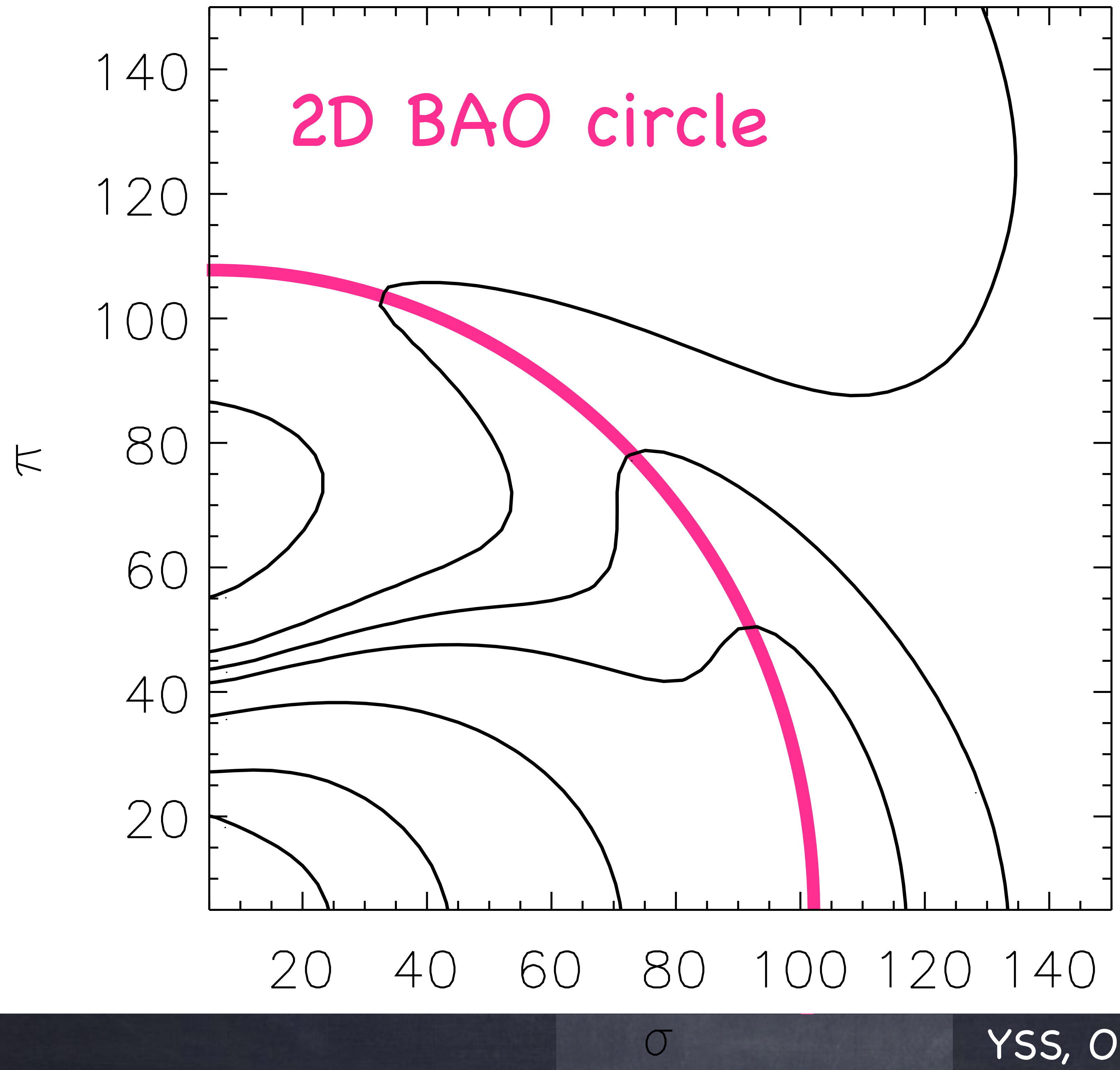
Gaztanaga, Cabre, Hui 2008

Alcock-Paczynski test using ξ(σ,π)



Alcock-Paczynski test using $\xi(\sigma,\pi)$

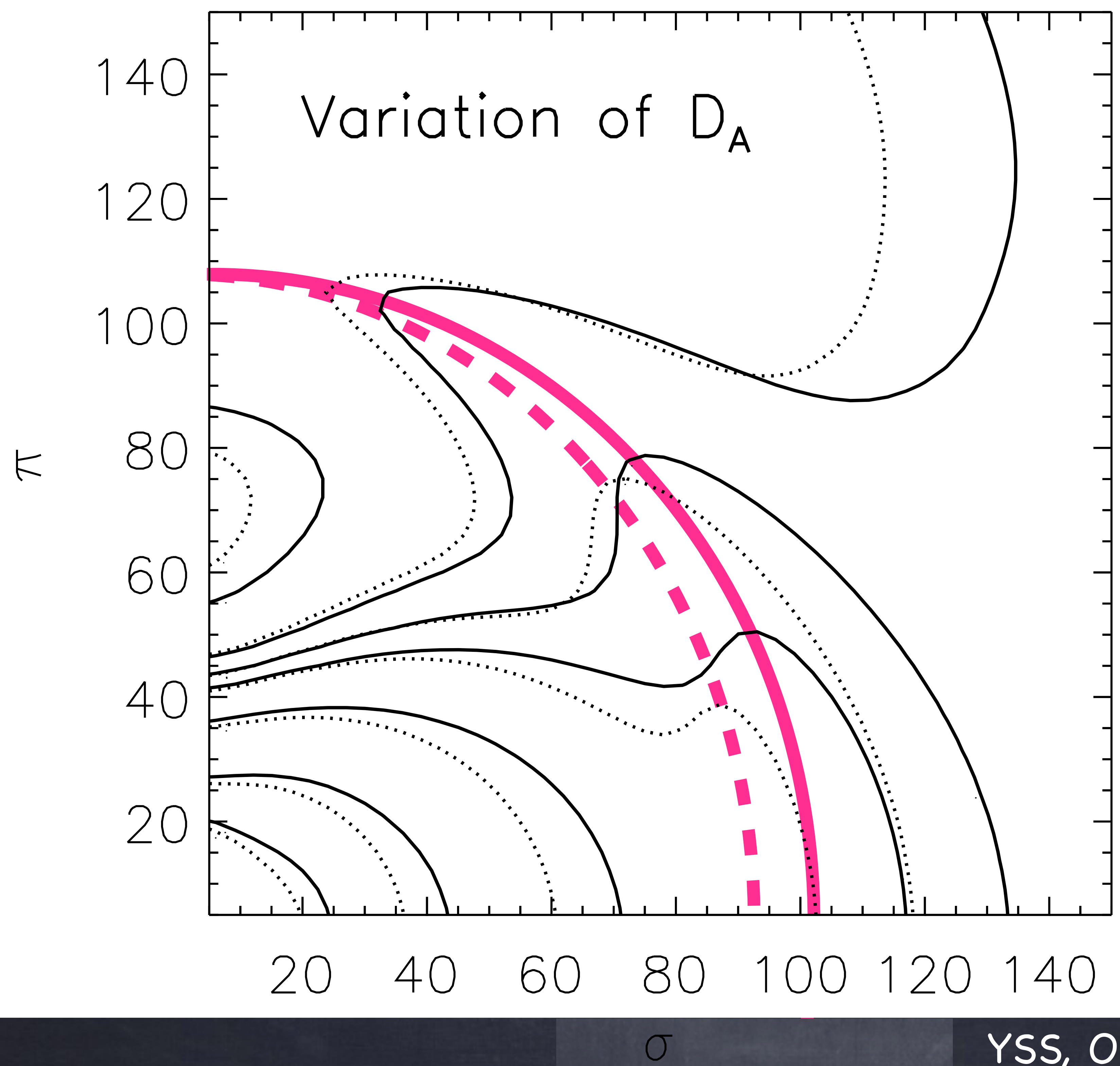
2D BAO circle is observed with known shape of spectra



YSS, Okumura, Taruya 2014

Alcock-Paczynski test using ξ(σ,π)

