Title: Cosmological Tests of Gravitational Physics using Large Scale Structure Formation

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Abstract: It is a prime interest to understand gravitational physics and to develop cosmological applications exploiting the next generation of surveys, scheduled to be launched in the near future, such as SDSS3, DES, XCS, JDEM or EUCLID. The future precision surveys are promising to resolve outstanding problems in modern physics. With the level of precision available in future surveys, we can use the high resolution maps expected to be gained from next-generation surveys to test the foundations of gravity and particle physics. The gravity known to us at solar system scales (GR: general relativity) is possibly challenged at cosmological scales. The measured cosmic acceleration that we have ascribed to the presence of dark energy (DE) could be a signal that GR is broken in some way.

Cosmological Tests of Gravitational Physics Using Large Scale Structure Formation.

Yong-Seon Song (ICG, Portsmouth)

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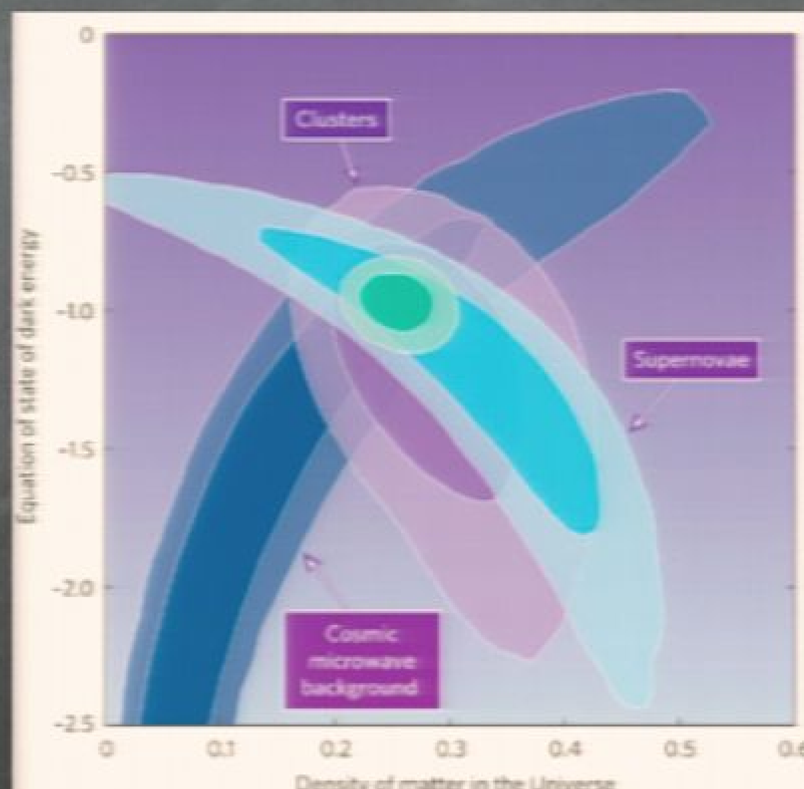
- With prolific auxiliary science available, these future surveys should be productive for the broader astrophysical community.

Epoch of Unknowns

The cosmic acceleration discovered from expansion history experiments establishes epoch of unknowns.

Dark energy



Dark matter

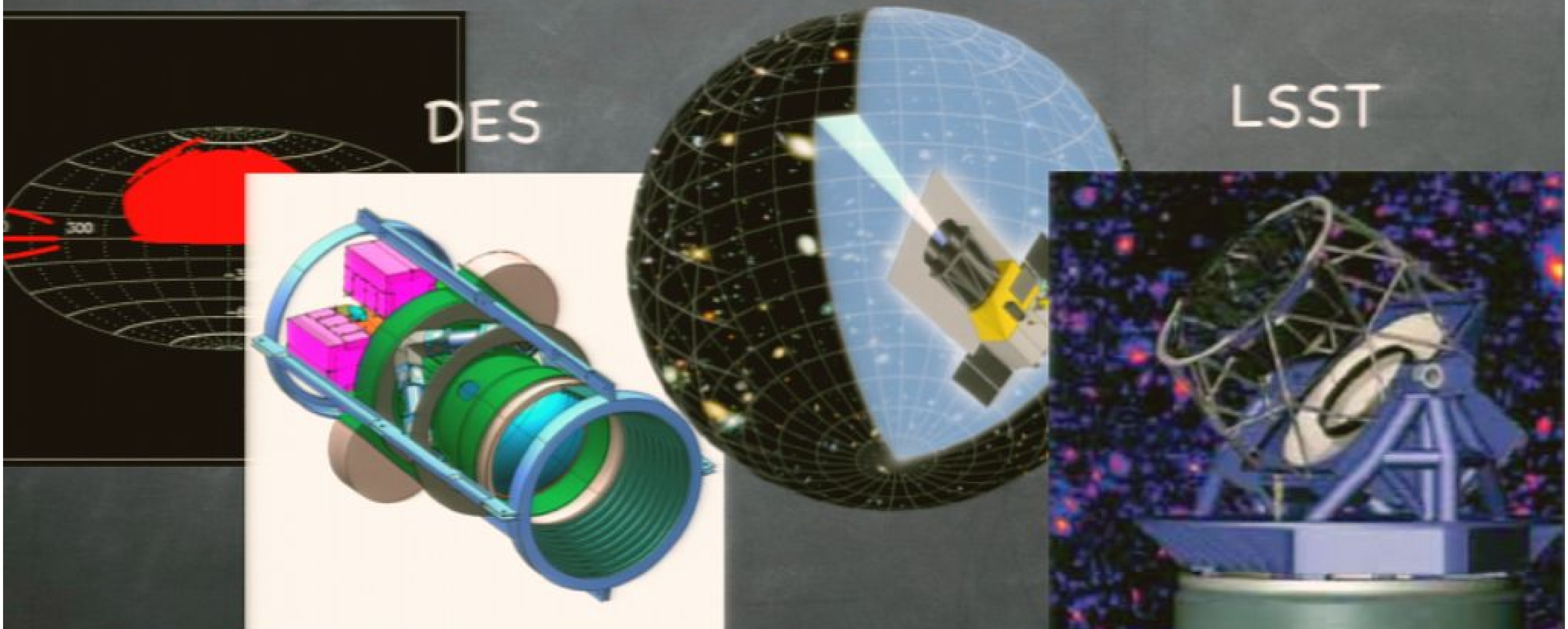
Allen et al. (2007)

Planned Surveys

2008 2010 2015 2020

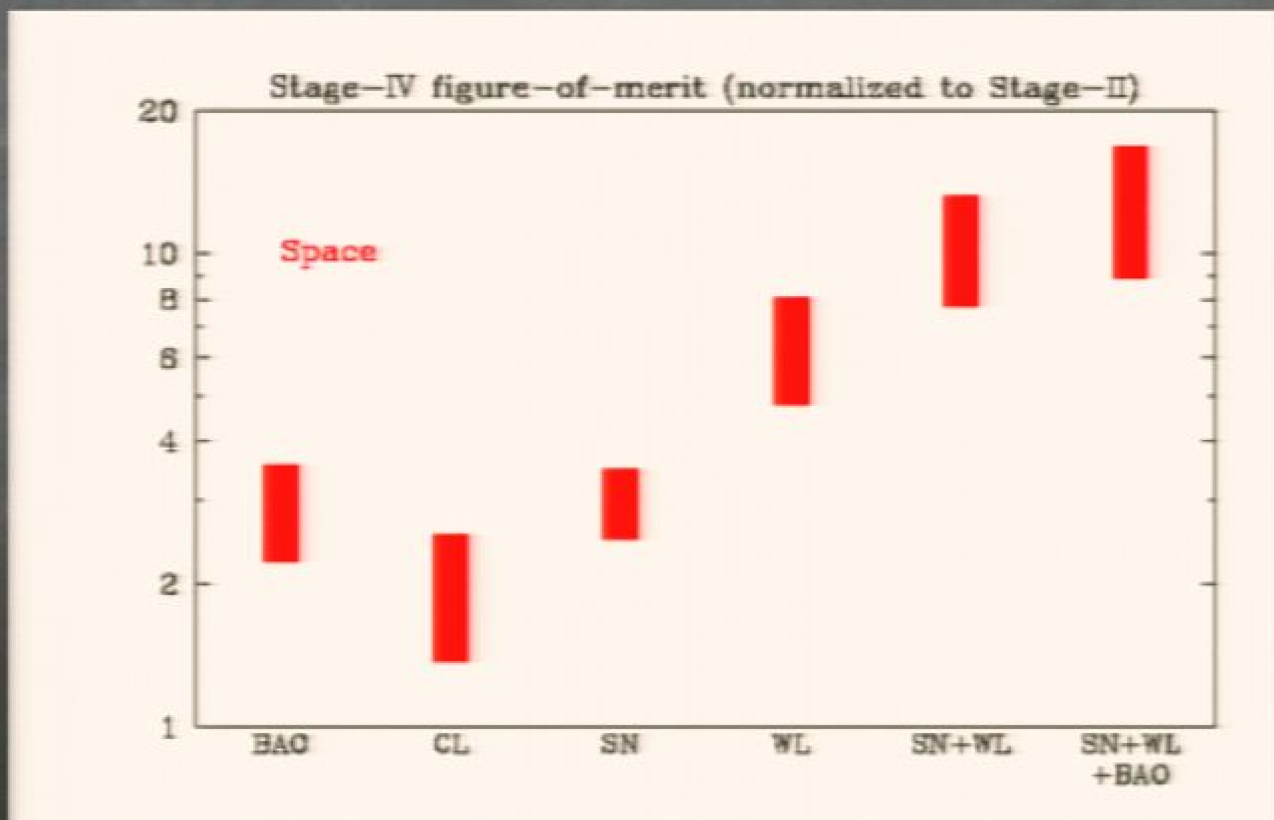
SDSS JDEM & EUCLID

DES LSST



Constraint on energy component

Those LSS observation is expected to improve constraints on expansion history. But ...



Albrecht et.al (2006)

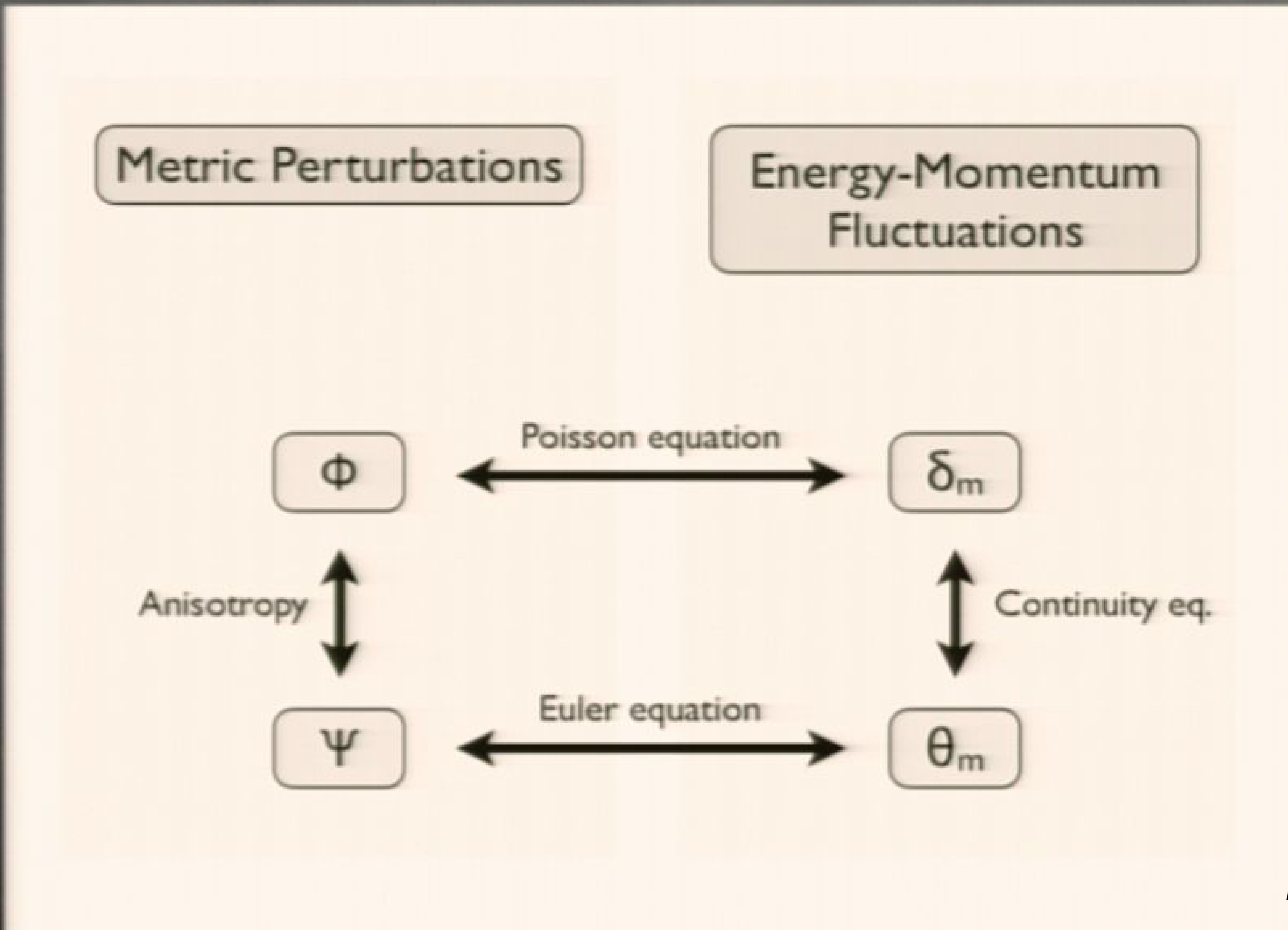
Constraint on energy component

Those LSS observation is expected to improve constraints on expansion history. But ...

... the measured structure formation has better information about underlying fundamental physics of our universe.

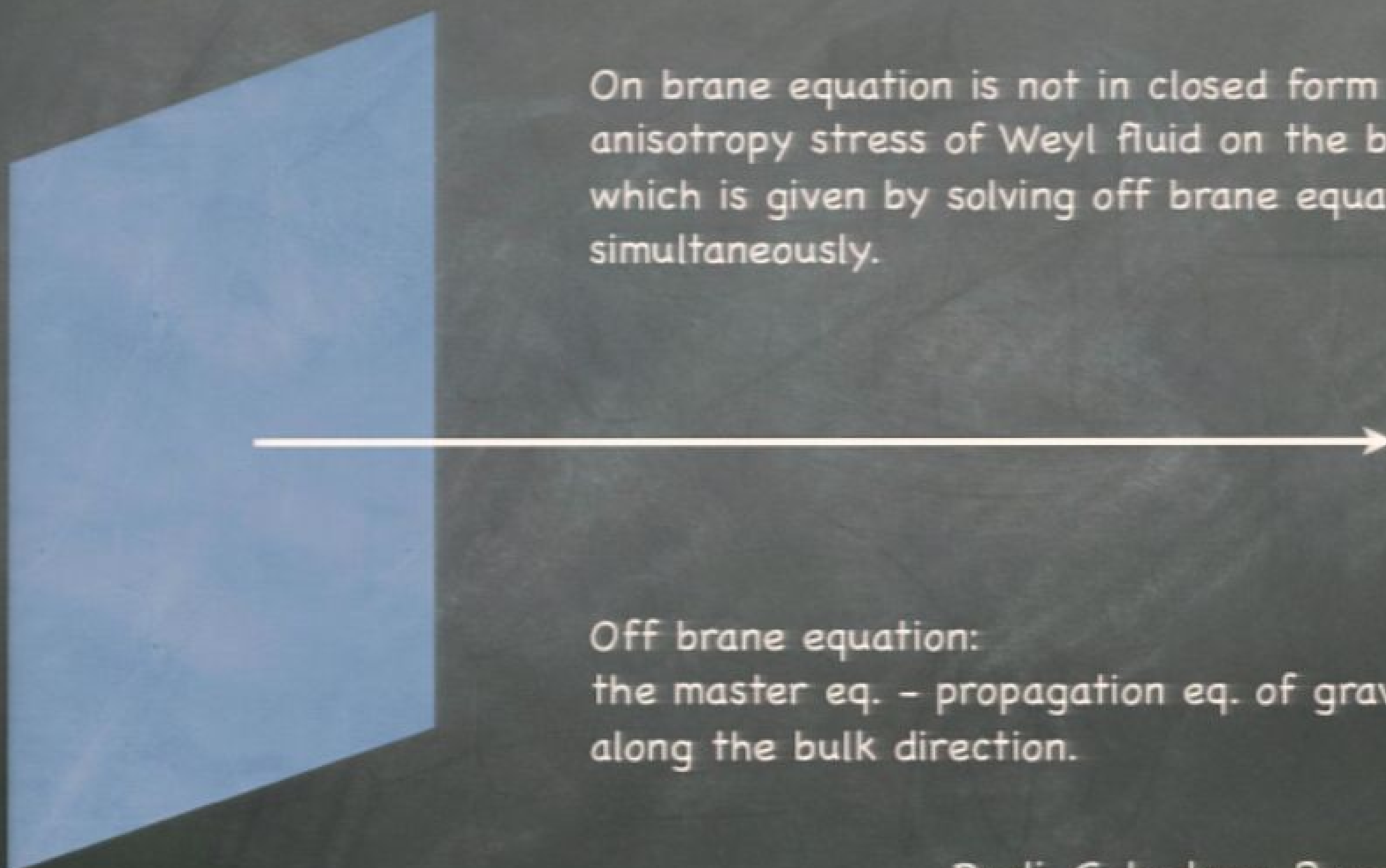
It unveils the local dynamics of inhomogeneity which will reveal the qualified nature of reasoning of cosmic acceleration.

Cosmological web



Case of DGP

On brane equation: the projected Einstein eq. + 4D continuity eq.



On brane equation is not in closed form due to anisotropy stress of Weyl fluid on the brane, which is given by solving off brane equation simultaneously.

Off brane equation:
the master eq. – propagation eq. of gravity along the bulk direction.

Dvali, Gabadage, Porrati(2000)

Deffayet (2002)

Case of DGP

- Mass screening effect

$$k^2\Phi = 4\pi a^2 G_N\, q(a)\, (\rho_m\Delta_m \pm \rho_E\Delta_E)$$

$$= 4\pi a^2 G_N\, Q(a)\, \rho_m\Delta_m$$

- Anisotropy stress

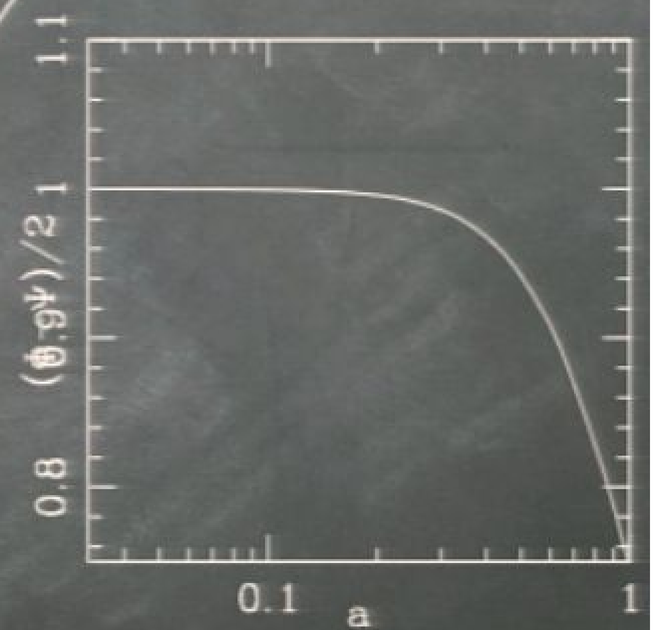
$$\Phi/\Psi = f(\pi_E) = -\eta(a)$$

Lue, Starkman (2004)

Koyama, Maartens (2006)

YSS, Sawicki, Hu (2006)

Case of DGP:mass screening effect



YSS (2007)

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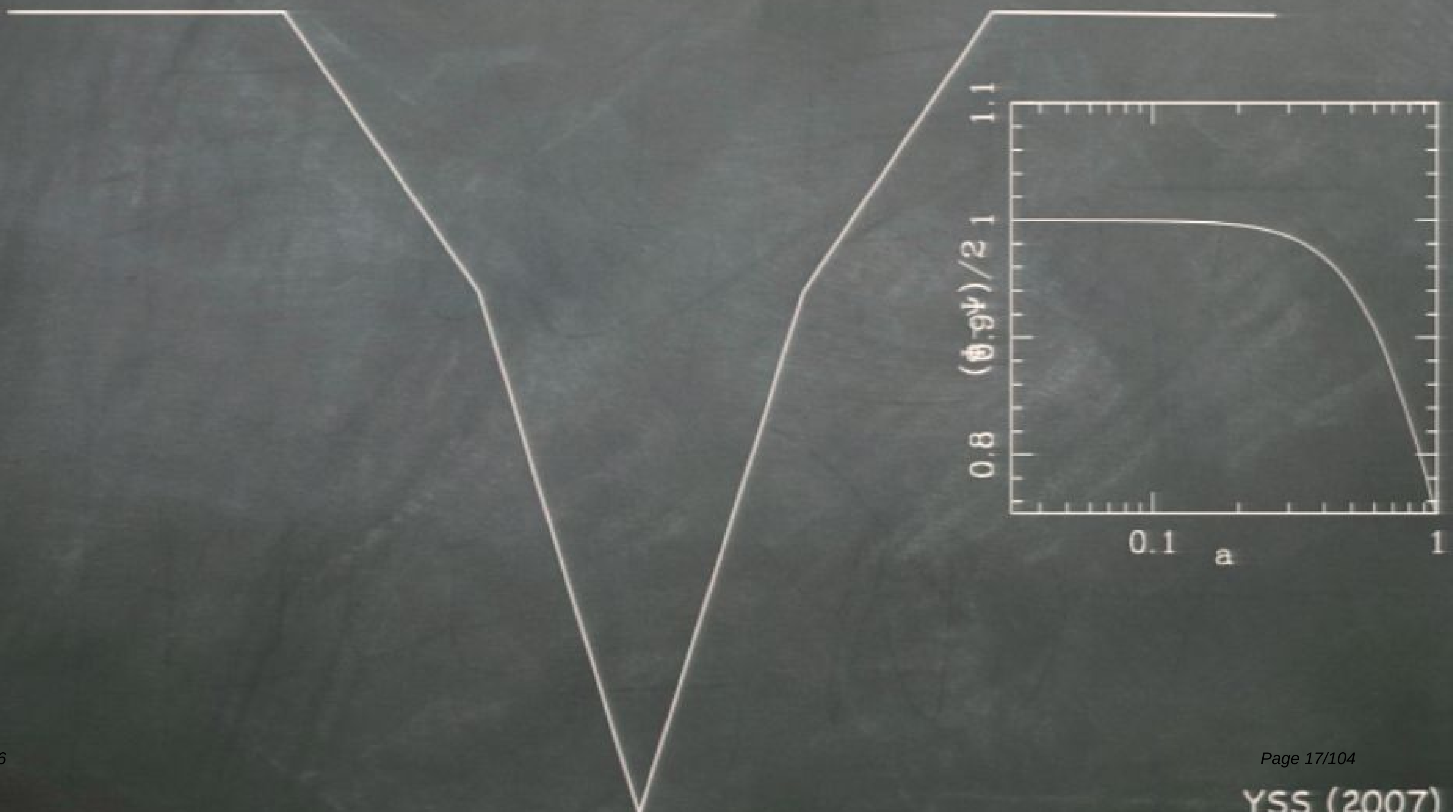
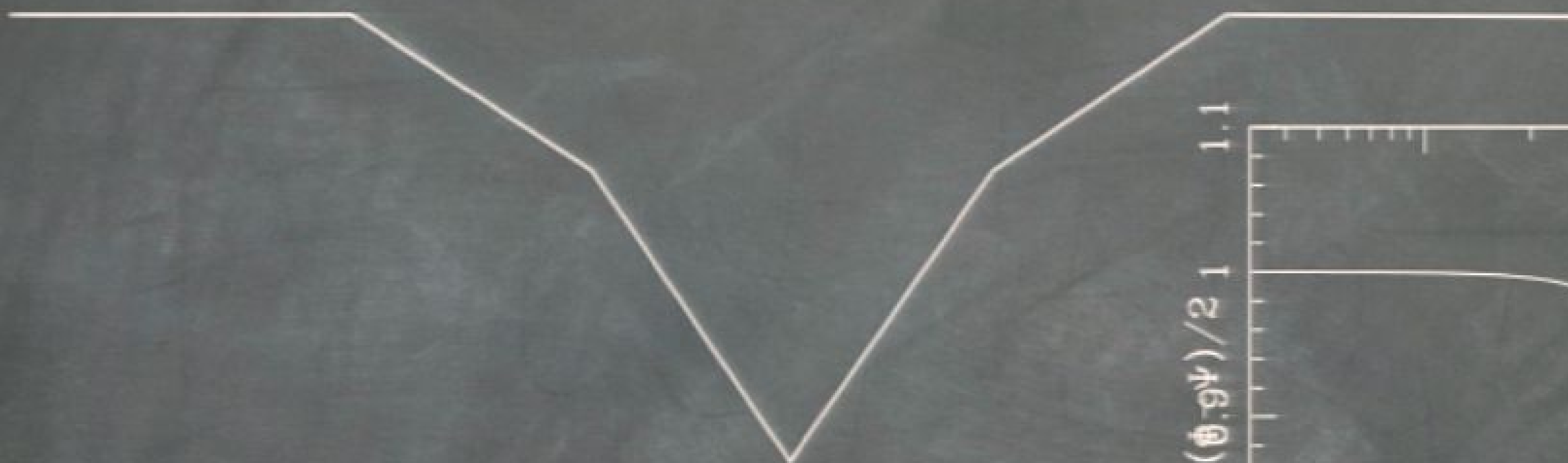
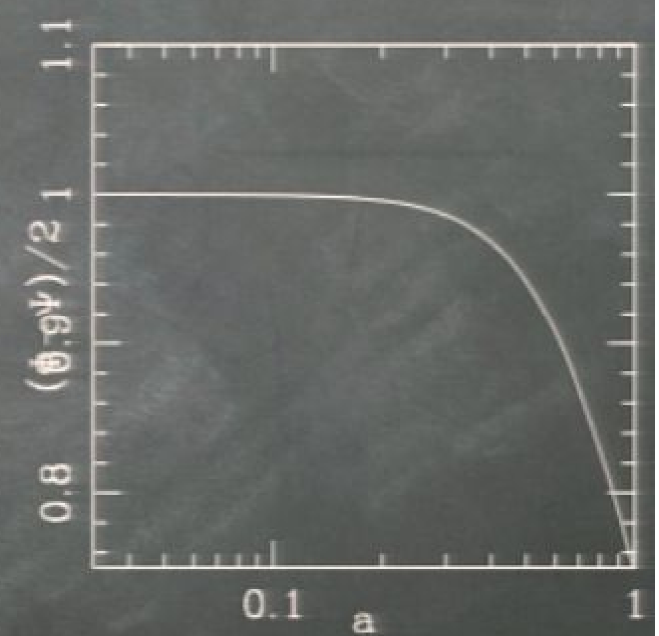


YSS (2007)

Case of DGP:mass screening effect

Entering cosmic acceleration era





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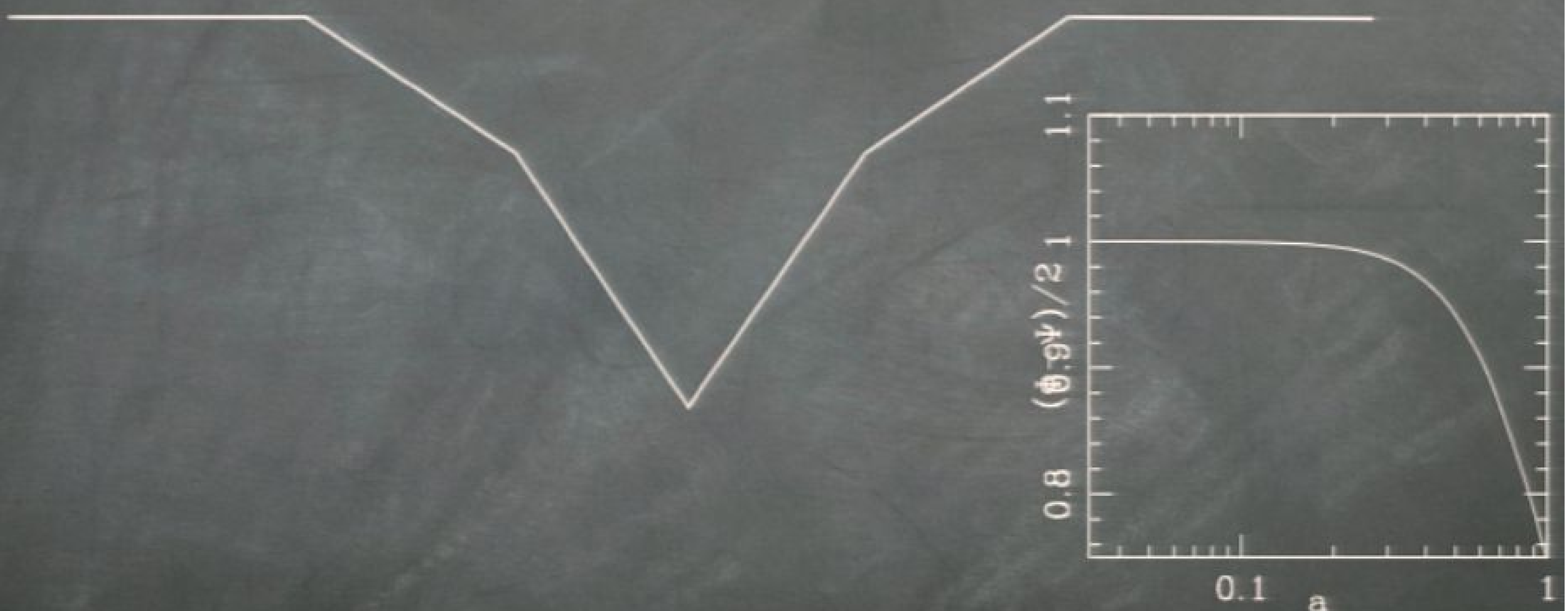
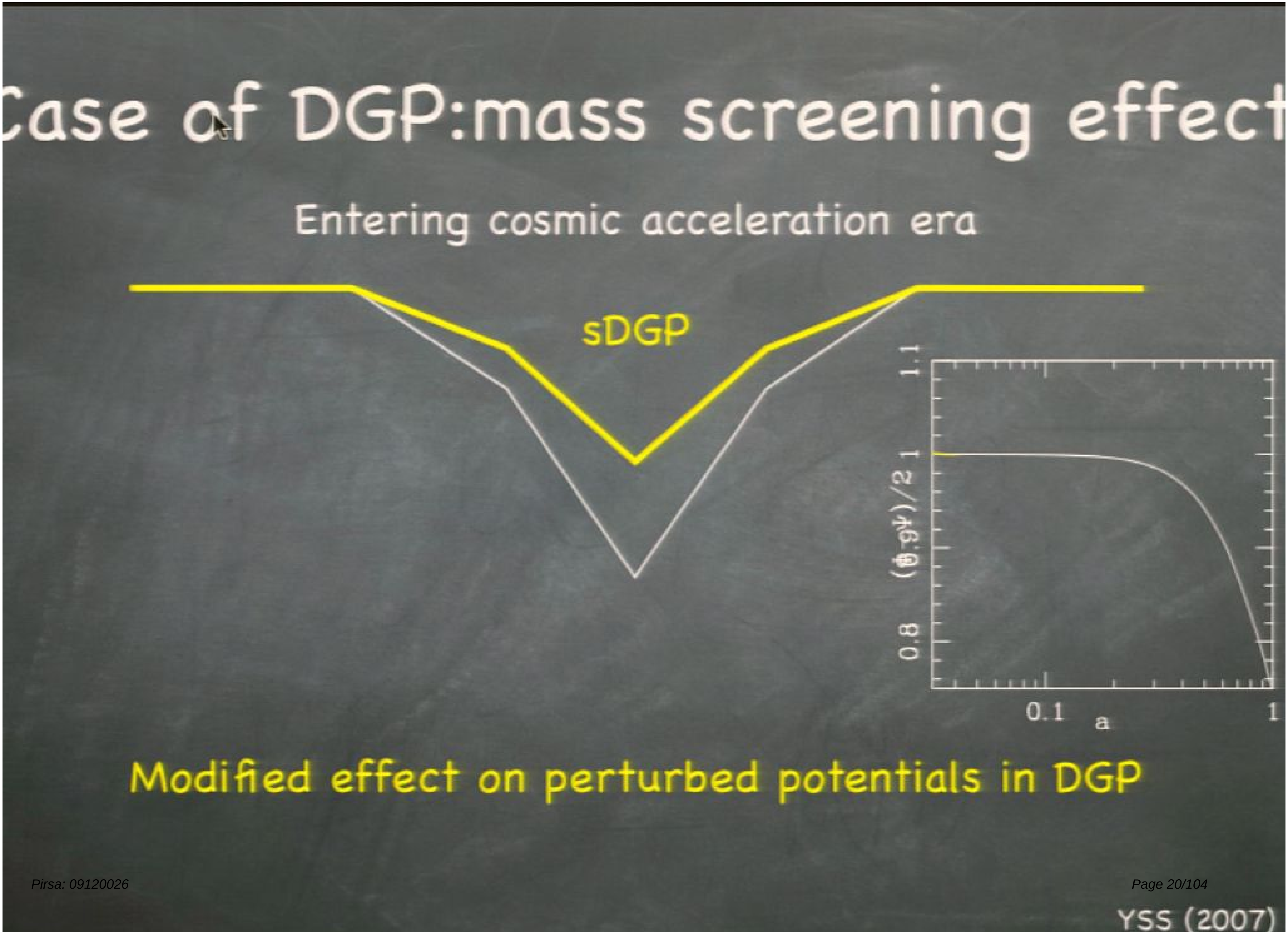


