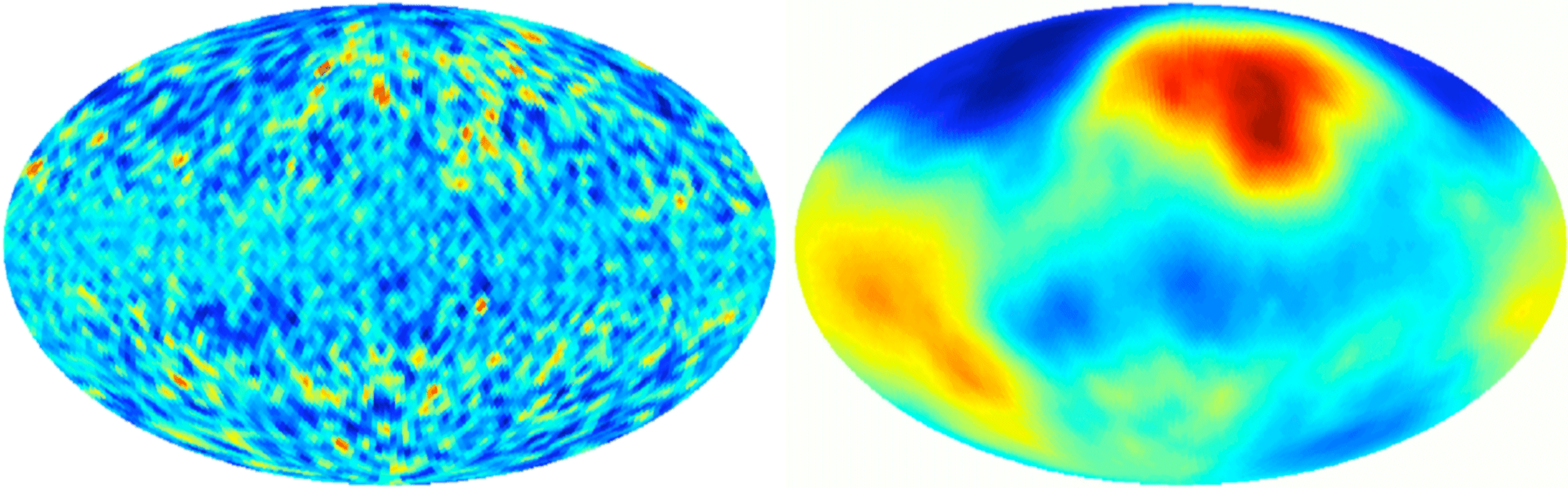
Probing Gravity with Galaxy Surveys



John Peacock Benasque 2 August 2010

Outline

- Motivation and targets

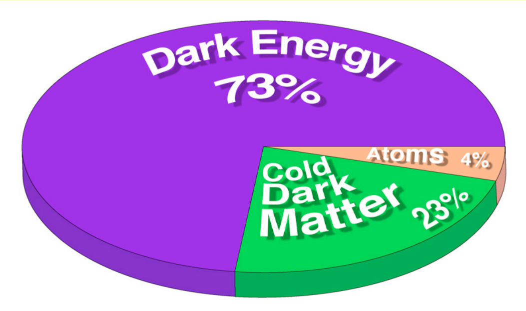
- The ISW foreground: estimation from 2MASS galaxies and photometric redshifts and implications for CMB anomalies

- Redshift-space distortions and the growth of density fluctuations

- Results from the GAMA survey and future prospects

Why modify gravity?

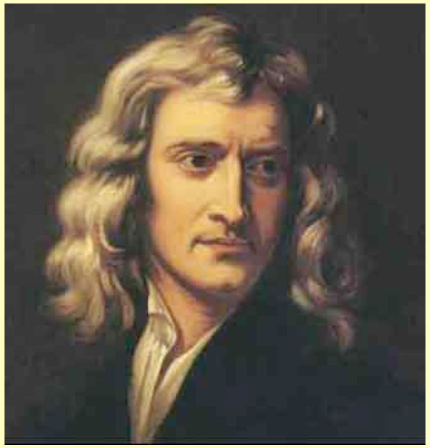
Better to prove GR correct, rather than just assume it

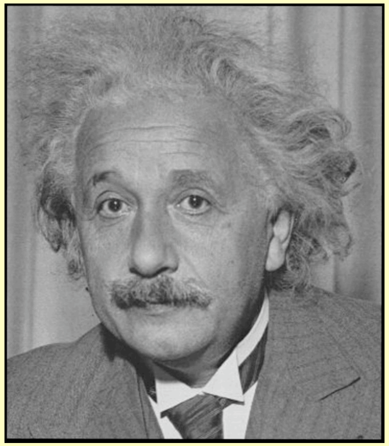


Dark energy: all current measurements relate to expansion rate, assuming H(z) comes from GR Friedmann equation

$$H^2(z) = H^2_0 \left[(1-\Omega)(1+z)^2 + \Omega_M (1+z)^3 + \Omega_R (1+z)^4 + \Omega_{DE} (1+z)^{3(1+w)} \right]$$

Curvature — matter — radiation — extra term from non-GR?





?

When is GR not GR?

- Definition of GR: write covariant equations
- Needs metric connection for general 4-vectors

$$\frac{d^2x^\mu}{d\tau^2} = 0 \rightarrow \frac{d^2x^\mu}{d\tau^2} + \Gamma^\mu_{\alpha\beta} U^\alpha U^\beta = 0$$

- RW metric comes entirely from symmetry
- Einstein gravity from Lagrangian

$$S = \int \mathcal{L} \sqrt{-g}\, d^4x^\mu; \quad \mathcal{L} = \mathcal{L}_{\mathrm{matter}} + (R + 2\Lambda)/16\pi G$$

- Generalise to e.g. f(R) Lagrangian
  - Still consistent with the principle of GR
- But want to account for dark energy without wrecking Solar System tests
  - Scope for scale dependence of gravity

Phenomenology of modified gravity

- Adopt longitudinal gauge (in effect gauge-invariant)

$$d\tau^2 = (1+2\Psi)dt^2 - (1-2\Phi)\gamma_{ij}\,dx^i\,dx^j$$

$$\text{Einstein: } \nabla^2\Phi/a^2 = 4\pi G\,\bar{\rho}\,\delta \text{ and } \Psi = \Phi$$

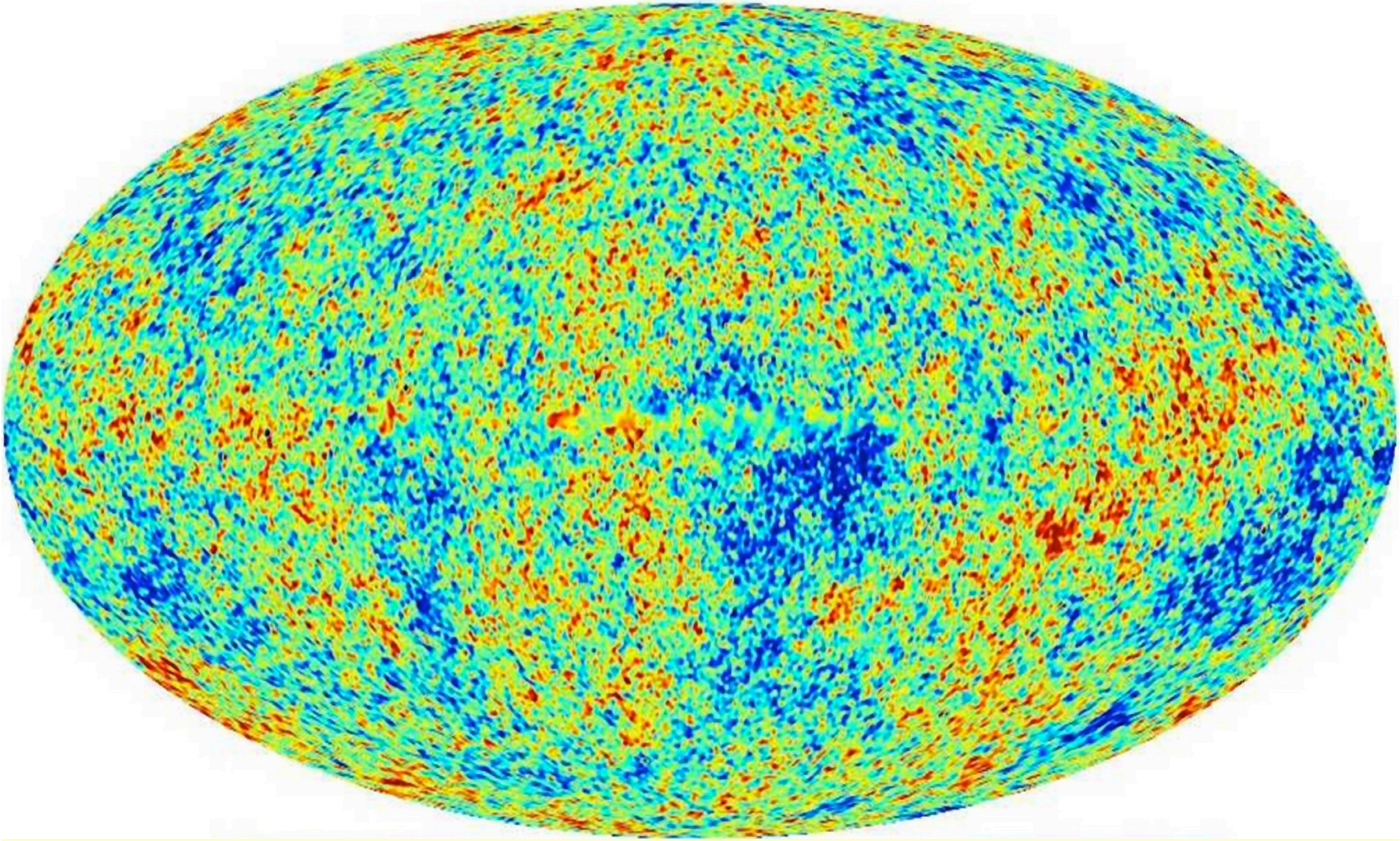
- In MG, potentials can differ (‘slip’: affects lensing), plus Poisson equation is modified.
- No standard notation. Good refs are Skordis (0806.1238) or Daniel et al. (1002.1962). Assume modifications negligible at high z, since no DE then:

$$\Phi = (1+\varpi(a,k))\Psi; \qquad \nabla^2\Phi = \mu(a,k)\,4\pi G\,\bar{\rho}\,\delta$$

- Combine to affect growth of fluctuations

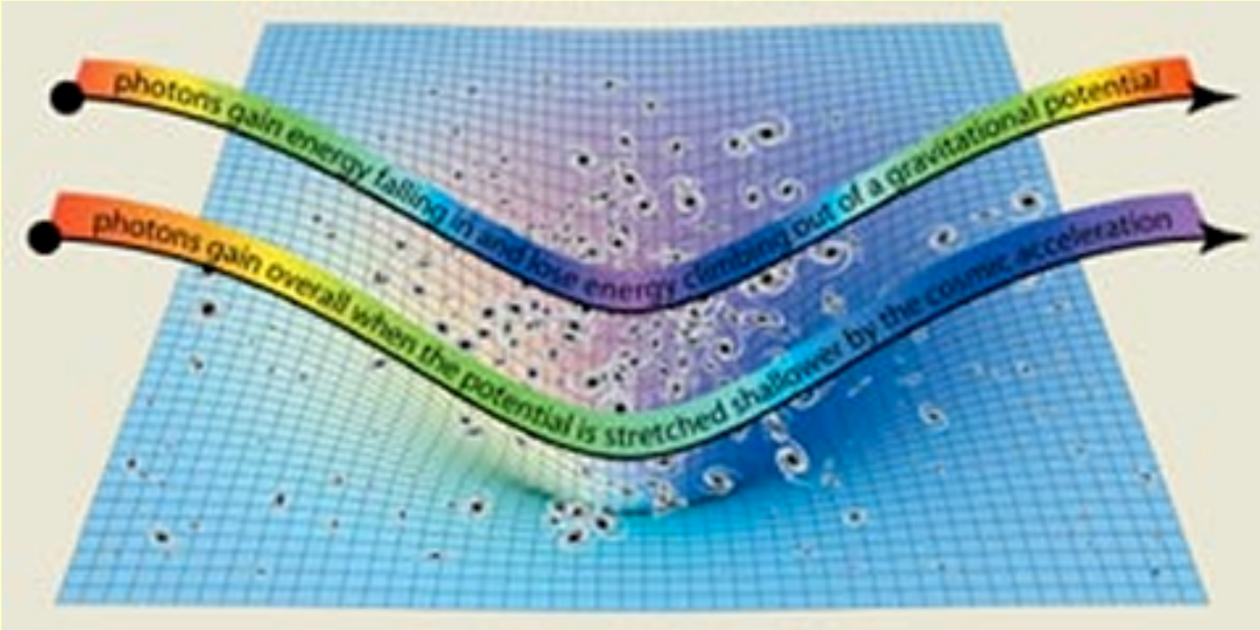
$$d\ln\delta/d\ln a \simeq \Omega_m(a)^\gamma; \qquad \gamma_{\rm Einstein} = 0.55$$

Testing gravity with CMB foregrounds



Metric fluctuations at z = 1100, but with additional foregrounds at z < 1

Integrated Sachs-Wolfe effect

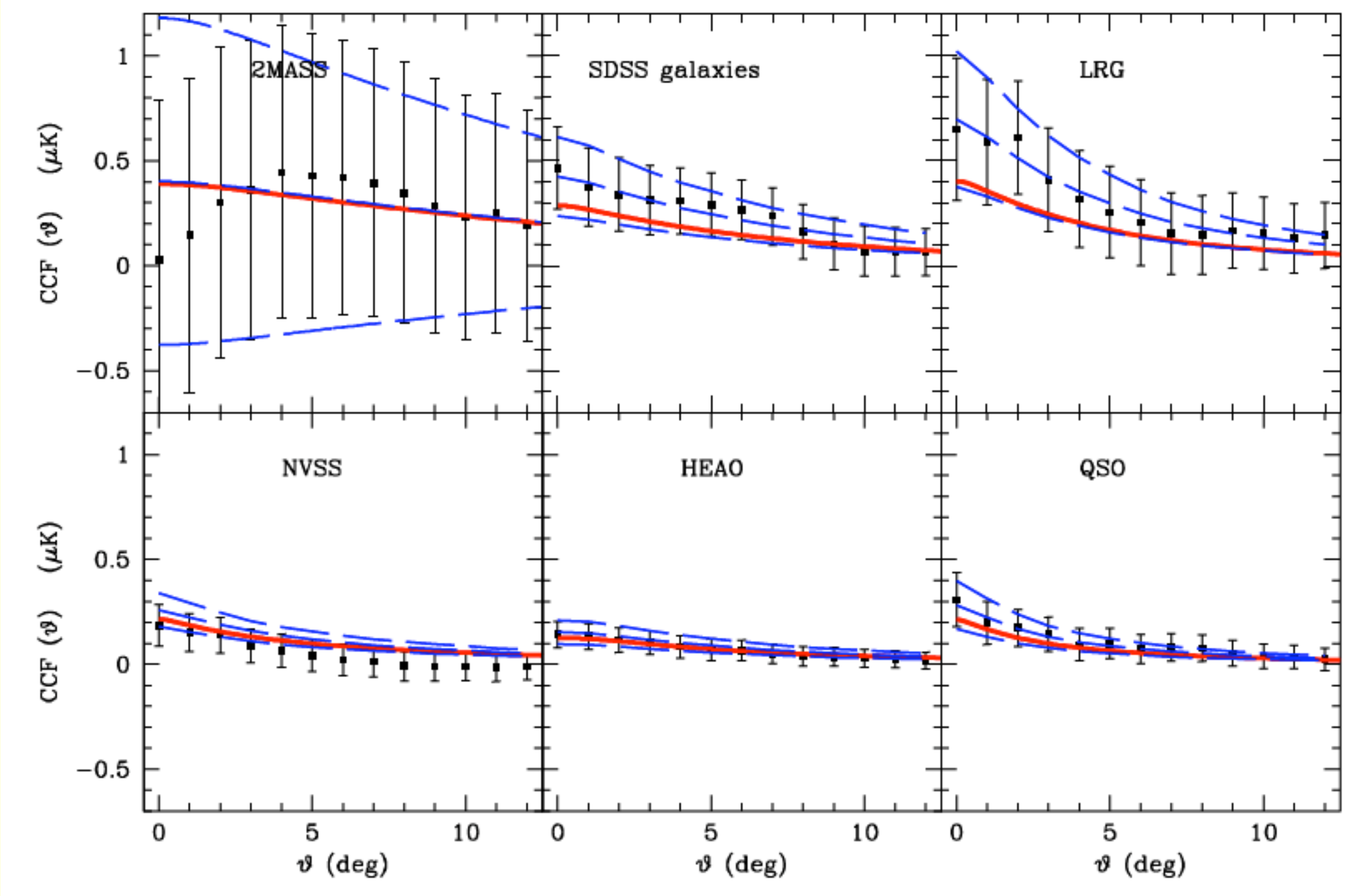


$$\frac{\Delta T^{\mathrm{ISW}}}{T_{\mathrm{CMB}}} = 2\int_{t_{\mathrm{LS}}}^{t_0} \frac{\dot{\Phi}(\vec{x}(t),t)}{c^2}\,\mathrm{d}t; \quad (\Psi + \Phi \to 2\Phi)$$

$$\frac{\Delta T_{\ell m}}{T} = -2\int \frac{d}{dt}\left[\frac{g(a)}{a}\right] \frac{a^2\Phi_{\ell m}(a)}{g(a)} \frac{dr}{c^3}$$

