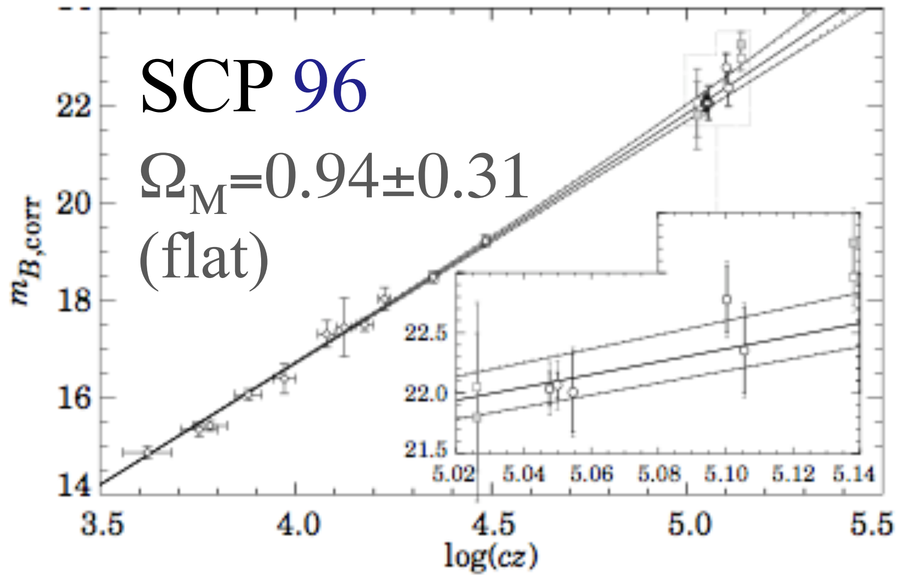
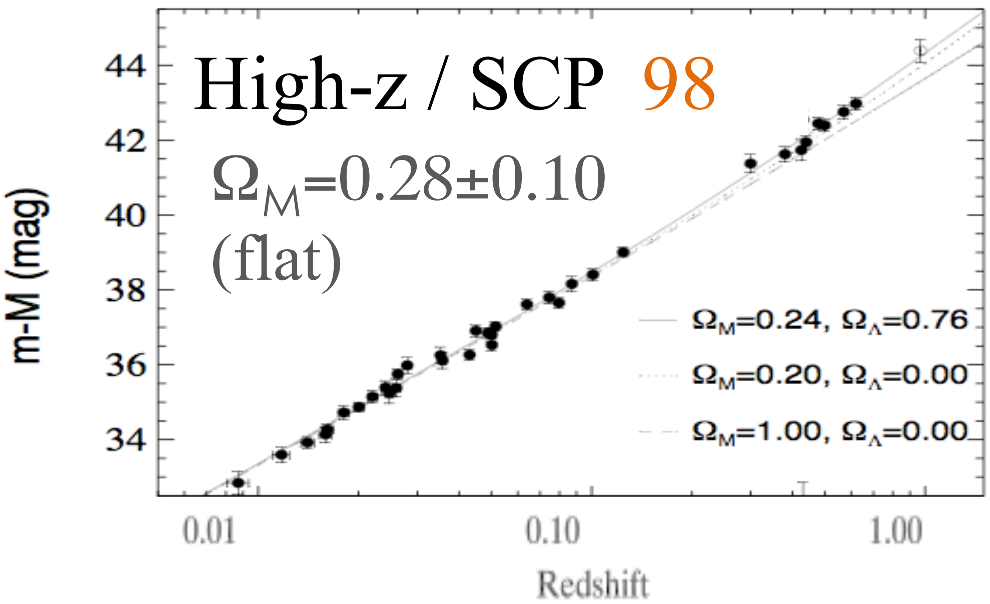
Baryon Acoustic Oscillations and Dark Energy

Bruce Bassett (AIMS/SAAO/UCT)

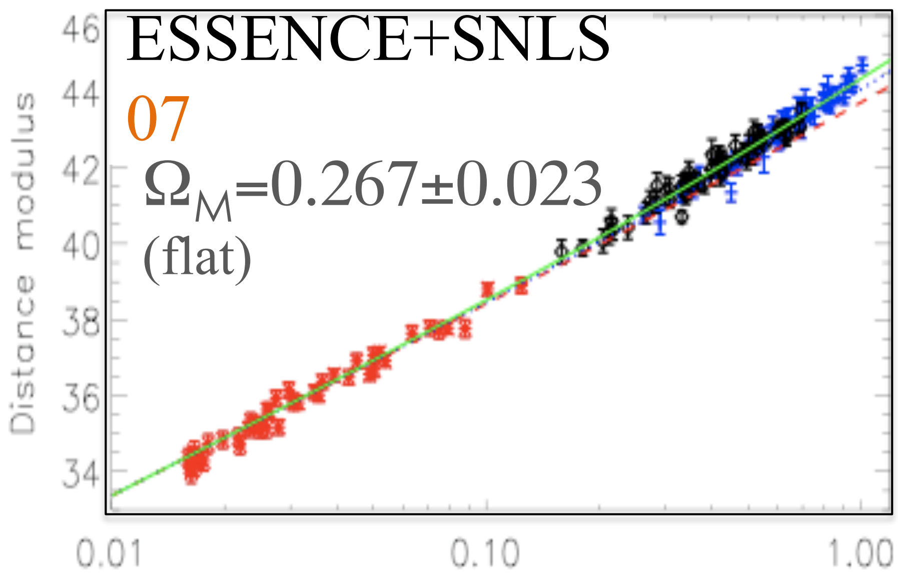
ArXiv:0910.5224

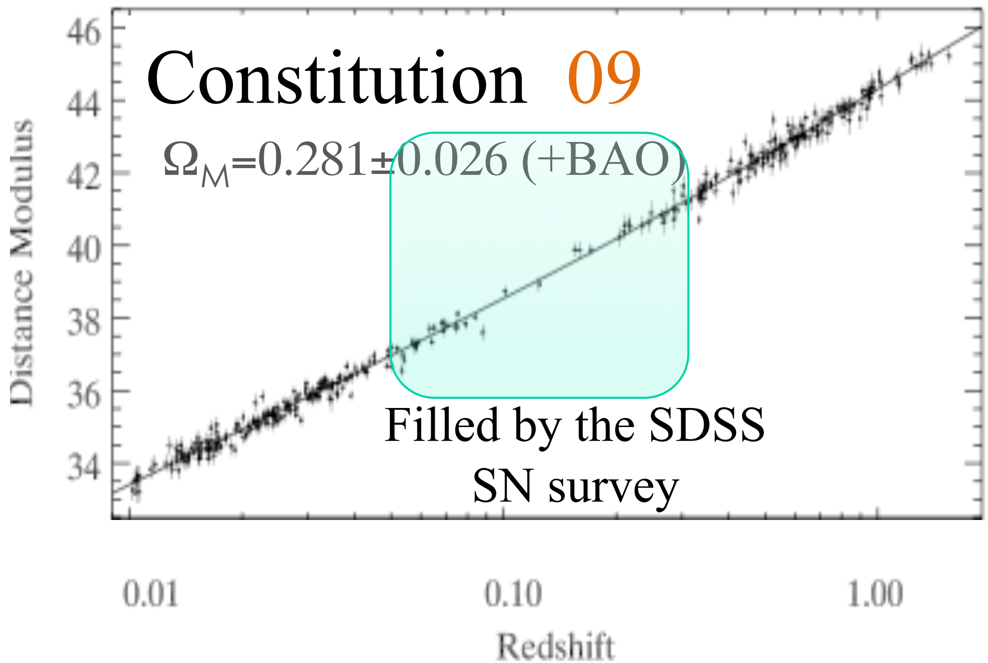
How far have we come since my first cosmology school?

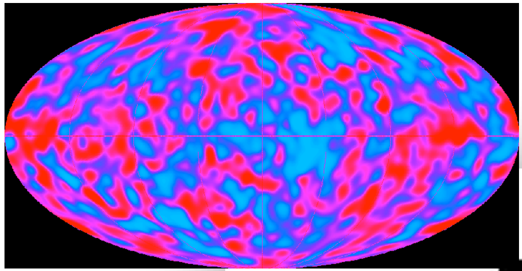




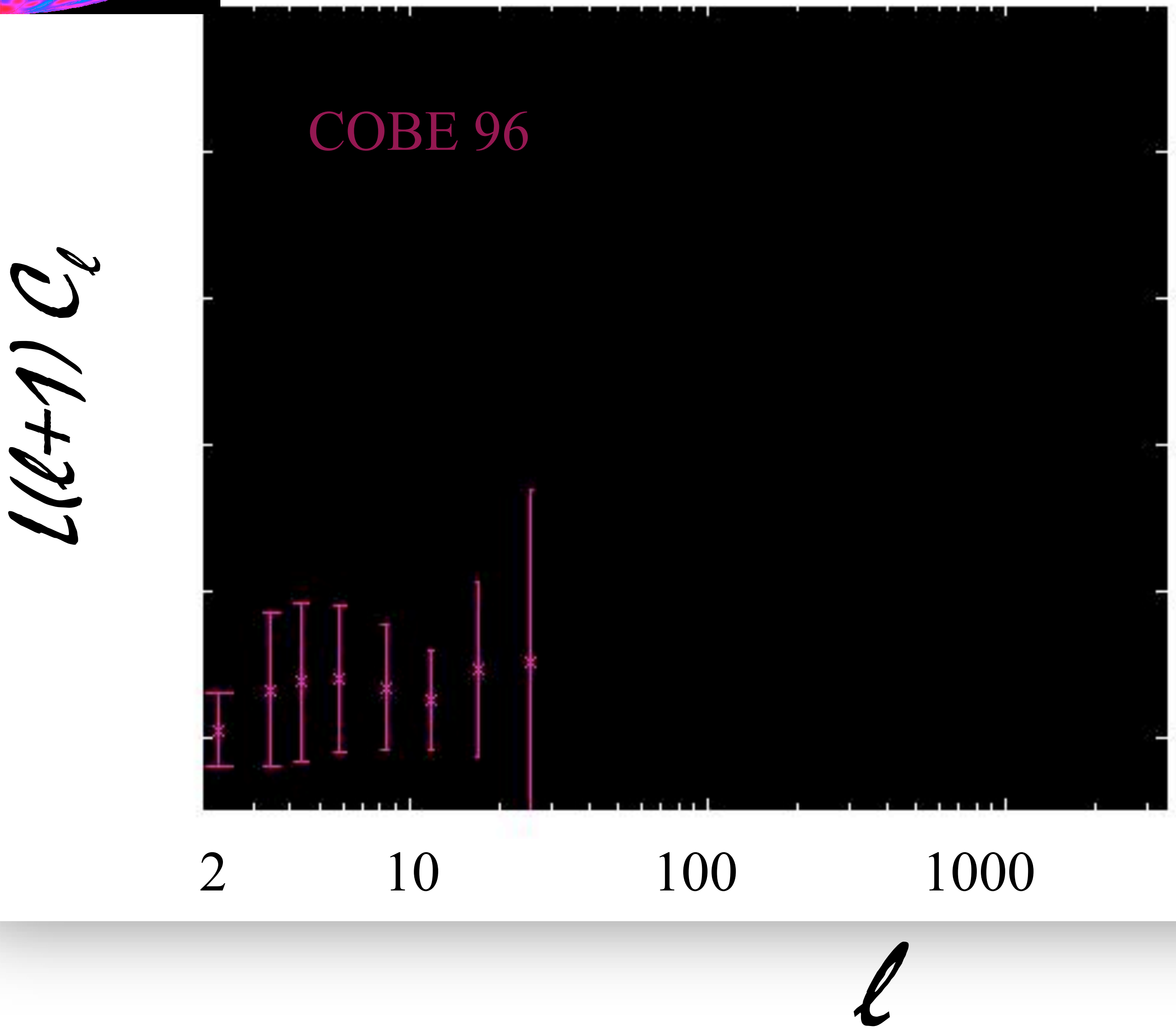
Evolution of the Hubble Diagram 1996-2009

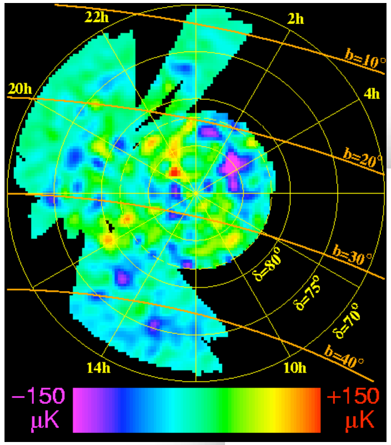


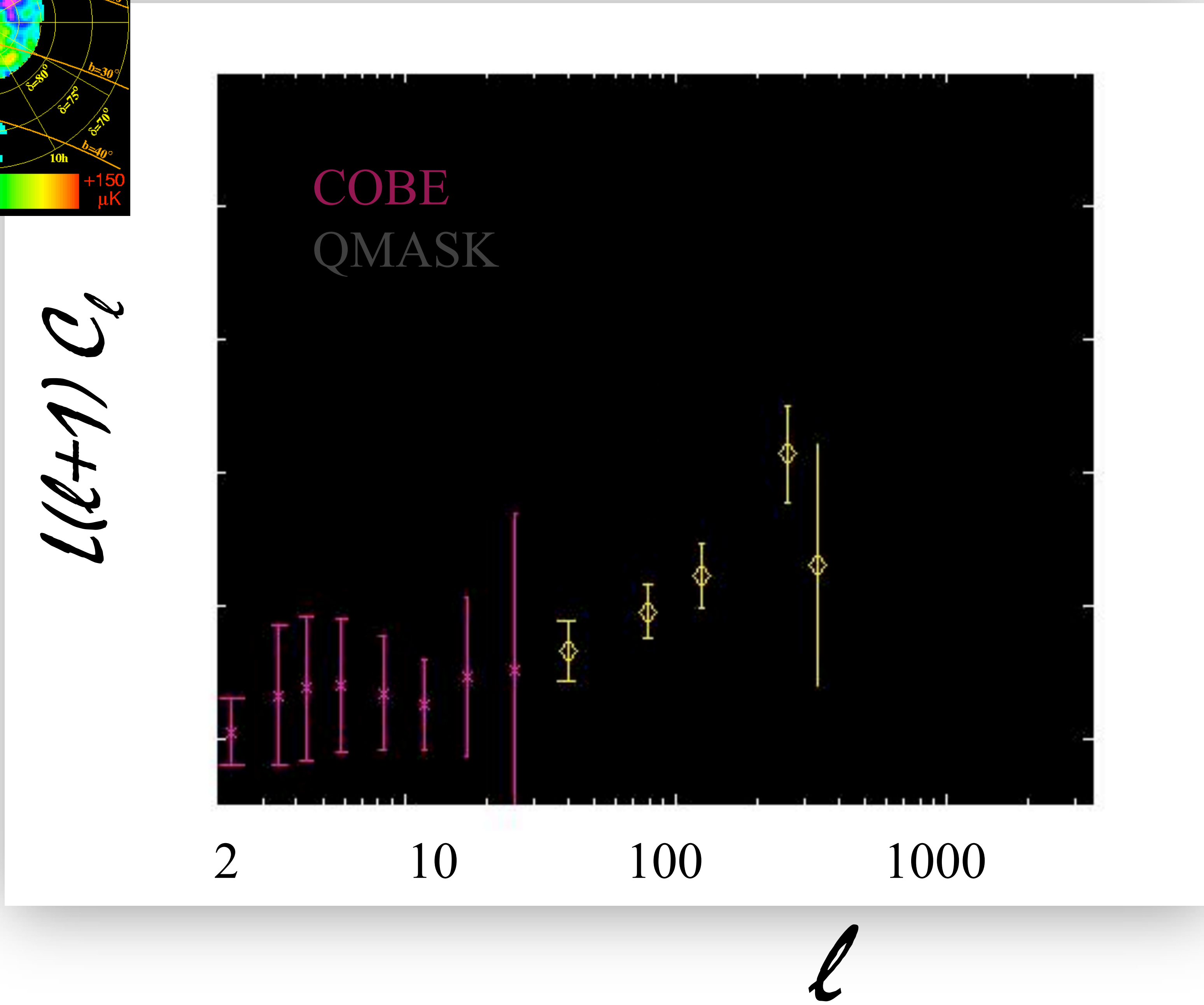


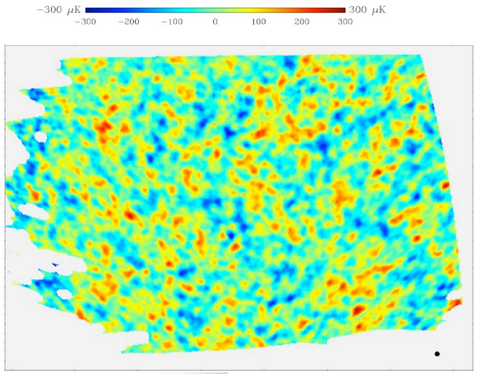


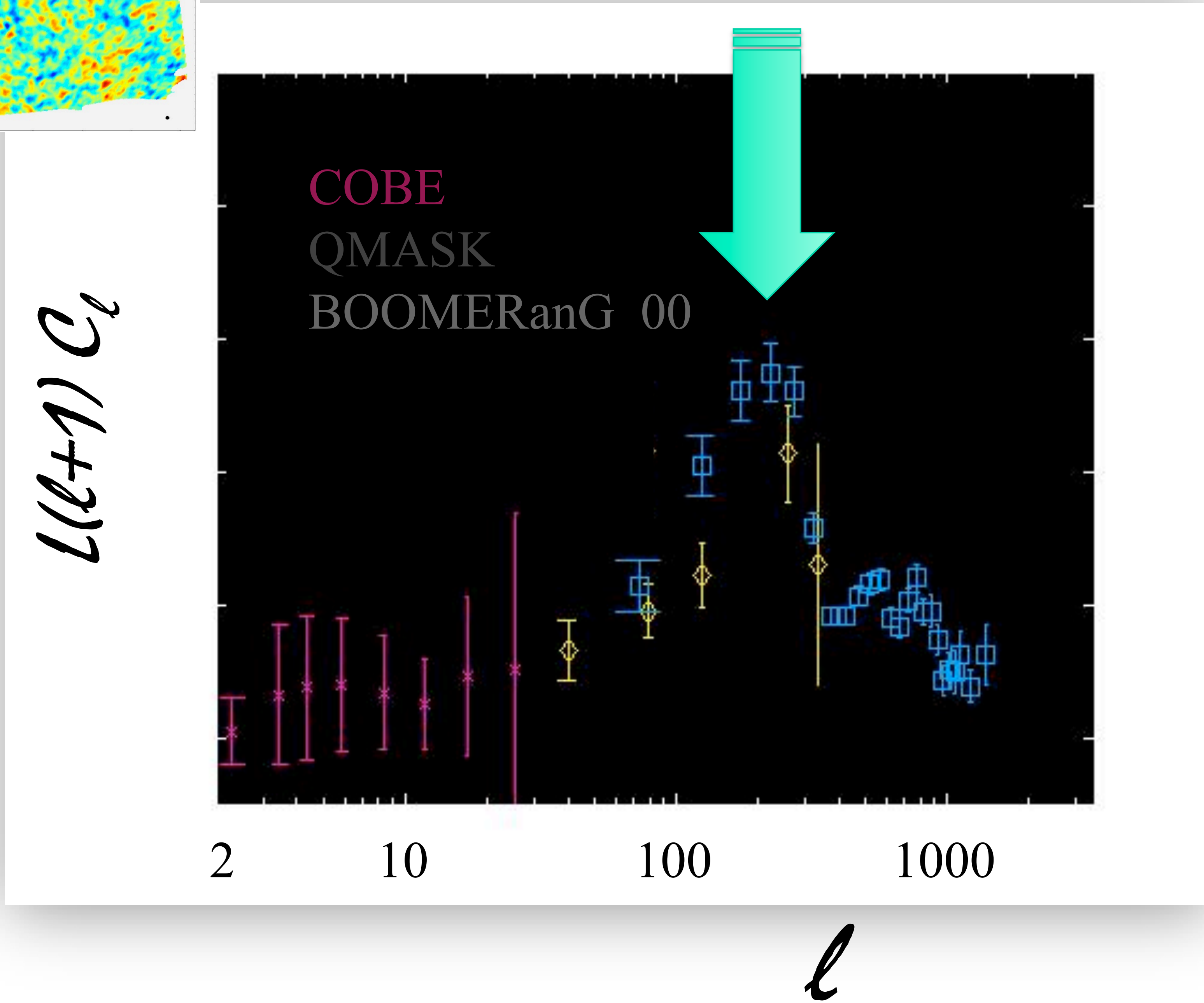
THE CMB

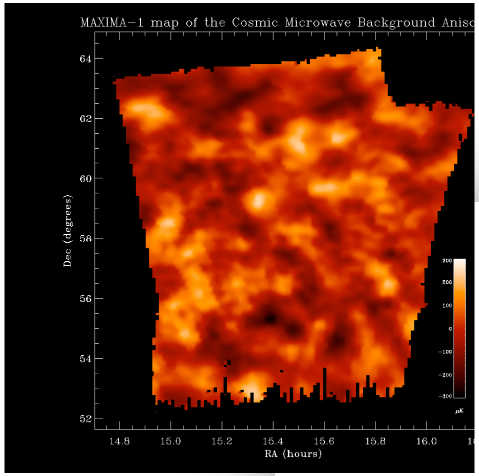



22h
2h
20h
4h
b=10°
b=20°
b=30°
b=40°
δ=80°
δ=75°
δ=70°
14h
10h
−150 μK
+150 μK

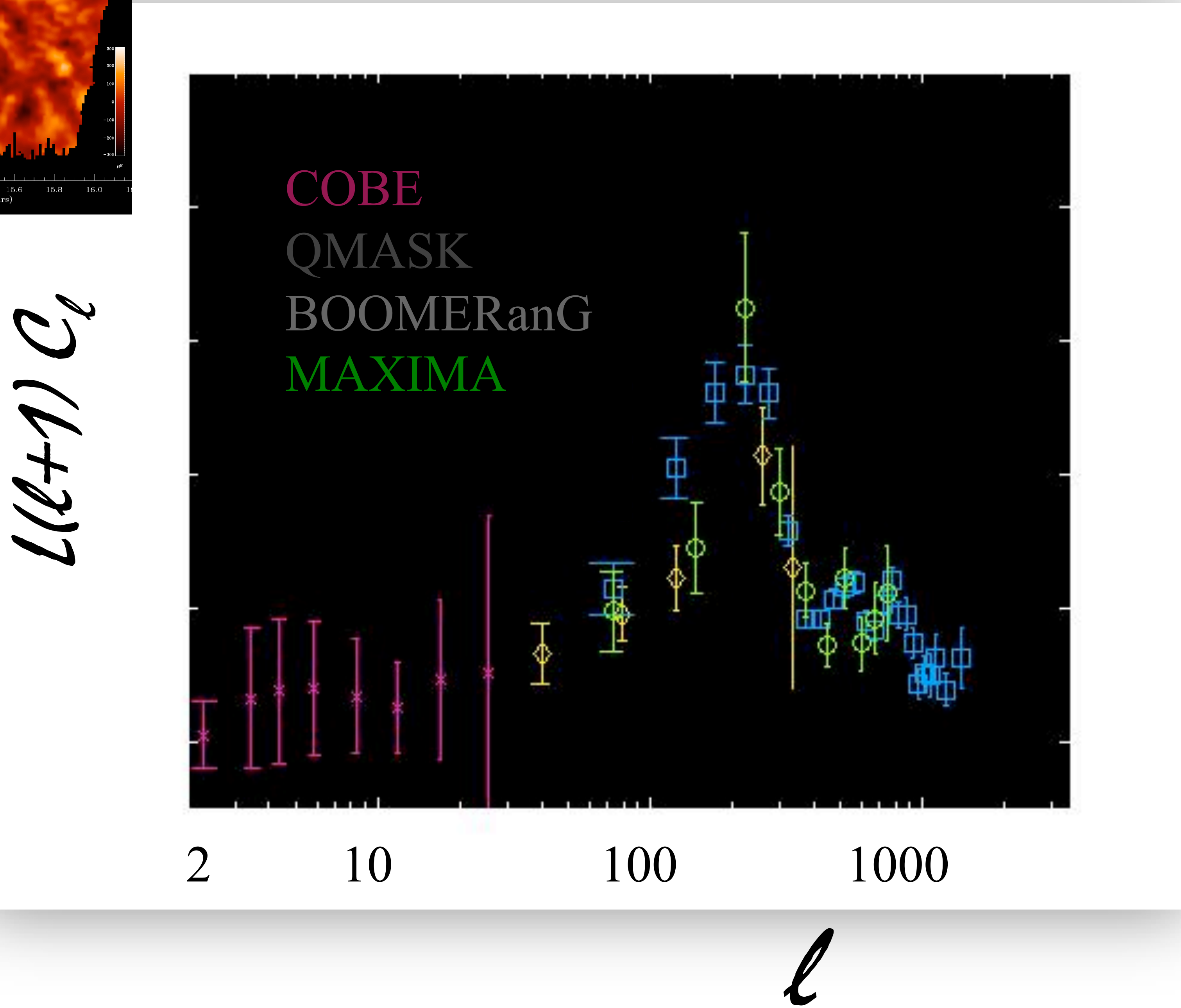

COBE
QMASK
$\ell(\ell+1)\,C_\ell$
2
10
100
1000
ℓ


−300 μK
300 μK
−300 −200 −100 0 100 200 300

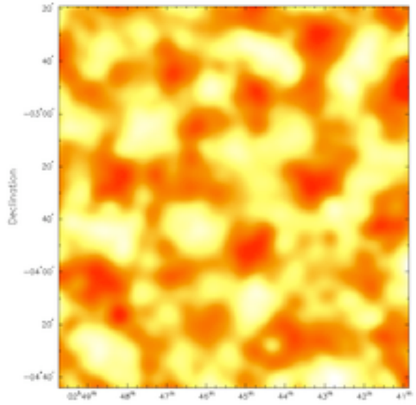

COBE
QMASK
BOOMERanG 00
$l(\ell+1)\,C_\ell$
2
10
100
1000
ℓ

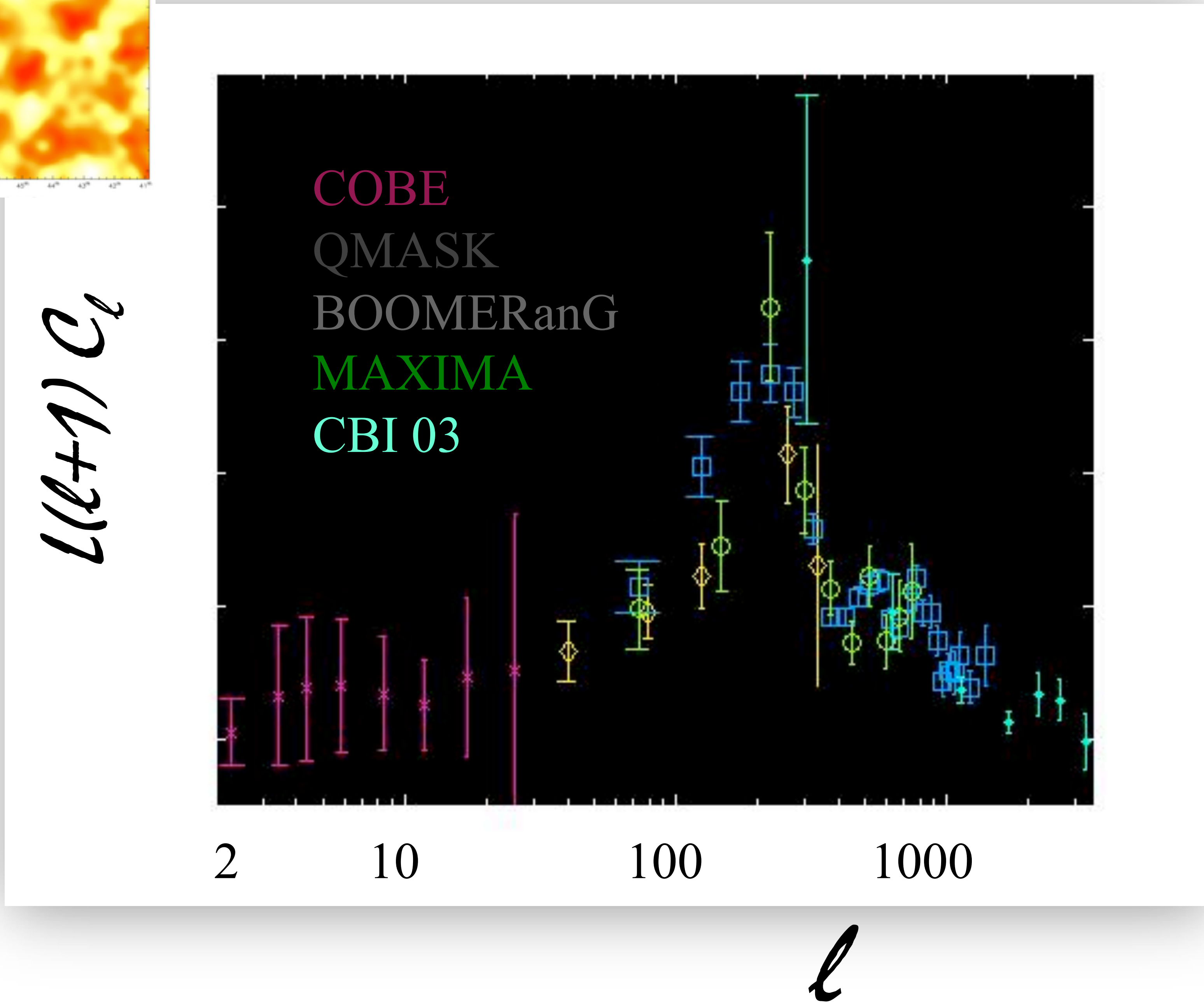


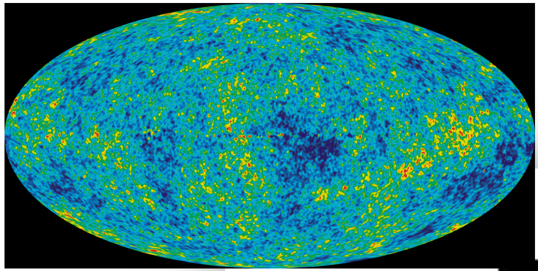
MAXIMA-1 map of the Cosmic Microwave Background Anisc
Dec (degrees)
RA (hours)
64
62
60
58
56
54
52
14.8
15.0
15.2
15.4
15.6
15.8
16.0

