Cosmological Implication of Large Scale Structure of the Universe

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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

Cosmological observable of primordial universe

Few ideas have had greater impact in cosmology than that of inflation. Inflation makes four predictions, three of which provide very good descriptions of data: the mean curvature of space is vanishingly close to zero, the power spectrum of initial density perturbations is nearly scale-invariant, and the perturbations follow a Gaussian distribution. As the data have improved substantially they have agreed well with inflation, whereas all competing models for explaining the large scale structure in the Universe have been ruled out.

We must note though that these three predictions are all fairly generic. Further, although existing models for the formation of structure have been ruled out, there is no proof of inflation's unique ability to lead to our Universe. Indeed, alternatives are being invented.

Cosmological observable of primordial universe

The fourth (and yet untested) prediction may therefore play a crucial role in distinguishing inflation from other possible early Universe scenarios. Inflation inevitably leads to a nearly scale-invariant spectrum of gravitational waves, which are tensor perturbations to the spatial metric. Detection of this gravitational wave background might allow discrimination between competing scenarios.

Parameterization of gravitational wave

There are four key observables of primordial spectra; scalar amplitudes, scalar tilt, tensor amplitude, tensor tilt. In single scalar field slow roll inflationary model,

Q_S (scalar amplitude): energy scale of inflation / slow roll speed

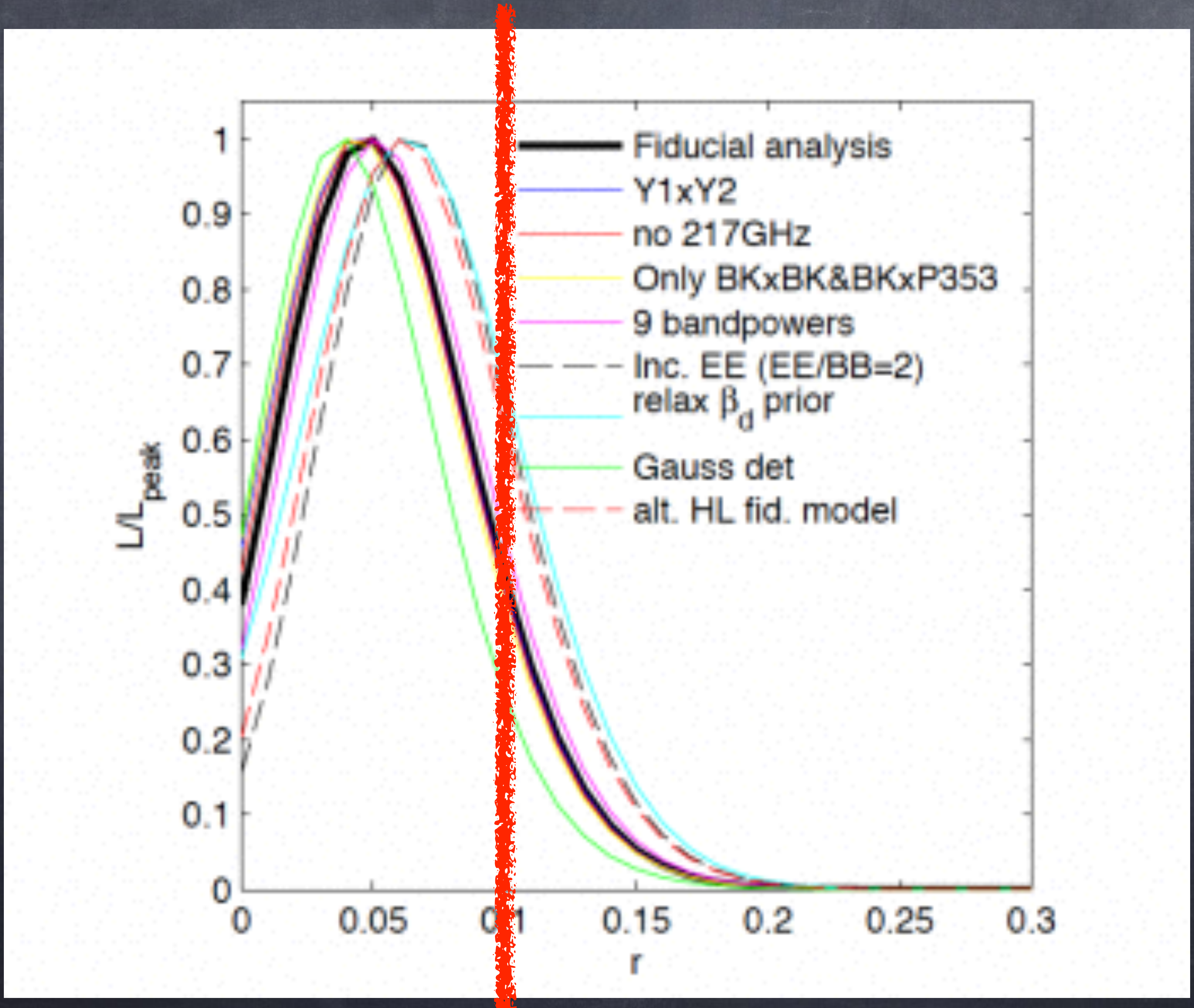
n_S (scalar tilt): slow roll speed

Q_T (tensor amplitude): energy scale of inflation

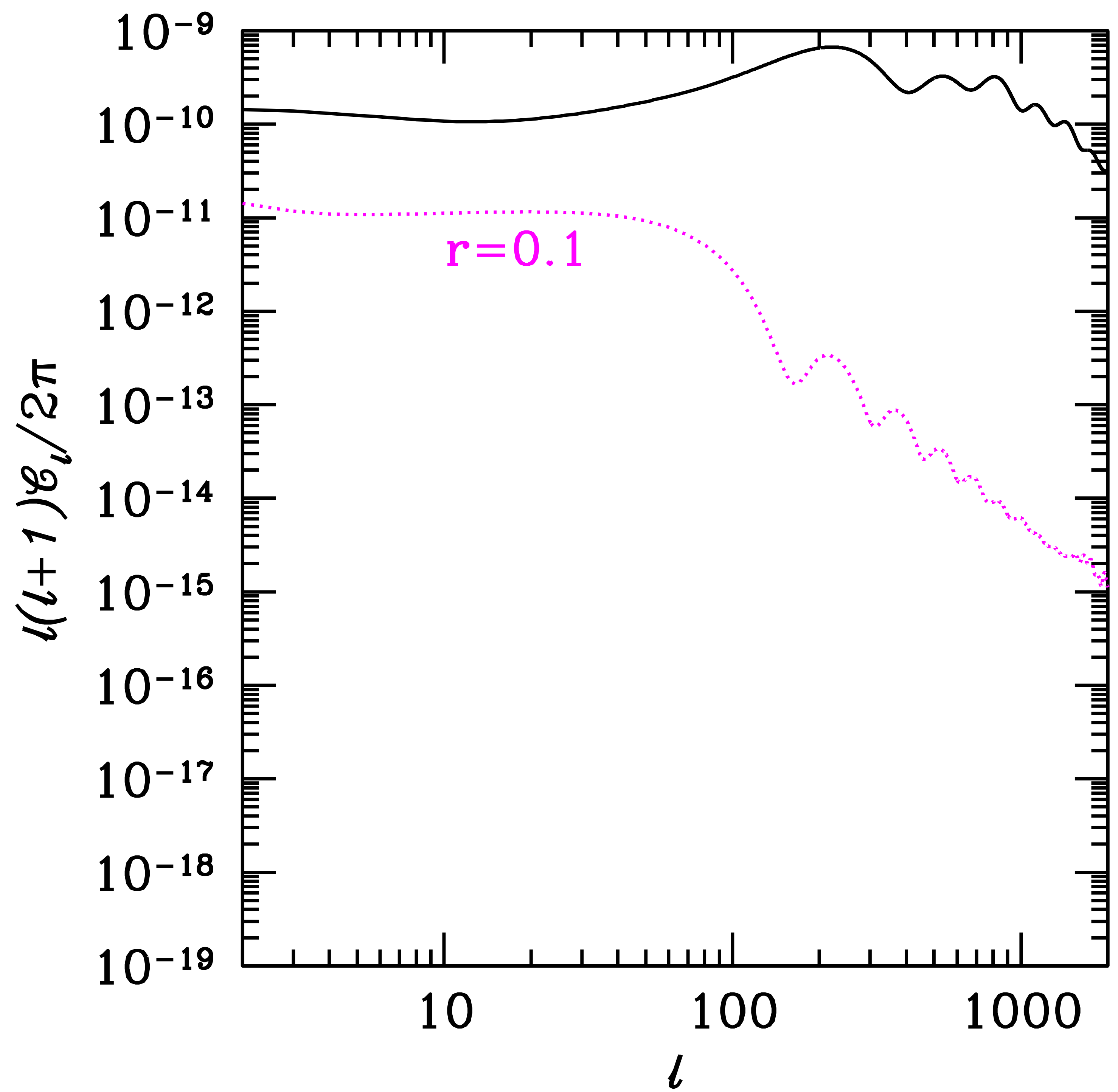
We parameterize the amplitude of tensor as r which is ratio between scalar and tensor amplitudes,

$$r = Q_T/Q_S$$

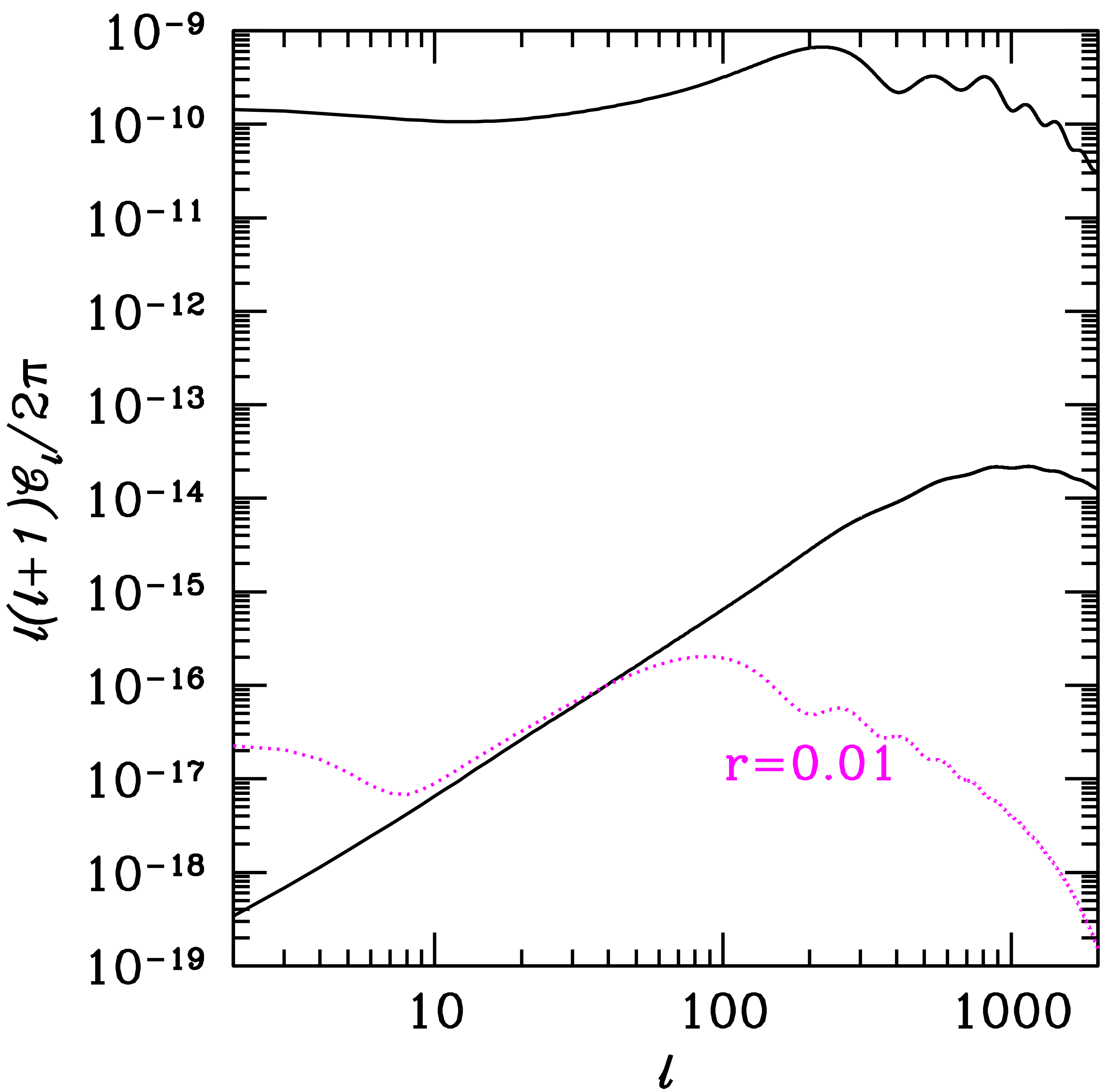
Current constraint on r



Constraint on r by TT mode



Constraint on r by BB before cleaning WL



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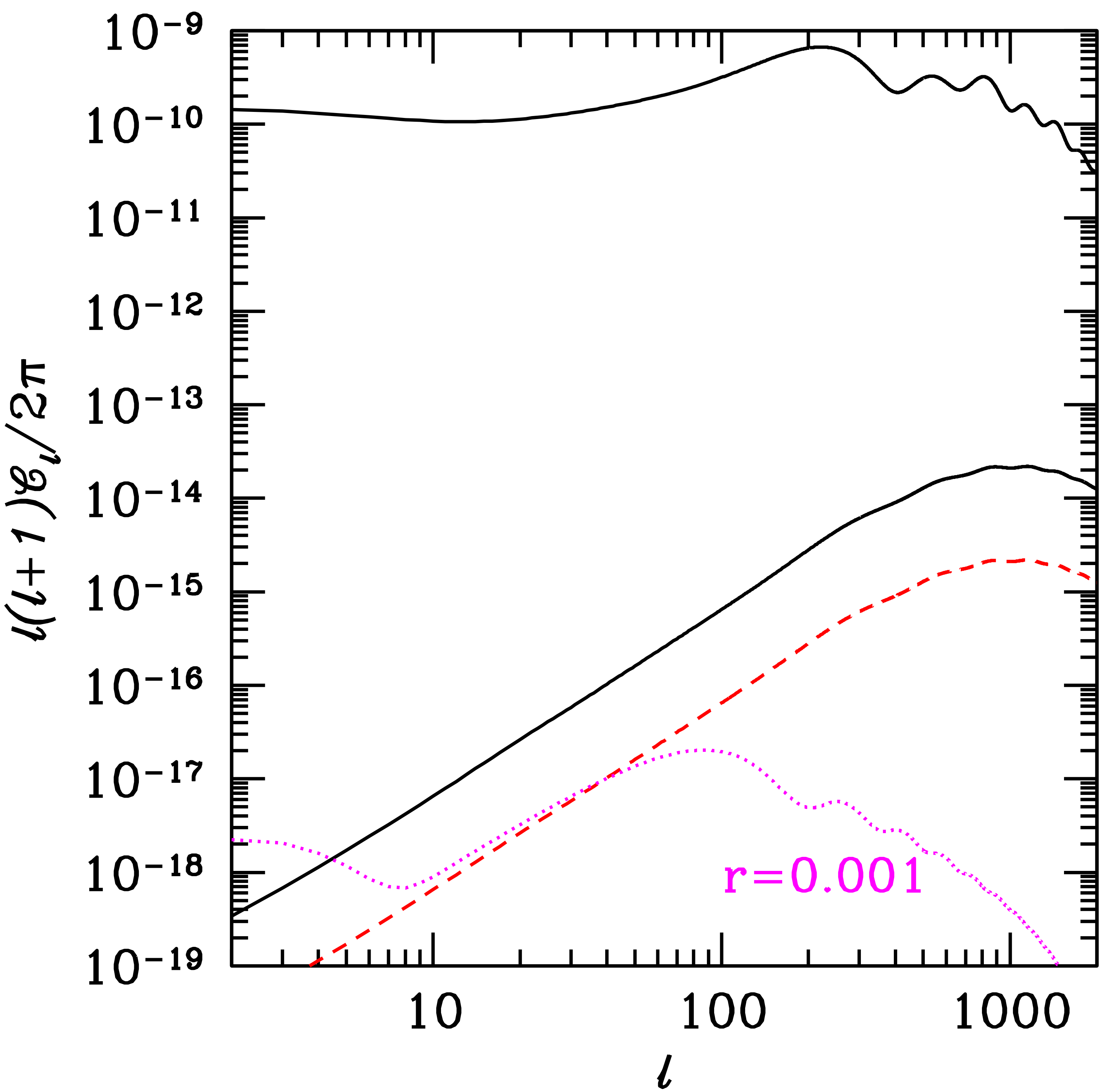


Knox, YSS

Reconstructed CMB lensing field

Weak lensing by the large scale structure of the Universe remaps the primary temperature field $\Theta(n) = \Delta T(n)/T$ and dimensionless Stokes parameters Q(n) and U(n),

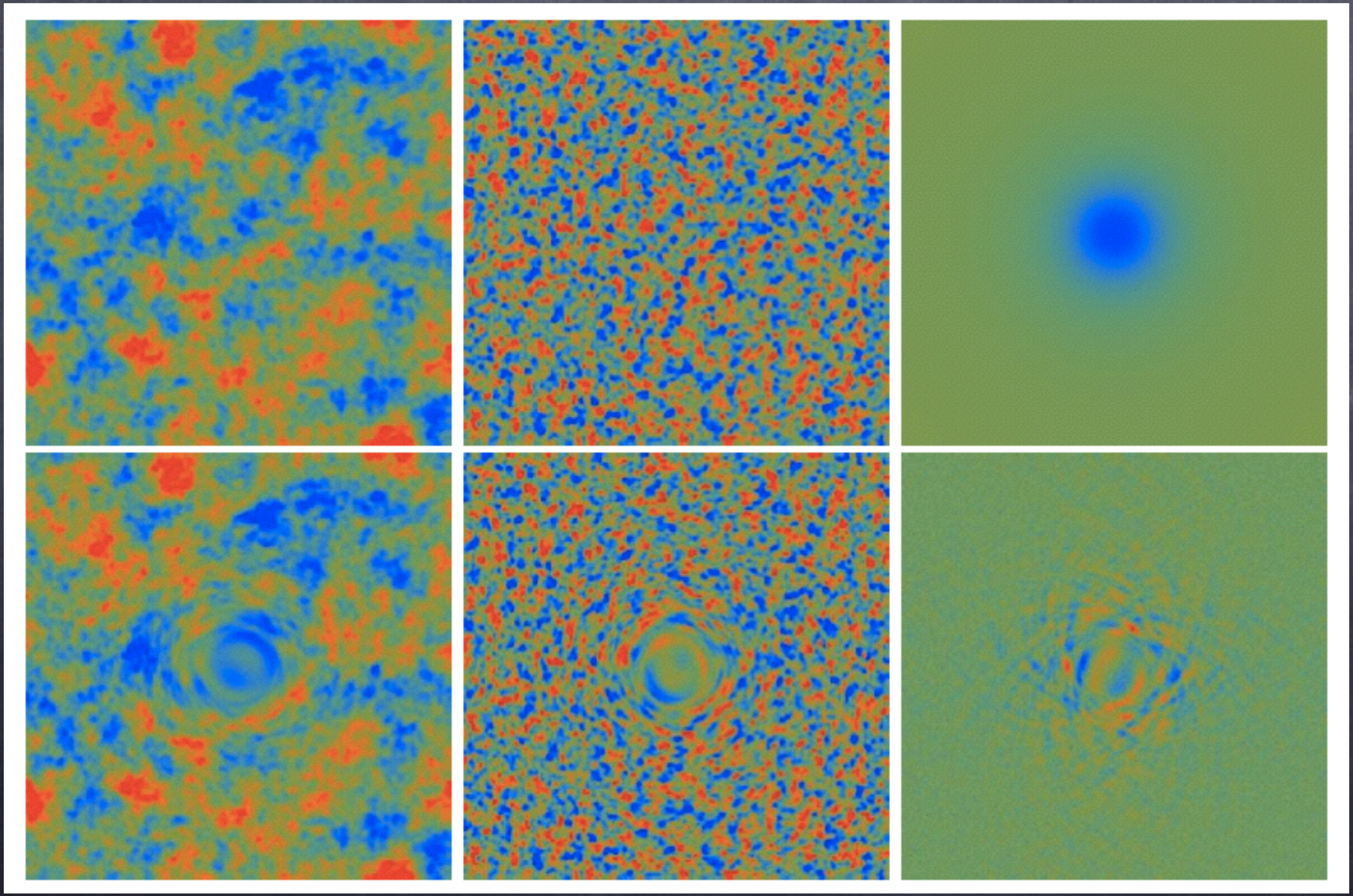
$$\Theta(\hat{\mathbf{n}}) = \tilde{\Theta}(\hat{\mathbf{n}} + \mathbf{d}(\hat{\mathbf{n}})) ,$$
$$[Q \pm iU](\hat{\mathbf{n}}) = [\tilde{Q} \pm i\tilde{U}](\hat{\mathbf{n}} + \mathbf{d}(\hat{\mathbf{n}})) ,$$

In this case, the temperature, polarization, and potential fields may be decomposed as

$$\Theta(\hat{\mathbf{n}}) = \int \frac{d^2 l}{(2\pi)^2} \Theta(\mathbf{l}) e^{i\mathbf{l}\cdot\hat{\mathbf{n}}} ,$$
$$[Q \pm iU](\hat{\mathbf{n}}) = -\int \frac{d^2 l}{(2\pi)^2} [E(\mathbf{l}) \pm iB(\mathbf{l})] e^{\pm 2i\varphi_{\mathbf{l}}} e^{i\mathbf{l}\cdot\hat{\mathbf{n}}} ,$$
$$\phi(\hat{\mathbf{n}}) = \int \frac{d^2 L}{(2\pi)^2} \phi(\mathbf{L}) e^{i\mathbf{L}\cdot\hat{\mathbf{n}}} ,$$

Reconstructed CMB lensing field

Illustration of CMB lensing effect by a point source



Reconstructed CMB lensing field

The reconstructed lensing field can be expressed by,

$$d_\alpha(\mathbf{L}) = \frac{A_\alpha(L)}{L}\int \frac{d^2 l_1}{(2\pi)^2} x(\mathbf{l}_1) x'(\mathbf{l}_2) F_\alpha(\mathbf{l}_1, \mathbf{l}_2)\,,$$