Large-scale (linear) effect. Integrate potential, using Poisson to relate to density field

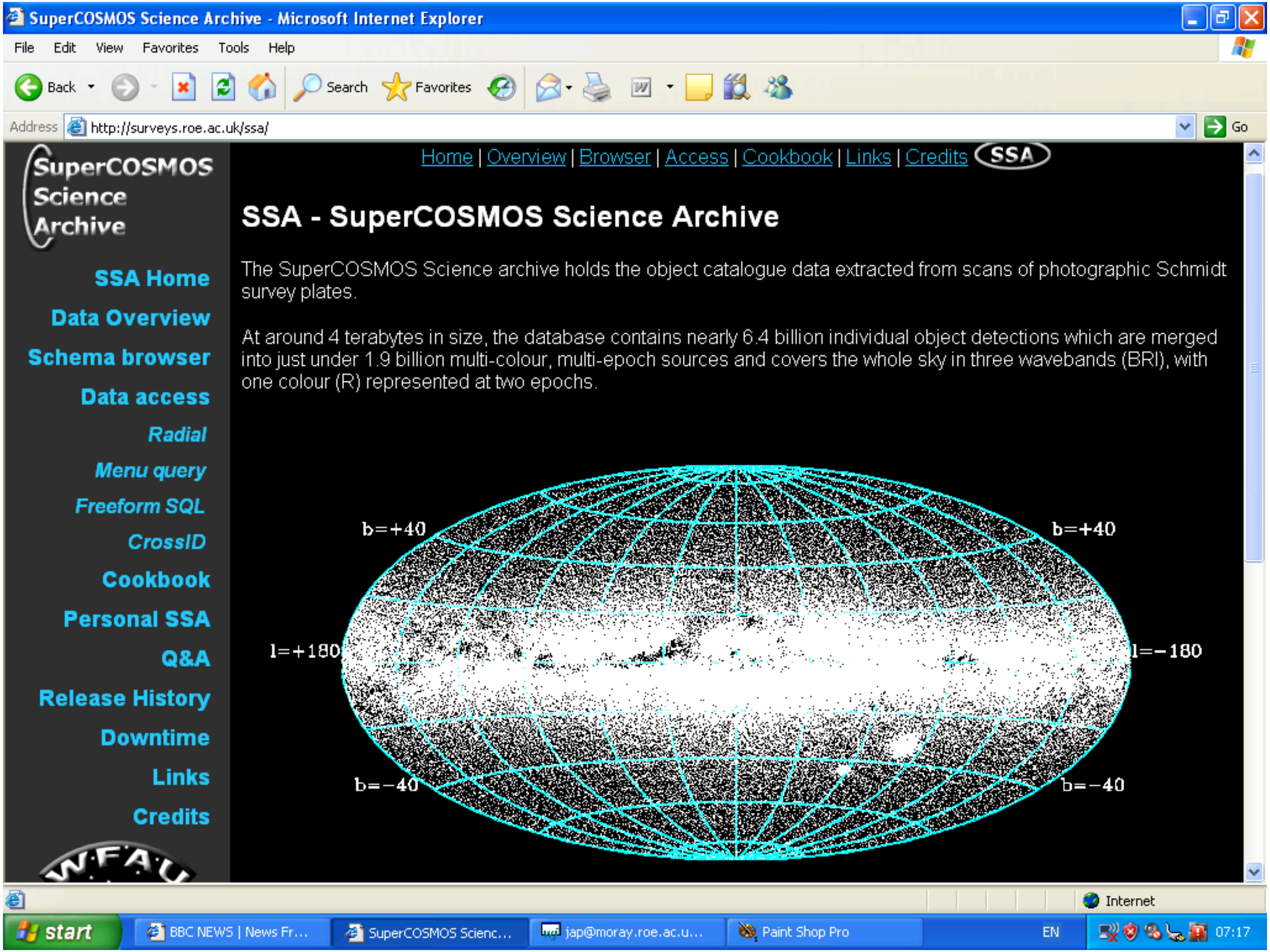
Giannantonio et al. 0801.4380



Claim >4 σ detection of ISW, combining various samples

ISW with 2MASS:
a tomographic study

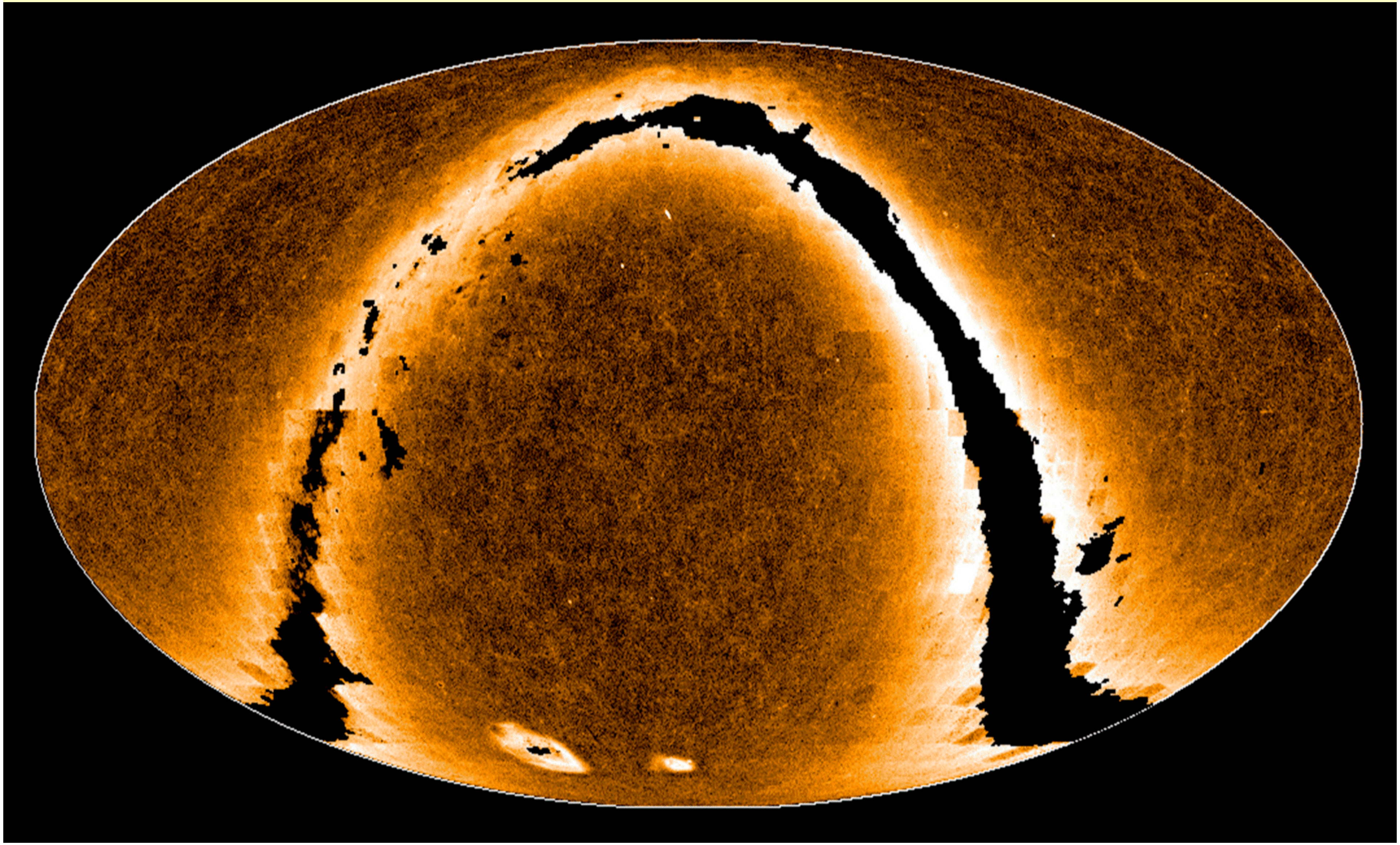
(Caroline Francis PhD:
see also 0909.2494 and 0909.2495)


SuperCOSMOS Science Archive - Microsoft Internet Explorer
File Edit View Favorites Tools Help
Back Search Favorites
Address http://surveys.roe.ac.uk/ssa/ Go
Home | Overview | Browser | Access | Cookbook | Links | Credits SSA
SuperCOSMOS Science Archive
SSA Home
Data Overview
Schema browser
Data access
Radial
Menu query
Freeform SQL
CrossID
Cookbook
Personal SSA
Q&A
Release History
Downtime
Links
Credits
WFAU
SSA - SuperCOSMOS Science Archive
The SuperCOSMOS Science archive holds the object catalogue data extracted from scans of photographic Schmidt survey plates.
At around 4 terabytes in size, the database contains nearly 6.4 billion individual object detections which are merged into just under 1.9 billion multi-colour, multi-epoch sources and covers the whole sky in three wavebands (BRI), with one colour (R) represented at two epochs.
b=+40
b=+40
l=+180
l=−180
b=−40
b=−40
Internet
start
BBC NEWS | News Fr...
SuperCOSMOS Scienc...
jap@moray.roe.ac.u...
Paint Shop Pro
EN
07:17

SuperCosmos Science Archive

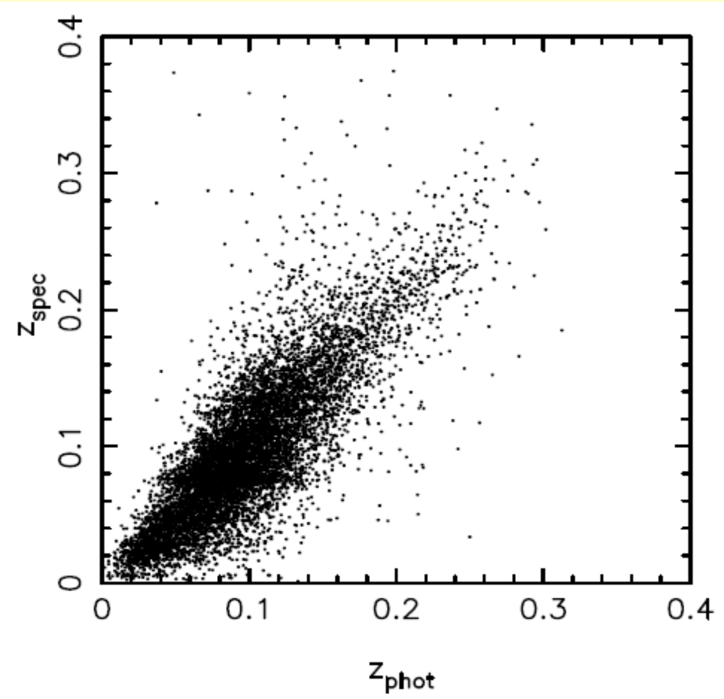
- All-sky catalogue built from scans of UKST and POSS2 photographic plates
- ~100 million galaxies to depths B = 21.8, R = 20.5
- Calibrated using SDSS and plate overlaps: photometry linear to ~ 1%
- Large-scale zero-point drifts eliminated using homogeneity of optical – 2MASS colours

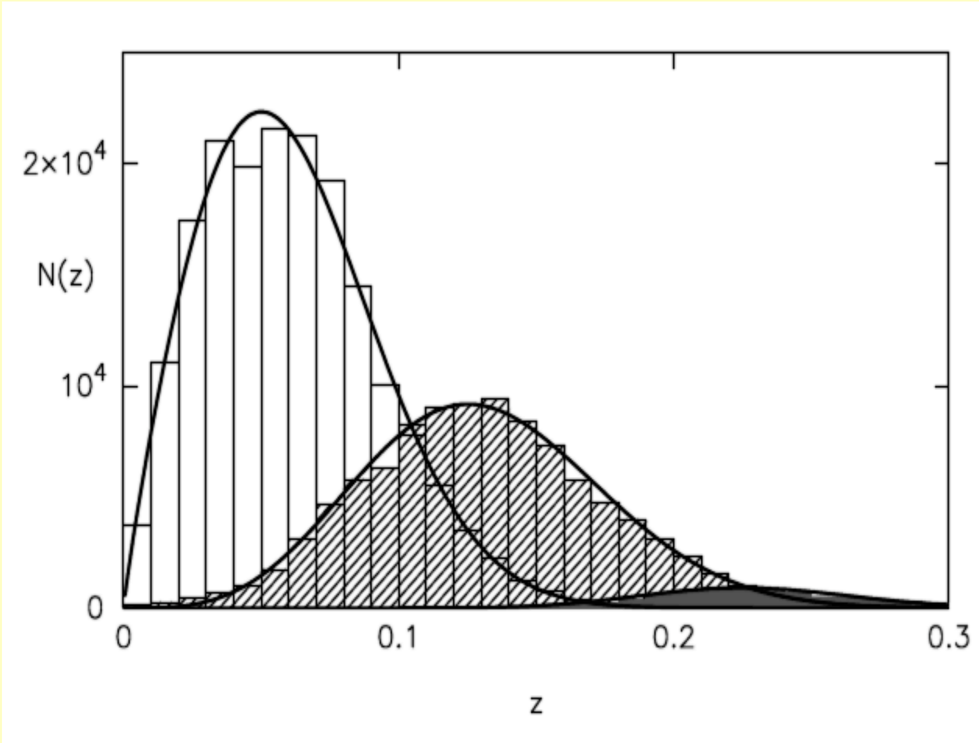
10^8 All-sky galaxies: SuperCOSMOS UKST + POSS2



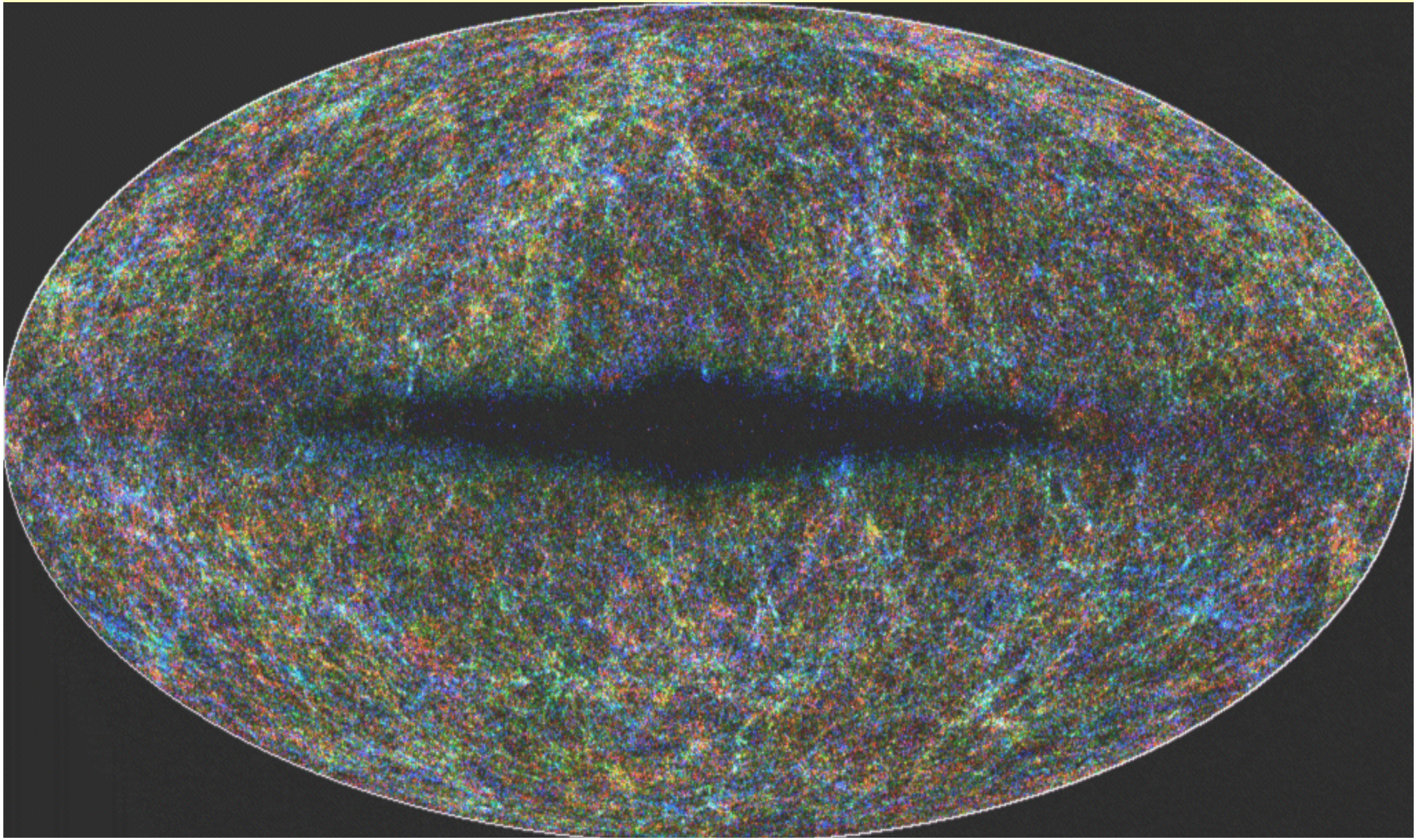
2MASS Photo-z estimation

- All-sky XSC: 1.6 million galaxies
- Match with SuperCOSMOS photographic photometry
- BRJHK ⇒ $\sigma_z / (1+z) = 0.033$