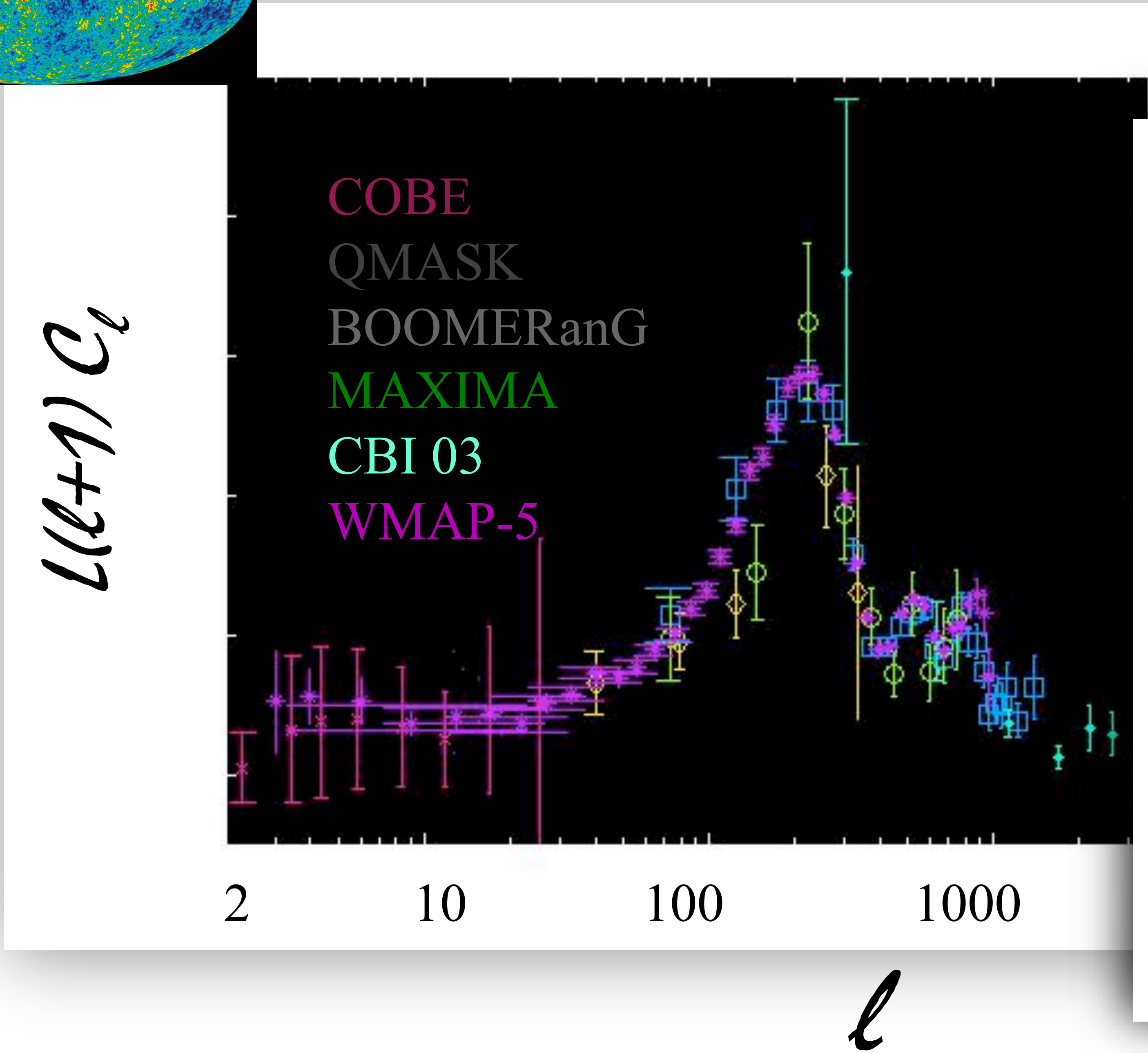


COBE
QMASK
BOOMERanG
MAXIMA
$l(\ell+1)\,C_\ell$
2
10
100
1000
ℓ



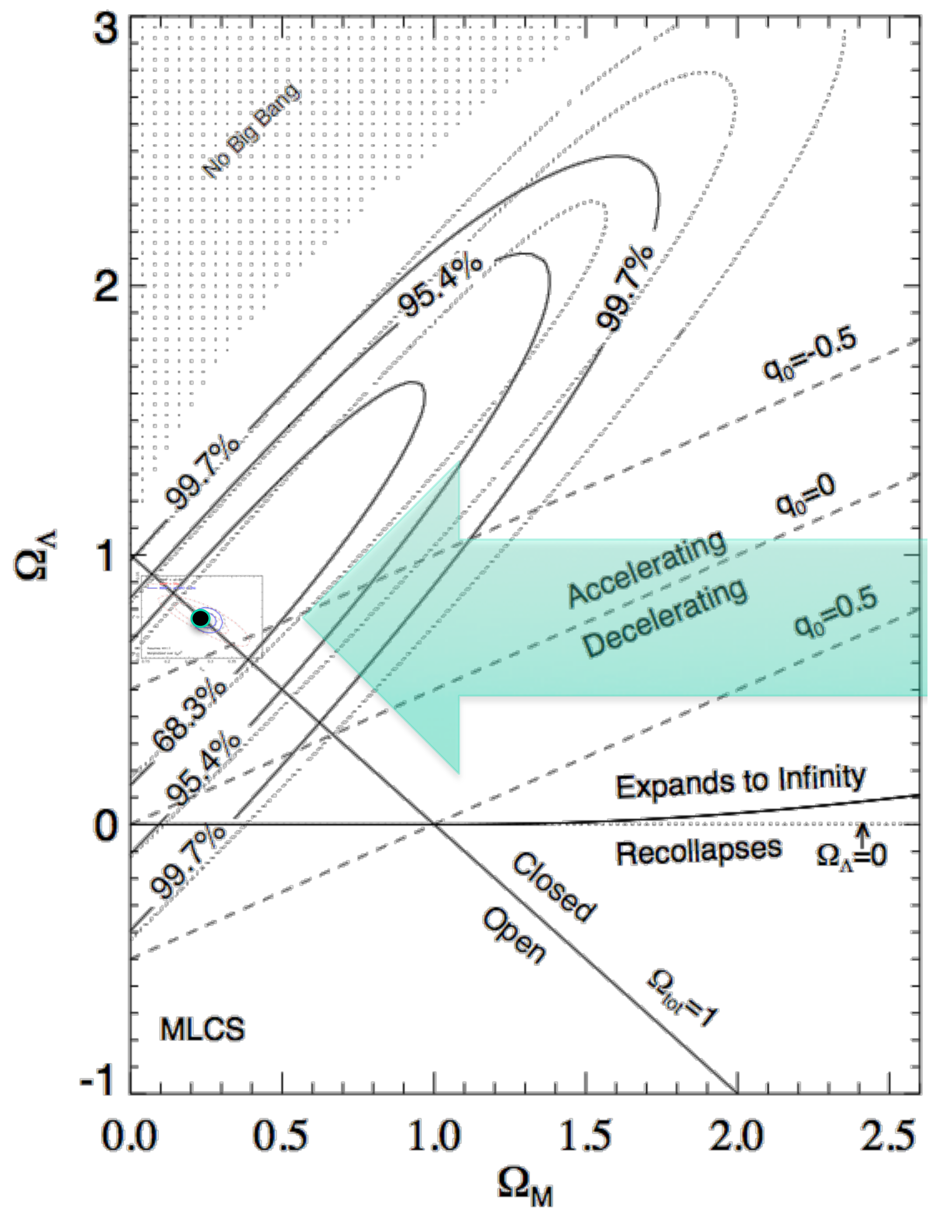

COBE
QMASK
BOOMERanG
MAXIMA
CBI 03
$\ell(\ell+1)\, C_\ell$
2
10
100
1000
ℓ



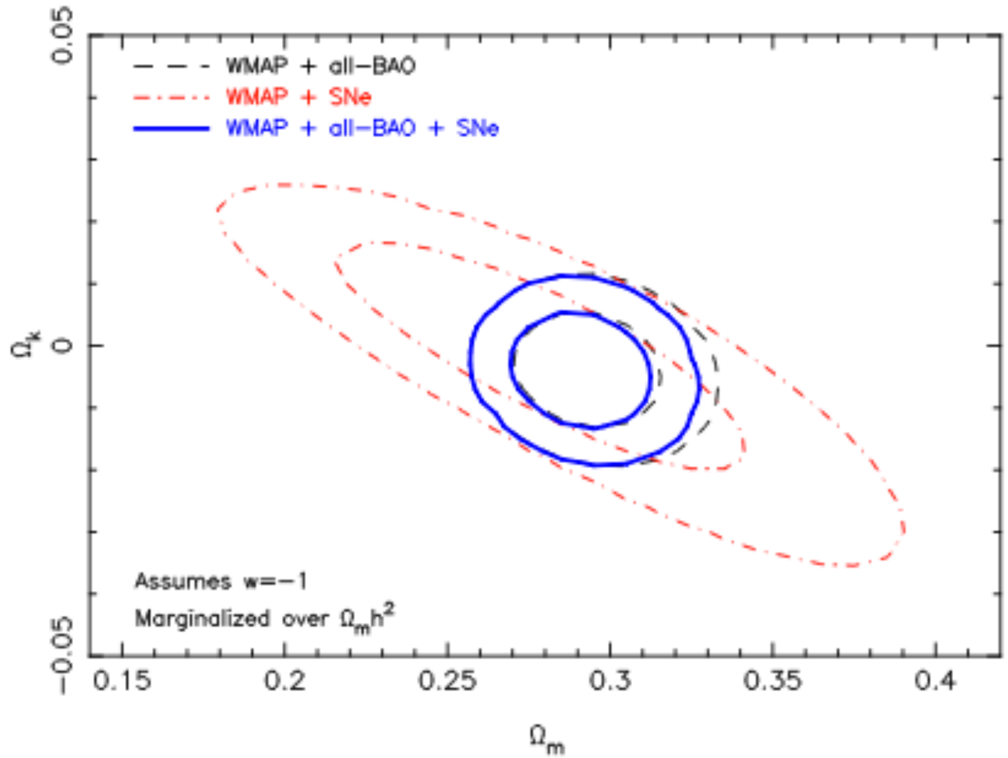


Did not show

SPT
ACT
BICEP
TOCO
ACBAR
VSA
SASKATOON
ARCHEOPS
DASI
PYTHON
FIRS
Tenerife
OVRO
SUZIE
AMI
ATCA
etc…



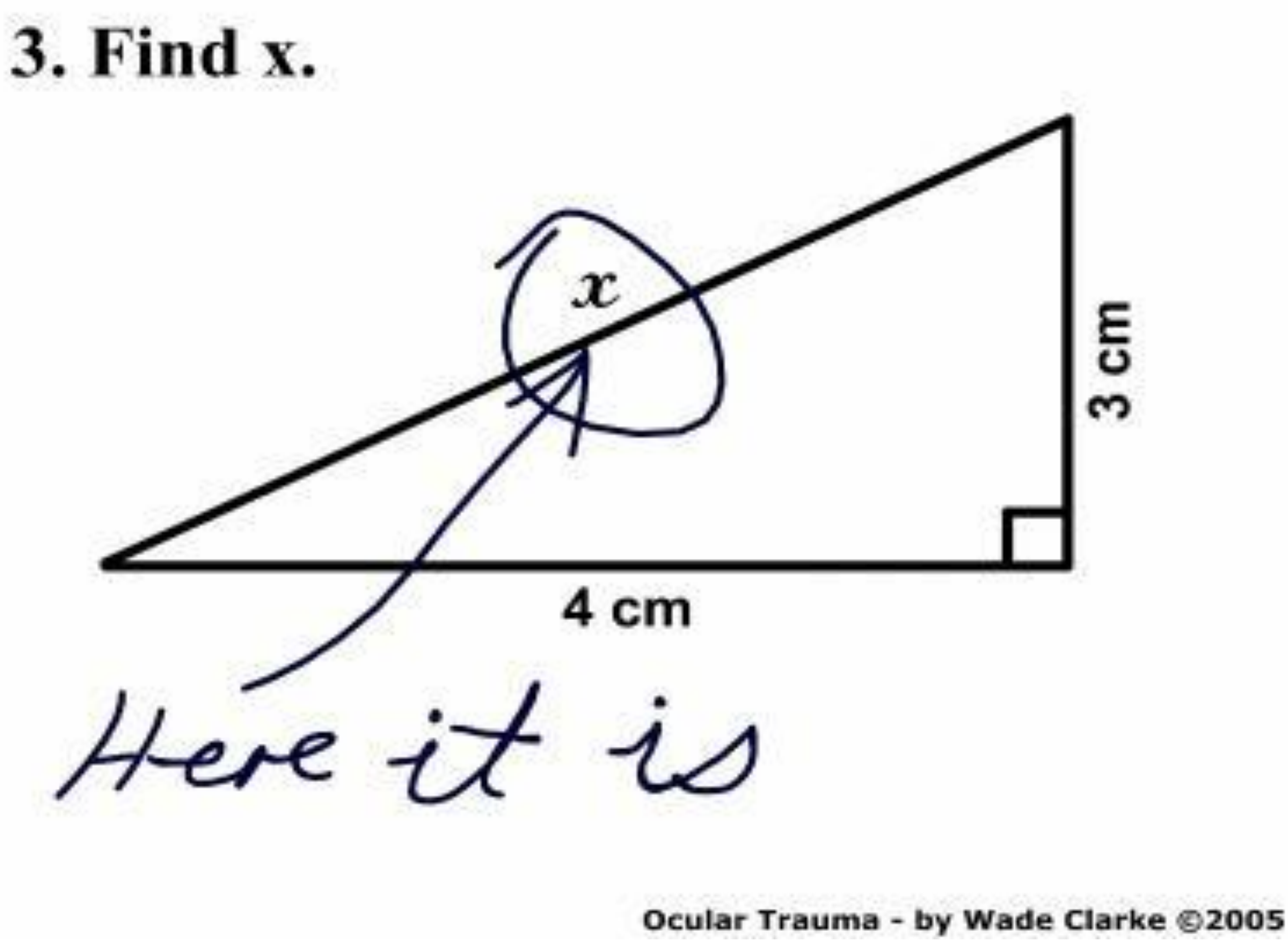
Riess *et al,* 1998

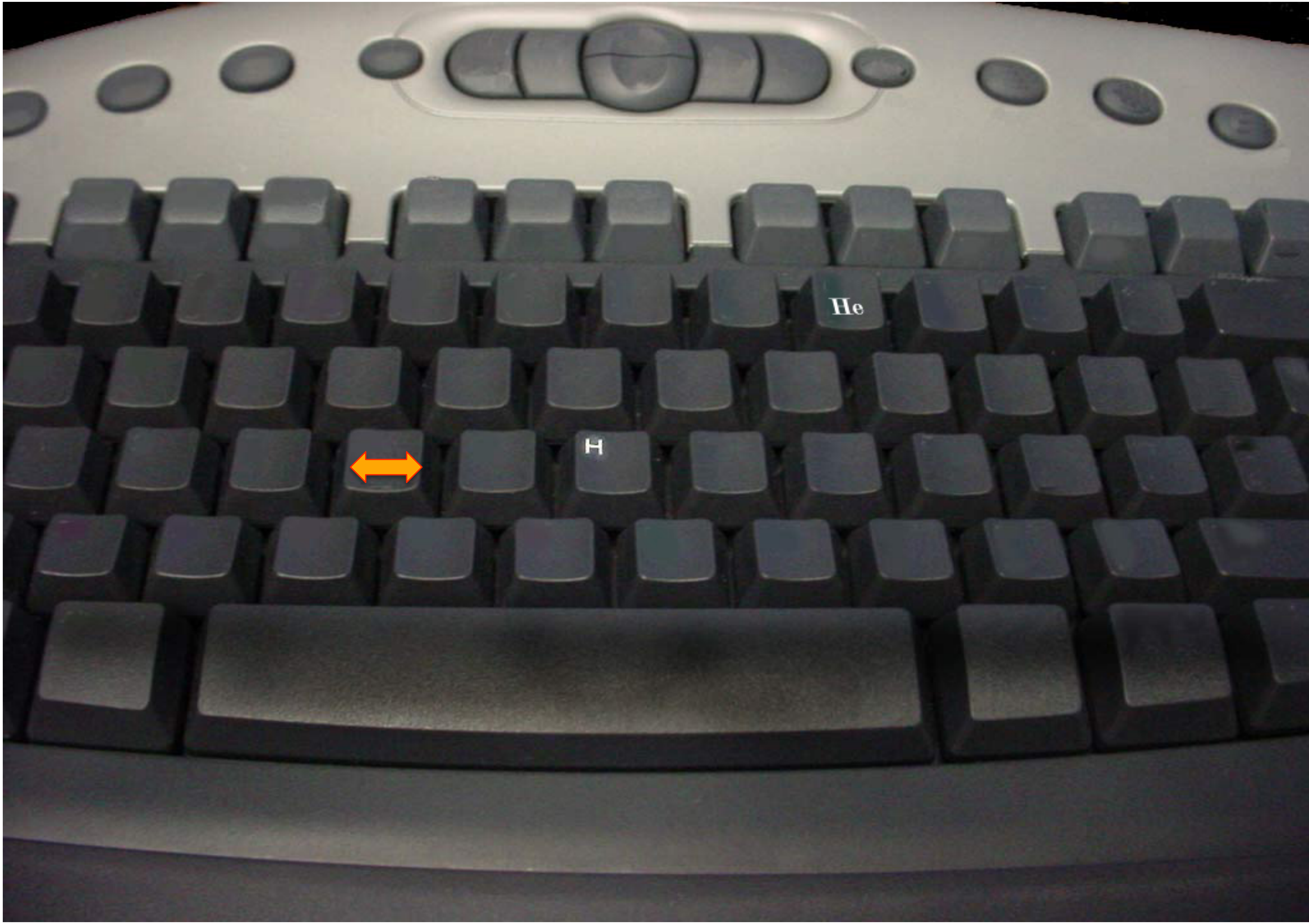


Blake *et al,* 2011

All assumes w = -1


NOKIA
connocting poopie
恒联诺基亚手机店
www.engrish.com


3. Find x.
x
3 cm
4 cm
Here it is
Ocular Trauma - by Wade Clarke ©2005


He
H

Overview of this lecture

- Power spectra
- Origins, uses & measurements of BAO
- Statistical Standard Rulers
- Targets for BAO surveys
- Some Complications
- Photometric vs spectroscopic BAO surveys

The power spectrum

- $P(k) = \langle|\delta_k|^2\rangle$ where δ_k is the Fourier transform of the density contrast

$$\delta_k = |\delta_k| \cdot e^{i\theta_k}$$

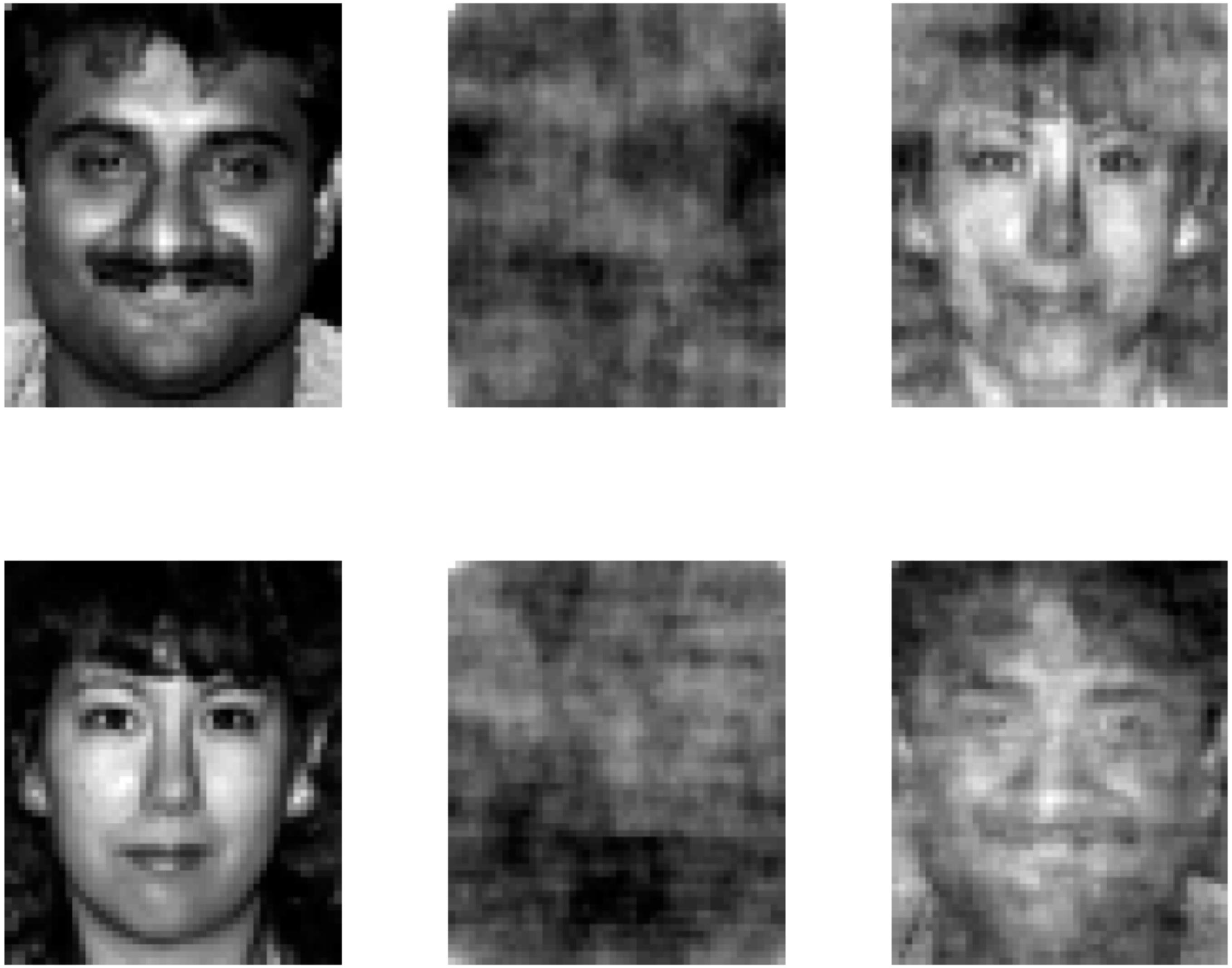
- Note there is no phase information, θ_k, in the power spectrum

- $P(k)$ contains all information about $\delta(x,t)$ if it is Gaussian distributed

Where is the information?

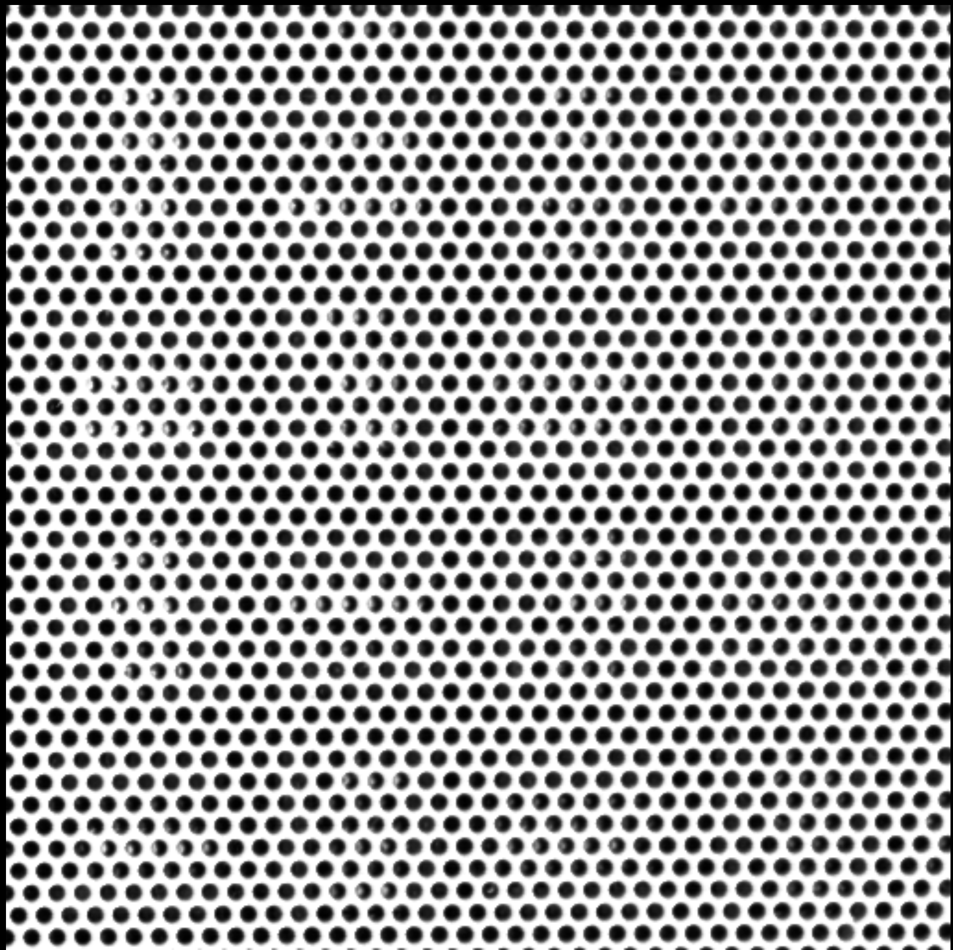
- The power spectrum actually contains relatively little information in our everyday life…
- Most of the information is in the phases, θ_k...
- (Except in cosmology where the power spectrum is much more important)

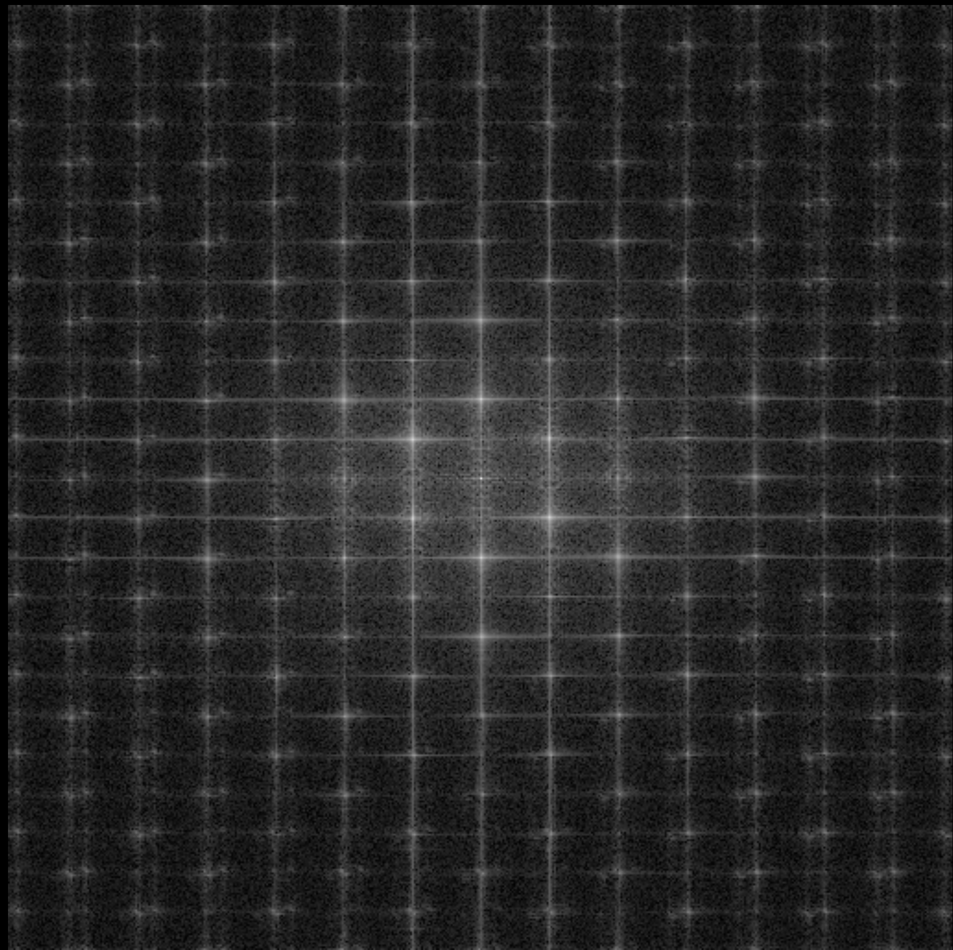
Originals | Random Phases | Swapped Phases

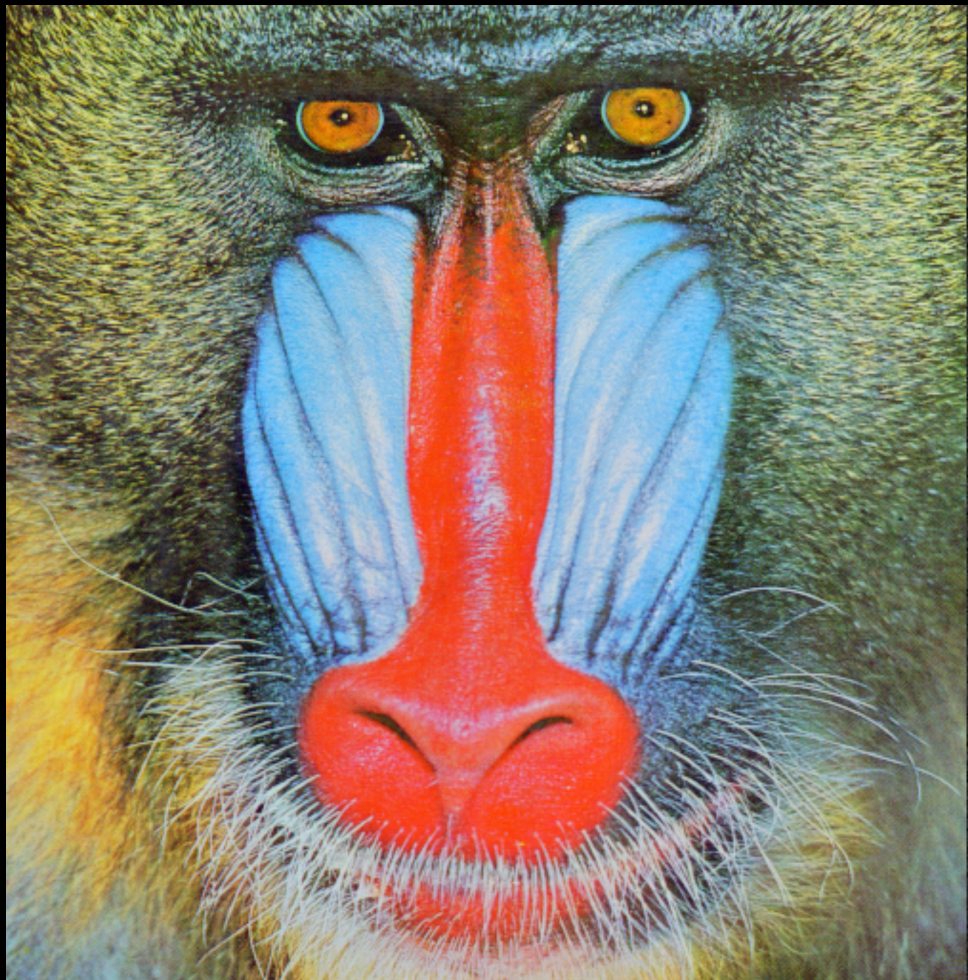


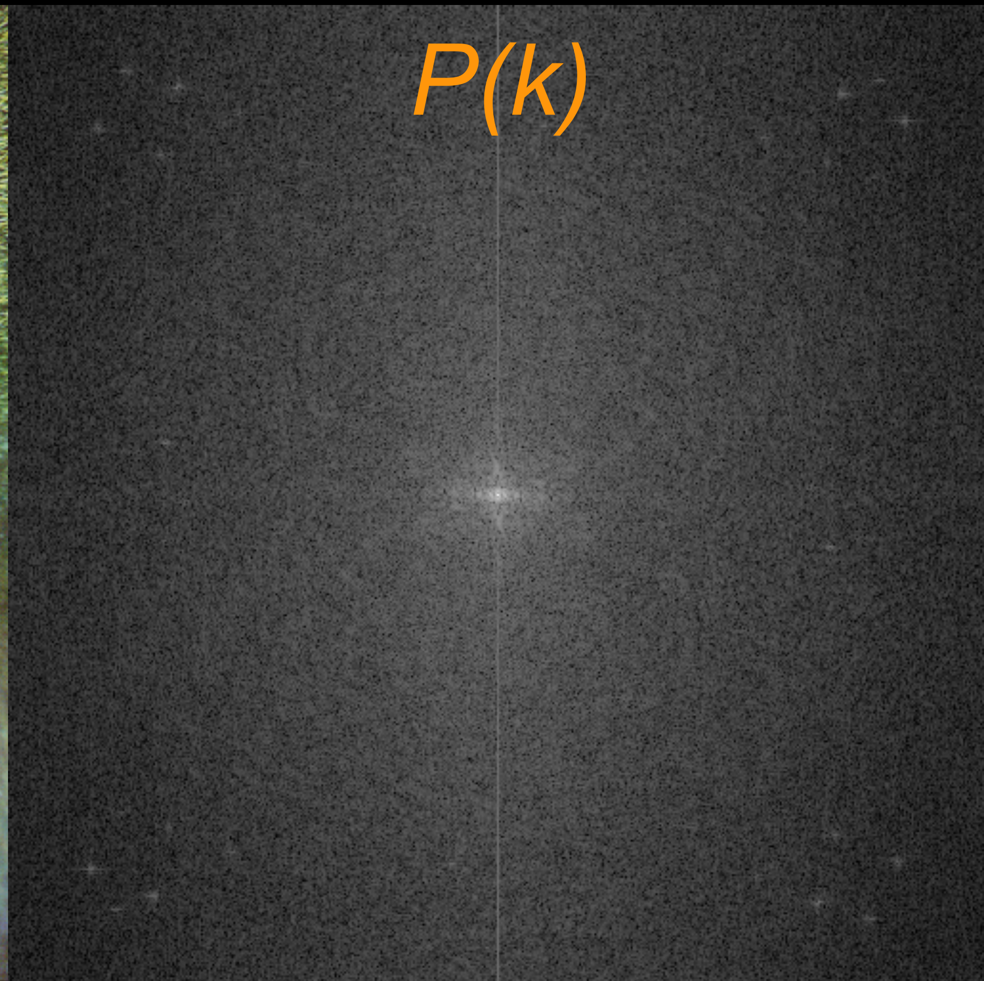
M.S. Bartlett, J. R. Movellan, T. J. Sejnowski, IEEE 2002

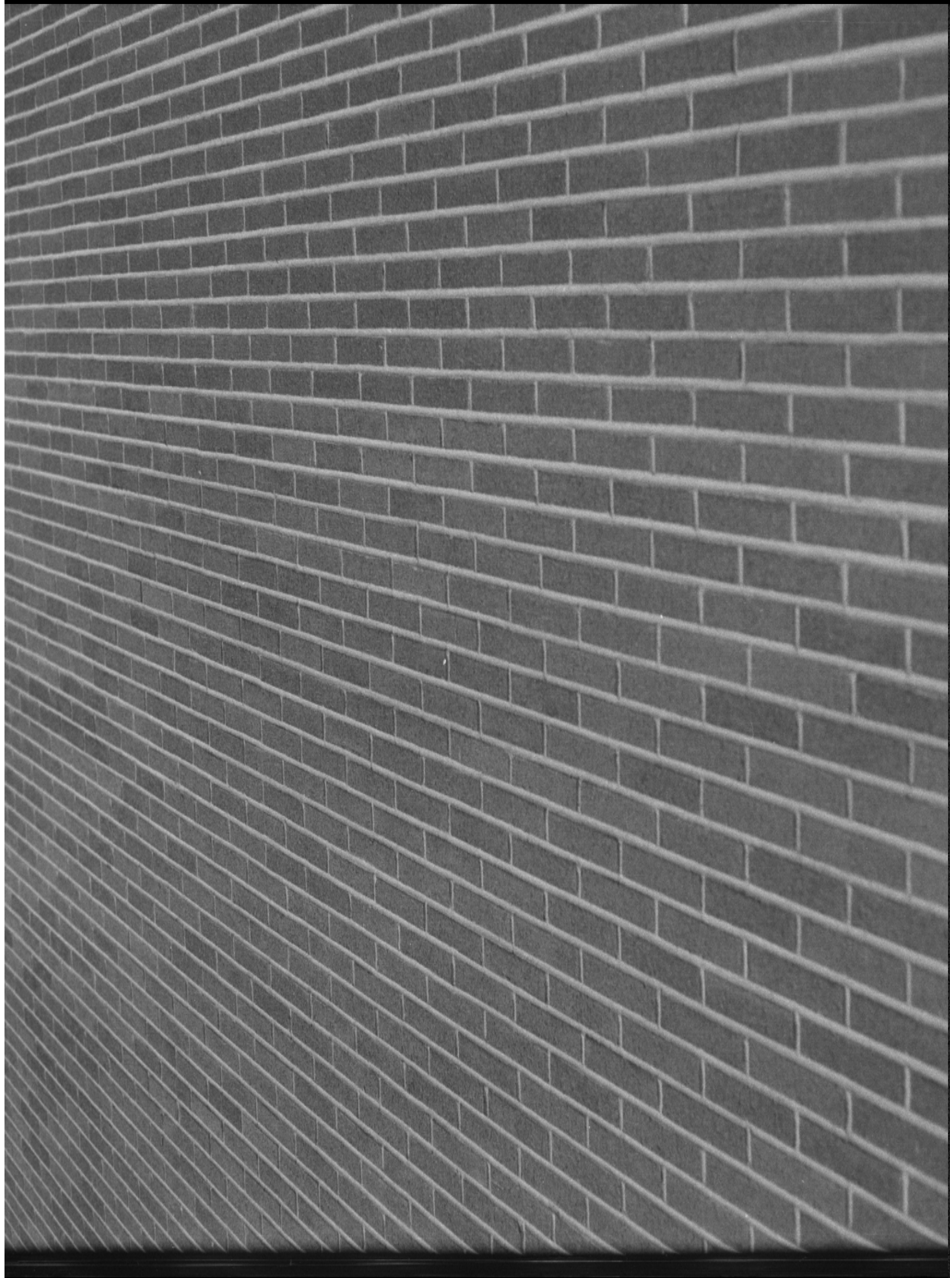
Some examples of images and their *P(k)*

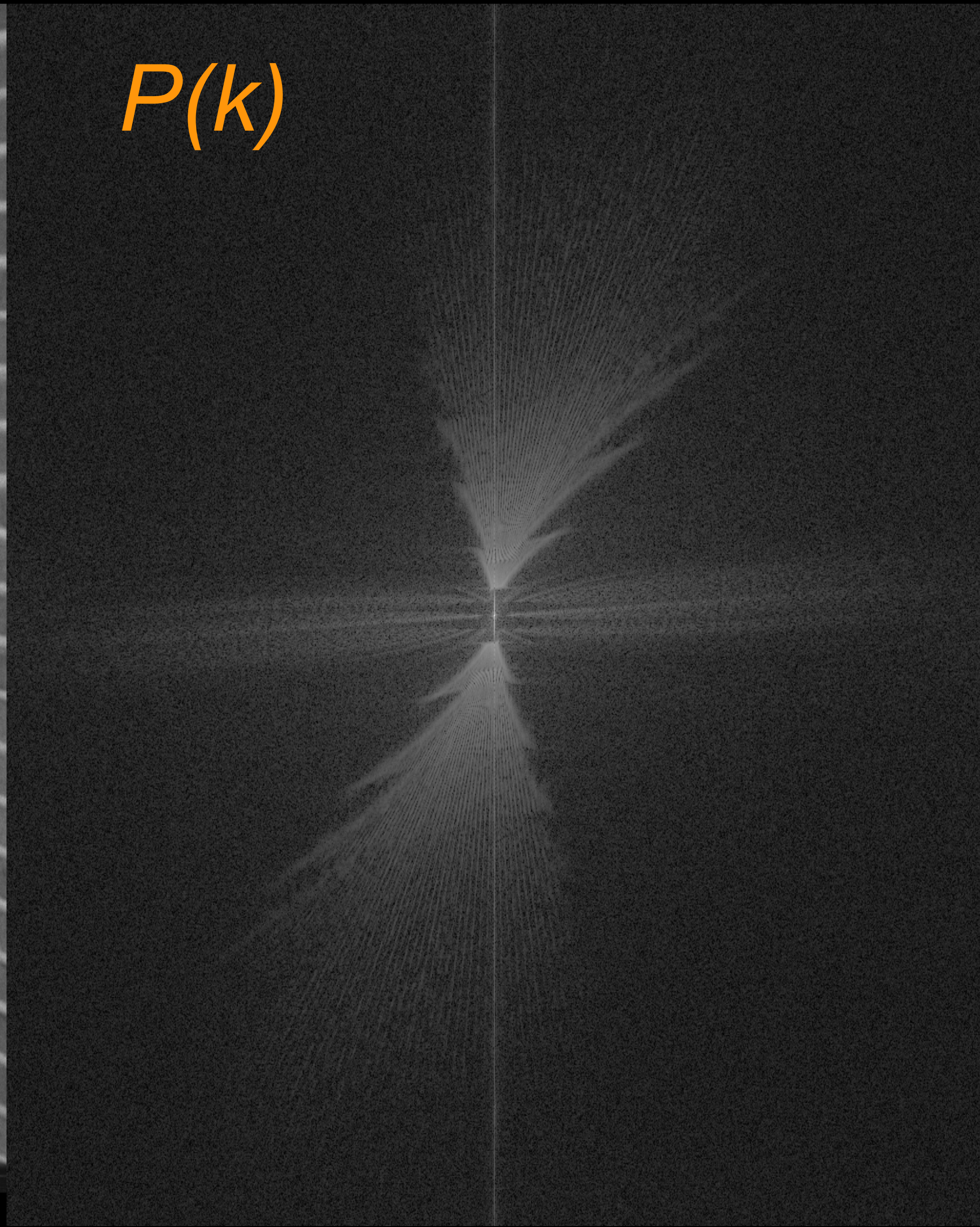







P(k)





P(k)

On small (nonlinear) scales phase is important though…

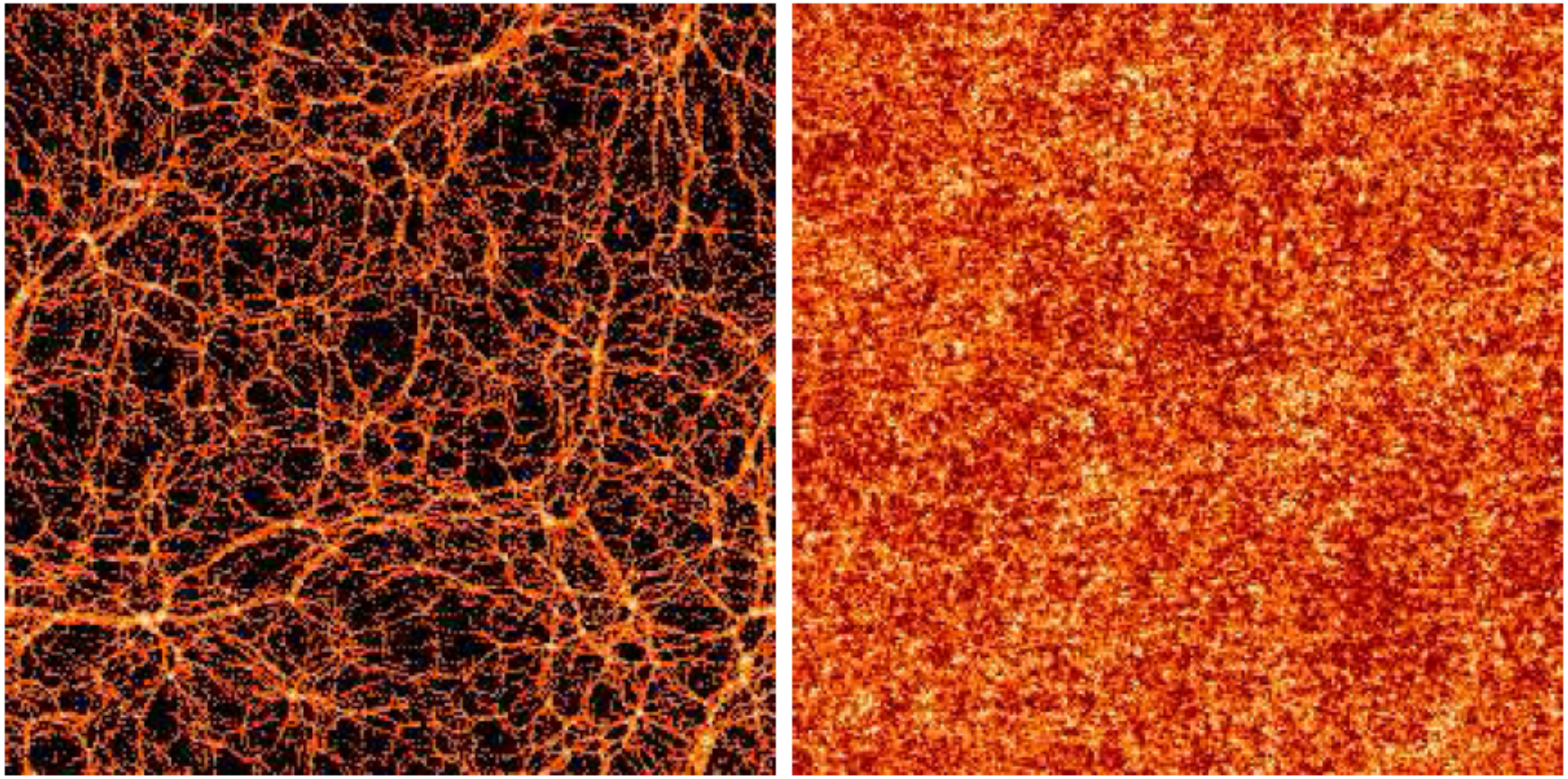


Figure 1. Numerical simulation of galaxy clustering (left) together with a version generated randomly reshuffling the phases between Fourier modes of the original picture (right).

