Clustering Wedges:
An Alternative Approach to Measuring $H(z)$ and $D_A(z)$

Eyal Kazin

In collaboration with:
Tamara **Davis**, Chris **Blake**, Ariel **Sánchez**

CAASTRO ARC CENTRE OF EXCELLENCE FOR ALL-SKY ASTROPHYSICS

SWINBURNE UNIVERSITY OF TECHNOLOGY

Sunday, August 5, 2012

What you will get from this talk

- For the **non-expert**:
  - How we **measure** the **geometry** of the Universe with galaxy clustering
  - In other words: the Alcock-Paczynski test on the Baryonic Acoustic Feature to constrain **$H(z)$, $D_A(z)$**
- For the **expert**:
  - practical aspects of **binning** your correlation functions: Multipoles, **Wedges**, RR(μ)

Credits

For usage of data, mock catalogues:
Marc **Manera**, Cameron **McBride**, The Sloan Digital Sky Survey, The WiggleZ Dark Energy Survey

The WiggleZ Group

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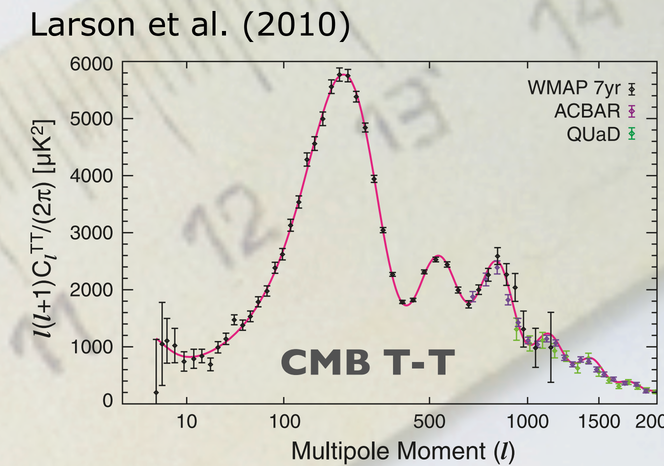
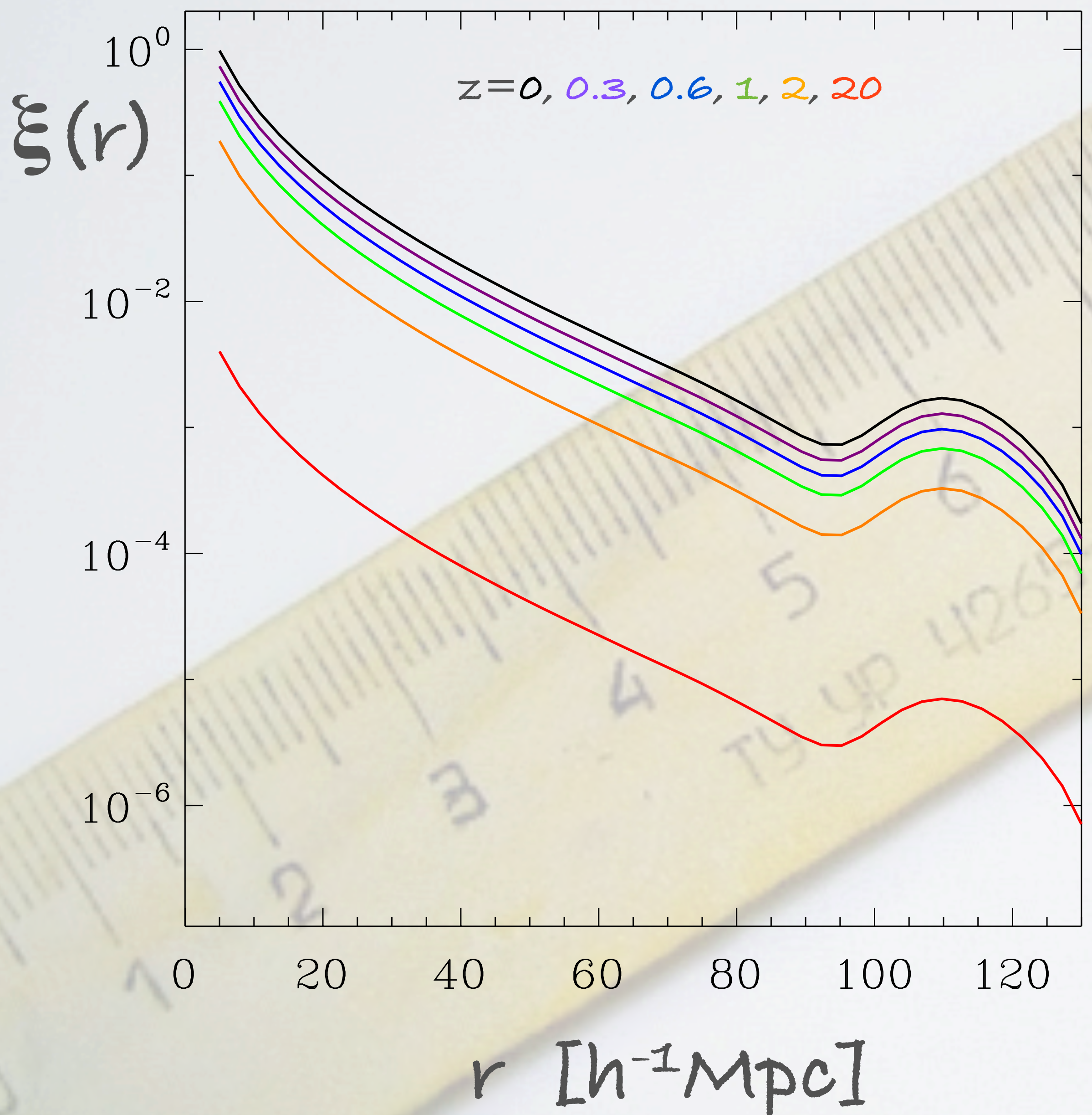
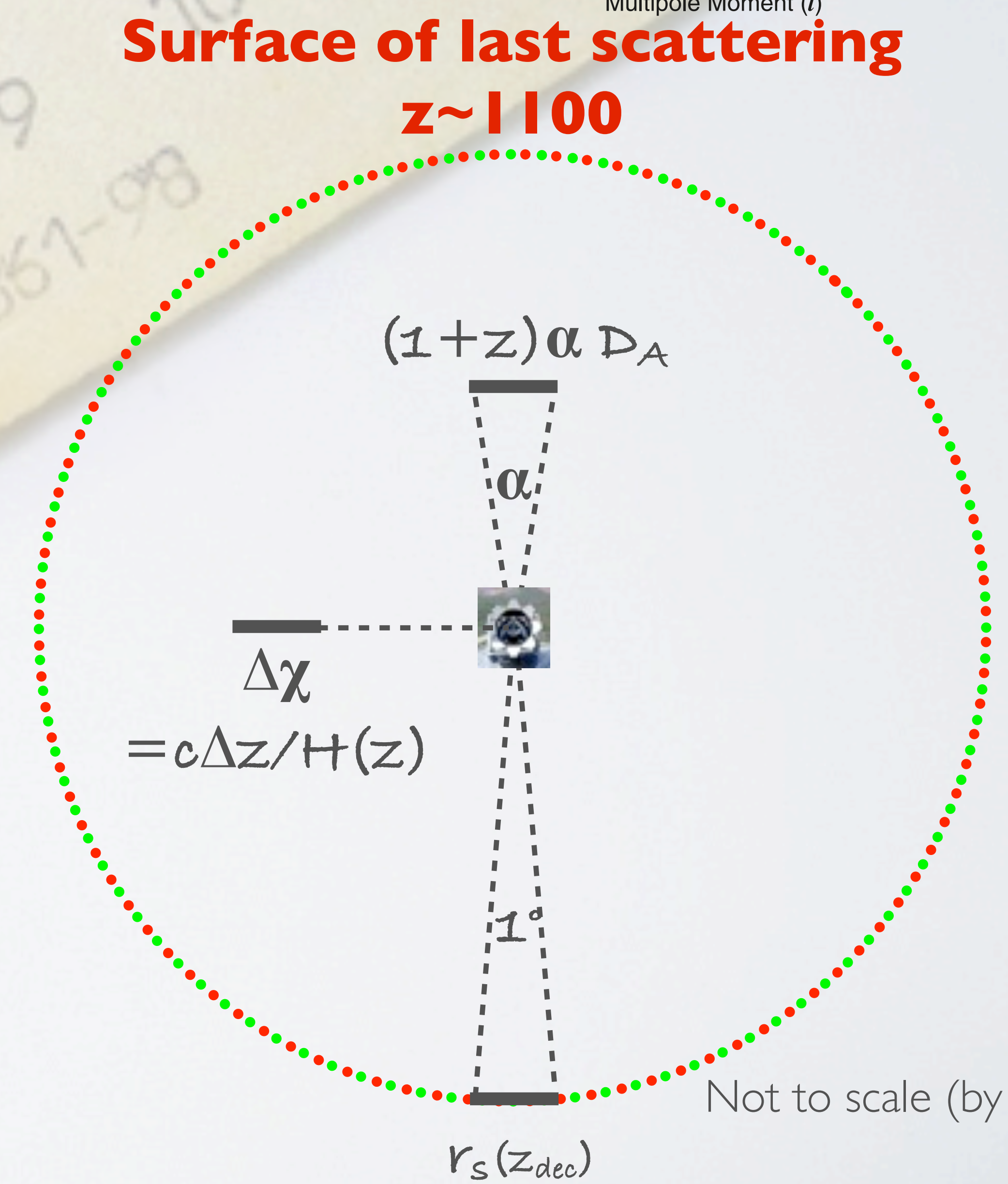
The Sloan Digital Sky Survey

The Baryonic Acoustic Feature as a Standard Ruler



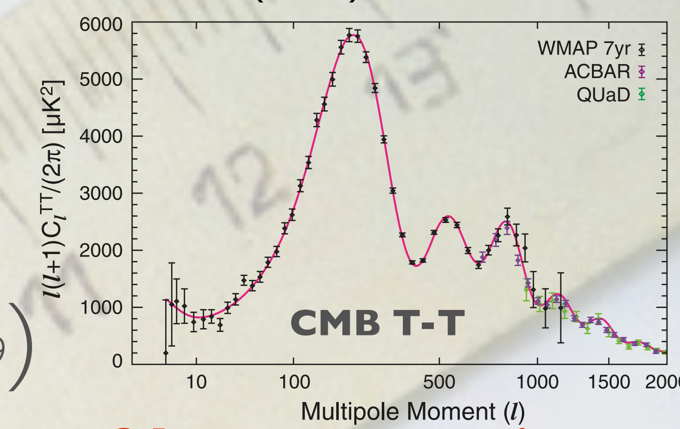




Not to scale (by far!)

The Baryonic Acoustic Feature as a Standard Ruler

- Early Universe (z_{dec}~1090):
  CMB temp fluctuations determines
  r_s~147 Mpc ($\delta r_s/r_s$ ~1.3%; WMAP-5 Komatsu et al. 2009)

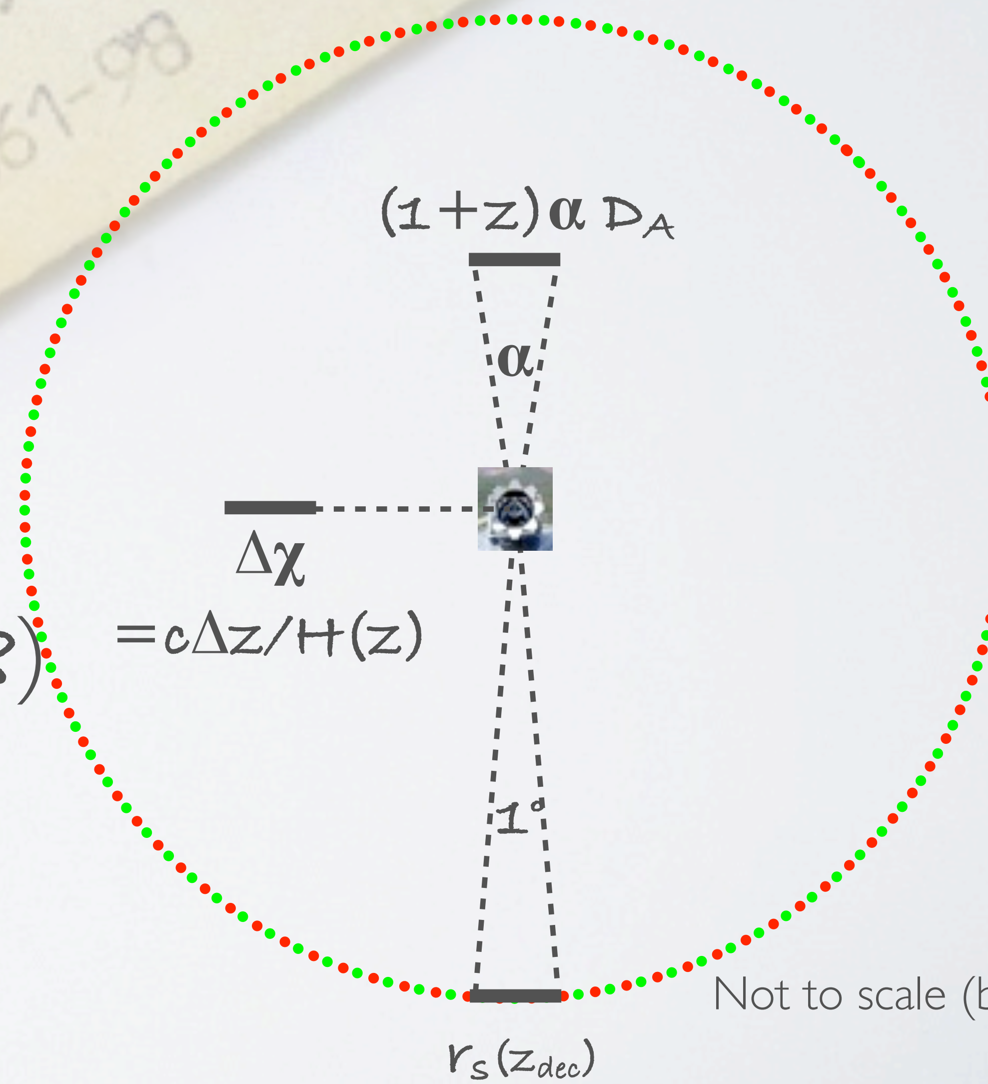


- Late Universe :
  SDSS-II, -III
  LRGs (z~ 0.3, 0.6)
  QSOs Lyman-α Forest (z>2.5)

  Wiggle-Z
  Blue Galaxies (z~ 0.2, 0.4, 0.6, 0.8)

  Galaxy Clusters

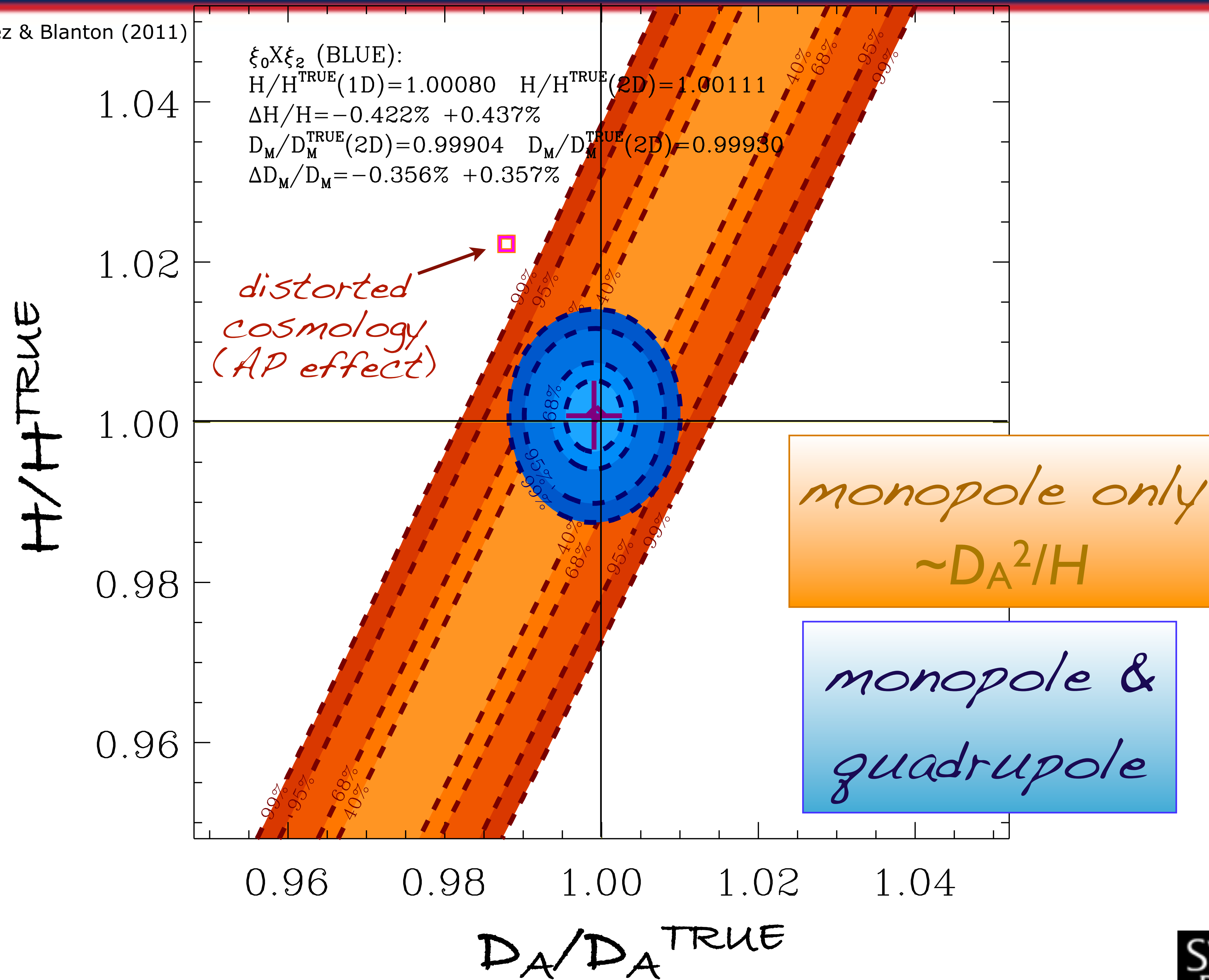
Surface of last scattering
z~1100



Not to scale (by far!)

