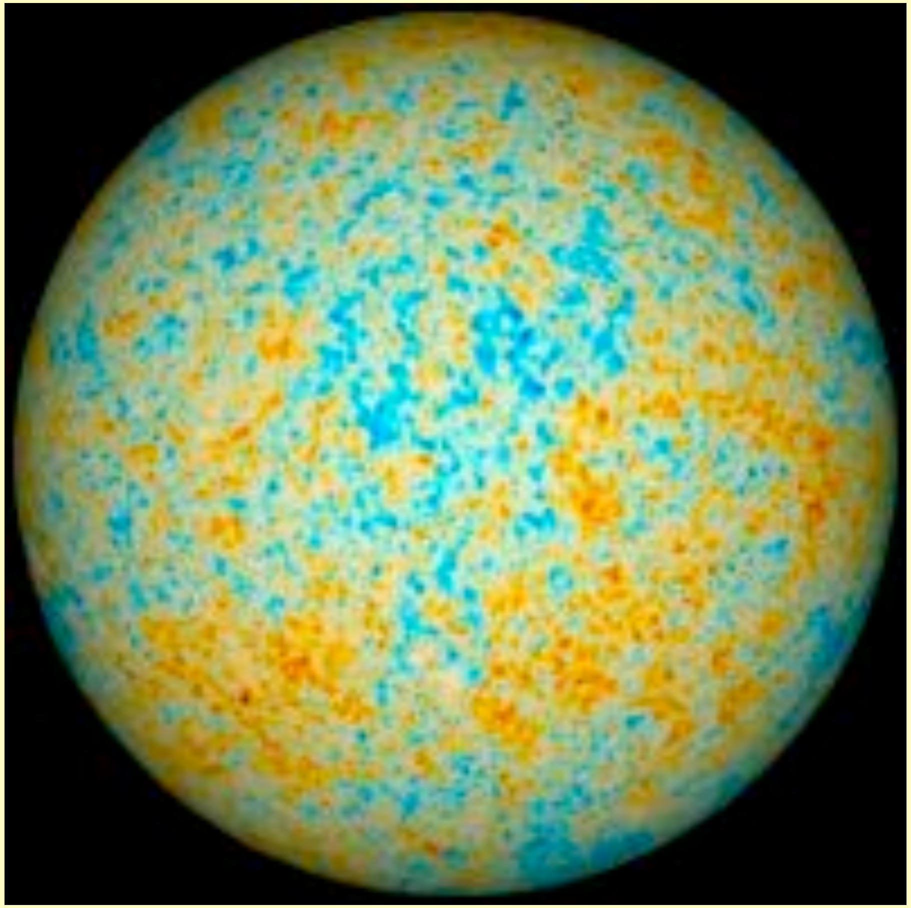
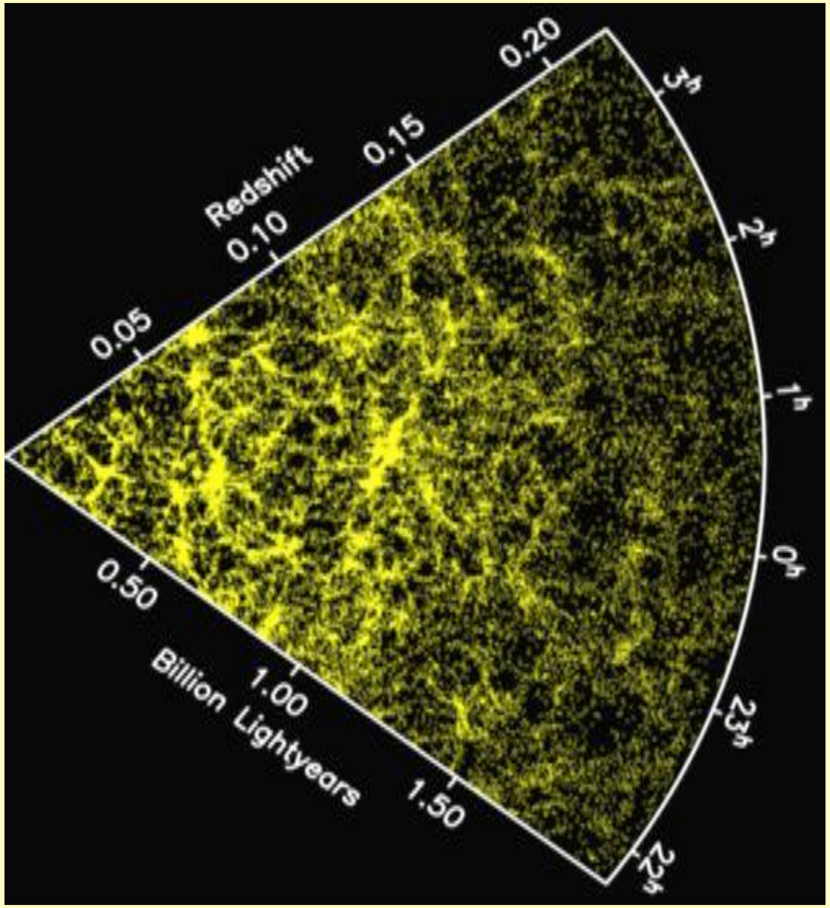
Radio galaxies and the large-scale statistical universe

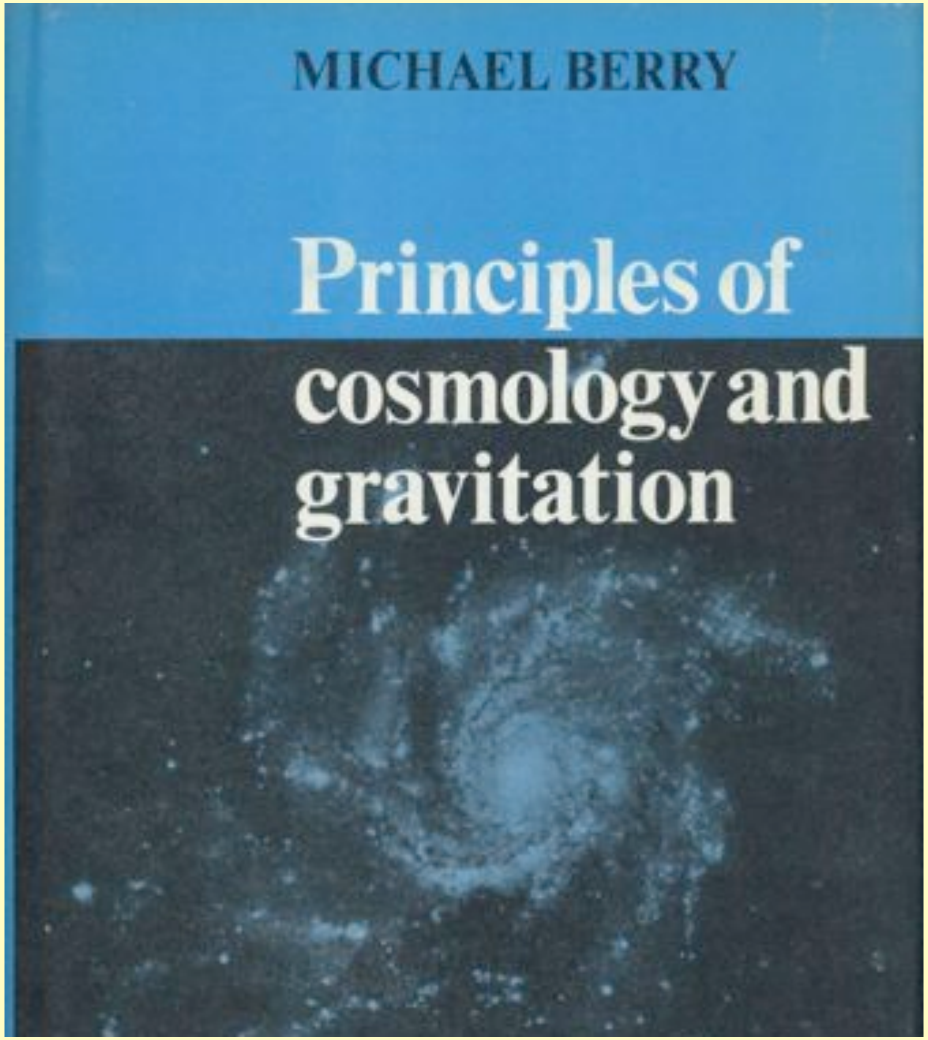


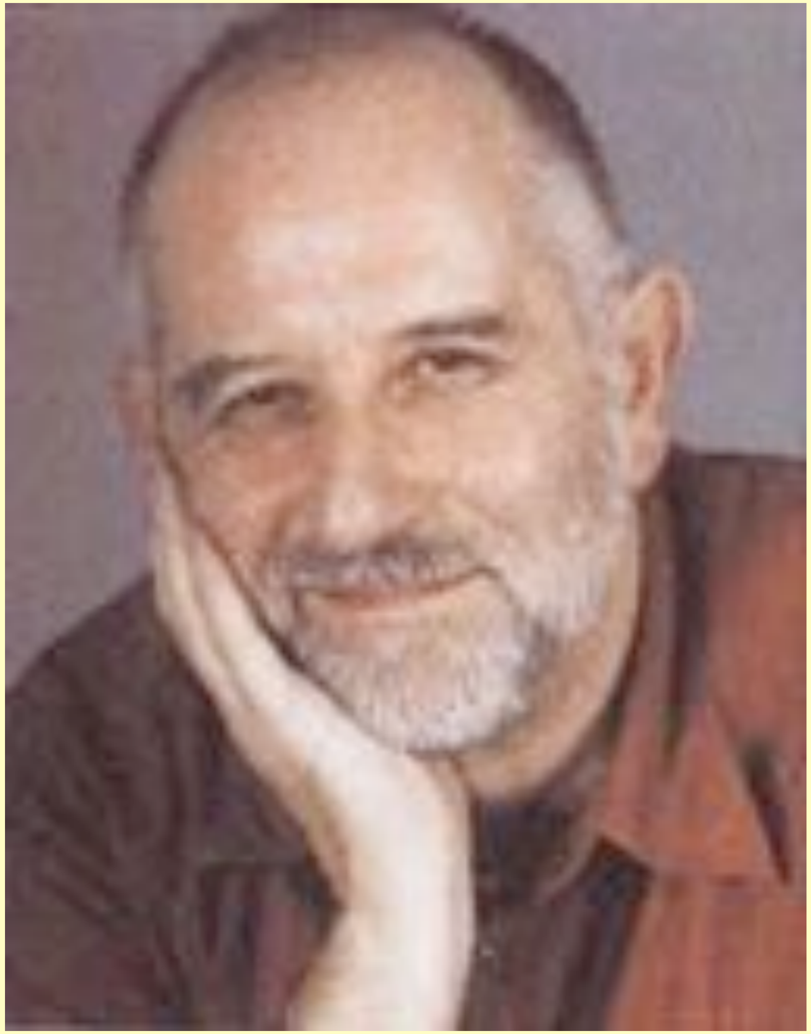


John Peacock JasFest 5 December 2018

…or Jas's influence on my path through cosmology

…or Jas's influence on my path through cosmology





1977-ish

Two formative lessons from Jasper in 1977-78

- The most perfect number in the universe is 4π

- Careful statistical treatment is a necessary first step before attempting physical explanation

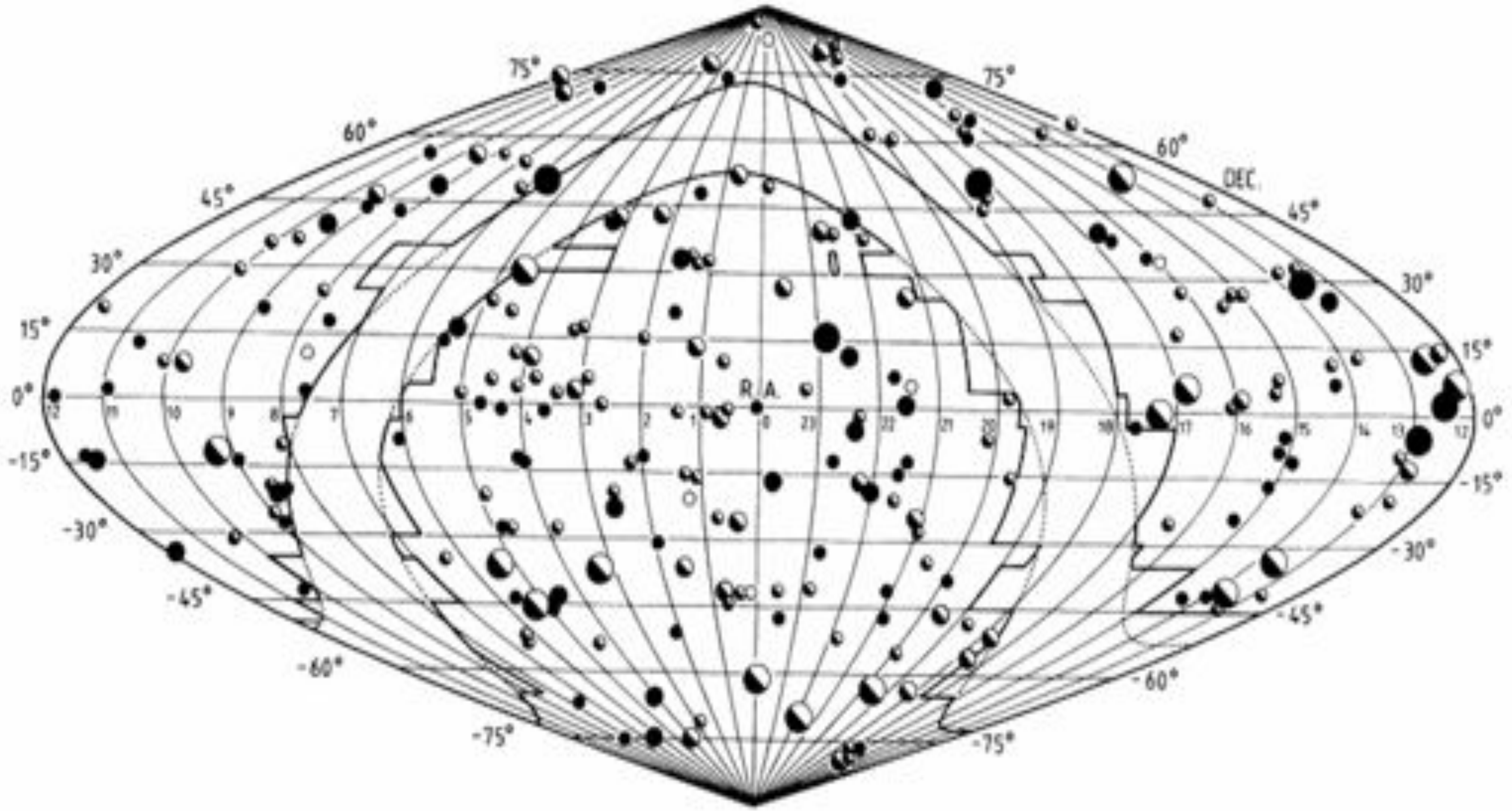
PRACTICAL STATISTICS FOR ASTRONOMERS

J.V. Wall

(based on a lecture to the new MRAO Research Students, 2 December 1977)

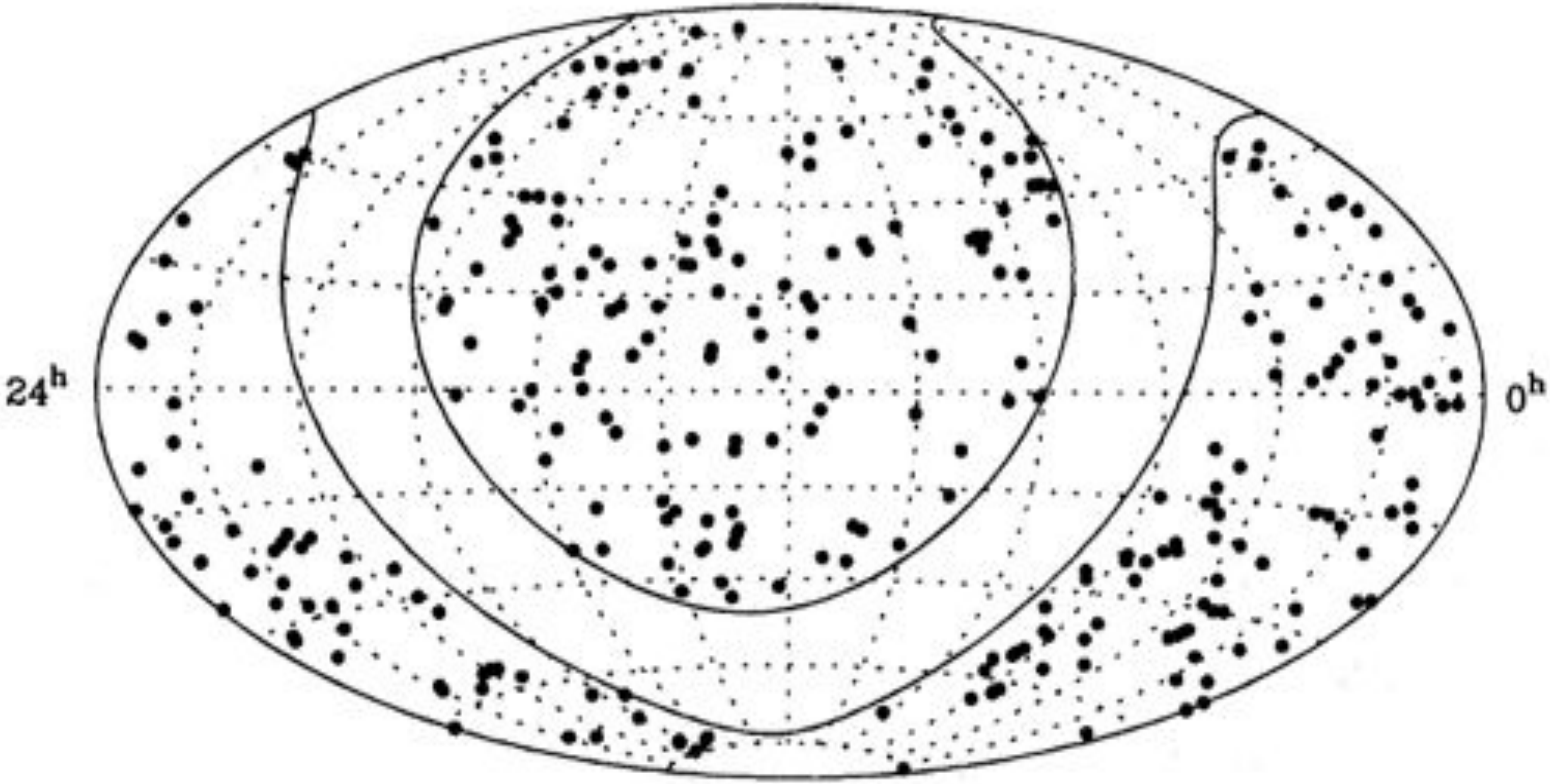
Astronomers cannot avoid statistics, and there are several reasons for this unfortunate situation. The most obvious is that every observational science is one of probabilities - none more so than astronomy, in which optical observers count individual photons from faint objects until they have collected 'enough', while their radio colleagues persist with receivers generating noise signals of amplitudes hundreds of times larger than those expected from faint sources. We have all been taught by our Masters that no quantity determined observationally is of the slightest use unless it has the proper error associated with it; this implies that we know and understand both our gear and some basic statistics. It also implies that other astronomers are going to quote results in statistical terms - e.g. standard errors, confidence limits - so that in self-defence, the implications of these statistics must be familiar to us. Now consider samples, rather than individual observations; we are frequently faced with making general statements about various constituents of the Universe on the basis of samples which are invariably small, and which are not easily augmented. How can we convince ourselves/colleagues that an effect in our sample indicates a Universal Truth? How likely is it that the effect is only due to chance, to good/bad luck, to the first Law of Experimentation?* We are not always aware that an appropriate test exists. It is possible, for example, to test whether the 'degree of woofliness' (arbitrarily defined scale) of a sample of 5 radio sources is correlated with, say, 3C number.