Coles 2002

We will look for the BAO in P(k)

…but what is the origin of the BAO?

3D Green's Function for Φ

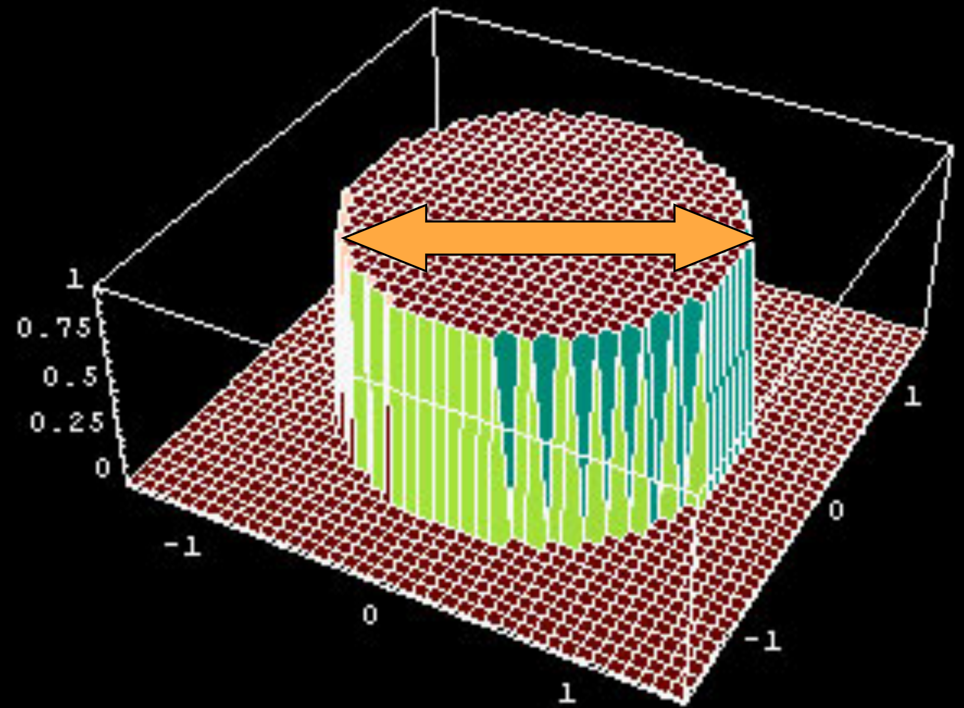
Speed of Sound

$$\phi^{(3)}(r,\tau) = \frac{3}{4\pi}(\underset{\uparrow}{c_s}\tau)^{-3}\,\theta(c_s\tau - r)$$

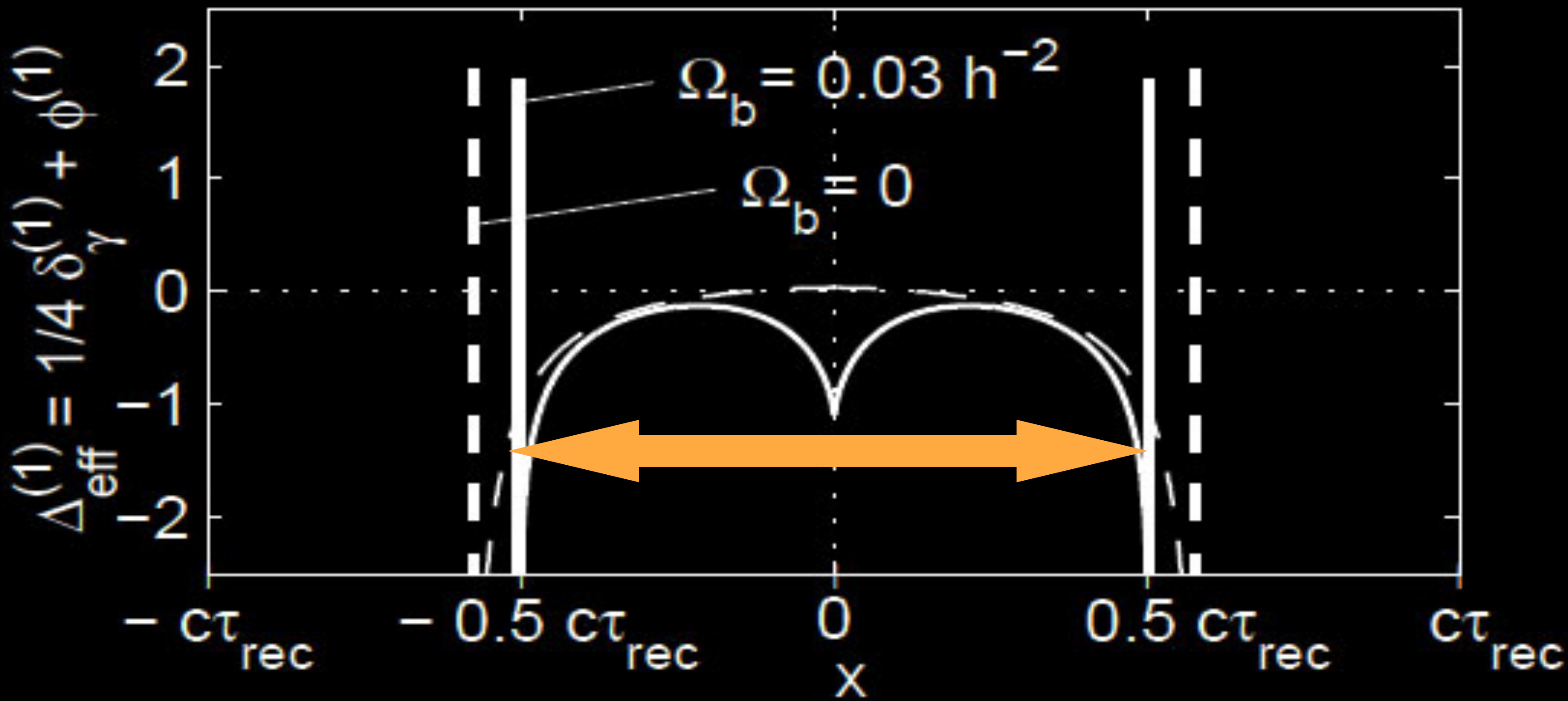
Sound Horizon

Bashinsky and Bertschinger, 2001

$$\phi^{(3)}(r,\tau) = \frac{3}{4\pi}(c_s\tau)^{-3}\,\theta(c_s\tau - r)$$



Real Space Transfer Function



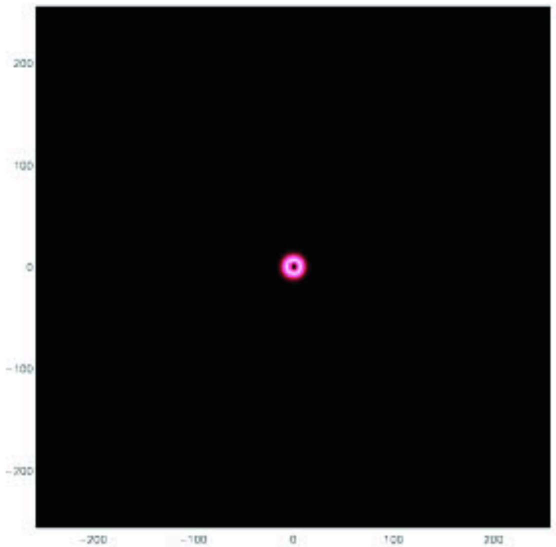
$$c_s^2 = (1/3)/[1 + (3\rho_{\rm b})/(4\rho_\gamma)]$$