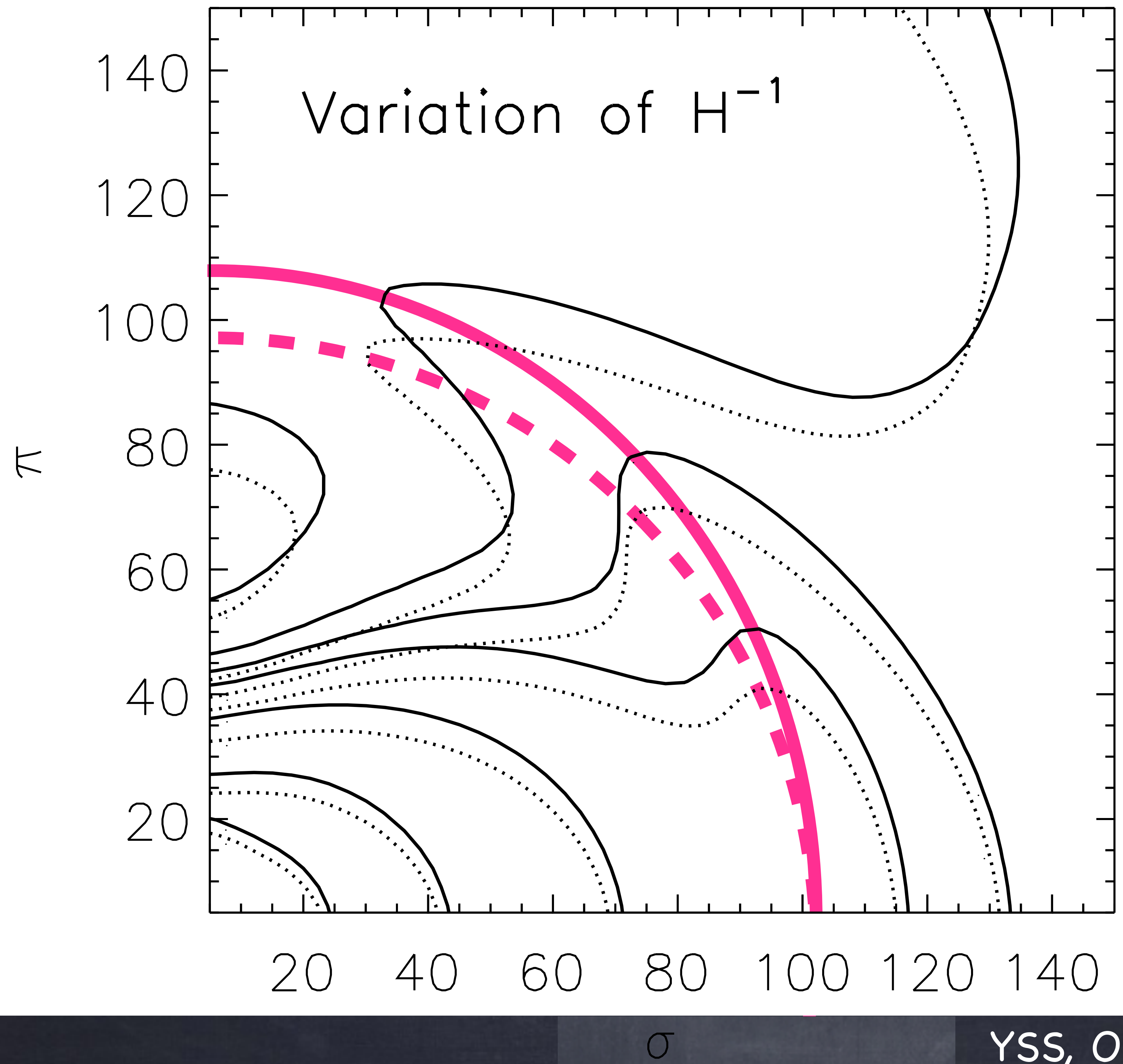
The 2D BAO circle is deformed along transverse direction



YSS, Okumura, Taruya 2014

Alcock-Paczynski test using ξ (σ ,π)

The 2D BAO circle is deformed along radial direction

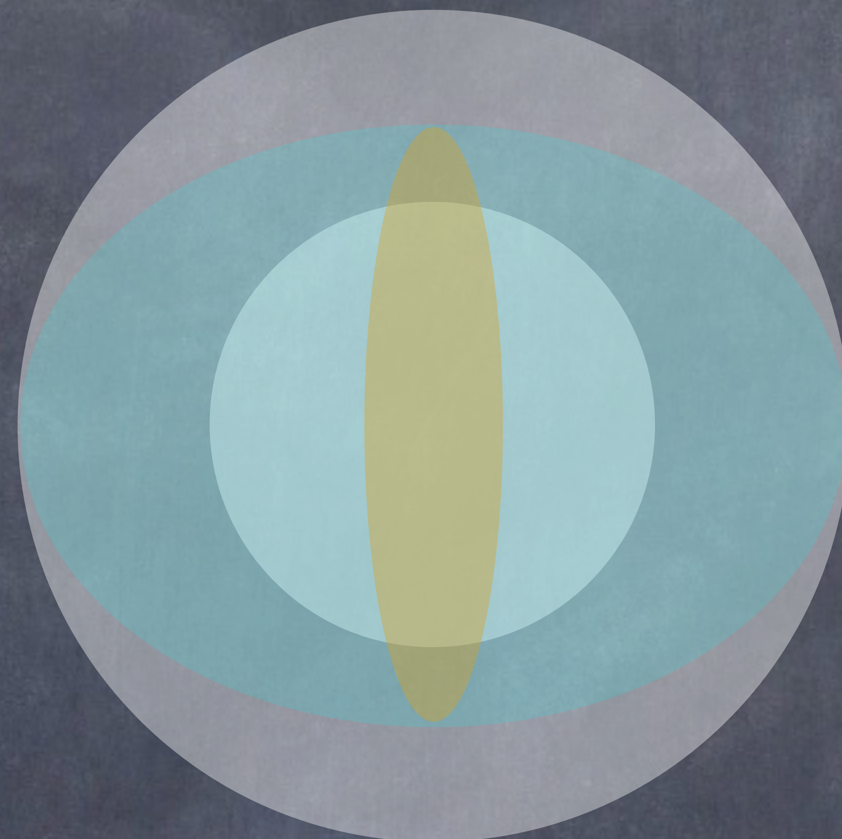


YSS, Okumura, Taruya 2014

Can we formulate RSD in precision cosmology?

Squeezing effect at large scales

(Kaiser 1987)



Finger of God effect at small scales

(Jackson 1972)

