

2419-14

Workshop on Large Scale Structure

30 July - 2 August, 2012

**Clustering Wedges: An alternative approach to measuring $H(z)$ and $D_a(z)$ with
galaxy clustering**

E.A. Kazin

Swinburne University of Technology

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

Eyal Kazin

In collaboration with:

Tamara **Davis**, Chris **Blake**, Ariel **Sánchez**



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- 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**, $RR(\mu)$

For usage of data, mock catalogues:

Marc **Manera**, Cameron **McBride**, The Sloan Digital Sky Survey, The WiggleZ Dark Energy Survey

The WiggleZ Group



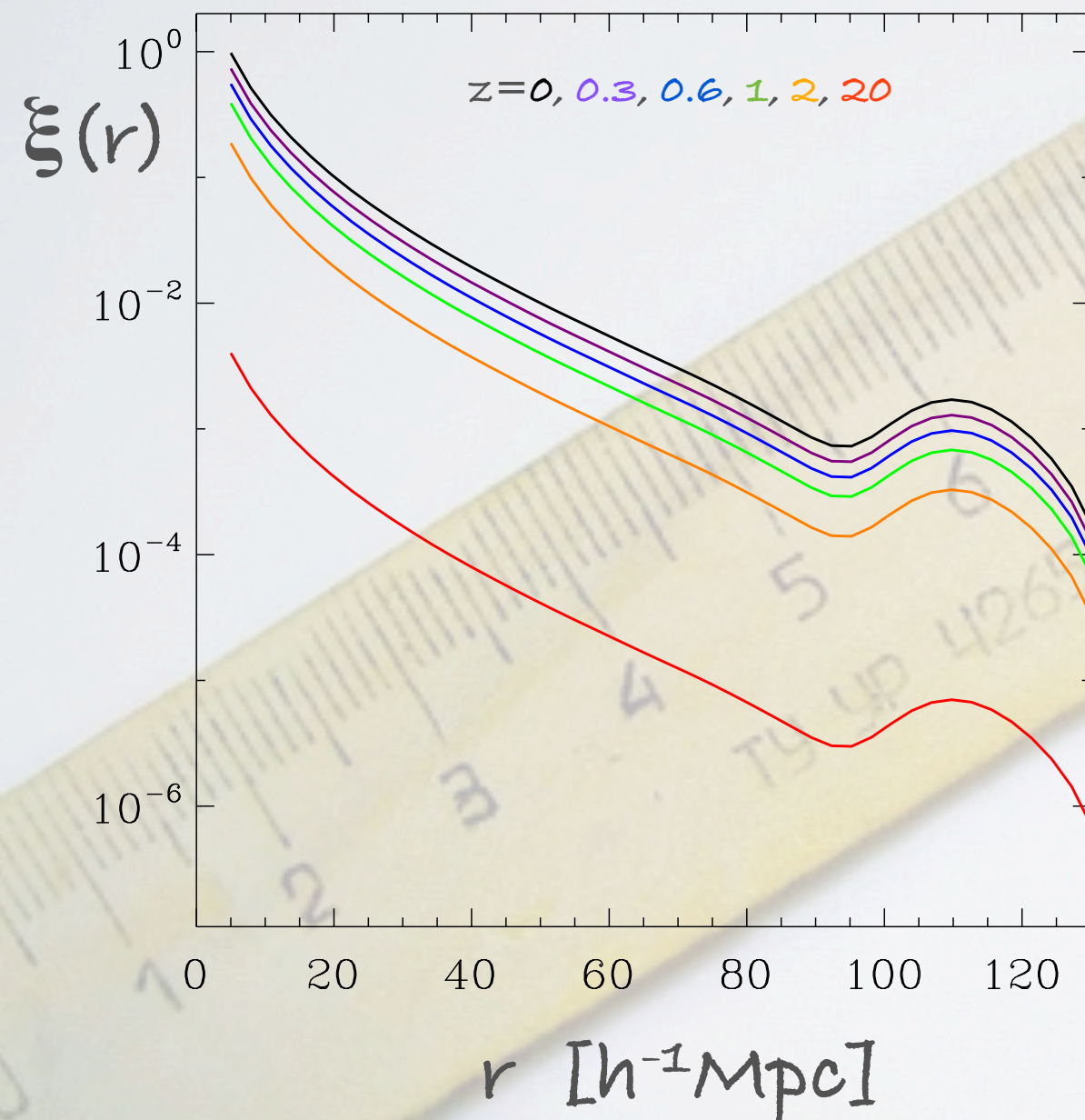
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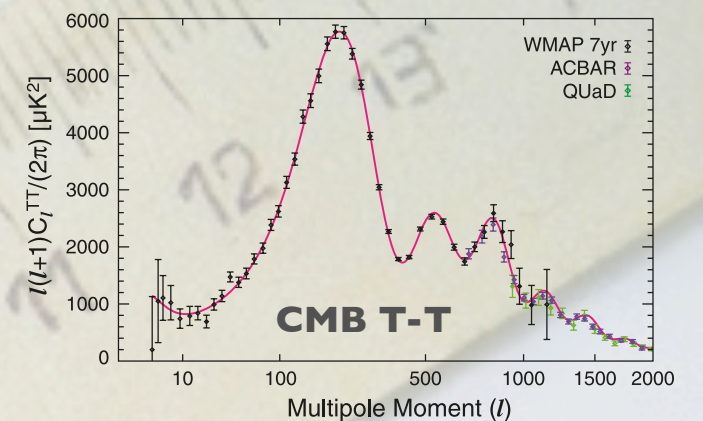
The Sloan Digital Sky Survey



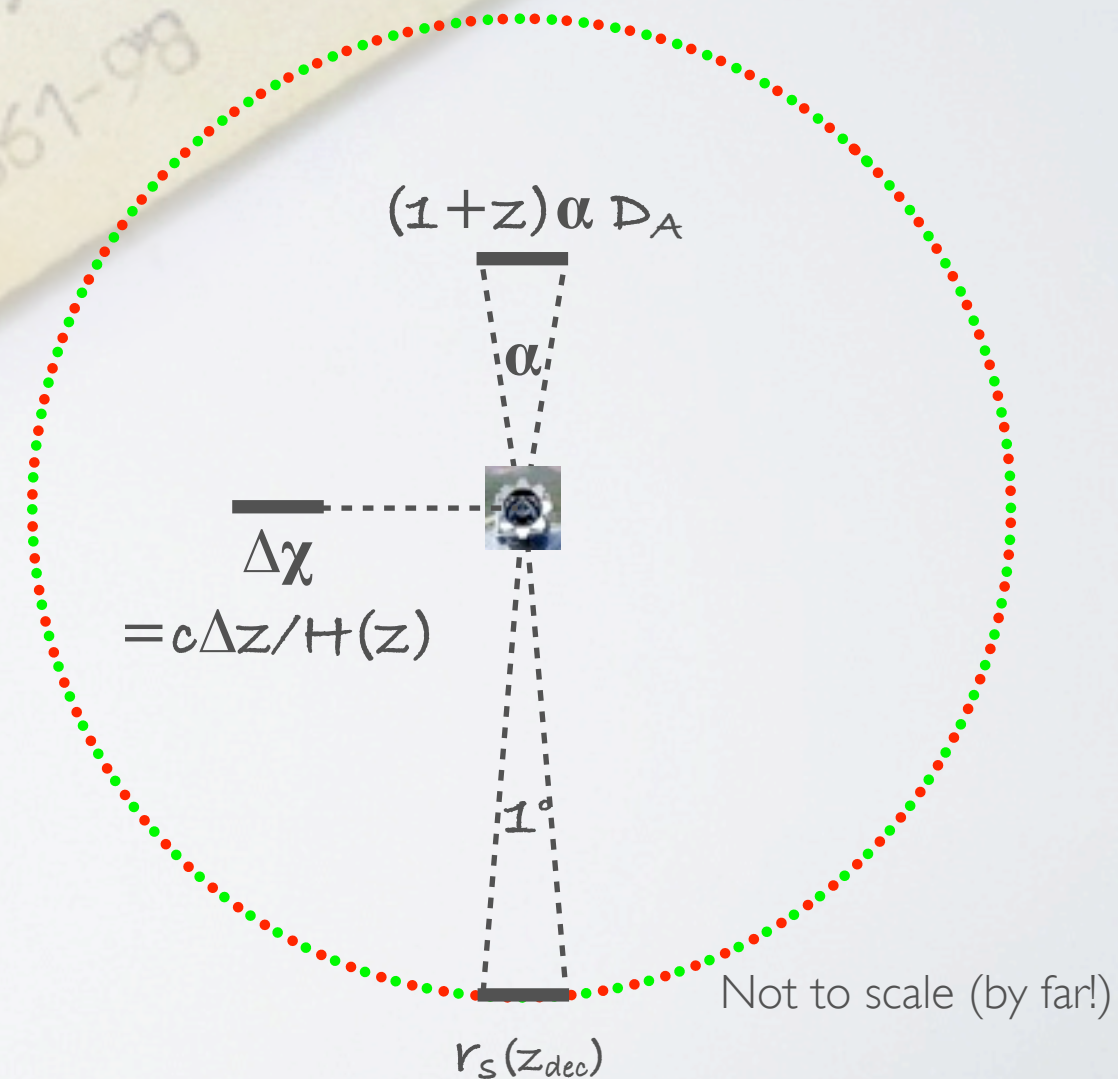
The Baryonic Acoustic Feature as a Standard Ruler



Larson et al. (2010)

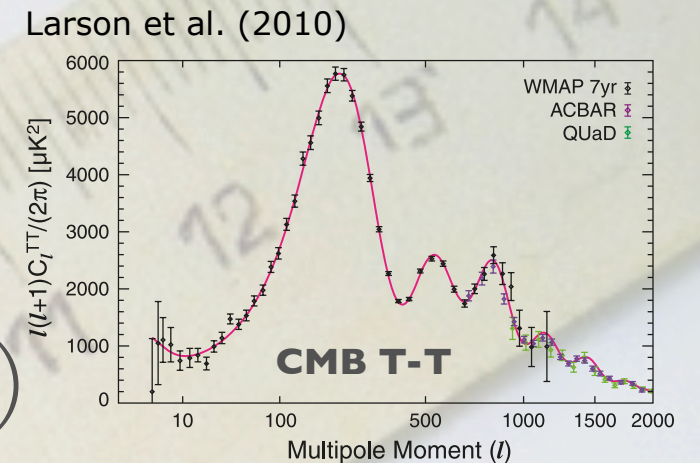


Surface of last scattering
 $z \sim 1100$



The Baryonic Acoustic Feature as a Standard Ruler

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

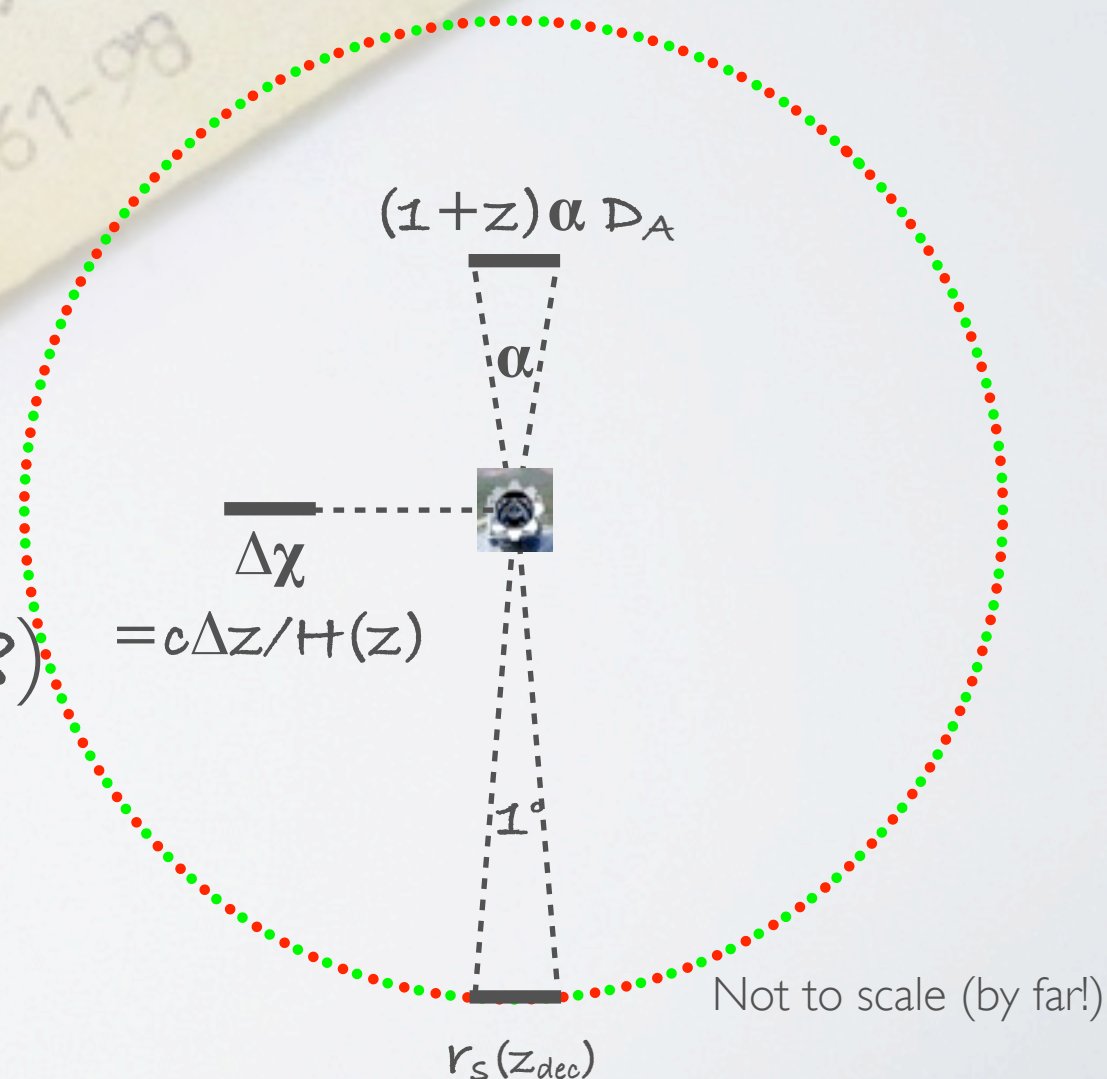


Late Universe :
SDSS-II, -III
LRGs ($z \sim 0.3, 0.6$)
QSOs Lyman- α Forest ($z > 2.5$)

Surface of last scattering
 $z \sim 1100$

Wiggle-Z
Blue Galaxies ($z \sim 0.2, 0.4, 0.6, 0.8$)

Galaxy Clusters

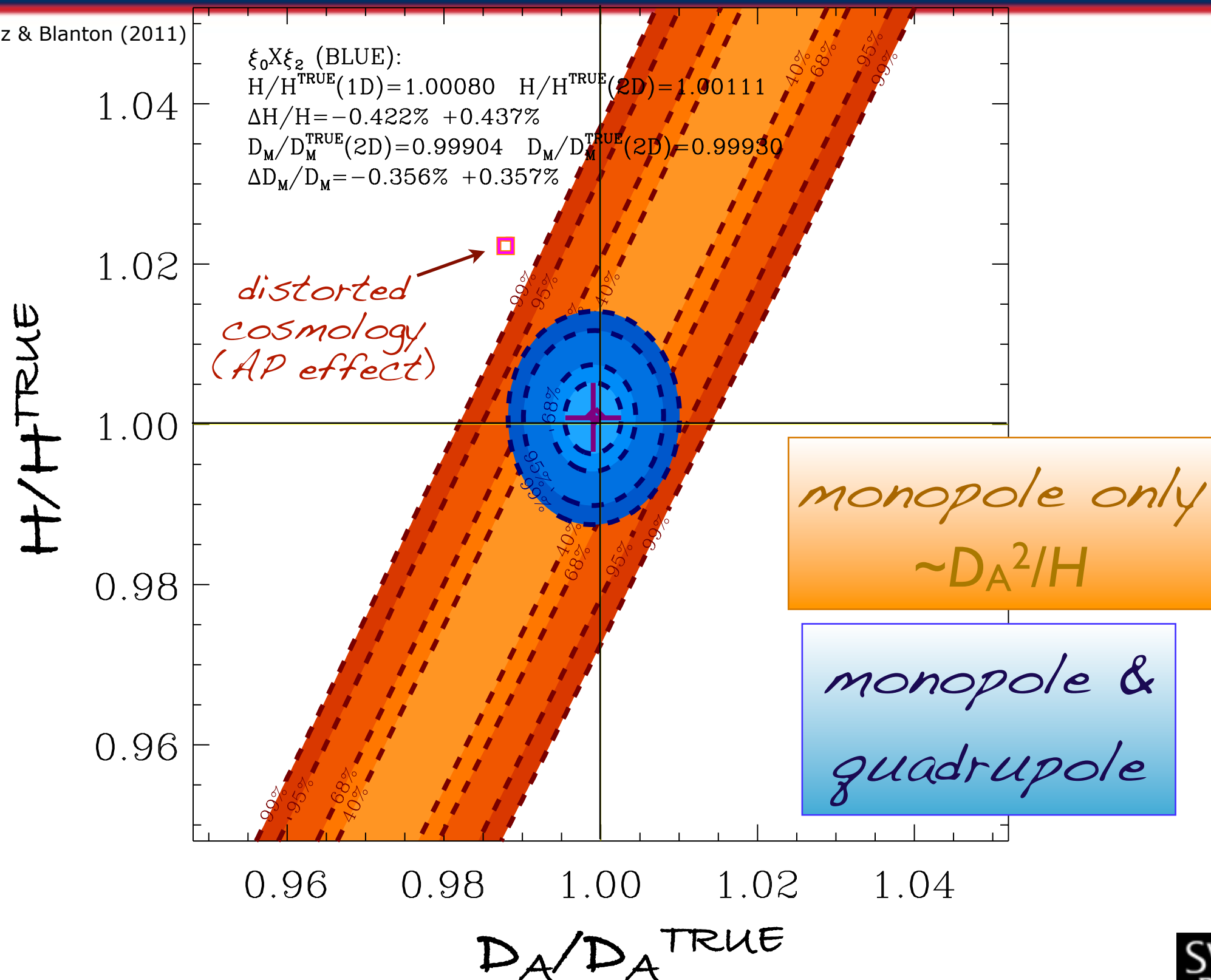




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Beyond the Monopole: The Importance of Anisotropic Clustering