Modified effect on perturbed potentials in DGP

YSS (2007)


Case of DGP:mass screening effect
Entering cosmic acceleration era
sDGP
(Φ-Ψ)/2
1.1
1
0.9
0.8
0.1
a
1
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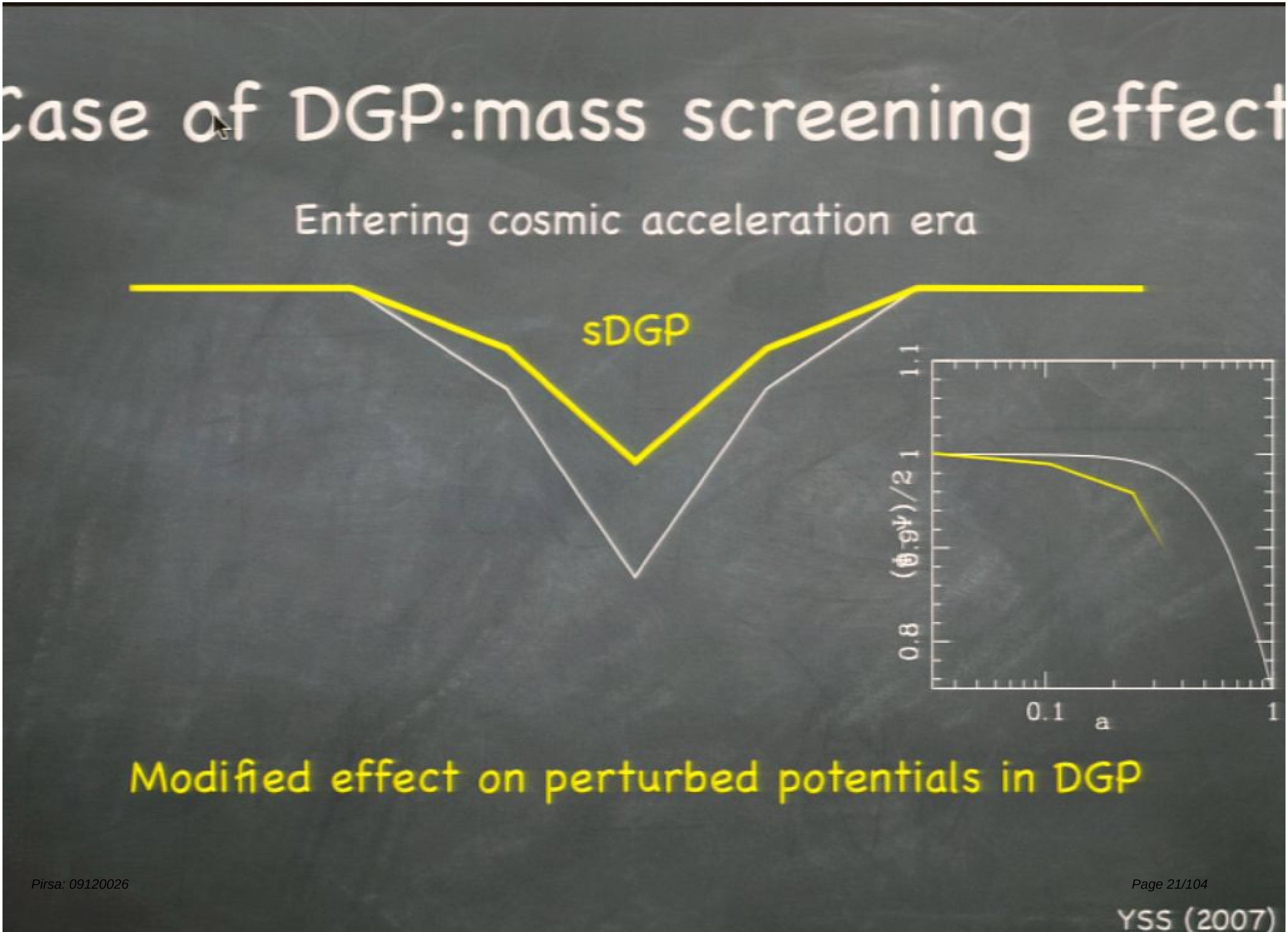
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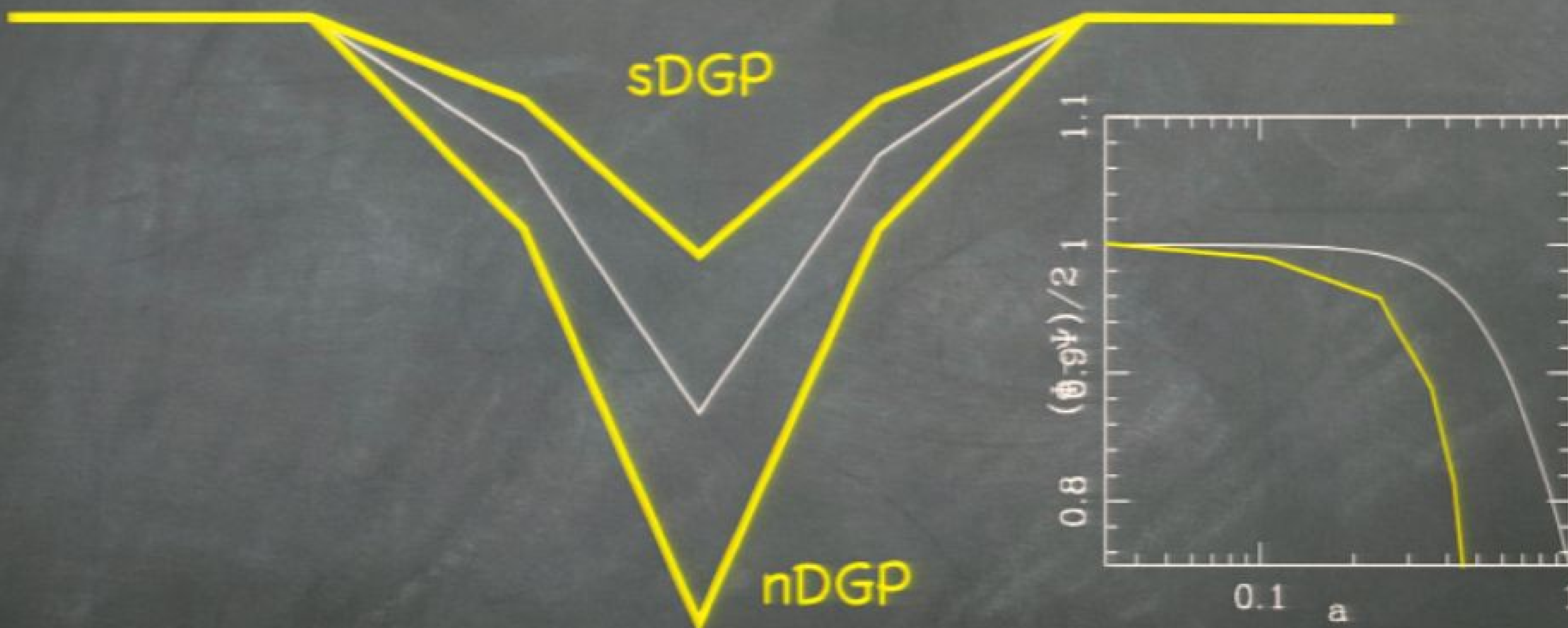

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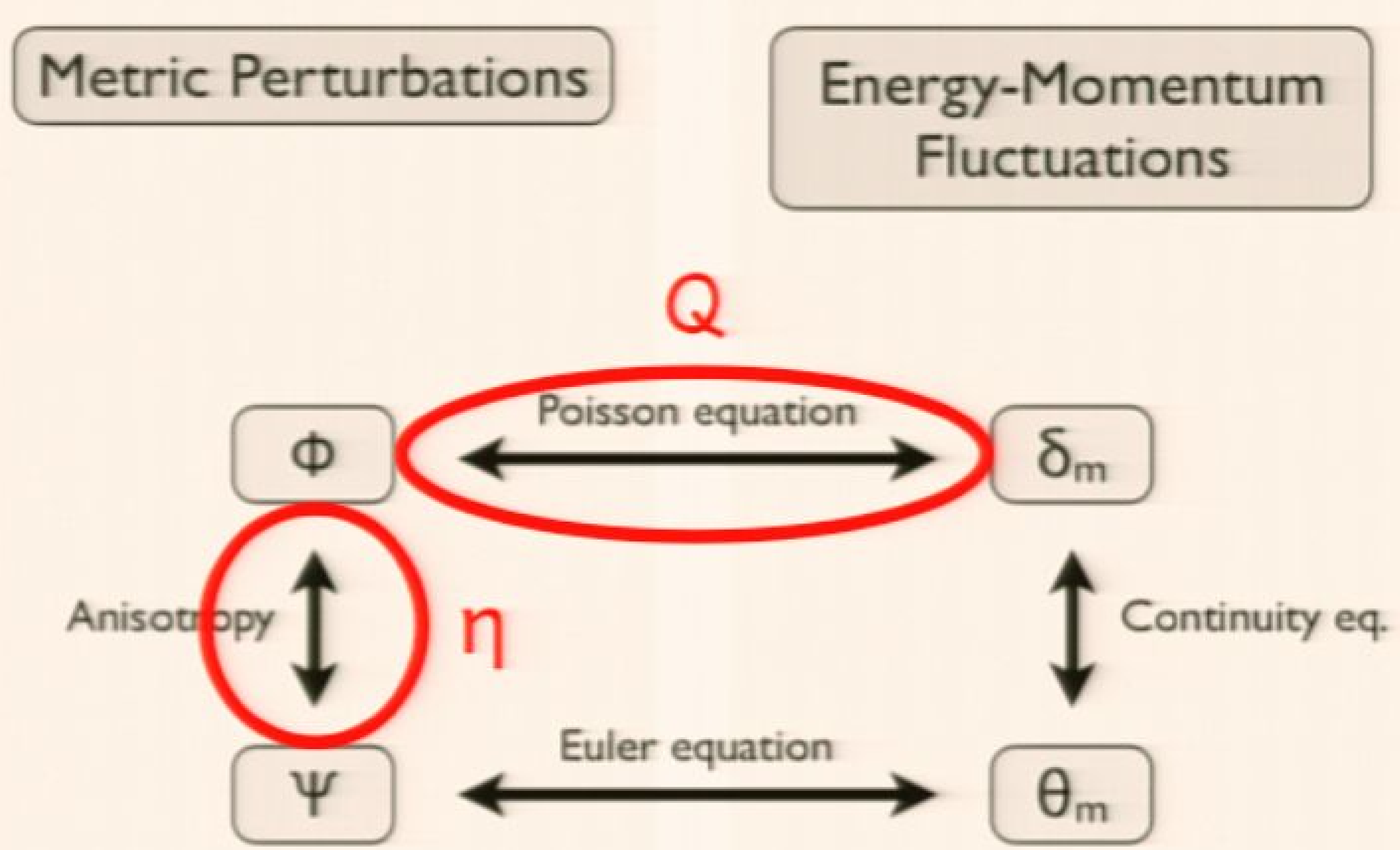
Cosmological web



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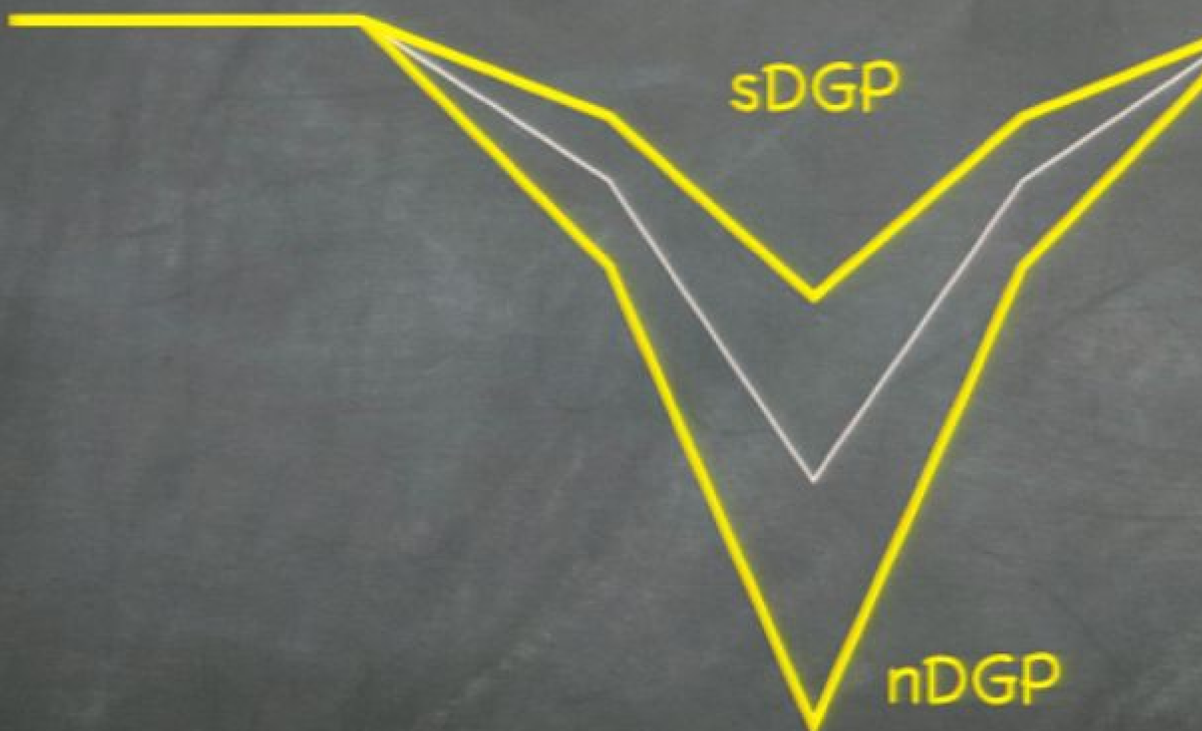

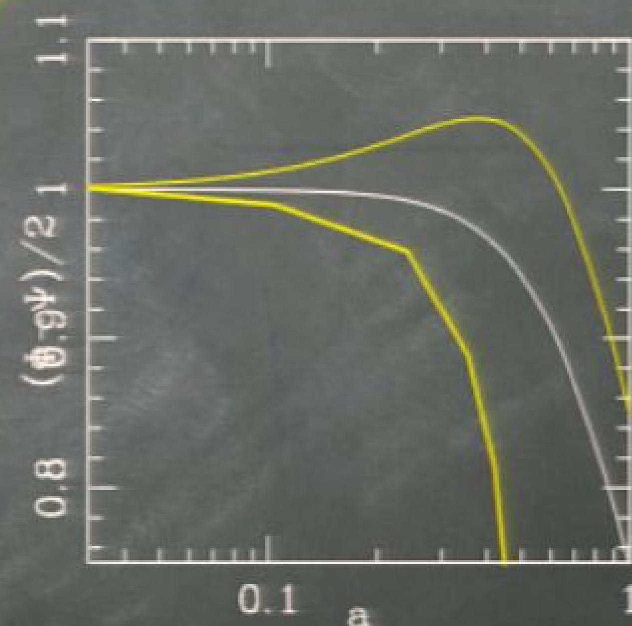

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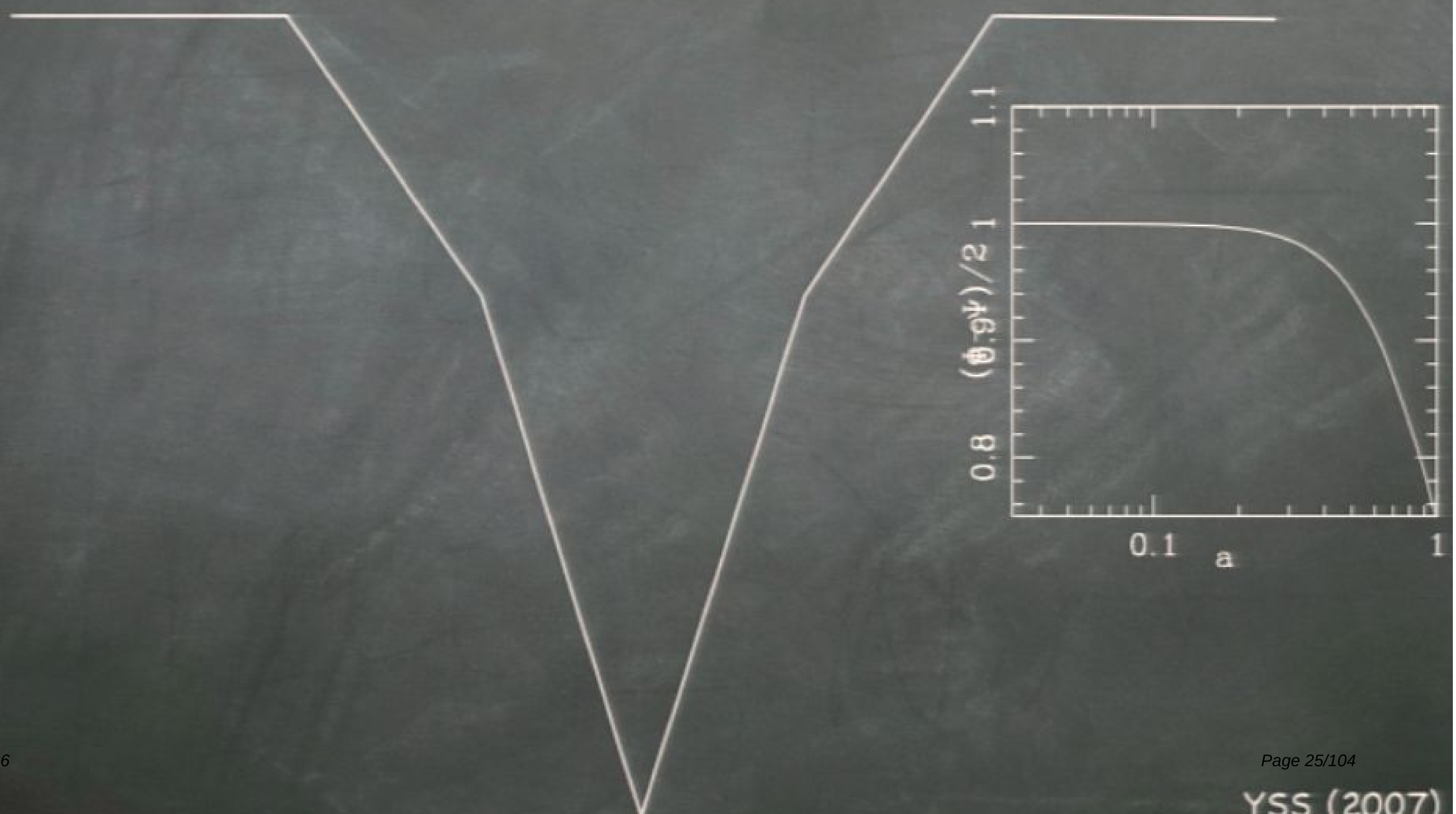

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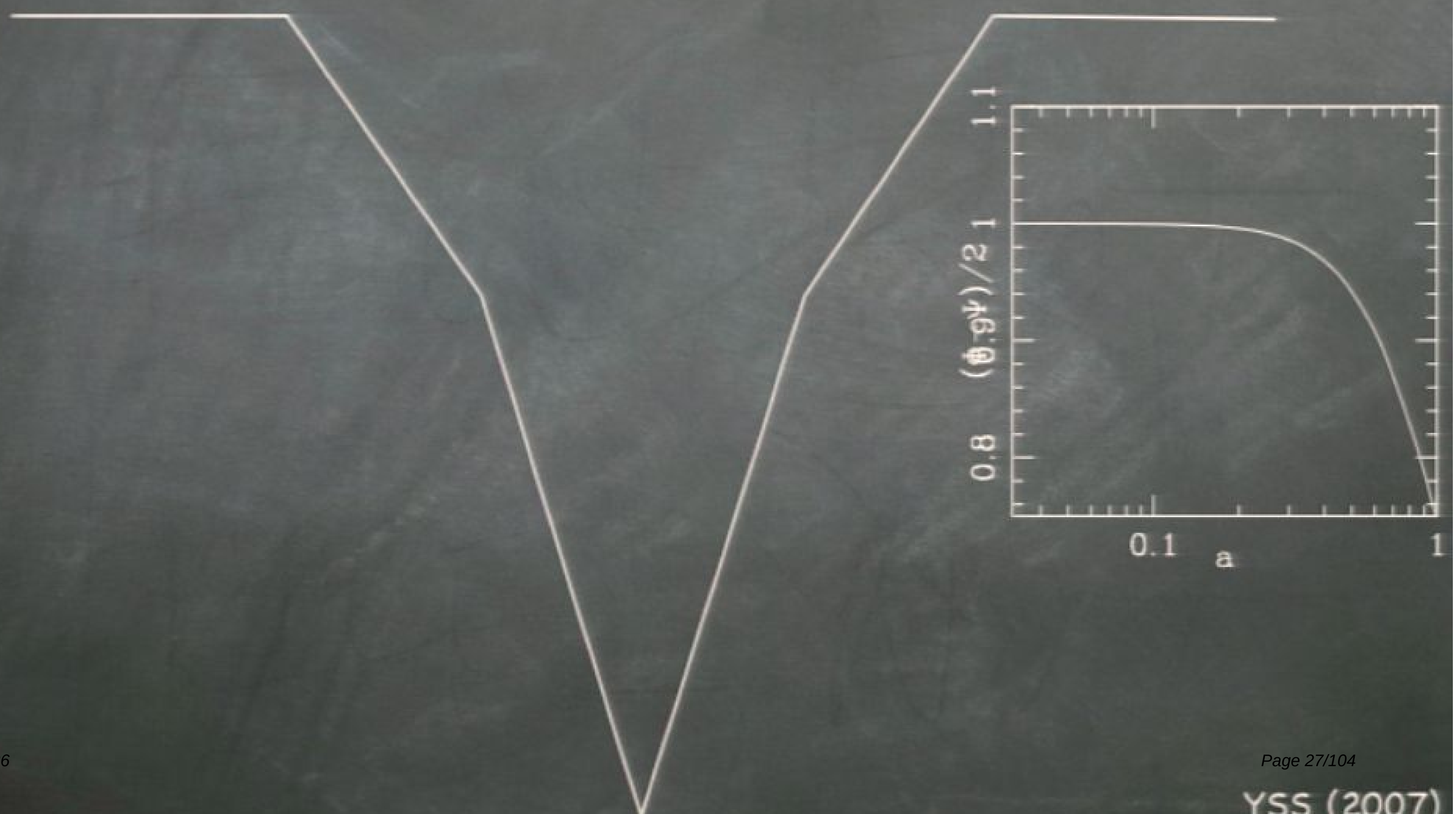

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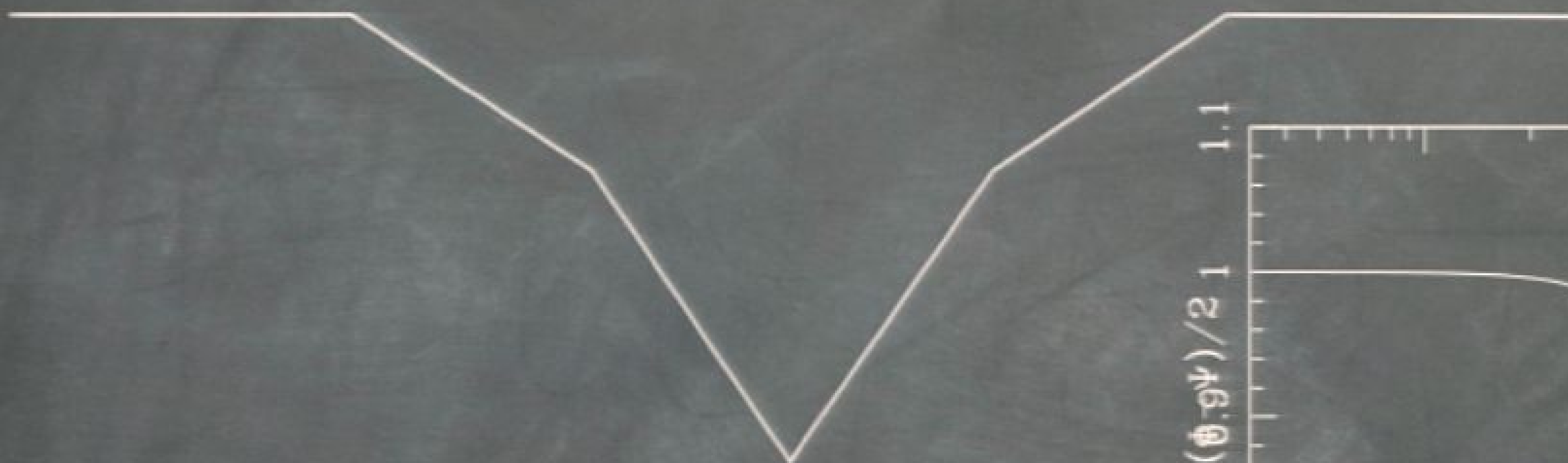

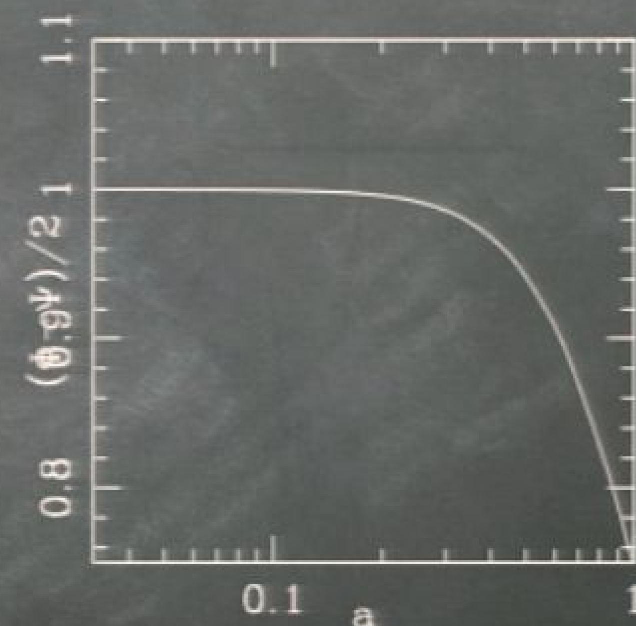

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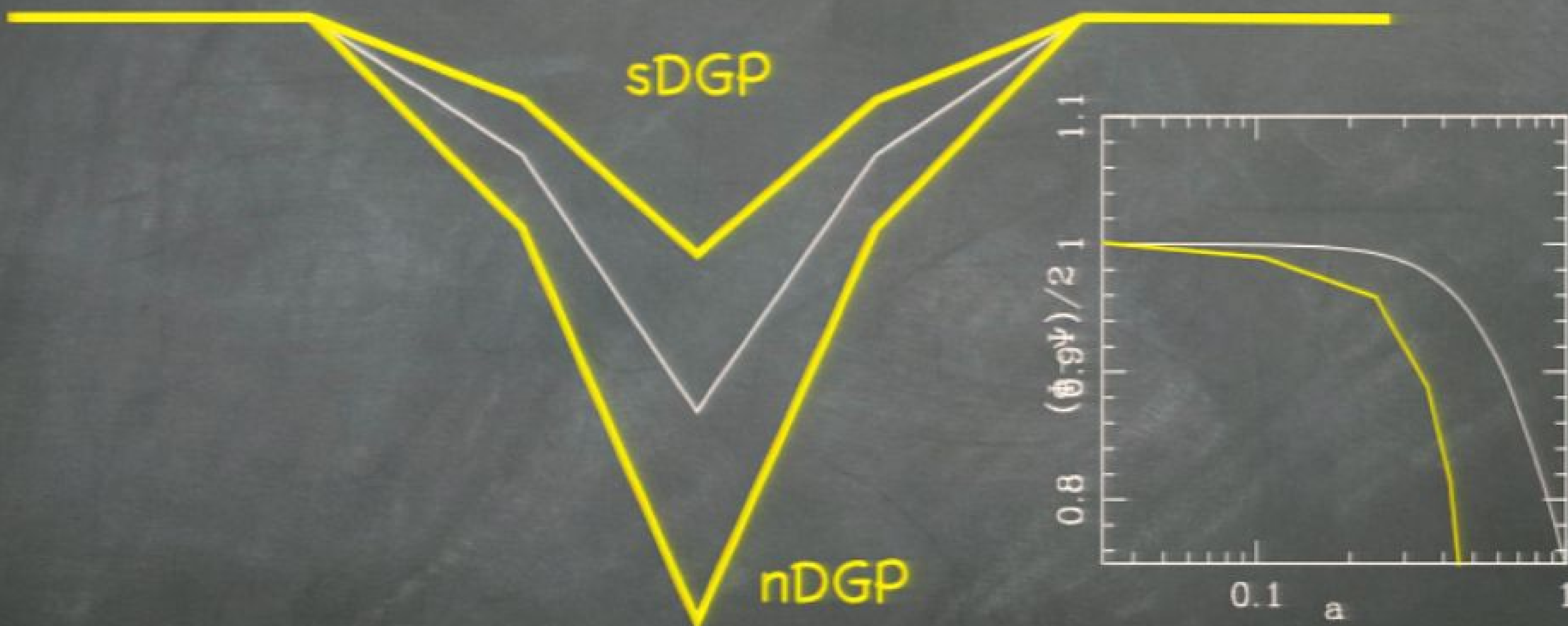

