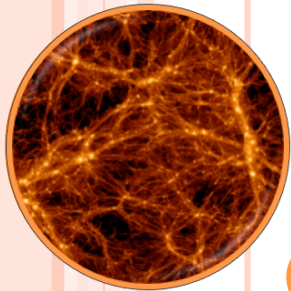


# MEASURING THE POWER SPECTRUM WITH PECULIAR VELOCITIES



**Edward Macaulay**

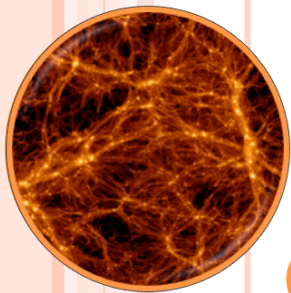
[edward.macaulay@astro.ox.ac.uk](mailto:edward.macaulay@astro.ox.ac.uk)

Hume Feldman, Pedro Ferreira, Andrew Jaffe,  
Shankar Agarwal, Mike Hudson, Rick Watkins

**ArXiv: 1111.3338**

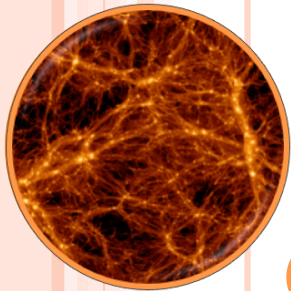
## MOTIVATION

- Peculiar velocities are a unique cosmological probe
  - Redshift survey:  $b^2P(k)$
  - Velocity survey:  $f^2P(k)$
- Is the high dipole a challenge to  $\Lambda$ CDM?



## OUTLINE

- Measuring peculiar velocities
- The high dipole
- Moments of the velocity field
- Power spectrum results
- Comparison to Fisher forecasts

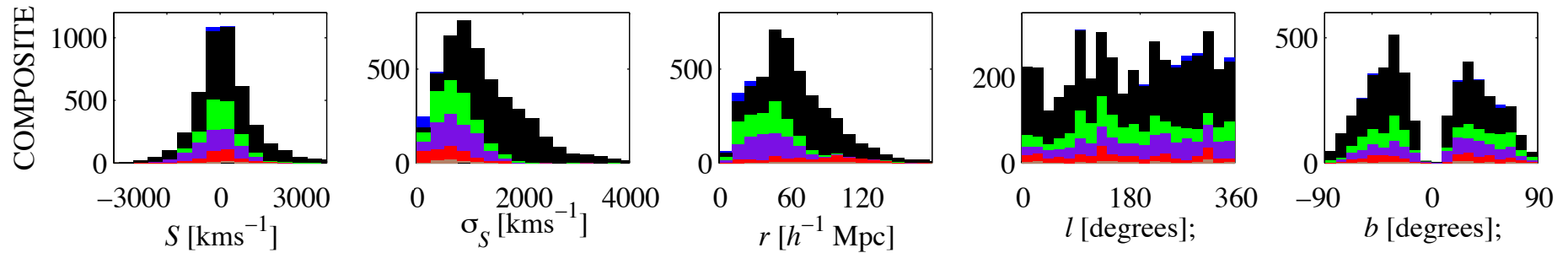


## MEASURING PECULIAR VELOCITIES

- $c z = H_0 d + v_p \cdot \hat{d}$
- Measure the redshift
- Luminosity distances
  - SN 1a: 5% uncertainty
  - Tully Fisher or Fundamental Plane: 10 to 20% uncertainty
- COMPOSITE Catalogue:
  - 4,500 measurements
  - $\sim 50 h^{-1} \text{Mpc}$



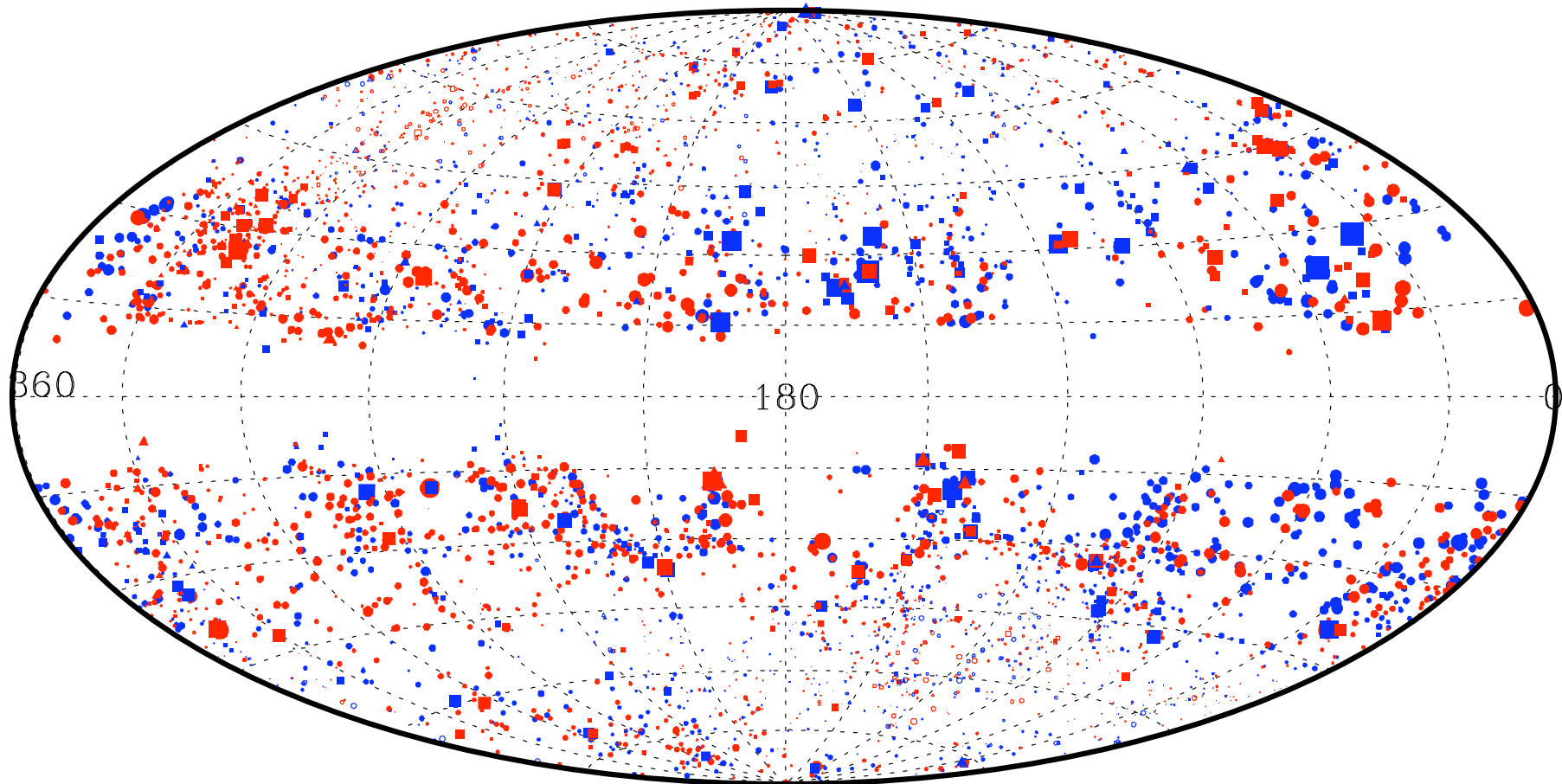
# SURVEY CATALOGUES



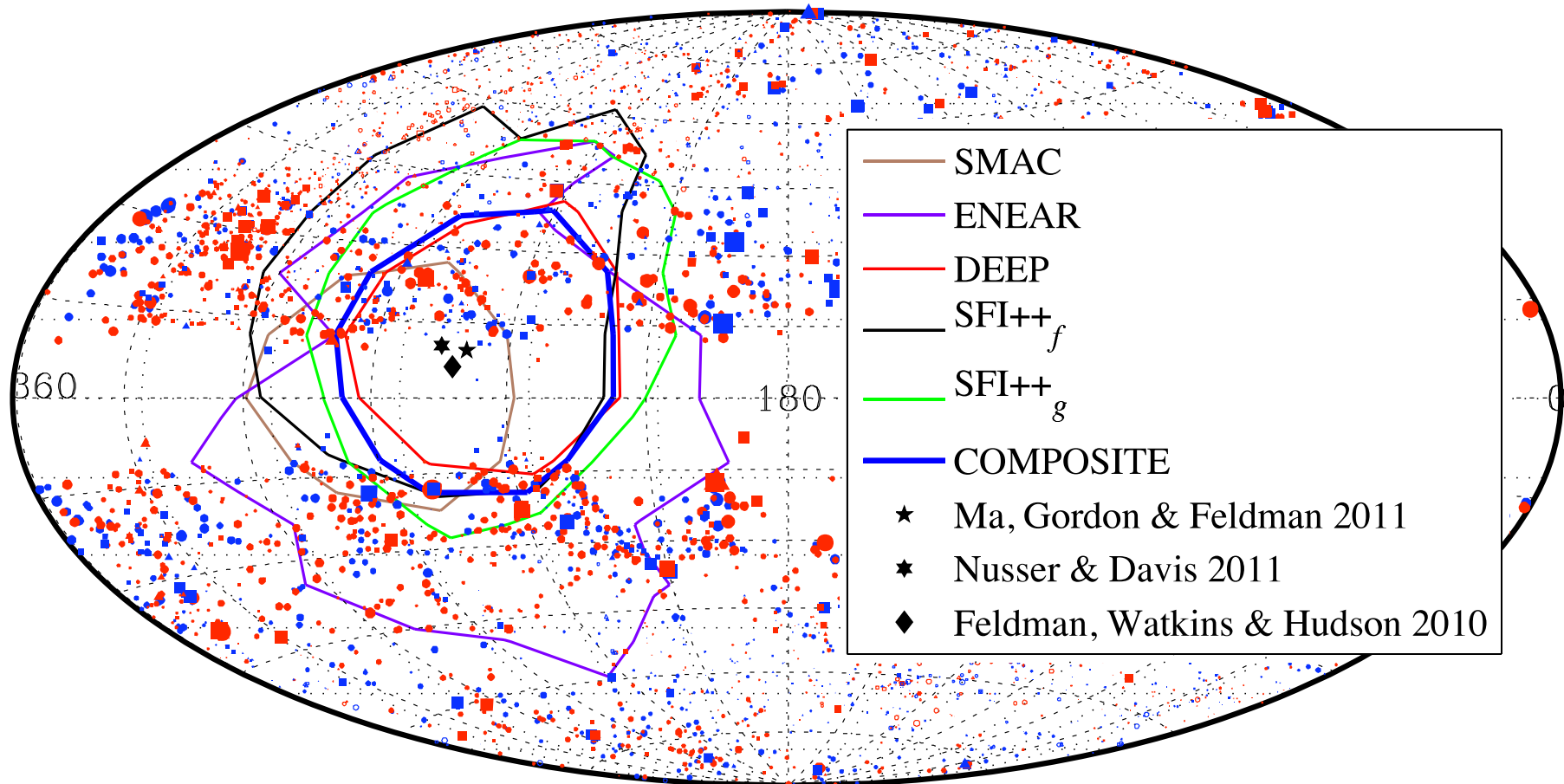
■ COMPOSITE	4537
■ SFI++ <sub>f</sub>	2720
■ SFI++ <sub>g</sub>	736
■ ENEAR	697
■ DEEP	294
■ SMAC	56