Kazin, Sánchez & Blanton (2011)





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

*Most of the plots here are from
mock catalogues.*



- 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: $N_{RR}(\mu) \neq \text{constant}$



Redshift Distortions: Dynamical and Geometrical

Dynamical: squashing (Kaiser 1987), Finger of God

comoving distance

z_{obs}

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

Geometrical: AP effect (Alcock & Paczynski 1979)



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The Alcock-Paczynski Effect

In the **anisotropic**
Baryonic Acoustic Feature

$$H \times D_A$$

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

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

$$r_1 = r_2$$

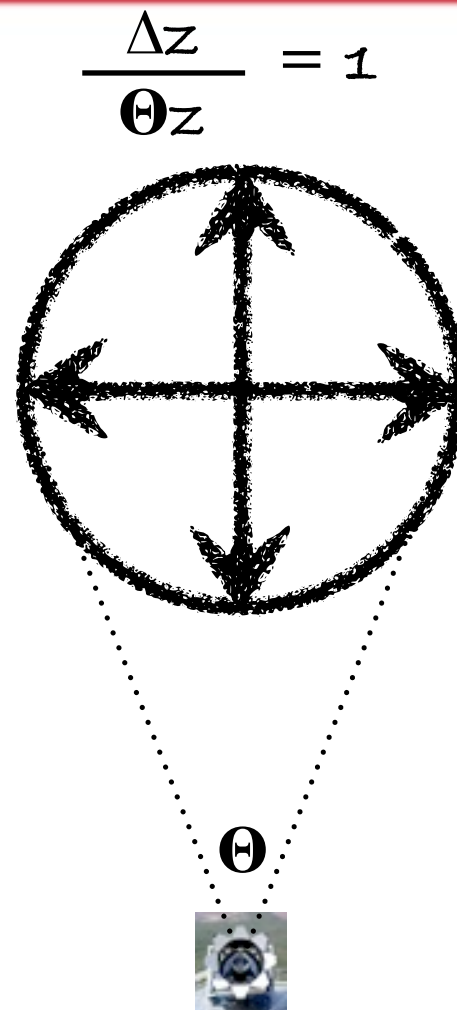
$$H \times D_A = c \Delta z / (1+z) / \Theta$$

In the **isotropic**
Baryonic Acoustic Feature

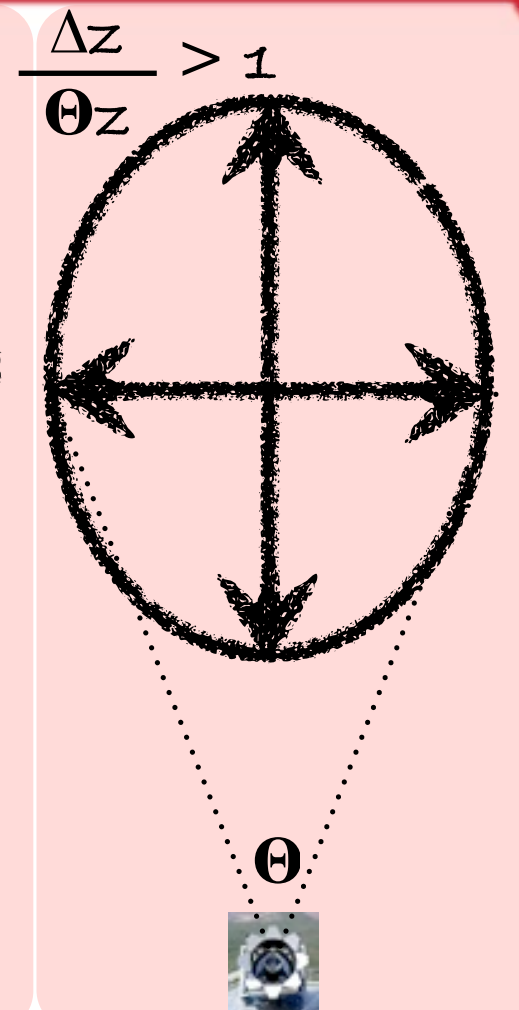
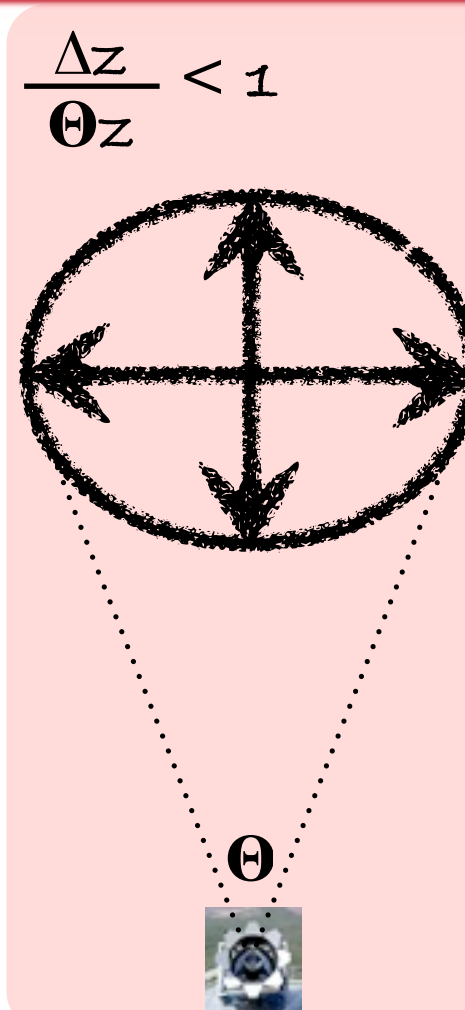
$$D_A^2 / H$$

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

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



Real Space



Redshift Space

$\longleftrightarrow \Theta z$
 $\updownarrow \Delta z$

$$\frac{\Delta z}{\Theta z} = z^{-1} [\Omega_\Lambda + \Omega_{m0} (1+z)^3]^{1/2} \int_1^{z+1} dy (\Omega_\Lambda + \Omega_{m0} y^3)^{-1/2}$$

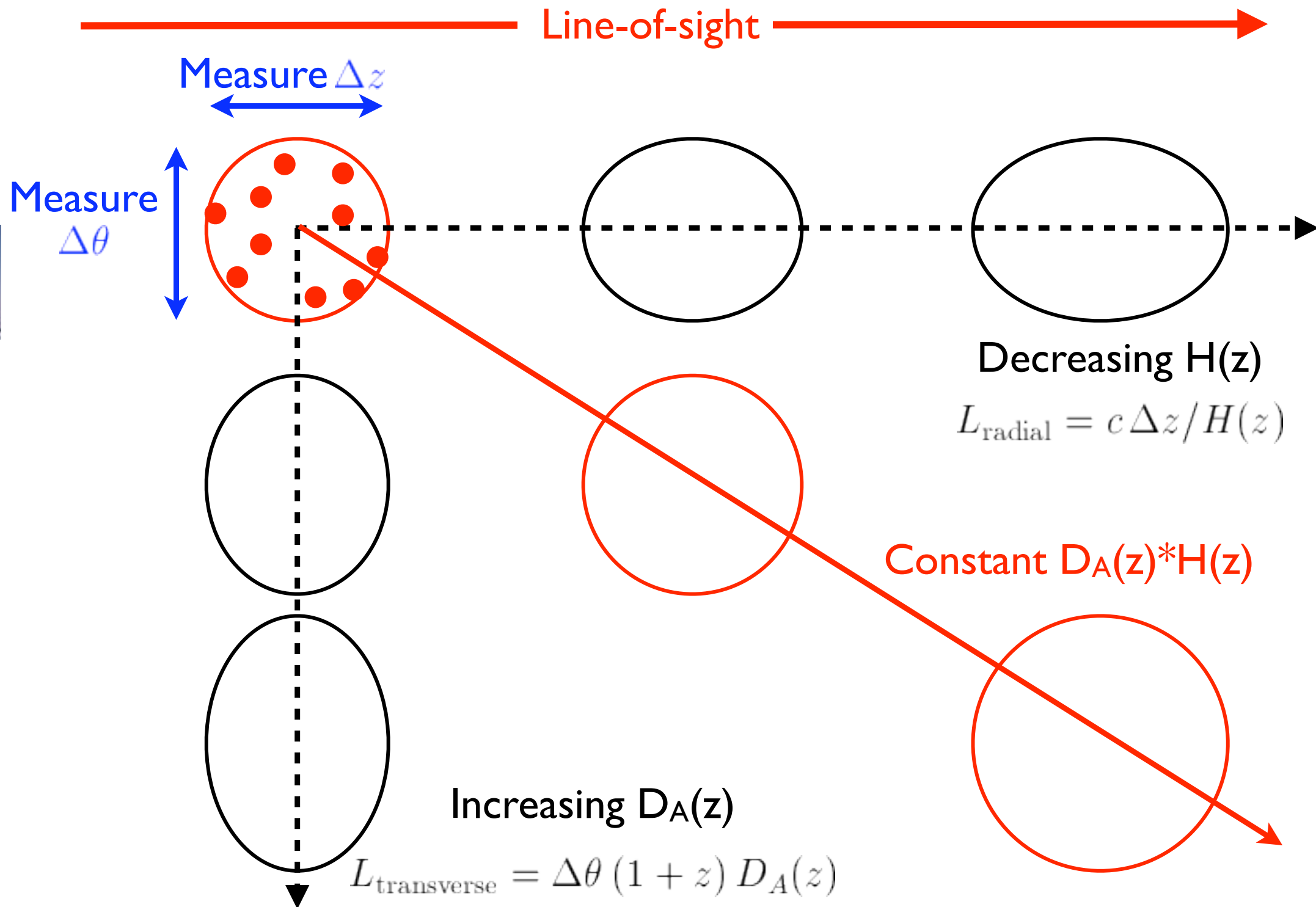


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The Alcock-Paczynski Effect

Plot Credit: Chris Blake





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)


 $\xi(s \sim \text{BA feature scale})$

 $s \text{ [h}^{-1}\text{Mpc]}$


LArge **S**uite of
DArk **MA**tter **S**ims

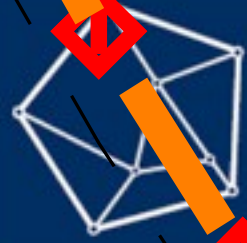


Emphasize on many
observational effects



Results in **most**
realistic uncertainties
of clustering of the SDSS-II
LRGs

public mocks: <http://lss.phy.vanderbilt.edu/lasdamas/>



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Geometrical Distortion Effects on the 2-Pt Correlation Function

ξ_0

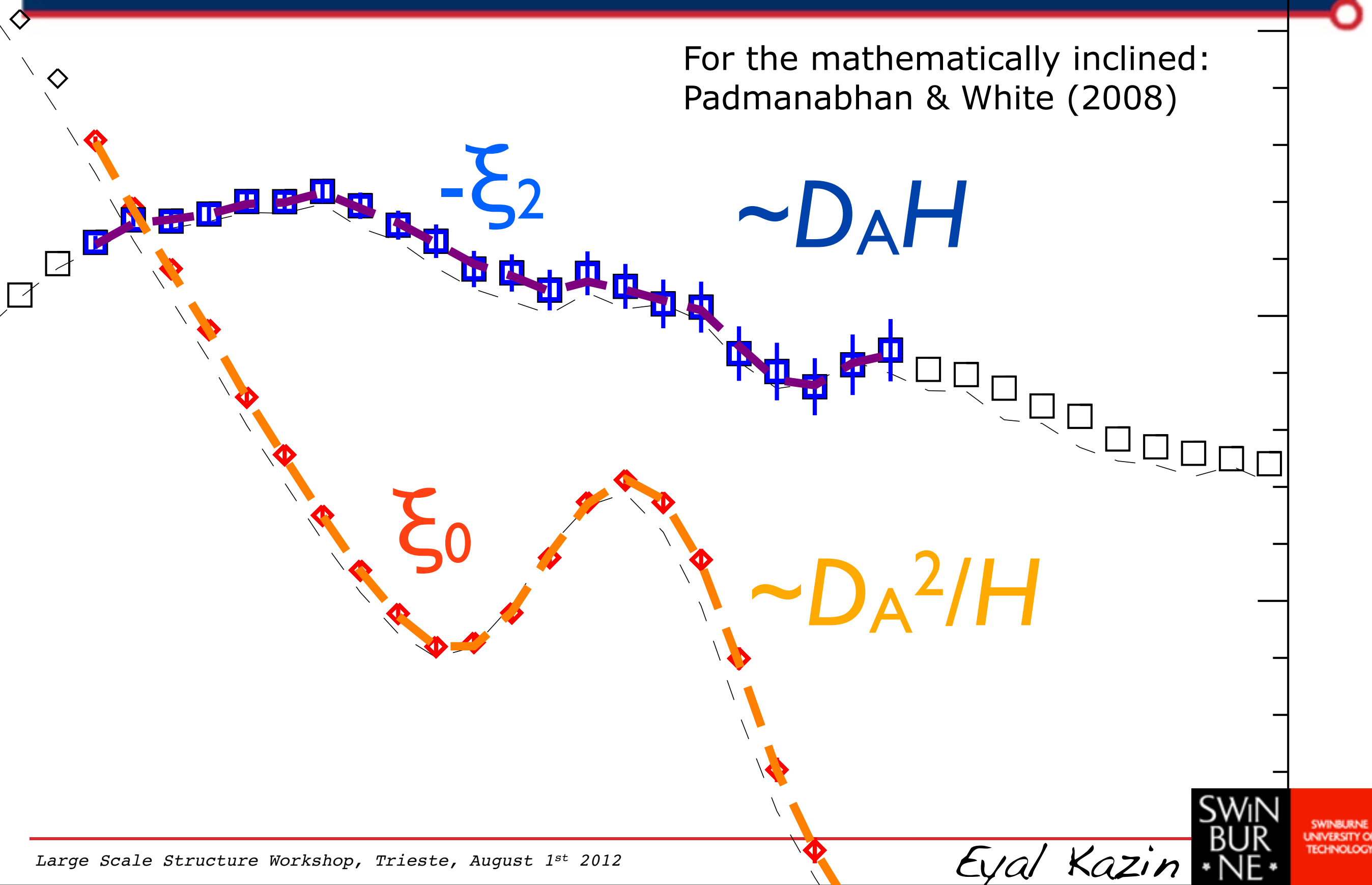
- Template (*here I use the true mock signal*)
- ◆ ``data'' (*here I use mock signal affected by AP*)
- - - fit (*here I fit Template to ``data'' varying H and D_A*)



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Geometrical Distortion Effects on the Clustering Multipoles

For the mathematically inclined:
Padmanabhan & White (2008)

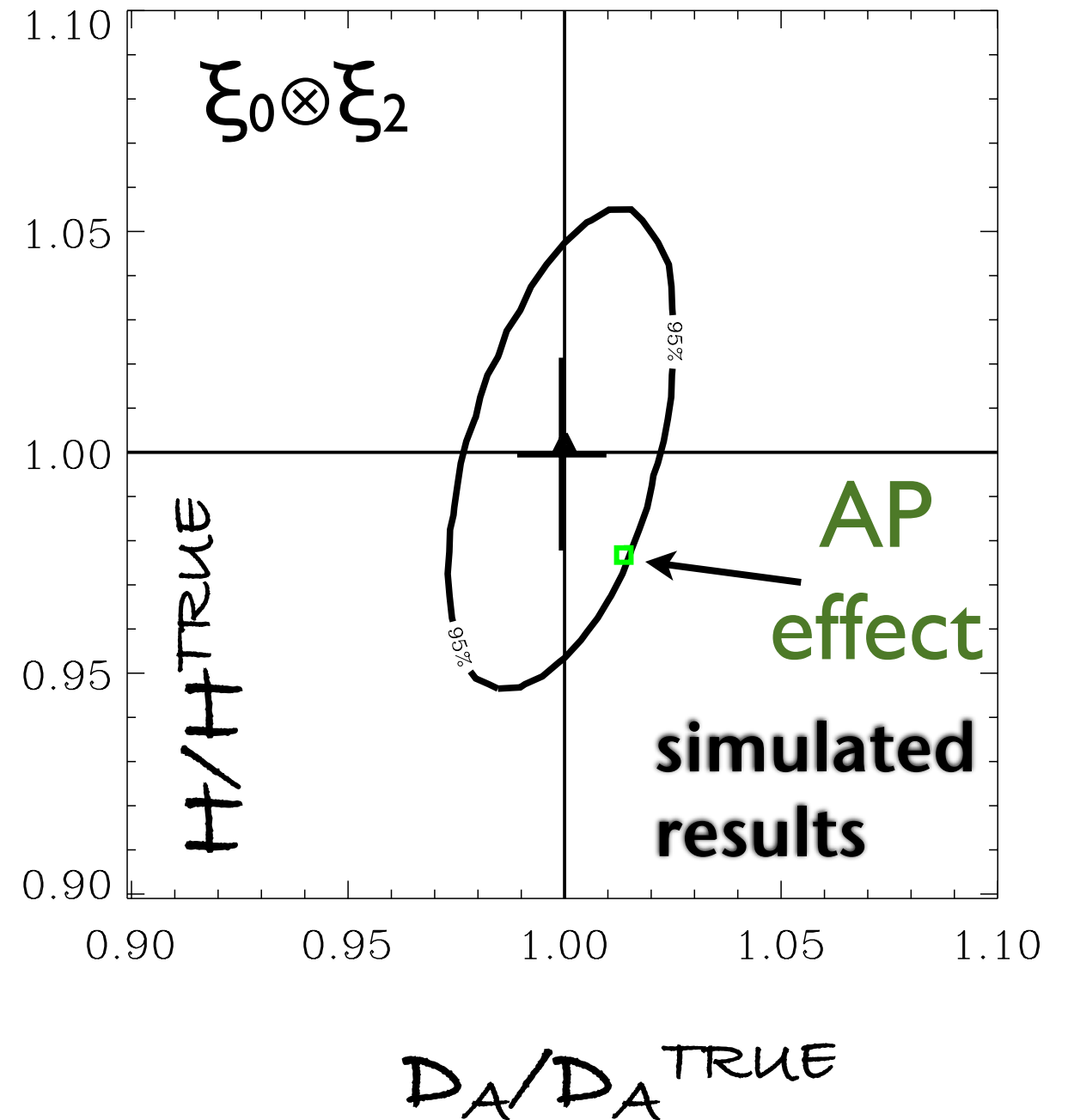
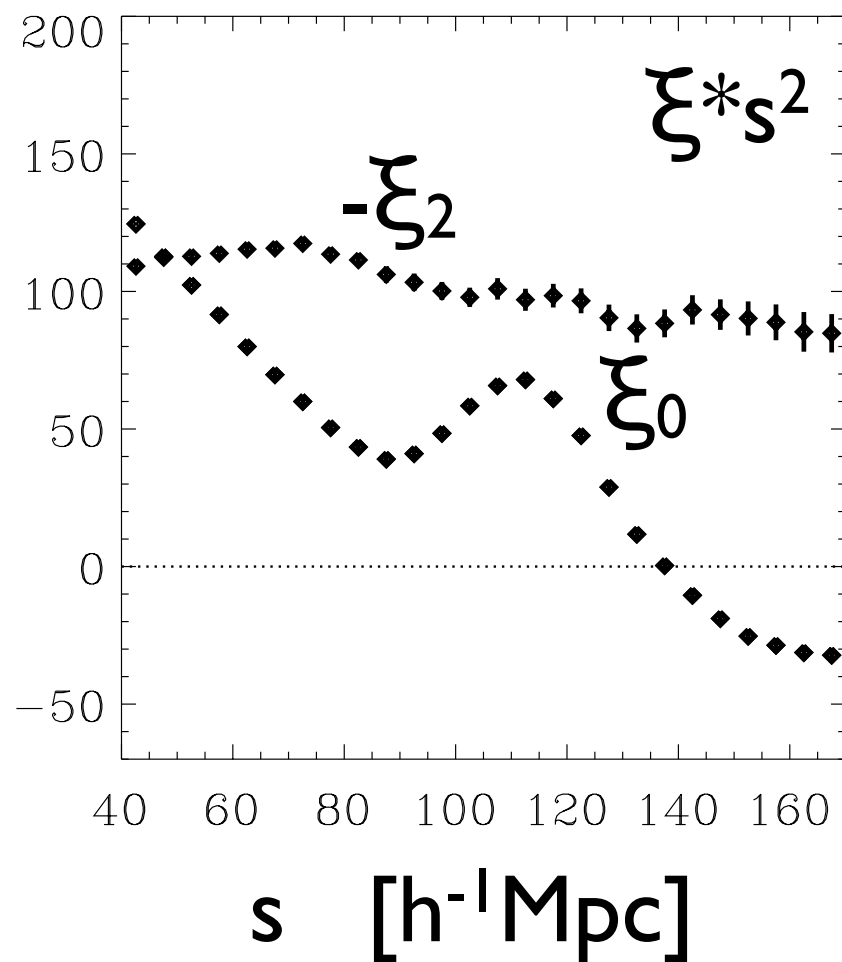




