Cross-correlation between spectroscopic and photometric maps

Feb 13th 2014

KIAS-NCTS Joint Workshop

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Key observables in spectroscopic surveys

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.

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

1) ΛCDM universe

2) Dynamical dark energy

2) Einstein's gravity at large scale

What is "Large Scale Structure formation" ?

Tracing invisible ripples using pattern of light on the bottom weak lensing

Tracing invisible ripples using fallen leaves on the water galaxy survey

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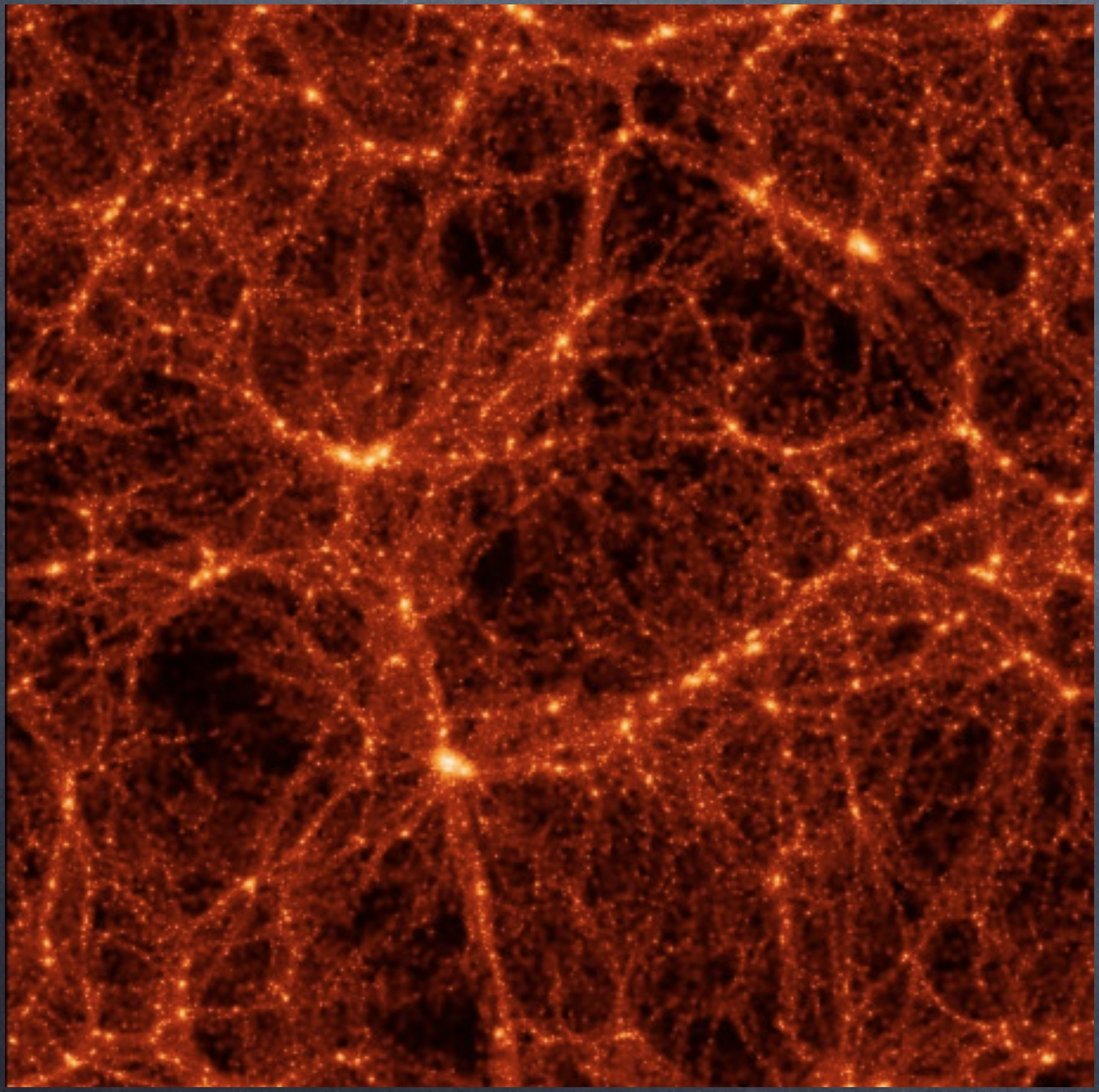
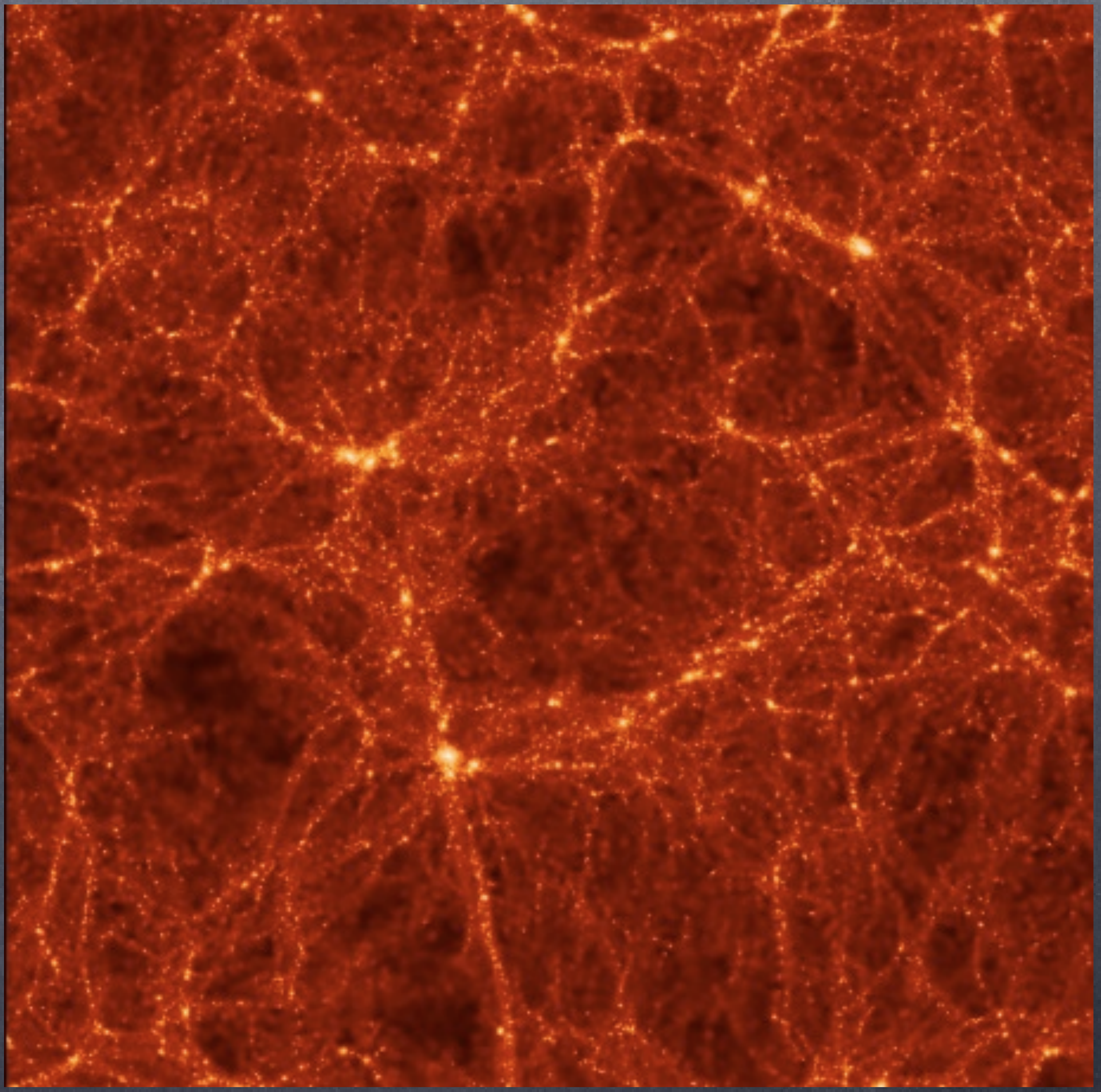
Signature of dark energy on LSS

The same physics weakening gravity dims SN light influences on the structure of galaxy formation at large scales.