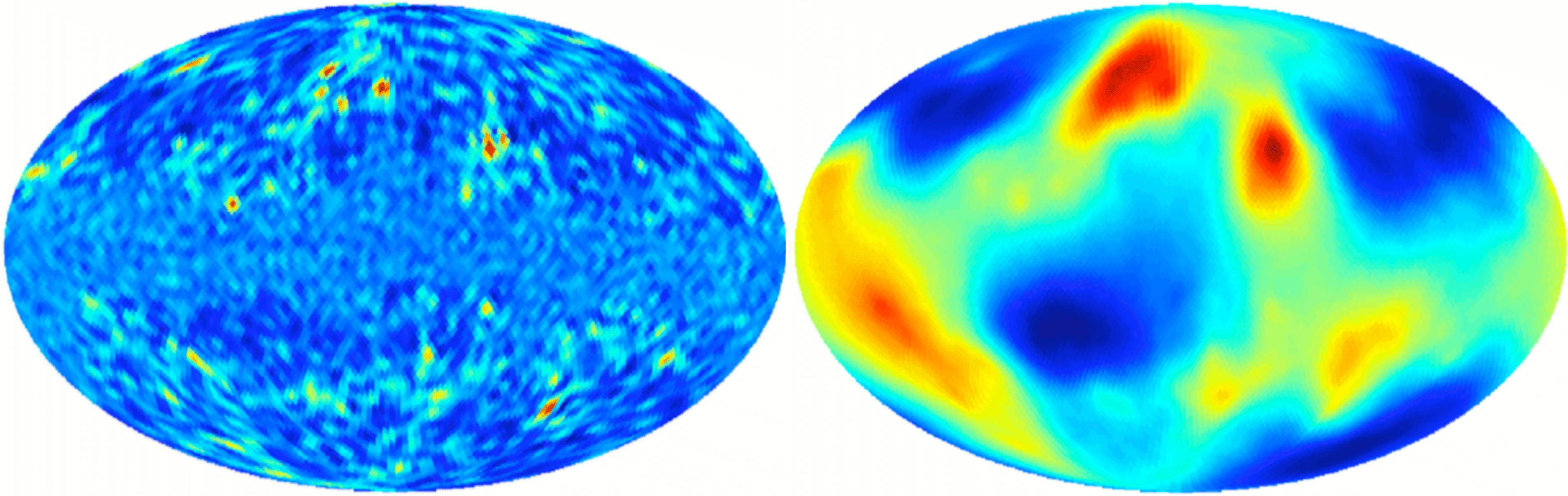




2MASS XSC: BRJHK photoz map

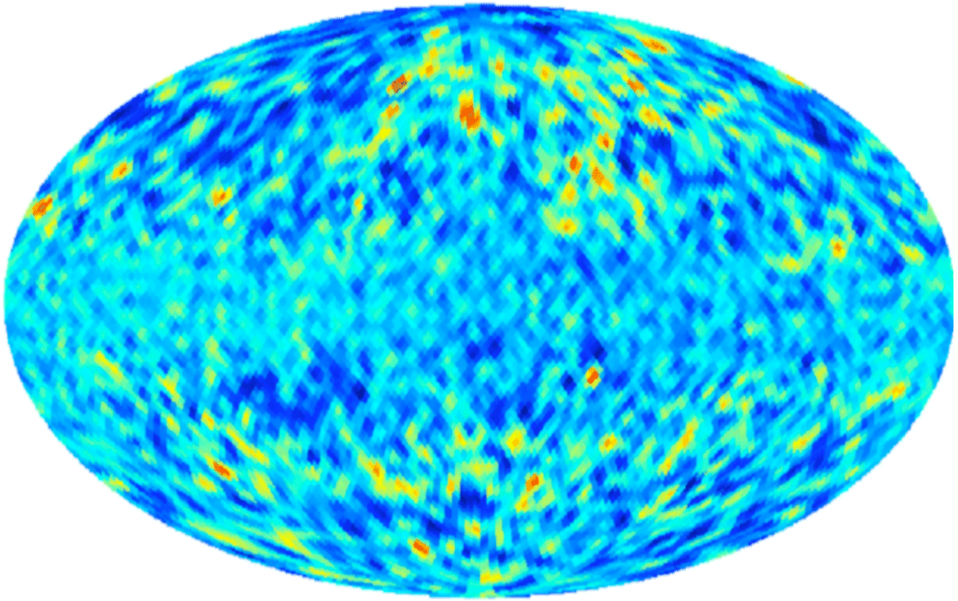


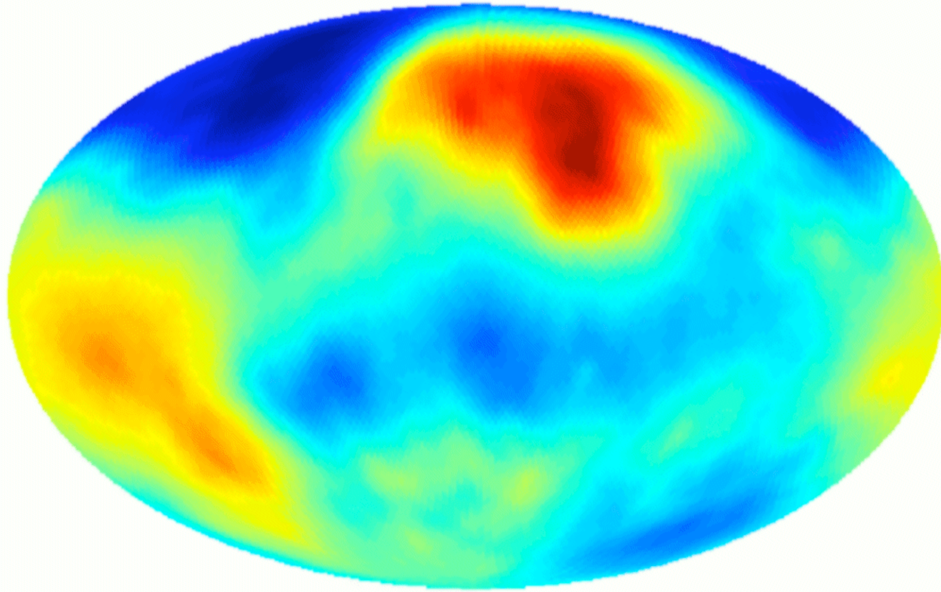
‘Observed’ ISW map: $z < 0.1$



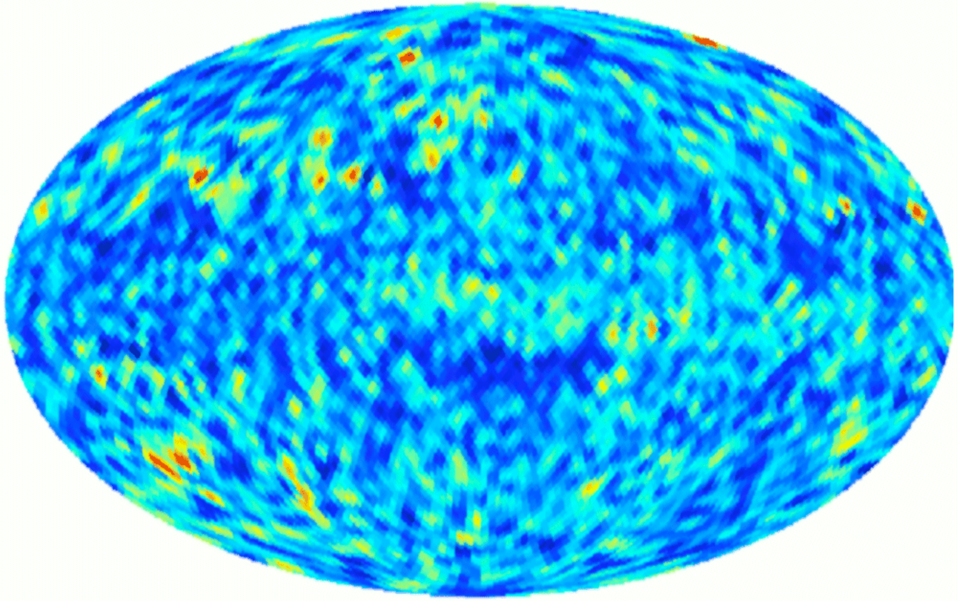
Fill in zone of avoidance using iterative Wiener filtering