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Extra Information from the Hexadecapole

KAZIN, SANCHEZ & BLANTON (2011)

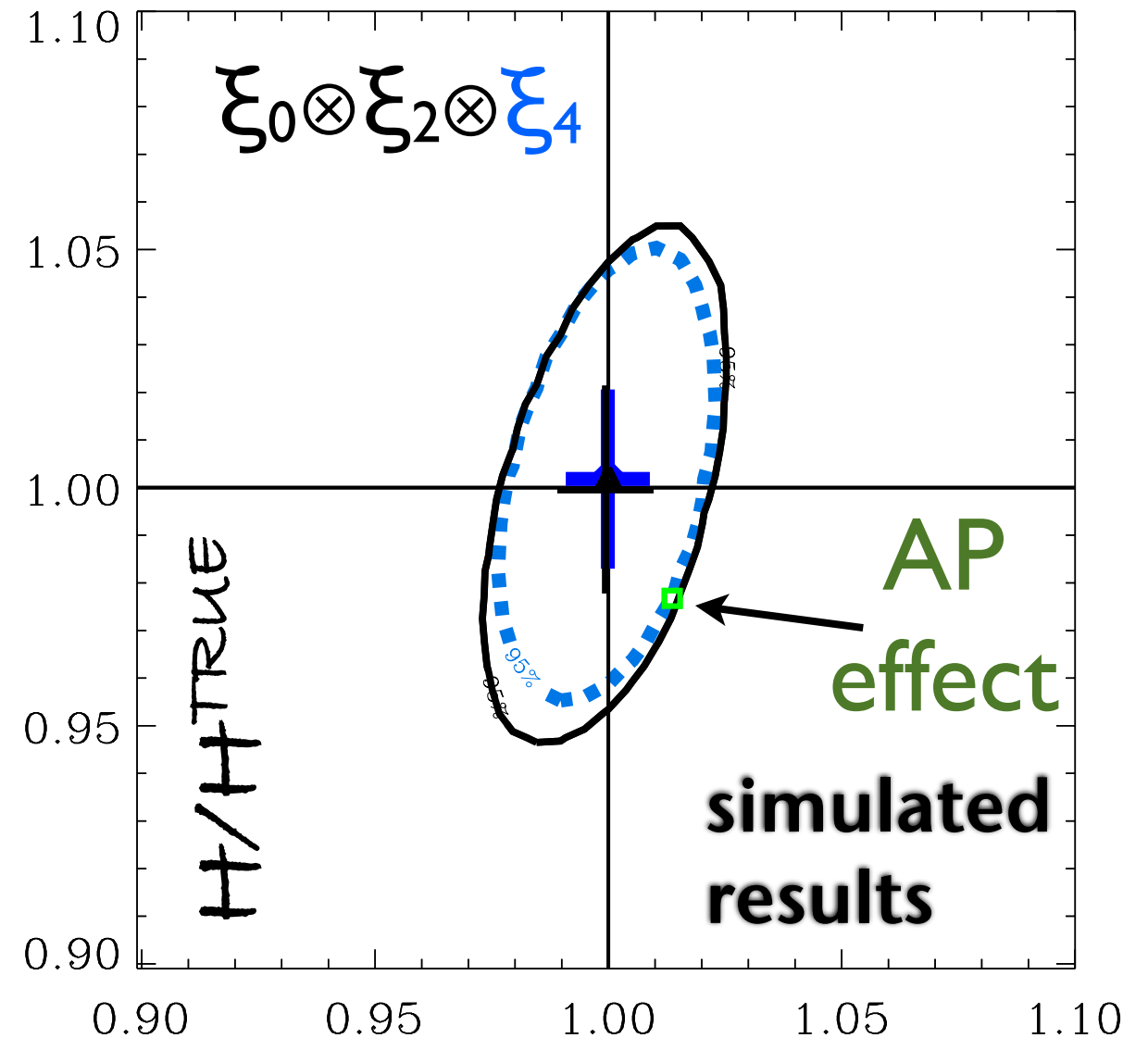
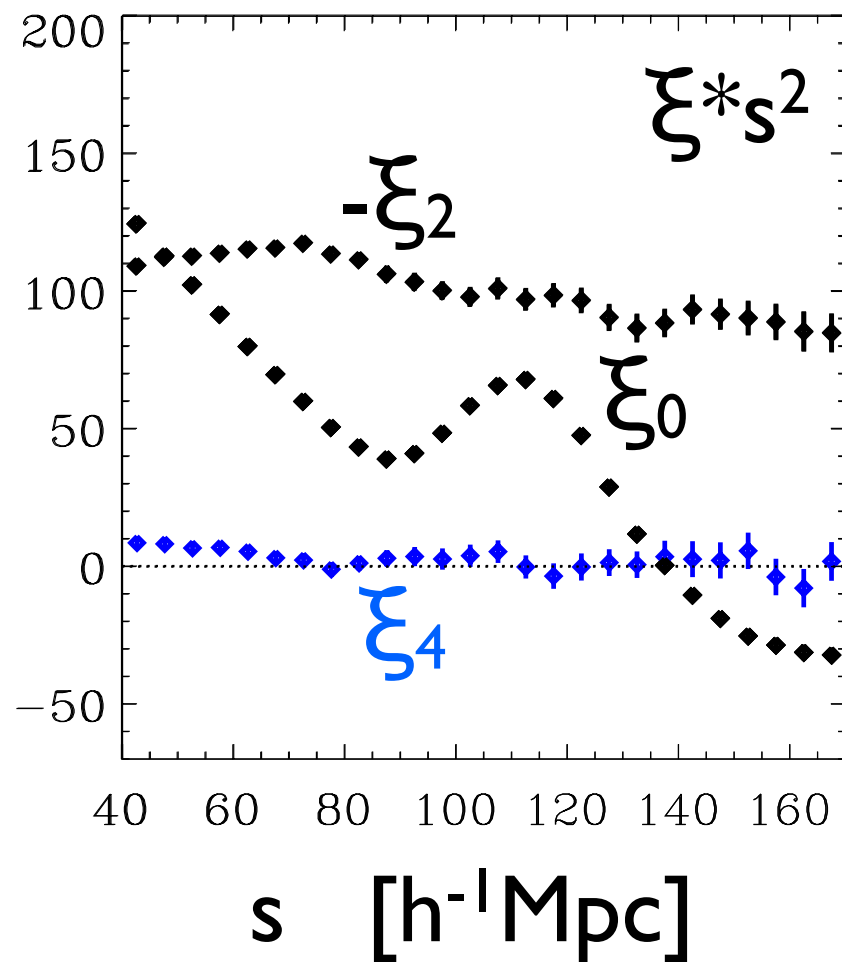




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Extra Information from the Hexadecapole

KAZIN, SANCHEZ & BLANTON (2011)



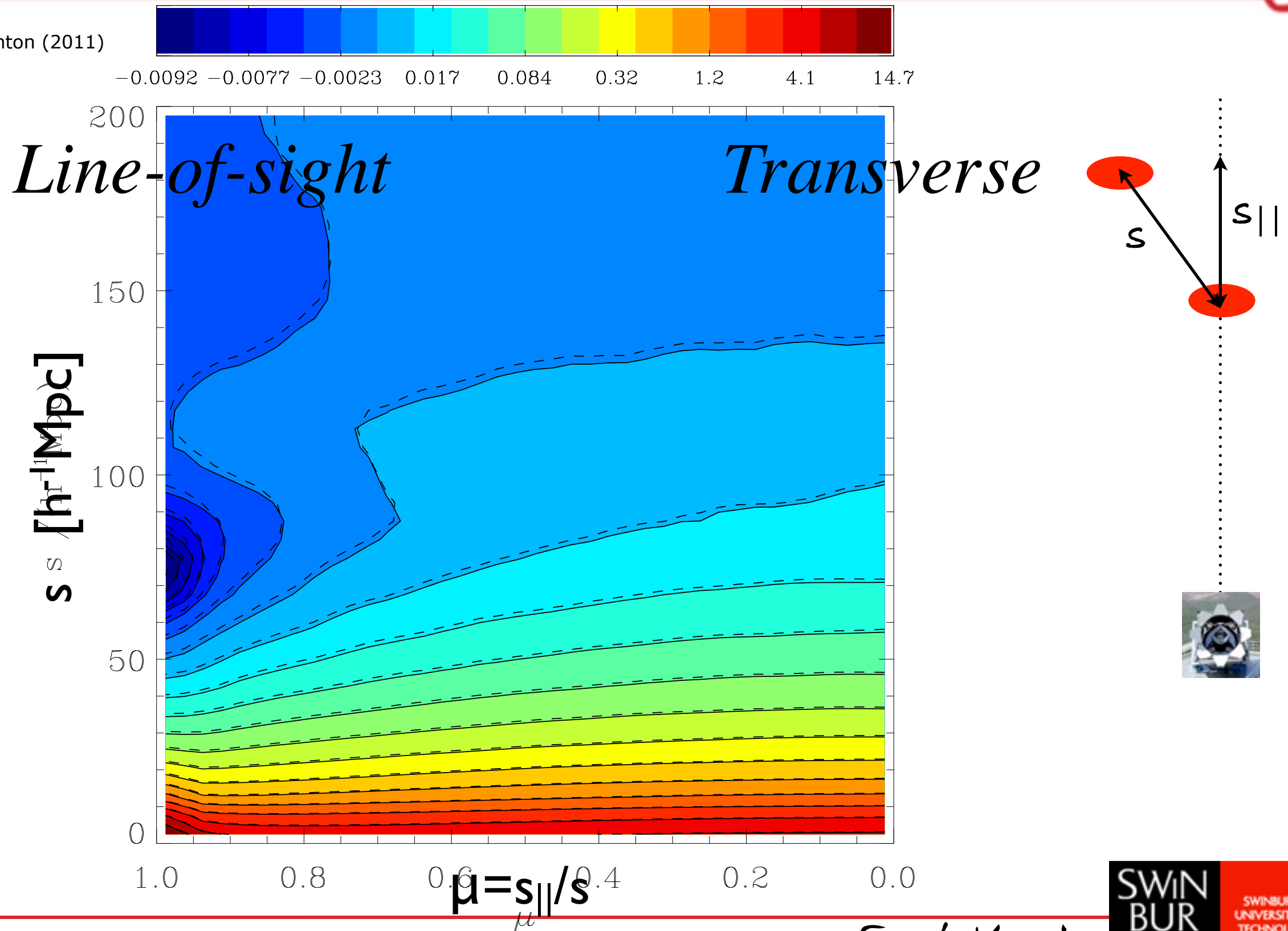
Hexadecapole ξ_4 improves constraints D_A/D_A^{TRUE}
(See also Taruya et al. 2011)



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

Kazin, Sanchez & Blanton (2011)

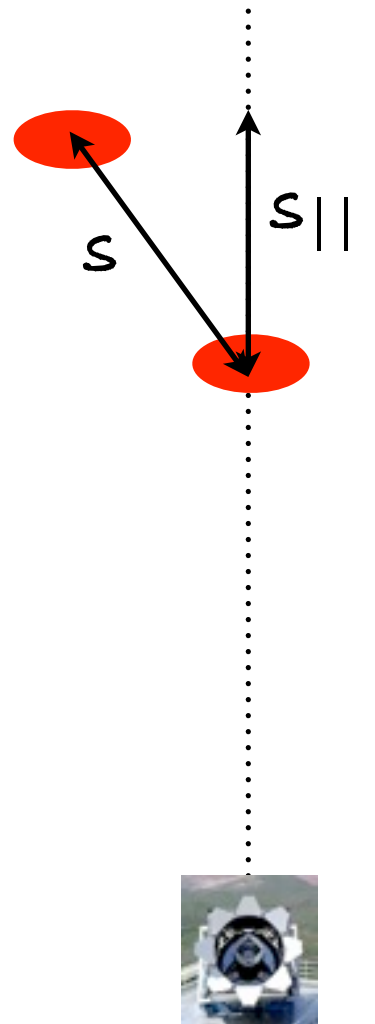
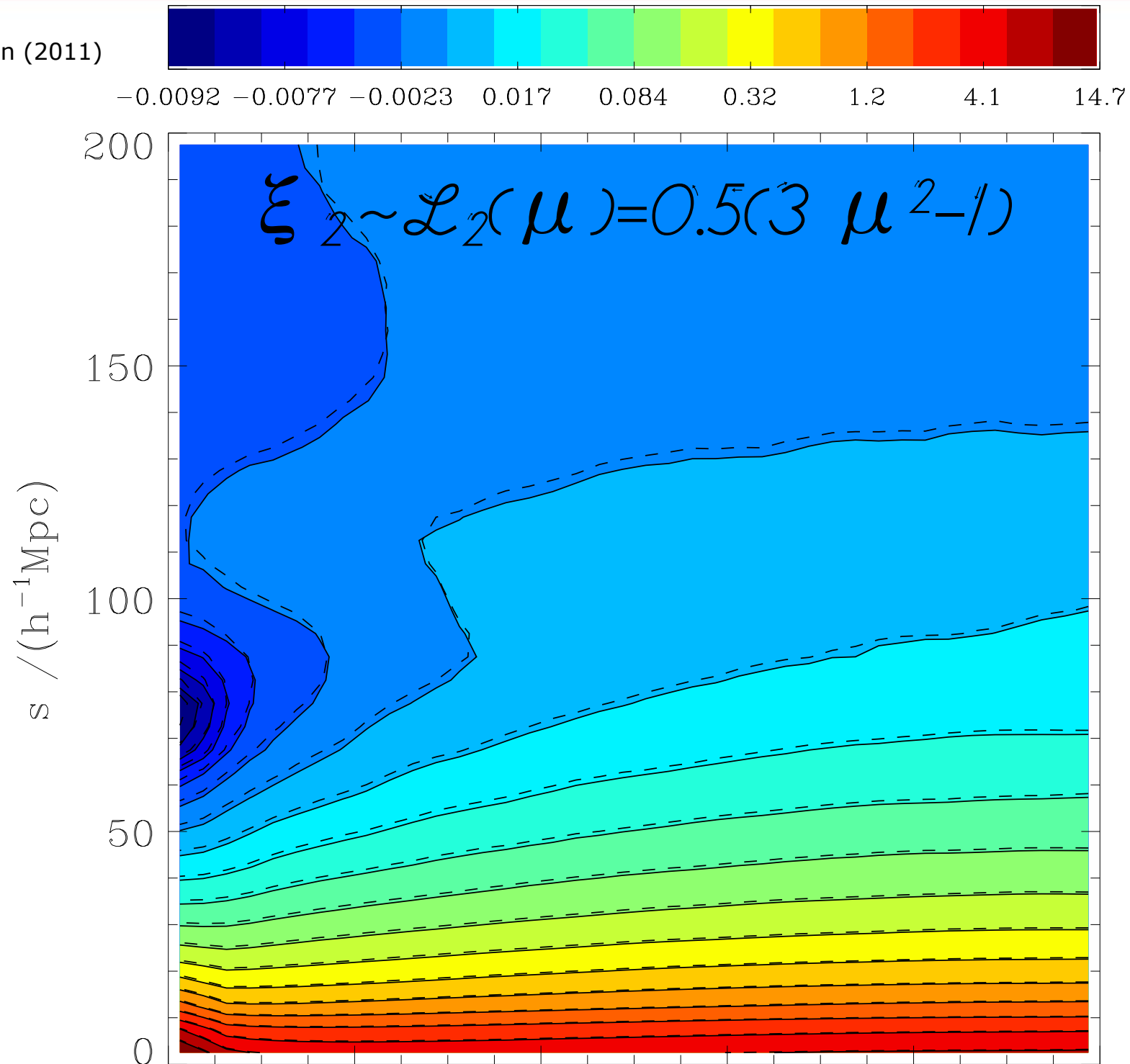