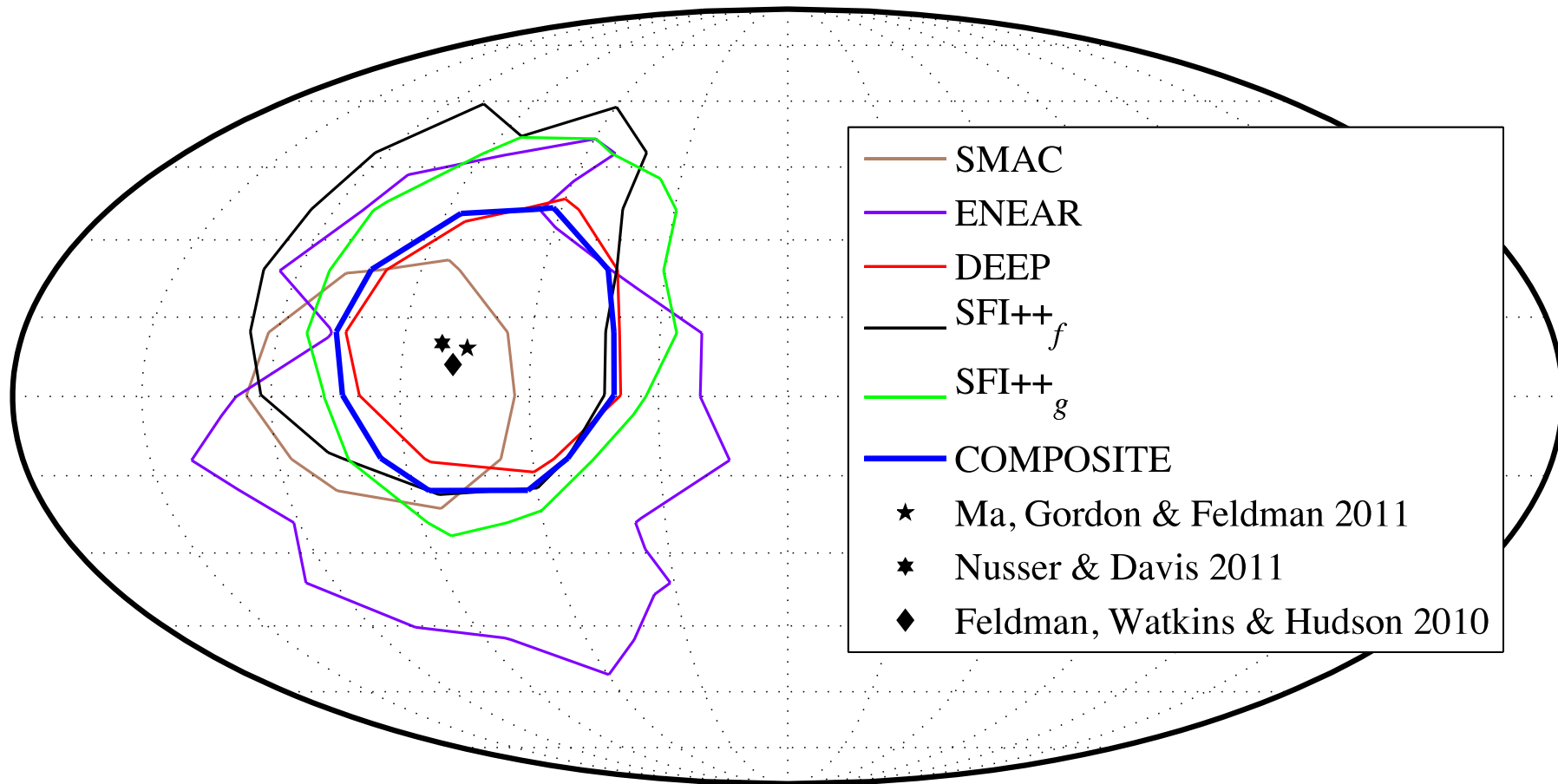
# DIPOLE DIRECTION



# DIPOLE DIRECTION

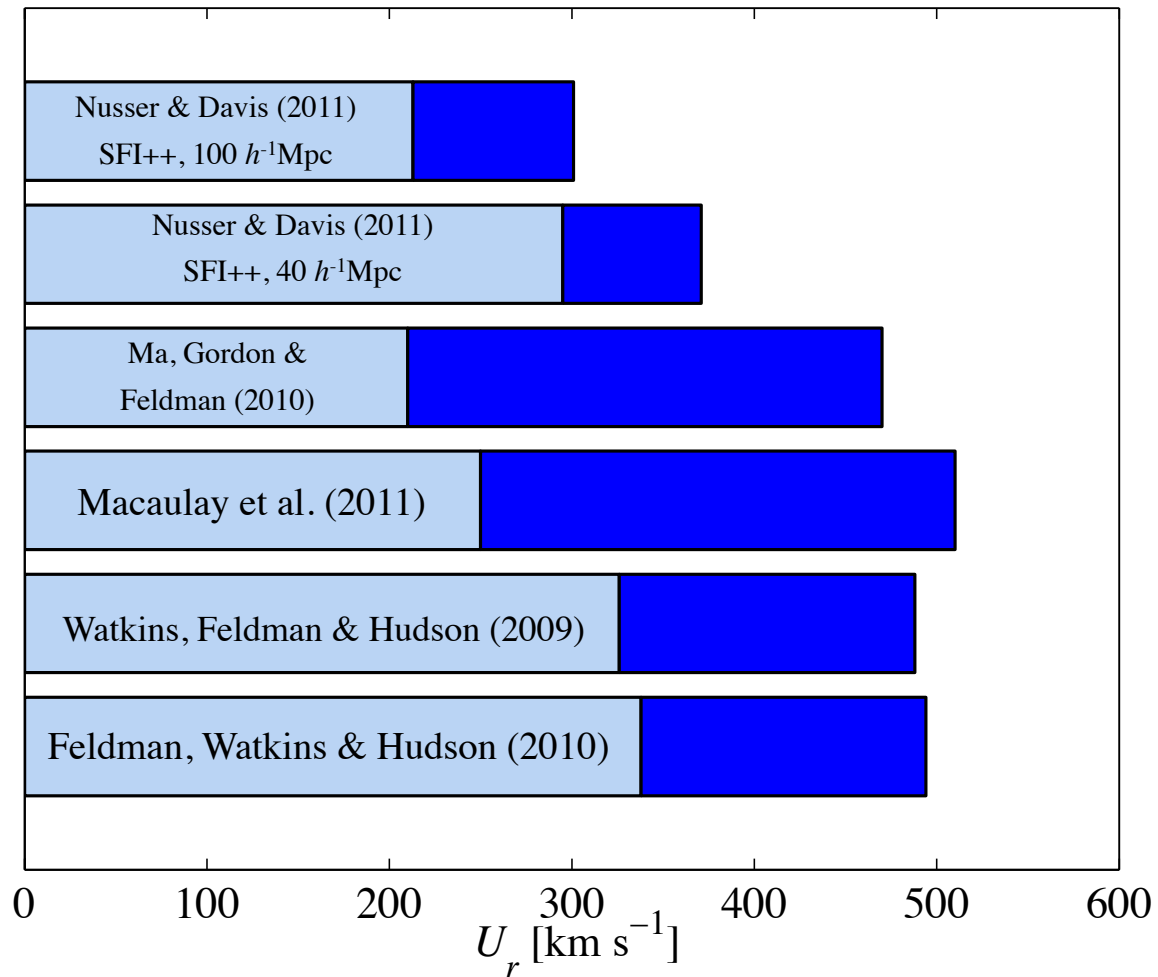


# DIPOLE DIRECTION

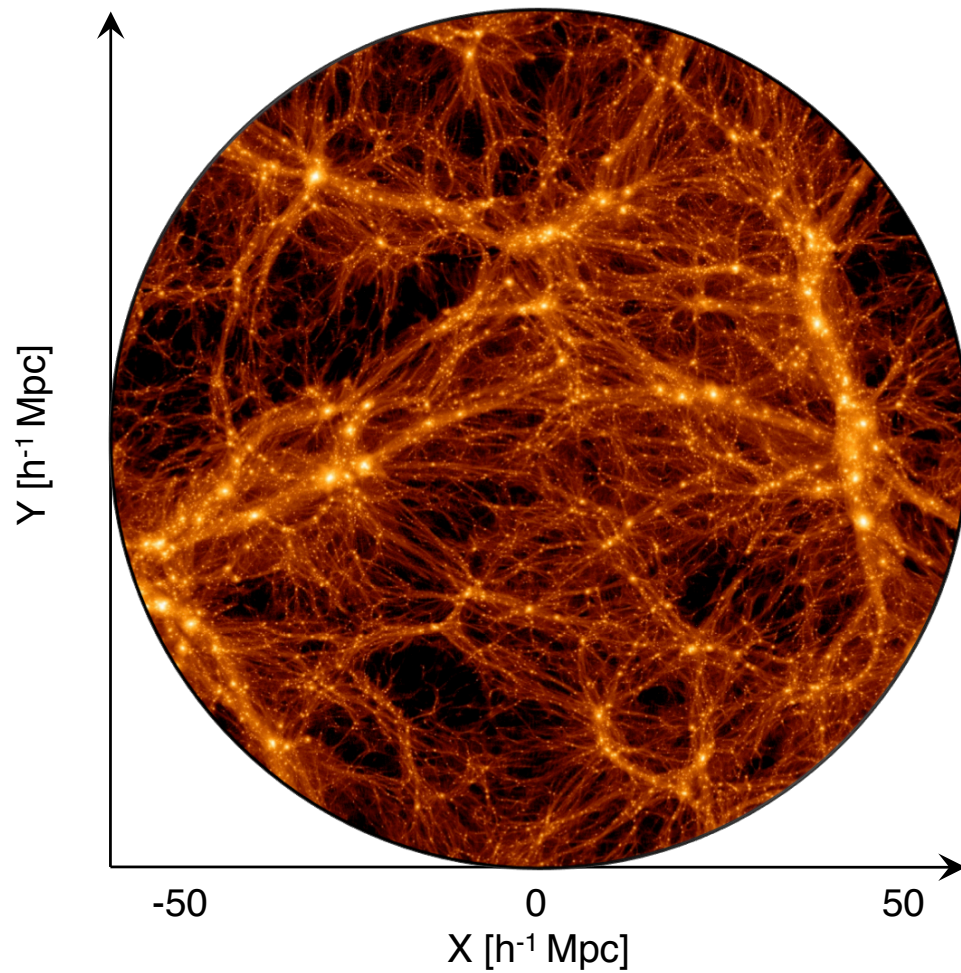




# DIPOLE MAGNITUDE



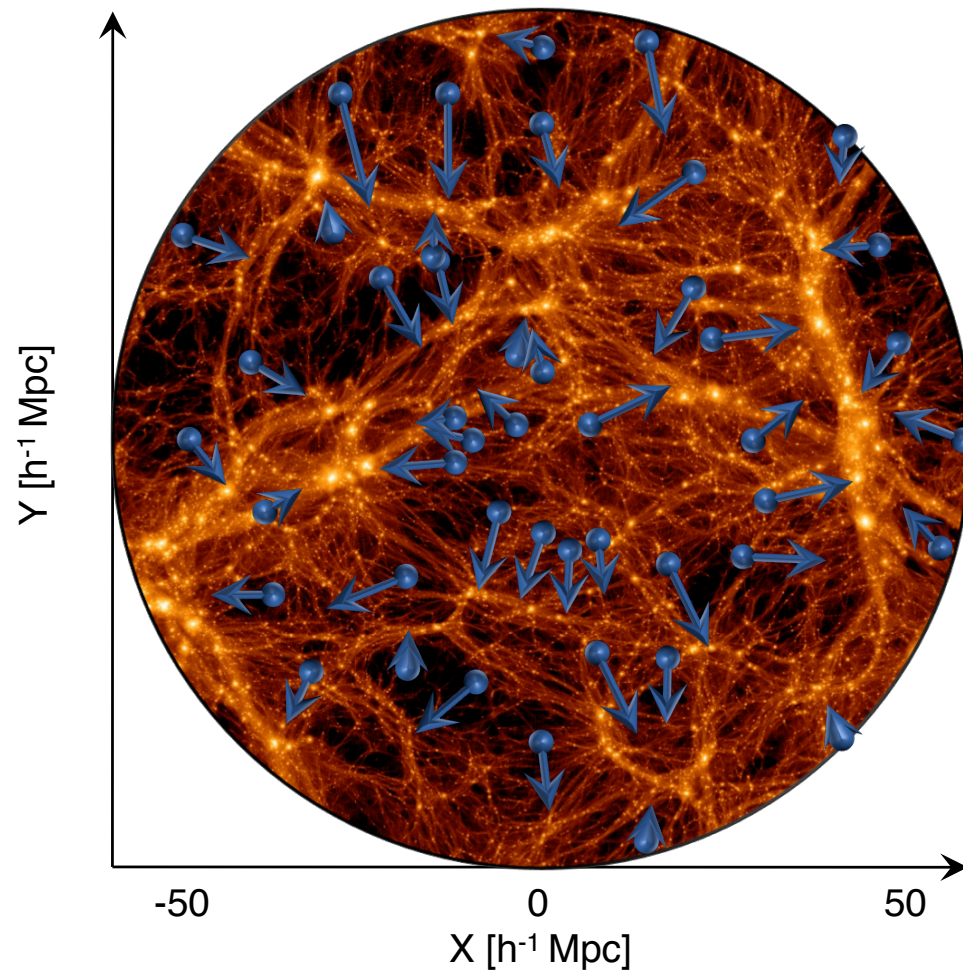
# UNDERLYING MATTER FIELD



Simulation image by Teyssier Romain 2007, Horizon Project  
<http://www.projet-horizon.fr/www.projet-horizon.fr/rubrique38.html>



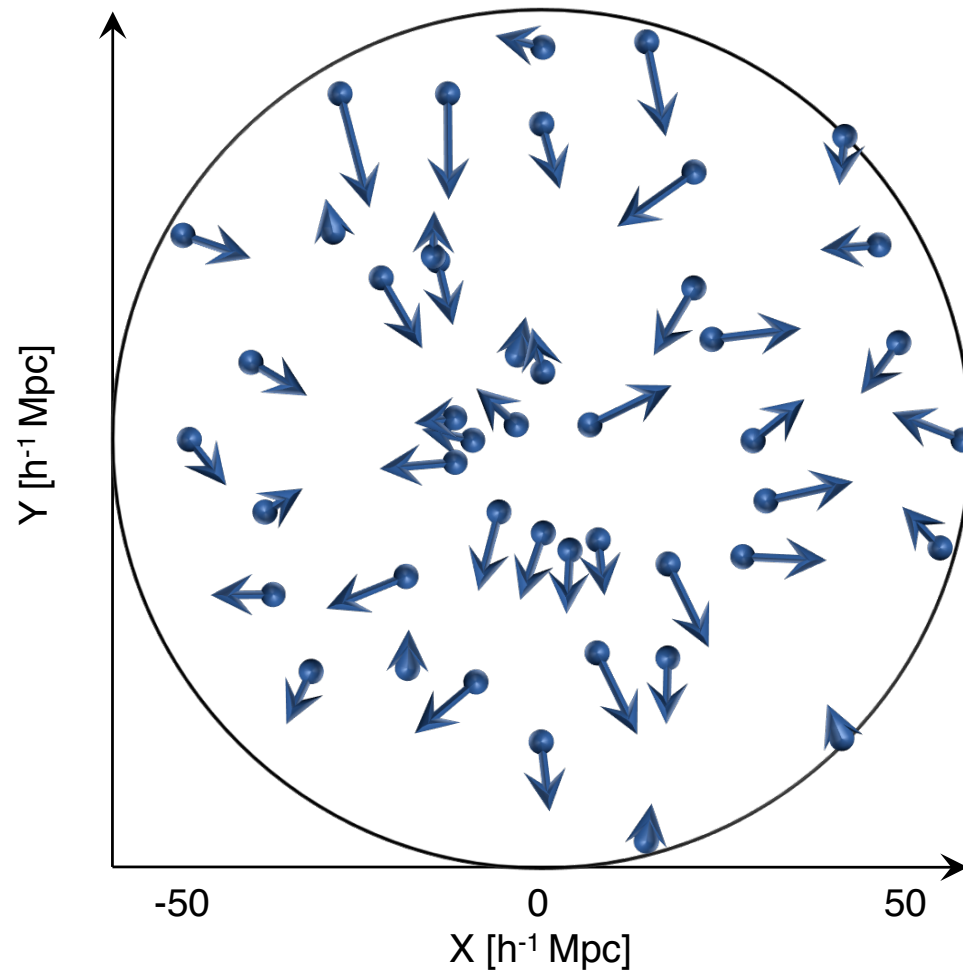
# VELOCITY FIELD



$$v(\vec{r}) = \frac{f}{4\pi} \int d^3r' \delta(r') \frac{(r' - r)}{|r' - r|^3}$$