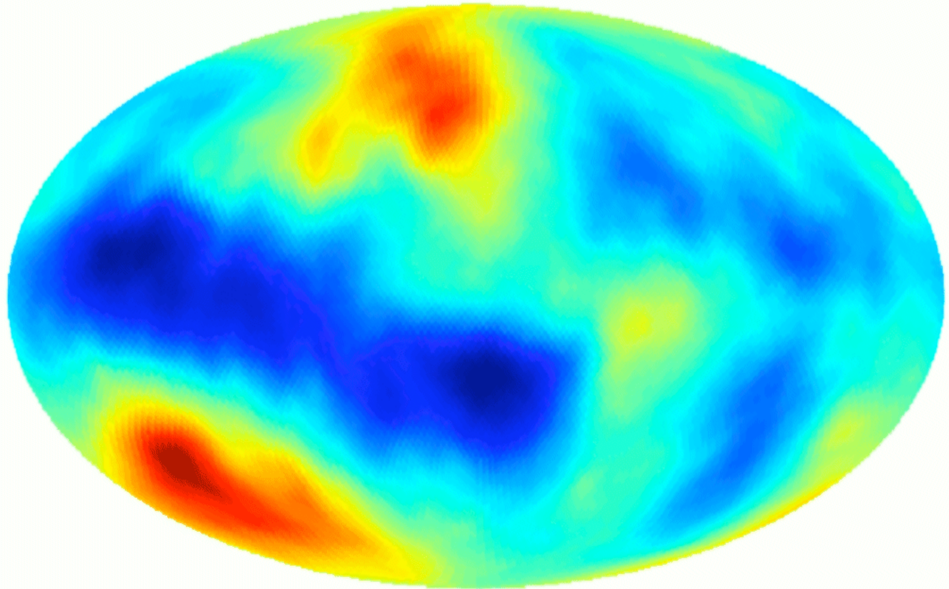
‘Observed’ ISW map: 0.1 < z < 0.2



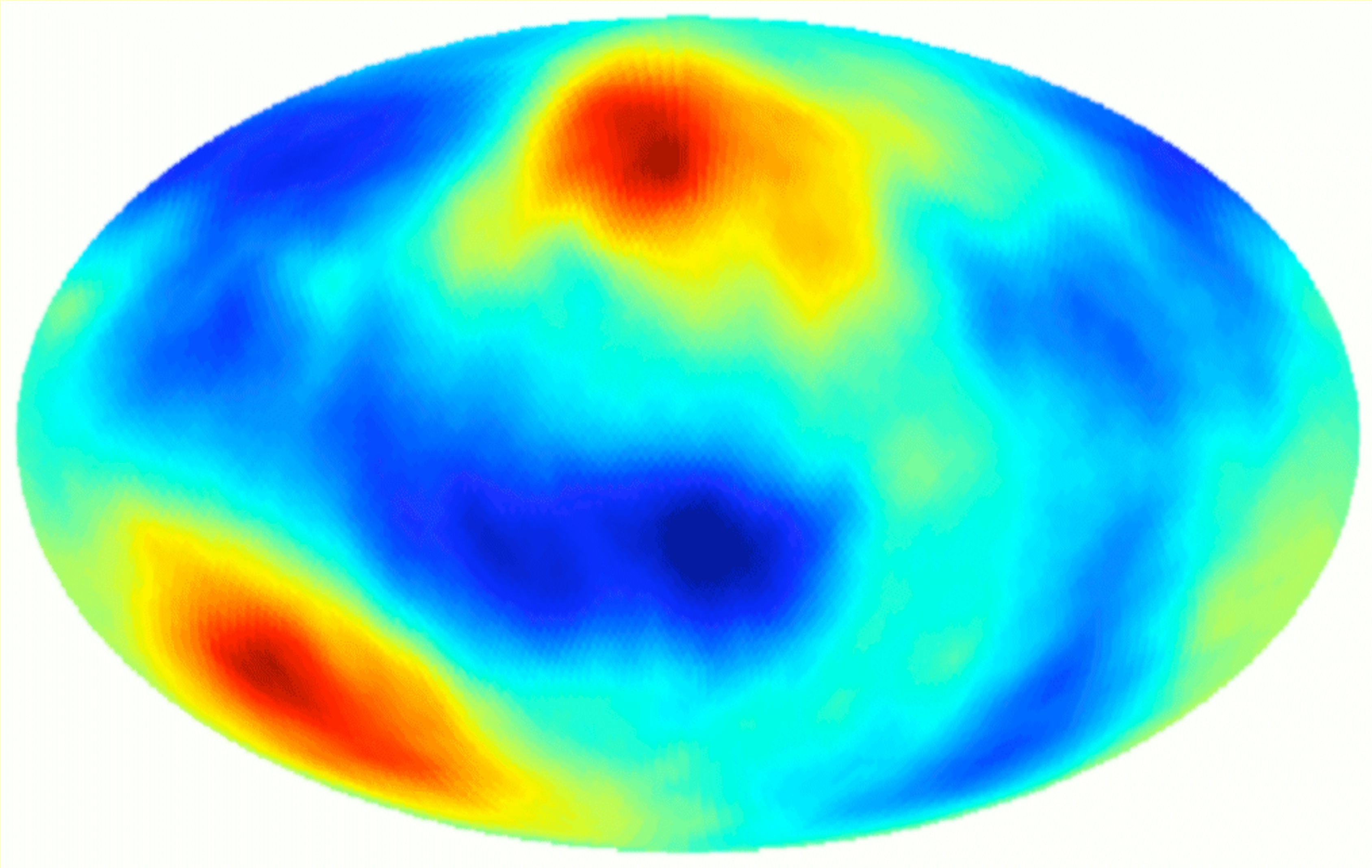


‘Observed’ ISW map: $0.2 < z < 0.3$





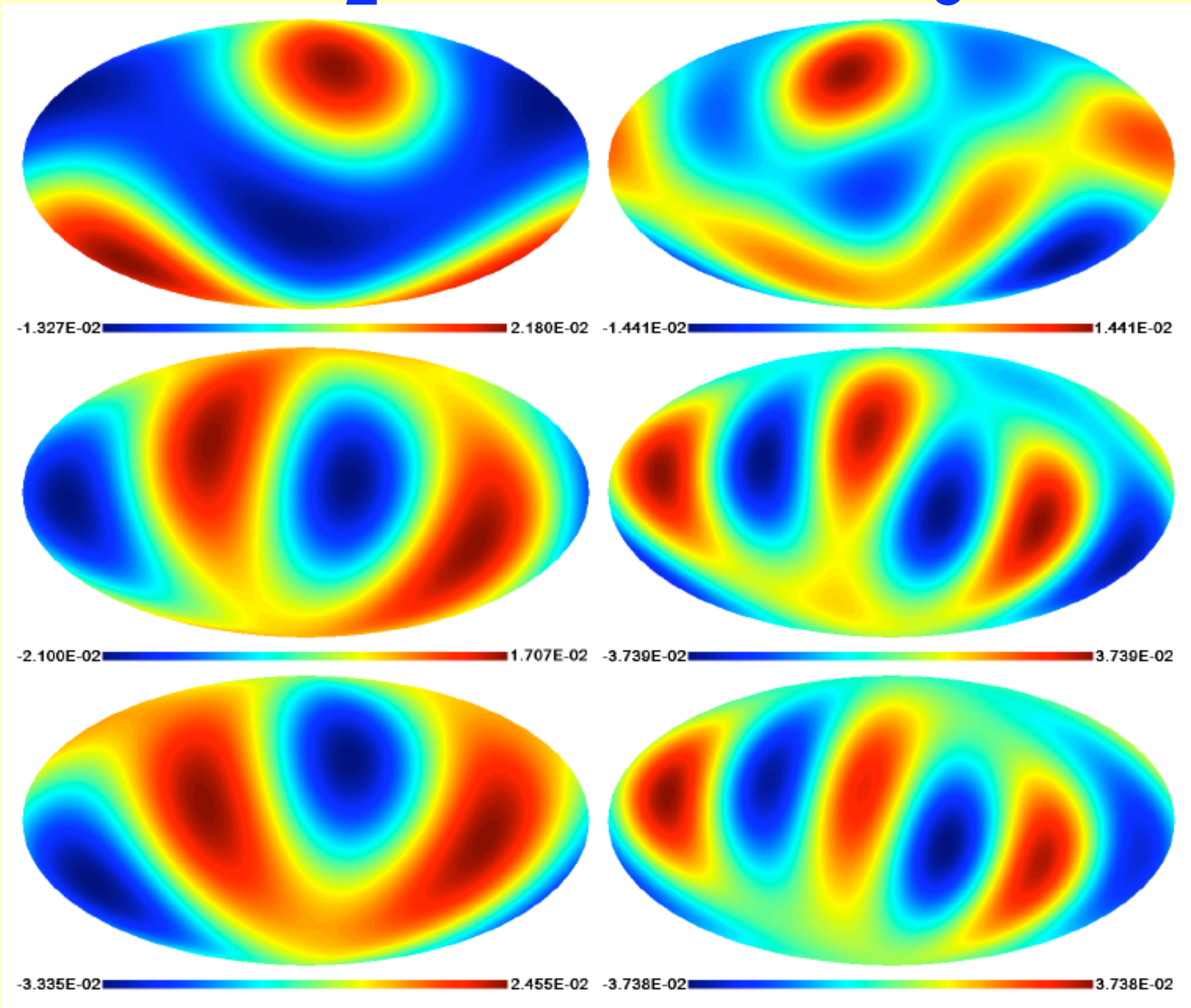
‘Observed’ ISW map: z < 0.3



rms 12 μK: 40% of $z_{max} \to \infty$ figure (cf. 80 μK for total CMB)

Effect on low-` ‘anomalies’

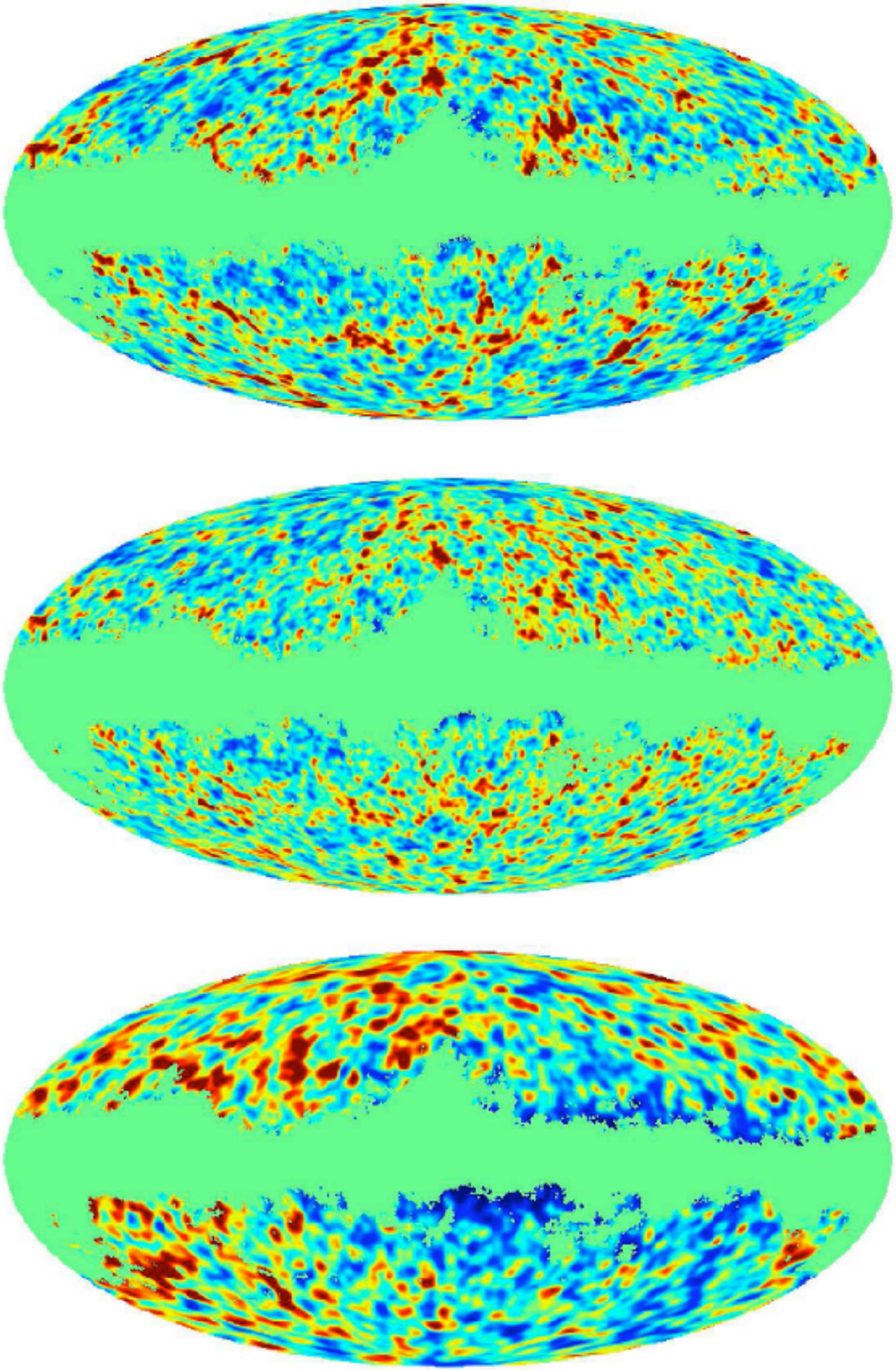
` = 2        ` = 3



ISW

WMAP

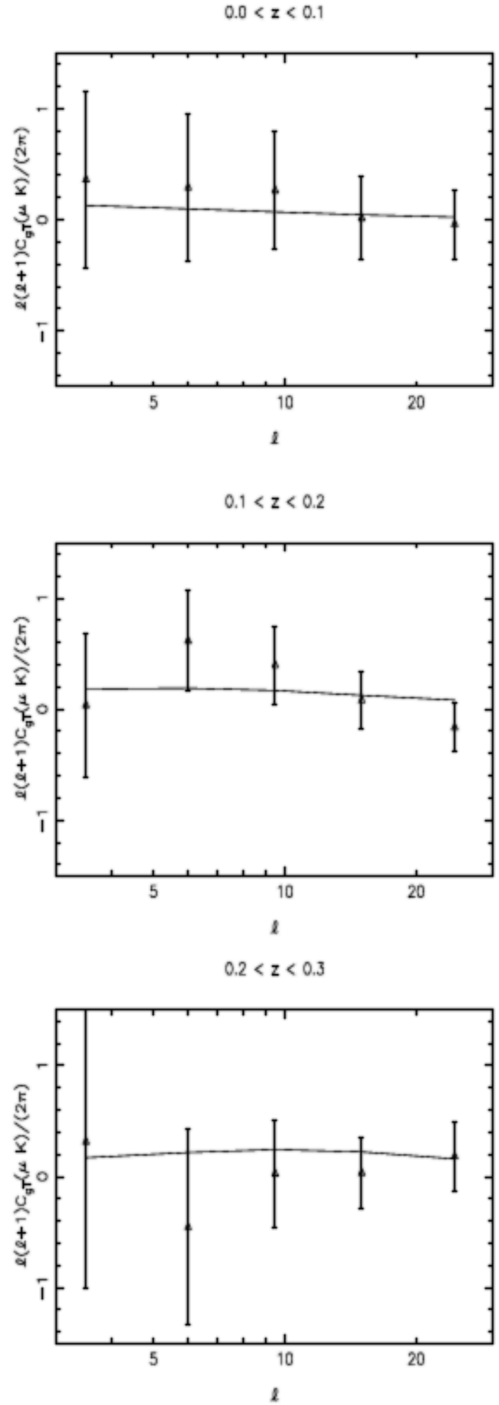
P < 1% →
P ~ 10%



2MASS:

no detection from harmonic space cross-correlation in redshift bands

(Caroline Francis); see also Rassat et al. 2006



Type I vs Type II errors

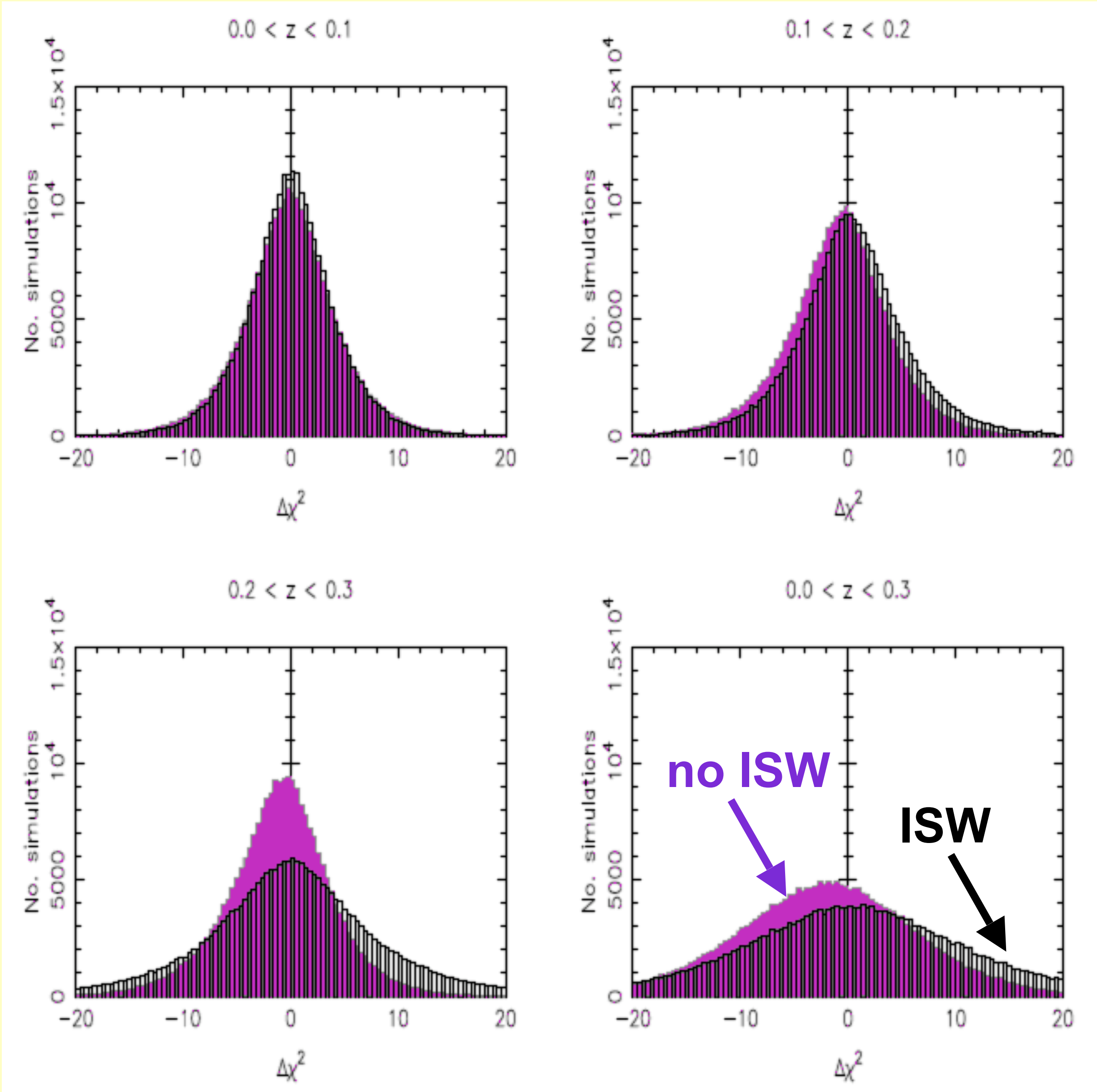
		Truth	
		1	2
Hypothesis	1	χ^2	χ^2
	2	χ^2	χ^2

1 = ISW

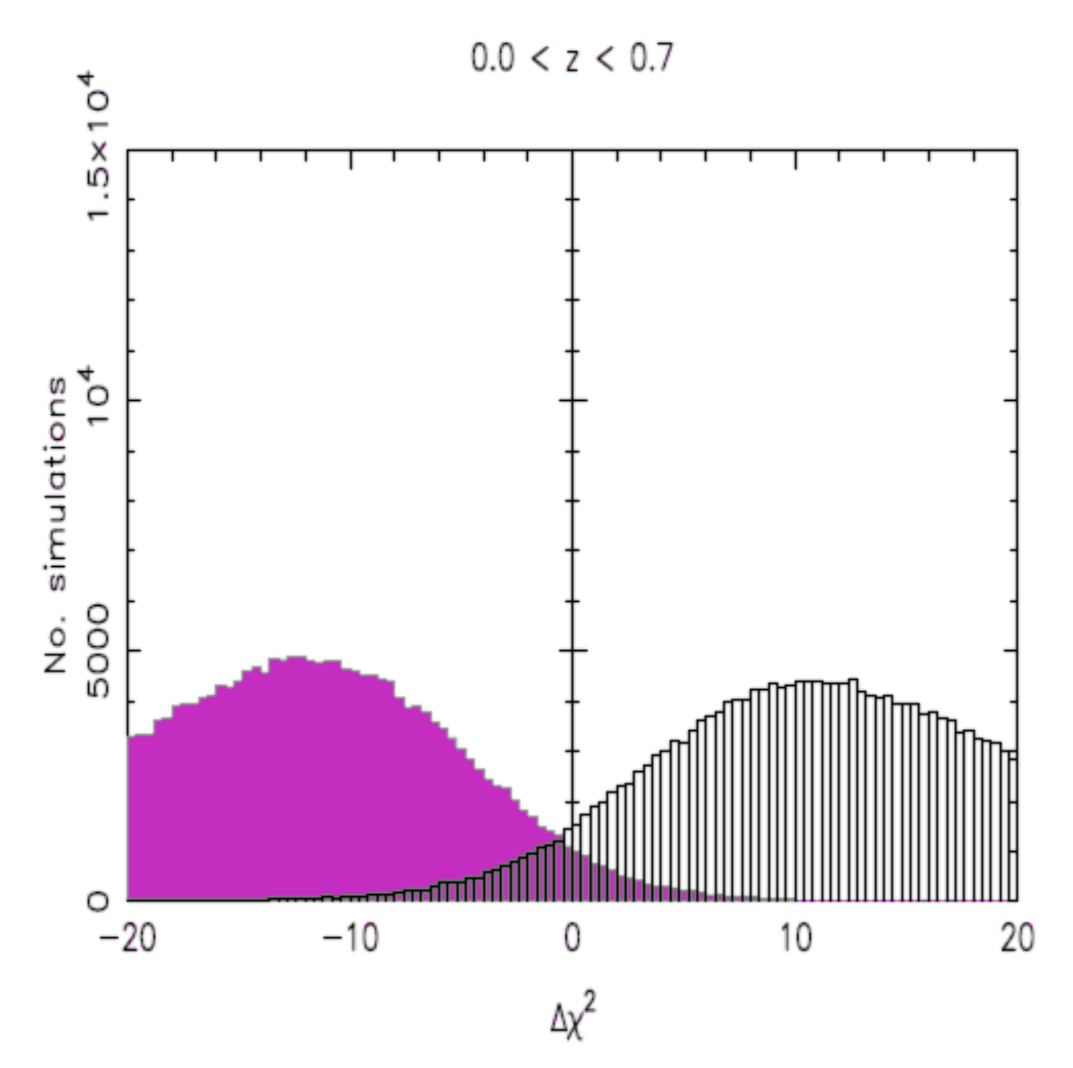
2 = no ISW

A powerful experiment would have $\Delta\chi^2$ favouring 1 if 1 is true and 2 if 2 is true

Realizations of type I & Type II errors



Almost perfect (masked) data



Probability of non-detection ~ 15%

So what use is ISW?