Wall & JAP (1985)



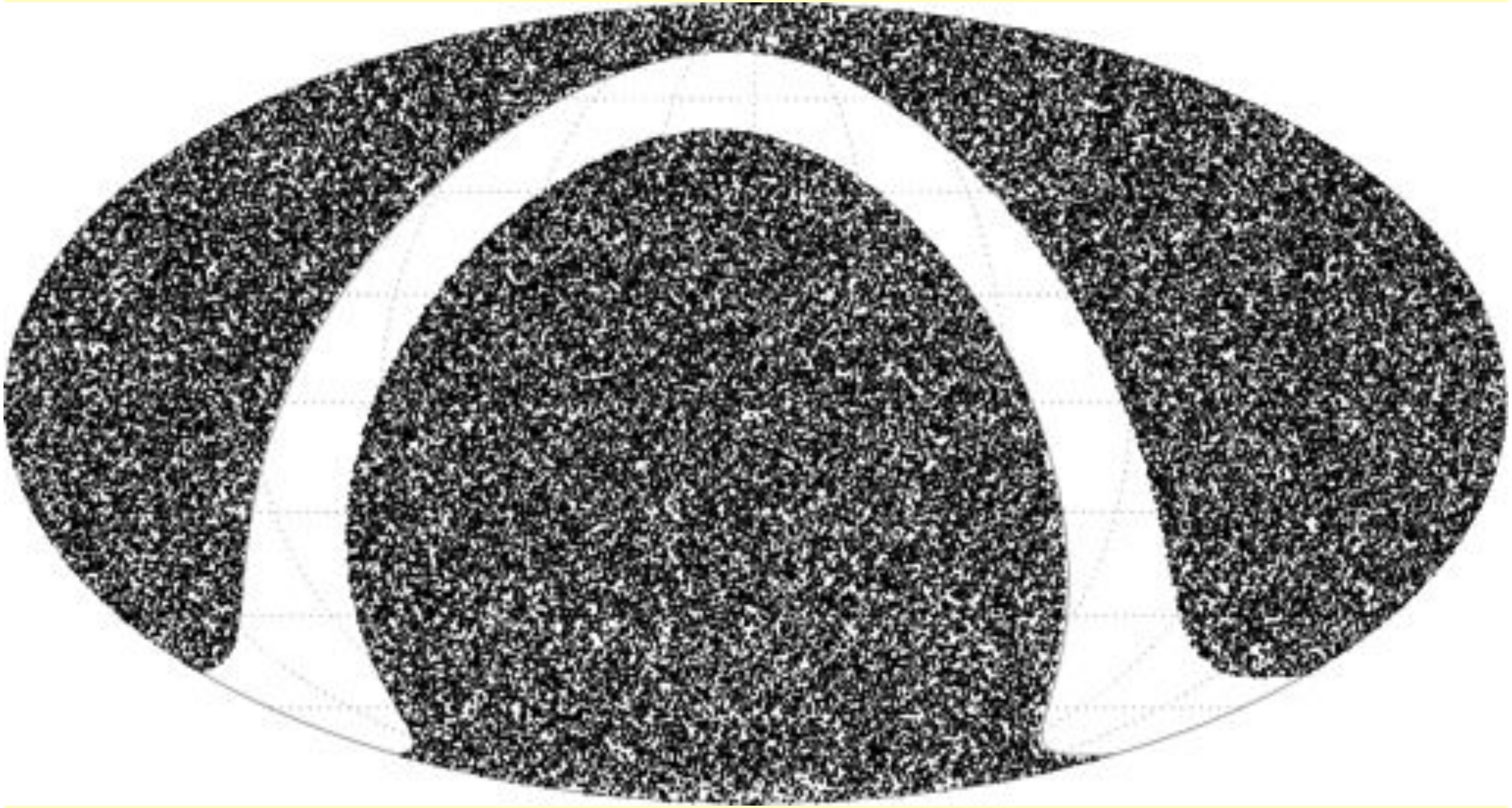
233 sources with S > 2 Jy at 2.7 GHz over 9.81 sr

JAP & Nicholson (1991)



329 sources at z < 0.1 with S > 0.5 Jy at 1.4 GHz over 9.31 sr

NVSS+SUMSS state of the art

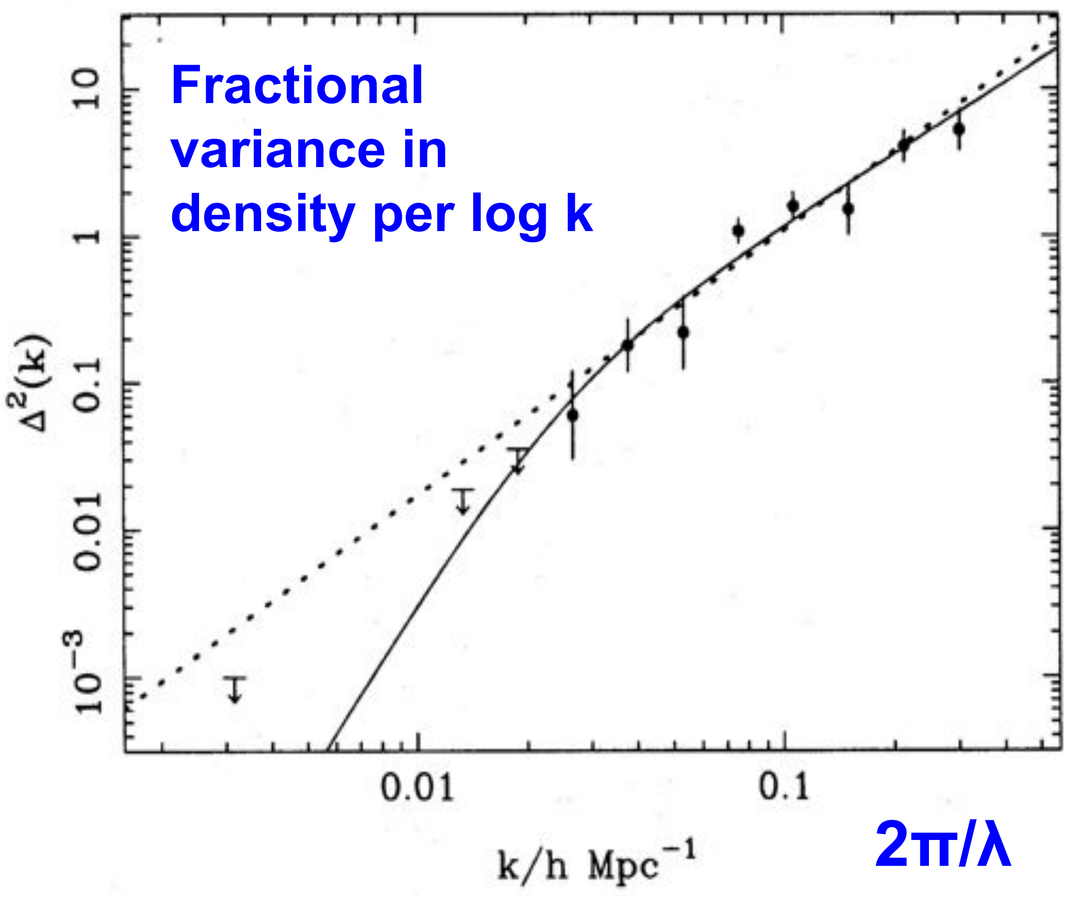


833,564 sources with S > 6 mJy at 1.4 GHz over 10.38 sr

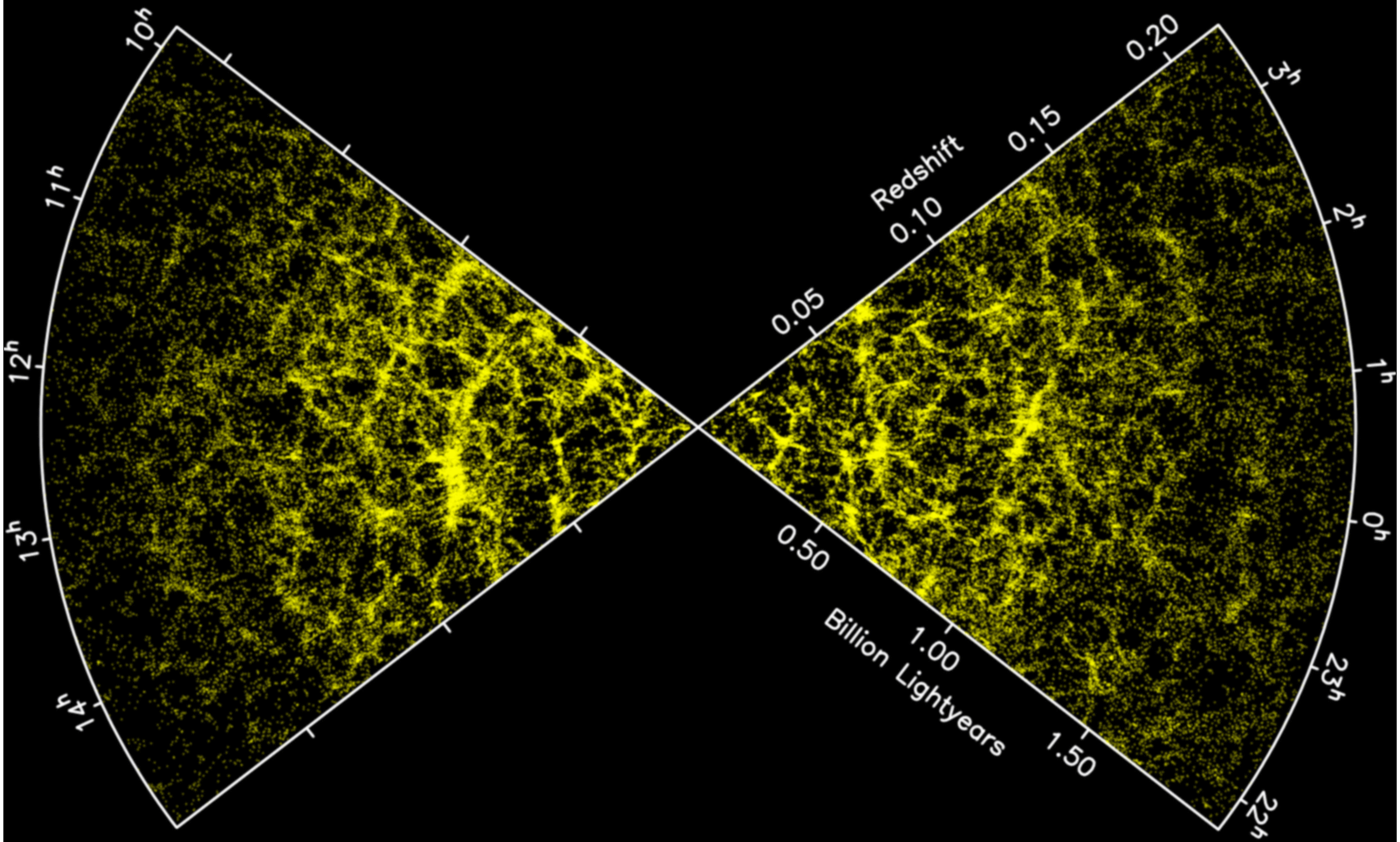
Radio galaxies and power spectra

Webster (1972): angular power spectra of radio catalogues consistent with zero => less than 3% variation in number between different 1Gpc cubes (wrongly ignored in 1990s by proponents of fractal universes)

JAP & Nicholson (1991): Measure 3D power spectrum from local sample. Large-scale break towards homogeneity − first direct 3D detection of CDM-like curvature of spectrum

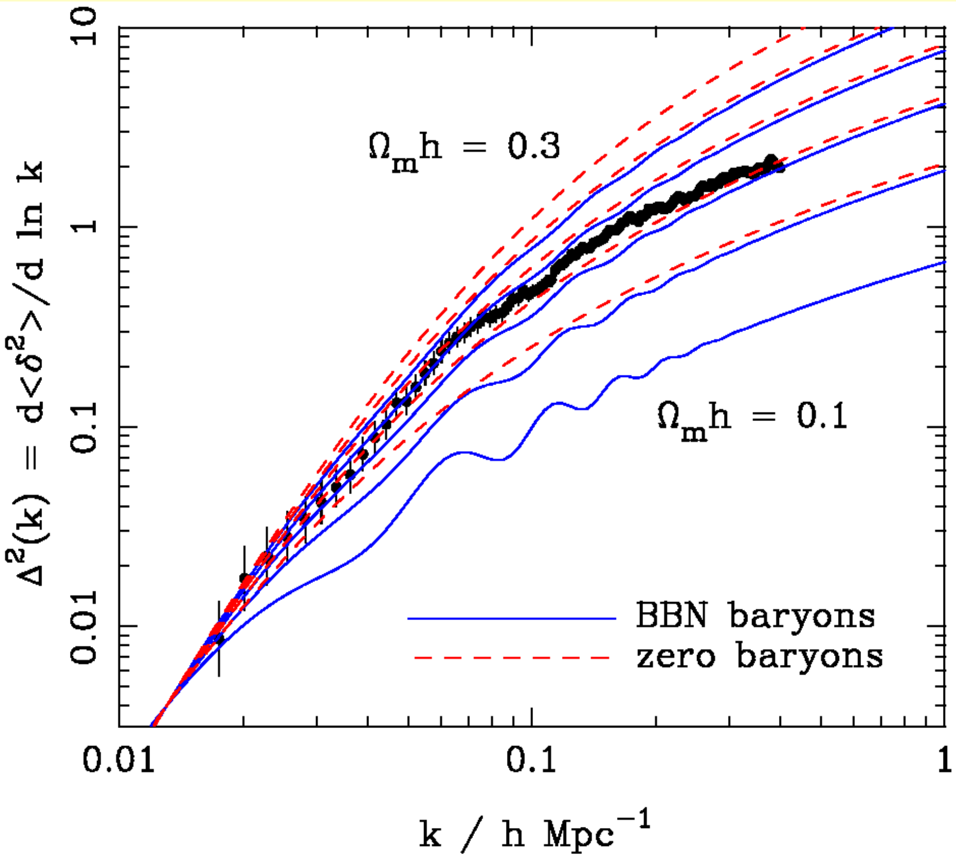


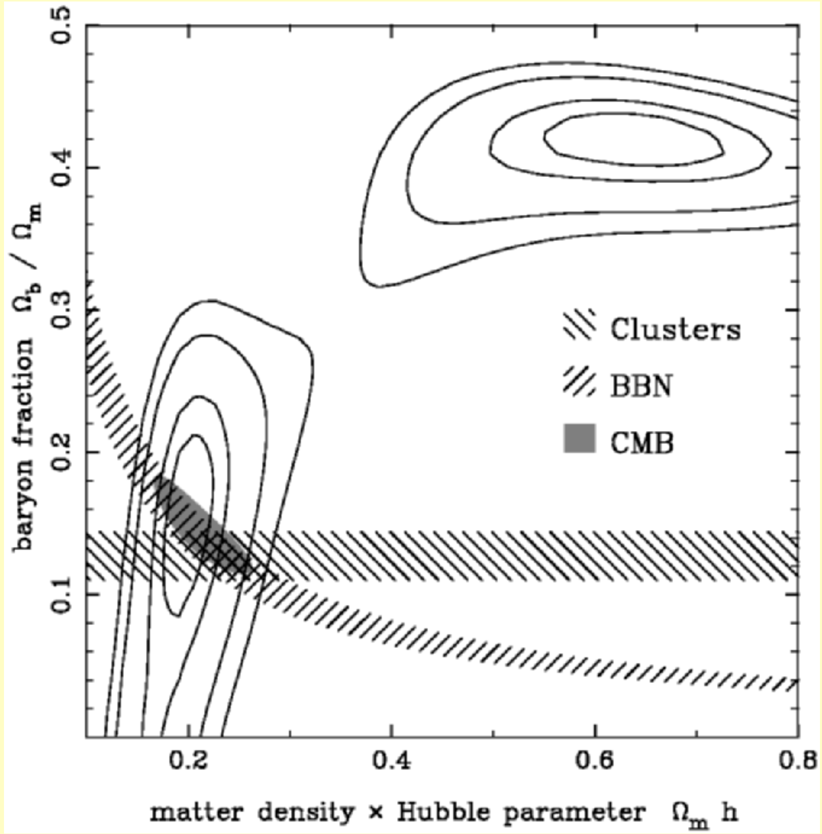
2dFGRS cone diagram: 4-degree wedge



220,000 z's with AAT 1997 - 2003

2001: 2dFGRS P(k)



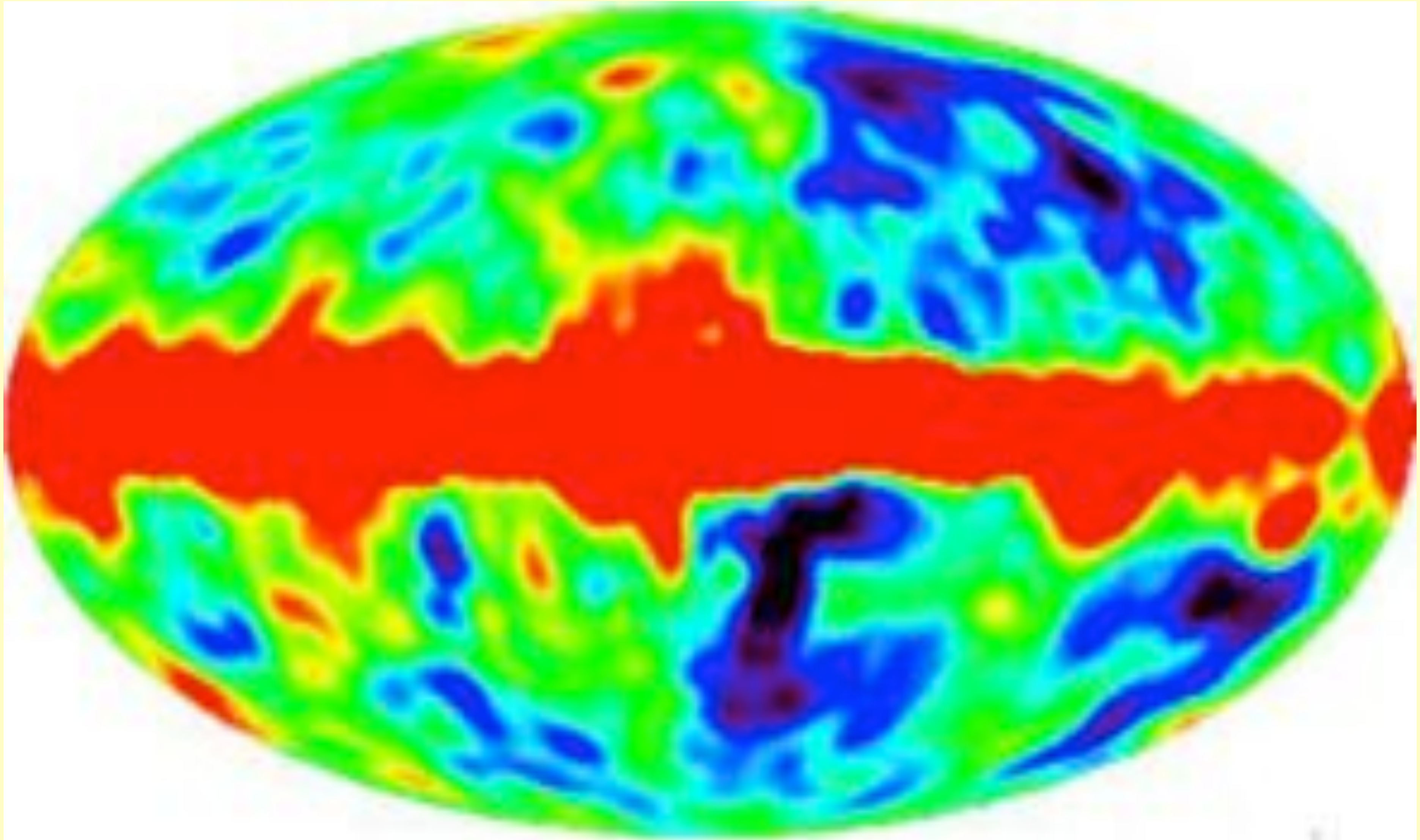


Establishment of standard model as we know it today

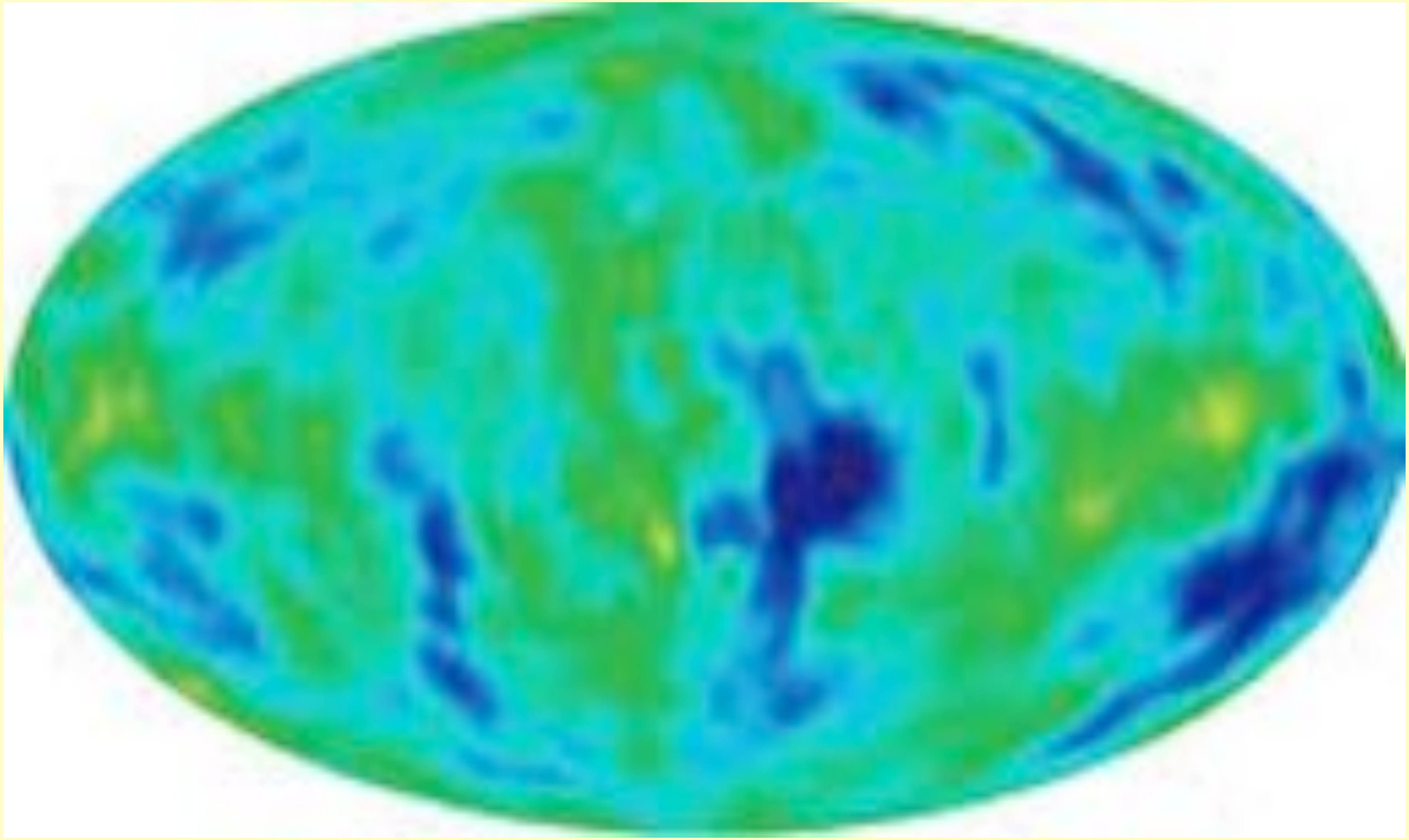
− smooth P(k) argues for collisionless DM