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Splitting $\xi(\mu, s)$ to Multipoles $\xi_\ell(s)$

Kazin, Sanchez & Blanton (2011)



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

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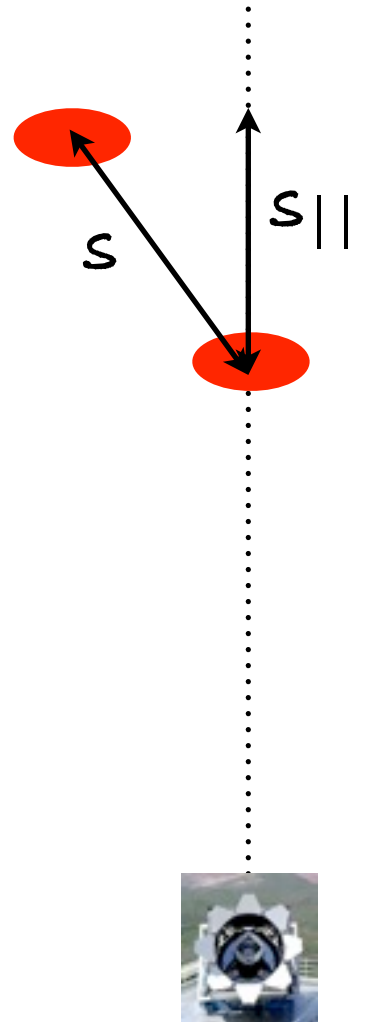
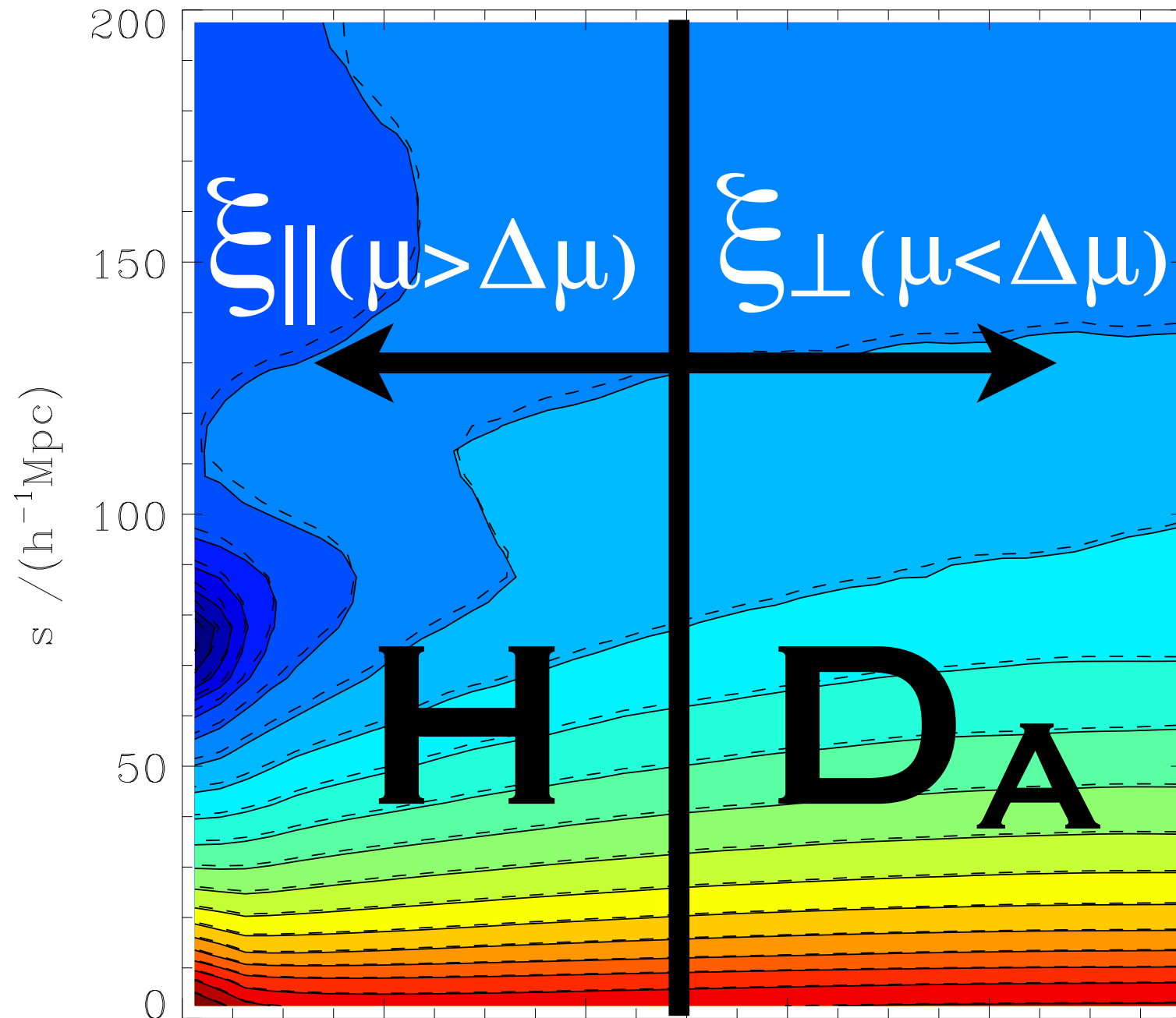
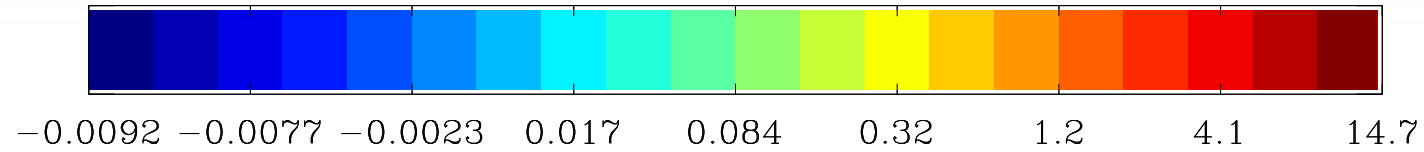




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Splitting $\xi(\mu, s)$ to Wedges $\xi(\Delta\mu, s)$

Kazin, Sanchez & Blanton (2011)



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

Eyal Kazin

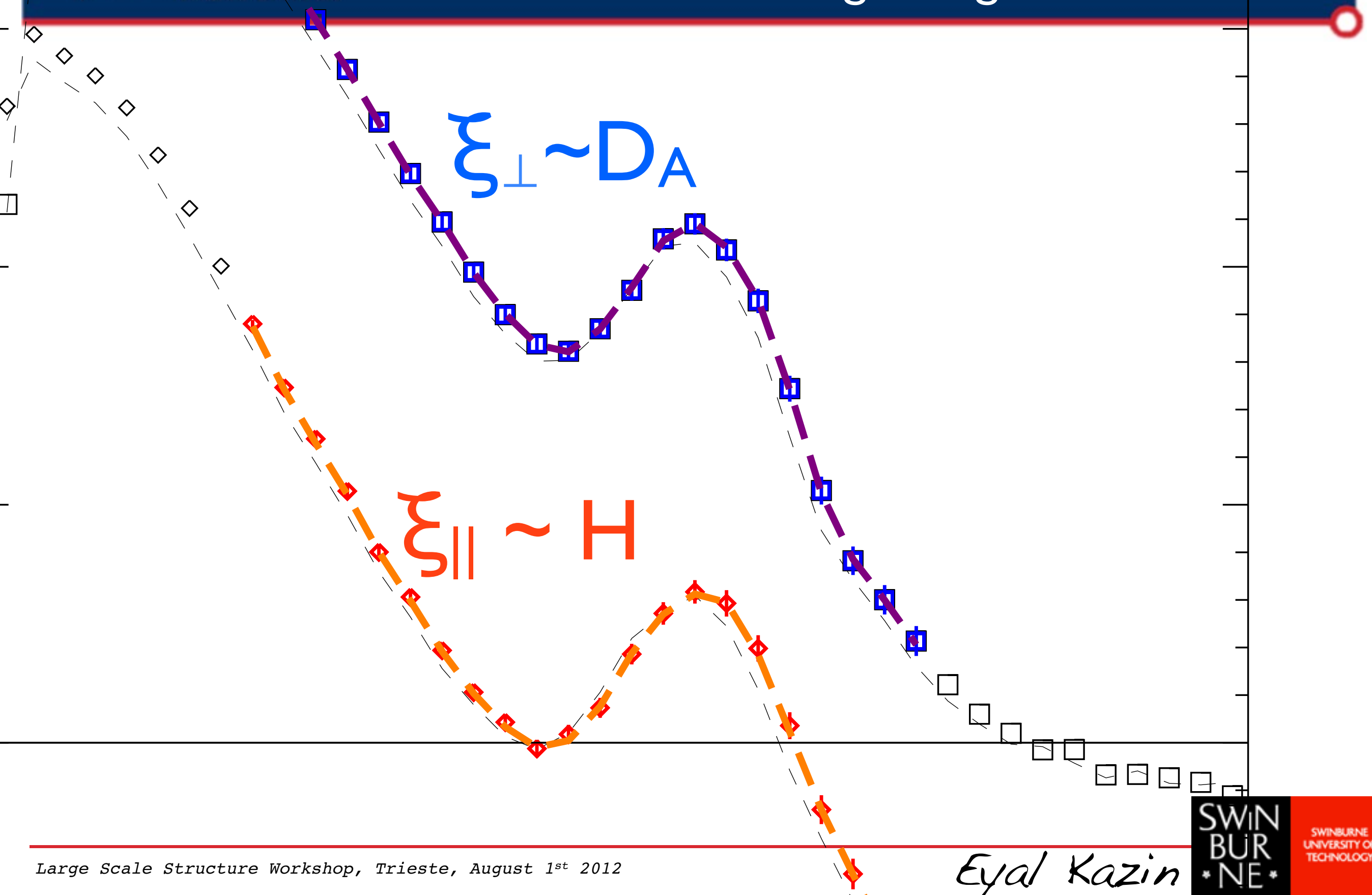
Large Scale Structure Workshop, Trieste, August 1st 2012





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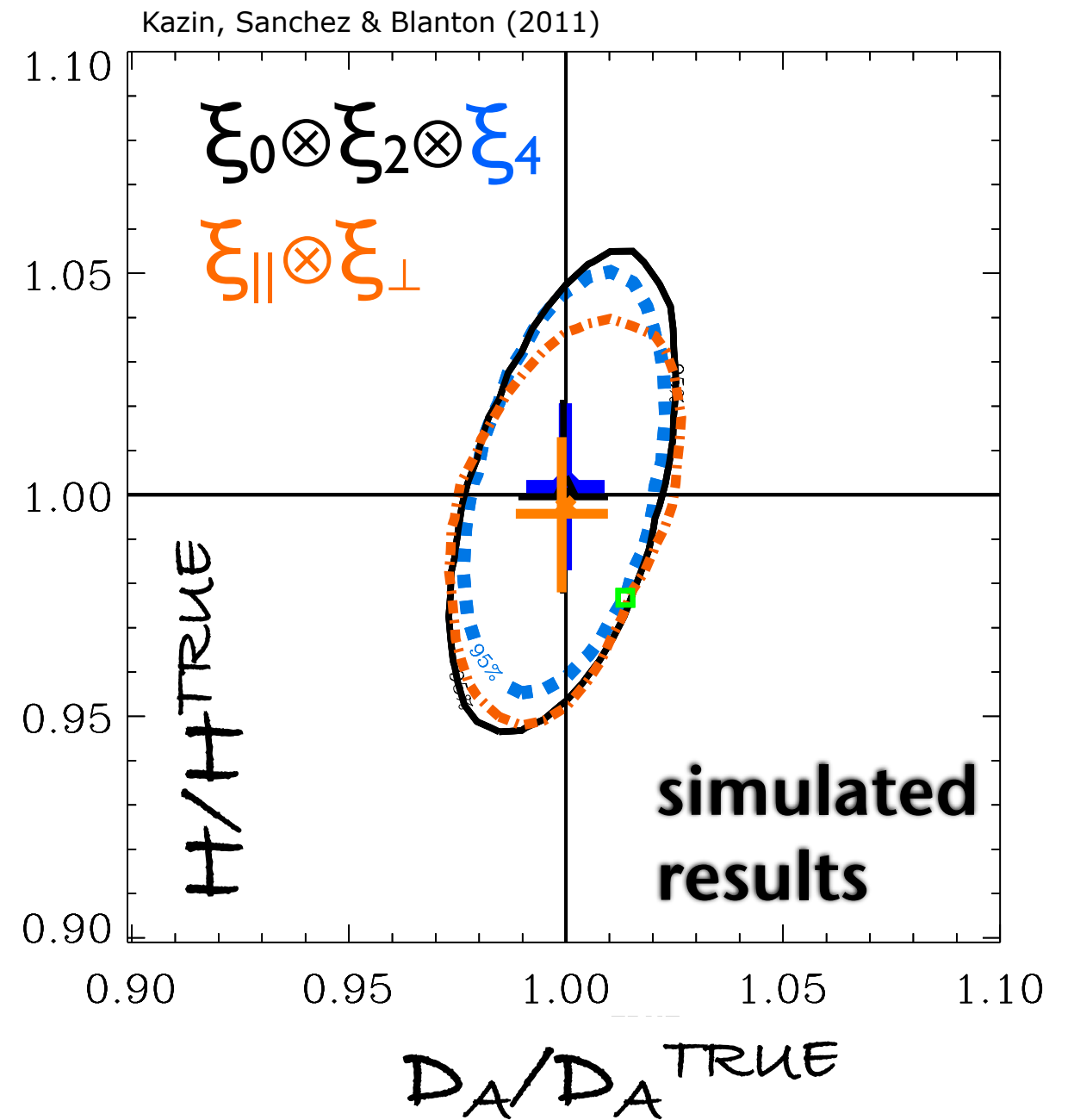
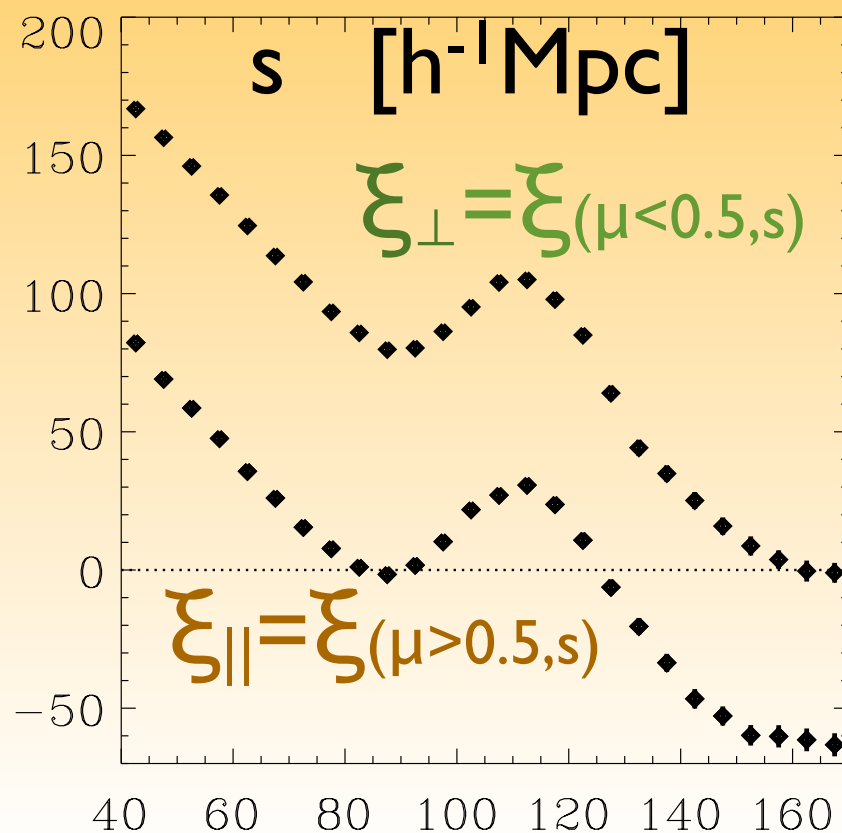
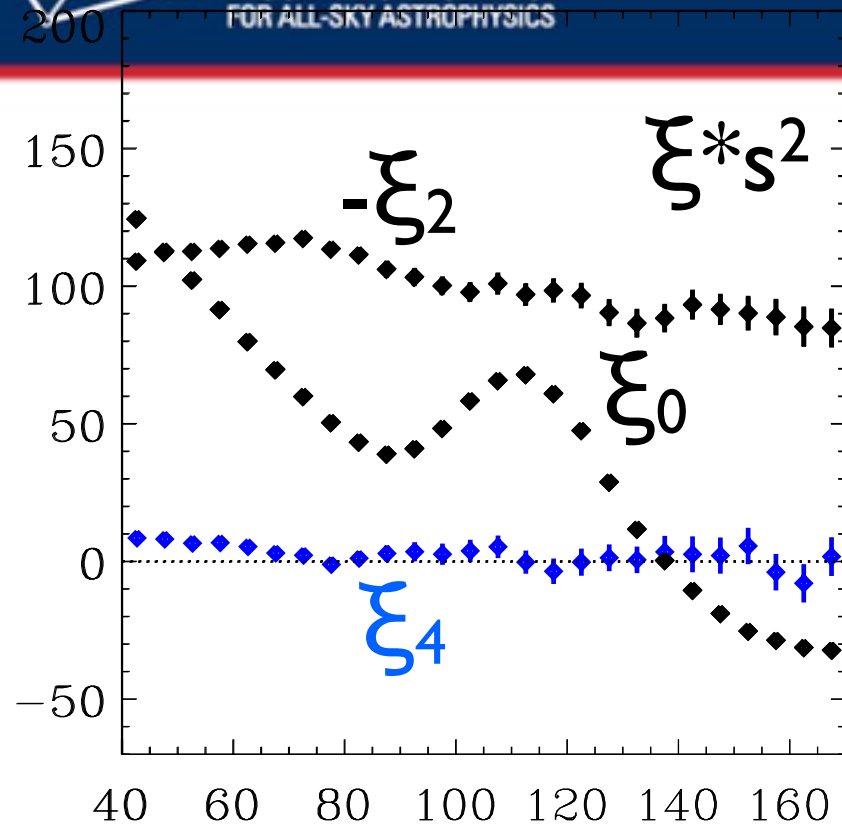
Geometrical Distortion Effects on the Clustering Wedges