without dark energy

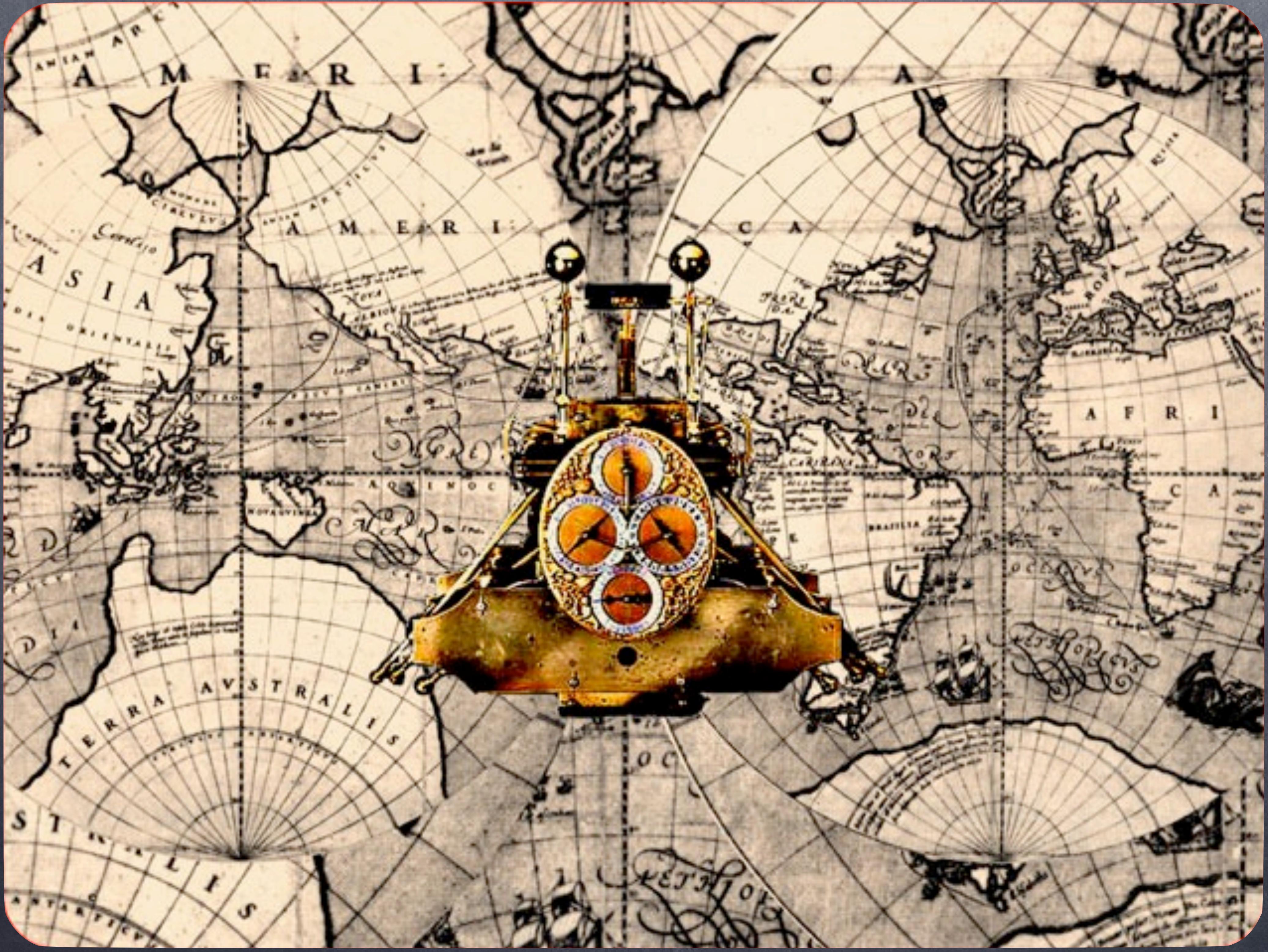


with dark energy



Longitude problem in 21st century

Measuring the redshift of the universe



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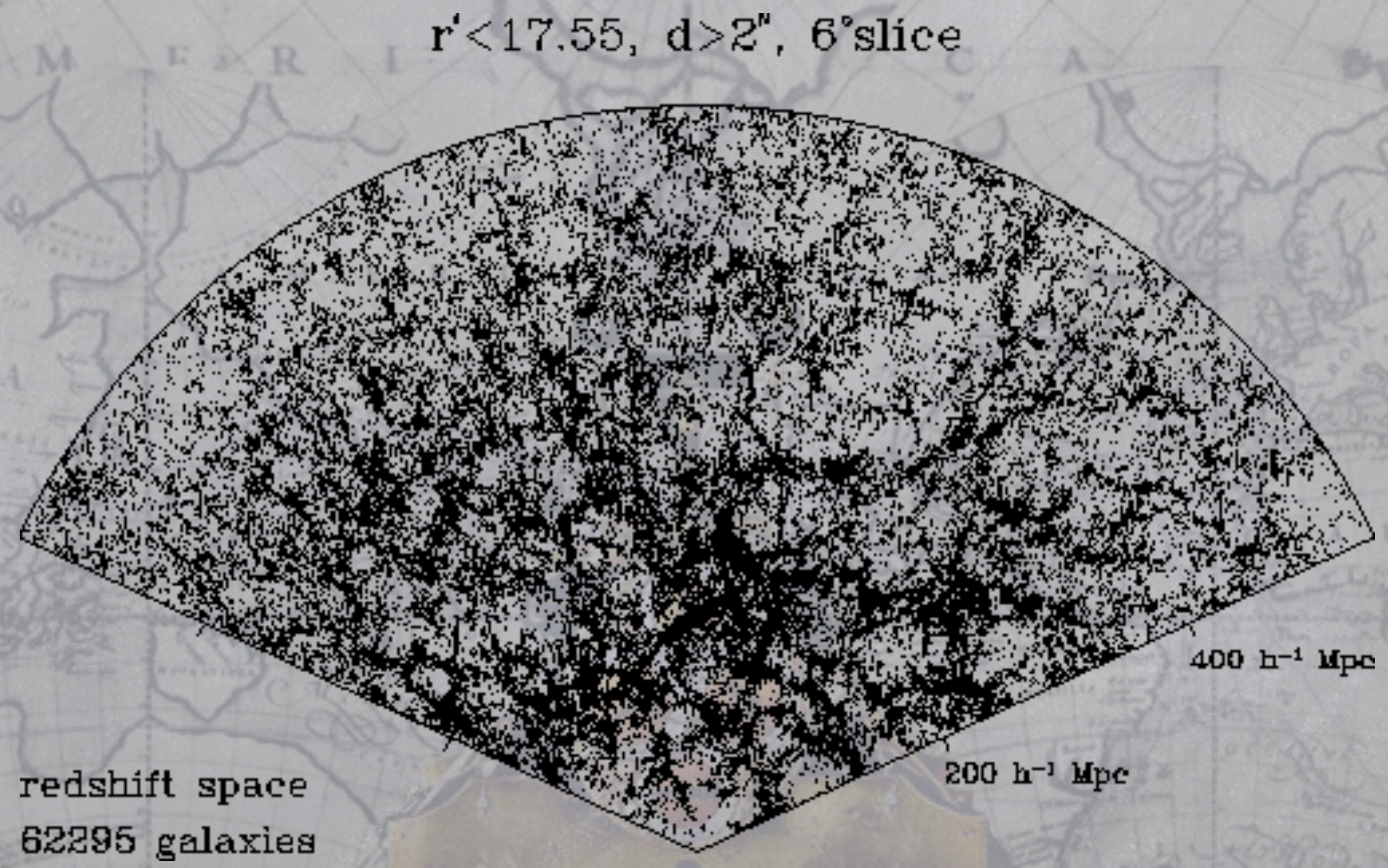
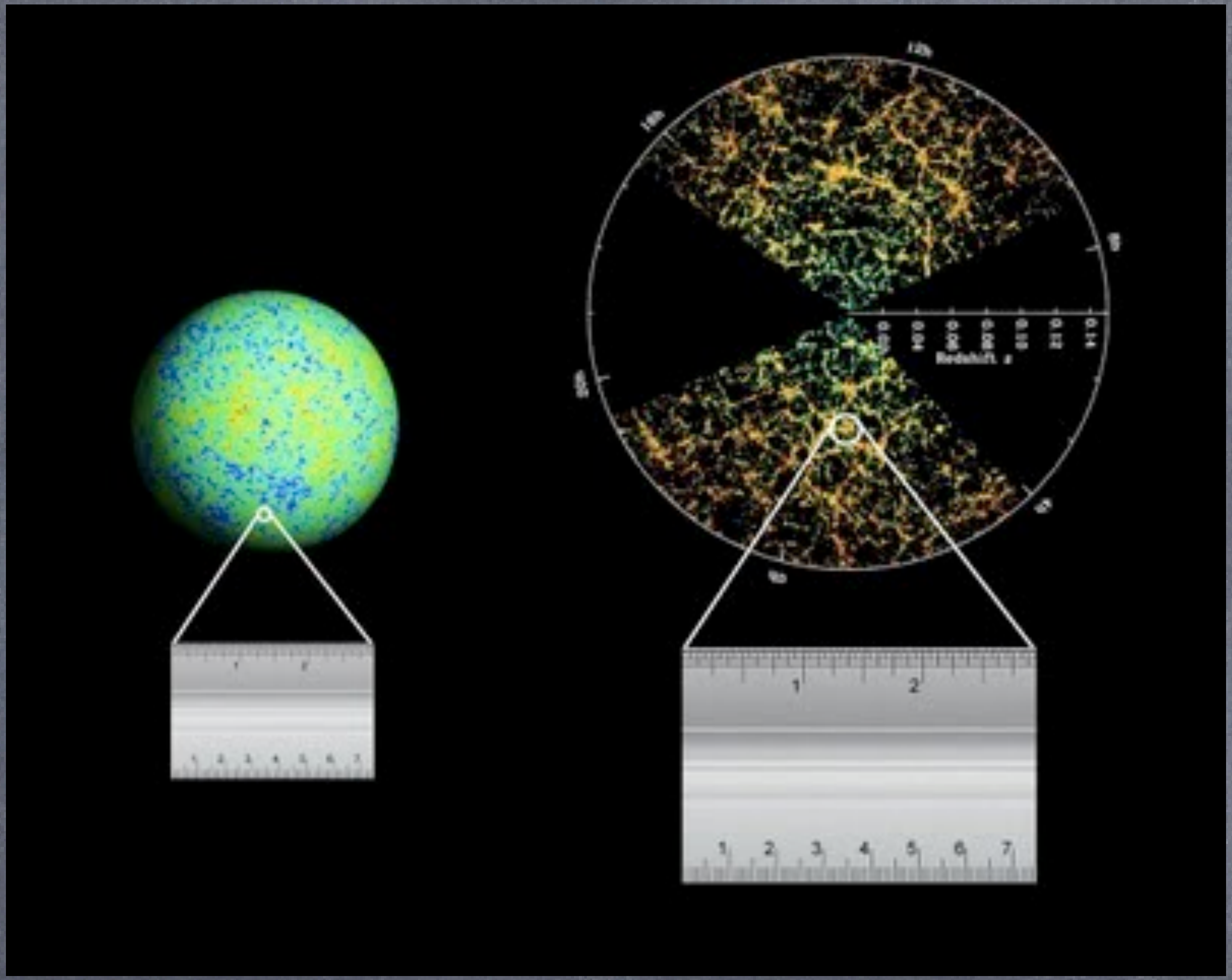


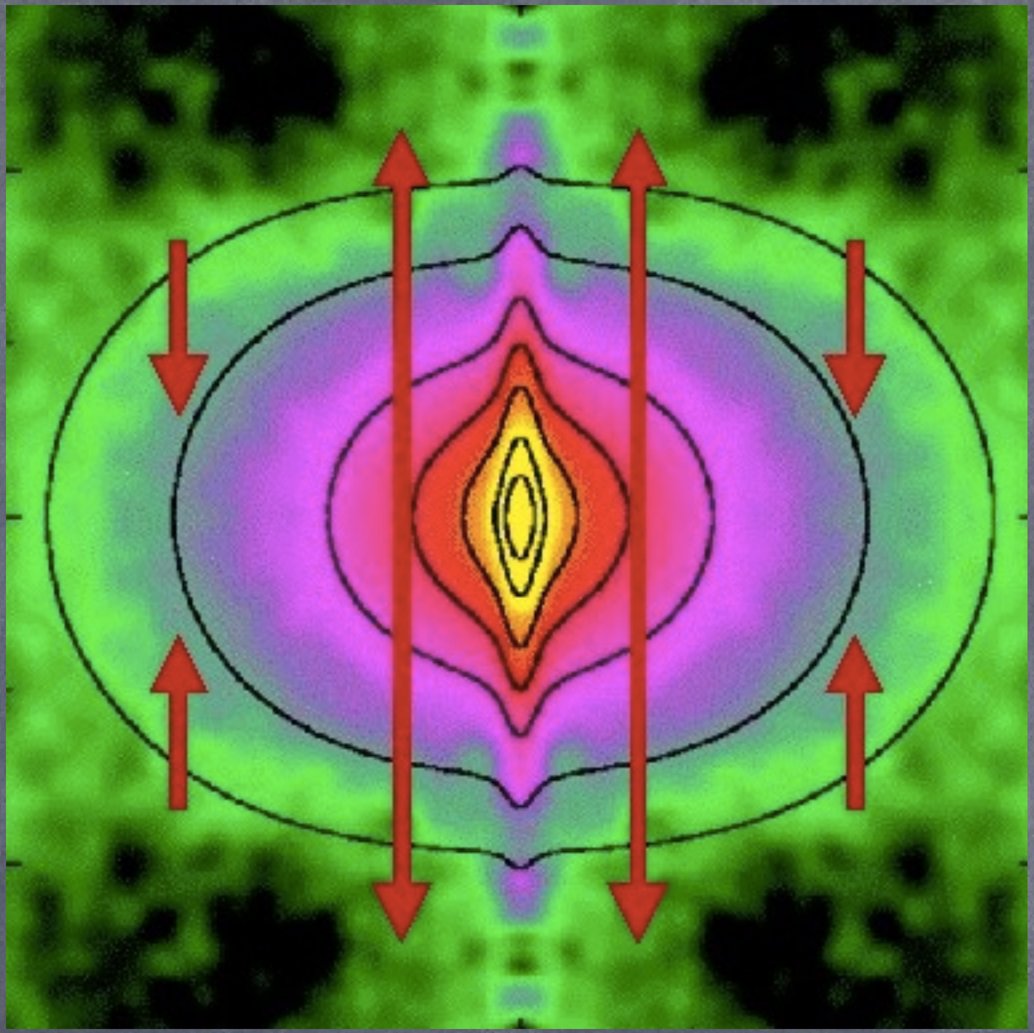
2dF scanned the first evidence of cosmic web of the universe. New spectroscopy technology allows us to locate the radial distance.

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



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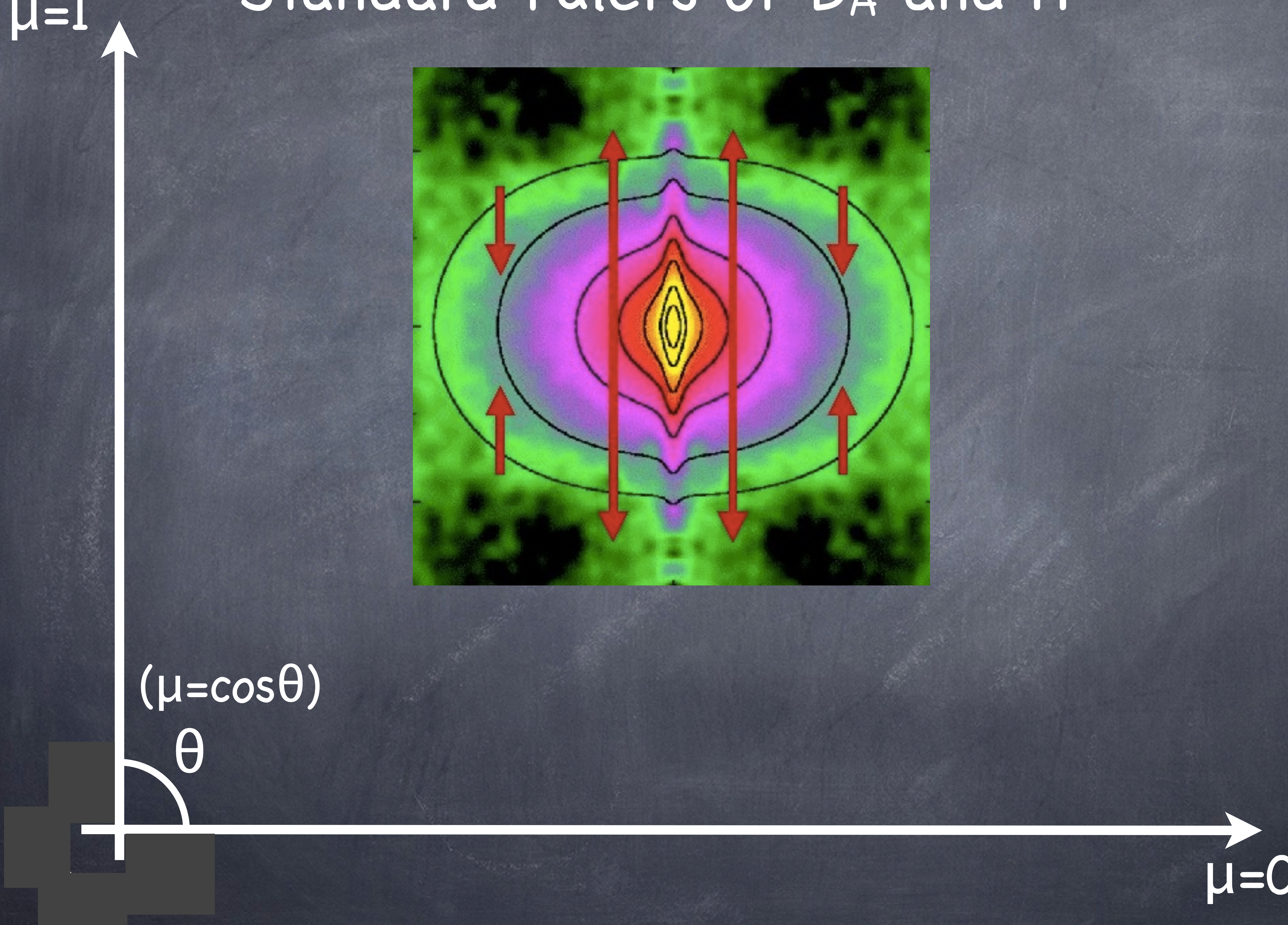
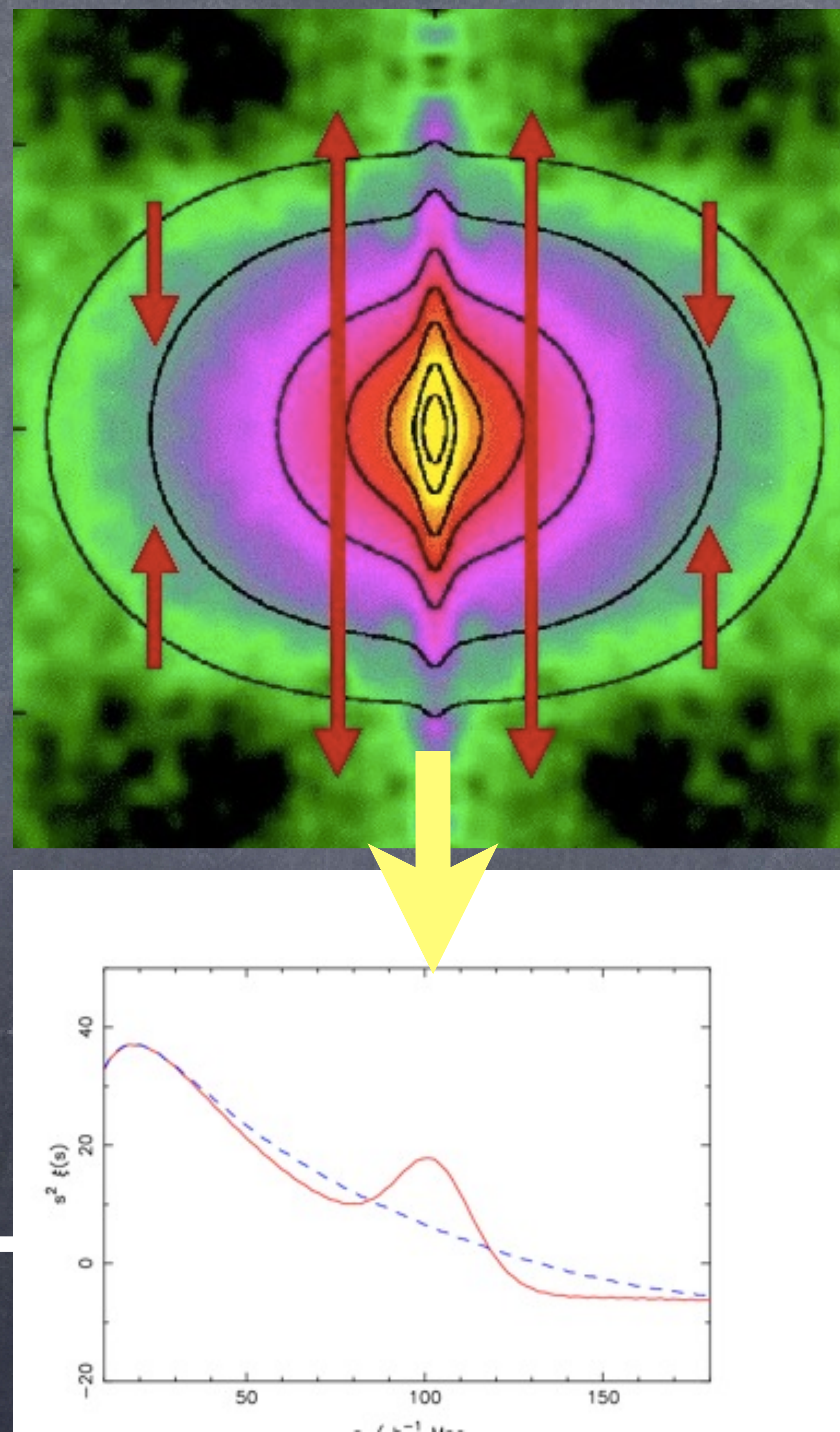
Standard rulers of D_A and H^{-1}



Standard rulers of D_A and H^{-1}

$\mu=1$



($\mu=\cos\theta$)