− only subsequent new ingredient is $n = 0.96$ tilt (WMAP 2006)

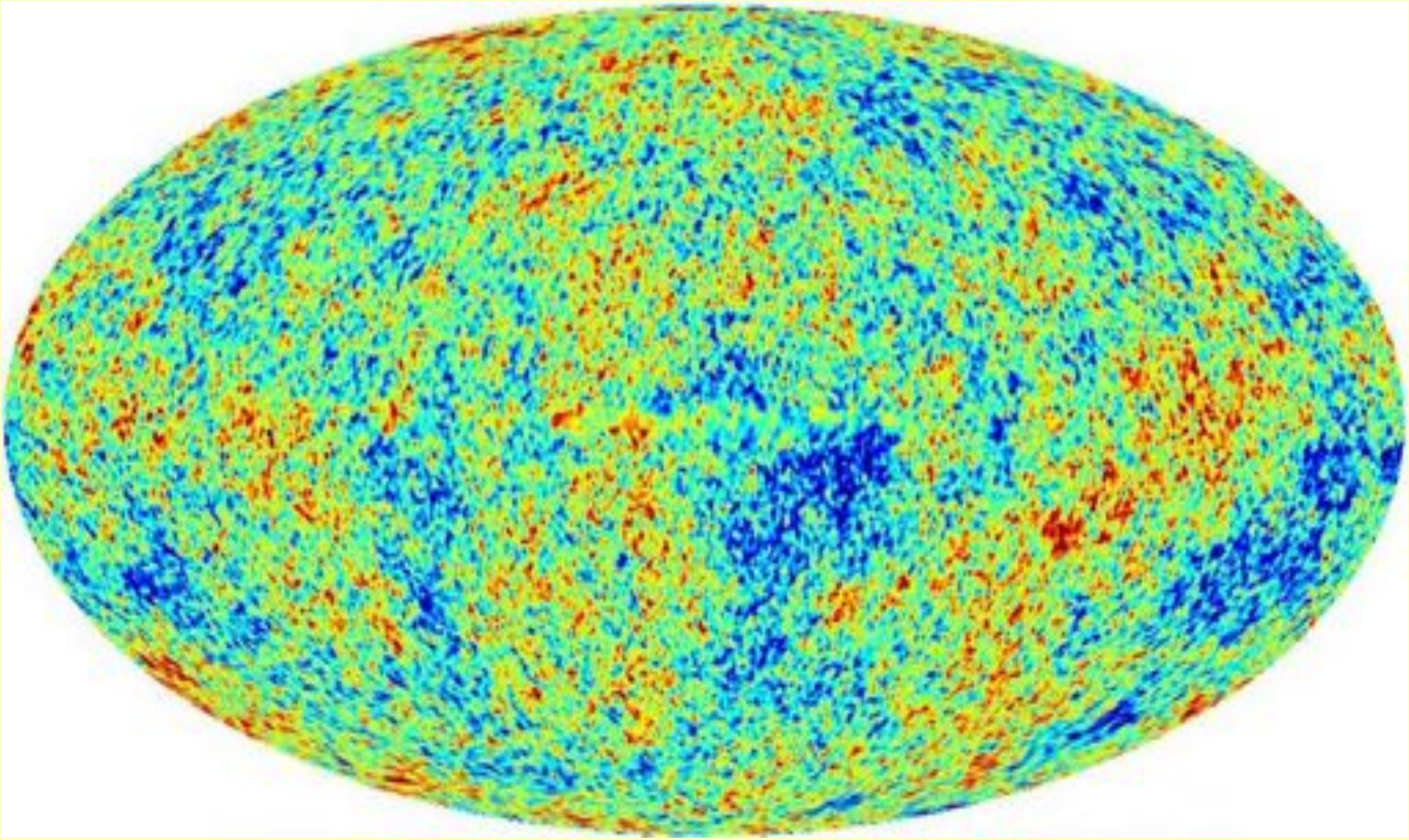
COBE 1992



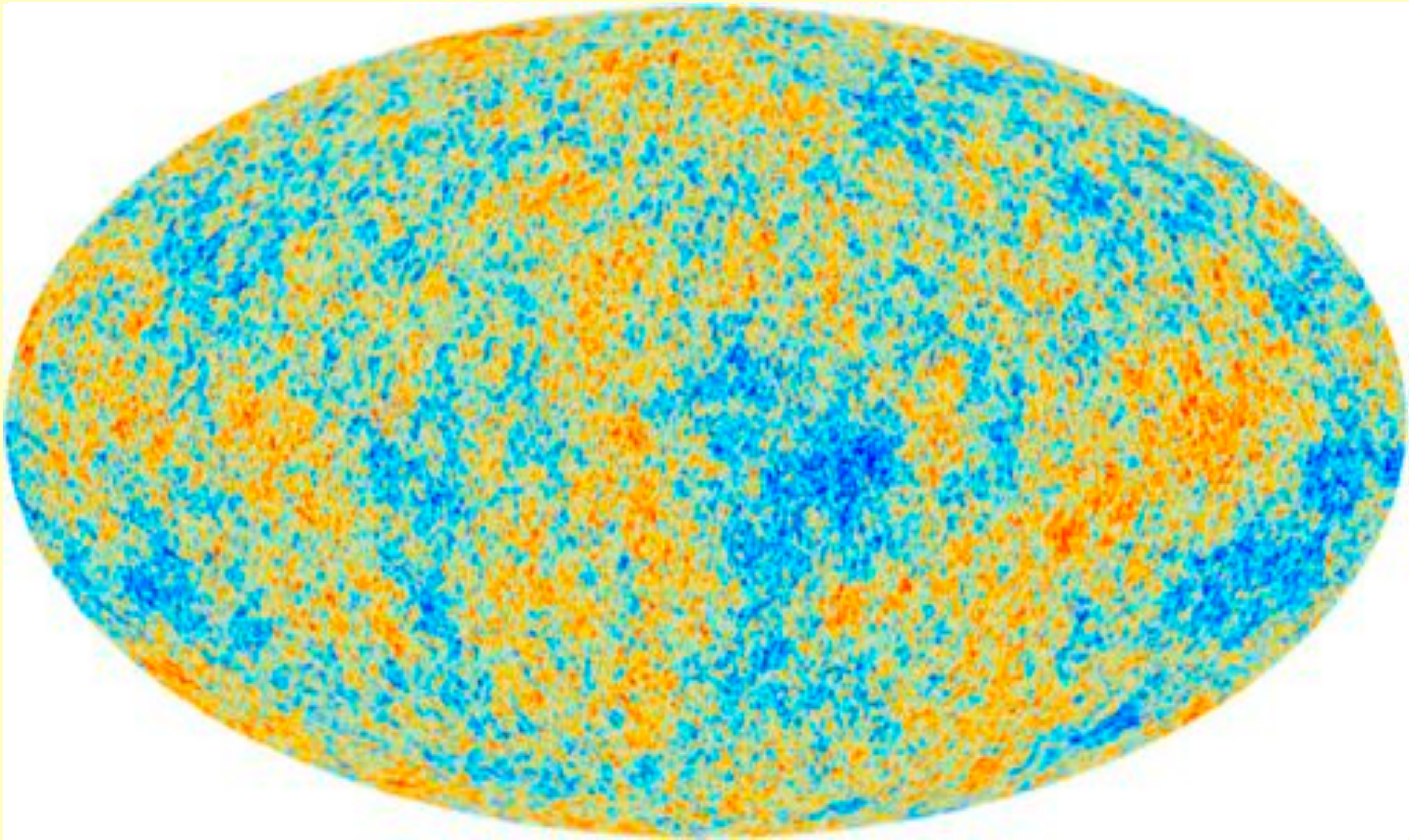
COBE 1992



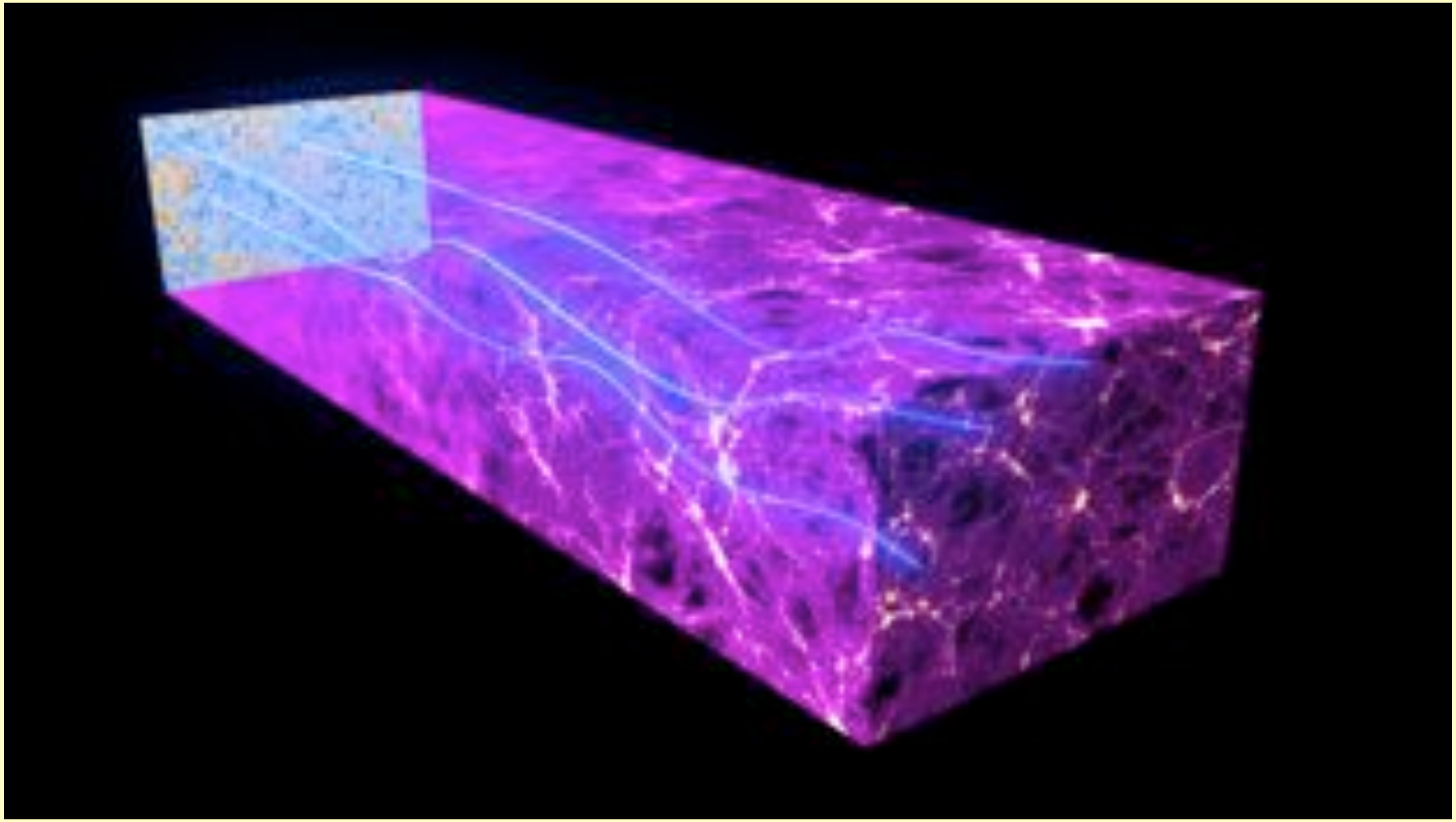
WMAP 2003



Planck 2013

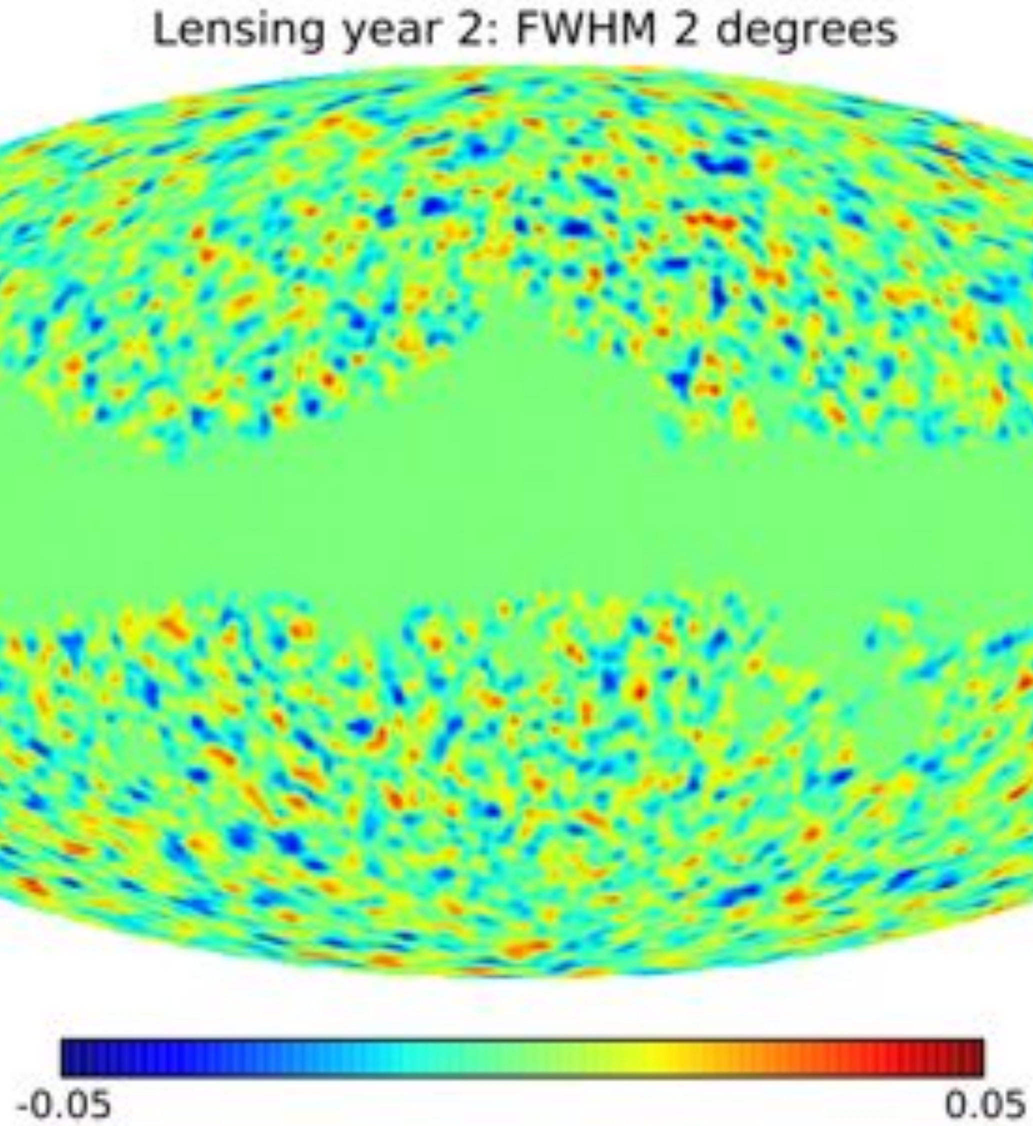


Gravitational lensing of the CMB



Foreground matter fluctuations deflect light and distort apparent CMB sky map

Planck lensing map



Lensing convergence: projected mass distribution back to z=1100

Can we measure where this signal originates?

– need an all-sky galaxy catalogue with redshifts

(with Maciek Bilicki, UCT/Leiden)

WISE

Wide-field Infrared Survey Explorer

Dec 2009 − Feb 2011

40cm telescope; FWHM > 6''

All-sky surveys
3.3, 4.7, 12, 23 microns (W1-W4)

~ 500M sources with W1<17
(roughly 50:50 stars & galaxies)