$$P_s(k,\mu) = P_{gg}(k) + 2\mu^2 P_{g\theta}(k) + \mu^4 P_{\theta\theta}(k)$$

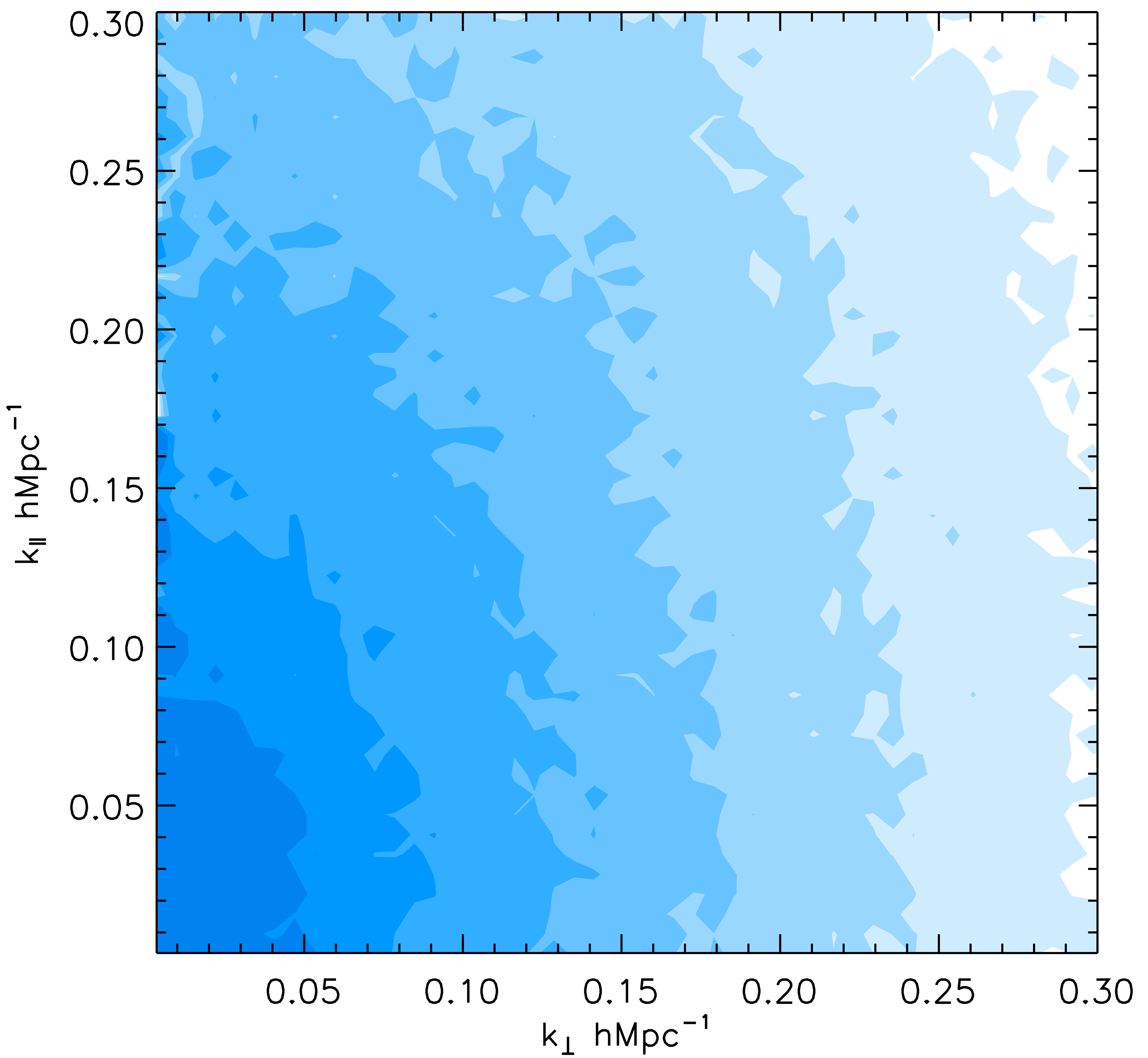
↓

$$P_s(k,\mu) = [P_{gg}(k) + \Delta P_{gg} + 2\mu^2 P_{g\theta}(k) + \Delta P_{g\theta} + \mu^4 P_{\theta\theta}(k) + \Delta P_{\theta\theta} + \mu^2 A(k) + \mu^4 B(k) + \mu^6 C(k) + \ldots] \exp[-(k\mu\sigma_p)^2]$$

Taruya, Nishimichi, Saito 2010; Taruya, Hiramatsu 2008; Taruya, Bernardeau, Nishimichi 2012