Detective: **"Is there any other point to which you would wish to draw my attention?“**

Holmes: **"To the curious incident of the dog in the night-time."**

Detective: **"The dog did nothing in the night-time."**

Holmes: **"That was the curious incident.“**

Conan Doyle: “Silver Blaze” (1892)

Non-standard growth rates can produce excessive ISW: already used to rule out low-density open models by Kamionkowski (1996)

$$\Omega_m(a) = \Omega_m a^{-3}/[\Omega_m a^{-3} + (1-\Omega_m)]; \quad \text{(flat)}$$
$$\Omega_m(a) = \Omega_m a^{-3}/[\Omega_m a^{-3} + (1-\Omega_m)a^{-2}]; \quad \text{(open)}$$

Large-scale structure in the galaxy distribution is also a direct probe of dark energy and modified gravity

Observing scales in redshift space

(1) Matter-radiation horizon:

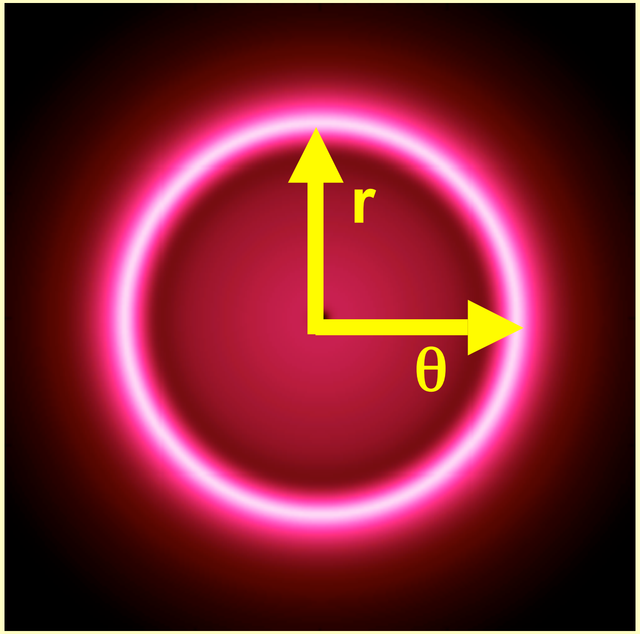
$123\ (\Omega_m h^2 / 0.13)^{-1}$ Mpc

(2) Acoustic horizon at last scattering :

$147\ (\Omega_m h^2 / 0.13)^{-0.25} (\Omega_b h^2 / 0.024)^{-0.08}$ Mpc

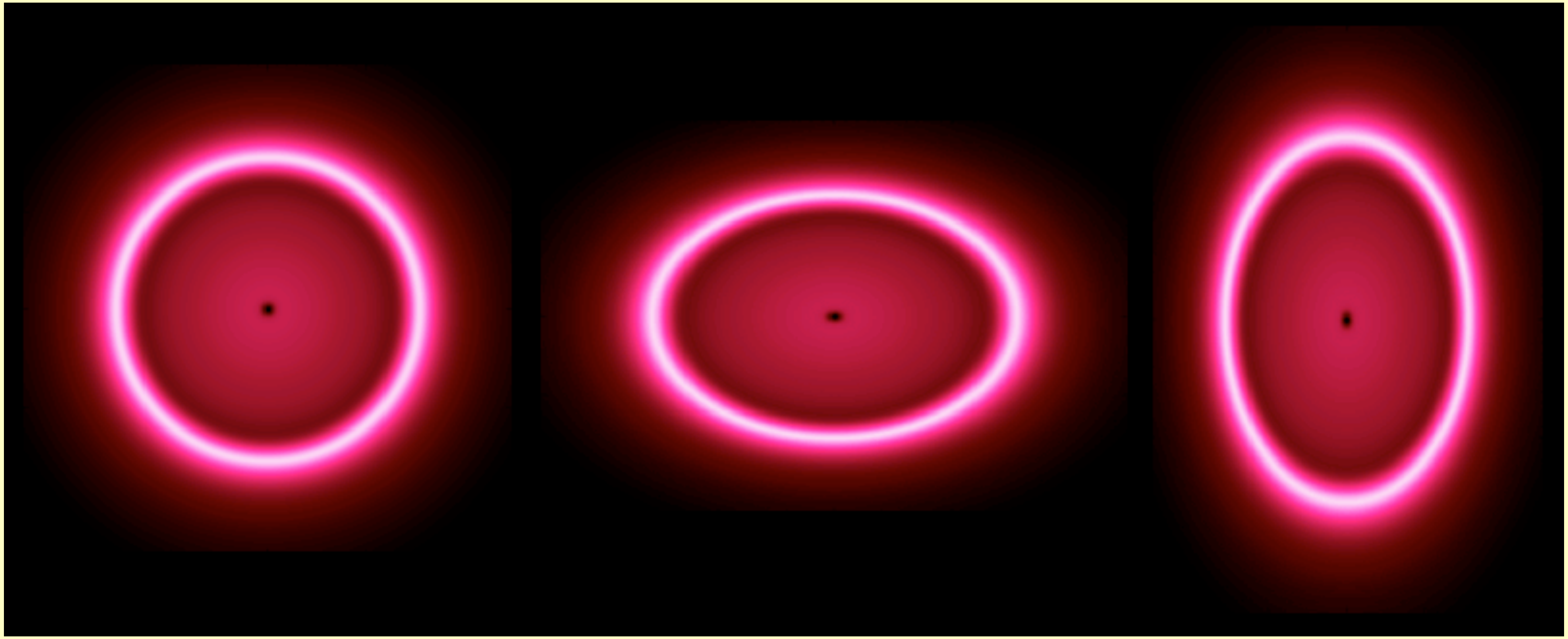
Observe transversely or radially:

$\theta = L / D(z)$ or $dz = L / [c/H(z)]$



Assume average scale depends on $D_V = (D^2 [c/H])^{1/3}$

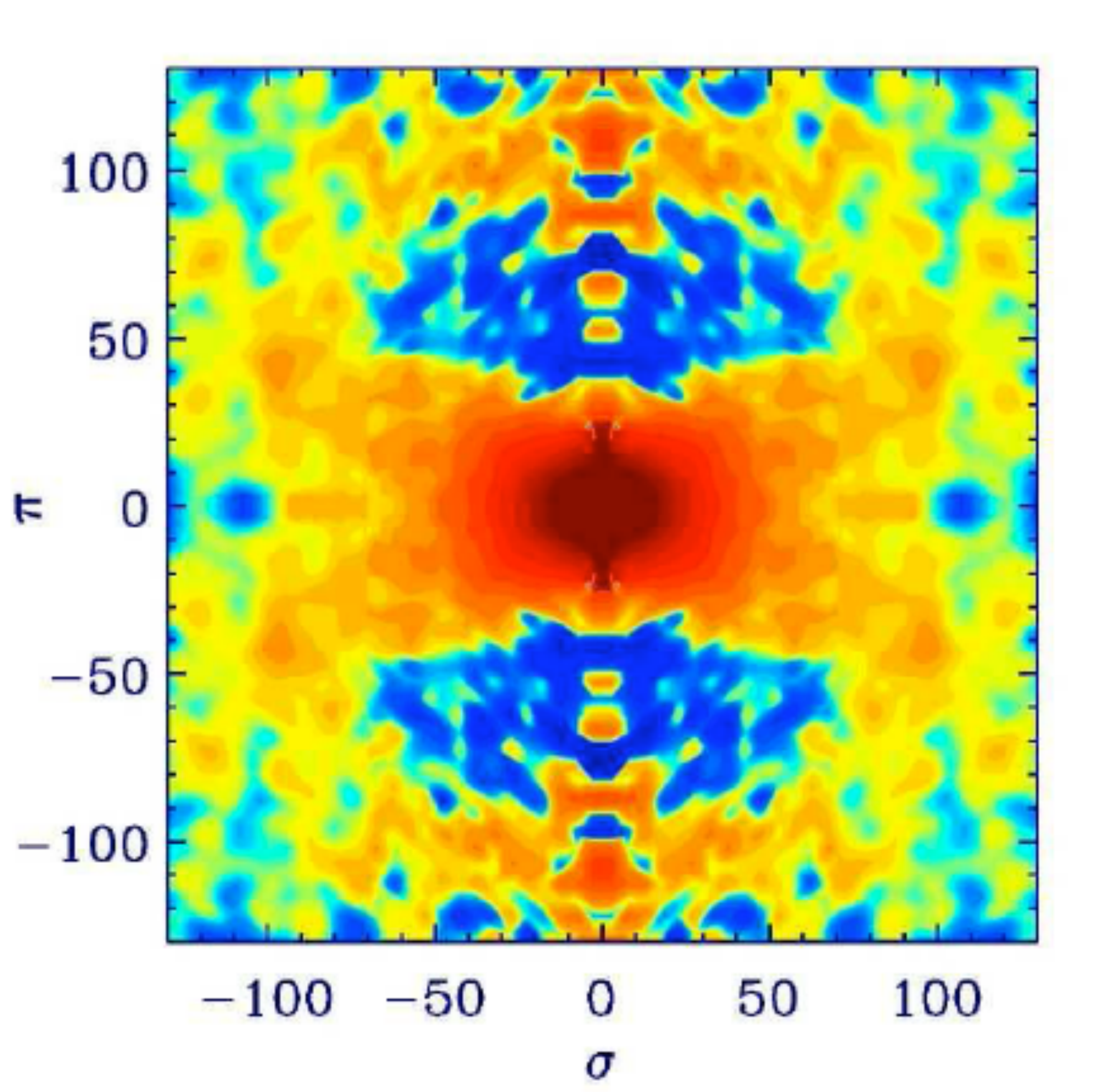
Alcock-Paczynski distortions



$$H(z) = H_0[\Omega_v(1+z)^{3+3w} + \Omega_m(1+z)^3 + (1-\Omega)(1+z)^2]^{1/2}$$
$$D(z) = \int_0^z \frac{c}{H(z)}\, dz$$

Radial/Transverse scalings: $f_\perp = D/D_{\rm ref}$, $f_\parallel = H_{\rm ref}/H$
Flattening factor: $F = f_\perp/f_\parallel$

Observed redshift-space clustering



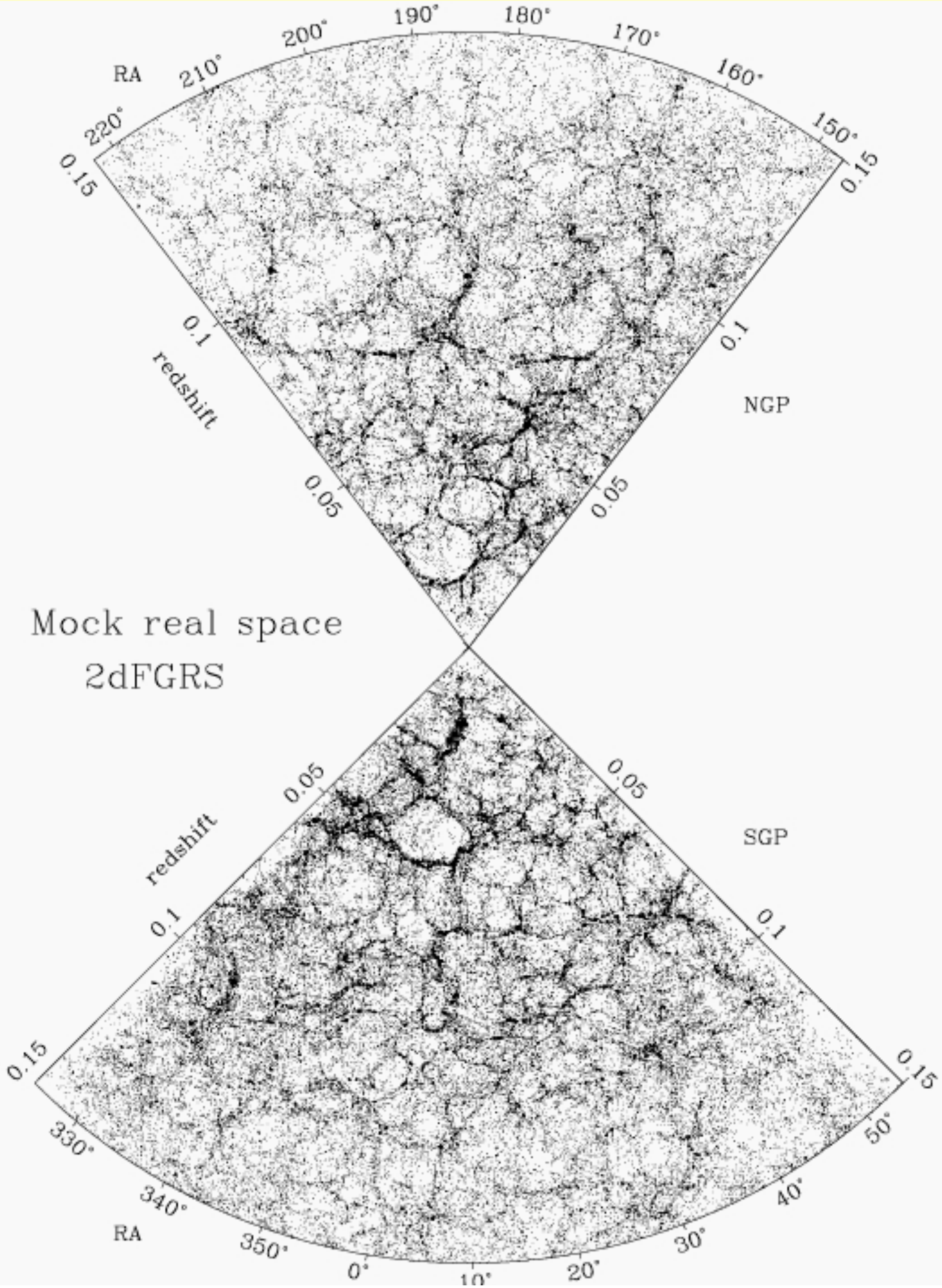
SDSS LRG Redshift-space 2D $\xi(\sigma,\pi)$ Gaztanaga et al. 0807.3551

BAO ring shows little flattening: no gross AP effect

– But note Kaiser flattening at ~ 10-20 Mpc from peculiar velocities.

Mock 2dFGRS from Hubble volume

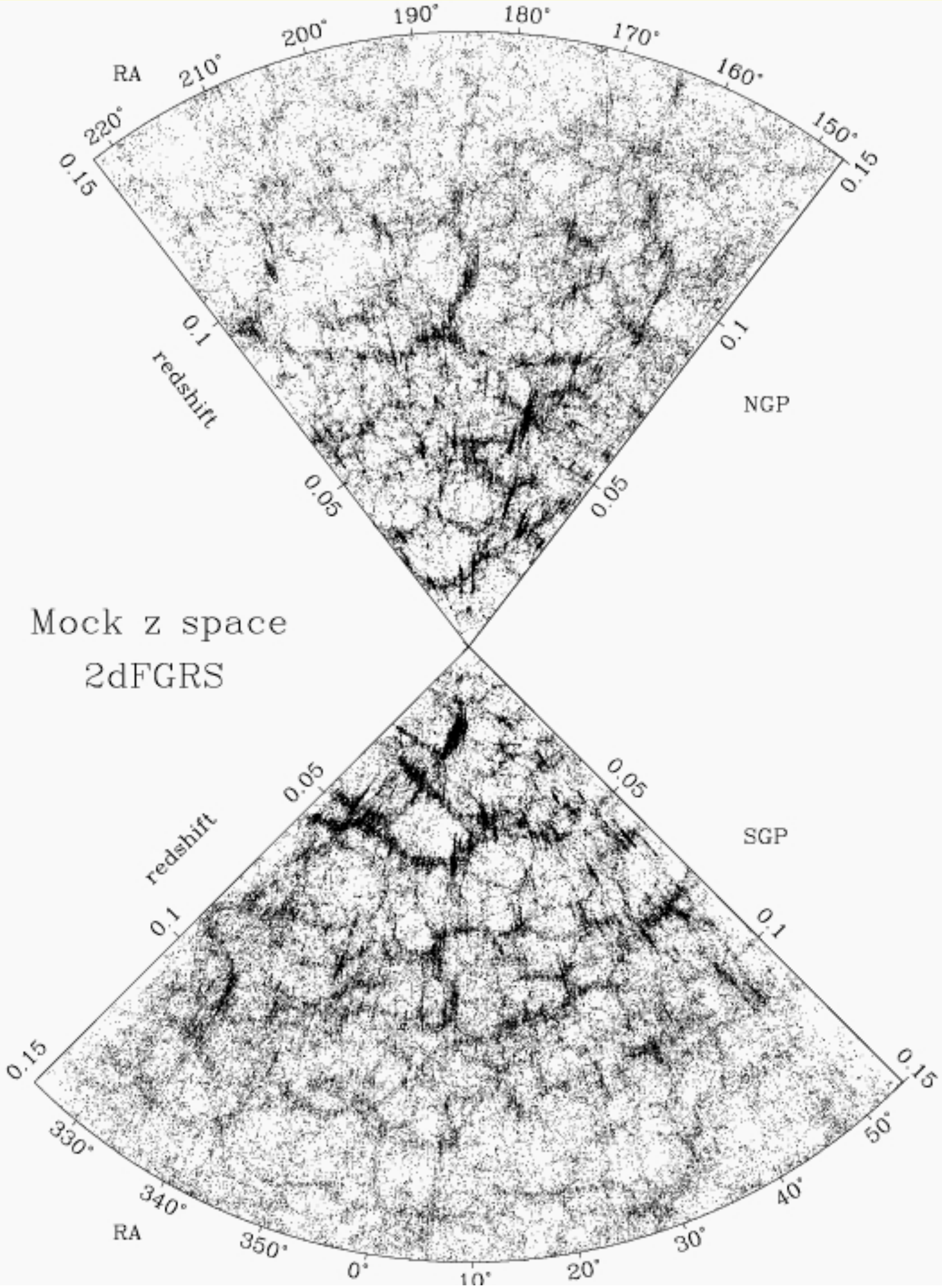
real space



Eke, Frenk, Cole, Baugh + 2dFGRS 2003

Mock 2dFGRS from Hubble volume

z-space



Eke, Frenk, Cole, Baugh + 2dFGRS 2003

Measuring the growth rate

- Peculiar velocities relate to $f_g(a)=d \ln \delta / d \ln a$, via continuity equation $\nabla \cdot \mathbf{u} = -d\delta/dt$

- But measure $\beta = f_g / b$
  - b from bispectrum?