Beyond the Monopole: The Importance of Anisotropic Clustering

Kazin, Sánchez & Blanton (2011)



An Apology

I am not going to
show BOSS clustering Wedges
results today. (but stay tuned ..)

Most of the plots here are from
mock catalogues.

Today's Talk

- z-distortions in practice: a brief practical recap
- There is information in the Hexadecapole $\xi_4(s)$
- In with the new (basis): Clustering Wedges $\xi(\Delta\mu,s)$
- Time Permitting: $N_{RR}(\mu) \neq$ constant

Redshift Distortions: Dynamical and Geometrical

Dynamical: squashing (kaiser 1987), Finger of God

comoving distance

$$\chi(z) = c \int_0^{z_{obs}} \frac{dz'}{H(z',\Omega)}$$

Geometrical: AP effect (Alcock&Paczynski 1979)

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The Alcock-Paczynski Effect

In the **anisotropic** Baryonic Acoustic Feature

$$\mathbf{H \times D_A}$$

$$r_1 = c\Delta z / H(z)$$

$$r_2 = (1+z) D_A(z) \Theta$$

$$r_1 = r_2$$

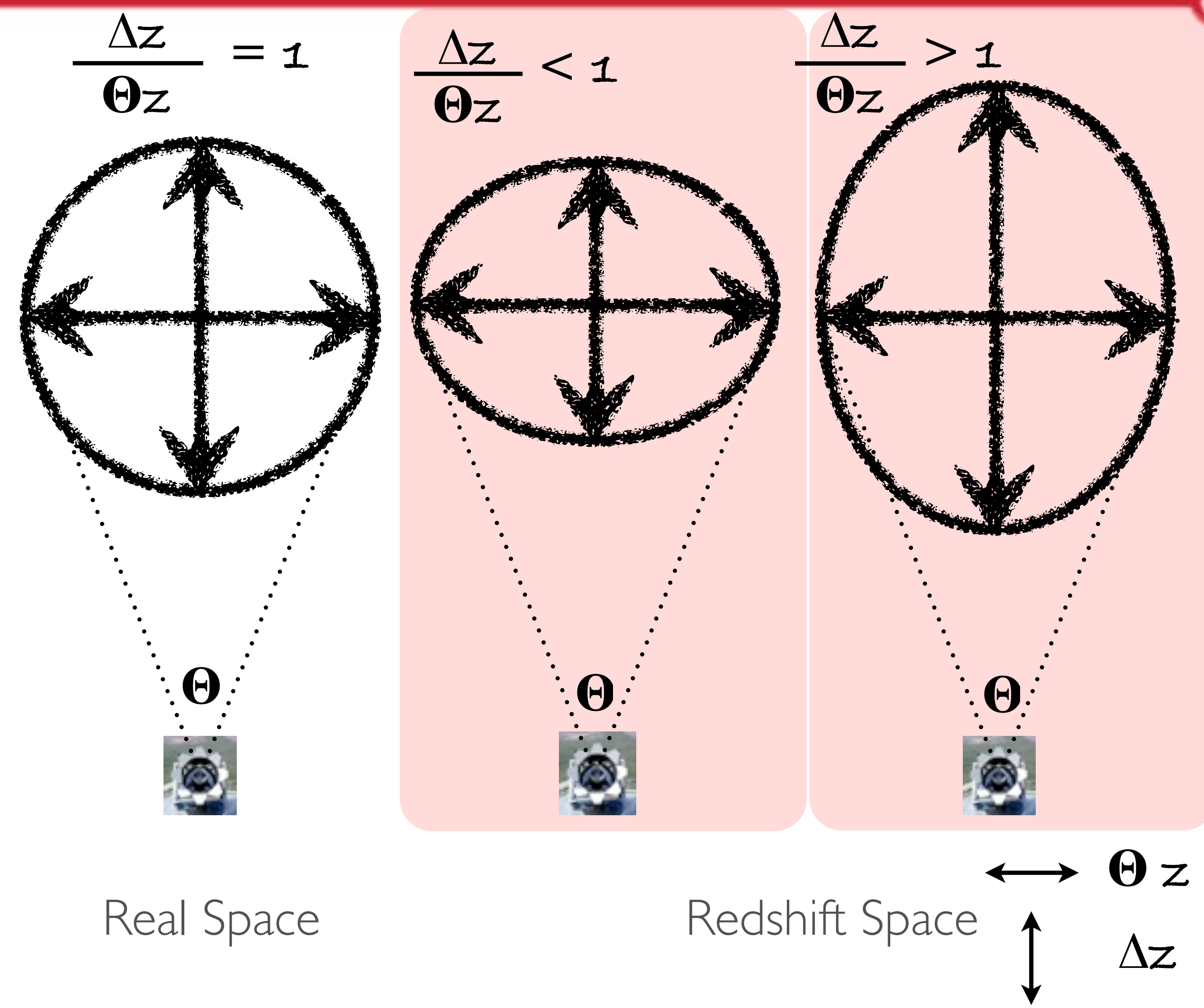
$$H \times D_A = c\Delta z / (1+z) / \Theta$$

In the **isotropic** Baryonic Acoustic Feature

$$\mathbf{D_A^2 / H}$$

$$d^3 s = \alpha d^3 s^D$$

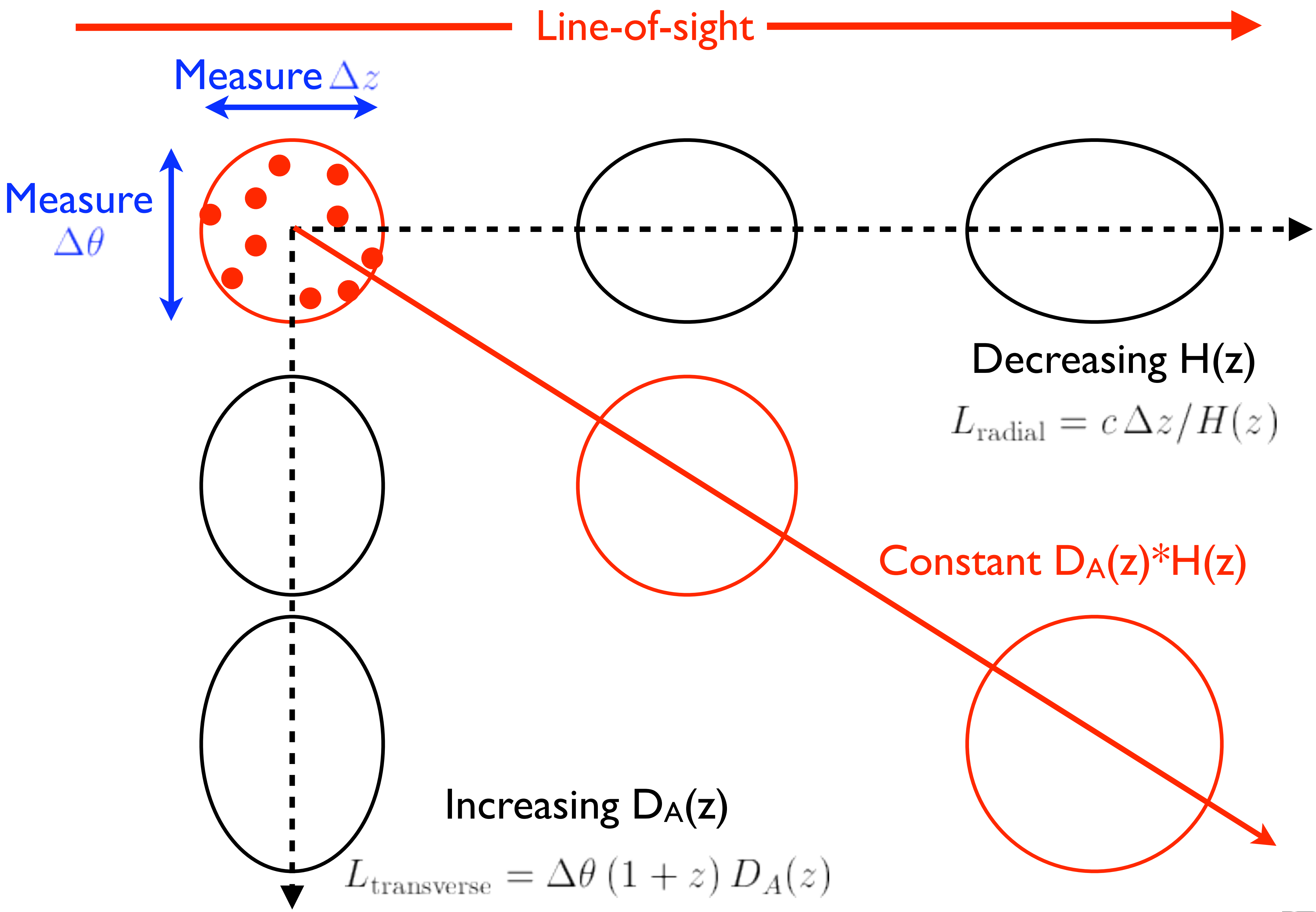
$$\alpha = \left(\frac{H^{\mathcal{D}}}{H}\right)^{1/3} \left(\frac{D_A}{D_A^{\mathcal{D}}}\right)^{2/3}$$



$$\frac{\Delta z}{\Theta z} = z^{-1}[\Omega_\Lambda + \Omega_{M0}(1+z)^3]^{1/2} \int_1^{z+1} dy \, (\Omega_\Lambda + \Omega_{M0} y^3)^{-1/2}$$

The Alcock-Paczynski Effect

Plot Credit: Chris Blake



Timely Jargon

z-distortions: General term for both types of distortions. Not solely Dynamical!

Dynamical:

Squashing (kaiser 1987), Non-linear etc..

Finger of God (velocity dispersion effect)

Geometrical:

Alcock-Paczynski effect (Alcock&Paczynski 1979)

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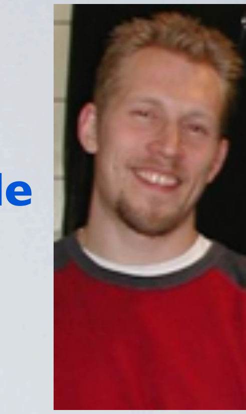
LasDamas Mock Simulations

McBride et al.; in prep.

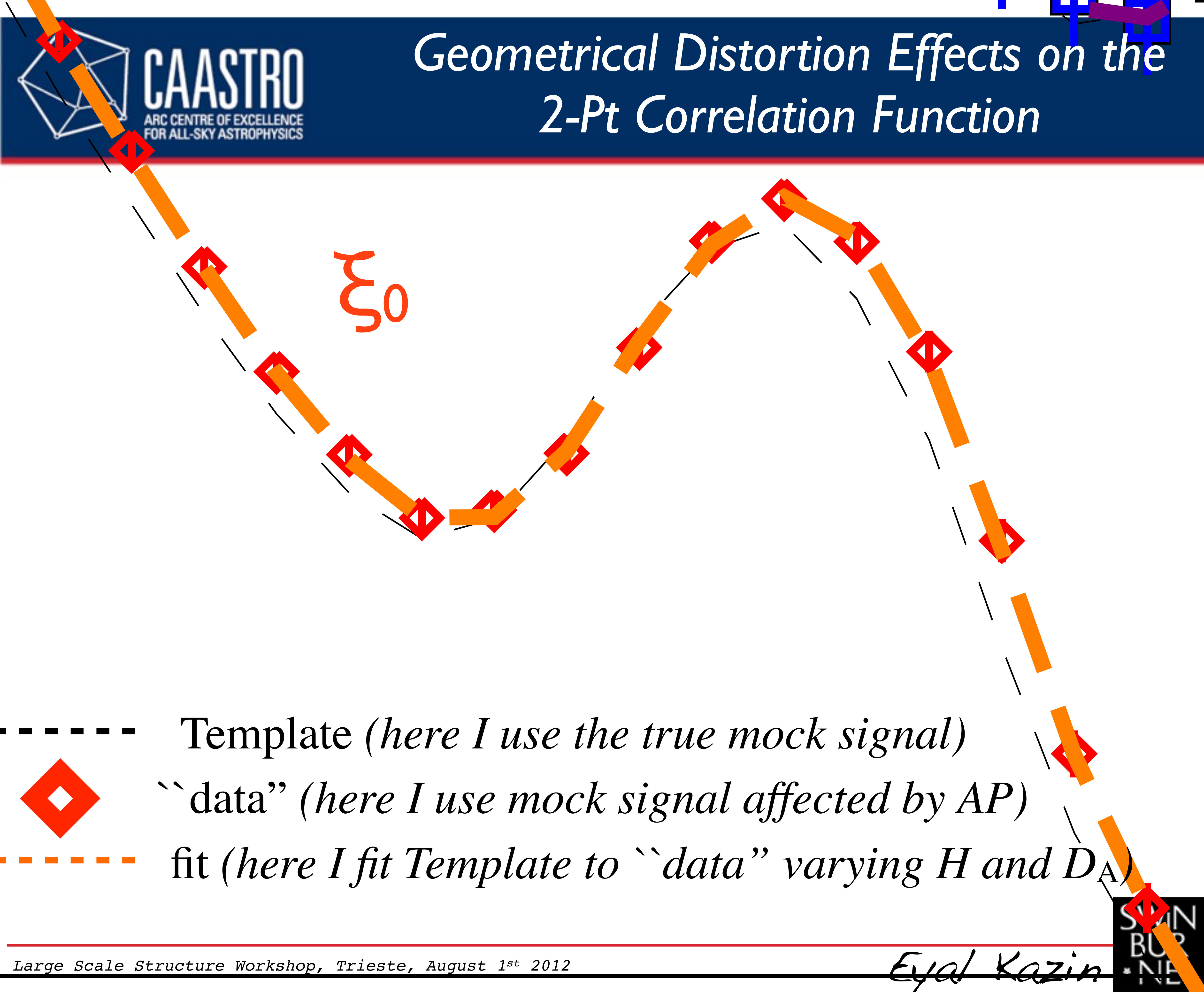
Andereas Berlind
Michael Busha
Jeff Gardner
Cameron McBride
Román Scoccimarro
Frank van den Bosch
Risa Wechsler



- **LA**rge **S**uite of **DA**rk **MA**tter **S**ims
- Emphasize on many observational effects
- Results in **most realistic uncertainties** of clustering of the SDSS-II LRGs

public mocks: **http://lss.phy.vanderbilt.edu/lasdamas/**

Geometrical Distortion Effects on the 2-Pt Correlation Function



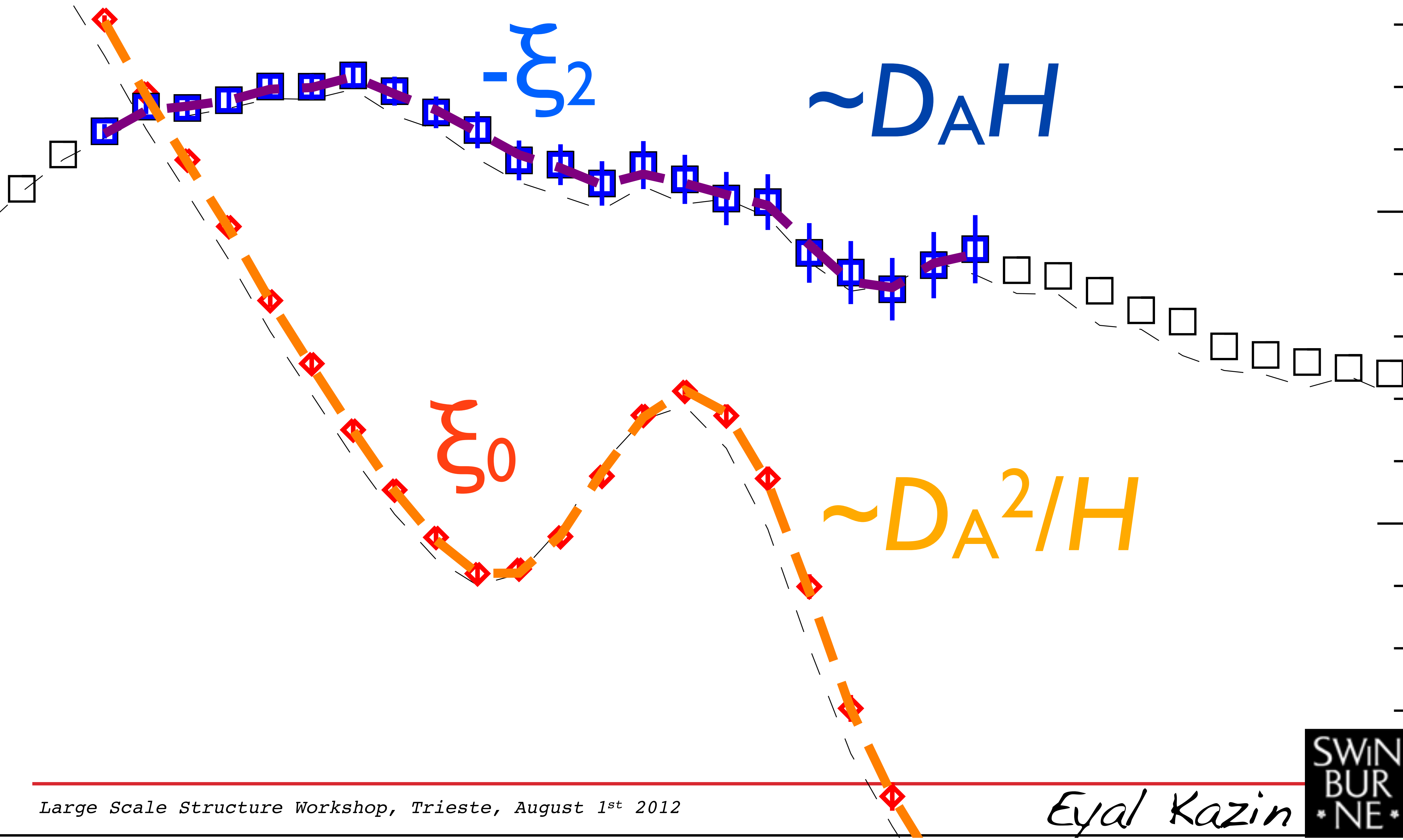
Template *(here I use the true mock signal)*