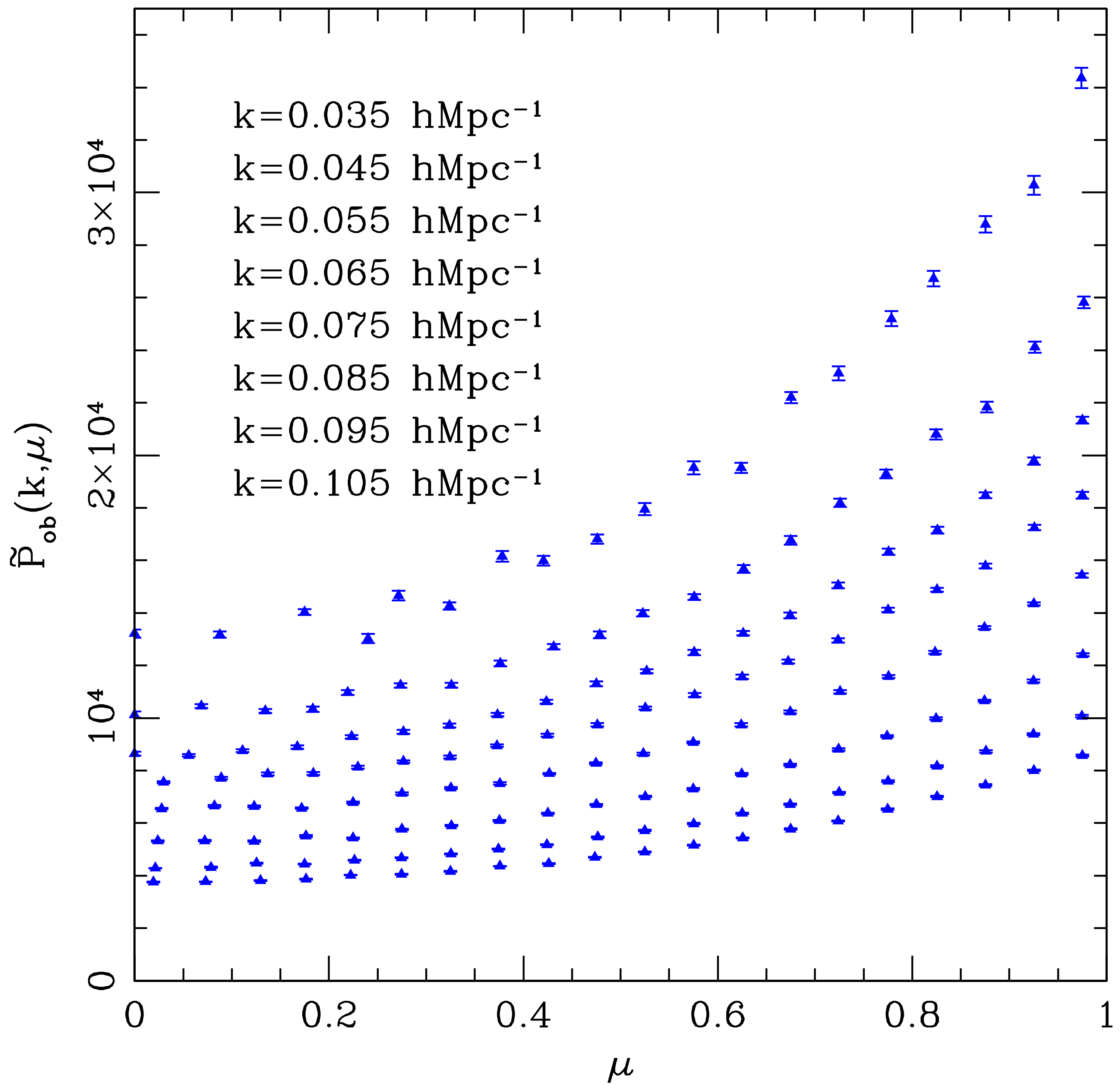
Observed spectra in Fourier space

$$P_s(k,\mu) = P_{gg}(k) + 2\mu^2 P_{g\theta}(k) + \mu^4 P_{\theta\theta}(k)$$



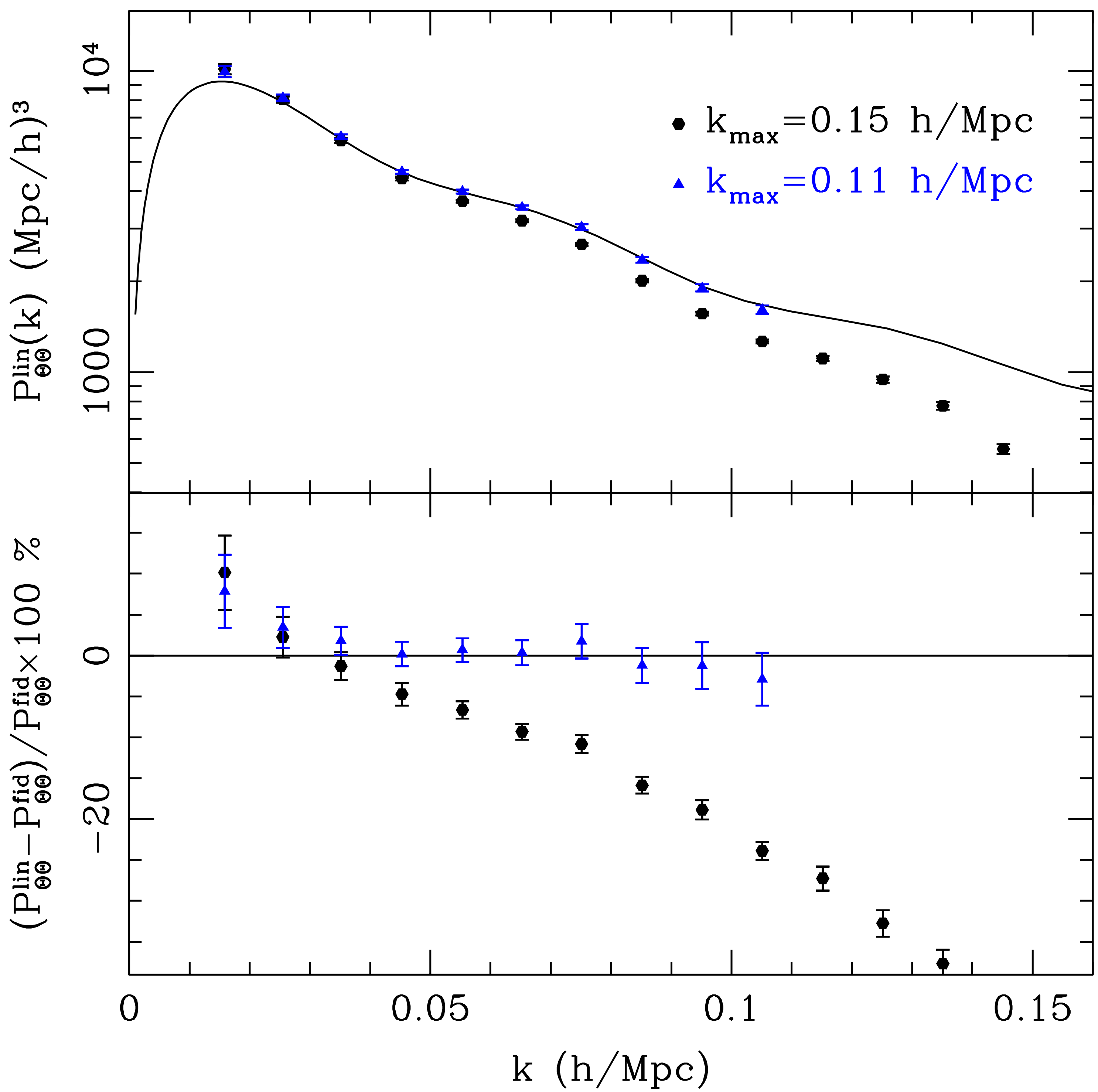
Observed spectra in Fourier space

$$P_s(k,\mu) = P_{gg}(k) + 2\mu^2 P_{g\theta}(k) + \mu^4 P_{\theta\theta}(k)$$



Measurements in Fourier space

Theoretical model of RSD is broken down at k_{max}=0.1h/Mpc.



YSS, Nishimichi, Taruya, Kayo 2013

Conversion into configuration space

$$P_s(k,\mu) = [Q_0(k) + \mu^2 Q_2(k) + \mu^4 Q_4(k) + \mu^6 Q_6(k)]\ \exp[-(k\mu\sigma_p)^2]$$

$$\xi(\sigma,\pi) = \int d^3k\ P(k,\mu) e^{ikx} = \Sigma\ \xi_l(s)\ \mathcal{P}_l(\nu)$$

$$\xi_l(s) = i^l \int k^2 dk\ P_l(k)\ j_l(ks)$$

$$P_0(k) = p_0(k)$$

$$P_2(k) = 5/2\ [3p_1(k) - p_0(k)]$$

$$P_4(k) = 9/8\ [35p_2(k) - 30p_1(k) + 3p_0(k)]$$

$$P_6(k) = 13/16\ [231p_3(k) - 315p_2(k) - 105p_1(k) + 5p_0(k)]$$

$$\vdots$$

$$p_n(k) = 1/2\ [\ \gamma(n+1/2,\kappa)/\kappa^{n+1/2} Q_0(k) + \gamma(n+3/2,\kappa)/\kappa^{n+3/2} Q_2(k)$$

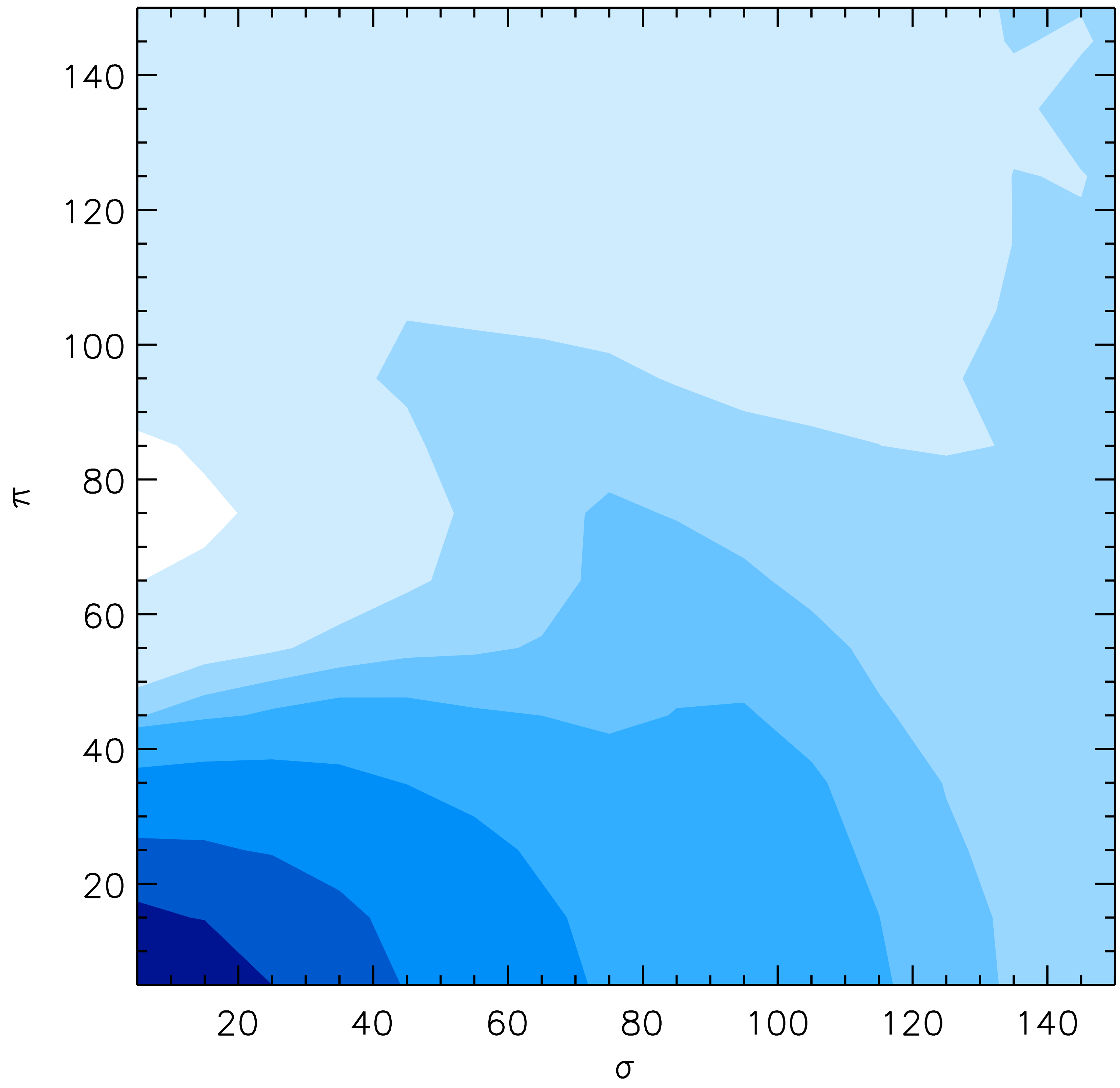
$$+ \gamma(n+5/2,\kappa)/\kappa^{n+5/2} Q_4(k) + \gamma(n+7/2,\kappa)/\kappa^{n+7/2} Q_6(k)$$