θ

$\mu=0$

Blake, Galzebrook 2004

Seo, Eisenstein 2004

Standard rulers of D_A and H^{-1}

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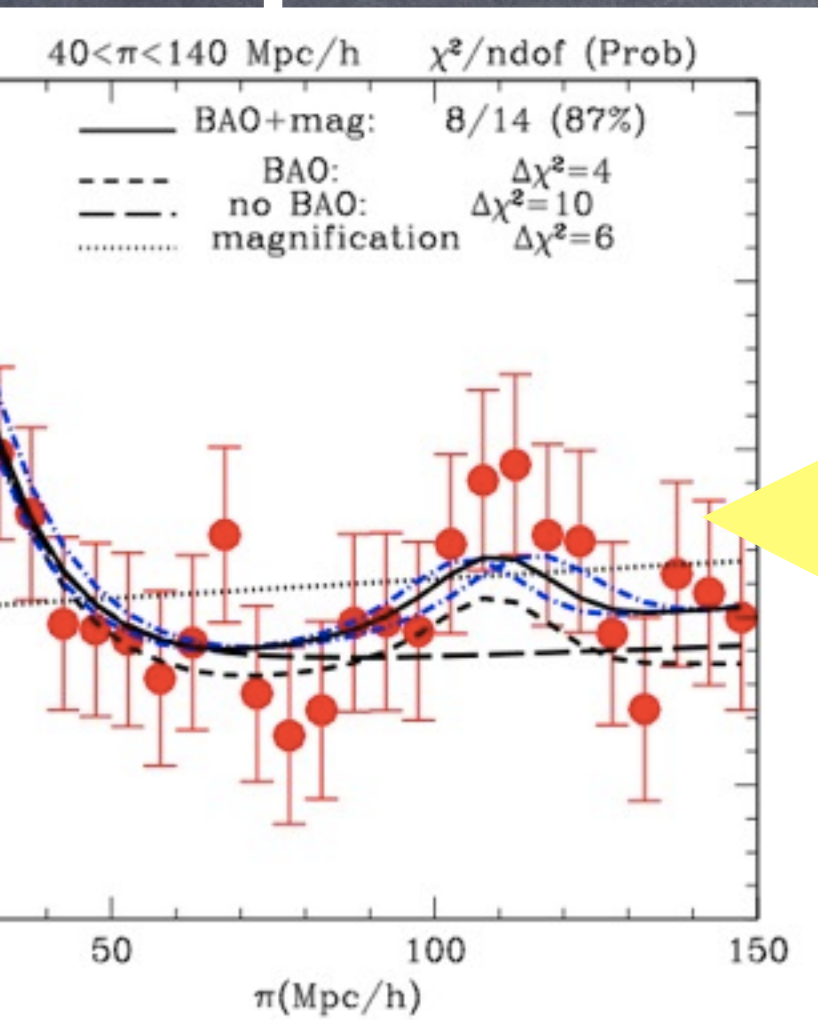
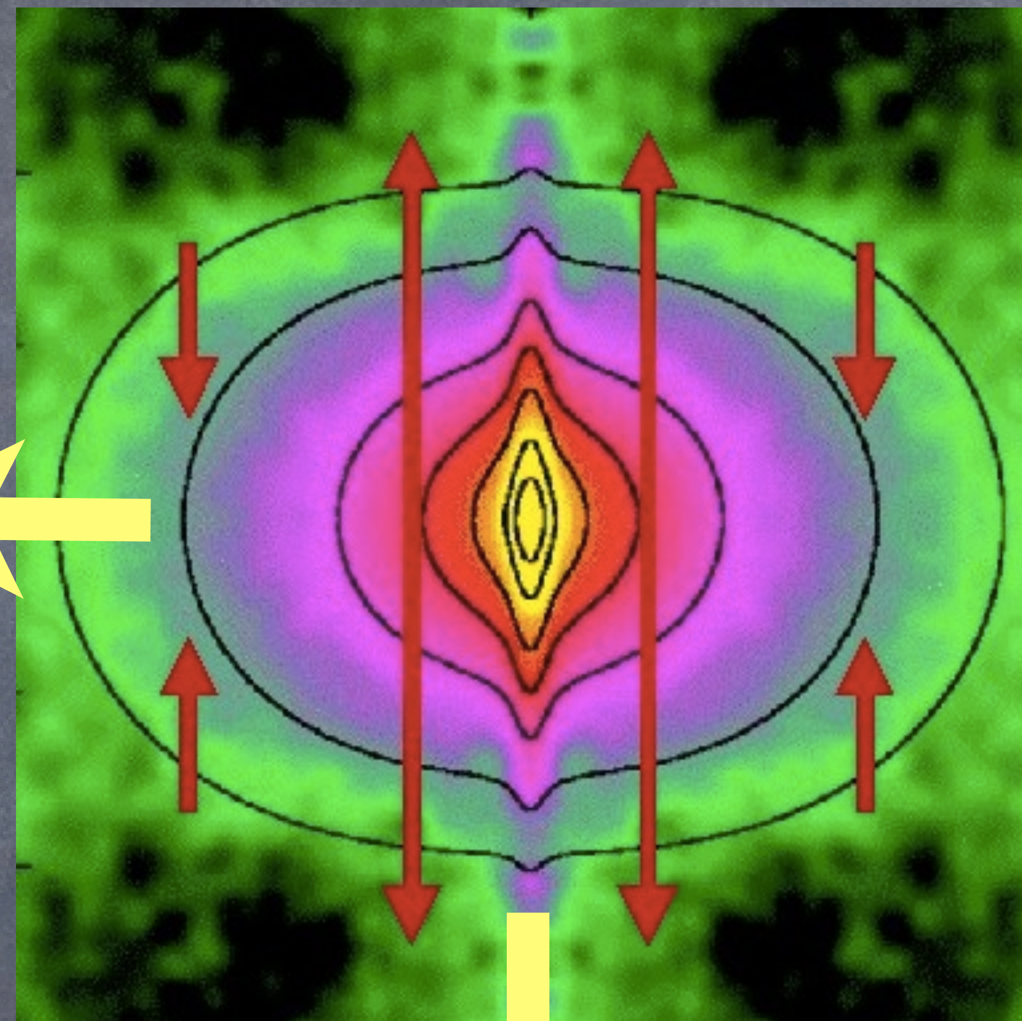
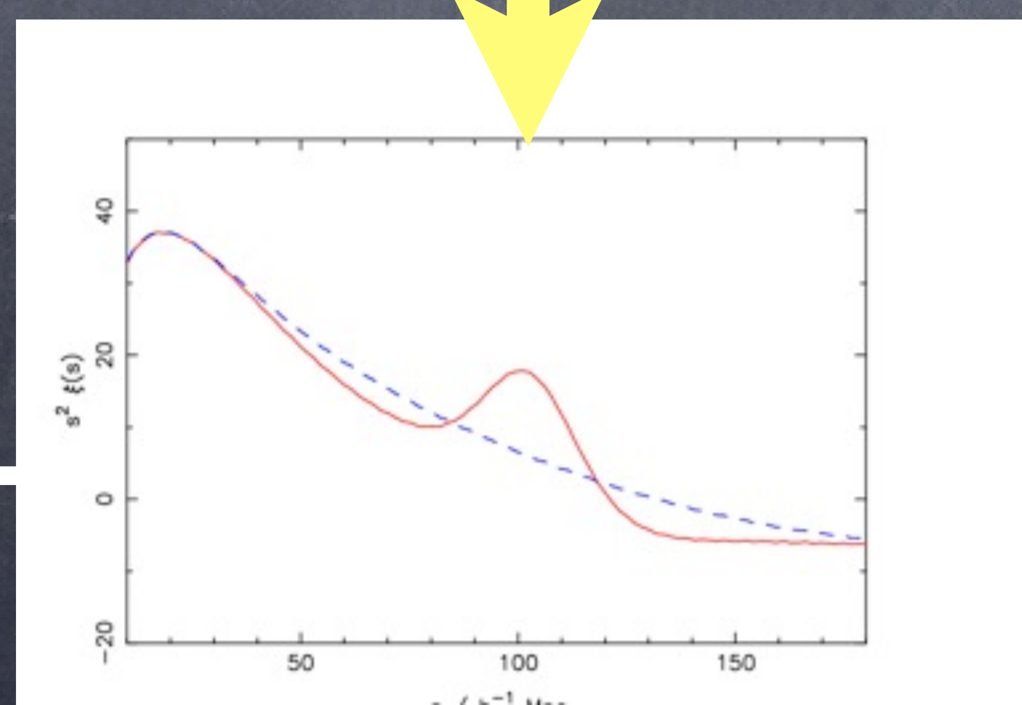




Gaztanaga, Cabre, Hui 2008

$(\mu=\cos\theta)$

θ



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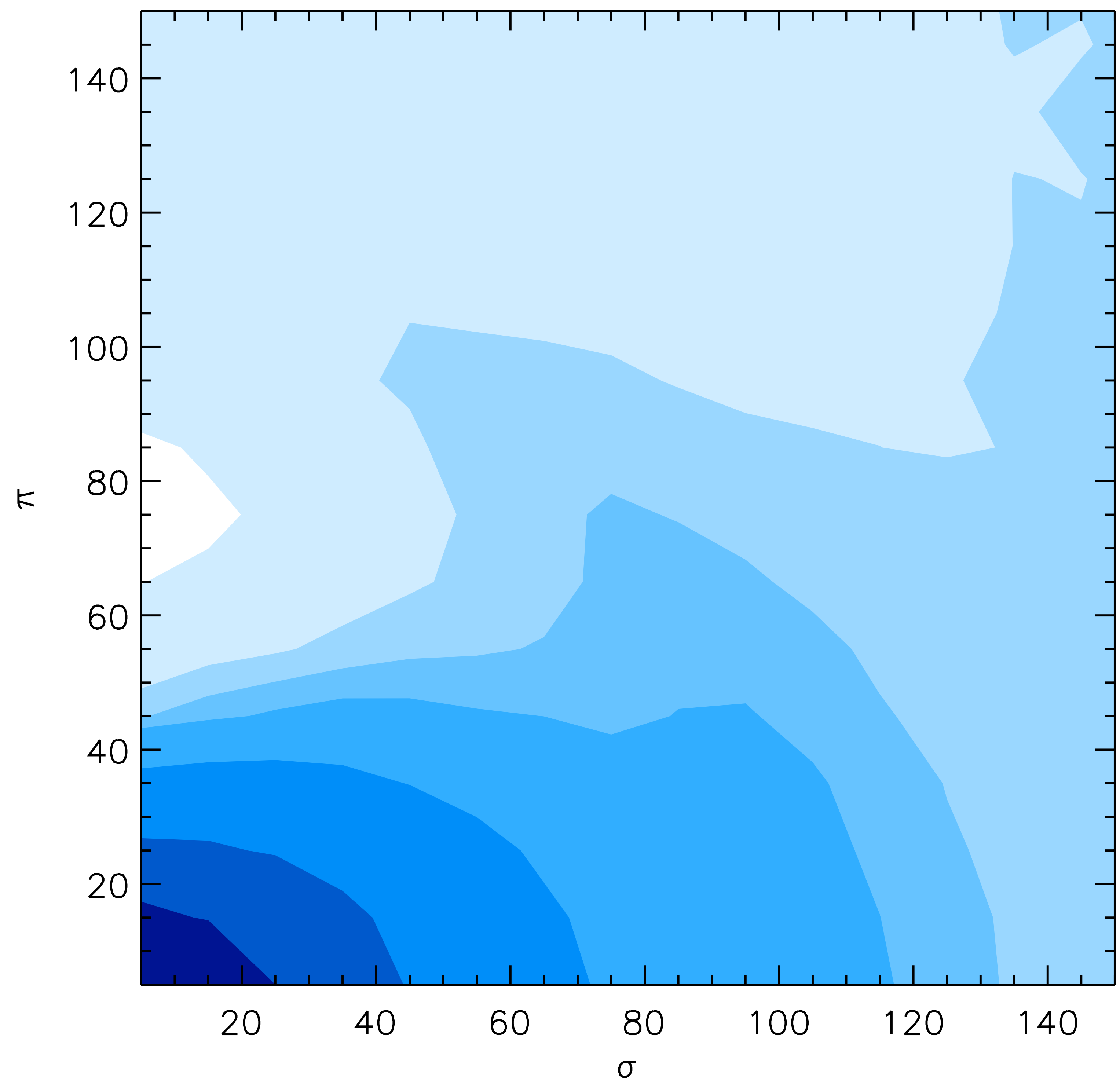
2D Anisotropy Analysis



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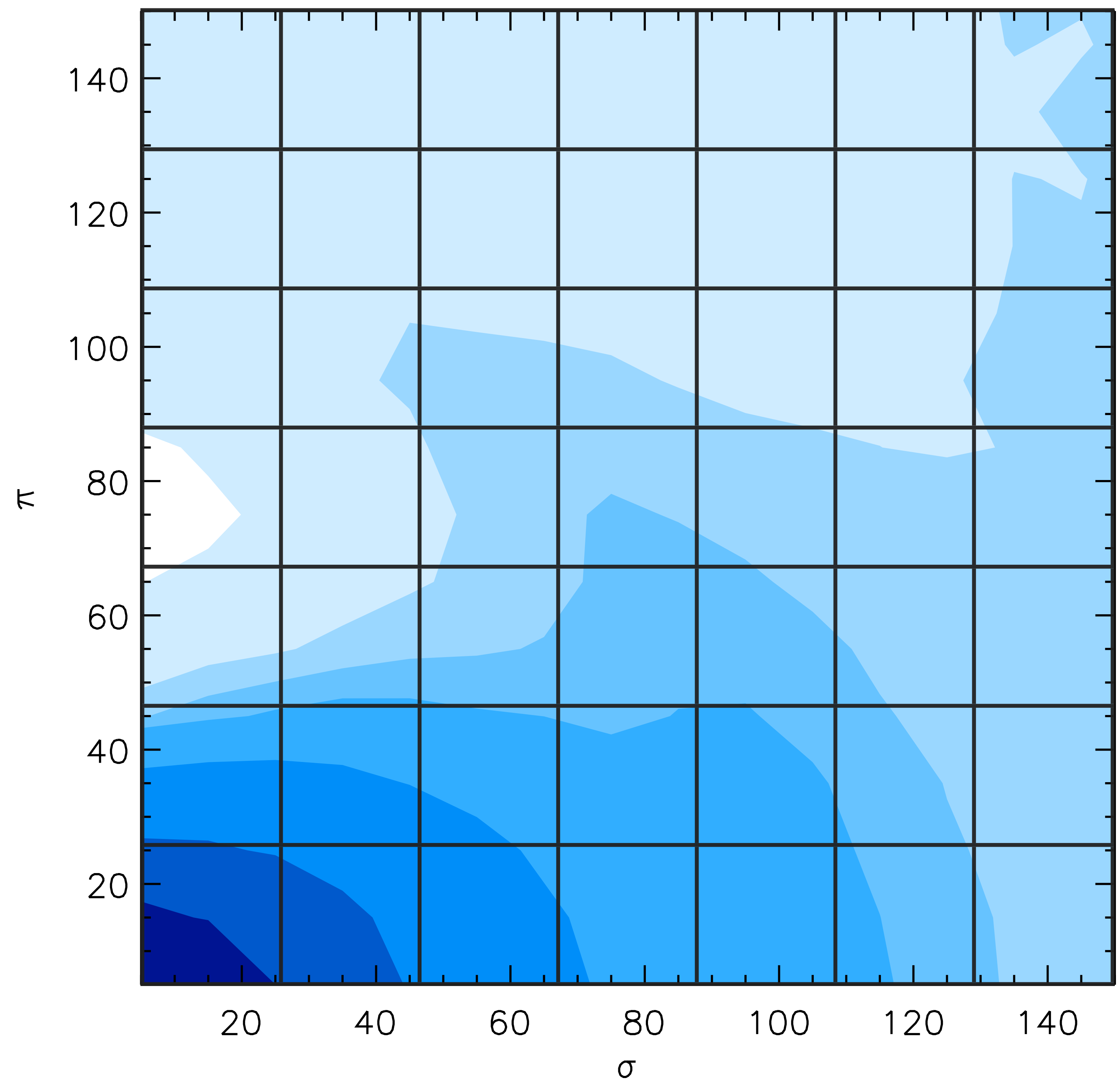