Hu, Okamoto

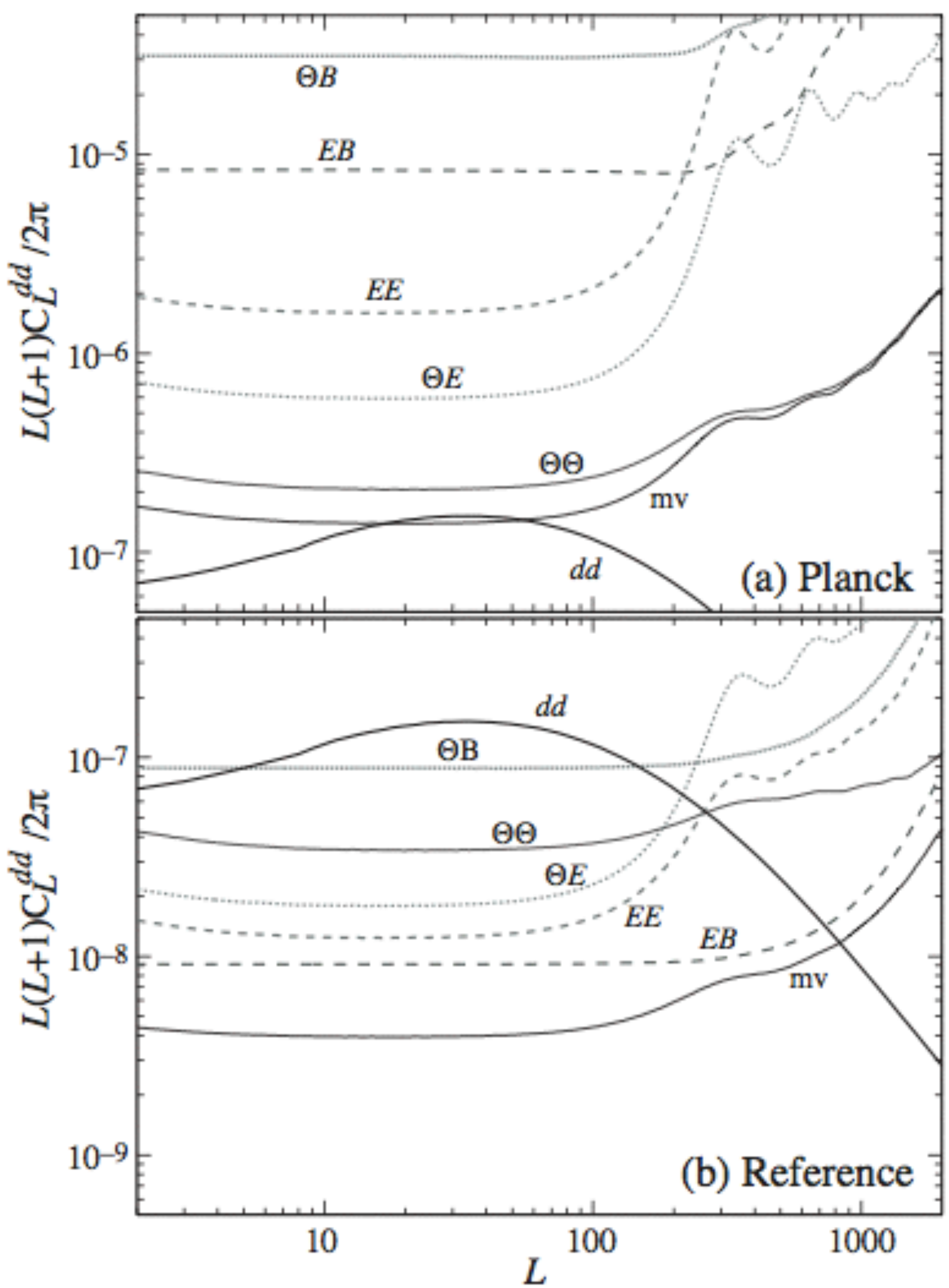
where d represents the gradient lensing potential φ . Then CMB lensing kernel is expressed by two point correlation function of reconstructed lensing potential which can be given by,

$$\sigma_0^2(\theta) = \int \frac{ldl}{2\pi} l^2 C_l^\phi (1 - J_0(l\theta))$$

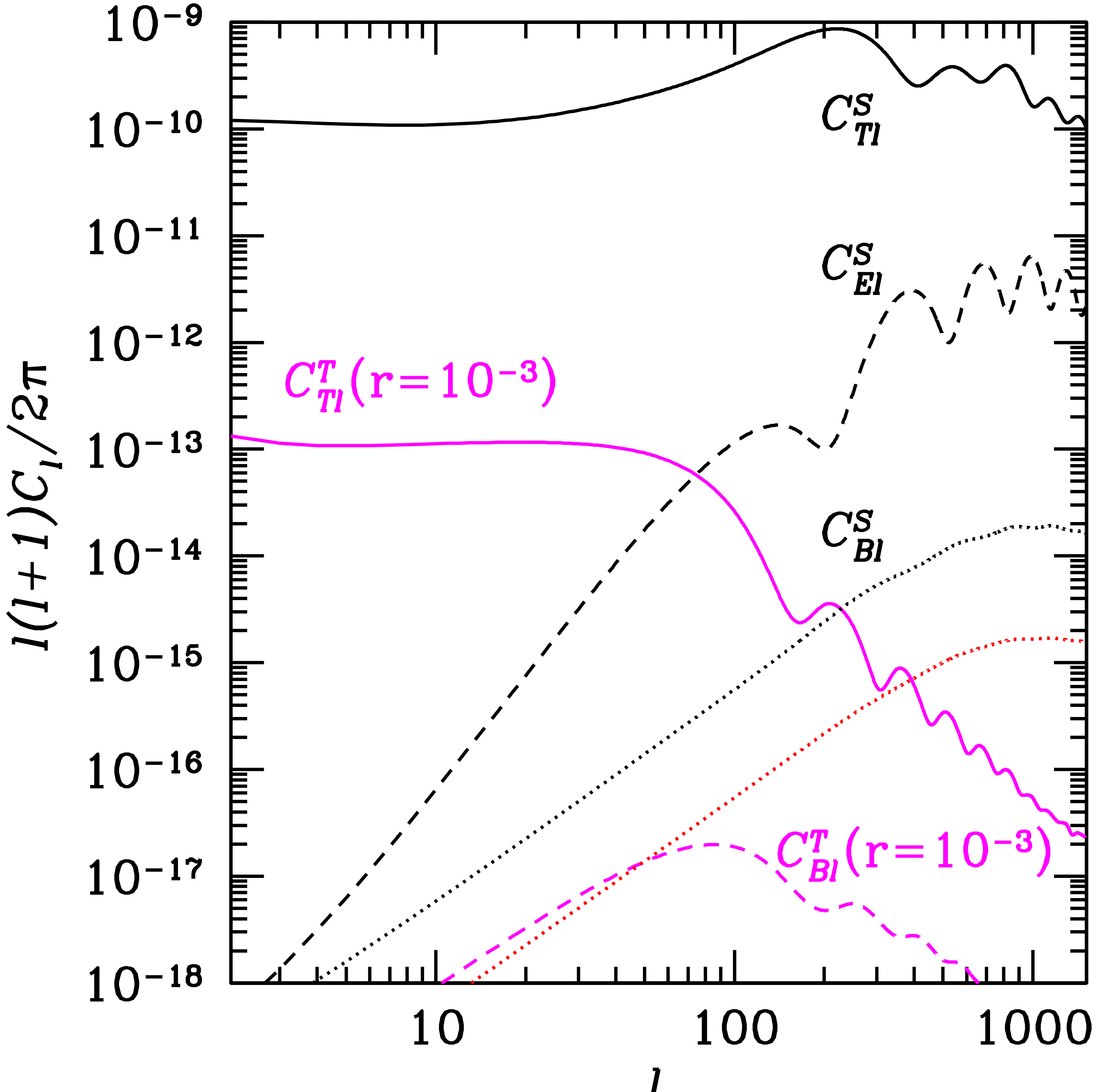
$$\sigma_2^2(\theta) = \int \frac{ldl}{2\pi} l^2 C_l^\phi J_2(l\theta)$$

Knox, YSS

Reconstructed CMB lensing field



Observational lower bound of GW by CMB



Knox, YSS

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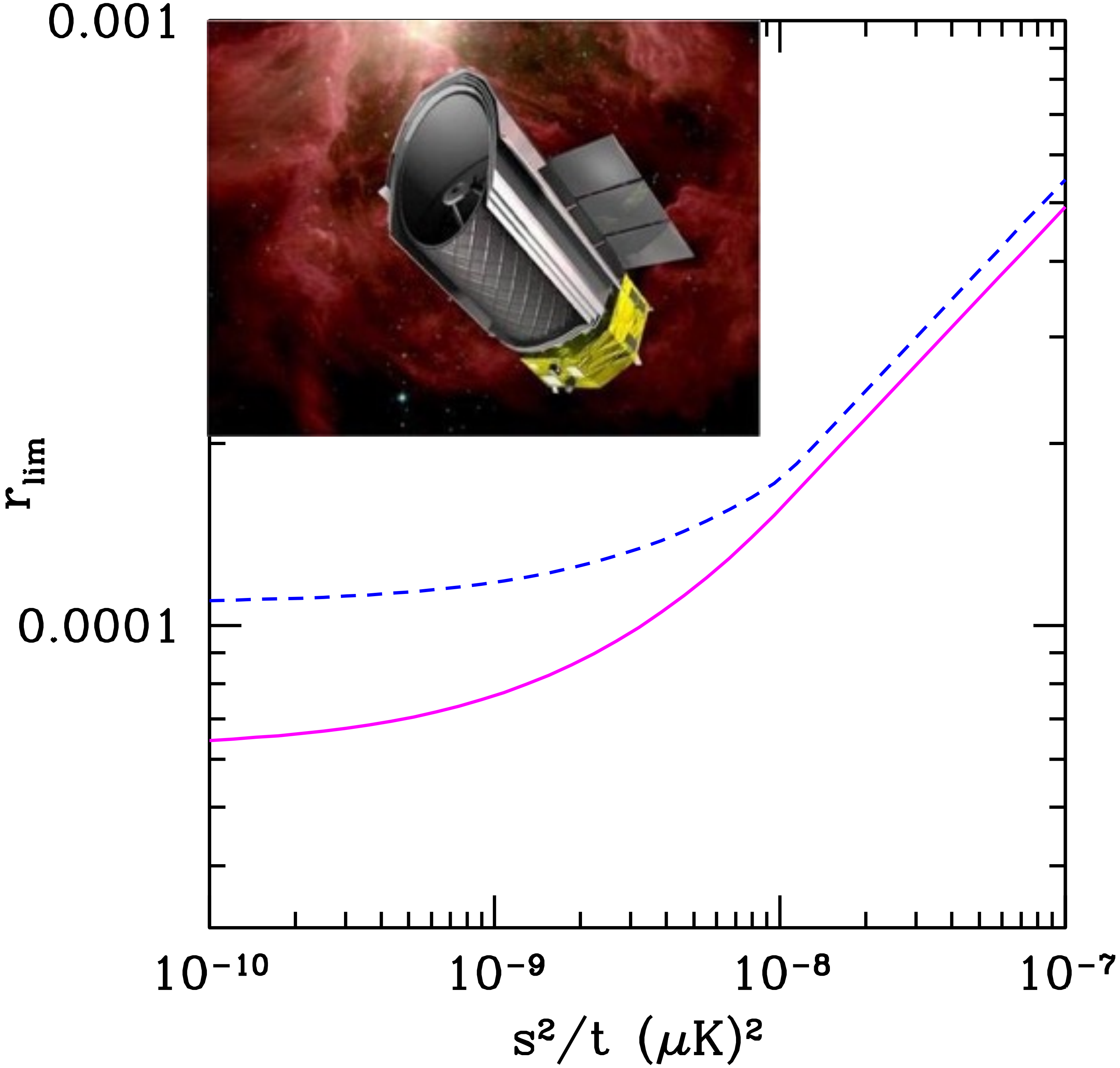


Knox, YSS

Observational lower bound of GW by CMB

Translation into inflationary limit

$$V_*^{1/4}/m_{Pl} = 1.2\langle Q_T^2 \rangle^{1/4} = 3.0 \times 10^{-3} r^{1/4}$$

We can probe the inflationary energy scale by 3.2×10^{15} GeV

CosKASI joining biggest WL experiment

We are a member from 2015

Probing the effective non-Gaussianity

Definition of scale dependence bias

$$b(k) = b_1 + \Delta b_{\rm NG}(k)$$

$$\delta_{g,l} = b_1\,\delta_l + \frac{d\ln n_g}{d\ln\sigma_R}\frac{d\ln\sigma_R}{d\varphi_l}\varphi_l = \left(b_1 - \frac{3H_0^2\Omega_m}{2T(k)D(z)k^2}\frac{d\ln n_g}{d\ln\sigma_R}\frac{d\ln\sigma_R}{d\varphi_l}\right)\delta_l .$$

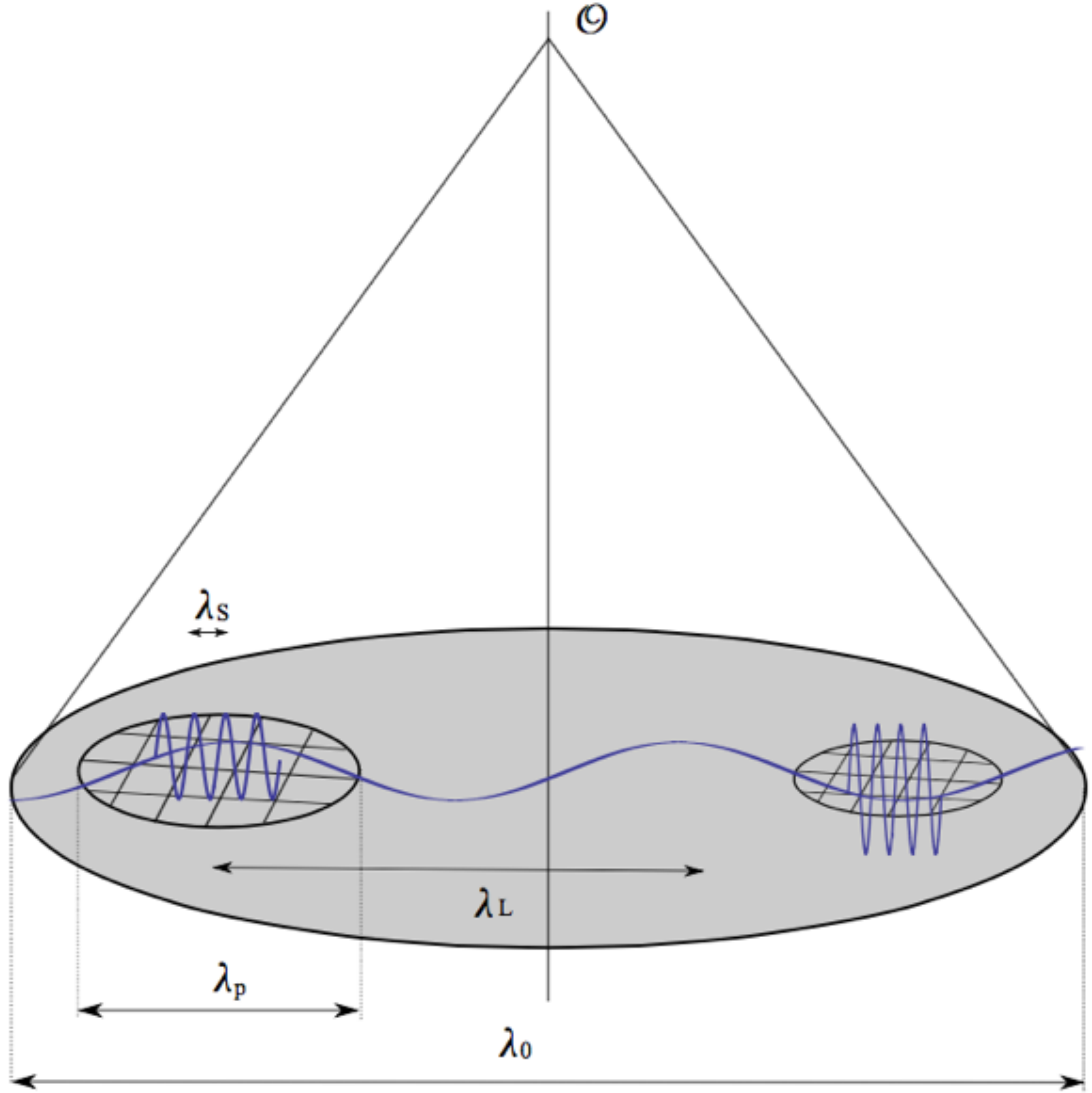
$$\Delta b_{\rm NG}(k) = 2\,f_{\rm NL}^{(\Delta b)}\frac{d\ln n_g}{d\ln\sigma_R}\frac{3H_0^2\Omega_m}{2T(k)D(z)k^2} .$$

Observable non-Gaussianity

$$f_{\rm NL}^{(\Delta b)} \stackrel{?}{=} -\frac{5}{12}(n_s - 1)\,,$$

$$f_{\rm NL}^{(\Delta b)} \stackrel{?}{=} -\frac{5}{3} - \frac{5}{12}(n_s - 1)\,.$$

The separate universe



The observable signature of the initial condition

The separate universe argument

$$\nabla^2 \Phi_N = -\frac{3}{2} a^2 H^2 \delta \,. \qquad \nabla^2 \zeta - 2\zeta \nabla^2 \zeta + \frac{1}{2} \left(\nabla \zeta\right)^2 = -\frac{5}{2} a^2 H^2 \delta \,.$$

In the leading order of expansion

$$\nabla^2 \zeta_L = -5 a^2 H^2 \delta_L / 2 \qquad \nabla^2 \zeta_S - 2\zeta_L \nabla^2 \zeta_S = -\frac{5}{2} a^2 H^2 \delta_S .$$

Under the same coordinate transformation

$$ds^2_{(3)} = e^{2\zeta_L} e^{2\zeta_S} \delta_{ij} dx^i dx^j = e^{2\zeta_S} \delta_{ij} d\tilde{x}^i d\tilde{x}^j \,.$$

$$\tilde{\nabla}^2 \tilde{\zeta}_S(\tilde{x}) = -\frac{5}{2} a^2 H^2 \tilde{\delta}_S(\tilde{x}).$$

$$\tilde{\sigma}^2_{\tilde{R}} = \sigma^2_R \,, \quad \text{where} \quad \tilde{R} = (1 + \zeta_L) R \,,$$

However …

But new coordinate are also Gaussian fields in x, and therefore non-linear functions of new coordinate are non-Gaussian intrinsically.

$$ds^2_{(3)} = e^{2\zeta_L} e^{2\zeta_S} \delta_{ij} dx^i dx^j = e^{2\zeta_S} \left[\delta_{ij} d\tilde{x}^i d\tilde{x}^j + O\big(|\tilde{x}|^2 \nabla^2 \zeta_L\big) \right] .$$

It is similar to the production of non-Gaussianity terms in redshift space distortions.

Effective non-Gaussianity due to GR effect

Here is summary of producing effective non-Gaussianity due to GR effect.

$$\Phi_N = \varphi + f_{\rm NL}\left(\varphi^2 - \langle\varphi^2\rangle\right), \qquad (1 + 2f_{\rm NL}\varphi_L)\nabla^2\varphi_S = -\frac{3}{2}a^2H^2\delta_S\,.$$

$$\left(1 - \frac{10}{3}\varphi_L\right)\nabla^2\varphi_S = -\frac{3}{2}a^2H^2\delta_S.$$

$$f_{\rm NL} = f_{\rm NL}^{\rm prim} + f_{\rm NL}^{\rm GR} = f_{\rm NL}^{\rm prim} - \frac{5}{3}\,.$$

SPHEREx

Cosmology with the SPHEREX All-Sky Spectral Survey

Olivier Doré[1,2], Jamie Bock[2,1], Matthew Ashby[9], Peter Capak[3], Asantha Cooray[8], Roland de Putter[1,2], Tim Eifler[1], Nicolas Flagey[11], Yan Gong[8], Salman Habib[10], Katrin Heitmann[10], Chris Hirata[6], Woong-Seob Jeong[7], Raj Katti[2], Phil Korngut[2], Elisabeth Krause[4], Dae-Hee Lee[7], Daniel Masters[3], Phil Mauskopf[12], Gary Melnick[9], Bertrand Mennesson[2], Hien Nguyen[1], Karin Öberg[9], Anthony Pullen[13], Alvise Raccanelli[5], Roger Smith[2], Yong-Seon Song[7], Volker Tolls[9], Steve Unwin[1], Tejaswi Venumadhav[2], Marco Viero[4], Mike Werner[1], Mike Zemcov[2]

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[11] *Institute for Astronomy, Hilo, HI 96720, USA*
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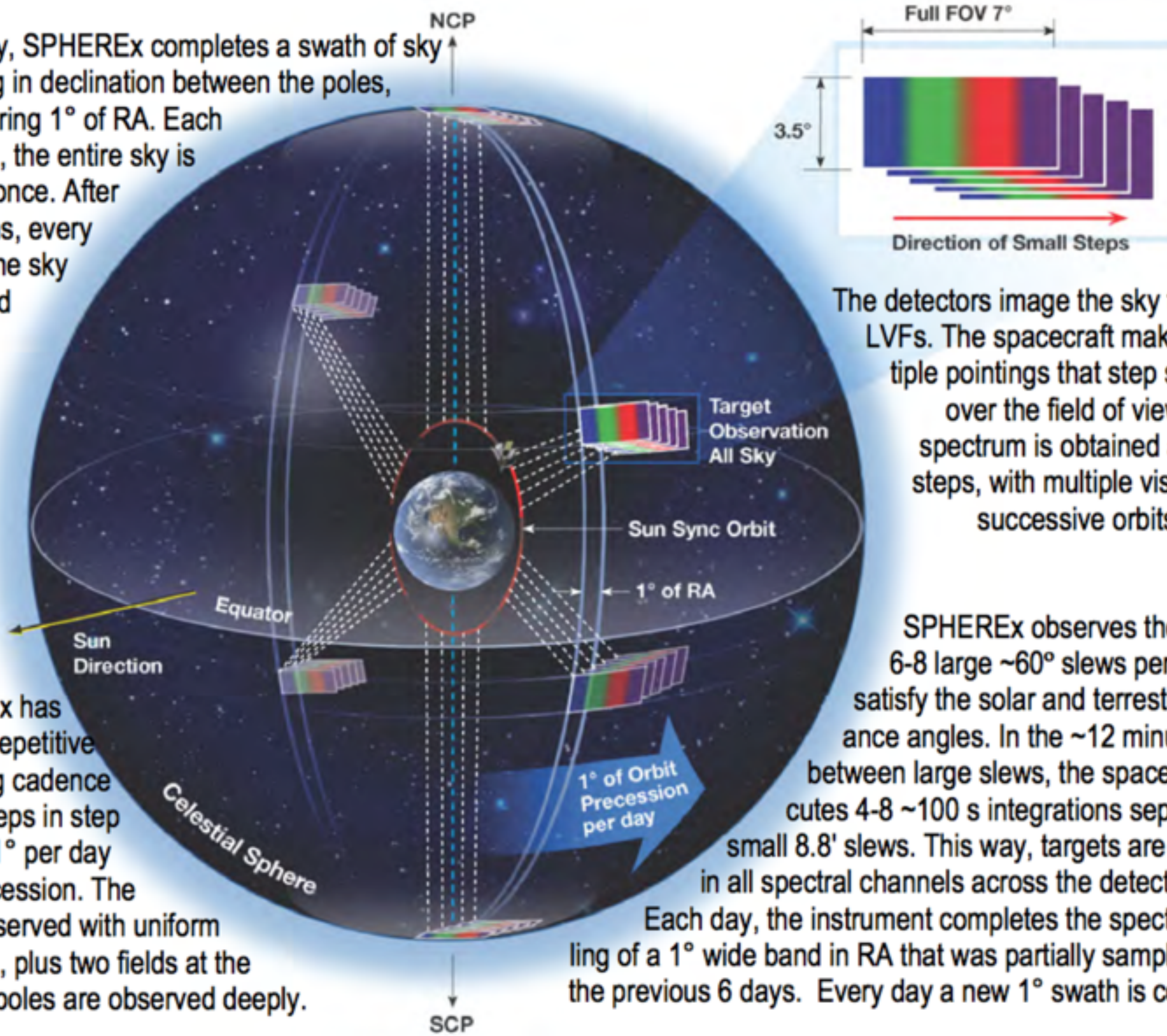
(Dated: March 27, 2015)

CosKASI is a member of SPHEREx from 2014

SPHEREx

Every day, SPHEREx completes a swath of sky extending in declination between the poles, and covering 1° of RA. Each 6 months, the entire sky is covered once. After 25 months, every point of the sky is covered 4 times.



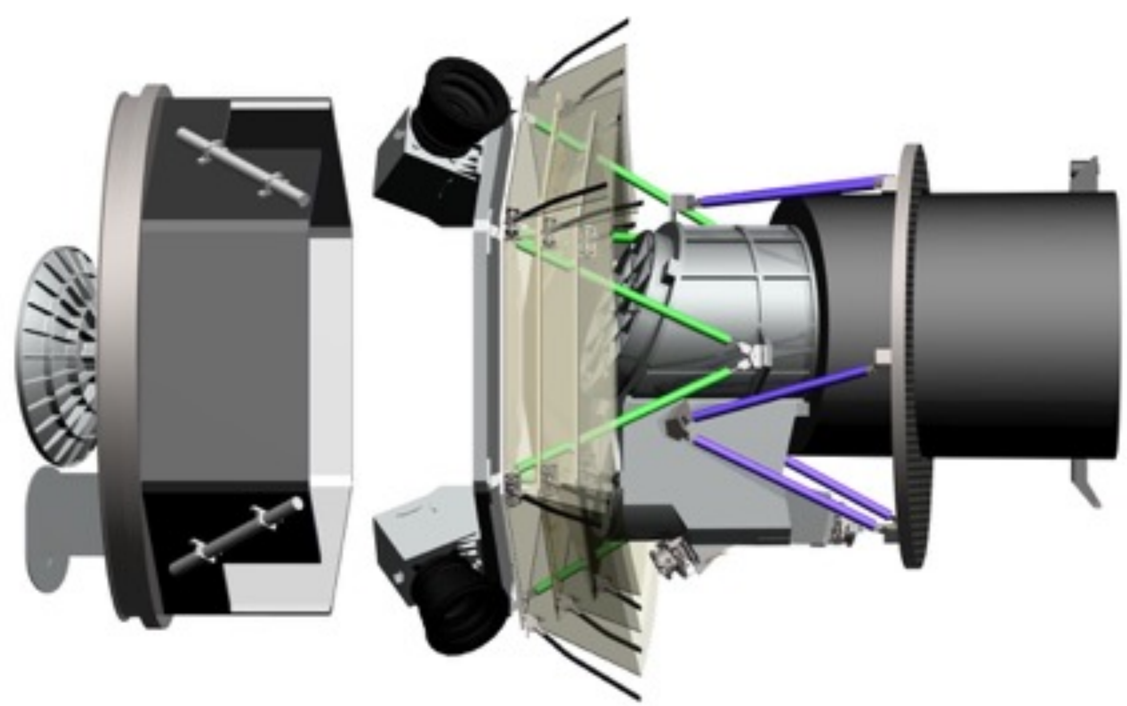
The detectors image the sky through LVFs. The spacecraft makes multiple pointings that step sources over the field of view. A full spectrum is obtained after 48 steps, with multiple visits over successive orbits.

SPHEREx has a highly repetitive observing cadence which keeps in step with the 1° per day orbit precession. The sky is observed with uniform coverage, plus two fields at the celestial poles are observed deeply.

SPHEREx observes the sky with 6-8 large ~60° slews per orbit that satisfy the solar and terrestrial avoidance angles. In the ~12 minute period between large slews, the spacecraft executes 4-8 ~100 s integrations separated by small 8.8' slews. This way, targets are observed in all spectral channels across the detector arrays. Each day, the instrument completes the spectral sampling of a 1° wide band in RA that was partially sampled during the previous 6 days. Every day a new 1° swath is completed.