``data" *(here I use mock signal affected by AP)*

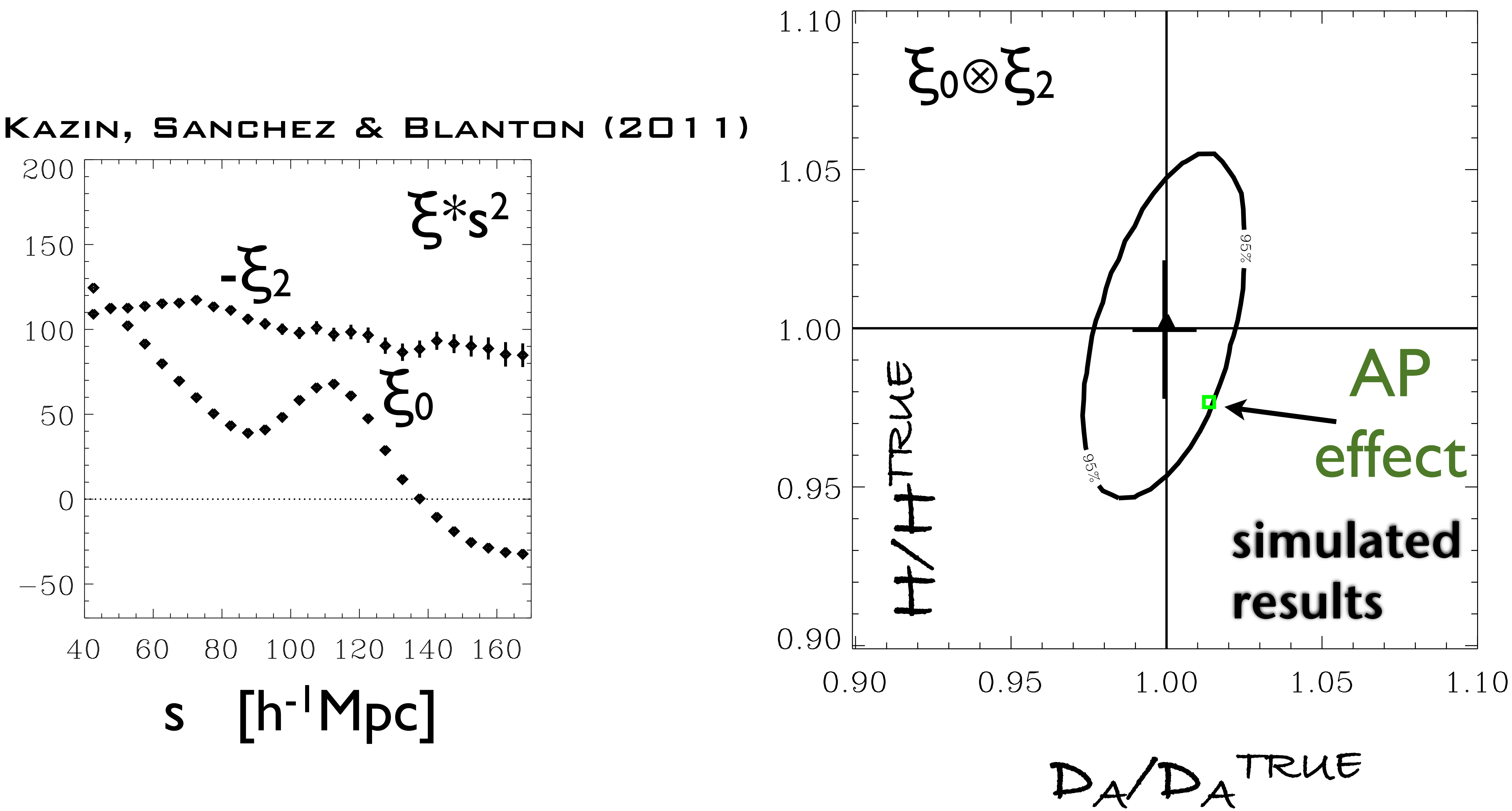
fit *(here I fit Template to ``data" varying H and D_A)*

Geometrical Distortion Effects on the Clustering Multipoles

For the mathematically inclined:
Padmanabhan & White (2008)

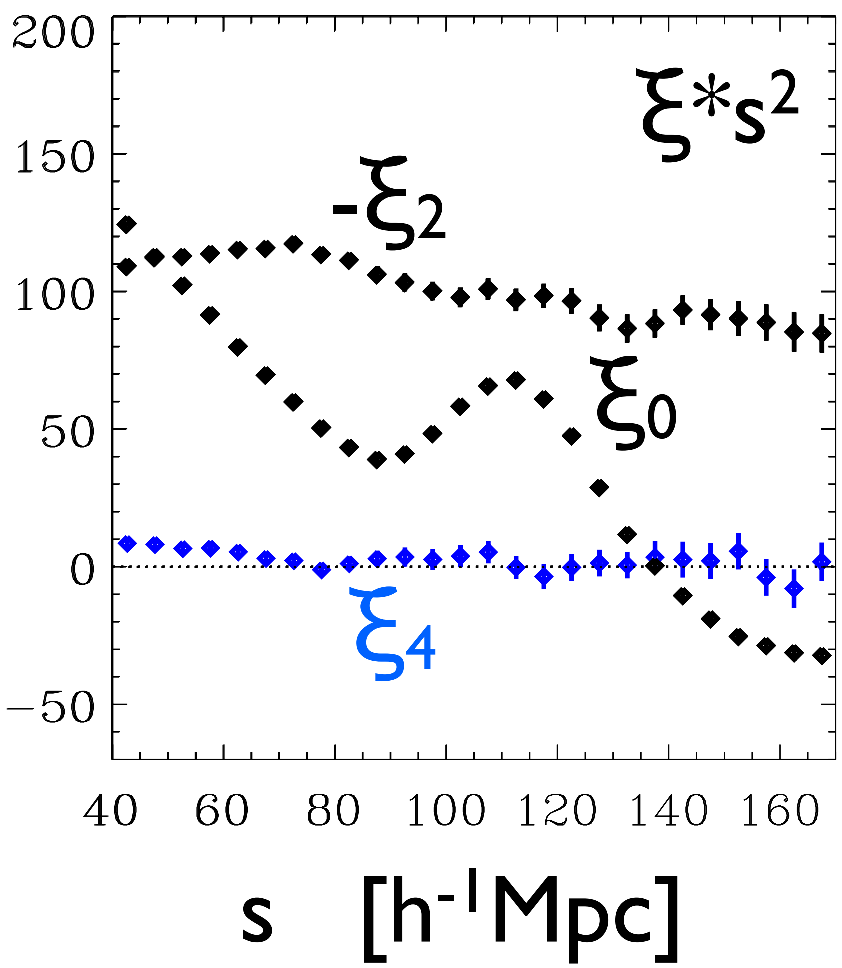


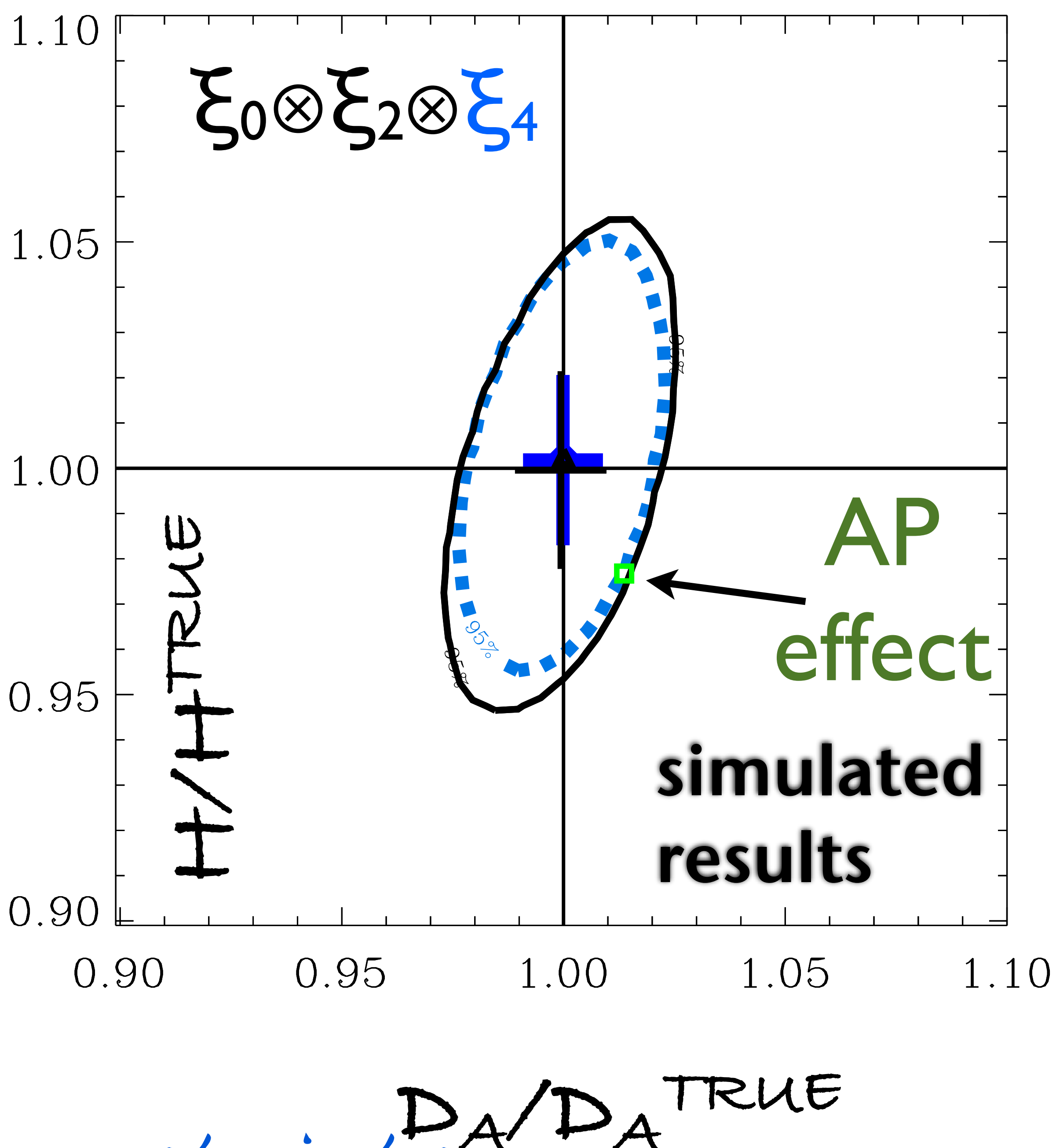
Extra Information from the Hexadecapole



Extra Information from the Hexadecapole

Kazin, Sanchez & Blanton (2011)



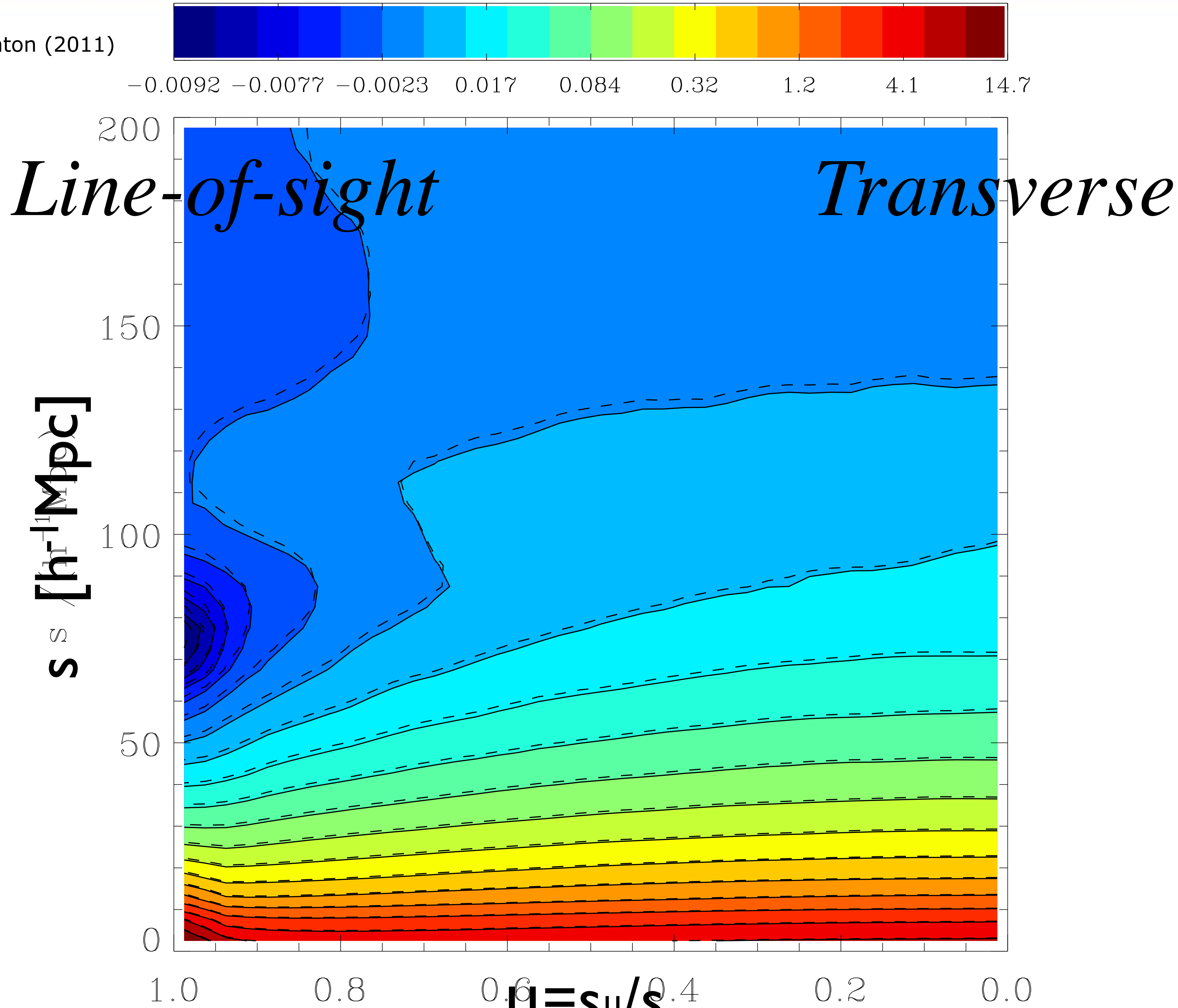


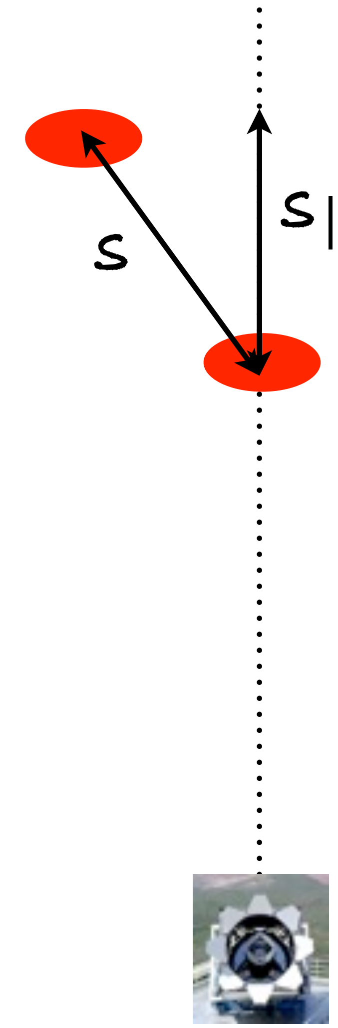
Hexadecapole ξ_4 improves constraints

(See also Taruya et al. 2011)

The 2D Clustering Plane $\xi(\mu,s)$

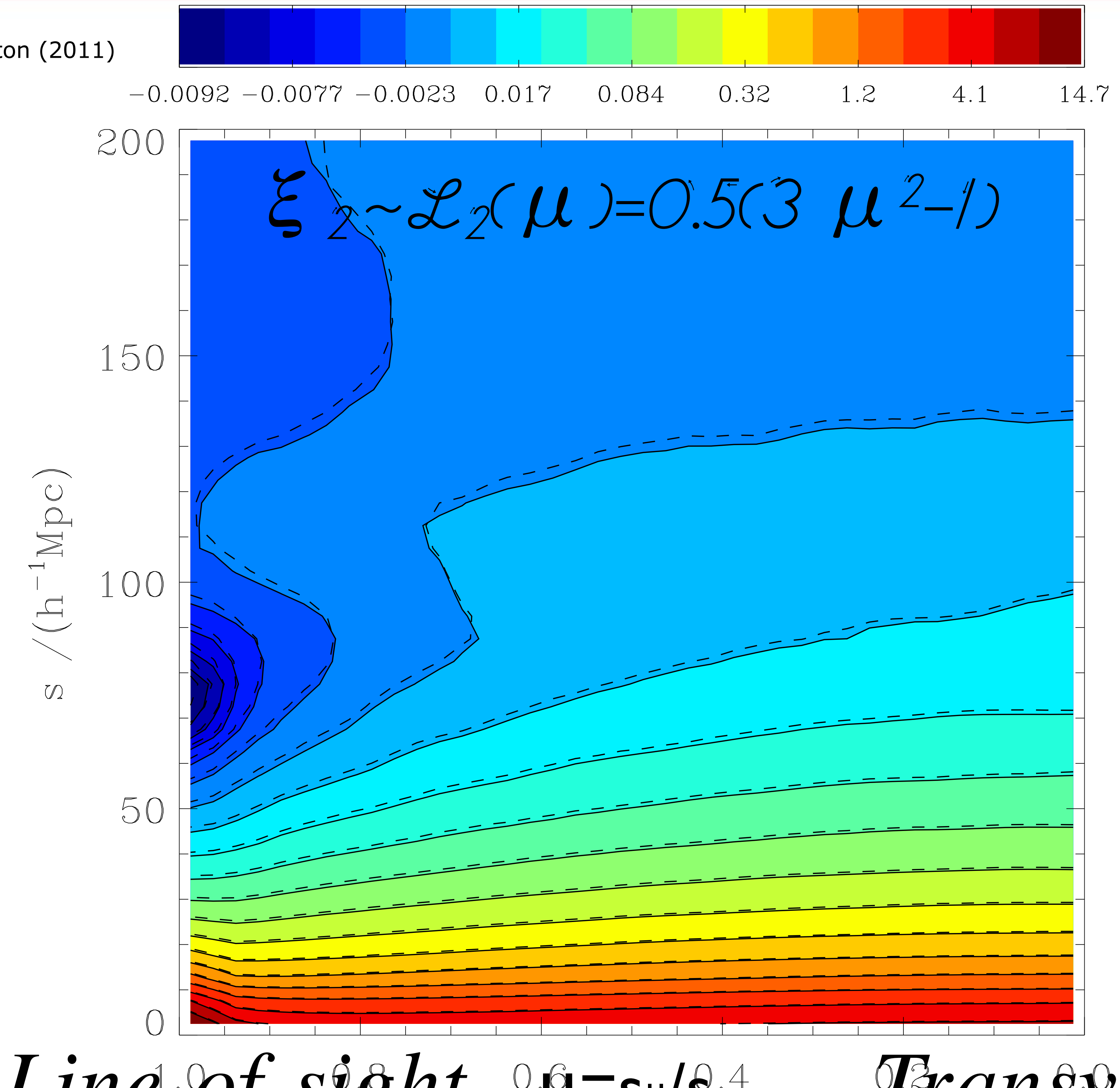
Kazin, Sanchez & Blanton (2011)