$$\kappa = k^2 \sigma^2_p$$

YSS, Okumura, Taruya in preparation   Taruya, Nichimishi, Saito 2010

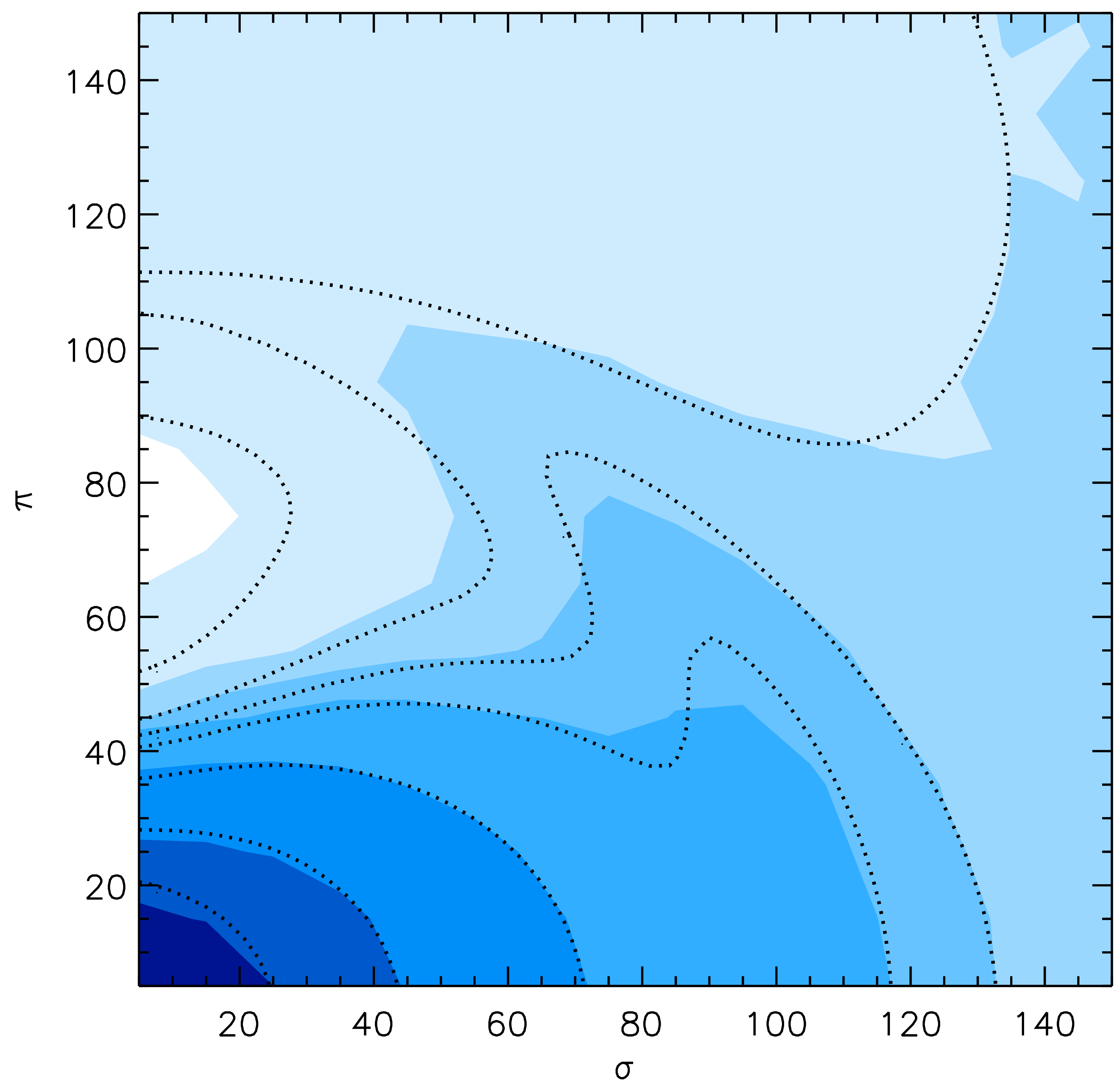
Theoretical reproduction of 2D BAO

Results from 611 BOSS mocks



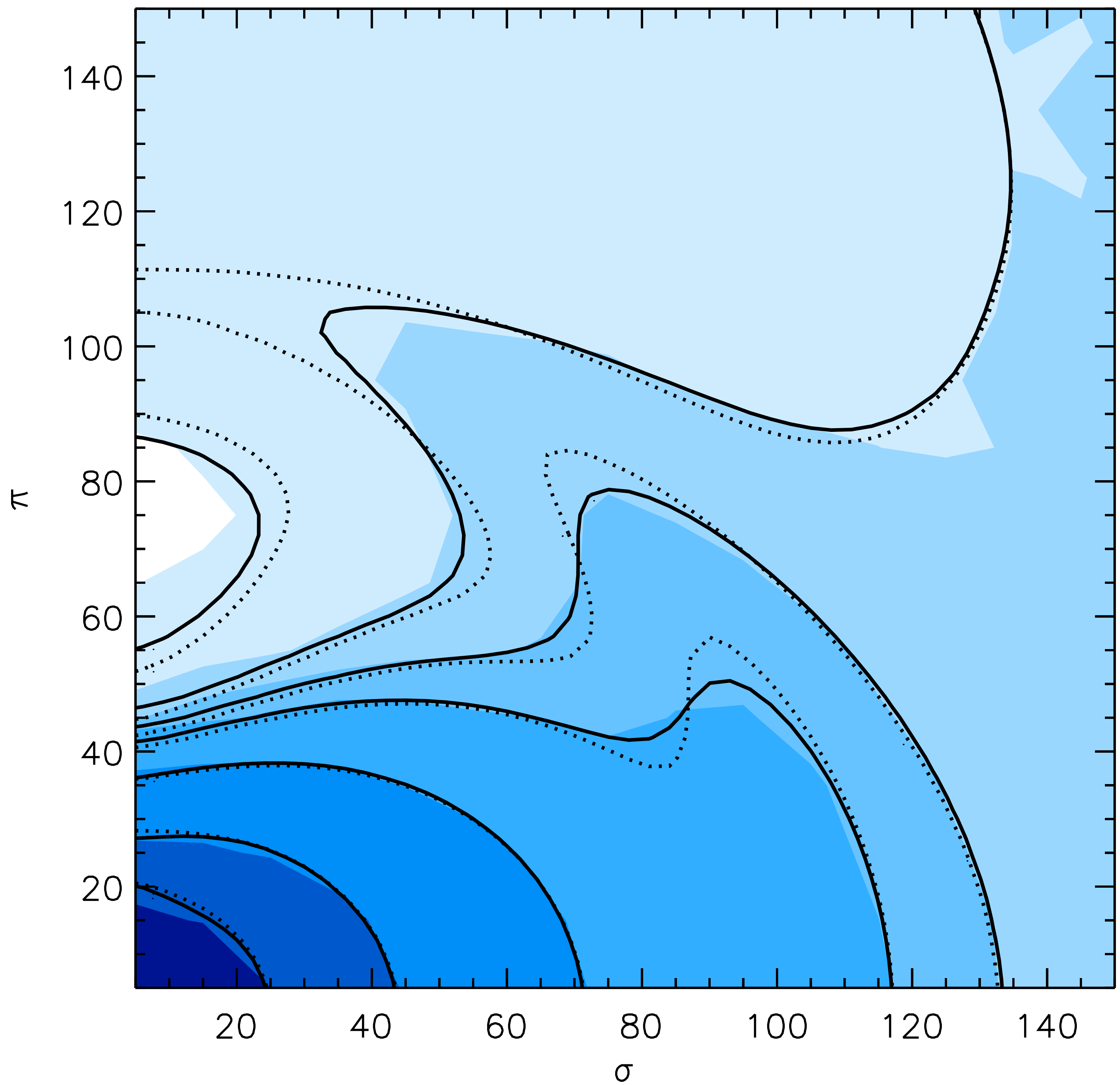
Theoretical reproduction of 2D BAO

$\xi(\sigma,\pi)$ with Kaiser+Gaussian FoG



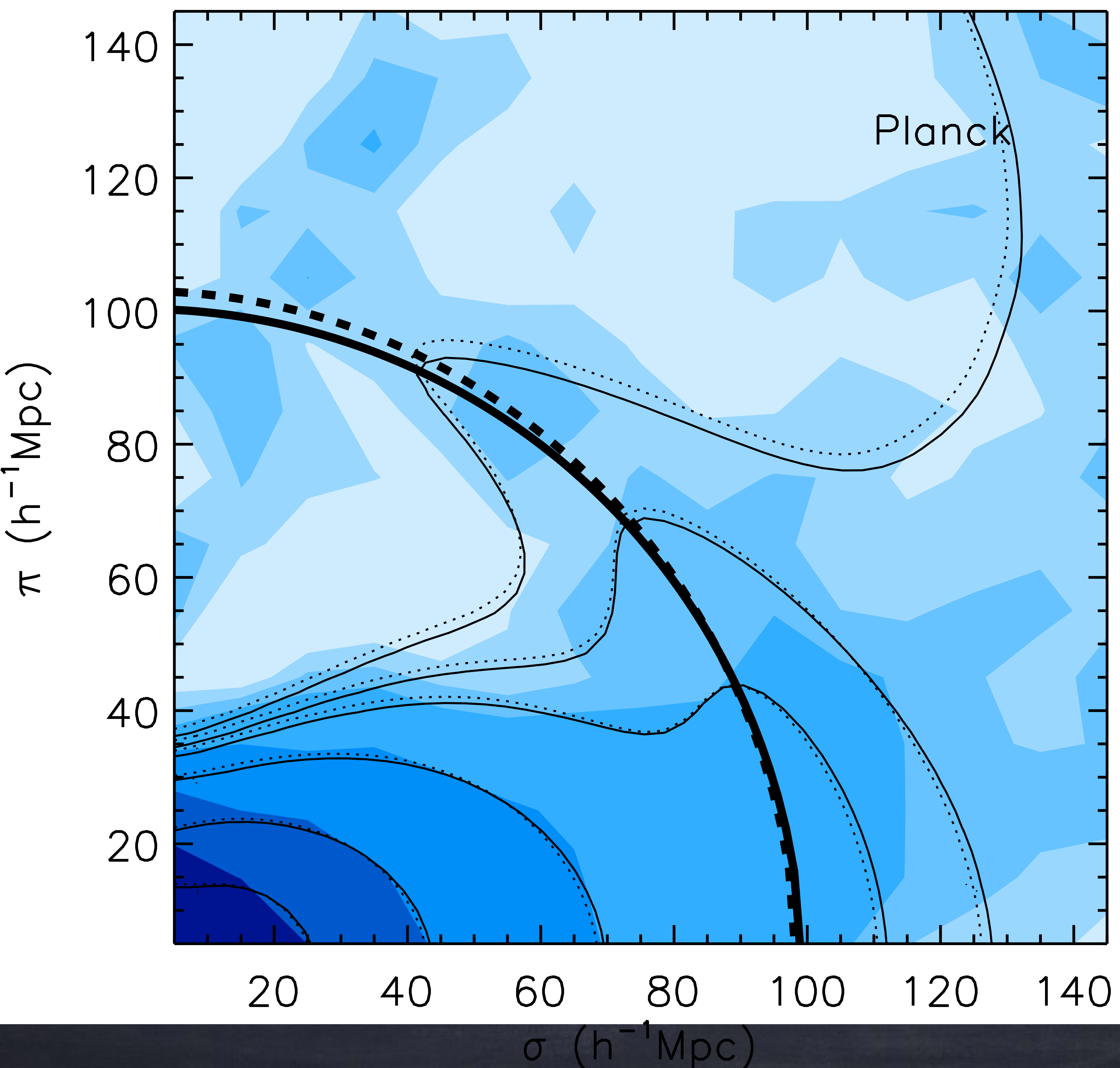
Theoretical reproduction of 2D BAO