SuperCOSMOS

All-sky optical catalogue from scans of 1980s UKST & POSS2 Schmidt surveys

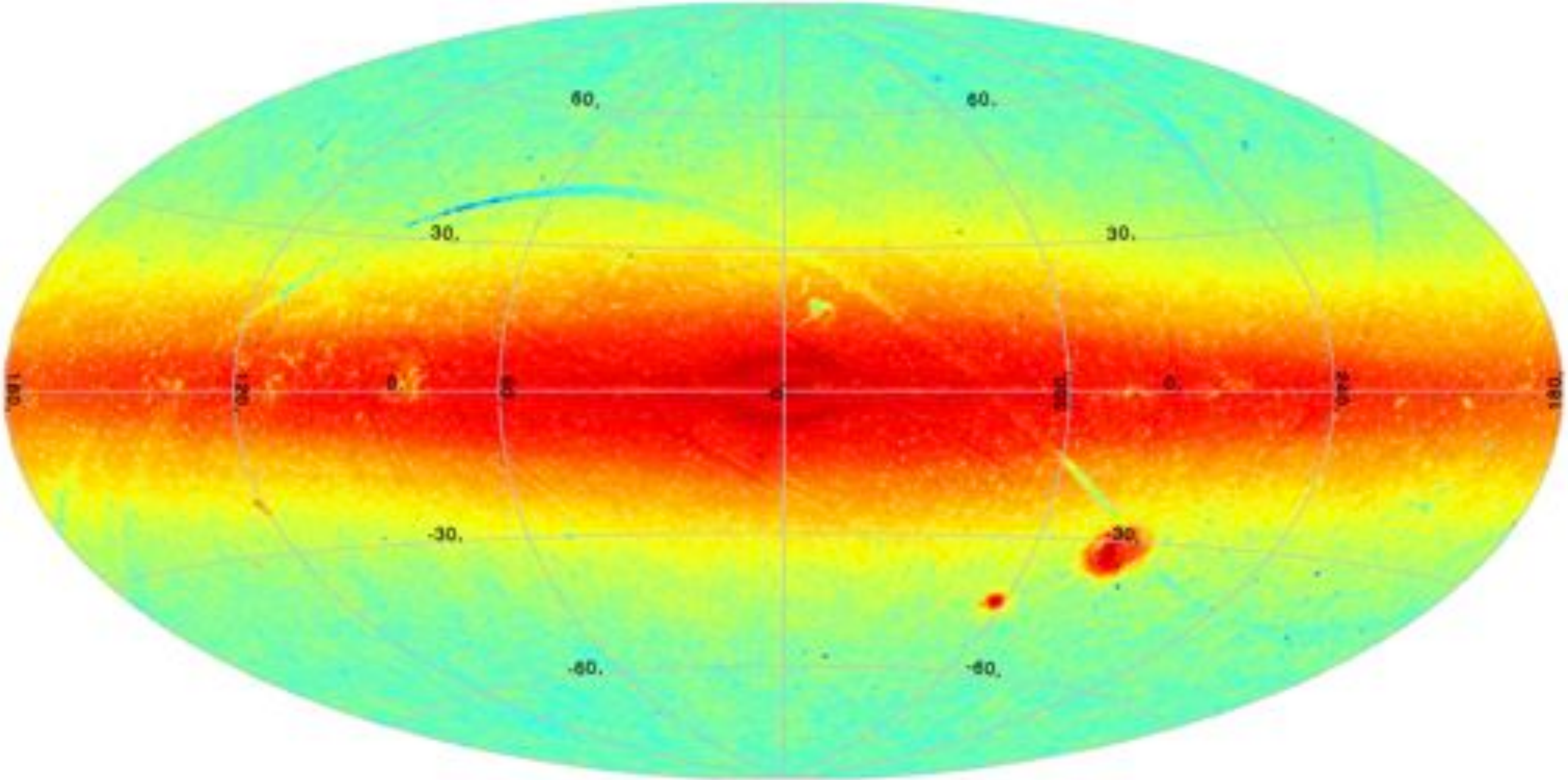
Depth B<21, R<19.5

Calibrated for 2dFGRS

~ 200M galaxies; ~ 1B stars

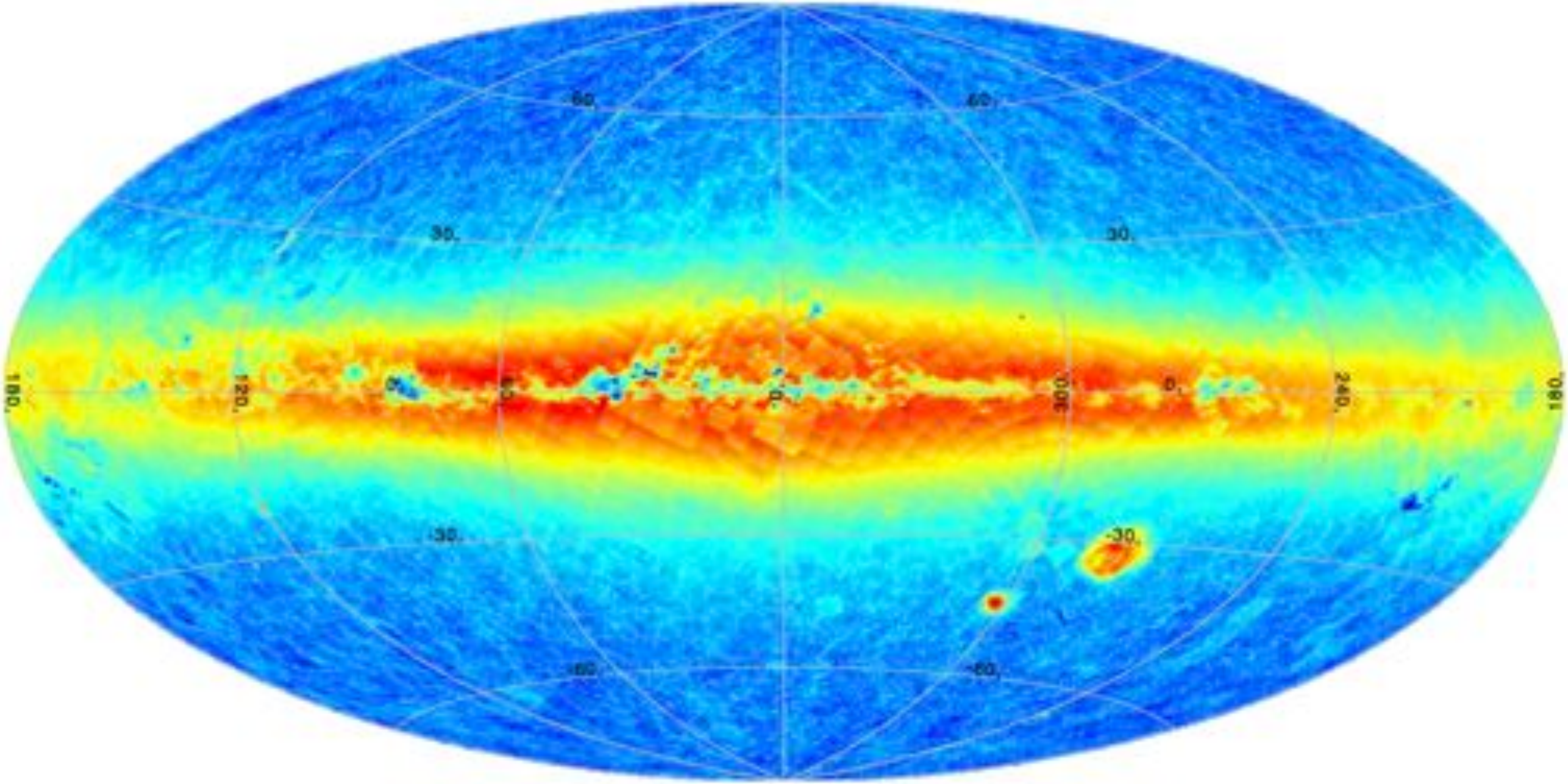
Curated by WFAU

WISE



W1<17: 488M

Super-COSMOS extended



B<21, R<19.5: 204M

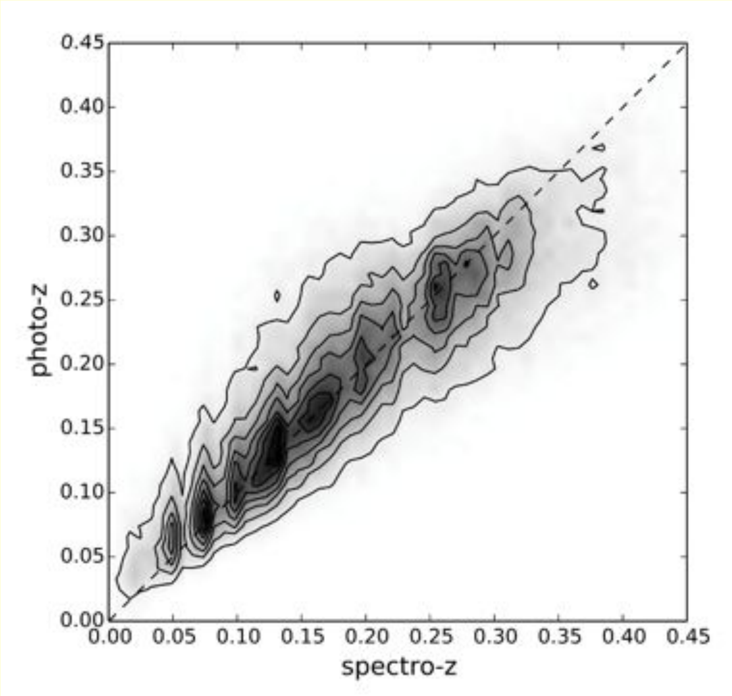
WIxSC: Public photometric redshifts

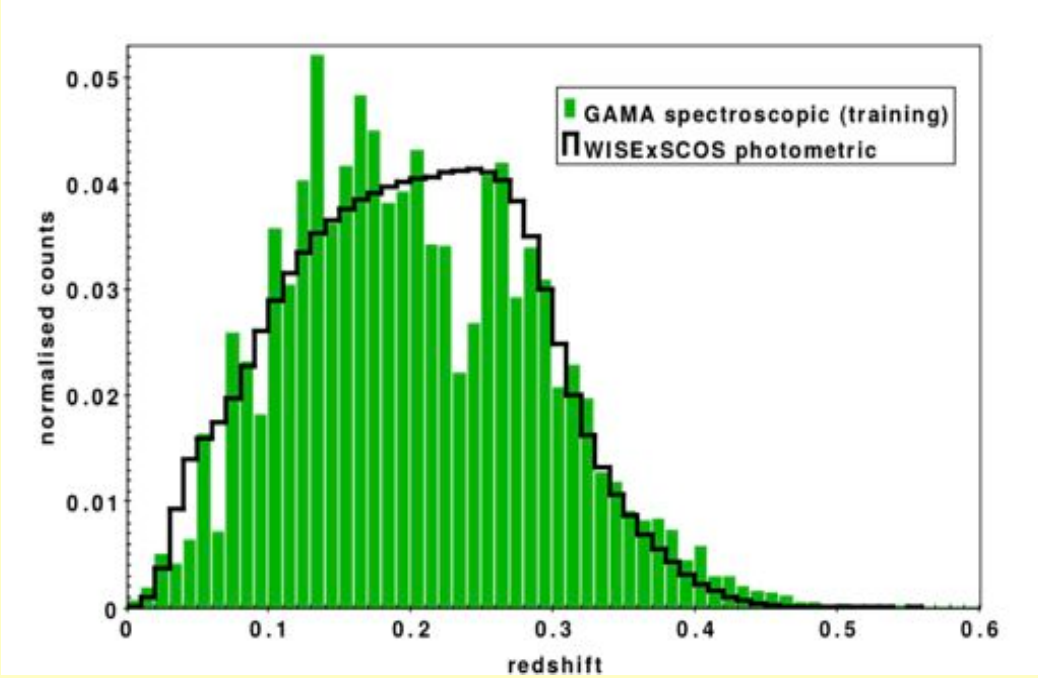
20 million galaxies over 8.7sr

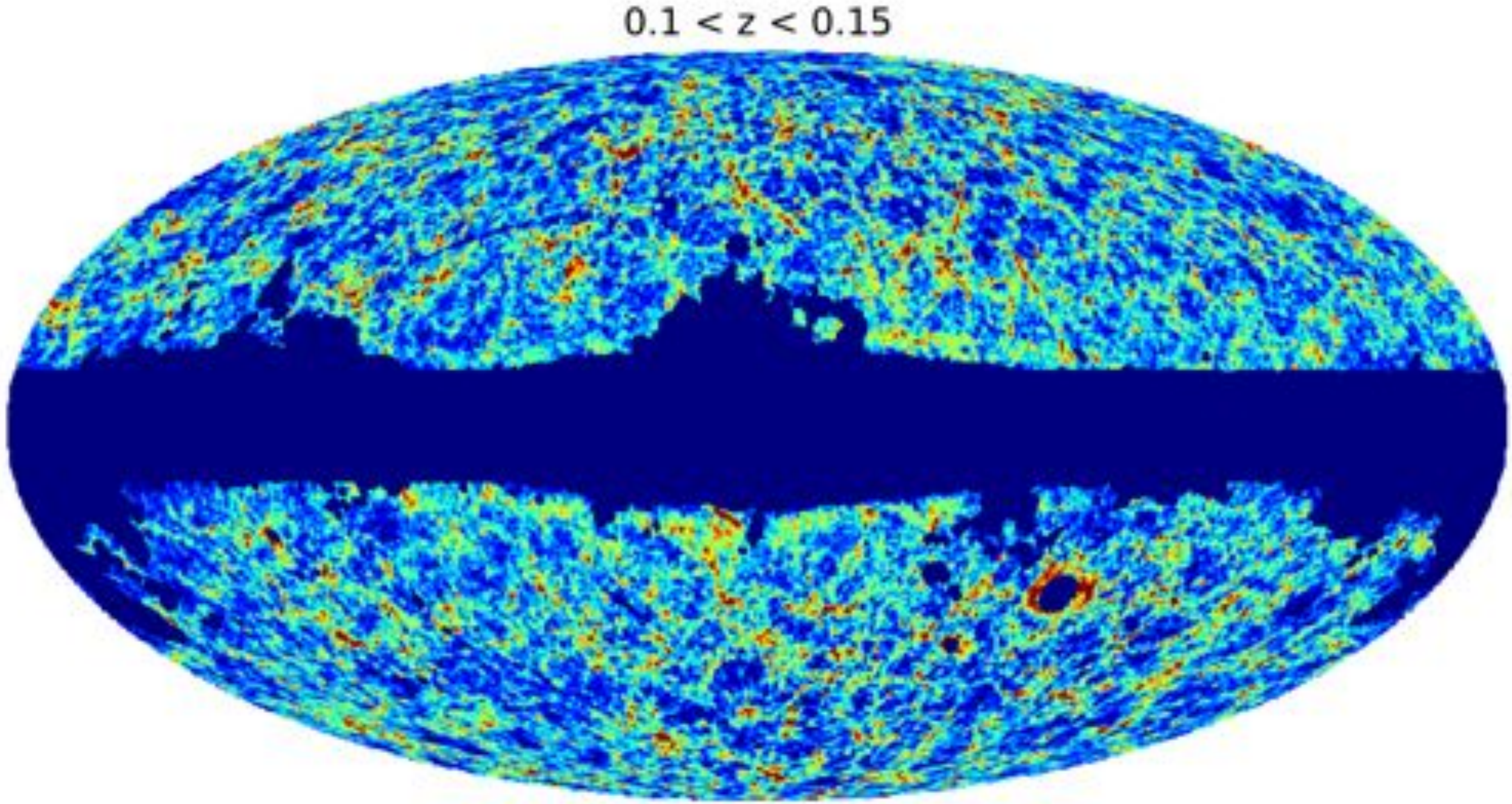
ANNz Using (B,R,W1,W2) and GAMA spectroscopy

σ_z / (1+z) = 0.032 (0.015 with 2MASS)

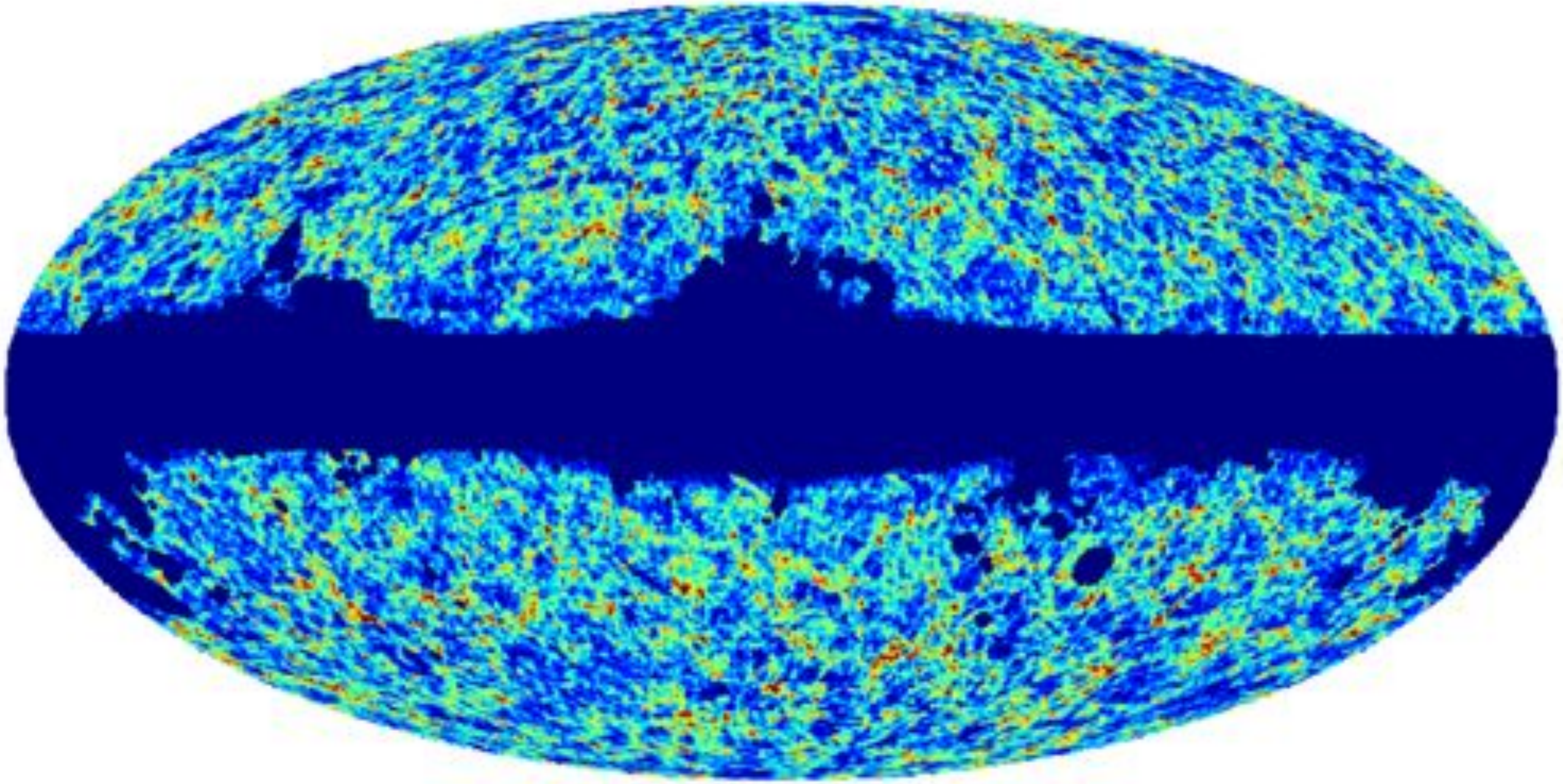
Median z = 0.2; useful signal out to z = 0.4 (double 2MASS)