Bashinsky and Bertschinger, 2001

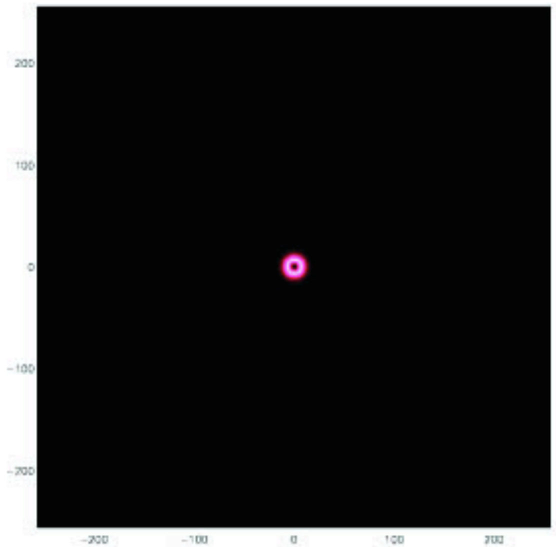
Evolution of a Spherical Overdensity

White, Eisenstein, Seo

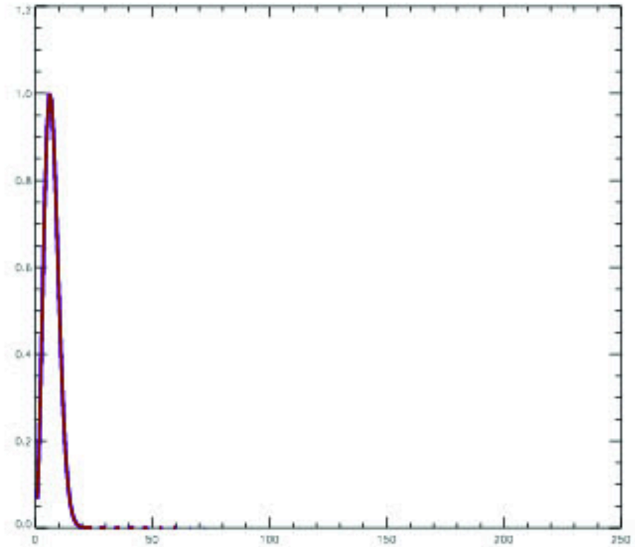
Baryon Density

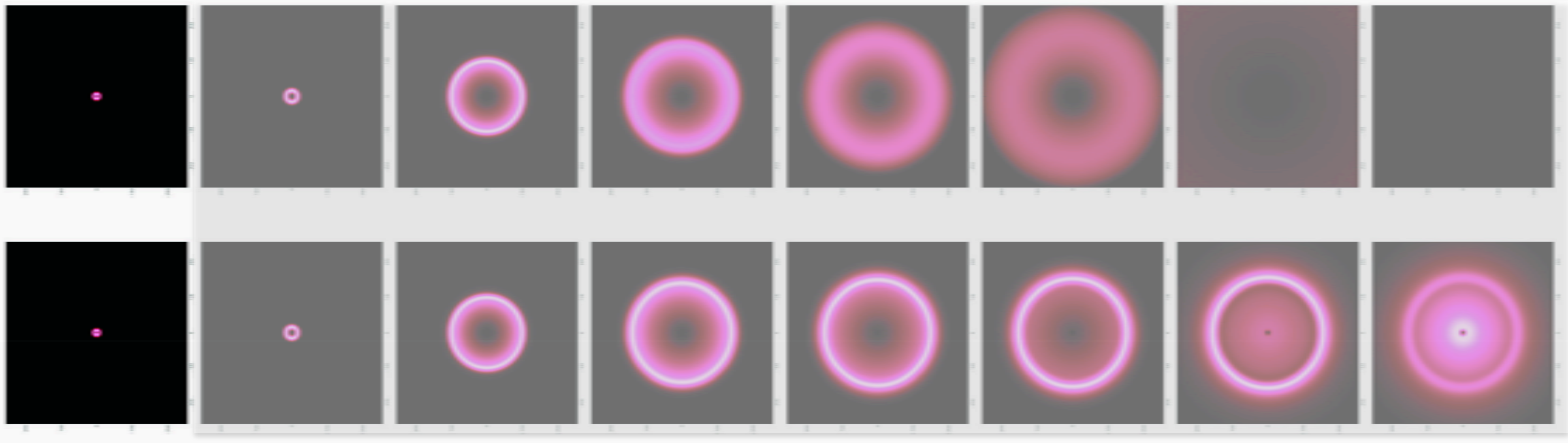


Photon Density

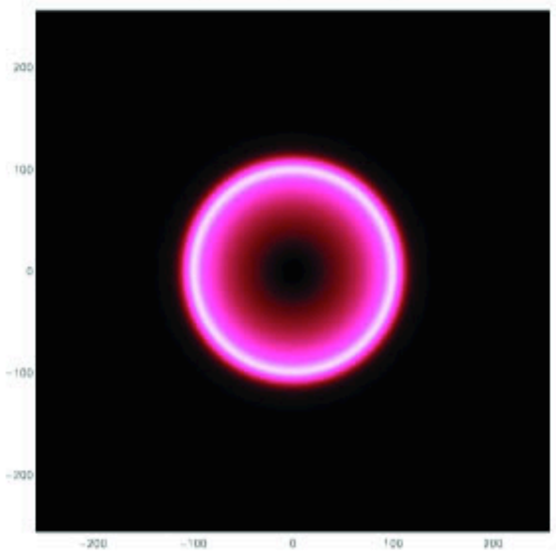


Mass Profiles

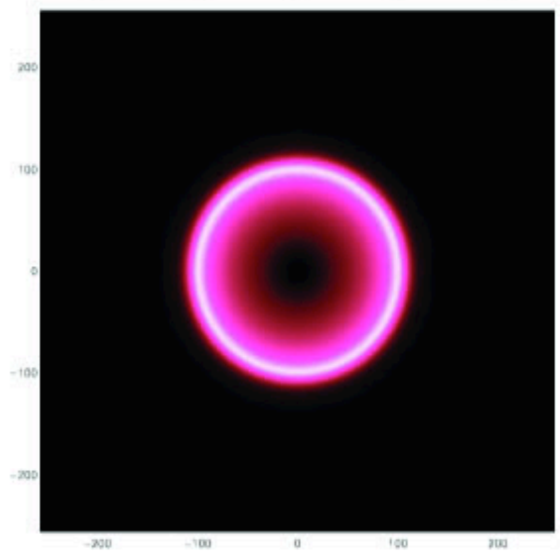




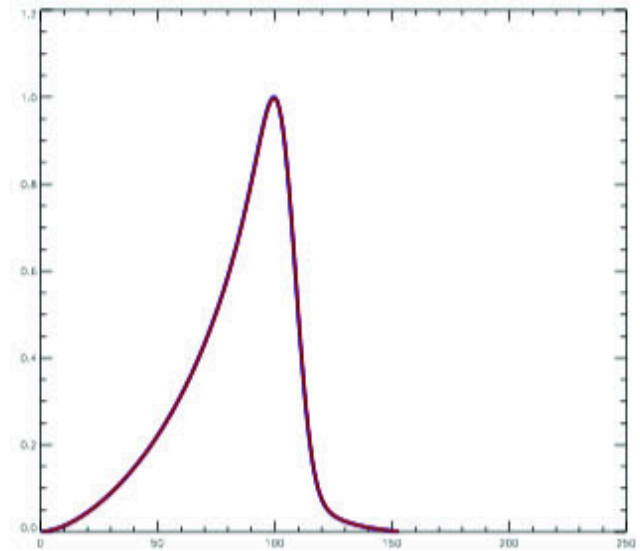
Baryon Density

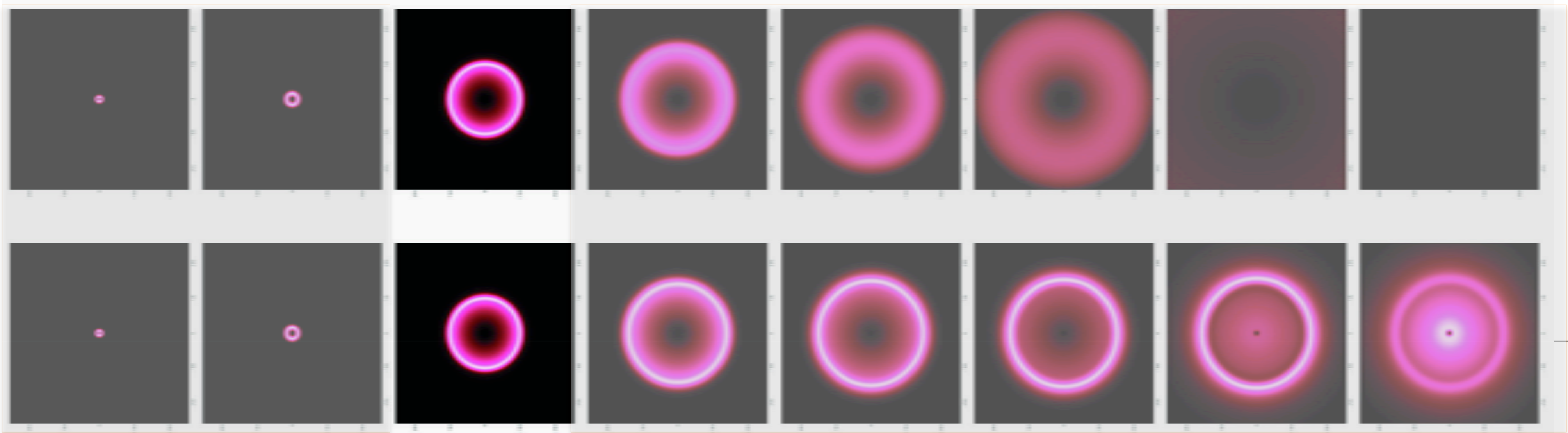


Photon Density

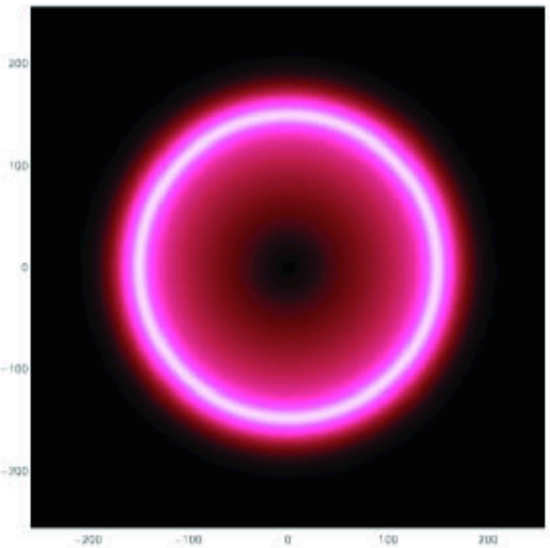


Mass Profiles

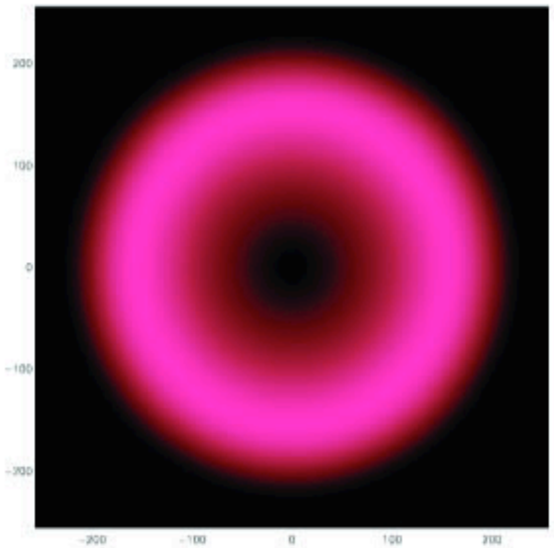




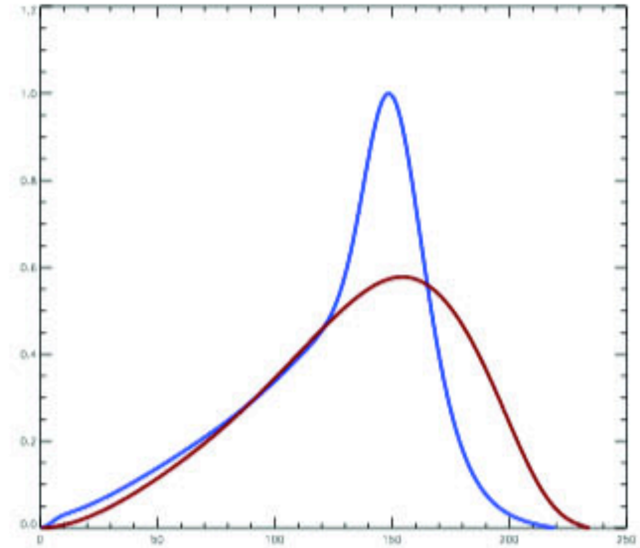
Baryon Density

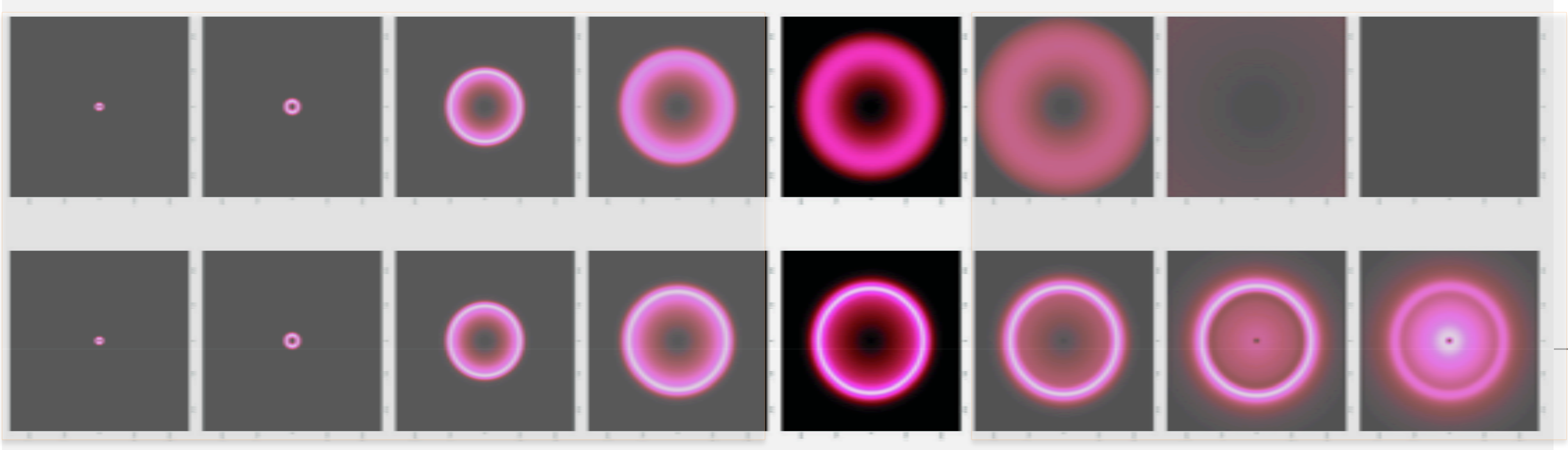


Photon Density

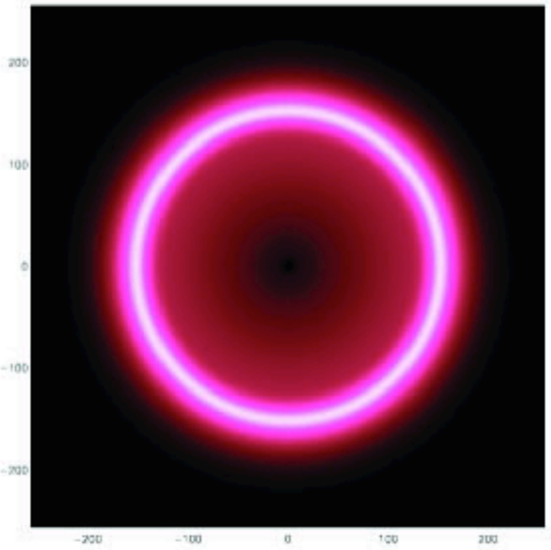


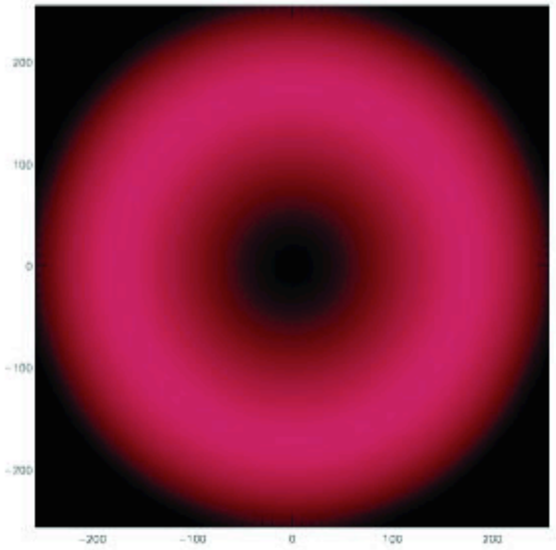
Mass Profiles

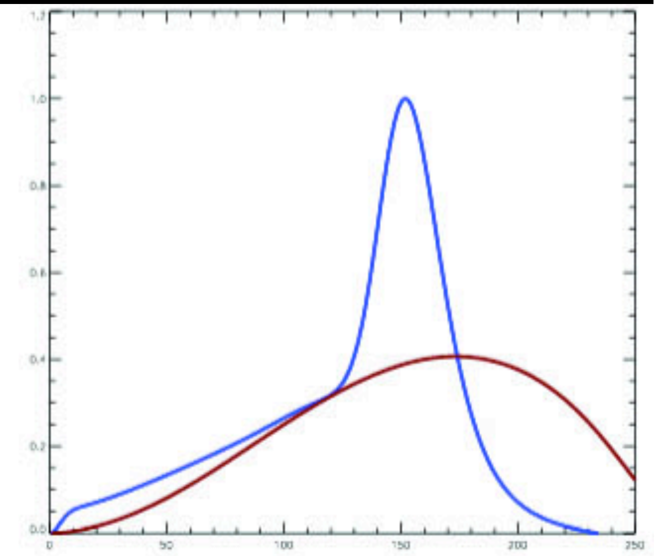


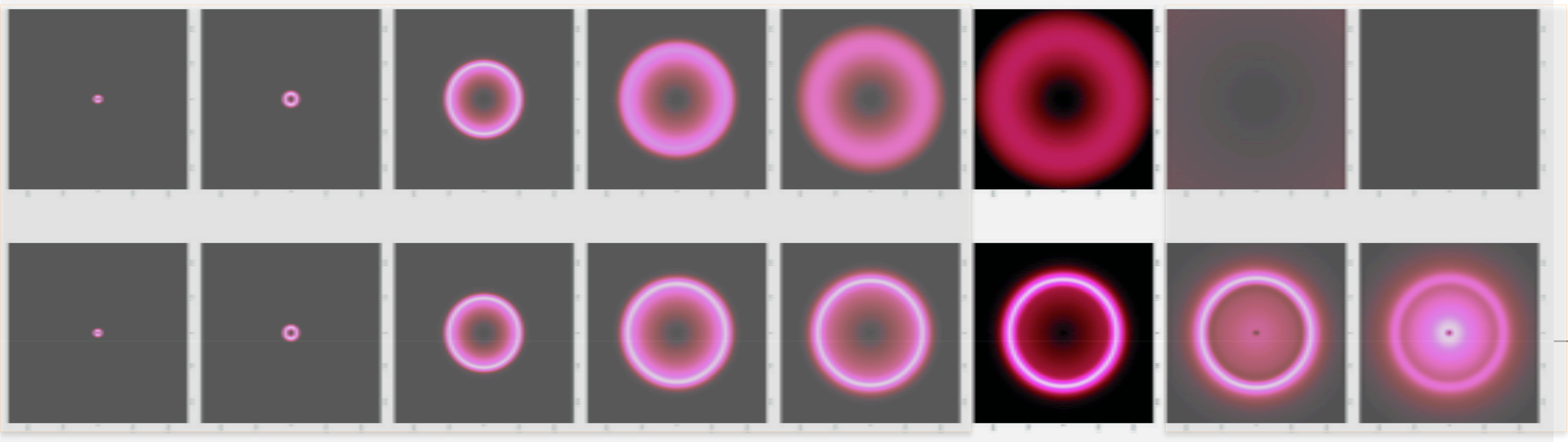


Baryon Density   Photon Density   Mass Profiles

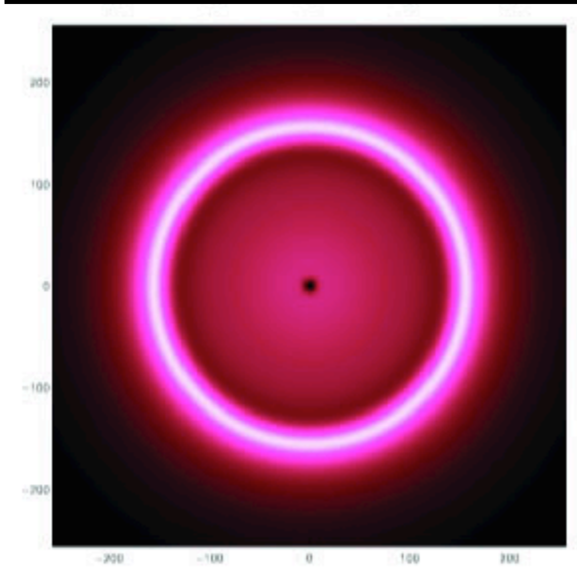




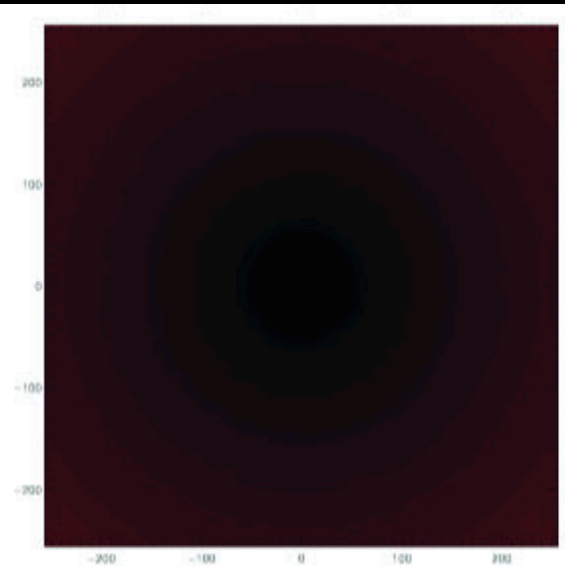




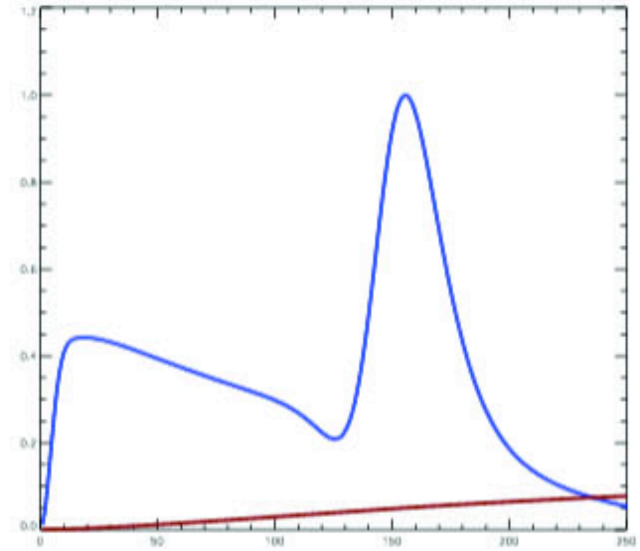
Baryon Density

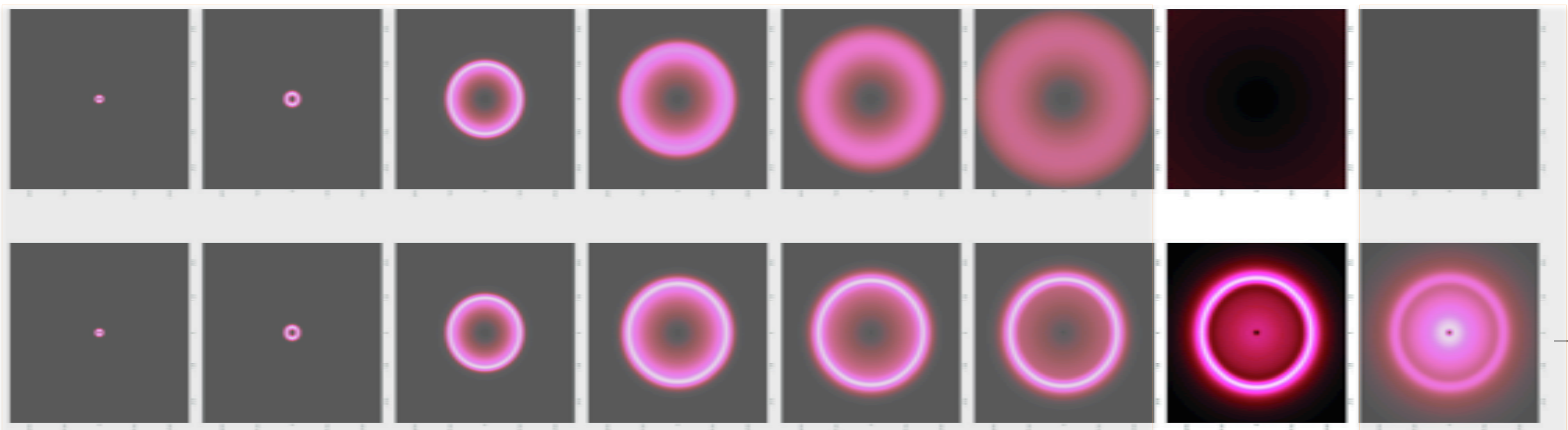


Photon Density



Mass Profiles

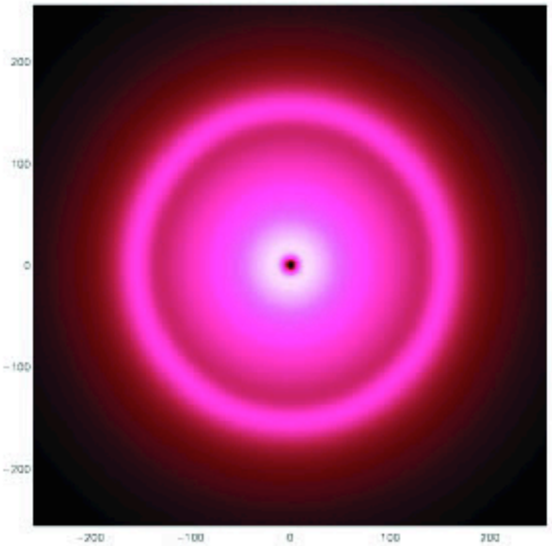


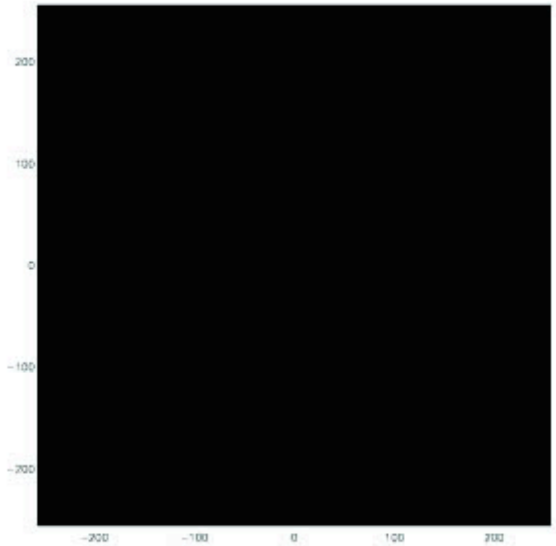


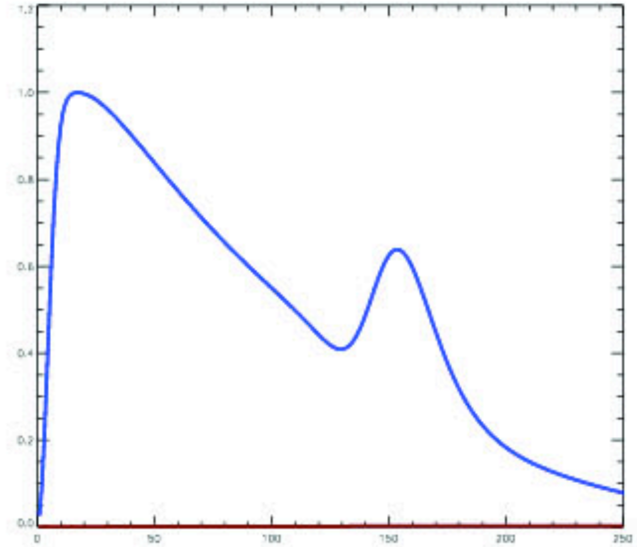
Baryon Density

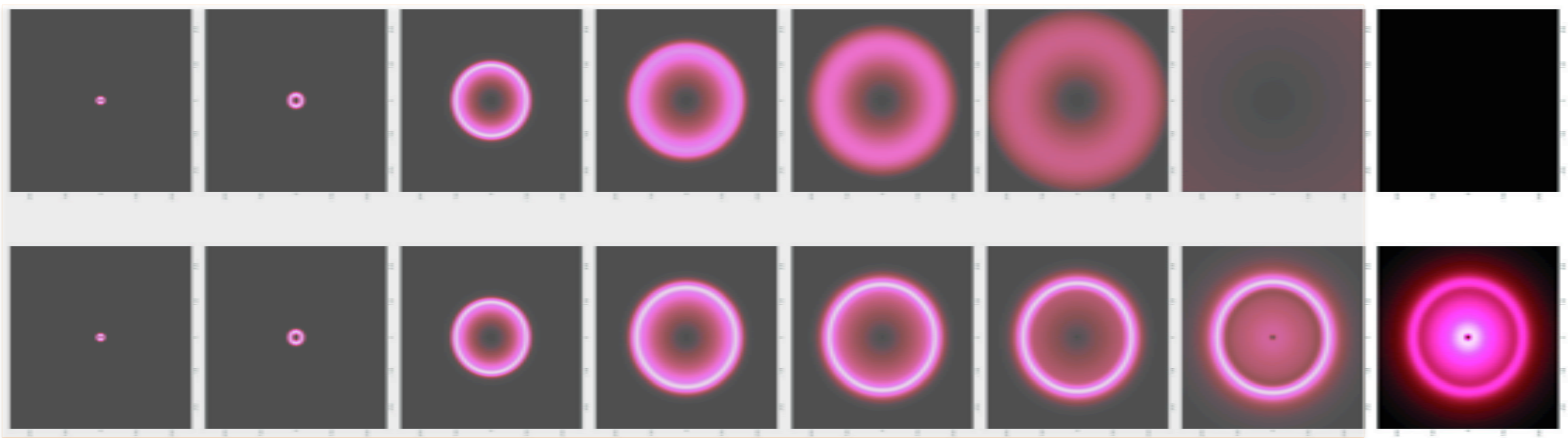
Photon Density

Mass Profiles

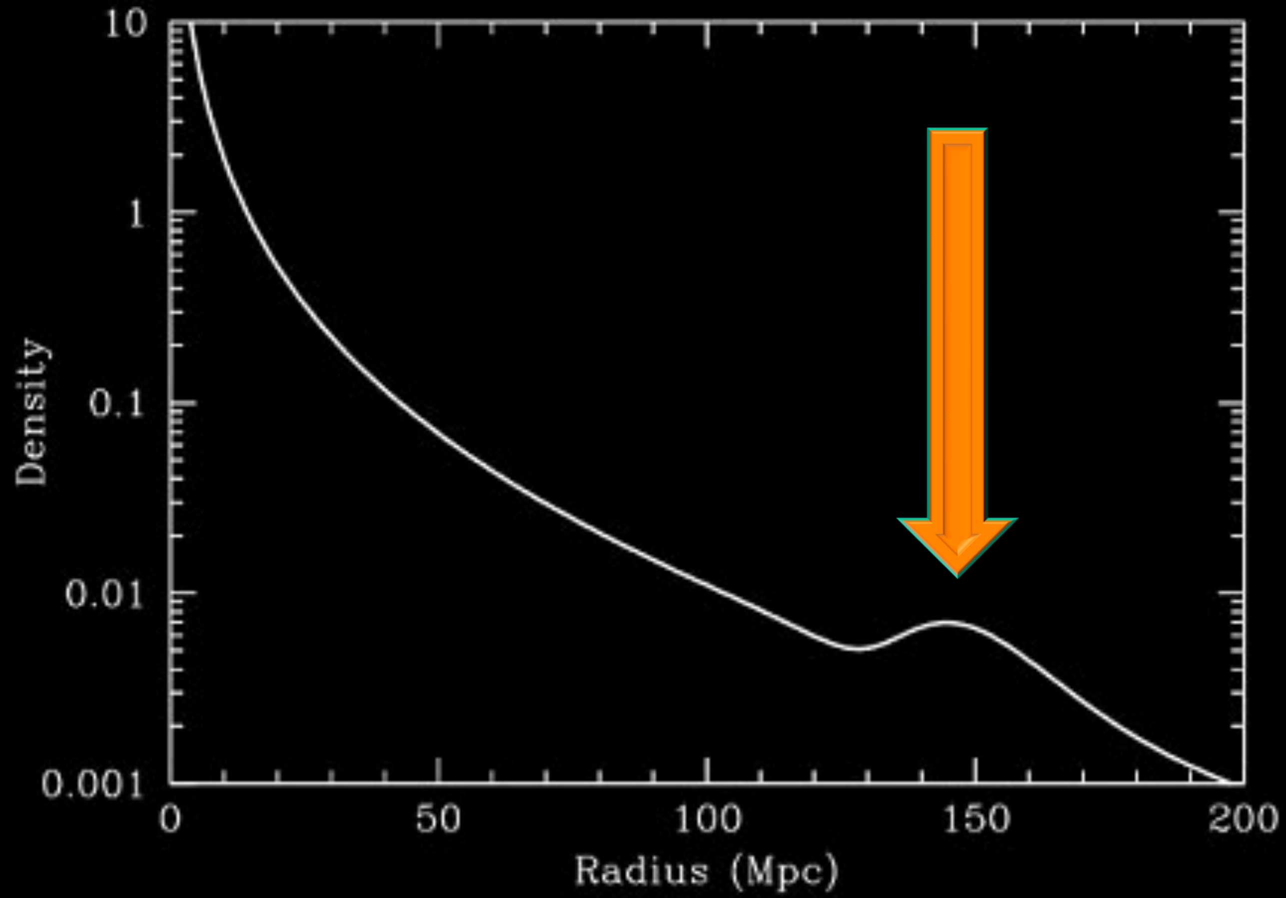


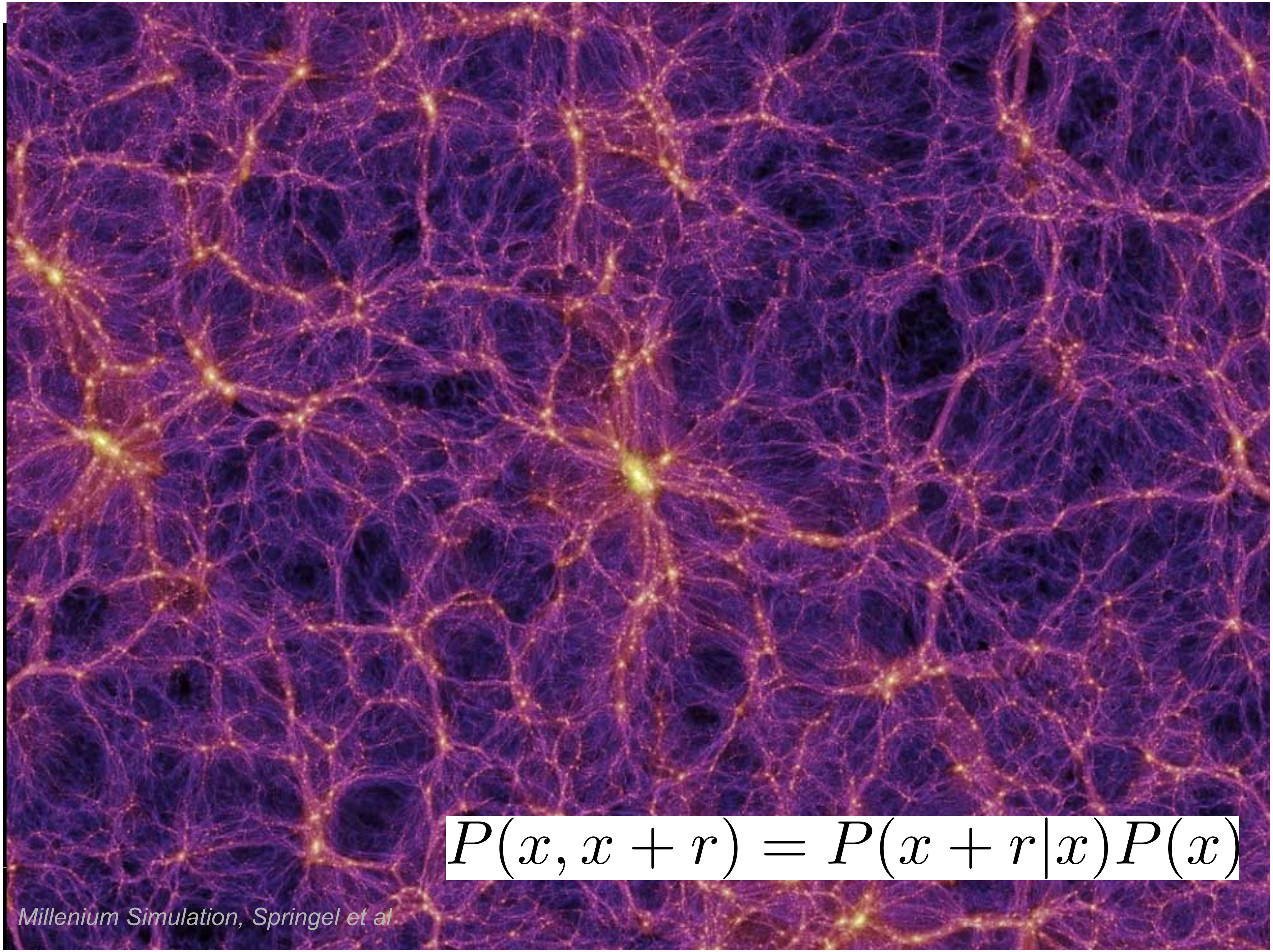






Baryon Acoustic Peak

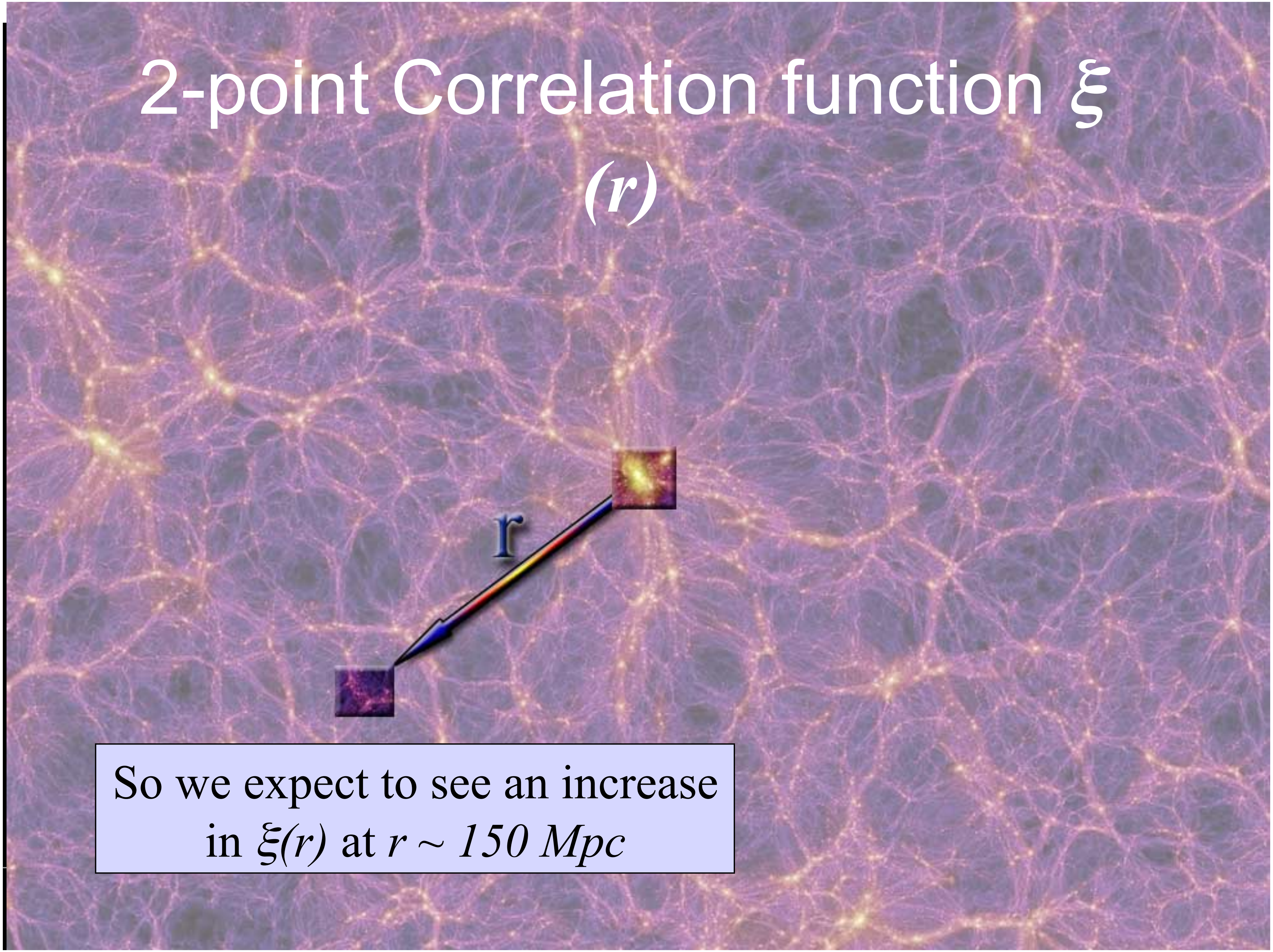




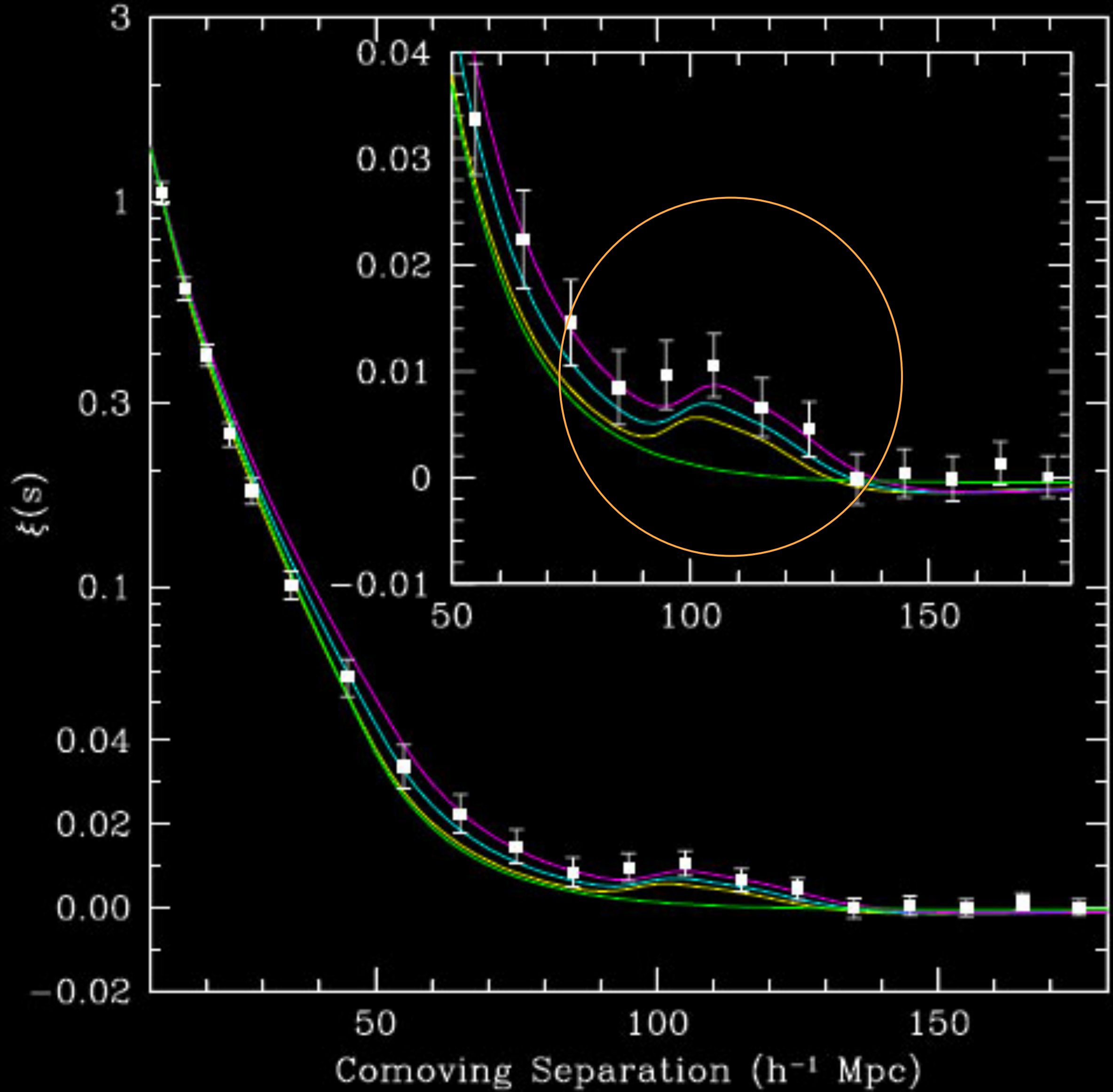
$$P(x, x+r) = P(x+r|x)P(x)$$

Millenium Simulation, Springel et al

2-point Correlation function $\xi(r)$

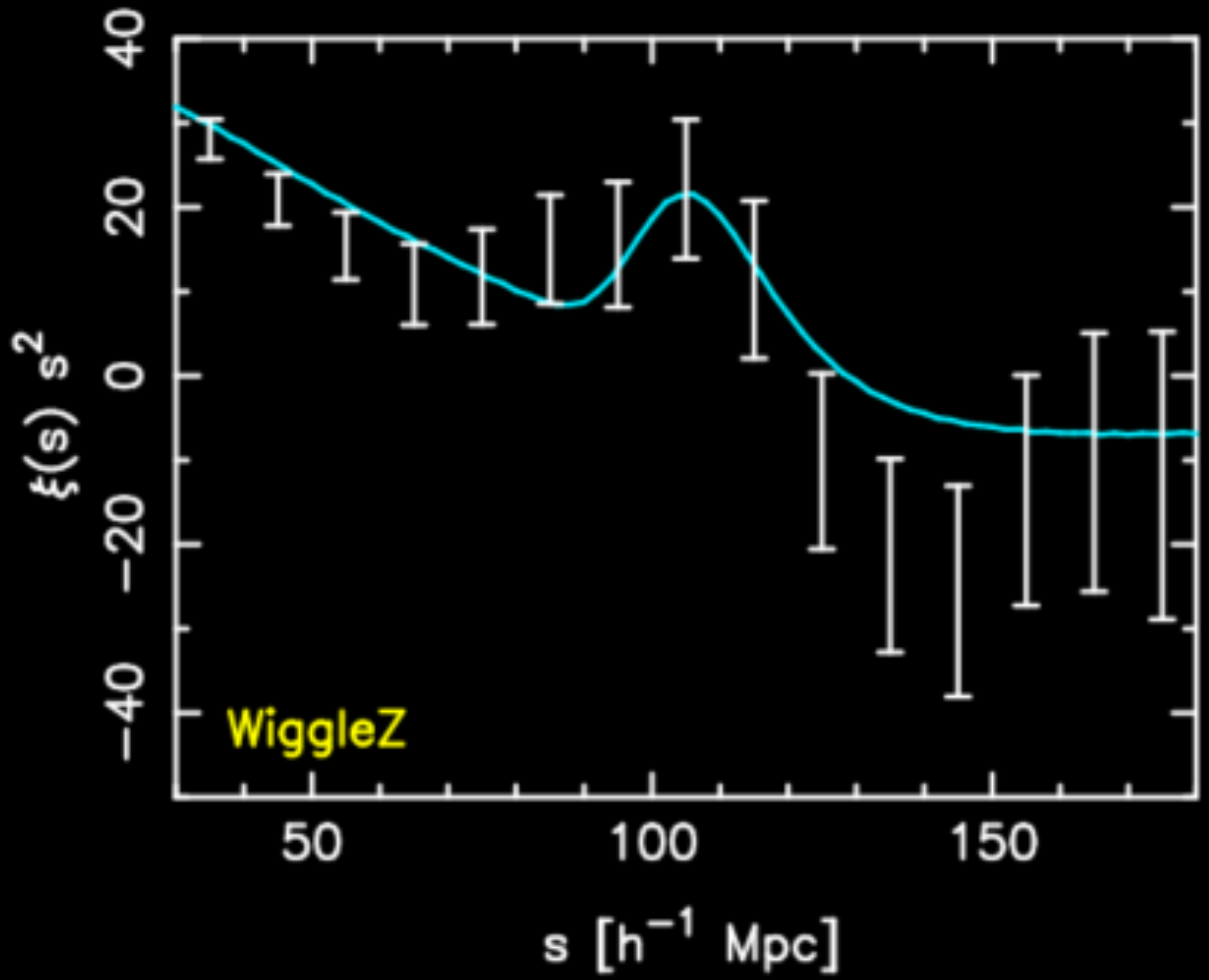


So we expect to see an increase in $\xi(r)$ at $r \sim 150\ Mpc$



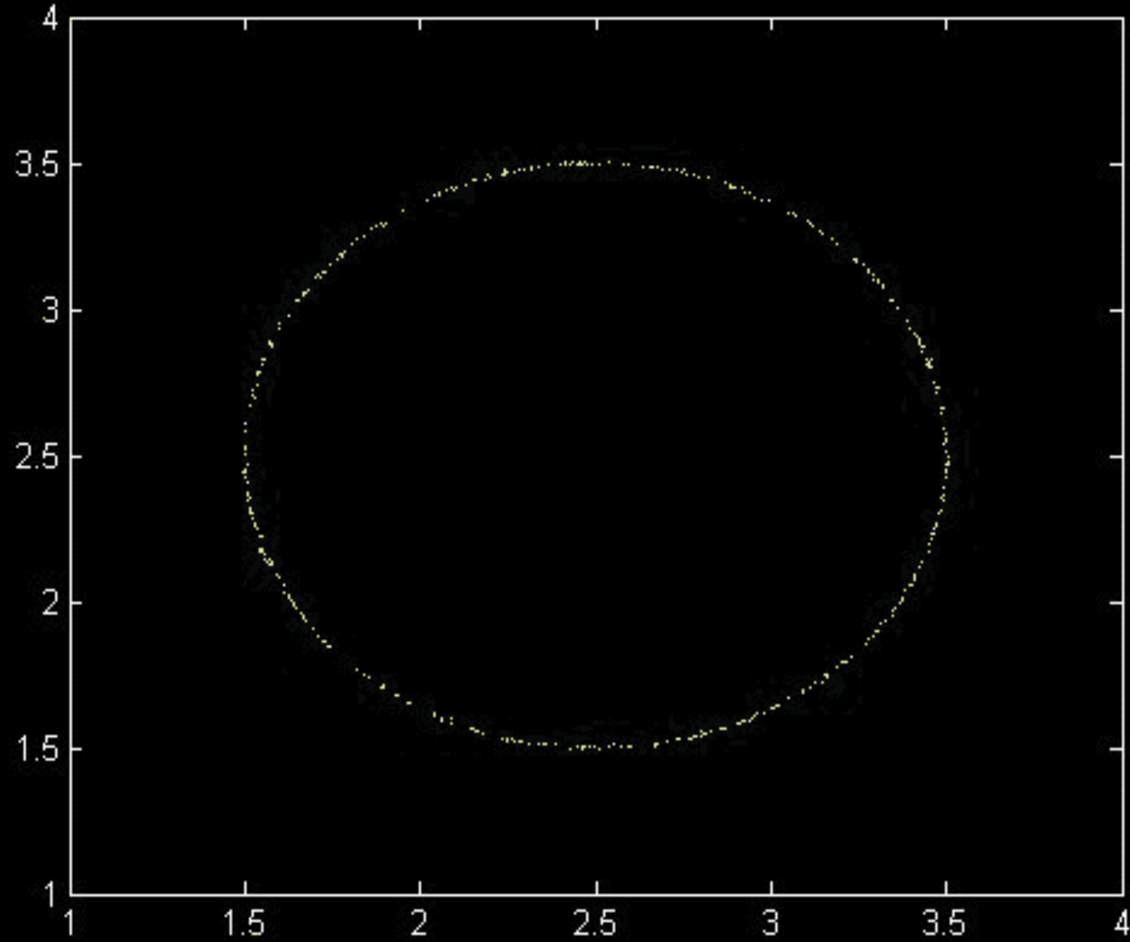
Eisenstein et al, 2005
SDSS LRGs

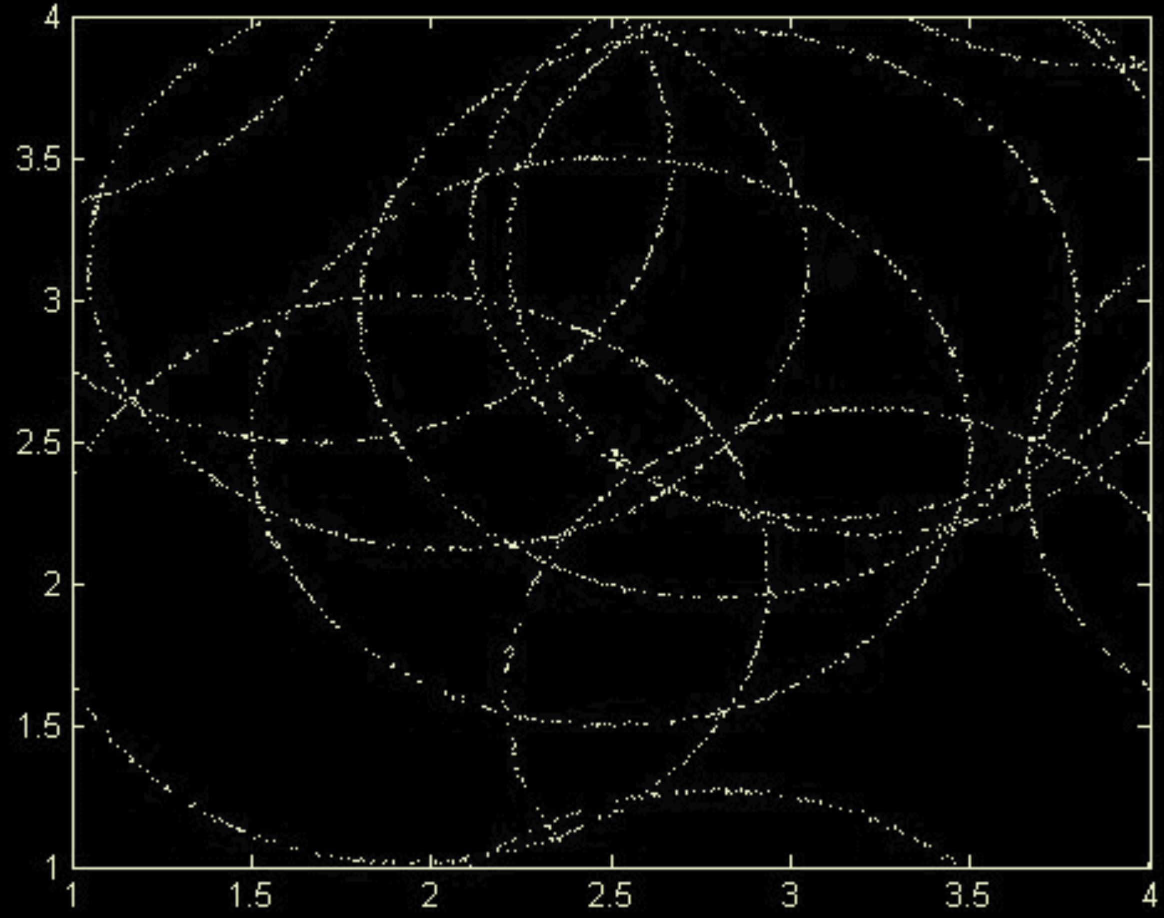
WiggleZ, Blake *et al*, 2011



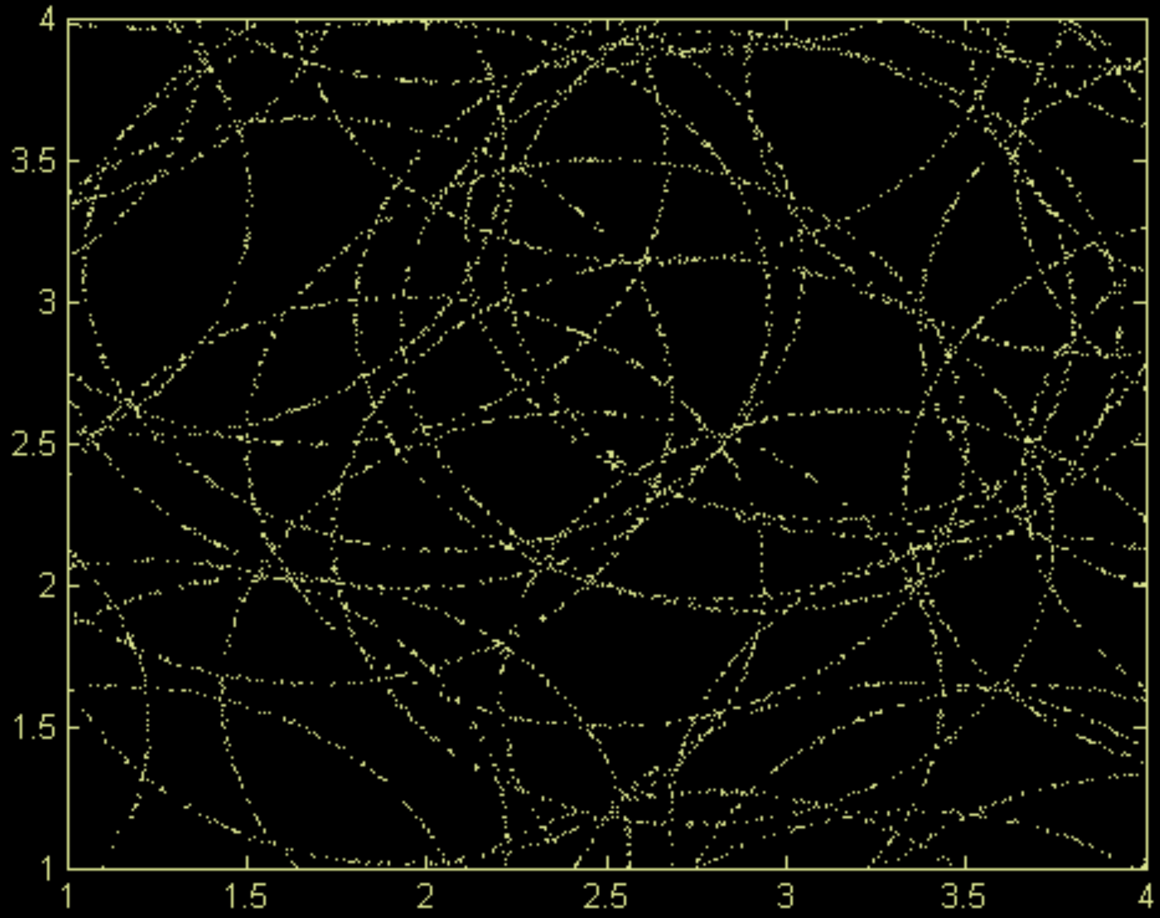
2 minute Exercise: Compute the size of the BAO scale today

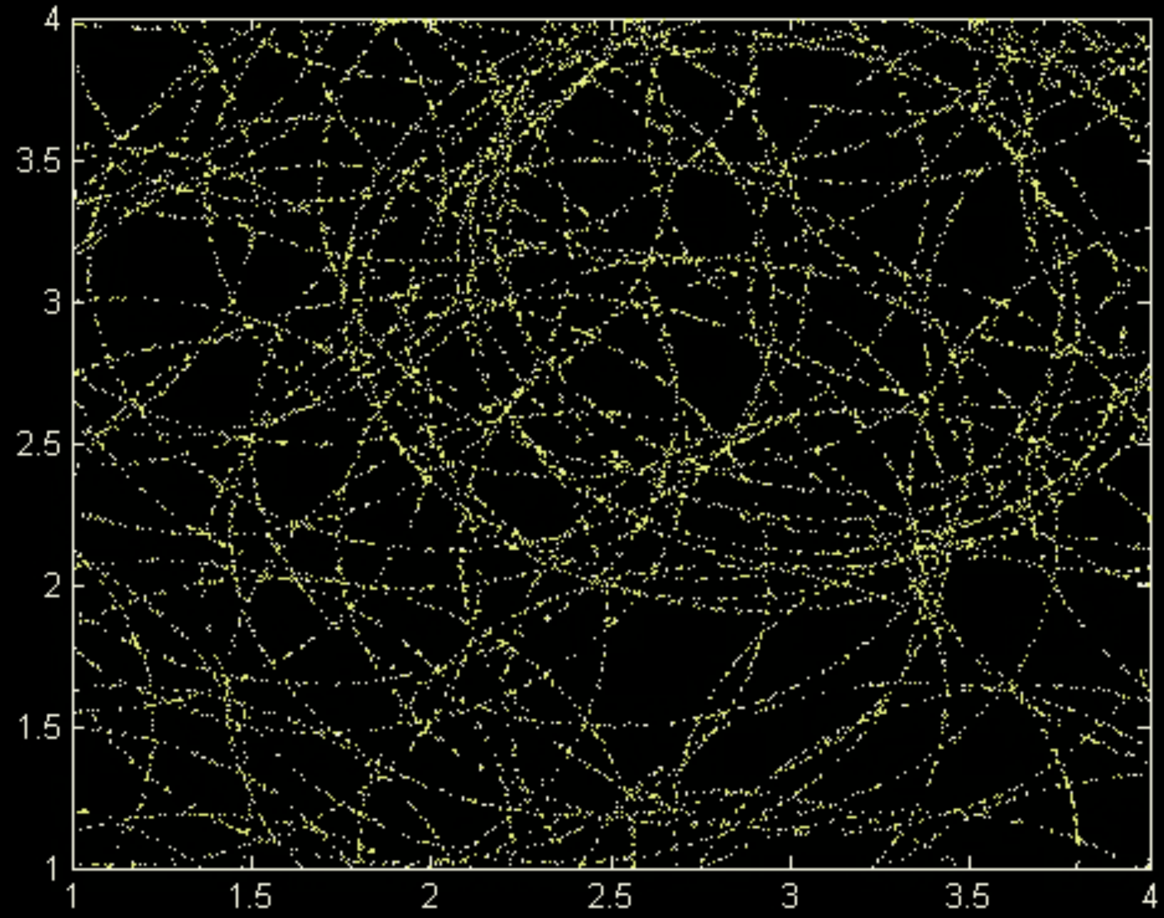
- i.e. Derive the BAO scale of 150 Mpc to within a factor of two