ξ(σ,π) with additional correction terms



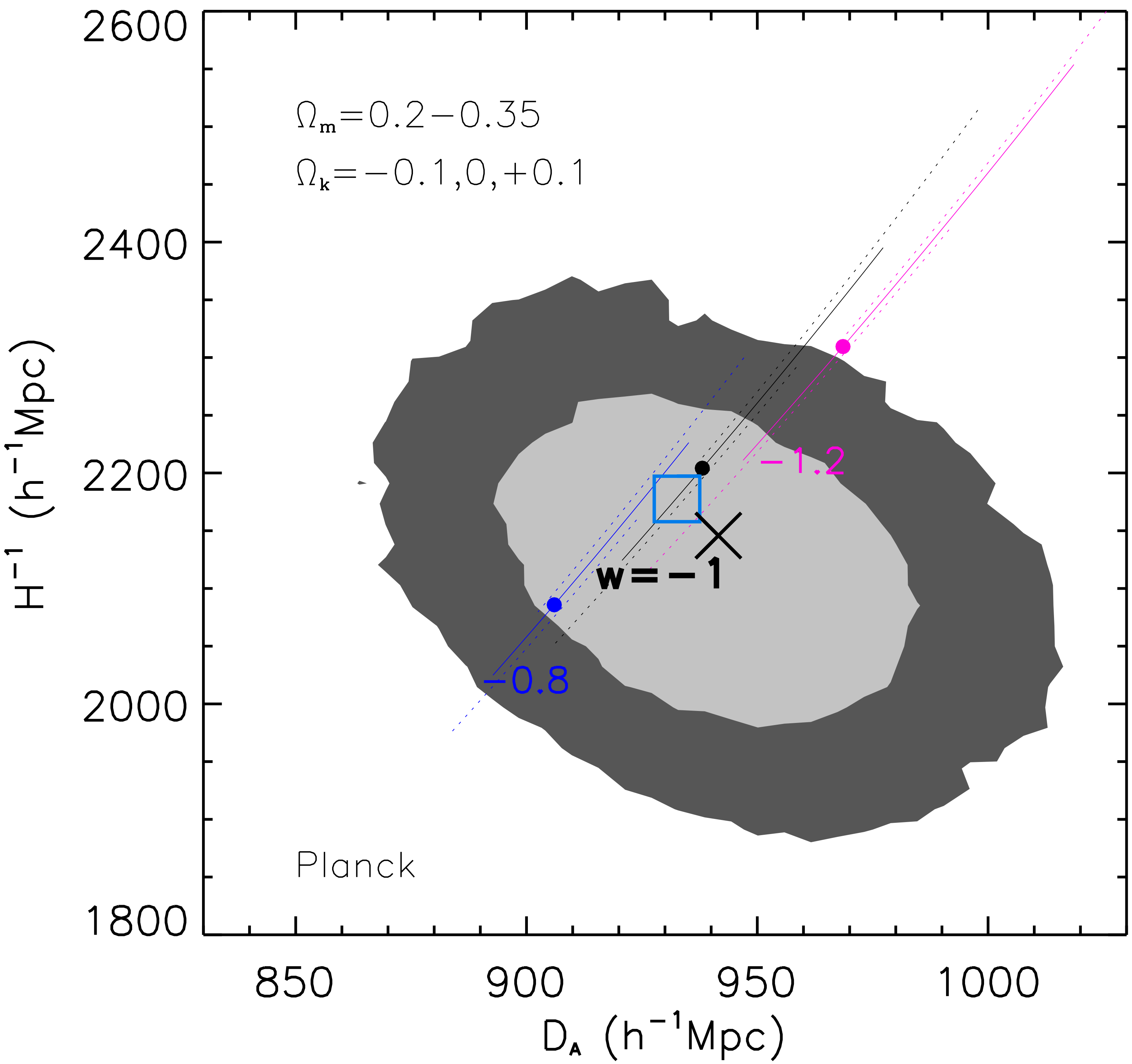
Restrictions due to non-perturbative effect

Results from BOSS DR9



Measured transverse and radial distances

It supports LCDM universe!



Targets using redshift distortions

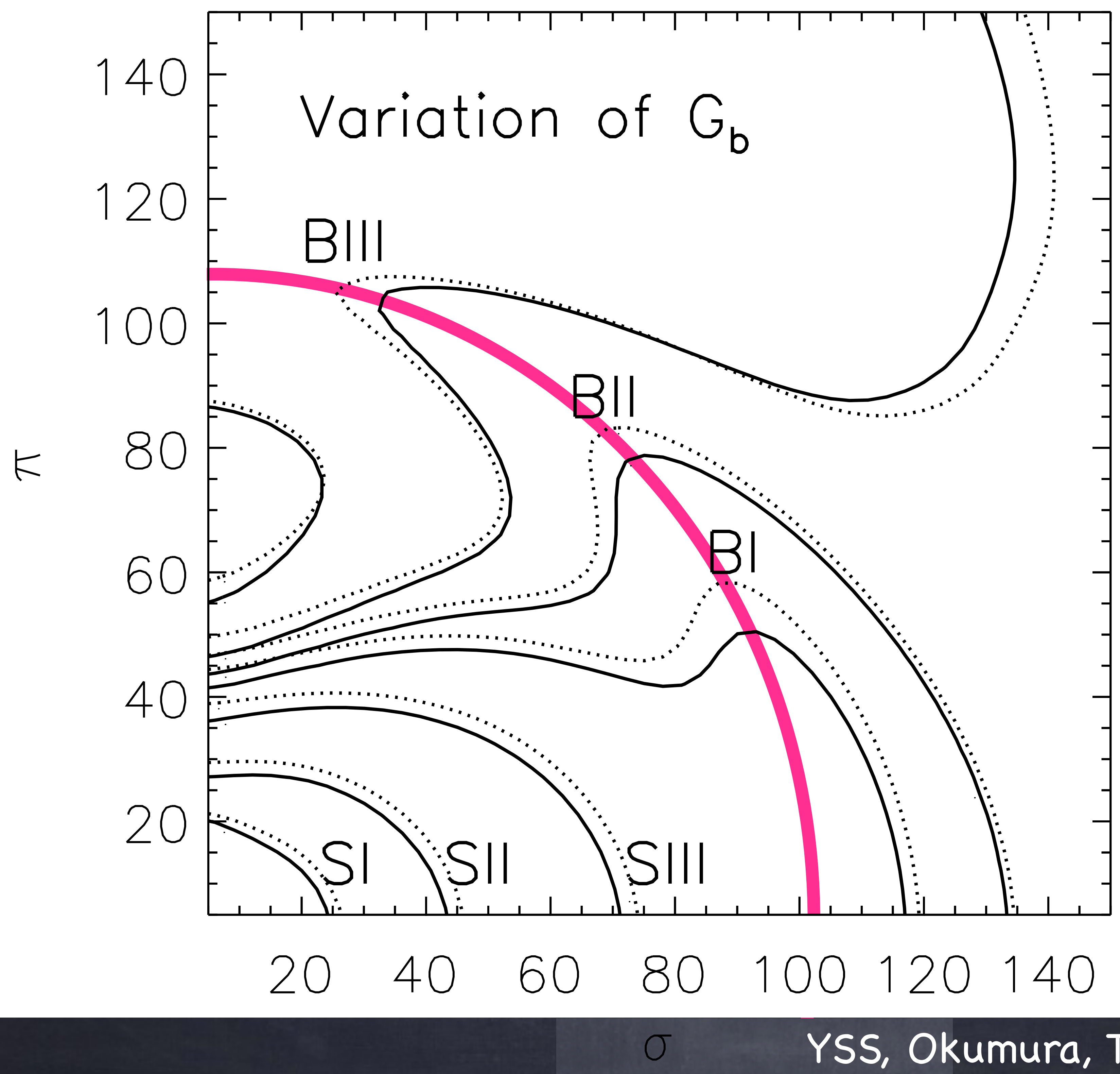
Angular diameter distance D
which measure the angular diameter distance and expansion rate as a function of redshift.