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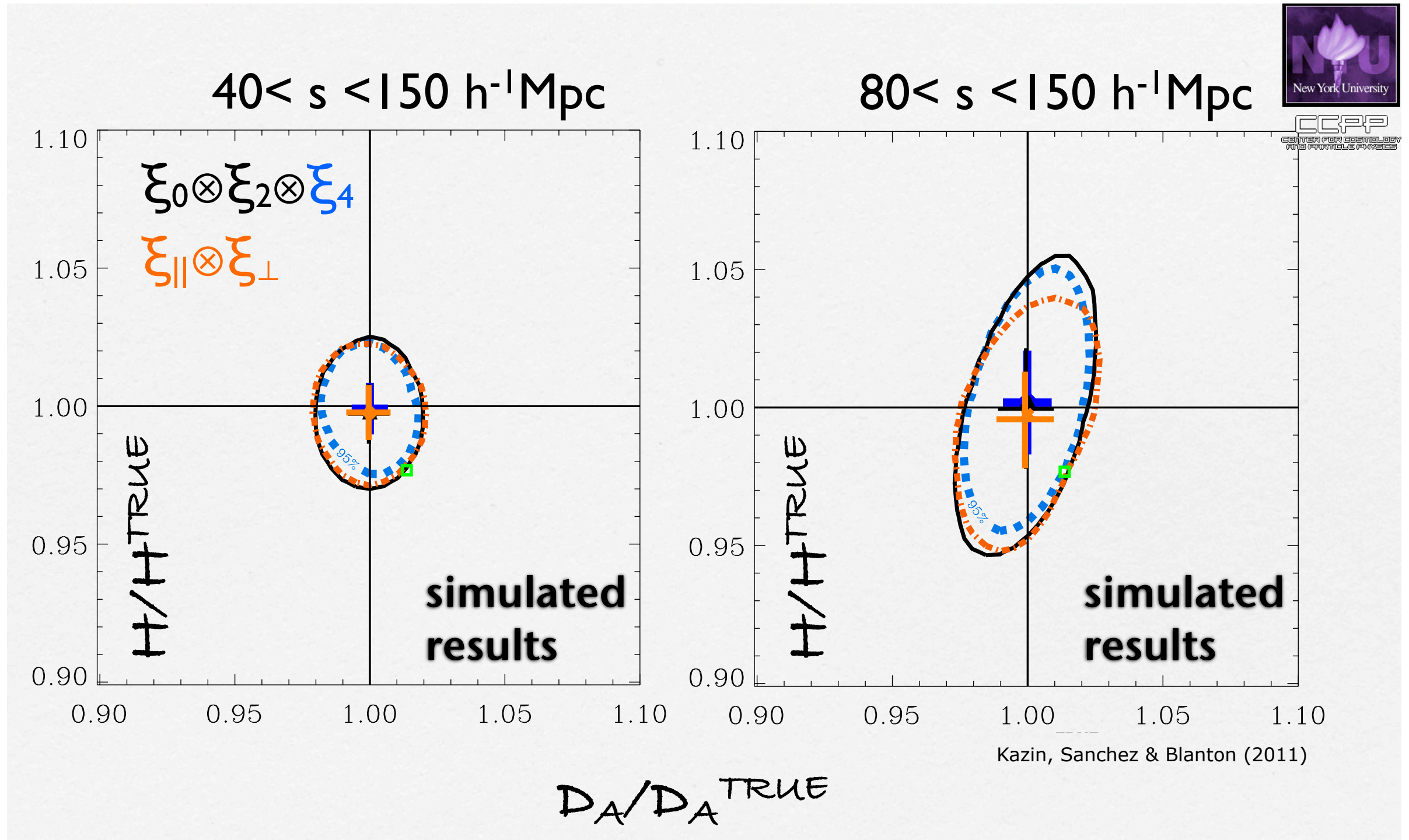
Wedges H , D_A Performance





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H, D_A information in the ξ Full Shape





Wedges: Basic Equations

Definition:

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

Basis Transform From Multipoles:

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

For $\Delta\mu=0.5$:

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



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

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

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

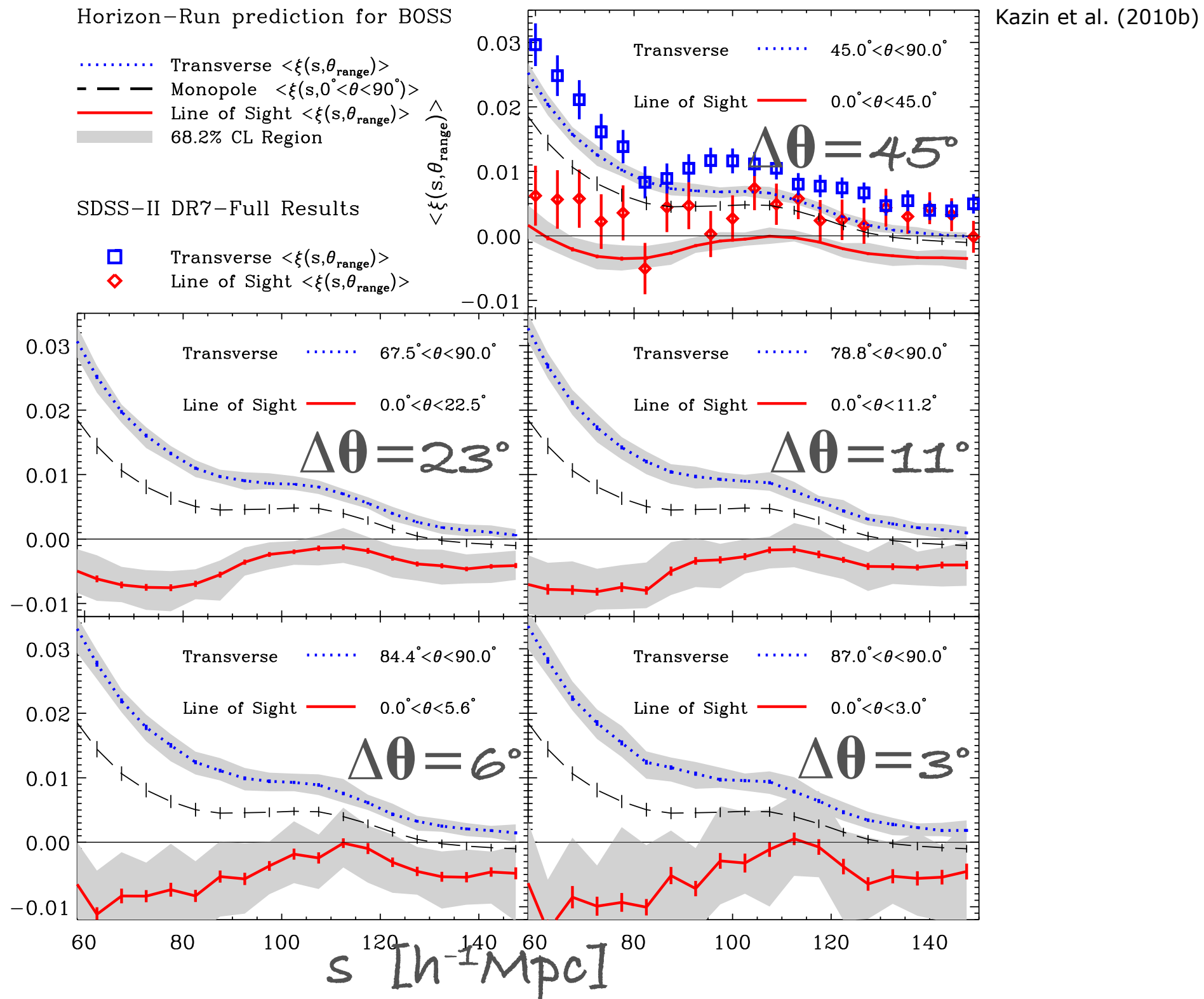
$$\mathcal{C}_{||}(\epsilon, \alpha) = \epsilon \left(-\frac{5}{4} \frac{d\xi_0(s)}{d \ln(s)} - \frac{19}{140} \frac{d\xi_2(s)}{d \ln(s)} + \frac{213}{140} \xi_2(\alpha s) \right)$$

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



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BOSS 2014 Predicted Wedges $\xi(\Delta\mu, s)$



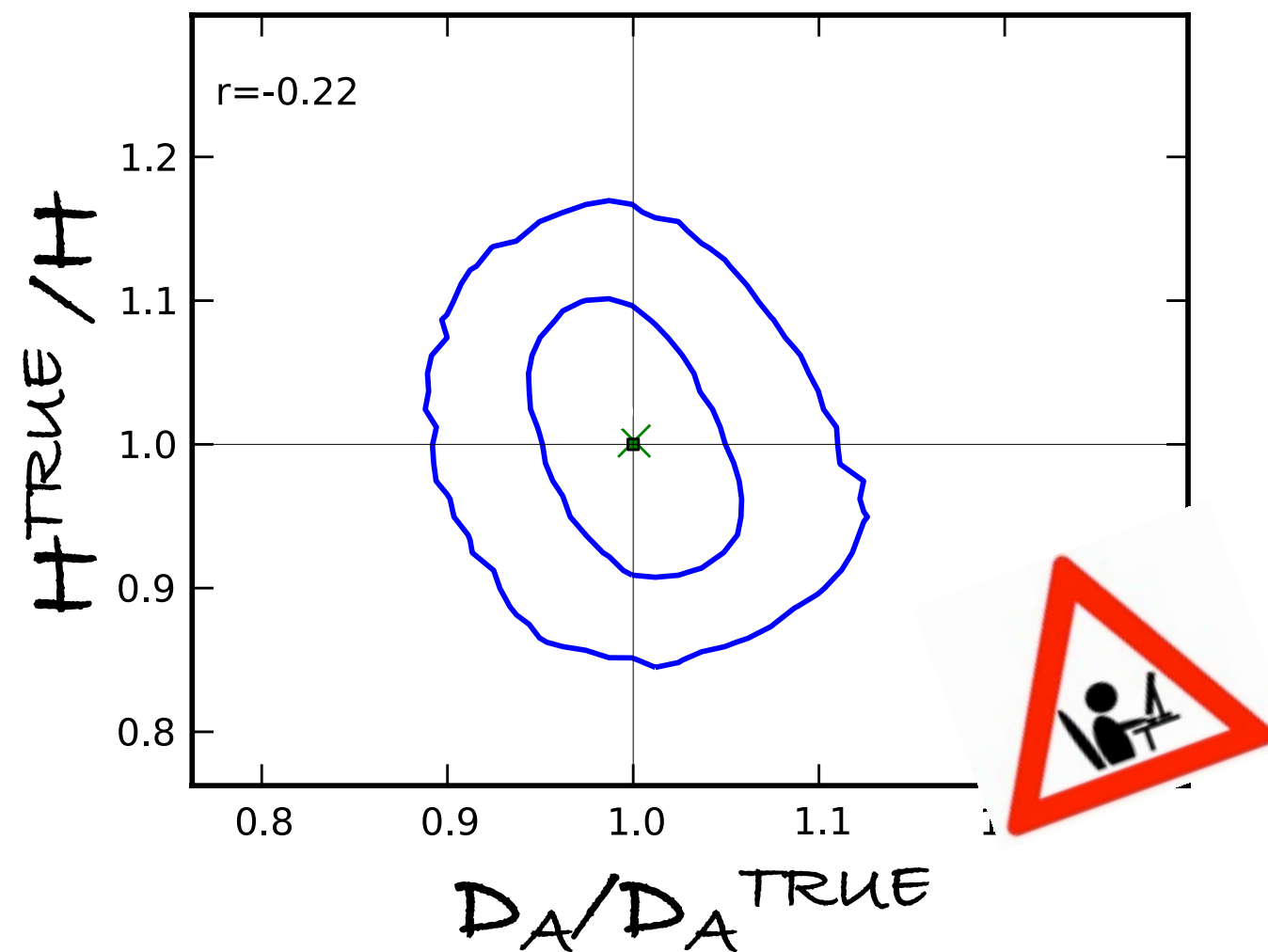
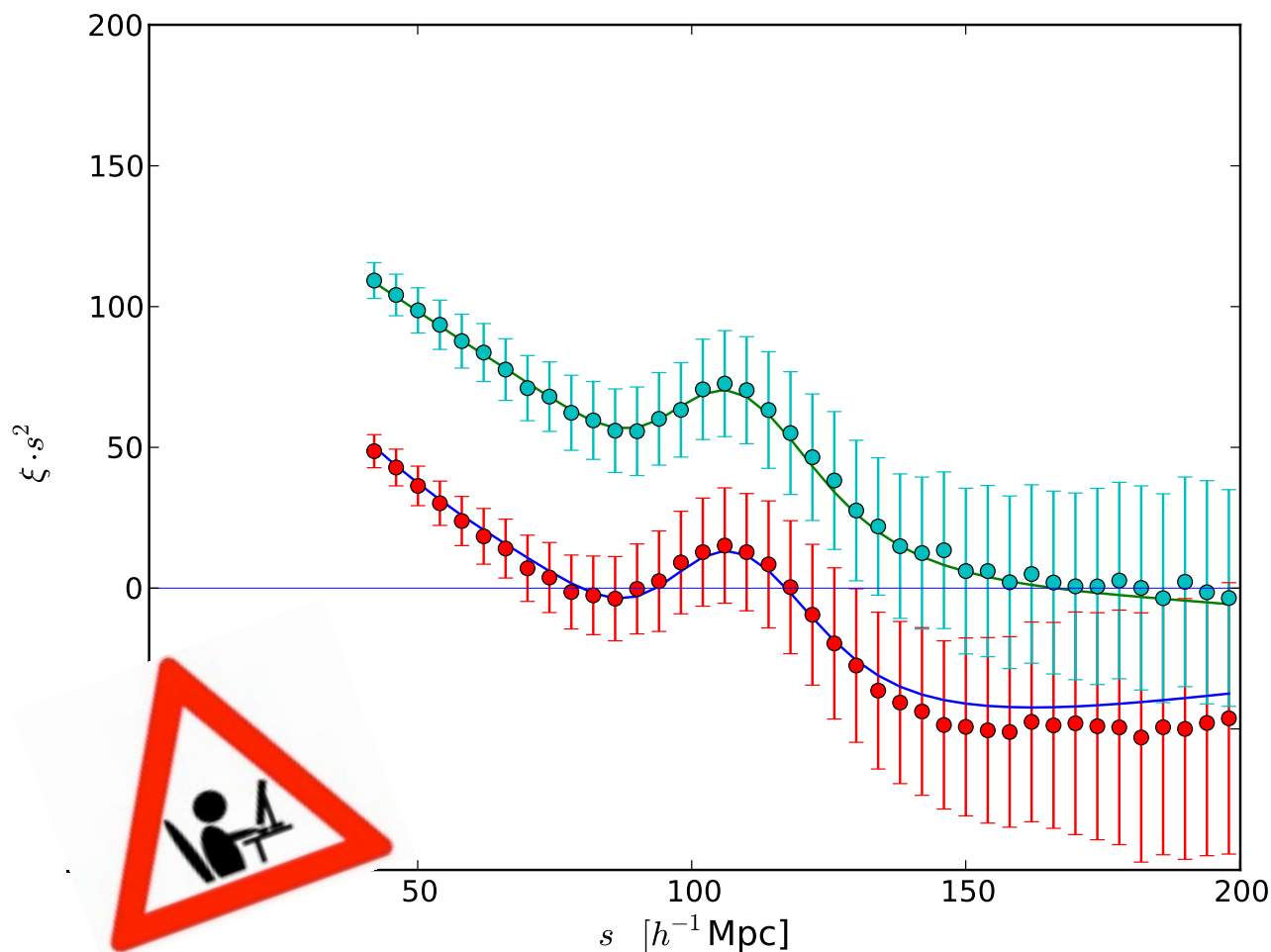


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Testing Model on Mock Wedges

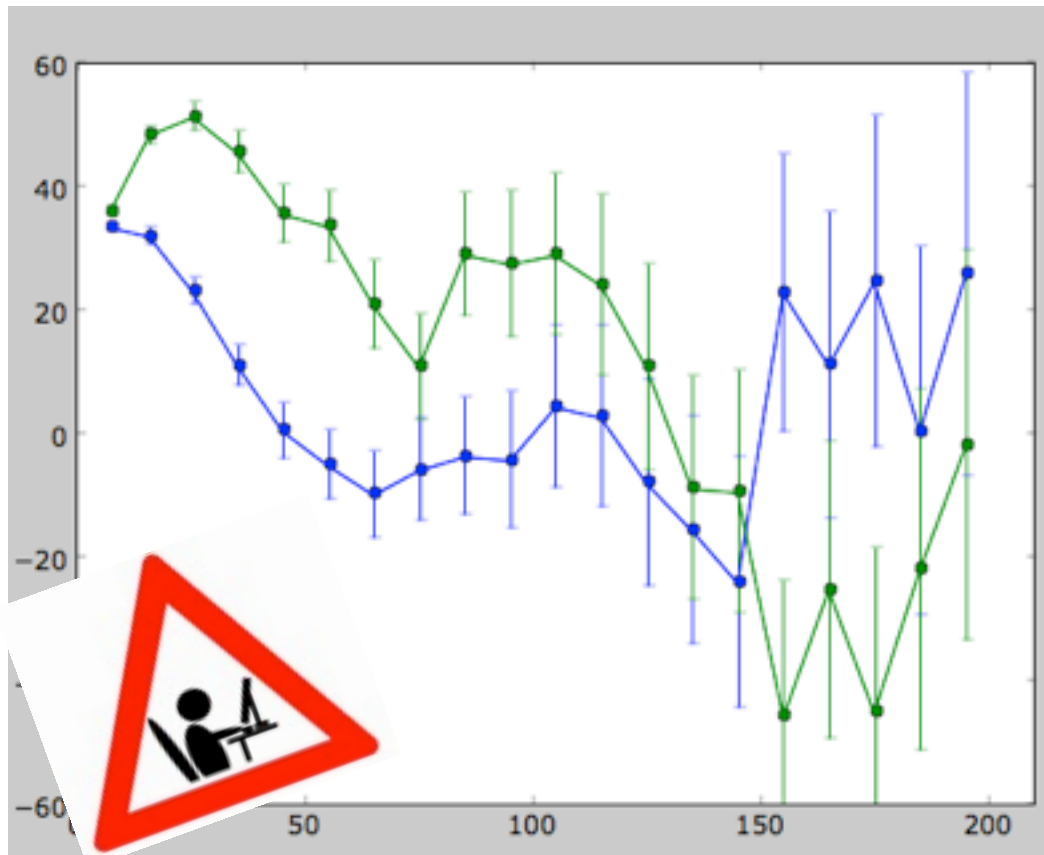
Simulated Data: BOSS PTHalos (of Manera et al. 2012)

Kazin, Sánchez & the SDSS (in prep.)