SPHEREx

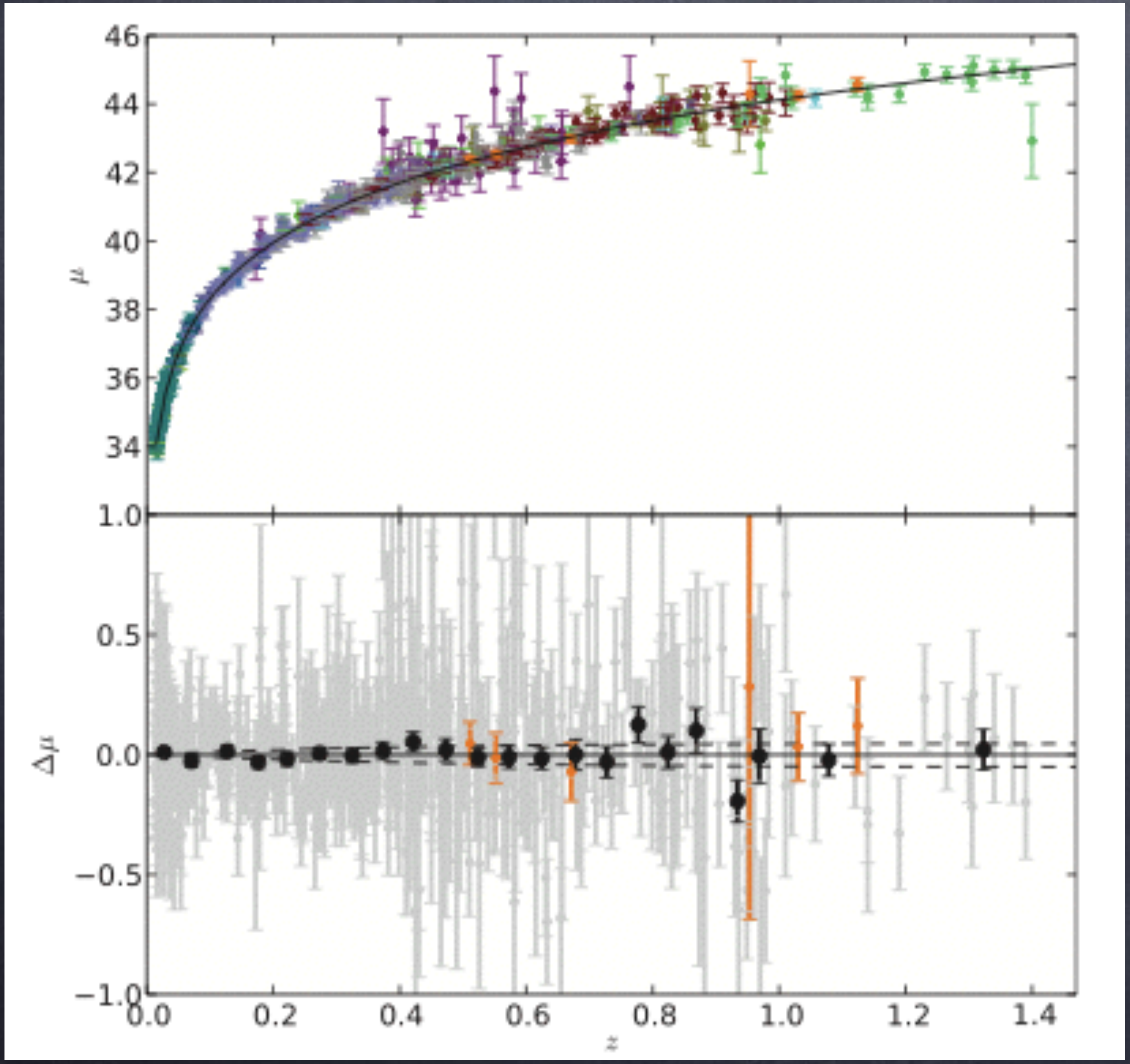
1σ errors	PS	Bispec	PS + Bispec	EUCLID	Current
$f_{\rm NL}^{\rm loc}$	0.87	0.23	0.20	5.59	5.8
Tilt n_s ($\times 10^{-3}$)	2.7	2.3	2.2	2.6	5.4
Running α_s ($\times 10^{-3}$)	1.3	1.2	0.65	1.1	17
Curvature Ω_K ($\times 10^{-4}$)	9.8	NC	6.6	7.0	66
Dark Energy FoM $= 1/\sqrt{\rm DetCov}$	202	NC	NC	309	25



First phase of cosmic acceleration physics

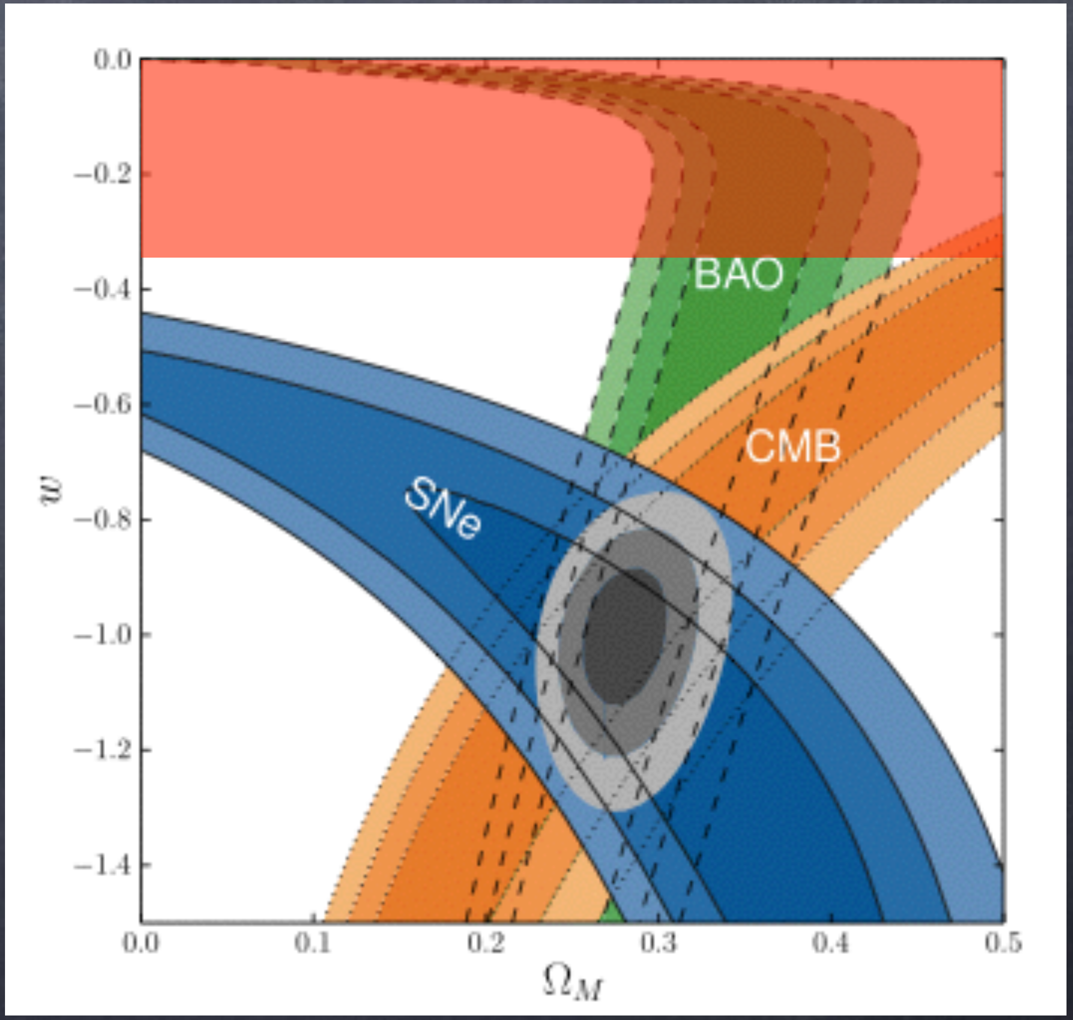
Confirmation of the existence of cosmic acceleration

Amanullah et.al. 2010, 557 SN



p = wρ

Cosmic acceleration at w<-1/3



Developed techniques

- Geometrical constraints on cosmic acceleration

  Standard candles by SN

  Standard ruler by BAO

  Standard siren by gravitational wave

- Constraints from large scale structure formation

  Weak lensing : measuring metric perturbations influencing photon trajectory

  Distribution of diverse tracers: measuring density fluctuations

  Coherent motions: measuring peculiar velocity

  ISW effect: measuring integrate effect of varying potential well

  All cross correlation statistics

- Direct measurement of dark energy in laboratory

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

Theoretical models to explain 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

Dynamical Dark Energy: modifying matter

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

  - Alternative mechanism to generate fine tuned vacuum energy
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Geometrical Dark Energy: modifying gravity

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

  - Presence of extra dimension
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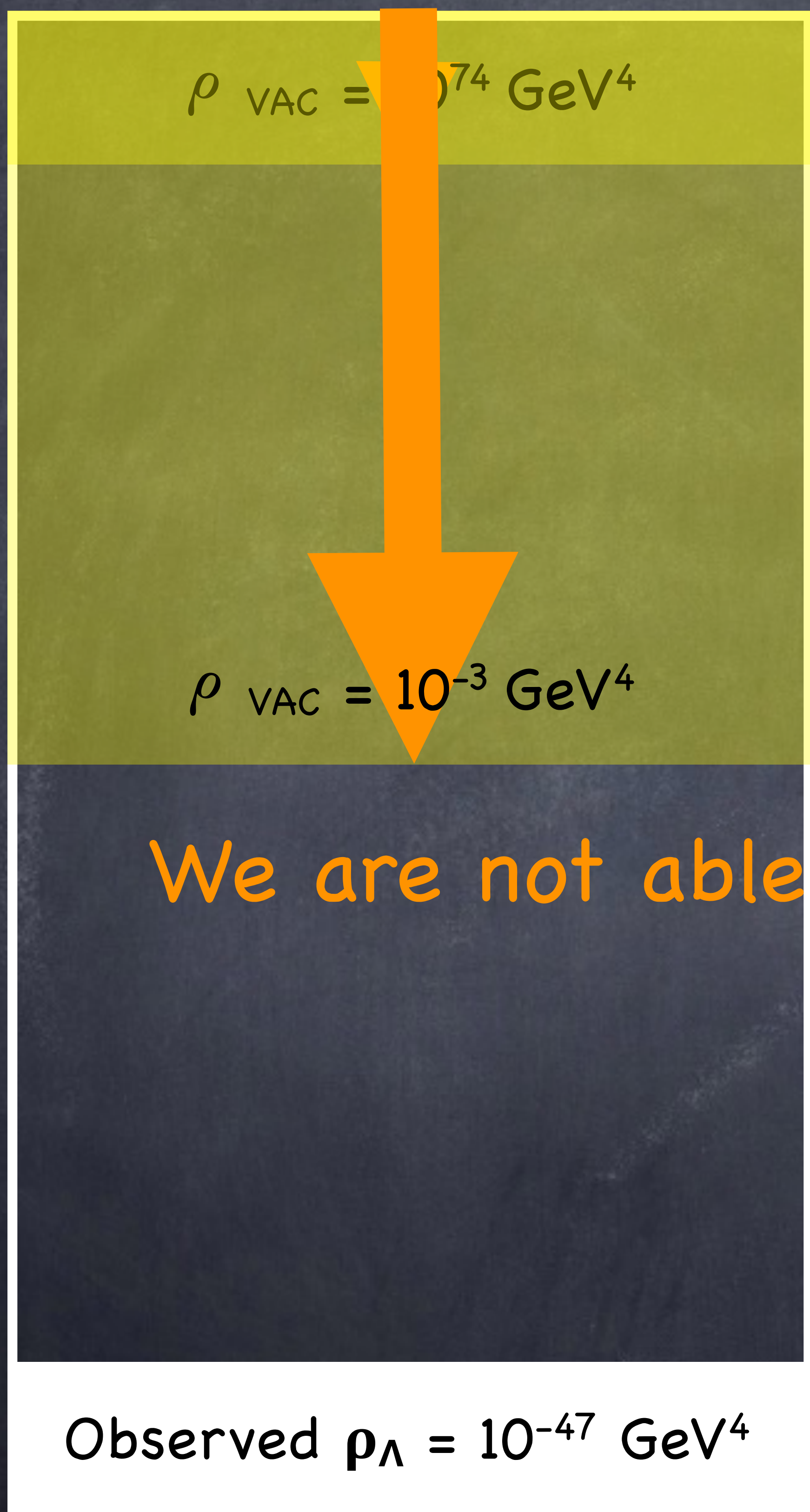
Λ ladder of vacuum energy from QFT



For each mode of quantum field, there is zero point energy $h\omega/2$, so that the energy density of the quantum vacuum is given by,

$$\rho_{VAC} = \Sigma_i \, g_i \, k^4_{max} / 16\pi^2$$

if k_{max} is given by the limit of quantum field theory defined on classical spacetime, then it can be Planck scale.

We are not able to explain Λ from known QFT

We can take an energy scale of QCD for k_{max}, then we can reduce the gap.

Pauli carried out this calculation in 1930's with electrons, and found that we are not able to reach even to the moon.

Weinberg (1989); Straumann (2002); Carroll (2000)

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Scalar field models of dark energy

The cosmological constant corresponds to a fluid with a constant equation of state w=-1. Scalar fields naturally arises in particle physics acting as candidates for dark energy.

$$S[g_{\alpha\beta},\phi] = \int d^4x\sqrt{-g}\{\frac{R}{2} - \frac{1}{2}\phi_{,\mu}\phi^{,\mu} + V(\phi)\}$$

the equation of state w is given by $w=p/\rho$,

Ratra, Peebles (1998)

$$\rho = -T^0_0 = \frac{1}{2}\dot{\phi}^2 + V(\phi)\,, \quad p = T^i_i = \frac{1}{2}\dot{\phi}^2 - V(\phi)\,.$$

There are two different classification of models, "thawing" and "freezing", depending on w and w_a (dw/dlna) representing position and velocity of fields. If w_a is roughly $w_a > 0$, then "thawing", and if w_a is roughly $w_a < 0$, then "freezing".

Linder, Caldwell (2005)

Phantom dark energy

The observed equation of state is not entirely at w>-1. Parameter space below w=-1 is as equally favored as w>-1, so we need to find a way to cross the boundary of w=-1. One can introduce ghost fields which has the opposite sign of the kinetic term to the ordinary scalar field.

Normal fields

$$w_\phi = \frac{p}{\rho} = \frac{\dot{\phi}^2 - 2V(\phi)}{\dot{\phi}^2 + 2V(\phi)} \, .$$

Phantom fields

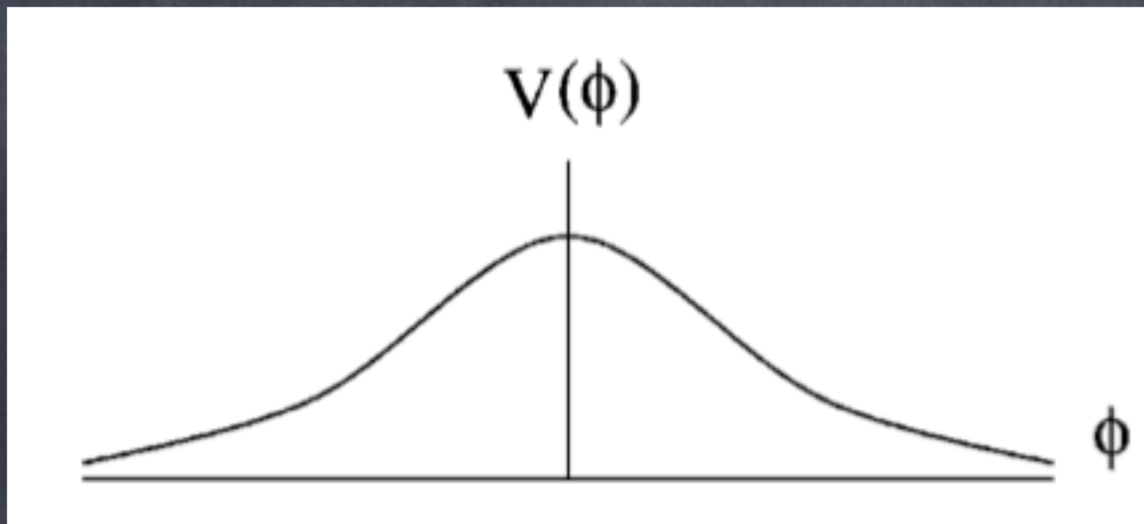
$$w_\phi = \frac{p}{\rho} = \frac{\dot{\phi}^2 + 2V(\phi)}{\dot{\phi}^2 - 2V(\phi)} \, .$$

In phantom dark energy models, Hubble rate diverges in the future, and curvature hits the singularity, which is called as "Big Rip".

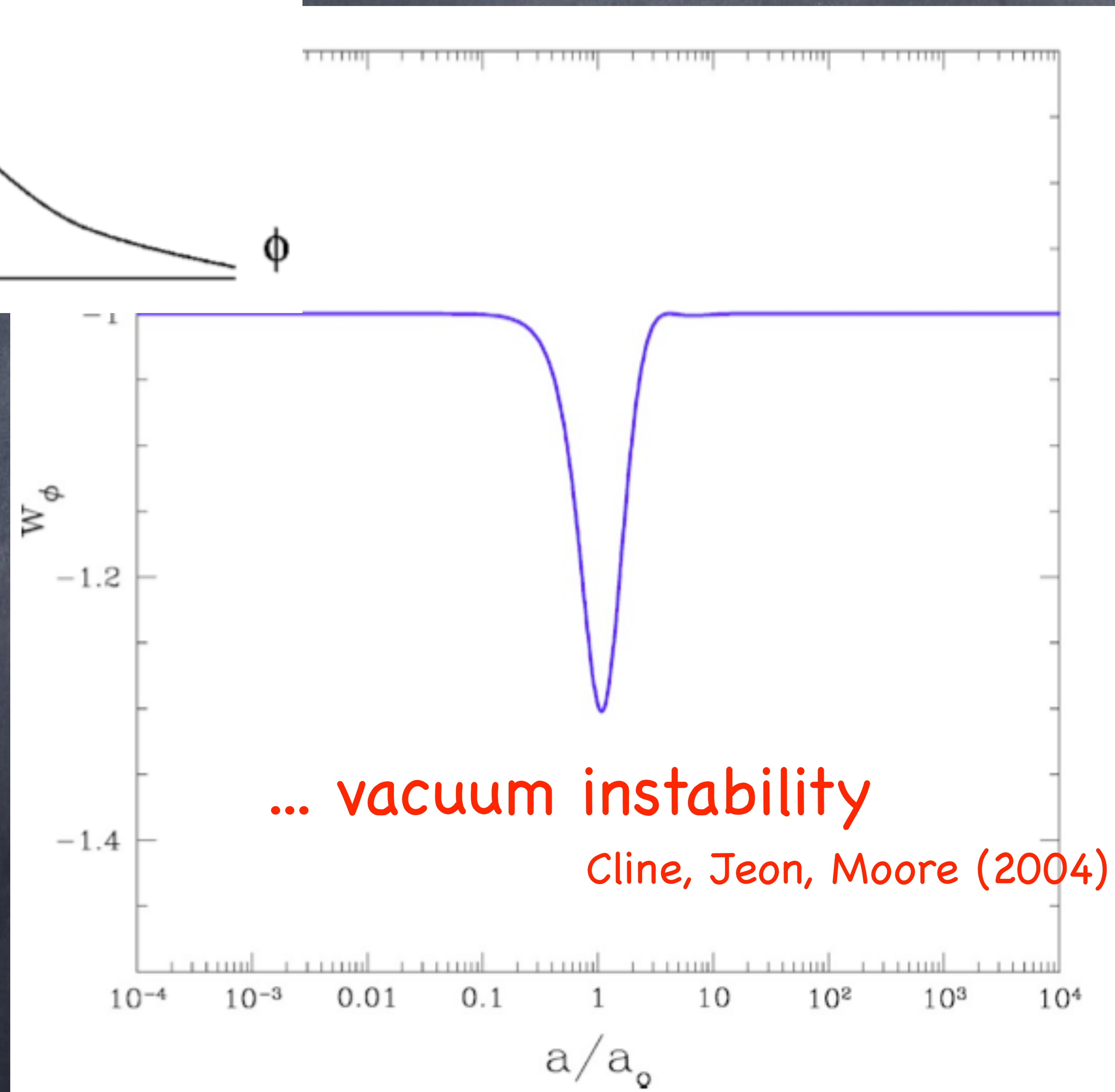
Big Rip can be avoided using some special types of potentials (top hat or exponential), but unfortunately phantom fields are generally plagued by severe UV quantum instabilities.

Carroll, Hoffman, Trodden (2002)

Phantom dark energy



Fields are stabilized on the top of the hill.



... vacuum instability

Cline, Jeon, Moore (2004)

Carroll, Hoffman, Trodden (2002)

K-essence

Scalar fields with non-canonical kinetic terms often appear in particle physics. The action is written as,

$$S = \int d^4x \sqrt{-g}\,[R/2 + P(\phi, X)] + S_M \qquad X = (\nabla\phi)^2$$

Low energy effective string theory: Gaspirini et.al (1993,2003)

$$S = \int d^4x \sqrt{-g}\,[R/2 + aX + bX^2 + \dots] + S_M$$

Ghost condensation: Arkani-Hammed et.al. (2004)

$$P = -X + X^2/M^4$$

UV stability for phantom-like models

DBI theory: Martin, Yamaguchi (2008); Guo, Ohta (2008)

$$P = -\sqrt{1-2fX} \,/\, f + 1/f + V$$

This class of models also provides later time cosmic acceleration with the equation of state,

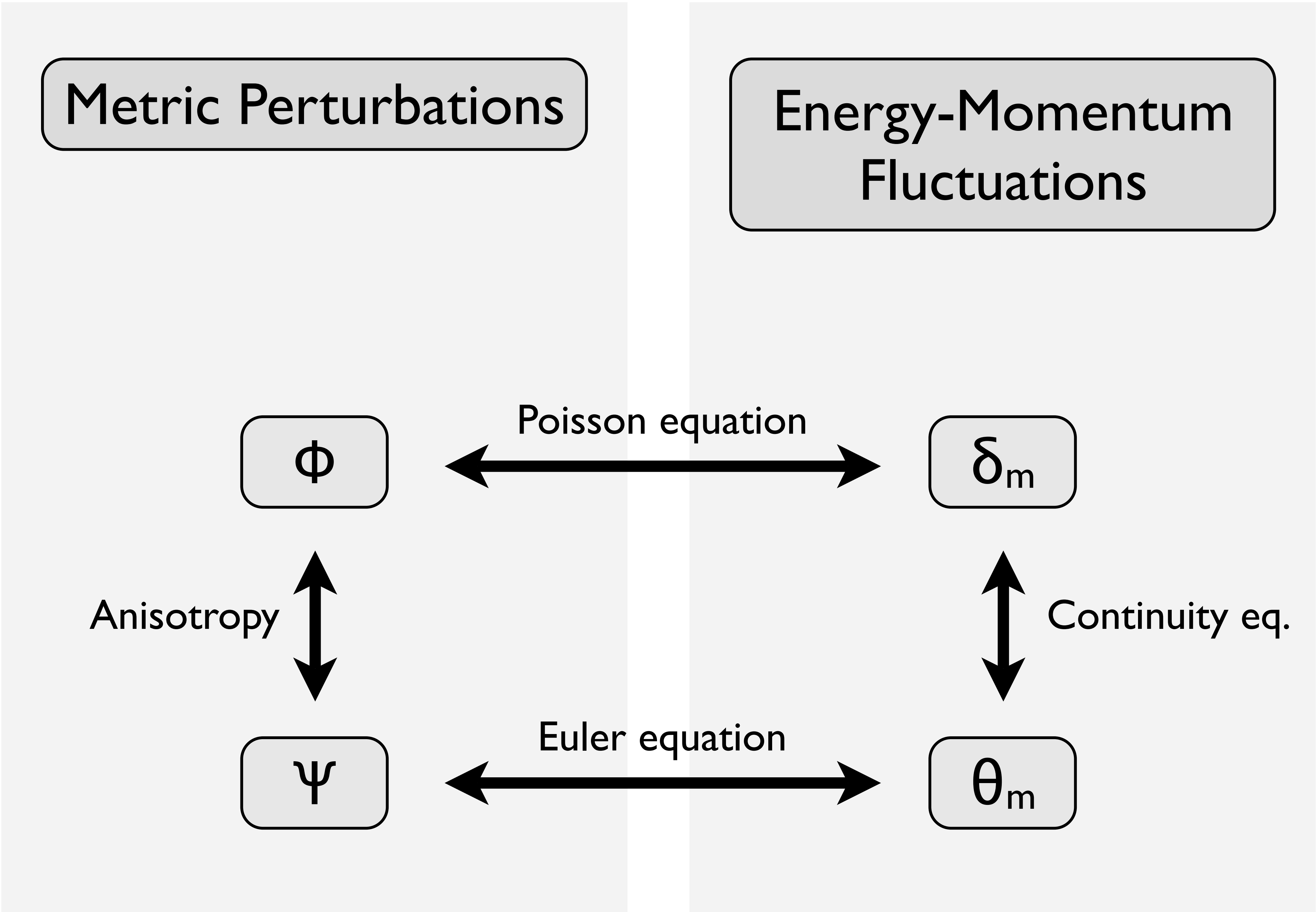
Creating non-trivial sound speed $c_s^2 \neq 1$,

determining stability of models depending on sign of c_s^2

$$w = (1-X/M^4) \,/\, (1-3X/M^4)$$

Chiba, Okabe, Yamaguchi (2000)

GR consistency relation



YSS 2006, YSS, Kazuya 2009

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Coupling between dark sectors