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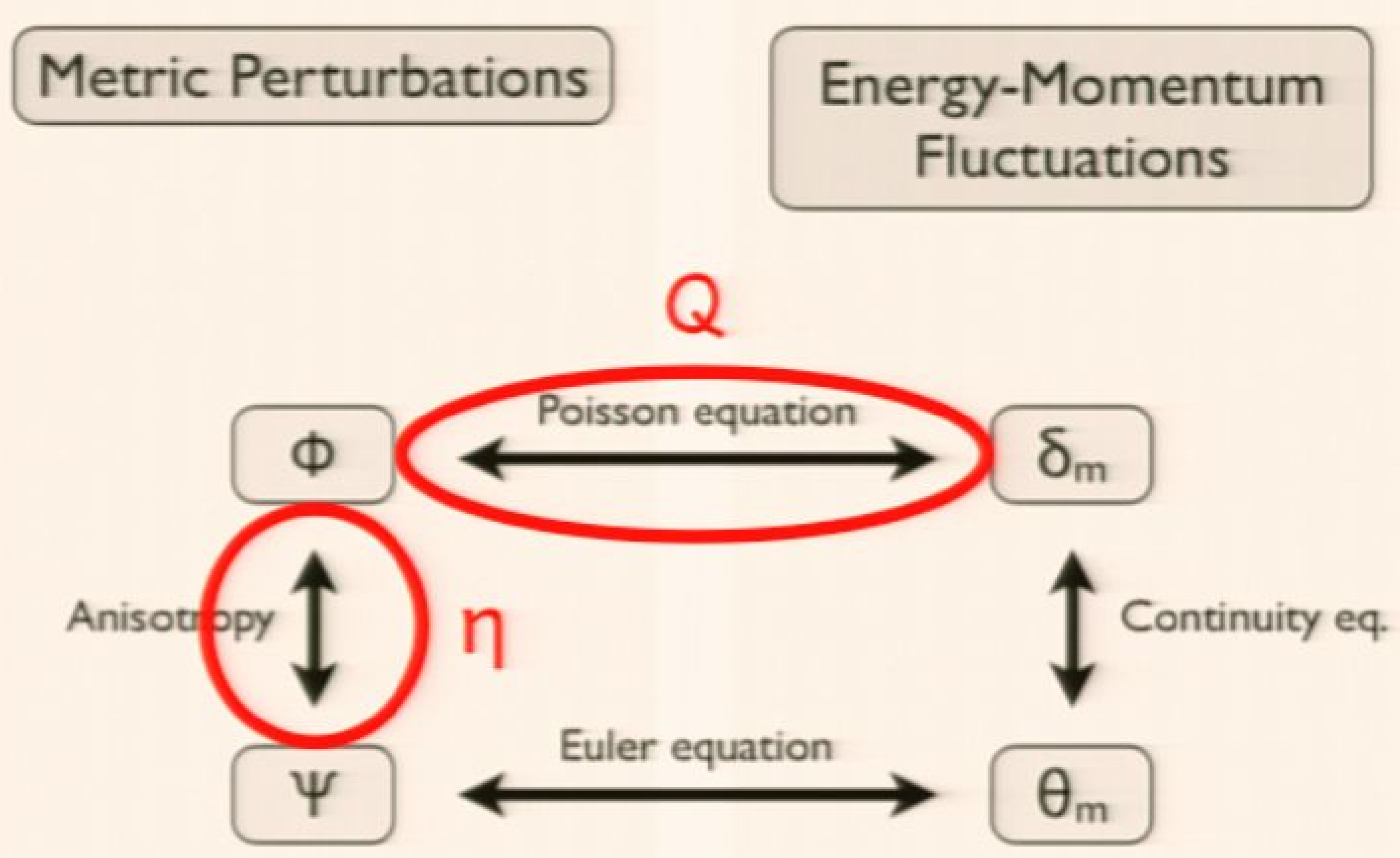

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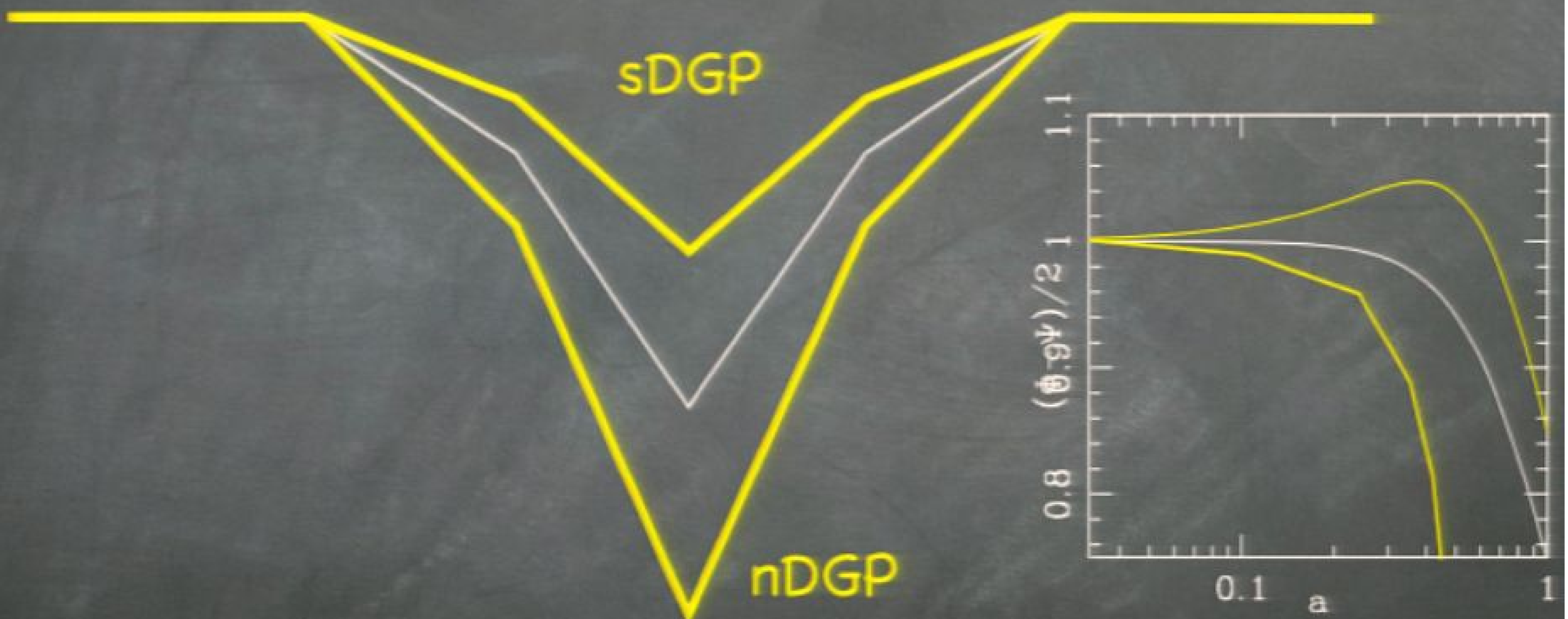

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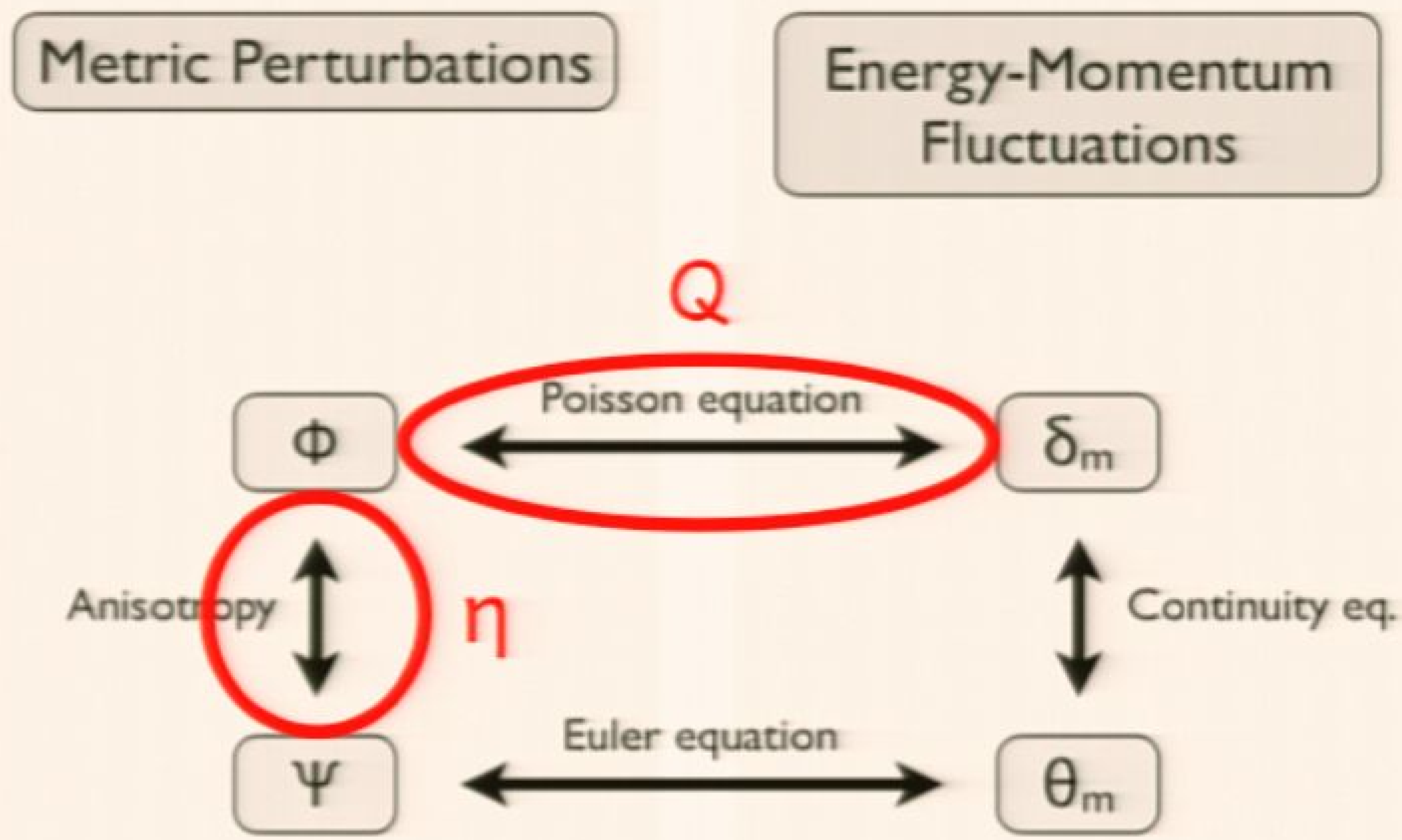

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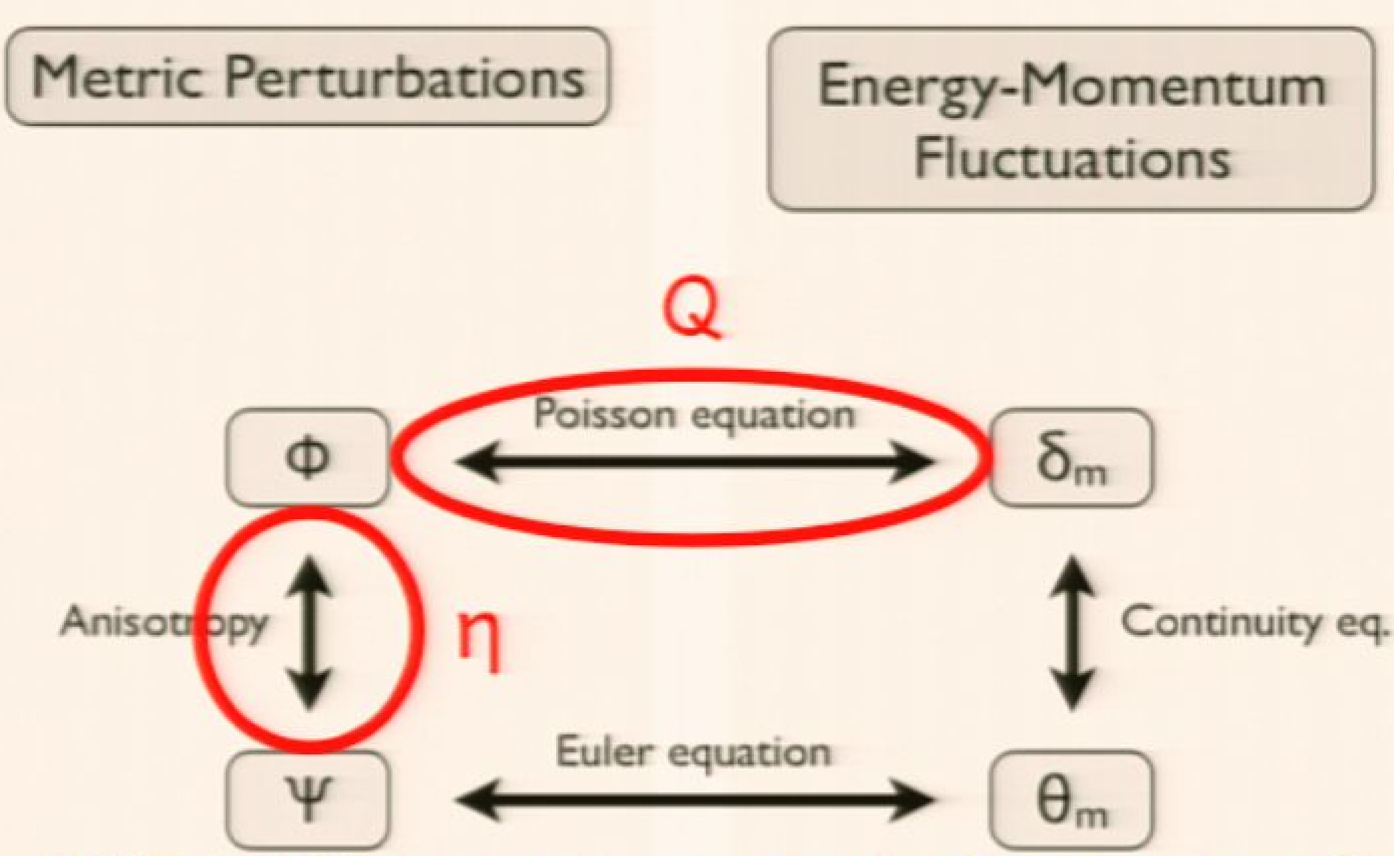


LSS will measure new degrees of freedom beyond GR

Induced Q and η: IDE

Dark energy can couple to dark matter via

$$d\rho_c/dt + 3H\rho_c = -C$$

$$d\rho_{DE}/dt + 3(1+w_{DE})H\rho_{DE} = C$$

Amendola (2004)

There are three different cases of coupling:

- $C=\Gamma_c\rho_c$: no modification on dynamics
- $C=\Gamma_{DE}\rho_{DE}$: continuity equation is broken
- $C=\Gamma_\Phi f(\Phi)$: equivalent principle is violated

Koyama, Maartens, YSS (2009)

Induced Q and η: IDE case I

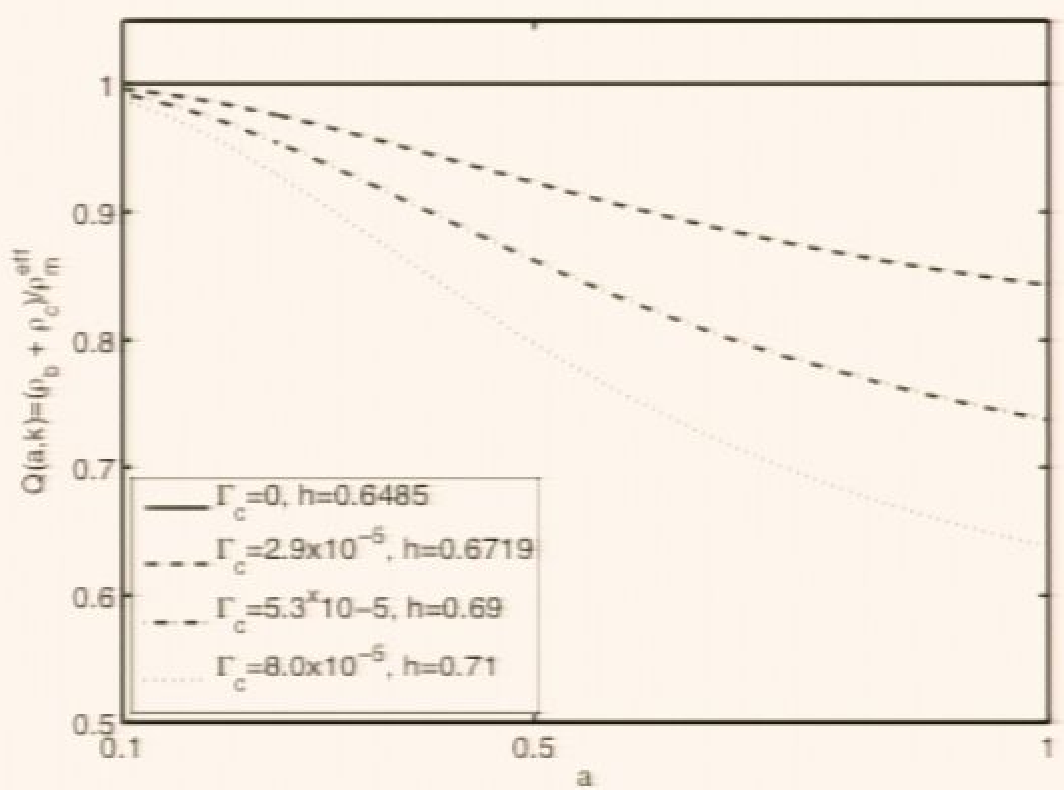
For the case of $\Gamma_c \rho_c$, dynamic equation is identical, but there is no way for us to measure the true matter component of ρ_c which is effectively estimated by ρ_c^{eff}, then

$$
\begin{aligned}
k^2\Phi &= 4\pi a^2 G_N (\rho_b \Delta_b + \rho_c \Delta_c) \\
&= 4\pi a^2 G_N (\rho_b + \rho_c)\Delta_m \\
&= 4\pi a^2 G_N [(\rho_b + \rho_c)/\rho_m^{eff}]\, \rho_m^{eff}\, \Delta_m \\
&= 4\pi a^2 G_N\, Q(a)\, \rho_m^{eff}\, \Delta_m
\end{aligned}
$$

But anisotropy stress is not induced, η=1.

YSS, Holenstein, Caleracabral, Koyama (2009)

Induced Q and η: IDE case I



Induced Q and η: IDE case II

For the case of $\Gamma_{DE}\rho_{DE}$, the continuity equation is broken, $\Delta_b \neq \Delta_c$, Q(a) is induced differently as,

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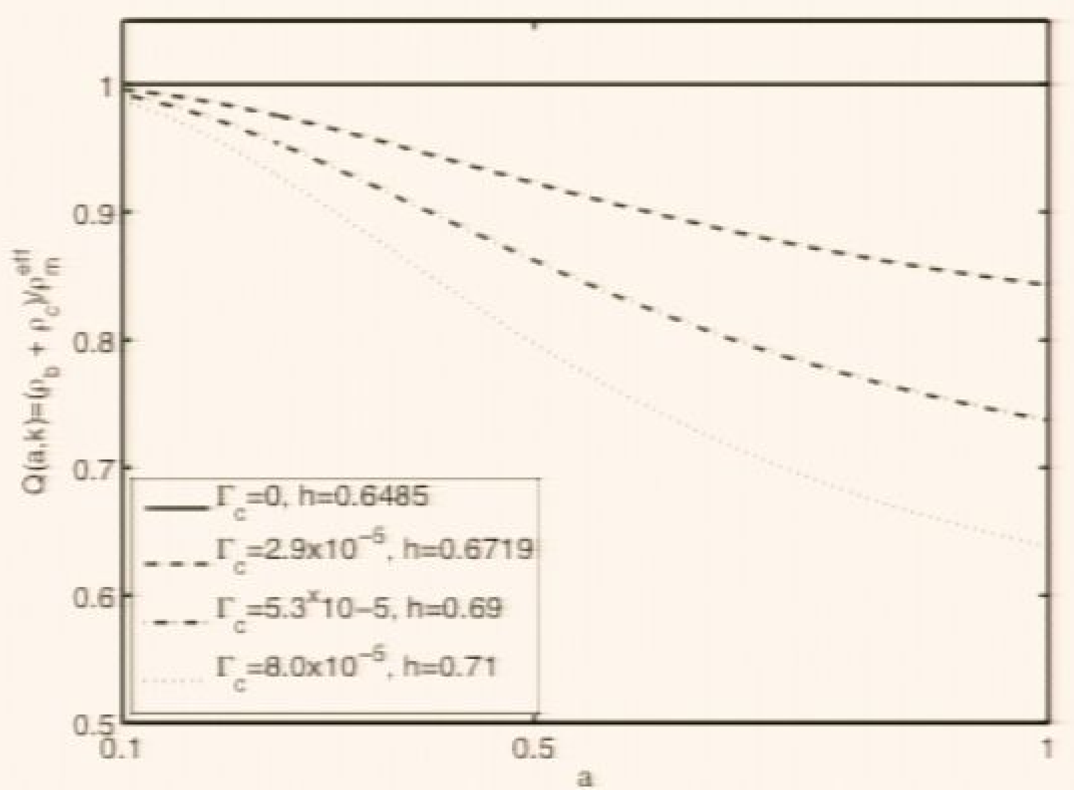

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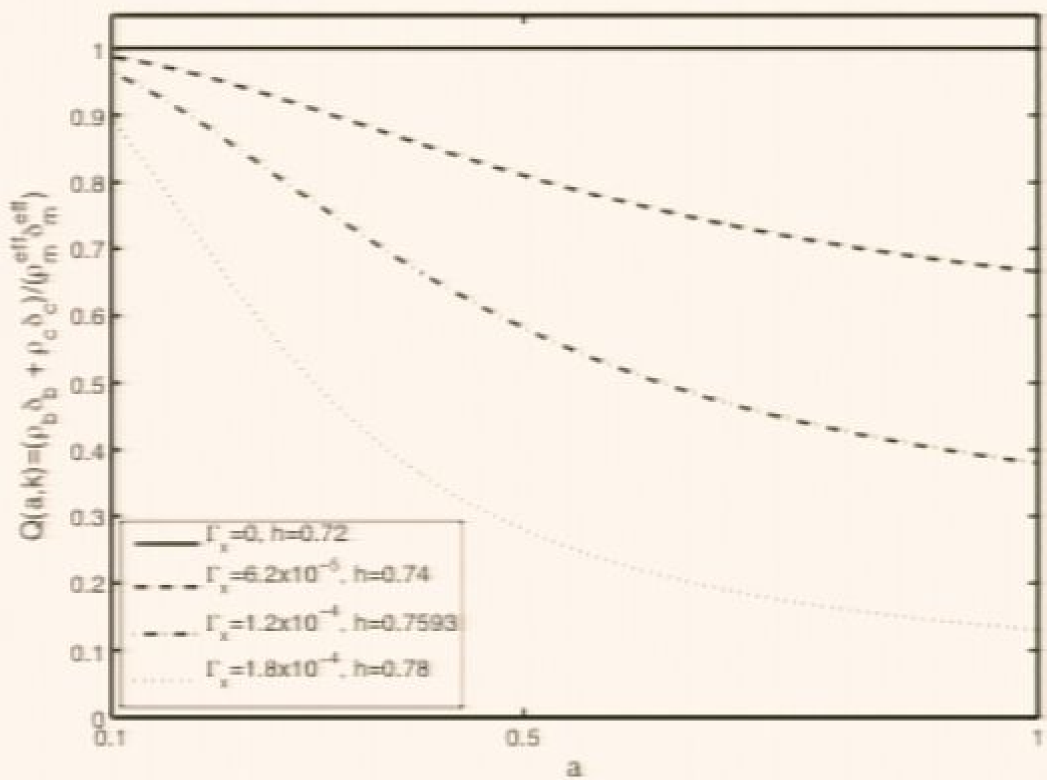

Induced Q and η: cDE

Dark energy can in principle support long-lived fluctuations

$$d\delta_{DE}/dt = -(1+w)\theta_{DE}/a + 3wH\delta_{DE} + -3H\delta P_{DE}/\rho_{DE}$$

$$d\theta_{DE}/dt = -H(1-3w)\theta_{DE} - (dw/dt)/(1+w)\, H\, \theta_{DE}$$
$$+ k^2/a[\delta P_{DE}/(1+w)\, \rho_{DE} - \sigma_{DE} + \Psi]$$

- δP_{DE}: $\delta P_{DE}/\rho_{DE} = c_P{}^2\delta_{DE} + g_P/k^2$
- σ_{DE}: $\sigma_{DE} = f_\sigma[c_P{}^2\delta_{DE}/(1+w)] + g_\sigma/k^2$

YSS, Holenstein, Calcagni, Koyama (2009)

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- σ_{DE}: $\sigma_{DE} = f_\sigma[c_P{}^2\delta_{DE}/(1+w)] + g_\sigma/k^2$

- Coherent growth: $g_P = g_\sigma = 0$, and

$d\theta_{DE}/dt = -H(1-3w)\theta_{DE} - (dw/dt)/(1+w)\ H\ \theta_{DE} + k^2/a[\delta P_{DE}/(1+w)\ \rho_{DE} - \sigma_{DE} + \Psi]$

$$\delta P_{DE}/(1+w)\ \rho_{DE} = \sigma_{DE} \longrightarrow f_\sigma = 1$$

- Scale dependent growth:

$g_P \neq 0$ $\qquad g_\sigma \neq 0$ $\qquad f_\sigma \neq 1$

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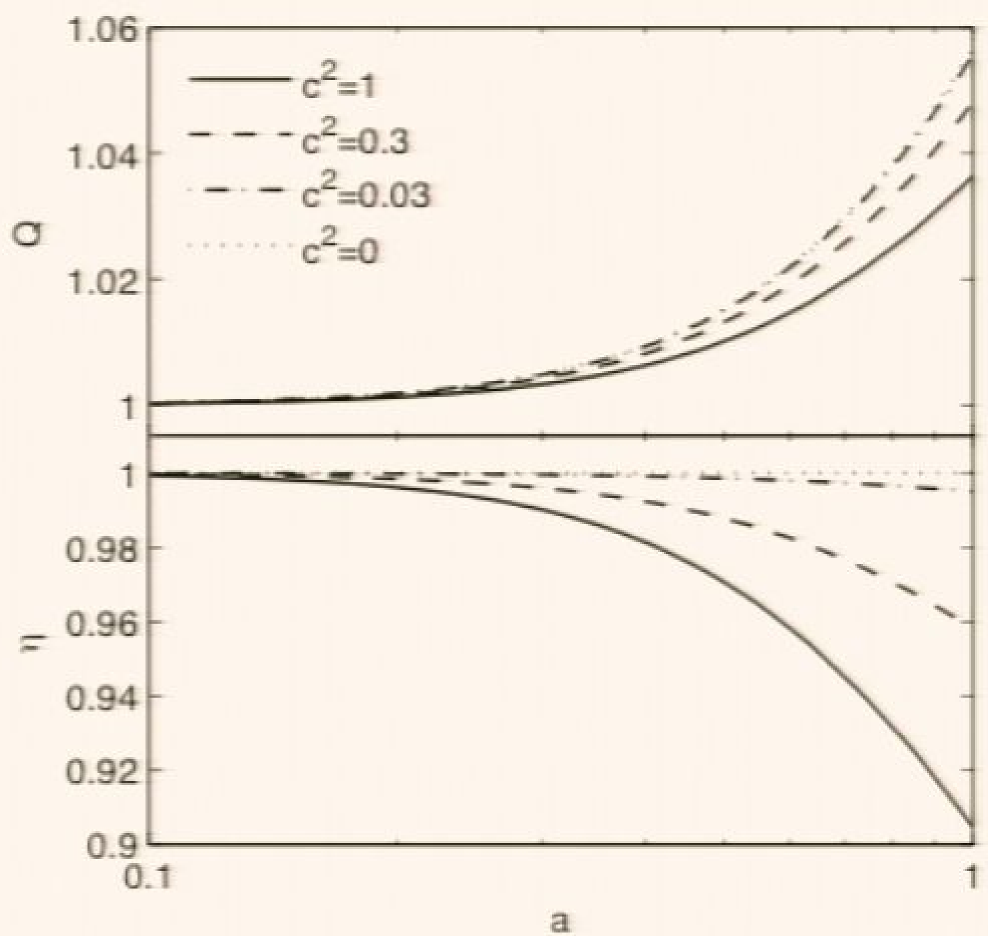
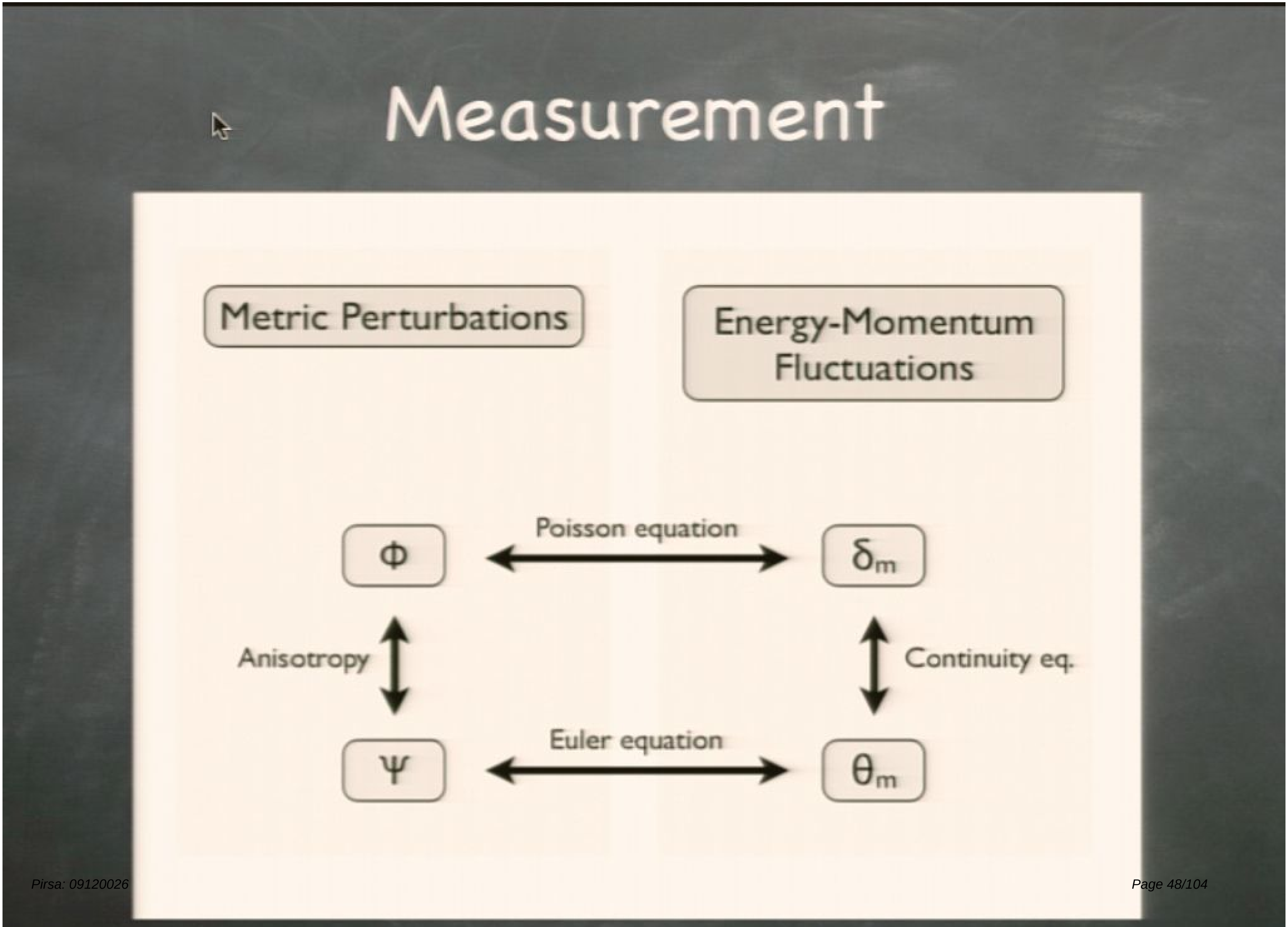