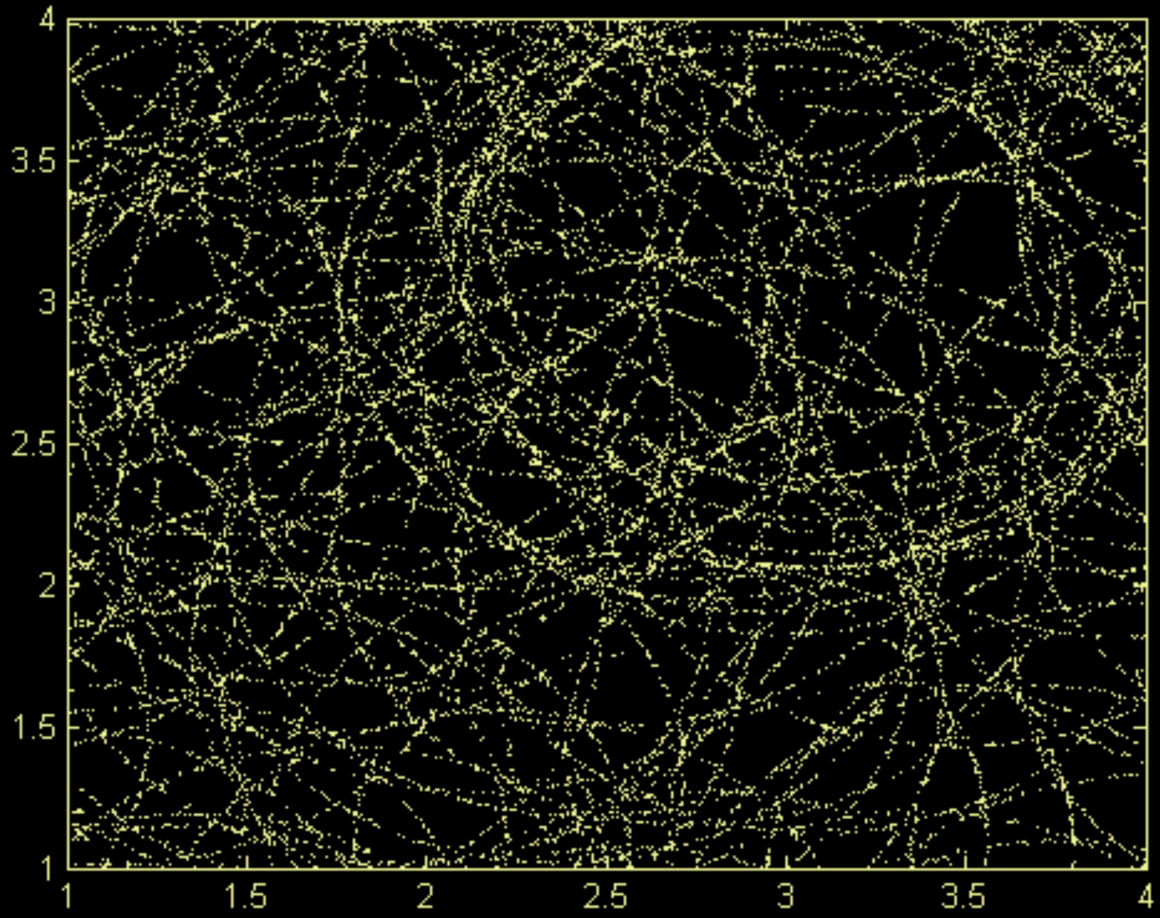

4
3.5
3
2.5
2
1.5
1
1
1.5
2
2.5
3
3.5
4

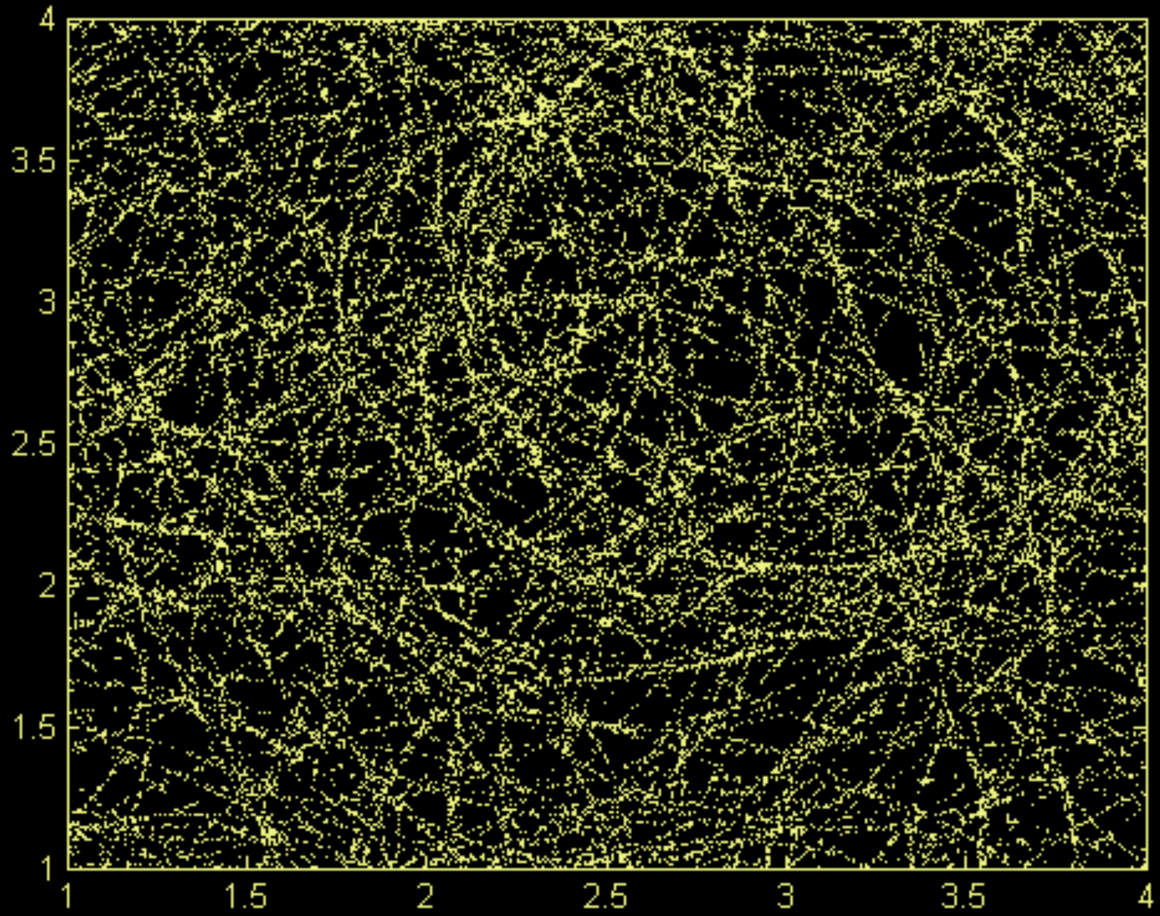


4
3.5
3
2.5
2
1.5
1
1
1.5
2
2.5
3
3.5
4

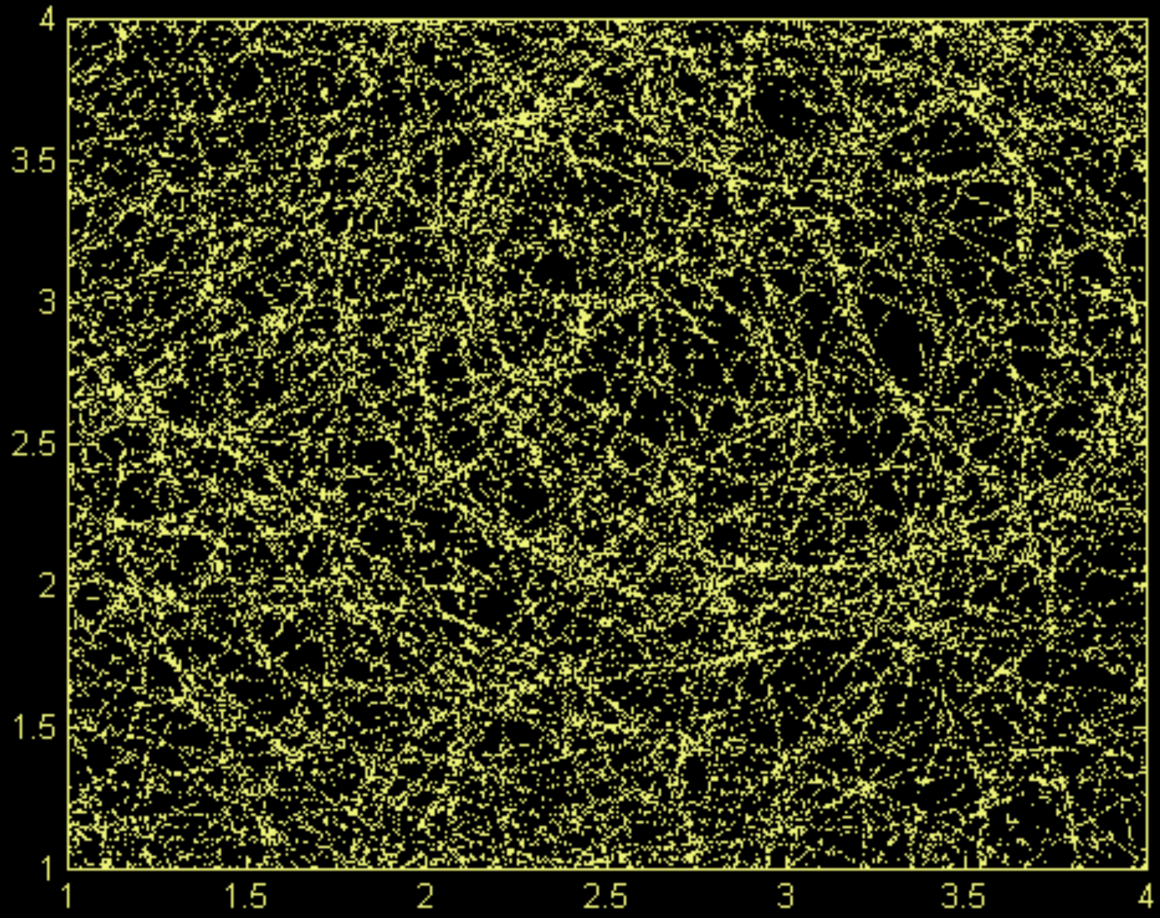

4
3.5
3
2.5
2
1.5
1
1
1.5
2
2.5
3
3.5
4


4
3.5
3
2.5
2
1.5
1
1
1.5
2
2.5
3
3.5
4

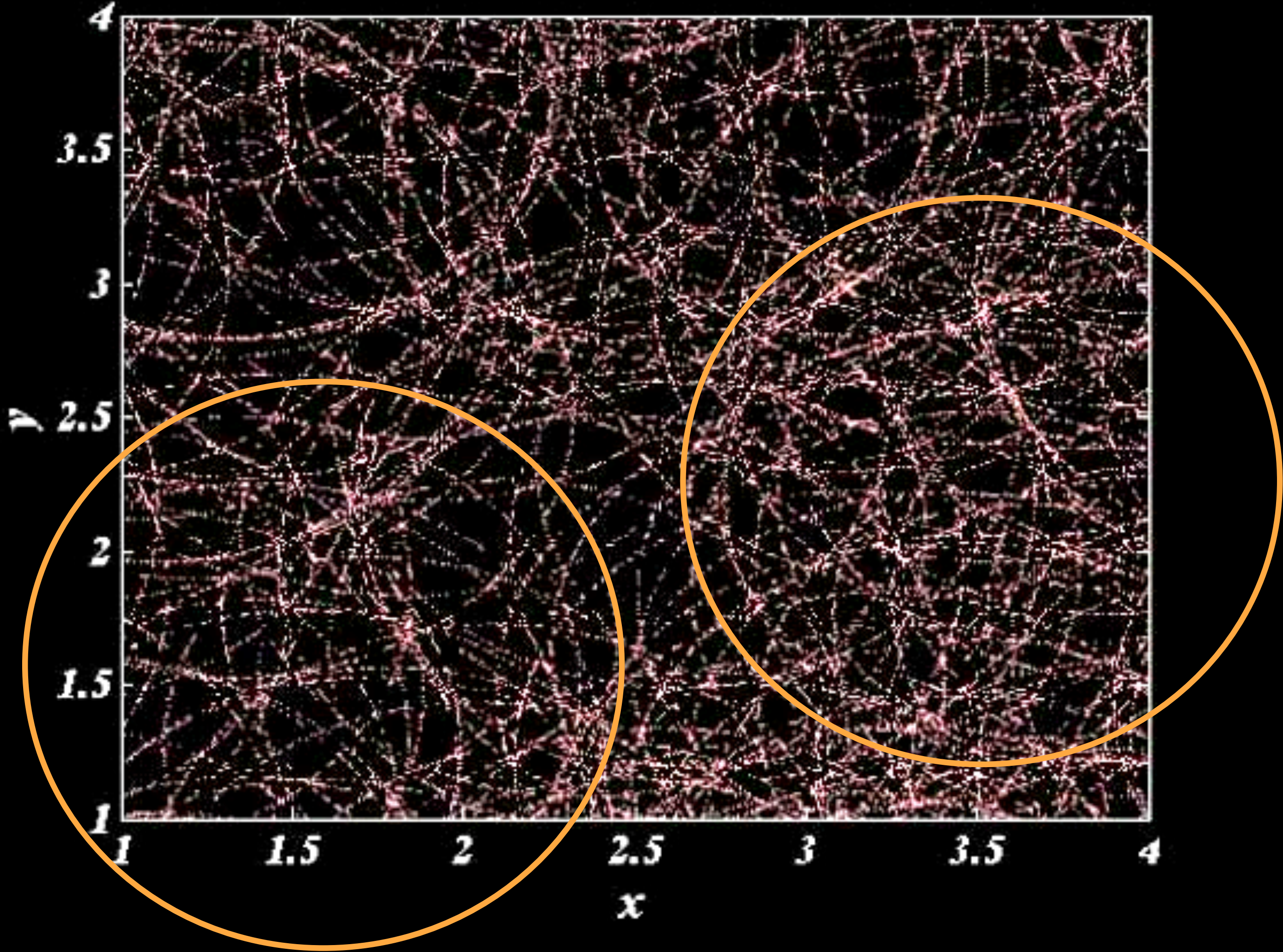

4
3.5
3
2.5
2
1.5
1
1
1.5
2
2.5
3
3.5
4



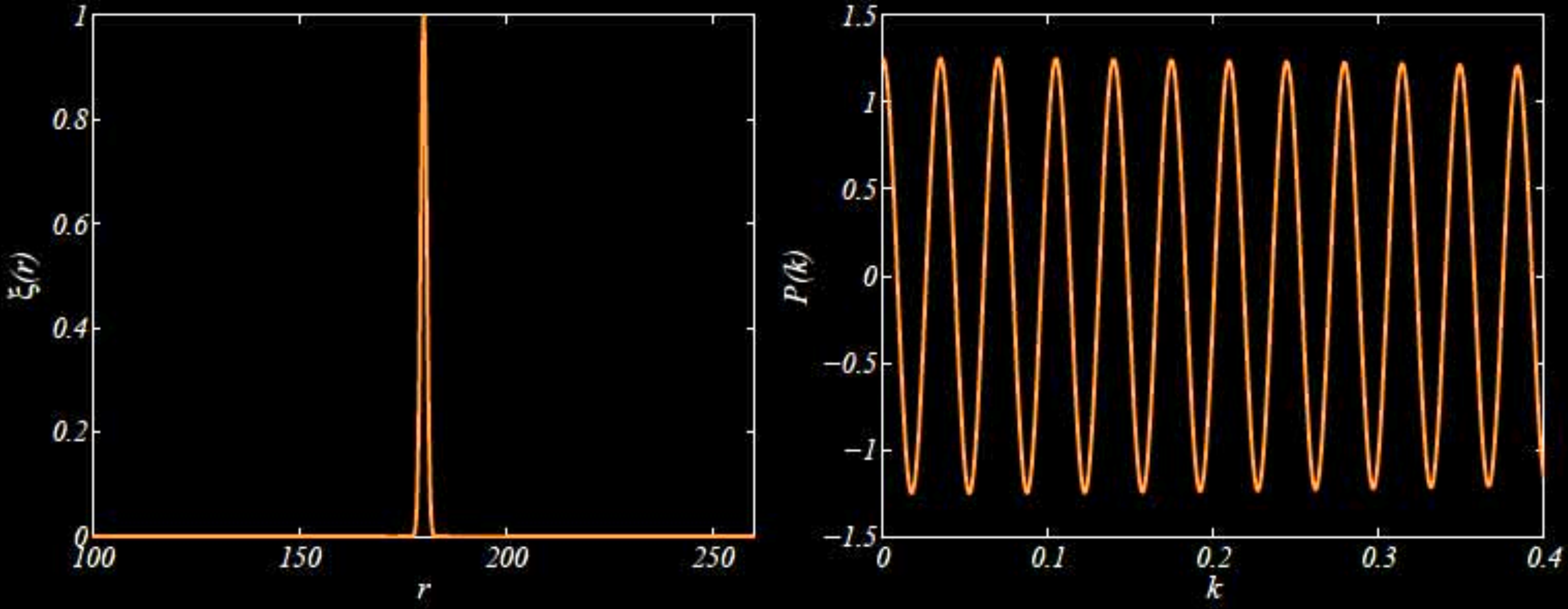
4
3.5
3
2.5
2
1.5
1
1
1.5
2
2.5
3
3.5
4


4
3.5
3
2.5
2
1.5
1
1
1.5
2
2.5
3
3.5
4

Statistical Standard Rulers

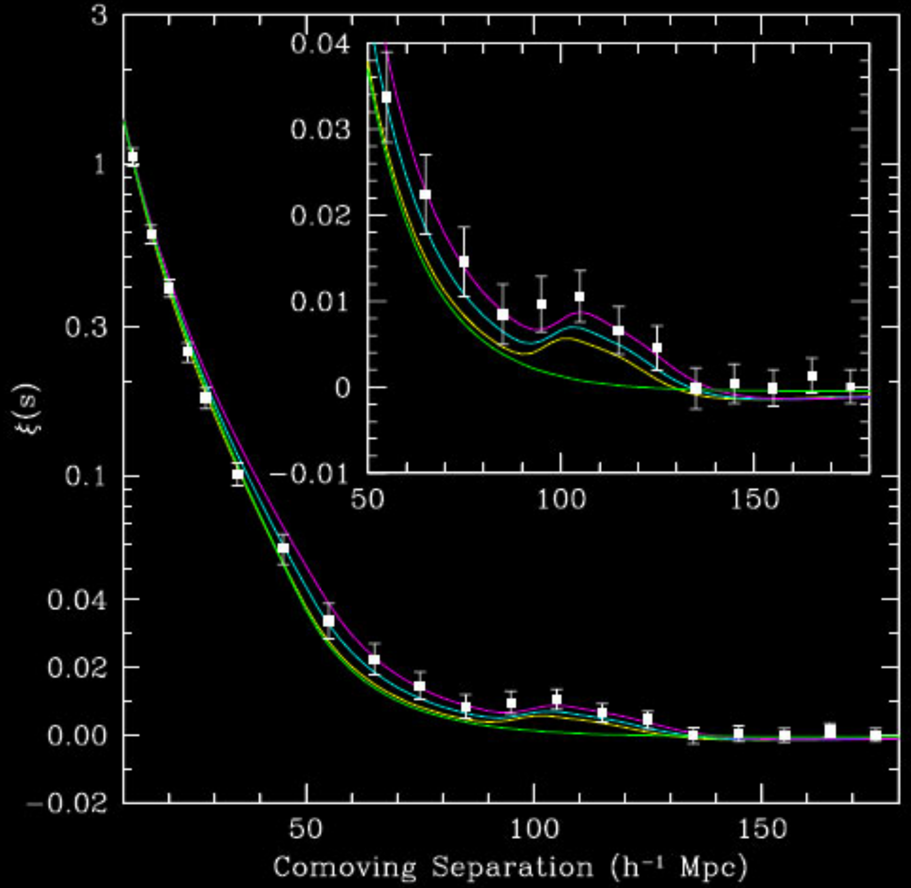


Where are the oscillations in BAO?

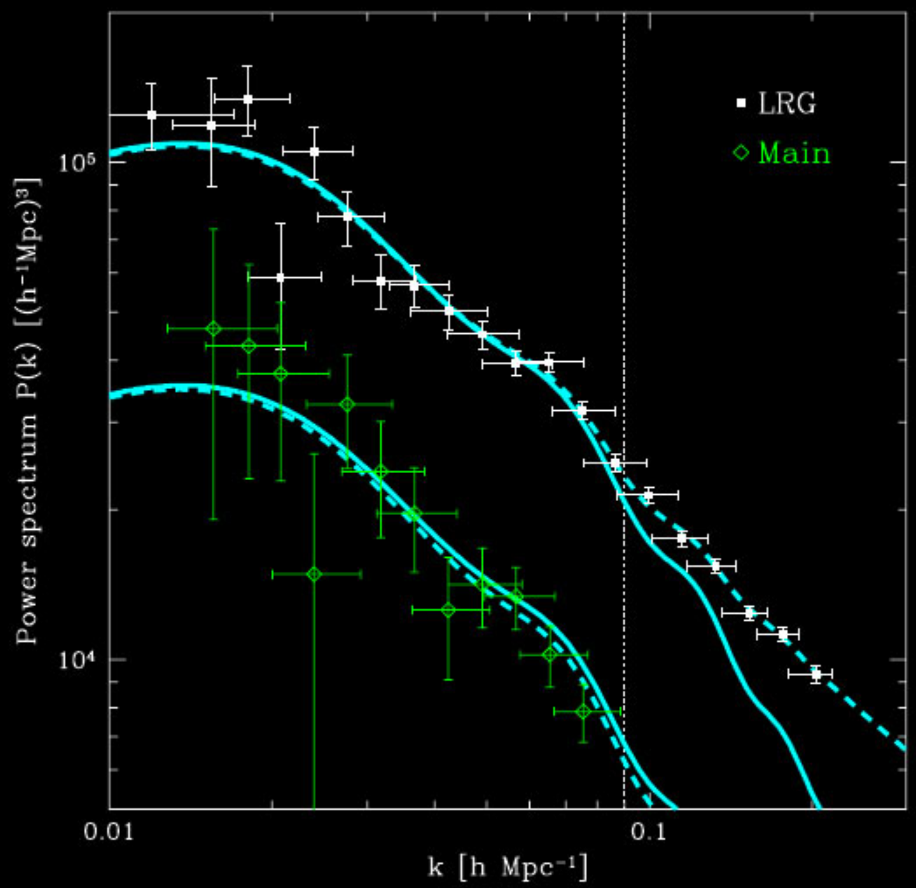


$\xi(r) \Longleftrightarrow P(k)$

Eisenstein et al.



Tegmark et al.



$\xi(r) \Longleftrightarrow P(k)$

BAP Detection Is Hard!

- Consider a typical Luminous Red Galaxy (LRG). How many LRGs do we expect in a BAP shell around it?
- n ~10^{-4} h^3 Mpc^{-3}
- Volume = 20 *Mpc* x 100^2 Mpc^2 x 5 ~ 10^6 h^{-3} Mpc^3

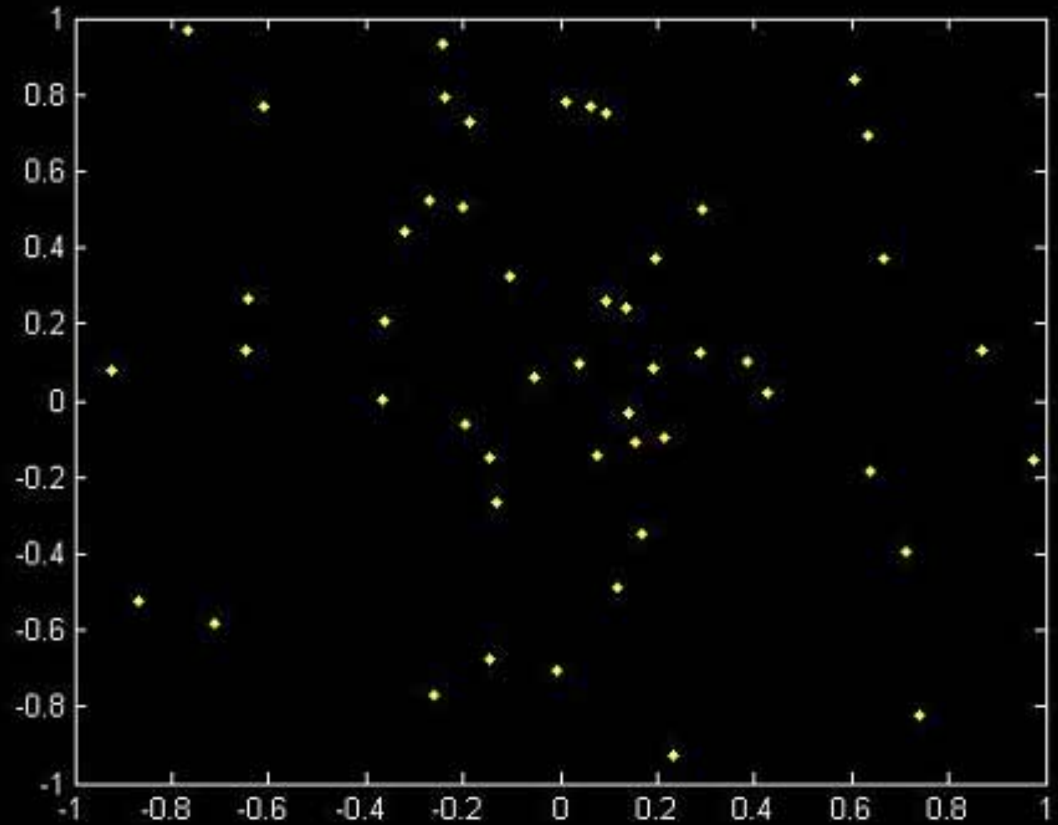
  → 100 LRGs from purely uniform distribution
- BAP in $\xi(r)$ gives ~1% excess probability
- So gives a *single extra LRG* on average.
- Need lots of volume and large numbers of galaxies…so we can see the extra galaxy on average!

Power Spectrum Errors

$$\frac{\delta P}{P} = \underbrace{\frac{1}{\sqrt{m}}\left(1\right.}_{\text{Cosmic Variance}} + \left.\underbrace{\frac{1}{nP}}_{\text{Shot Noise}}\right)$$

m = number of Fourier modes measured in the survey
n = mean galaxy number density in the survey