Dark matter is currently only detected via its gravitational effects, and there is an unavoidable degeneracy between dark matter and dark energy within General Relativity. There could be a hidden non-gravitational coupling between dark matter and dark energy, and thus it is interesting to develop ways of testing for such an interaction

$$\rho_c' = -3\mathcal{H}\rho_c + aQ_c\,,$$
$$\rho_x' = -3\mathcal{H}(1+w_x)\rho_x + aQ_x\,, \quad Q_x = -Q_c\,,$$

there are three different types of interactions,

$$Q_c^\mu = -\Gamma\rho_c\,u_c^\mu\,,$$

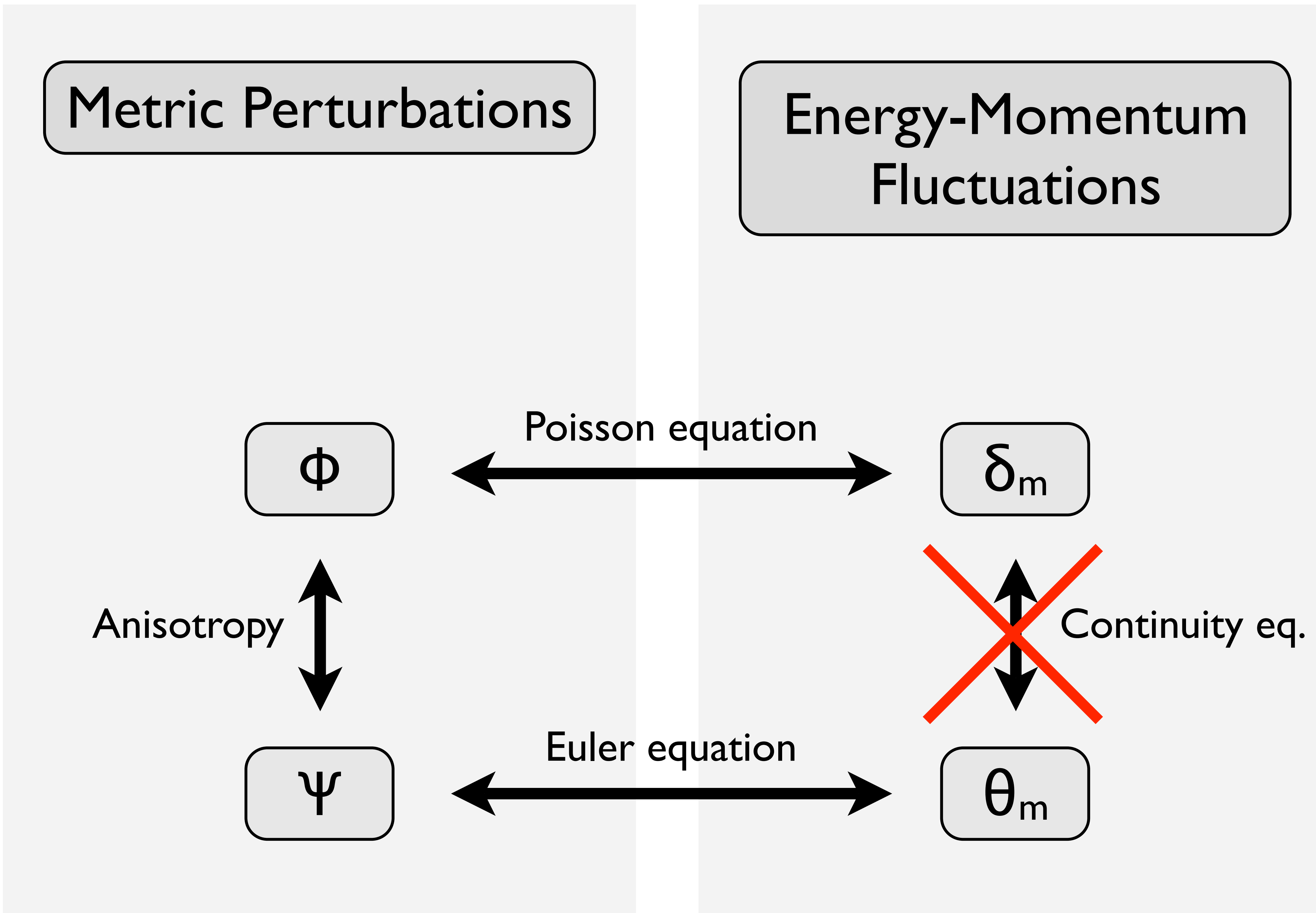
$$Q_c^\mu = -(\Gamma_c\rho_c + \Gamma_x\rho_x)\,u_c^\mu\,,$$

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

Amendola (2004)

Koyama, Maartens, YSS (2009)

GR consistency relation



YSS 2006, YSS, Kazuya 2009

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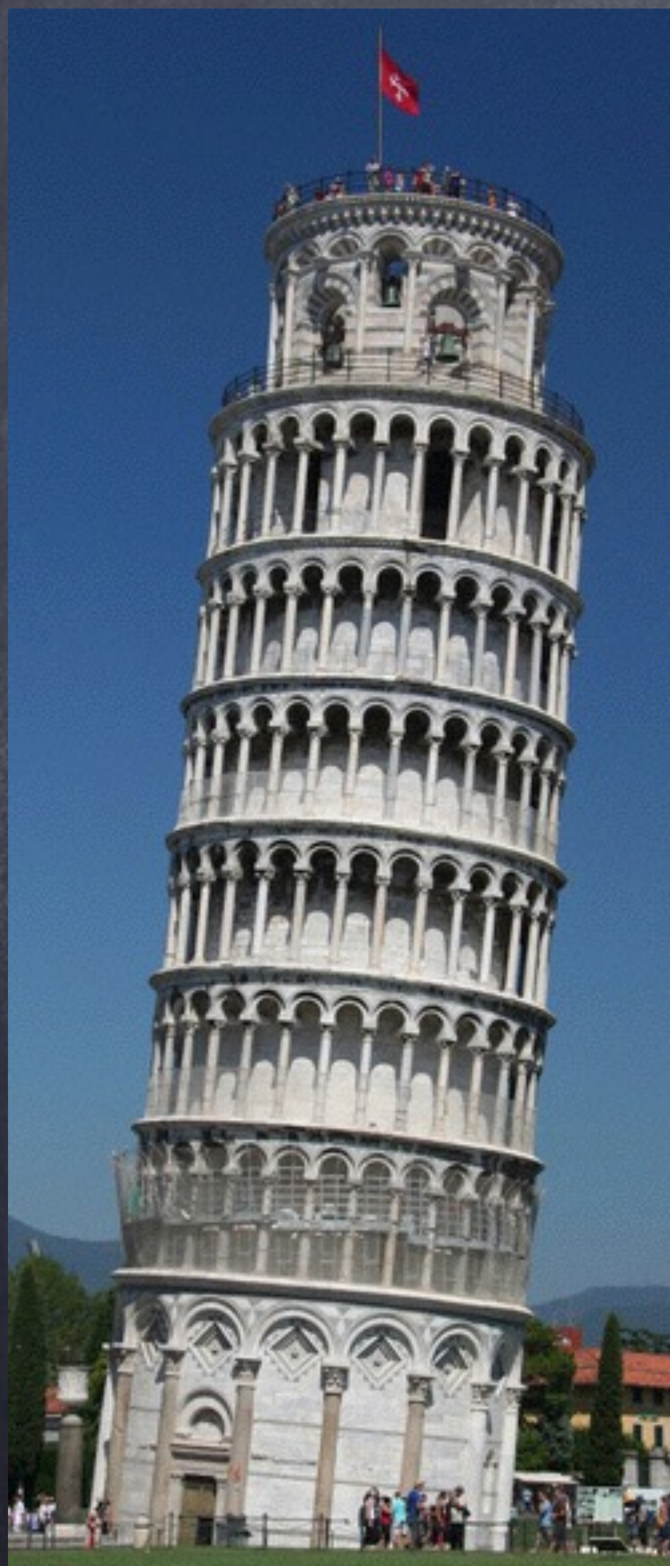
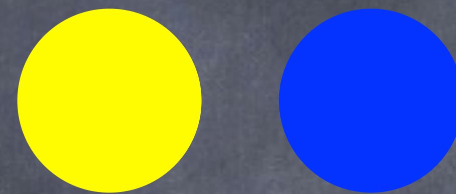


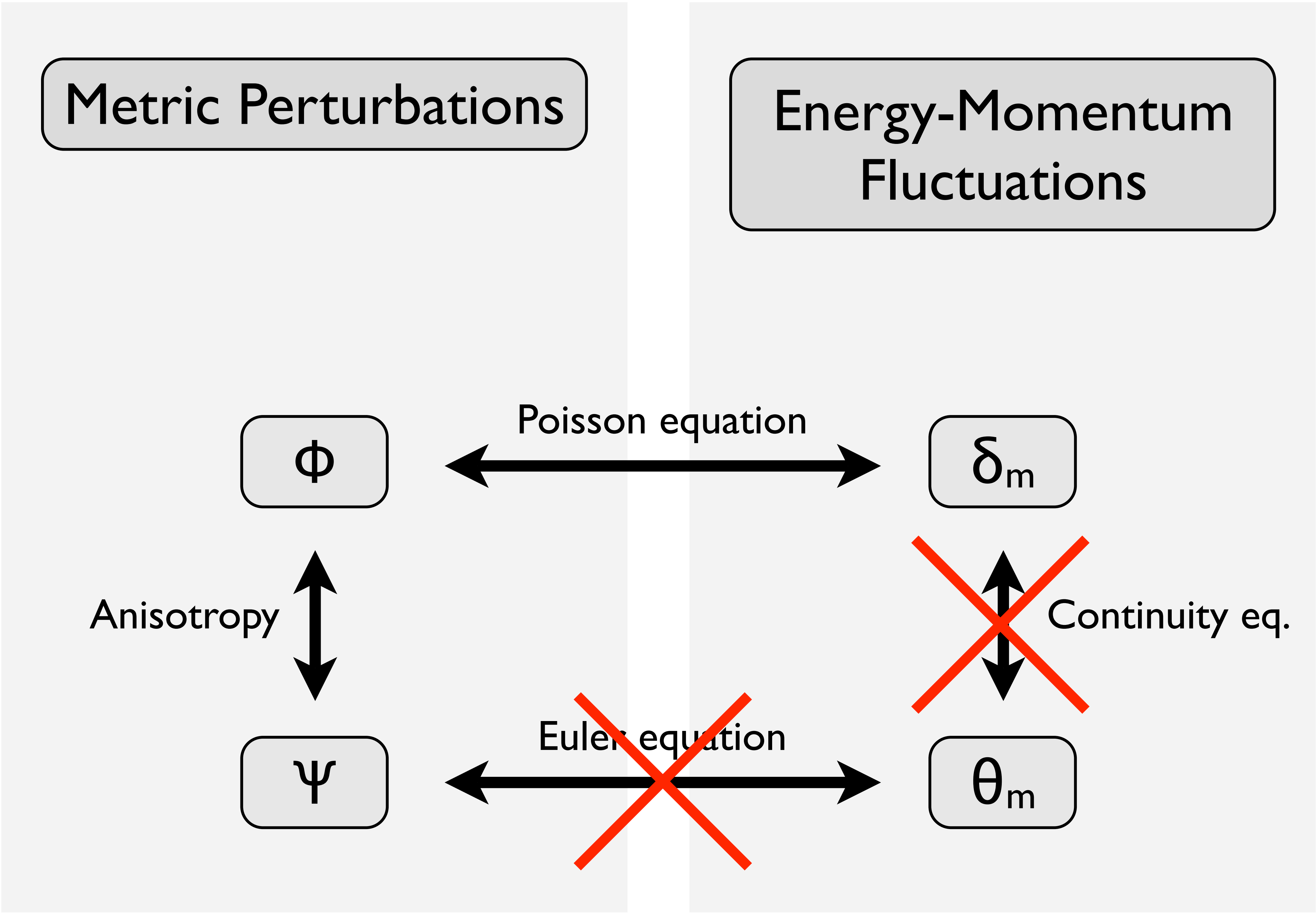
Baryon CDM



$$Q^{\mu}_{c} = -\alpha \rho_c \nabla^{\mu} \varphi \,,$$

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.

GR consistency relation



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- Failure of standard cosmology model: our understanding of the universe is still standing on assumptions:
    - Inhomogeneous models: LTB, back reaction

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)

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

The f(R) gravity model in this talk is given by,

$$f(R) = -2\,\kappa^2 \rho_\Lambda + |f_{R0}|\, R_0{}^2/R^2$$

LSS of f(R) gravity

Dynamic equations of perturbations

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

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

$$k^2\phi = 3/2\ H_0{}^2\Omega_m\ \delta_m/a\ F(\epsilon)$$

$$k^2\psi = -3/2\ H_0{}^2\Omega_m\ \delta_m/a\ G(\epsilon)$$

which are not closed without knowing ϵ evolution

For the case of DGP, dynamics equations with extra variable are closed with a constraint equation, but for the case of f(R) gravity, it is closed with an extra dynamic equation of ϵ.

$$\epsilon'' + \left(\frac{7}{2} + 4p_B\right)\epsilon' + \frac{2}{B}\epsilon = \frac{1}{B}F(\Phi_-, S, Hq)$$

LSS of f(R) gravity

Dynamic equations of perturbations

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$$k^2\psi = -3/2\ H_0{}^2\Omega_m\ \delta_m/a\ G(\epsilon)$$

which are not closed without knowing ϵ evolution

Mass screening effect:

$$k^2\phi_{fR} = \phi_{GR}\ F(\epsilon)$$

Geometrical anisotropy:

$$k^2\phi_{fR} + k^2\psi_{fR} = -3H_0{}^2\Omega_m\ \delta_m/a\ [F(\epsilon) - G(\epsilon)]$$

Change on photon trajectory:

$$\phi_{fR} - \psi_{fR} = (\phi_{GR} - \psi_{GR})$$

LSS of f(R) gravity

Dynamic equations of perturbations

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

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

$$k^2\, \phi = 3/2\; H_0{}^2\Omega_m\; \delta_m/a\; F(\epsilon)$$

$$k^2\, \psi = -3/2\; H_0{}^2\Omega_m\; \delta_m/a\; G(\epsilon)$$

Introducing the Brans-Dicke parameter φ

$$\phi_{fR} - \psi_{fR} = \varphi$$

$$k^2\, \psi = -3/2\; H_0{}^2\Omega_m\; \delta_m/a - 1/2\; k^2\varphi$$

$$(1+w_{BD})\; k^2/a^2\, \varphi = 3H_0{}^2\Omega_m\; \delta_m/a - I(\varphi)$$

where $I(\varphi)$ is given by

$$I(\varphi) = M_1(k)\varphi(k) + 1/2 \int\cdots\int d^3k_1\cdots d^3k_n\, M_1(k)\cdots M_n(k)\; \varphi(k_1)\cdots\varphi(k_n)$$

LSS of f(R) gravity

Dynamic equations of perturbations

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

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

$$k^2 \phi = 3/2\ H_0{}^2\Omega_m\ \delta_m/a\ F(\epsilon)$$

$$k^2 \psi = -3/2\ H_0{}^2\Omega_m\ \delta_m/a\ G(\epsilon)$$

Later time growth functions are given by,

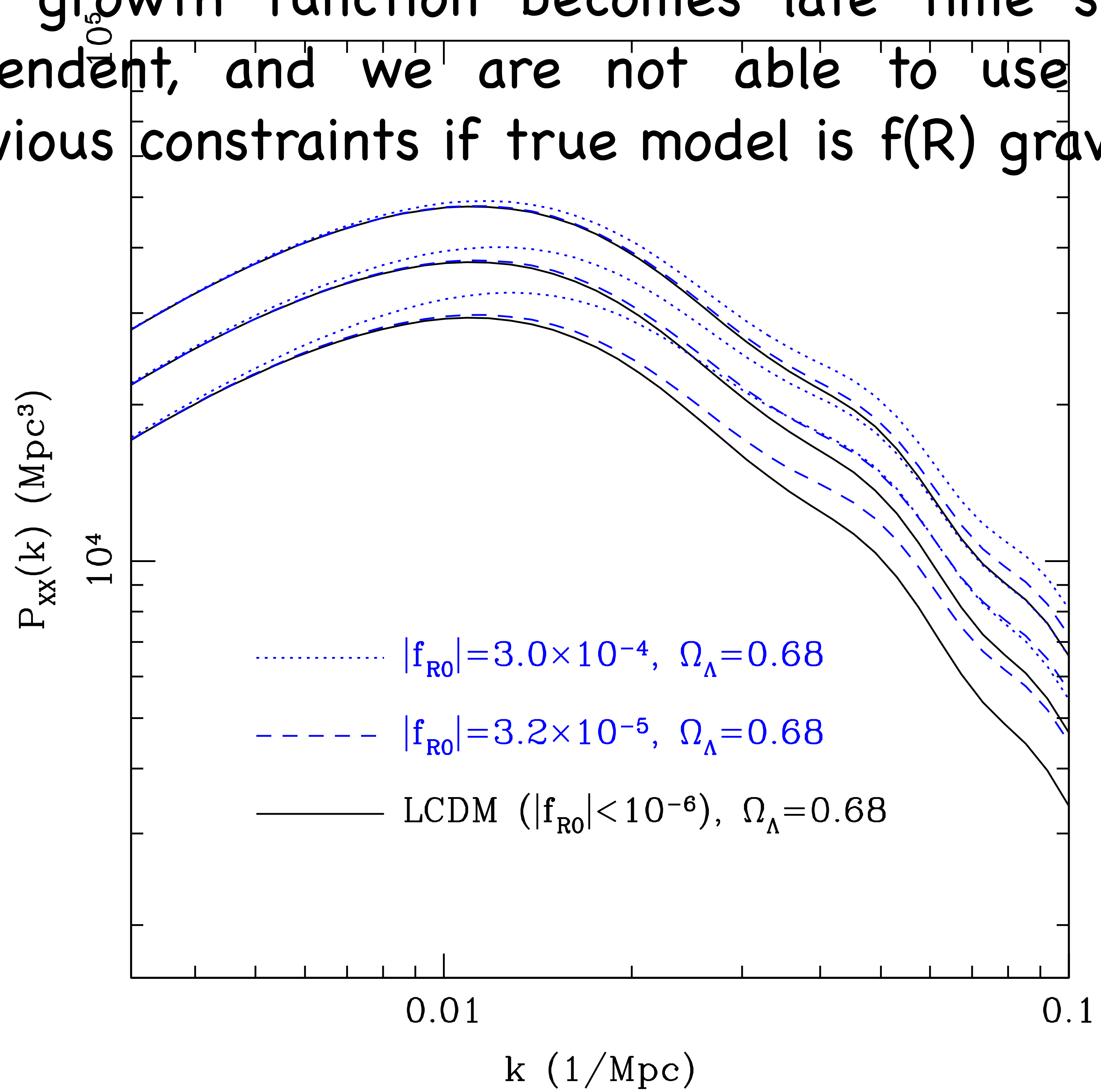
$$D^\delta(k,t) = G_\delta(t)\ F_\delta(k,t;M_1)$$

$$D^\Theta(k,t) = G_\Theta(t)\ F_\Theta(k,t;M_1)$$

We are not able to constrain f(R) gravity models using measured growth functions with the assumption of coherent growing after last scattering surface.

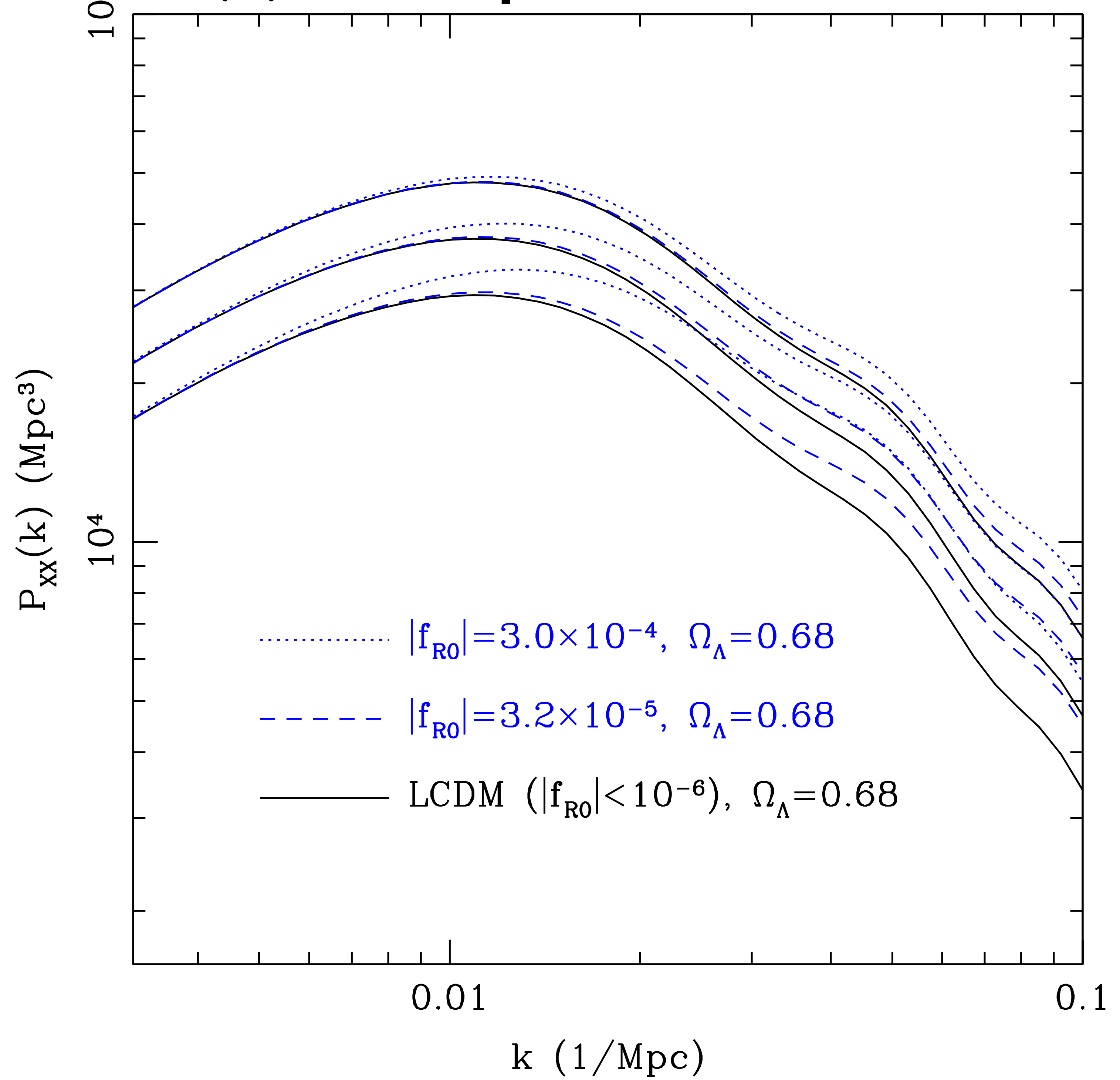
Linear power spectra with running f(R)

The growth function becomes late time scale dependent, and we are not able to use the previous constraints if true model is f(R) gravity