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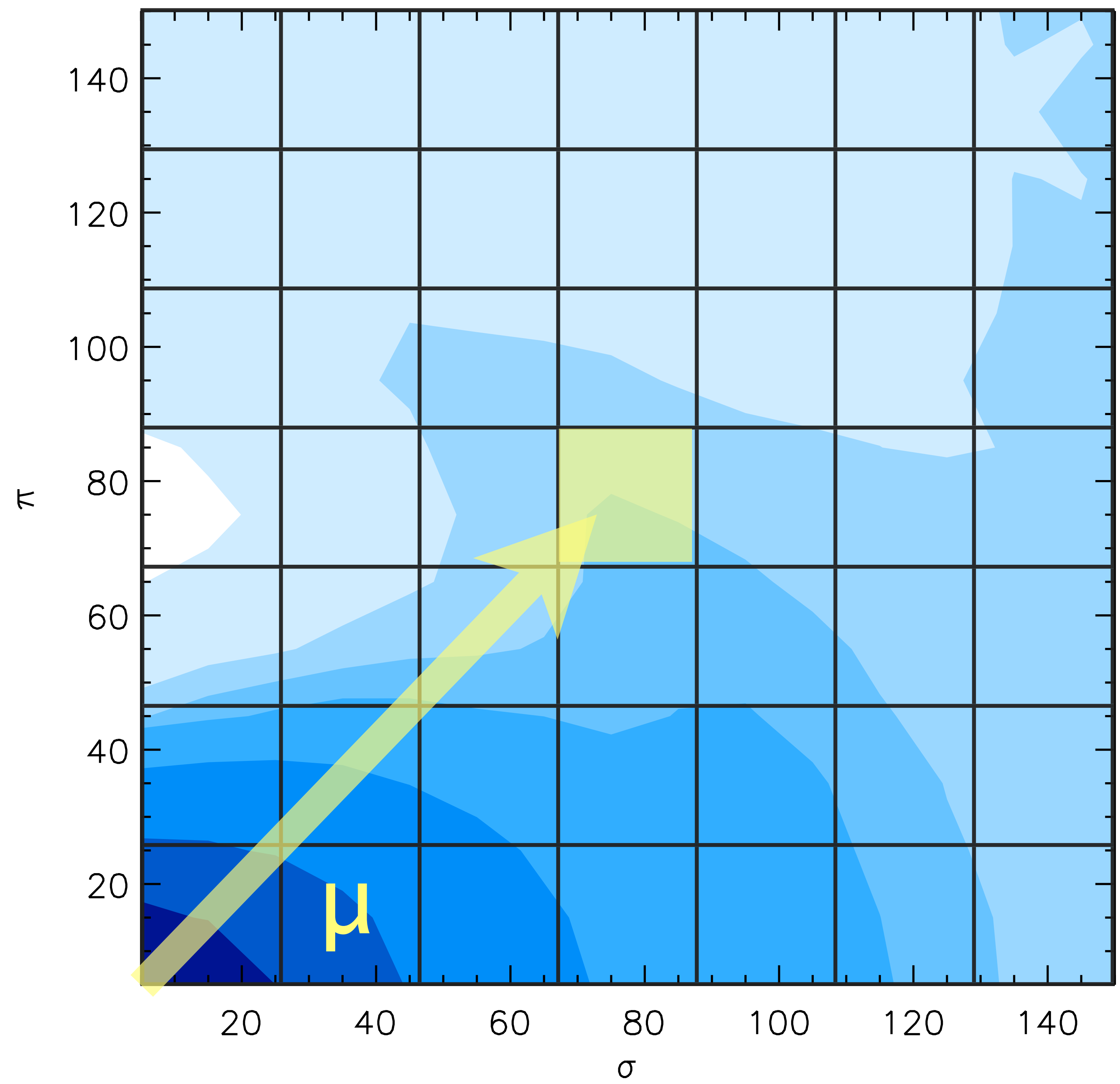
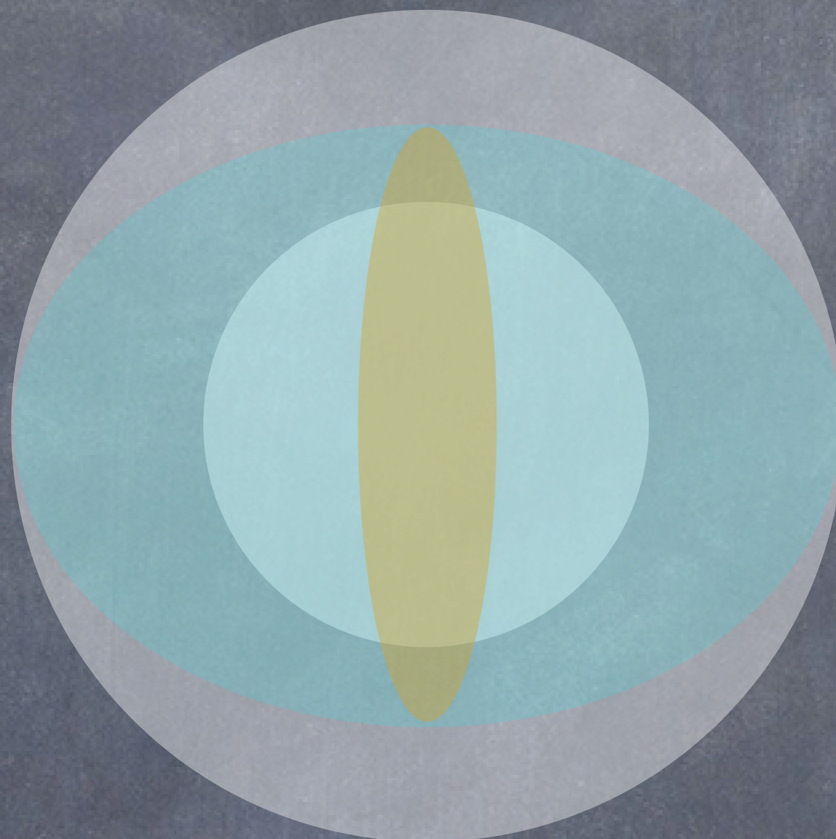


Can we formulate RD in precision cosmology?

Squeezing effect at large scales

(Kaiser 1987)



Finger of God effect at small scales

(Jackson 1972)

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

$$\downarrow$$

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

Taruya, Nichimishi, Saito 2010

Conversion into configuration space

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

YSS, Okumura, Taruya 2013 Taruya, Nichimishi, Saito 2010

Conversion into configuration space

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$$\xi(\sigma,\pi) = \int d^3k\, P(k,\mu) e^{ikx} = \sum \xi_\ell(s)\, \mathcal{P}_\ell(\nu)$$

$$\xi_\ell(s) = i^\ell \int k^2 dk\, P_\ell(k)\, j_\ell(ks)$$

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

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

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

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

$$\vdots$$

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

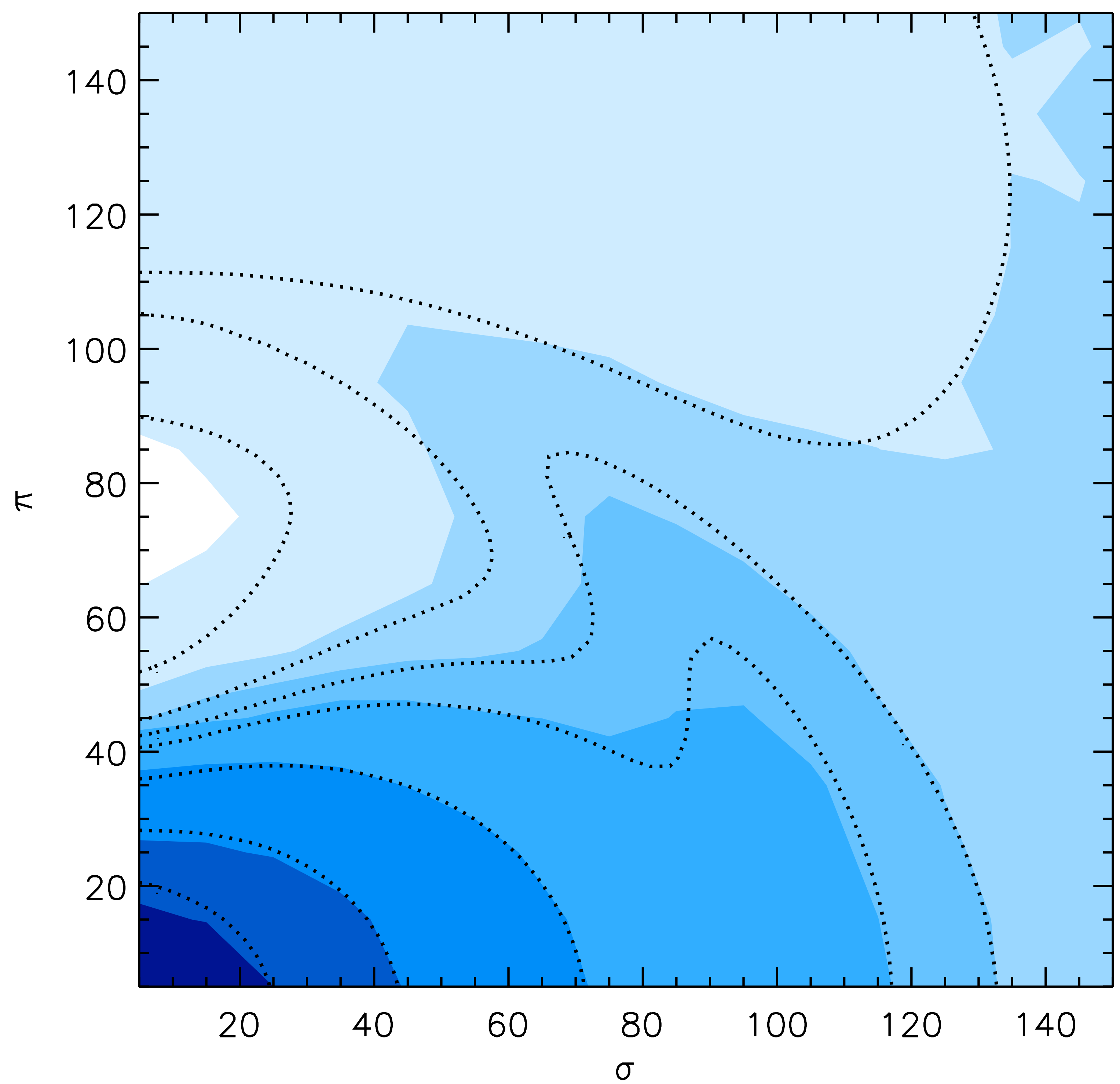
$$+ \gamma(n+5/2,\kappa)/\kappa^{n+5/2} Q_4(k) + \gamma(n+7/2,\kappa)/\kappa^{n+7/2} Q_6(k)$$

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

YSS, Okumura, Taruya 2013 Taruya, Nichimishi, Saito 2010

Theoretical reproduction of 2D BAO

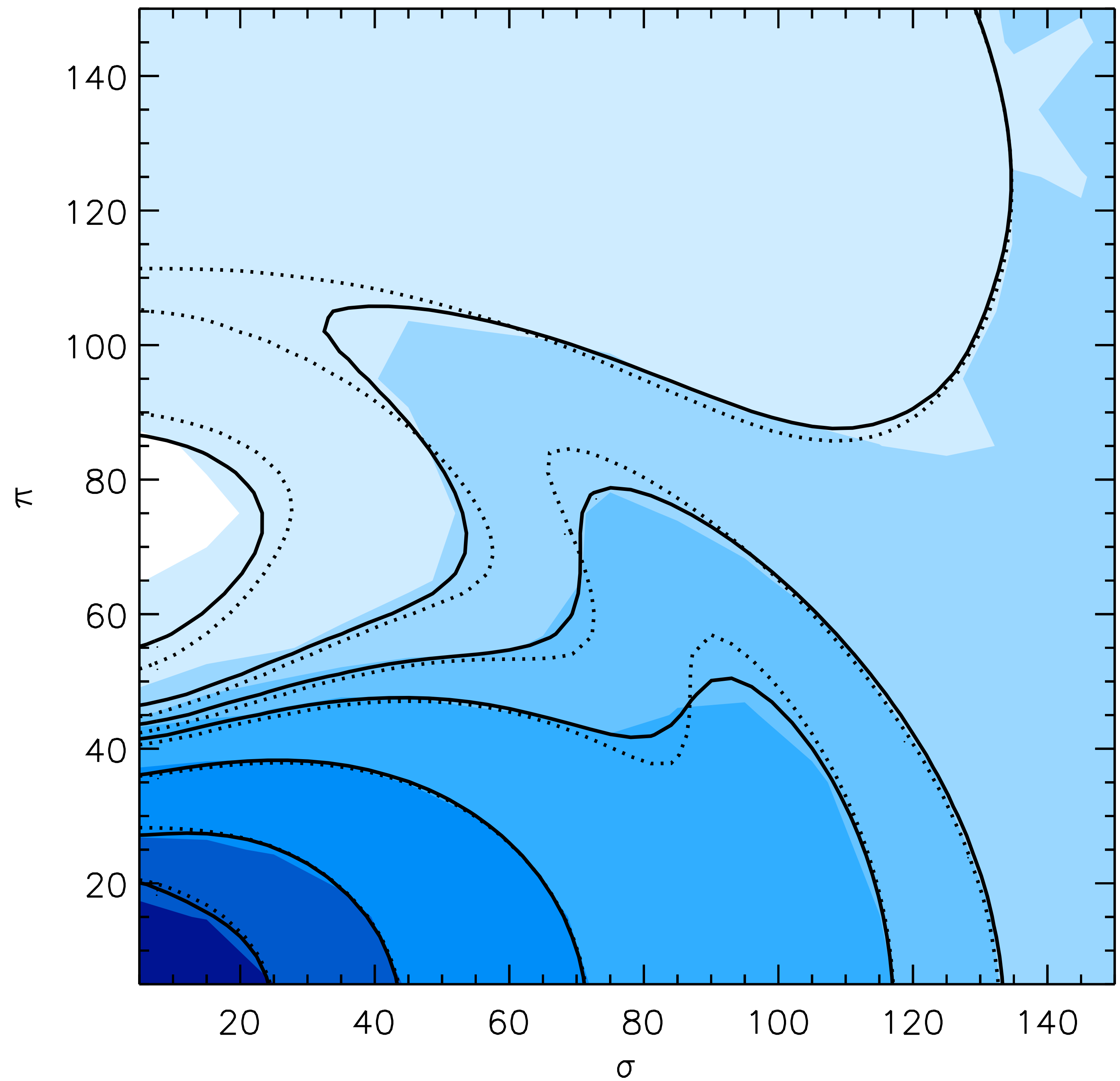
$\xi(\sigma,\pi)$ with Kaiser+Gaussian FoG