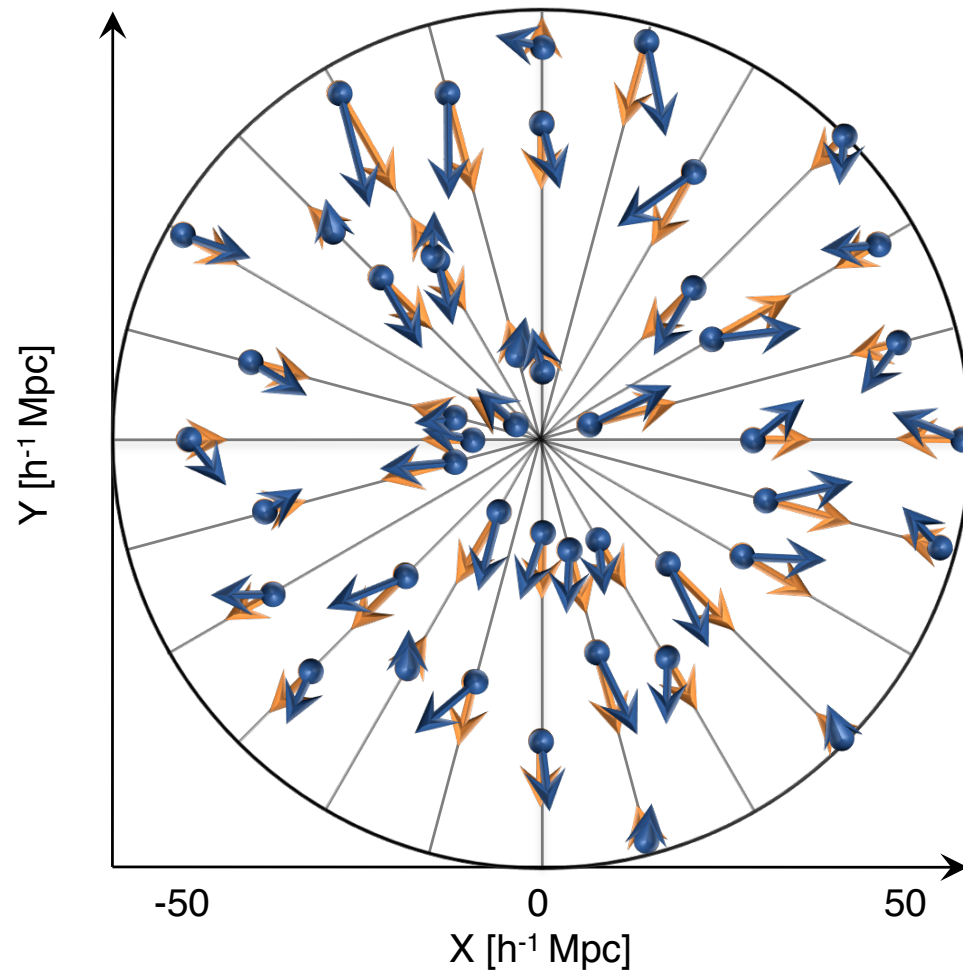
# VELOCITY FIELD



$$v(\vec{r}) = \frac{f}{4\pi} \int d^3r' \delta(r') \frac{(r' - r)}{|r' - r|^3}$$



# VELOCITY FIELD

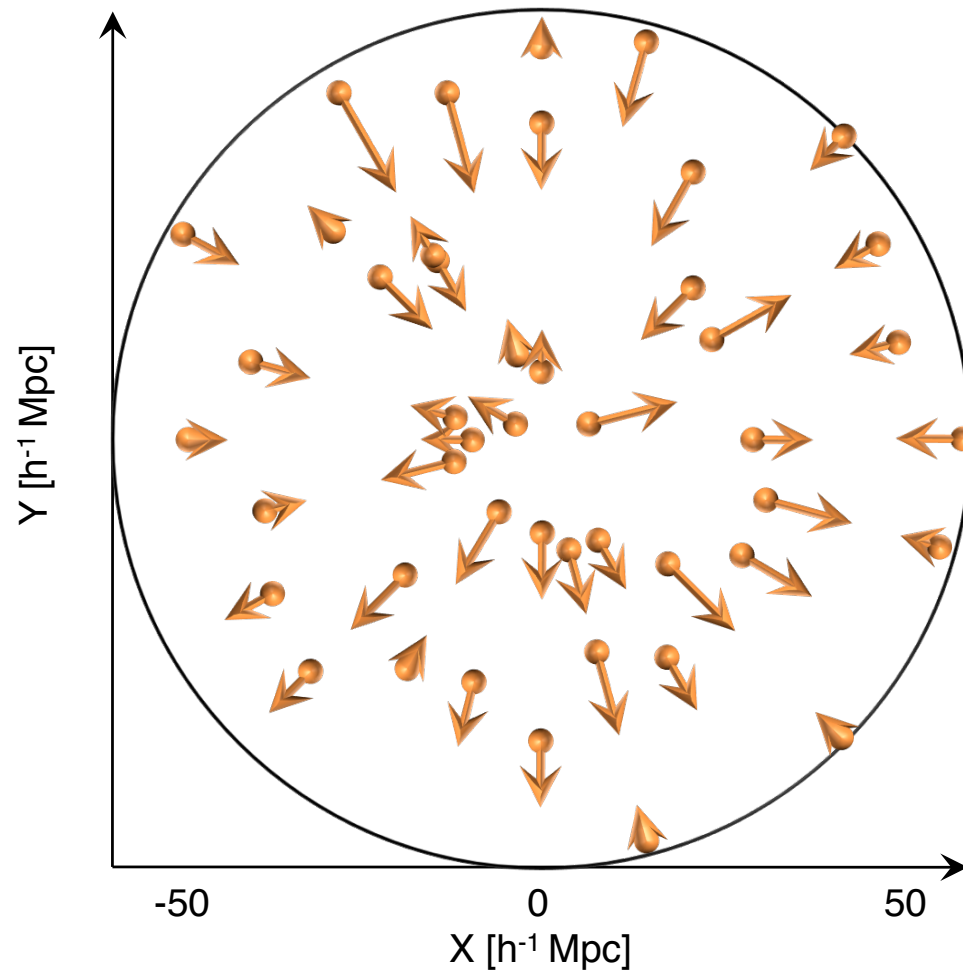


$$\mathbf{v}(\vec{r}) = \frac{f}{4\pi} \int d^3r' \delta(r') \frac{(\vec{r}' - \vec{r})}{|\vec{r}' - \vec{r}|^3}$$

$$s(\vec{r}) = \mathbf{v}(\vec{r}) \cdot \hat{r}$$



# VELOCITY FIELD

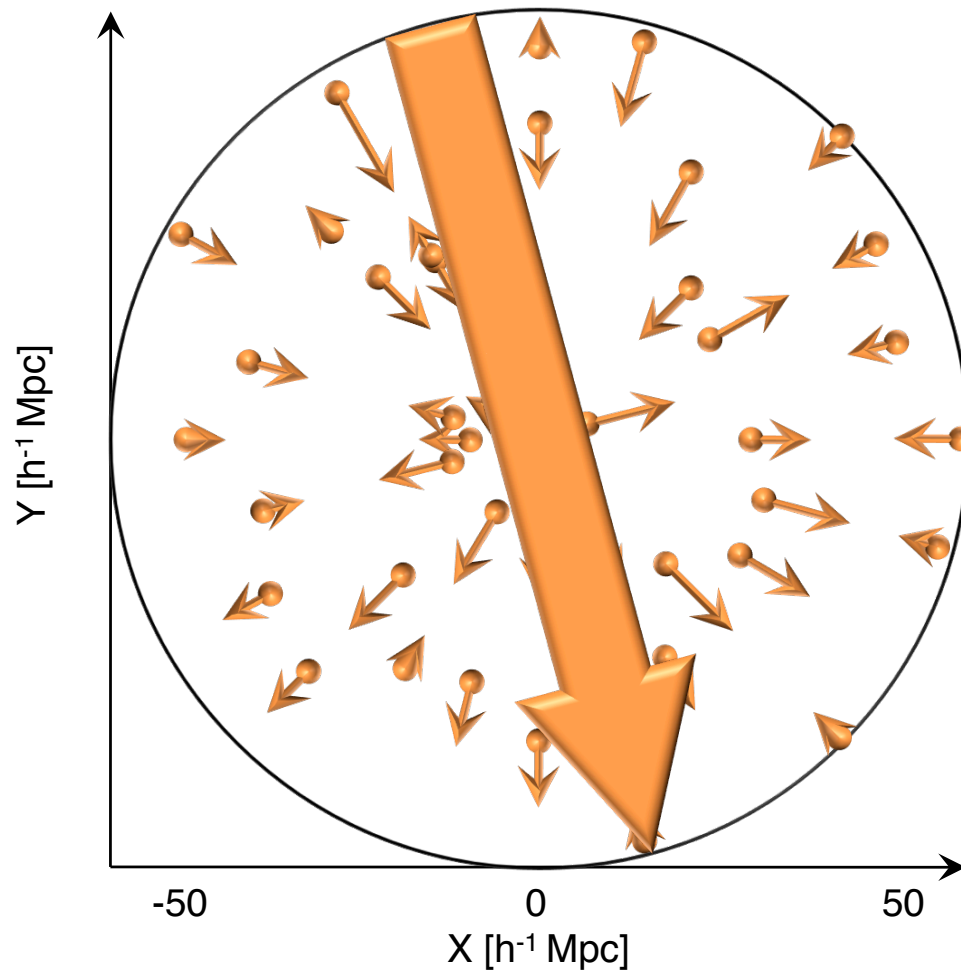


$$\mathbf{v}(\vec{r}) = \frac{f}{4\pi} \int d^3r' \delta(r') \frac{(\vec{r}' - \vec{r})}{|\vec{r}' - \vec{r}|^3}$$

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# VELOCITY FIELD



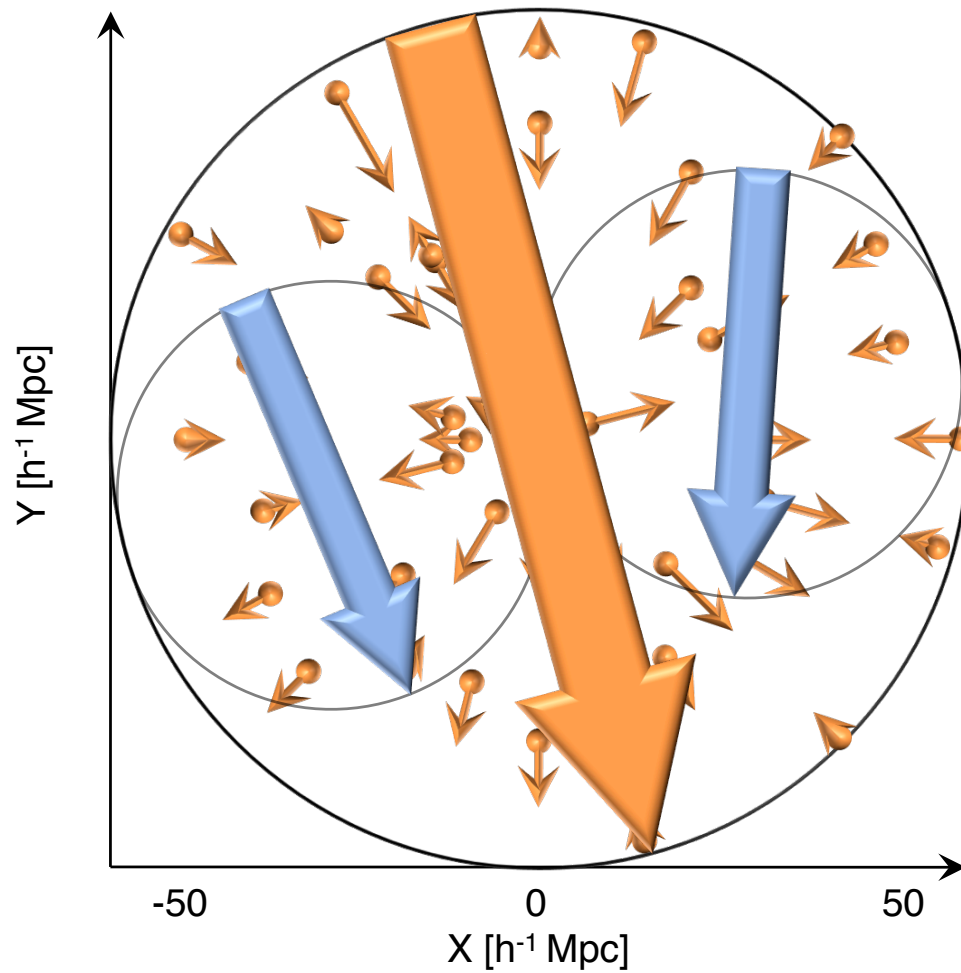
$$v(\vec{r}) = \frac{f}{4\pi} \int d^3 r' \delta(r') \frac{(\vec{r}' - \vec{r})}{|\vec{r}' - \vec{r}|^3}$$

$$s(\vec{r}) = v(\vec{r}) \cdot \hat{r}$$

$$s(\vec{r}) \approx U_i \hat{r}_i$$



# VELOCITY FIELD



$$v(\vec{r}) = \frac{f}{4\pi} \int d^3r' \delta(r') \frac{(\vec{r}' - \vec{r})}{|\vec{r}' - \vec{r}|^3}$$

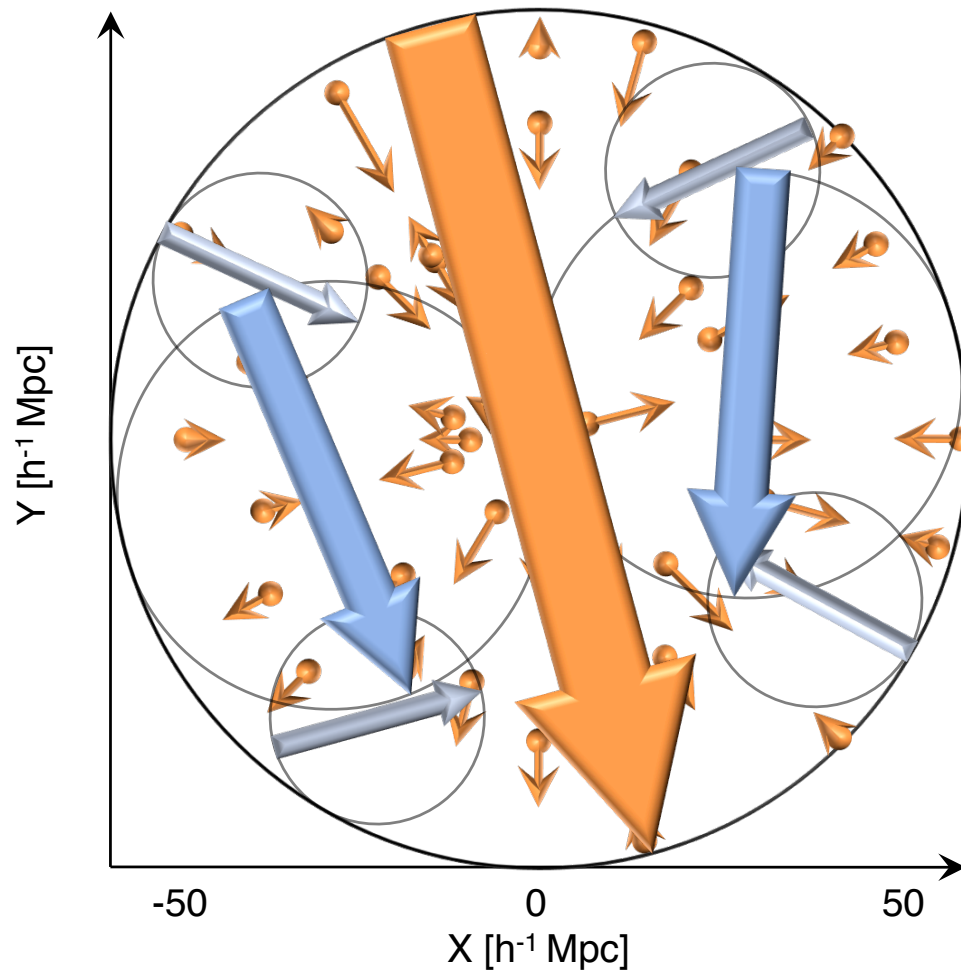
$$s(\vec{r}) = v(\vec{r}) \cdot \hat{r}$$

$$s(\vec{r}) \approx U_i \hat{r}_i + U_{ij} r \hat{r}_i \hat{r}_j$$





# VELOCITY FIELD



$$v(\vec{r}) = \frac{f}{4\pi} \int d^3 r' \delta(r') \frac{(r' - r)}{|r' - r|^3}$$