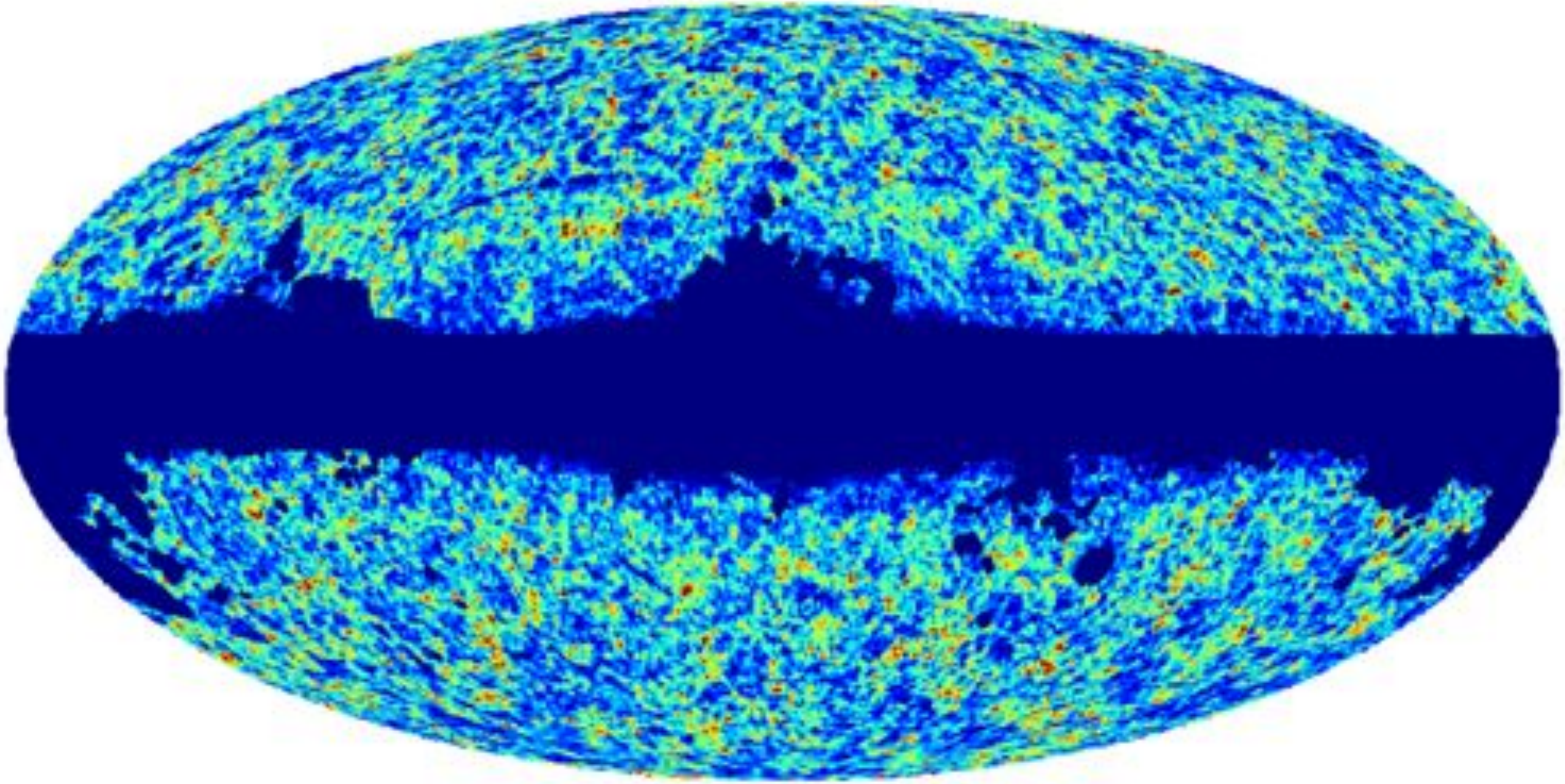


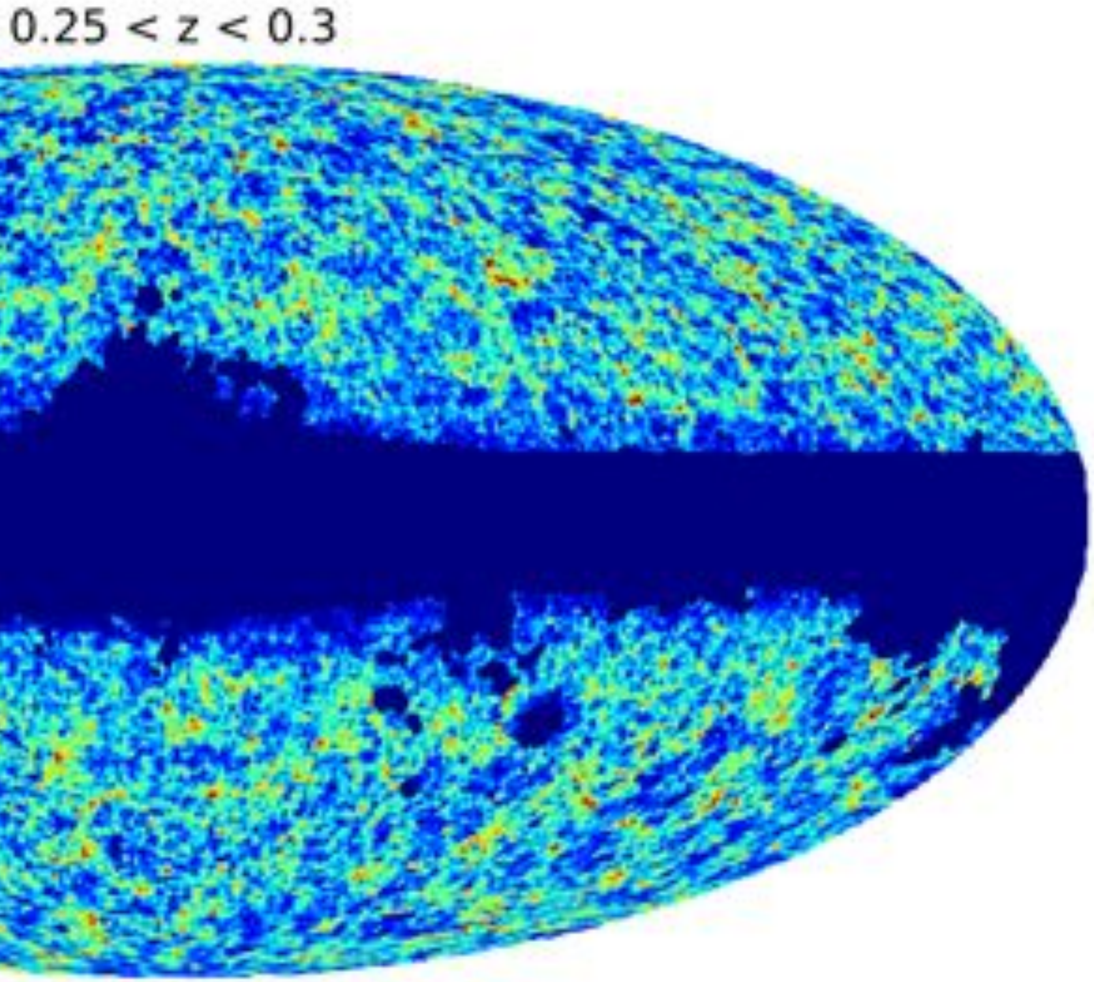

0.1 < z < 0.15

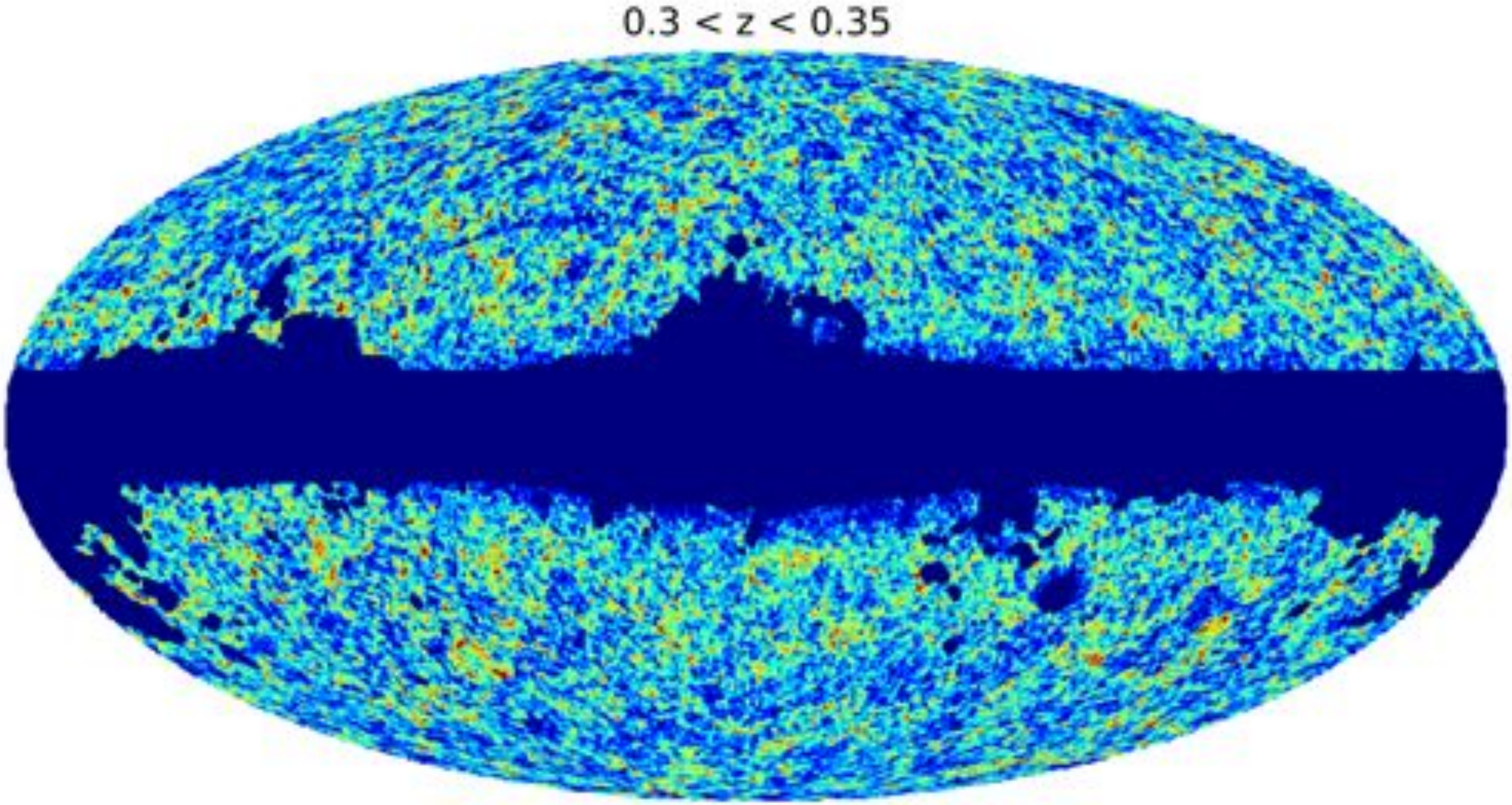
0.15 < z < 0.2



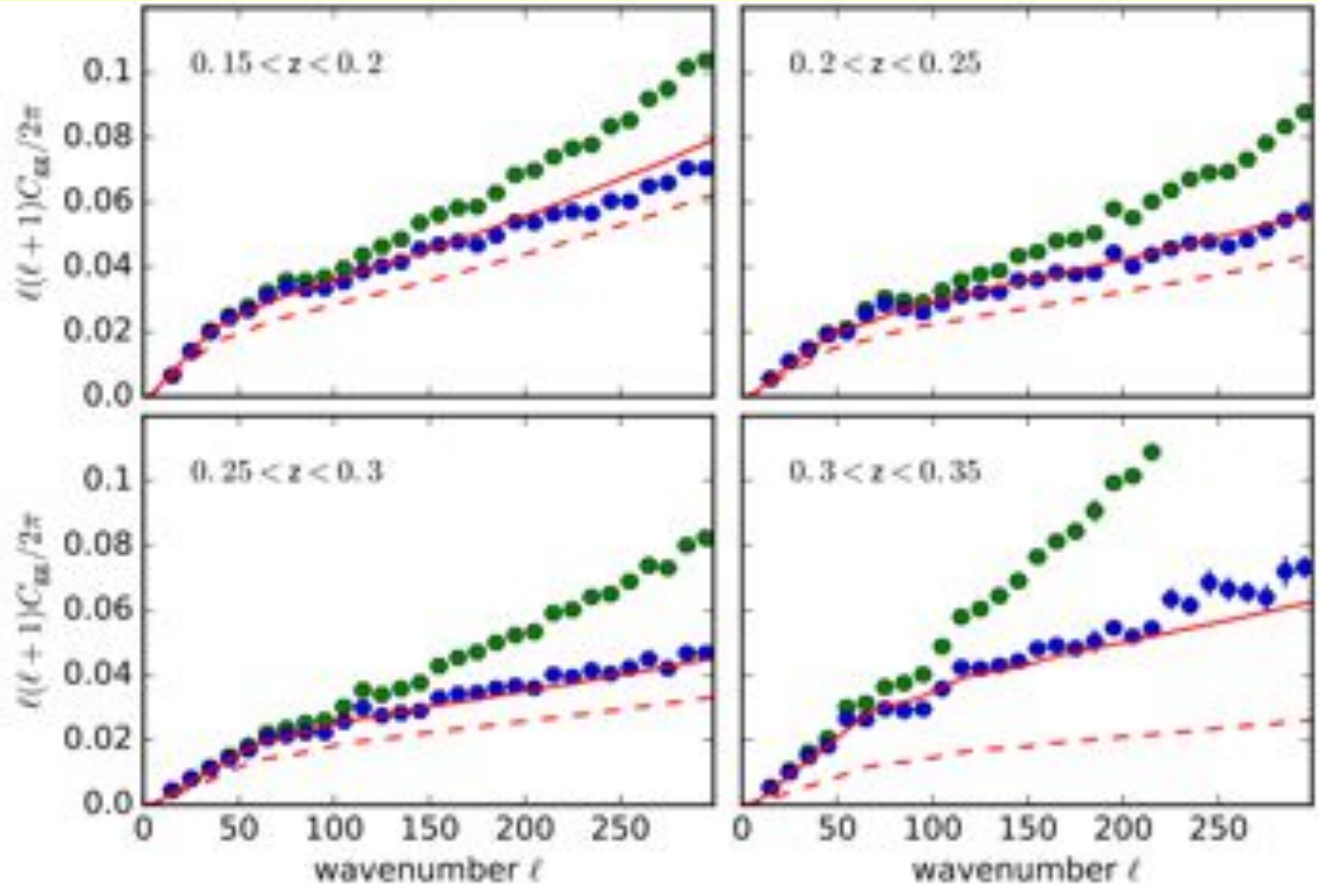
0.2 < z < 0.25



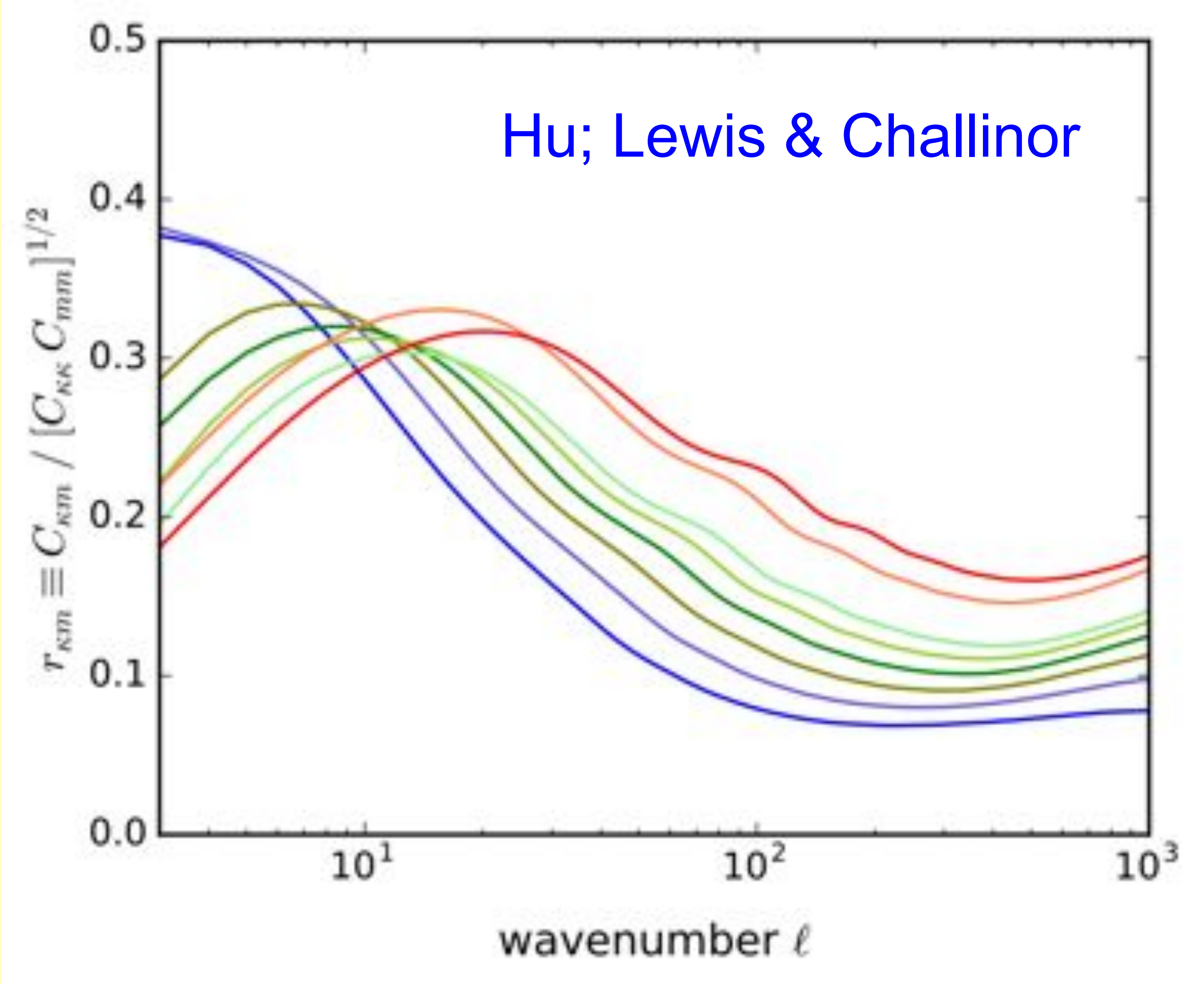

0.25 < z < 0.3


0.3 < z < 0.35

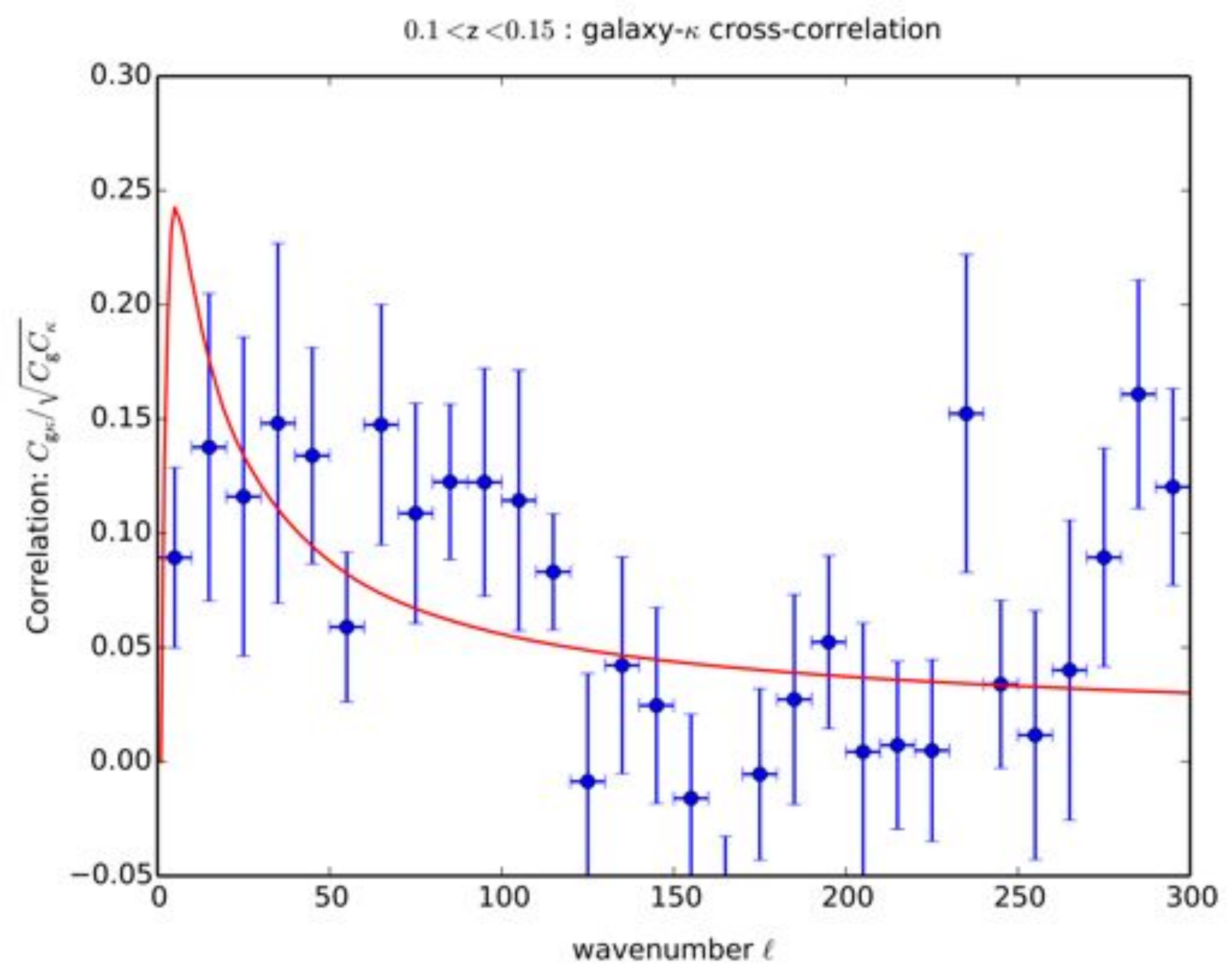
Precise angular power spectra



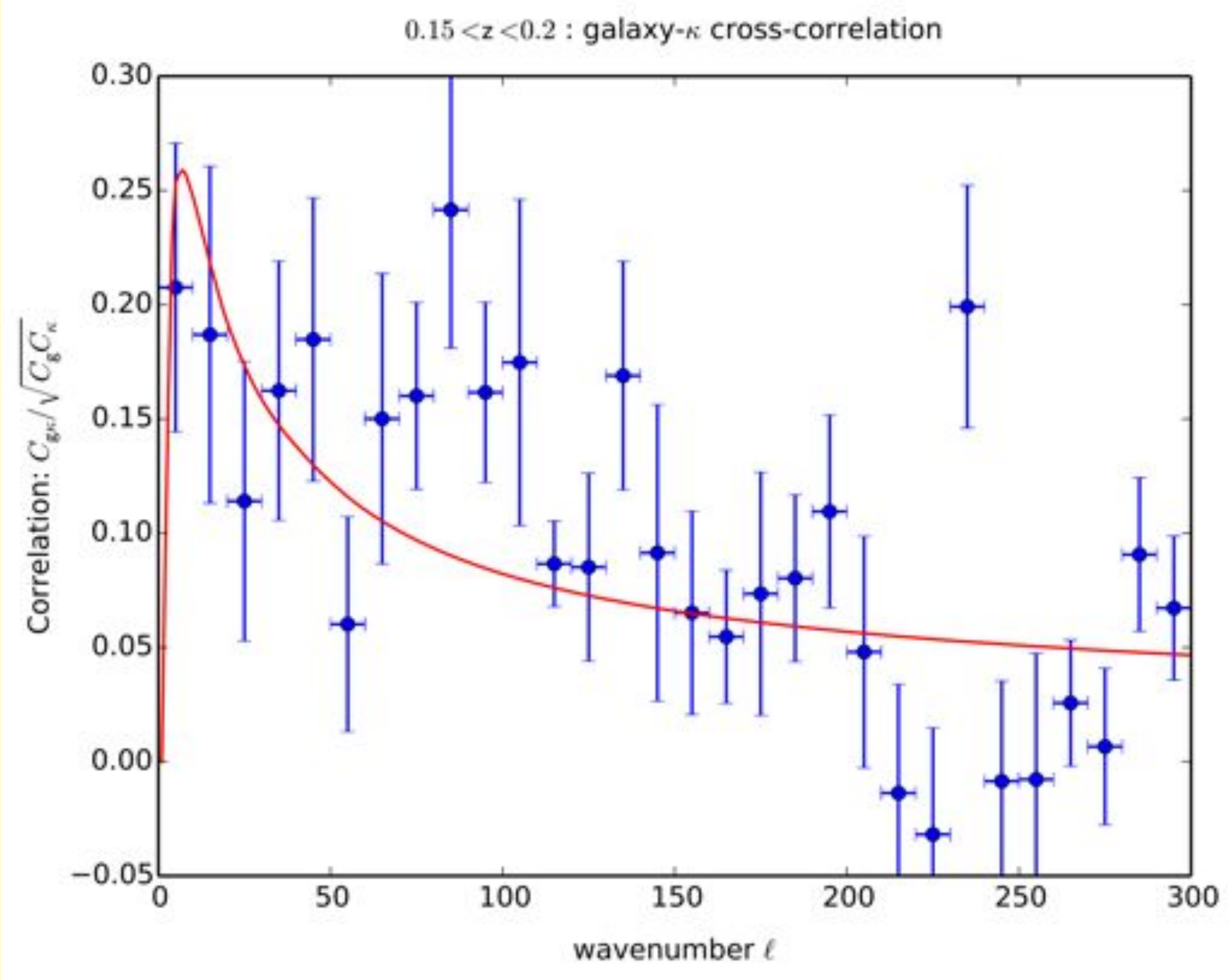
Predicted cross-correlation of lensing and tomographic density



