Cosmology in the Era of Large Surveys

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A Long, Long Time Ago...

The State of Cosmology in 1996

- COBE measurements had shown that the Cosmic Microwave Background was constant to one part in 10^5 at recombination. COBE DMR had measured CMB anisotropy correlations on very large scales. Ground and balloon based experiments were pushing to $\sim 1^\circ$ scales.

- Measurements of galaxy clustering in the local universe were largely limited to photometric data. Spectroscopic surveys were mostly focused on measuring bulk velocity flows.

- Big Bang Nucleosynthesis measurements had put strong constraints on the baryon density ($\Omega_b h^2$) but not much else.

- Fundamental questions about the **size** and **shape** of the Universe were still very much open.

1996 Great Age Debate

Two camps on the value of Hubble's Constant:

- Cepheid variable stars in nearby galaxies gave $H_0 \sim 80$ km/s/Mpc.
- Measurements using nearby supernovae as standard candles yield $H_0 \sim 55$ km/s/Mpc.
- In both cases error bars are small ($\sim 5-10$).

Sidney van den Bergh:
$H_0 = 81 \pm 8$!!!

1996 Great Age Debate

Gustav Tammann:
$H_0 = 55 \pm 10$!!!

Lurking in the background, the Age Crisis:

- For an Einstein-deSitter universe ($\Omega_{\rm M} = 1$), the age of the universe is $t_0 = 2/3\ H_0^{-1}$
- Measurements of stellar ages in globular clusters put $t_0 > 11.5$ Gyr (as high as $t_0 > 17$ Gyr in some estimates)
- Either $\Omega_{\rm M} < 1$ or $H_0 < 50$ km/s/Mpc

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The Shape of the Universe

- Peebles 1995 summary on the state of $\Omega_{\rm M}$

Observation	$\Omega_{\rm M} = 1$	$\Omega_{\rm M} \sim 0.1$
Dynamics & biasing on scales ≤ 3 Mpc	NO	YES
Dynamics on scales ≥ 10 Mpc	YES	YES
Expansion time $H_0 t_0$	???	YES
Radial and angular size distances	NO (?)	YES (?)
Plasma mass fraction in clusters	NO	YES
Models for structure formation	YES (?)	YES (?)

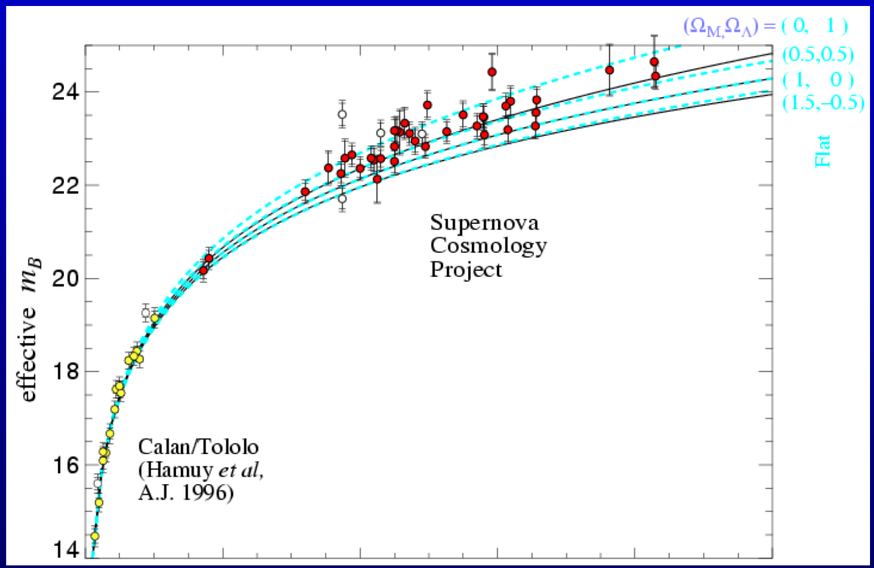
- Theoretical bias toward $\Omega_{\rm M} = 1$, given COBE & inflation

- Strong gravitational lensing: $\Omega_\Lambda < 0.65$ at 95% confidence for flat universes (Kochanek 1996)

Ten Years Later...

Two Major Improvements

- **Better Data**
  - ⋆ More Supernovae
  - ⋆ Finer CMB Anisotropies
  - ⋆ Bigger Galaxy Surveys
- **Better Analysis**
  - ⋆ Fisher Matrix
  - ⋆ Markov Chain Monte Carlo
  - ⋆ Machine Learning & Data Mining



Permutter et al. (1998)

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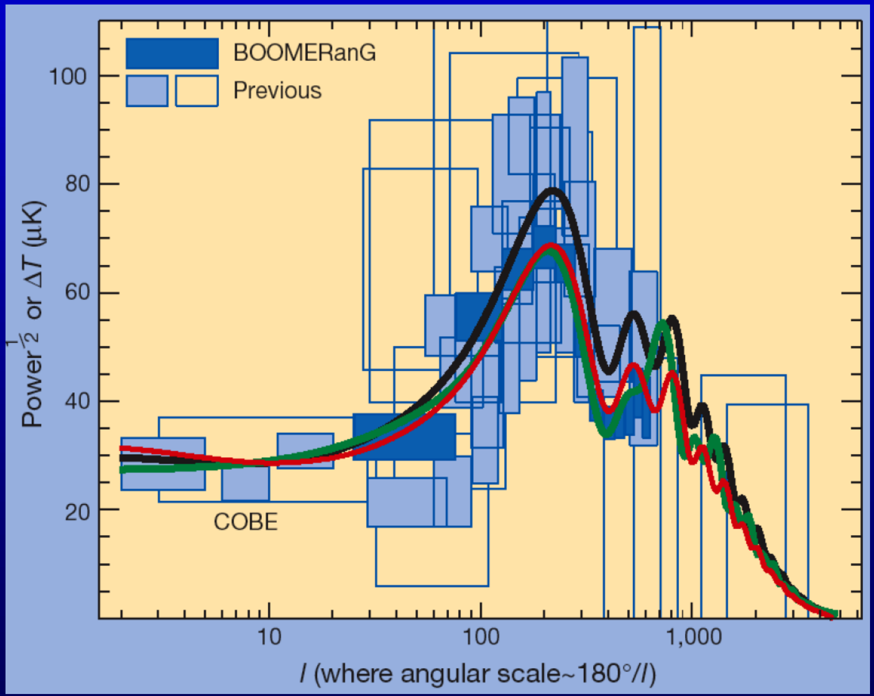

Hu (2000)

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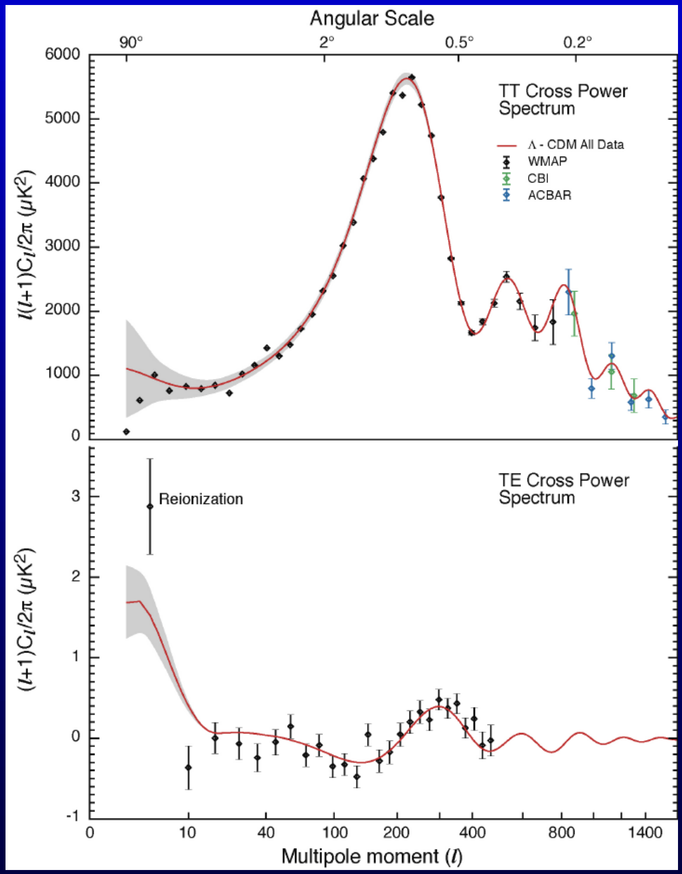

WMAP (2003)

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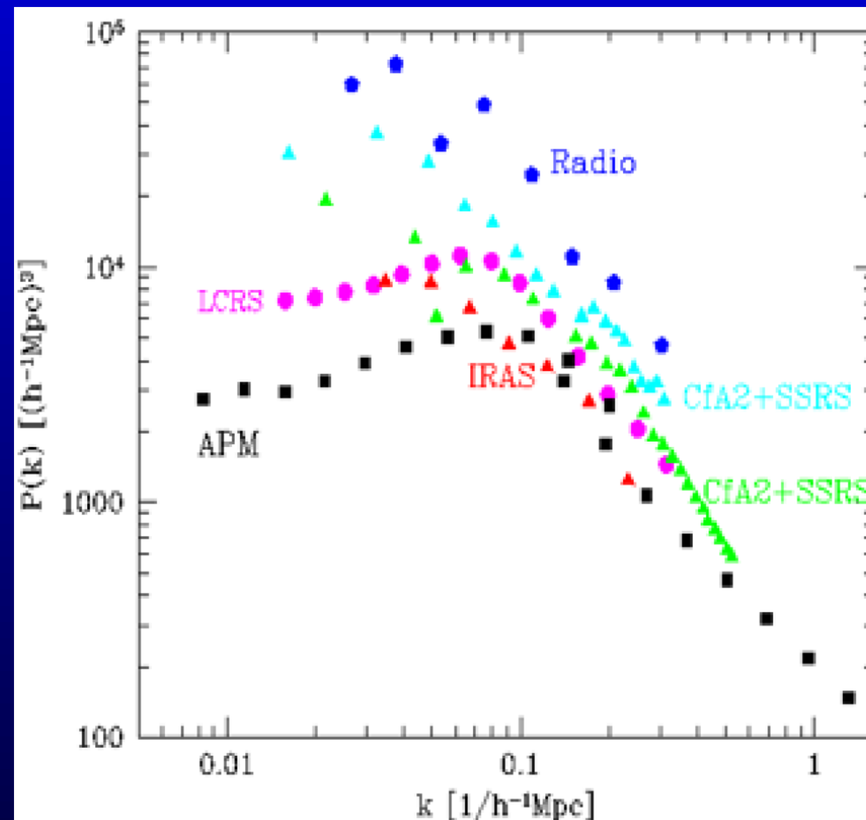

Vogeley (1997)

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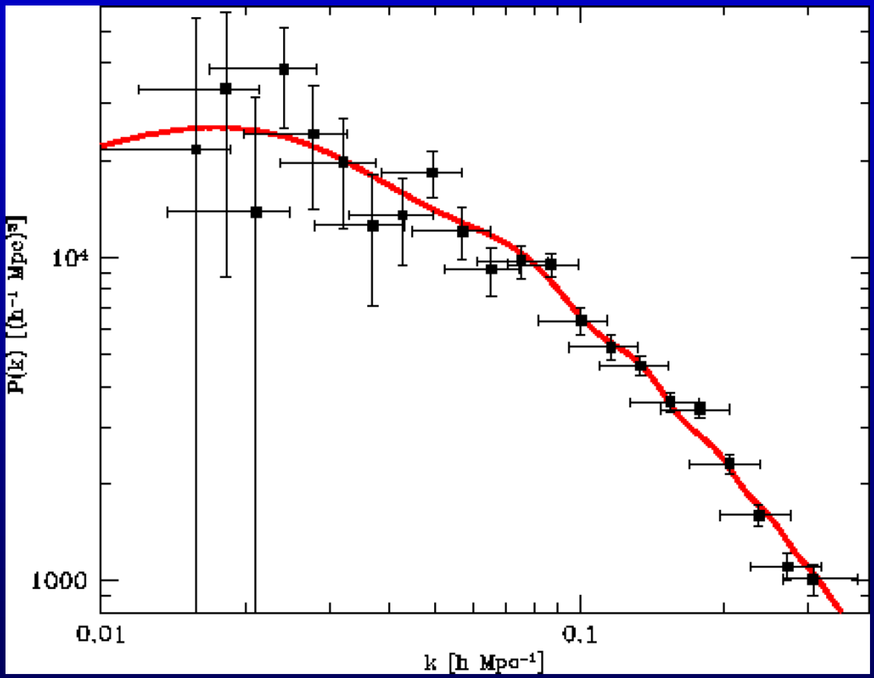