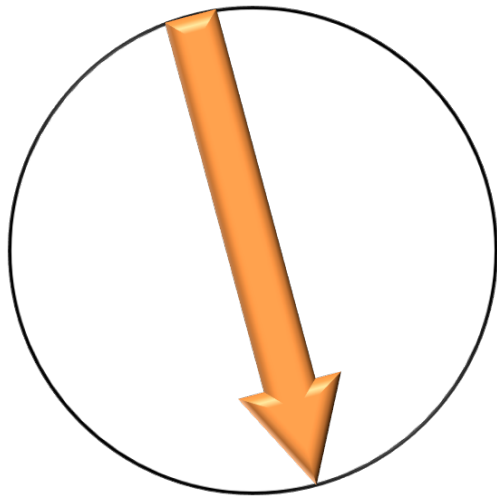
$$s(\vec{r}) = v(\vec{r}) \cdot \hat{r}$$

$$s(\vec{r}) \approx U_i \hat{r}_i + U_{ij} r \hat{r}_i \hat{r}_j + U_{ijk} r^2 \hat{r}_i \hat{r}_j \hat{r}_k$$

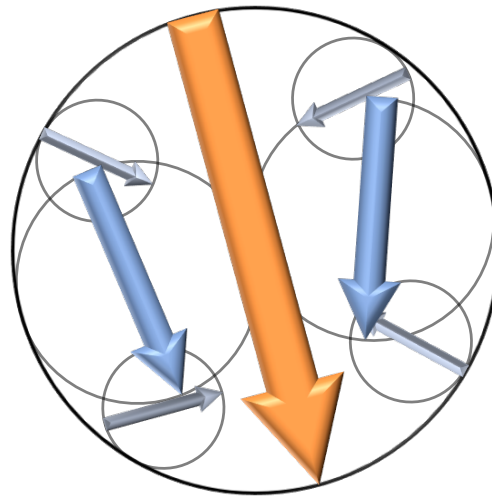


# VELOCITY FIELD

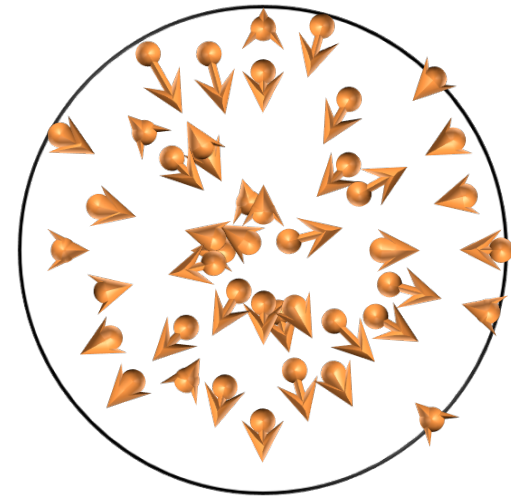
DIPOLE



MOMENTS



CATALOGUE



# RELATING MEASUREMENTS TO $P(k)$

$$L \propto \frac{1}{2\pi^{N/2} |R_{mn}|^{1/2}} \exp\left(-\frac{1}{2} S_m R_{mn}^{-1} S_n\right)$$

$$R_{mn} = R_{mn}^{(v)} + R_{mn}^{(e)}$$

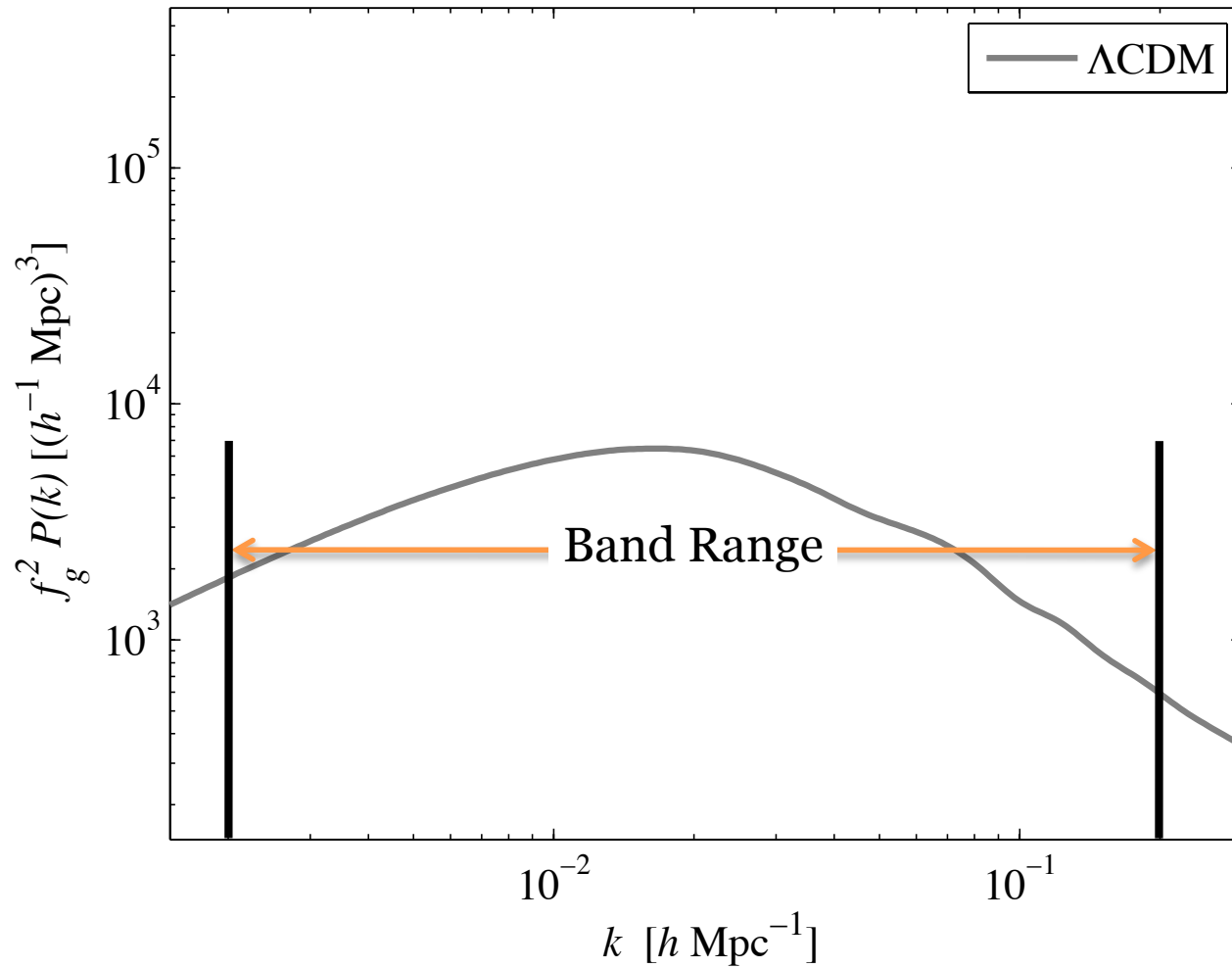
$$R_{mn}^{(v)} = \int \frac{4\pi k^2 dk}{(2\pi)^3} P_v(k) f_{mn}(k)$$

$$R_{mn}^{(e)} = (\sigma_m^2 + \sigma_*^2) \delta_{mn}$$

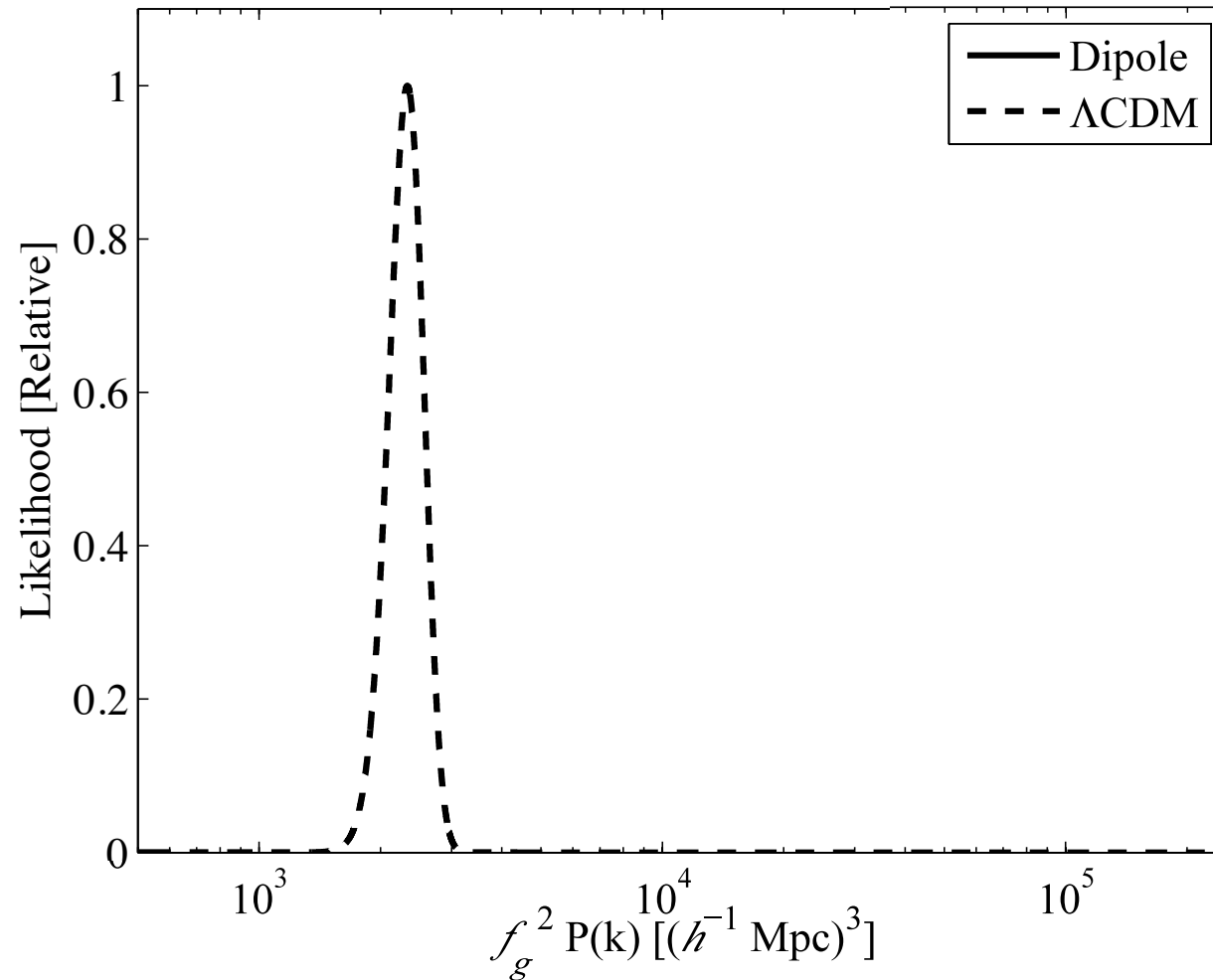
$$P_v(k) = \left(\frac{H_0 a}{k}\right)^2 f_g^2 P(k) \quad f_{mn}(k) = \hat{r}_{m,i} \hat{r}_{n,j} \int \frac{d^2 \hat{k}}{4\pi} \hat{k}_i \hat{k}_j e^{ik\hat{k} \cdot (r_m - r_n)}$$