- Safer to say $b = \sigma_{gal} / \sigma_m$(CMB | pars)
  - But remember σ_{gal} is affected by A-P

Kaiser and A-P degeneracy

Simple theory (linear + Finger of God):

$$P_{\rm gal}(k) = b^2 P_m(k)\ \left[1+\beta\mu^2\right]^2 D\left(k\mu\sigma_p\right); \quad \beta \equiv f_g/b$$

But Kaiser dynamical flattening is approximately degenerate with A-P geometrical flattening: $\beta_{\bf eff}$=(F-1)/2

$$P'_{\rm gal}(k') = \frac{1}{f_\perp^2 f_\parallel} b^2 P_m\left(\frac{k'}{f_\perp}\sqrt{1+\mu'^2\left(\frac{1}{F^2}-1\right)}\right) \times\left[1+\mu'^2\left(\frac{1}{F^2}-1\right)\right]^{-2} \times\left[1+\mu'^2\left(\frac{\beta+1}{F^2}-1\right)\right]^2 D\left(\frac{k'_\parallel\sigma_p}{f_\parallel}\right),$$

Ballinger et al. 1996

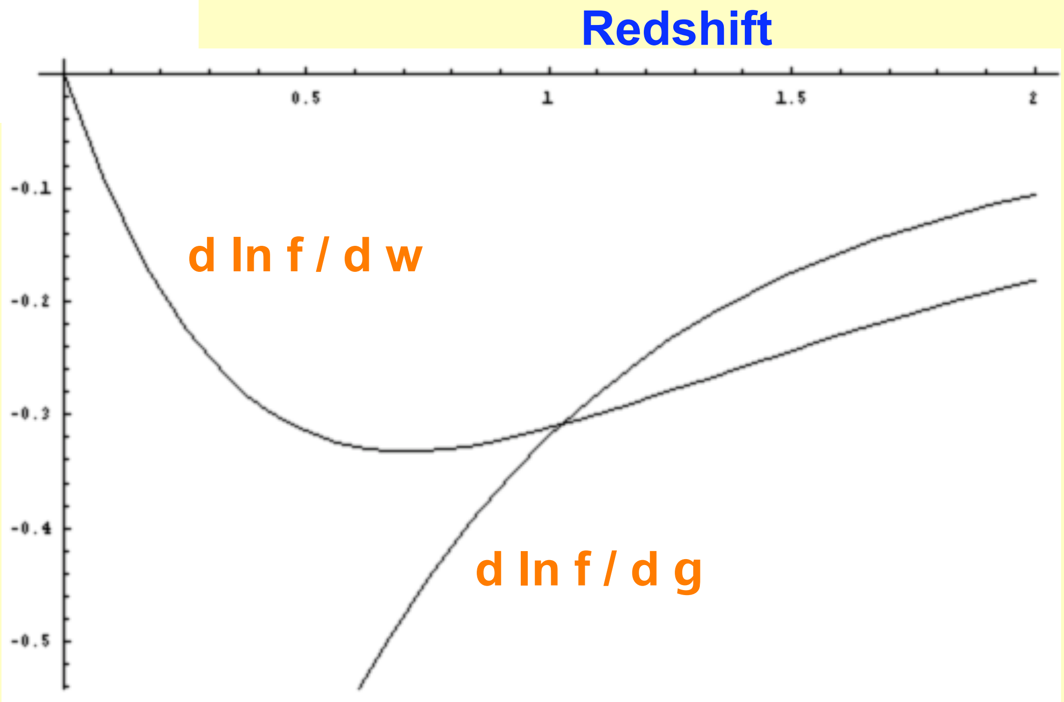
Combining RSD and BAO

BAO depend on just w if matter content is known (assumed from CMB). RSD depend on both w and γ.

$$f \equiv \frac{d \ln \delta}{d \ln a} = \Omega_m(a)^\gamma \quad \Rightarrow$$

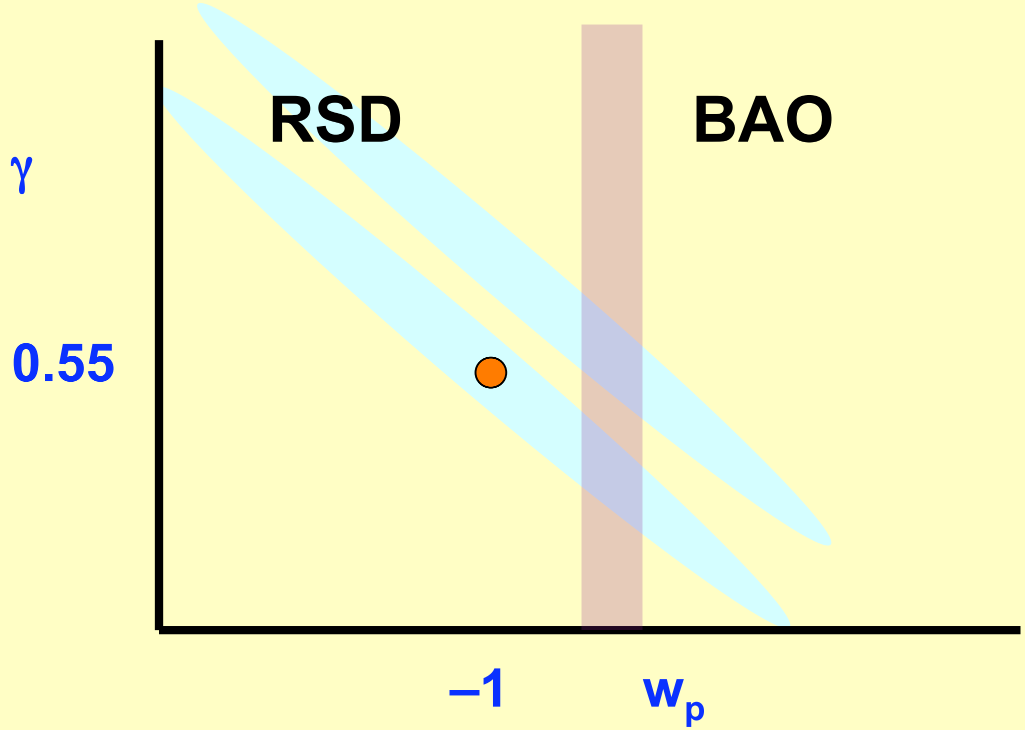
$$\frac{\partial \ln f}{\partial \gamma} = \ln \Omega_m(a)$$

$$\frac{\partial \ln f}{\partial w} = \gamma \frac{\partial \ln \Omega_m(a)}{\partial w}$$



Both derivatives around -0.3 at z = 1

DE-gravity degeneracy



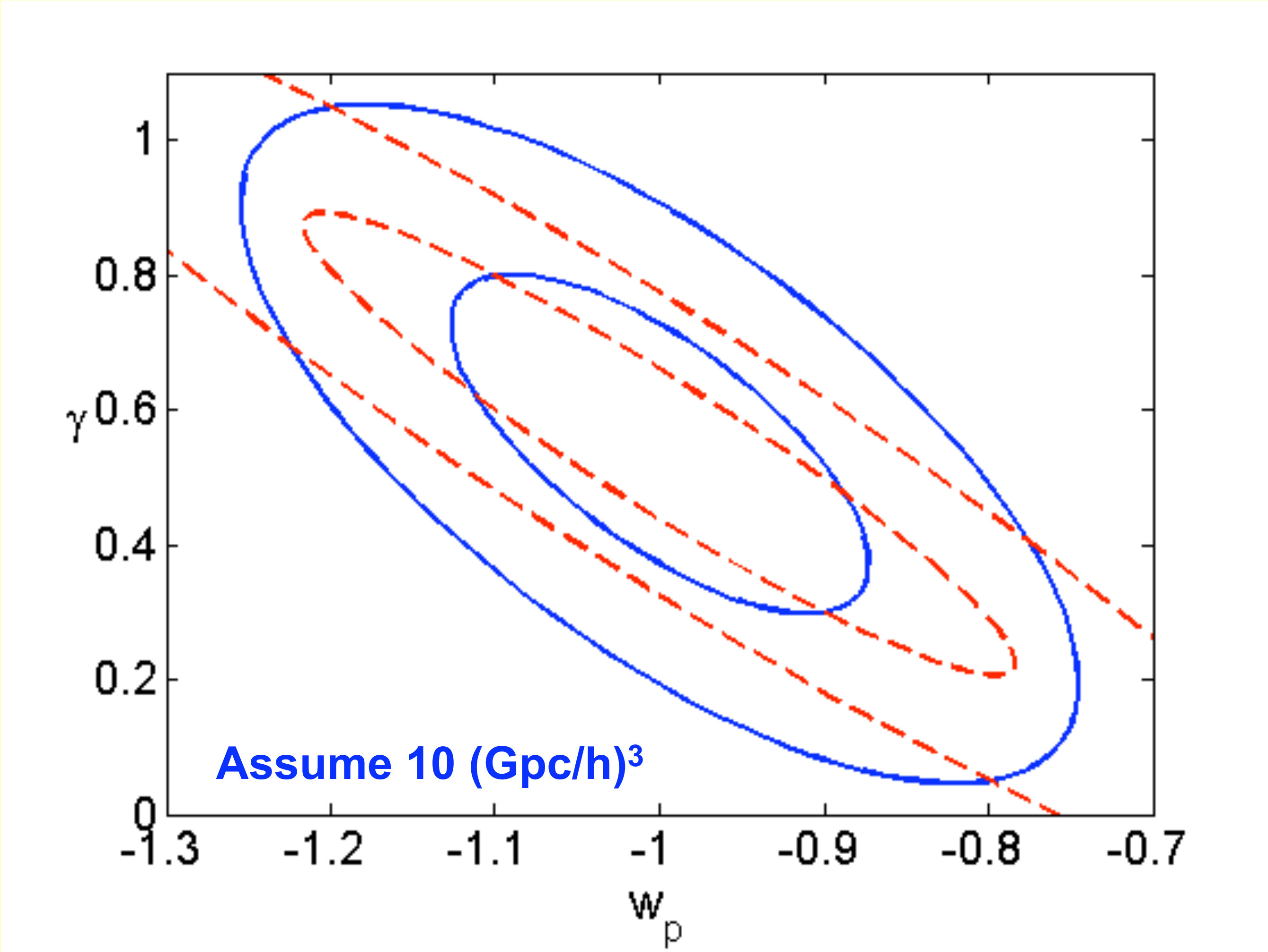
$\gamma + w = a \pm b$

$w = c \pm d$

Good to have both errors comparable.

Good case for FoM based on joint area of confidence ellipsoid in this plane

Allowing for Alcock-Paczynski

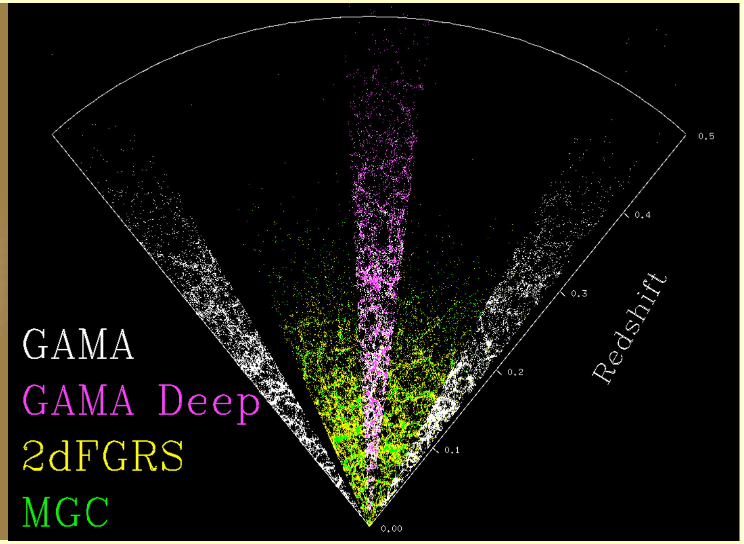


Fergus Simpson + JAP: 0910.3834

Overall uncertainty in γ can be ~2.5 x figure for w = -1

Must not claim MG if assuming w = -1 (Bean)

Galaxy And Mass Assembly – GAMA



- 250 deg^2 in 5 fields
- to r < 19.4 / 19.8 (GAMA deep) – cf. SDSS 17.8
- Aim for >200,000 redshifts
- First 3 observing seasons:
  - 63 AAT nights 08/09/10 – 75% clear
  - 140k new z’s; 96% success
  - Over 160k including 2dFGRS/SDSS

GAMA Team

WORKING GROUPS/HEADS

SCIENCE	CATS	DATABASE	OBS	MOCKS	RADIO	SPEC. PIPE.	IMAGE. PIPE.
Peacock	Baldry	Liske	Driver	Norberg	Hopkins	Loveday	Bamford
(ROE)	(LJMU)	(ESO)	(PI, St And)	(ROE)	(USyd)	(Sussex)	(Nott.)