Tegmark et al. (2003)

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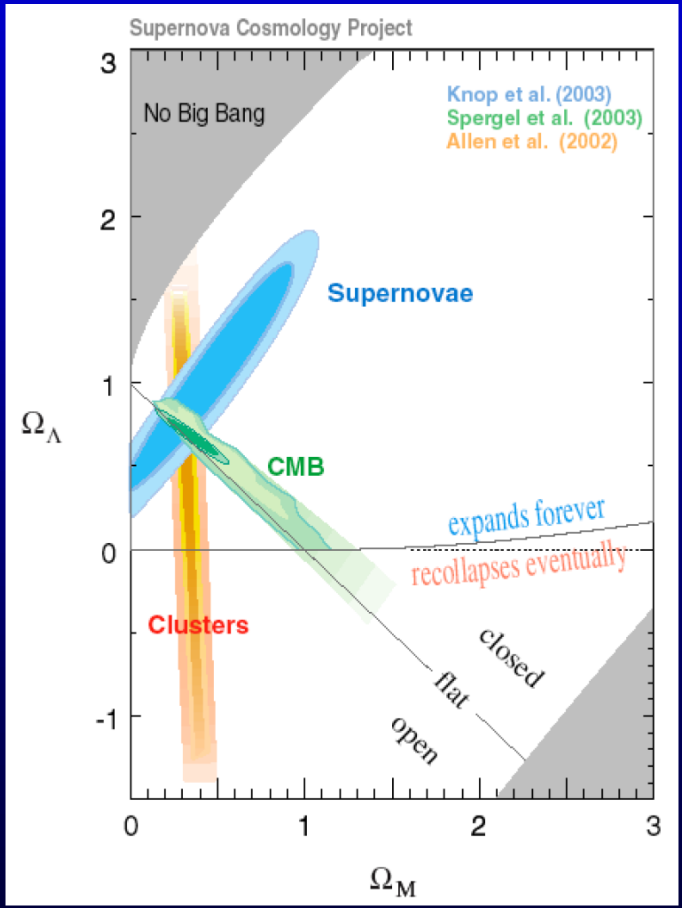

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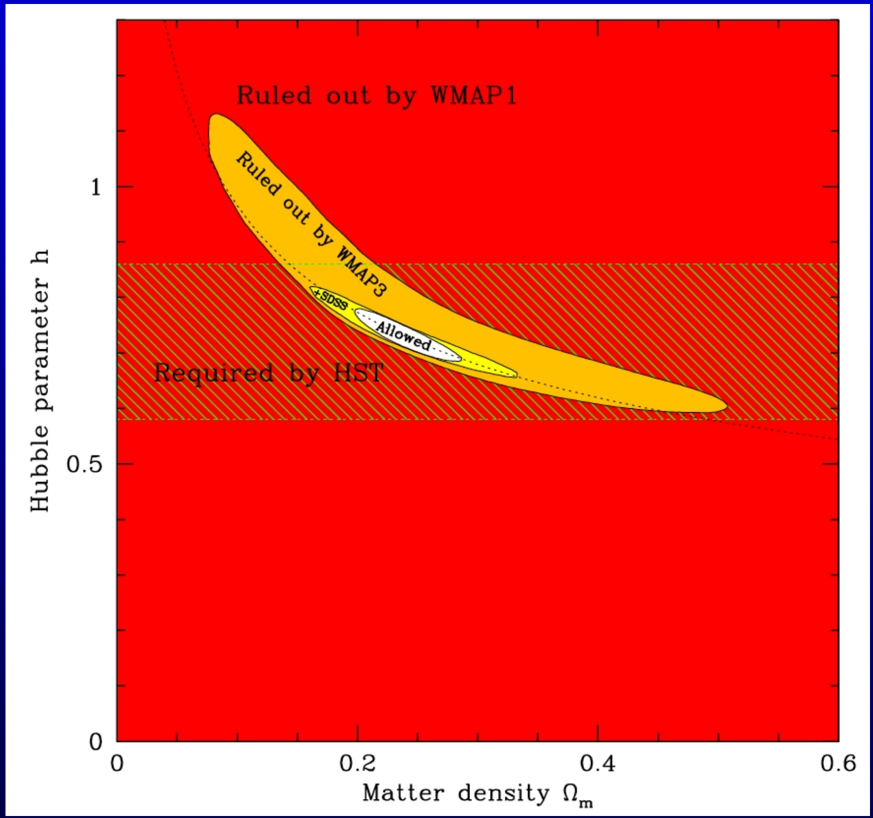
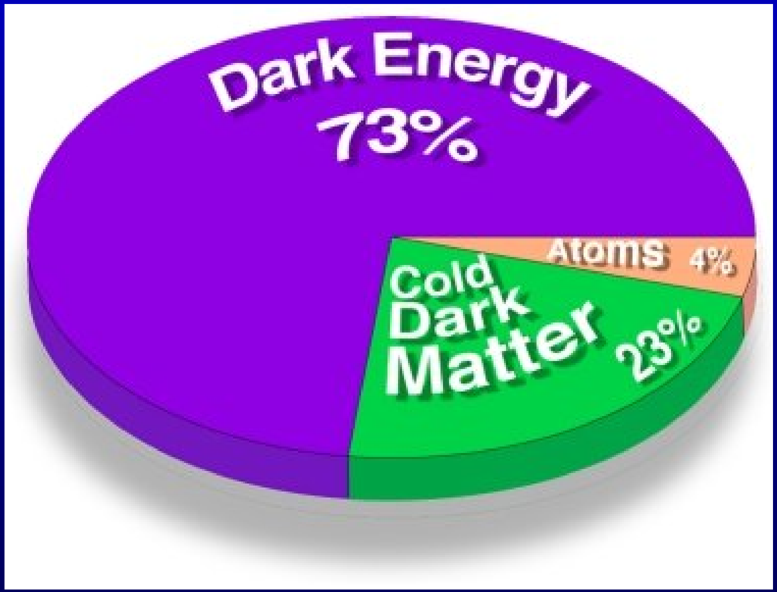


Tegmark et al. (2006)

Current Picture of Reality

- Very good evidence that the universe is flat ($\Omega = 1$), but that $\Omega_{\mathrm{M}} \sim 0.3,\ \Omega_{\Lambda} \sim 0.7$.
- Doing astronomy with millions of objects (instead of dozens) gives us power to investigate dark matter and dark energy in ways that were previously impossible.
- Examples of Precision Cosmology: **Cosmic Magnification** & **Integrated Sachs-Wolfe Effect**

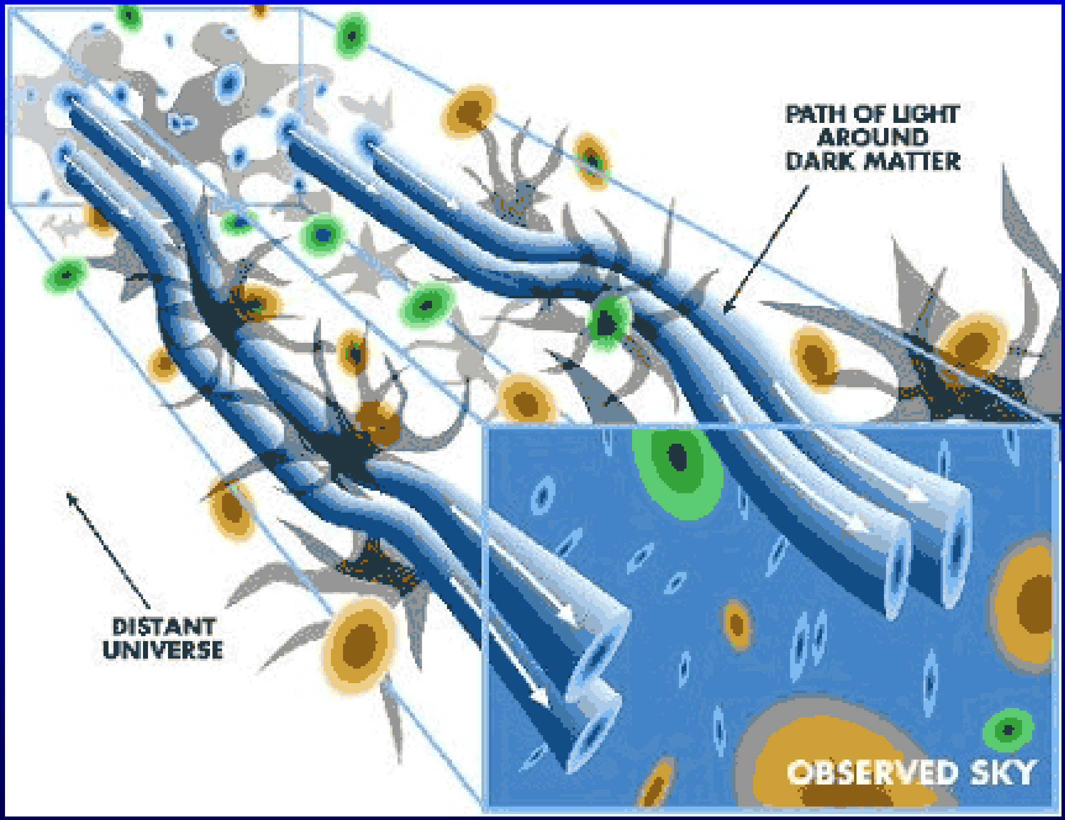


WMAP

Tracking Dark Matter:

Cosmic Magnification
with Galaxies and Quasars

Two Effects of Gravitational Lensing



Wittman (2000)