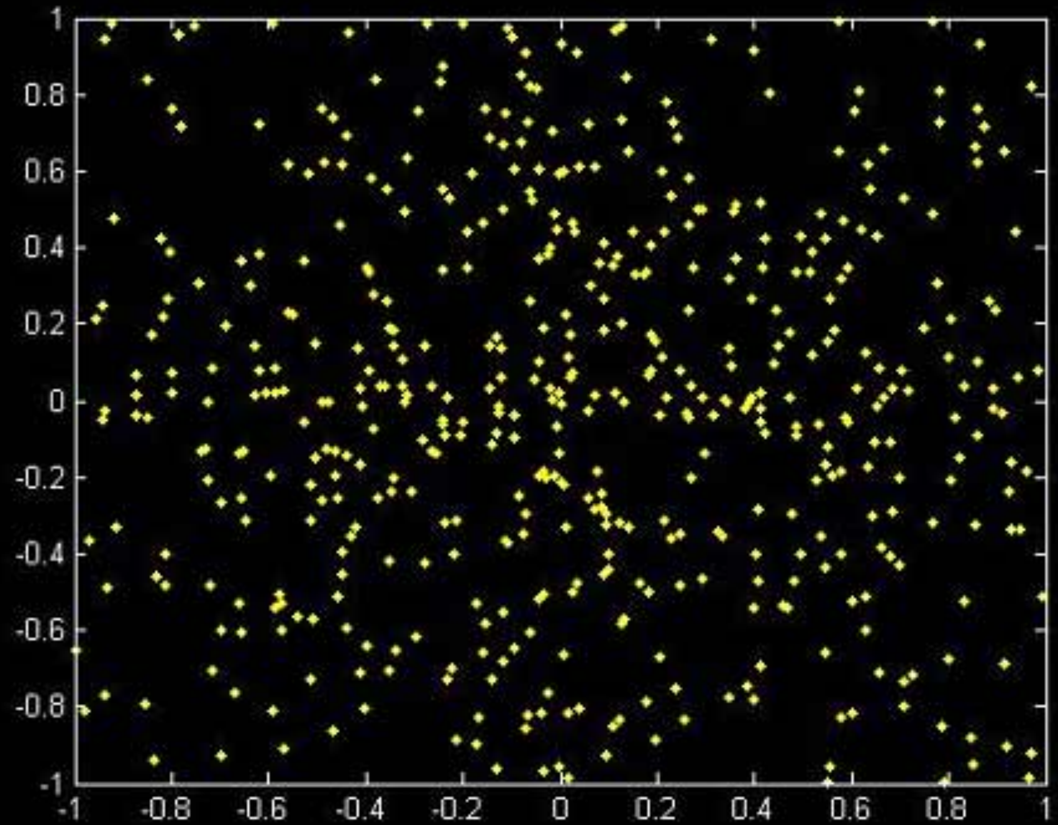
Shot Noise



Fixed Volume

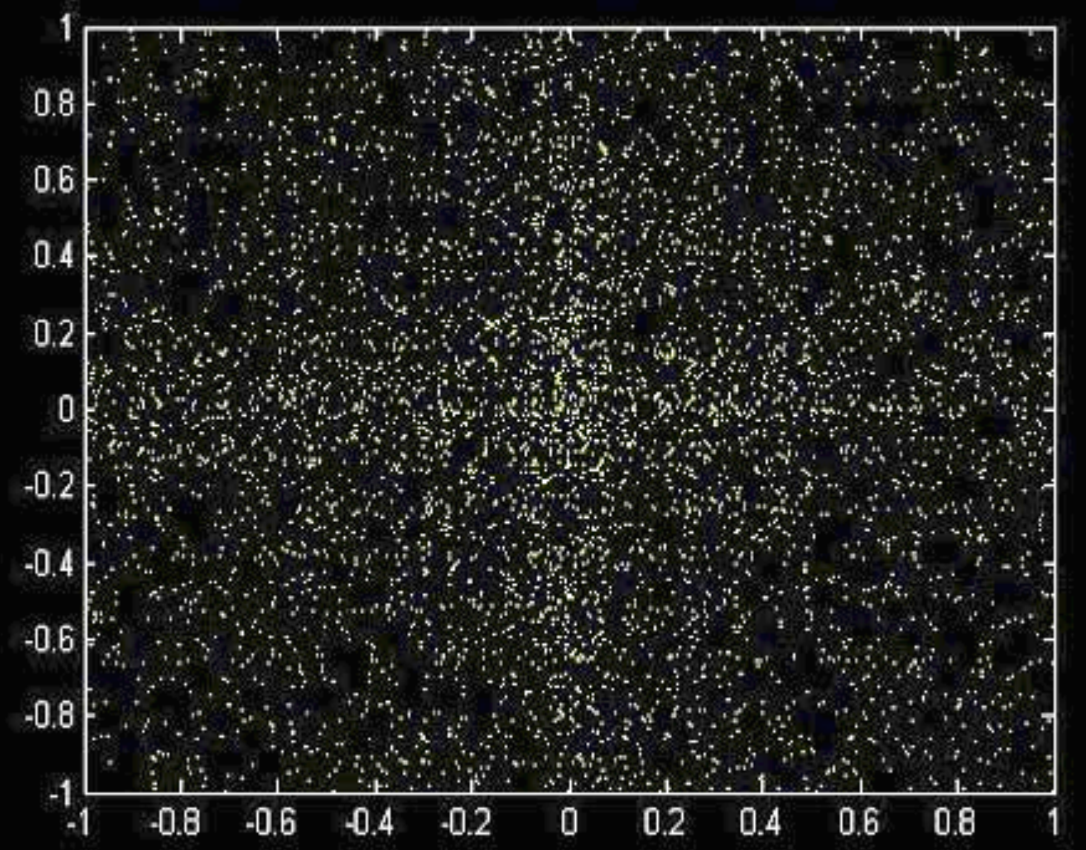
50 points

Shot Noise



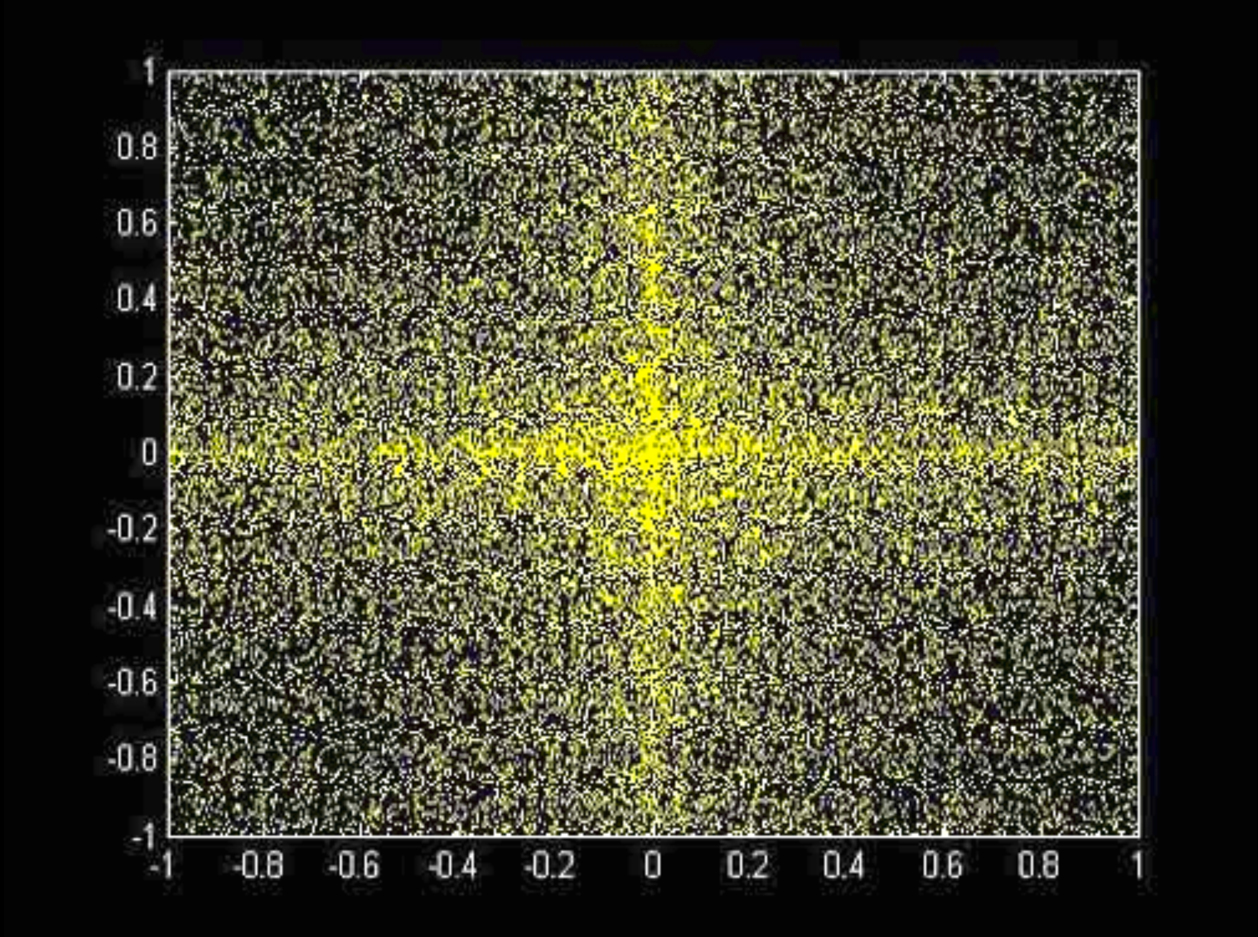
Fixed Volume 500 points

Shot Noise



Fixed Volume 5000 points

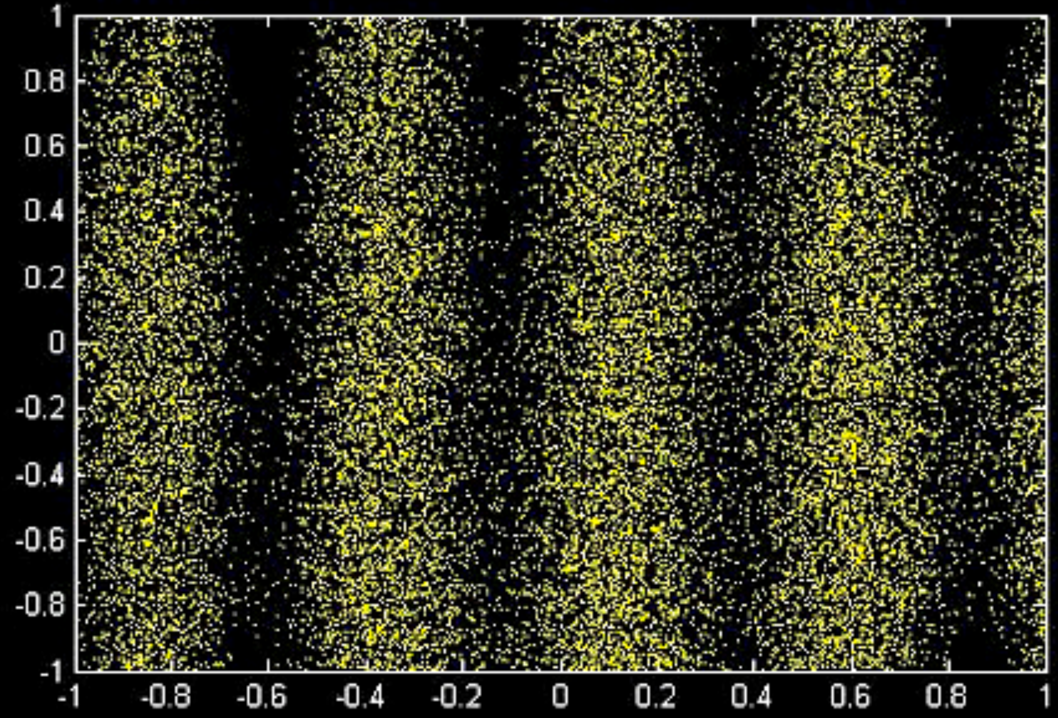
Shot Noise



Fixed Volume

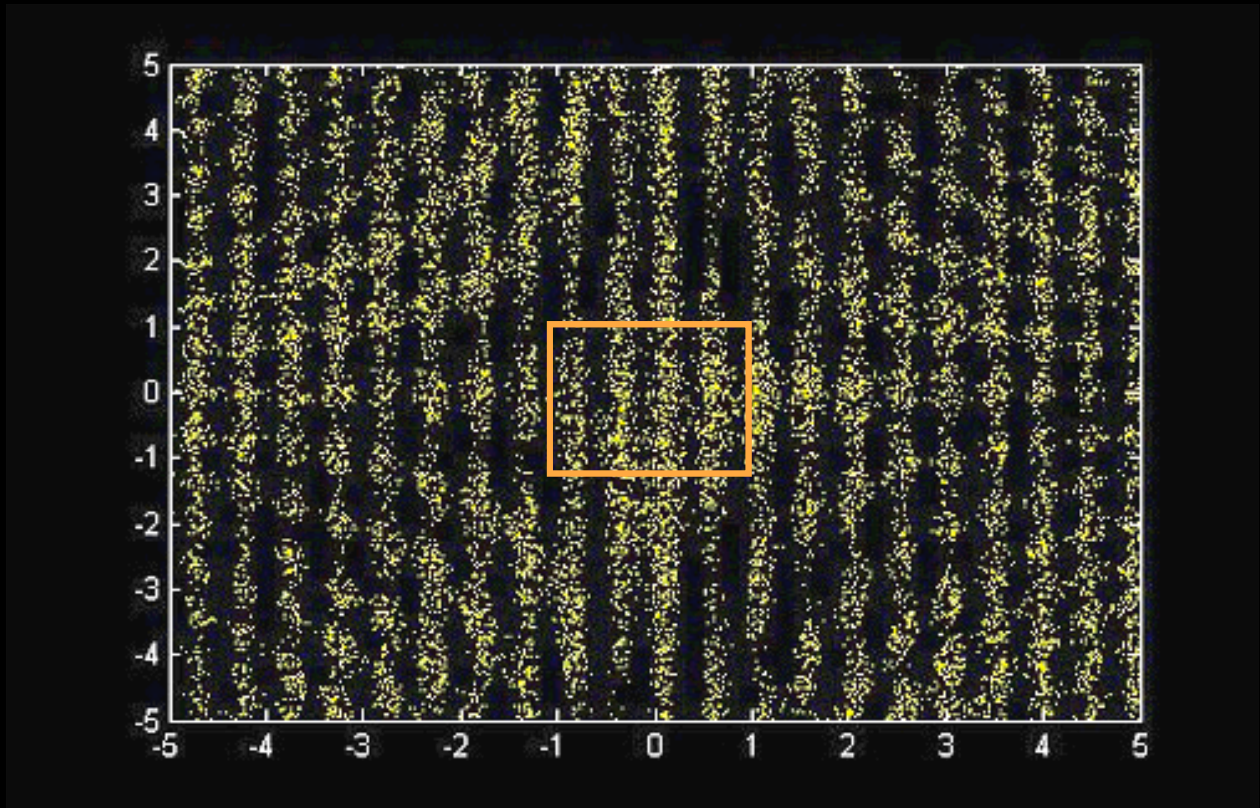
50k points

Cosmic Variance



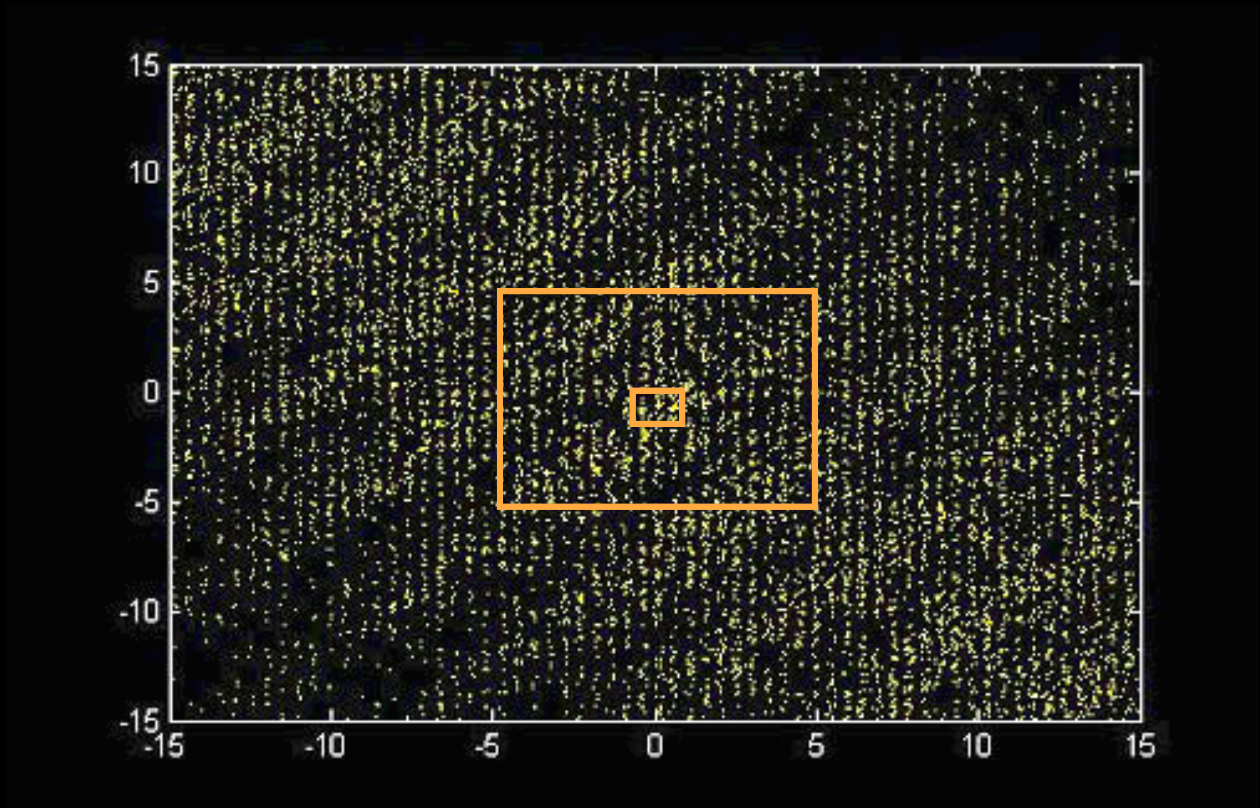
1 x Volume Fixed 50k points

Cosmic Variance



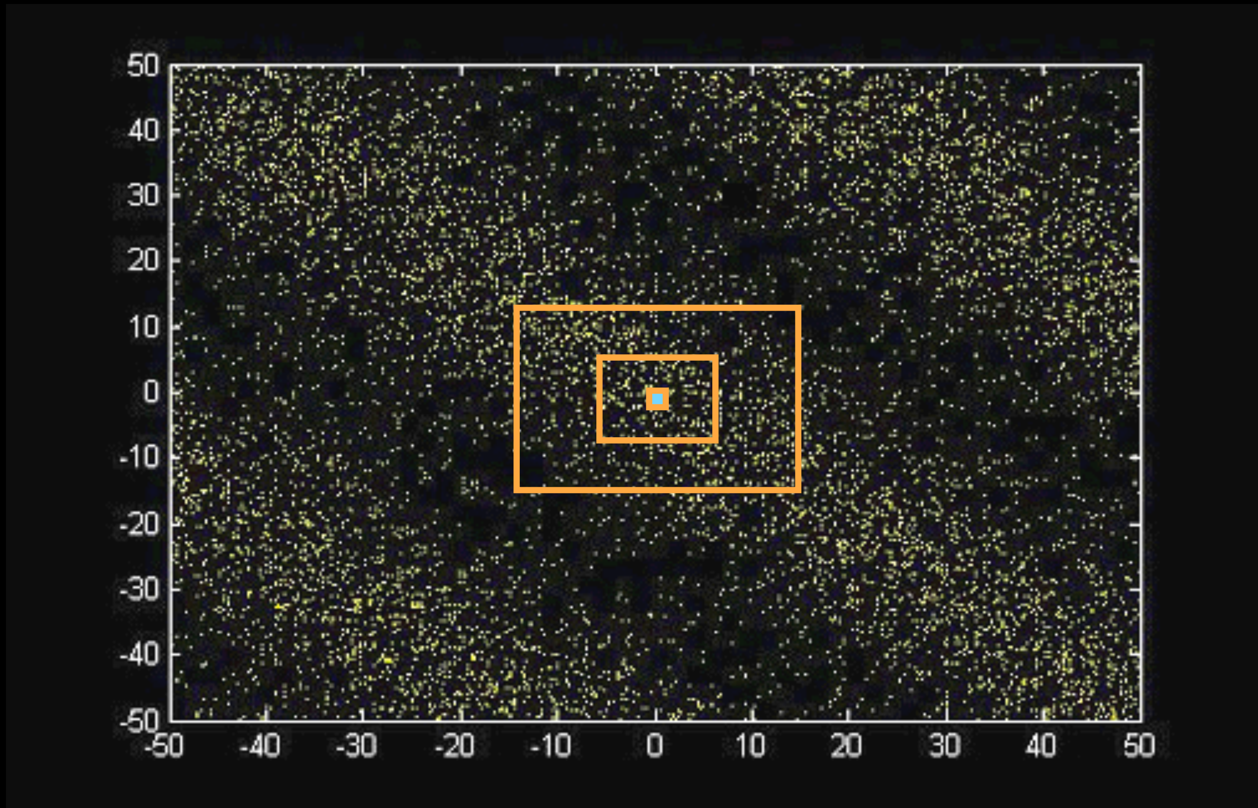
25 x Volume   Fixed 50k points

Cosmic Variance



225 x Volume   Fixed 50k points

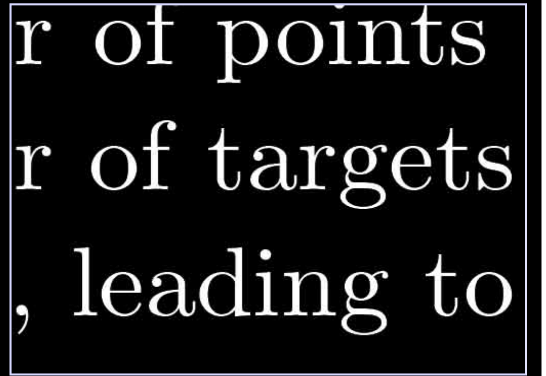
Cosmic Variance

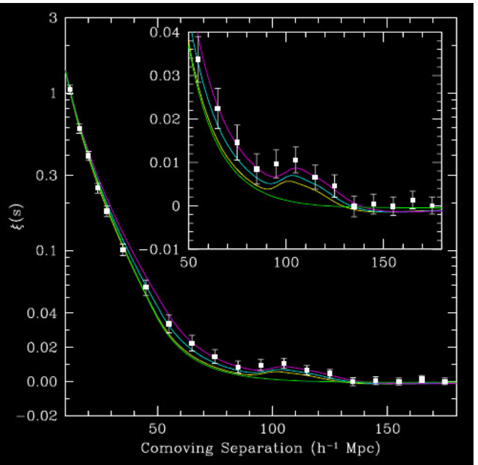


2200 x Volume   Fixed 50k points

Optimal Survey Design

- What is the optimal sampling of a page of text?
- Depends what information you want.
- E.g. what language it is written in…
- E.g. what page layout is being used…
- Trade-off between the two…
- $nP \sim$ 1-5 is typically optimal
- Chat to Marina!





Fun Exercise

- In groups of 2 or alone write pseudo-code to compute the spherically averaged *ξ(r)* for the original SDSS DR3 data (available from me)

- Data is RA, DEC, z, weights
- Easiest to use the simple estimator $1 + \xi = DD/RR$
- The random catalogue is big ($\sim 10^6$ points)

Thanks to Dan Eisenstein

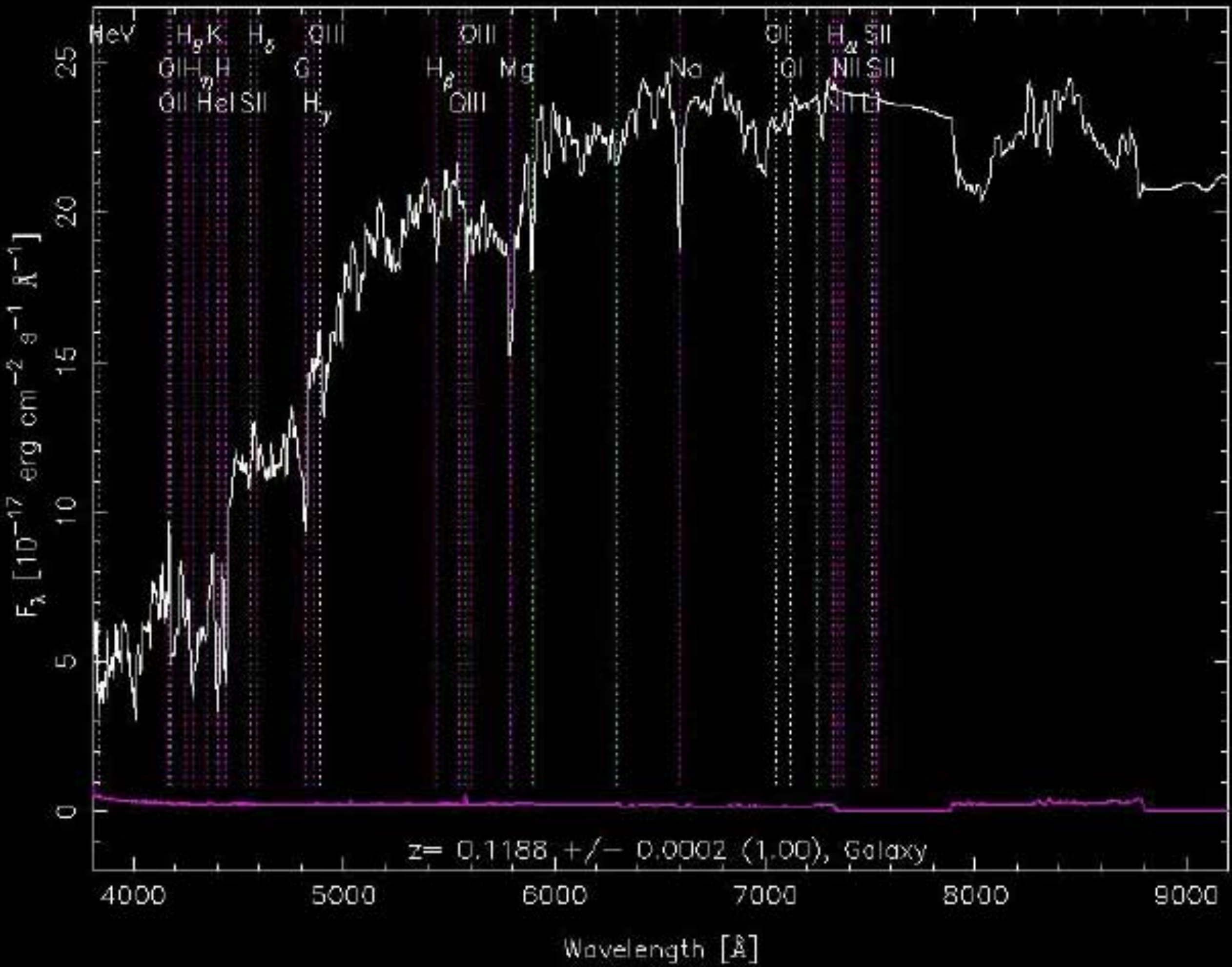
DATA

From Dan Eisenstein

- http://dl.dropbox.com/u/8961705/SDSS_LRG_BAO_exercise/readme_SDSS_LRG_BAO **(http://tinyurl.com/4ypwsvq)**
- http://dl.dropbox.com/u/8961705/SDSS_LRG_BAO_exercise/readme.LRG **(http://tinyurl.com/3k4mbrs)**
- http://dl.dropbox.com/u/8961705/SDSS_LRG_BAO_exercise/Random_sample14.212_232.z16_47.gz **(http://tinyurl.com/3sbf5ot)**
- http://dl.dropbox.com/u/8961705/SDSS_LRG_BAO_exercise/lrg_sample14.212_232.z16_47.gz **(http://tinyurl.com/3wo6945)**

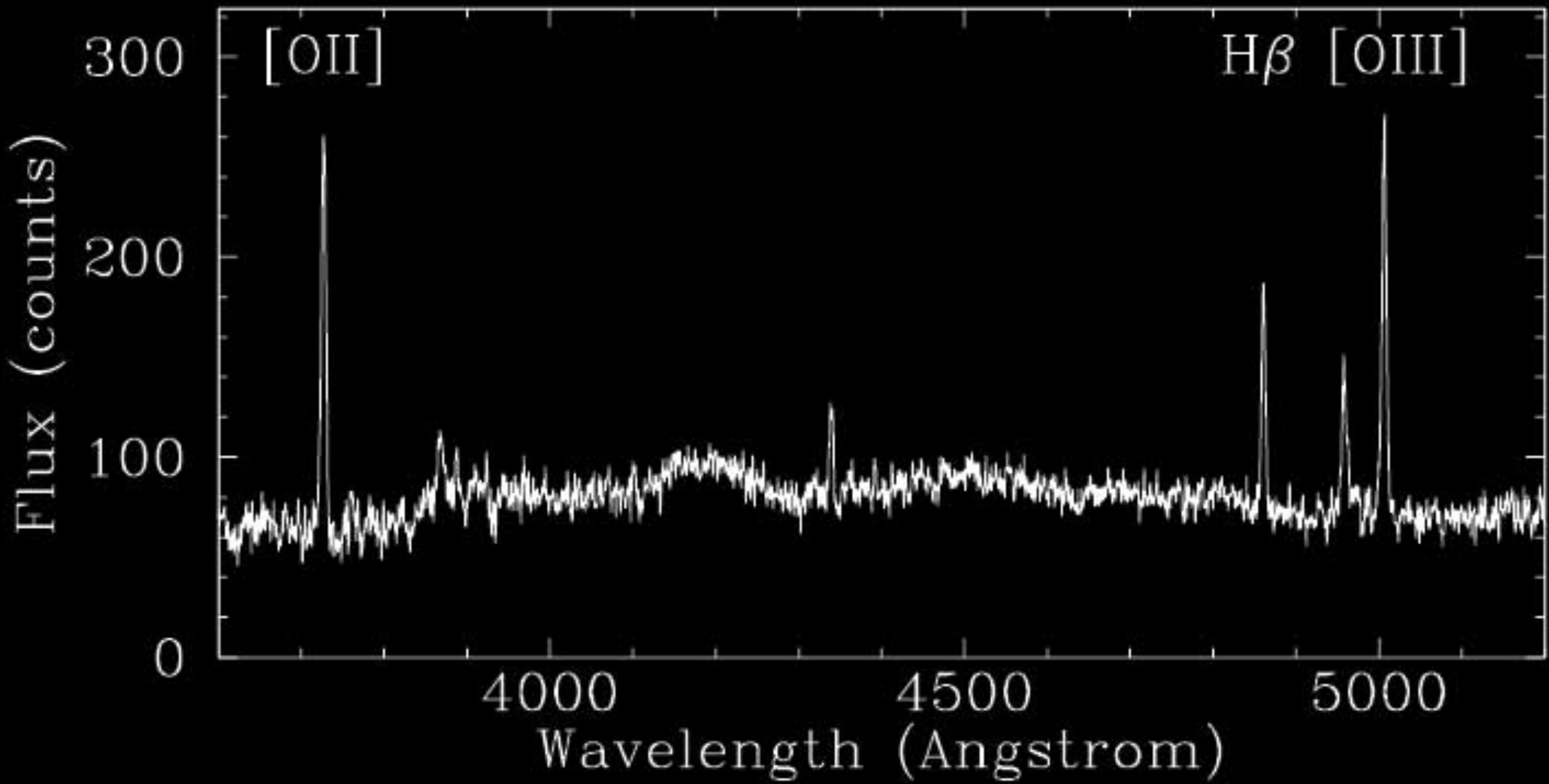
What choice of target should one use for BAO?

Luminous Red Galaxies (LRGs)



e.g. SDSS, BOSS,…

Blue galaxies…



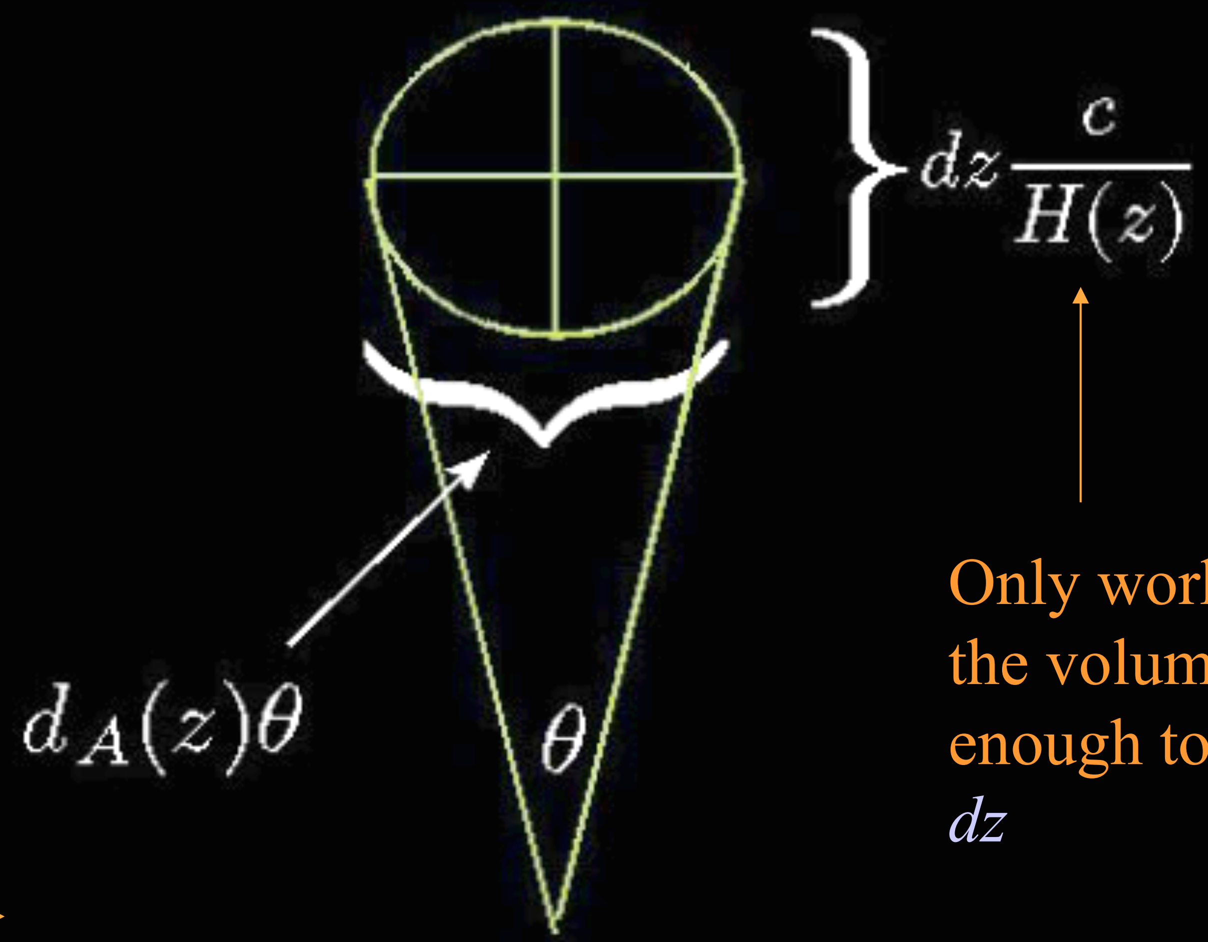
e.g. WiggleZ,…

(Statistical) Standard Rulers

Beyond spherical averaging

- In the SDSS exercise you computed the spherical average of $\xi(r)$ to give an average distance D_V.
- With enough data we can do much better than that however…

The Beauty of Standard Volumes



Radial

Tangential

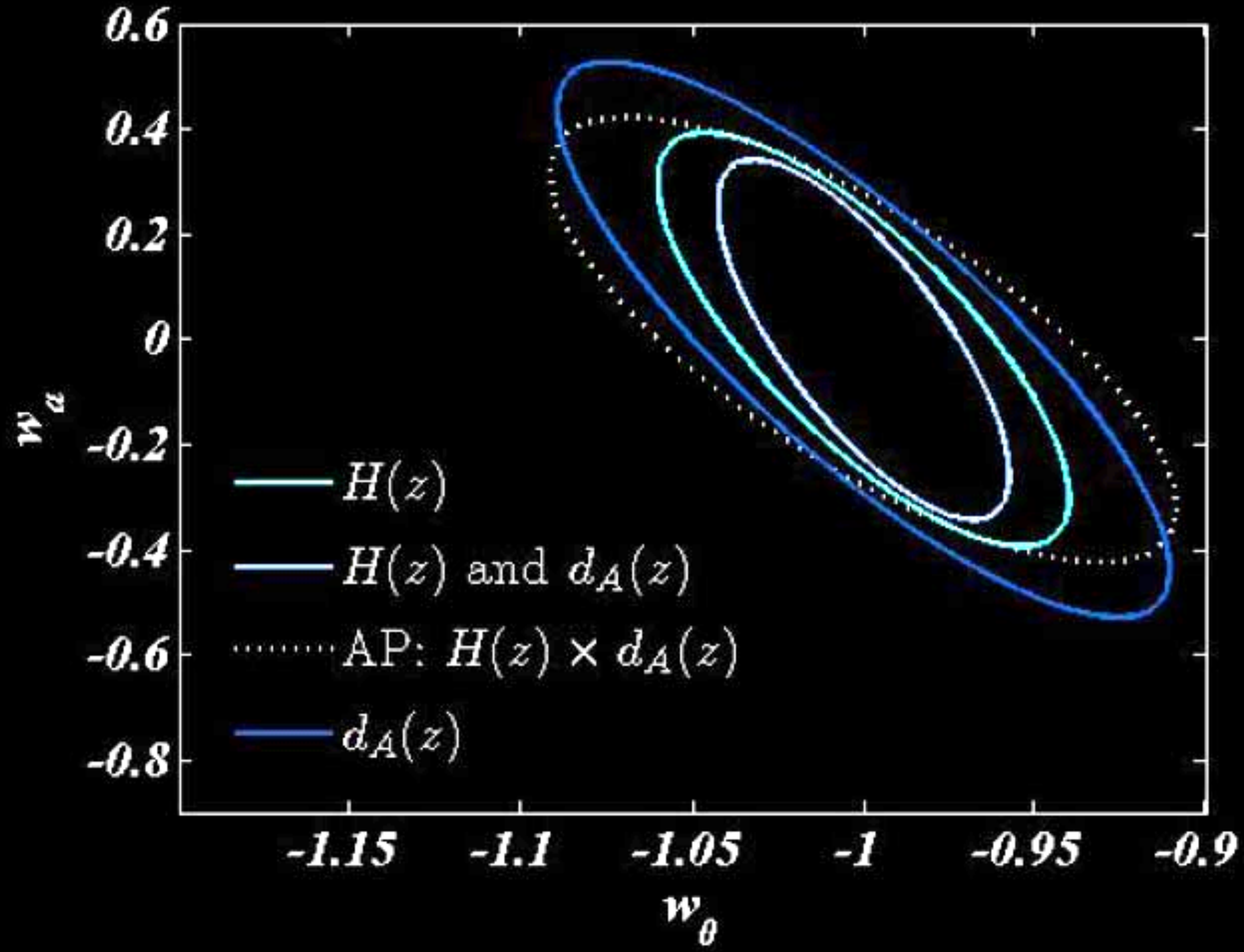
Us

Only works if the volume is big enough to measure *dz*

BAO and AP

- If we *only* know the volume is *spherical*, then we constrain the product $H(z)\ d_A(z)$ (the Alcock-Paczynski (AP) test)
- If we also know the *absolute* sizes in both radial and tangential directions (like with BAO), we constrain both $d_A(z)$ and $H(z)$ separately.
- BAO thus provide an *absolute* AP test.

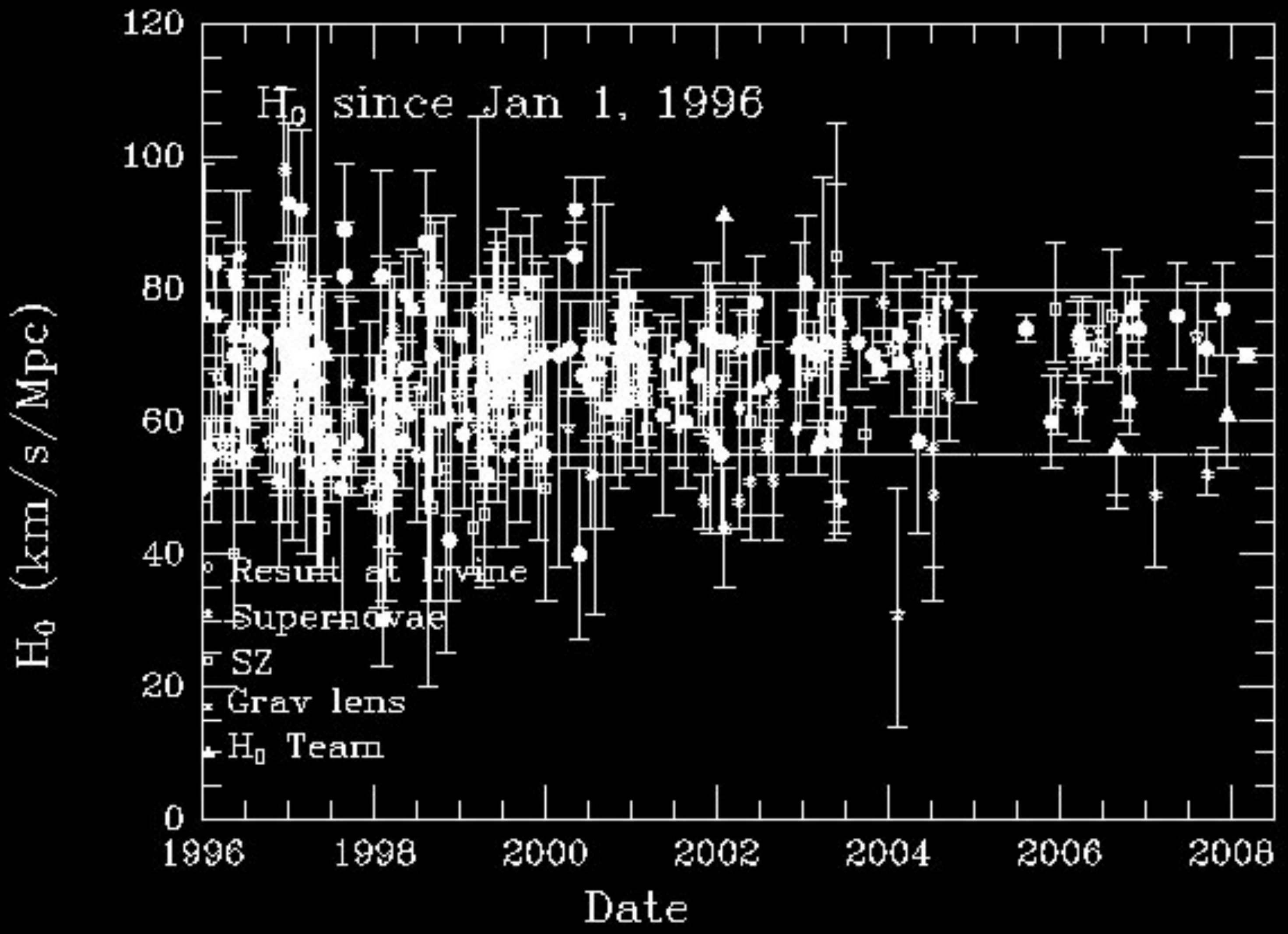
$$d_A(z) = \frac{1}{\sqrt{-\Omega_k}\,(1+z)} \sin\left(\sqrt{-\Omega_k} \int_0^z \frac{H_0}{H(z')} dz' \right)$$


0.6
0.4
0.2
0
-0.2
-0.4
-0.6
-0.8
w_a
$H(z)$
$H(z)$ and $d_A(z)$
AP: $H(z) \times d_A(z)$
$d_A(z)$
-1.15
-1.1
-1.05
-1
-0.95
-0.9
w_0

“Standard” is a Crucial Ingredient of Standard Rulers

BAO

have provided the *first* ever low-z cosmic distance measure based on *linear* physics


H0 since Jan 1, 1996
120
100
80
60
40
20
0
H0 (km/s/Mpc)
1996
1998
2000
2002
2004
2006
2008
Date
Result at Irvine
Supernovae
SZ
Grav lens
H0 Team

J. Huchra

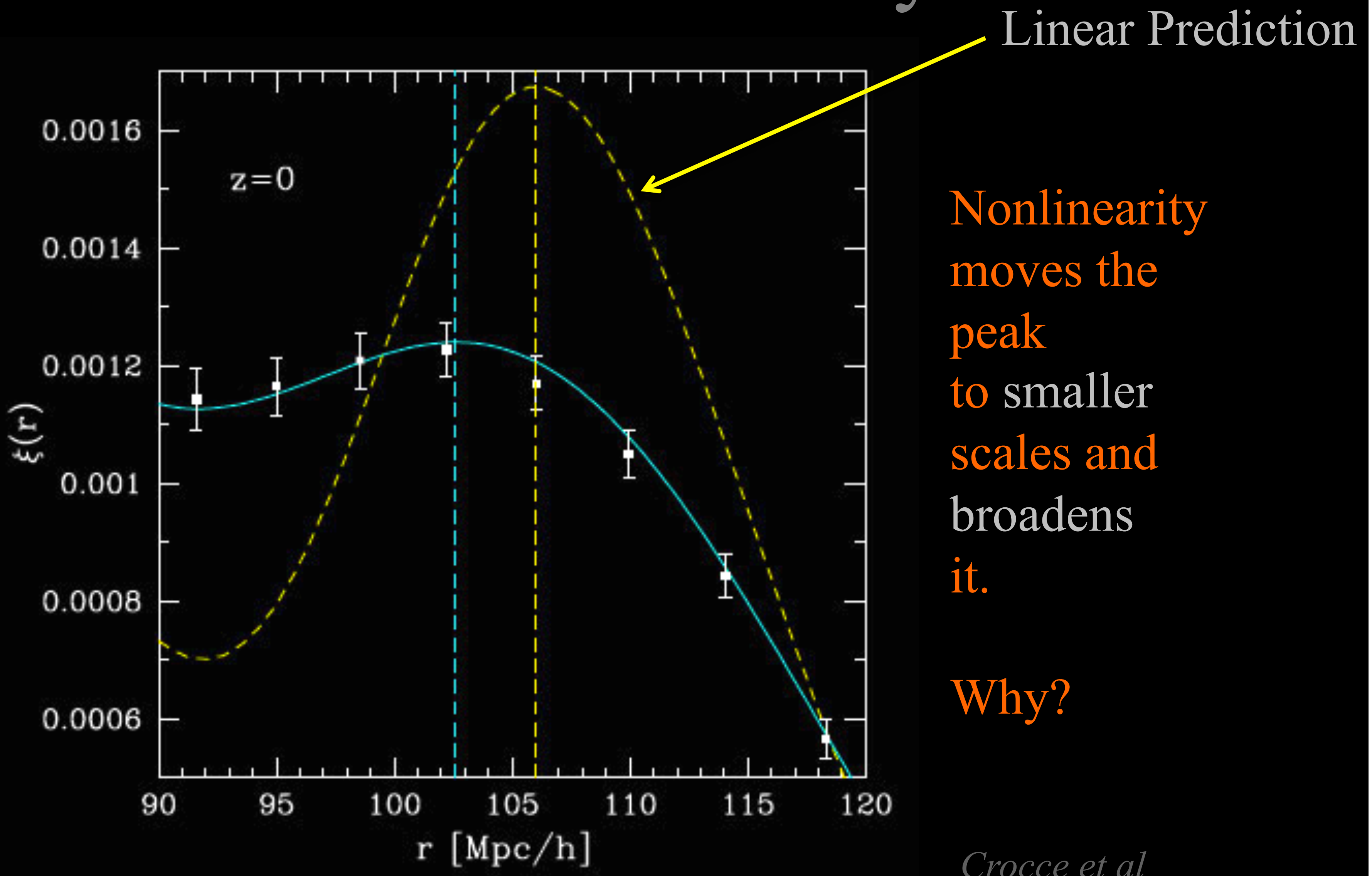
Complications

A man falls from a window and on the way down someone asks…``*how's it going*''?

The man replies: "*So far so good!*"

Cosmological Methods are similar – they have a free-fall zone and a hard, systematic "floor" where things get tough

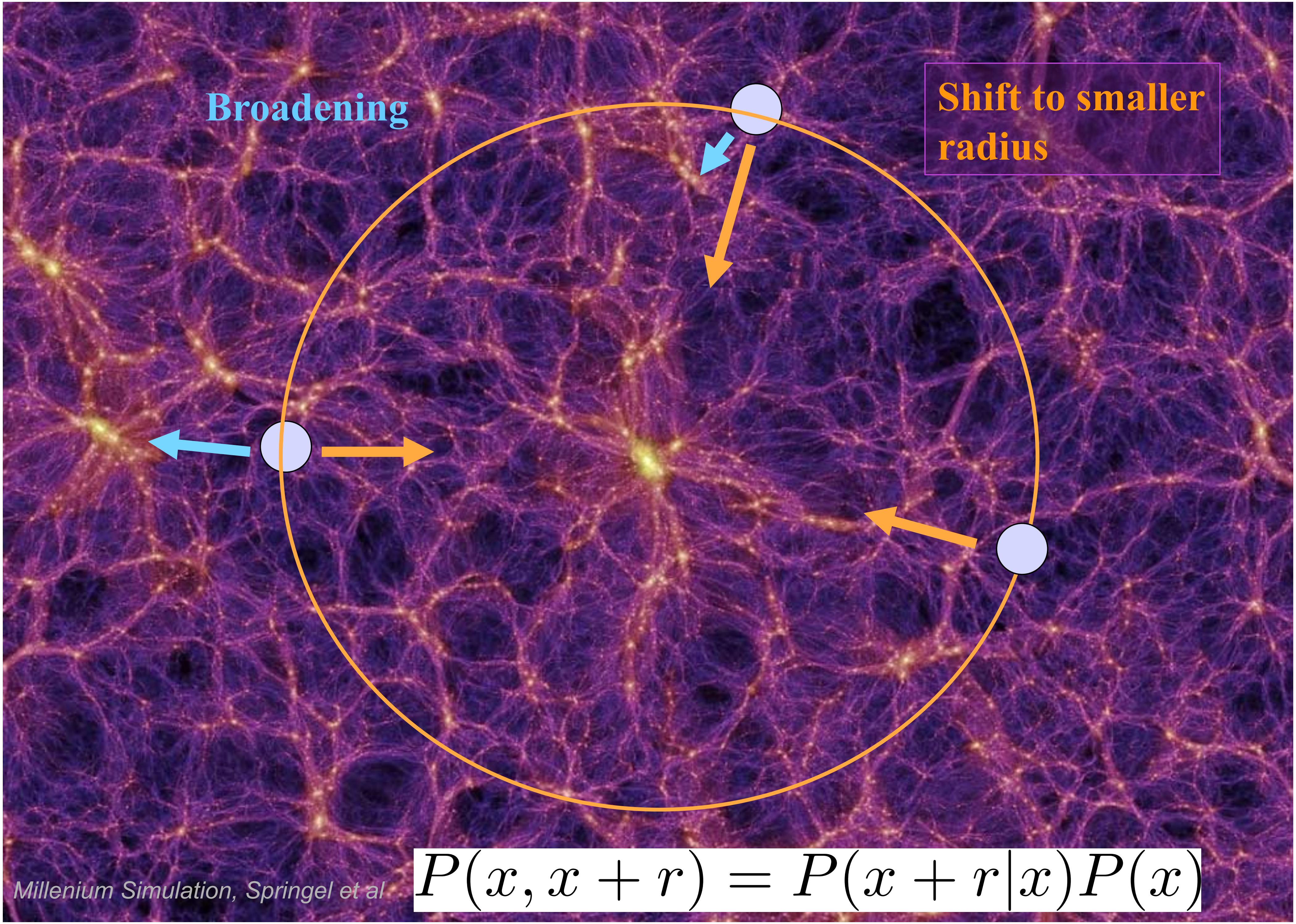
BAO and Nonlinearity



Nonlinearity moves the peak to smaller scales and broadens it.