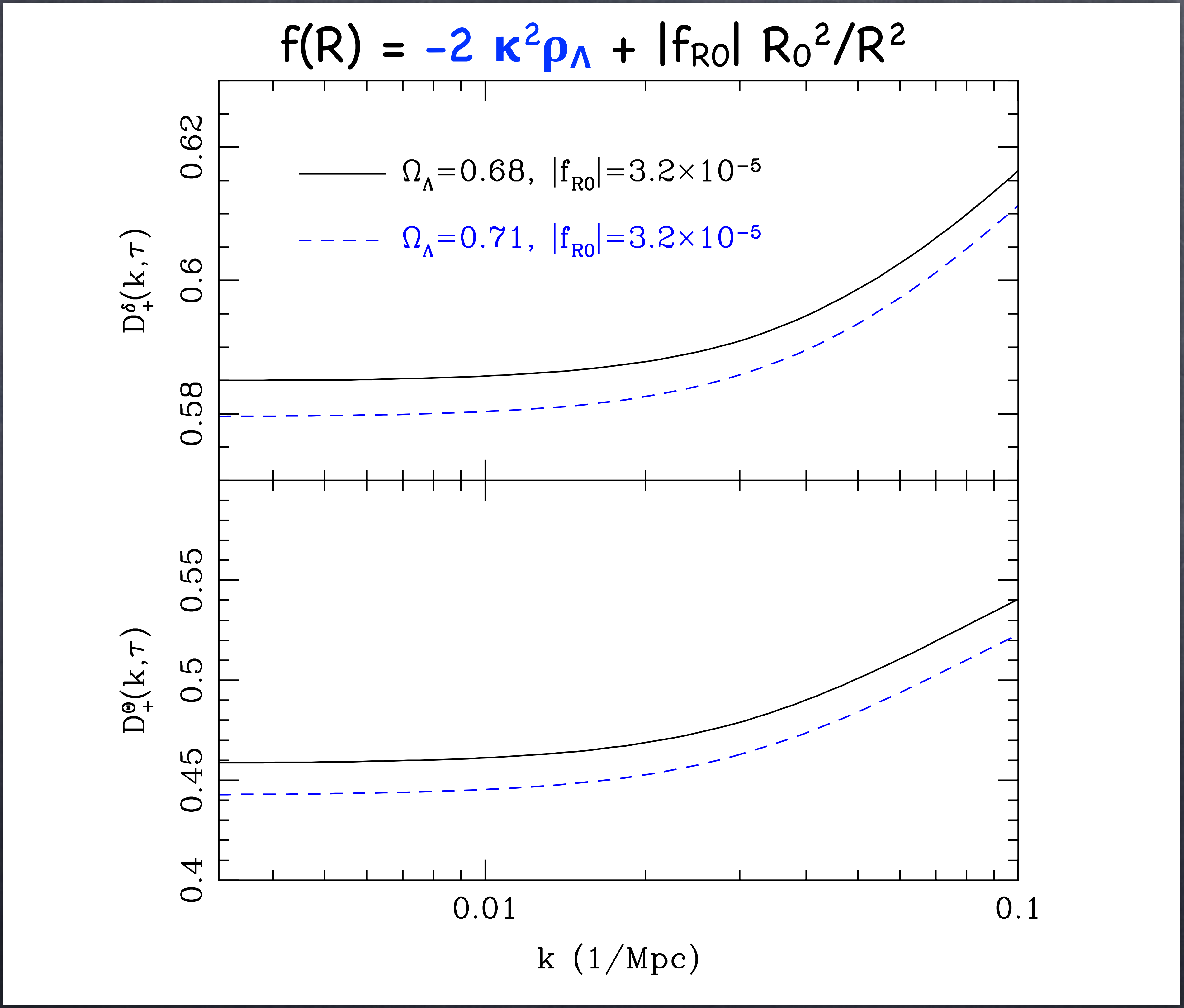


Parameterisation of f(R) gravity model

$f(R) = -2\,\kappa^2 \rho_\Lambda + |f_{R0}|\, R_0^2/R^2$



Parameterisation of f(R) gravity model



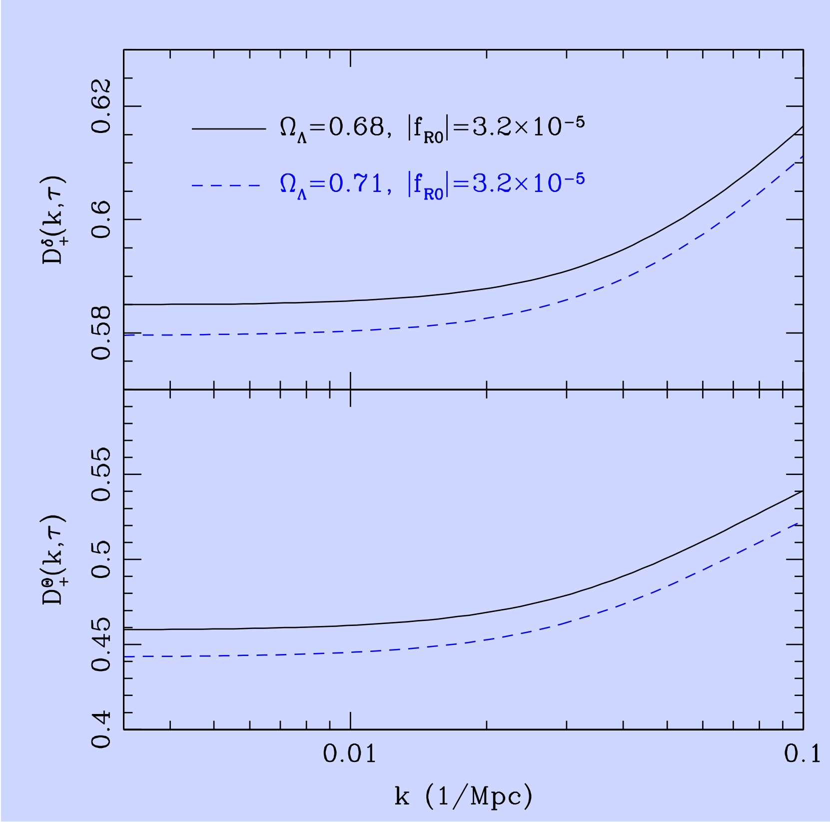
Parameterisation of f(R) gravity model

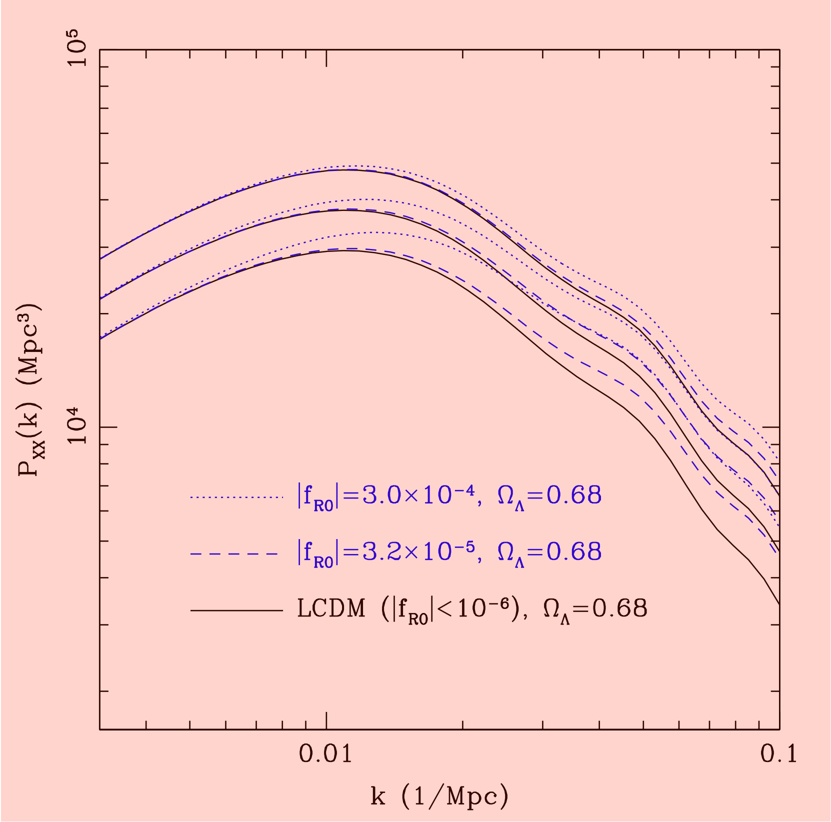
$$f(R) = -2\,\kappa^2\rho_\Lambda + |f_{R0}|\,R_0^2/R^2$$

We find that both coherent growth factors and scale dependent growth factors are separable in the following sense,

$$D^\delta(k,t) = G_\delta(t)\,F_\delta(k,t;M_1)$$

$$D^\Theta(k,t) = G_\Theta(t)\,F_\Theta(k,t;M_1)$$





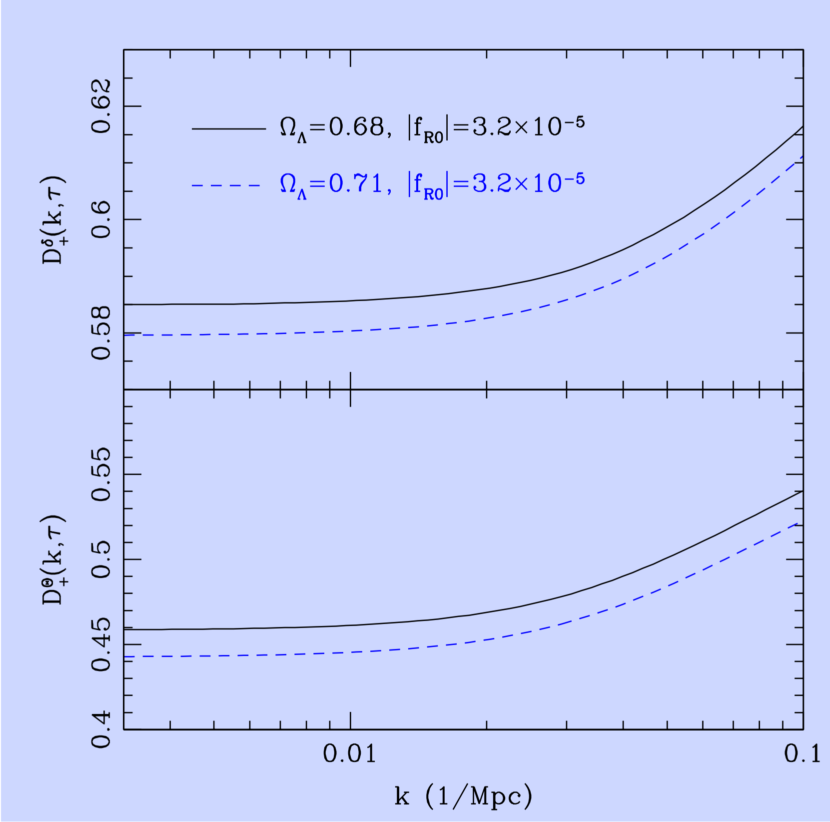
Parameterisation of f(R) gravity model

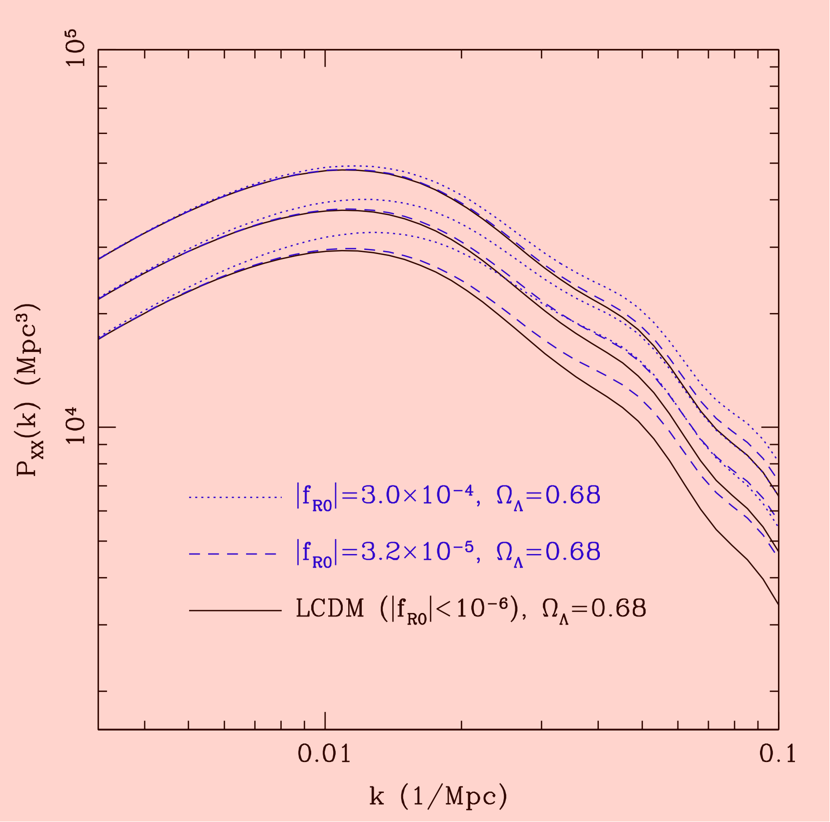
$$f(R) = -2\,\kappa^2\rho_\Lambda + |f_{R0}|\,R_0^2/R^2$$

Parameter space is (D_A, H^{-1}, G_δ, G_Θ, FoG, $|f_{R0}|$)

$$D^\delta(k,t) = G_\delta(t)\,F_\delta(k,t;M_1)$$

$$D^\Theta(k,t) = G_\Theta(t)\,F_\Theta(k,t;M_1)$$

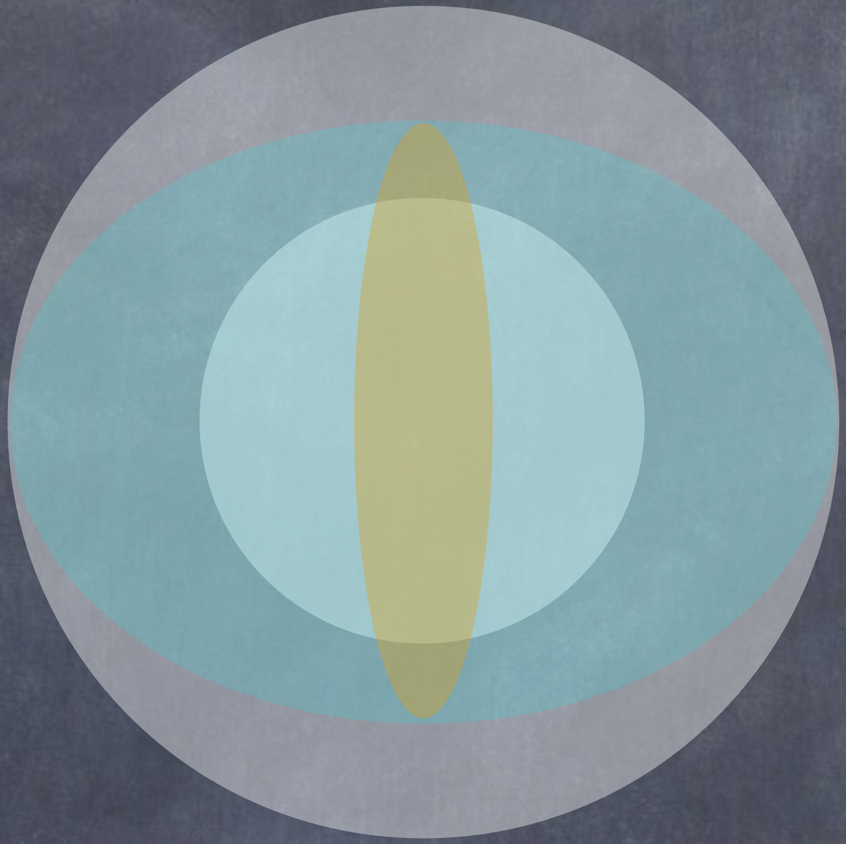




Structure formation of RSD

Squeezing effect at large scales

(Kaiser 1987)



Finger of God effect at small scales

(Jackson 1972)

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

↓

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

Structure formation of RSD

The non-linear solution is derived from

$$d\delta_m/dt + \nabla[(1+\delta_m)v_m]/a = 0$$

$$dv_m/dt + Hv_m + (v_m\nabla)v_m/a = -\nabla\psi/a$$

$$\phi_{fR} - \psi_{fR} = \varphi$$

$$k^2\,\psi = -3/2\; H_0{}^2\Omega_m\; \delta_m/a - 1/2\; k^2\varphi$$

$$(1+w_{BD})\; k^2/a^2\, \varphi = 3H_0{}^2\Omega_m\; \delta_m/a - I(\varphi)$$

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

↓

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

Structure formation of RSD

The higher order polynomials are given by,

$$A(k,t) = b^3 \Sigma_n \Sigma_{a,b}\, \mu^{2n}(G_\Theta/b)^{2a+b-1} \int d^3k \int dr \int dx$$

$$\times\, [A^n_{ab}(r,x) B_{2ab}(p,k-p,-k) + A^n_{ab}(r,x) B_{2ab}(k-p,p,-k)$$

$$B(k,t) = b^4 \Sigma_n \Sigma_{a,b}\, \mu^{2n}(-G_\Theta/b)^{2a+b-1} \int d^3k \int dr \int dx$$

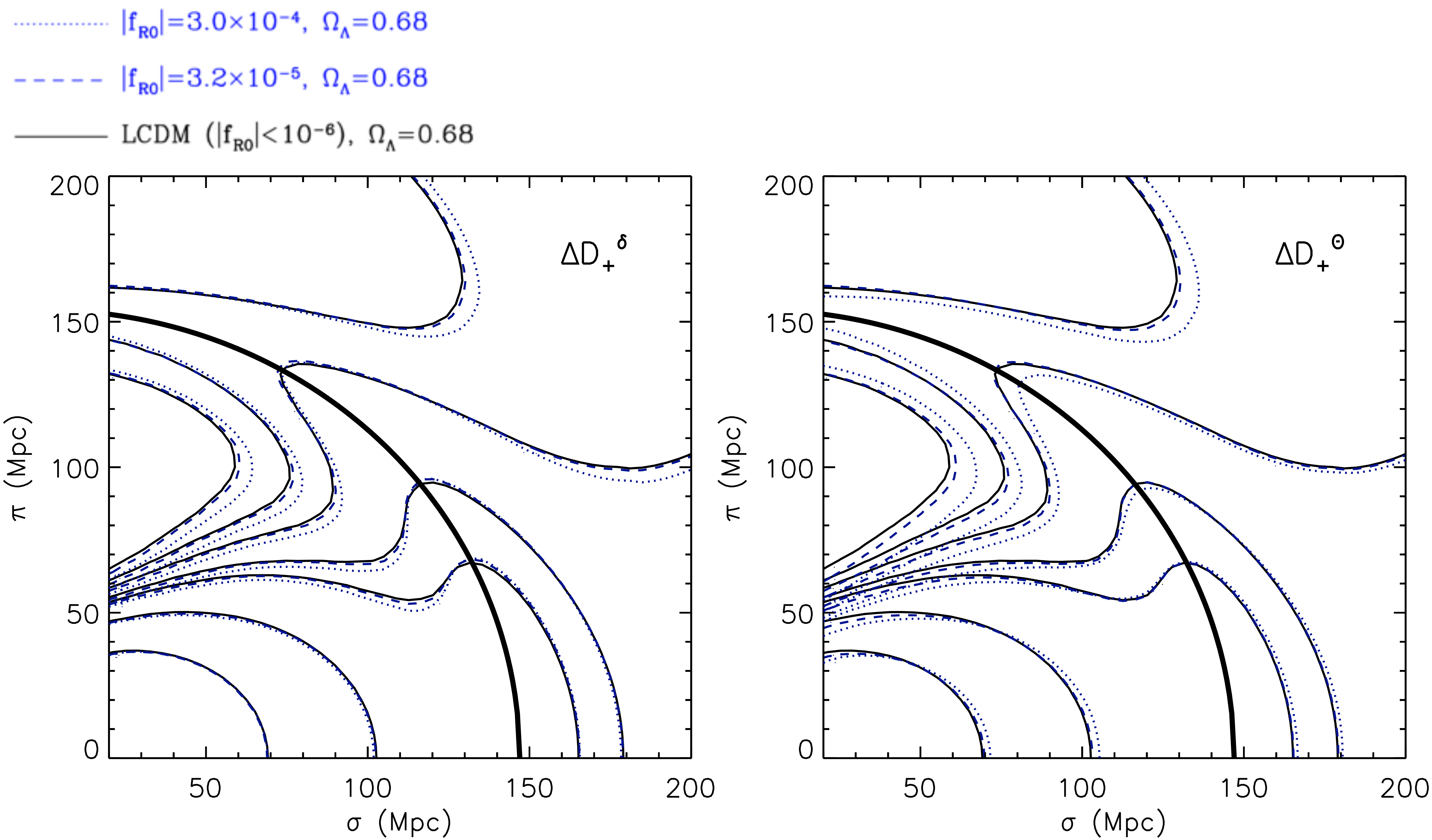
$$\times\, B^n_{ab}(r,x) P_{a2}(k\sqrt{1+r^2-2rx}) P_{b2}(kr)/(1+r^2-2rx)^a$$

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

↓

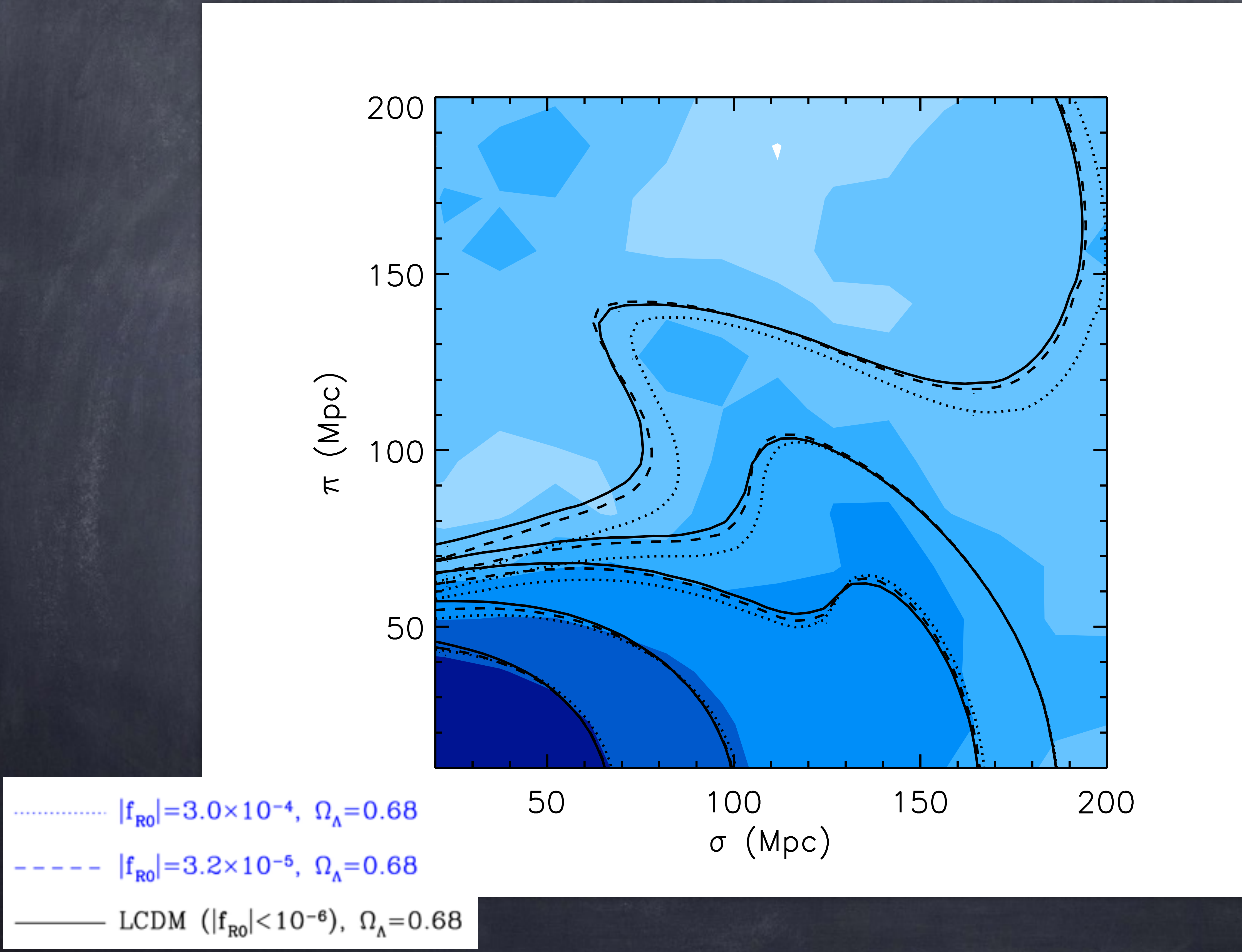
$$P_s(k,\mu) = [P_{gg}(k) + \Delta P_{gg} + 2\mu^2 P_{g\theta}(k) + \Delta P_{g\theta} + \mu^4 P_{\theta\theta}(k) + \Delta P_{\theta\theta}$$
$$+ \mu^2 A(k) + \mu^4 B(k) + \mu^6 C(k) + \ldots]\, \exp[-(k\mu\sigma_p)^2]$$