Light from distant sources is **magnified** and **distorted** by dark matter

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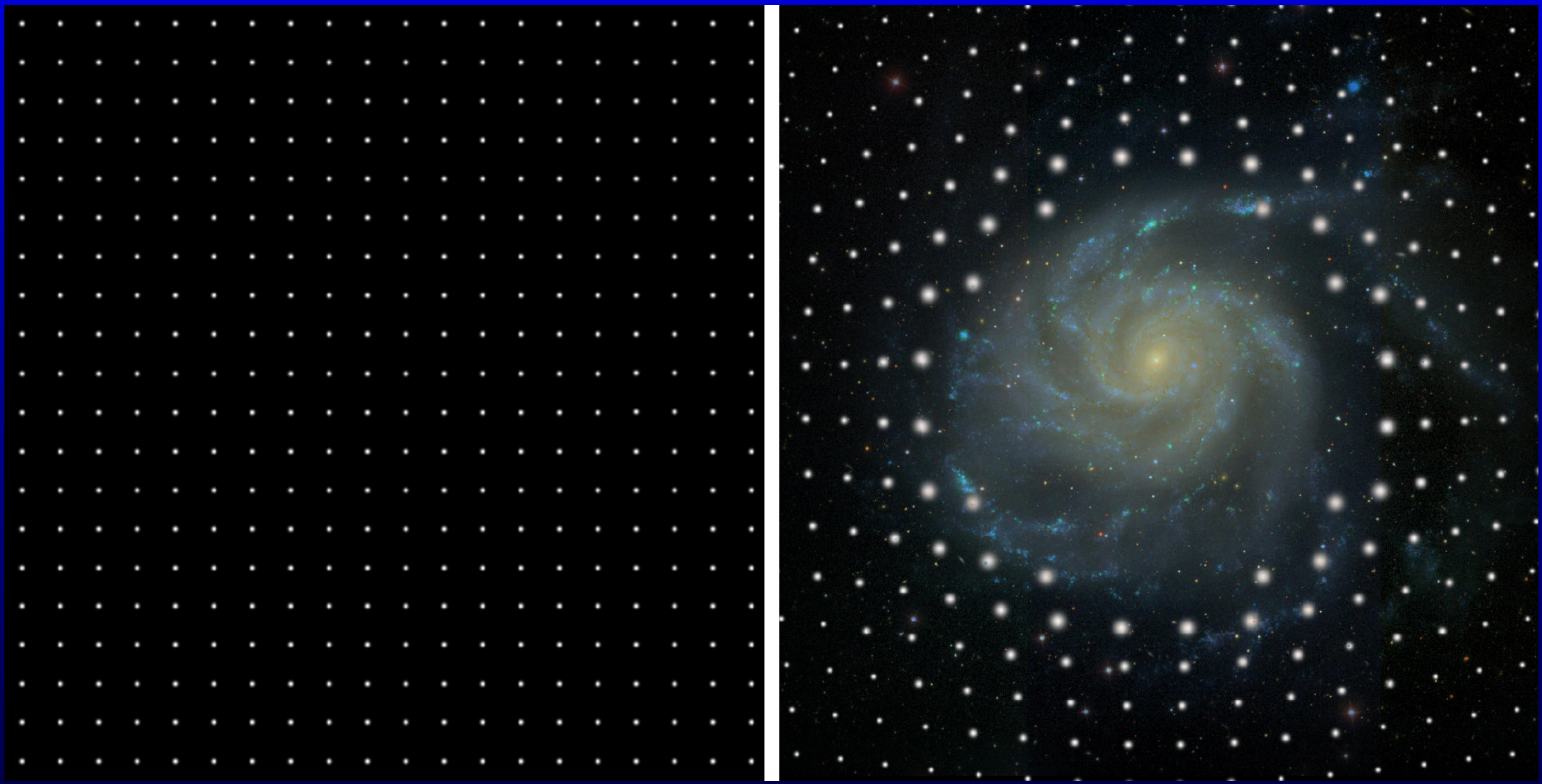


Magnification (μ) increases flux (amplification); decreases density (dilution)

Quantifying Cosmic Magnification

- If we are in the weak lensing regime ($\mu \approx 1$),

$$\begin{aligned} w_{\rm GQ}(\theta) &= 12\pi^2\Omega_{\rm M}\left(\alpha(m)-1\right)\int {\rm d}\chi{\rm d}kk\mathcal{K}(k,\theta,\chi)P_{gm}(k,\chi) \\ &= (\alpha(m)-1)\times w_0(\theta), \end{aligned} \quad (1)$$

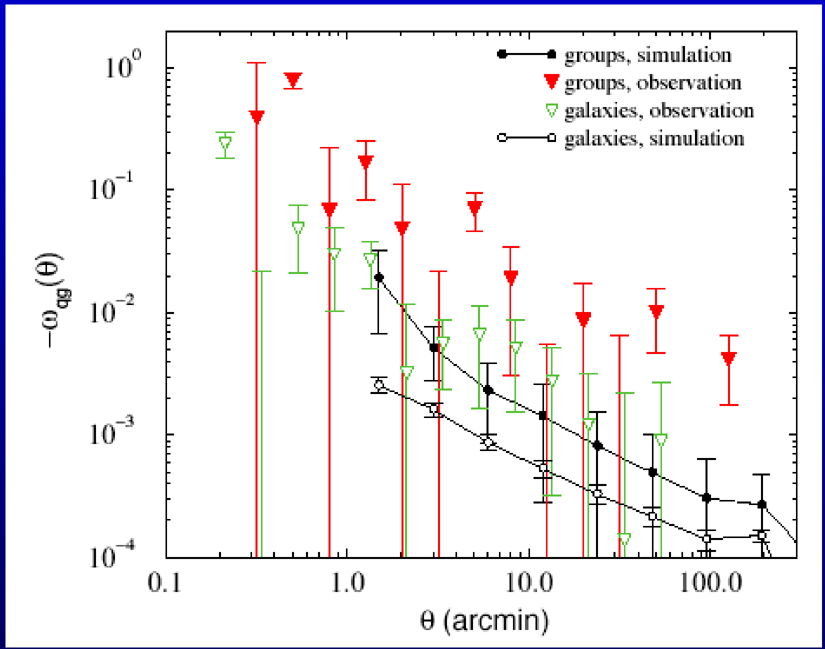
  where $\alpha(m)$ is the power-law slope of the QSO number counts, $\mathcal{K}$ depends on the foreground and background redshift distributions and $P_{gm}(k)$ is the galaxy-dark matter power spectrum.

- For $\alpha(m) > 1$, increasing amplification outweighs the dilution effect, inducing a positive cross-correlation between foreground and background objects. For $\alpha(m) < 1$, dilution wins and the cross-correlation is negative.

- The lensing magnification is less than 1% per object, so we need to average over many, many QSOs.

Controversy – Is $\Omega_{\rm M} \approx 1$?

- First lensing motivated measurements in late 1980s and early 1990s
  - ⋆ Lick, IRAS & APM galaxies, Abell & Zwicky clusters
  - ⋆ UVX and radio-selected QSOs
- More recently, Guimares, Myers & Shanks (2003) used 2dF QSOs + APM & SDSS galaxy groups
- Consistently detect signal $\sim 3 - 10 \times$ the expected lensing



Guimares, Myers, & Shanks (2003)

The Four Horsemen

- Photometric Calibration
  - Small amplification effect requires excellent photometry
  - Photographic plates not up to the challenge
- Uniform Selection
  - Photographic plates have variable depth of field and numerous defects
  - Spectroscopic surveys require detailed selection function
- Redshift Overlap
  - Physical Clustering dominates lensing signal
  - Require either spectroscopy or photometric redshifts for each object
- Object Density
  - Poisson errors dominate
  - When object density is low, only systematic signal is detected.

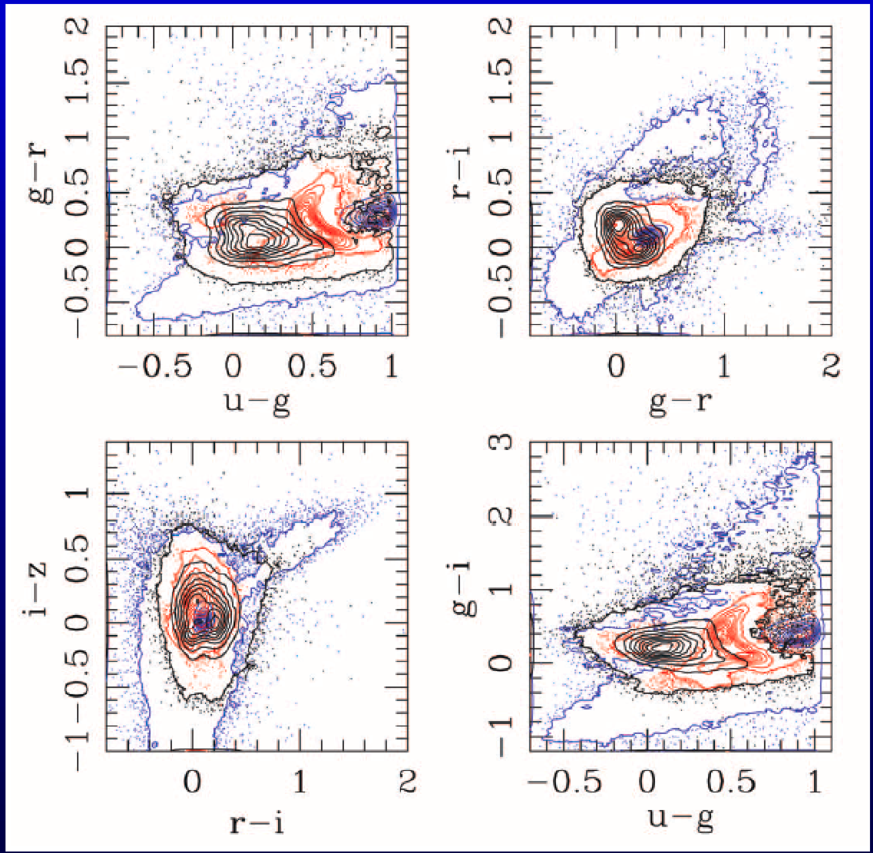
Photometric QSO Selection

- Traditional QSO selection involves cuts in 2-D color projections

- Kernel Density Estimation (KDE) using full 4-D color space
  - ⋆ 2 training sets: QSOs & stars
  - ⋆ compute distance in color space to assign new objects

- SDSS spectroscopic selection 85% efficient for $i' < 19$

- KDE selection $> 95\%$ for $g' < 21 \Rightarrow 10\times$ density



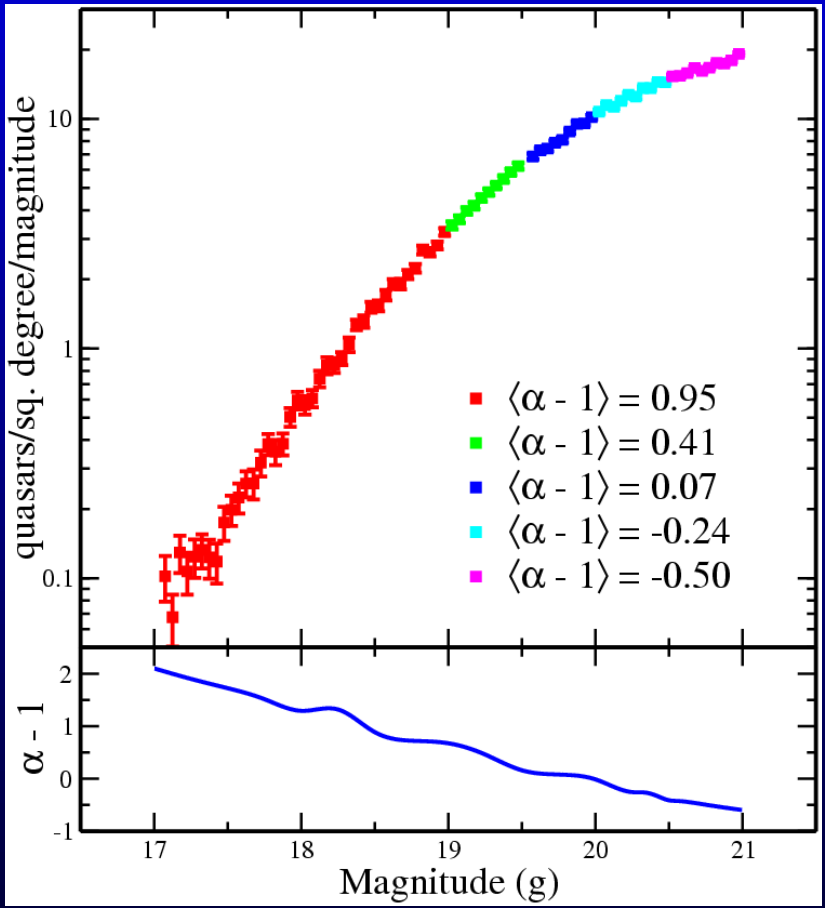
Richards et al. (2004)

Measurement in g'