TEAM MEMBERS

Bridges (AAO)
Bland-Haw'n (U.Syd)
Cameron (St And)
Conselice (Nott.)
Couch (Swin.)
Croom (U.Syd)
Cross (Edin.)
Frenk (Durham)
Graham (Swin)
Hill (StA)

Edmonson (Ports)
Jones (AAO)
Kuijken (Leiden)
Lahav (UCL)
Nichol (Ports.)
Oliver (Sussex)
Parkinson (Edin.)
Phillipps (Bristol)
Popescu (UCLan)
Eales (Cardiff)

Ellis (USyd)
Prescott (LJMU)
Proctor (Swin.)
Sharp (AAO)
Staveley-Smith (UWA)
Sutherland (Camb.)
Tuffs (MPIK)
van Kampen (Innsbruck)
Warren (Imperial)
Dunne (Nottingham)

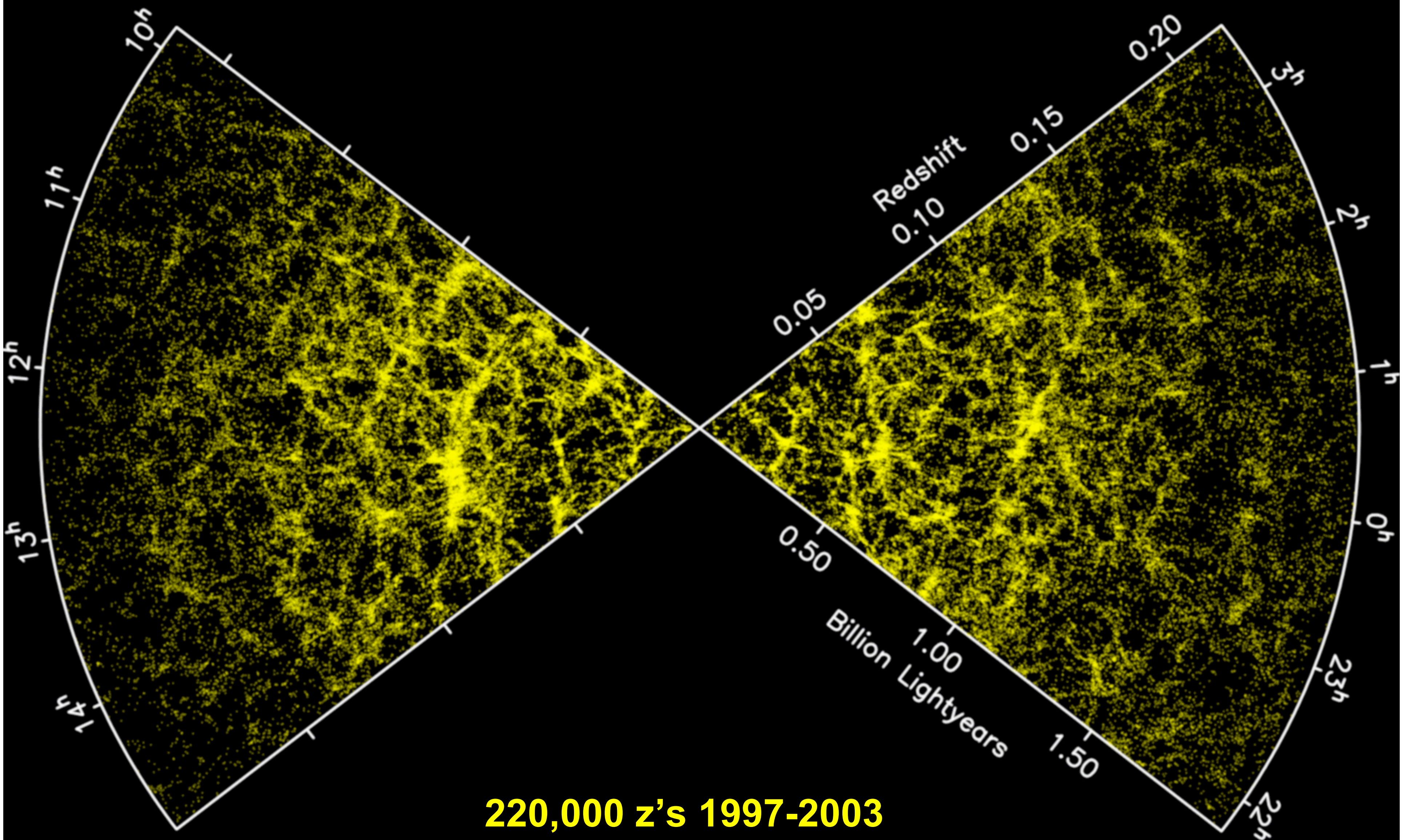
TEAM AFFILIATIONS:

UKIRT/LAS, VST/KIDS, VISTA/VIKING, HERSCHEL-ATLAS, DURHAM ICC

WEBSITE:

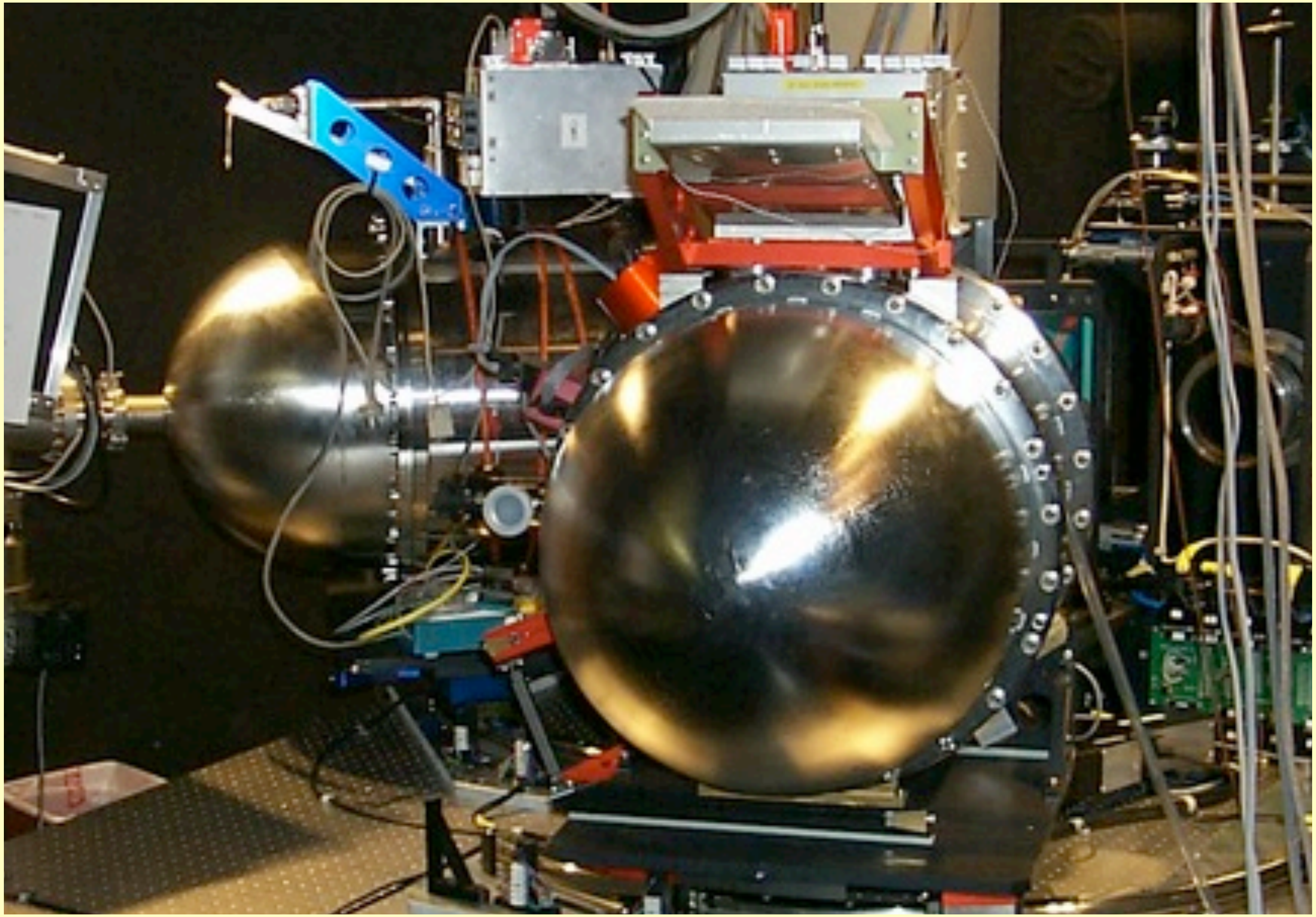
http://www.eso.org/~jliske/gama/

Cosmology after 2dFGRS

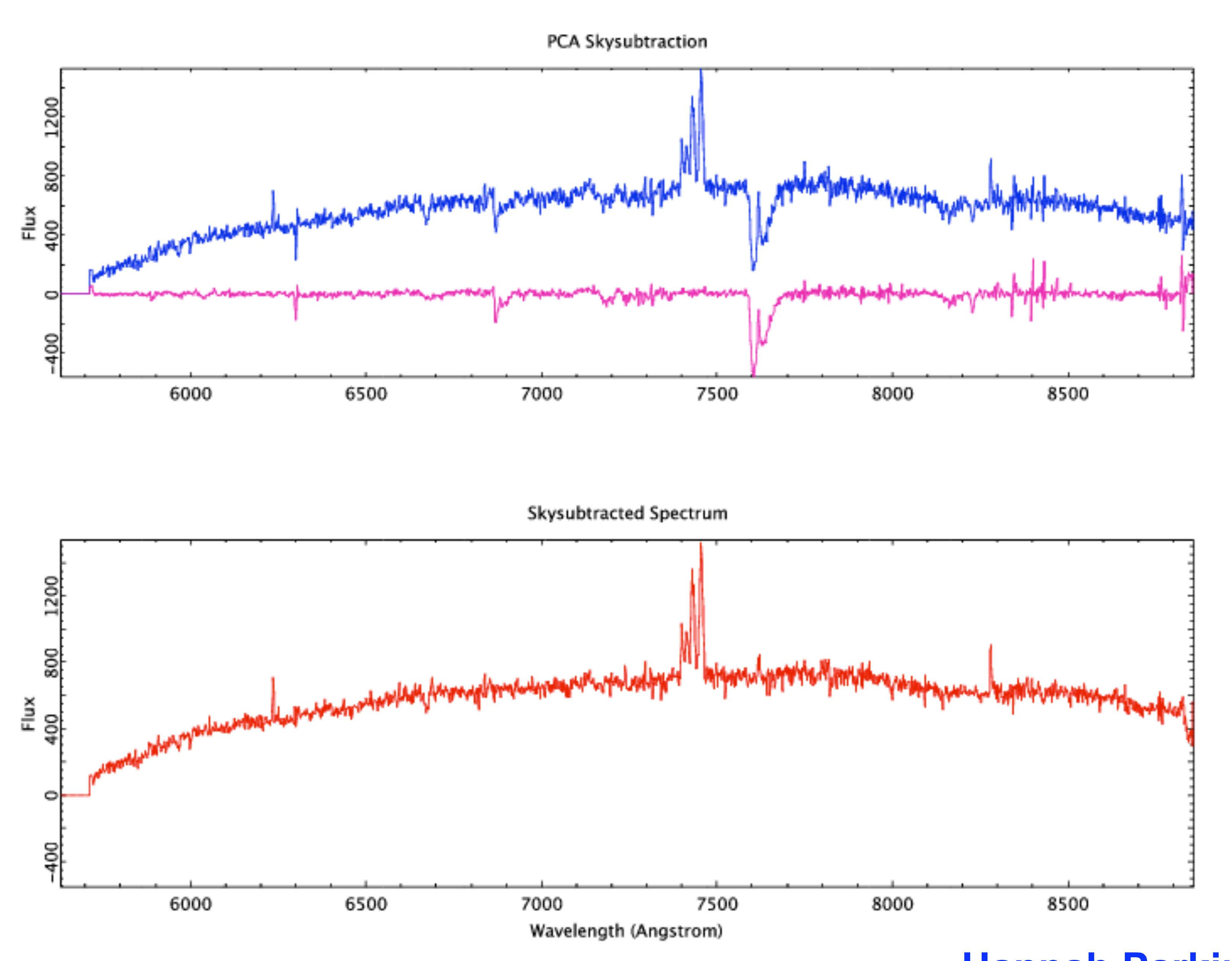


220,000 z's 1997-2003

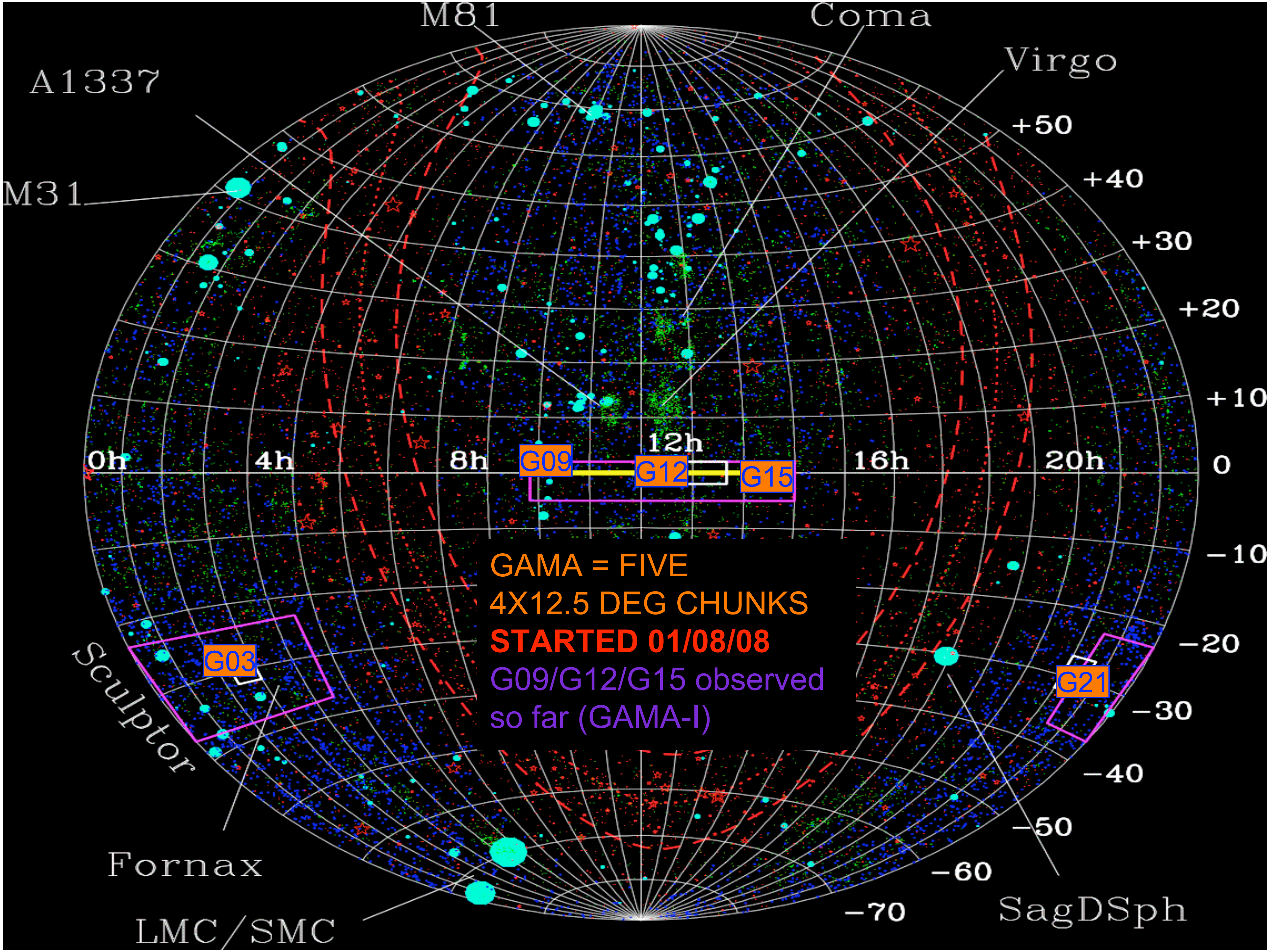
AAΩ: new VPH spectrographs

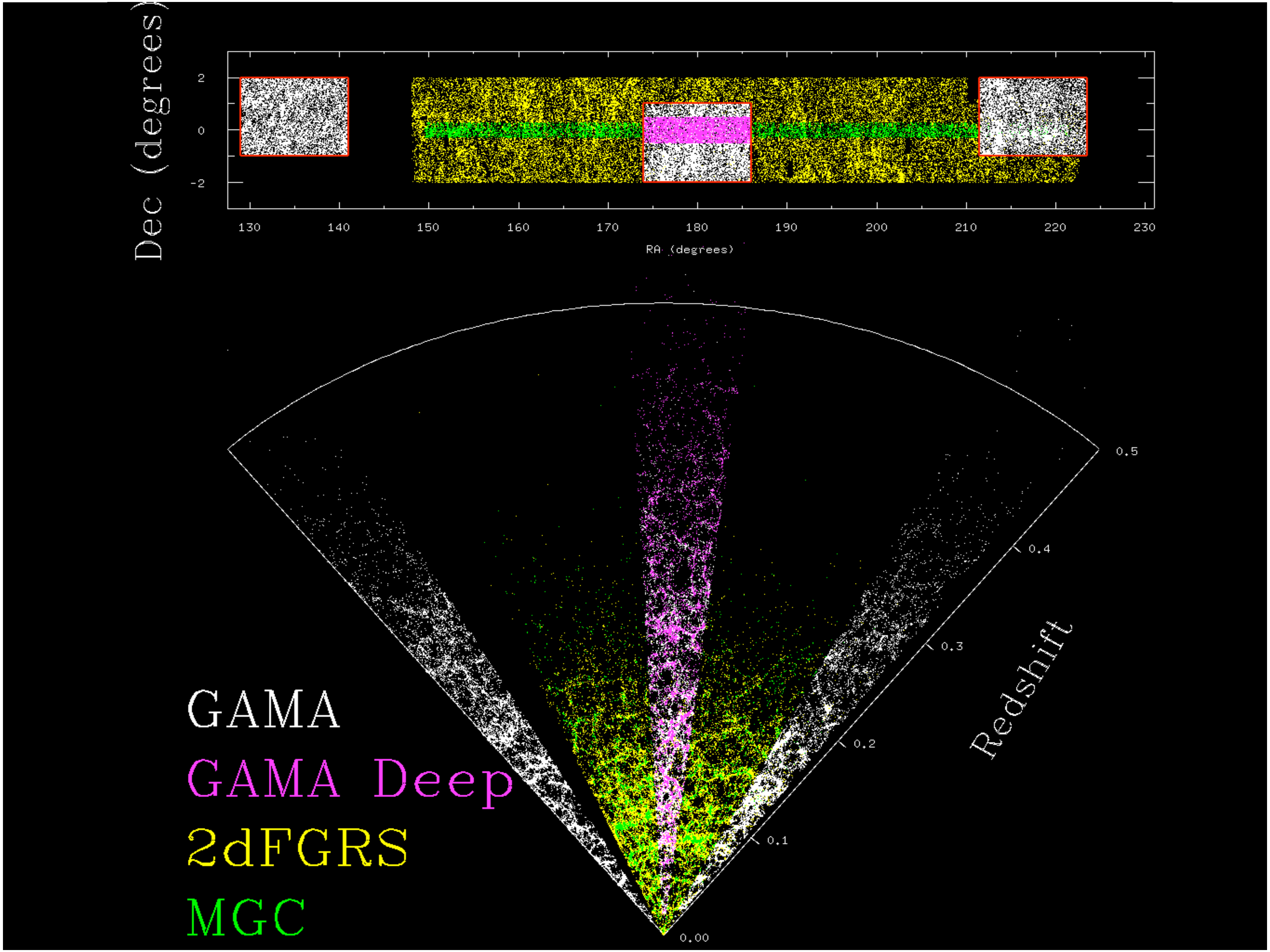


PCA sky subtraction

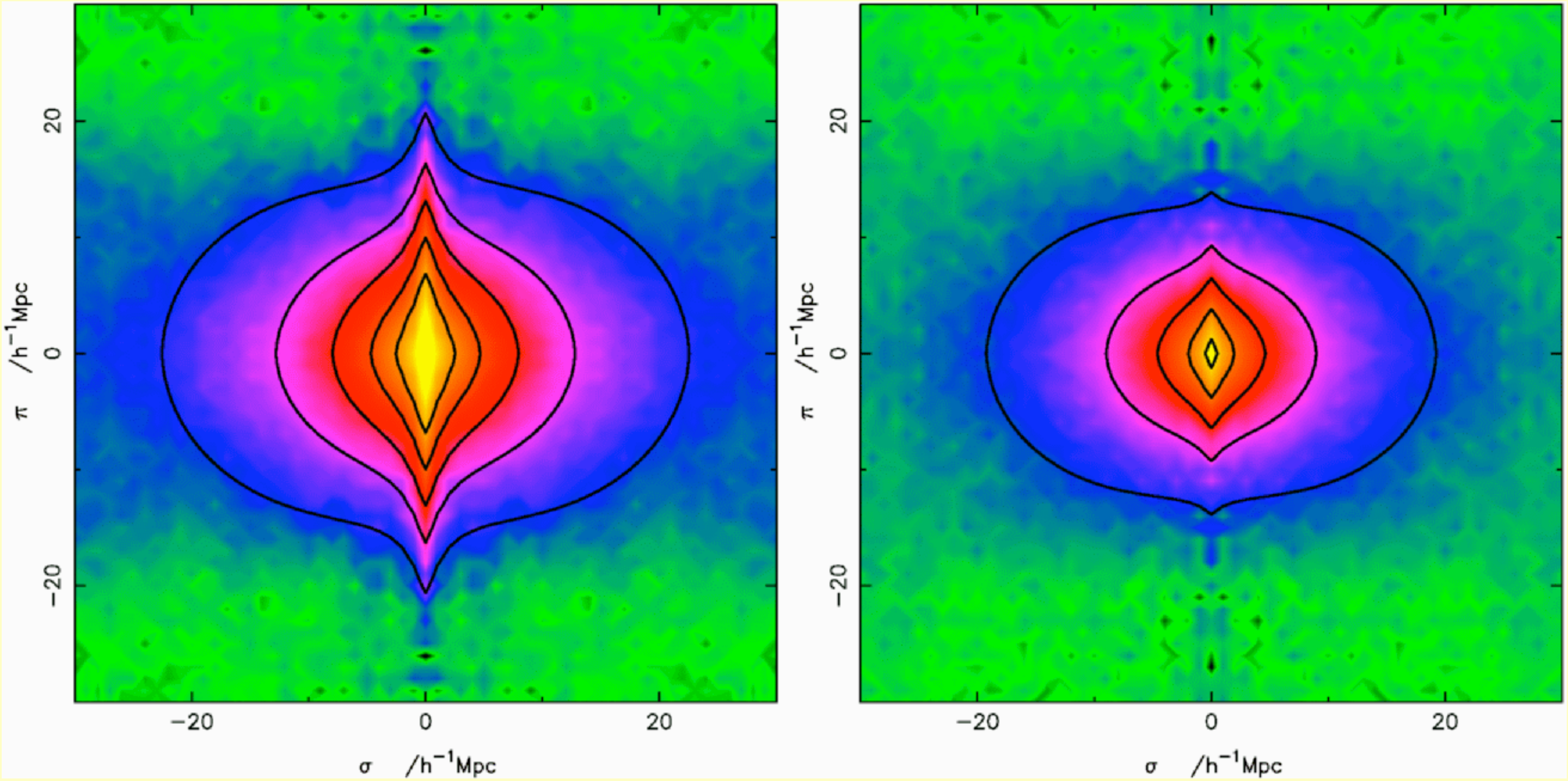


Hannah Parkinson


M81
Coma
Virgo
A1337
M31
+50
+40
+30
+20
+10
0
−10
−20
−30
−40
−50
−60
−70
0h
4h
8h
12h
16h
20h
G09
G12
G15
G03
G21
GAMA = FIVE
4X12.5 DEG CHUNKS
STARTED 01/08/08
G09/G12/G15 observed
so far (GAMA-I)
Sculptor
Fornax
LMC / SMC
SagDSph


Dec (degrees)
2
0
-2
130
140
150
160
170
180
190
200
210
220
230
RA (degrees)
0.5
0.4
0.3
0.2
0.1
0.00
Redshift
GAMA
GAMA Deep
2dFGRS
MGC

2dFGRS: redshift-space distortions and galaxy type



Red:

$\beta = \Omega^{0.6}/b = 0.46 \pm 0.13$

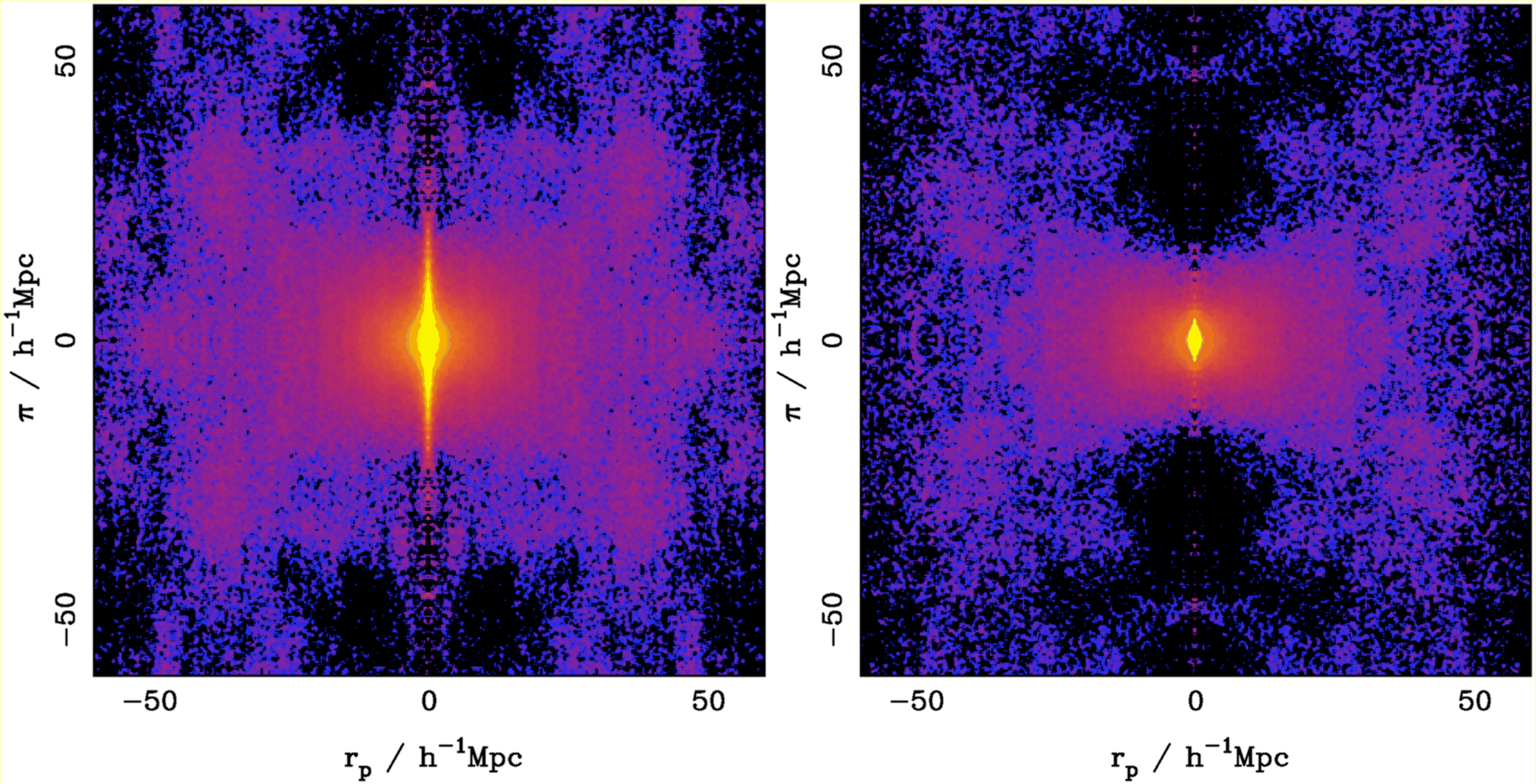
$\sigma_p = 618 \pm 50$ km s^{-1}

Blue:

$\beta = \Omega^{0.6}/b = 0.54 \pm 0.15$

$\sigma_p = 418 \pm 50$ km s^{-1}

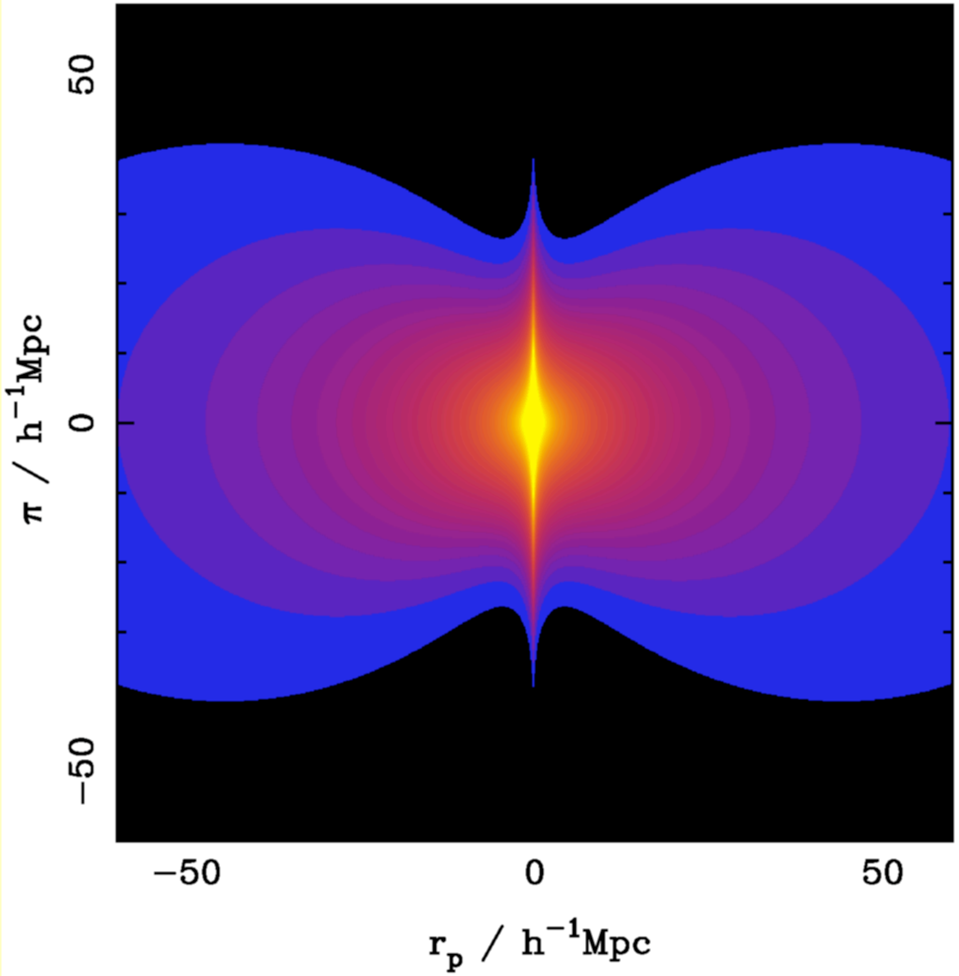
GAMA: redshift-space distortions

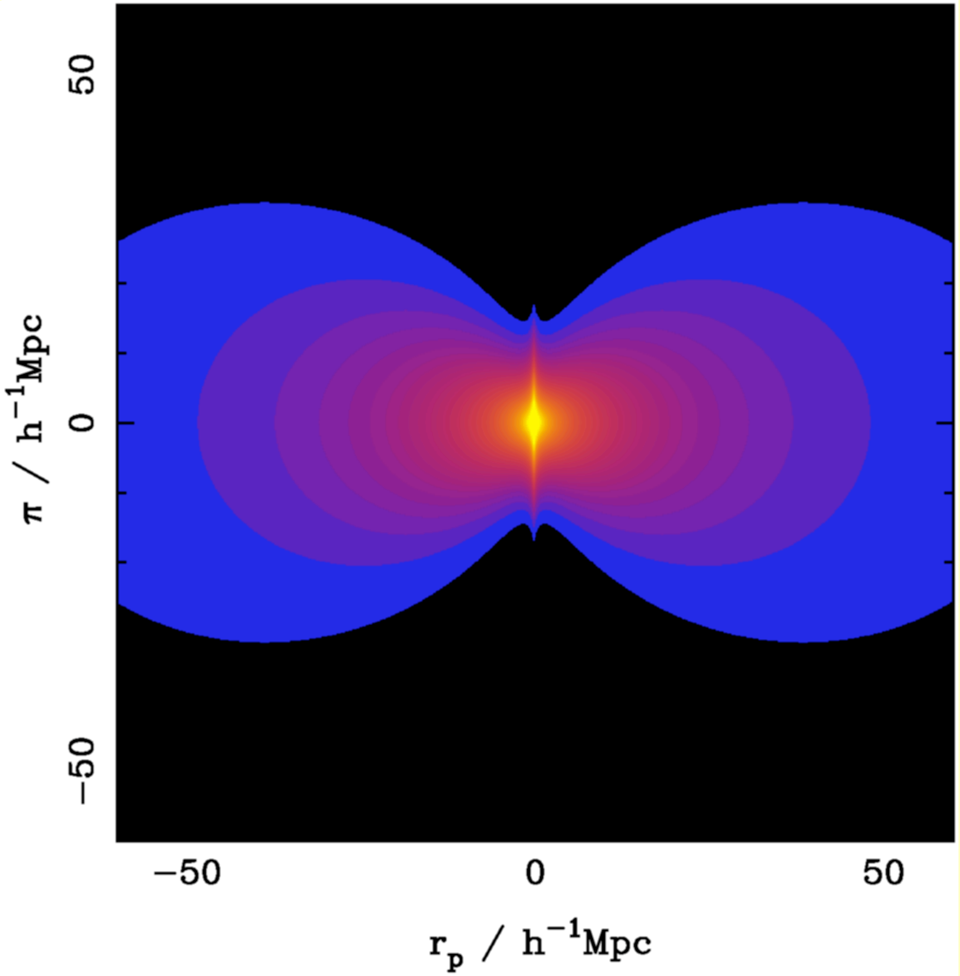


Red

Blue

redshift-space models





Red **Blue**

Preliminary: $\beta_{\rm red} = 0.76$; $\beta_{\rm blue} = 0.97$. β ratio $= 1.28$ but bias ratio $= 1.38$

In summary

- ISW is a weak effect
  - Consistent with standard gravity
  - May never be convincingly detected
  - But powerful null test
  - And large enough to have major impact in CMB ‘anomalies’

- GAMA is developing into a worthy successor to 2dFGRS
  - Will deliver important test of RSD systematics
  - Watch out for year-1 data release this summer, and flood of Herschel/GAMA SDP papers