# REAL DATA

## ONE BAND POWER SPECTRUM

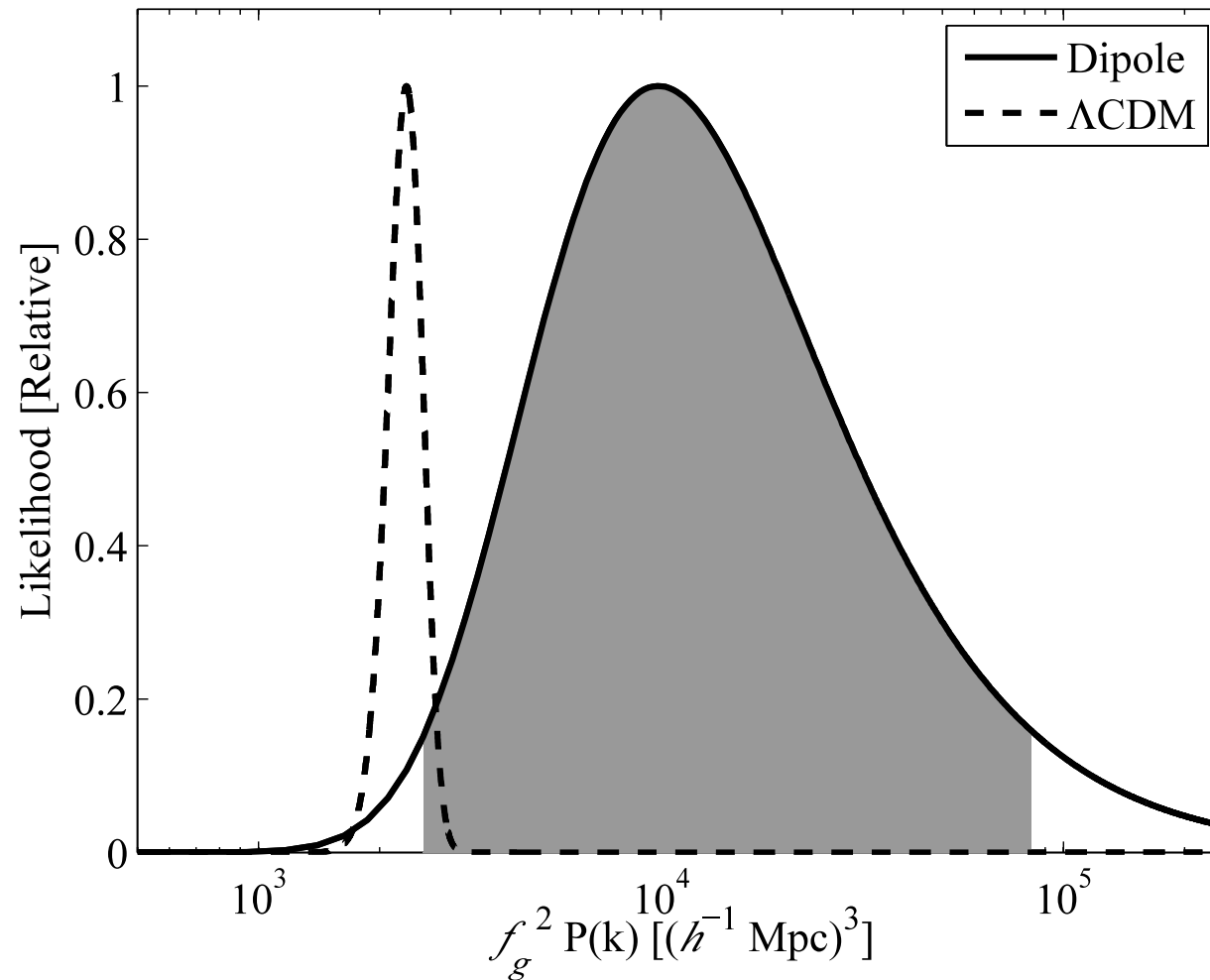


# REAL DATA ONE BAND POWER SPECTRUM

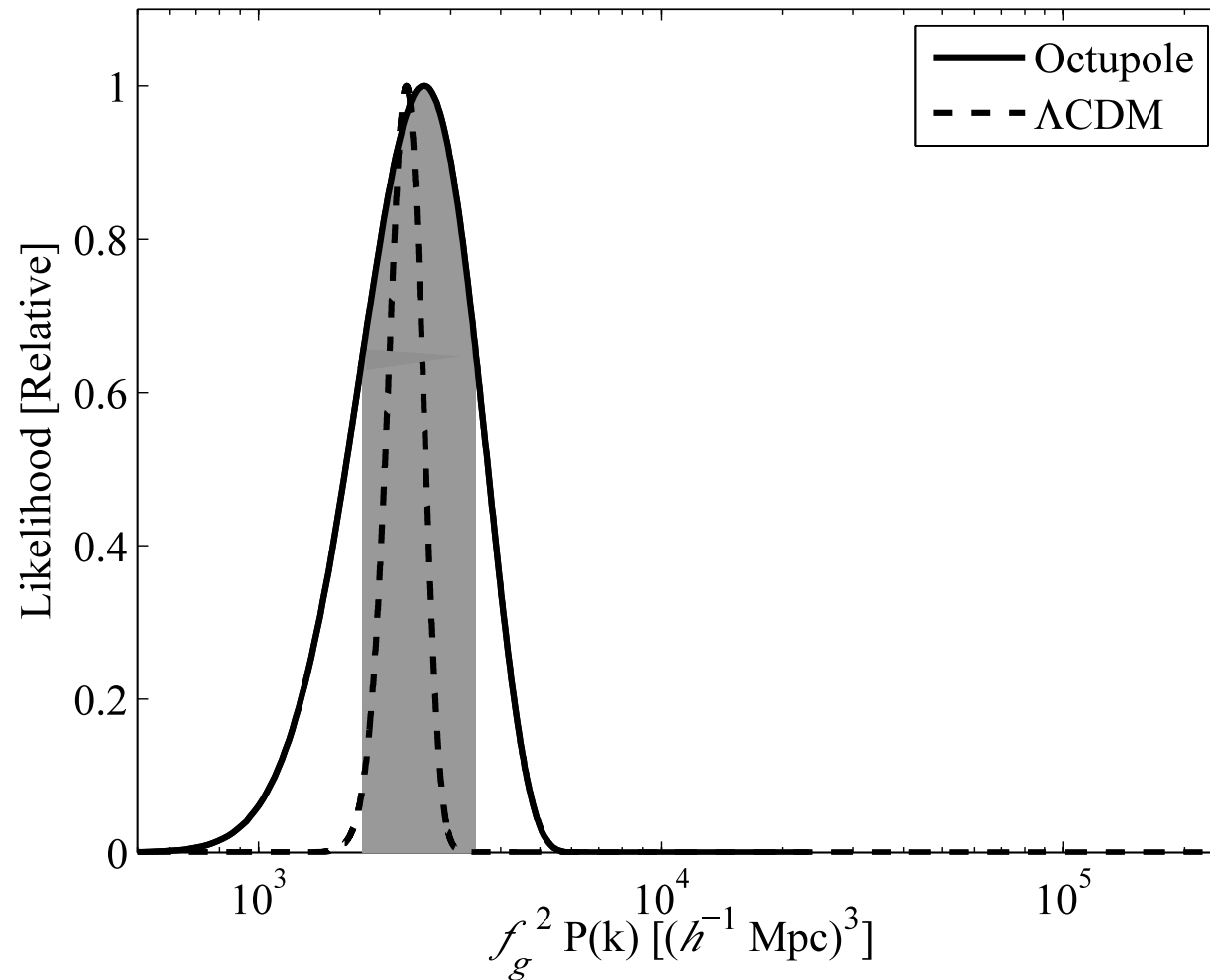


# REAL DATA: DIPOLE ONLY

## ONE BAND POWER SPECTRUM

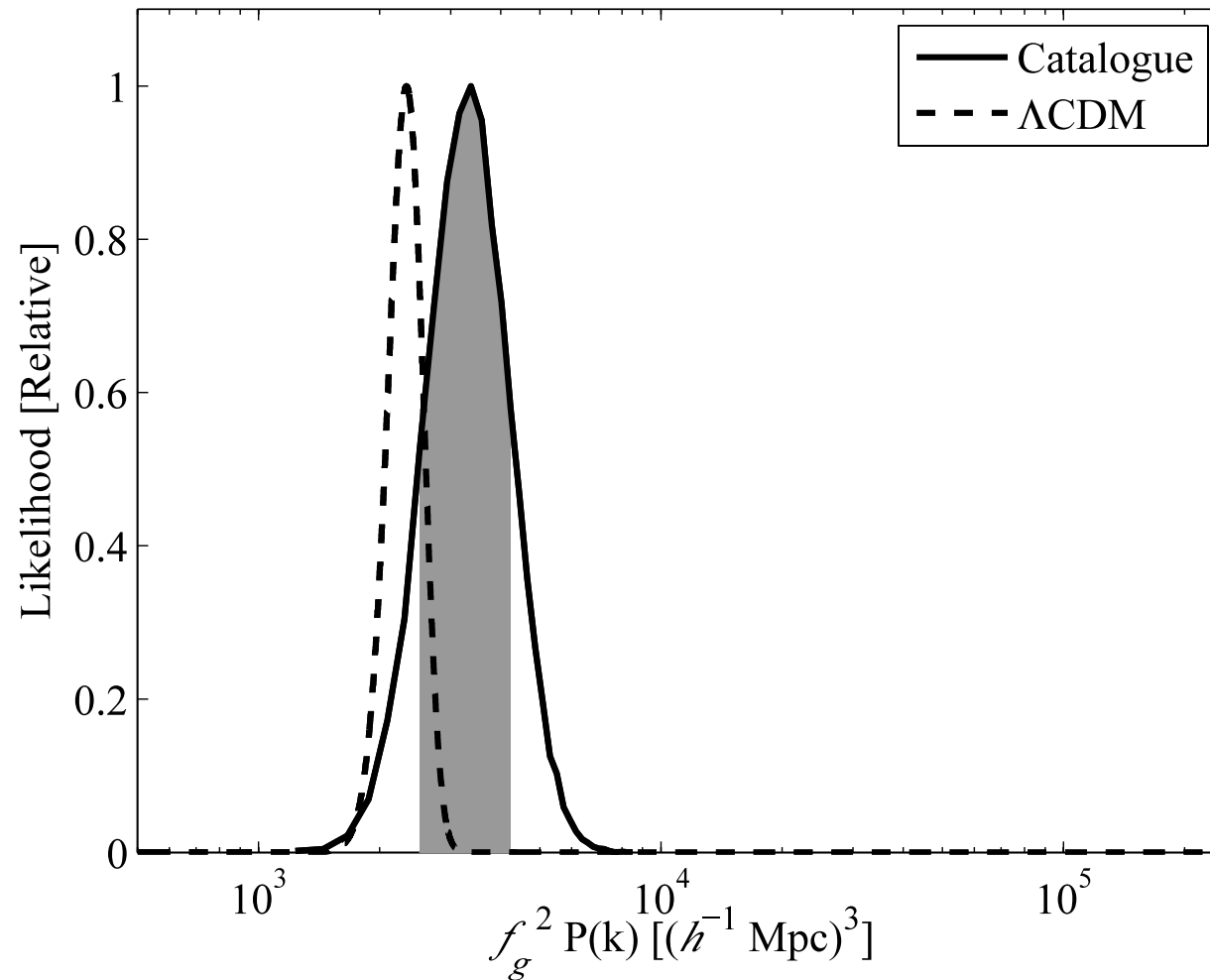


# REAL DATA: DIPOLE, SHEAR & OCTUPOLE ONE BAND POWER SPECTRUM



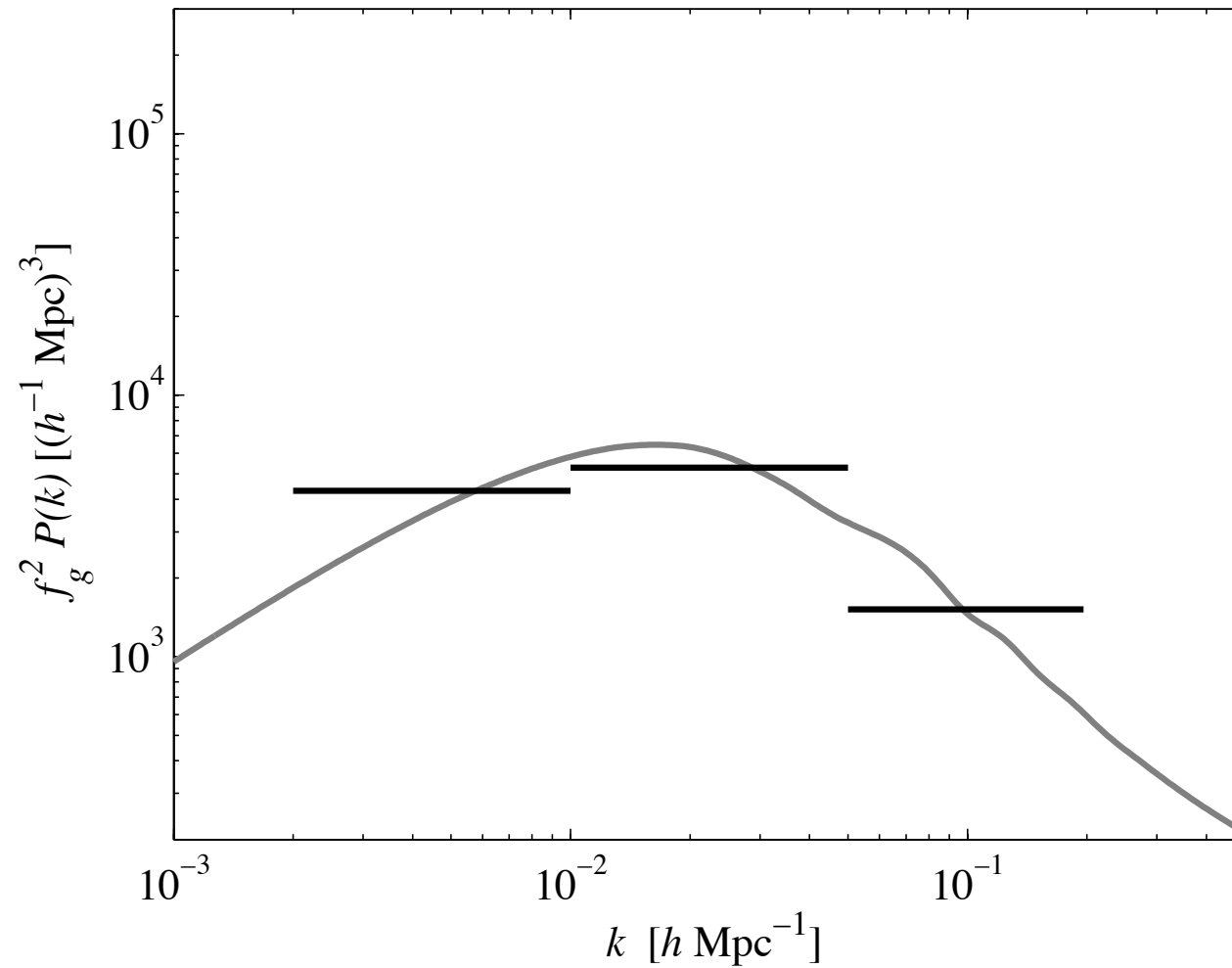
# REAL DATA: CATALOGUE METHOD

## ONE BAND POWER SPECTRUM



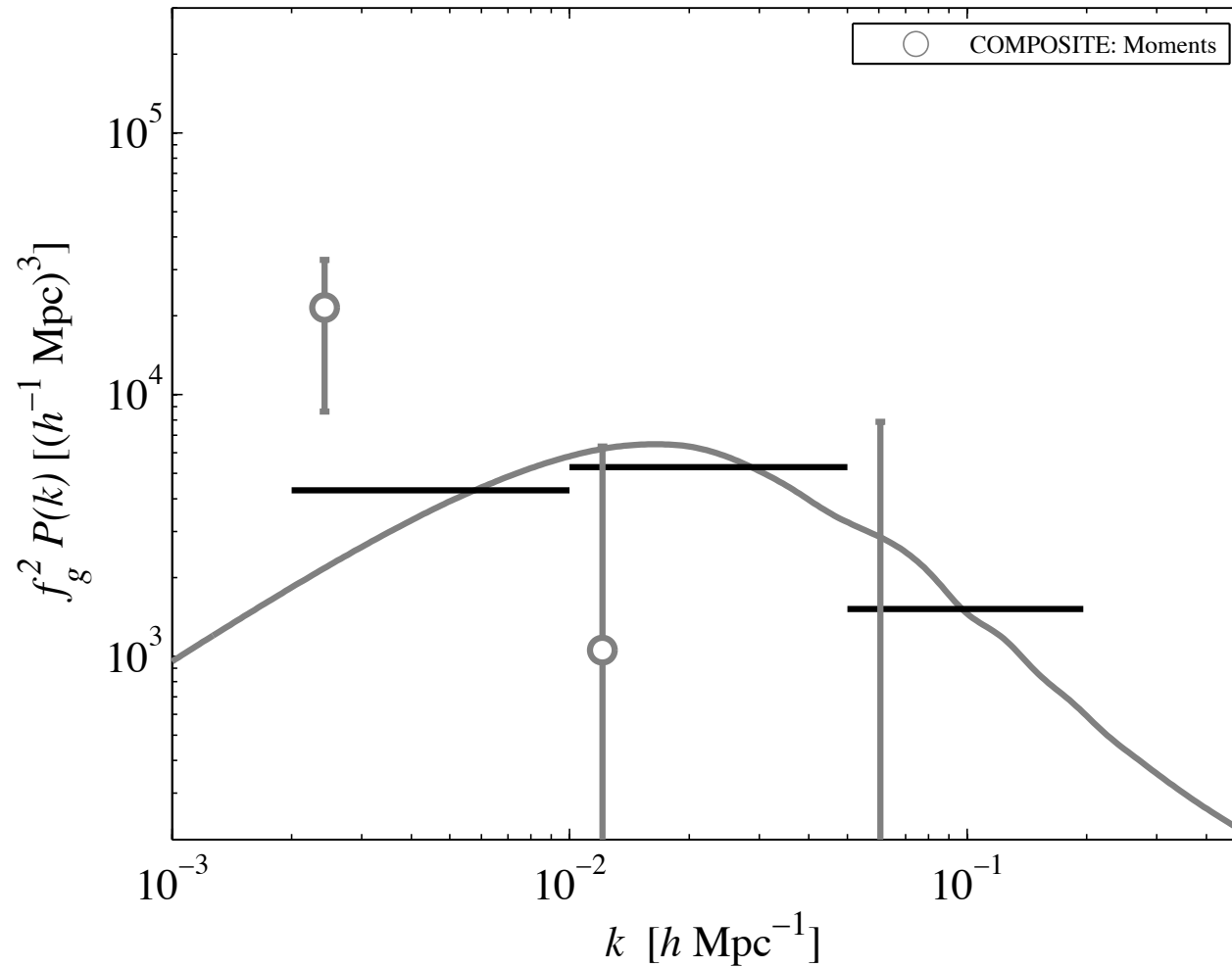