- Select 5 magnitude bins in g': $17 < g' < 19$, $19 < g' < 19.5$, $19.5 < g' < 20$, $20 < g' < 20.5$, $20.5 < g' < 21$
- Calculate $\langle \alpha - 1 \rangle$ in each bin:

$$\langle \alpha - 1 \rangle = \frac{\int \mathrm{N}(m)\,(\alpha(m) - 1)}{\int \mathrm{N}(m)} \quad (2)$$

- Expect to see positive correlation for $g' < 19.5$ and negative correlation for $g' > 20$



Scranton et al. (2005)

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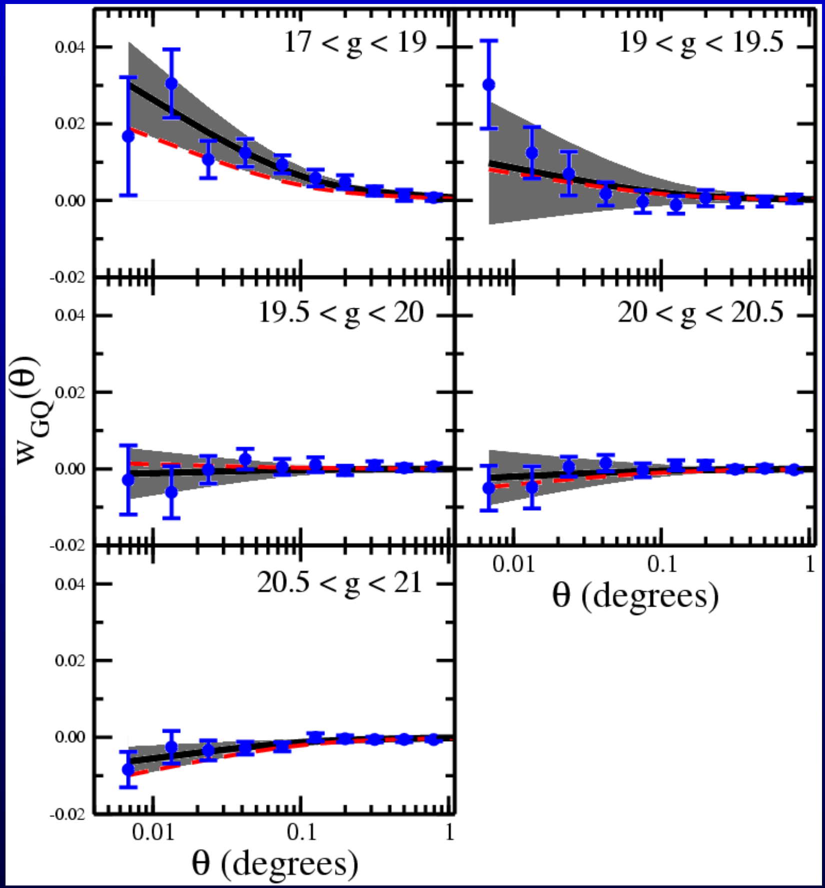


Scranton et al. (2005)

Optimal Signal

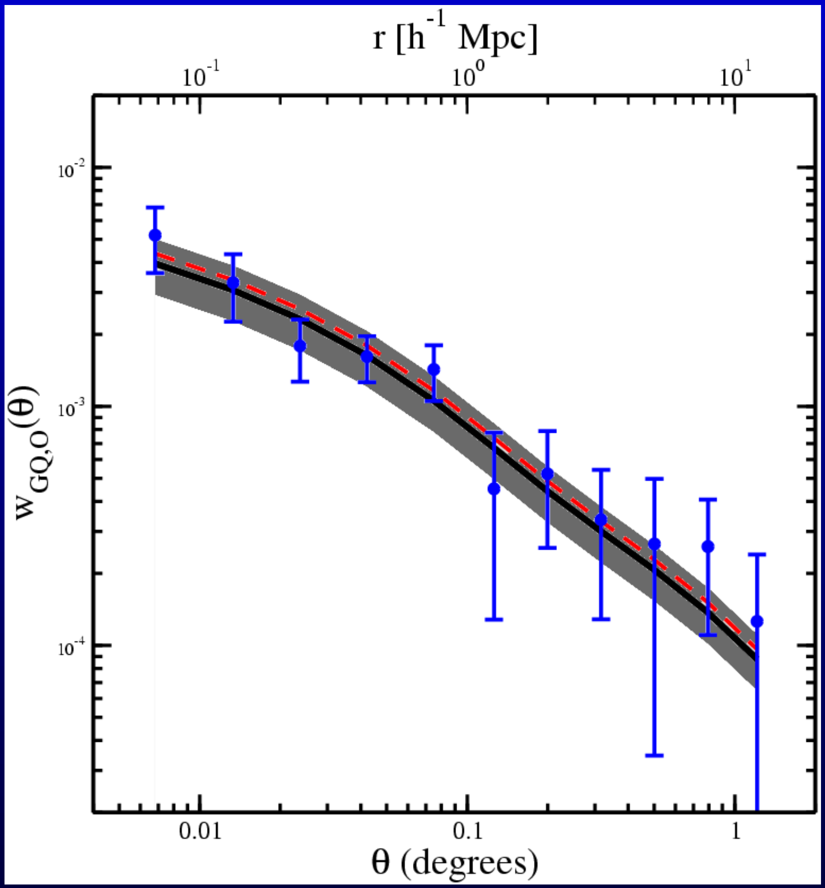
- Magnitude bin measurements track expected signal as $\langle \alpha - 1 \rangle$ varies from bright to faint QSOs
- $\langle \alpha - 1 \rangle \approx 0$ for full QSO sample
- To extract the full statistical significance for lensing measurement, use second moment:
  - ⋆ Re-calculate estimator weighting each QSO by $\alpha(m) - 1$
  - ⋆ Expected signal:

$$w_{\mathrm{GQ},0}(\theta) = \langle (\alpha - 1)^2 \rangle \times w_0(\theta) \quad (4)$$

- Instead of canceling, positive and negative correlations add coherently

Optimal g'

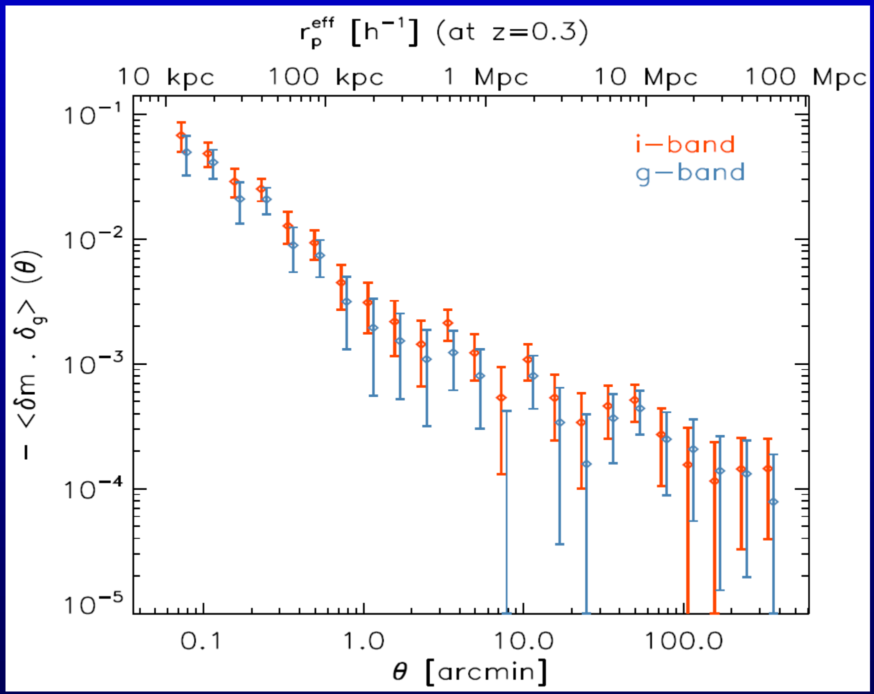
- 105,000 QSOs & 13 million galaxies
- 8σ detection of lensing against null signal
- Excellent match to expected signal
- For $z \sim 0.3$, detecting lensing on scales from 60 kpc$/h$ to 10 Mpc$/h$



Scranton et al. (2005)

Flip the Script

- Correlate QSO flux with galaxy density
- Differences between bands indicates wavelength-dependent extinction
- Reconstruct dust halo profile of average galaxy & environment
- Key systematic consideration for SNe missions



Menard & Scranton et al. (2007)

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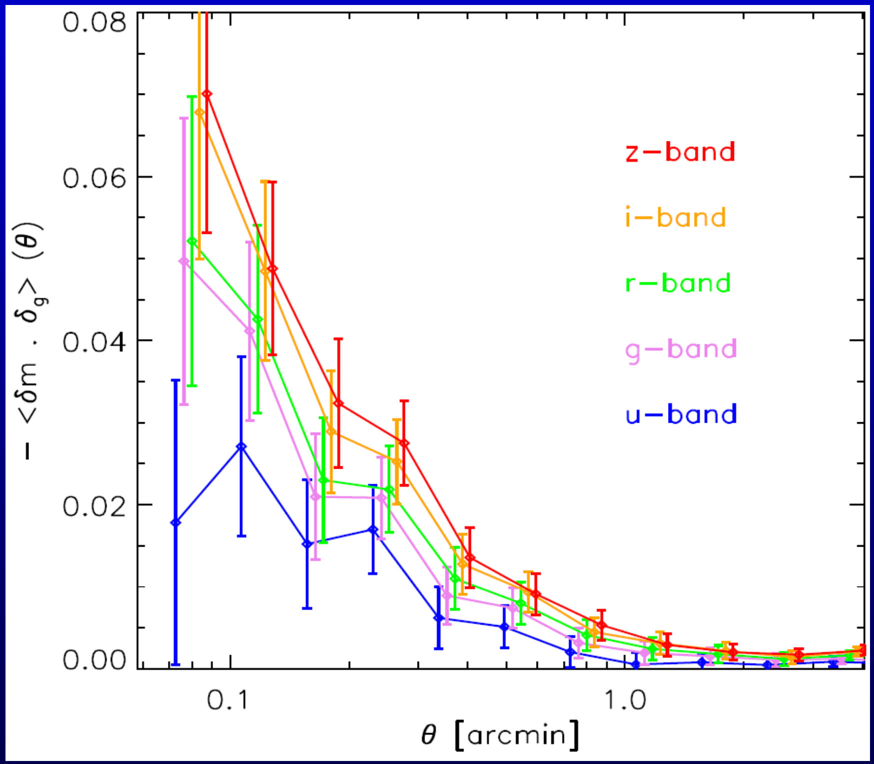

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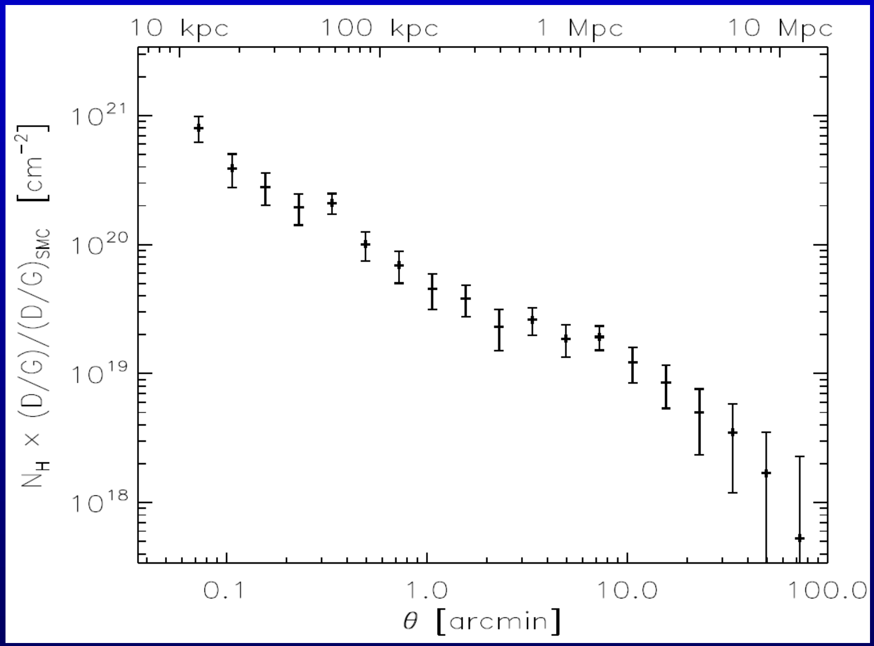