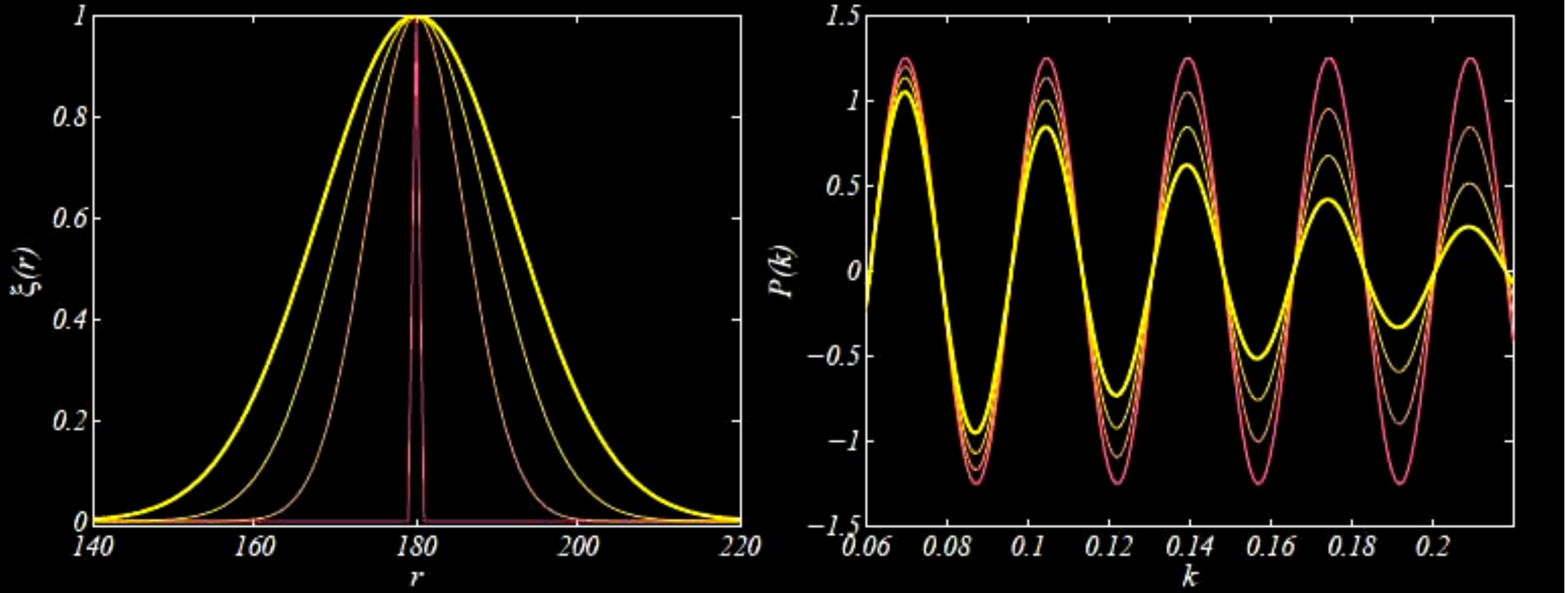
Why?

Crocce et al

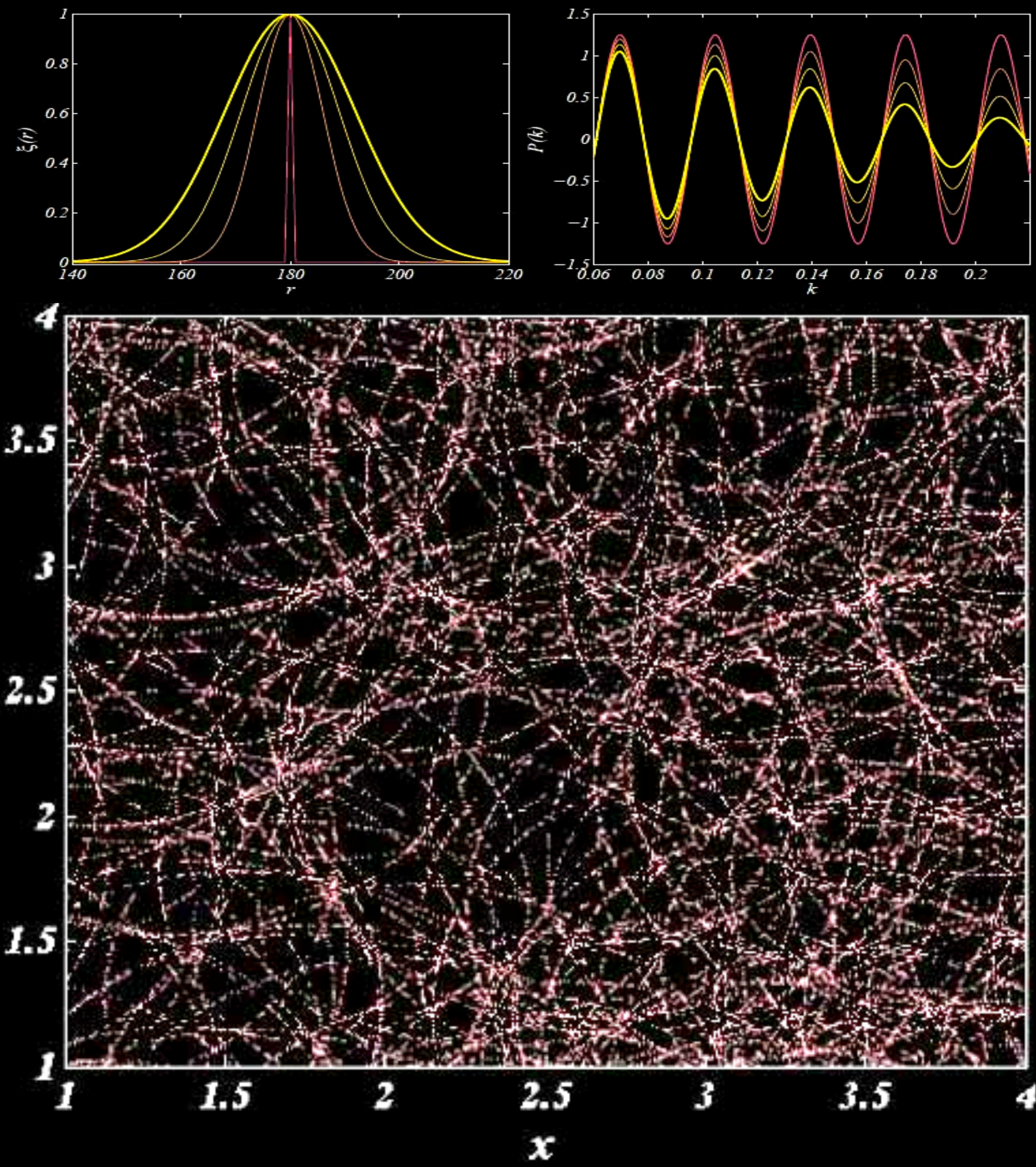


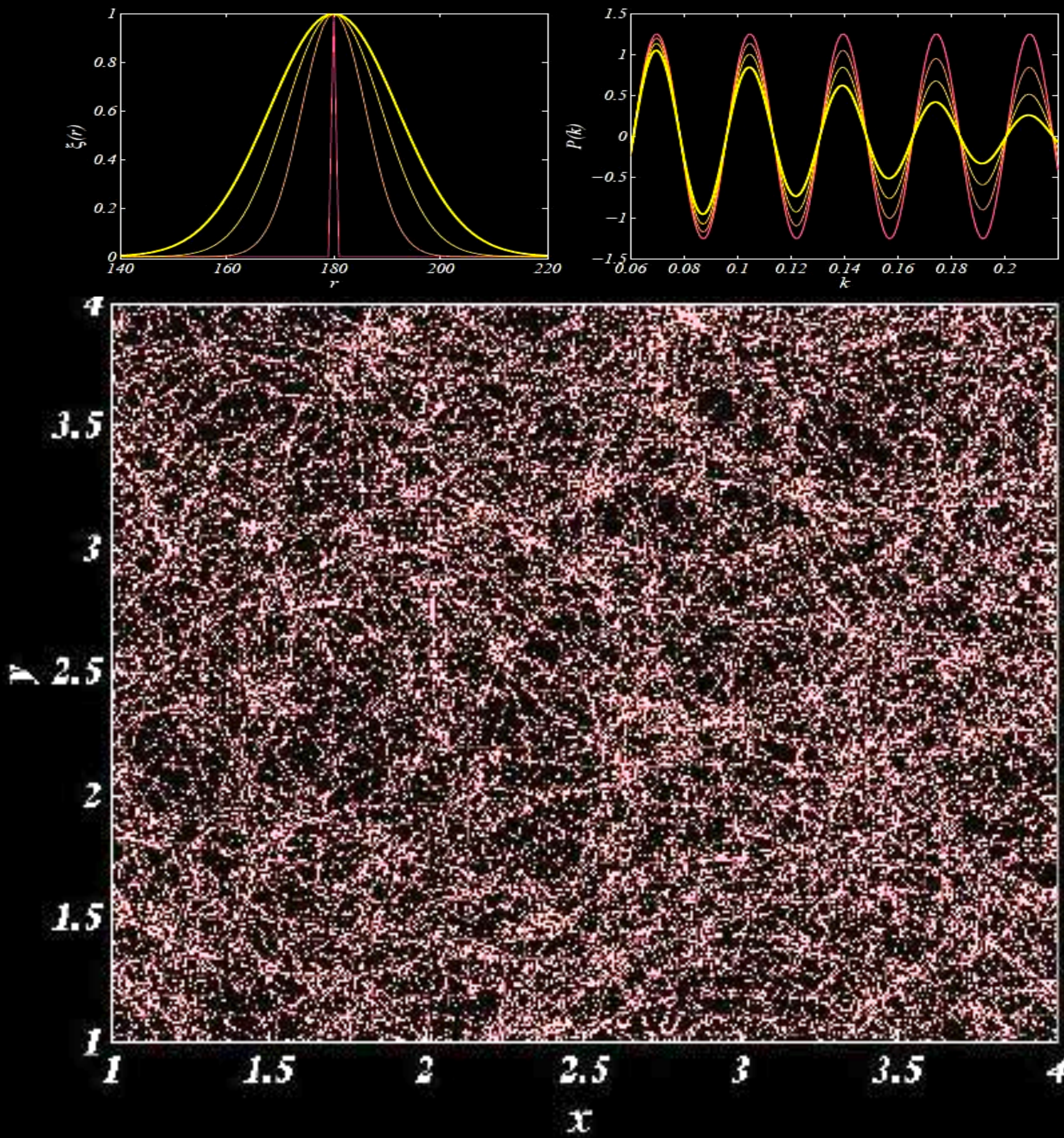
Millenium Simulation, Springel et al

$$P(x, x+r) = P(x+r|x)P(x)$$

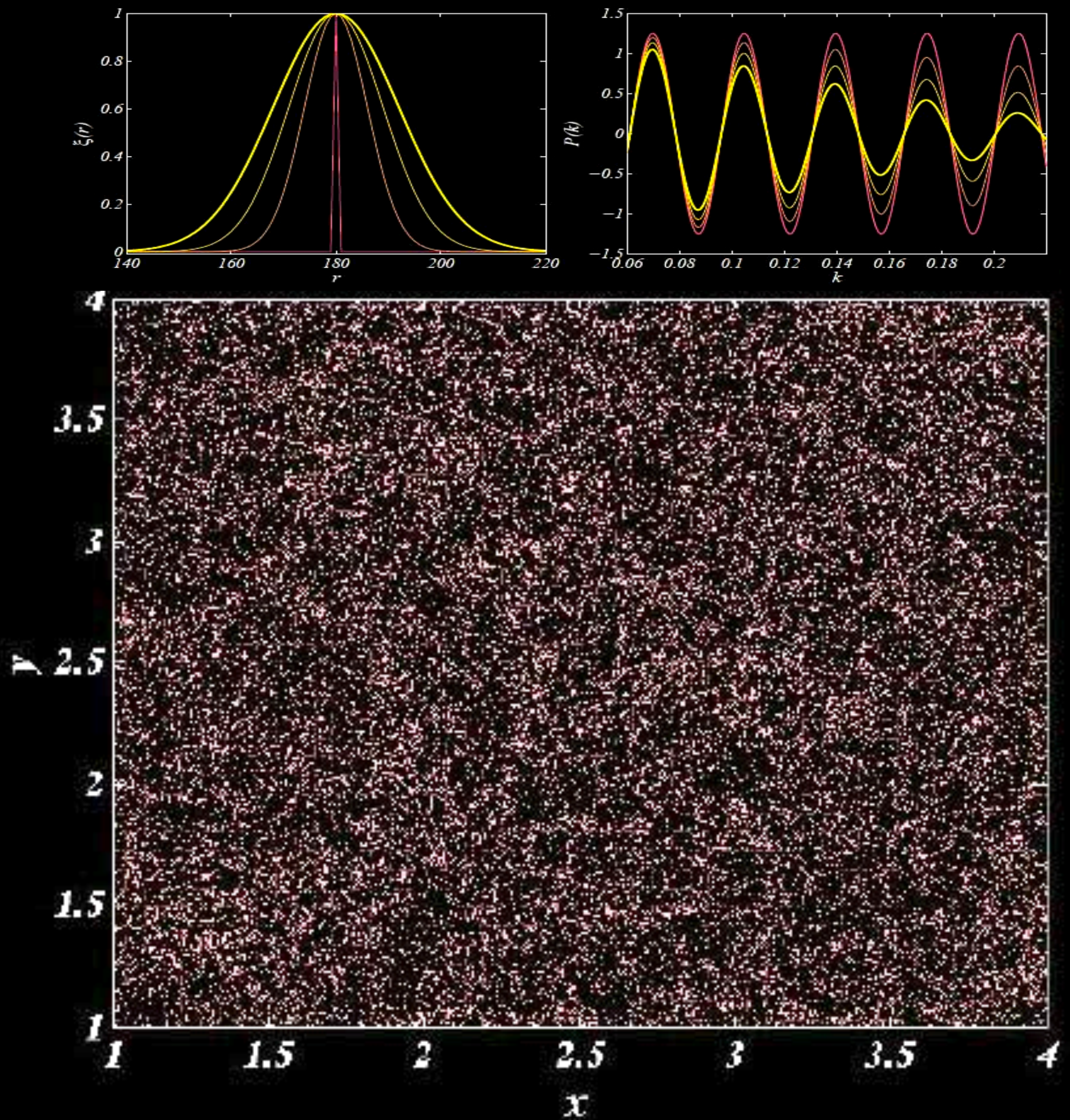


$\xi(r) \Longleftrightarrow P(k)$


ξ(r)
r
P(k)
k
y
x



ξ(r)
r
P(k)
k
y
x


ξ(r)
r
P(k)
k
y
x

Calibrating Nonlinearity

- Although it is (weakly) nonlinear, gravity is still quite clean (compare turbulent MHD in strong gravitational field)
- Good reasons to believe the nonlinear effects can be calibrated at the 1% level for BAO/BAP
- Still needs more theoretical and numerical study

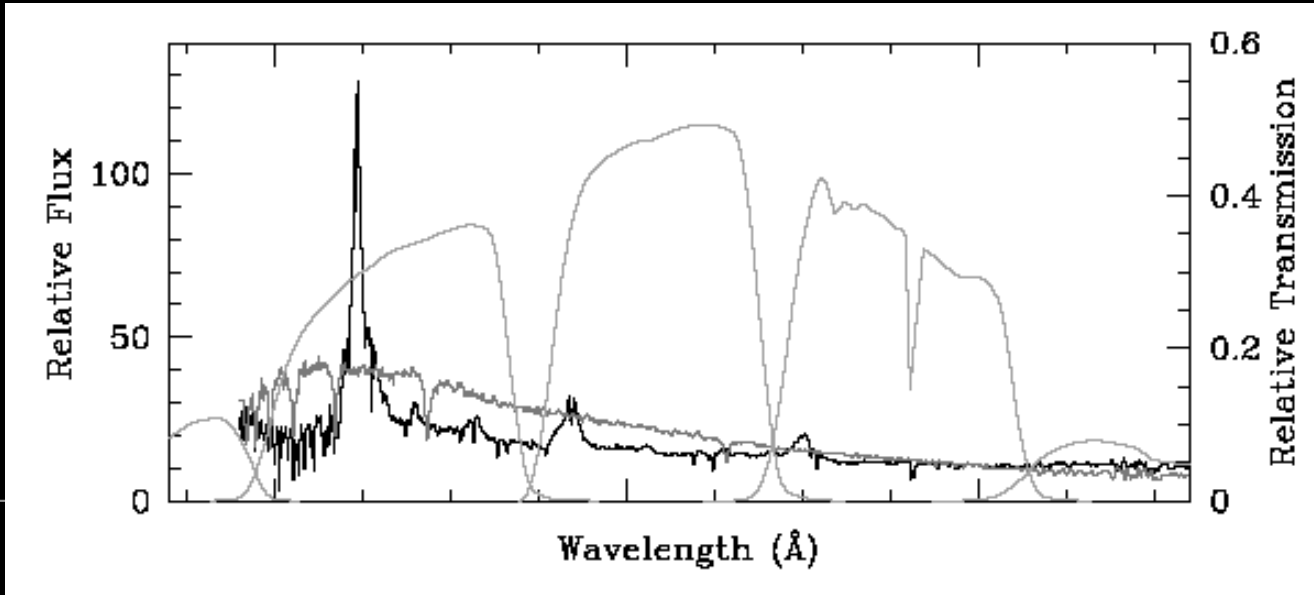
Photometric BAO Surveys

It is tempting to want to just do an imaging survey instead of taking spectra

Photometric BAO surveys primarily sacrifice *H(z)* information and need much larger volume to compete.

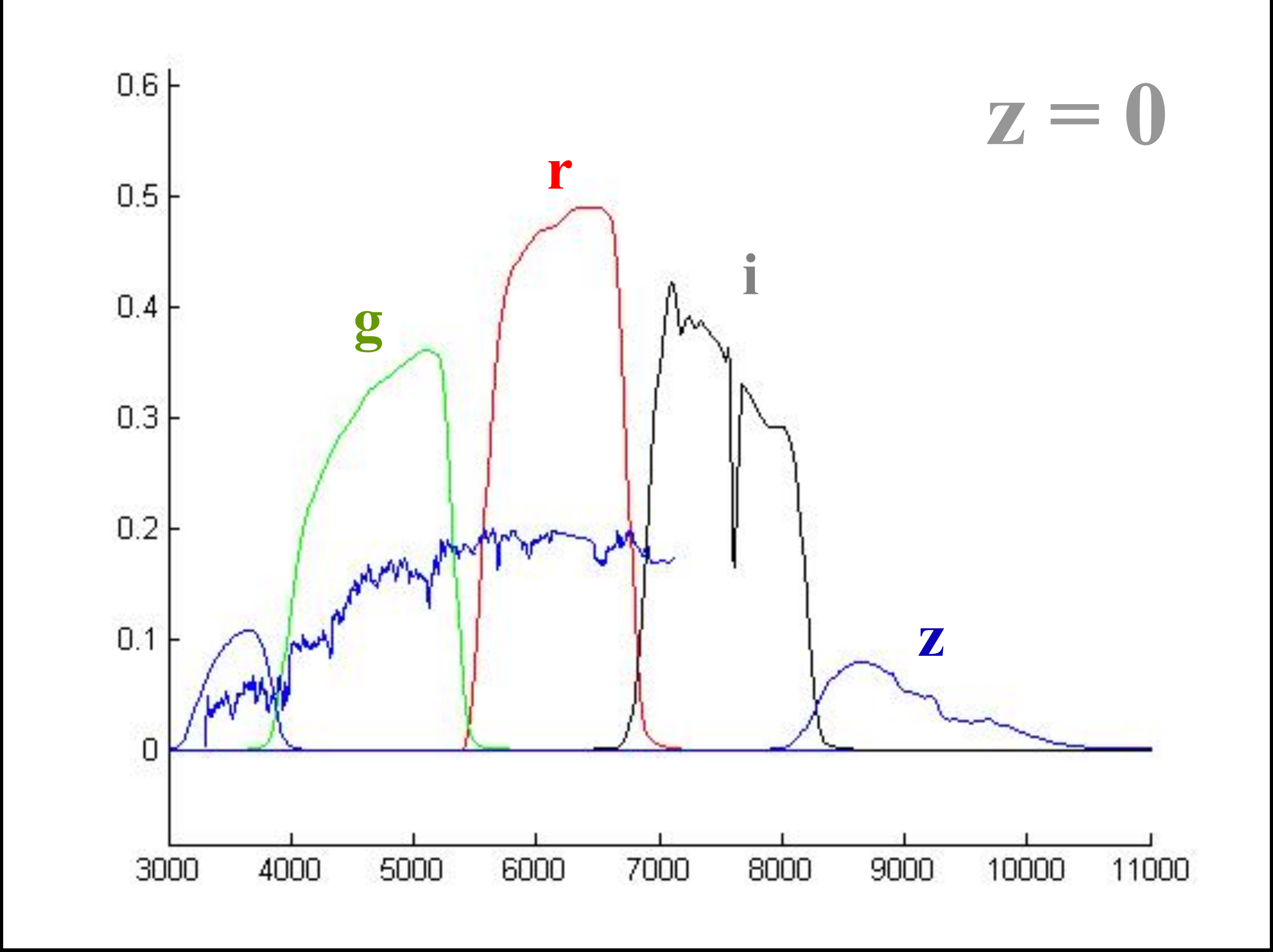
Photometric surveys

- Do we have to take spectra? This is slow and expensive…
- If we don't need accurate redshifts we can do multi-band imaging and compute photometric redshifts instead
- This works by learning how the colours depend on redshift (as emission/absorption features move through the filters)