Radial distance H
anisotropy to decompose the radial distance represented by the inverse of Hubble rate as a function of redshift.

Coherent motion G_θ: The coherent motion, or flow, of galaxies can be statistically estimated from their effect on the clustering measurements of large redshift surveys, or through the measurement of redshift space distortions.

Alcock-Paczynski test using $\xi(\sigma,\pi)$

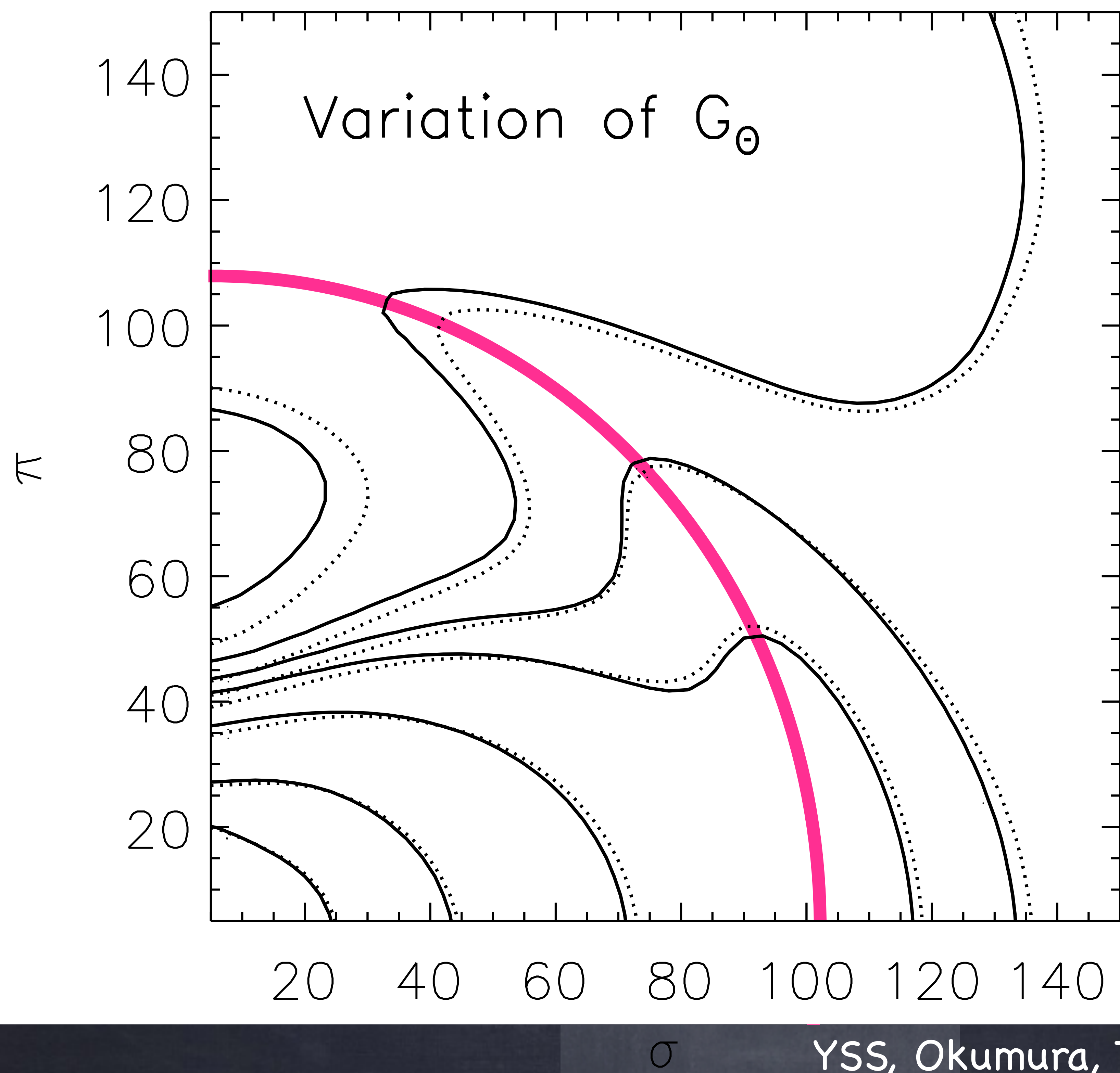
Peak points rotate along the 2D BAO circle



YSS, Okumura, Taruya in preparation

Alcock-Paczynski test using $\xi(\sigma,\pi)$

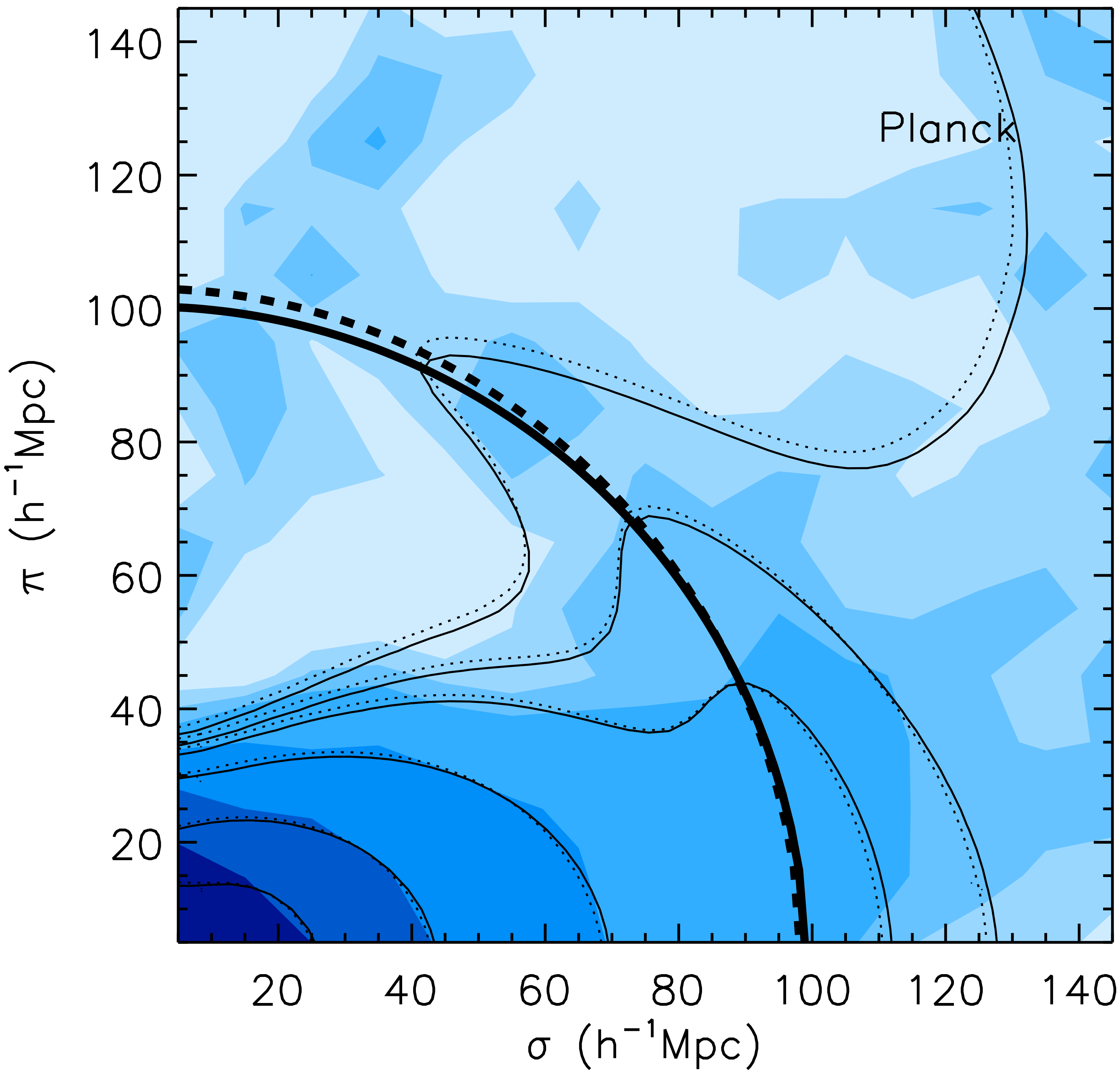
Peak points mitigate along the 2D BAO circle