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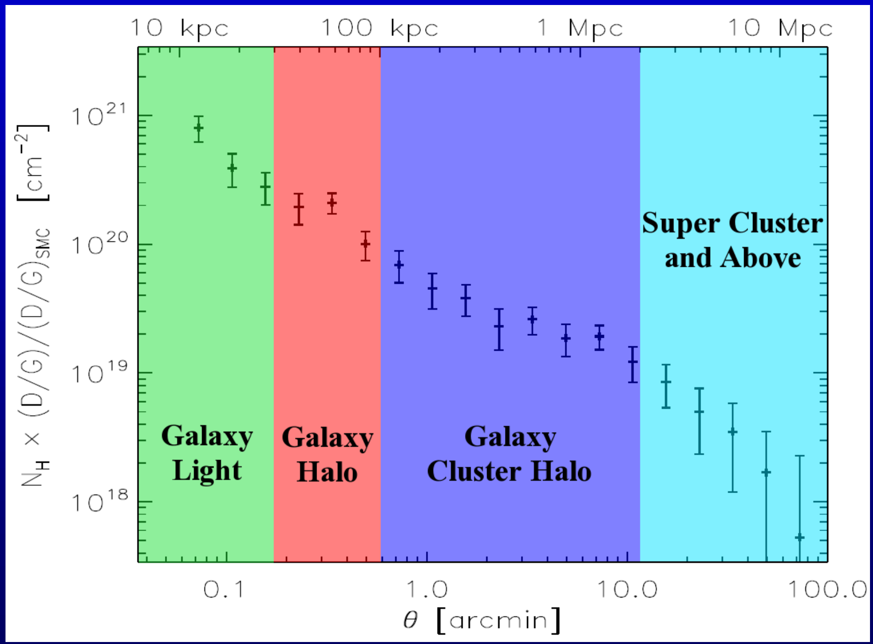


Menard & Scranton et al. (2007)

The Future of Cosmic Magnification

- Using photometric QSOs and galaxies from SDSS DR3, we observe a signal with the expected lensing amplitude. The signal also exhibits the expected variation in amplitude and sign with changing $\alpha(m)$.

- Optimally combining all of our g'-selected QSOs, we detect cosmic magnification of QSOs at $> 8\sigma$. Earlier conflicting $\Omega_{\rm M}$ values are resolved.

- Correlating QSO flux and galaxy density gives us the first ever measurement of galaxy dust halo shapes & will be critical for flux-based observations like future SNe.

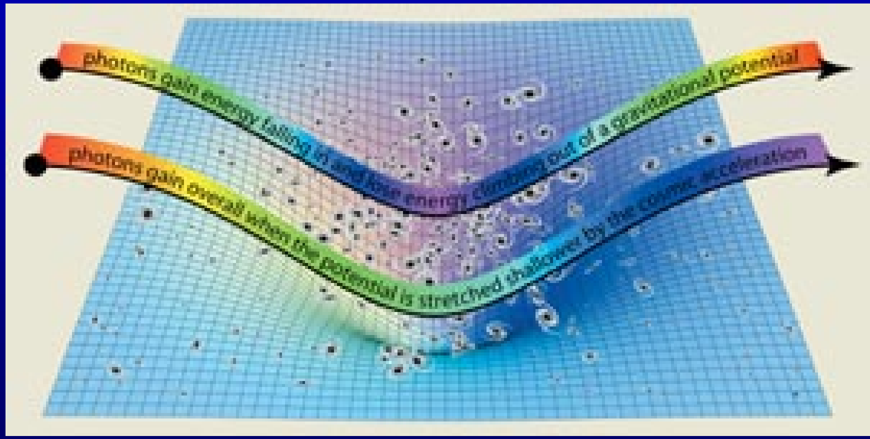
- The techniques used for efficient QSO selection are readily applicable to next generation of large, multi-band surveys. Cosmic magnification with galaxies or QSOs is an excellent (**free!**) complement to planned cosmic shear surveys (same physics & cosmology, different systematics).

Detecting Dark Energy:

Integrated Sachs-Wolfe Effect

Integrated Sachs-Wolfe Effect in 2 Minutes

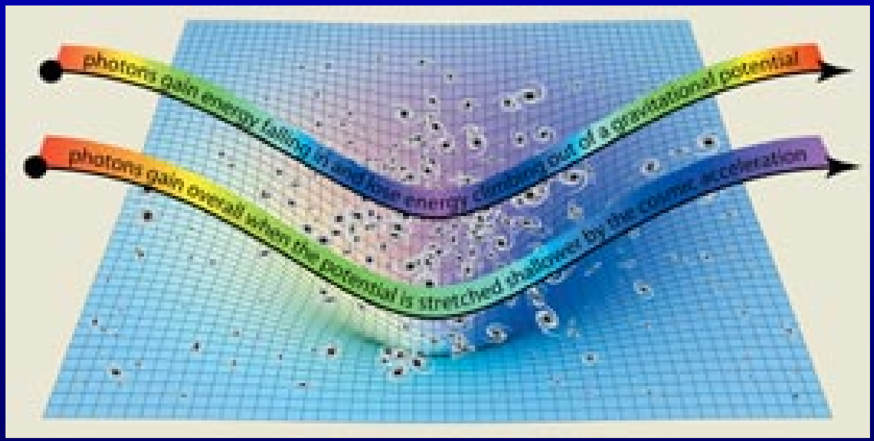
- After matter-radiation equality, dark matter falls into potential wells set up during inflation.
- For open or ΛCDM universes, universe expands faster than potentials, leading to potential decay
- CMB photons passing through potentials see net blue-shift in energy $\Rightarrow$ positive correlation with foreground structure



Physics Web

Integrated Sachs-Wolfe Effect in 2 Minutes

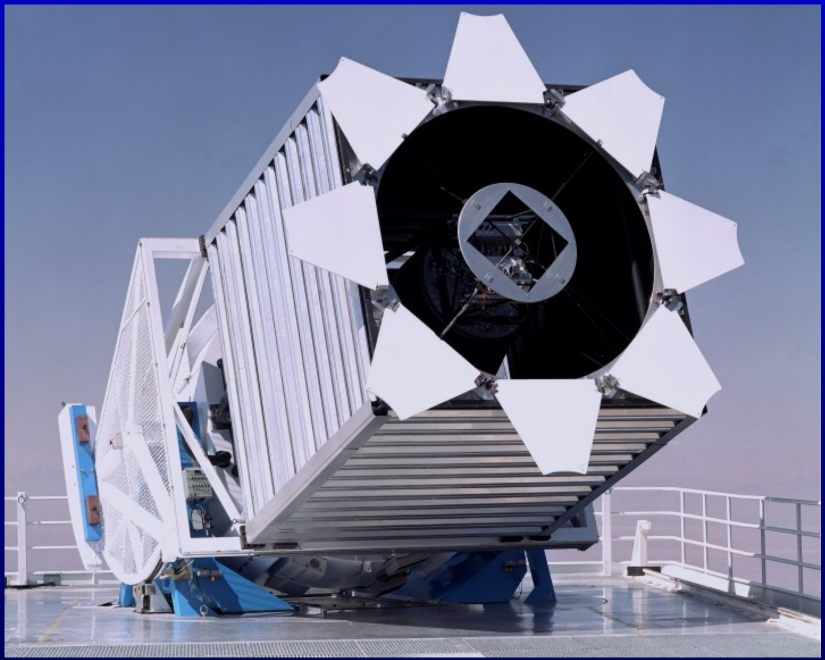
- From WMAP, we know that the overall geometry of the universe is very close to flat ($\Omega = 1$).
- Hence, detecting ISW signal is a clear signature of dark energy.
- Orthogonal to SNe detection. ISW signal related to growth of structure, while SNe signal is due to expansion history.



Physics Web

The Galaxy Data Set

- Initially began with LRGs from SDSS (Scranton et al., 2003); detection at $\sim 3\sigma$
- Increased sample to include galaxies from 2MASS, FIRST and NVSS
- New galaxy sample contains 15 galaxy maps spanning $0 < z < 2.5$ and wavelengths from radio to IR to optical to near-UV.



SDSS Telescope, APO

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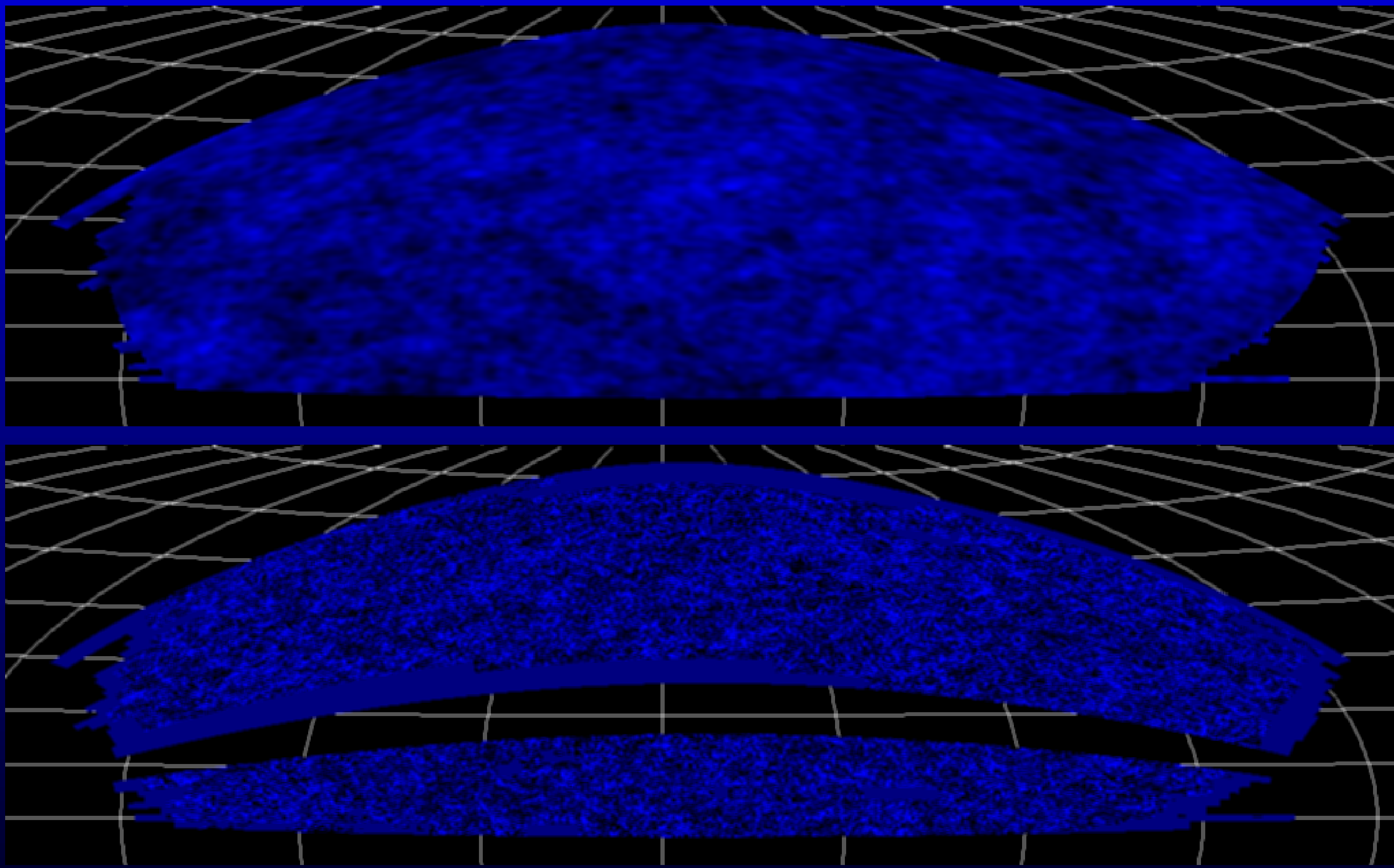
2MASS 2 MICRON ALL SKY SURVEY