Correlation function of f(R) gravity model



The variation of D^{δ} | The variation of D^{Θ}

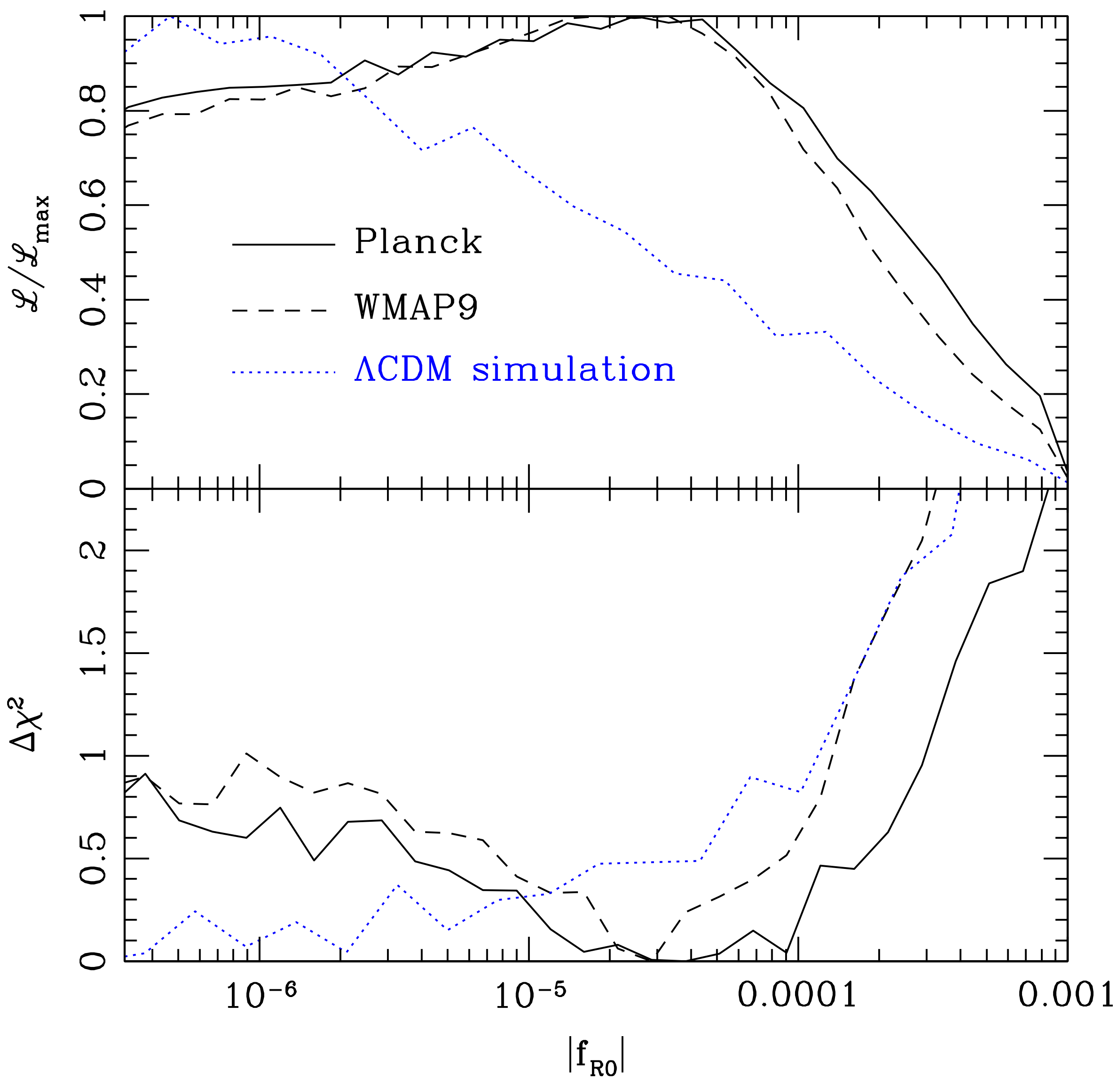
The measurement and best fit models



Constraints on f(R) gravity model

We find new constraints on f(R) gravity models using BOSS DR11

$|f_{R0}| < 8\times10^{-4}$ at 95% confidence limit



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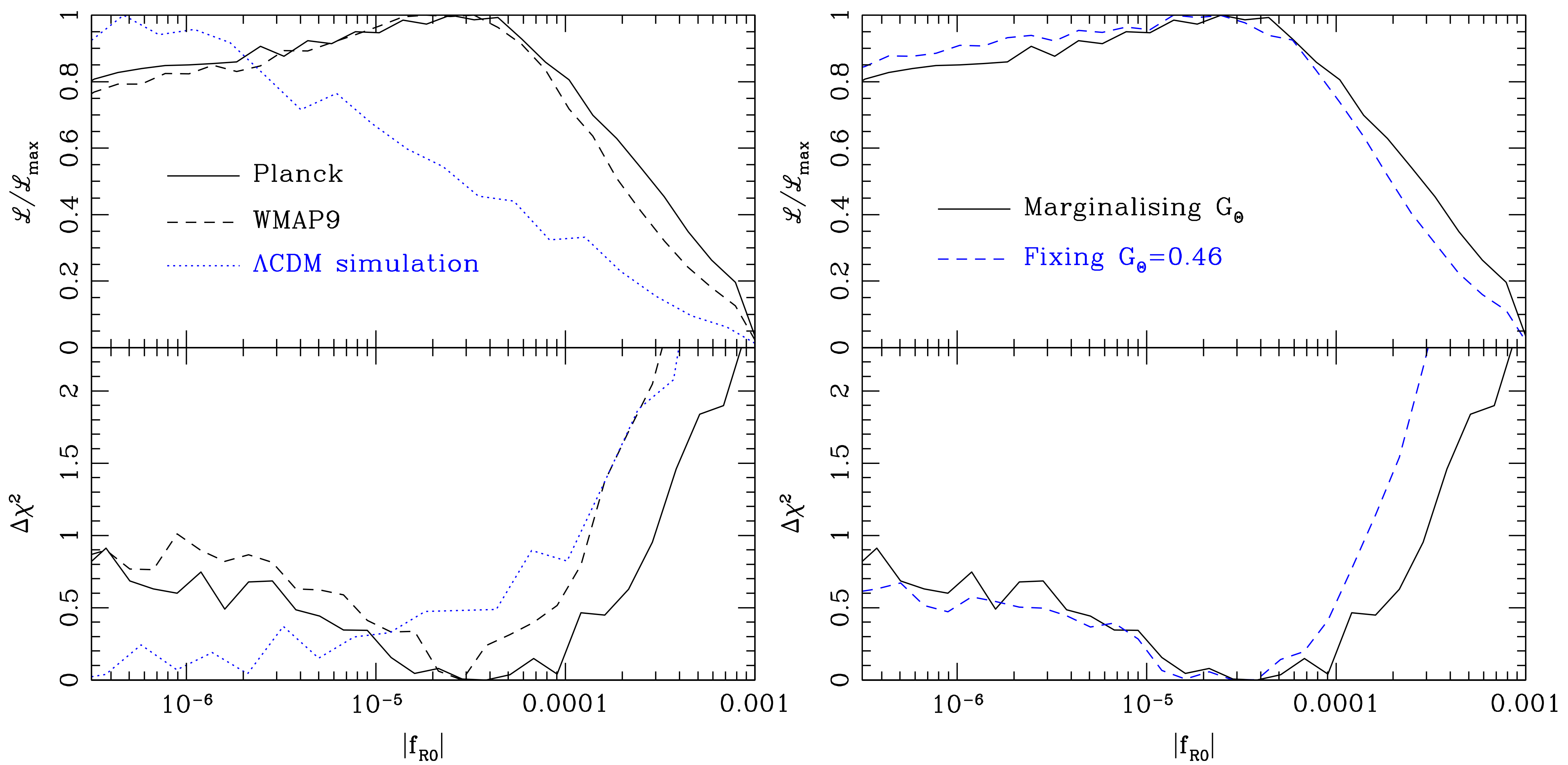
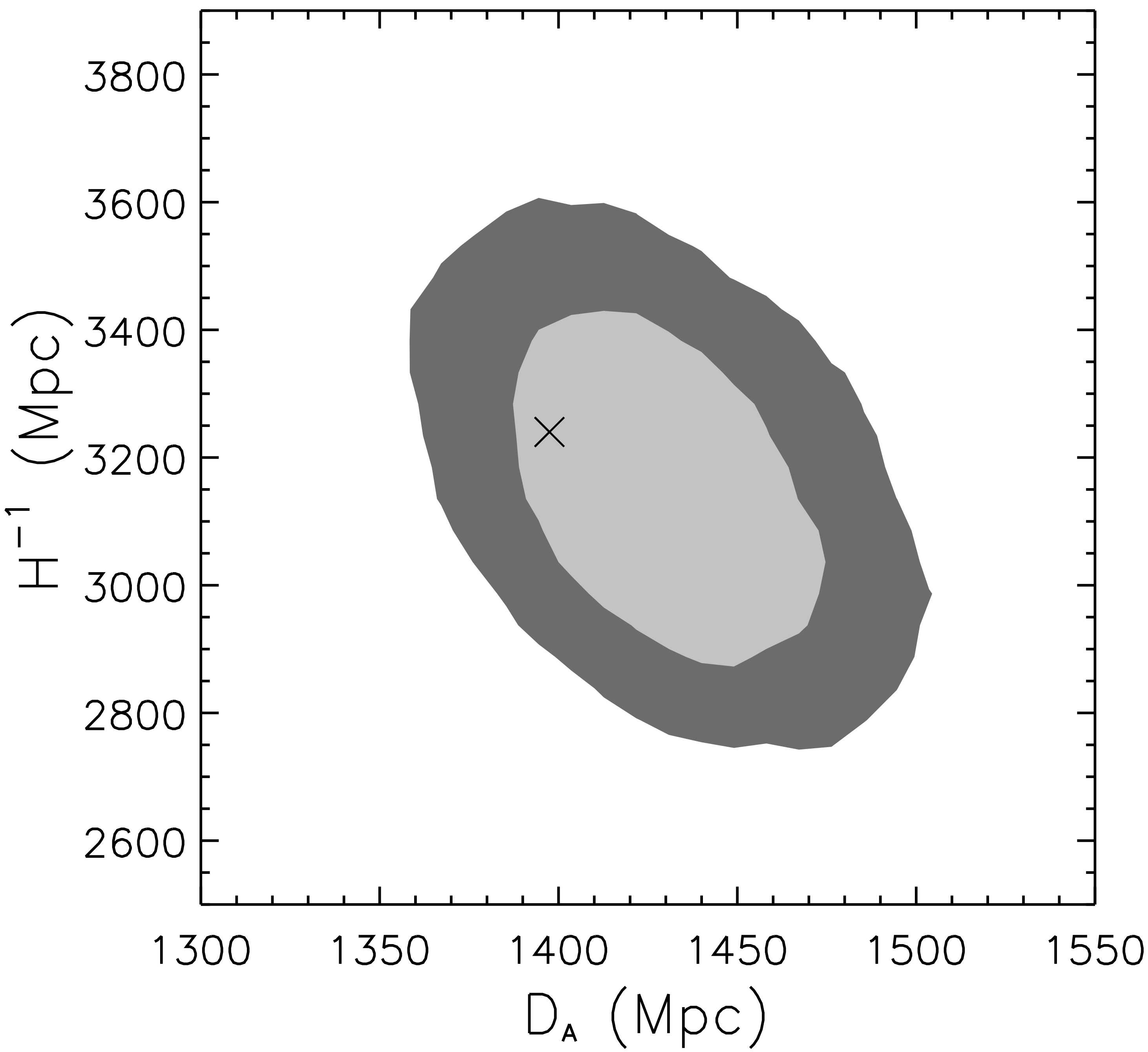


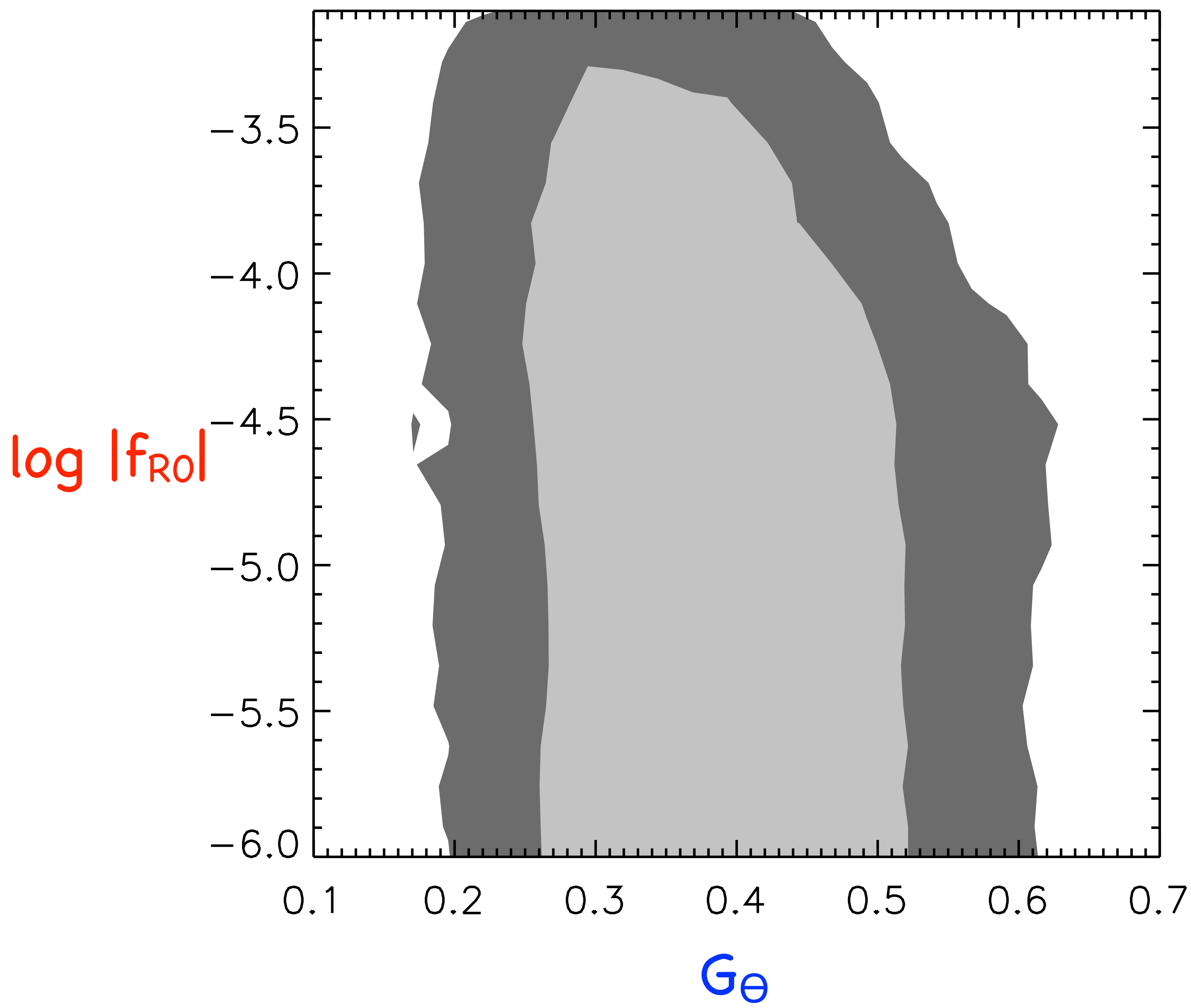
Constraints on distance measures

Measured distances are consistent with LCDM model



Constraints on growth functions

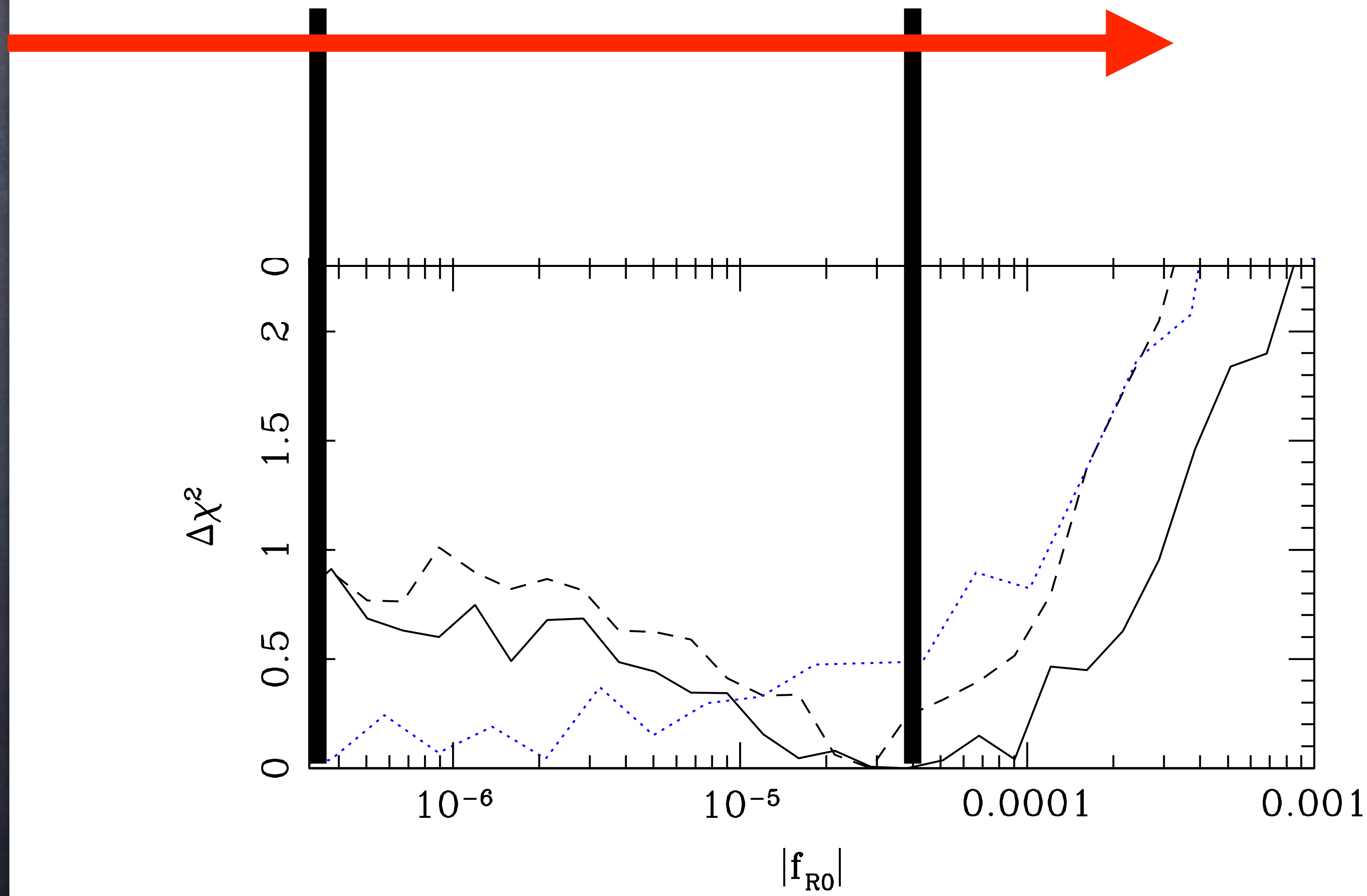
$$D^{\Theta}(k,t) = G_{\Theta}(t)\ F_{\Theta}(k,t;M_1)$$



Constraints on f(R) now and future

Invisible difference from LCDM model using BOSS

Need a factor of 10 improvement



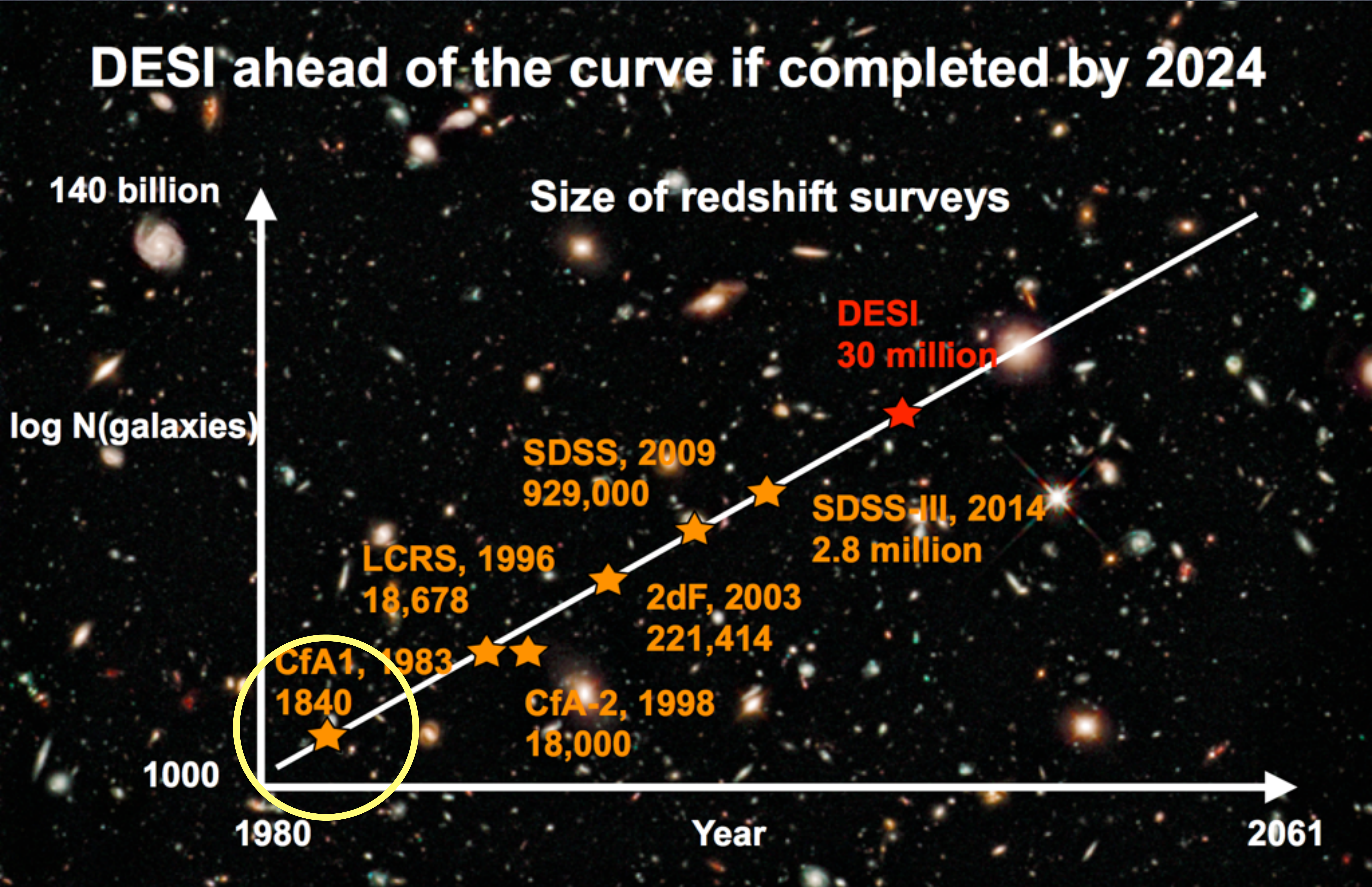
Key observables in cosmological science

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.

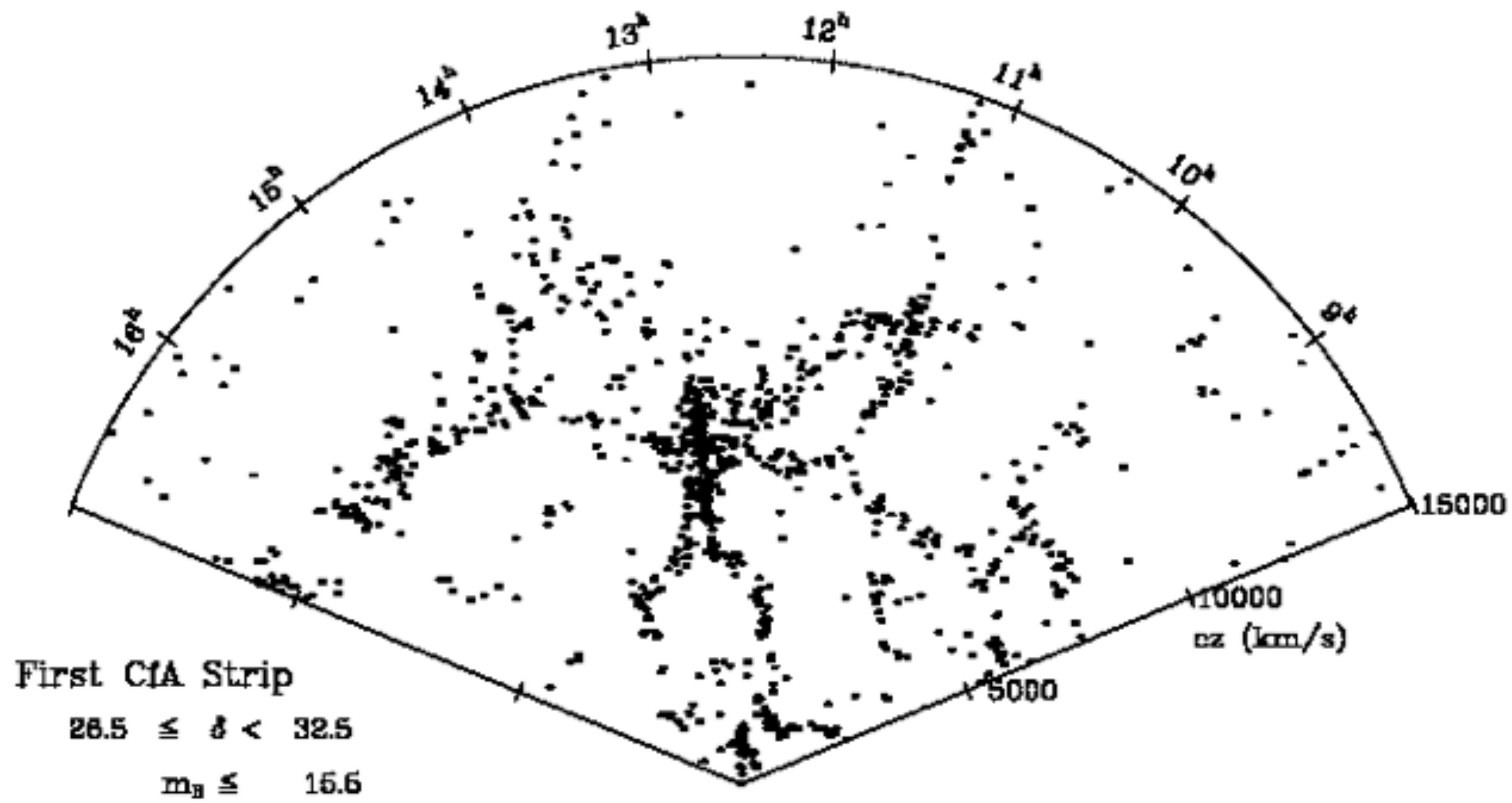
Coherent motion G_θ: The coherent motion, or flow, of galaxies can be statistically estimated from their effect on the clustering measurements of large redshift surveys, or through the measurement of redshift space distortions.

Where we are, and where will we go?