# REAL DATA THREE BAND POWER SPECTRUM



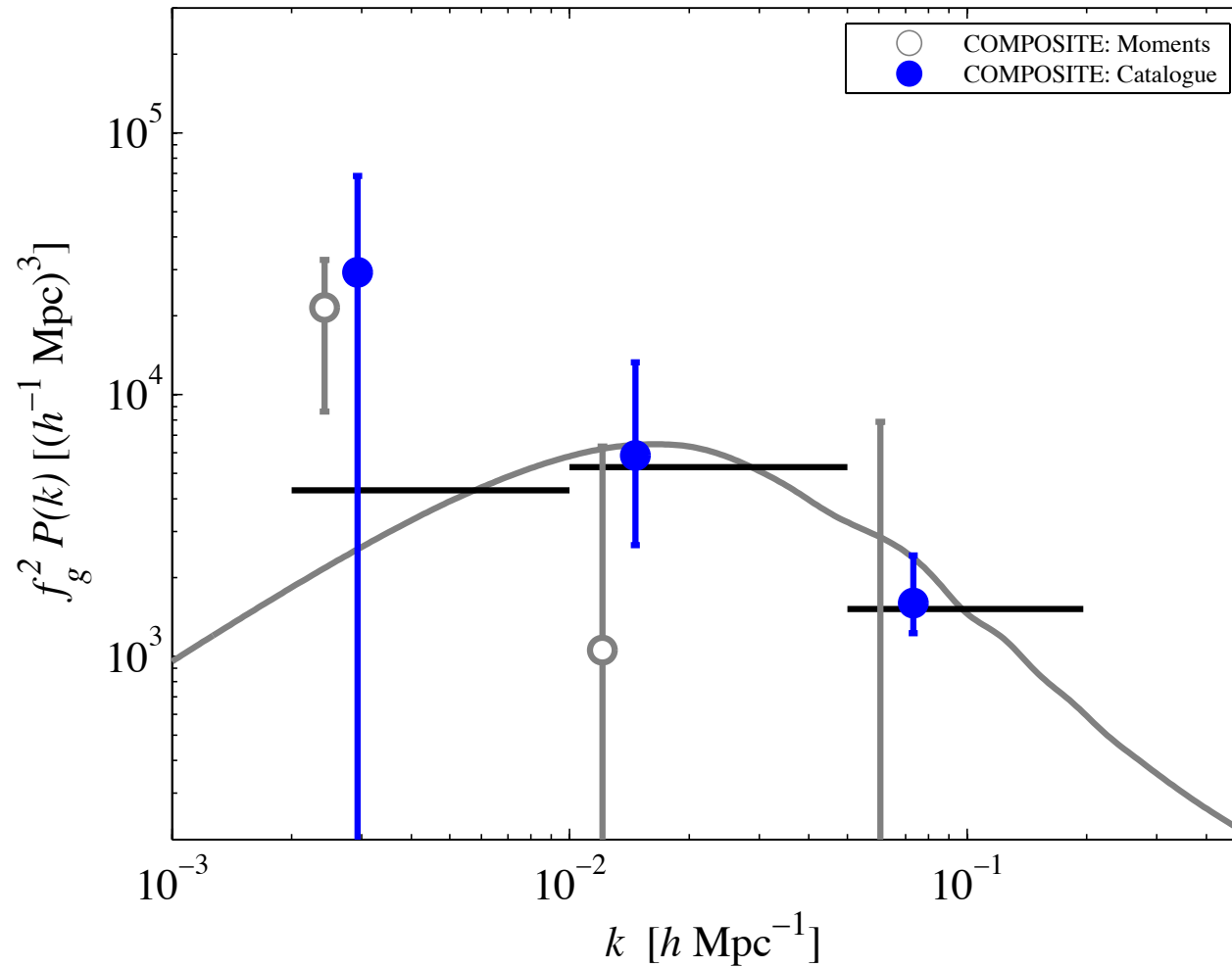
# REAL DATA

## THREE BAND POWER SPECTRUM



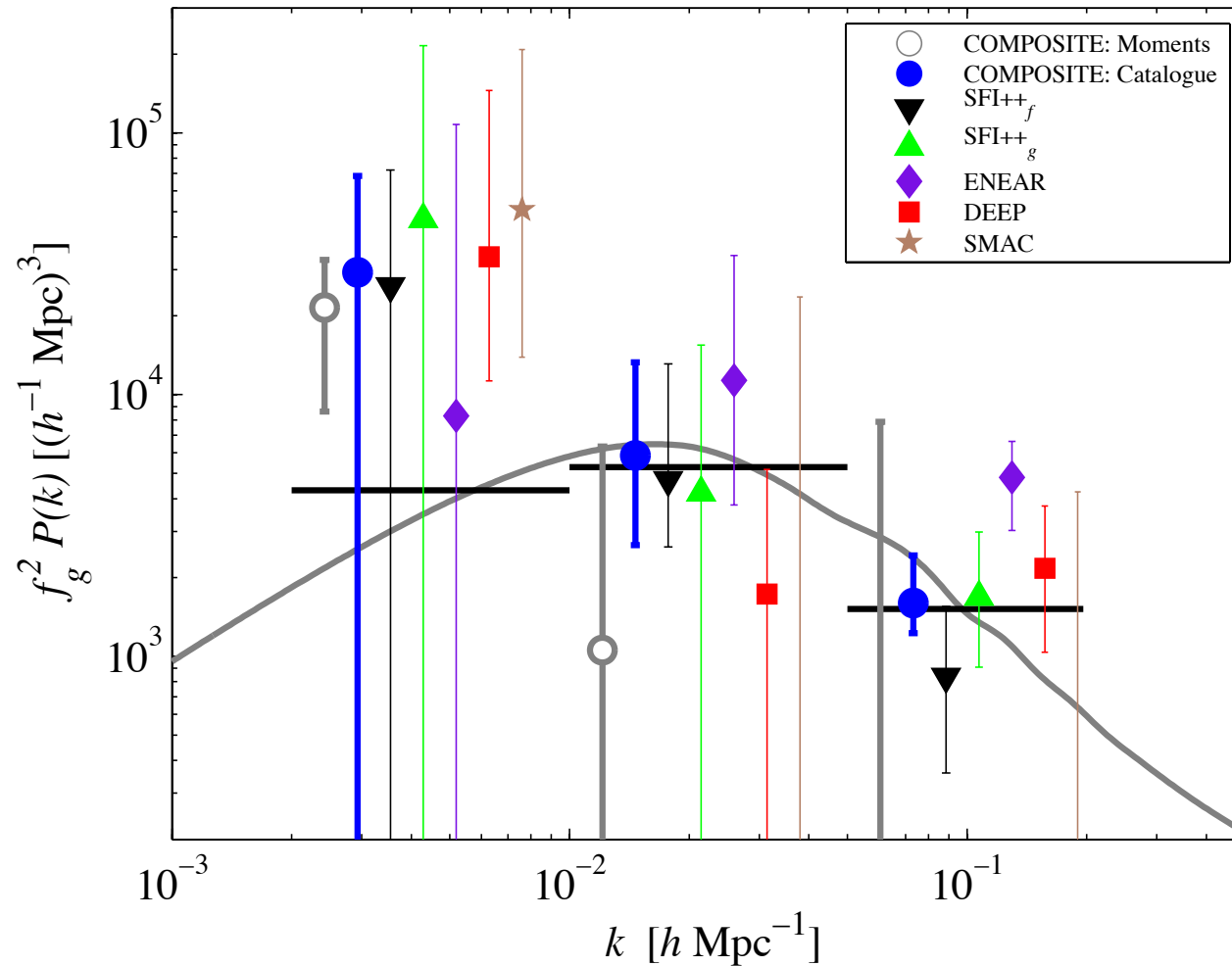
# REAL DATA

## THREE BAND POWER SPECTRUM

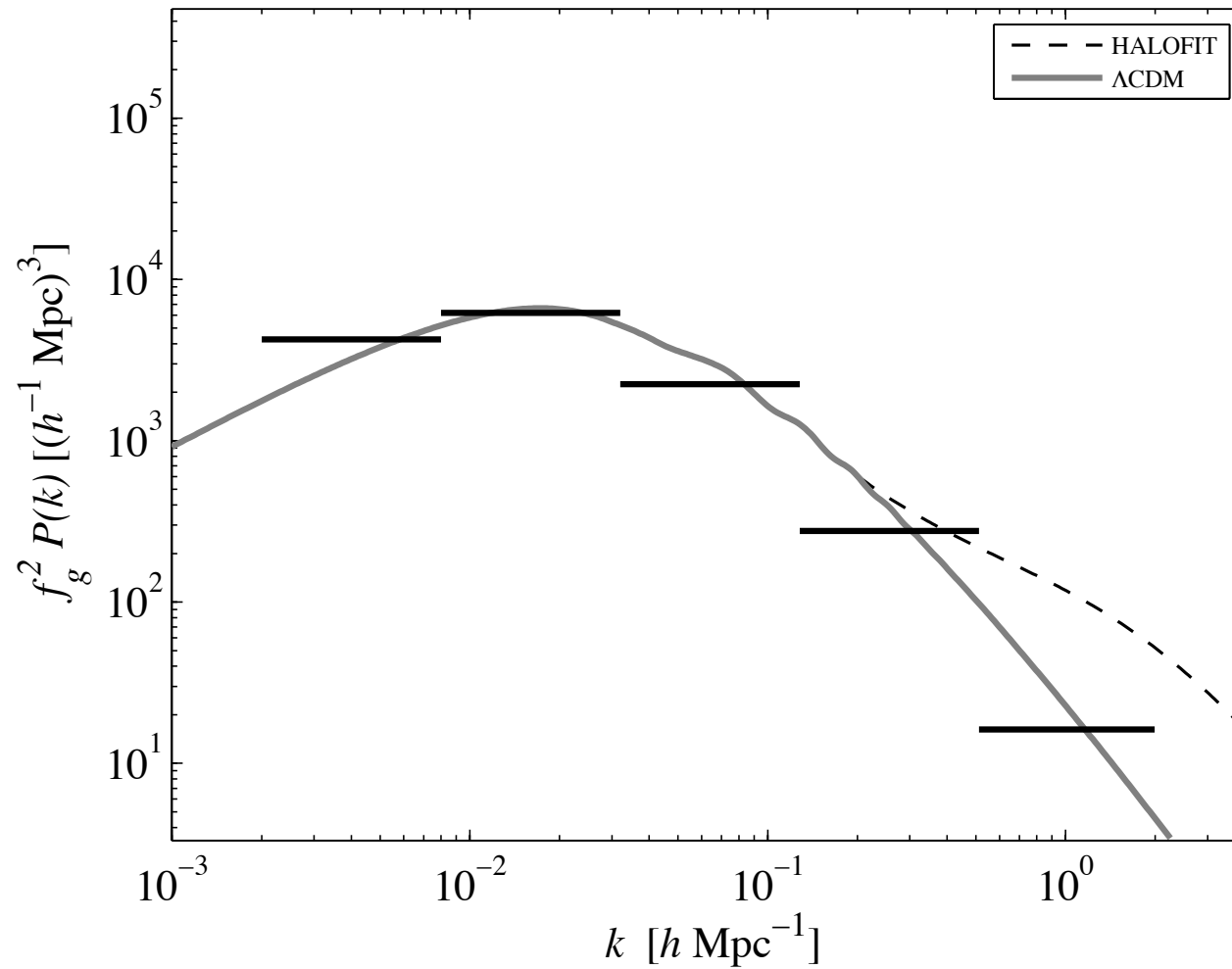


# REAL DATA

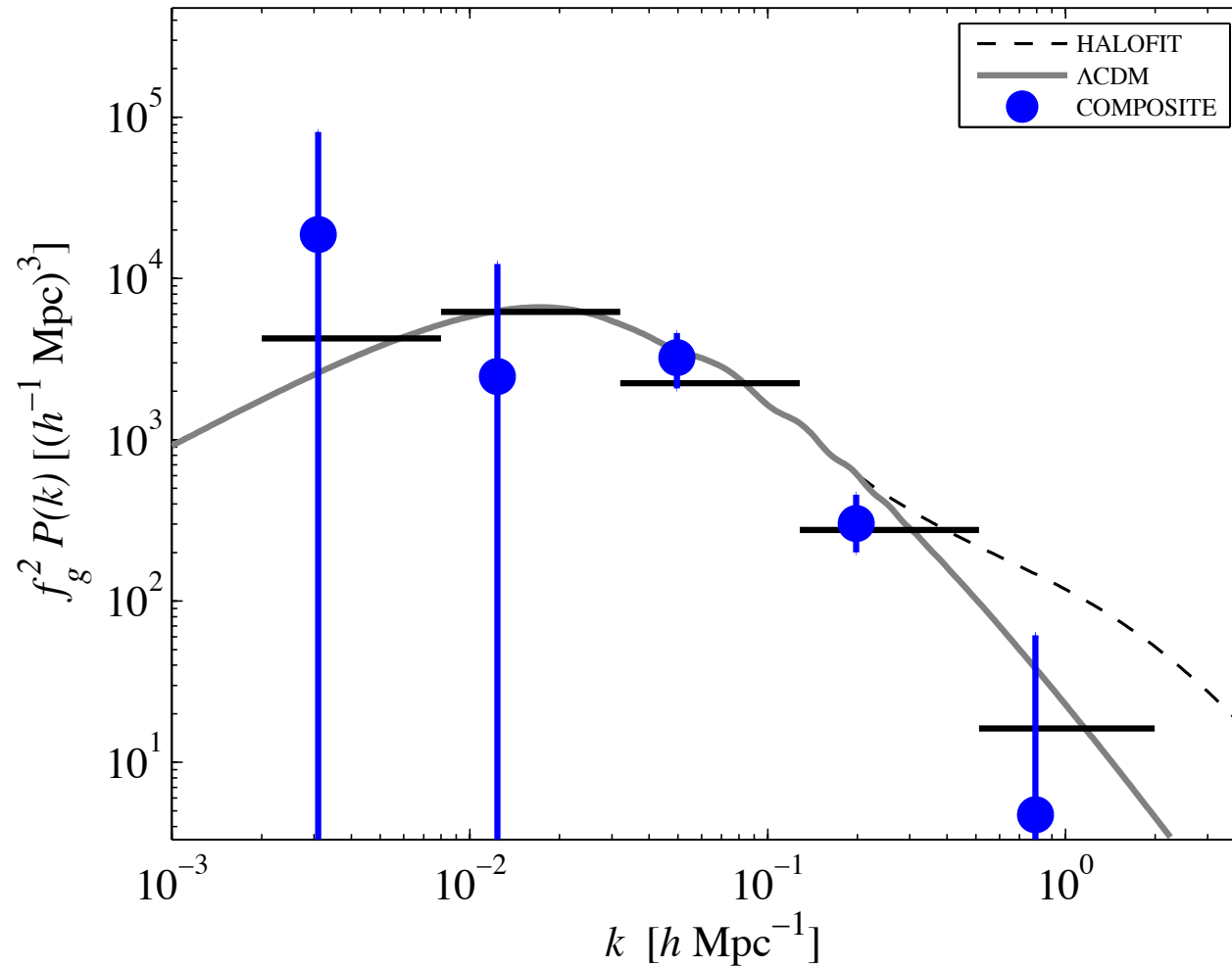
## THREE BAND POWER SPECTRUM



# REAL DATA FIVE BAND POWER SPECTRUM

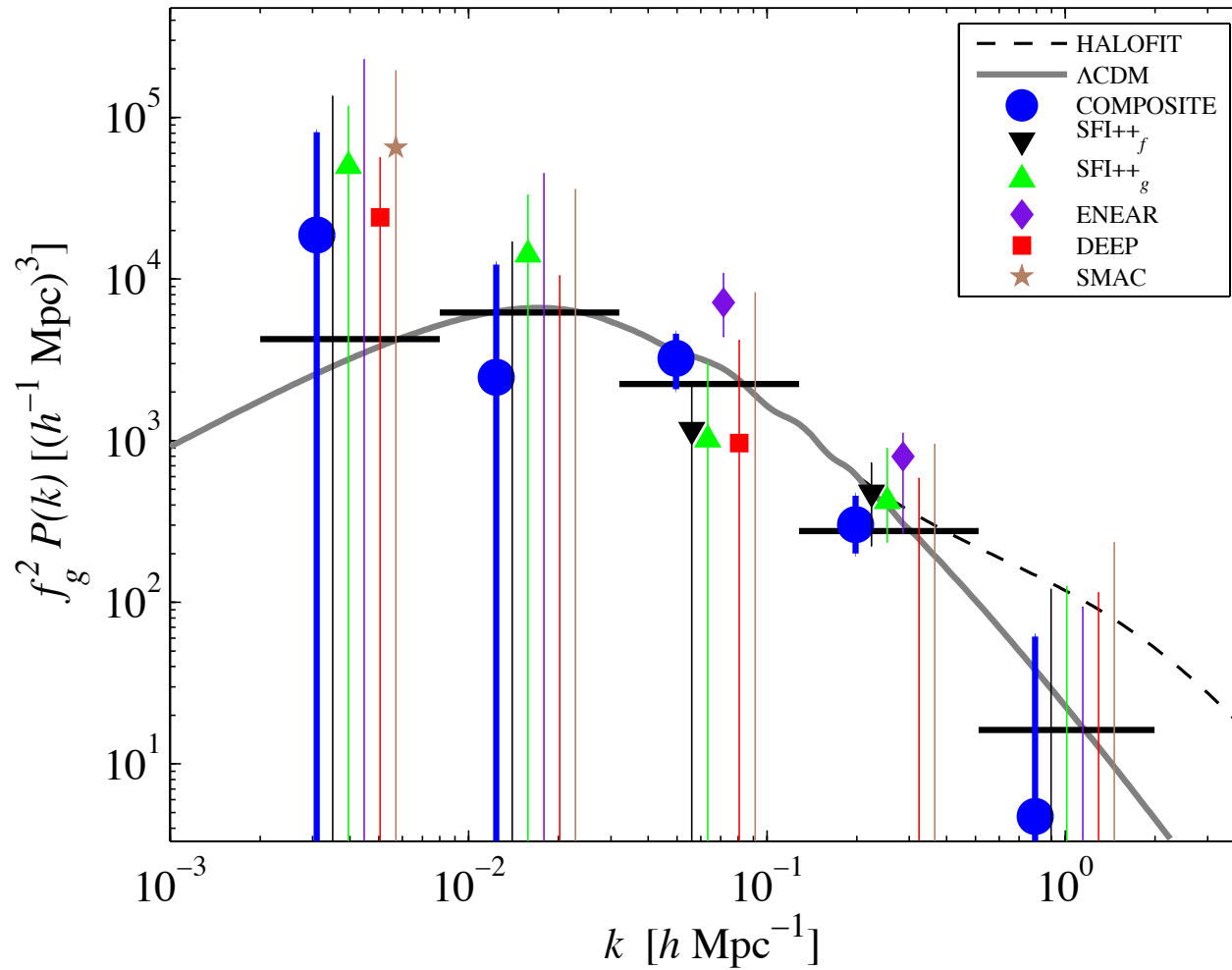


# REAL DATA FIVE BAND POWER SPECTRUM

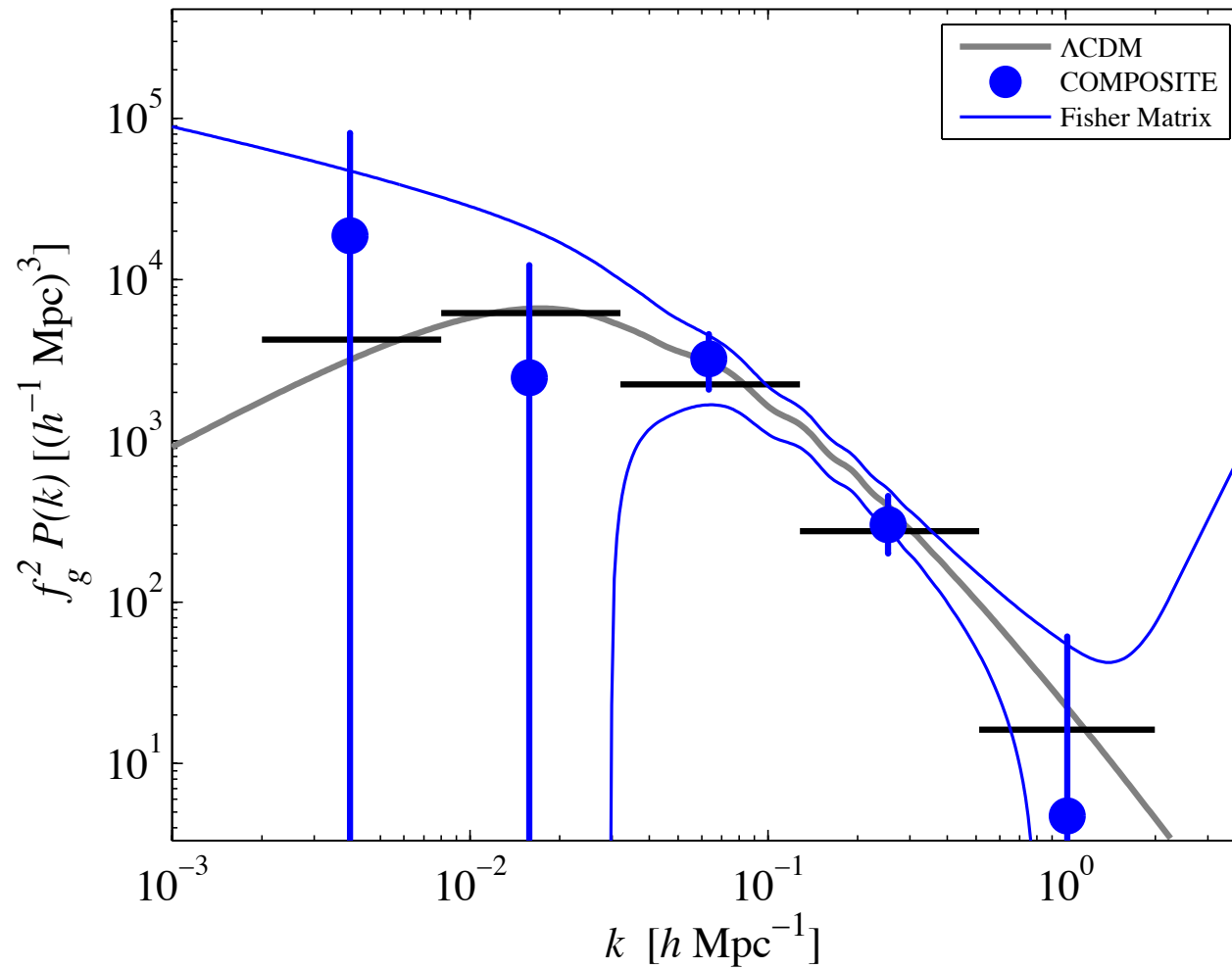