Sloan Digital Sky Survey Mapping the Universe

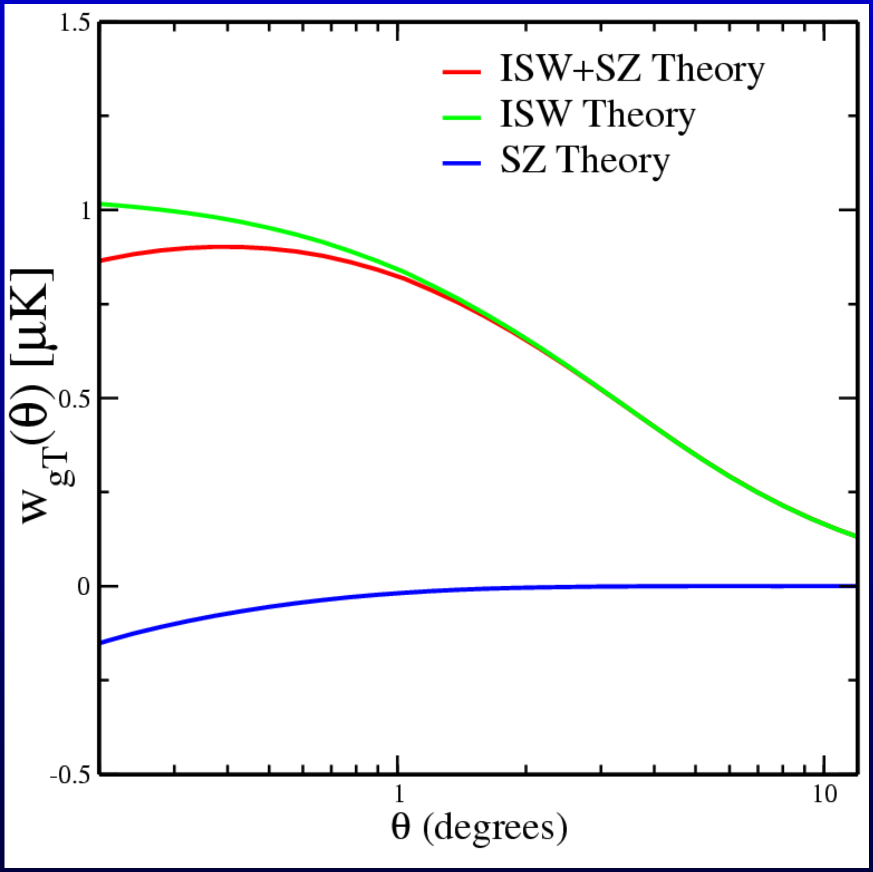
FIRST

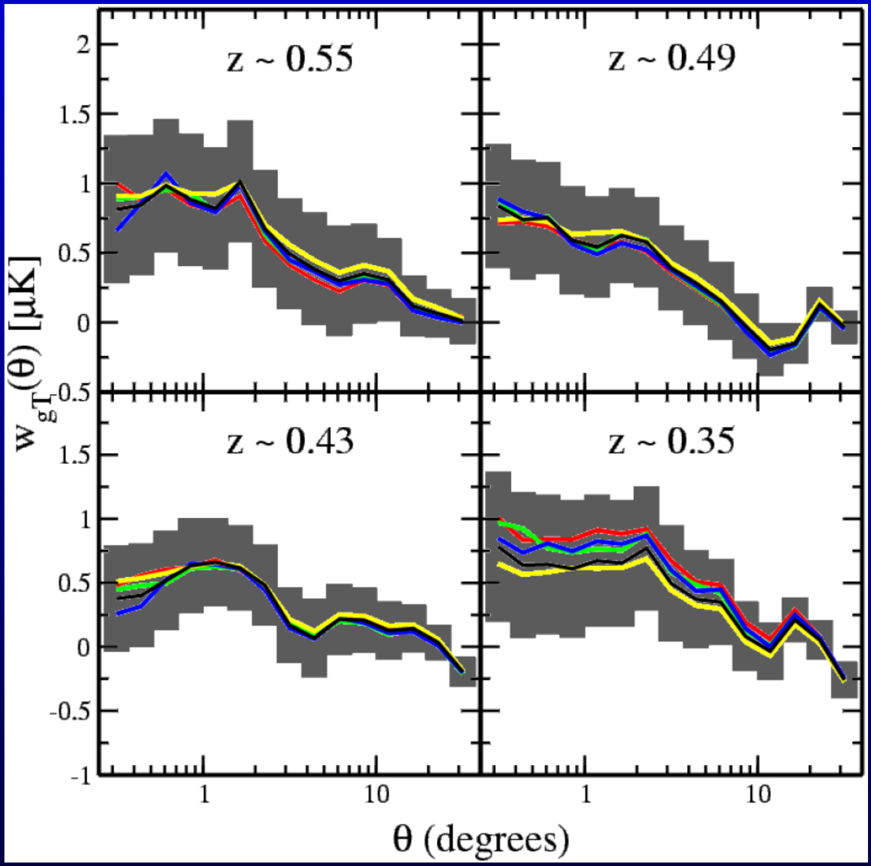
NVSS

Map Comparison



Results





Scranton et al. (2003)

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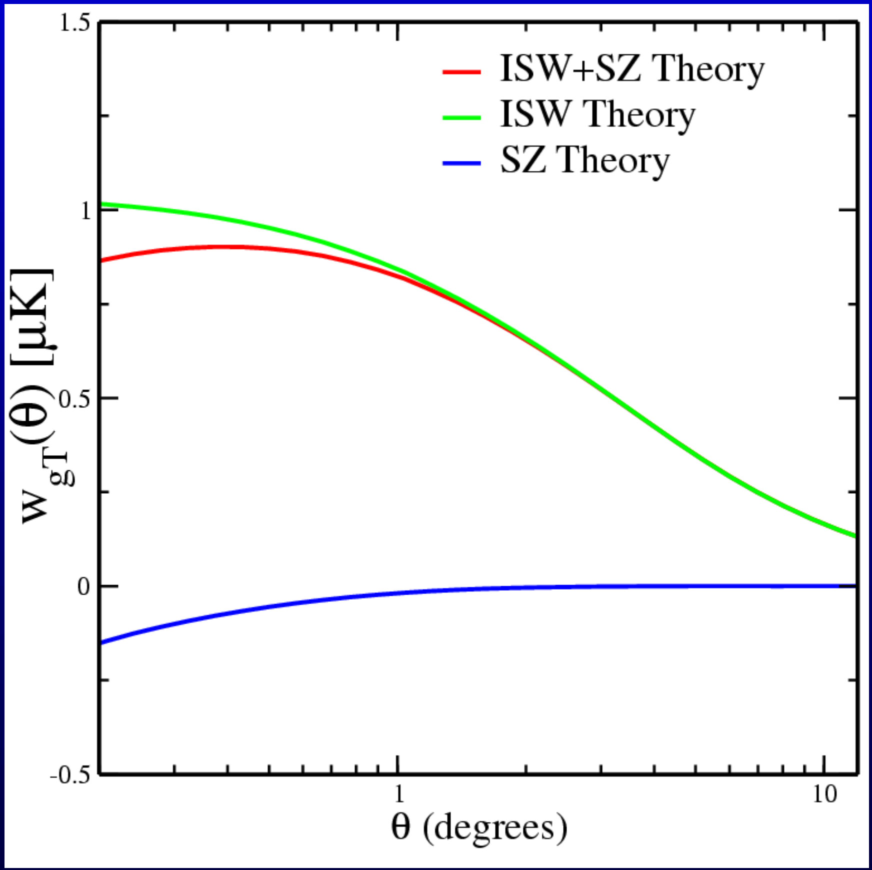

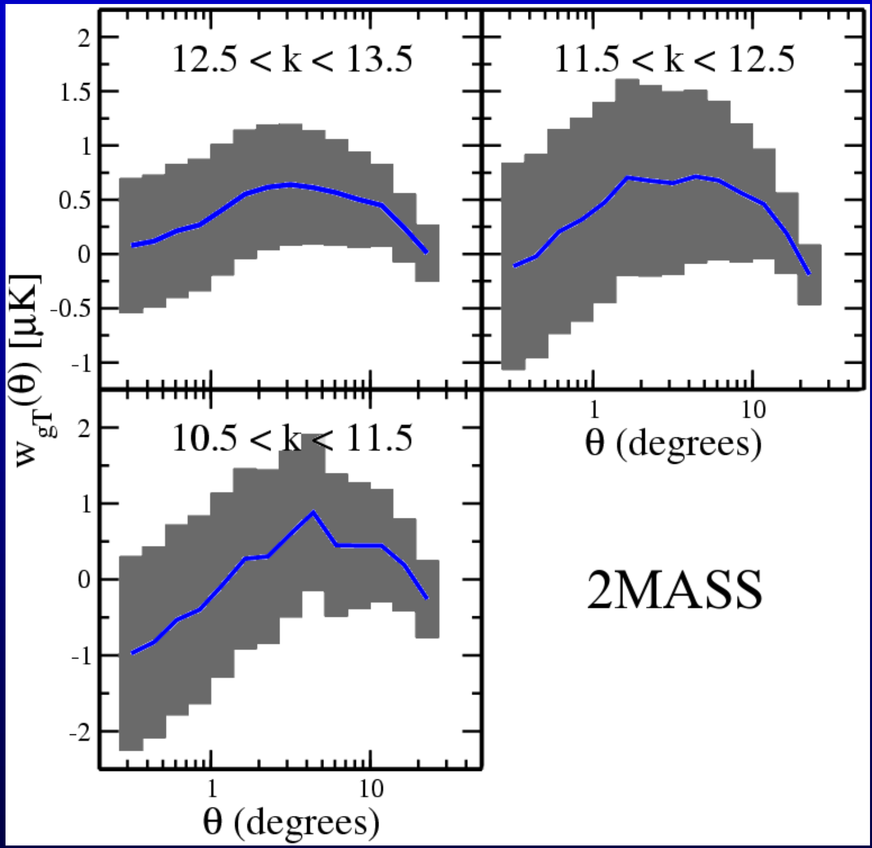

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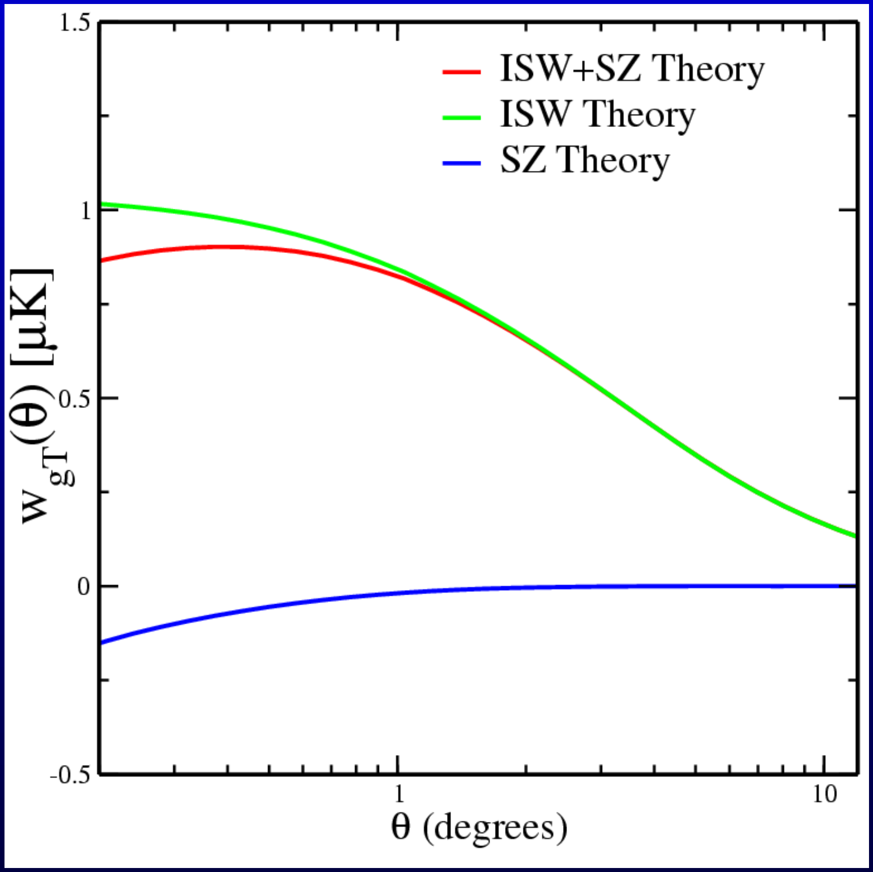