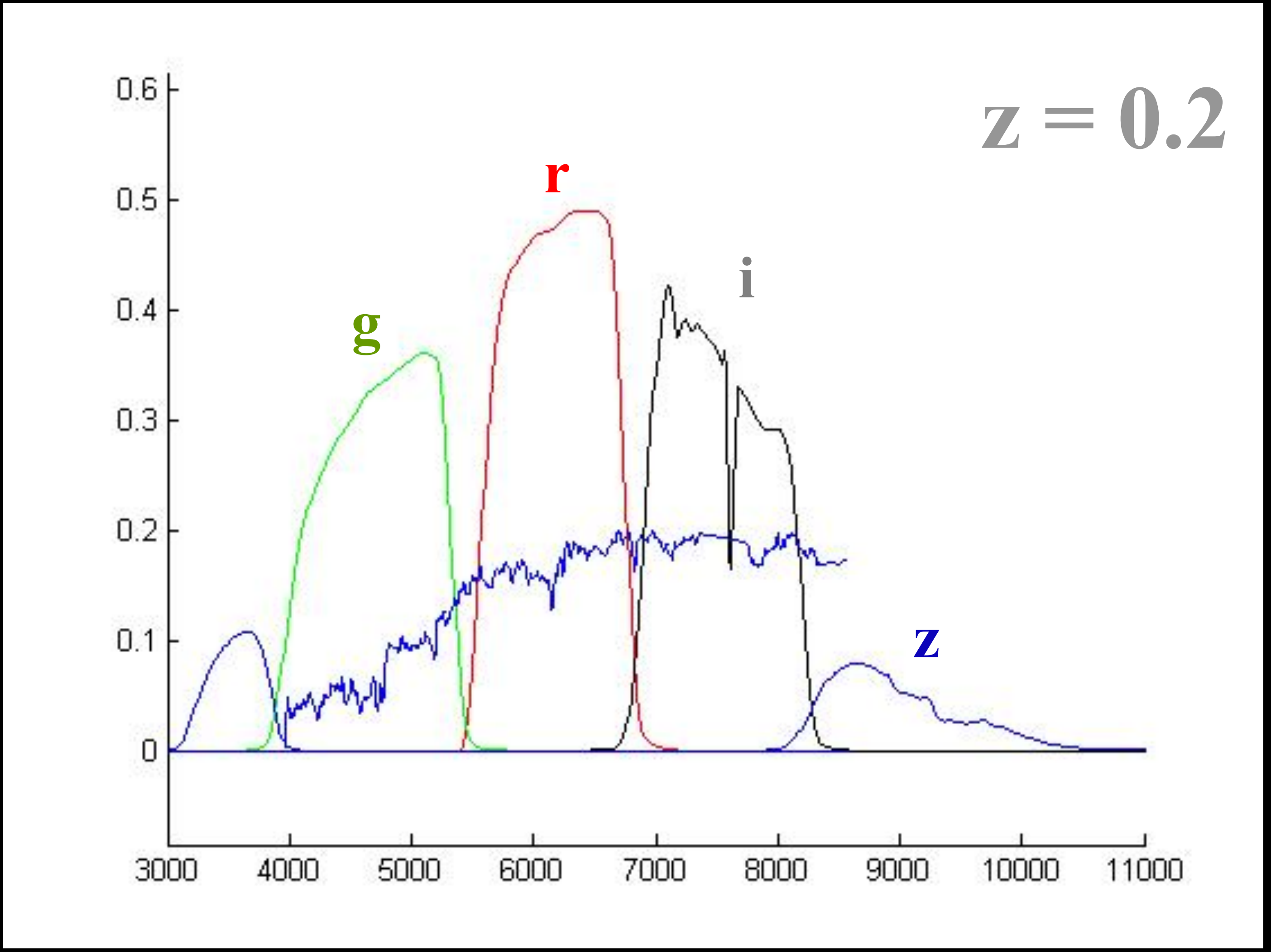
Visualising the underlying physics

Flux
(arbitrary units)
For an LRG
spectrum
And SDSS
Filter
Transmission
curves



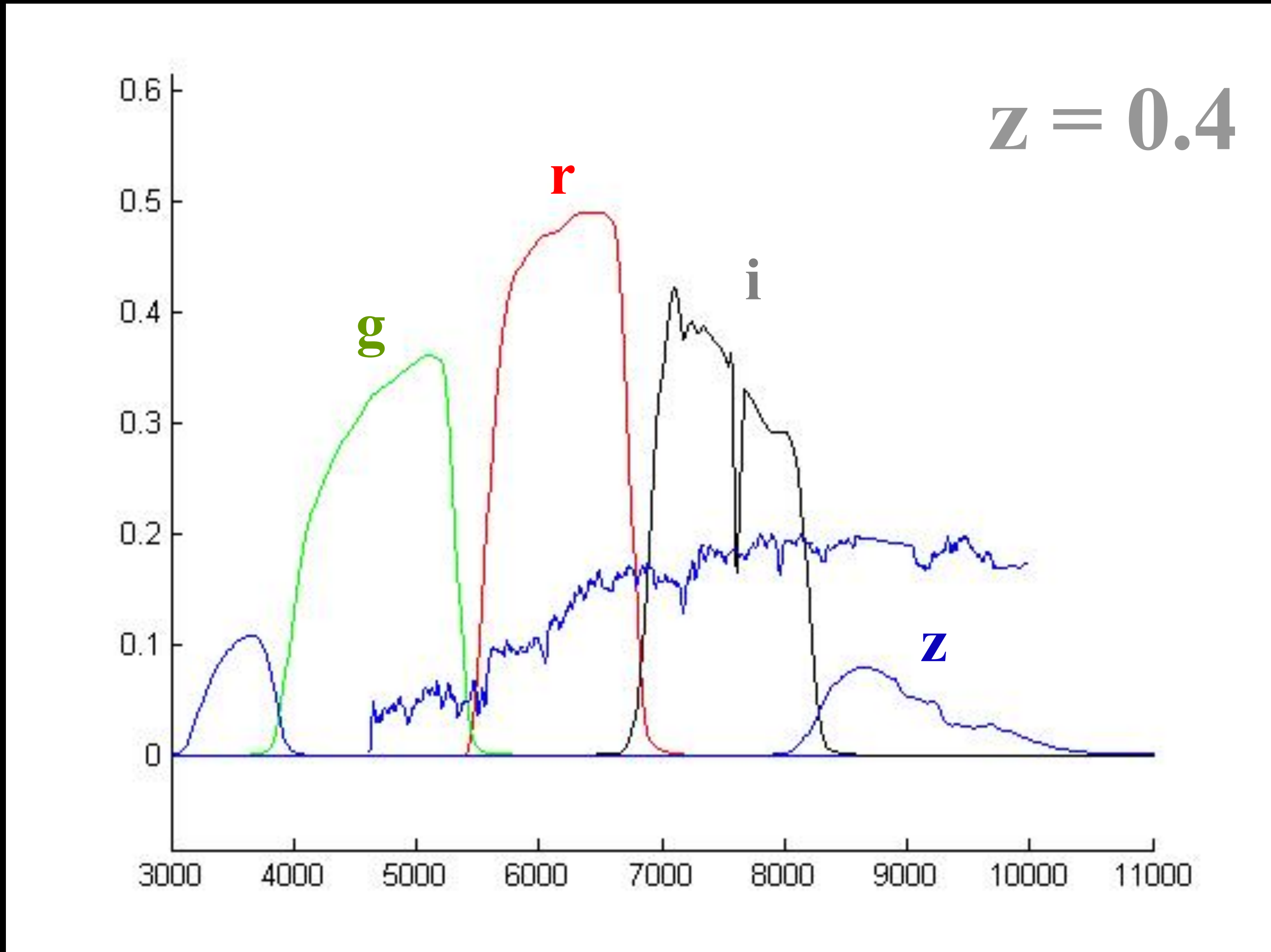
Visualising the underlying physics

For an LRG spectrum



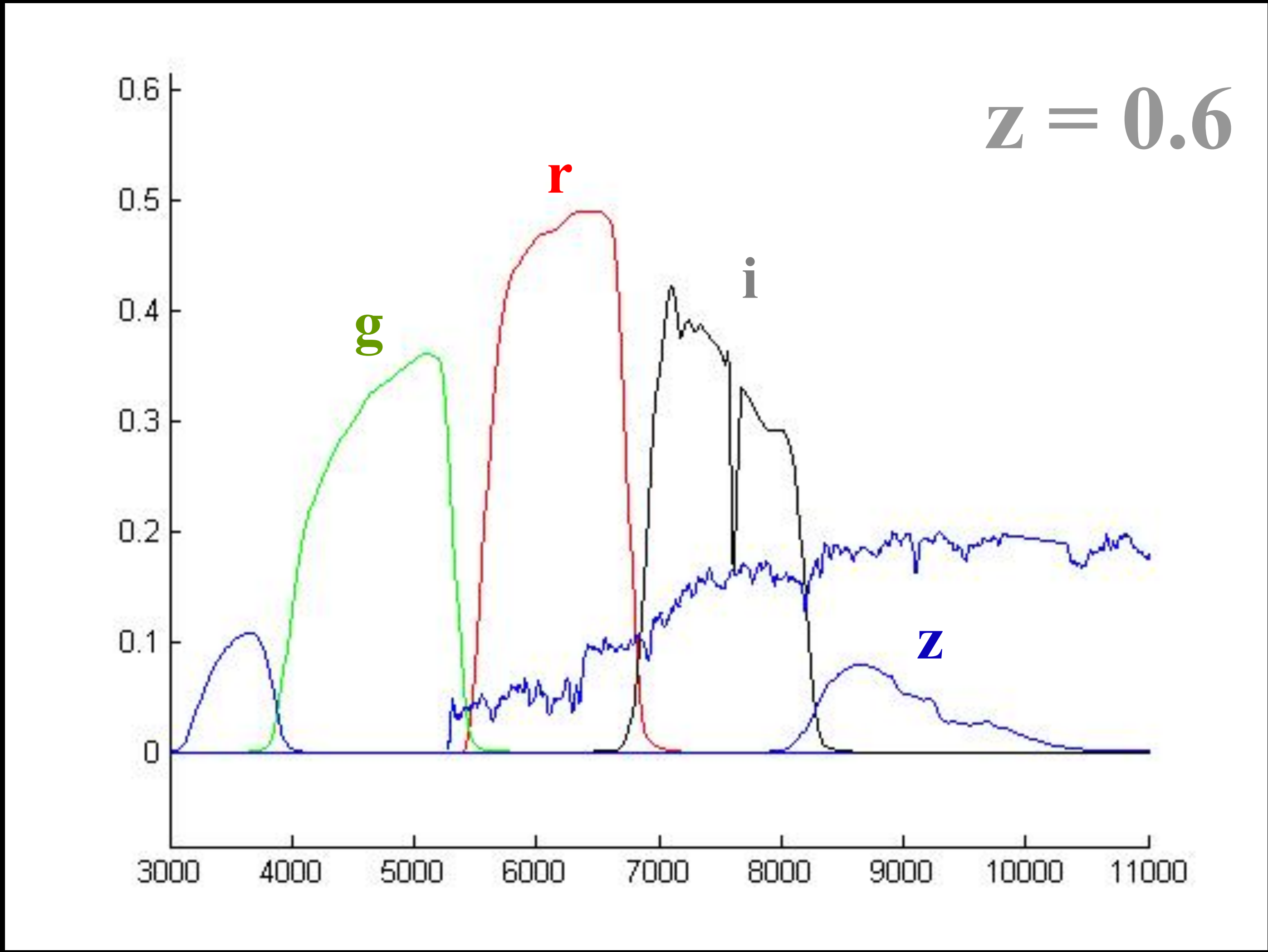
Visualising the underlying physics

For an LRG spectrum



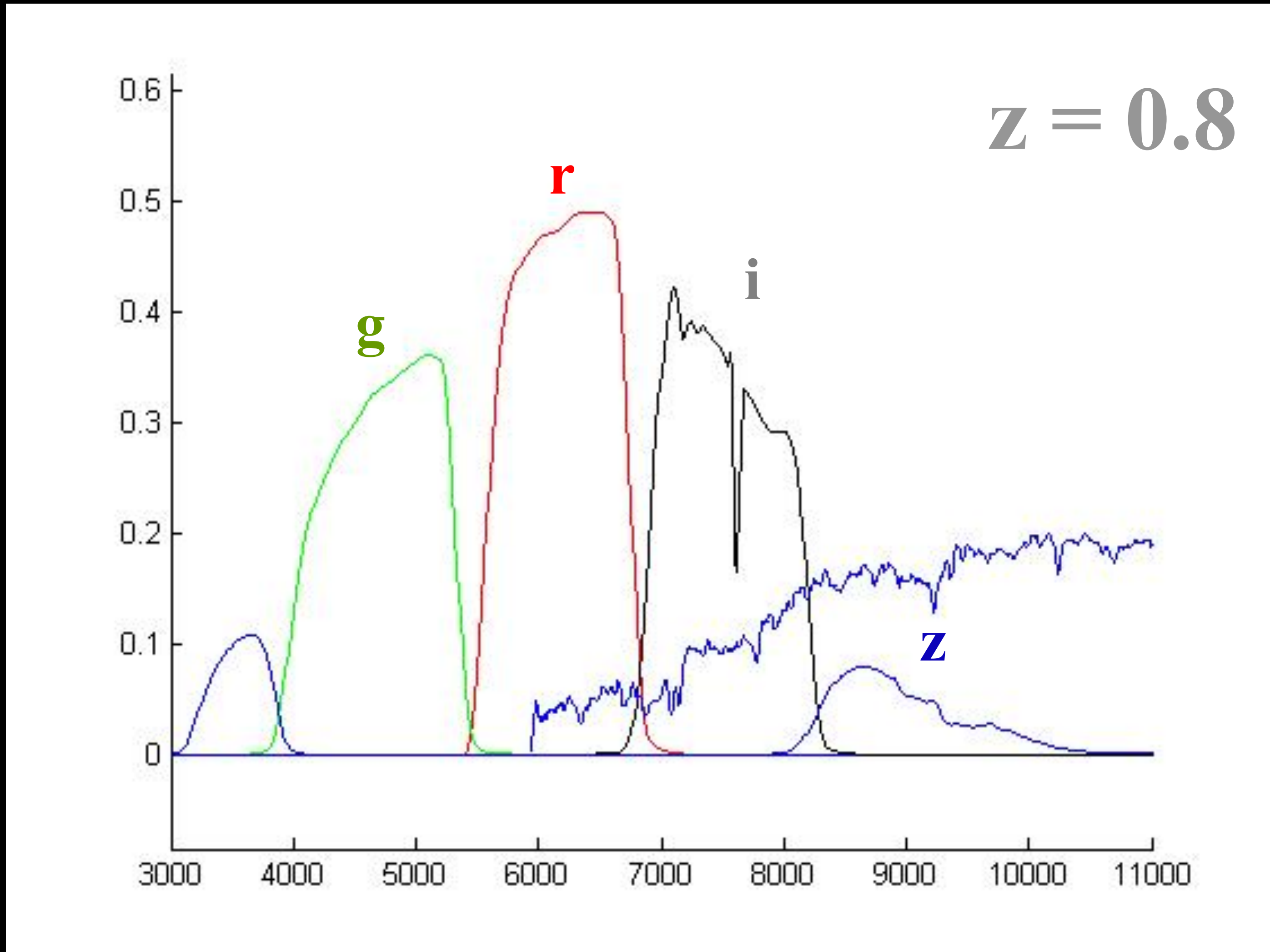
Visualising the underlying physics

For an LRG spectrum



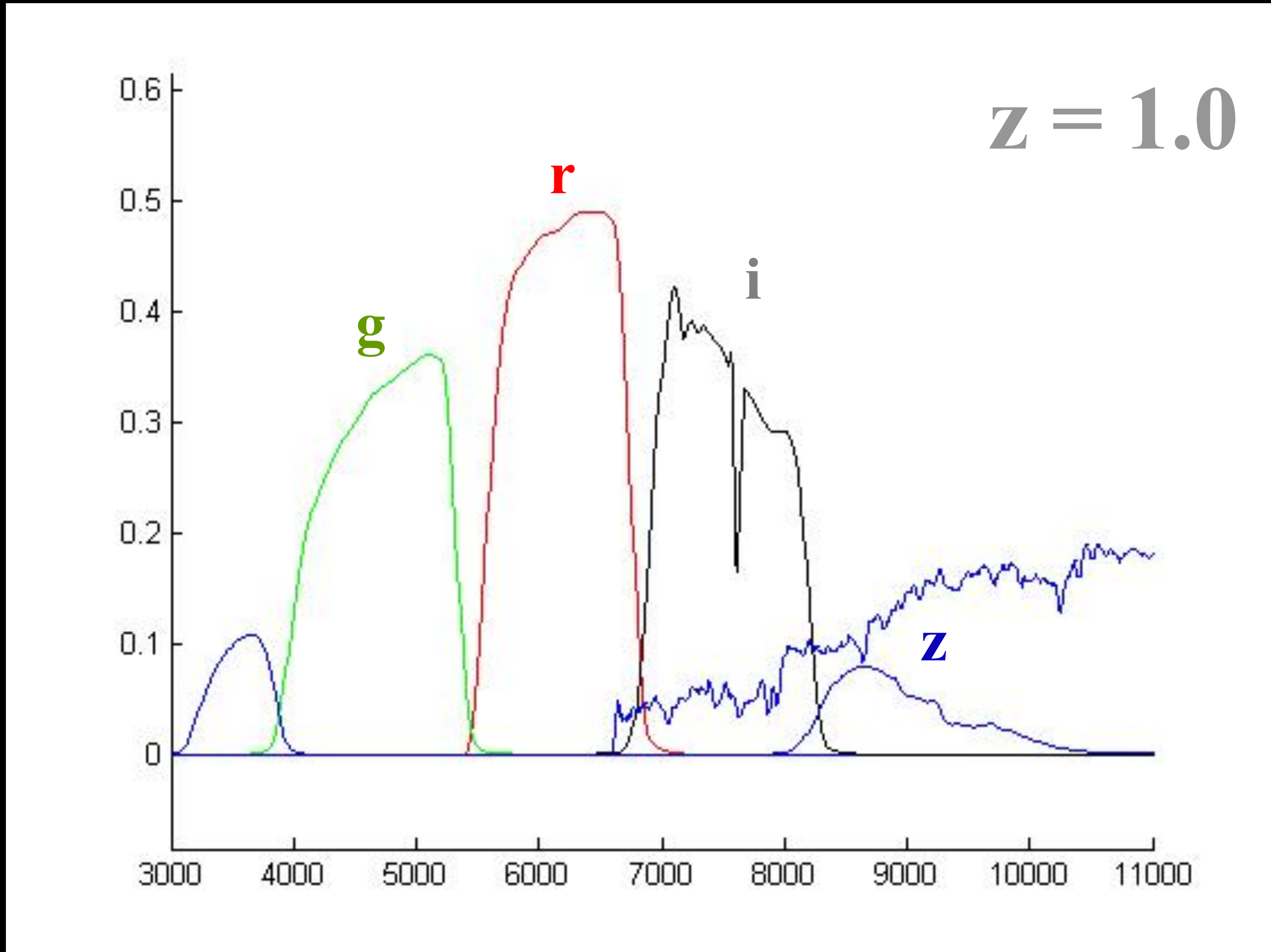
Visualising the underlying physics

For an LRG spectrum



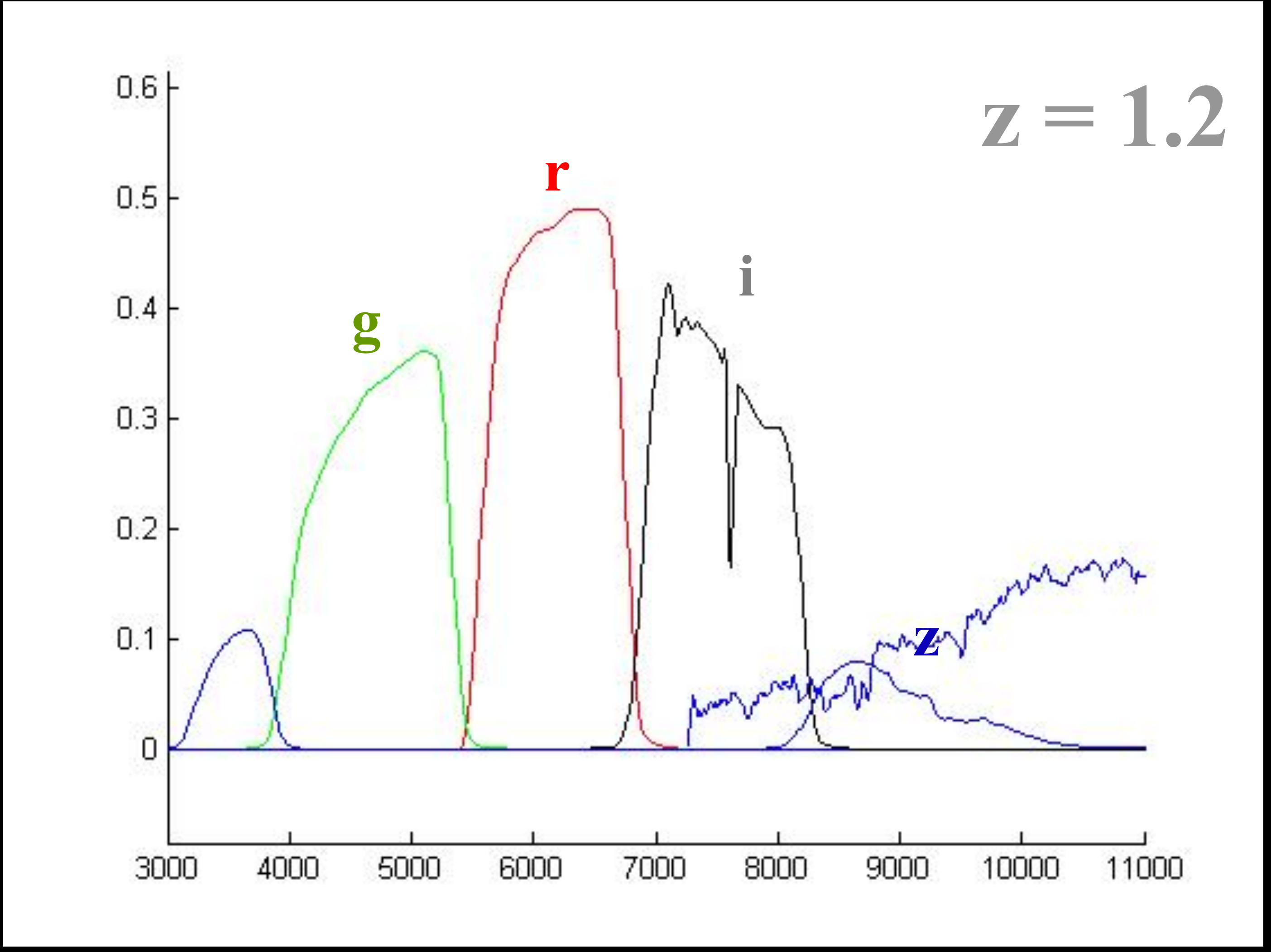
Visualising the underlying physics

For an LRG spectrum



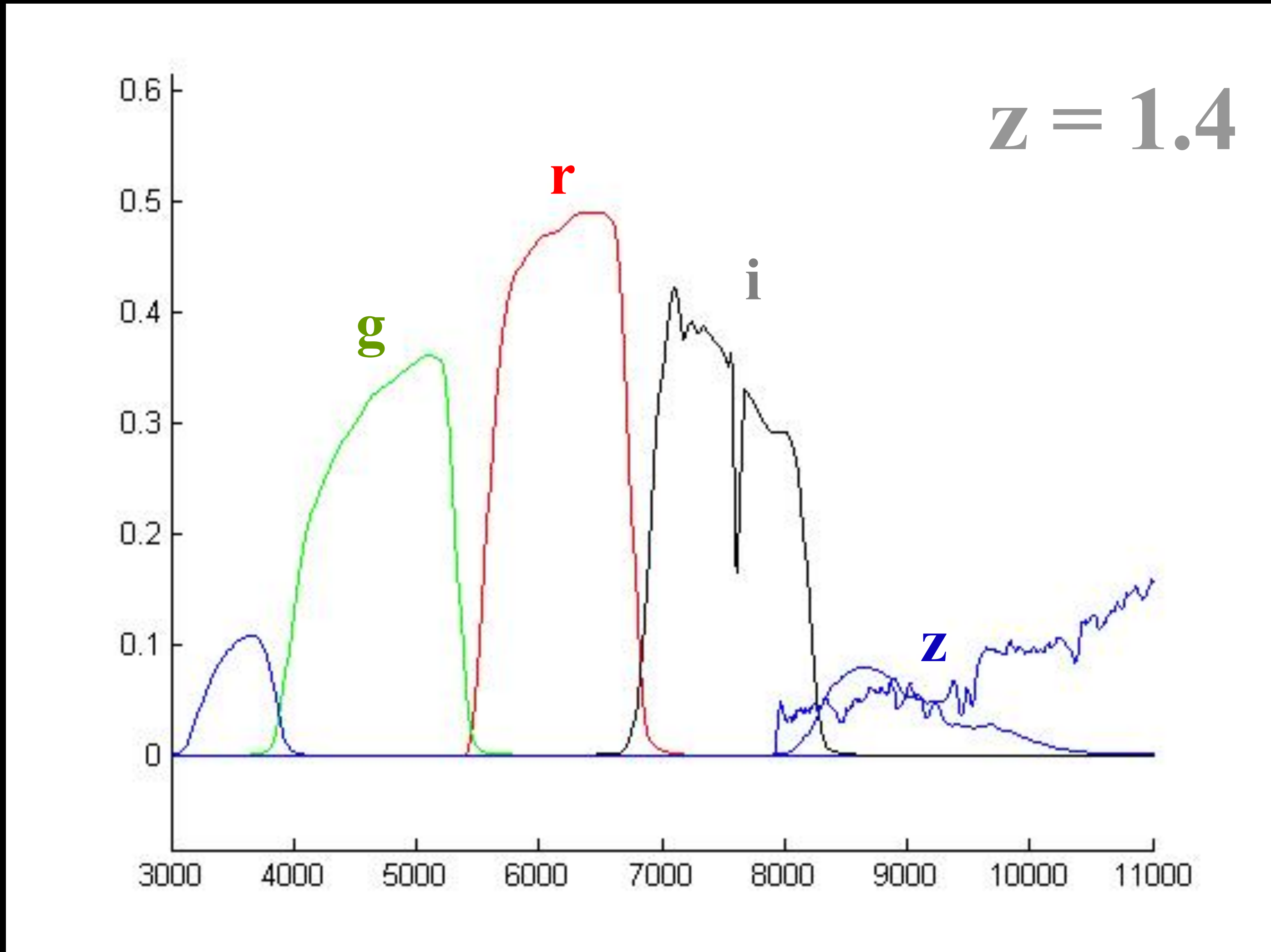
Visualising the underlying physics

For an LRG spectrum



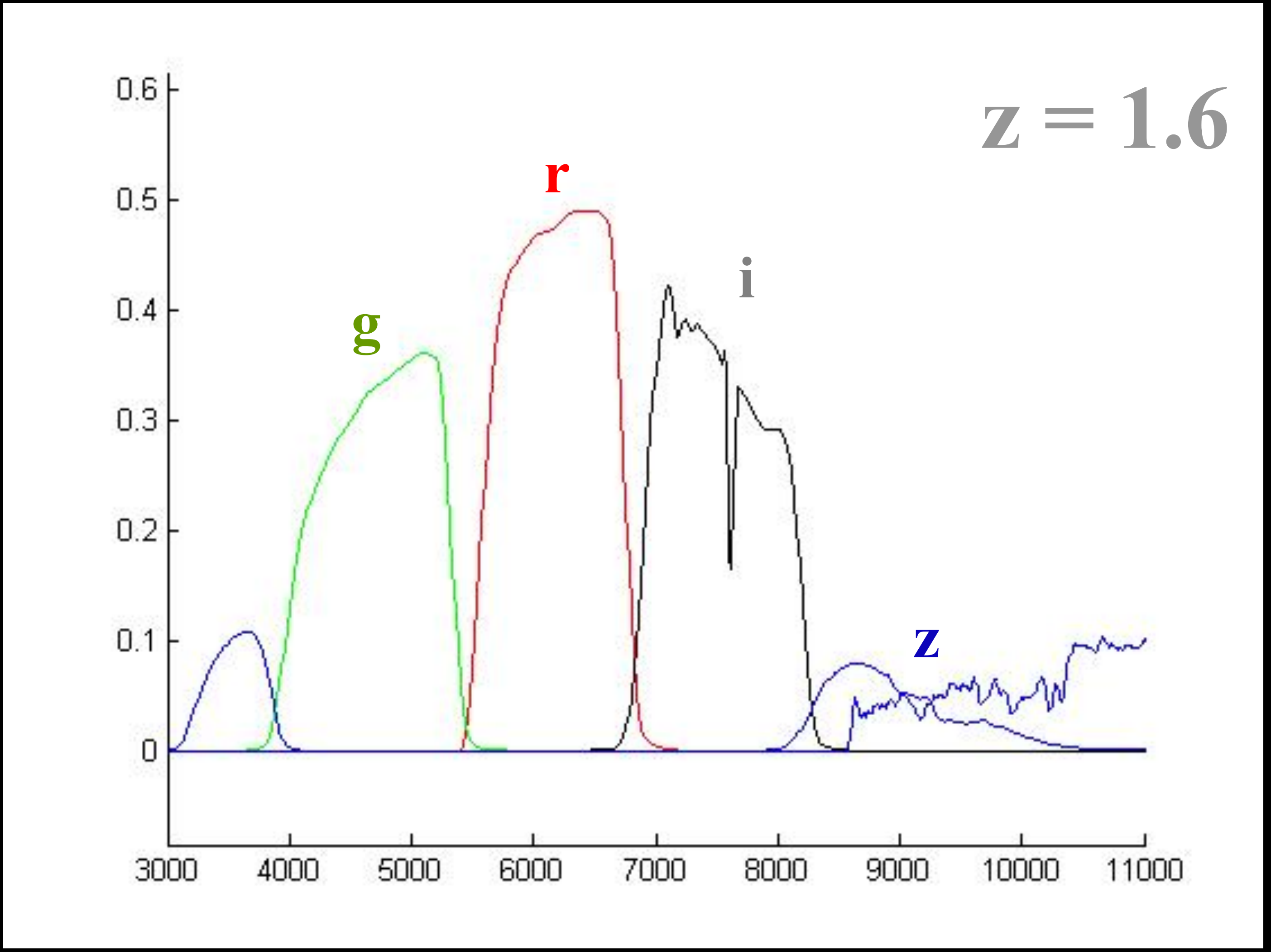
Visualising the underlying physics

For an LRG spectrum



Visualising the underlying physics

For an LRG spectrum

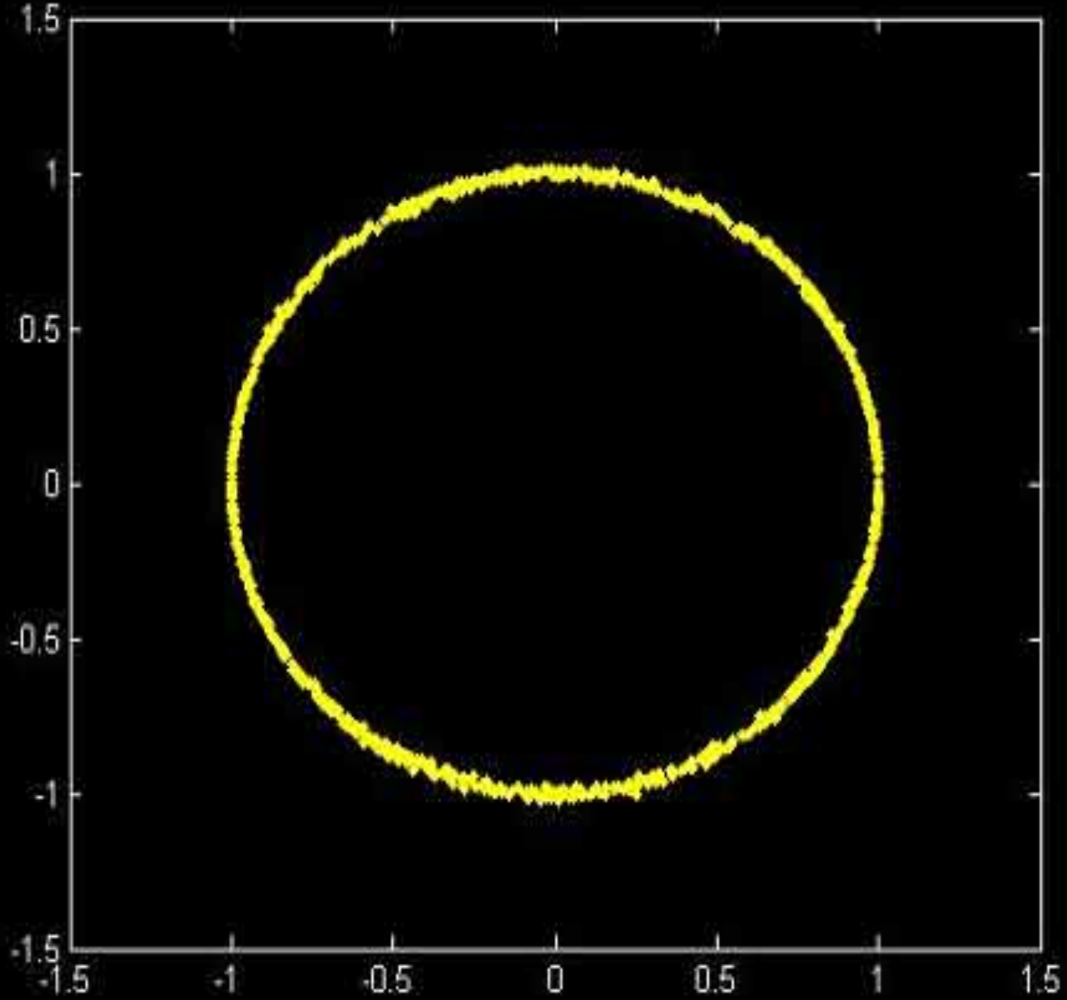


5 minute exercise: photometric redshifts

- Given two non-overlapping, but contiguous top-hat filters of width $\Delta\lambda$ and perfect transmission, covering the range 5000-9000Å, work out the ratio of fluxes in the two bands as a function of z, for a crude approximation to an LRG spectrum consisting of two flat continuum regions with flux f_1, f_2 separated by a step at 4000Å.

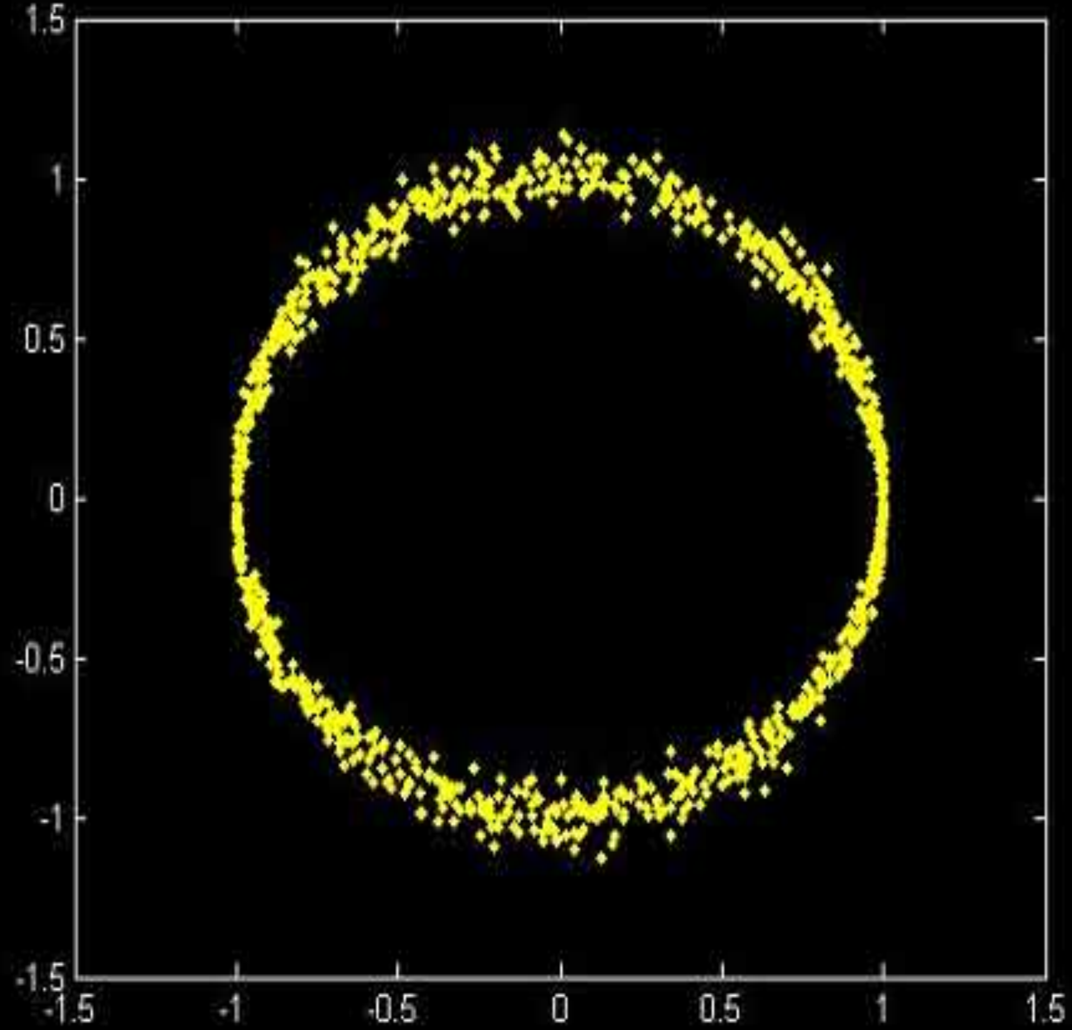
- How does the width of the filter determine the photo-z accuracy?

BAO and photo-z errors

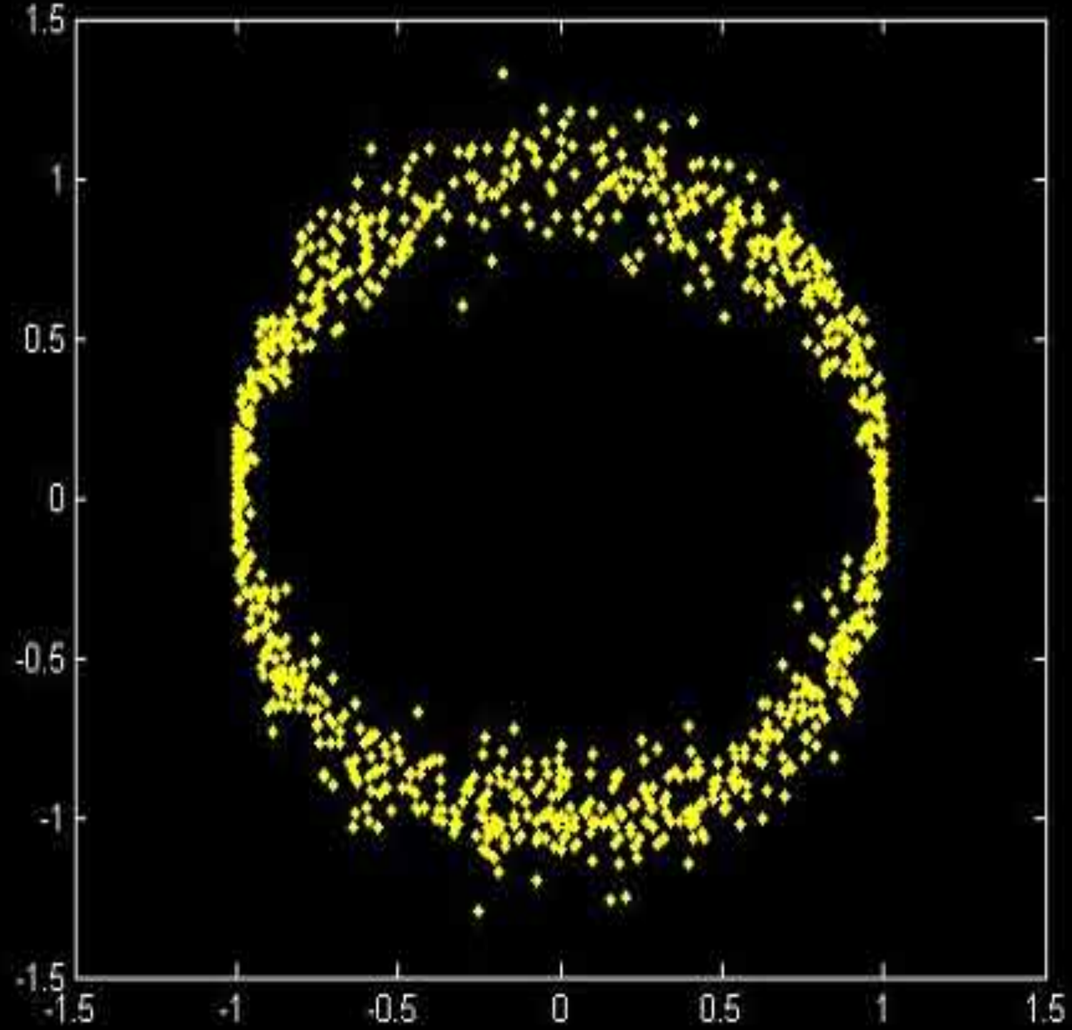


Us

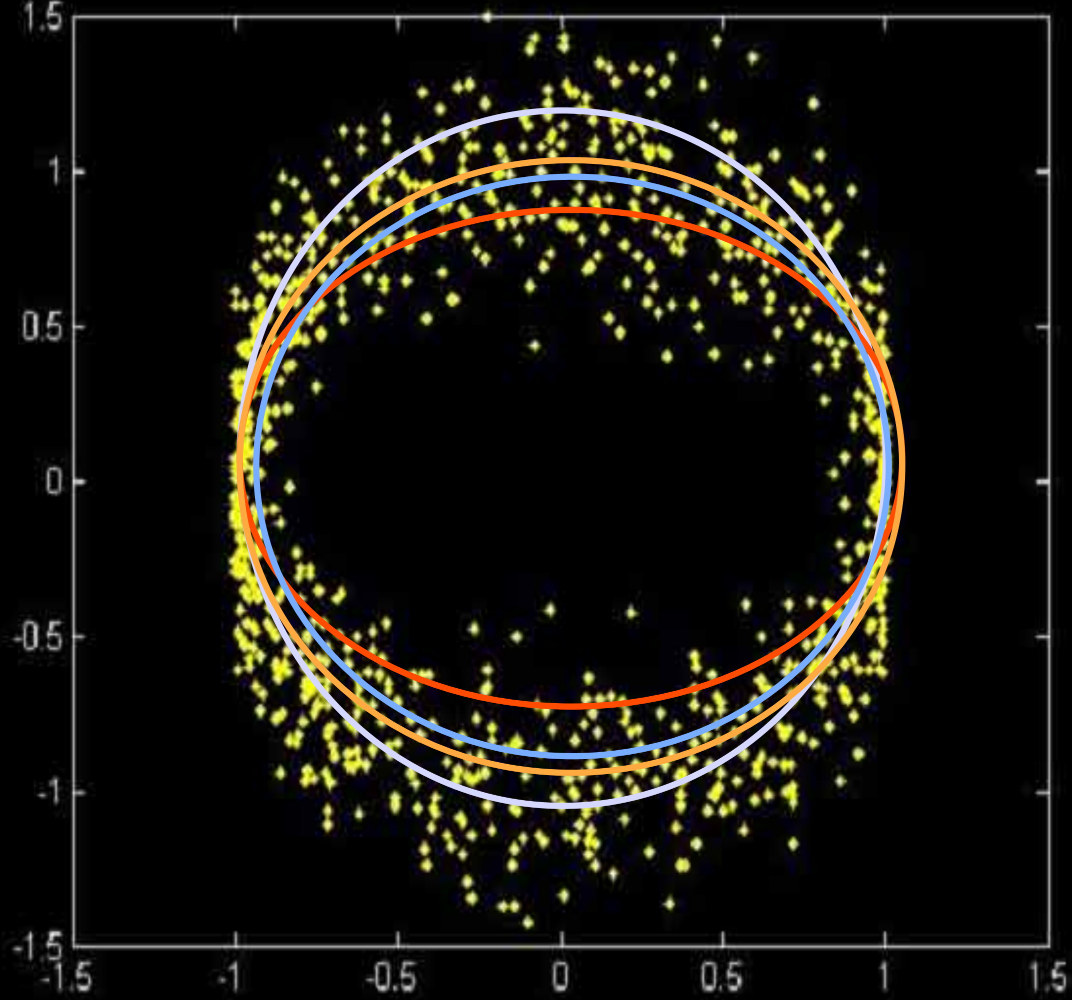
Increasing Photo-z Error

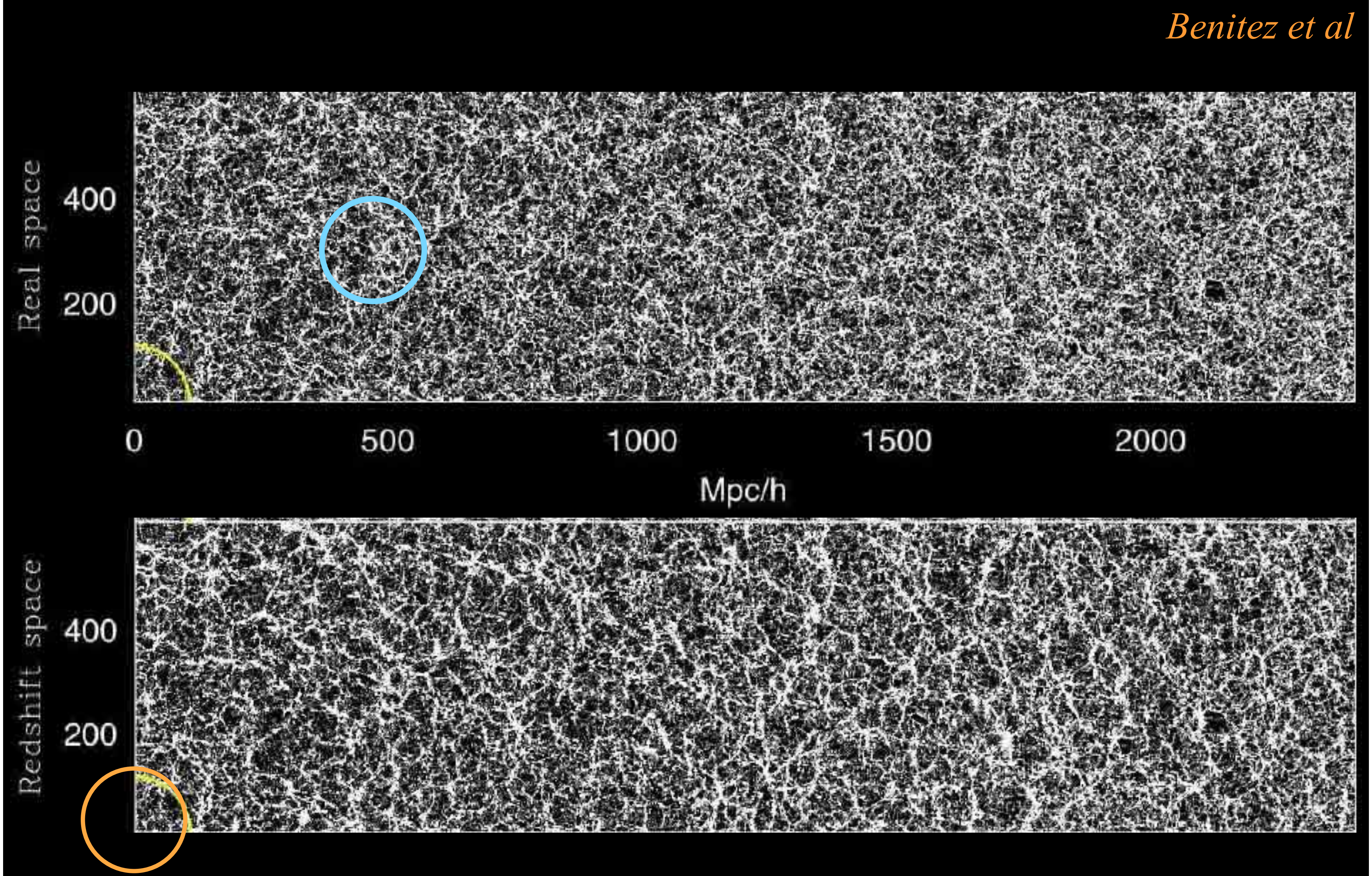


Increasing Photo-z Error

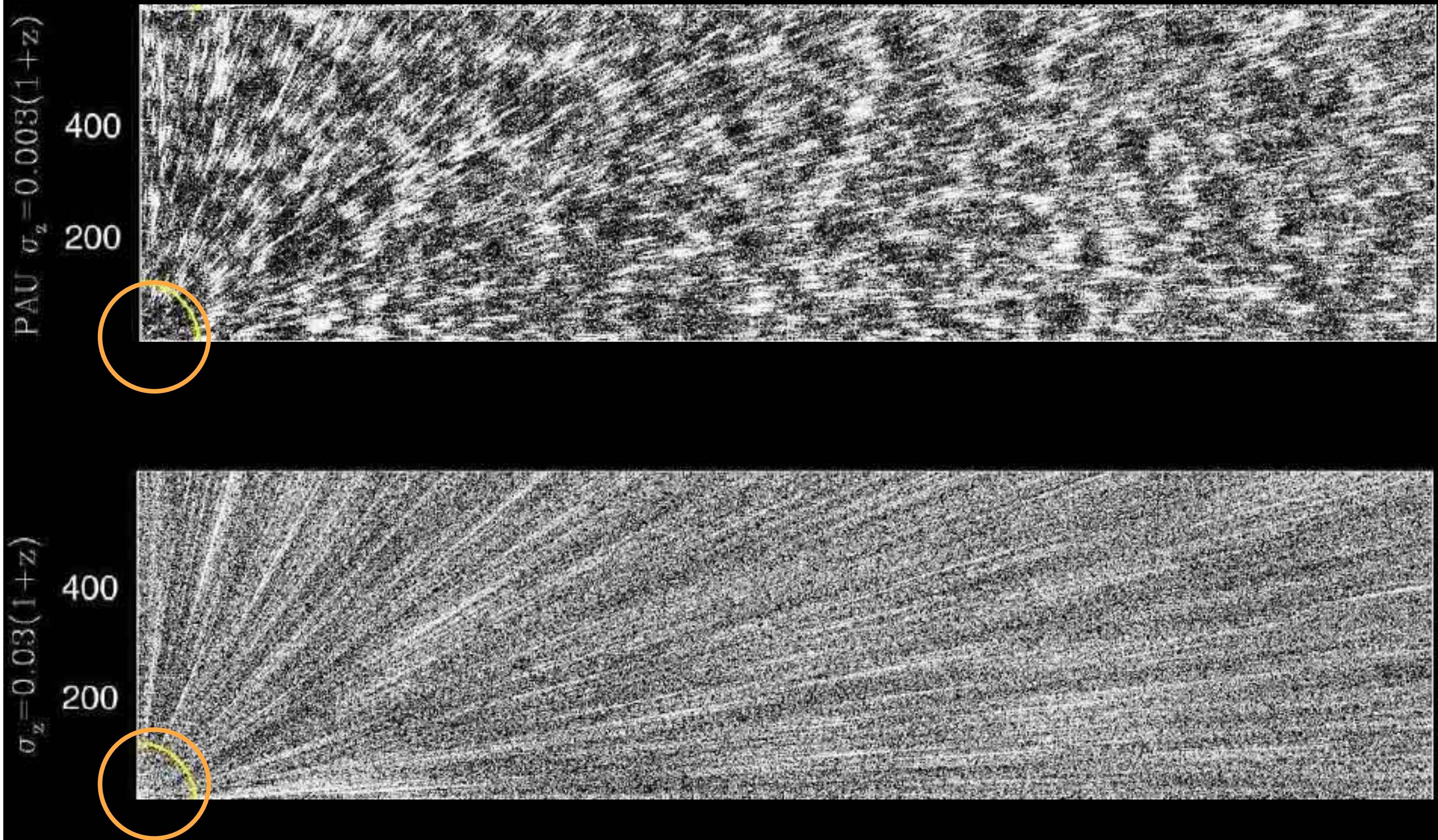


Increasing Photo-z Error




Benitez et al
Real space
400
200
0
500
1000
1500
2000
Mpc/h
Redshift space
400
200

Benitez et al



The Future for BAO

- DES
- BOSS
- BigBOSS
- LSST
- EUCLID
- WFIRST
- SKA and other 21cm

Conclusions

- BAO/BAP measurements are arguably the cleanest probe of cosmic expansion we have
- They can provide both distance, $d_A(z)$ and expansion rate, $H(z)$
- There is a systematic floor beyond which nonlinearities, nonlinear bias, redshift distortions etc… must be carefully included but these also provide exciting opportunities if we can understand them fully…