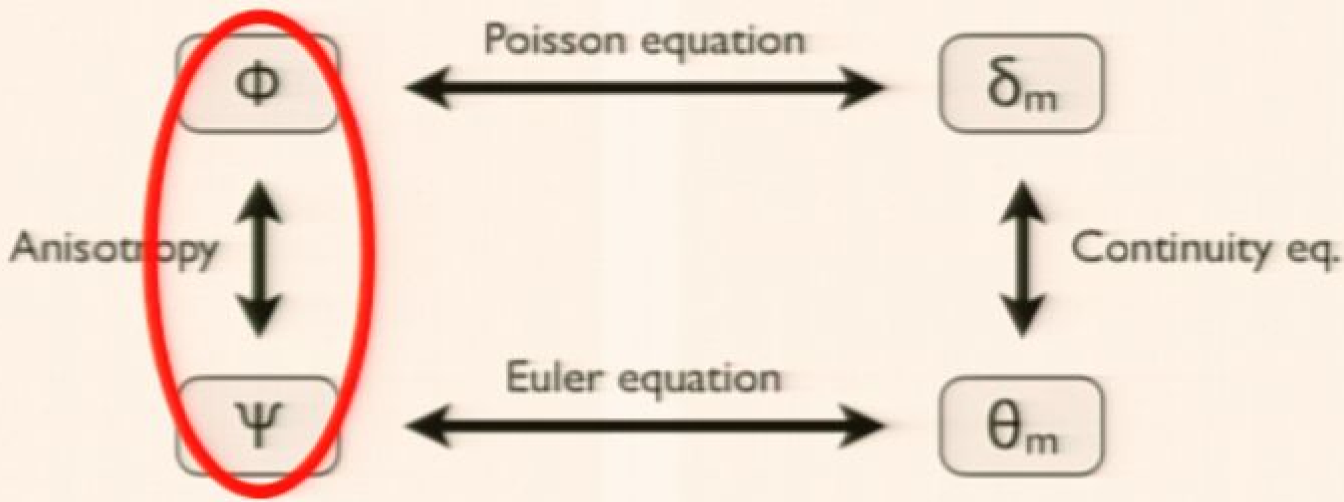

Measurement
Metric Perturbations
Energy-Momentum Fluctuations
Φ
Poisson equation
δ_m
Anisotropy
Continuity eq.
Ψ
Euler equation
θ_m

Measurement

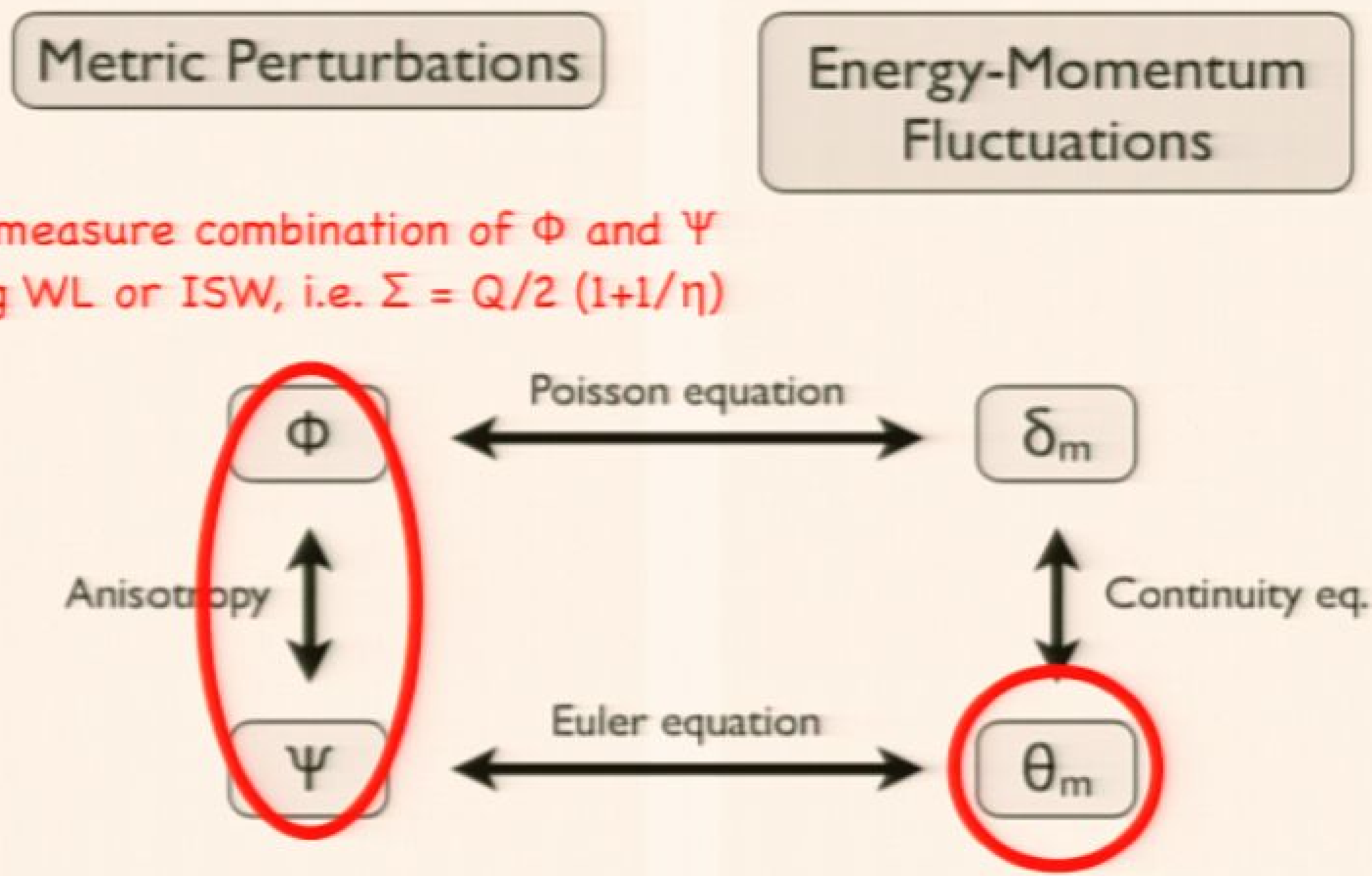
Metric Perturbations

Energy-Momentum Fluctuations

We measure combination of Φ and Ψ using WL or ISW, i.e. $\Sigma = Q/2\,(1+1/\eta)$



Measurement



We measure combination of Φ and Ψ using WL or ISW, i.e. $\Sigma = Q/2\,(1+1/\eta)$

We reconstruct Ψ using peculiar velocity experiment, i.e. $\mu = Q/\eta$

Unique trajectory on Σ & μ plane

Unique trajectory on Σ & μ plane

BD type modified gravity model

μ

$$Q(a) = (2+2w_{BD})/(3+2w_{BD})$$

$$\eta(a) = (1+w_{BD})/(2+w_{BD})$$

↓

1

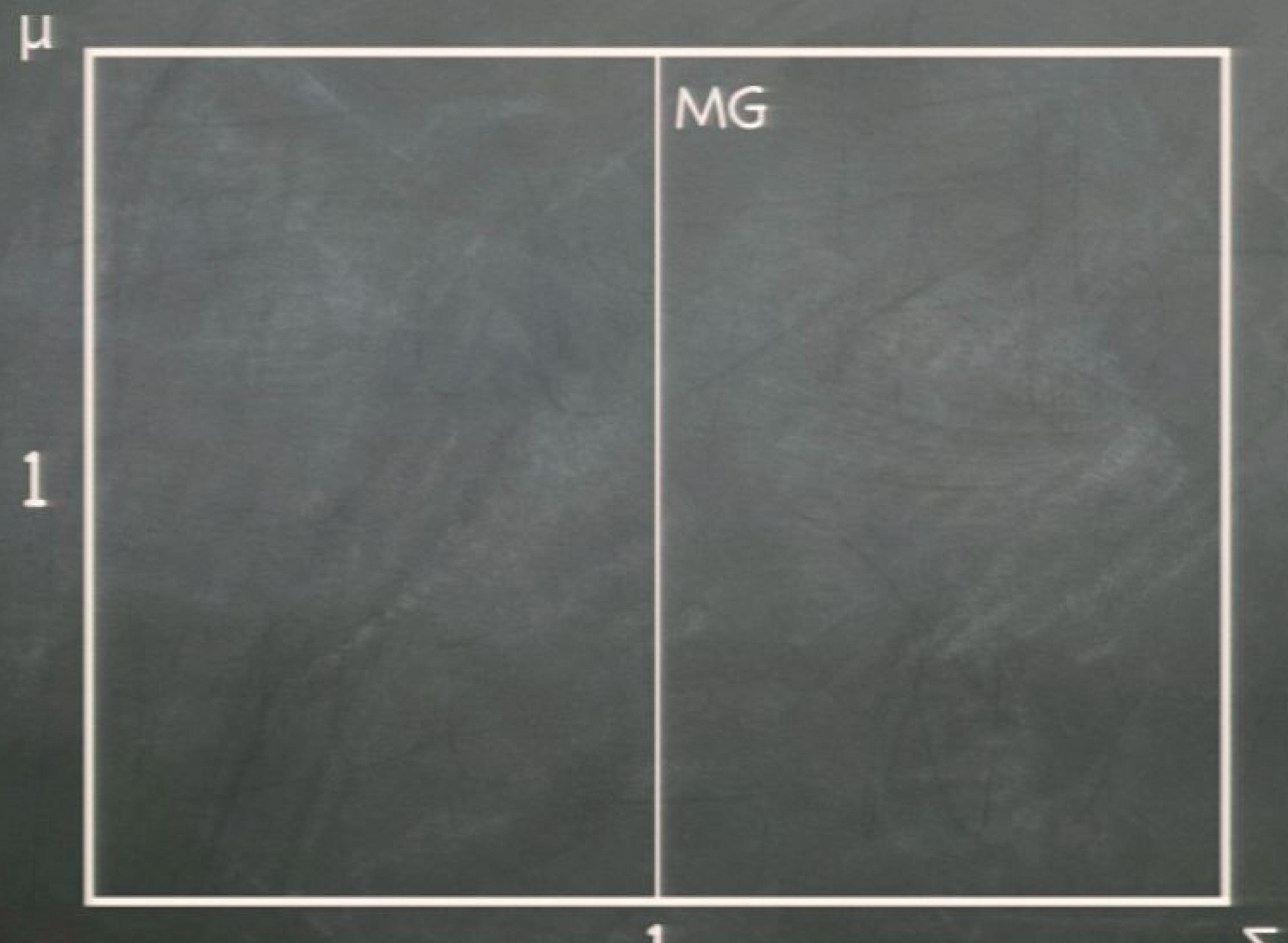
$$\Sigma(a) = 1$$

$$\mu(a) = (4+2w_{BD})/(3+2w_{BD})$$

1 Σ

Unique trajectory on Σ & μ plane

BD type modified gravity model



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1

Σ

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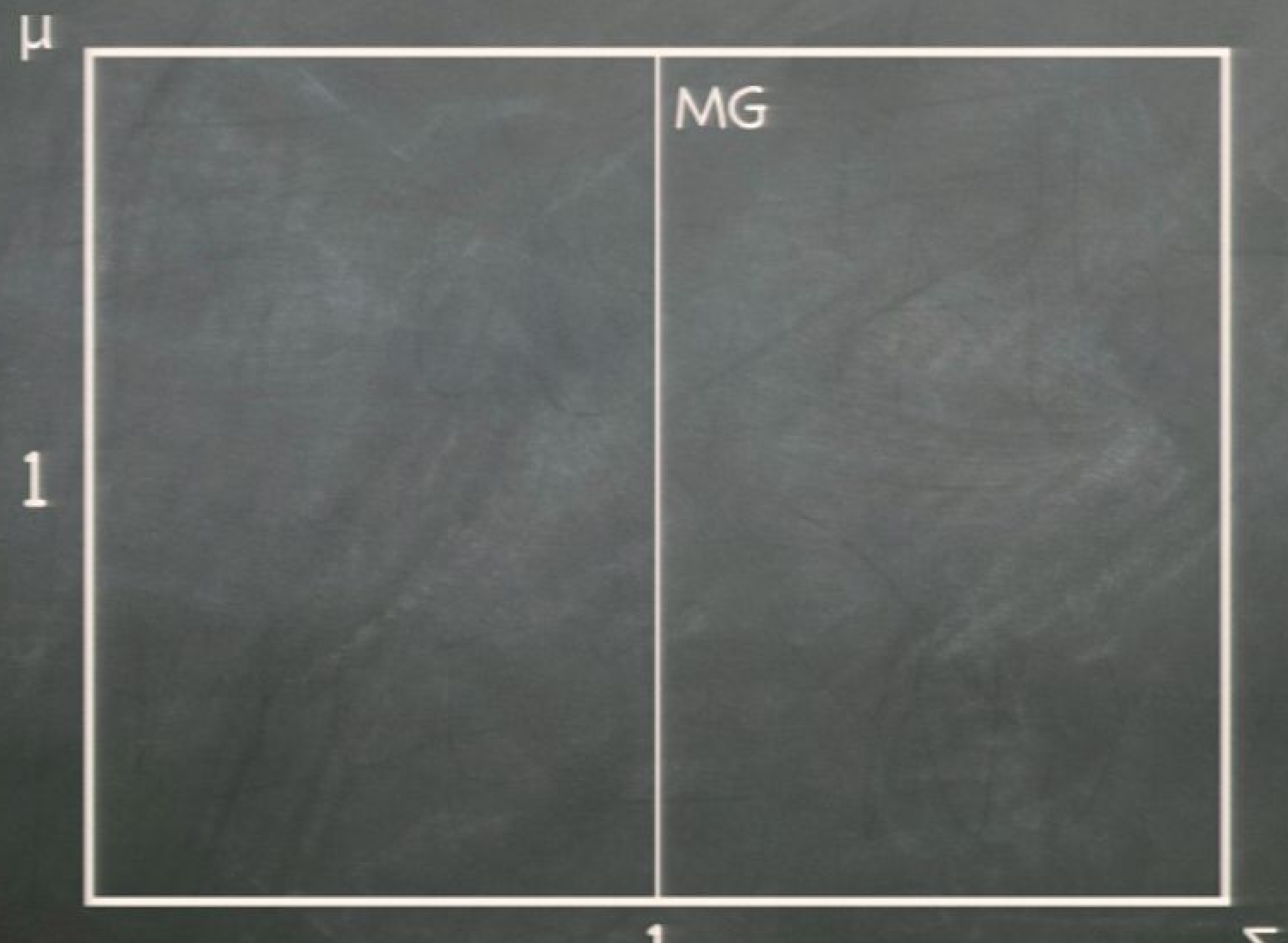
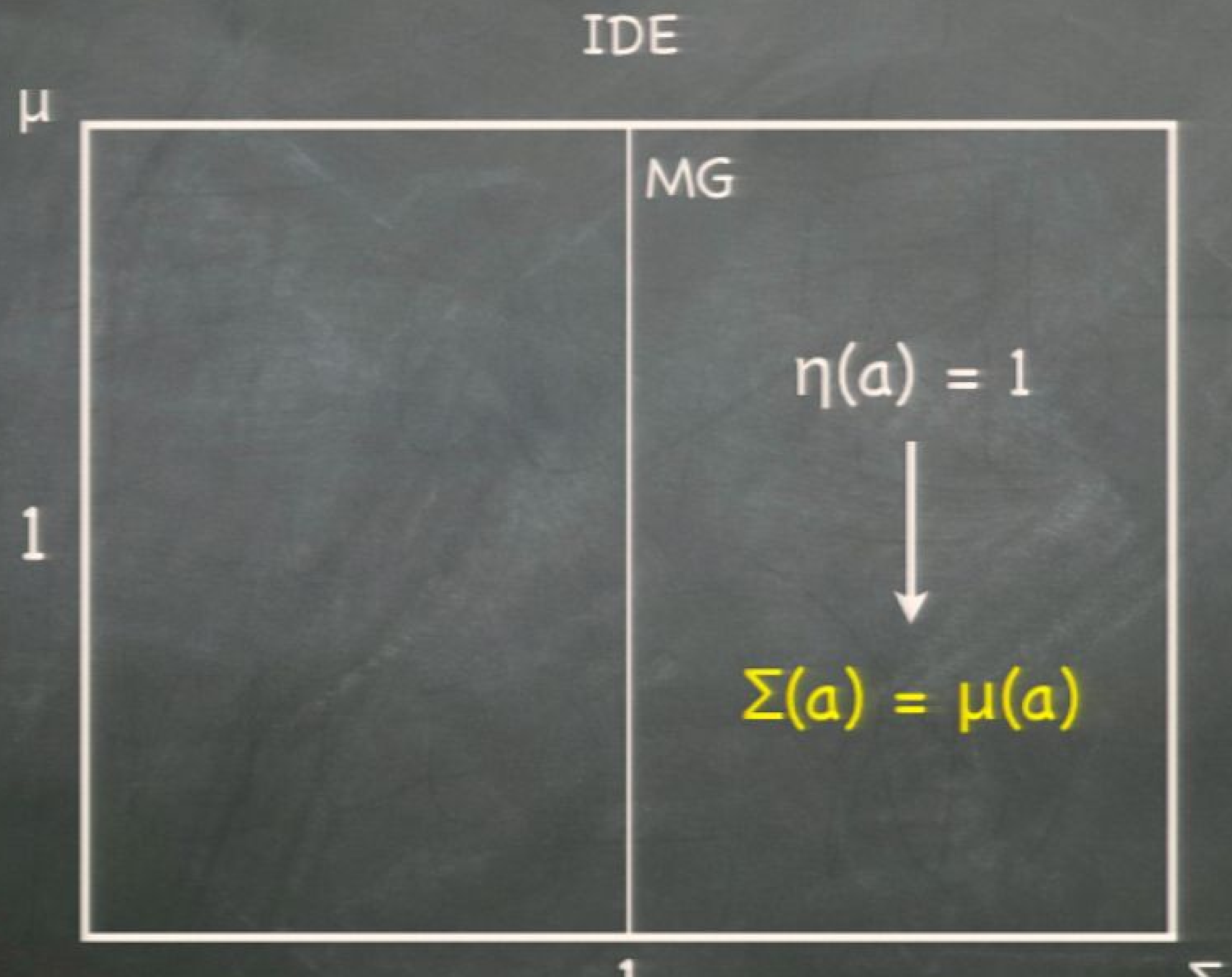


Unique trajectory on Σ & μ plane



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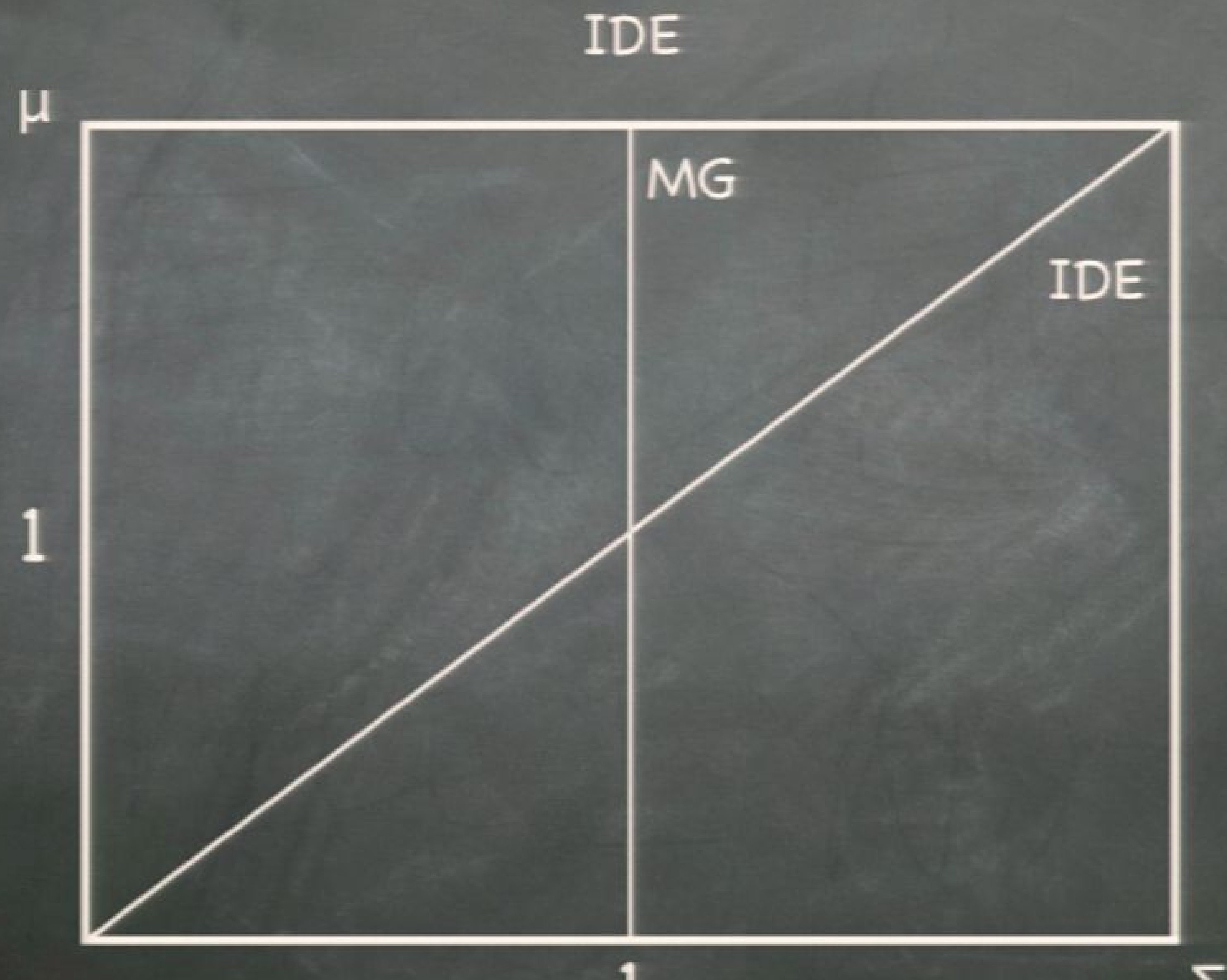
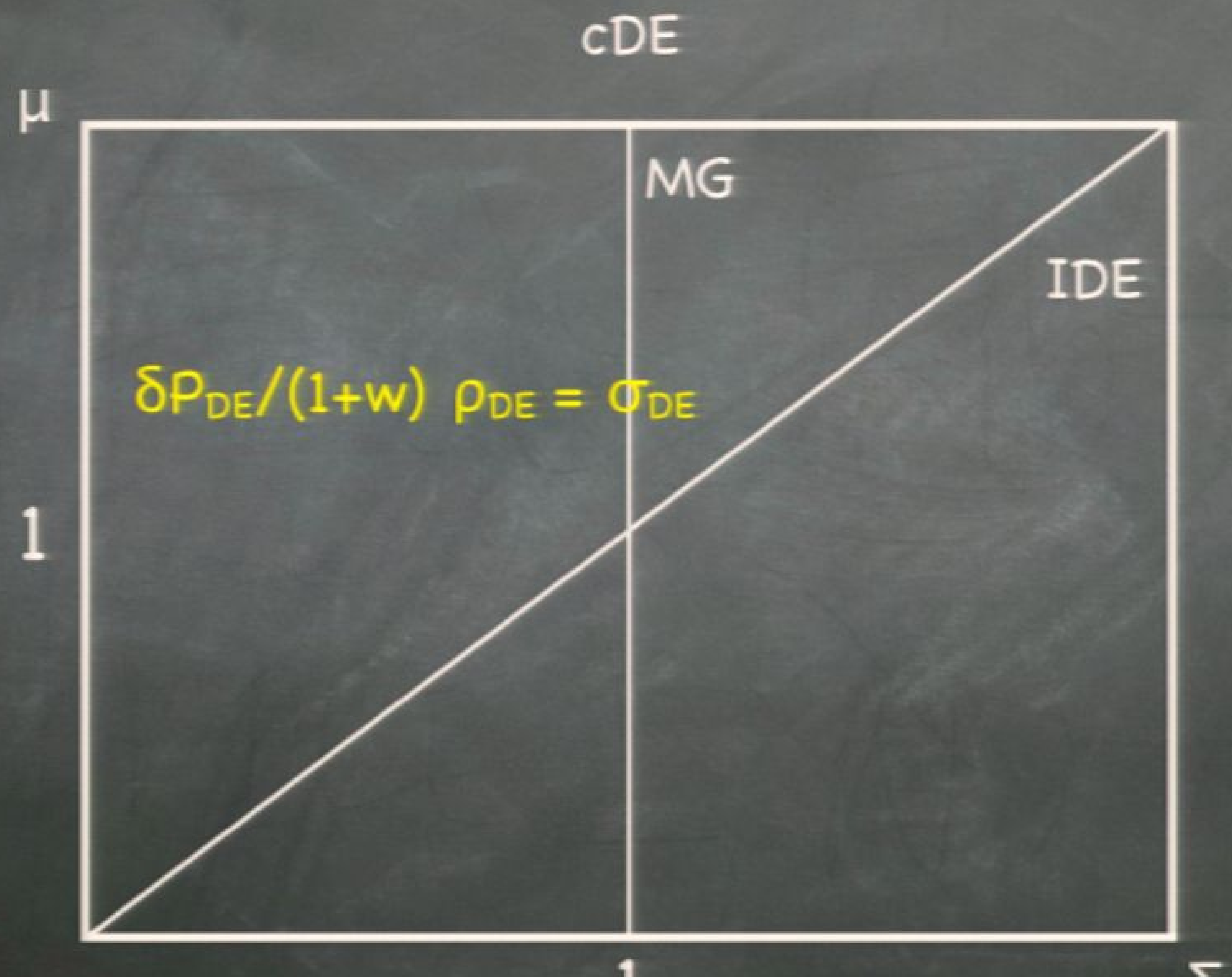


Unique trajectory on Σ & μ plane

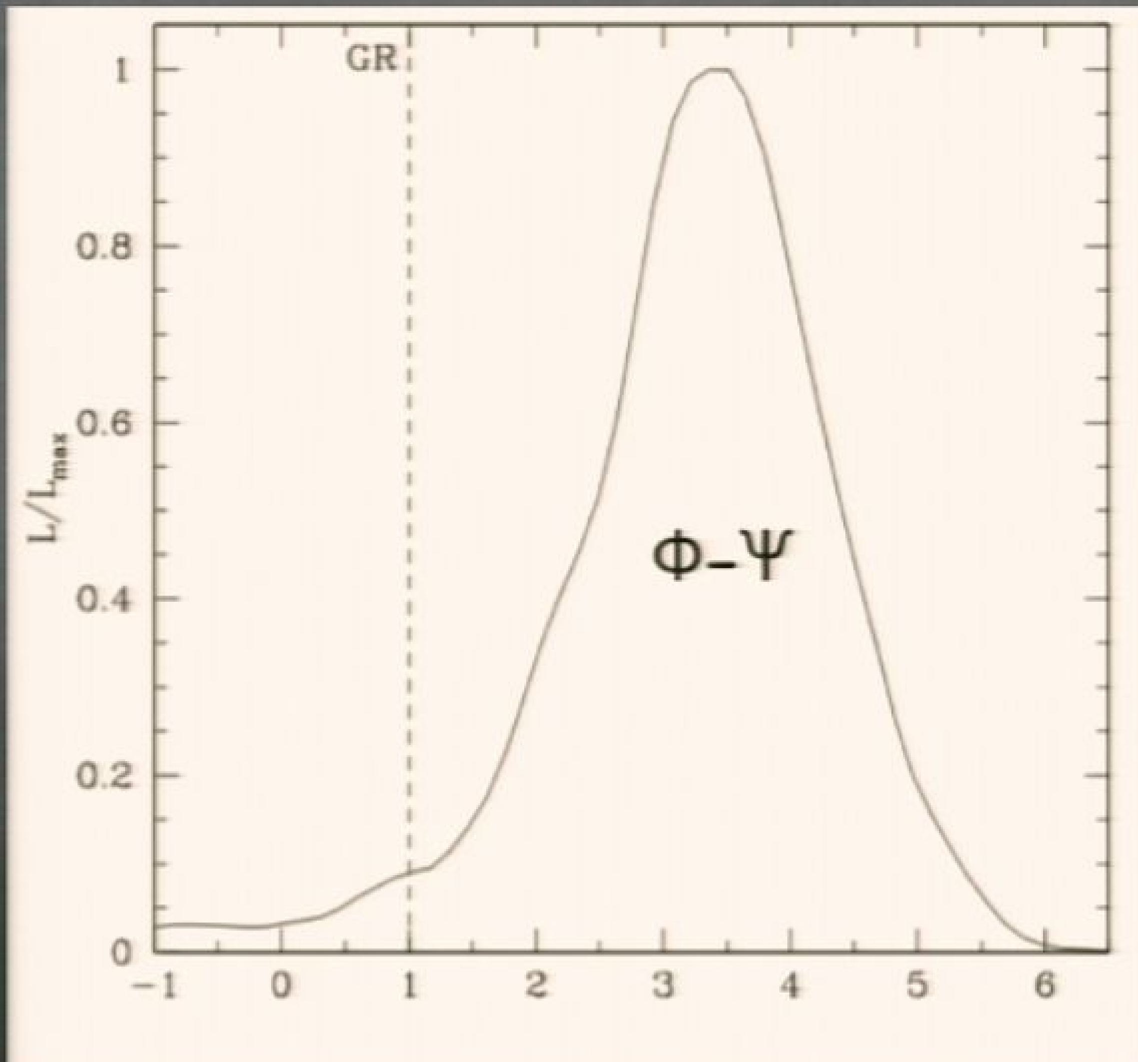


Unique trajectory on Σ & μ plane

YSS, Holenstein, Caleracabral, Koyama (2009)