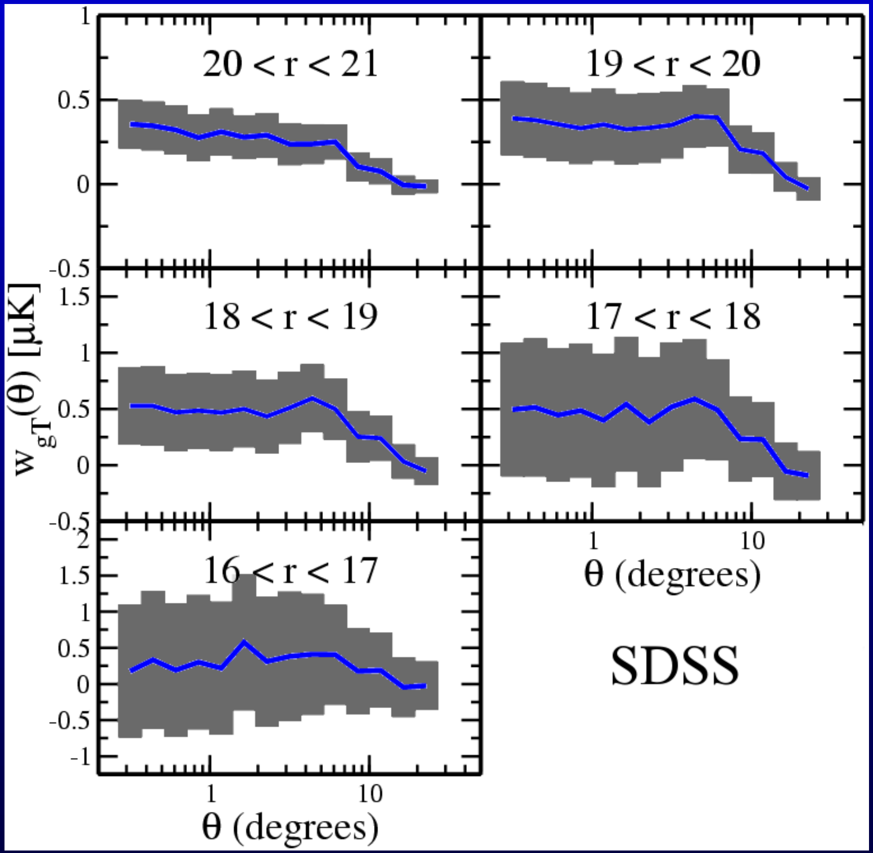

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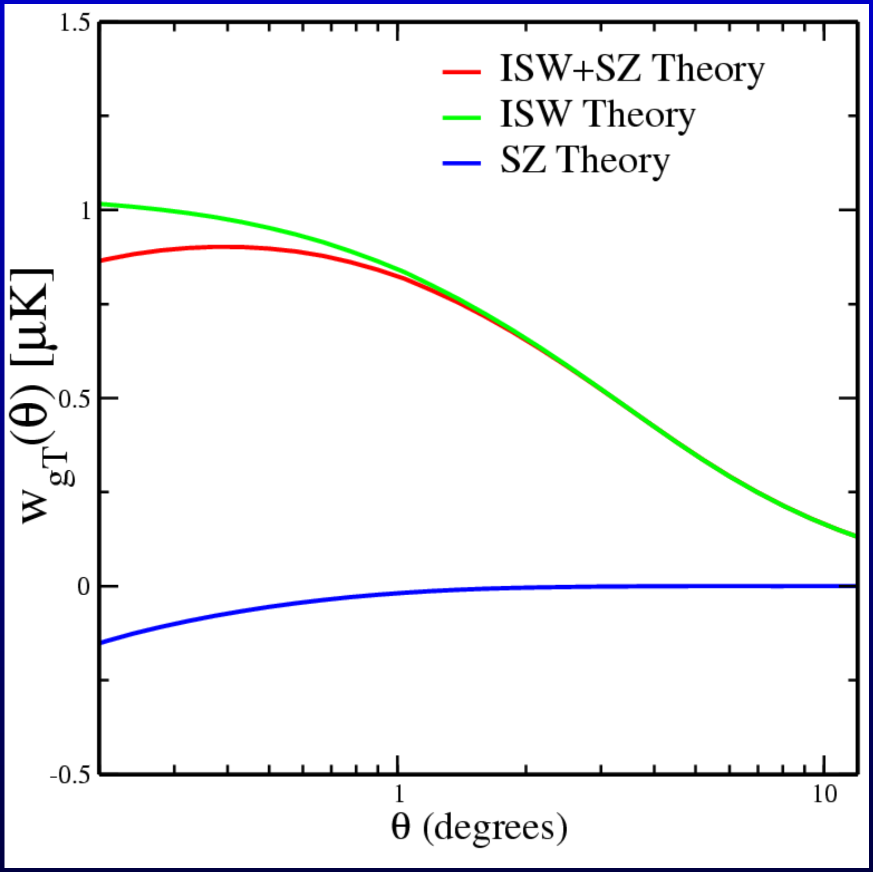

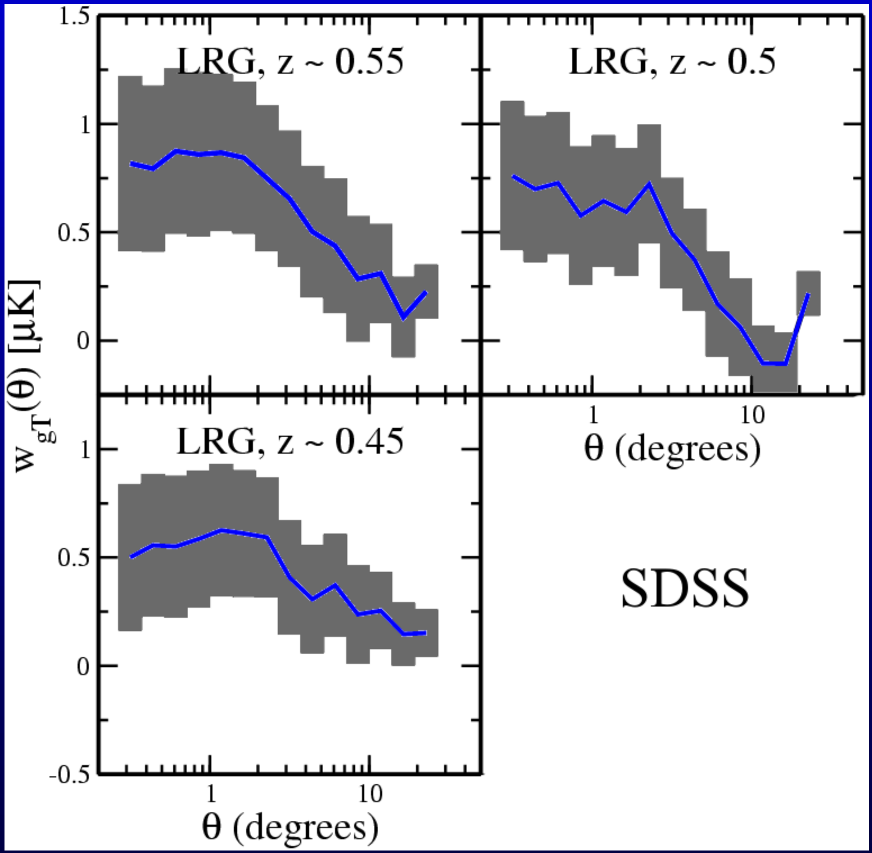

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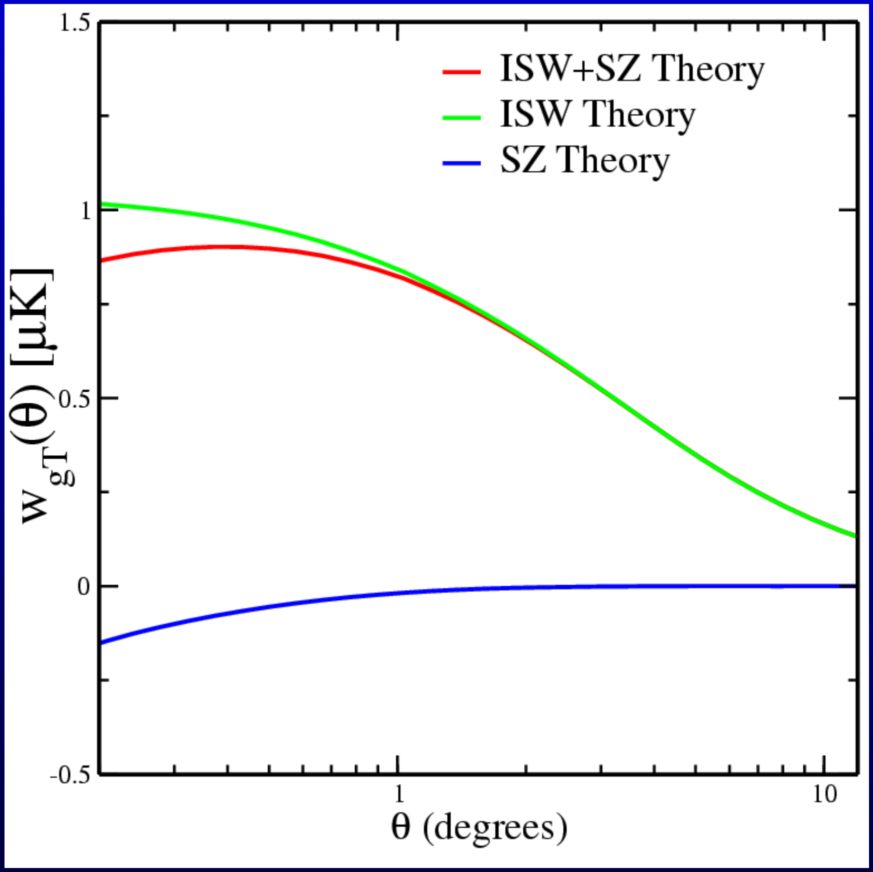