YSS, Okumura, Taruya 2013

Theoretical reproduction of 2D BAO

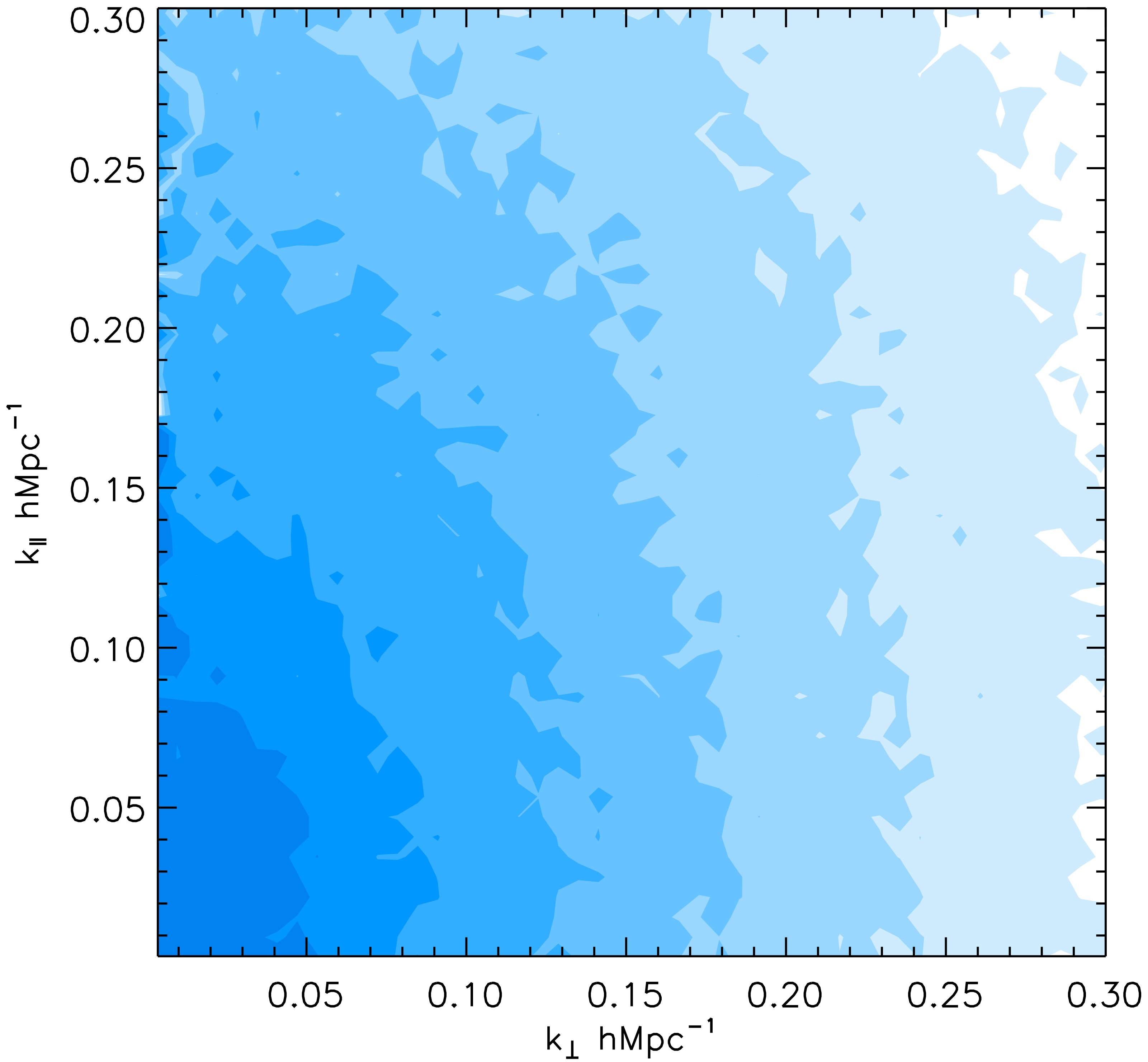
$\xi(\sigma,\pi)$ with additional correction terms



YSS, Okumura, Taruya 2013

Observed spectra in Fourier space

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



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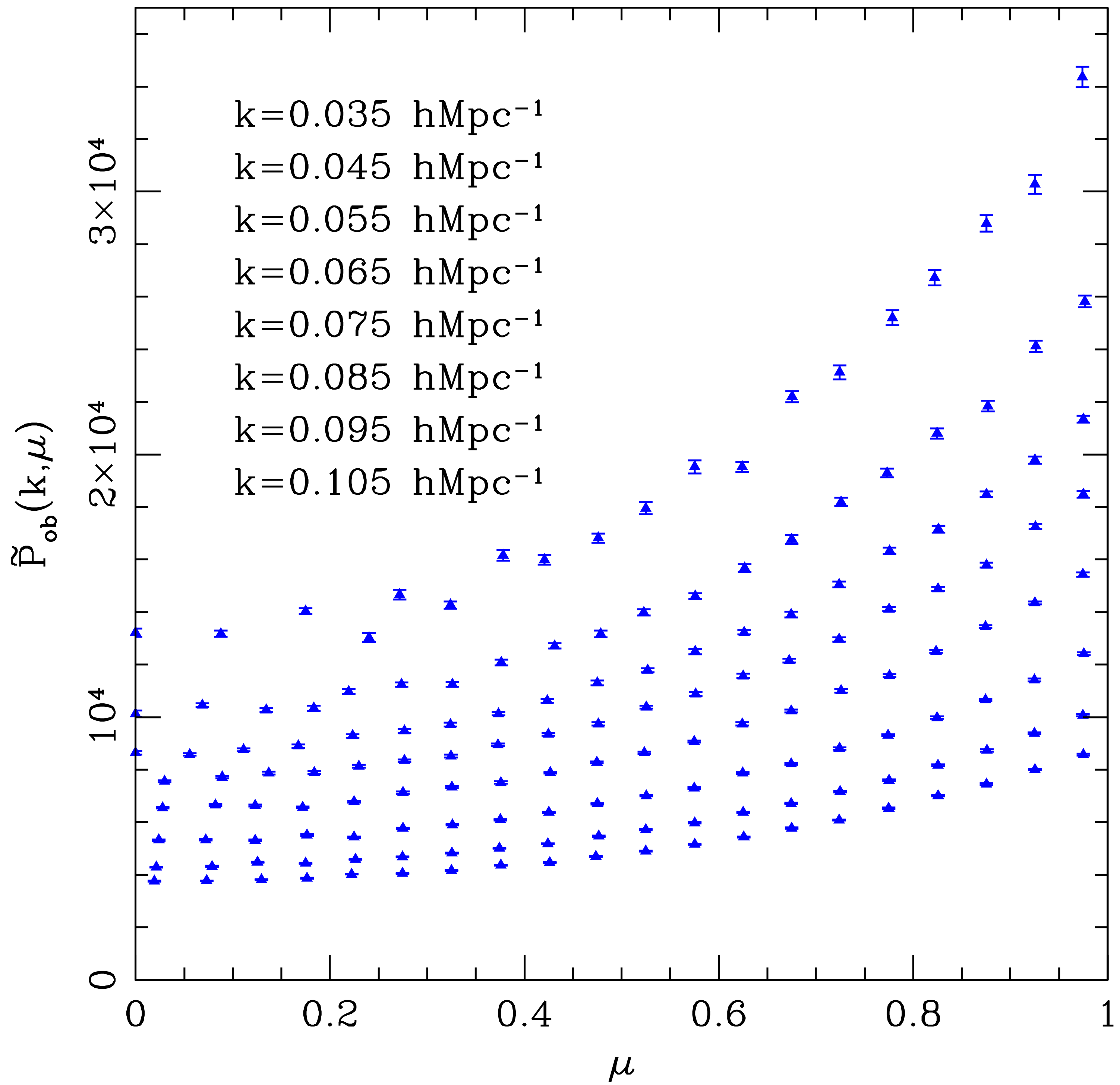
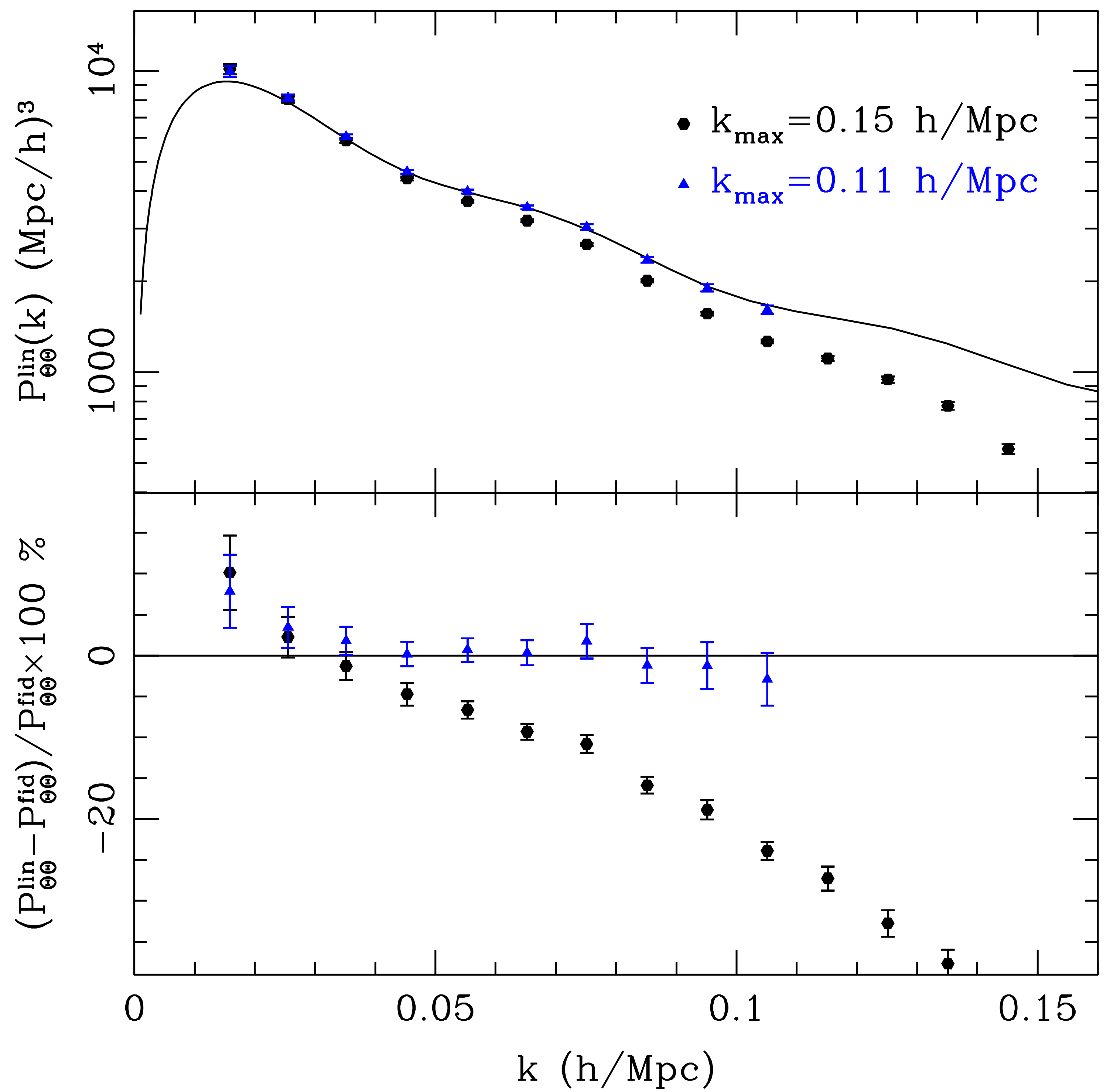


Effect of non-linear correction terms

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



YSS, Nichimishi, Taruya, Kayo 2013

Dark Energy Spectroscopy Instrument

Dark Energy Probes

Providing 50M LRG or ELG galaxies at northern hemisphere, to observe BAO and RSD which are essential for dark energy.

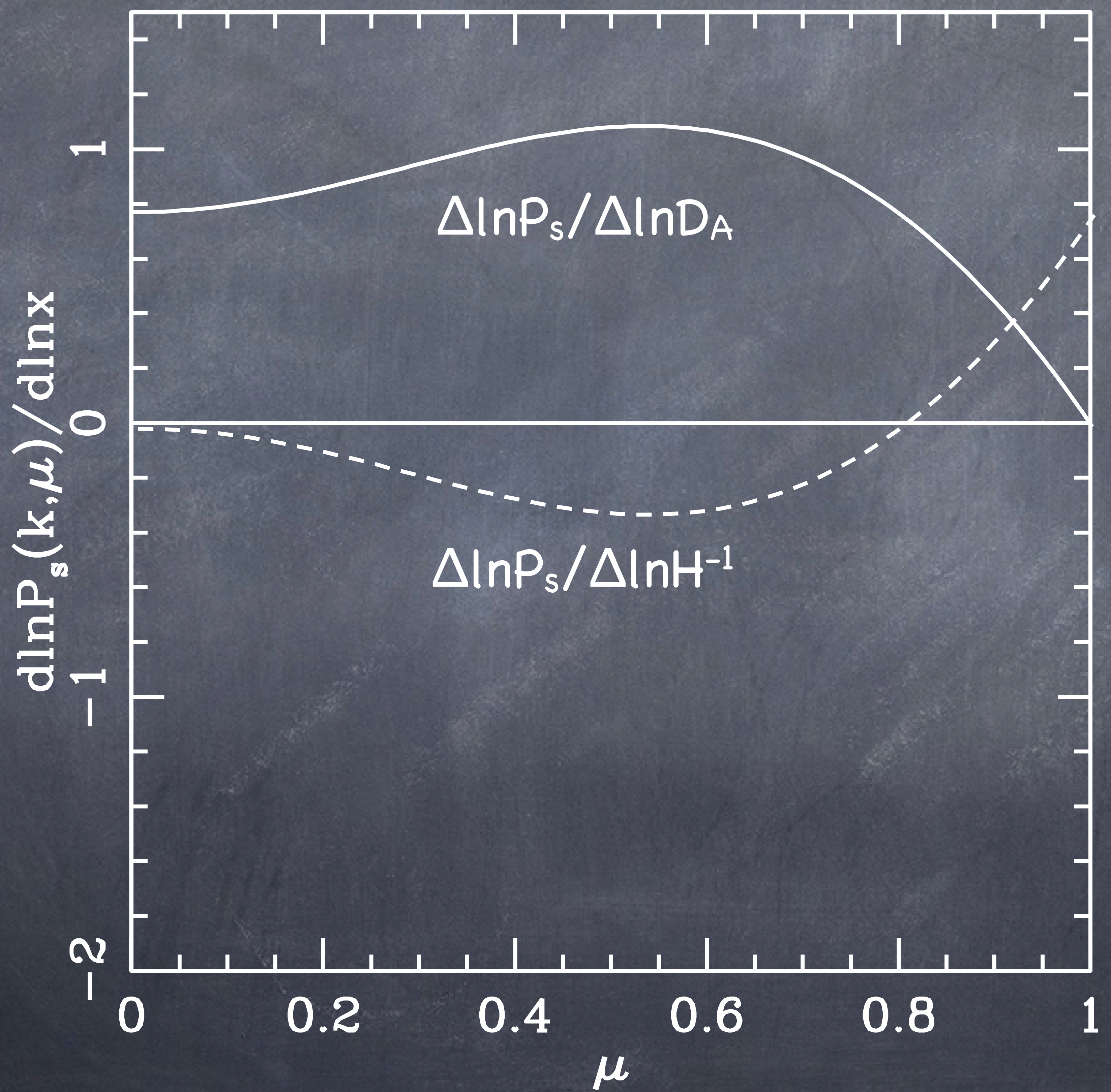
Probing Neutrino mass

Observing high redshift quasars to get Lyman alpha forest, and providing linear spectra at small scaes to probe neutrino mass.

KASI's participation from 2013

KASI will become an associate institute from 2013. We take part in scientific efforts to probe dark energy using spectroscopy wide-deep field survey. We start to invite researchers to collaborate DESI project.

RD version of Alcock-Paczynski effect



YSS 2013

The maximal information from RD

Maximal Fisher matrix description in 3D

$$F_{\alpha\beta} = \int \frac{d^3k}{2(2\pi)^3} \frac{\partial P(k,\mu)}{\partial p_\alpha} \frac{\partial P(k,\mu)}{[P(k,\mu) + 1/n_{gal}]^2} \frac{\partial P(k,\mu)}{\partial p_\beta}$$

$$\sim \frac{1}{2(2\pi)^3} \Sigma l \ \Sigma_{\mu=0}^{\mu=1} \ l^2 \Delta l \Delta\mu \ \frac{\partial P(l,\mu)}{\partial p_\alpha} \frac{\partial P(l,\mu)}{[P(l,\mu) + 1/n_{gal}]^2} \frac{\partial P(l,\mu)}{\partial p_\beta}$$

YSS, Gaztanaga, Martin prepared

The alternate method using 2D

The expression can be effectively reduced using 2D projected spectra

$$F_{\alpha\beta} = \sum \frac{\partial C_{ij}}{\partial p_\alpha} \Theta^{-1}{}_{ij,mn} \frac{\partial C_{mn}}{\partial p_\beta}$$

We probe both radial and transverse distances, and coherent motions along the line of sight using spectroscopy surveys. But when we use the 2D projected spectra, it is not quite clear how we can include the information of radial distance and coherent motion growth function.