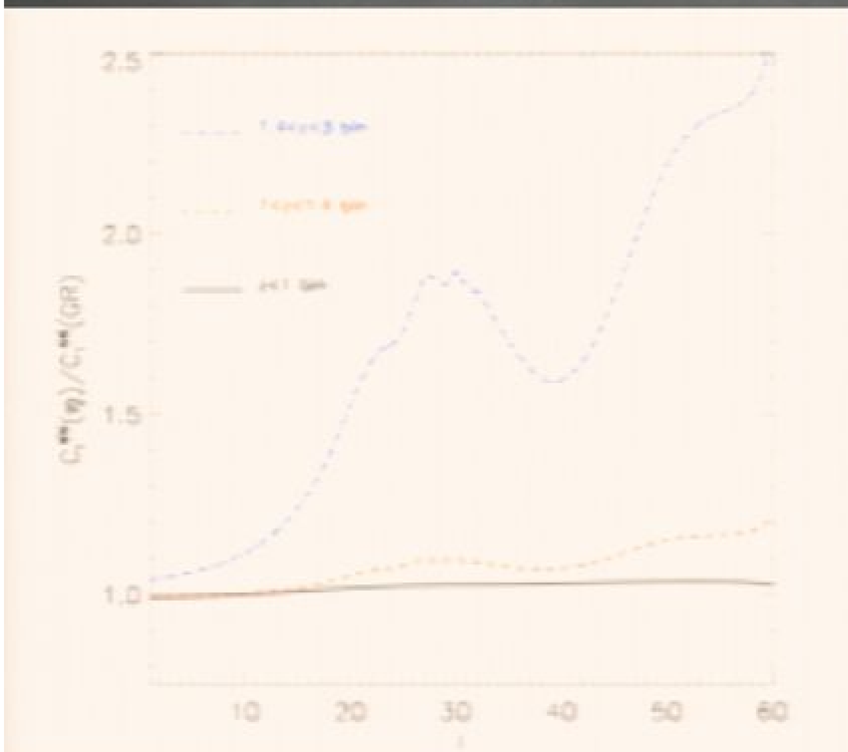
Constraint on Σ & μ

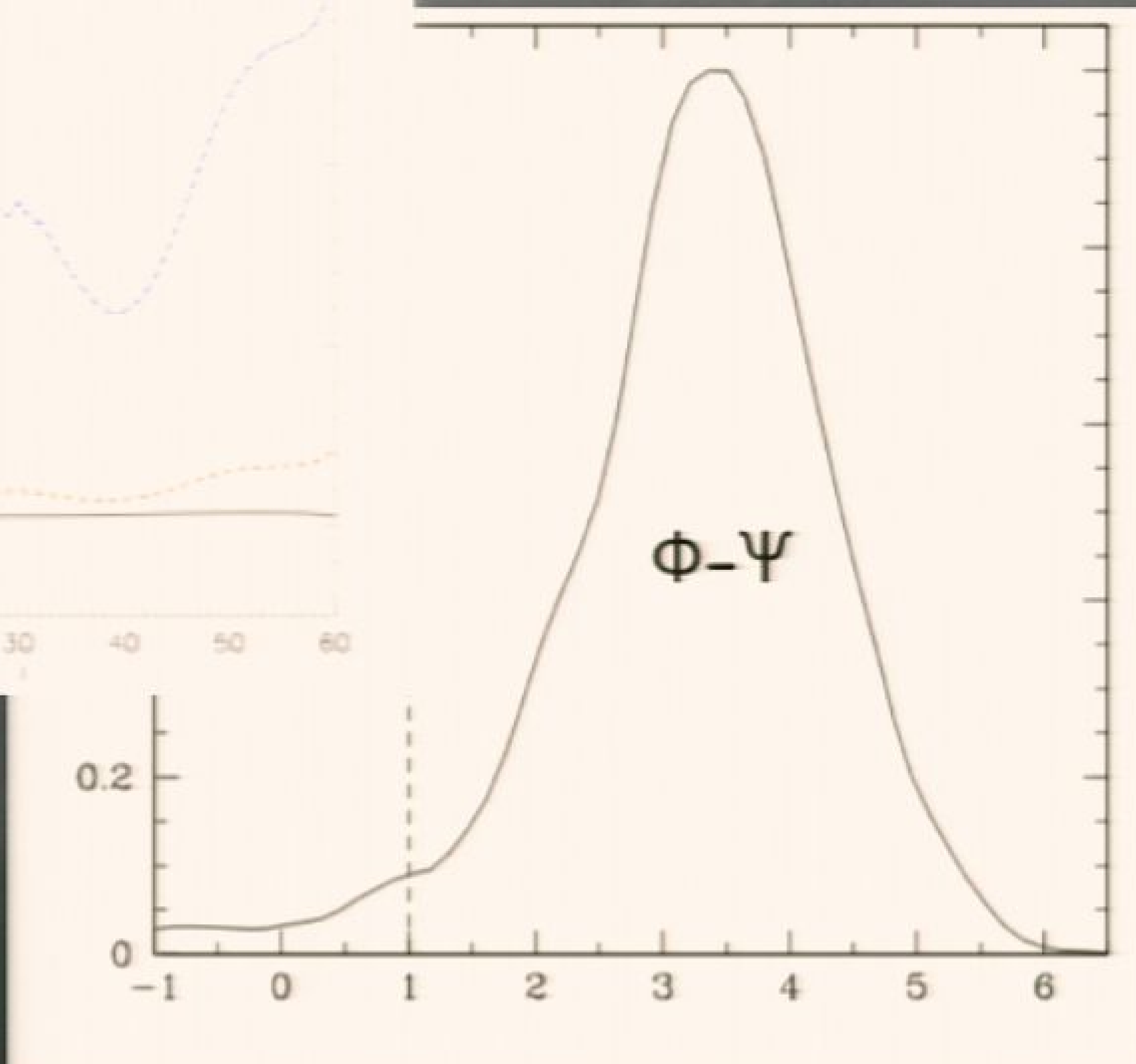
R. Bean



Constraint on Σ & μ

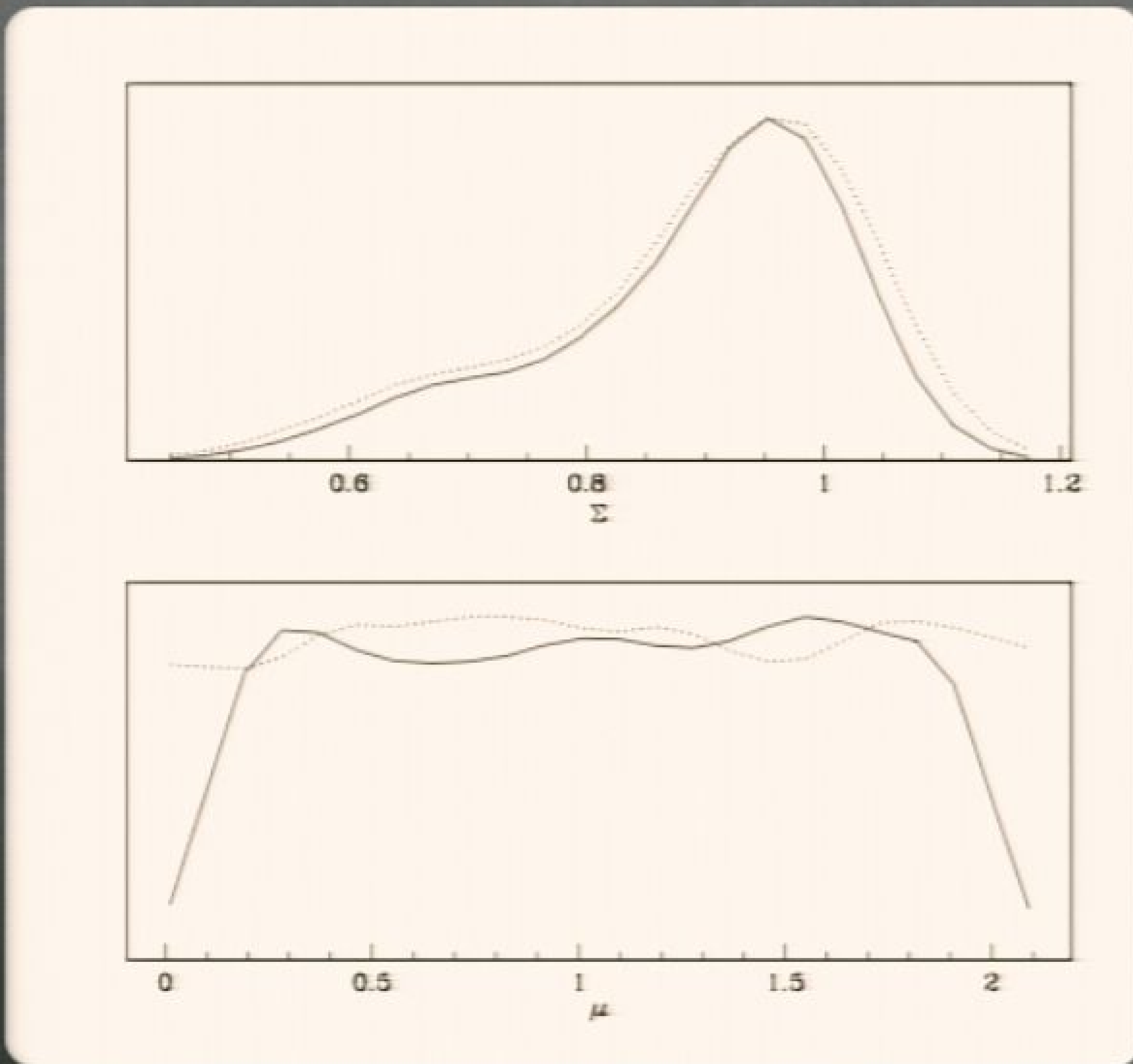
R. Bean



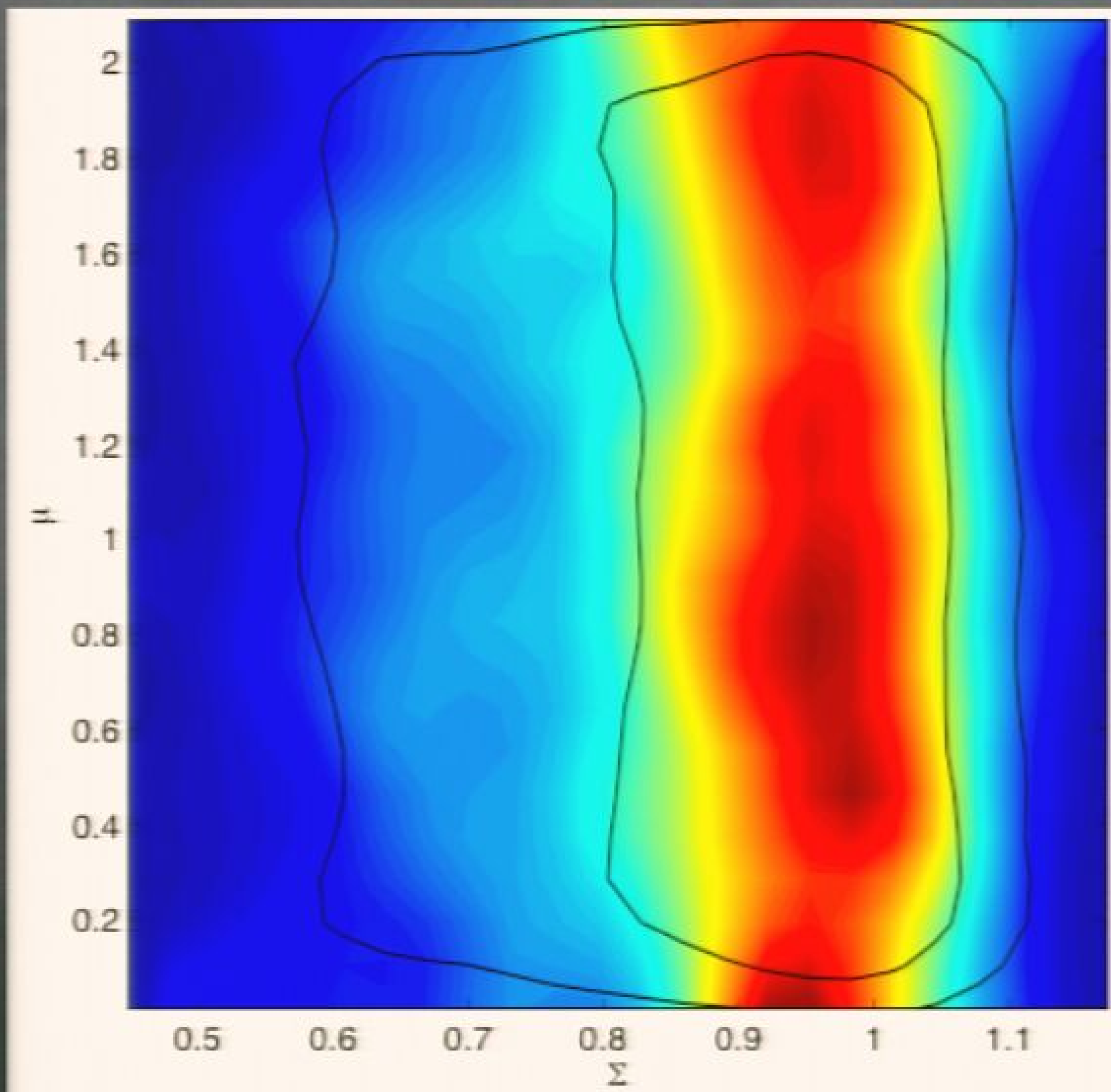


Constraint on Σ & μ

WMAP+CFHTLS

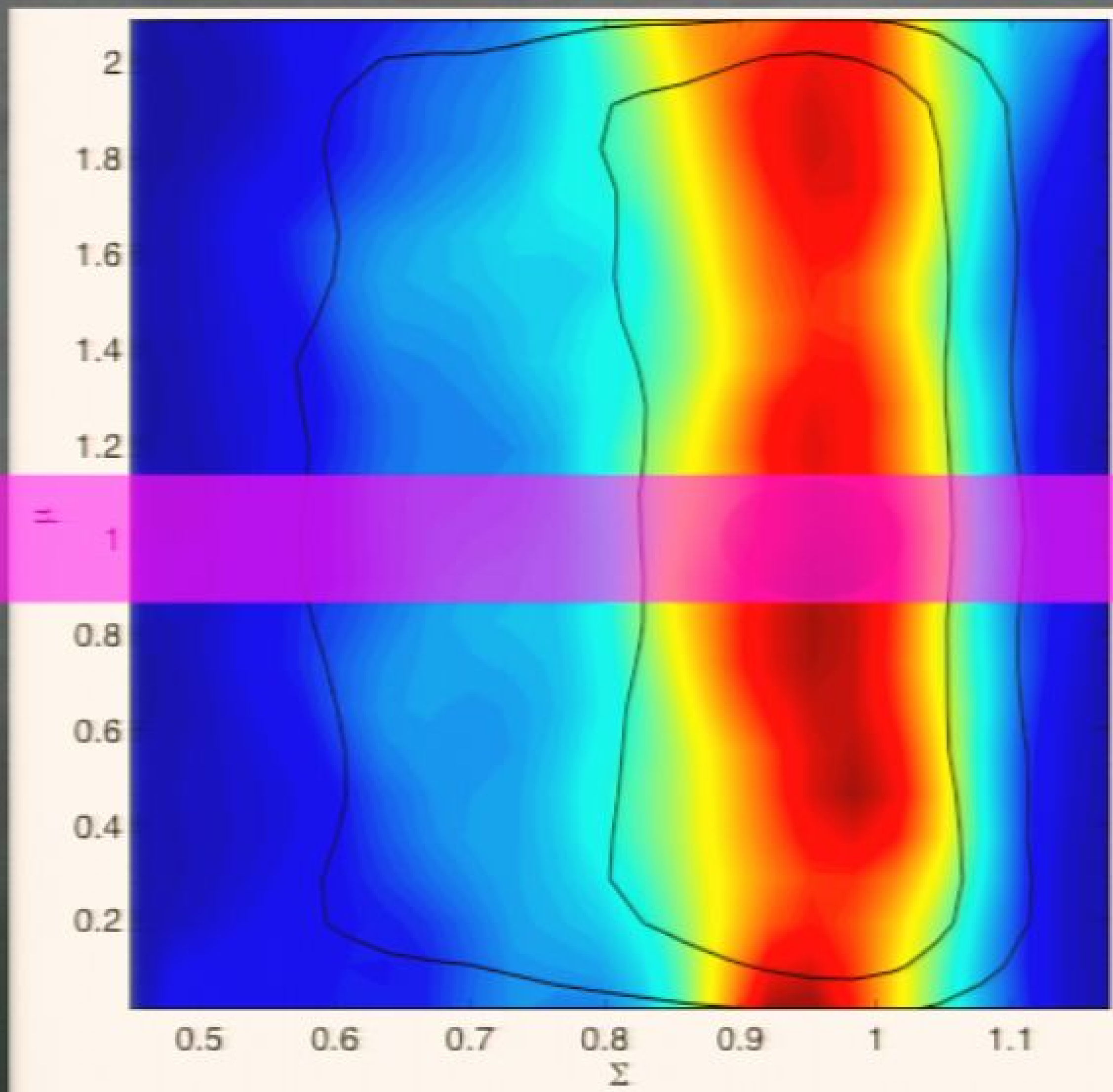


Constraint on Σ & μ

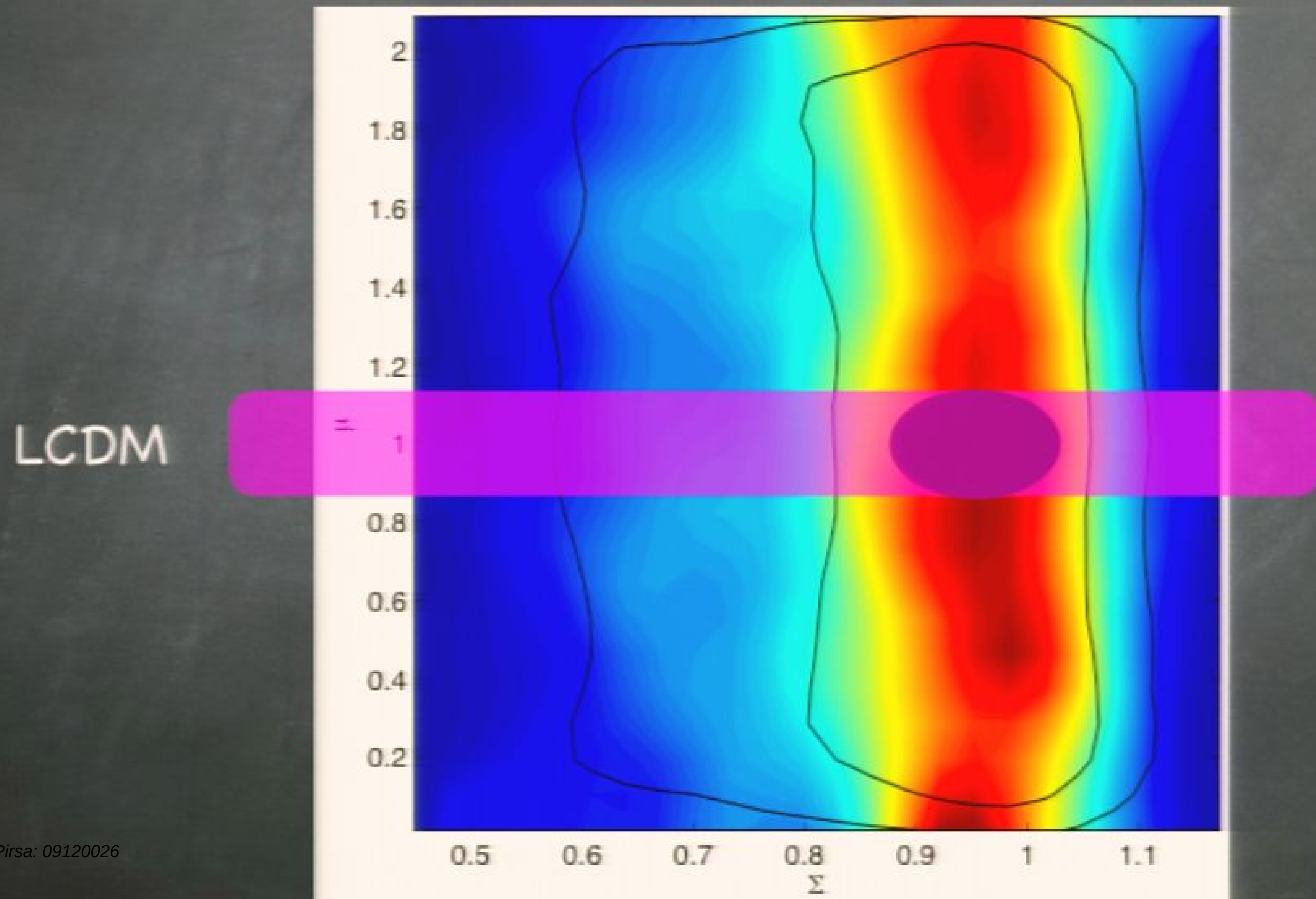


Constraint on Σ & μ

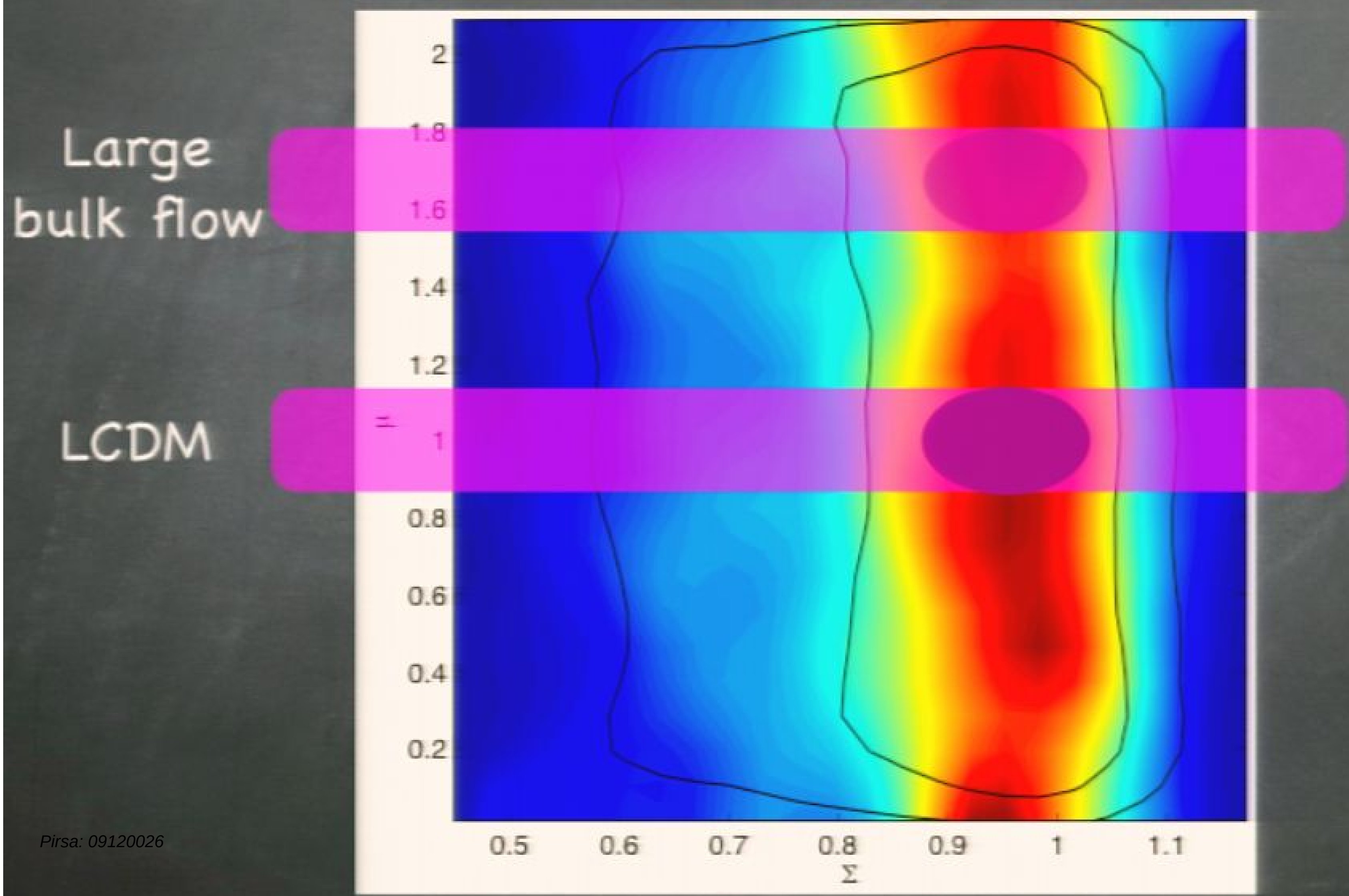
LCDM



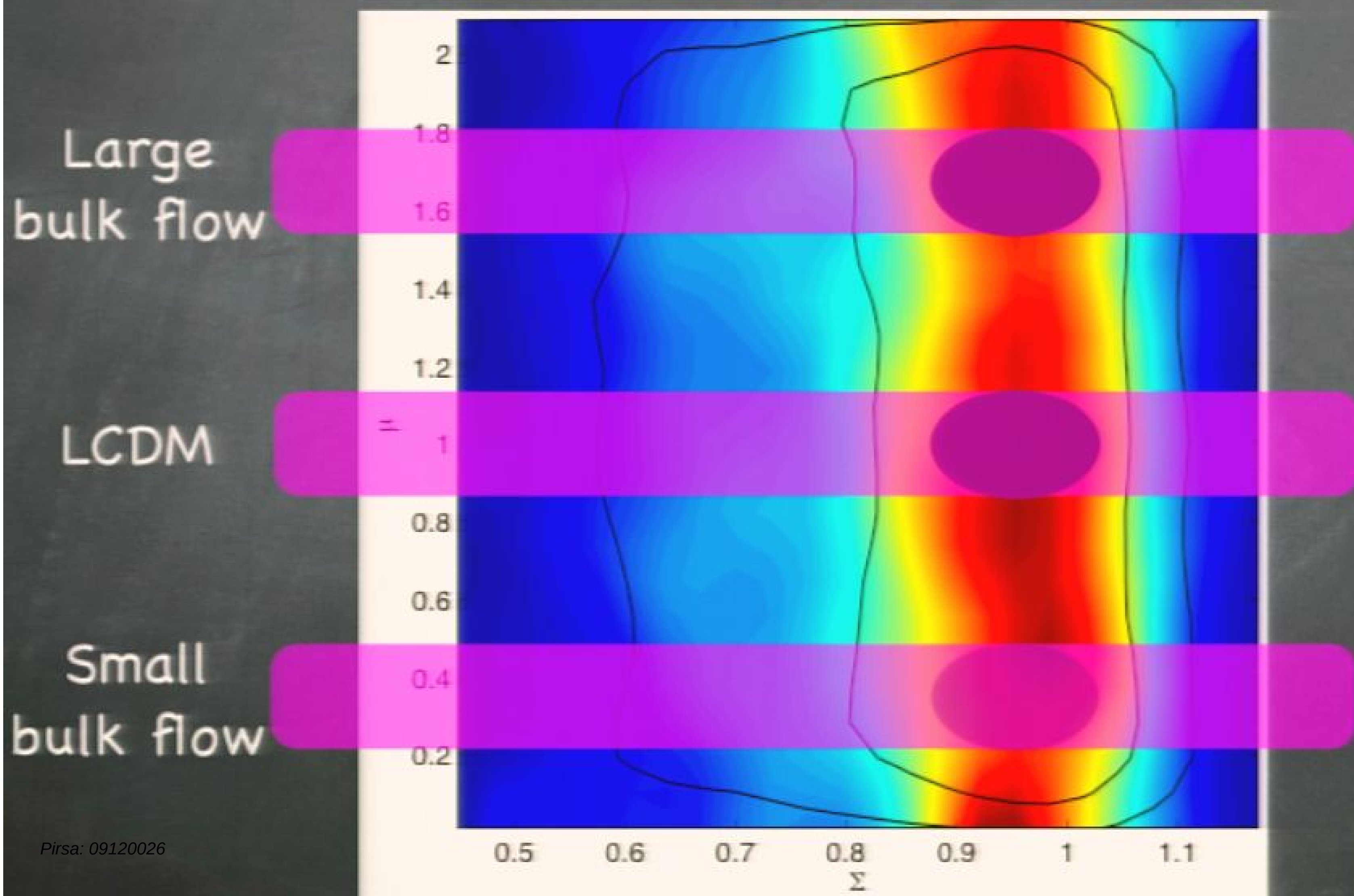
Constraint on Σ & μ



Constraint on Σ & μ

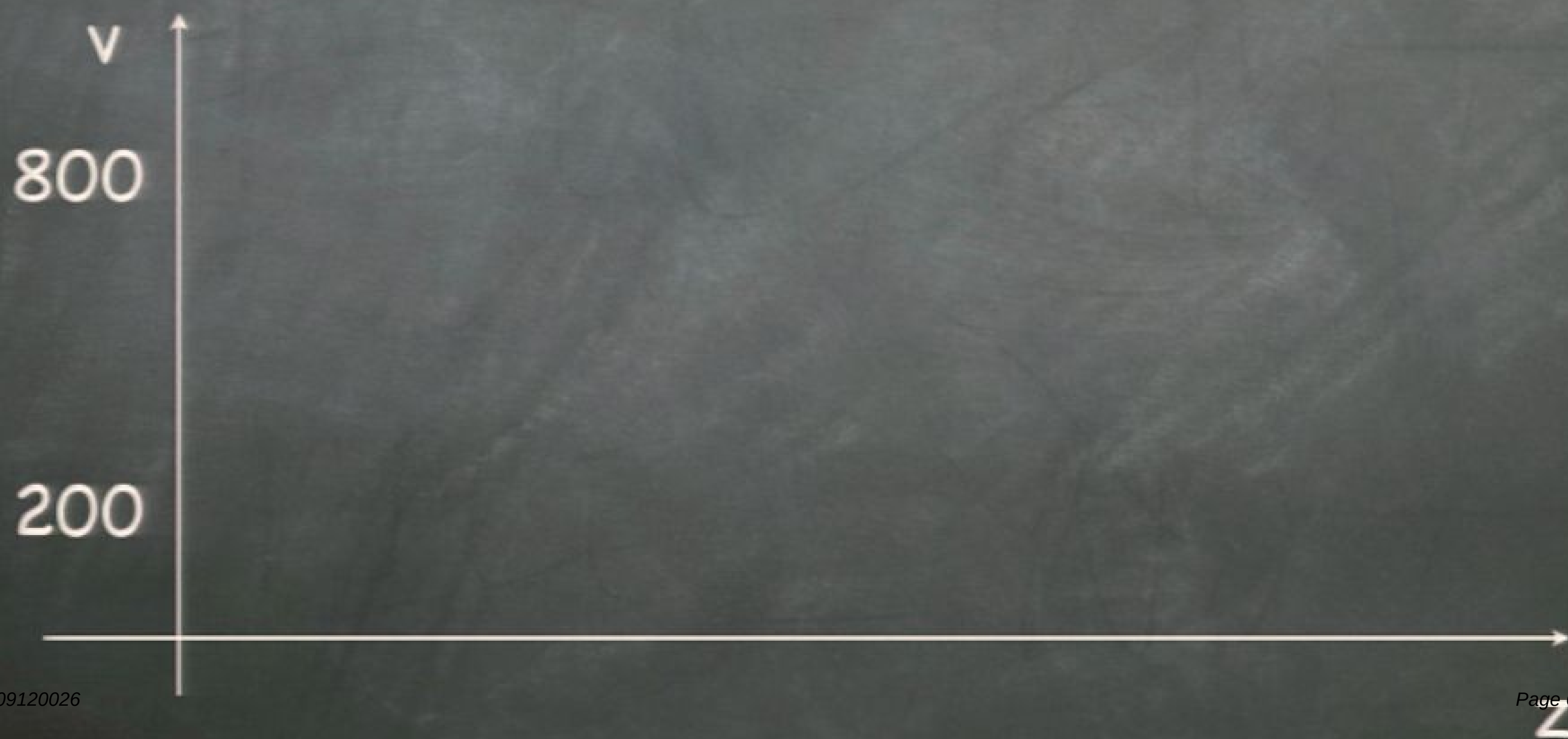


Constraint on Σ & μ



Determination of bulk flow

Direct measurement of bulk flow v at local universe



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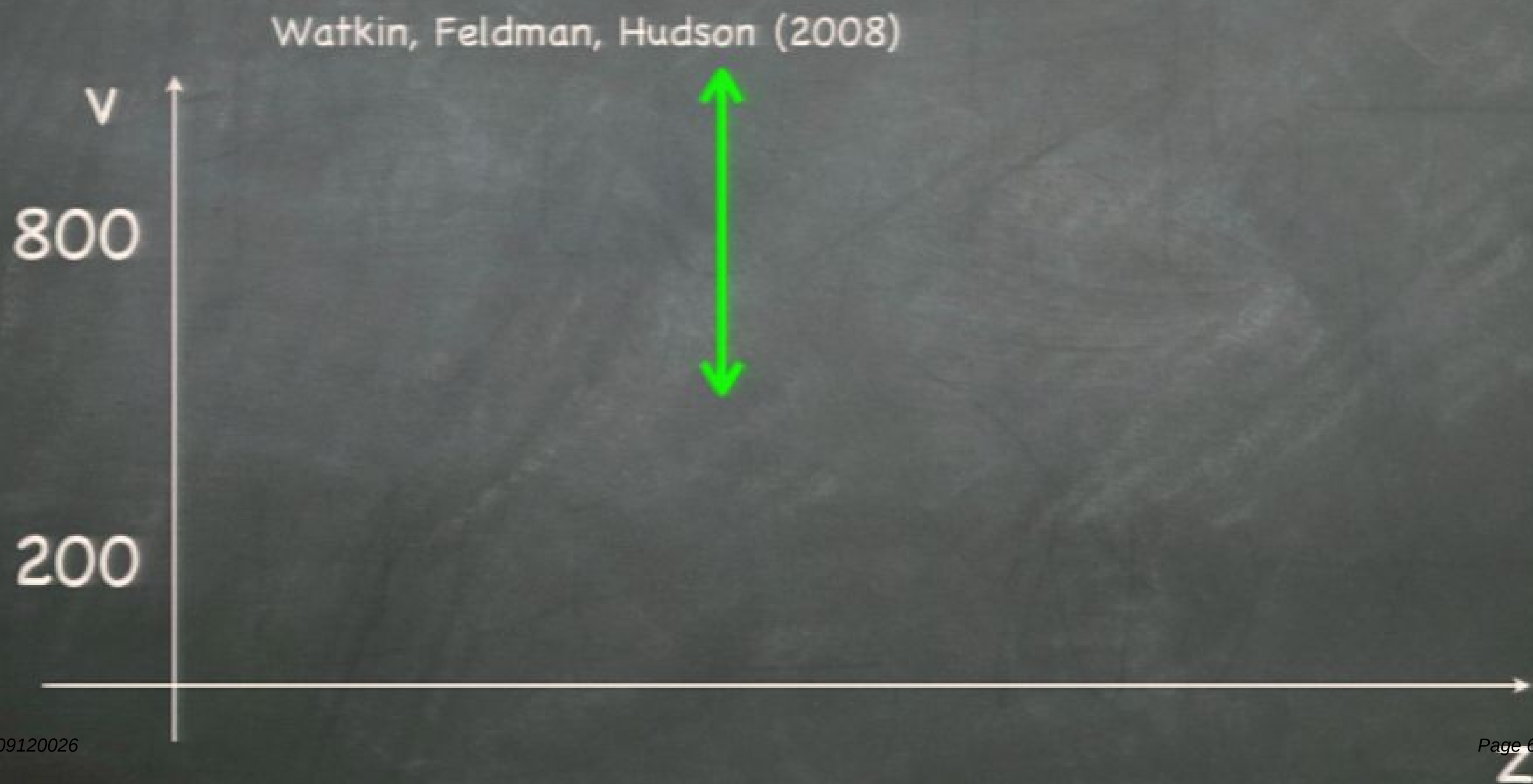

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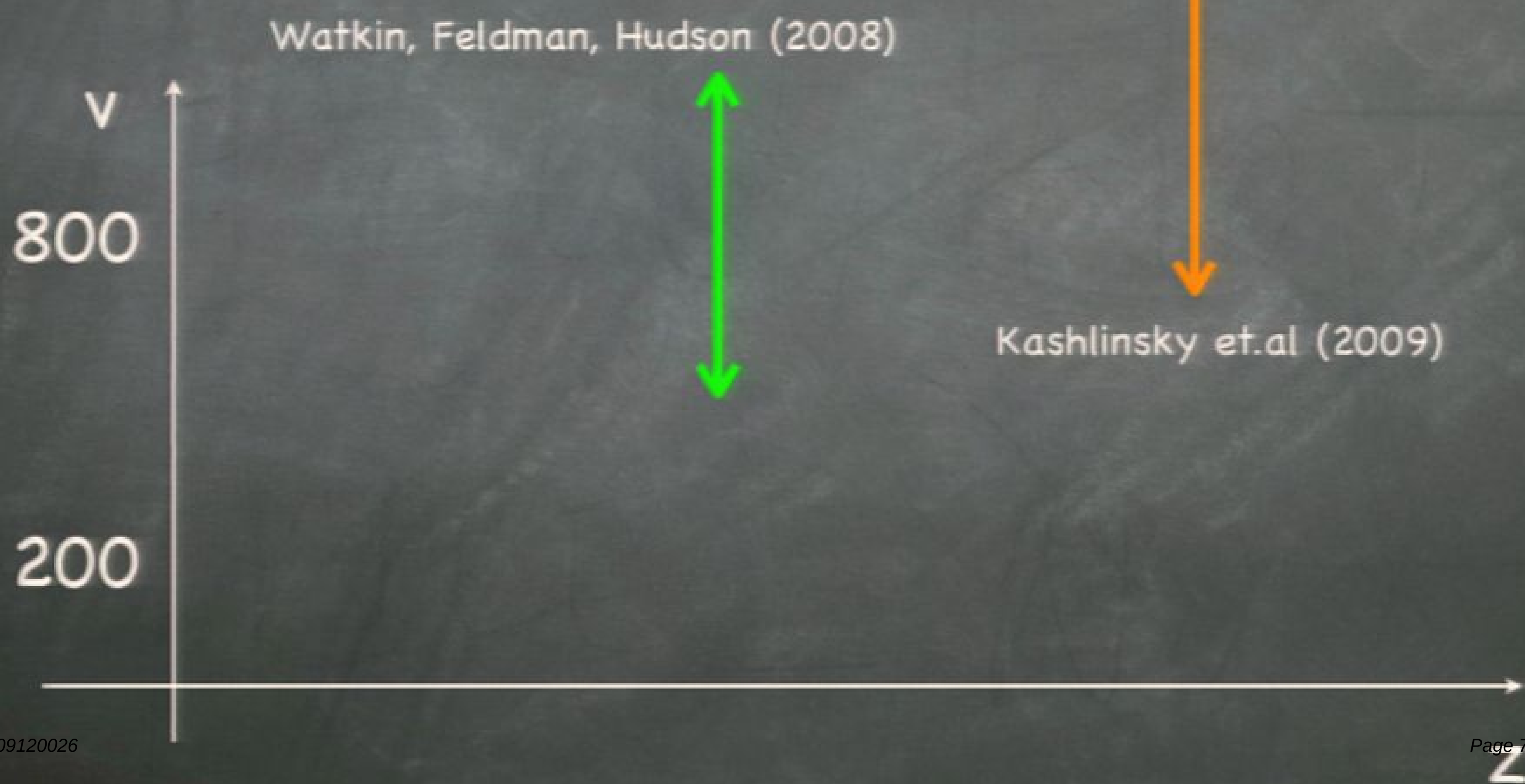

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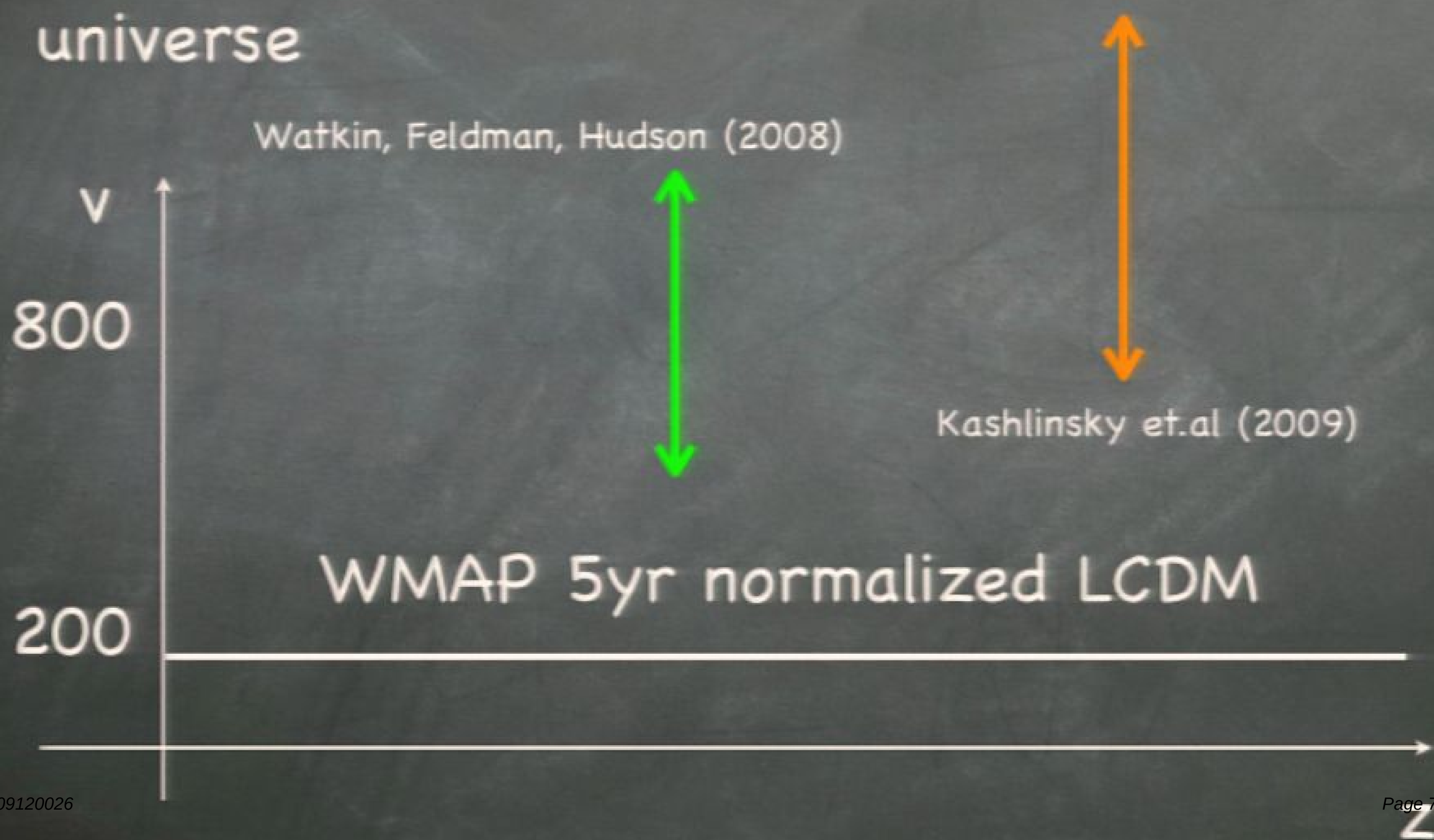
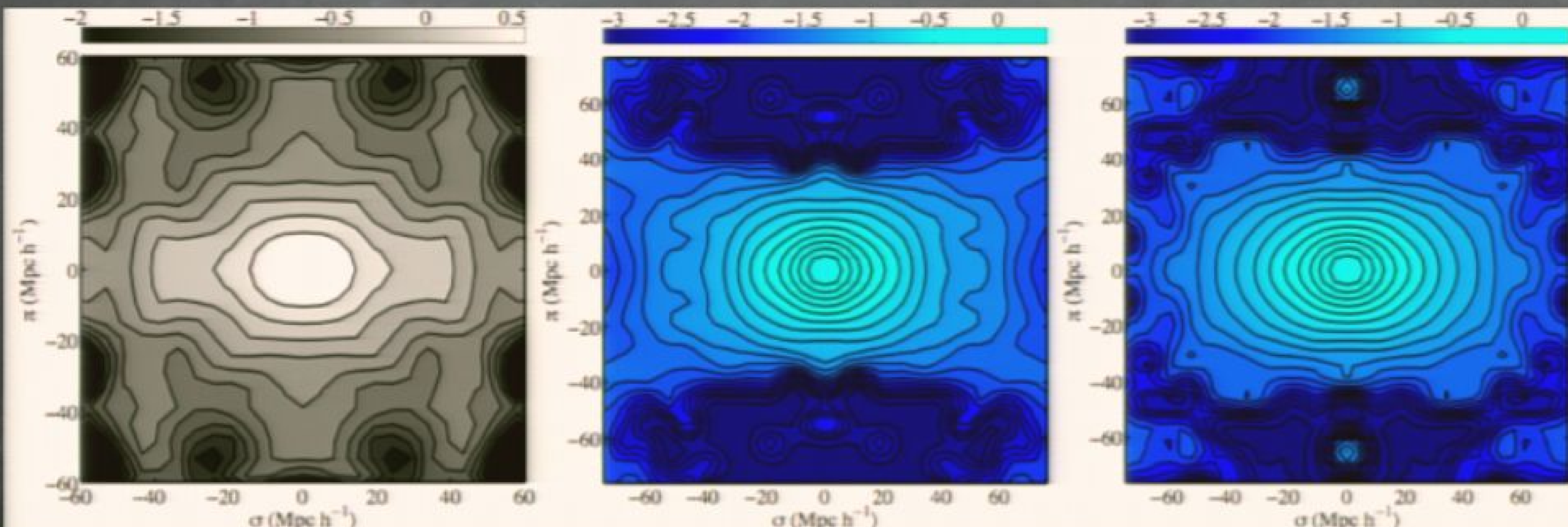


Statistical determination

ξ_s diagram



Cluster (DR4)

Galaxy (LRG)

YSS, Sabiu, Nichol and Miller (2009)

Correlation function in red-space