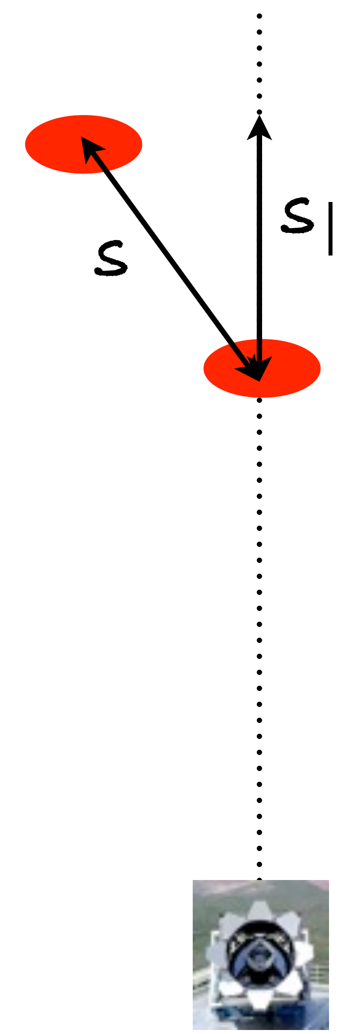




Splitting $\xi(\mu,s)$ to Multipoles $\xi_\ell(s)$

Kazin, Sanchez & Blanton (2011)

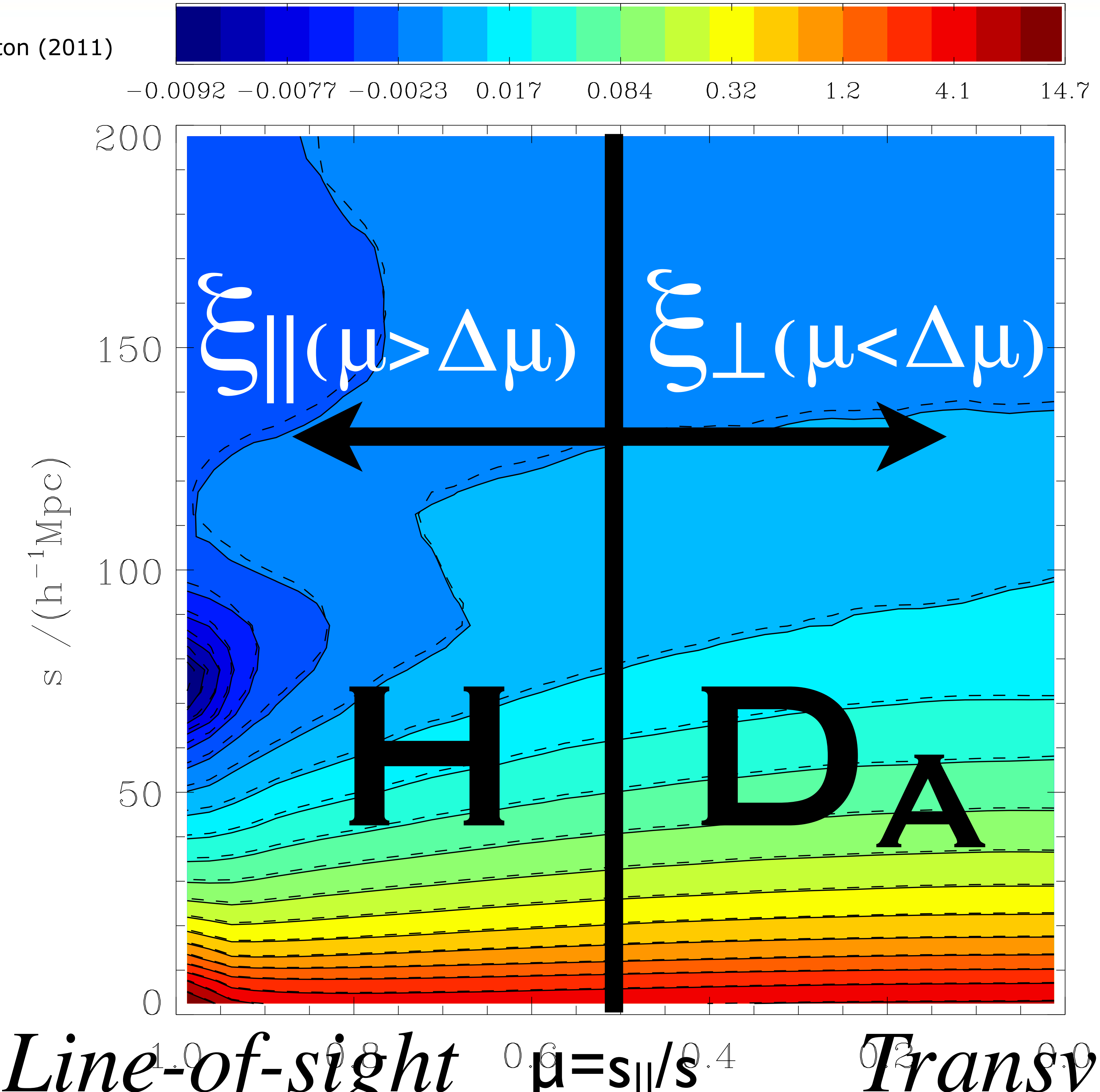


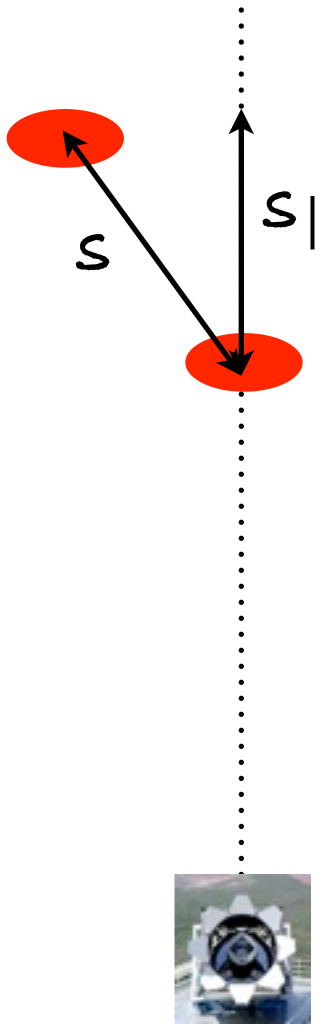


Line-of-sight $\mu = s_{||}/s$ **Transverse**

Splitting $\xi(\mu,s)$ to Wedges $\xi(\Delta\mu,s)$

Kazin, Sanchez & Blanton (2011)





Line-of-sight μ=s||/s *Transverse*

Geometrical Distortion Effects on the Clustering Wedges

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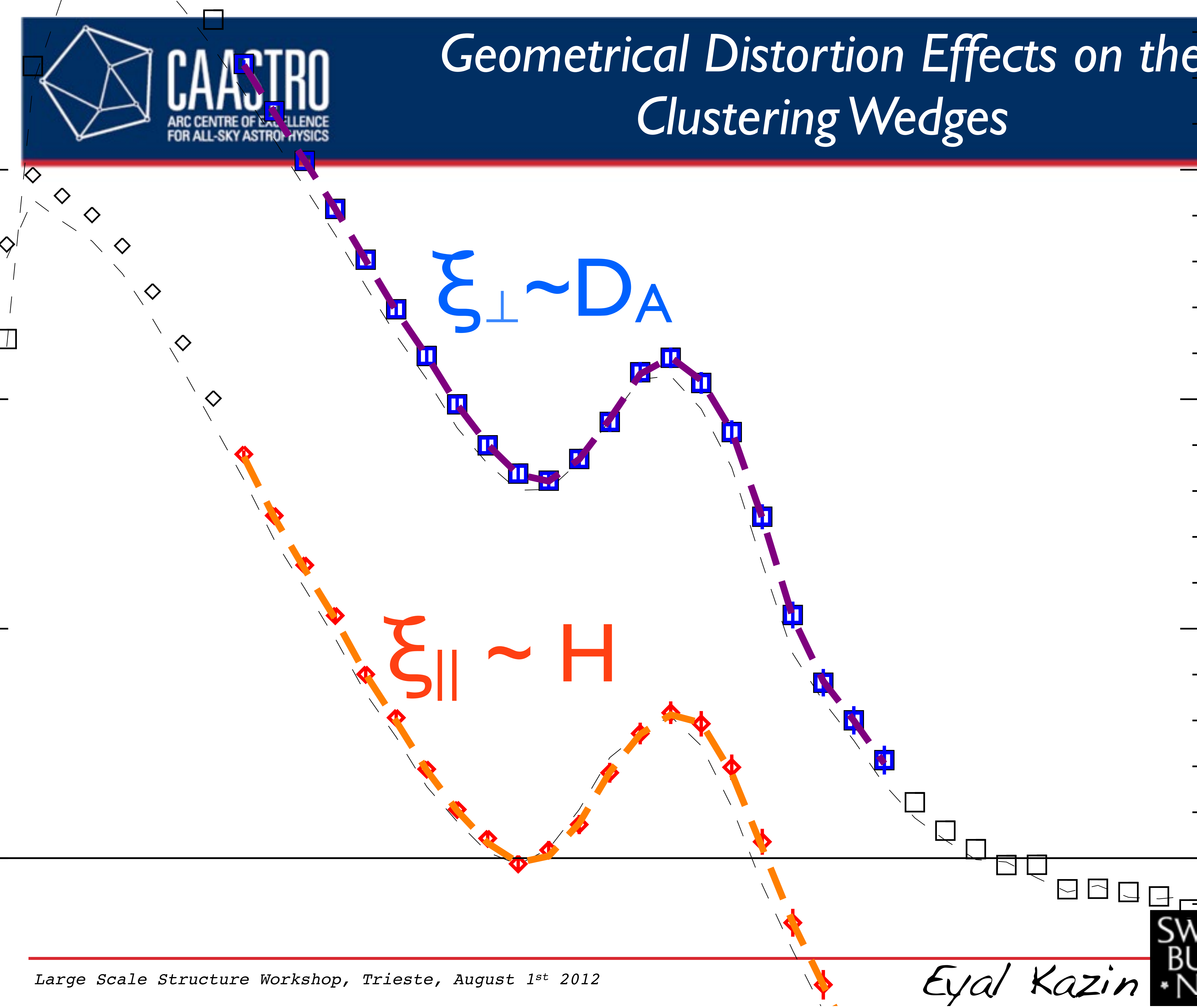
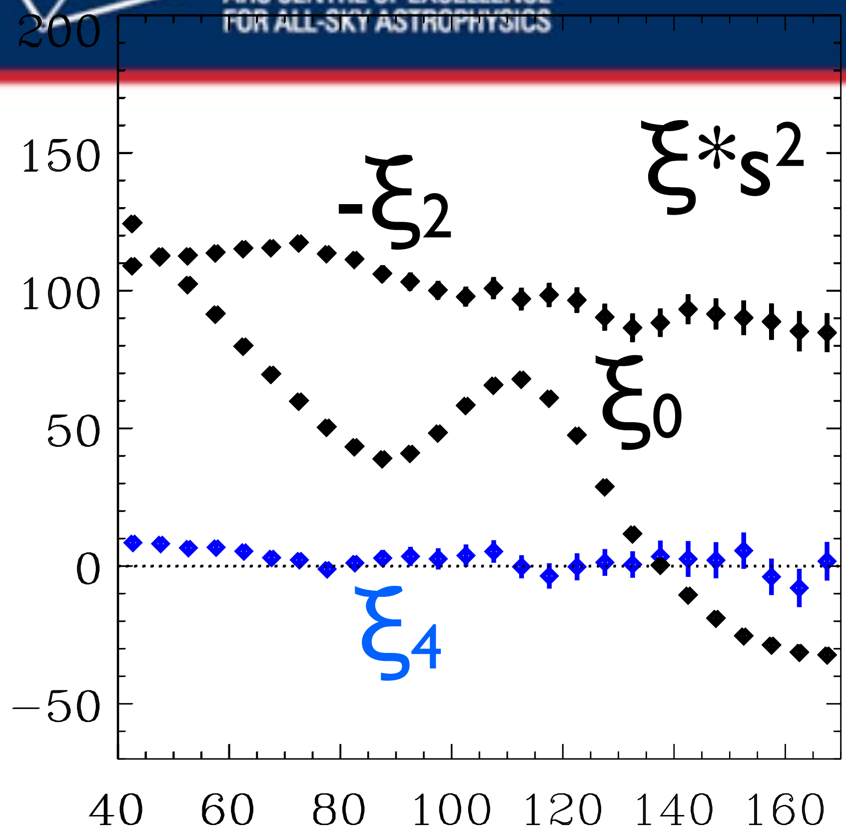
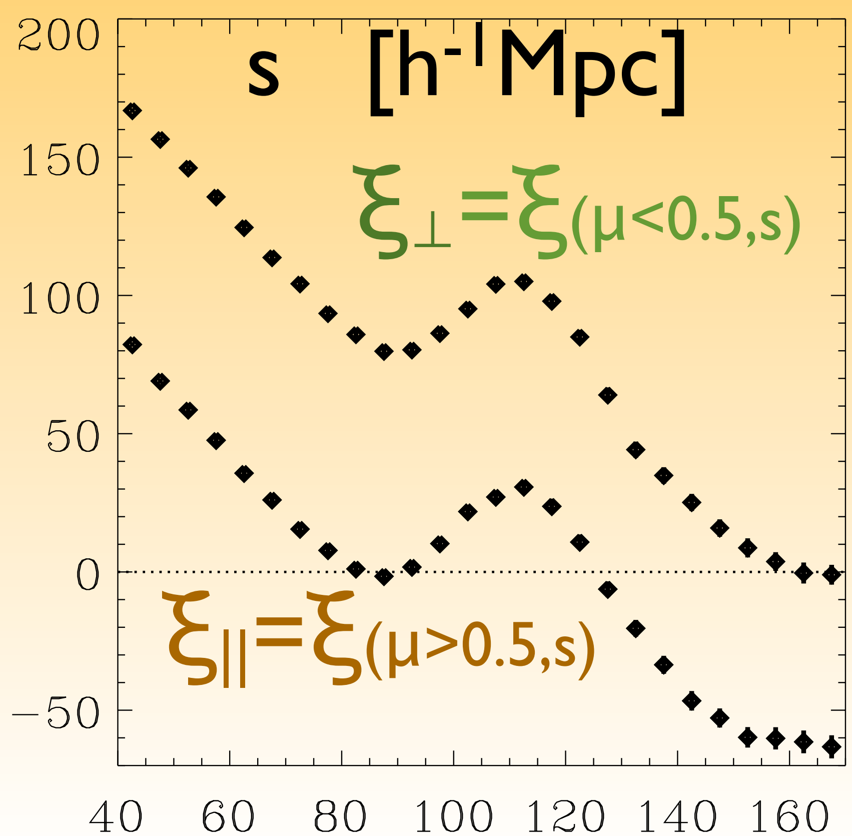
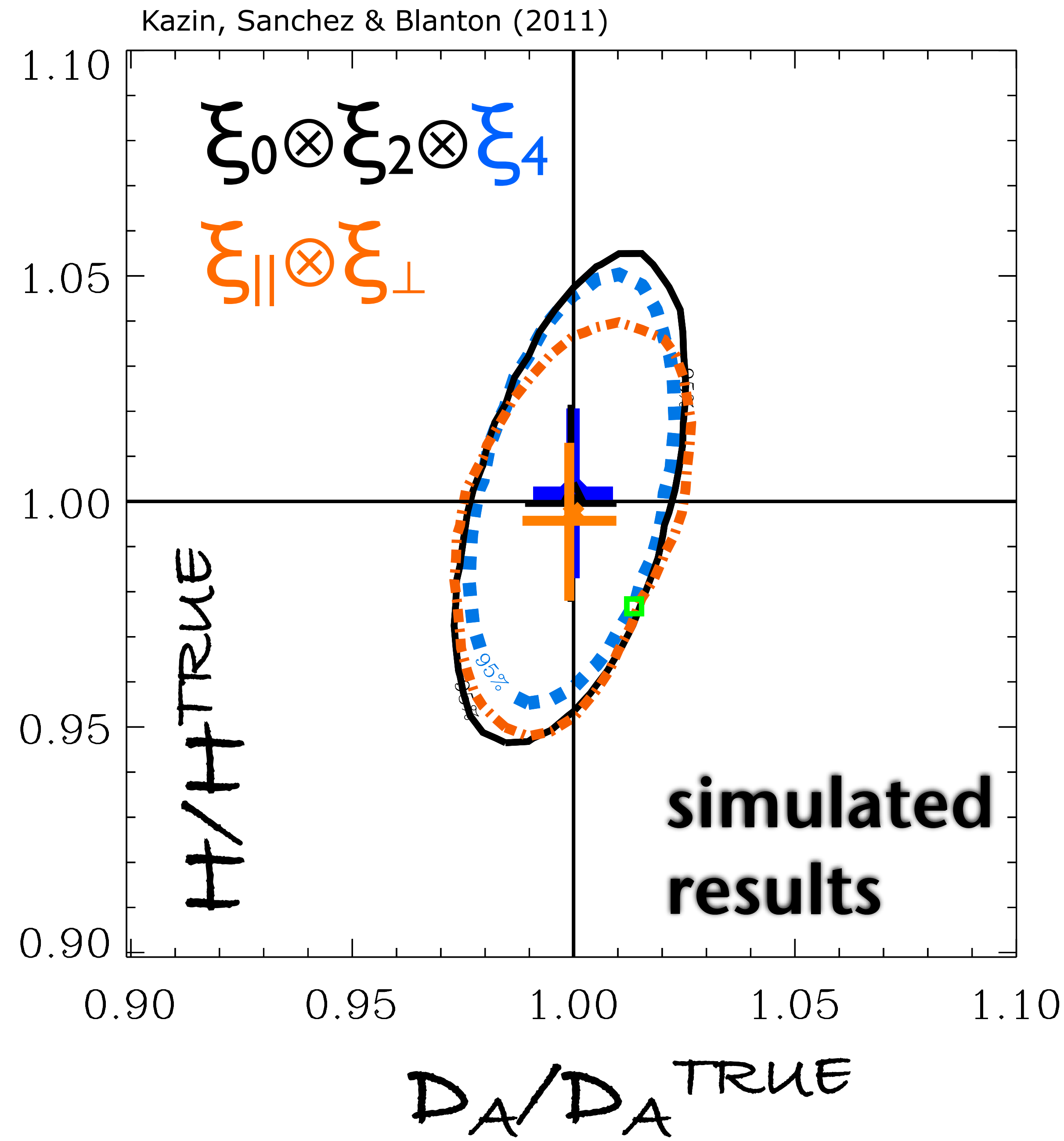