Gaztanaga et.al. 2011

Solution: thin slicing approximation for C_l

Full AP effect and the influence of coherent motion can be employed using thin enough binning

$$F_{\alpha\beta} = \sum \frac{\partial C_{ij}}{\partial p_\alpha} \Theta^{-1}{}_{ij,mn} \frac{\partial C_{mn}}{\partial p_\beta}$$

Therefore cross correlation between two bins are not fully independent

Gaztanaga et.al. 2011

The agreement is under investigation

Maximal Fisher matrix description in 3D

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Full AP effect and the influence of coherent motion can be employed using thin enough binning

Due to some unknown reasons, the consistency is not easy to be achieved

$$F_{\alpha\beta} = \Sigma \frac{\partial C_{ij}}{\partial p_\alpha} C^{-1}_{ij,mn} \frac{\partial C_{mn}}{\partial p_\beta}$$

YSS, Gaztanaga, Martin prepared

The benefit of 2D expression

more comprehensive in cross correlation between spectroscopy and photometry maps

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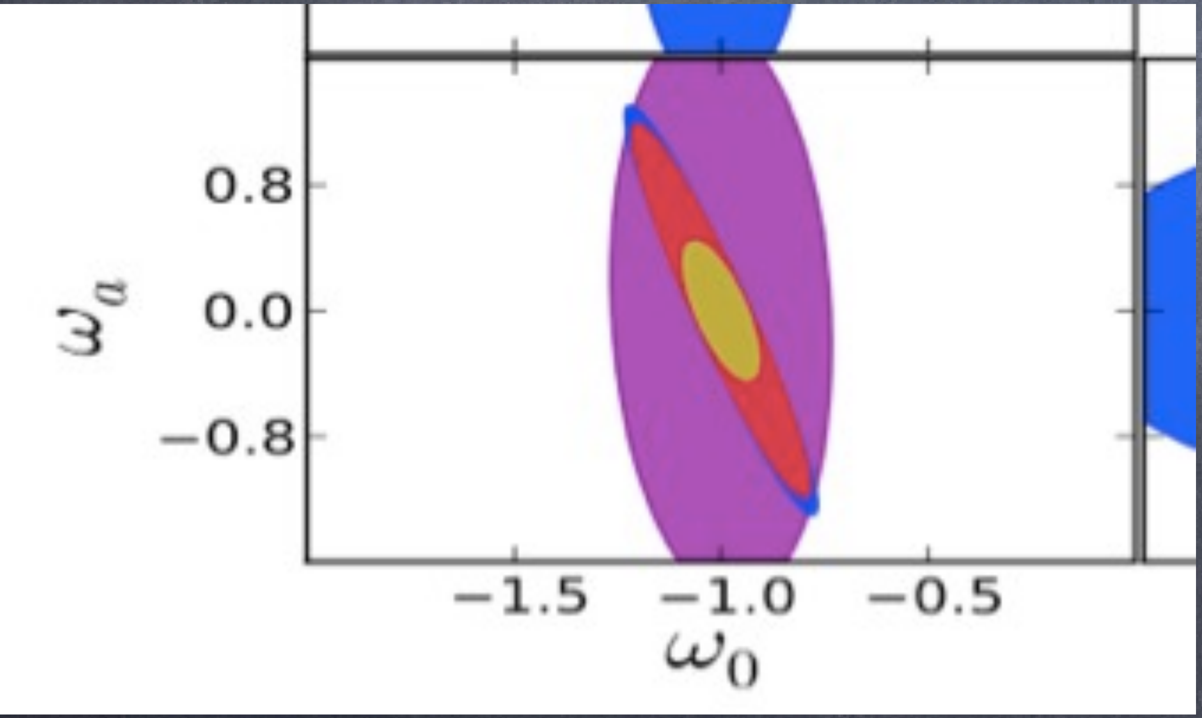
$$F_{\alpha\beta} = \sum \frac{\partial C_{ij}}{\partial p_\alpha} \Theta^{-1}{}_{ij,mn} \frac{\partial C_{mn}}{\partial p_\beta}$$

$FoM_{F\times B} > FoM_{F+B}$



Gaztanaga et.al. 2011

Kirk et.al. 2013

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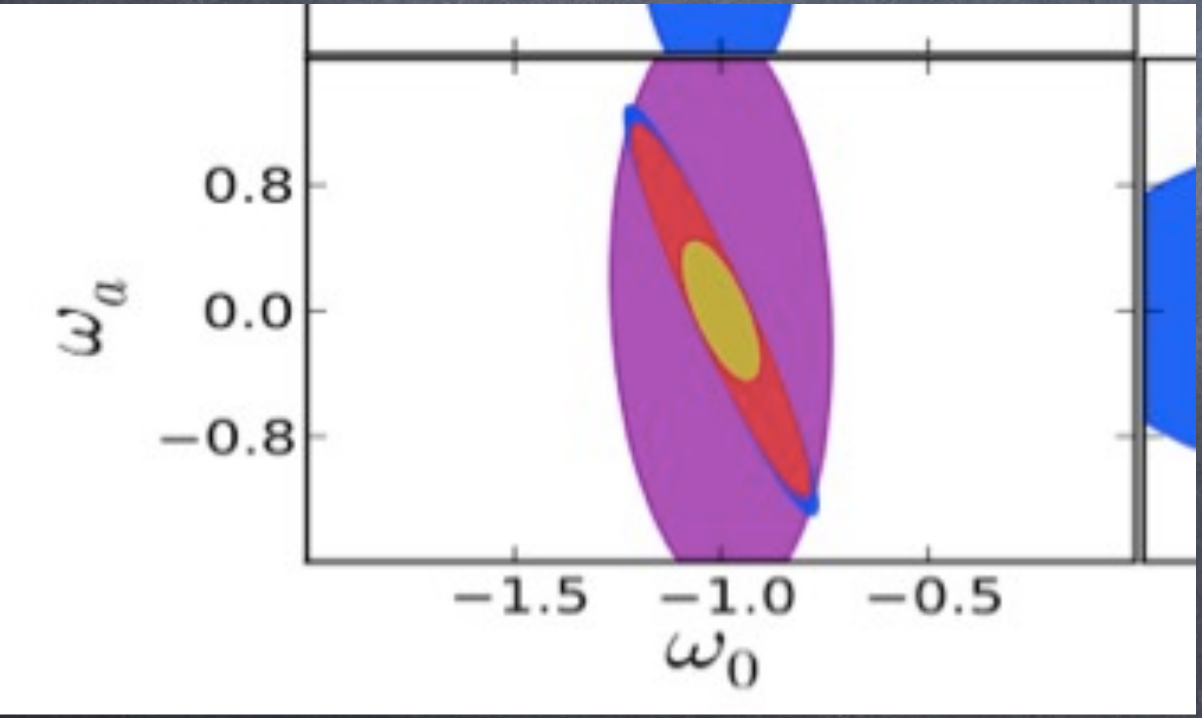

Gaztanaga et.al. 2011

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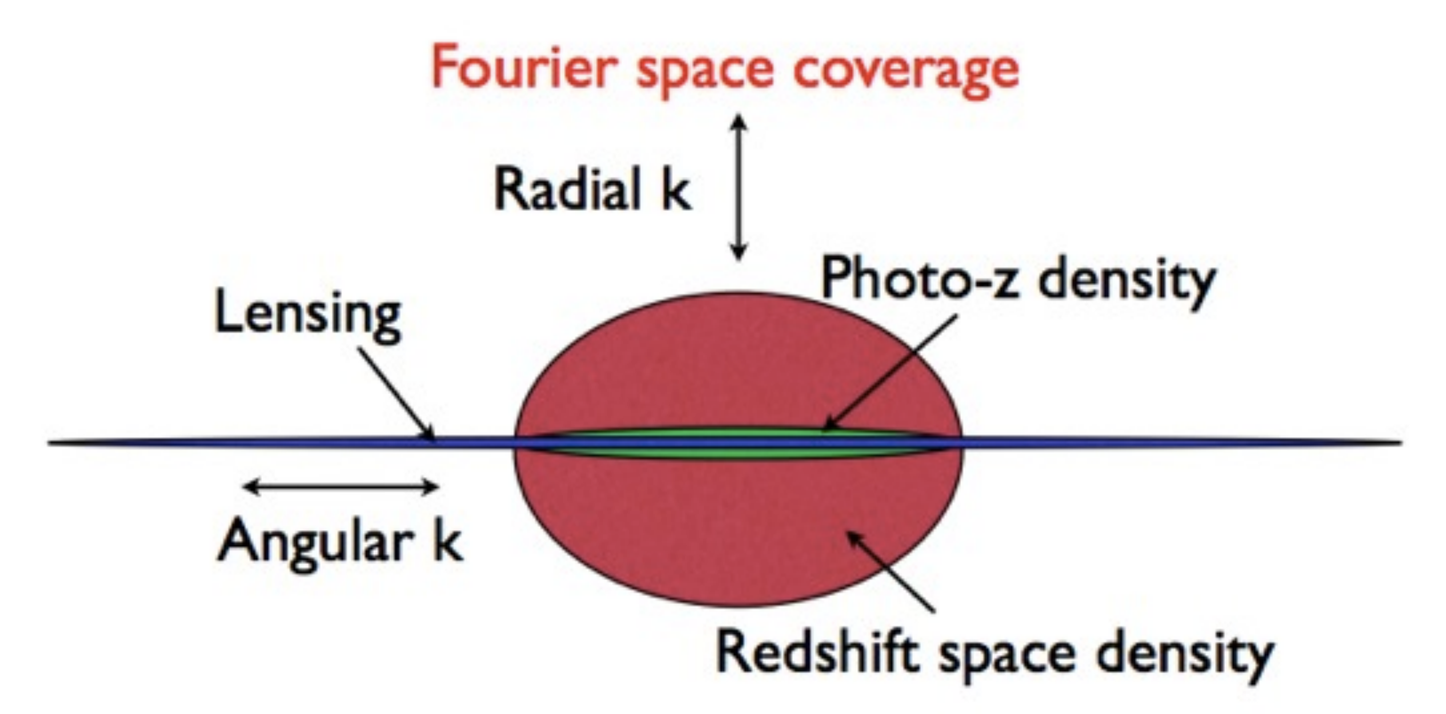


Font-Rivera et.al. 2013

Roland et.al. 2013

The origin of disagreement

FoM from F+B = $\boxed{}$

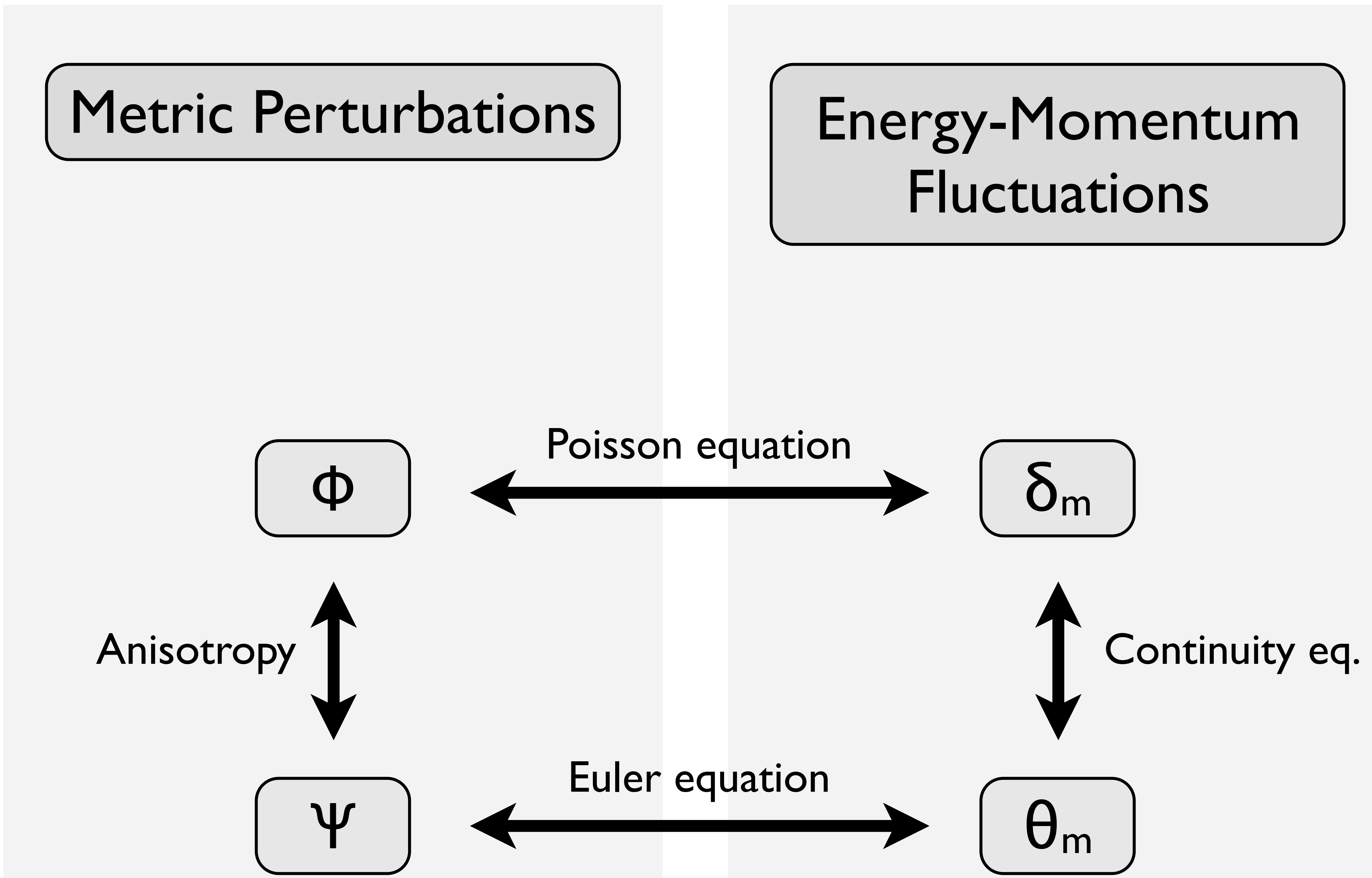
FoM from F×B = $\boxed{}$ + loss + gain

FF×FF		FF×BB loss
	FB×FB gain	
BB×FF loss		BB×BB

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

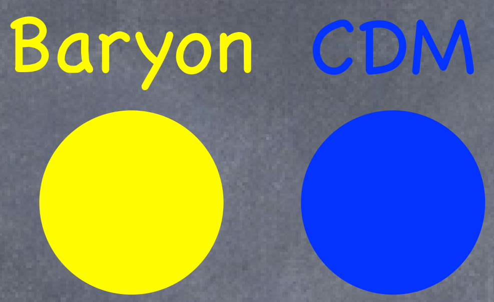
Motivation for the same sky survey



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

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.

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.