ξ_s: streaming model – using probabilistic distribution (for smaller scales)

ξ_s: Kaiser model – conversion from the known power spectra in Fourier space (for larger scales)

$$\xi_s = (g_b^{\,2} + g_b g_v/3 + g_v^{\,2}/5)\ \xi_0 P_0$$
$$-(4/3 g_b g_v + 4/7 g_v^{\,2})\ \xi_2 P_2$$
$$+8/35 g_v^{\,2}\ \xi_4 P_4$$

YSS, Sabiu, Nichol and Miller (2009)

Correlation function in red-space

Monopole: $(g_b^2+g_b g_v/3+g_v^2/5)\ \xi_0\, P_0$

Scale dependent ξ_0 is determined by WMAP prior, and monopole moment is effectively determined by coherent growth coefficient g_b.

Quadrupole: $-(4/3 g_b g_v+4/7 g_v^2)\ \xi_2\, P_2$

Scale dependent ξ_2 is determined by WMAP prior, and quadrupole moment is effectively determined by coherent growth coefficient $g_b g_v$.

YSS, Sabiu, Nichol and Miller (2009)

Correlation function in red-space

$$\xi_s = (g_b^2+g_b g_v/3+g_v^2/5)\ \xi_0 P_0$$
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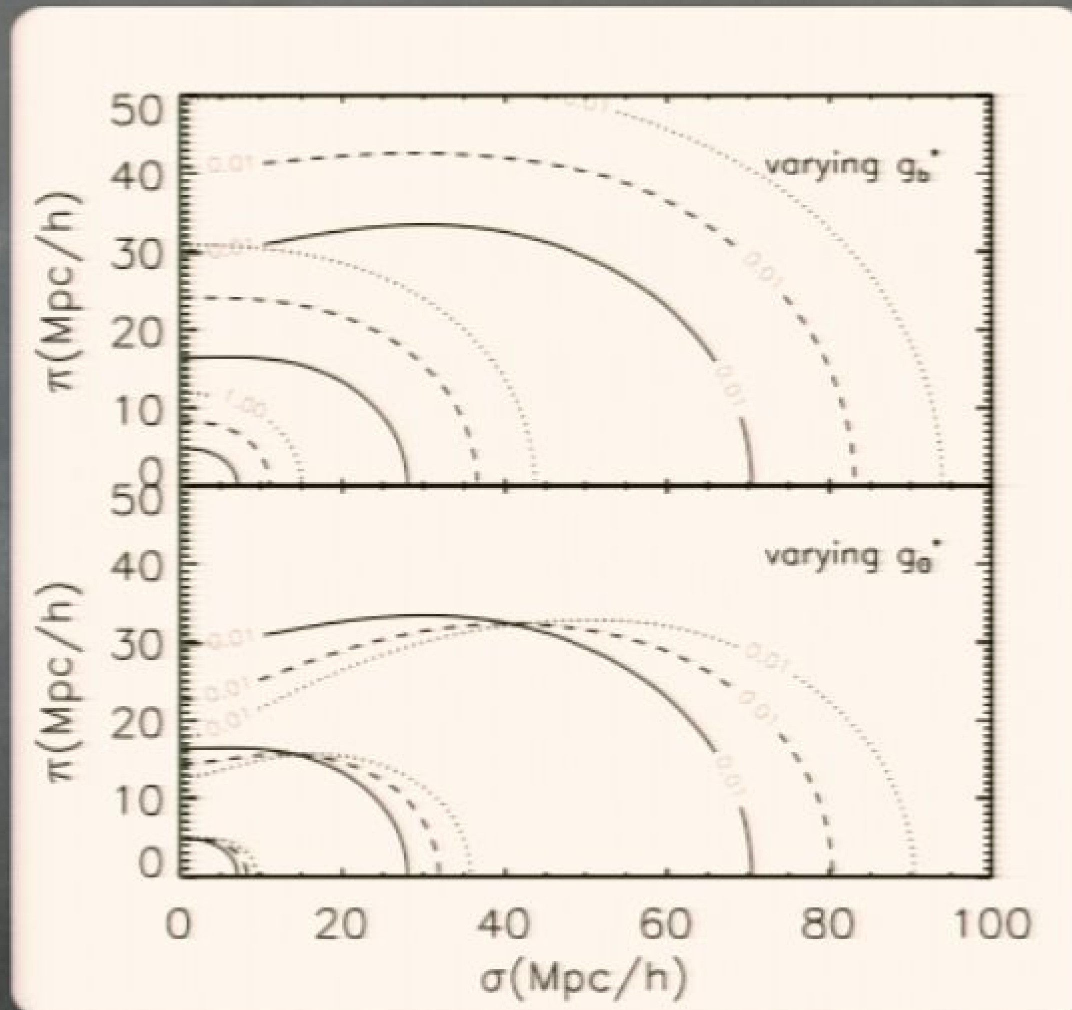
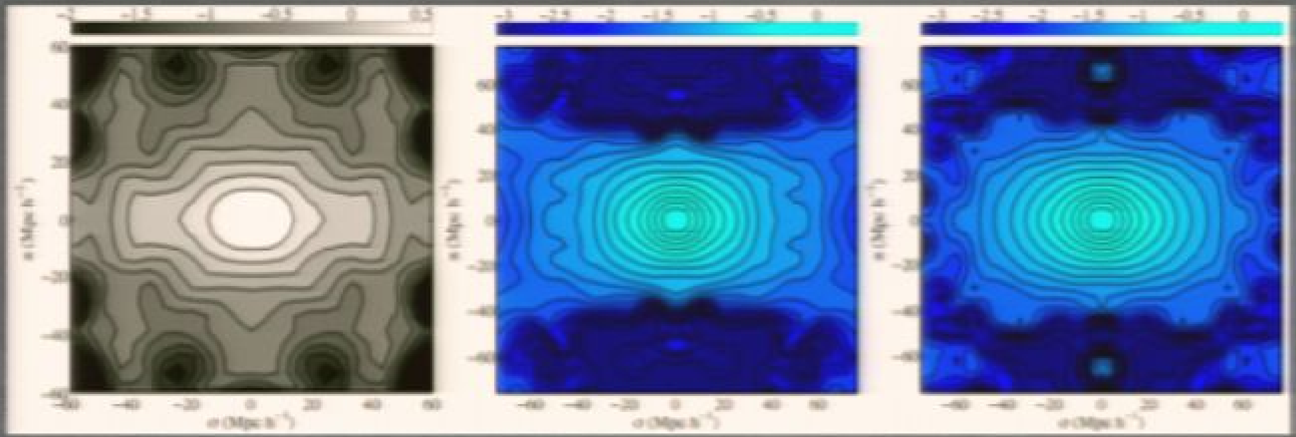
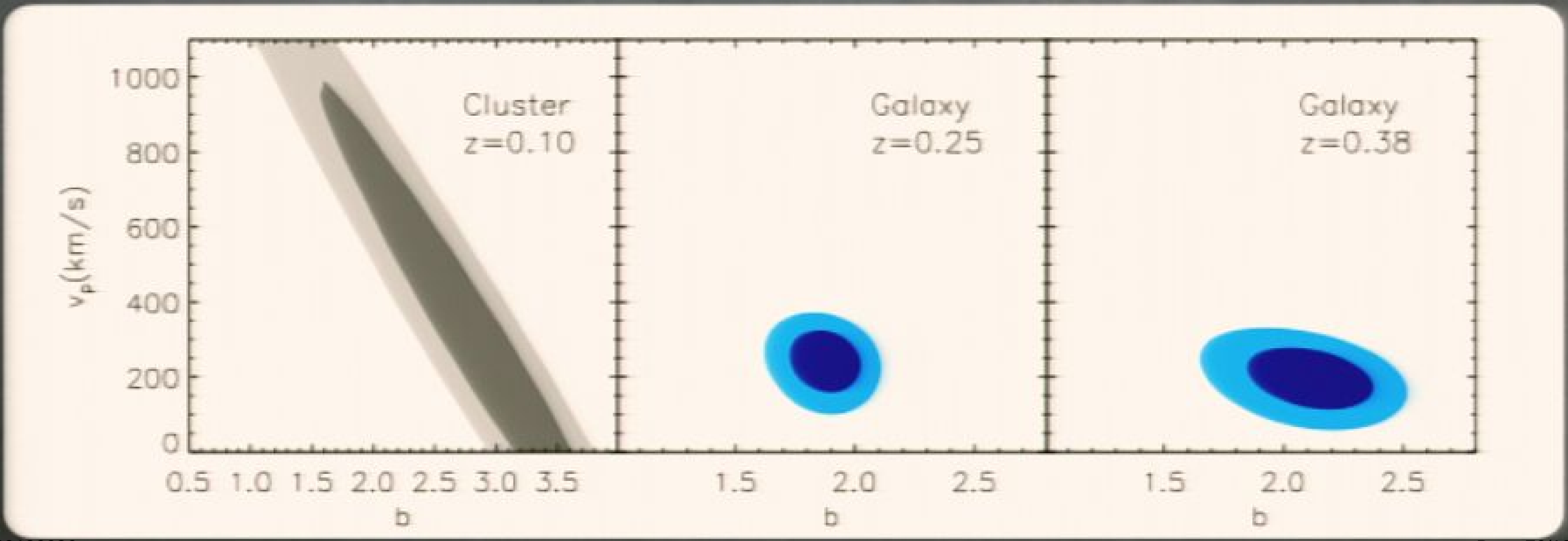


YSS, Sabiu, Nichol and Miller (2009)

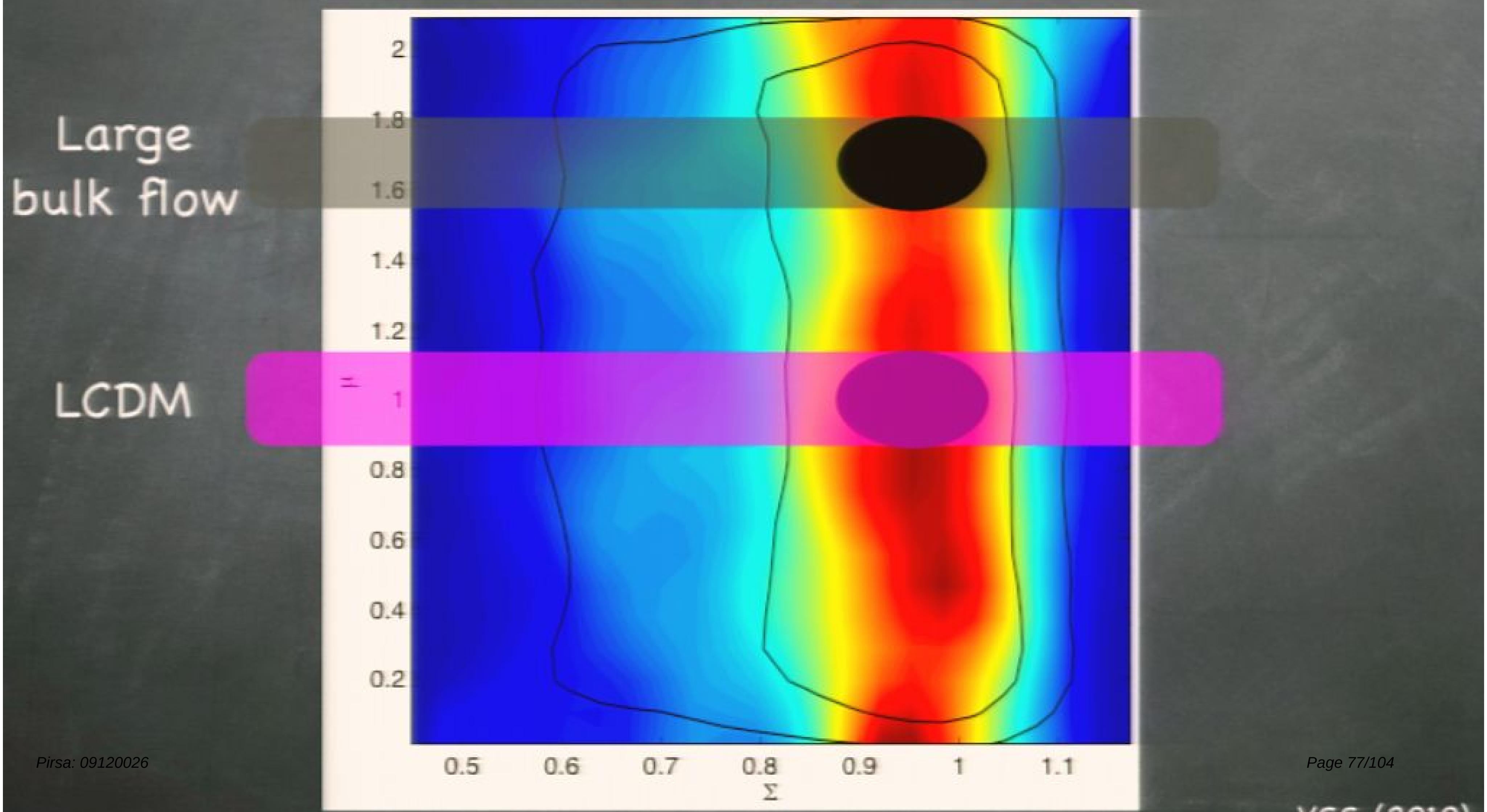
Statistical determination of b & v





YSS, Sabiu, Nichol and Miller (2009)