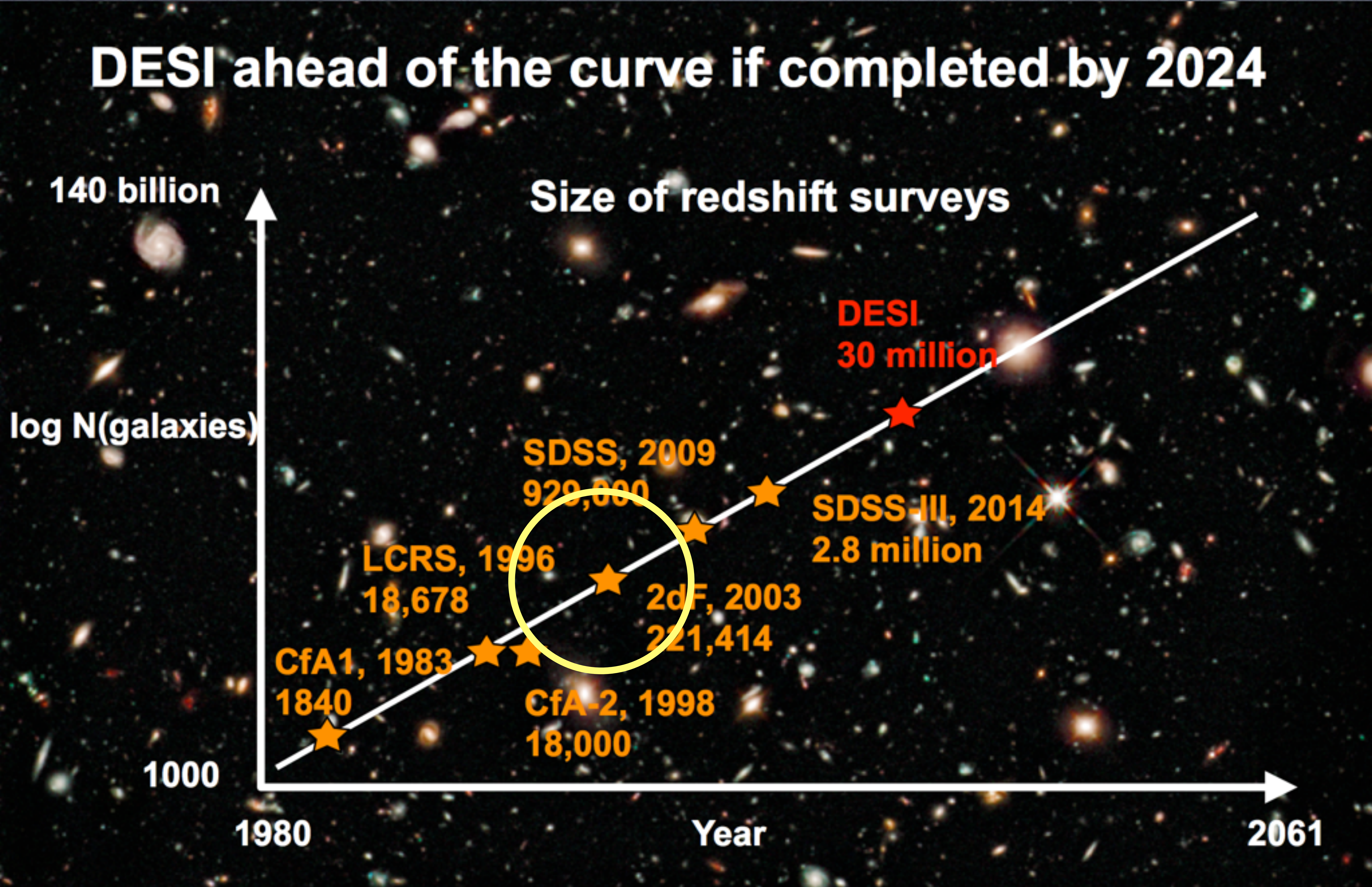


Second generation by CfA1

1830 galaxies in 1983

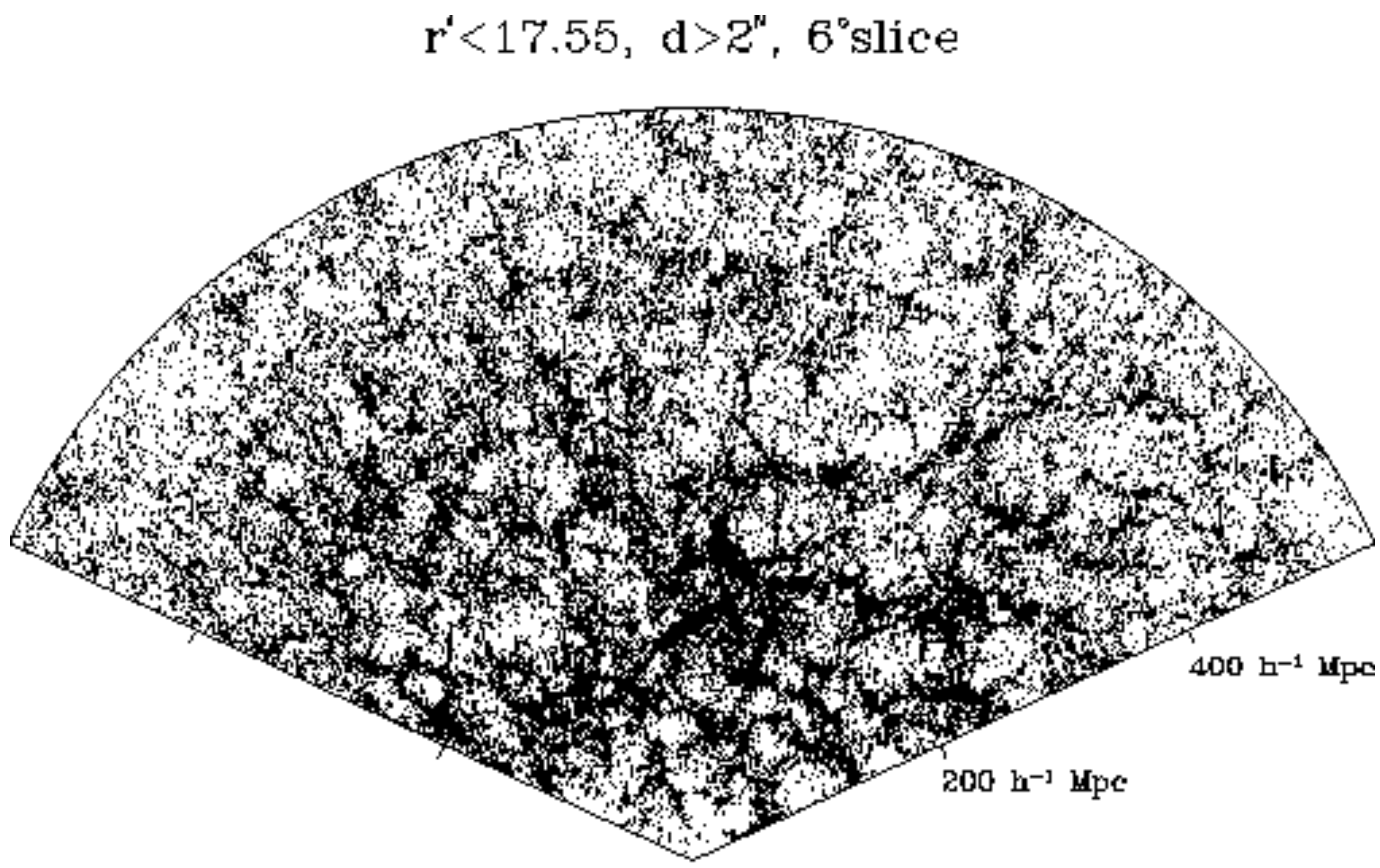


Where we are, and where will we go?



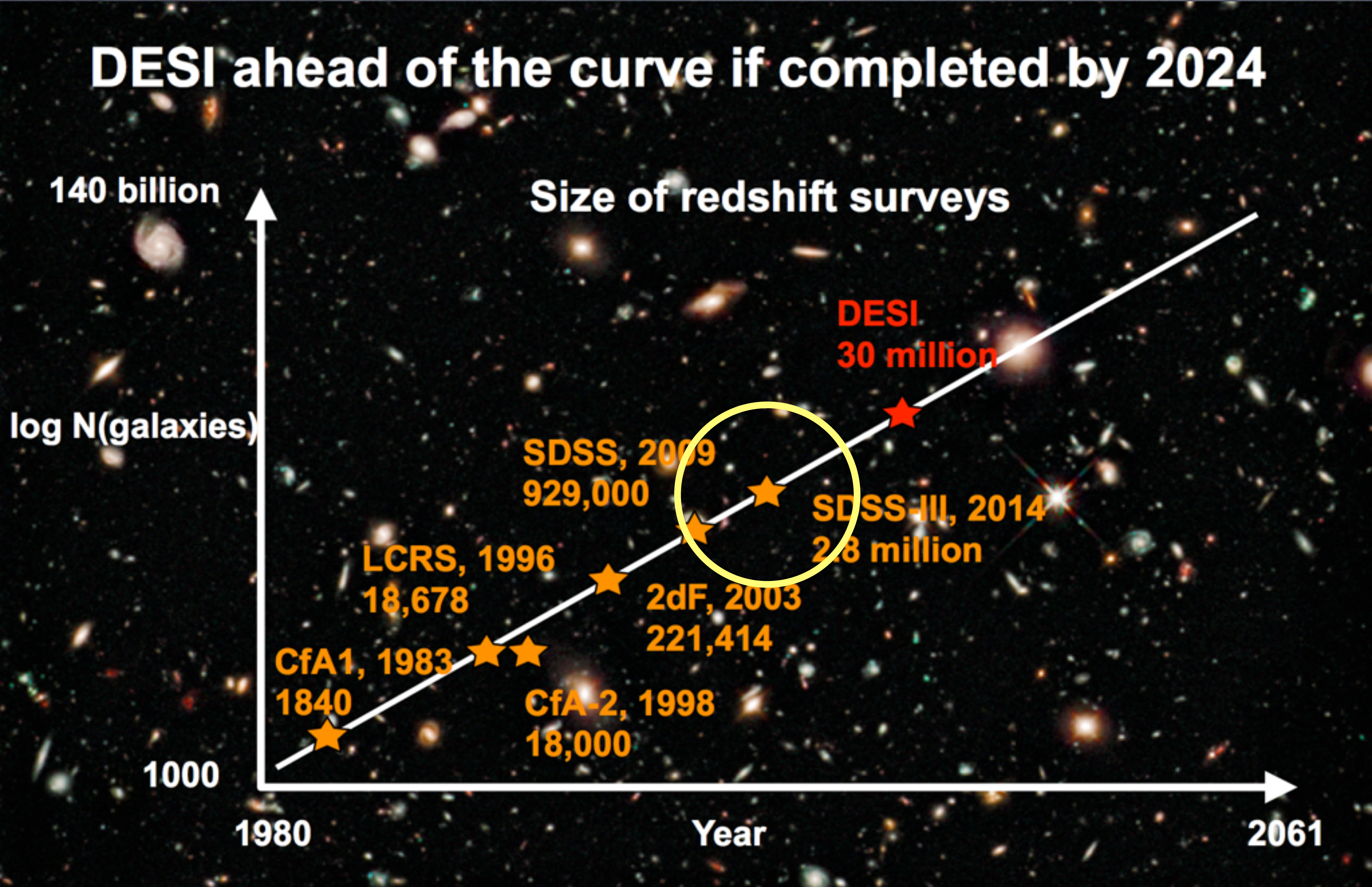
First generation by 2dF

221,414 galaxies in 2003



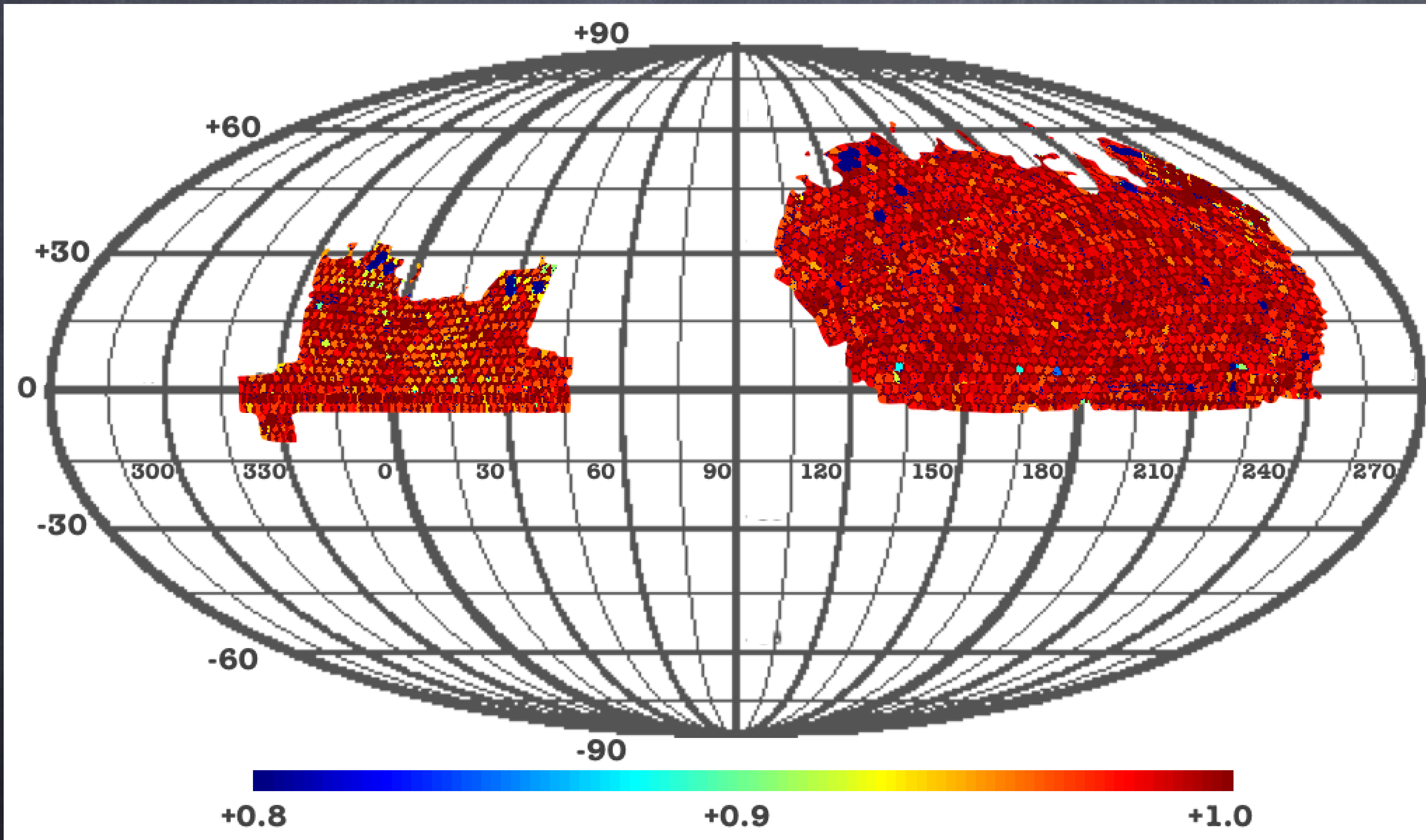
2dF scanned the first evidence of cosmic web of the universe. New spectroscopy technology allows us to locate the radial distance.

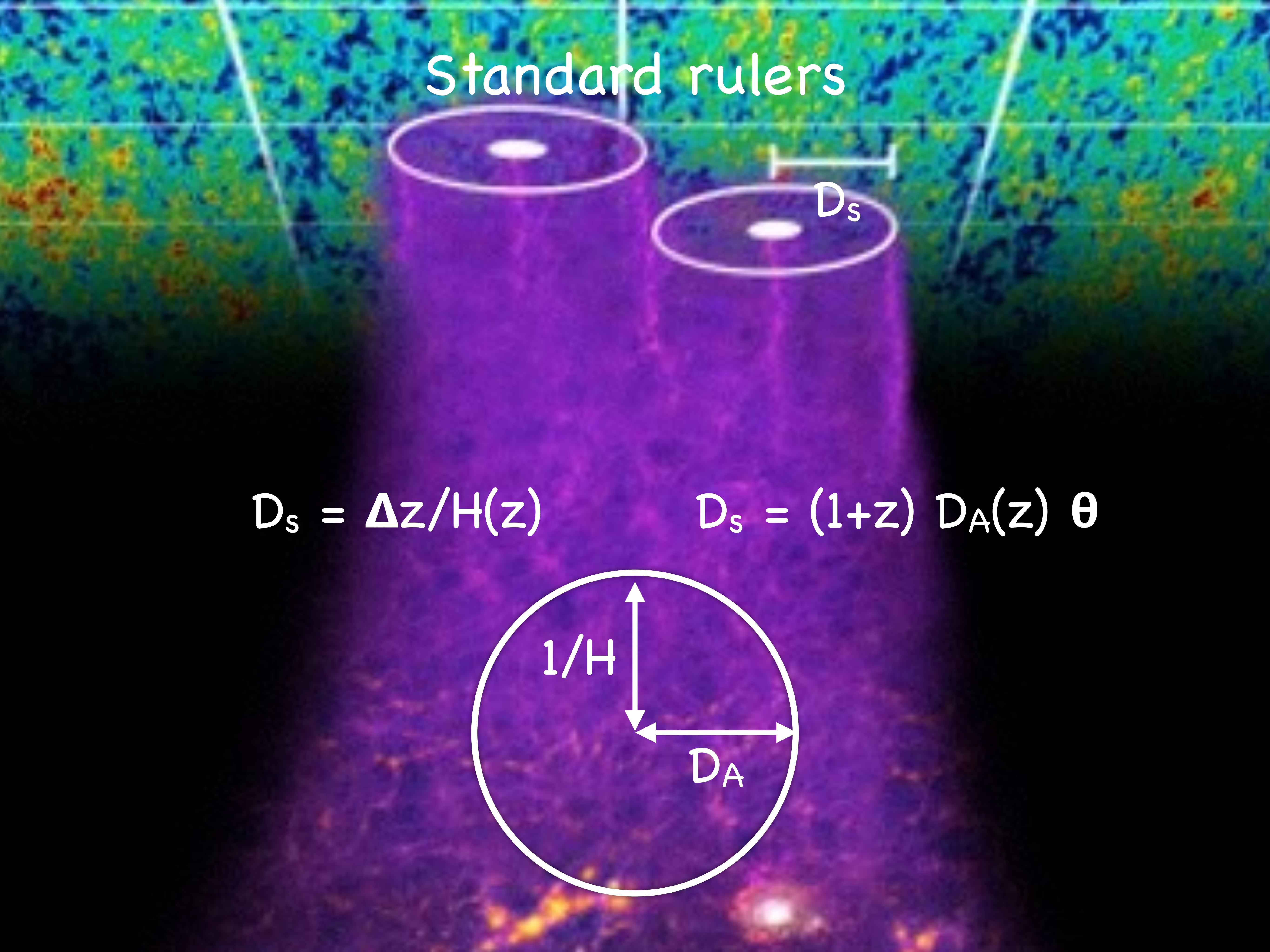
Where we are, and where will we go?



Spectroscopy wide deep field survey

BOSS DR11 catalogue with 2.8 M galaxies

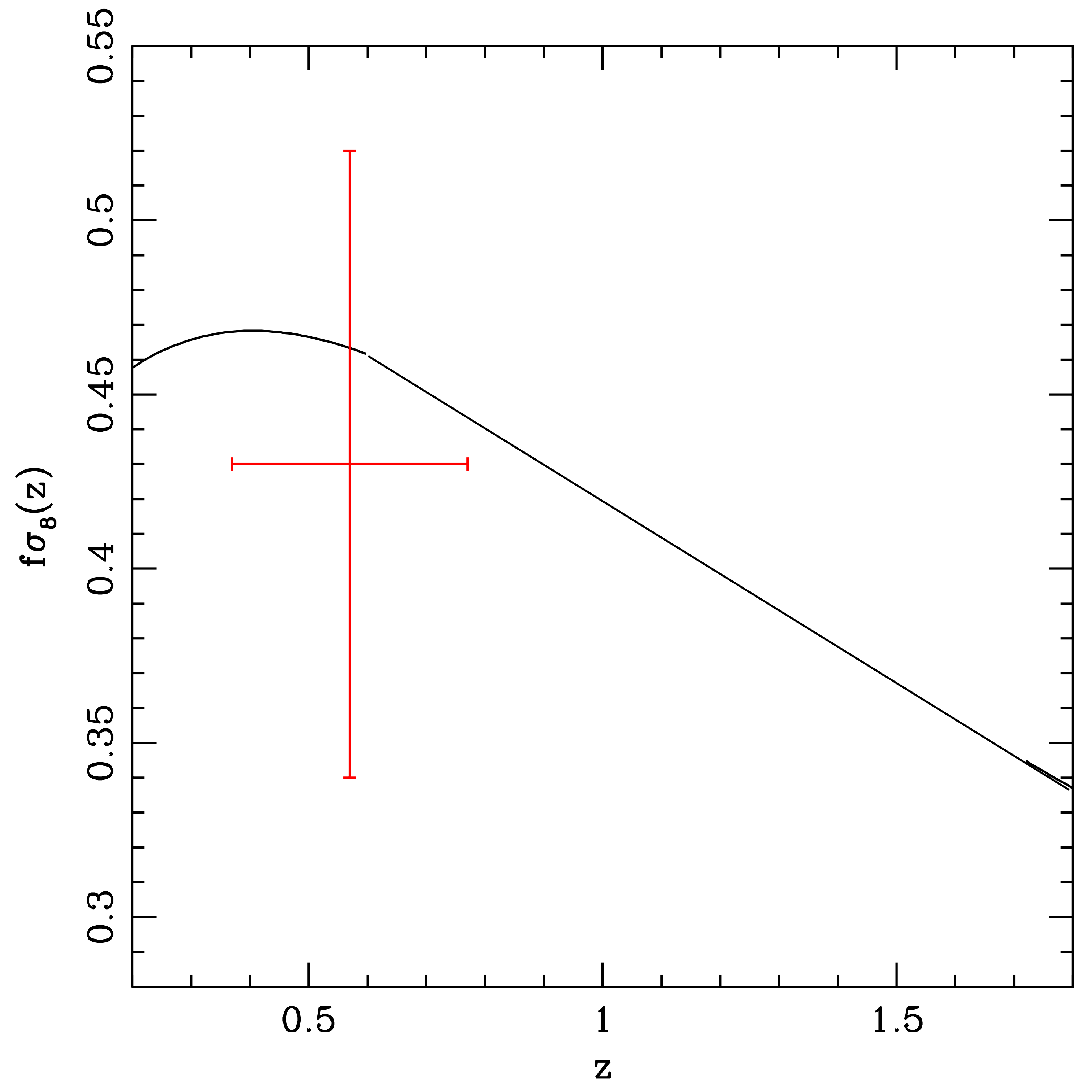



Standard rulers
D_s
$D_s = \Delta z/H(z)$
$D_s = (1+z)\, D_A(z)\, \theta$
1/H
D_A