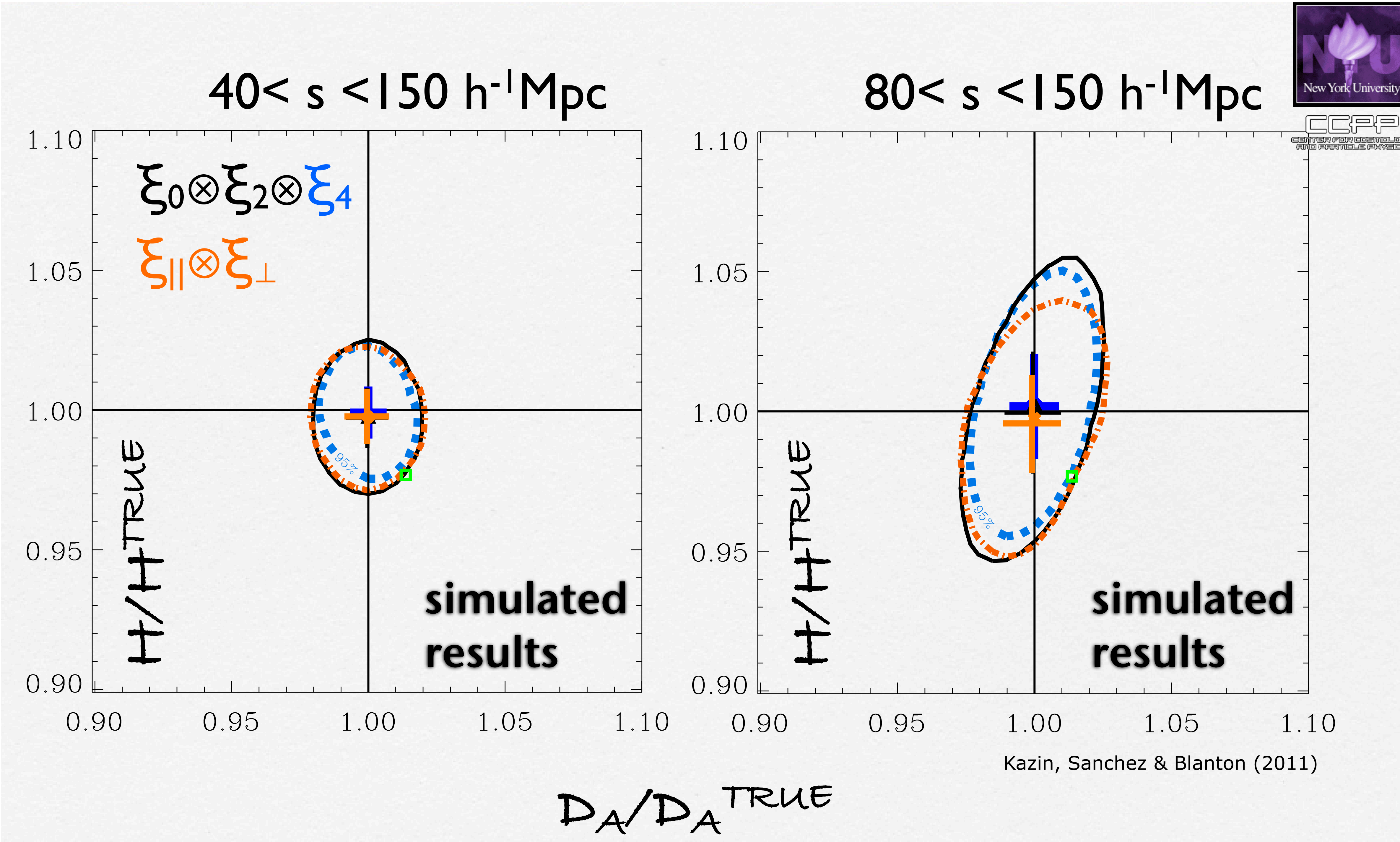
Wedges H, D_A Performance







H, D_A information in the ξ Full Shape



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Wedges: Basic Equations

Definition:

$$\xi(\Delta\mu, s) \equiv \frac{\int_{\mu_{\rm min}}^{\mu_{\rm max}} \xi(\mu', s)\mathrm{d}\mu'}{\int_{\mu_{\rm min}}^{\mu_{\rm max}} \mathrm{d}\mu'}$$

Basis Transform From Multipoles:

$$\xi(\Delta\mu, s) = \xi_0 + \frac{1}{2}\left(\frac{\mu_{\rm max}^3 - \mu_{\rm min}^3}{\mu_{\rm max} - \mu_{\rm min}} - 1\right)\xi_2$$

For $\Delta\mu=0.5$:

$$\begin{pmatrix} \xi_{||} \\ \xi_{\perp} \end{pmatrix} = \begin{pmatrix} 1 & \frac{3}{8} \\ 1 & -\frac{3}{8} \end{pmatrix} \begin{pmatrix} \xi_0 \\ \xi_2 \end{pmatrix}$$

Wedges: The Alcock Paczynski Effect

$$\xi_{||}^{\mathcal{D}}(s) = \xi_{||}\left(\frac{H^{\mathcal{D}}}{H}s\right) + \mathcal{C}_{||}(\epsilon),$$

$$\xi_{\perp}^{\mathcal{D}}(s) = \xi_{\perp}\left(\frac{D_{\rm A}}{D_{\rm A}^{\mathcal{D}}}s\right) + \mathcal{C}_{\perp}(\epsilon),$$

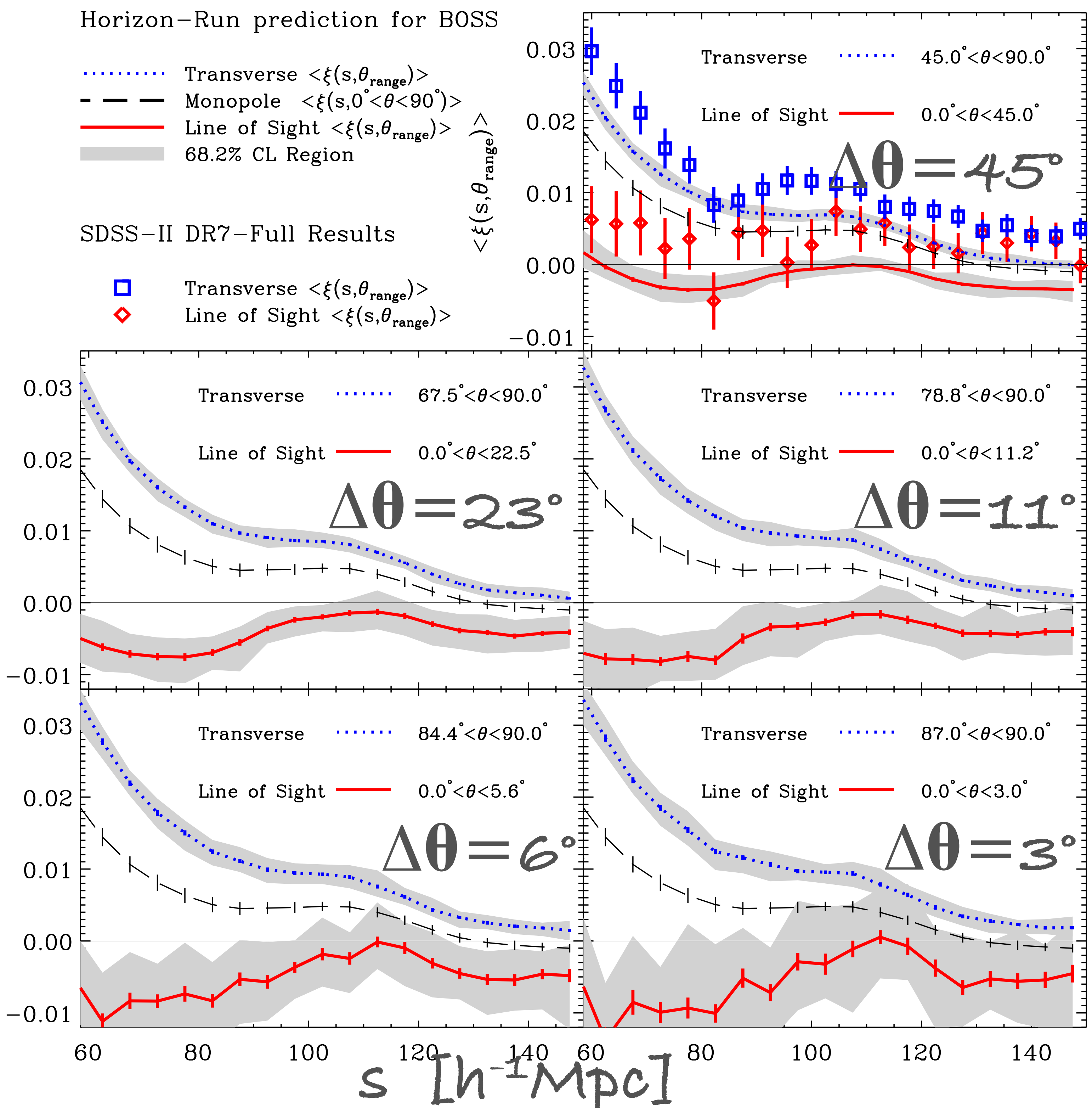
Inter-mixing terms (not a pretty sight ...):

$$\mathcal{C}_{||}(\epsilon,\alpha) = \epsilon\left(-\frac{5}{4}\frac{d\xi_0(s)}{d\ln(s)} - \frac{19}{140}\frac{d\xi_2(s)}{d\ln(s)} + \frac{213}{140}\xi_2(\alpha s)\right)$$

$$\mathcal{C}_{\perp}(\epsilon,\alpha) = \epsilon\left(\frac{1}{4}\frac{d\xi_0(s)}{d\ln(s)} - \frac{53}{280}\frac{d\xi_2(s)}{d\ln(s)} + \frac{123}{140}\xi_2(\alpha s)\right)$$

BOSS 2014 Predicted Wedges ξ(Δμ,s)

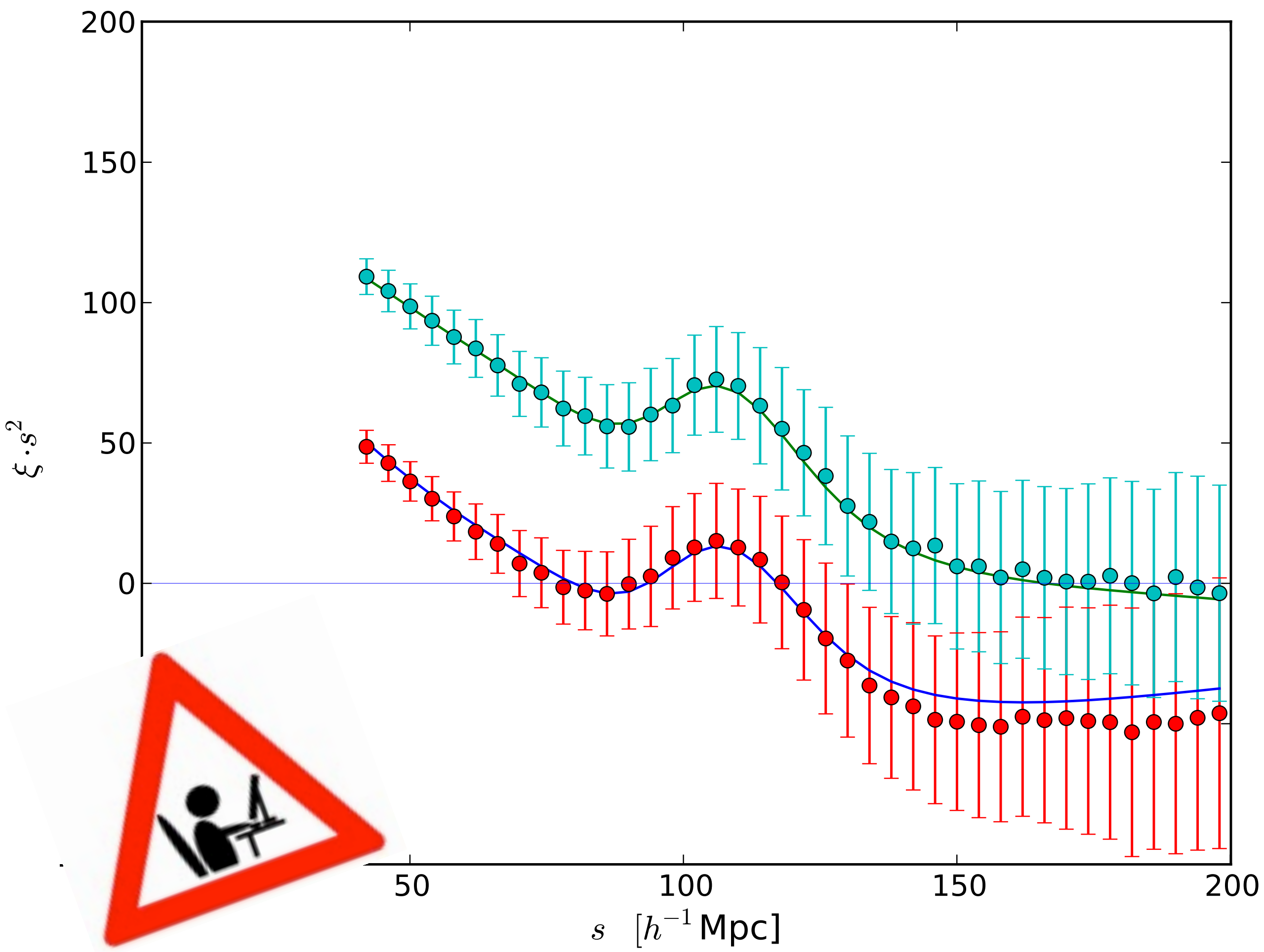
Kazin et al. (2010b)

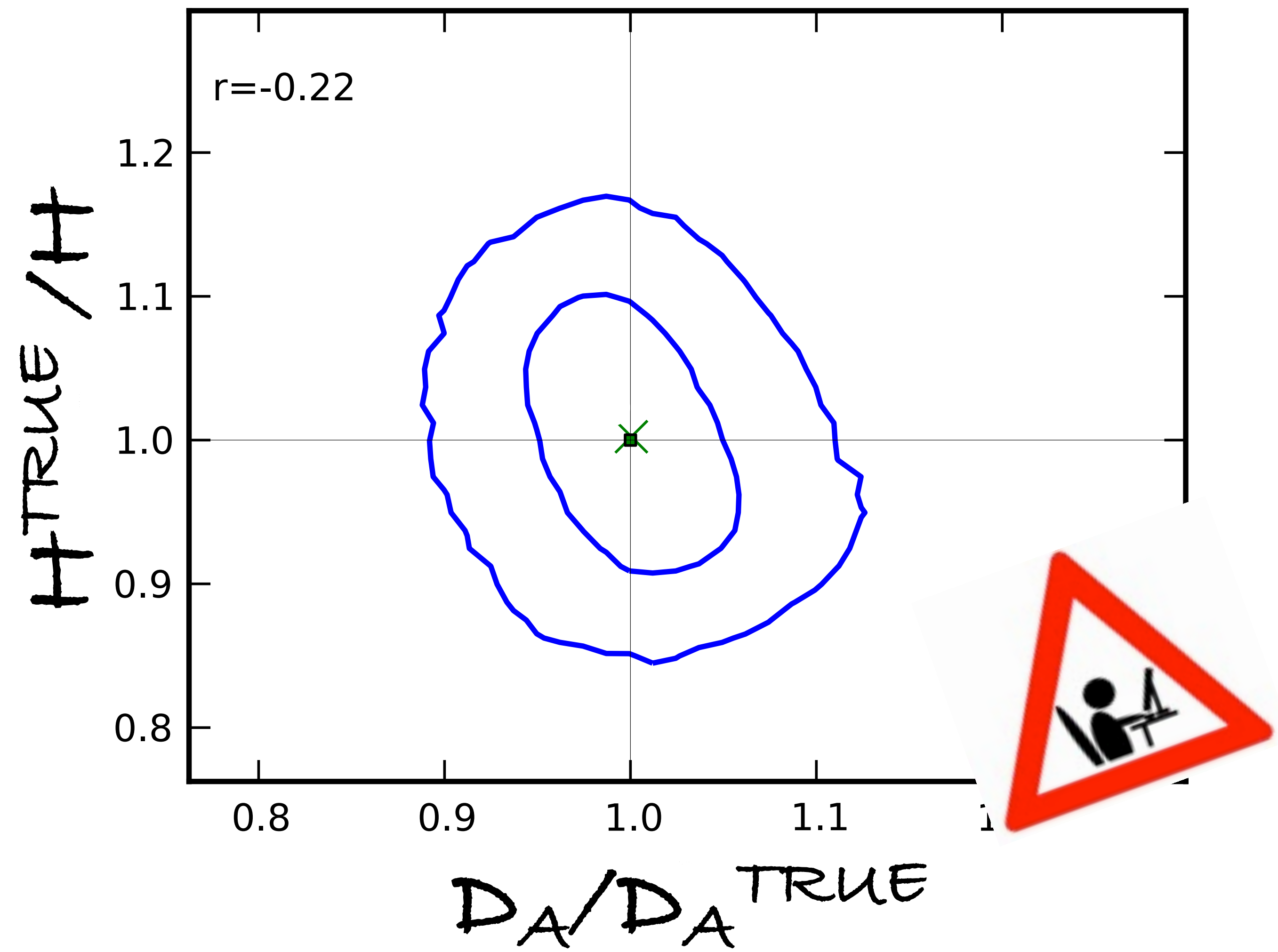


Testing Model on Mock Wedges

Simulated Data: BOSS PTHalos (of Manera et al. 2012)