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

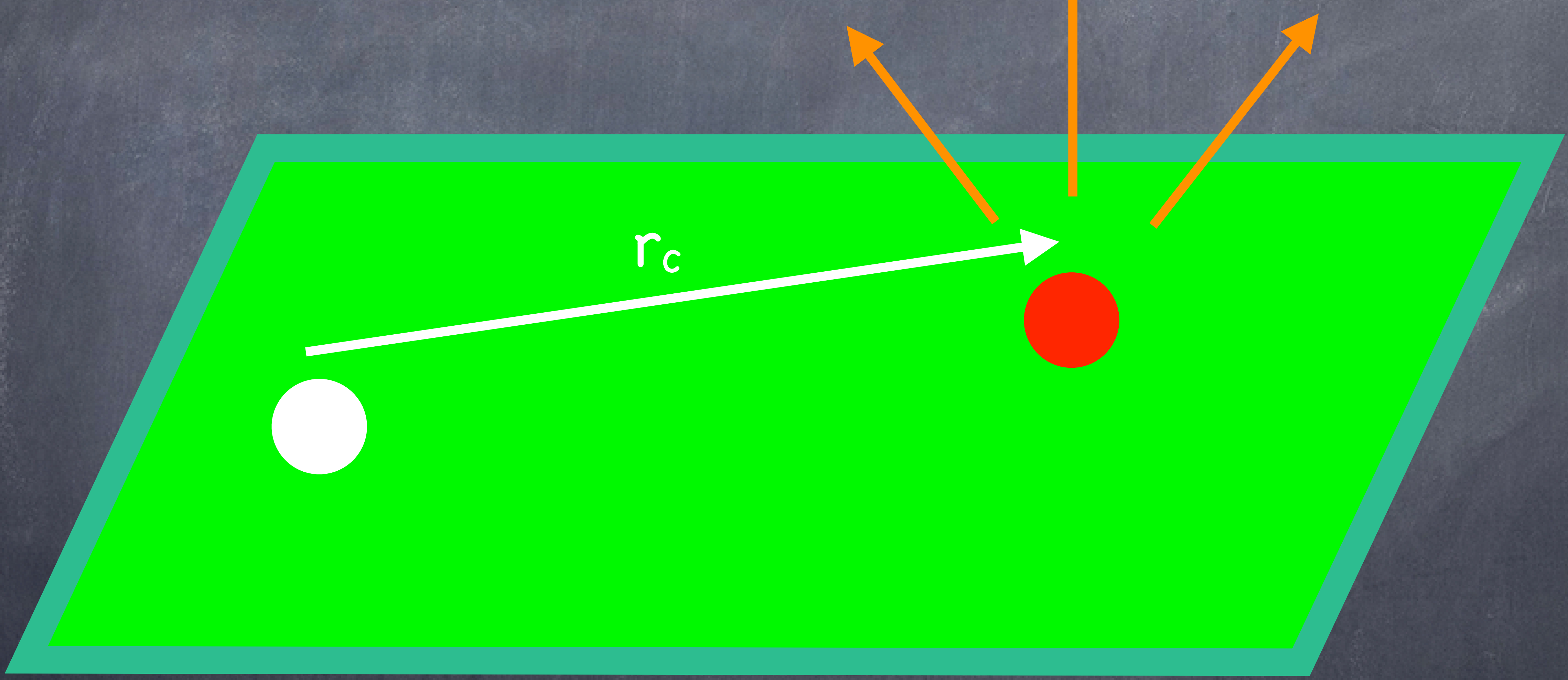
The ratio of the two scales defines a cross-over radius beyond which the four dimensional gravitational theory transition into a five dimensional regime,

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

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.

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,

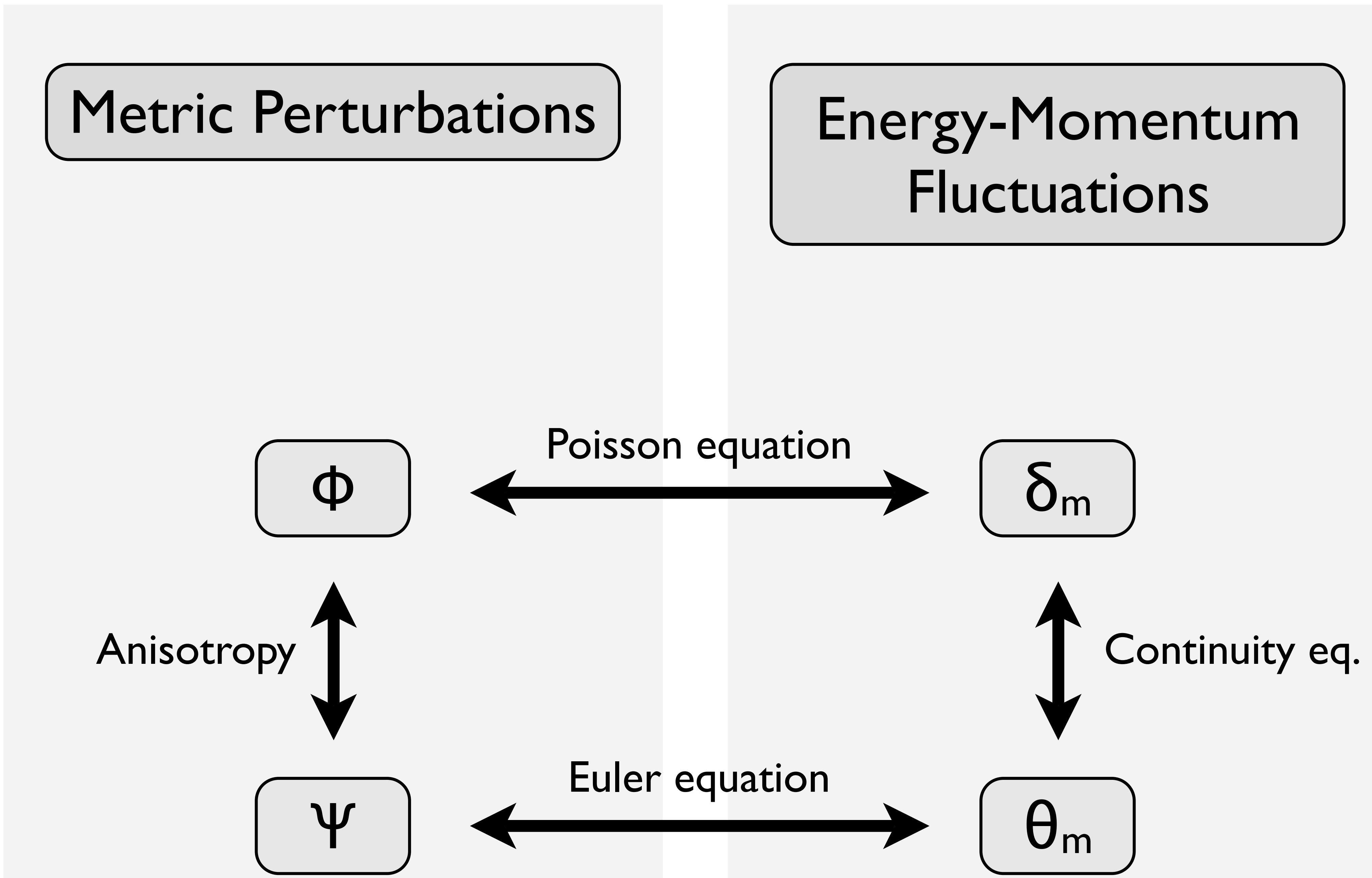
$f_{RR} = d^2f/dR^2 < 0$ Unstable

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

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

YSS, Hu, Sawicki (2007)

Motivation for the same sky survey



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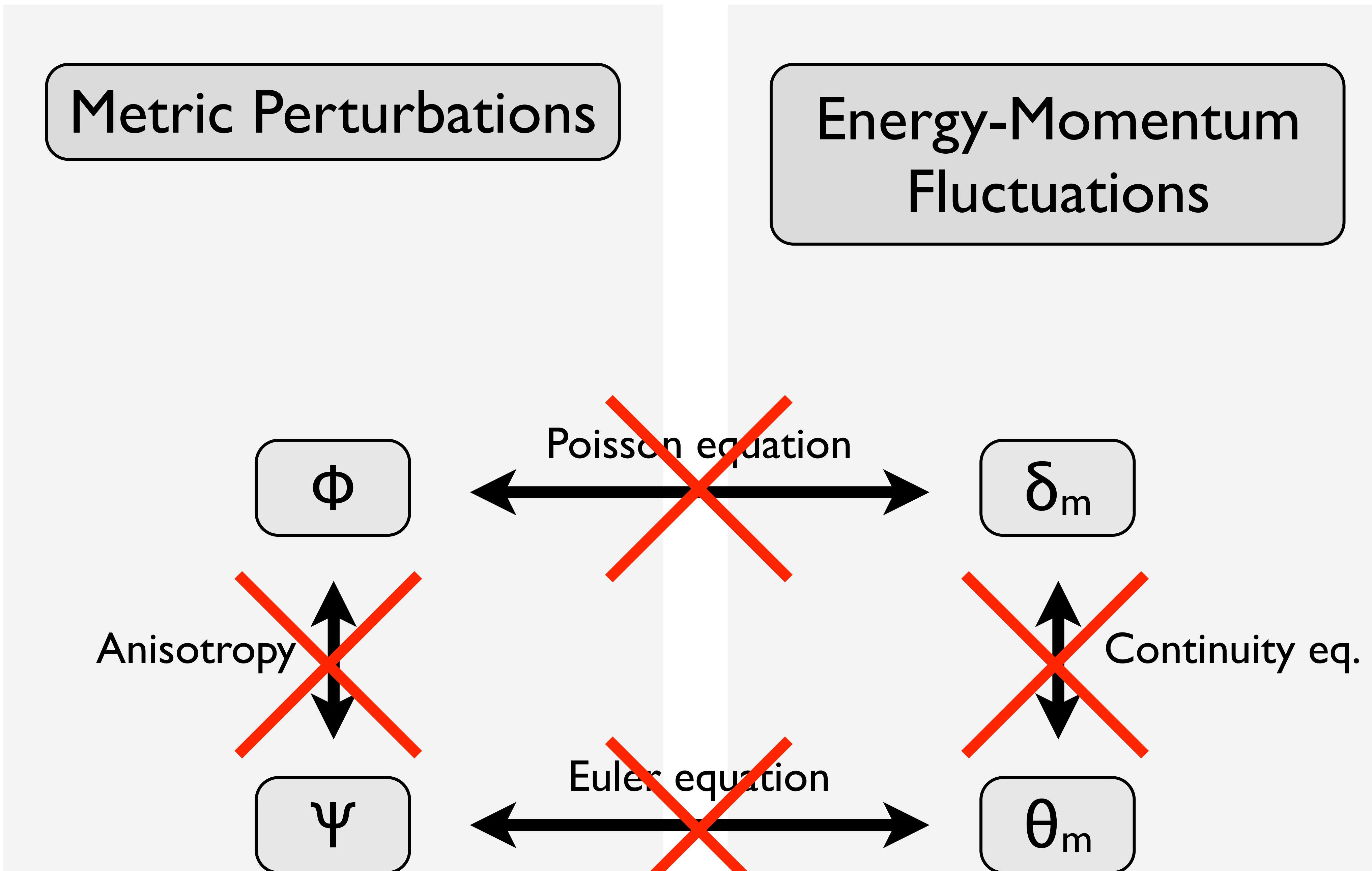

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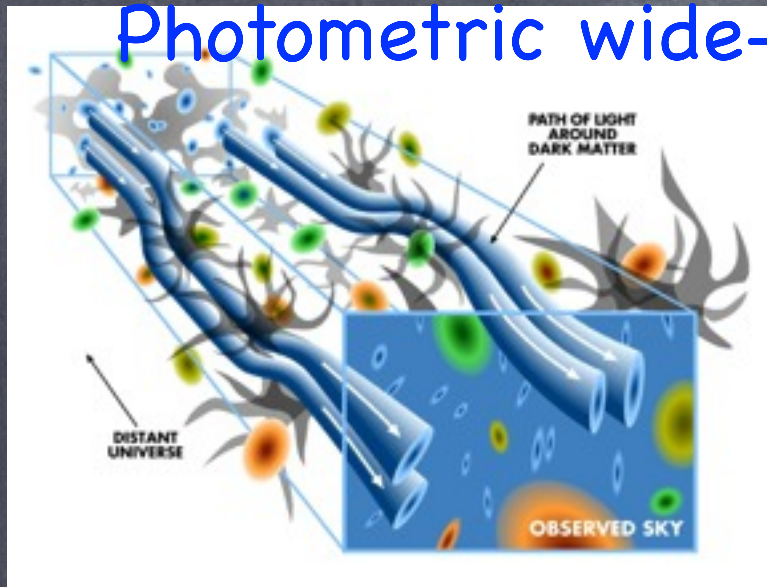
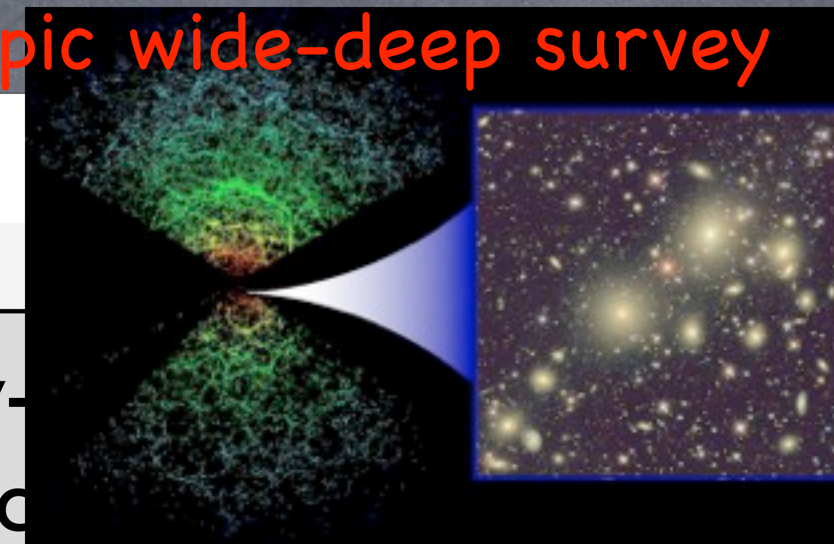
Structure formation

Photometric wide-deep survey



Spectroscopic wide-deep survey



urbations

Energy-
Fluc

WL measures Φ-Ψ

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

What is good to scan both at the same fields?

At different regions, we will make only parametrized test on different dark energy models.

What is good to scan both at the same fields?

With scanning the same fields, we are able to make fully covariant test of different dark energy models.