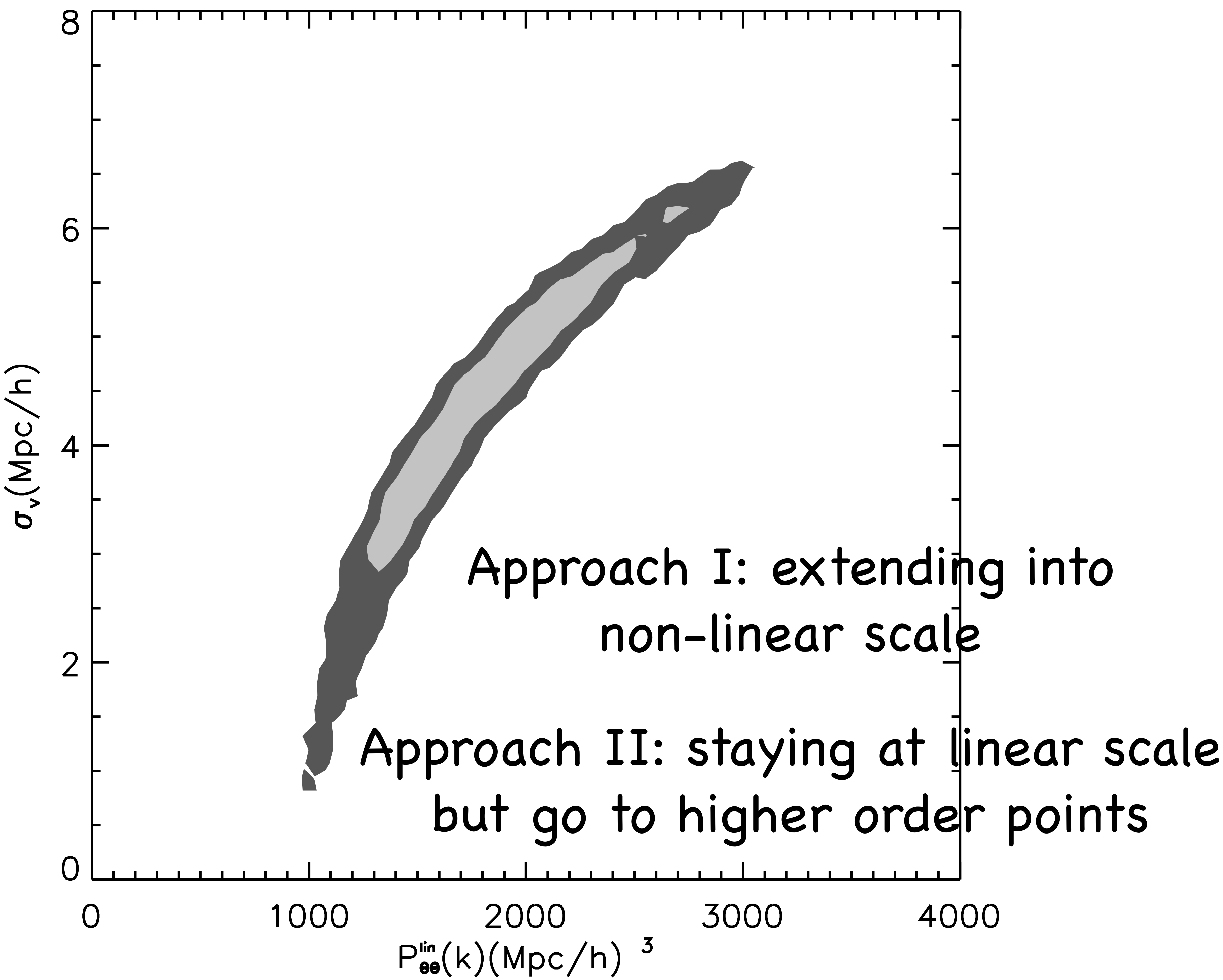
YSS, Sabiu, Okumura, Oh, Linder2014

Measured coherent motion

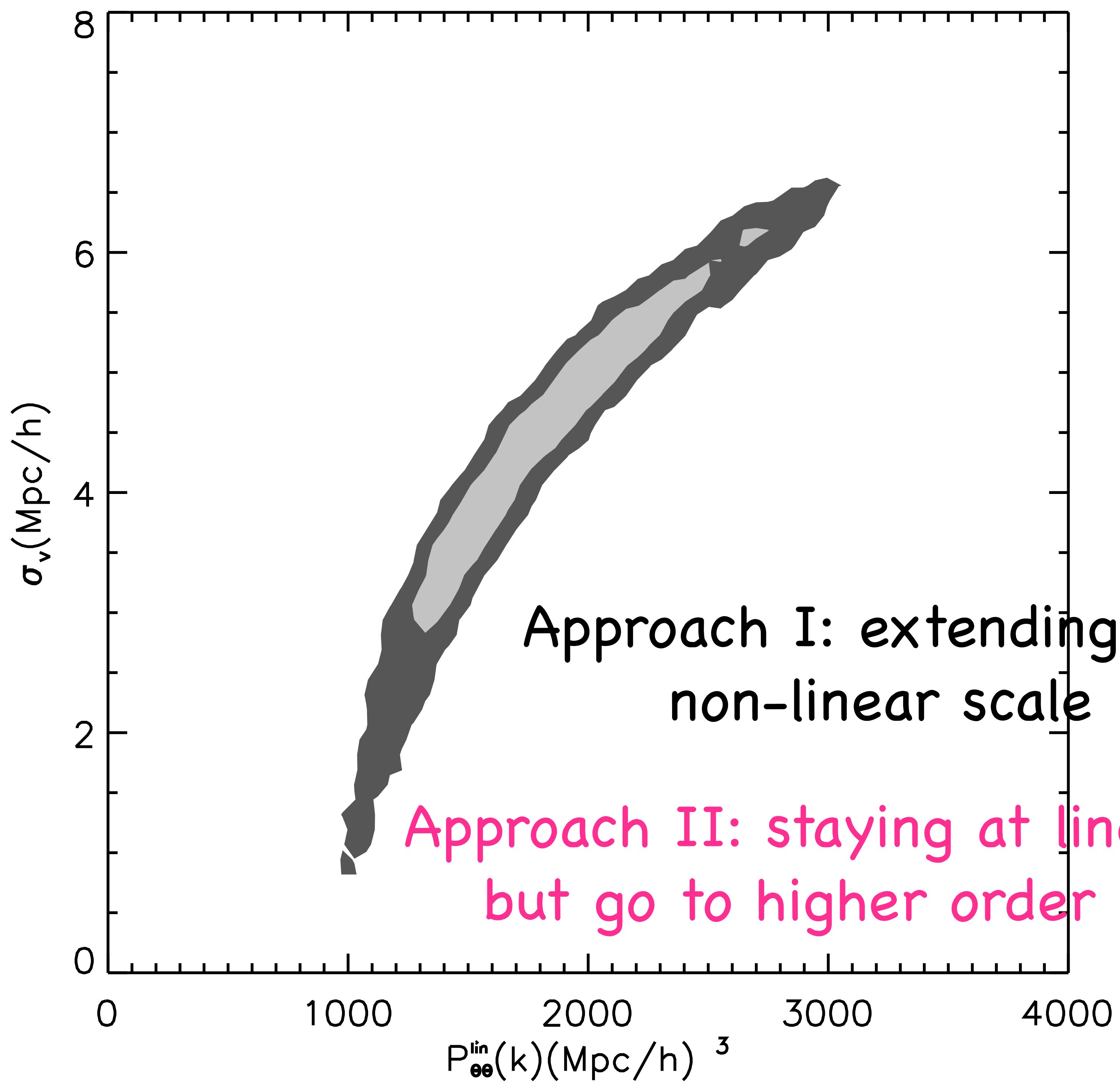
Results from BOSS maps



Degeneracy for coherent motions



Degeneracy for coherent motions



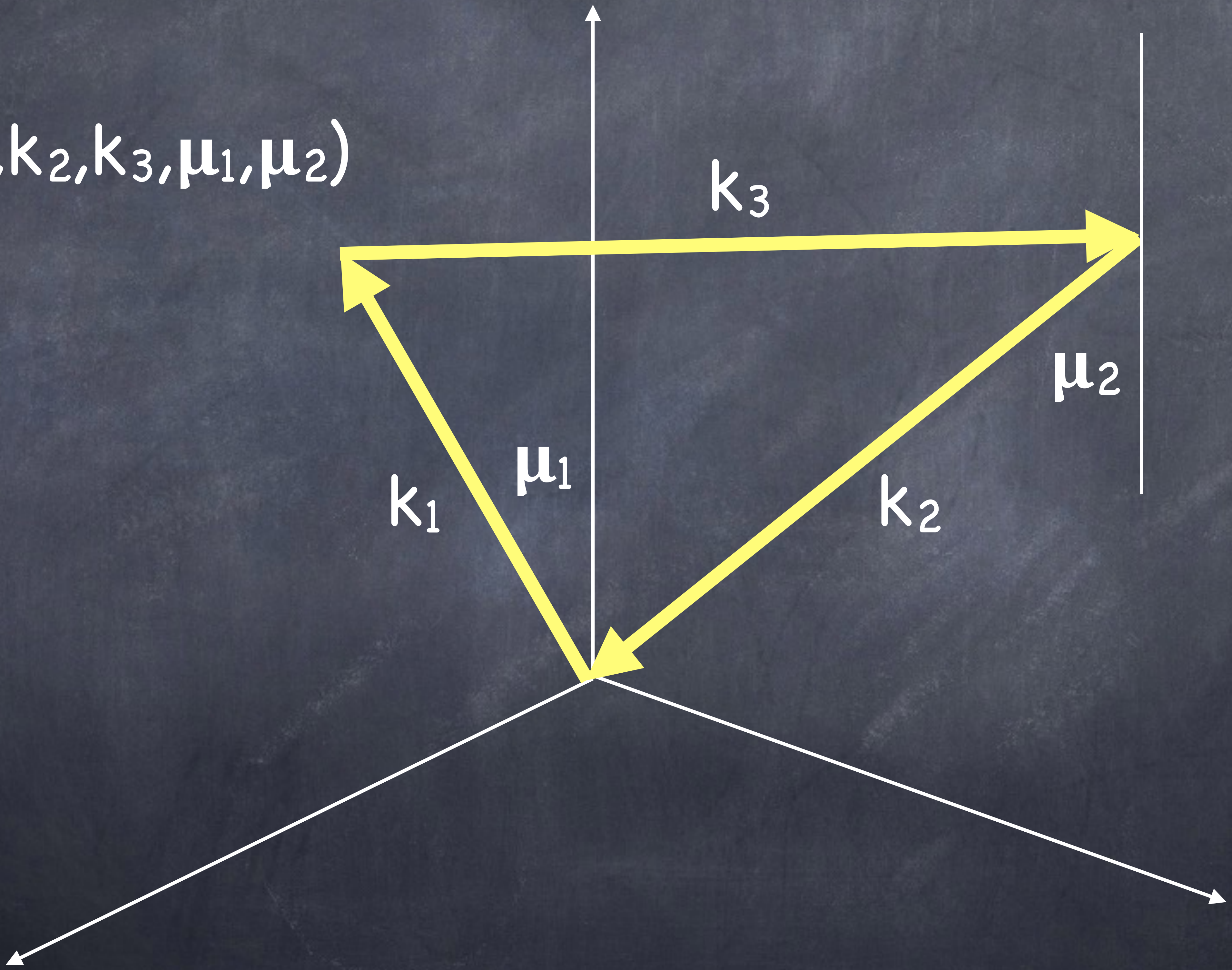
Approach I: extending into non-linear scale

Approach II: staying at linear scale but go to higher order points

Bispectrum Alcock-Paczynski effect

Configuration in redshift space

$B(k_1,k_2,k_3,\mu_1,\mu_2)$



YSS, Taruya, Oka 2015

Error forecast using power and bi combination

$$F_{\alpha\beta} = \Sigma_k \Sigma_{k1k2k3} (\partial S/\partial p_\alpha)\, C^{-1}\, (\partial S/\partial p_\beta)$$

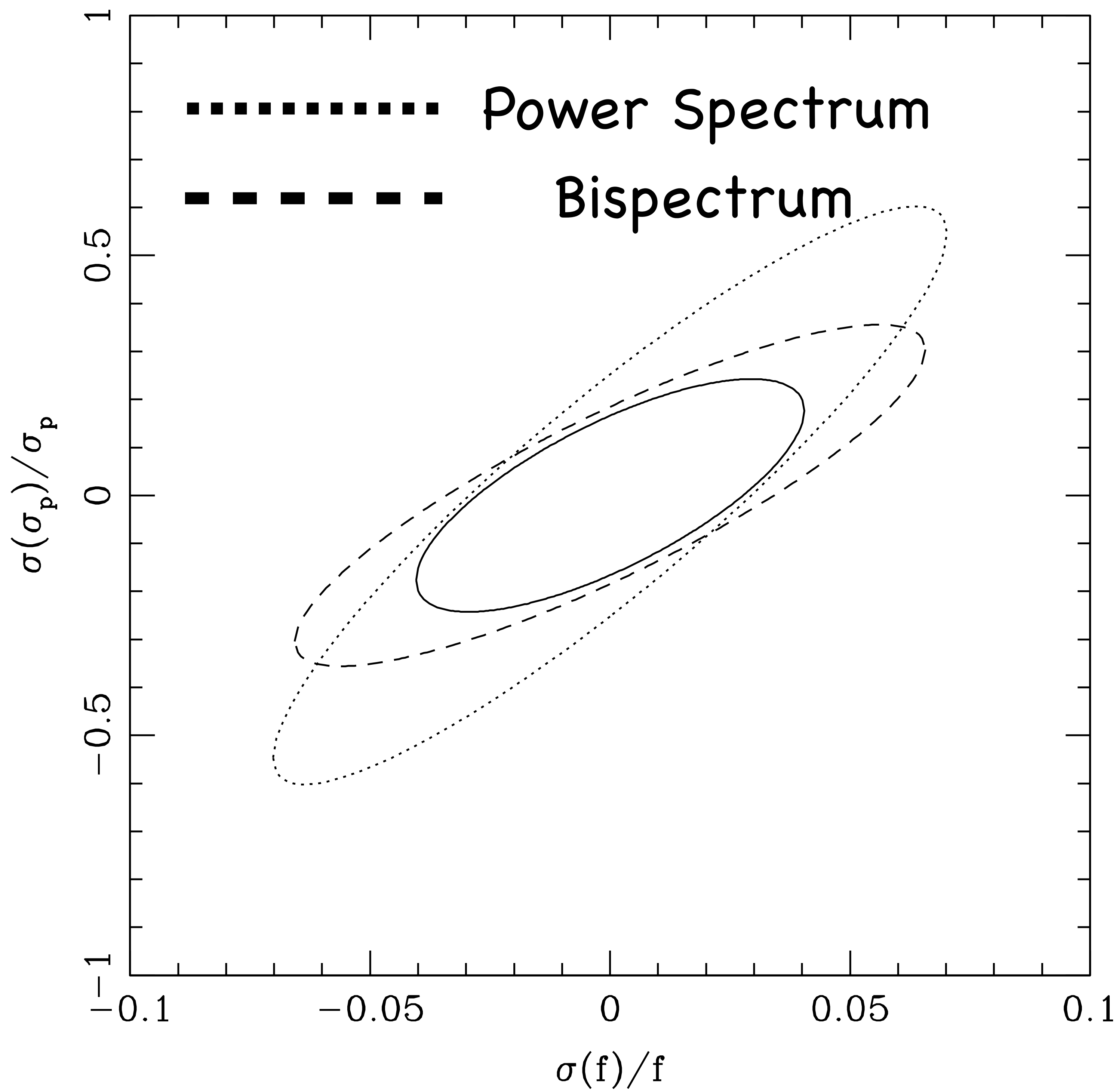
$$S = \begin{pmatrix} P(k,\mu) \\ B(k_1,k_2,k_3,\mu_1,\mu_2) \end{pmatrix}$$

$$C^{-1} = \begin{pmatrix} M & -MC_{PB}C_{BB}^{-1} \\ -C_{BB}^{-1}C_{BB}^{-1}M & C_{BB}^{-1}+C_{BB}^{-1}C_{Bp}MC_{PB}C_{BB}^{-1} \end{pmatrix}$$

$$M = (C_{pp}-C_{PB}C_{BB}^{-1}C_{BP})^{-1}$$

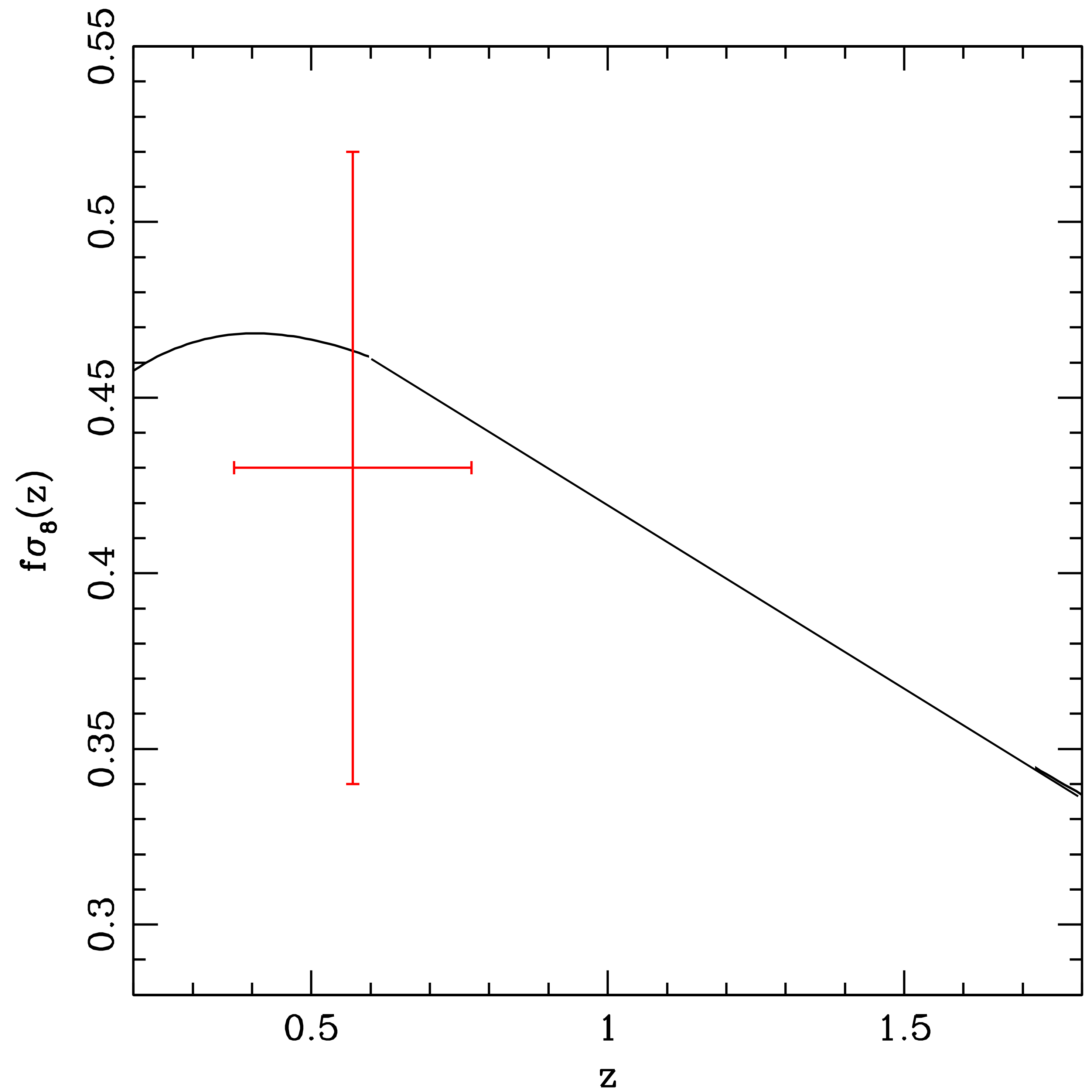
YSS, Taruya, Oka 2015

Degeneracy in coherent and random motions



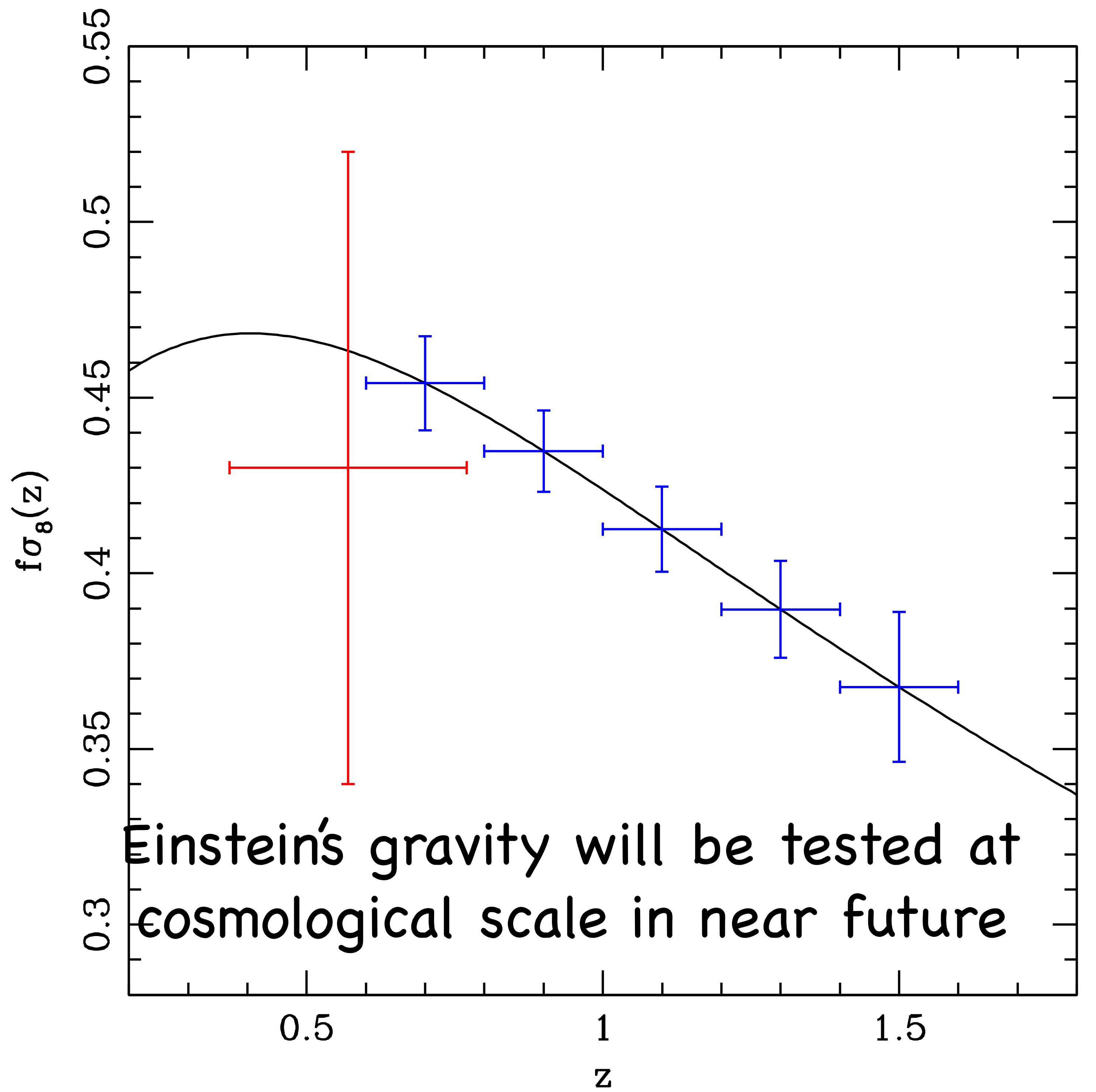
Measured coherent motion

Results from BOSS maps



Future constraints

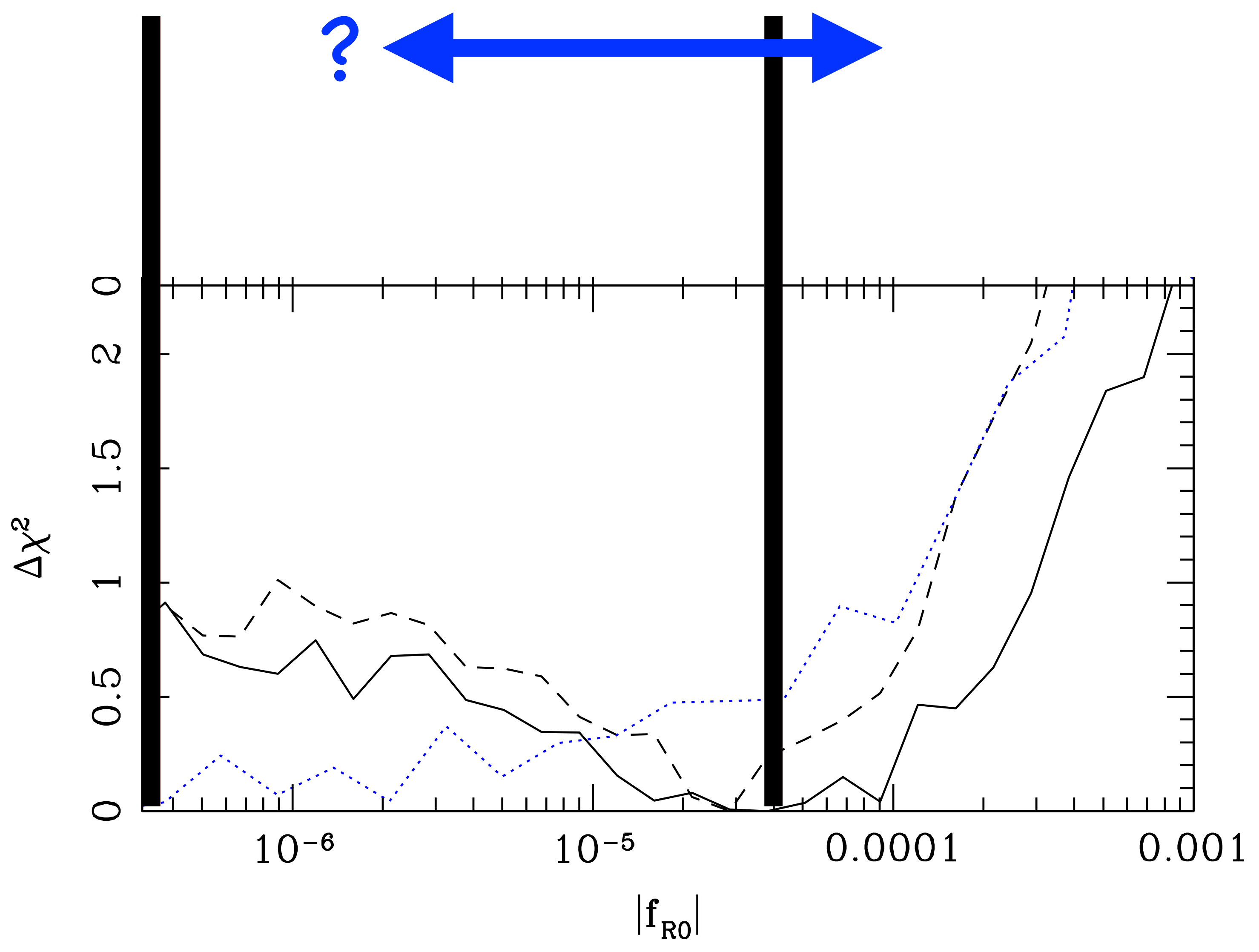
Expectation from DESI



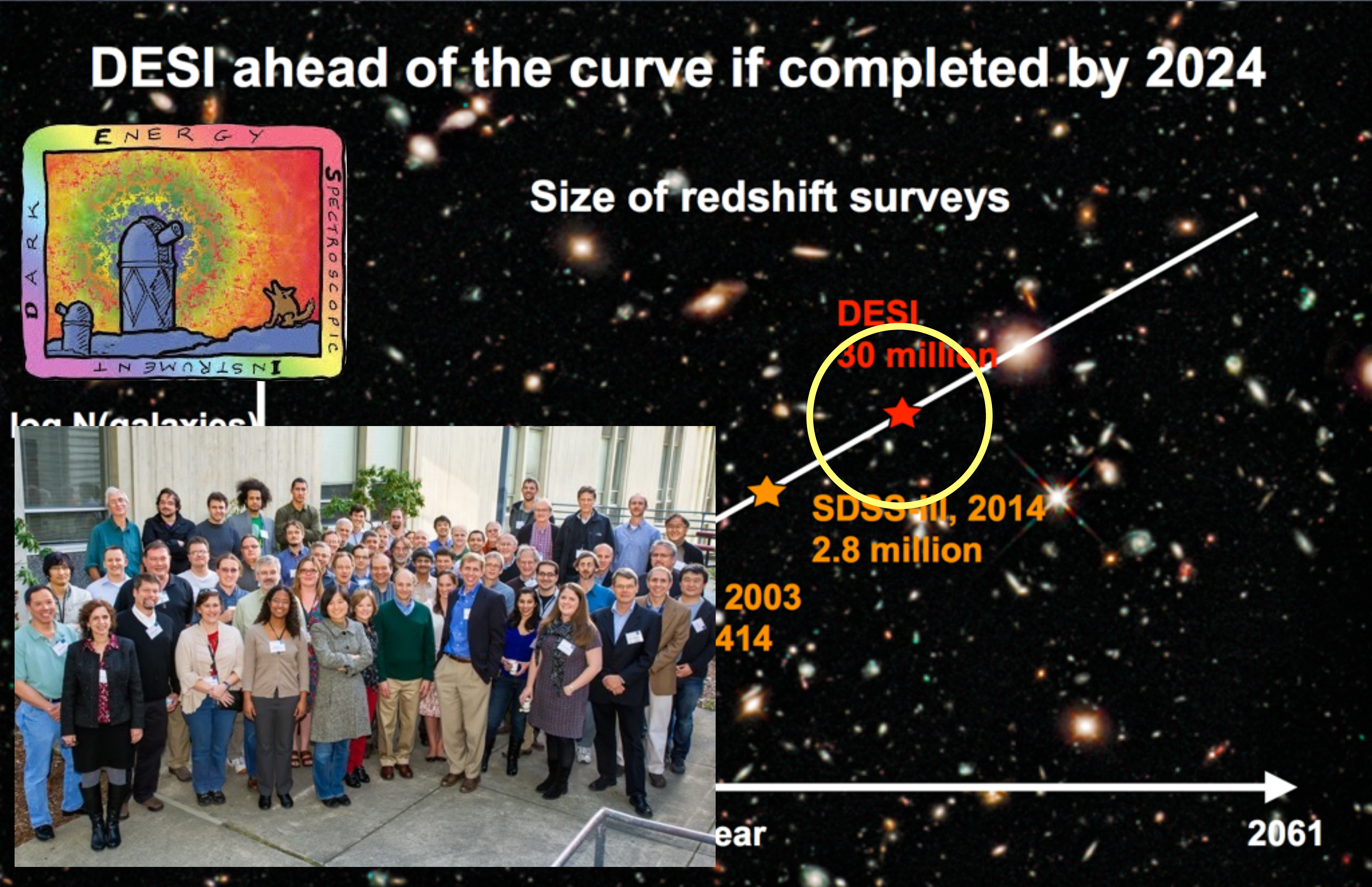
Future work

Invisible difference from LCDM model using BOSS

then can we tell the difference in future?



Where we are, and where will we go?



Conclusion

- We succeed in measuring both distances and growth function simultaneously using RSD, and ready to test Einstein's gravity at cosmological scales through duality between distances and growth functions.

- We understand all systematics due to non-linear physics, and the perturbative description works fine the resolution of current experiment, at least two point correlation level.

- Now we face new challenge to meet the precision level of the high resolution experiment like DESI.

- We work out the Alcock-Paczynski effect on bispectra, and find that the combined constraint of power spectrum and bispectrum improves the detectability of growth function.

- We initiate new roadmap to accomplish this combination for the future experiment.