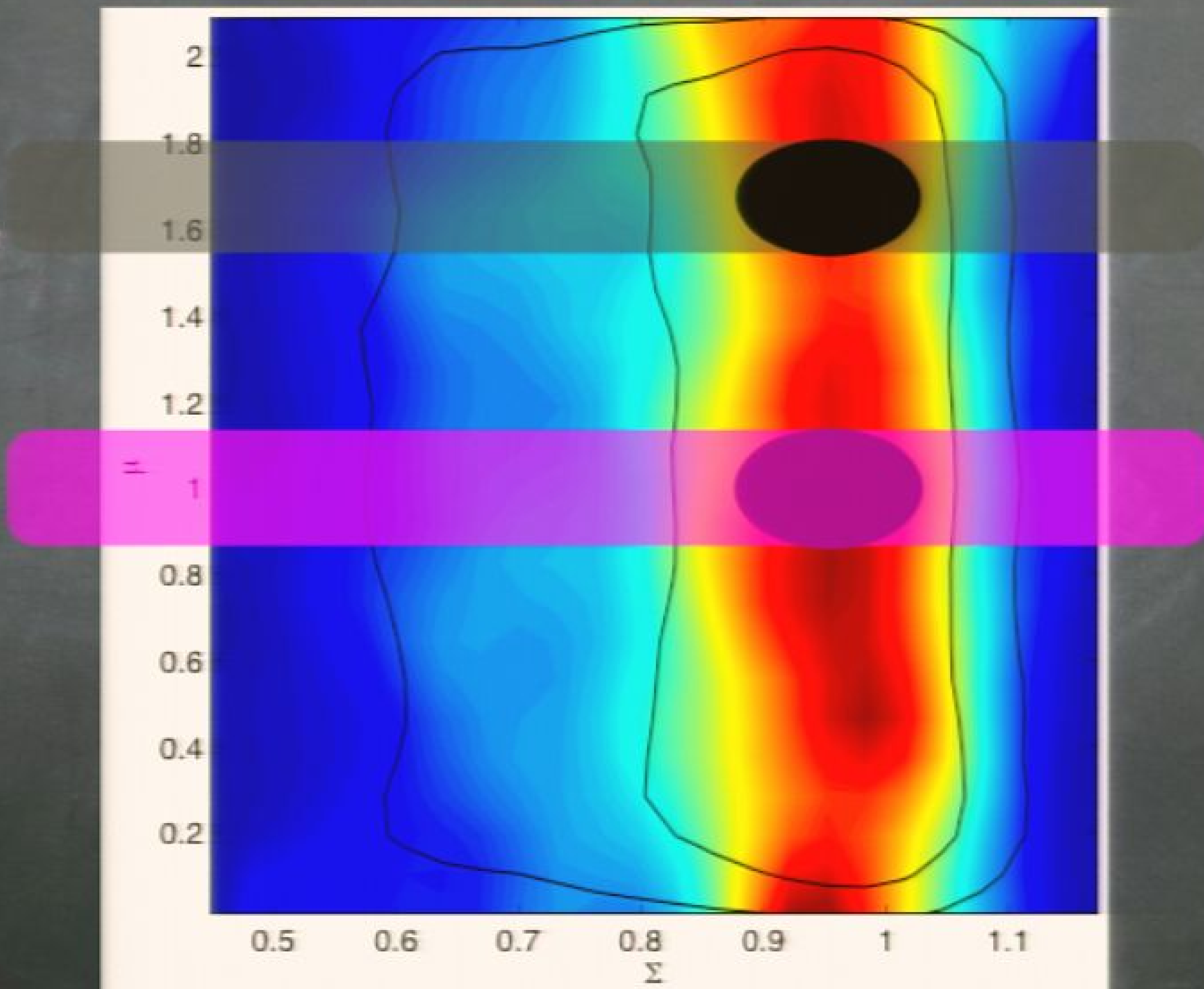
Constraint on Σ & μ



Constraint on Σ & μ

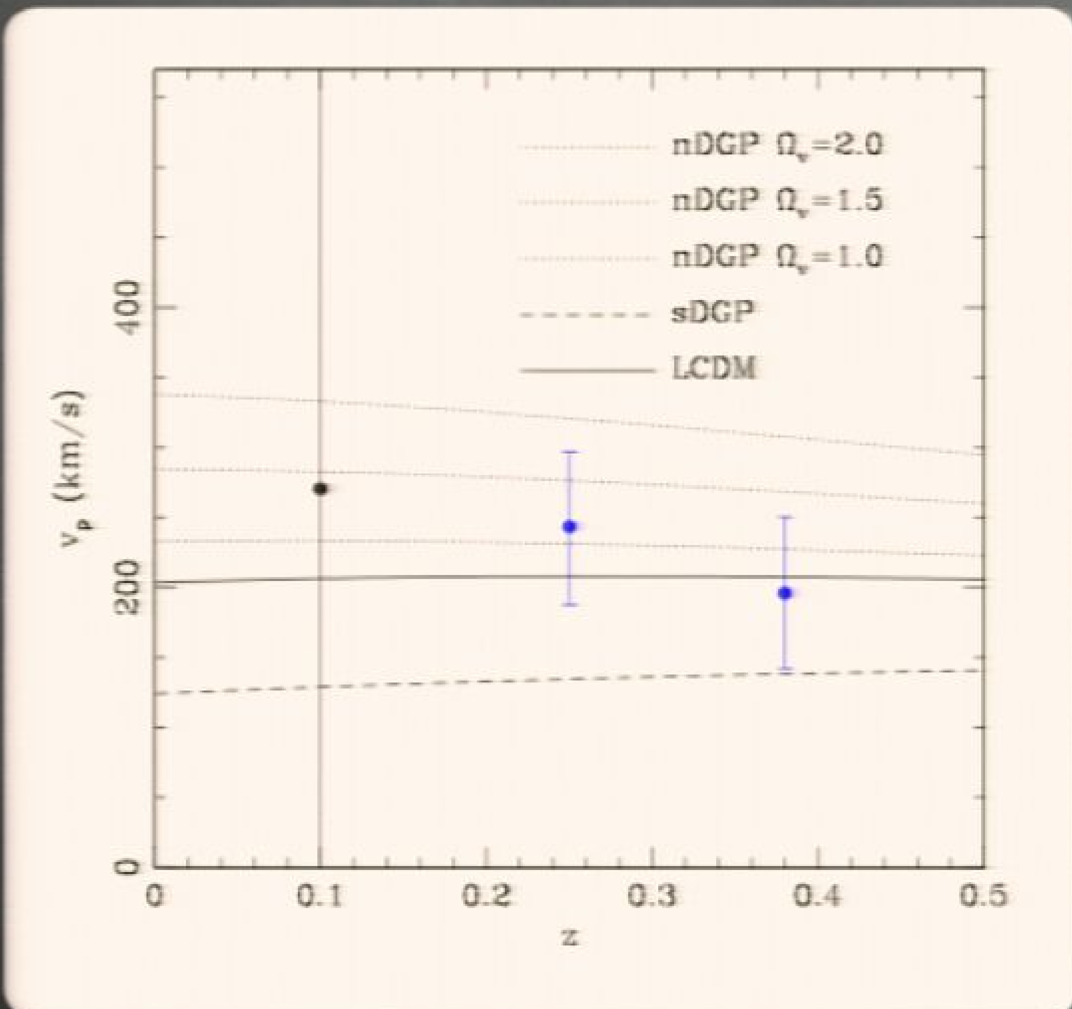
Large bulk flow

LCDM



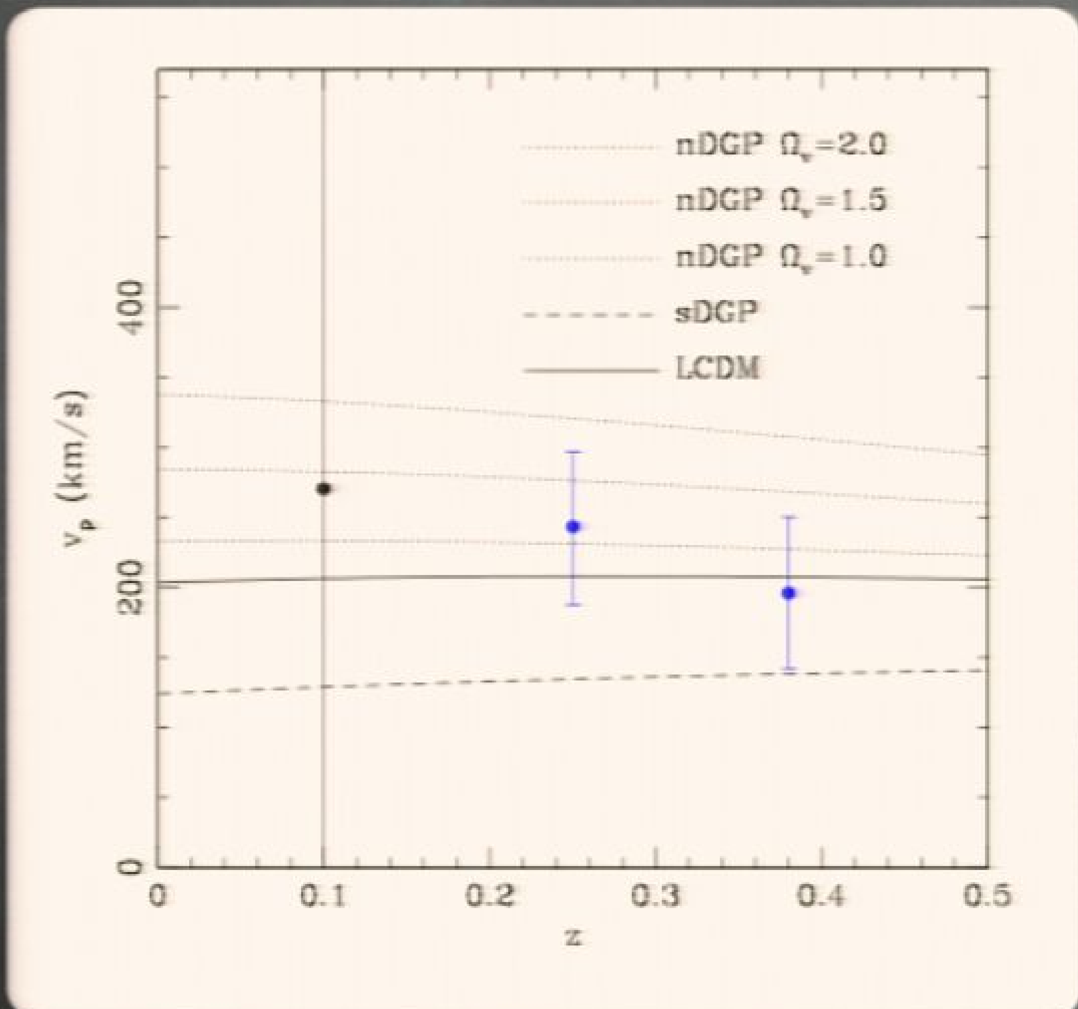
YSS (2010)

Unbiased history of LSS



YSS, Sabiu, Nichol (2010)

Unbiased history of LSS

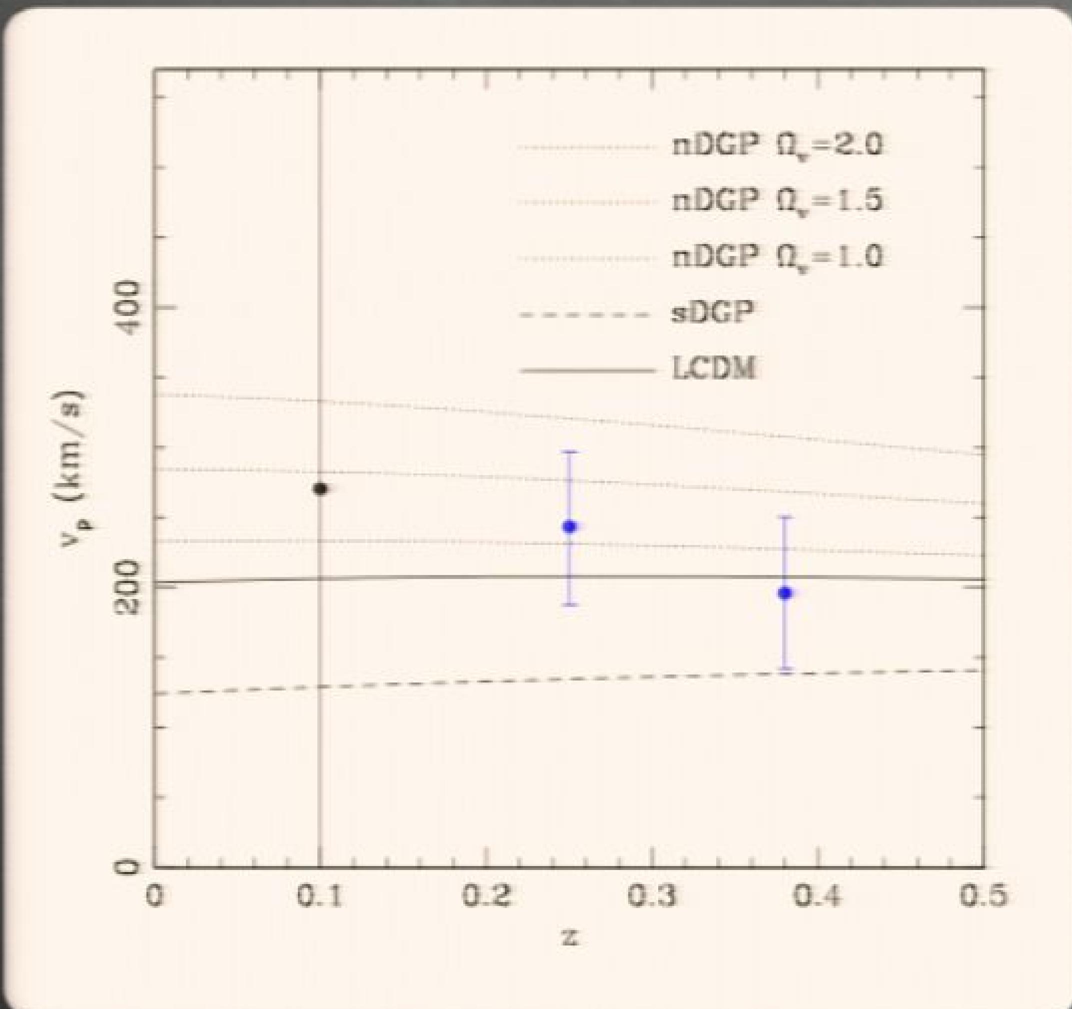


Wiggle Z

↕

YSS, Sahiu, Nichol (2010)

Unbiased history of LSS

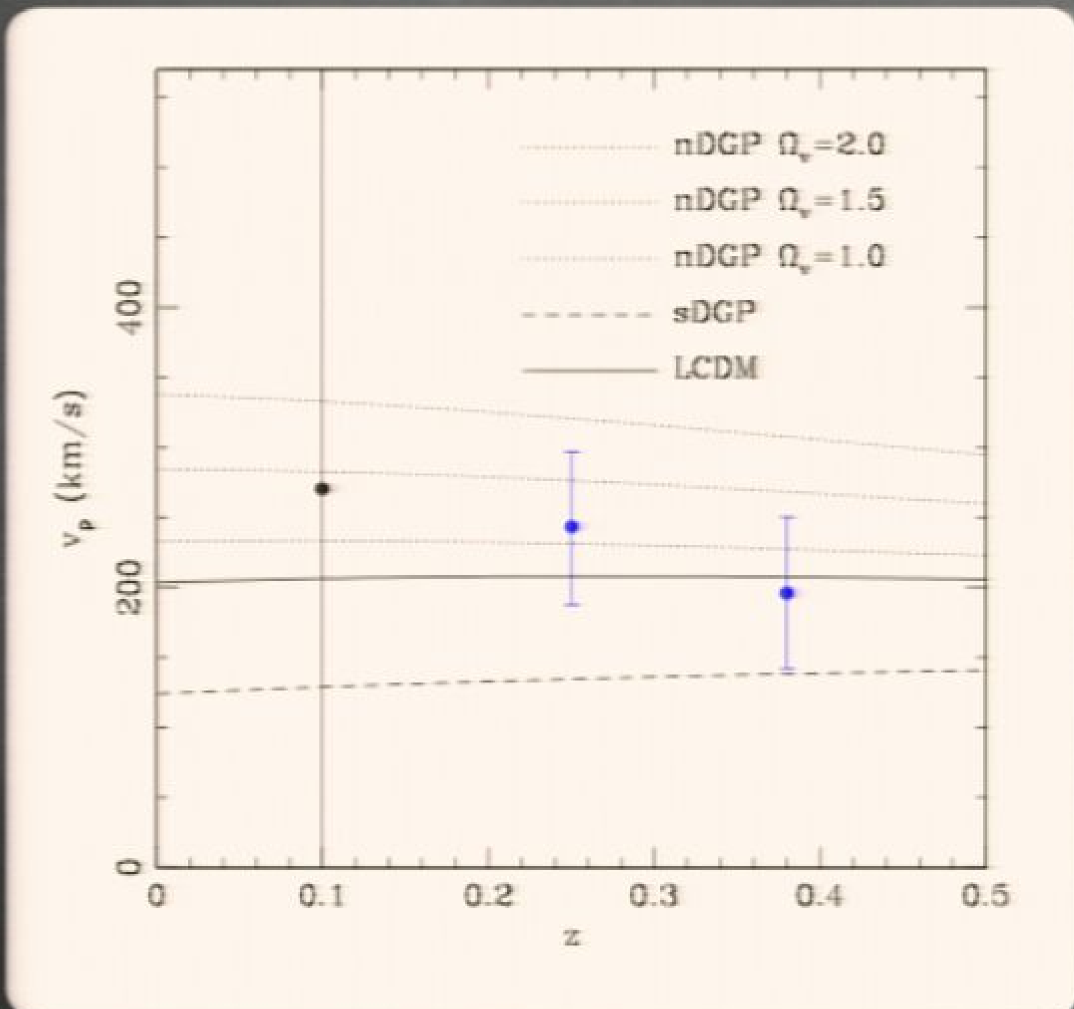


Slaq

Wiggle Z

YSS, Sahiu, Nichol (2010)

Unbiased history of LSS



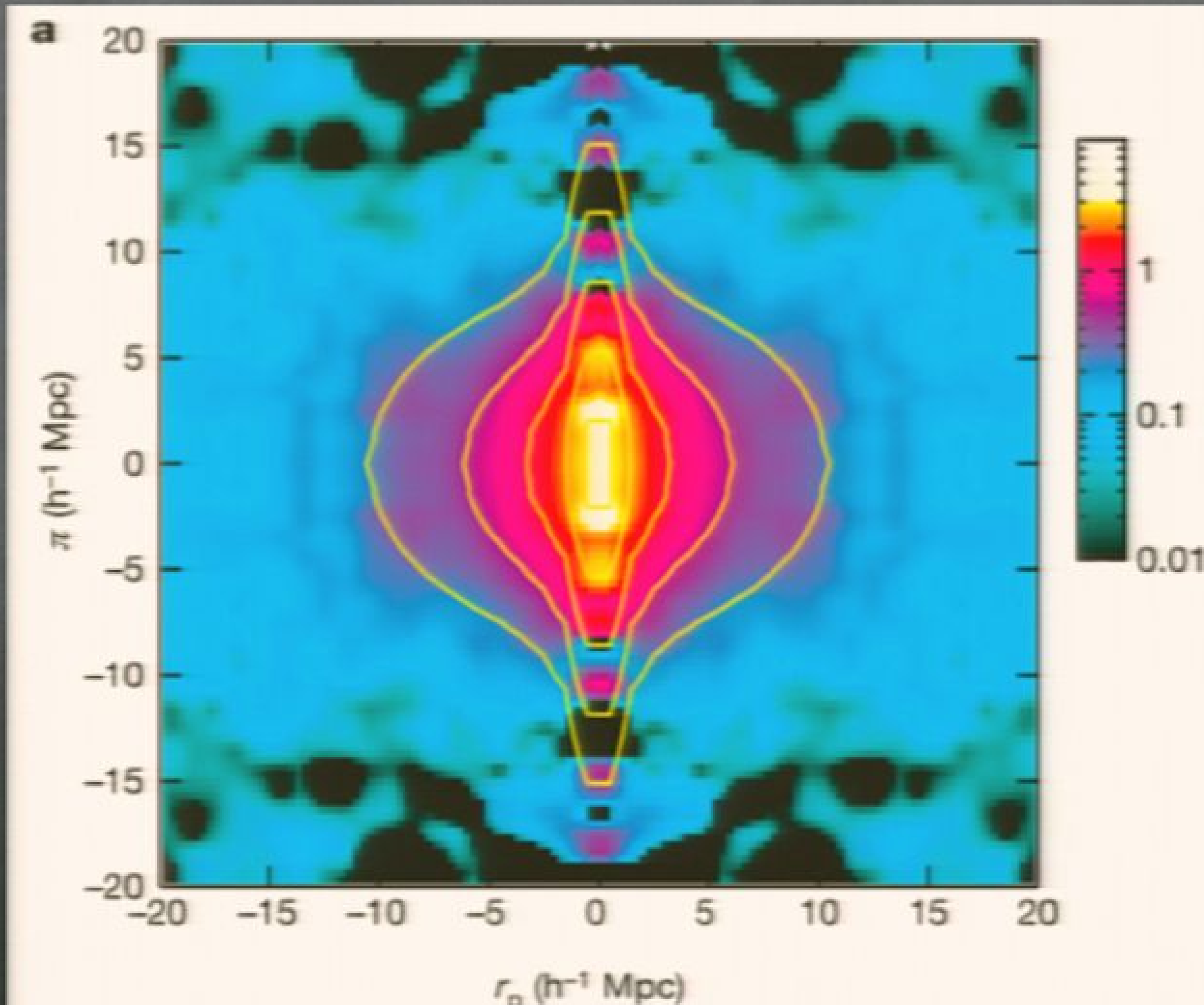
Slaq

Wiggle Z

...future

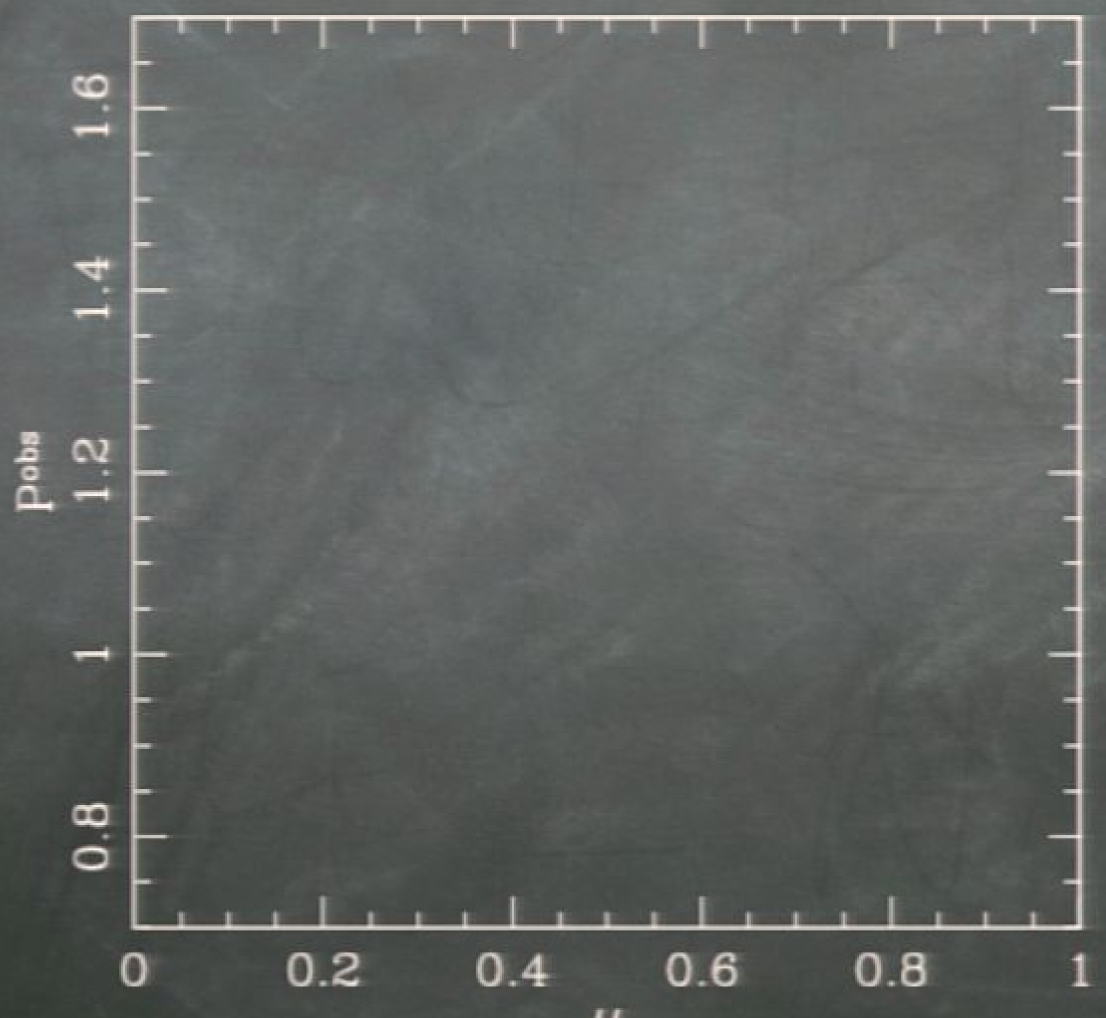
YSS, Sahni, Nichol (2010)

Optimizing redshift survey



Optimizing redshift survey

$$P^{obs}(k,\mu) = P_{gg} + 2\mu^2 P_{g\Theta} + \mu^4 P_{\Theta\Theta} \qquad (\Theta=\theta/aH)$$



Finger of God effect

$$P^{obs}(k,\mu) = (P_{gg} + 2\mu^2 P_{g\Theta} + \mu^4 P_{\Theta\Theta})\ G_{FoG}(k,\mu)$$

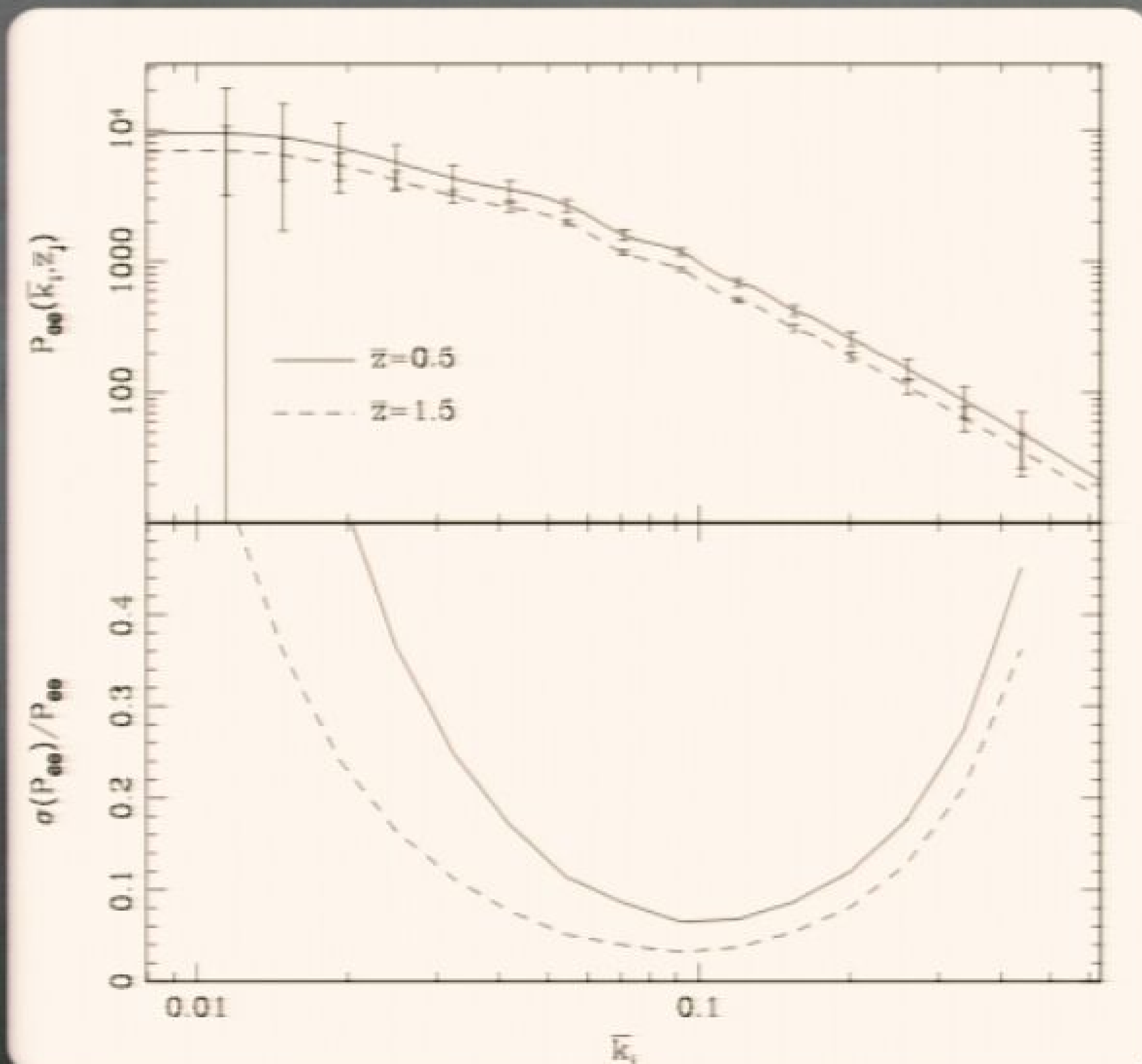
Finger of God effect

$$P^{obs}(k,\mu) = (P_{gg} + 2\mu^2 P_{g\Theta} + \mu^4 P_{\Theta\Theta})\ G_{FoG}(k,\mu)$$

We weight down the Fisher matrix at scales where FoG effect becomes non-negligible,

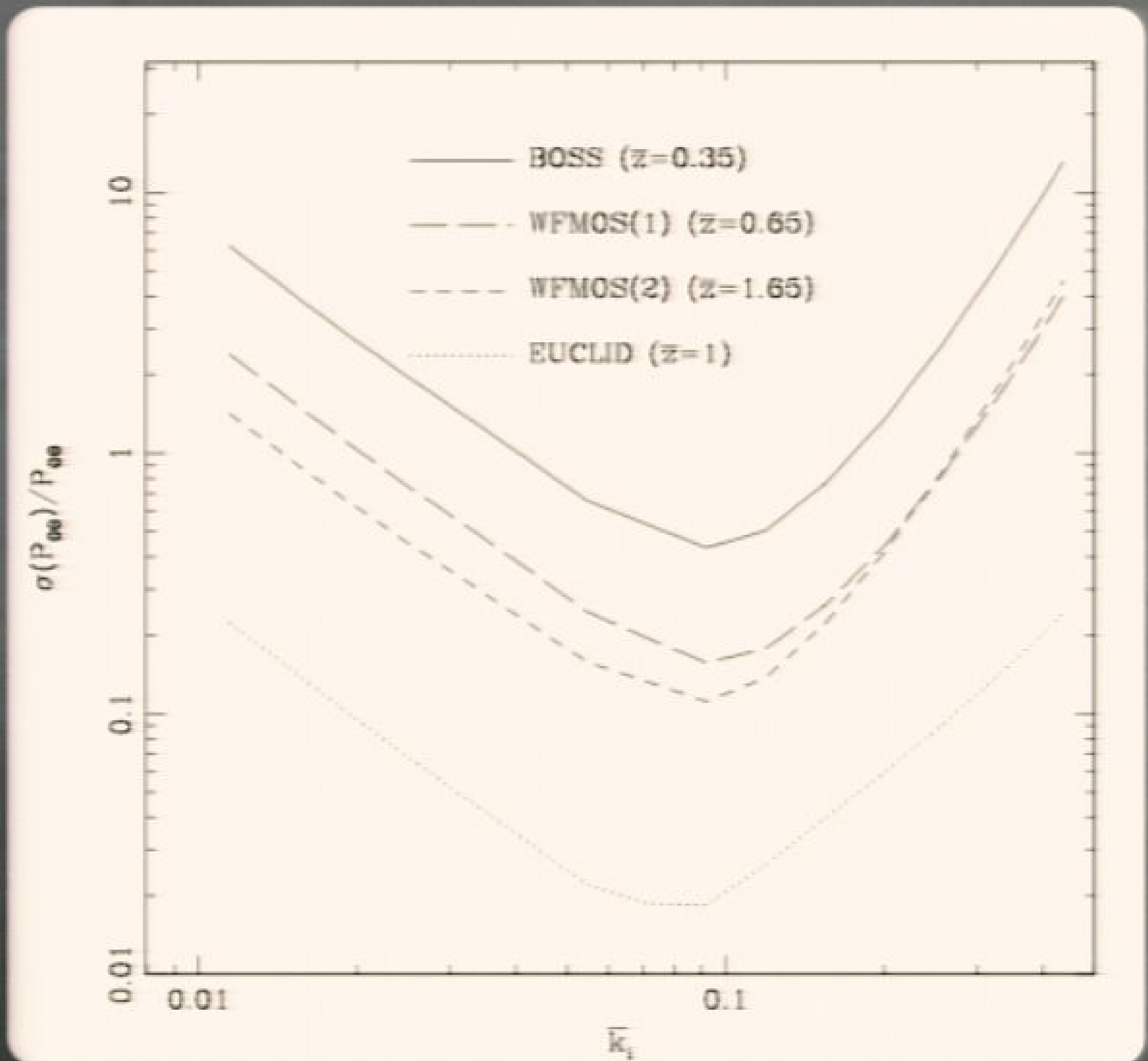
$$F_{ij} = 1/2 \int d^3k\ (\partial \ln P_{obs}/\partial p_i)\ (\partial \ln P_{obs}/\partial p_j)\ V_{eff}(k,\mu)\ w_{FoG}(k,\mu)$$