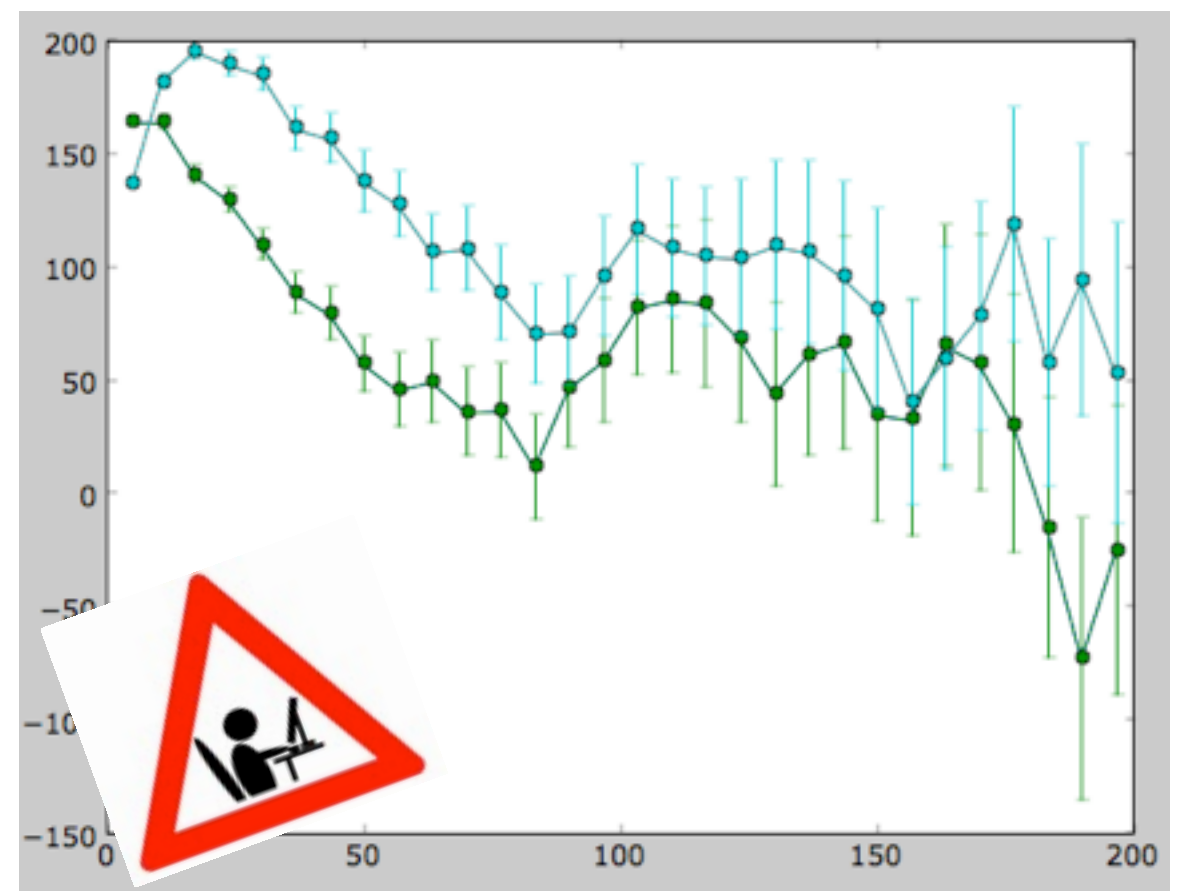
Clustering Wedges in the Data

Davis, Kazin & the WiggleZ (in prep.)



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

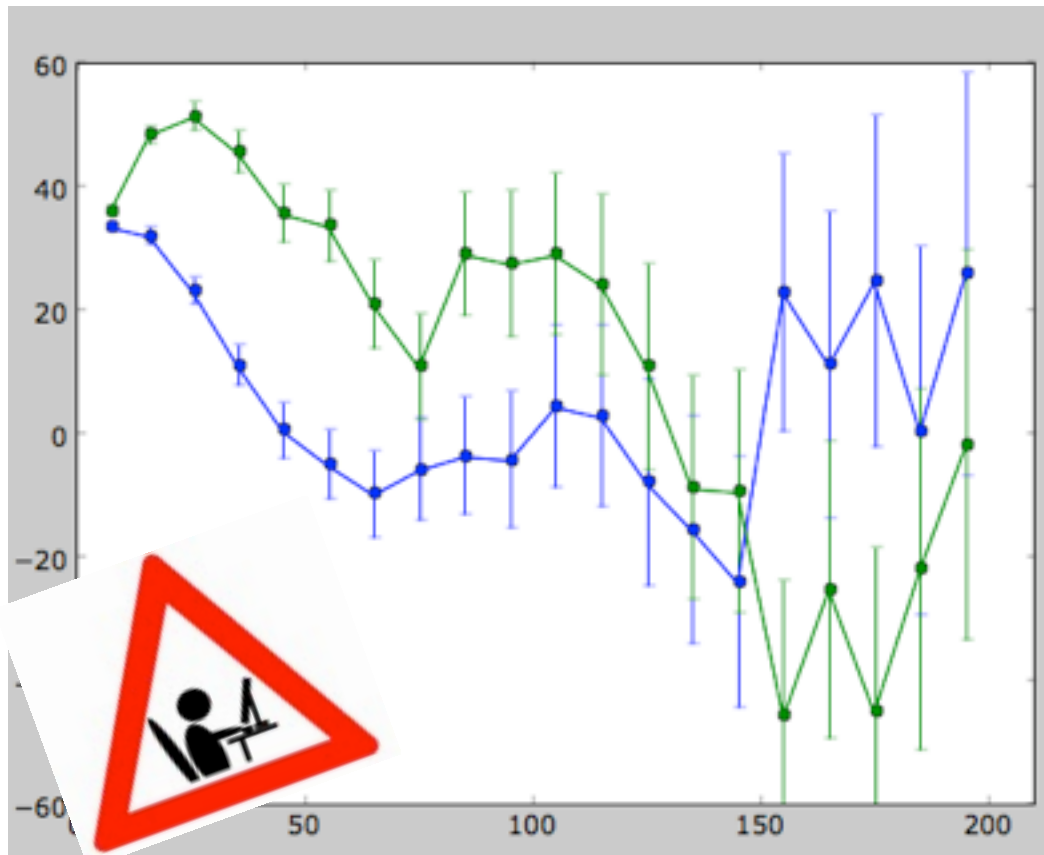
SDSS-II LRGs ($0.16 < z < 0.44$)
(bias ~ 2.2)



Sánchez & Kazin (in prep.)

Clustering Wedges in the Data

Davis, Kazin & the WiggleZ (in prep.)



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

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

Credit for reconstructed data: **Nikhil Padmanabhan**



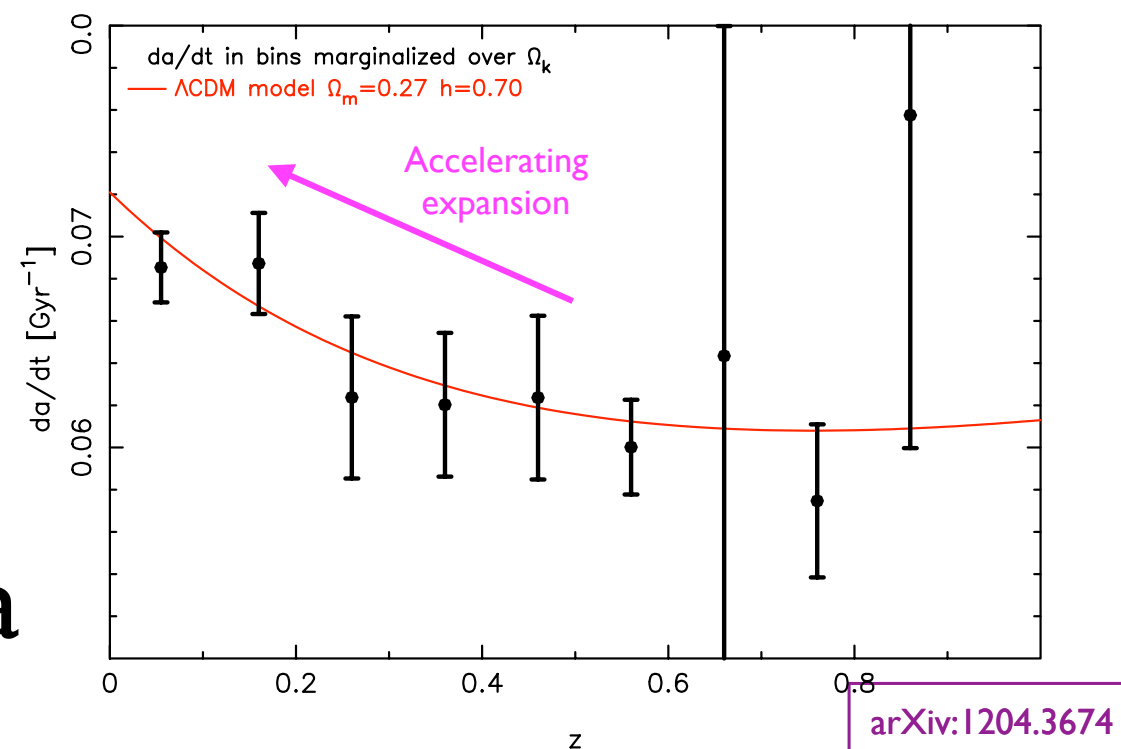
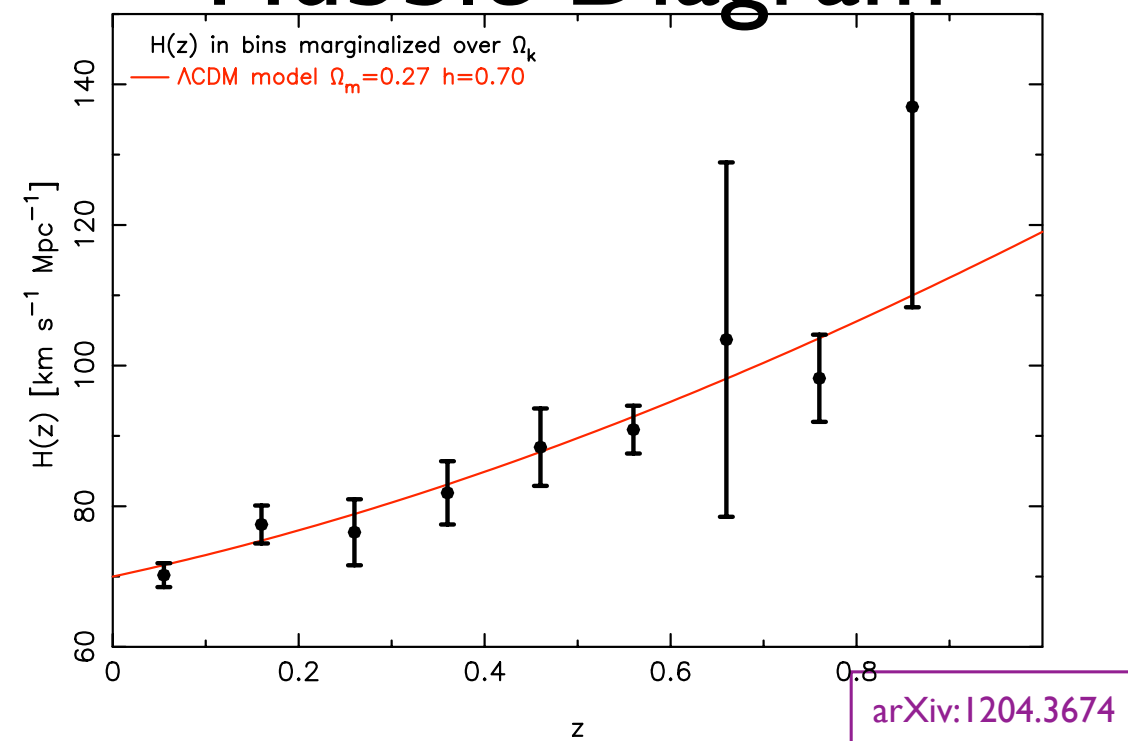
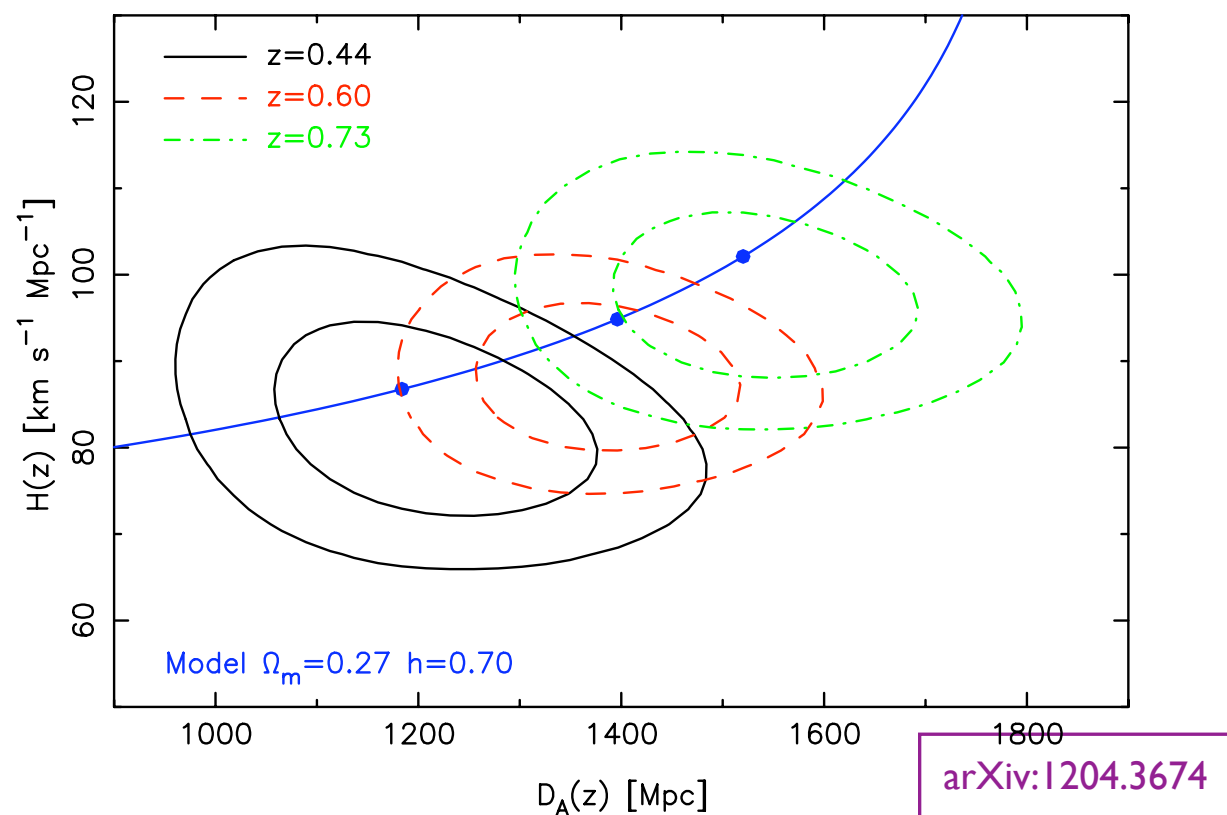
Reconstructed

Sánchez & Kazin (in prep.)

WiggleZ H - D_A Results

Blake & the WiggleZ (2012)

Hubble Diagram



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

- $\xi(\Delta\mu, s)$ wedges more practical 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 ...



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Warning!

slides contain
t might not be
individuals
periodic box.

The following
information that
appropriate for
that live inside a



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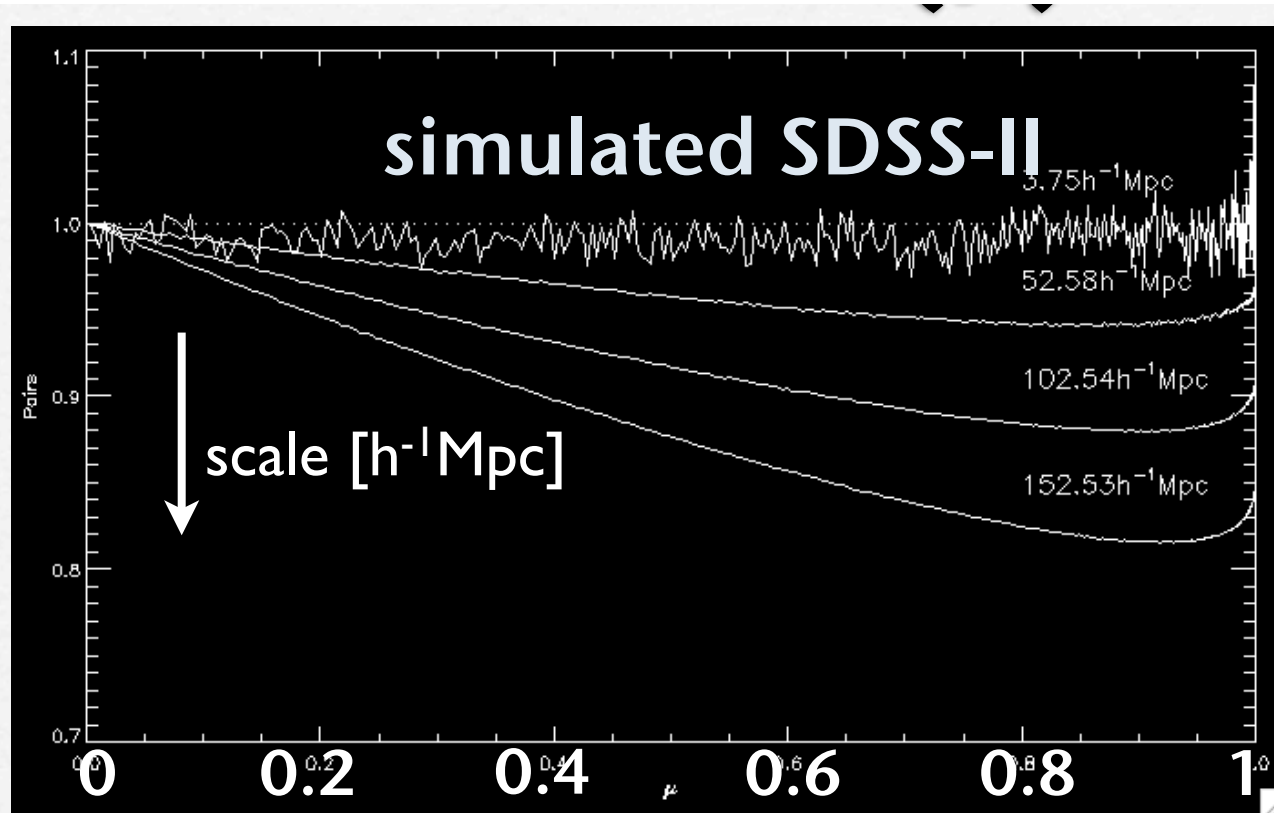
Warning!