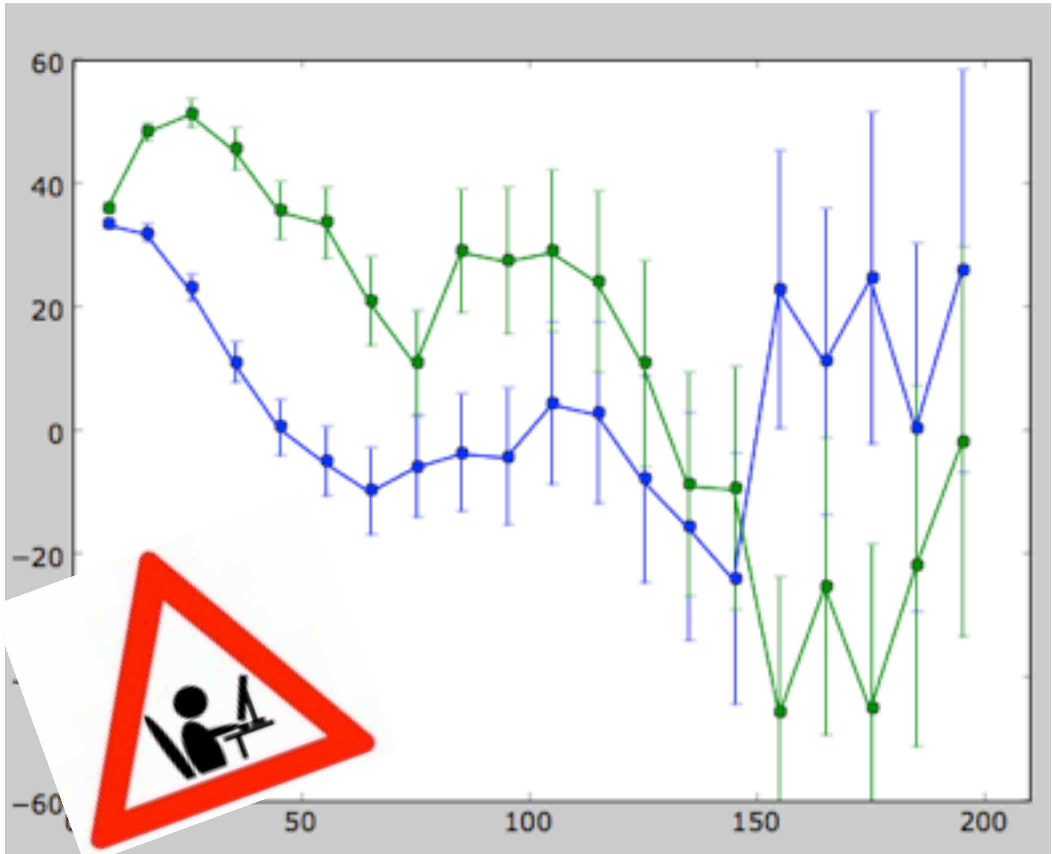
Kazin, Sánchez & the SDSS (in prep.)





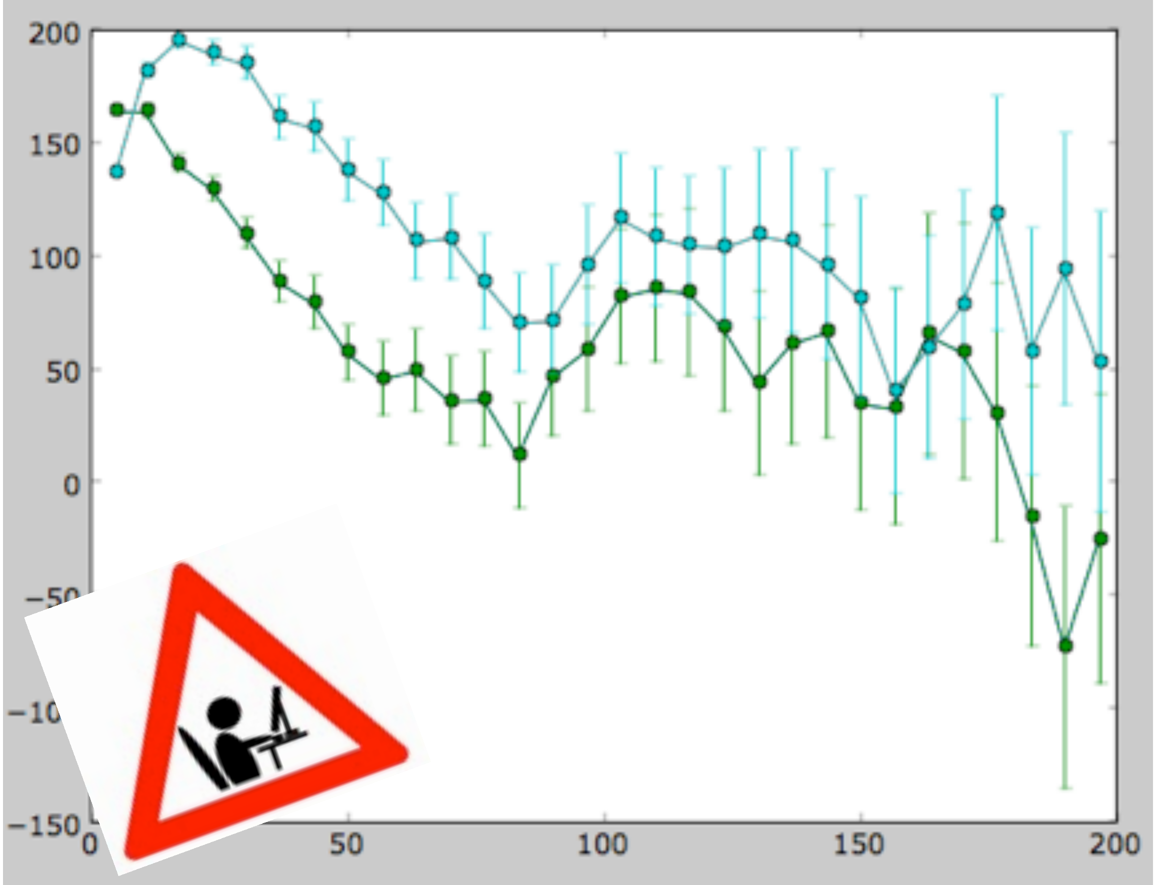
Clustering Wedges in the Data

Davis, Kazin & the WiggleZ (in prep.)



WiggleZ (0.2<z<1)
(bias ~ 1)

SDSS-II LRGs (0.16<z<0.44)
(bias ~ 2.2)



Sánchez & Kazin (in prep.)

Clustering Wedges in the Data

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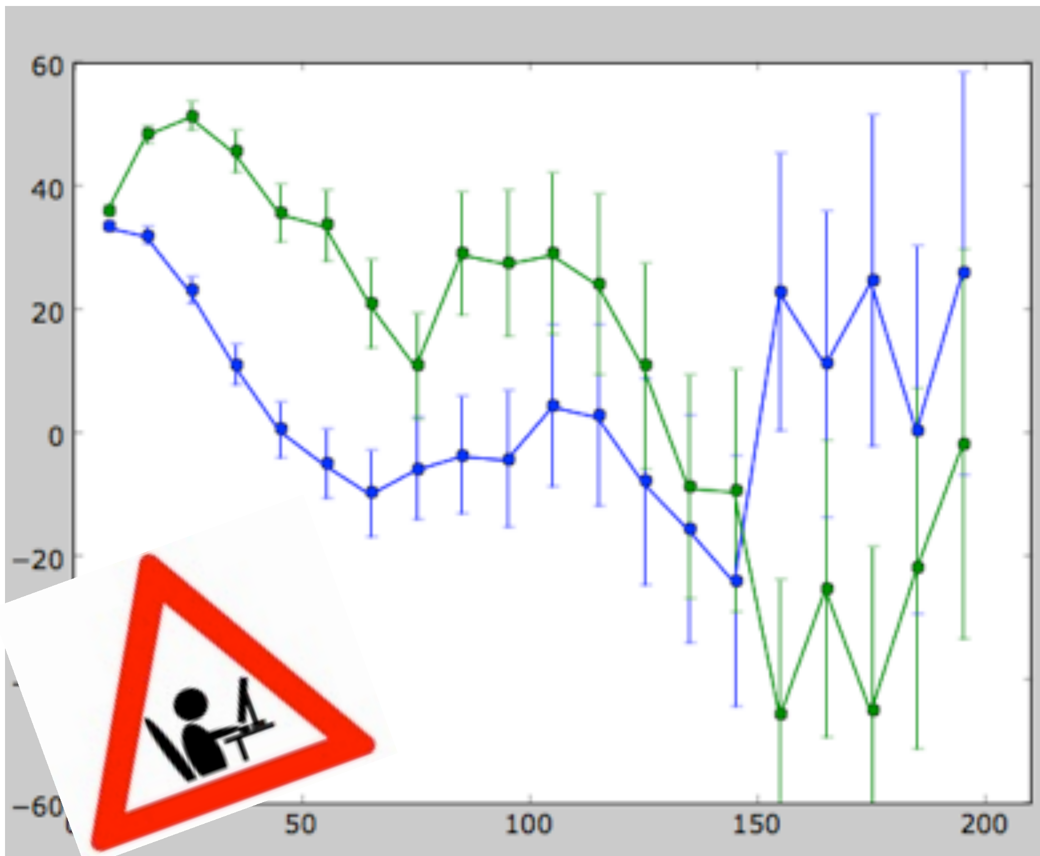

WiggleZ (0.2<z<1)
(bias ~ 1)

SDSS-II LRGs (0.16<z<0.44)
(bias ~ 2.2)

Credit for reconstructed data: **Nikhil Padmanabhan**

Sánchez & Kazin (in prep.)

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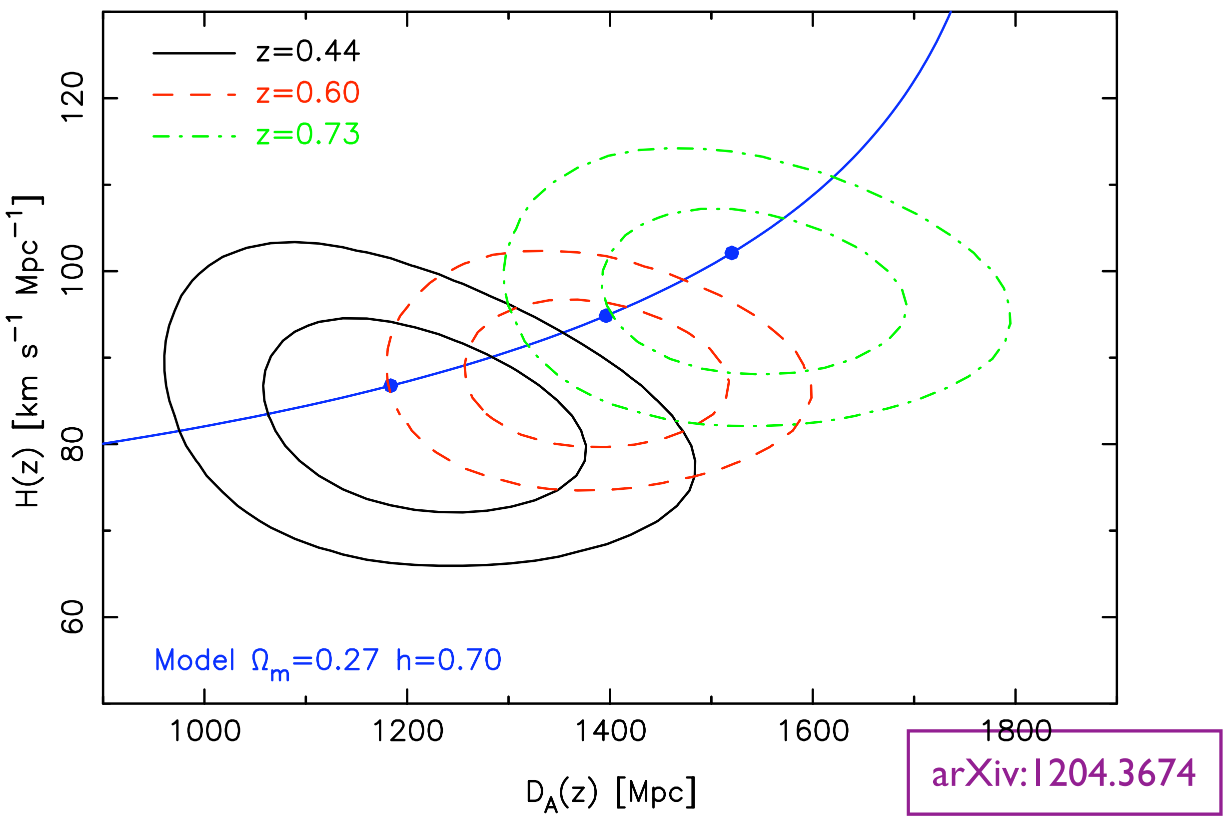
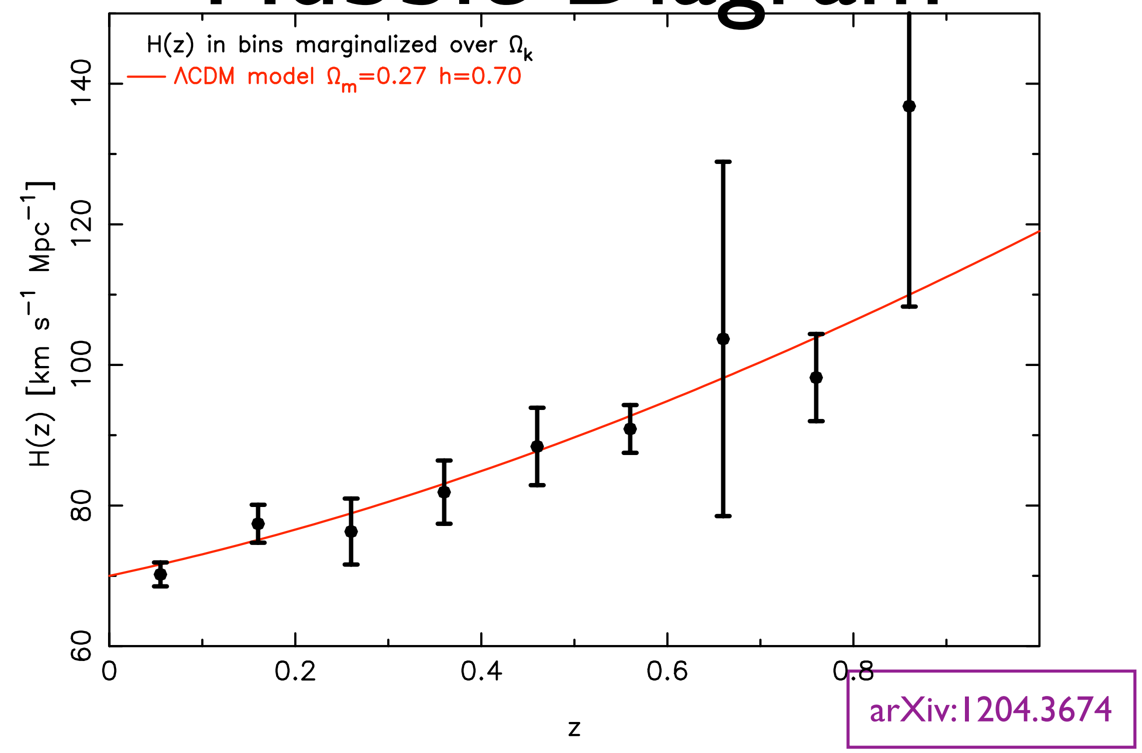
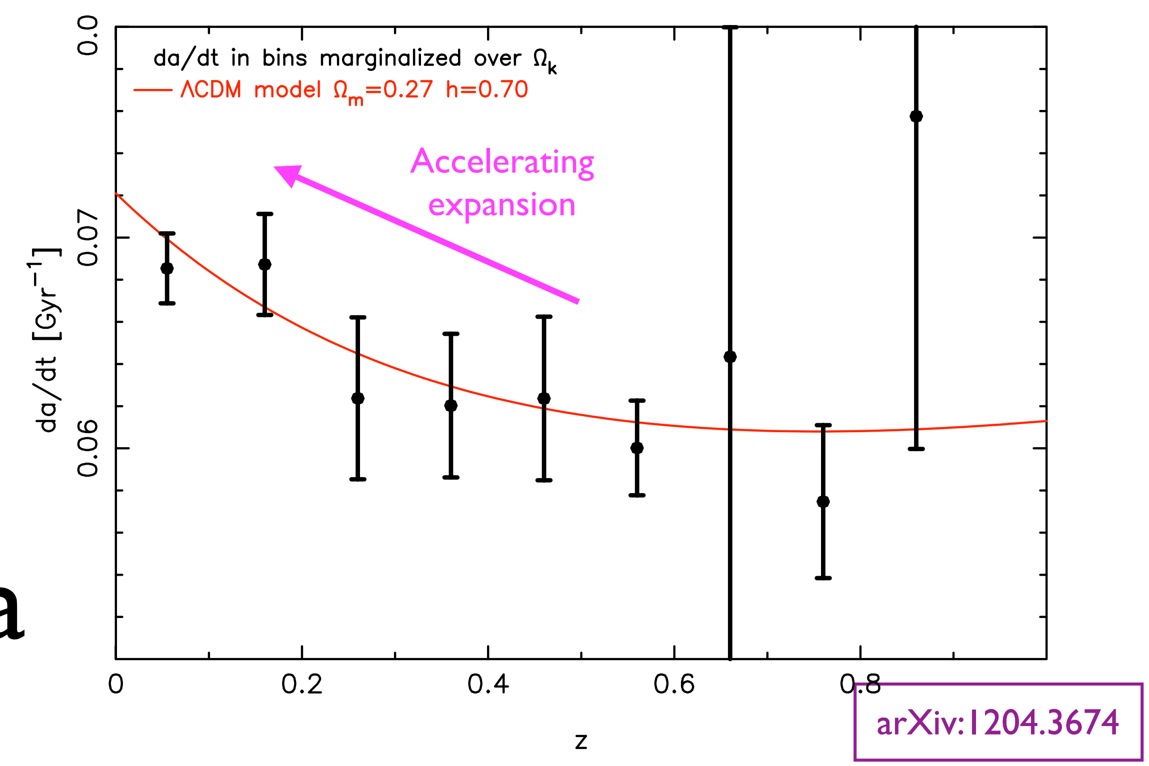
WiggleZ H-D_A Results

Blake & the WiggleZ (2012)



Hubble Diagram





Same-same but different: $da/dt = H \cdot a$

Clustering Wedges (temporary) Summary

- $\xi(\Delta\mu,s)$ wedges more practical than than 2D $\xi(\mu,s)$ plane because:
  - Higher S/N
  - Much cheaper (=easier) covariance matrix
- Compared to multipoles $\xi_\ell(s)$ in constraining H, D_A, f:
  - Is one basis better than the other?
  - Are two peaks more useful than one?
  - to be continued ...