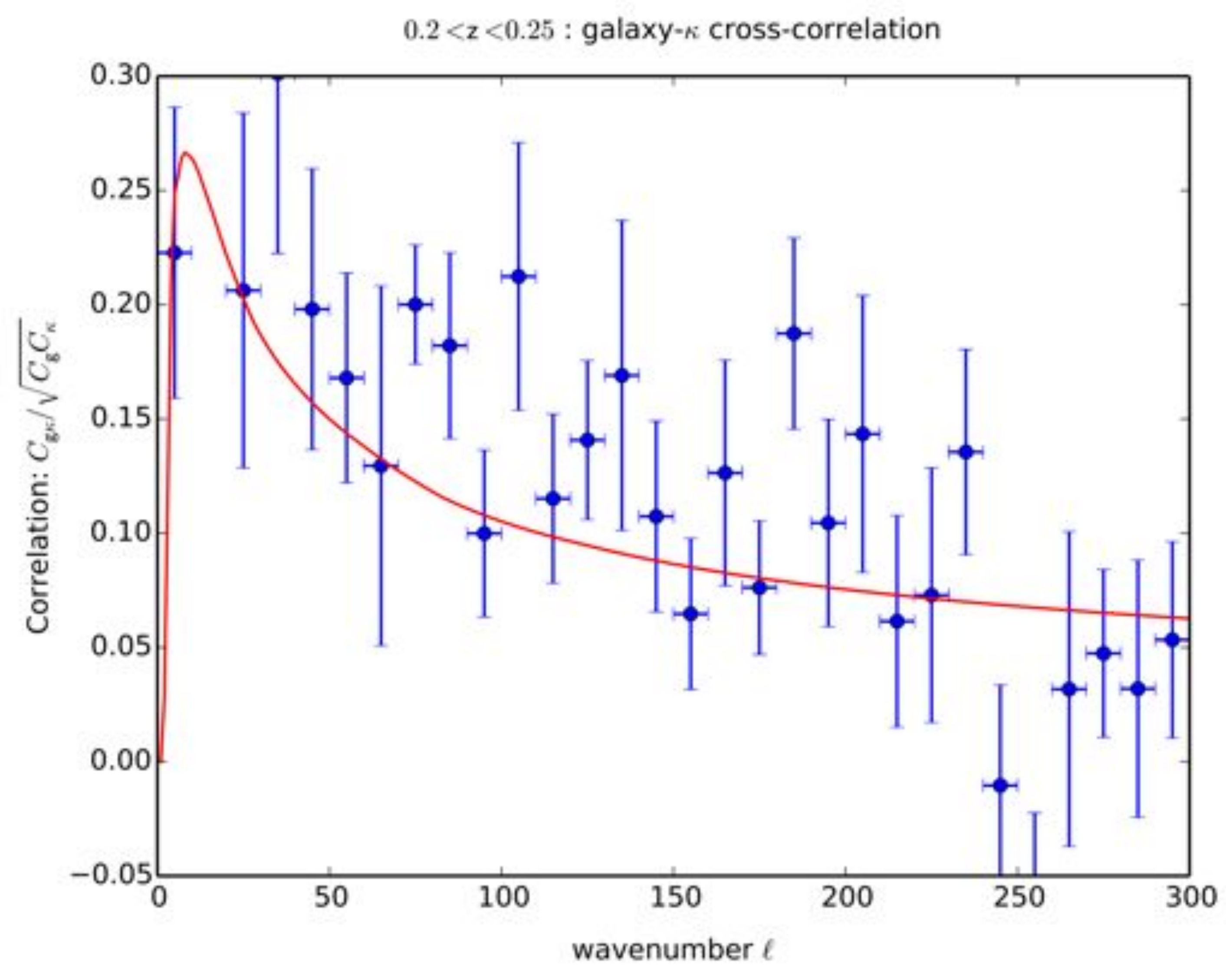
Expect correlation 0.1 − 0.3 in all dz = 0.05 slices



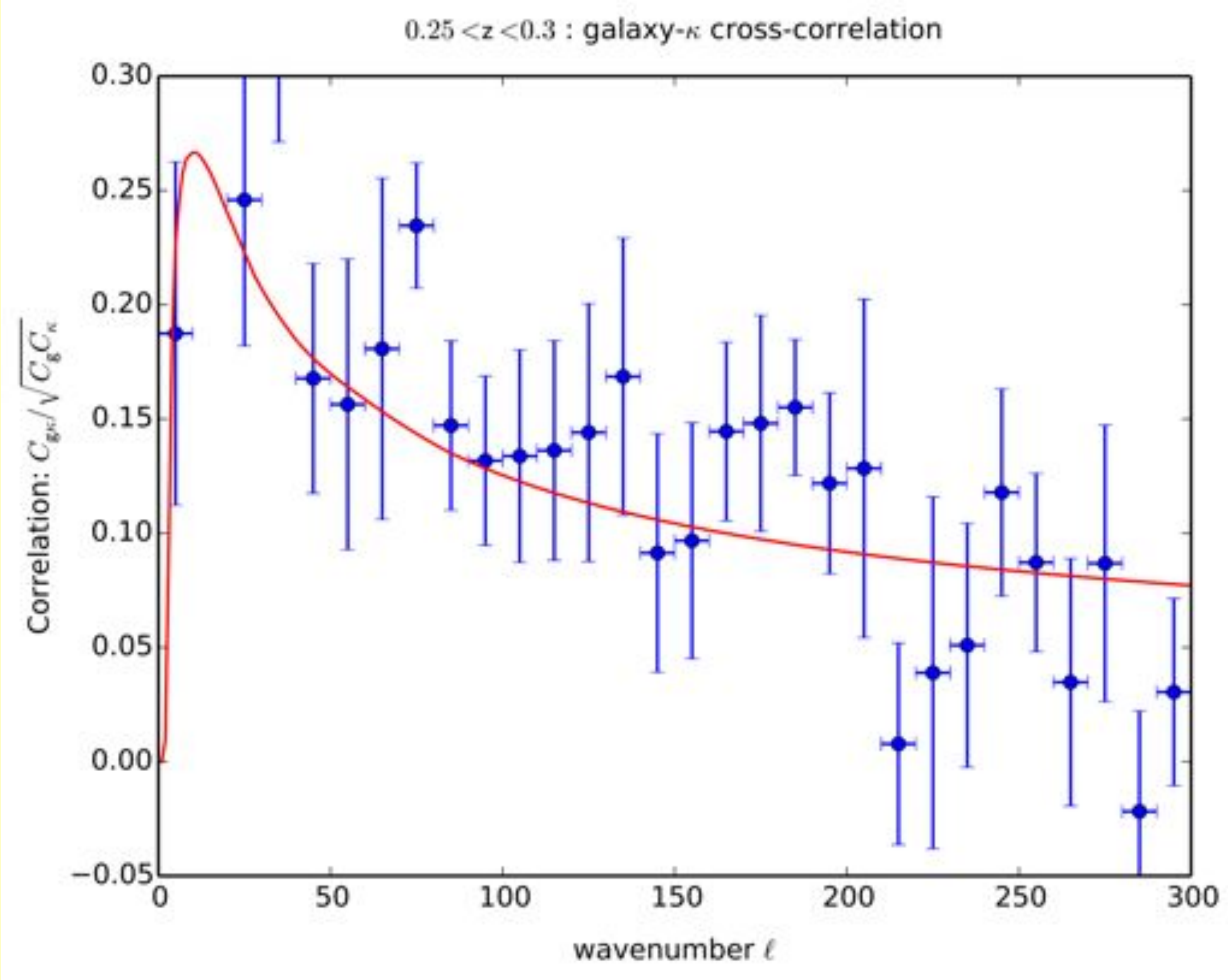
0.1 < z < 0.15 : galaxy-κ cross-correlation
Correlation: $C_{g\kappa}/\sqrt{C_g C_\kappa}$
wavenumber ℓ
0.30
0.25
0.20
0.15
0.10
0.05
0.00
−0.05
0
50
100
150
200
250
300

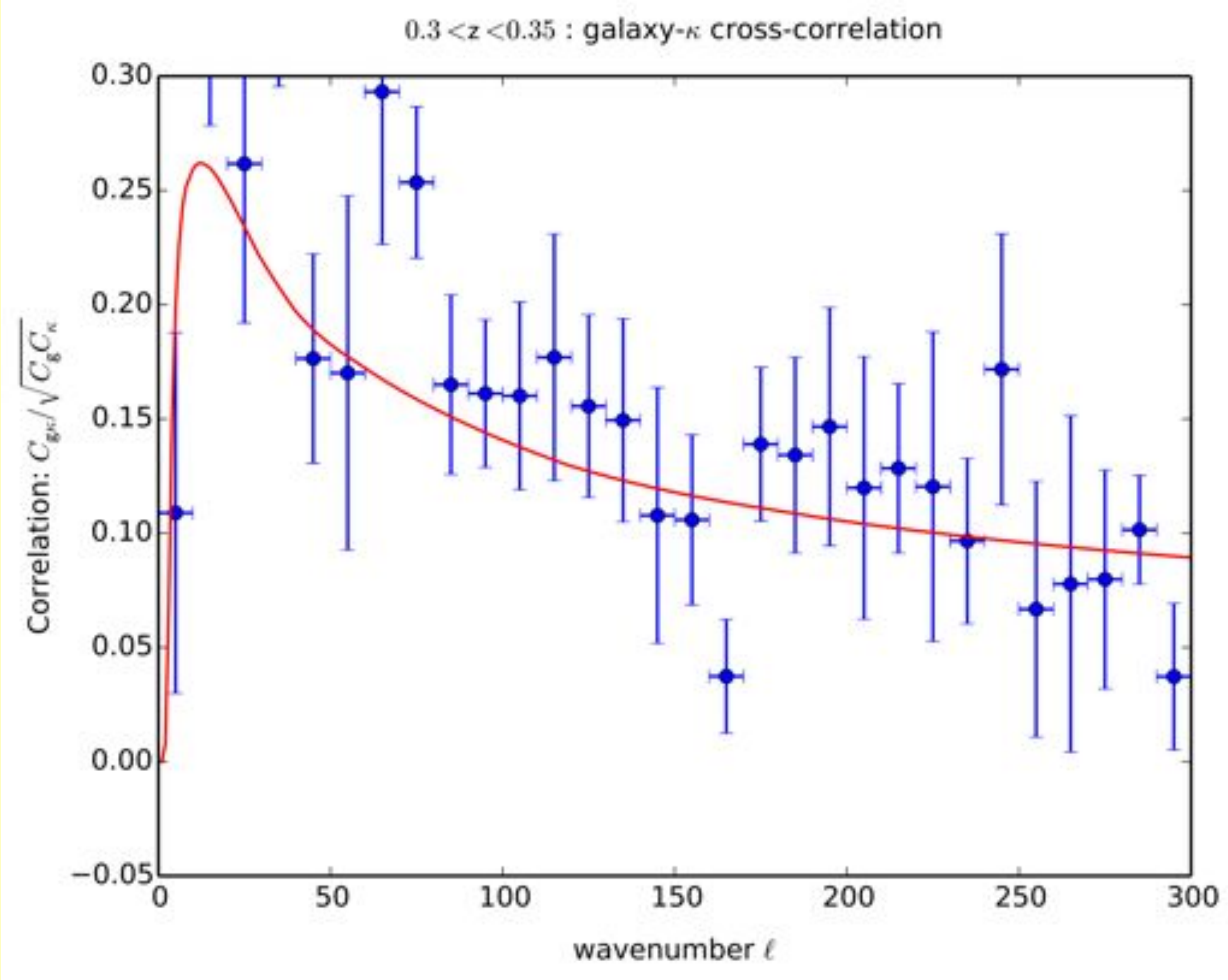


$0.15 < z < 0.2$: galaxy-κ cross-correlation
Correlation: $C_{g\kappa}/\sqrt{C_g C_\kappa}$
wavenumber ℓ
0.30
0.25
0.20
0.15
0.10
0.05
0.00
−0.05
0
50
100
150
200
250
300



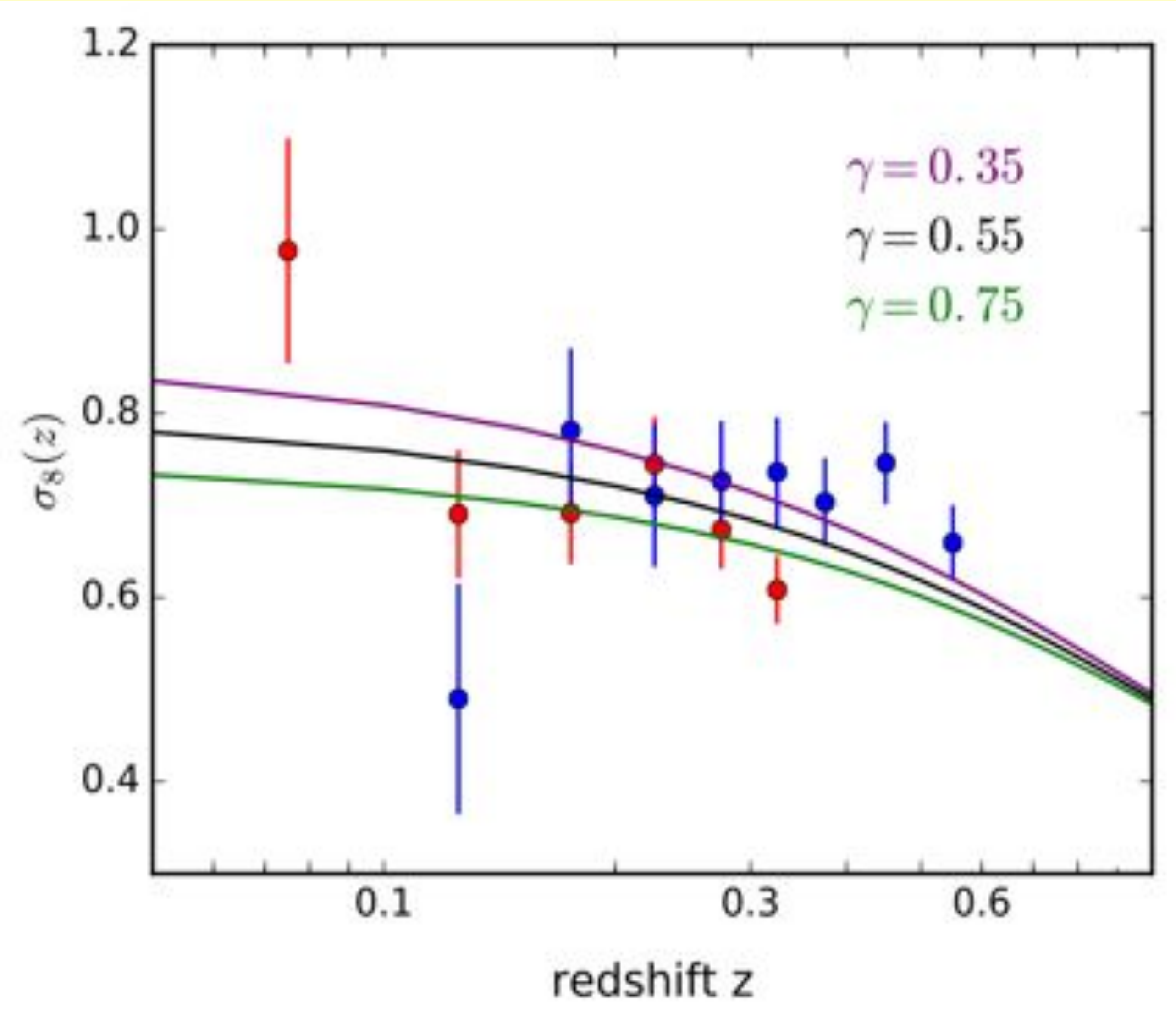
$0.2 < z < 0.25$: galaxy-κ cross-correlation
Correlation: $C_{g\kappa}/\sqrt{C_g C_\kappa}$
wavenumber ℓ
0.30
0.25
0.20
0.15
0.10
0.05
0.00
−0.05
0
50
100
150
200
250
300


$0.25 < z < 0.3$: galaxy-κ cross-correlation
Correlation: $C_{g\kappa}/\sqrt{C_g C_\kappa}$
wavenumber ℓ
0.30
0.25
0.20
0.15
0.10
0.05
0.00
−0.05
0
50
100
150
200
250
300



0.3 < z < 0.35 : galaxy-κ cross-correlation
Correlation: $C_{g\kappa}/\sqrt{C_g C_\kappa}$
0.30
0.25
0.20
0.15
0.10
0.05
0.00
−0.05
0
50
100
150
200
250
300
wavenumber ℓ

The build-up of structure



Growth from z=2 to present roughly right (for fixed fiducial cosmlogy)

$$\frac{d \ln \delta}{d \ln a} \simeq \Omega_m(a)^\gamma$$

Growth index
ϒ=0.77 ± 0.18

(0.55 for Einstein)

Future LSS probes

DESI

DOE project for KPNO 4m over 2019-2024:

5000 Fibres; 3-deg field

30M galaxies

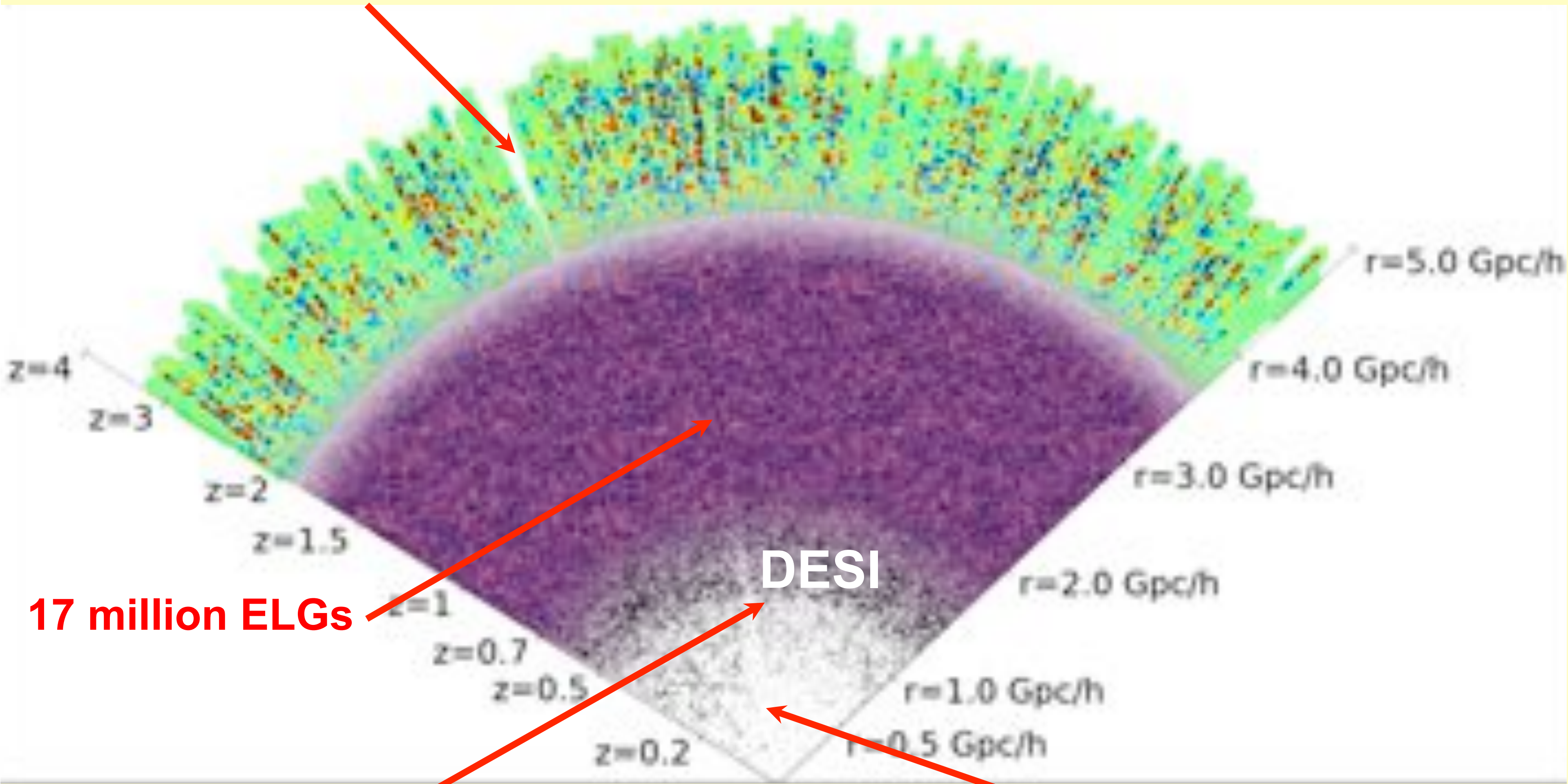
− LRGs to $z = 0.9$

− OII ELGs to $z = 1.7$

− QSOs to $z = 3$

DESI redshift coverage

3 million QSOs

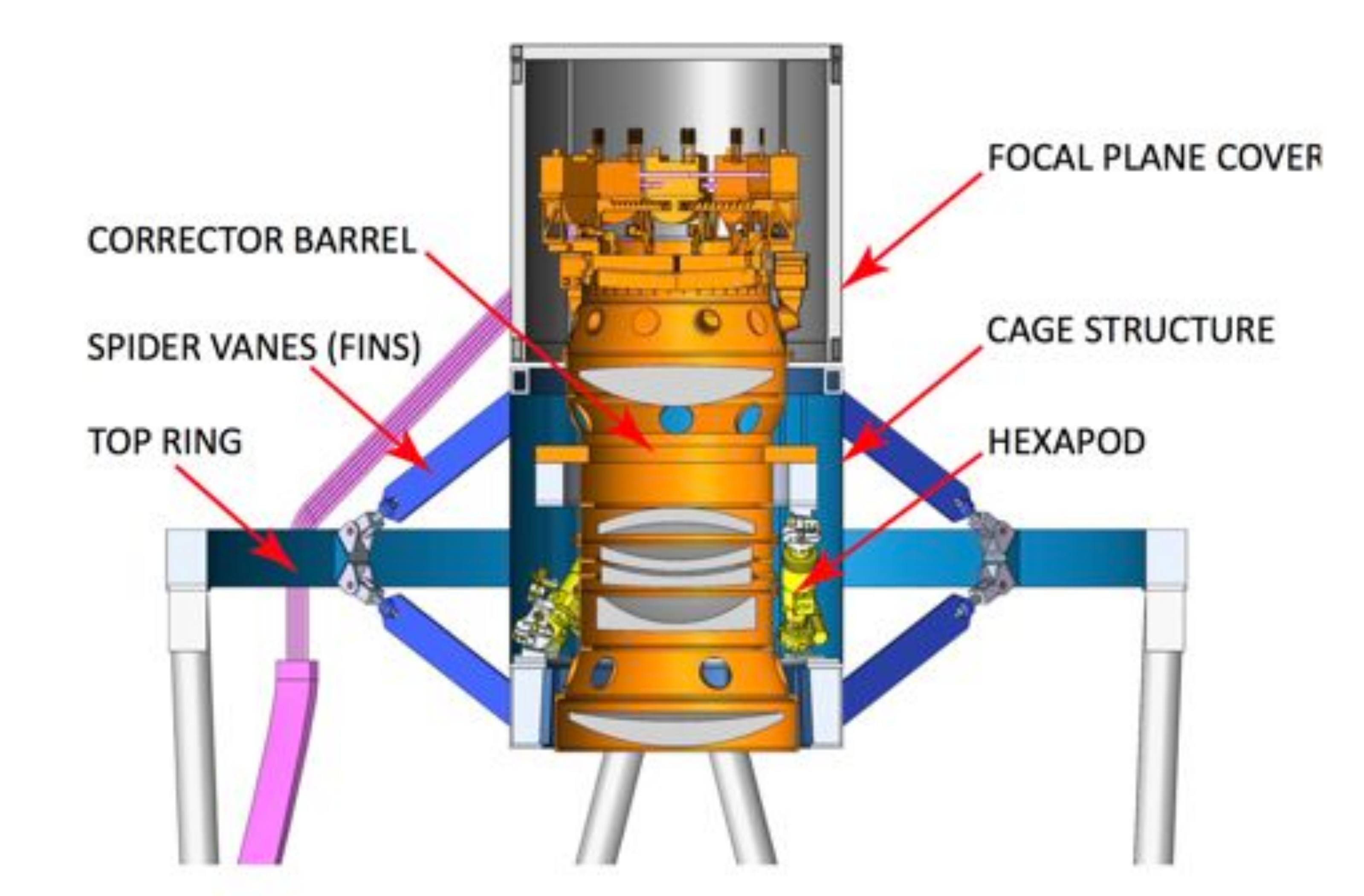


17 million ELGs

4 million LRGs

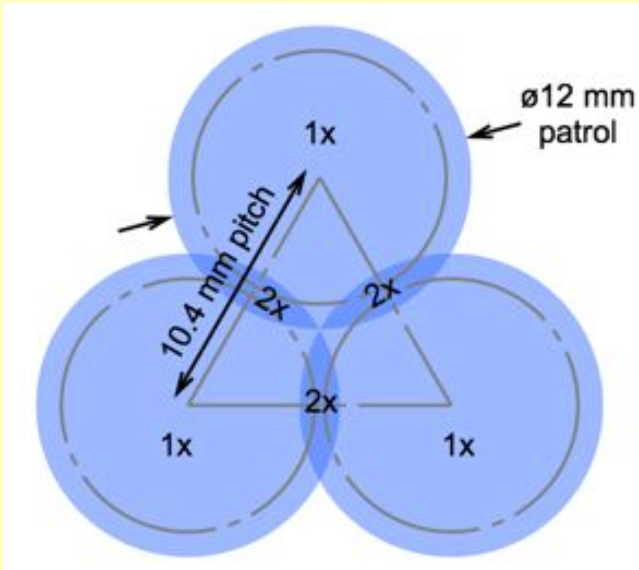
10 million BGs
(r < 19.5)

DESI corrector and positioner

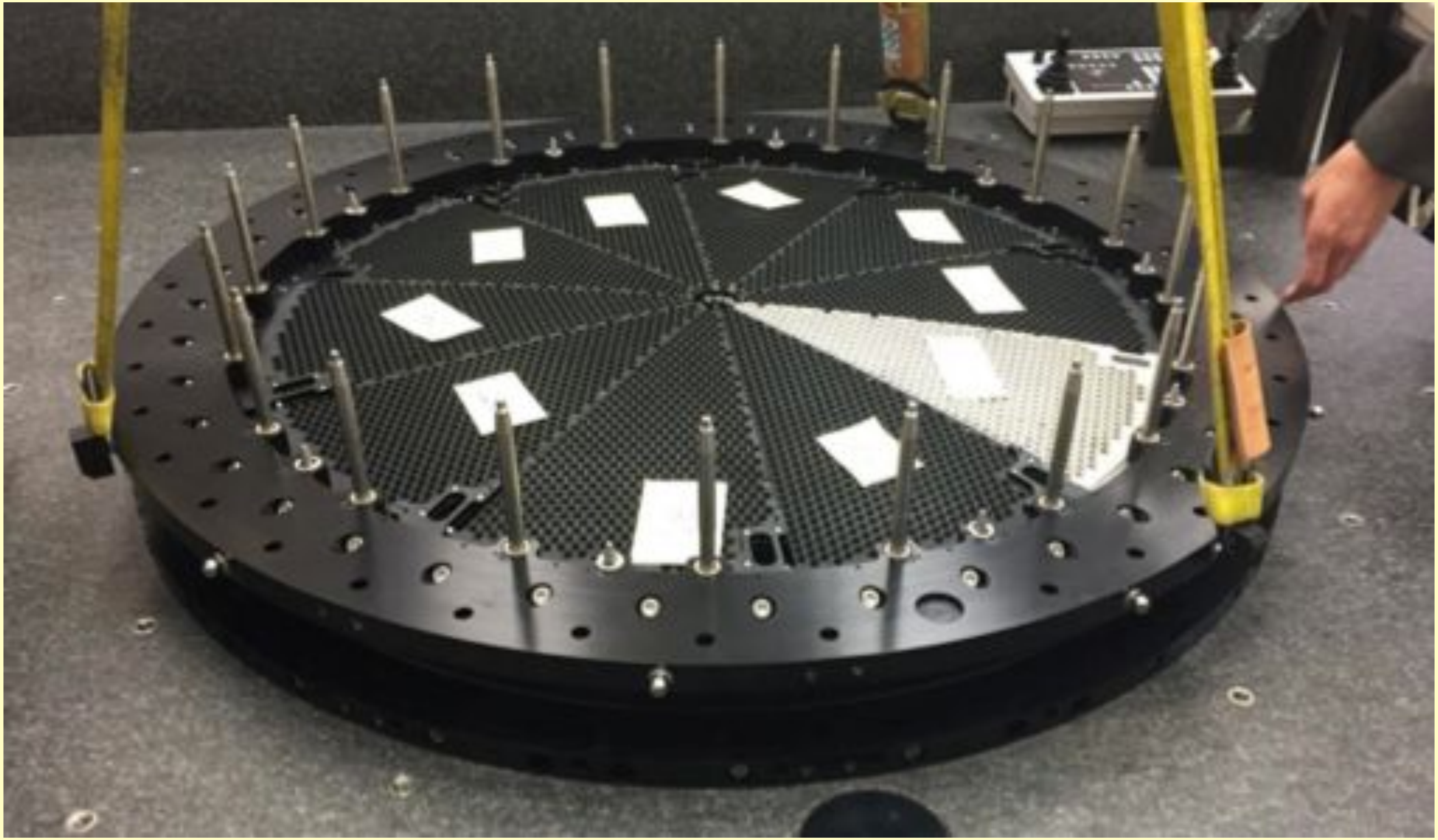


DESI positioner

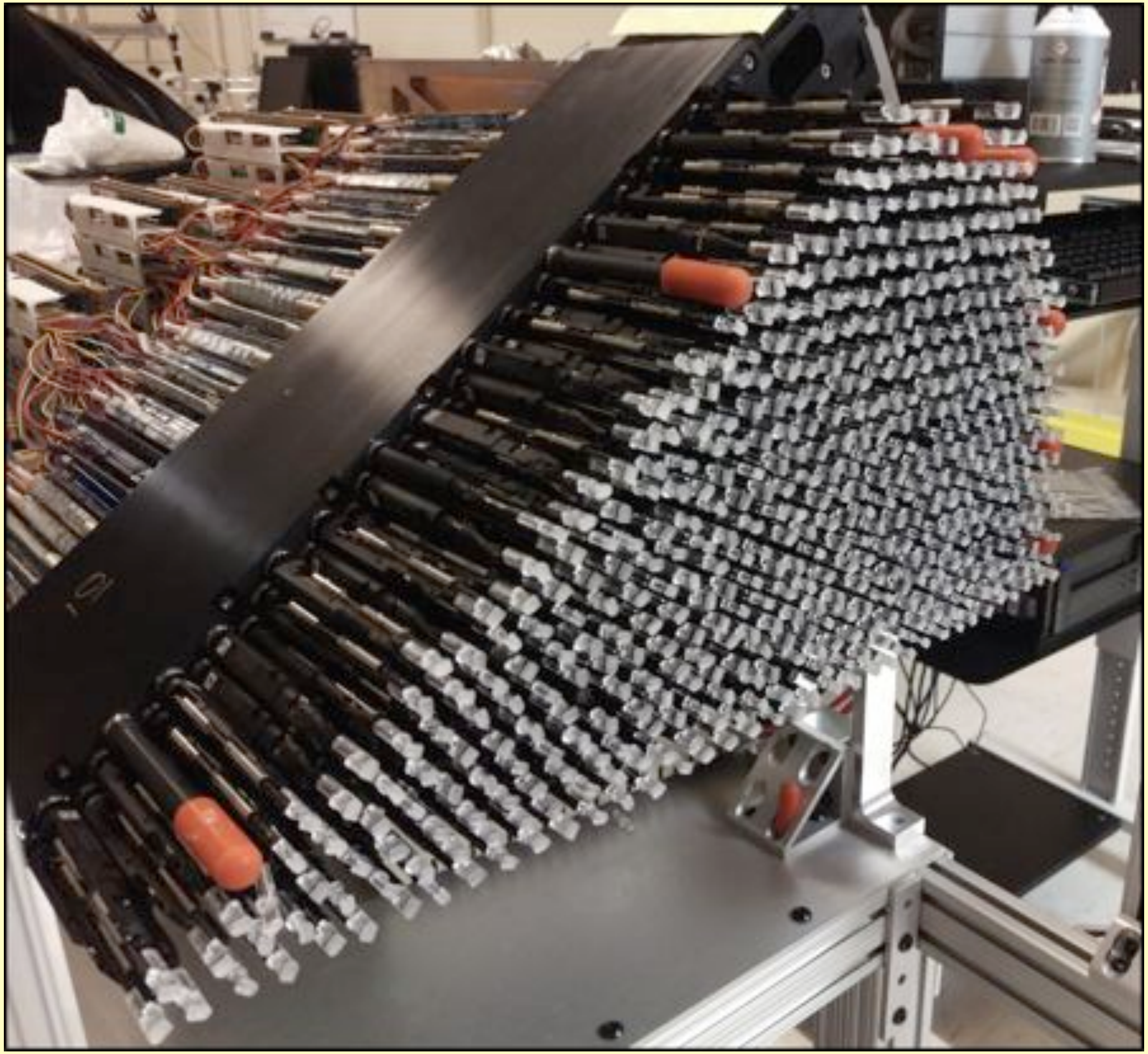
5000 twin r-theta epicyclic positioners, mounted in petals



DESI positioner



DESI positioner



But back to statistics…

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No Bayes??

Definitions of probability:

- "nothing but a swindle" (Chevalier de Mere 1654)
- Frequentist: frequency of event in repeated trials
- Bayesian: subjective degree of belief in a proposition
  - Applies to unique events with no ensemble

$$\mathrm{P(Hypothesis|data)} \propto \mathrm{P(Hypothesis)} \times \mathrm{P(Data|Hypothesis)}$$

Prior Likelihood

i.e. update your prejudice about a hypothesis according to how likely a new set of results are under this hypothesis.

Why I am not a Bayesian

..... sometimes

Good Bayes: Inference

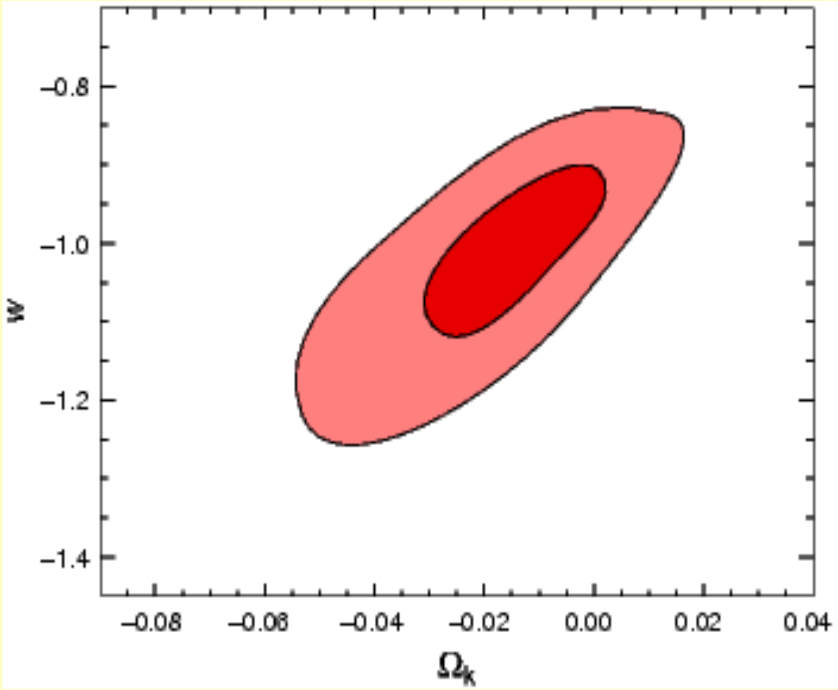
Consider parameter p:

P(p | data) ~ P(p) x L(data | p)

Weak dependence on prior P(p)

− but often unimportant if Likelihood has sharp peak

− thus tend to choose uninformative priors, deliberately set to be broader than peak in L



Problematic Bayes: Model selection

A hypothesis is in two parts: M, the model, and p, the values of the parameter(s) within the model. So the relative probability of two models is

$$\frac{P(M_1|D)}{P(M_2|D)} = \frac{P(M_1)}{P(M_2)} \times \frac{\int L_1 \, P(p_2) \, d^n p_1}{\int L_2 \, P(p_2) \, d^n p_2}$$

$$\simeq \frac{P(M_1)}{P(M_2)} \times \frac{L_1^{\max}}{L_2^{\max}} \times \frac{\int (L_1/L_1^{\max}) \, P(p_1) \, d^n p_1}{\int (L_2/L_2^{\max}) \, P(p_2) \, d^n p_2}$$

A B C

A: Prior ratio: Should penalize complex models. Should be called “Ockham factor”

B: Likelihood ratio: main info about relative goodness of fit

C: Volume ratio: how much of parameter space is ruled out?

e.g. compare model with 1 free parameter with one with none: C ~ σ / L

− new parameter always disfavoured with sufficiently uninformative prior width L

− so now you need to believe in your prior. How do we get this faith?

But it gets worse….

Vulnerability to Priors

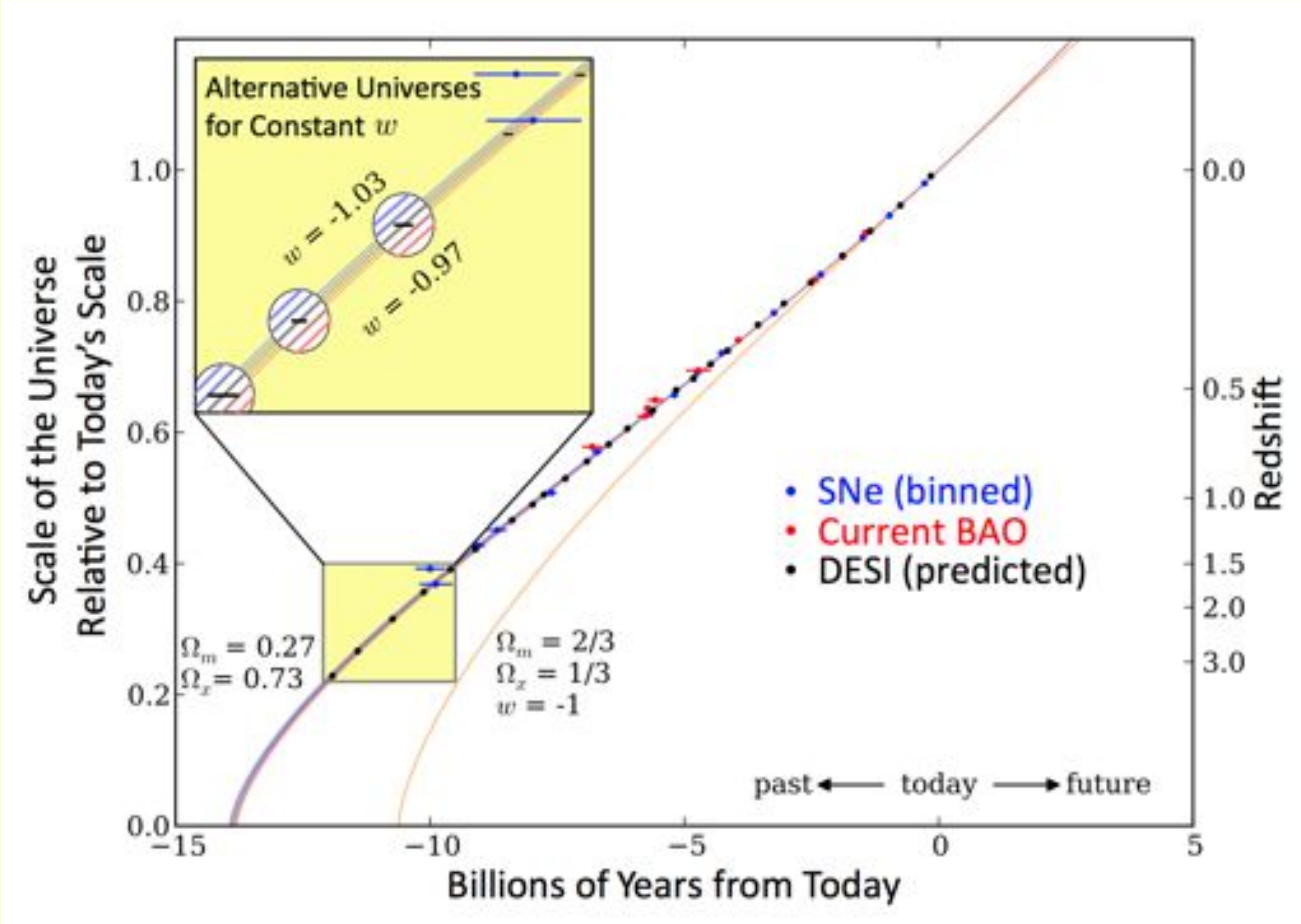
Will we believe any ‘detections’ of new physics?

P(model | data) ~ L(data | model) P(model)

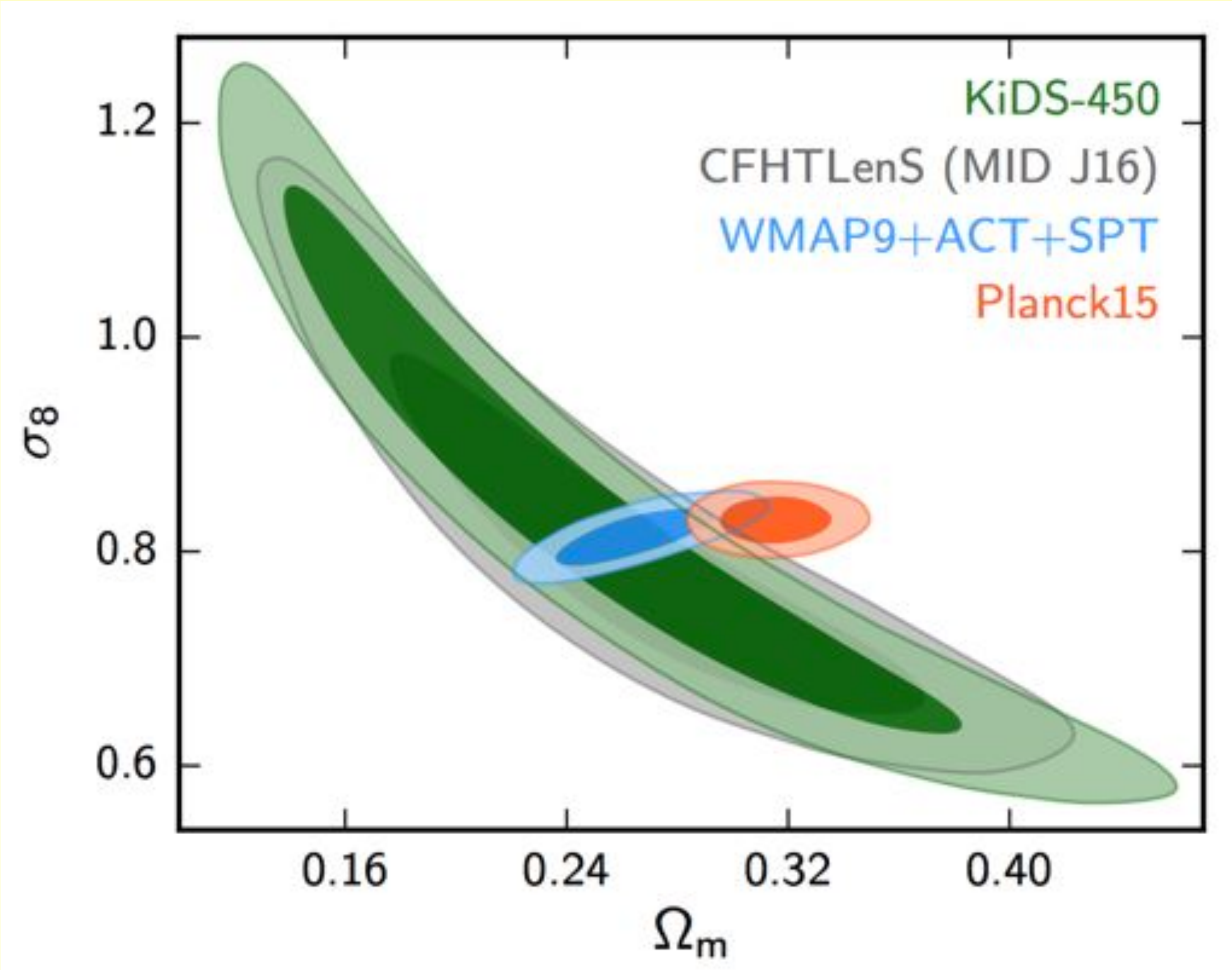
− Moderate prior belief in simplest neutrino hierarchy
− Strong prior belief in unevolving Λ
− Even stronger prior belief in Einstein gravity

Already plenty of ‘detections’ that are ignored: e.g. Λ in 1990s; Bean 2009 GR disproof; 2014 Beutler et al. massive neutrino detection.