YSS, Okumura, Taruya in preparation

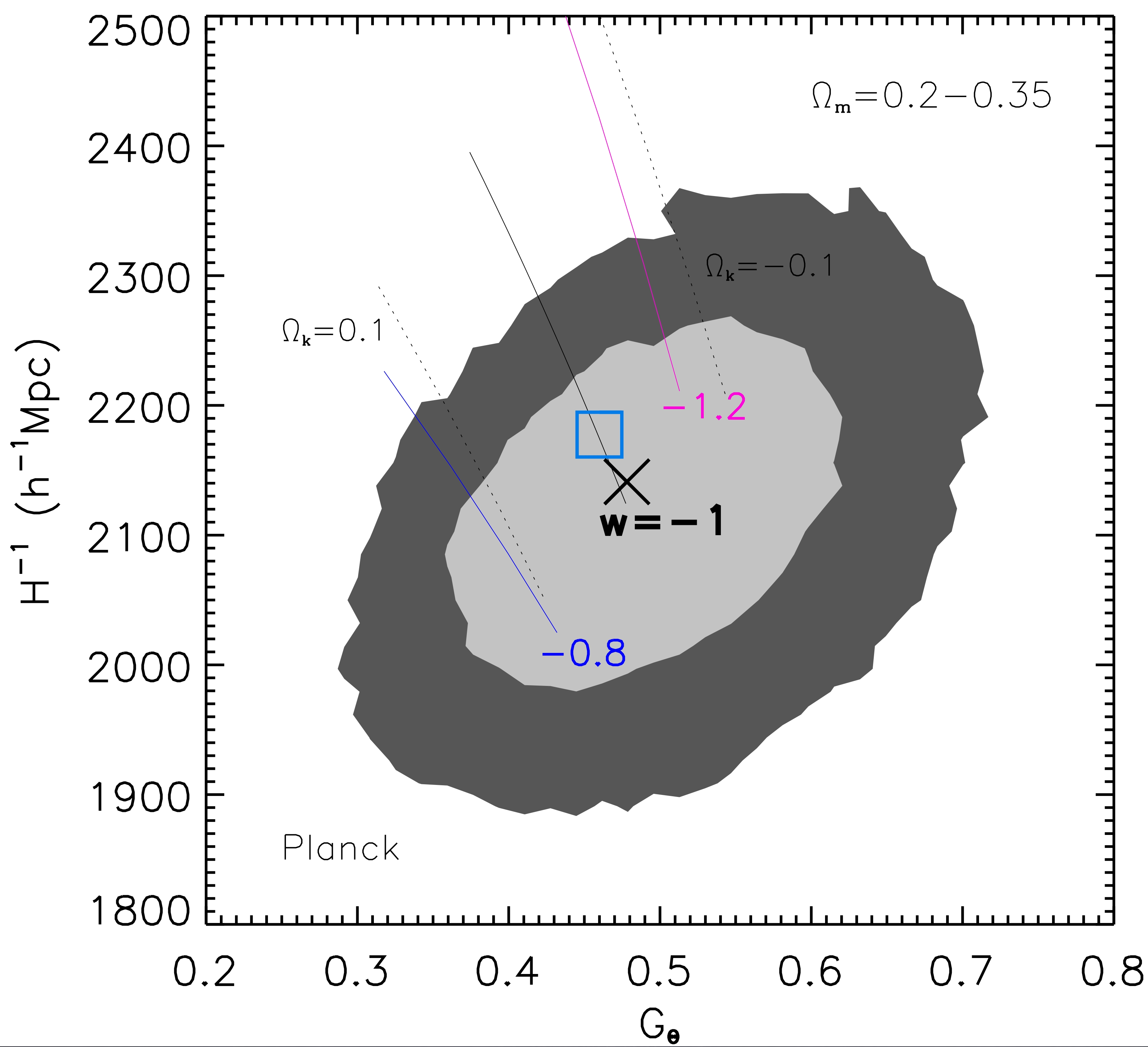
The location of measured peaks on 2D circle

Again LCDM works fine with conservative bound!



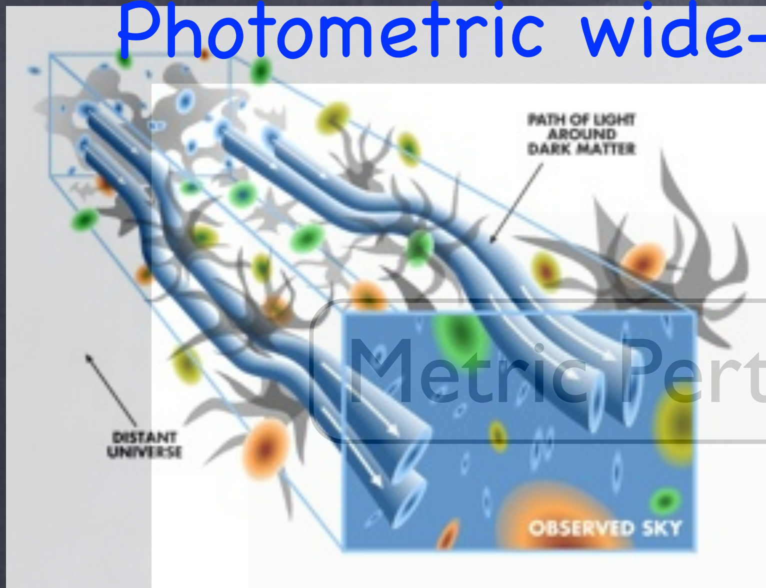
Measured coherent motions and H^{-1}

Undeniable confirmation of LCDM!

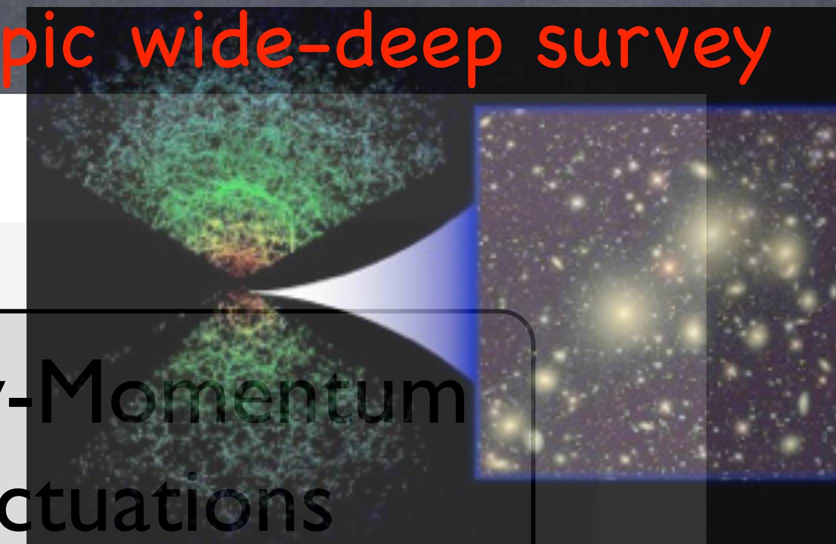


Future wide deep field survey

Photometric wide-deep survey



Spectroscopic wide-deep survey



Metric Perturbations

Energy-Momentum Fluctuations

WL measures $\phi - \psi$

Galaxy-Galaxy correlation

Φ ← Poisson equation → δ_m

Modified by mass screening effect

YSS, Sawicki, Hu 2007

Anisotropy

Continuity eq.

Ψ ← Euler equation → θ_m

Coherent motions

$$G_{\mu\nu} = 4\pi G_N T_{\mu\nu}$$

YSS 2006, YSS, Kazuya 2009

Conclusion

- Spectroscopy wide-deep field survey provides us with a unique opportunity to simultaneously probe 1) angular diameter distance, 2) Hubble rate and 3) coherent motion through Alcock-Paczynski effect on redshift distortions.

- The 2D BAO circle works as a platform to perform AP test while the shape of spectra is given by CMB experiments.

- The 2D BAO is precisely reproduced using an improved redshift distortion model.

- Using BOSS simulation, we successfully measure the angular diameter distance, the Hubble rate and the coherent growth function.

- Currently, we apply our proven techniques for BOSS data released in 2012.