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



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



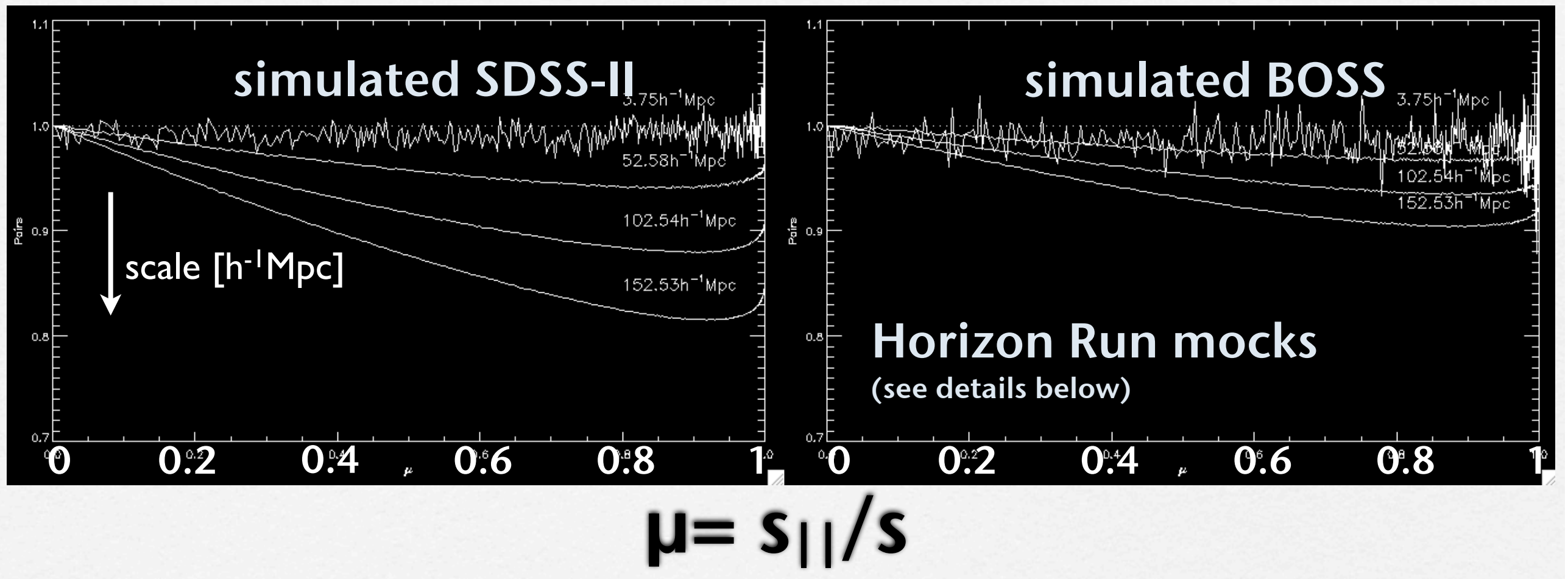
$$\mu = s_{||}/s$$

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



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



LasDamas (SDSS-II geometry)
 $0.16 < z < 0.44$ volume limited
8000 deg^2 , SDSS sky-coverage

Horizon Run (~BOSSish 2014)
 $0.16 < z < 0.6$ volume limited
10,300 deg^2 ($\pi \text{ str}$) BOX



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BOSS Advertisement

Now in your nearest browser!

More than 800,000 spectra in over 3,000 deg²

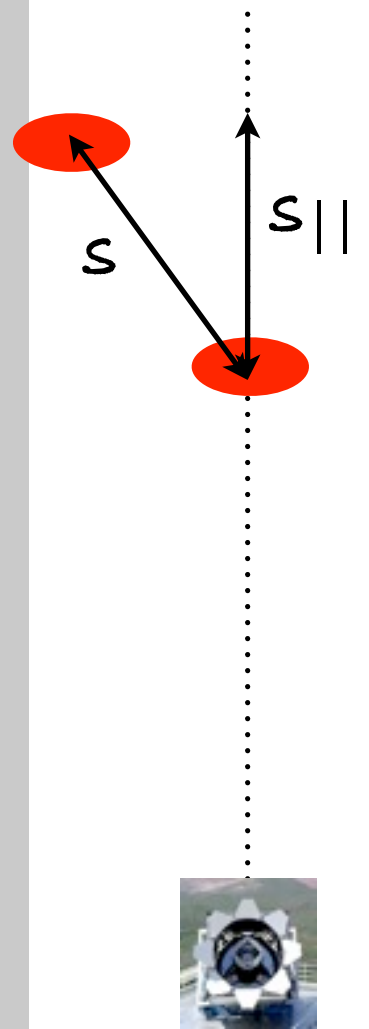
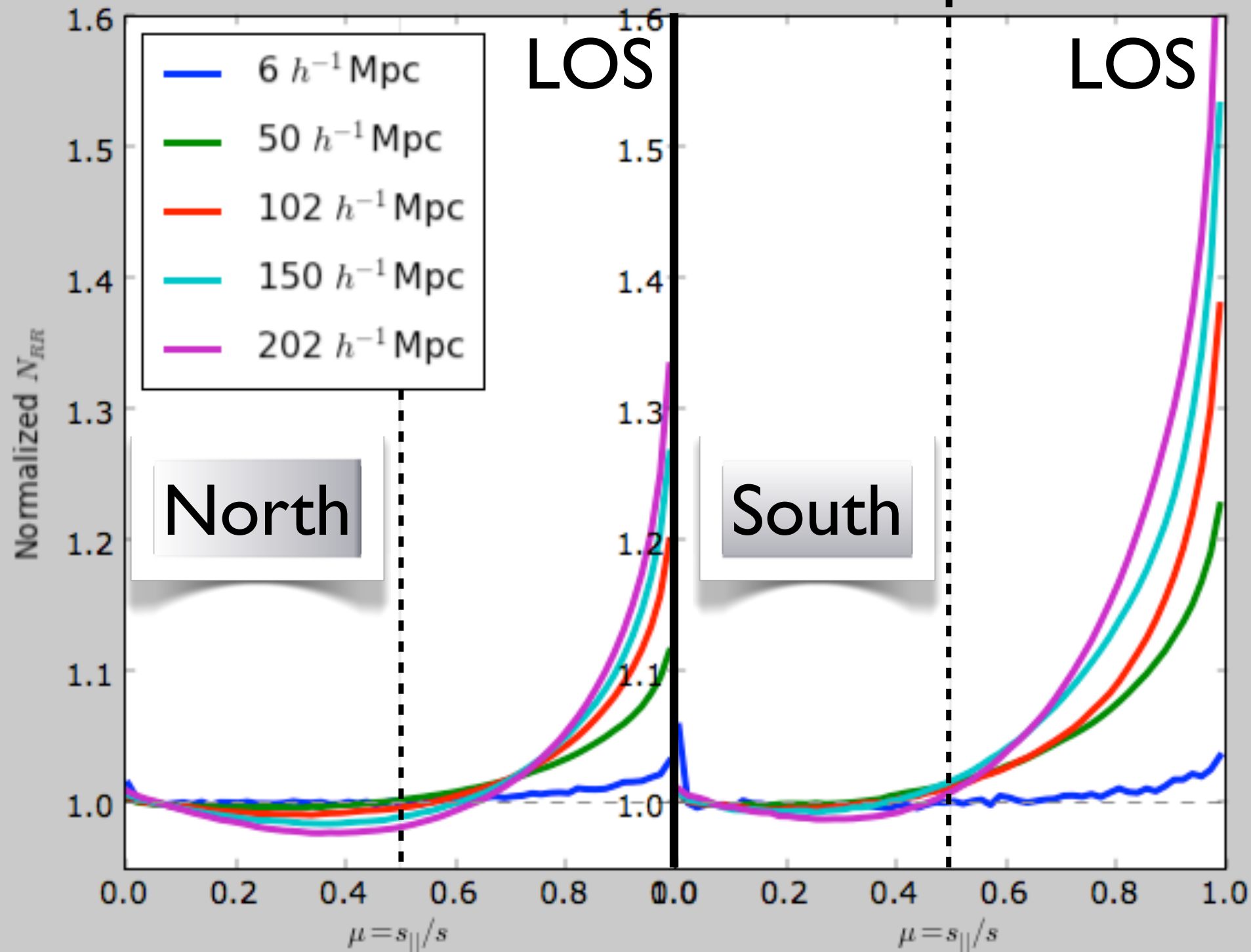
<http://sdss3.org/dr9/>



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

BOSS CMASS DR9- now public!





ξ Estimators: Direct vs Integrated

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

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

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



ξ Estimators: Direct vs Integrated

ξ INTEGRATED

$$\mathcal{P}_0 = 1$$

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

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

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



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

ξ DIRECT

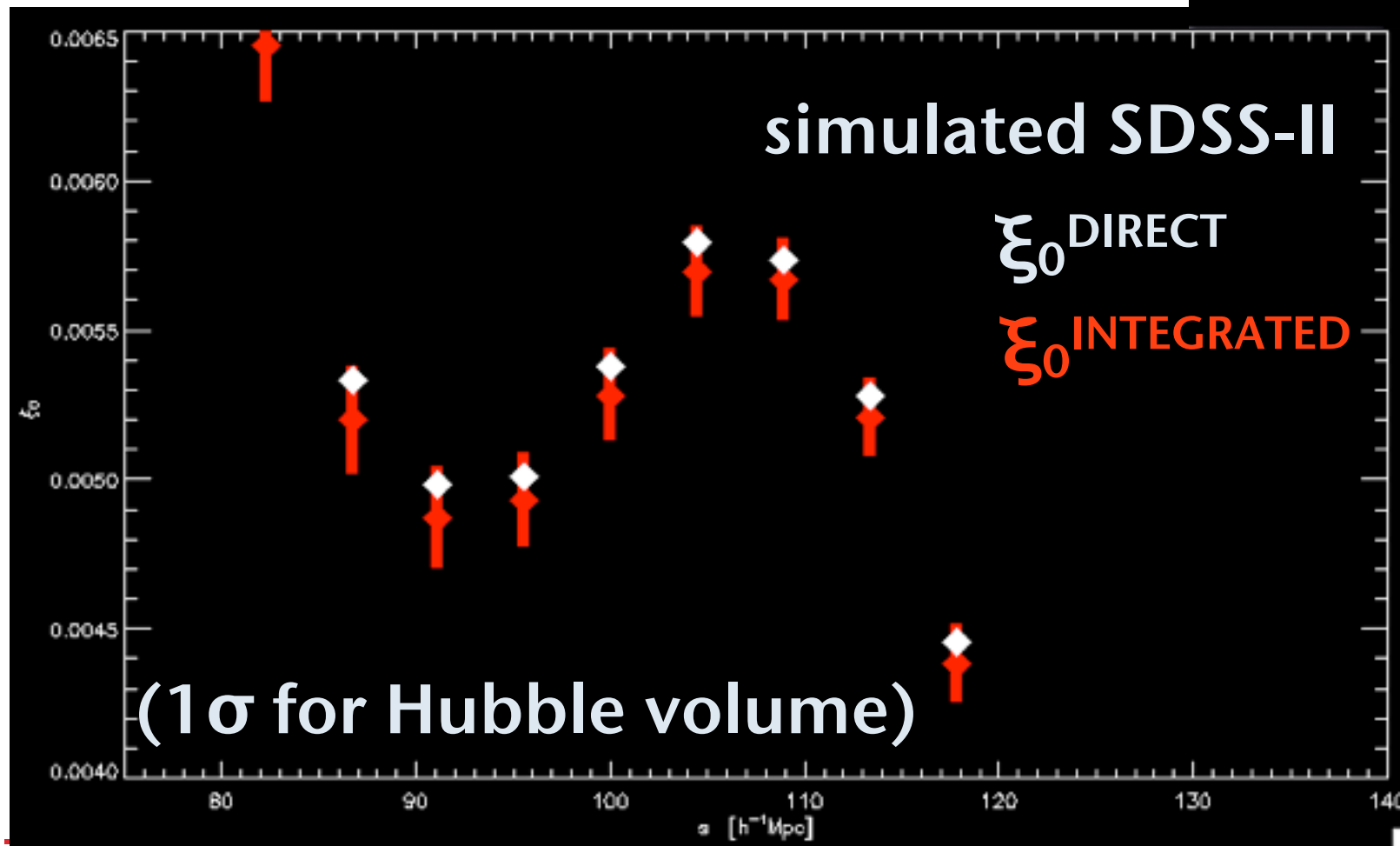
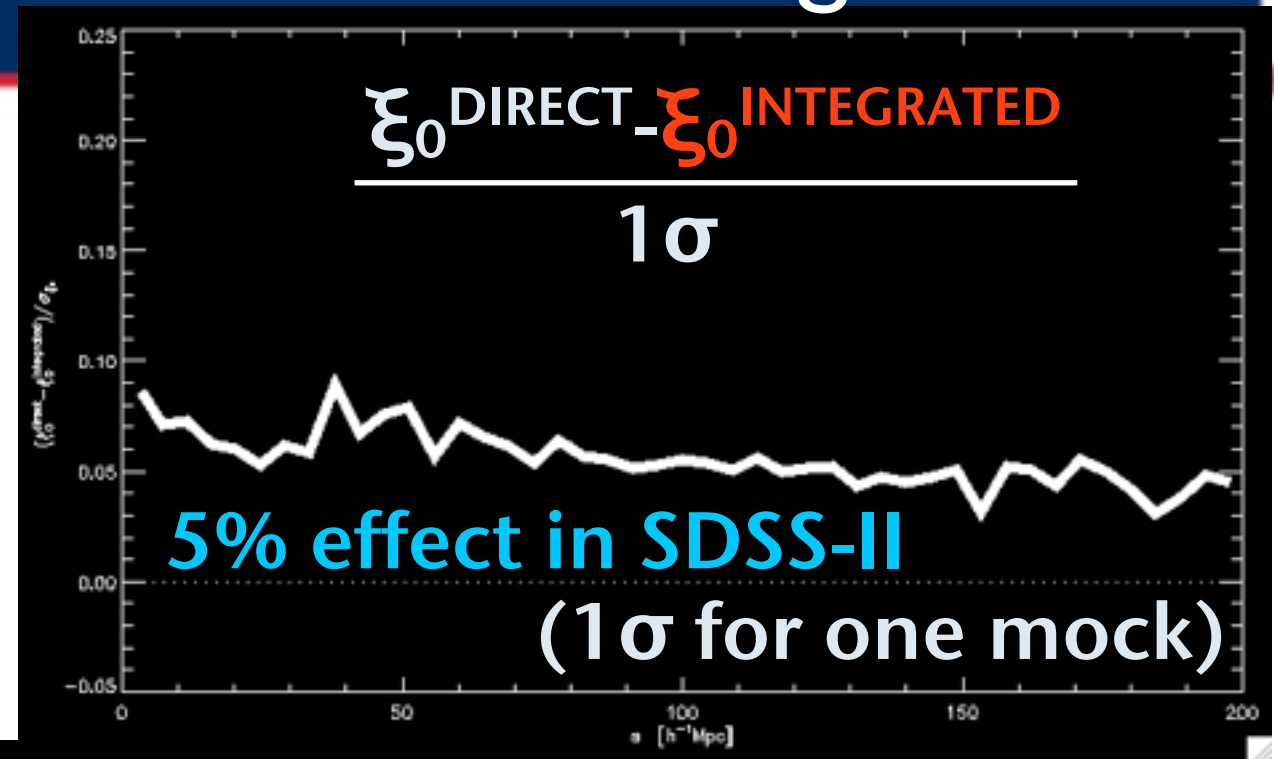


$$\xi_0(s) = \frac{DD(s) - RR(s)}{RR(s)} = \int_{-1}^{+1} d\mu \frac{DD(\mu, s) - RR(\mu, s)}{RR(\mu, s)} \cdot \frac{RR(\mu, s)}{RR(s)}$$