Also: precision is challenging



e.g. the lensing-CMB σ_8 tension



Evidence for Modified Gravity?

− or just systematics?

1606.05338

Two distinct issues

(1) Are several datasets consistent or inconsistent?

− Various tests exist:
  - − Joint χ^2 vs χ^2 for subsets
  - − Bayesian evidence ratio (Marshall++2011; DES)
  - − Index of Inconsistency (Lin & Ishak 2017)

(2) How do we combine datasets?

− Standard answers for consistent data:
  - − Multiply likelihoods; reciprocal variance weights

− But what about inconsistent data?
  - − And is consistent = perfect the right assumption?

Combining data in the possible presence of systematics

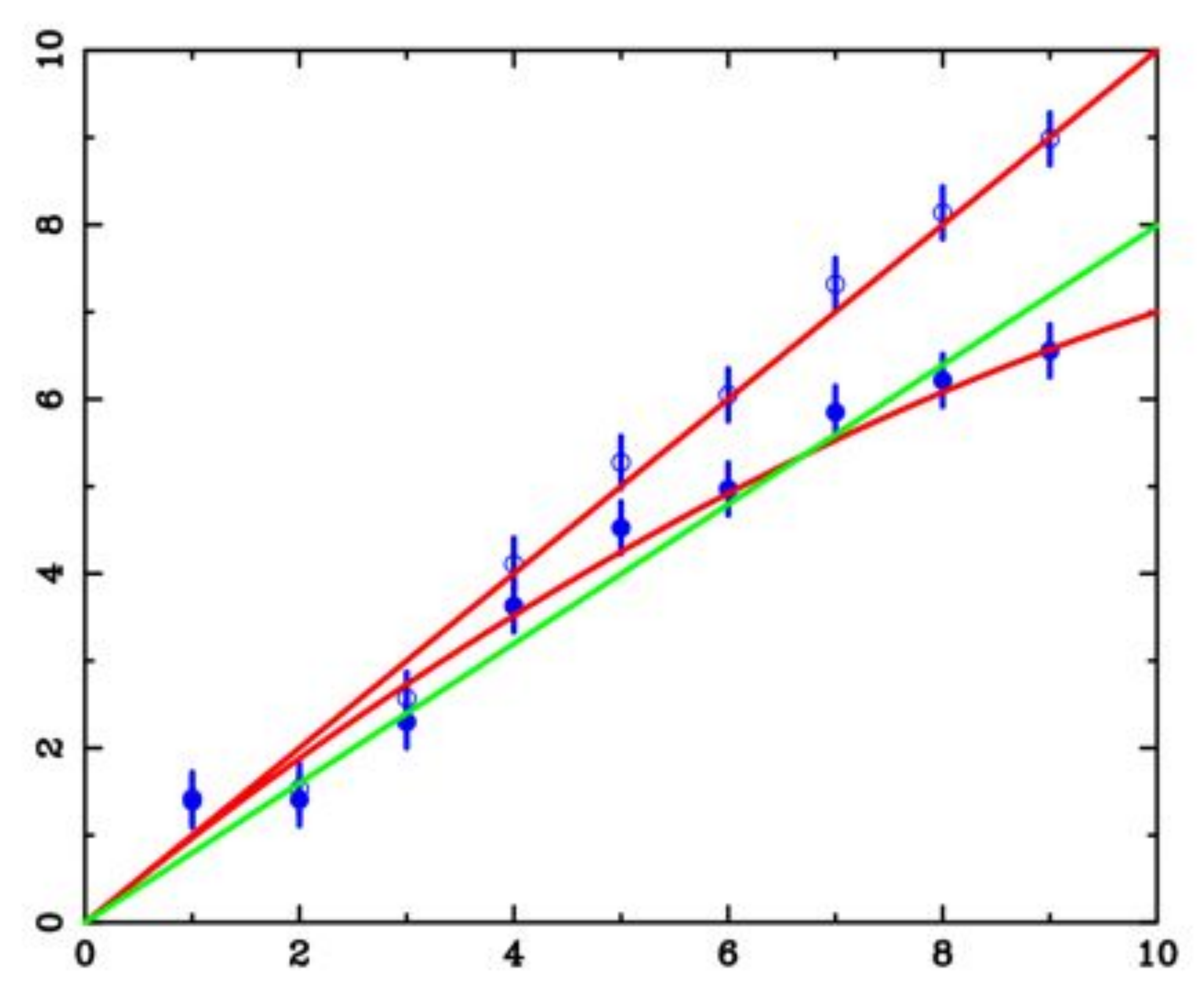
(with Jose Bernal, University of Barcelona)

Explaining case of trying to explain one parameter from multiple datasets − but it generalises

The wisdom of Donald Rumsfeld (2002)

"There are known knowns. There are things we know that we know. There are known unknowns. That is to say, there are things that we now know we don't know. But there are also unknown unknowns. There are things we do not know we don't know"

Illustrative example



Model: $y = a\,x$

Plus systematic $dy = b\,x^2$

− looks like shift in a plus high χ^2

− linear systematics completely undetectable internally

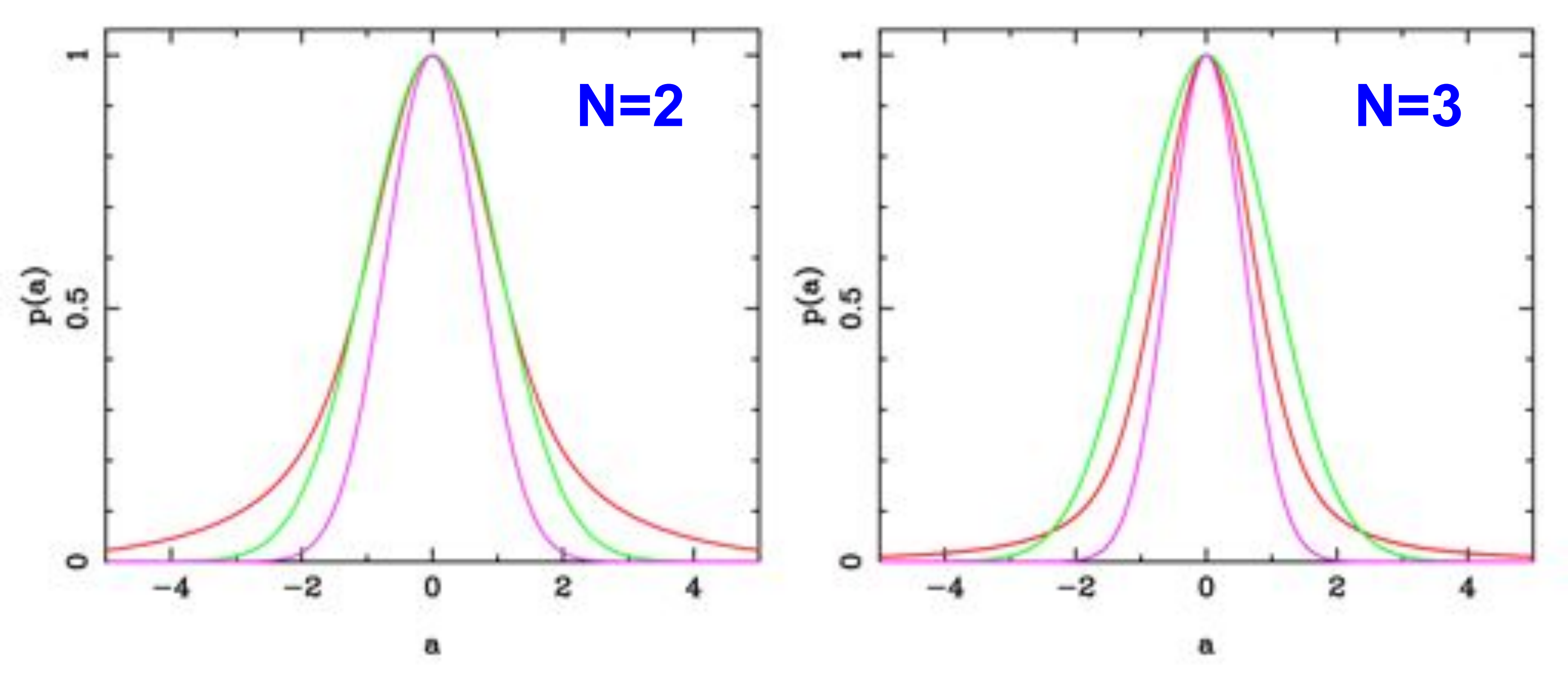
Marginalising over shifts and error scaling

$$L(a) \propto \prod_i \alpha_i^{n_i/2} \exp[-\alpha_i \chi_i^2/2] \; p_i[\alpha_i^{1/2}(a - a_i + \Delta_i)]$$

- May still rescale χ^2 if too high (fails null tests)
  - but normally a small correction
- Assume all experiments equally likely to have shifts
- Shifts are drawn from a Gaussian prior
  - Need to marginalise over shifts − AND over unknown width of prior (or covariance, in n-D parameter space)

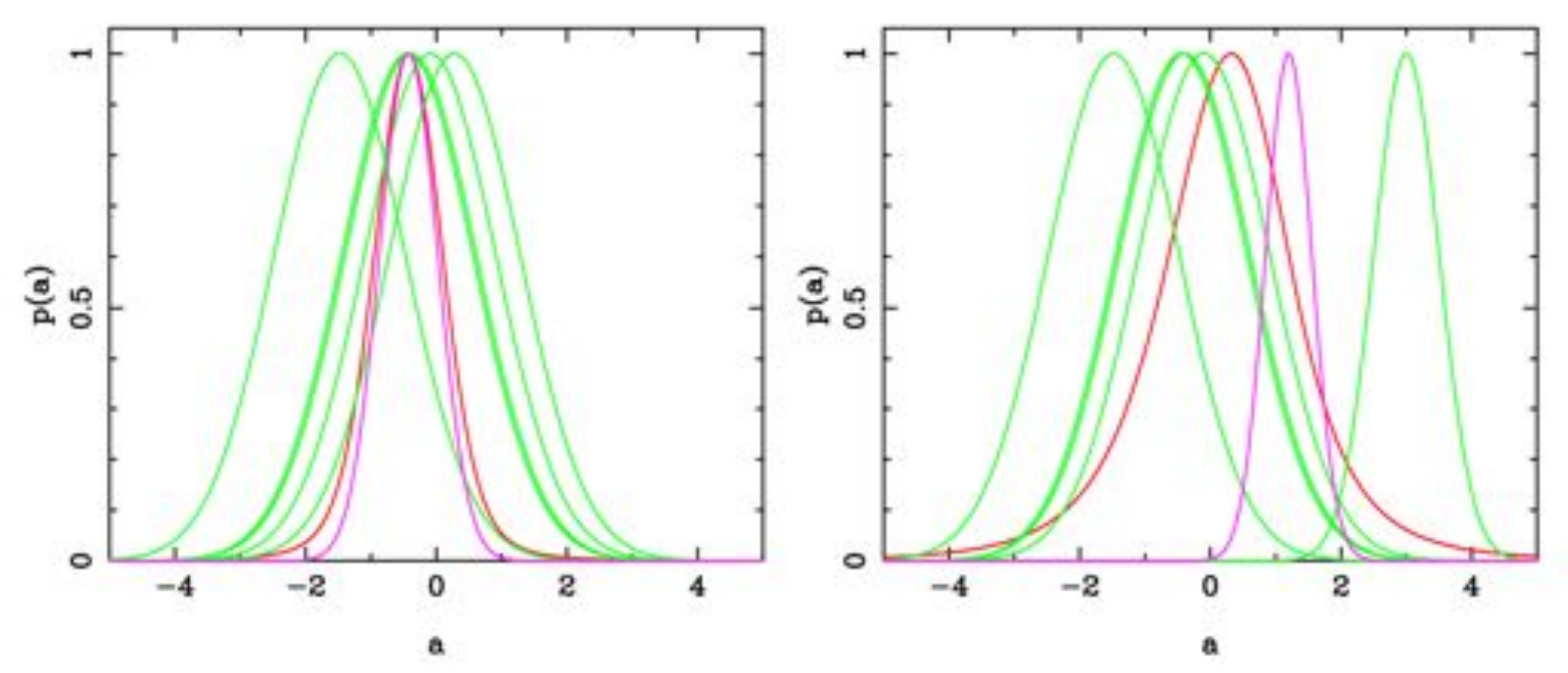
Some consequences

- One measurement tells you nothing
- Two consistent measurements doesn't give any improvement in error − just limits size of systematics
- Possibility of large systematics leads to large tails on posteriors: Prob ~ $(\Delta\, \text{par})^{1-N}$ for N datasets



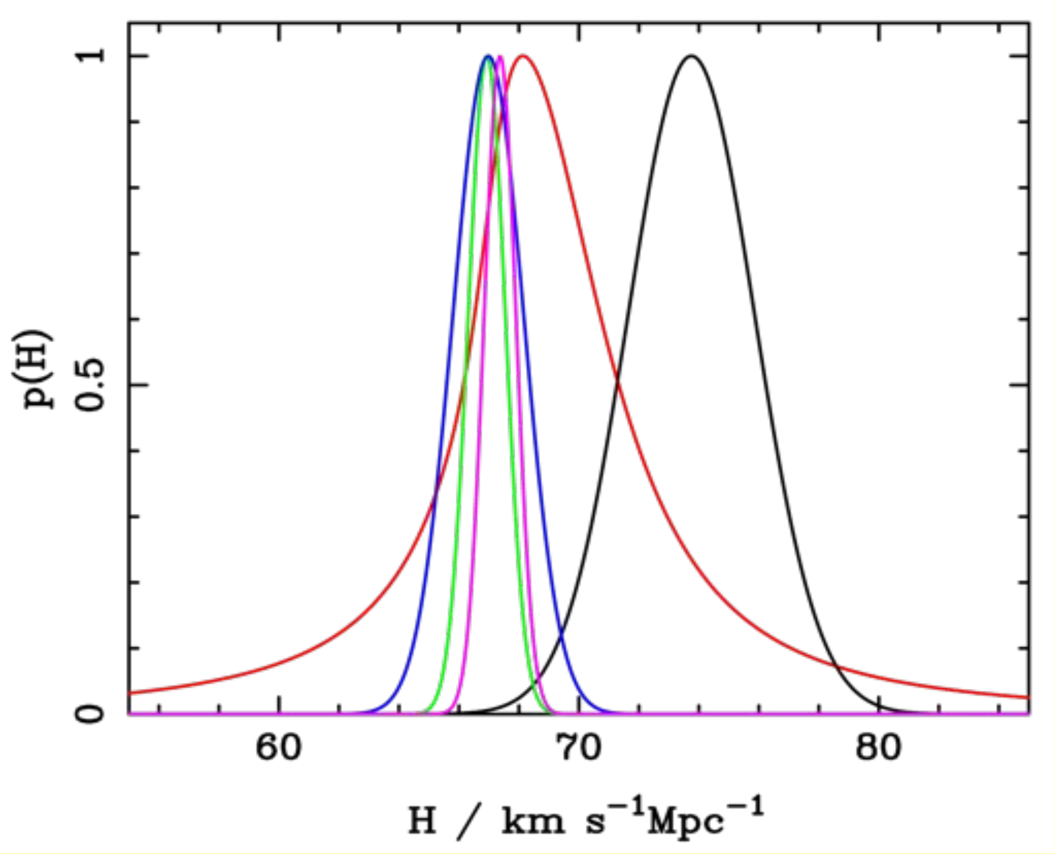
Consistent vs inconsistent

- Sufficient data can identify outliers automatically, even though prior is that all might be affected



Simple application to H_0

- 73.75 ± 2.11 (Riess et al. Cepheids++); 66.93 ± 0.62 (Planck CMB); 66.98 ±1.18 (Addison et al. BAO+BBN).

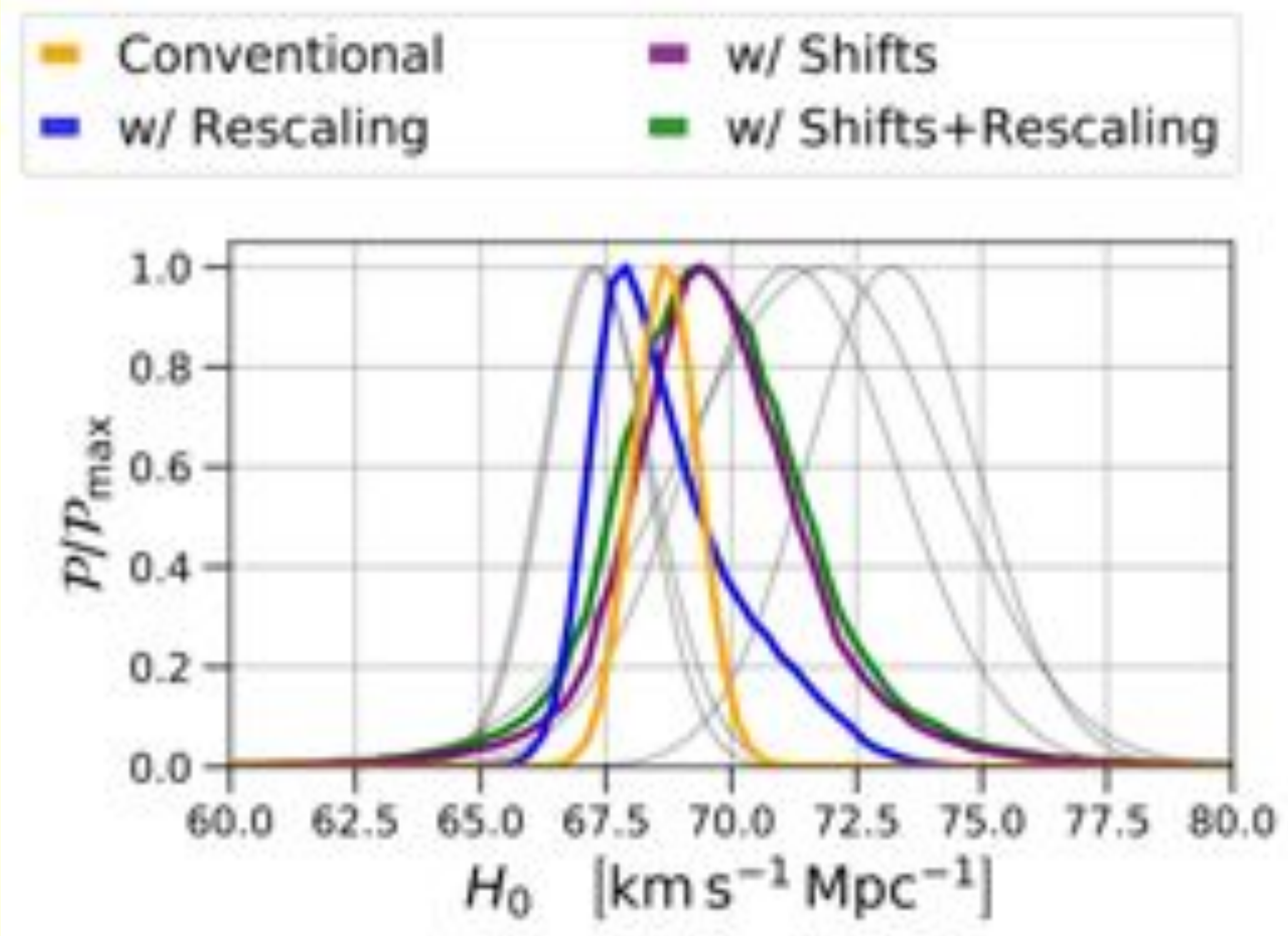


68% confidence: 65.2 – 73.2; 95% confidence: 57.0 – 84.2 !

Need more data to remove tails − value in modest accuracy experiments

Application to H_0 – more

- + DES; H0LICOW



68% confidence: 68.0 – 71.5; 95% confidence: 65.6 – 74.3

Conclusions

- Large-areas surveys important in fundamental cosmology
  - Establishing and validating ΛCDM as the standard model
  - 10x improvement in precision due over next decade
  - Systematics will be the dominant issue
- 'Unknown unknowns' can be treated
  - 'Guilty till proven innocent' principle
  - Must allow for shifts in parameter space
  - Realistic degree of precision is less than we thought
- Will we have the theoretical courage to believe radical results?

Thanks Jas

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