# REAL DATA

## FIVE BAND POWER SPECTRUM

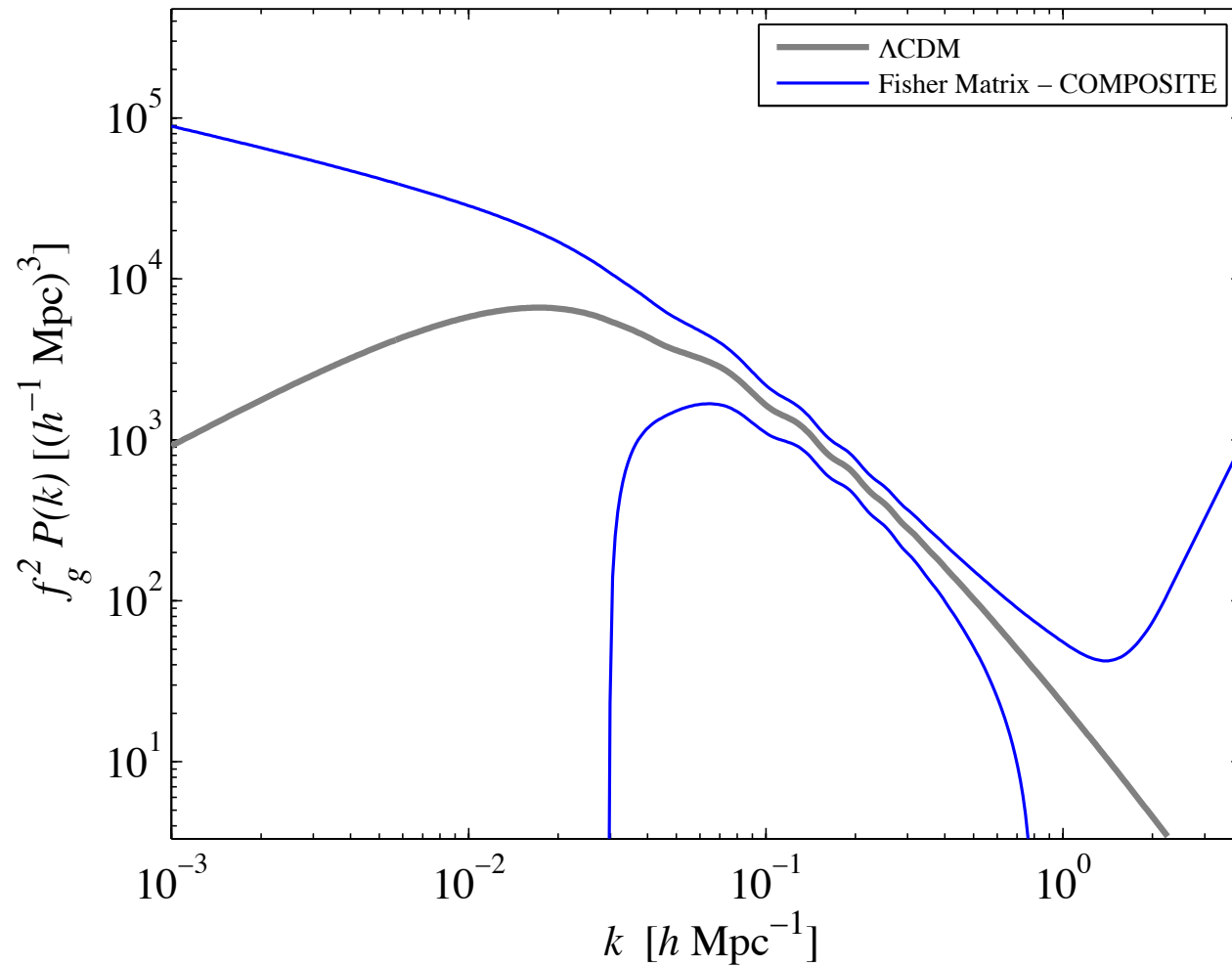


# FISHER MATRIX COMPARISON

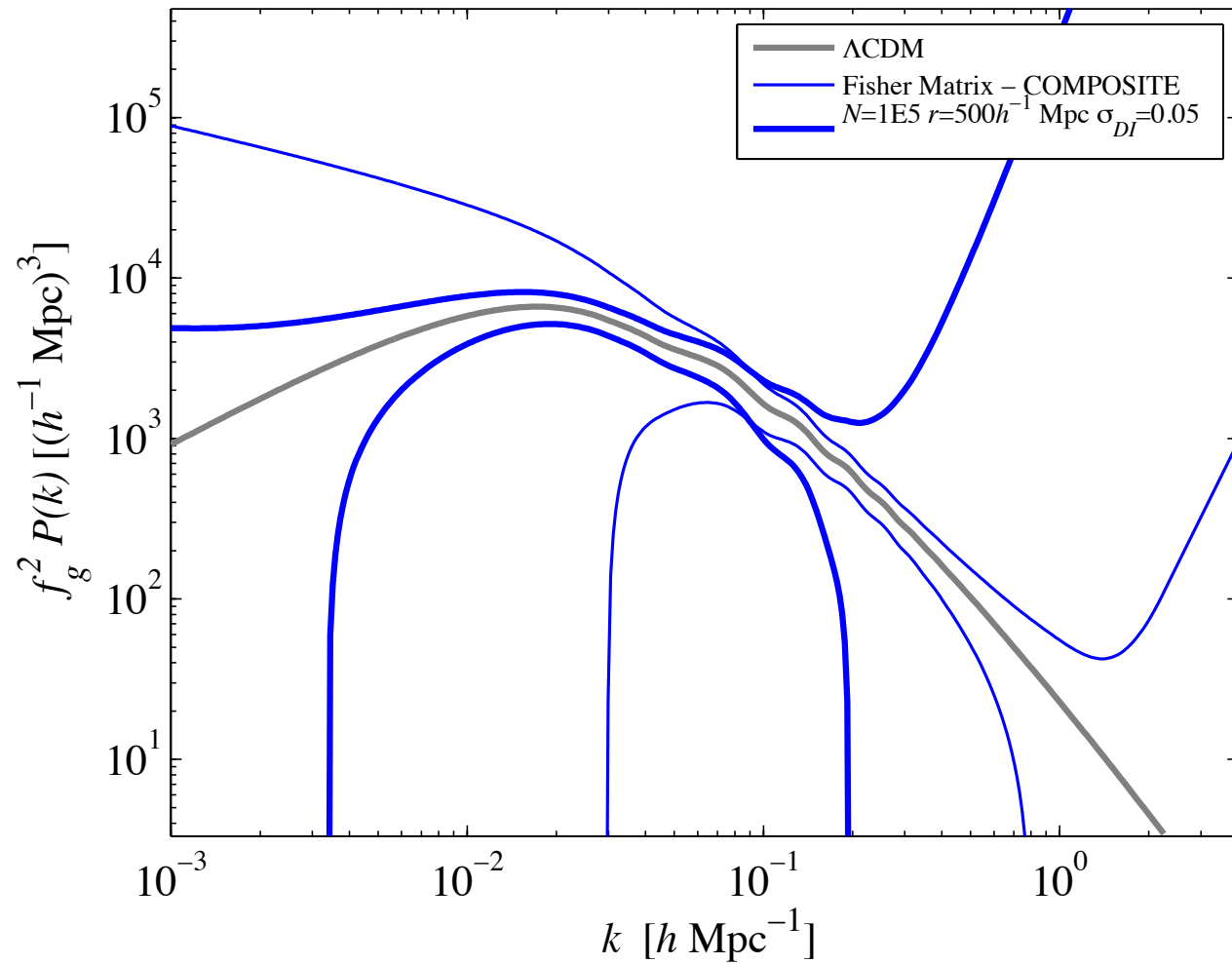




# FISHER MATRIX COMPARISON

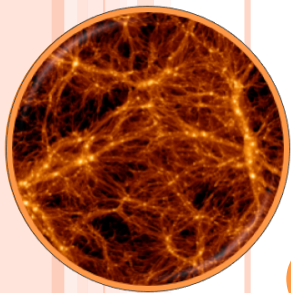


# FISHER MATRIX COMPARISON



## CONCLUSIONS

- New, independent power spectrum measurements at  $z=0$
- The high dipole is not challenging to  $\Lambda$ CDM
- Exciting prospects for future measurements



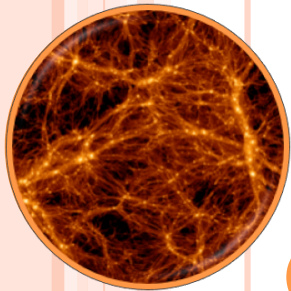