Estimated $P_{\Theta\Theta}$



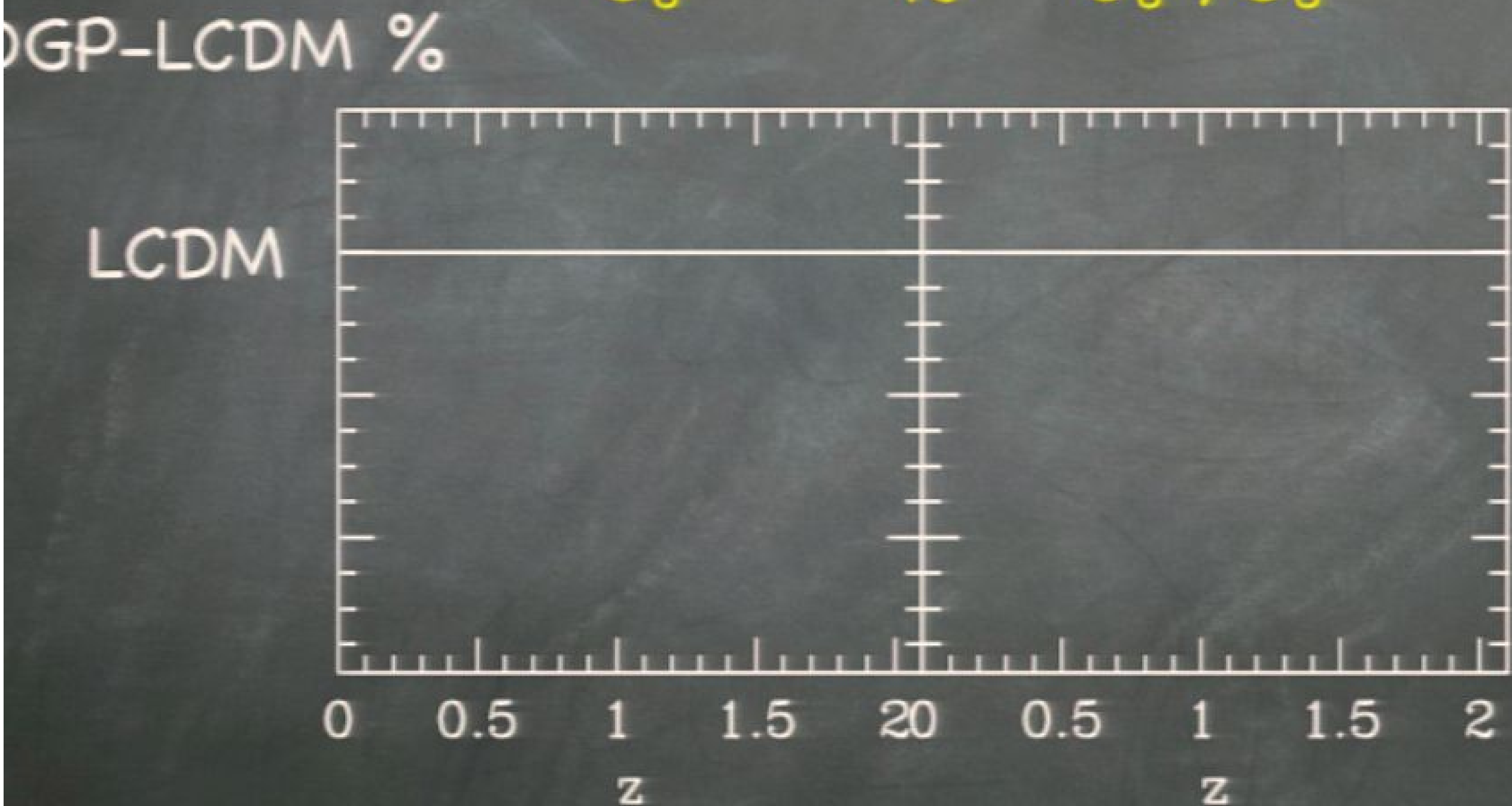
White, XSS, and Percival (2008)

Estimated $P_{\Theta\Theta}$



Constraint on DGP model

σ_8^θ vs $\sigma_8^\theta/\sigma_8^\delta$

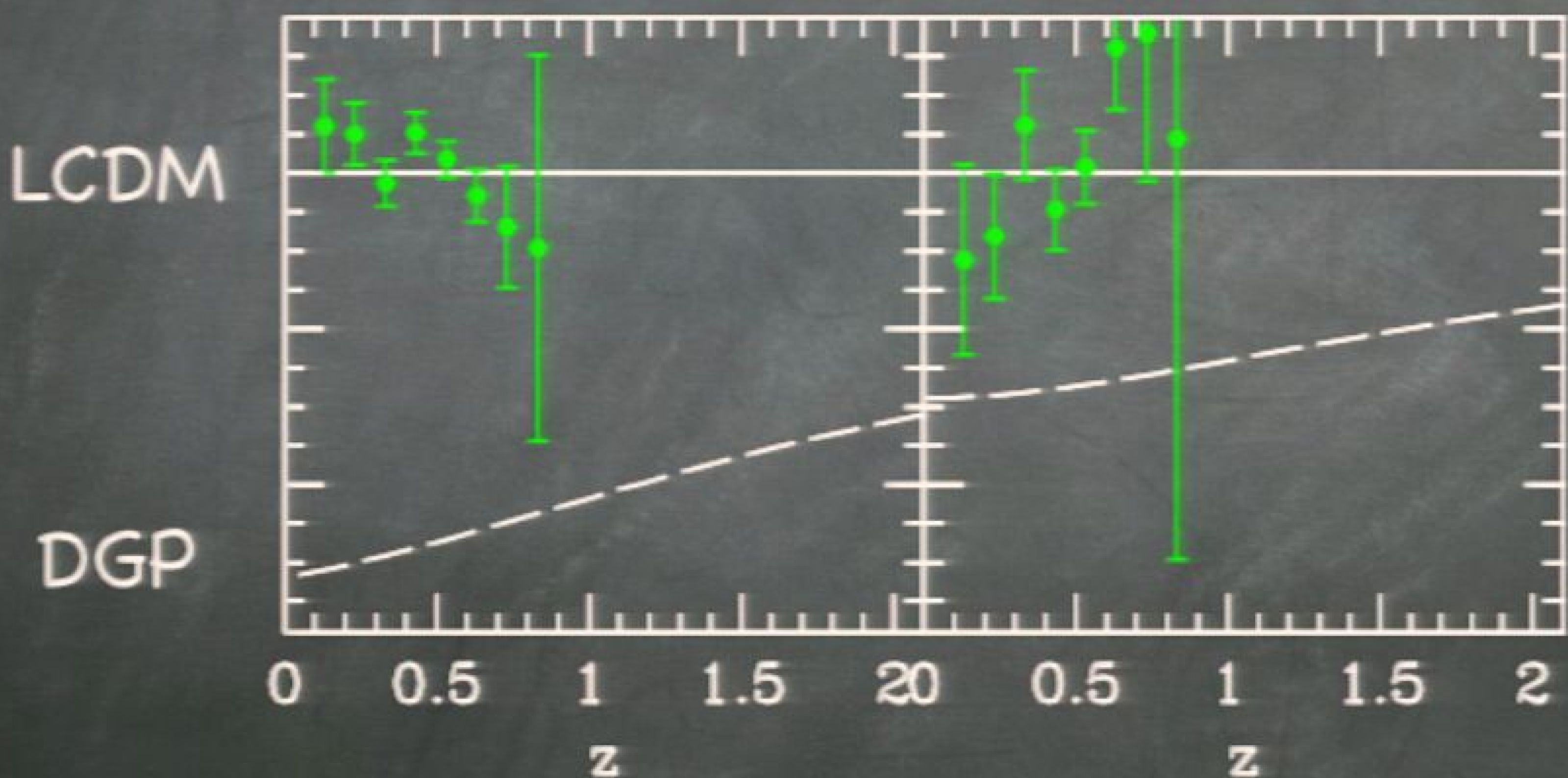


Guzzo et. al. (2008)
YSS and Percival (2008)

Constraint on DGP model

σ_8^θ vs $\sigma_8^\theta/\sigma_8^\delta$

DGP-LCDM %



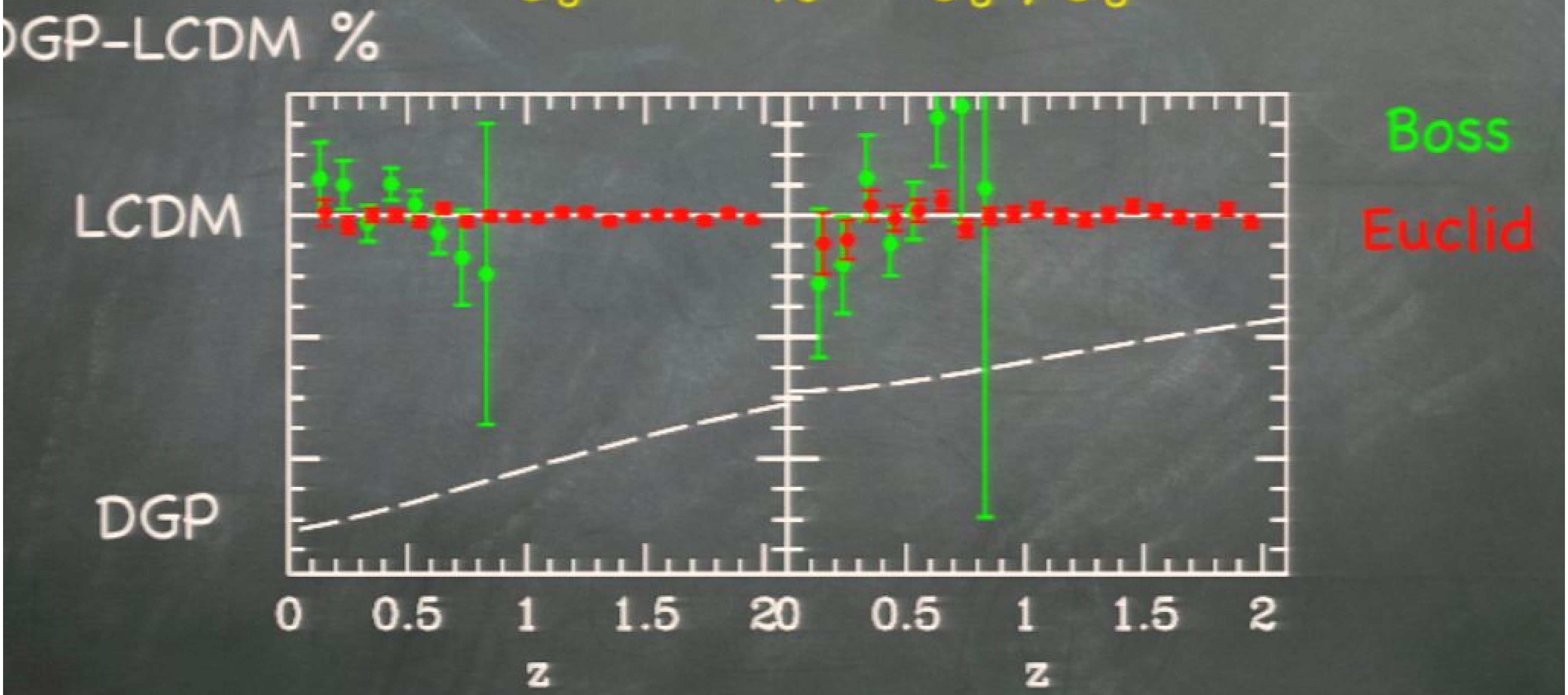
Boss

Guzzo et. al. (2008)

YSS and Percival (2008)

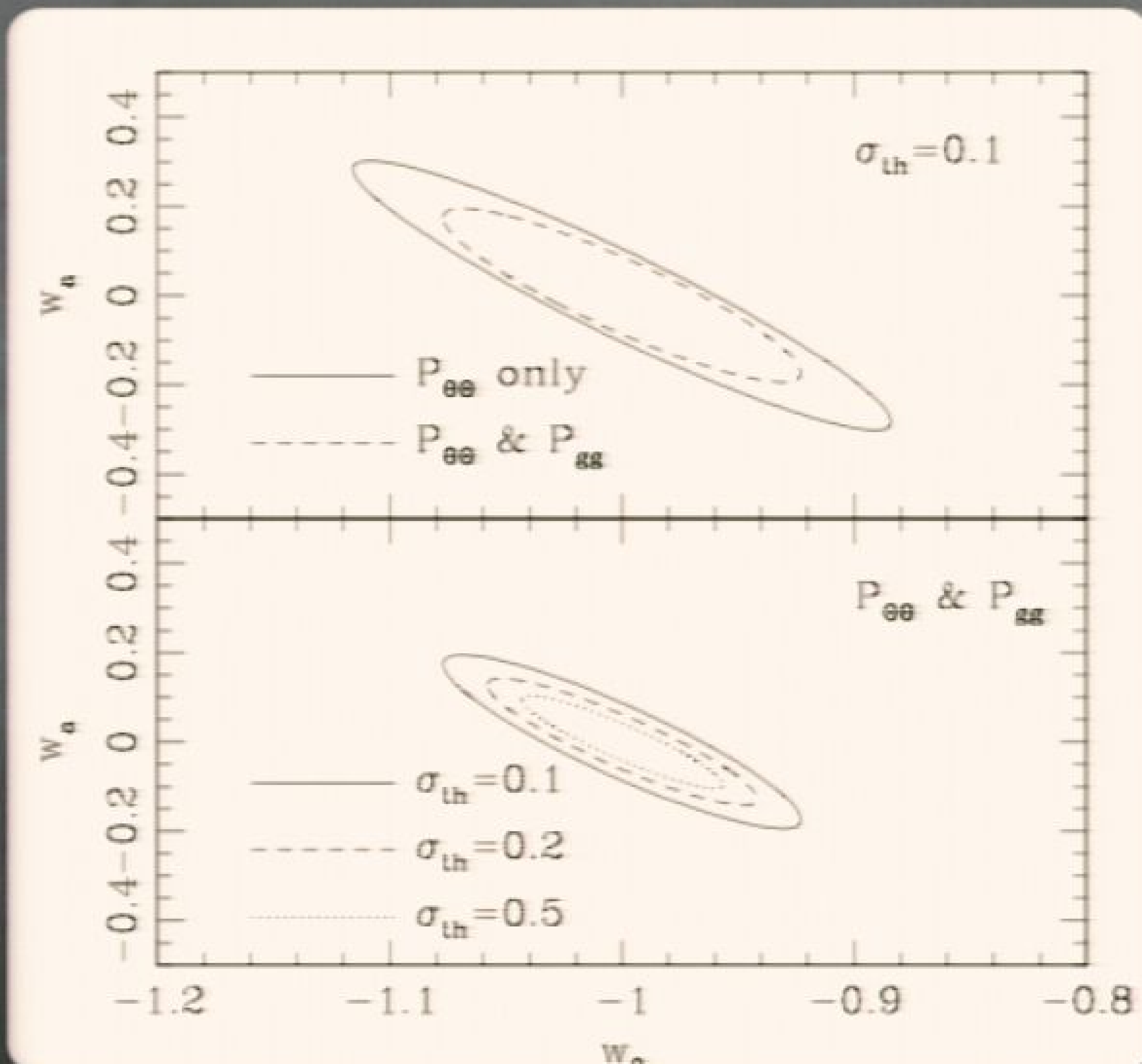
Constraint on DGP model

$\sigma_8{}^\theta$ vs $\sigma_8{}^\theta/\sigma_8{}^\delta$



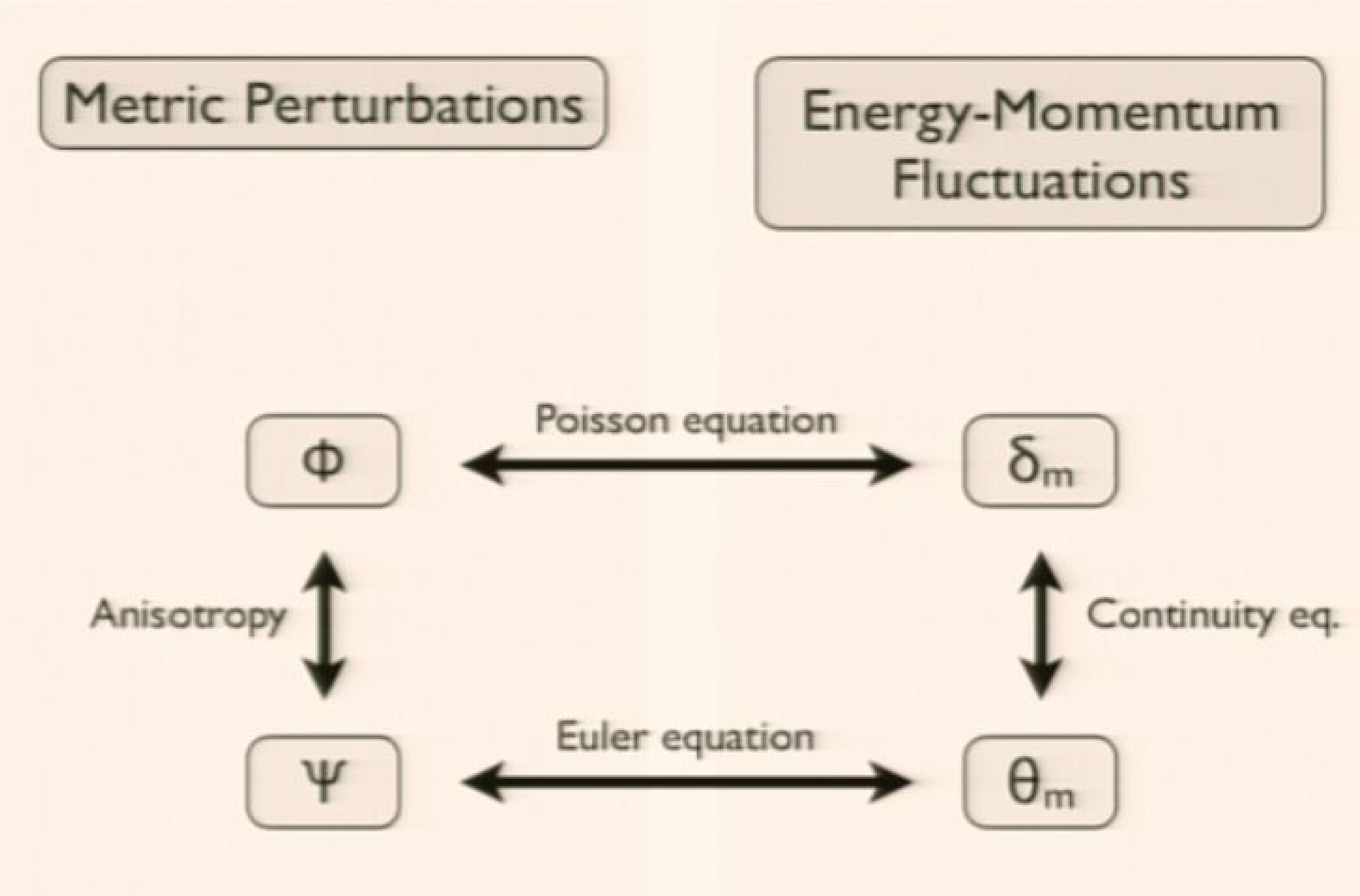
Guzzo et. al. (2008)
YSS and Percival (2008)

Combined constraint on DE



YSS (2010)

Consistency test of Weak Lensing



Non-dynamical test I: Integrated

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

$\Delta^2_{\Phi\Phi}$ $\quad C_l^{\delta_m \delta_m}$

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

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

YSS and Koyama (2008)

YSS and Dore (2008)

Non-dynamical test I: Integrated

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

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

$$C_l^{\kappa\kappa} = \sum \Delta D\, W'^2\, C_l^{\delta_m\delta_m}$$

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YSS and Koyama (2008)

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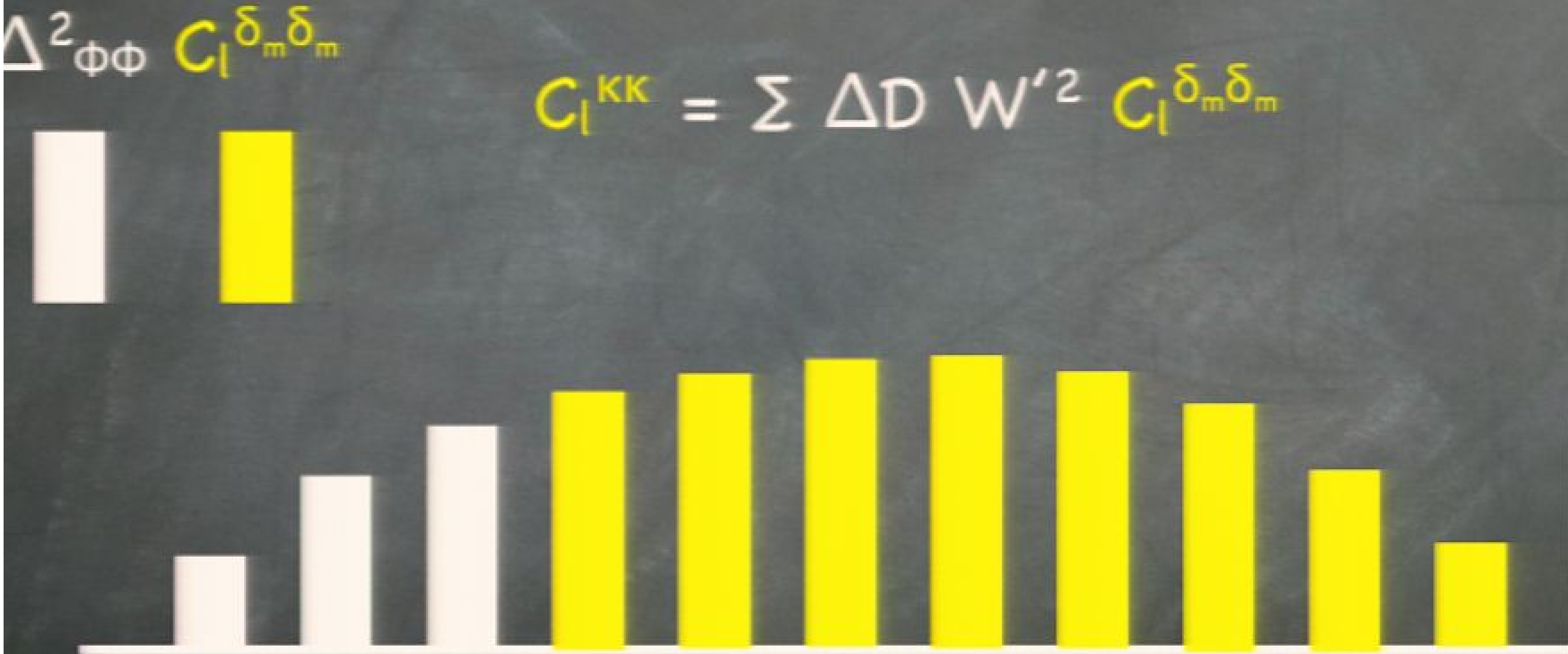
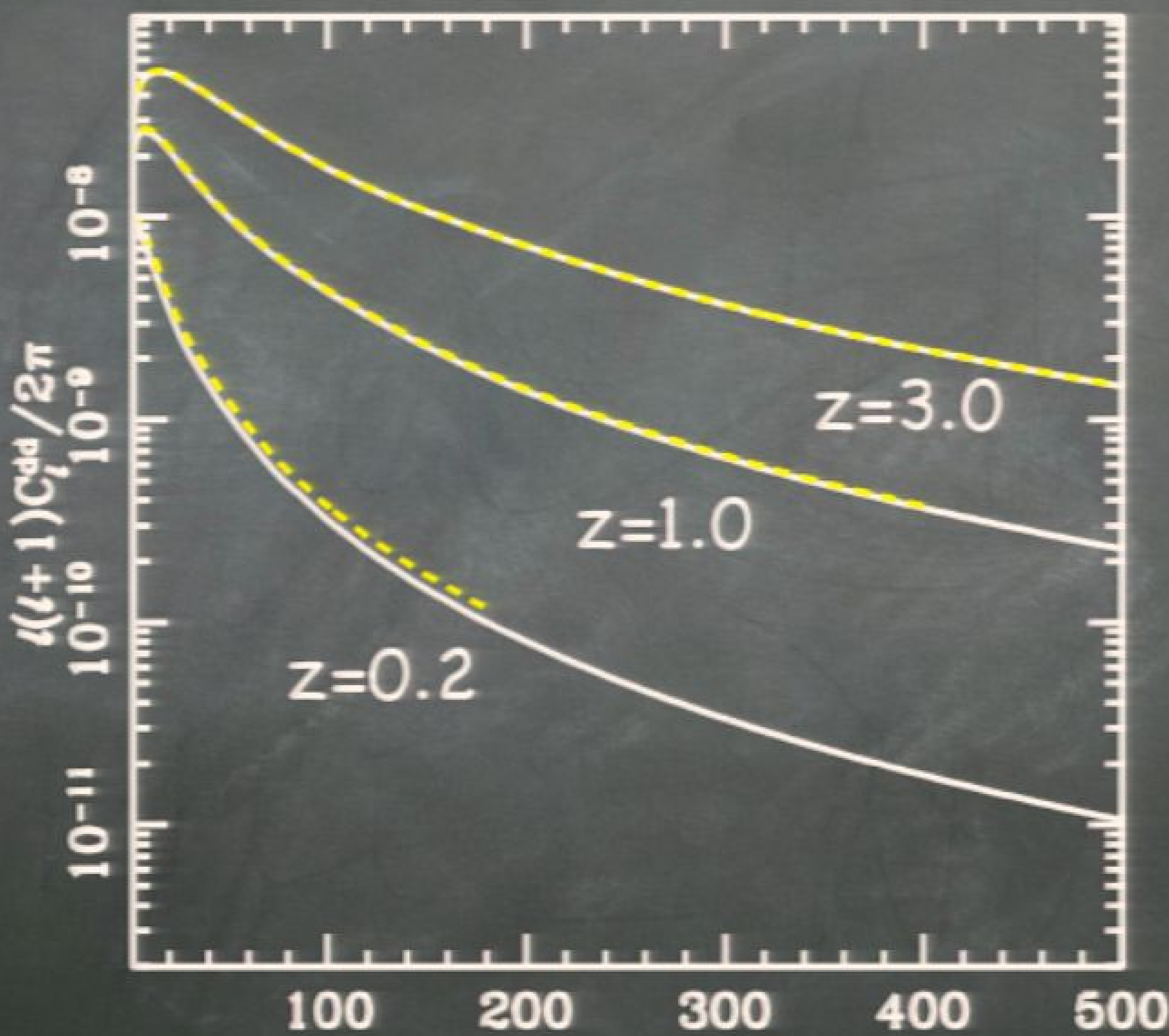


$$k^2\Phi = 4\pi G_N\, a^2\, \rho_m \delta_m$$

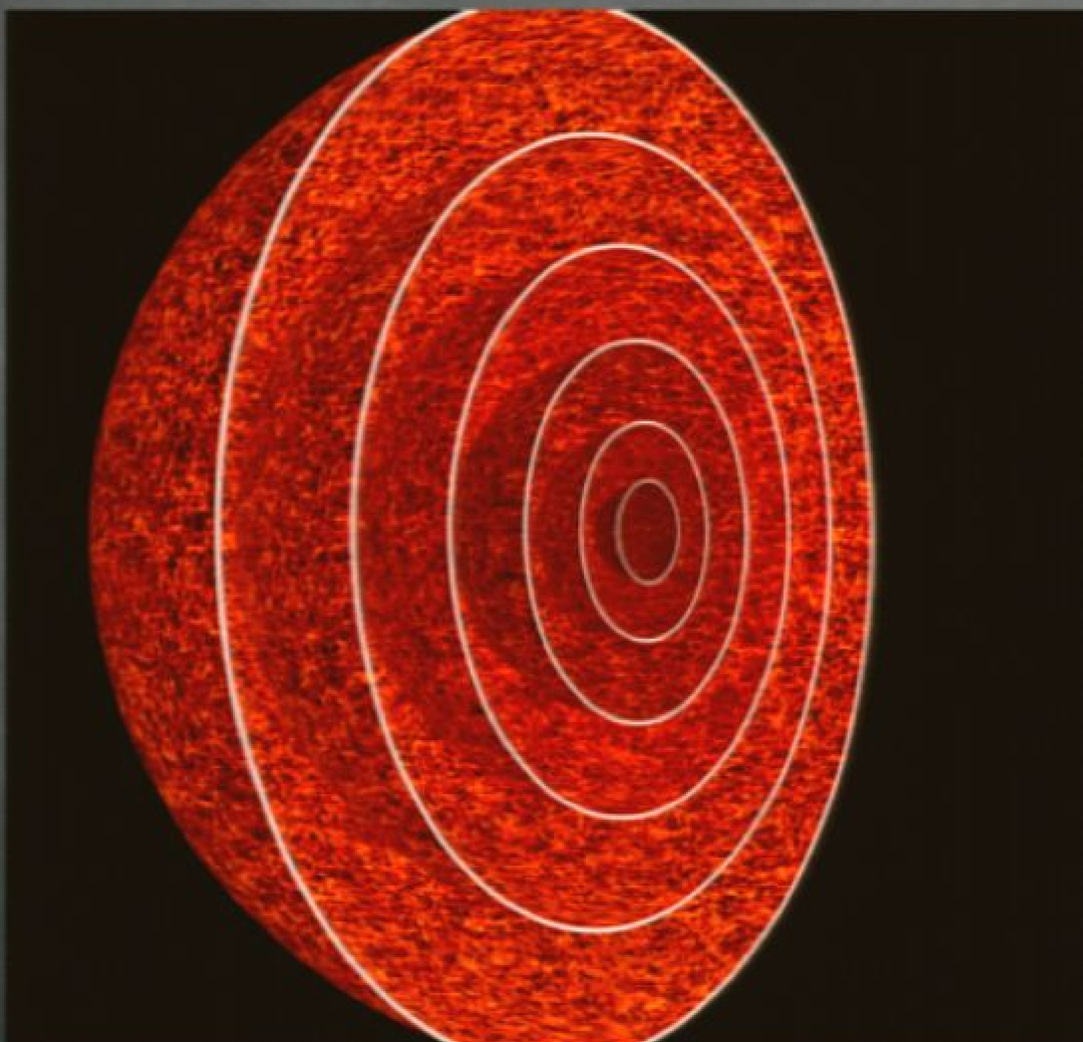
YSS and Koyama (2008)

YSS and Dore (2008)

Reconstruction of C_l^{dd}



Future work: using maps



$$\kappa_i = \Sigma_j \, w(i,j) \, \delta_j$$

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

Two faces of consistency test

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- When we trust systematic uncertainty of WL experiment: GR test

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- Recommendation for future survey design targeting to probe structure formation: It should do both WL and redshift surveys

Two faces of consistency test

- When we trust systematic uncertainty of WL experiment: GR test
- When we believe GR priors strongly: WL systematic uncertainty test
- Recommendation for future survey design targeting to probe structure formation: It should do both WL and redshift surveys
- With this consistency test, we can trust our constraints on cosmic acceleration in better way

Conclusion

- **Extended cosmological parameter space**
  - The measured Σ and μ constrain theoretical models more strongly
  - I develop tools to constrain Σ and μ with WL and peculiar velocity
- **Peculiar velocity**
  - Developing statistical determination of peculiar velocity
  - I complete evolution of structure formation using pv
  - Extracting pv from N-body map to know the optimized set-up
- **Optimizing redshift survey**
  - I propose new way to optimize redshift survey
  - Reconstructing Newtonian potential & bias in model independent way
- **Consistency test of WL survey**
  - Testing with mocking maps
  - Developing this technique to test systematic of WL survey