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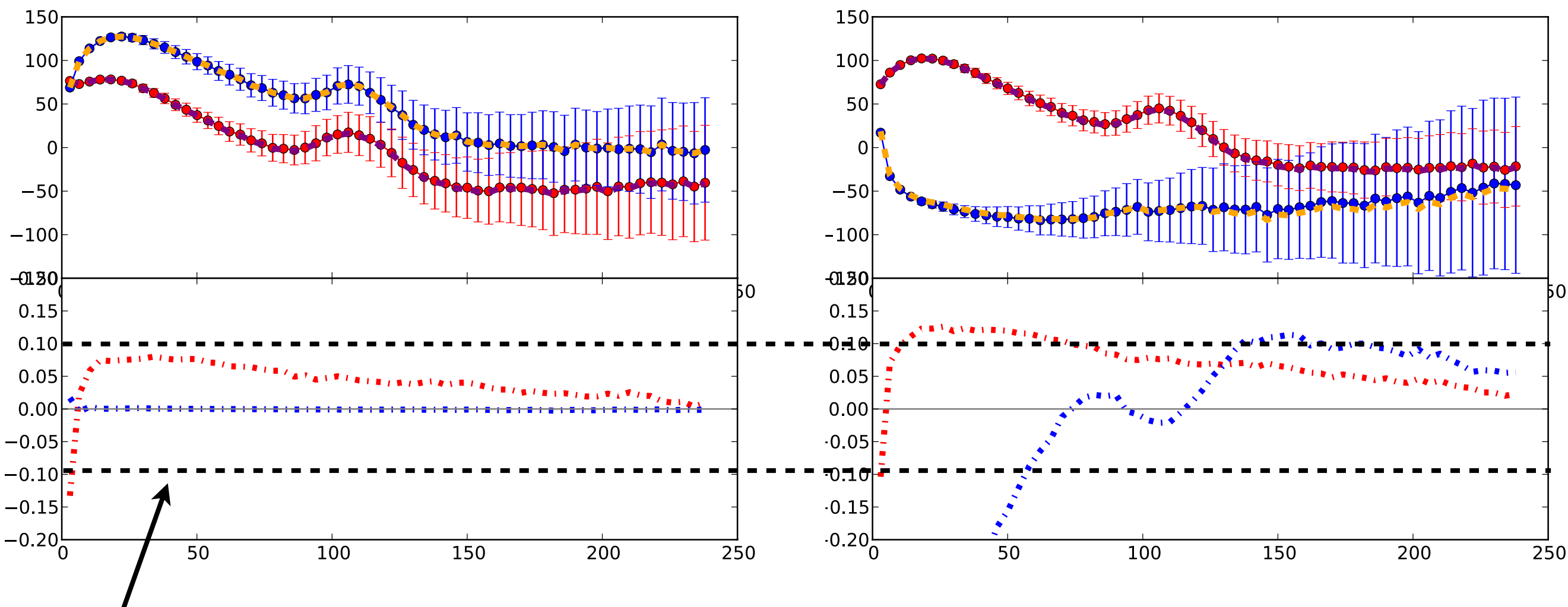
ξ Estimators: Direct vs Integrated



ξ Estimators: Direct vs Integrated

Investigating 610 BOSS Mocks

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



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

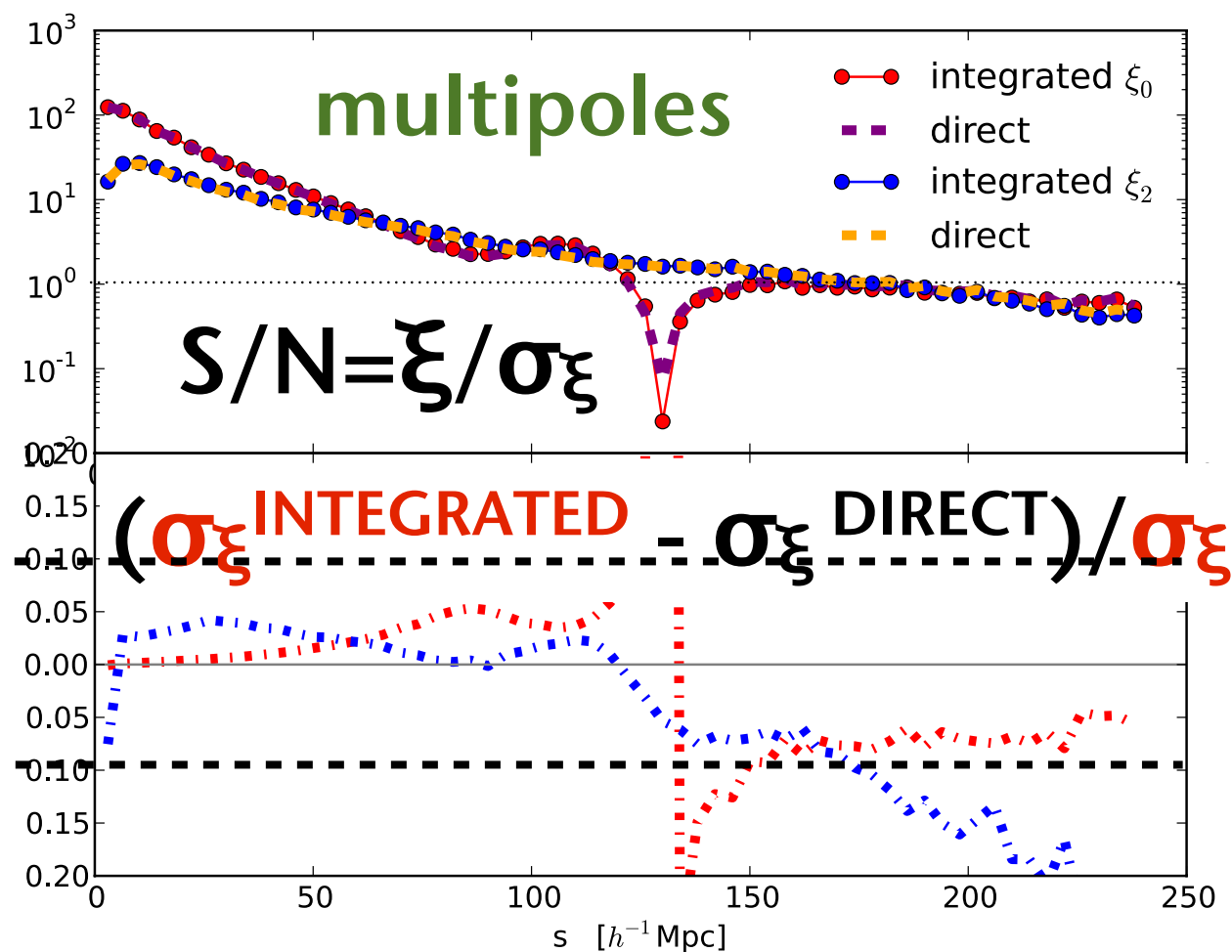
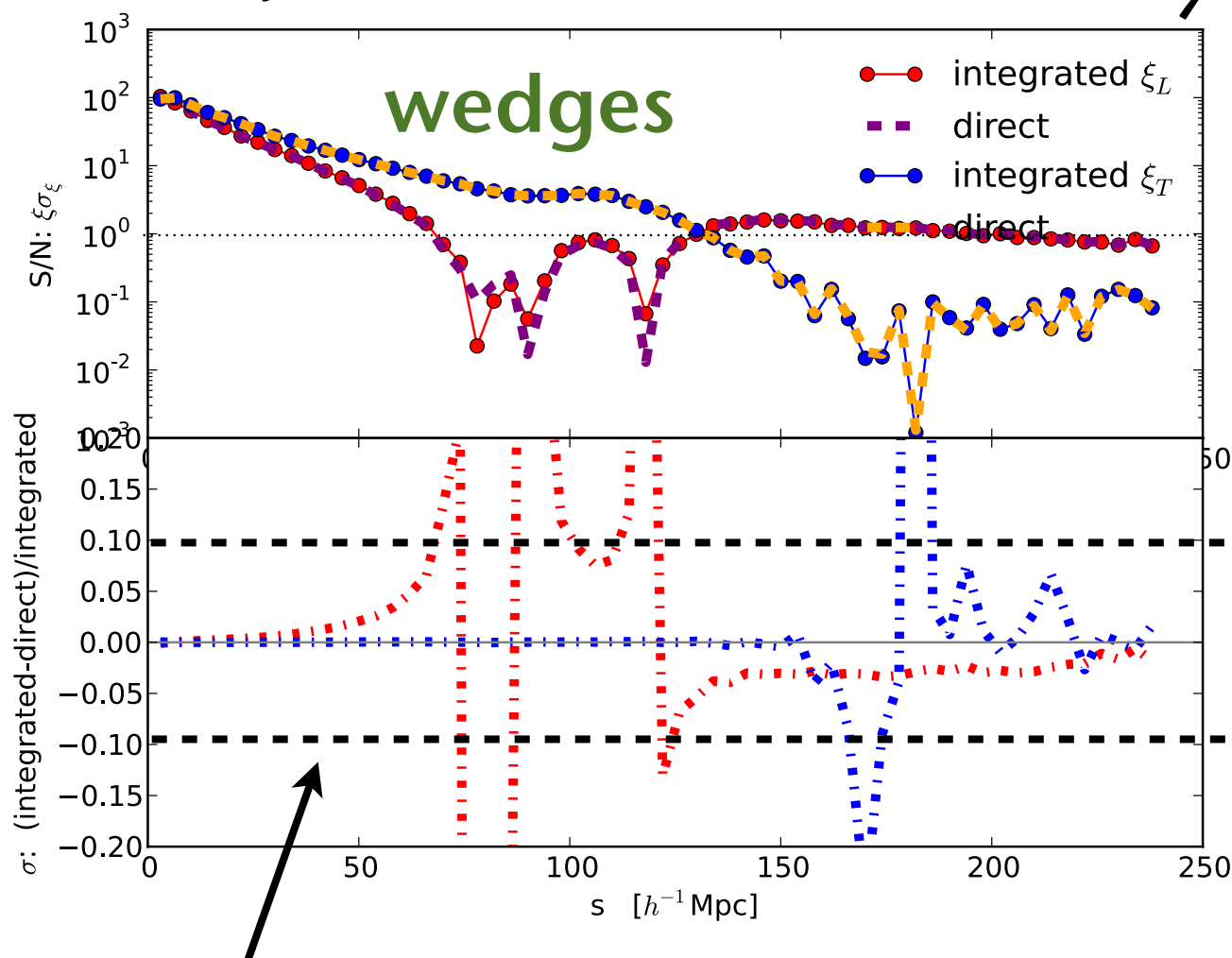


*But, don't you degrade
the C_{ij} ,
when integrating
over noisy data bins?*

ξ Estimators: Direct vs Integrated

Investigating 610 BOSS Mocks

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



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

Clustering Wedges (temporary) Summary

- $\xi(\Delta\mu, s)$ wedges more practical 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

3D $\rightarrow$ 2D $\rightarrow$ 1D

- $\xi(\Delta\mu, s)$ wedges more practical 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

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

- Con
to ξ
cons



- $\xi(\Delta\mu, s)$ wedges more practical 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!



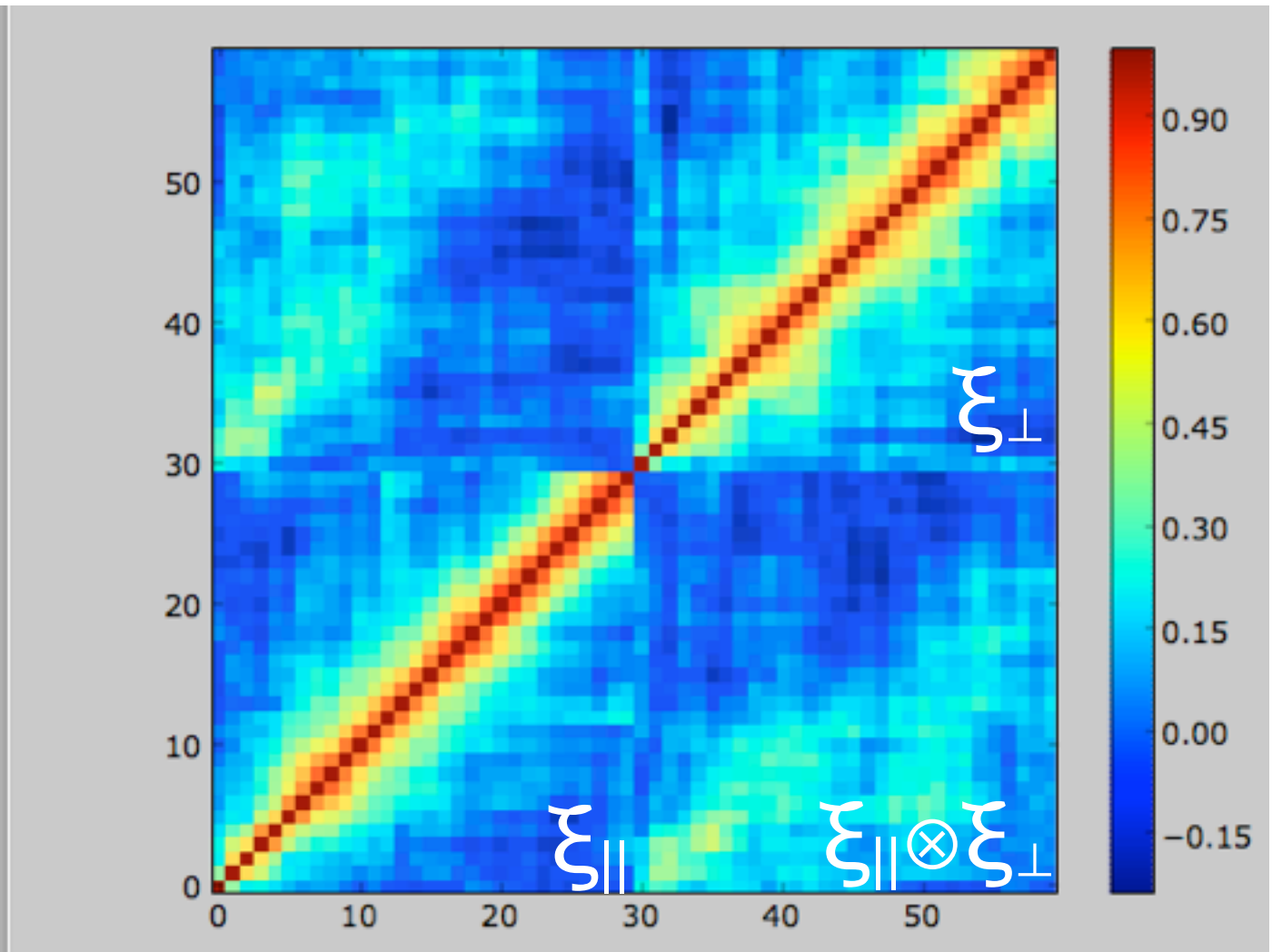
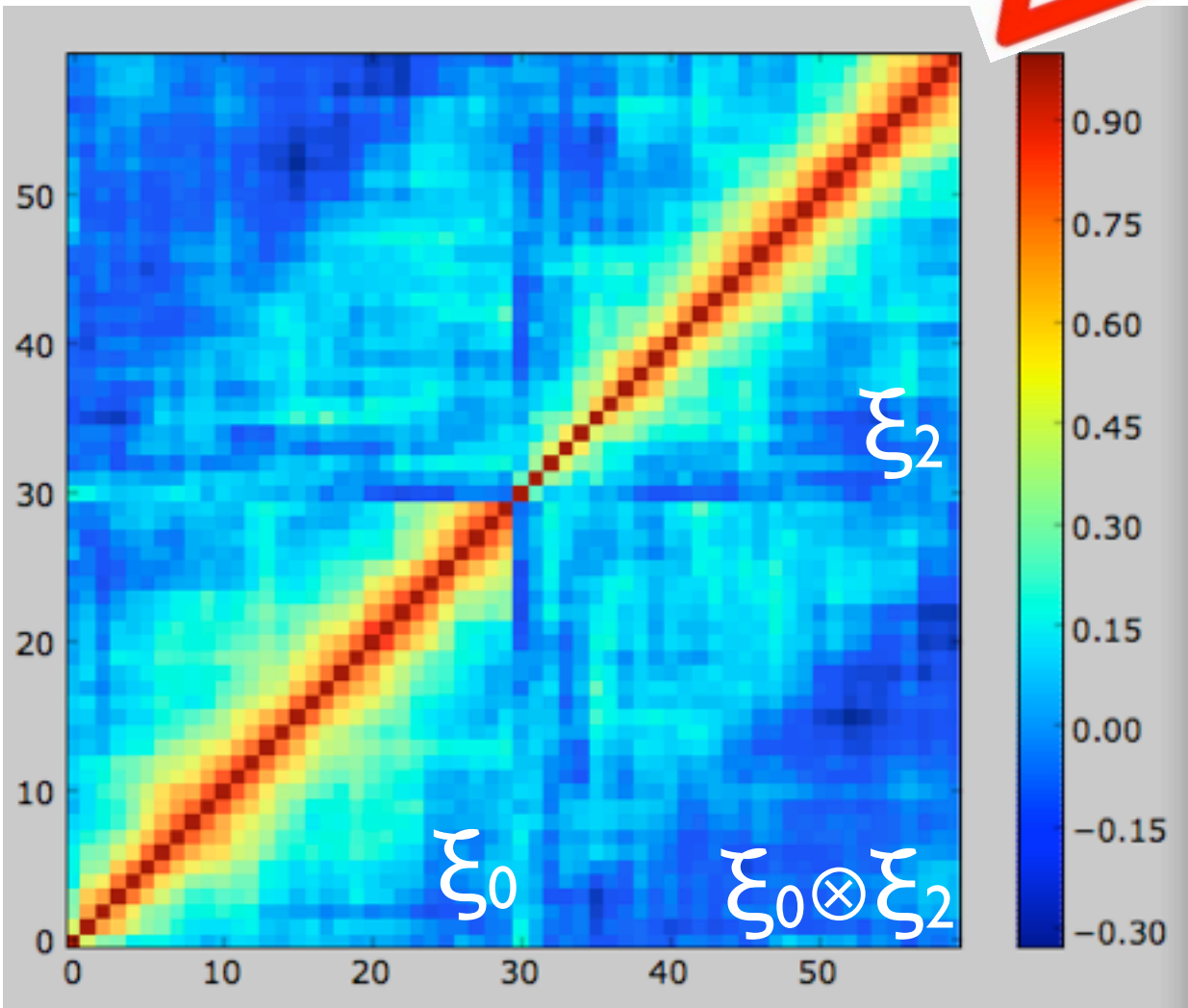
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Covariance Matrix Comparison (Normalized)



$$\xi_{\ell}(s)$$

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



5 100 200 5 100 200
 $h^{-1}\text{Mpc}$

5 100 200 5 100 200
 $h^{-1}\text{Mpc}$

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

$\Delta s = 6.7 h^{-1}\text{Mpc}$ range 5-197 $h^{-1}\text{Mpc}$