Warning!

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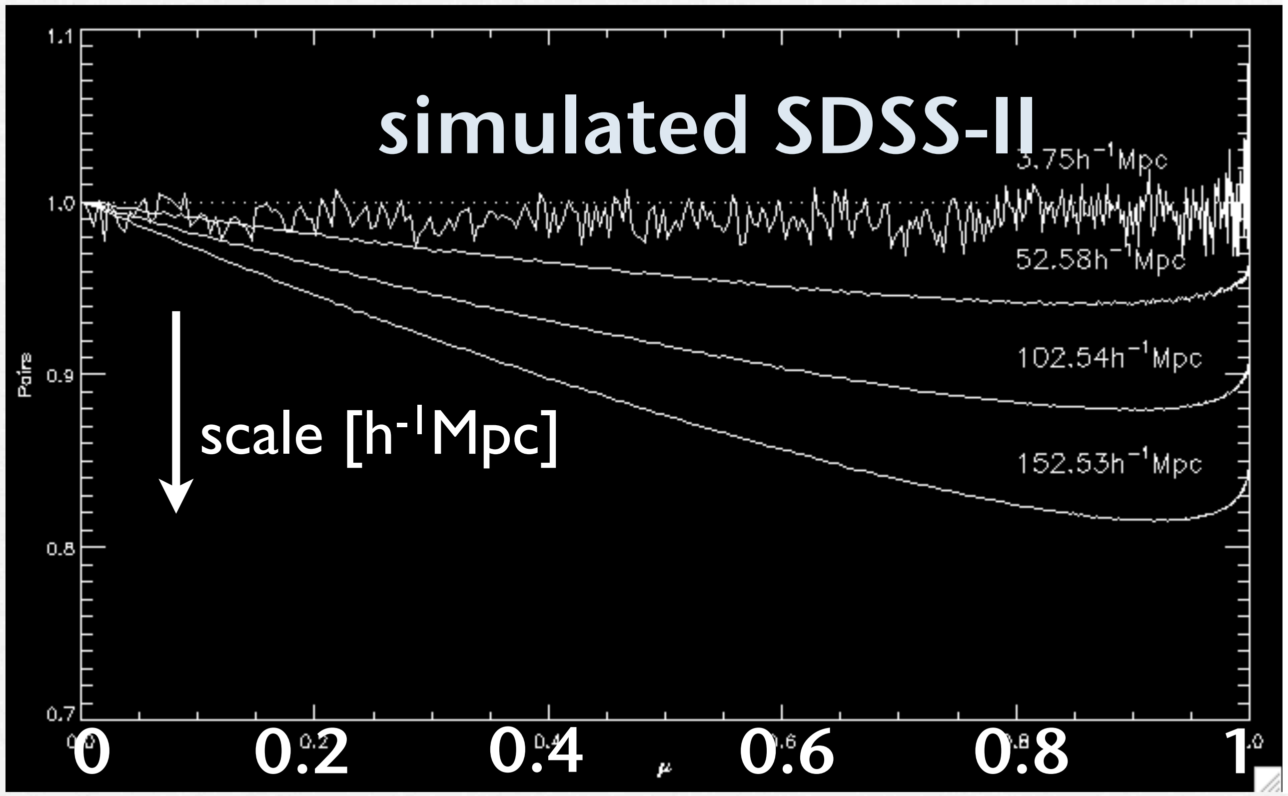
Warning!

The following slides contain information that might not be appropriate for individuals that live inside a periodic box.

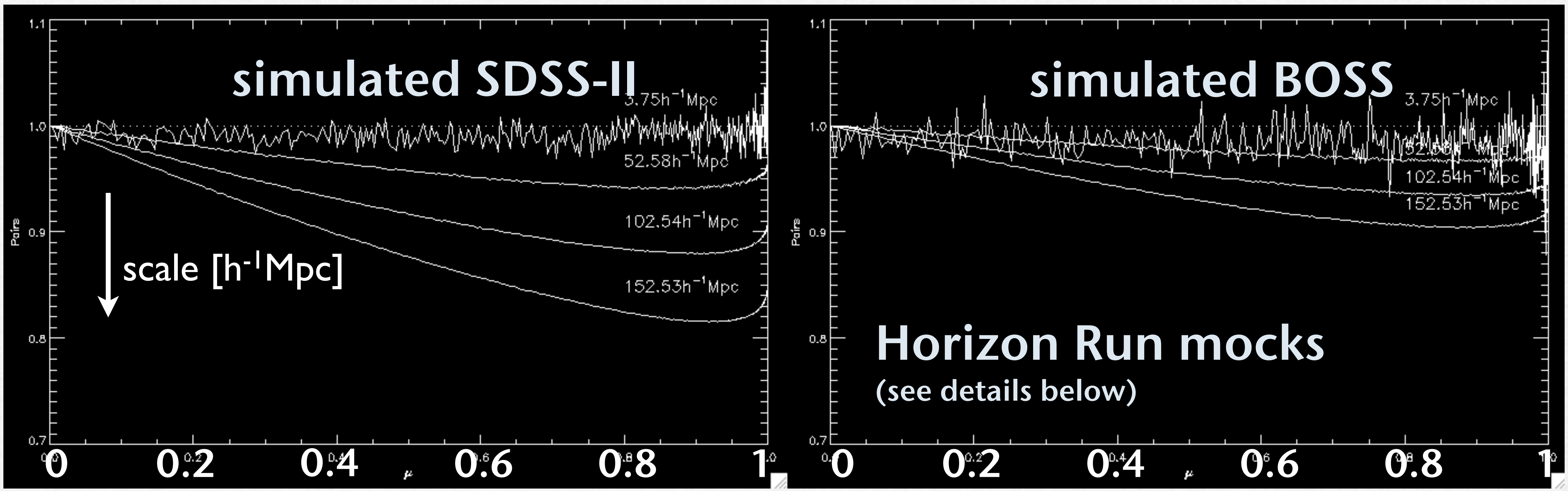
$N_{RR}(\mu) \neq$ constant



$\mu = s_{||}/s$

LasDamas (SDSS-II geometry)
0.16<z<0.44 volume limited
8000 deg², SDSS sky-coverage

$N_{RR}(\mu) \neq$ constant



$\mu = s_{||}/s$

LasDamas (SDSS-II geometry)
0.16<z<0.44 volume limited
8000 deg², SDSS sky-coverage

Horizon Run (~BOSSish 2014)
0.16<z<0.6 volume limited
10,300 deg² (π str) BOX

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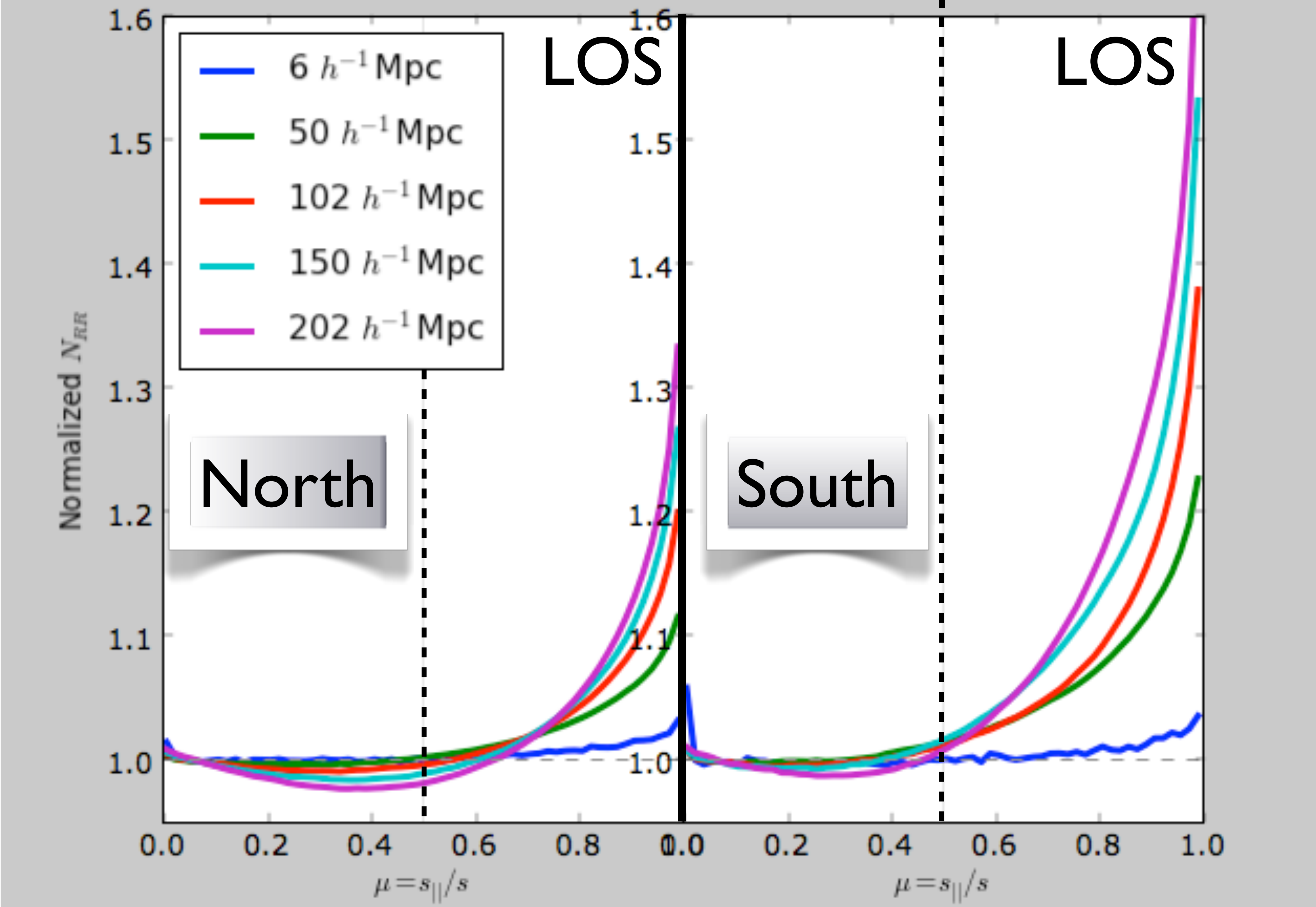
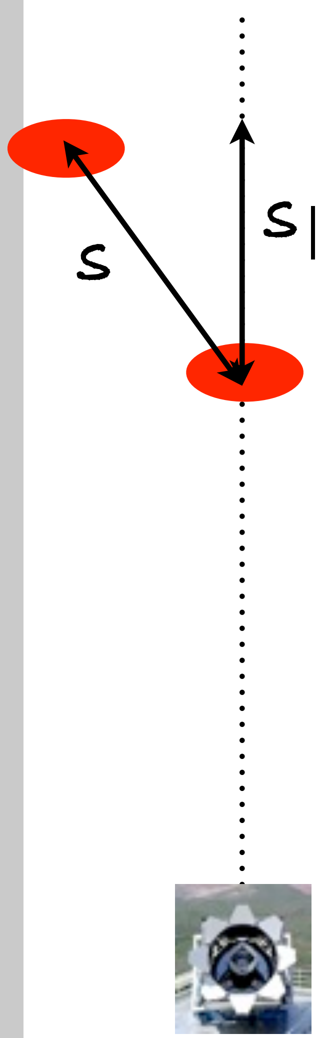
http://sdss3.org/dr9/

$N_{RR}(\mu) \neq$ constant

BOSS CMASS DR9- now public!





ξ Estimators: Direct vs Integrated

$$\mathcal{P}_0 = 1$$
$$\mathcal{P}_2 = \frac{1}{2}\left(3\mu^2 - 1\right)$$

[up to (2ℓ+1)/2]

$$\xi_\ell \equiv \int_{-1}^{+1} \mathrm{d}\mu \mathcal{P}_\ell(\mu)\xi(\mu, s) = \int_{-1}^{+1} \mathrm{d}\mu \mathcal{P}_\ell(\mu) \frac{DD(\mu, s) - RR(\mu, s)}{RR(\mu, s)}$$

ξ Estimators: Direct vs Integrated

$$\mathcal{P}_0 = 1$$
$$\mathcal{P}_2 = \frac{1}{2}\left(3\mu^2 - 1\right)$$

[up to $(2\ell+1)/2$]

$\xi^{\text{INTEGRATED}}$

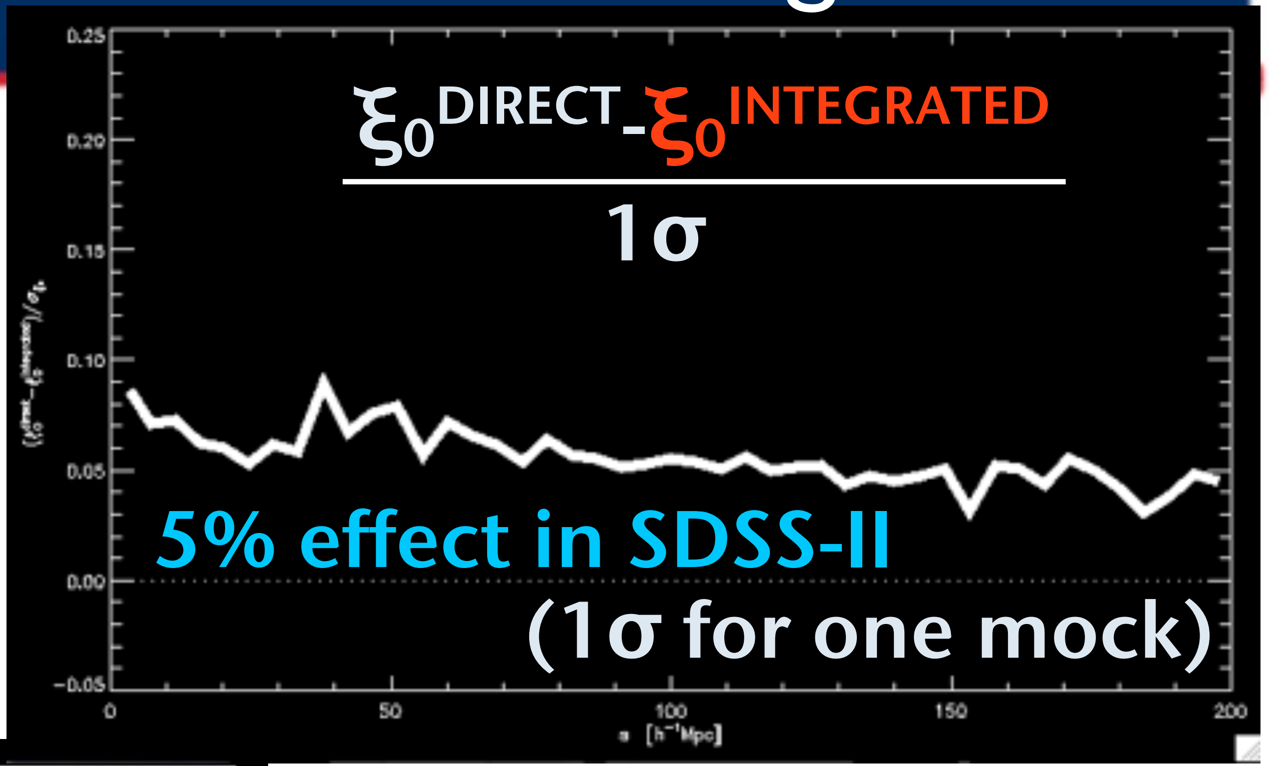
$$\xi_\ell \equiv \int_{-1}^{+1} \mathrm{d}\mu \mathcal{P}_\ell(\mu)\xi(\mu, s) = \int_{-1}^{+1} \mathrm{d}\mu \mathcal{P}_\ell(\mu) \frac{DD(\mu, s) - RR(\mu, s)}{RR(\mu, s)}$$