Test of mass screening effect

$$C_l^{\kappa\kappa} = \Sigma\ \Delta D\ W^2\ \Delta^2_{\Phi\Phi}$$

Song, Kazuya 2010

Test of mass screening effect

$$C_l^{\kappa\kappa} = \Sigma\, \Delta D\, W^2\, \Delta^2_{\Phi\Phi}$$

$$C_l^{\kappa\kappa} = \Sigma\, \Delta D\, W'^2\, C_l^{\delta\delta}$$

$\Delta^2_{\Phi\Phi}$ $C_l^{\delta\delta}$

Dynamical DE

$C_l^{\kappa\kappa} = C_l^{\kappa\kappa}$

Geometrical DE

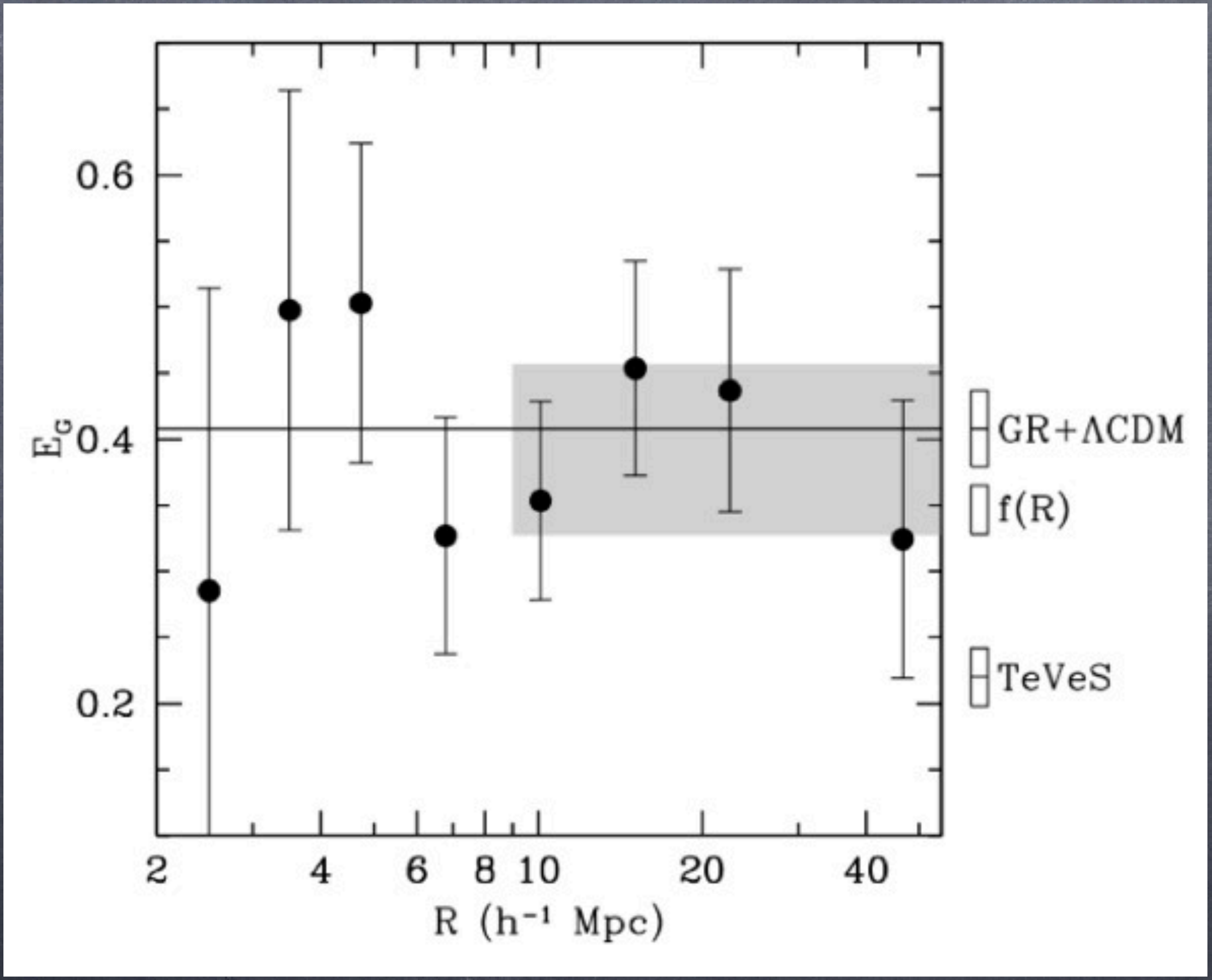
$C_l^{\kappa\kappa} \neq C_l^{\kappa\kappa}$

$$k^2\Phi = 4\pi G_N\, a^2\, \rho_m \delta_m$$

Song, Kazuya 2010

Consistency test using cross-correlation

$$E_G(R) = \frac{1}{\beta} \frac{\Upsilon_{gm}(R)}{\Upsilon_{gg}(R)}.$$



Zhang et.al. 2009 Reyes et.al. 2010

Generation of wide field survey

Photometric (WL) Spectroscopic (BAO, topology, coherent motions)

	Ground	Space
Second 2004-2009	CFTHLS	
	SDSS II	$0.1<z<0.5$, N=100,000
Third 2011-2015	DES	
	SDSS III (BOSS)	$0.2<z<0.8$, N=1,500,000
Next 2018-2023	LSST	WFIRST, EUCLID
	DESI	WFIRST, EUCLID

Missing component at ground telescope

Photometric (WL) Spectroscopic (BAO, topolog s)

	Ground	
Second	CFTHLS	
	SDSS II	
Third	DES	
	SDSS III (BOSS)	$0.2<z<0.8$, N=1,500,000
Next 2018-2023	LSST	WFIRST, EUCLID
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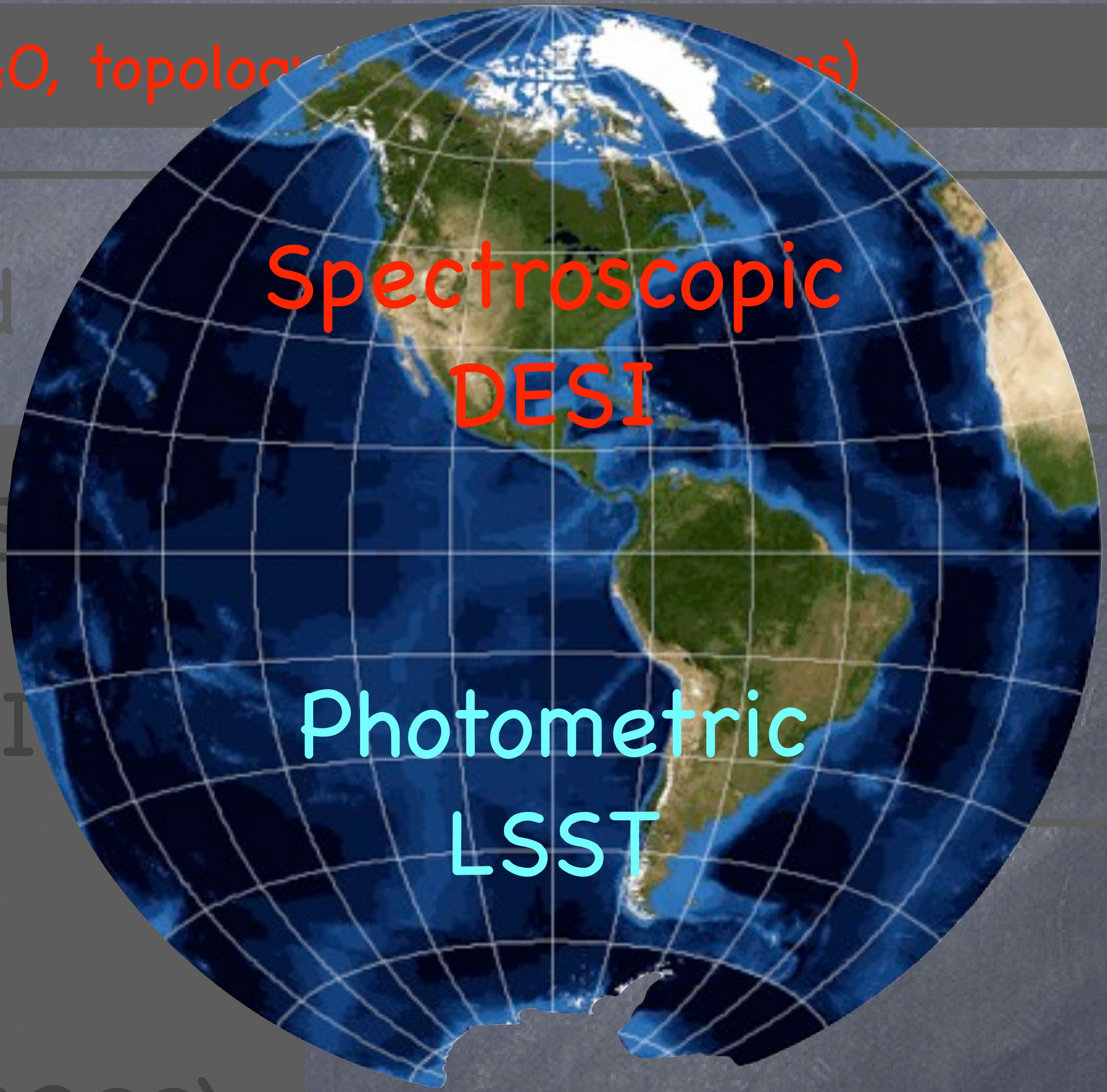

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4m Multi Object Spectroscopic Telescope

Major Science Drivers

GAIA follow up

Providing full 6D coordinates for stellar science in Milky way. Aiming dynamical structure of Milky Way.

eROSITA follow up

Surveying >50,000 southern galaxy clusters. Investigating the evolution of galaxy populations in clusters.

4m Multi Object Spectroscopic Telescope

Major Science Drivers

GAIA follow up

Providing full 6D coordinates for stellar science in Milky way. Aiming dynamical structure of Milky Way.

eROSITA follow up

Surveying >50,000 southern galaxy clusters. Investigating the evolution of galaxy populations in clusters.

Alternative Science Goals

4MOST will provide a unique opportunity to determine the nature of dark energy by cross-correlating photometric and spectroscopic wide deep field surveys in southern sky.

European spectroscopy wide deep survey

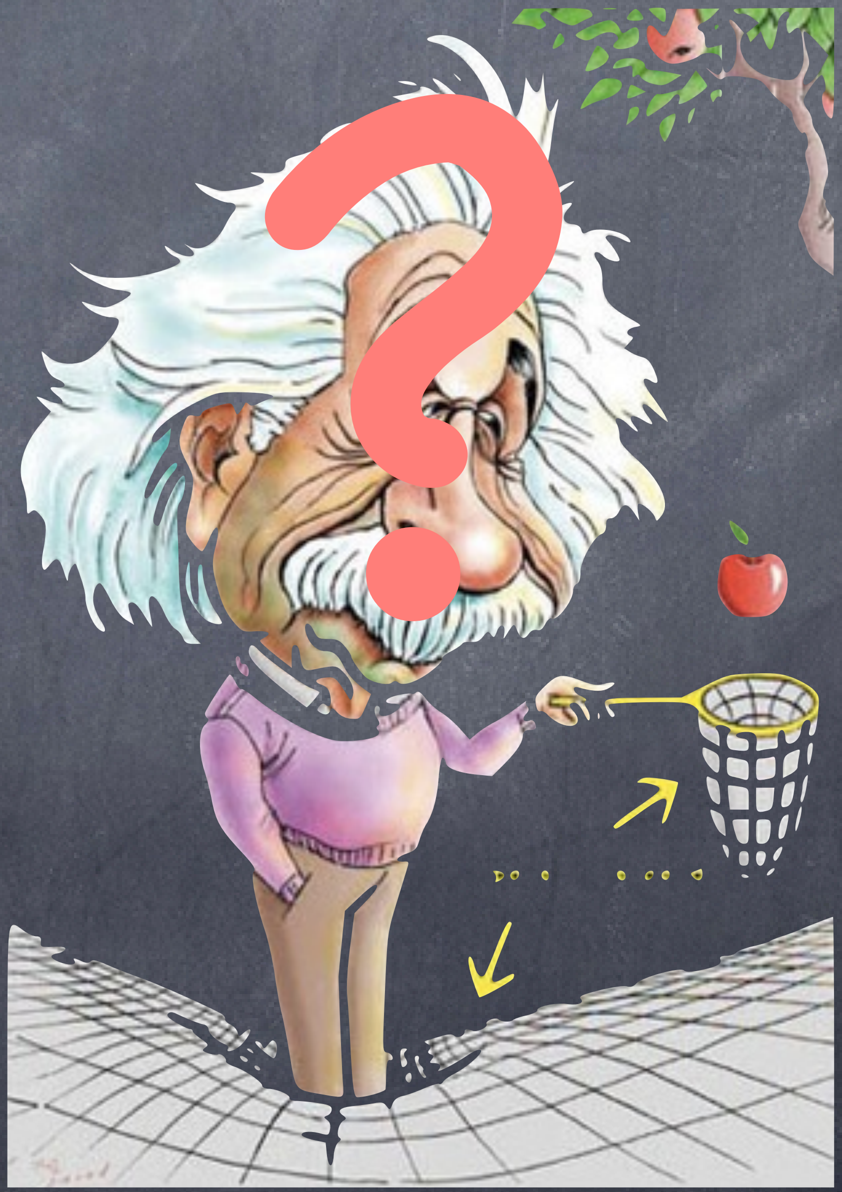
in Chile

THE window
for the same sky survey

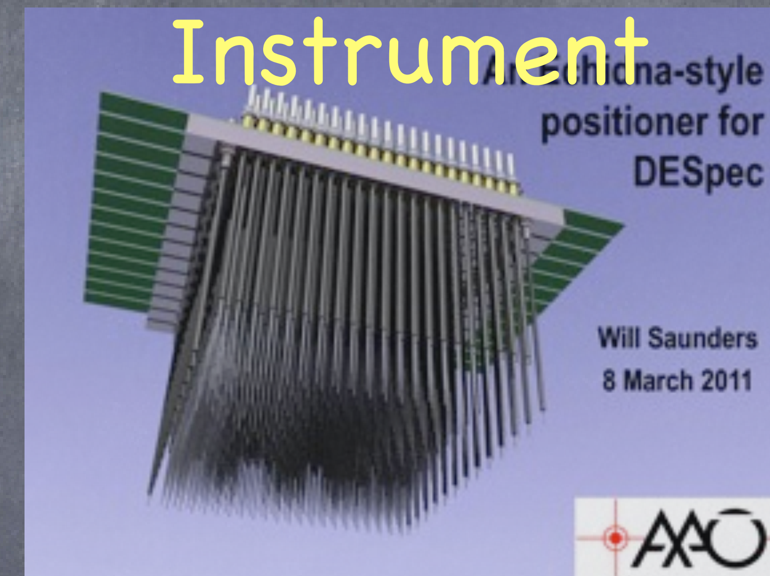
	Baseline	Goal
class	4m	-
FoV	3 deg	>5 deg
Fiber pos	1500	>3000
Area	$10000deg^2$	$20000deg^2$
Objects	5M	>20M

European spectroscopy wide deep survey

The ultimate cosmological test of Einstein's gravity

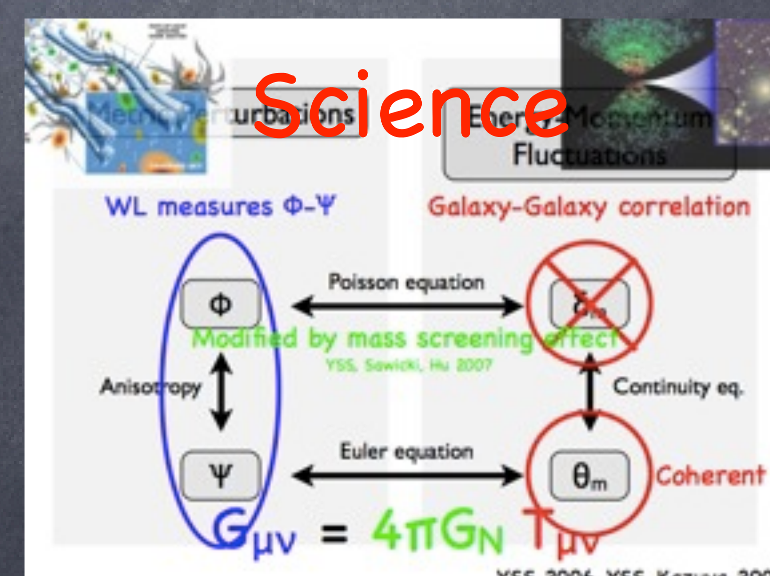


Concepts of participation



AAO-KASI collaboration

+



Conclusion

- We are interested in the same sky survey of the photometry and spectroscopy wide deep survey in southern hemisphere.
    - Enhancing dark energy constraint by the same sky survey
    - Key observables to test general relativity cosmologically
    - Understanding the nature of dark energy in model independent way

- We plan to launch the collaboration group to study strong lens probe of the universe.
    - The follow-up strong lensing observation targeted by DES or LSST
    - Probing dark matter and dark energy simultaneously
    - An independent probe for dark energy science

- We are interested in starting asteroid search using 0.5m telescope in southern hemisphere.