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**Edward Macaulay**

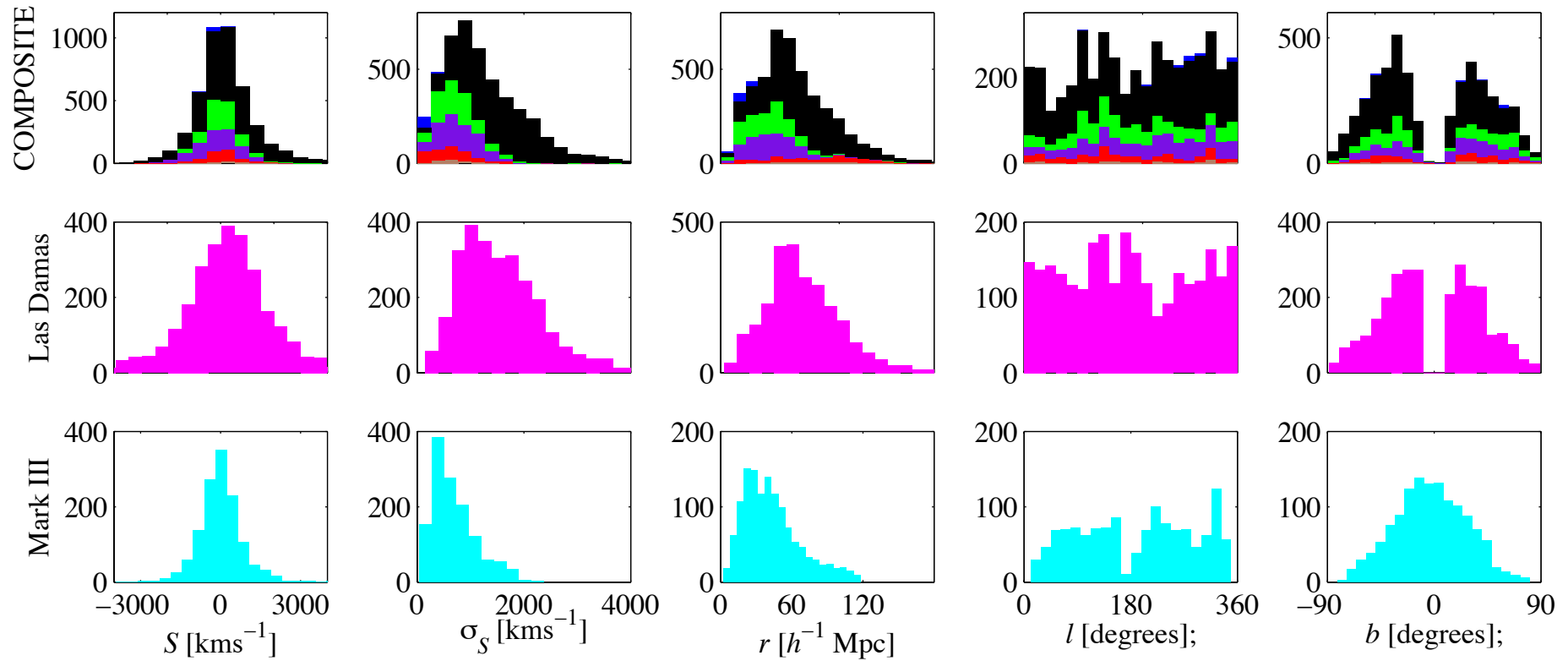
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**ArXiv: 1111.3338**

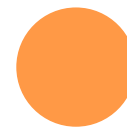
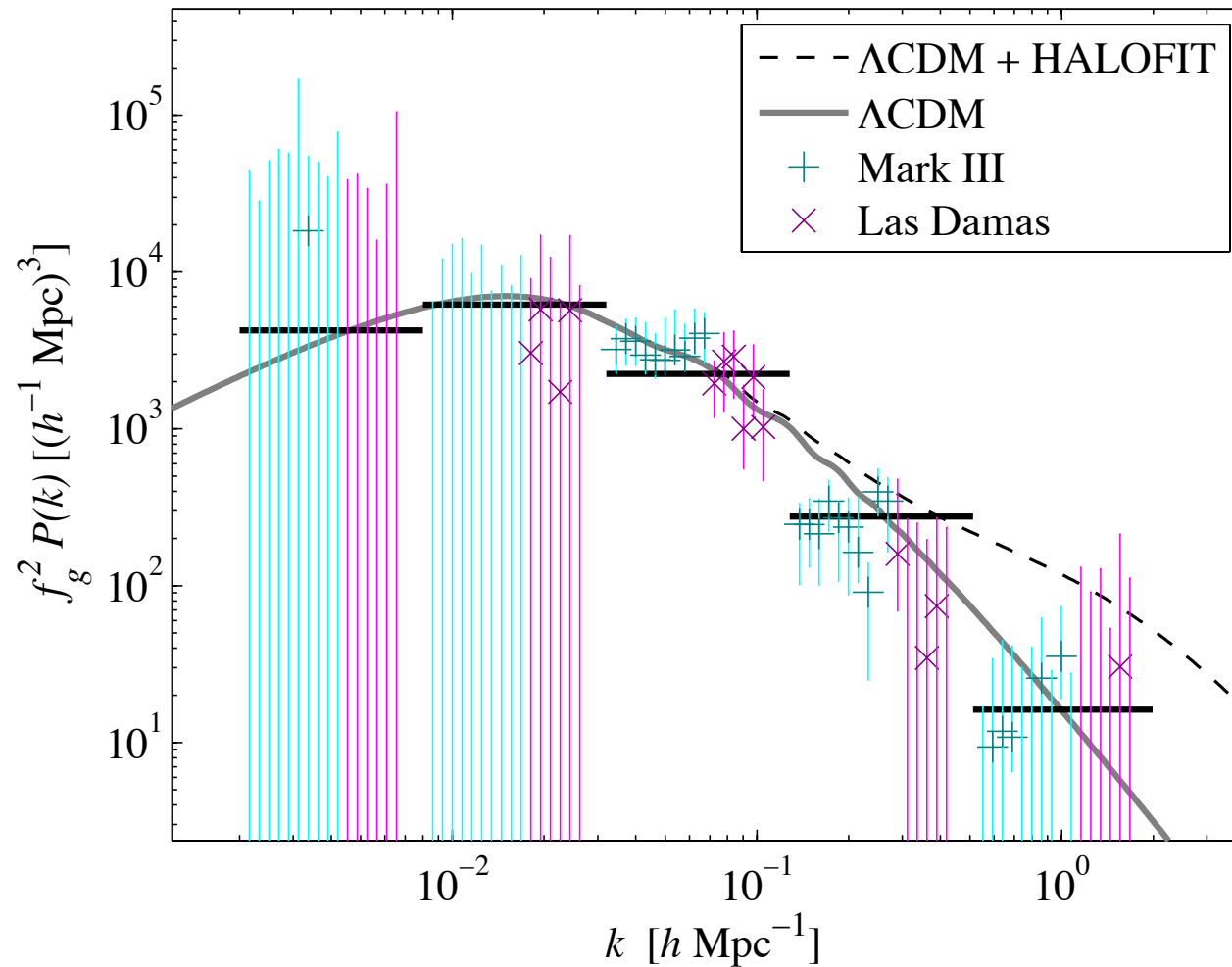


# SURVEY CATALOGUES



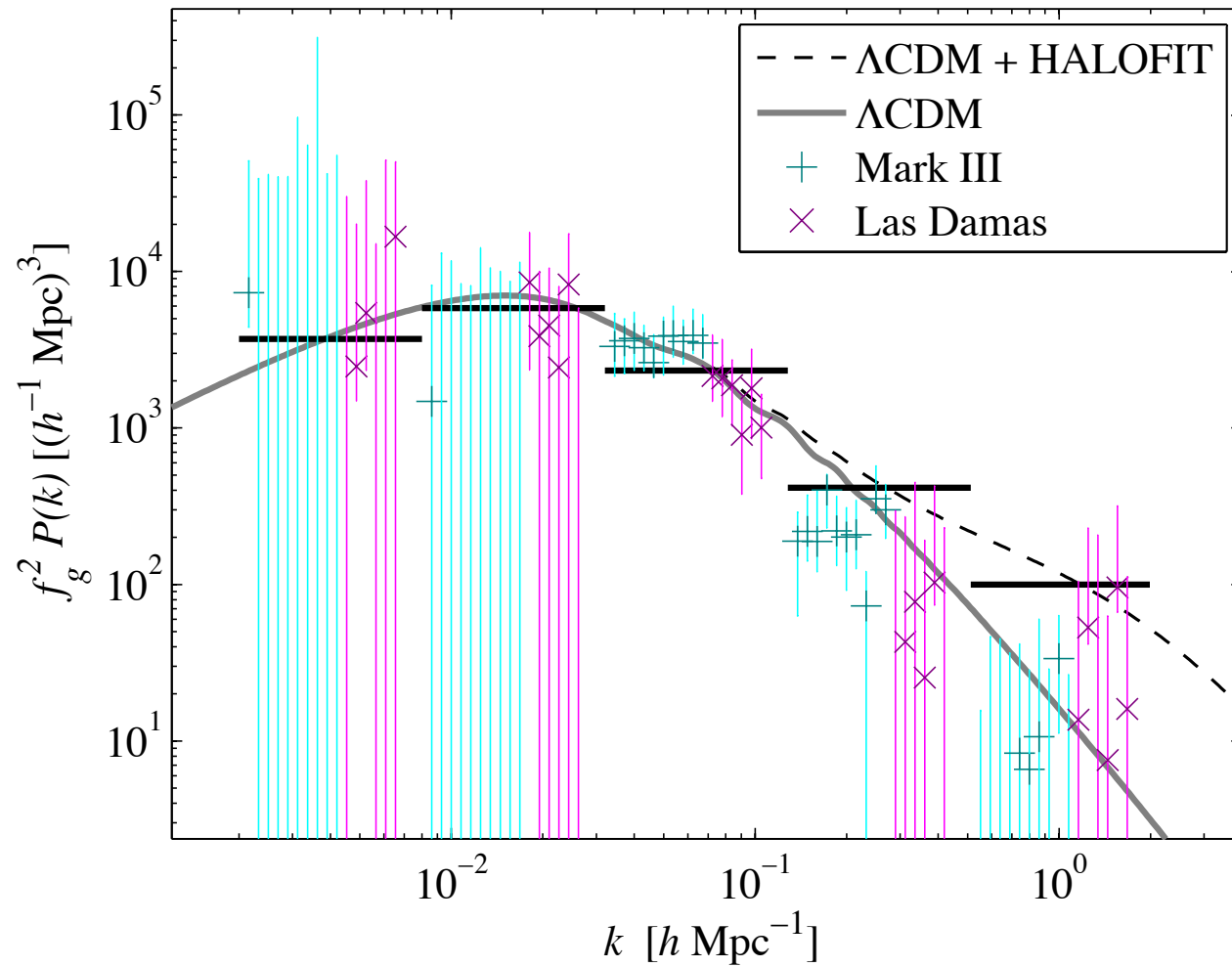
# SIMULATED DATA

## FIVE BAND POWER SPECTRUM



# SIMULATED DATA

## FIVE BAND POWER SPECTRUM



# REAL DATA WINDOW FUNCTIONS