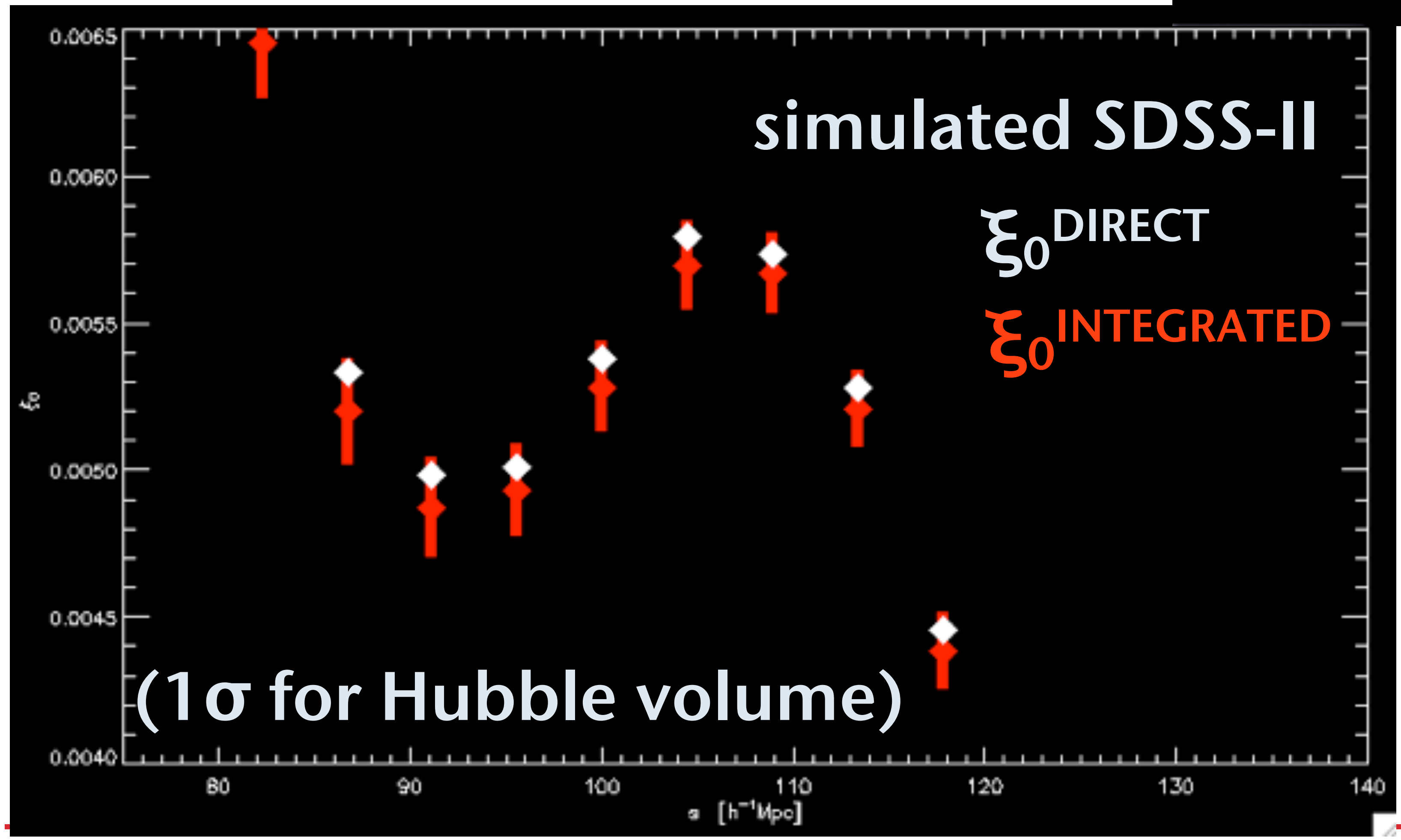
$$\xi_0(s) = \frac{DD(s) - RR(s)}{RR(s)} \neq \int_{-1}^{+1} \mathrm{d}\mu \frac{DD(\mu, s) - RR(\mu, s)}{RR(\mu, s)}$$

ξ^{DIRECT}

$$\xi_0(s) = \frac{DD(s) - RR(s)}{RR(s)} = \int_{-1}^{+1} \mathrm{d}\mu \frac{DD(\mu, s) - RR(\mu, s)}{RR(\mu, s)} \cdot \frac{RR(\mu, s)}{RR(s)}$$

ξ Estimators: Direct vs Integrated





Large Scale Structure Workshop, Trieste, August 1st 2012

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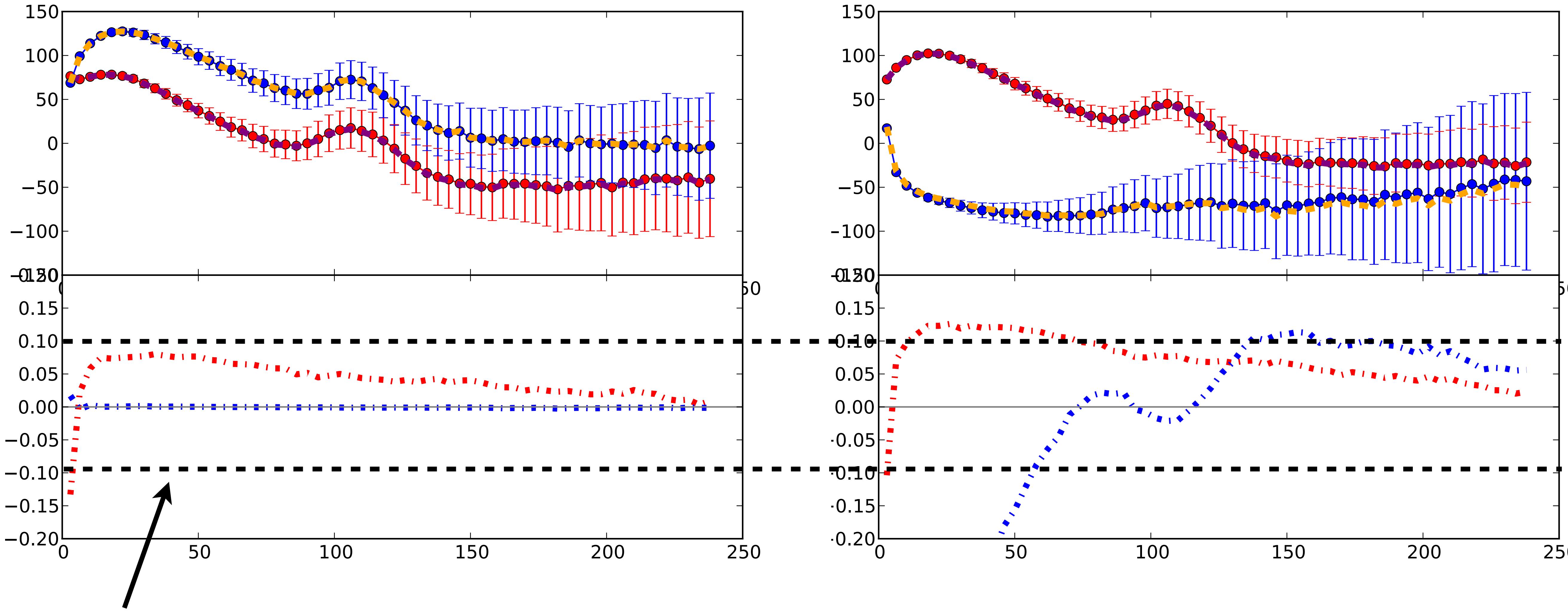
ξ Estimators: Direct vs Integrated Investigating 610 BOSS Mocks

$(\xi^{\mathrm{INTEGRATED}} - \xi^{\mathrm{DIRECT}})/\sigma_\xi$



10% of $1\sigma_\xi$ line: indicating **wedges are less sensitive to method of estimator**

ξ Estimators: Direct vs Integrated

But, don't you degrade
the C_{ij},
when integrating
over noisy data bins?

ξ Estimators: Direct vs Integrated
Investigating 610 BOSS Mocks

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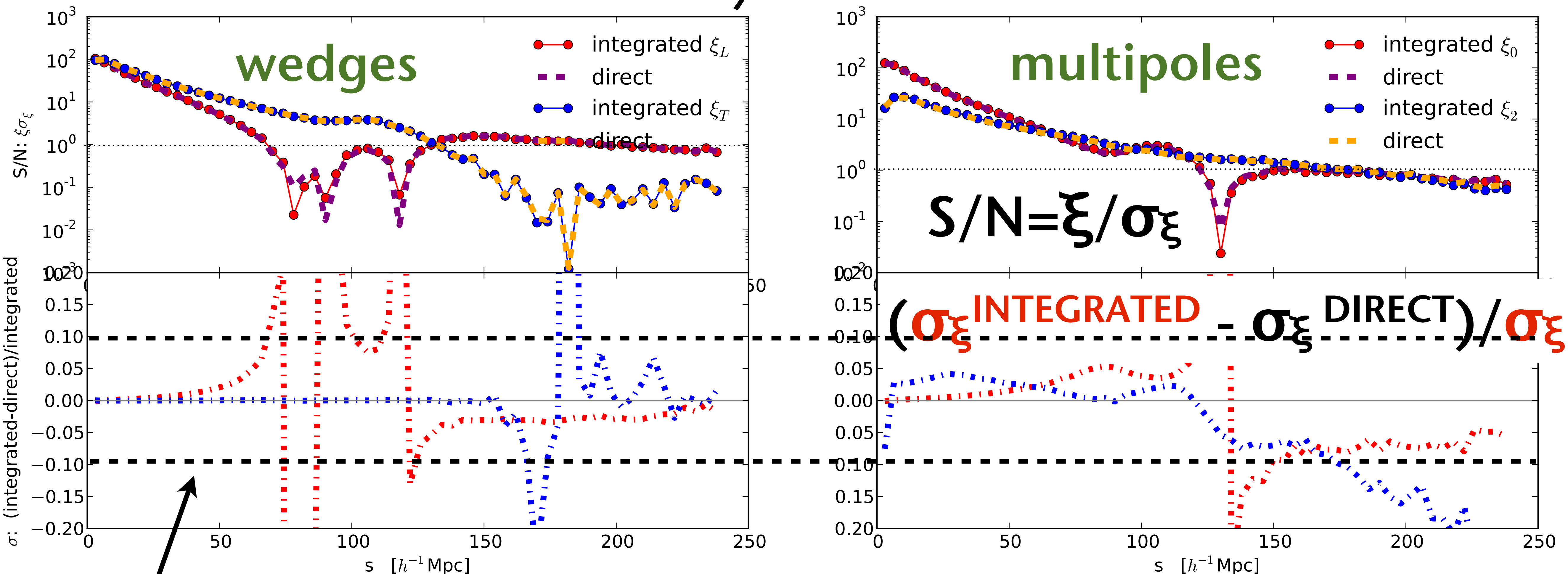
increase in noise?
no, not too shabby (on most scales)...



10% of 1σξ line: indicating **wedges are less sensitive to method of estimator**

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Clustering Wedges (temporary) Summary

- $\xi(\Delta\mu, s)$ wedges more practical than than 2D $\xi(\mu, s)$ plane because:
  - Higher S/N
  - Much cheaper (=easier) covariance matrix

3D -> 2D -> 1D

- Comparing $\xi(\Delta\mu)$ wedges to $\xi_\ell(s)$ multipoles in constraining H, D_A, f

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Clustering Wedges (temporary) Summary

- $\xi(\Delta\mu,s)$ wedges more practical than than 2D $\xi(\mu,s)$ plane because:
  - Higher S/N
  - Much cheaper (=easier) covariance matrix

- Comparing $\xi(\Delta\mu)$ wedges to $\xi_\ell(s)$ multipoles in constraining H,D_A,f

Clustering Wedges (temporary) Summary

- ξ(Δμ,s) wedges more practical than than 2D ξ(μ,s) plane because:
  - Higher S/N
  - Much cheaper (=easier) covariance matrix

- Com
  to ξ
  cons

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Clustering Wedges (temporary) Summary

- $\xi(\Delta\mu,s)$ wedges more practical than than 2D $\xi(\mu,s)$ plane because:
  - Higher S/N
  - Much cheaper (=easier) covariance matrix

- Compared to multipoles $\xi_\ell(s)$ in constraining H,D_A,f:
  - Is one basis better than the other?
  - Are two strong peaks more useful than one?
  - to be continued ...

Thank You!

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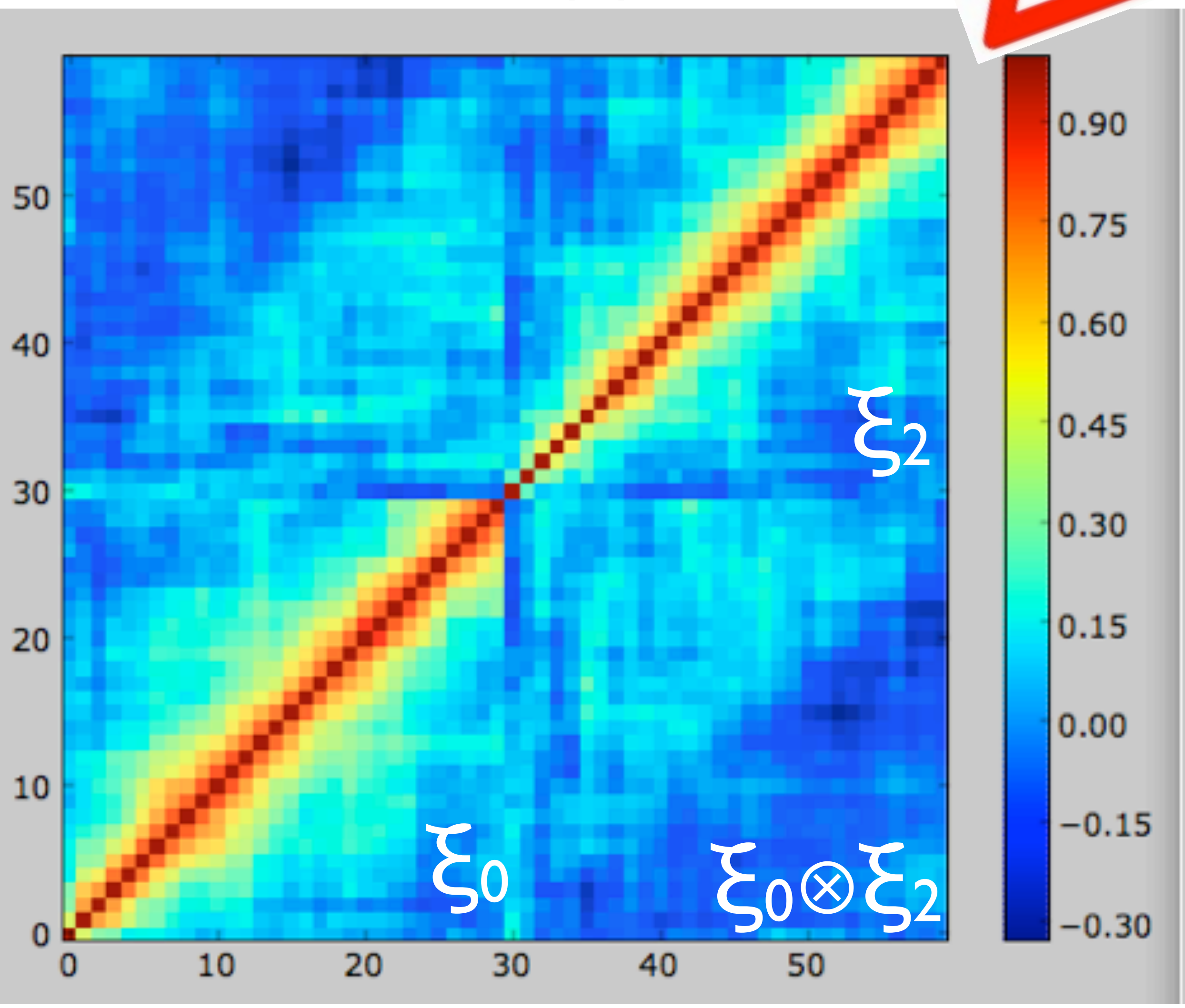
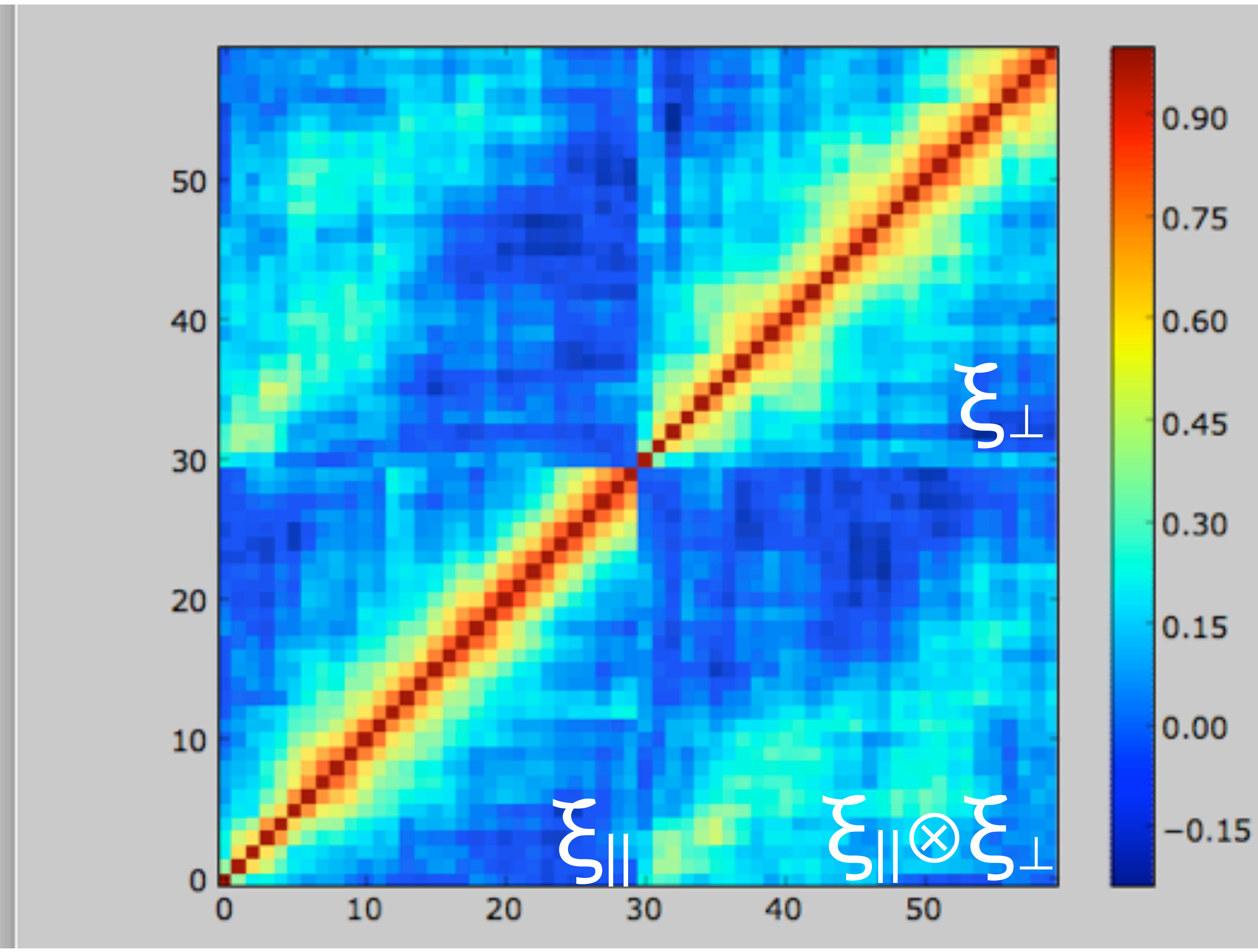
Covariance Matrix Comparison (Normalized)

$\xi_\ell(s)$



5 100 200 5 100 200
h^{-1}Mpc

$\xi(\Delta\mu,s)$



5 100 200 5 100 200
h^{-1}Mpc

C_{ij} from LasDamas *0.16<z<0.44* (of McBride et al. in prep)

Δs=6.7 h^{-1}Mpc range 5-197 h^{-1}Mpc

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