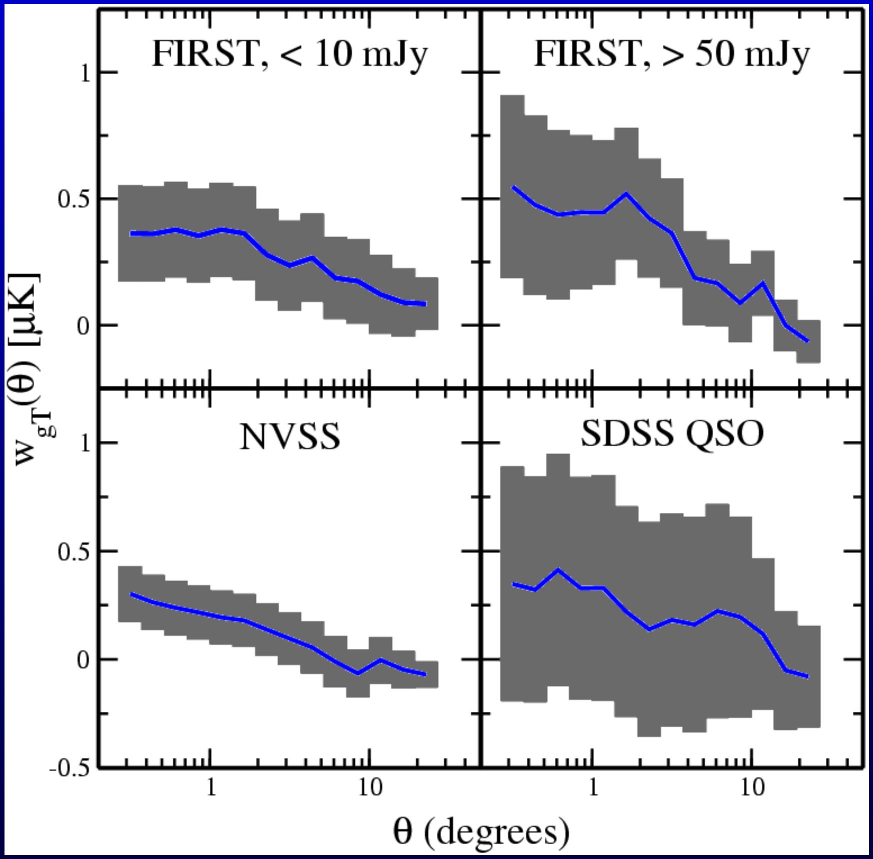

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- Angular bins within measurements and between measurements highly correlated
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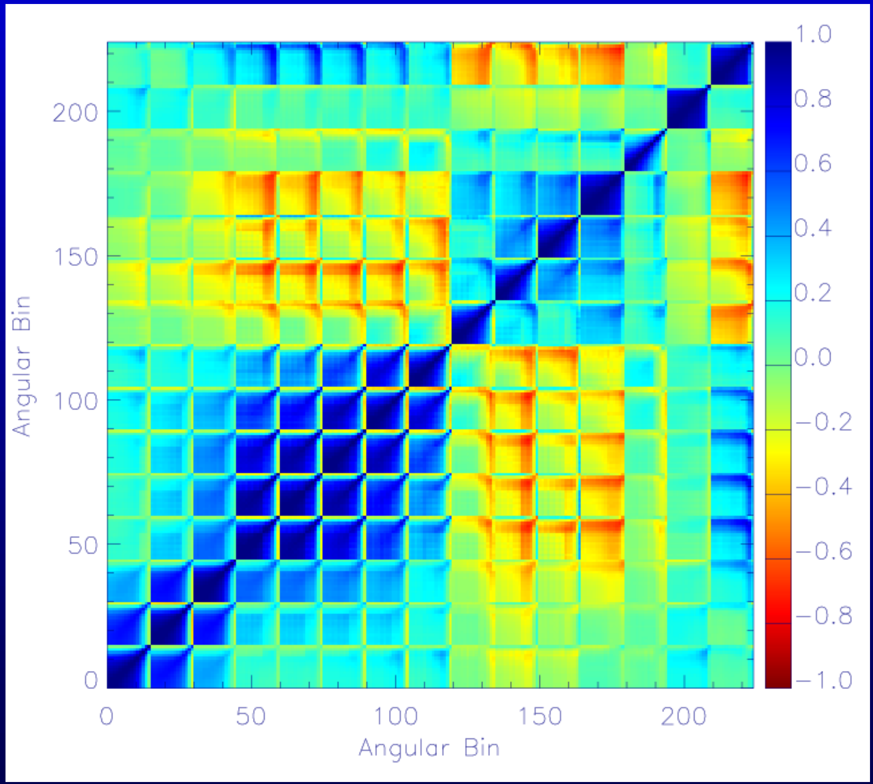

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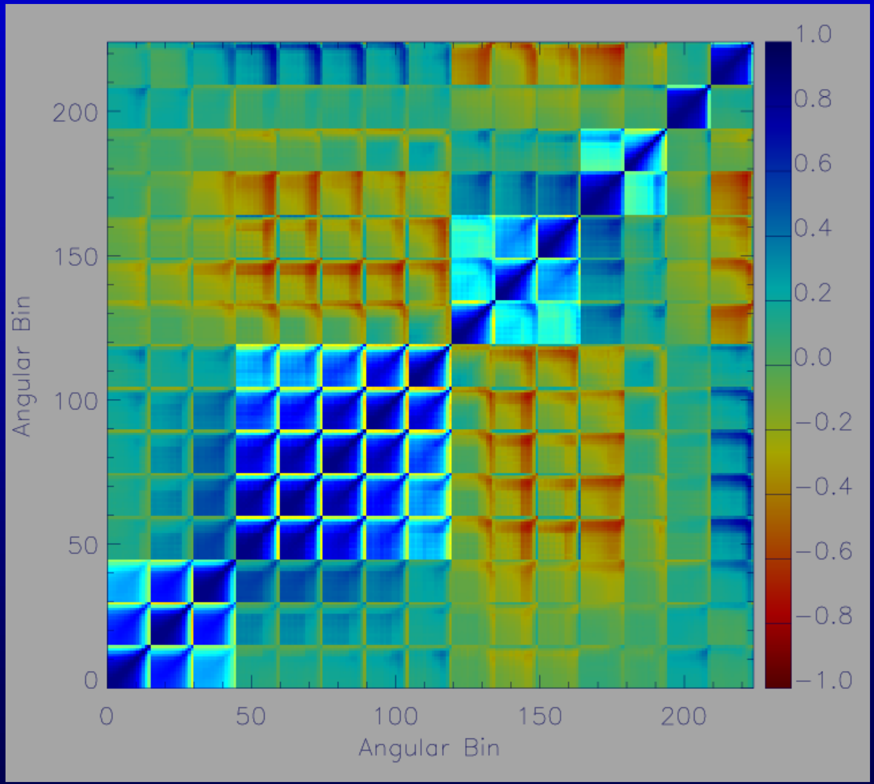


Scranton et al. (2007)

The Future of ISW

- Using all current large scale galaxy surveys (2MASS, SDSS, NVSS, & FIRST) covering $0 < z < 2.5$, we detect ISW at $> 5\sigma$. This dark energy signature is completely independent of SNe evidence based on acceleration.

- Efforts to turn this detection in cosmological constraints are underway (Scranton et al., 2007).

- ISW signal is sensitive to changes in dark energy over time, but noise from primary CMB anisotropies keeps (S/N) low ($\sim 6 - 10\sigma$).

- Future galaxy surveys with larger areas and deeper samples can constrain dark energy equation of state to 5% (Hu & Scranton, 2004).

- Measurements combining ISW & magnification effects may also offer another lever arm for describing dark energy.

Our Dark Energy Future...

A Riddle Wrapped in a Mystery Inside an Enigma

- The current crop of surveys have largely resolved the issues surrounding $\Omega_{\rm M}$ and H_0 from 10 years ago.

- Along the way, however, they discovered the existence of dark energy (so named in 1999), which is even more puzzling.

- Currently, dark energy theory is in a state of maximal ignorance. We don't know
  - ⋆ what the dark energy equation of state ($w \equiv P_{DE}/\rho_{DE}$) is
  - ⋆ whether $w = w(z)$
  - ⋆ whether dark energy clusters (Hu & Scranton, 2004; Bean & Dore, 2003)
  - ⋆ whether "dark energy" is actually a change in gravity (DGP, 2000; Knox, Song & Tyson, 2005; Linder & Huterer, 2006)

A Riddle Wrapped in a Mystery Inside an Enigma

- With no theoretical guidance, the two new questions to answer are
  - ⋆ **What is the Universe's expansion history over the last 10 Gyr?**
  - ⋆ **What is the rate of large scale structure growth over the last 10 Gyr?**
- No longer 2 parameters; now we have to constrain two functions.
- We will need measurements that handle the first question (**supernovae, baryon acoustic oscillations**), the second question (**ISW**) and both (**weak lensing, cluster abundance**).
- Just as importantly, we will need to be able to combine these measurements in a statistically meaningful way.

New Instruments, New Realities

- Next generation of surveys to focus on weak lensing, supernovae, baryon acoustic oscillations (BAO), and galaxy clusters.
- Ground based galaxy surveys (LSST), CMB cluster finders (SPT), space-based surveys (SNAP)
- Much larger data sets with more complicated geometries, selection functions, time domain data, etc.

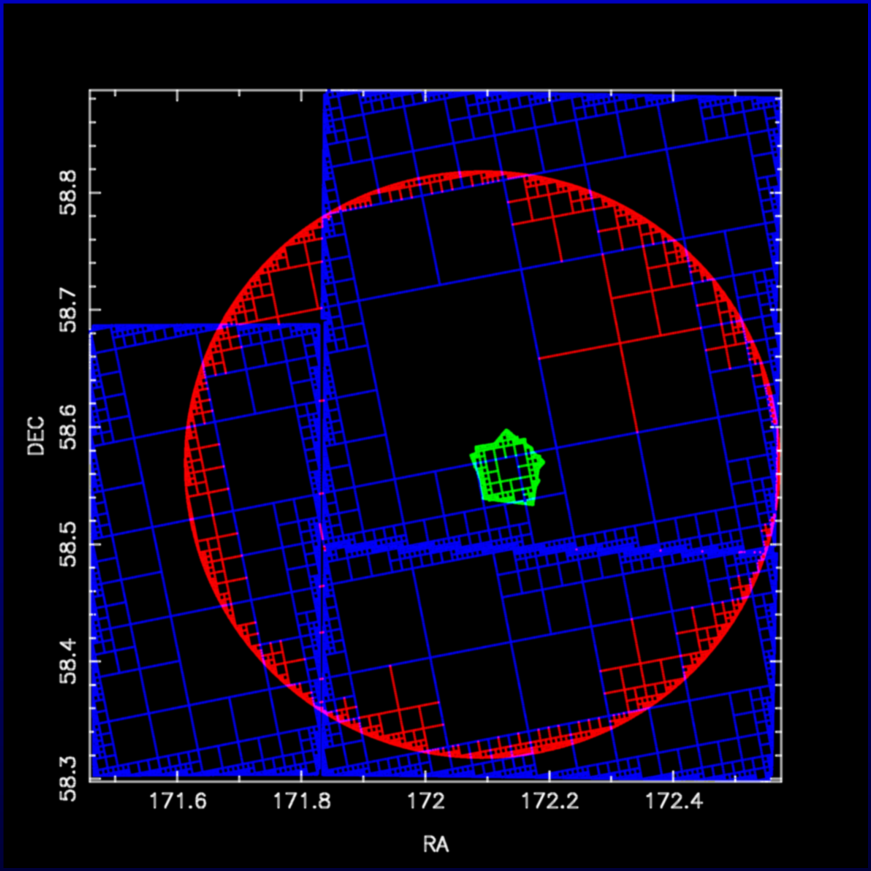
New Instruments, New Realities

- Greater data size & complexity demands new statistical & algorithmic tools and a new way of looking at data.
- Maximizing primary and secondary science (galaxy evolution, cluster physics, stellar physics) will require moving easily between surveys & between measurements.
- Need a unified survey language (**STOMP**) and a single point of access & exploration (**The Google Thing**).

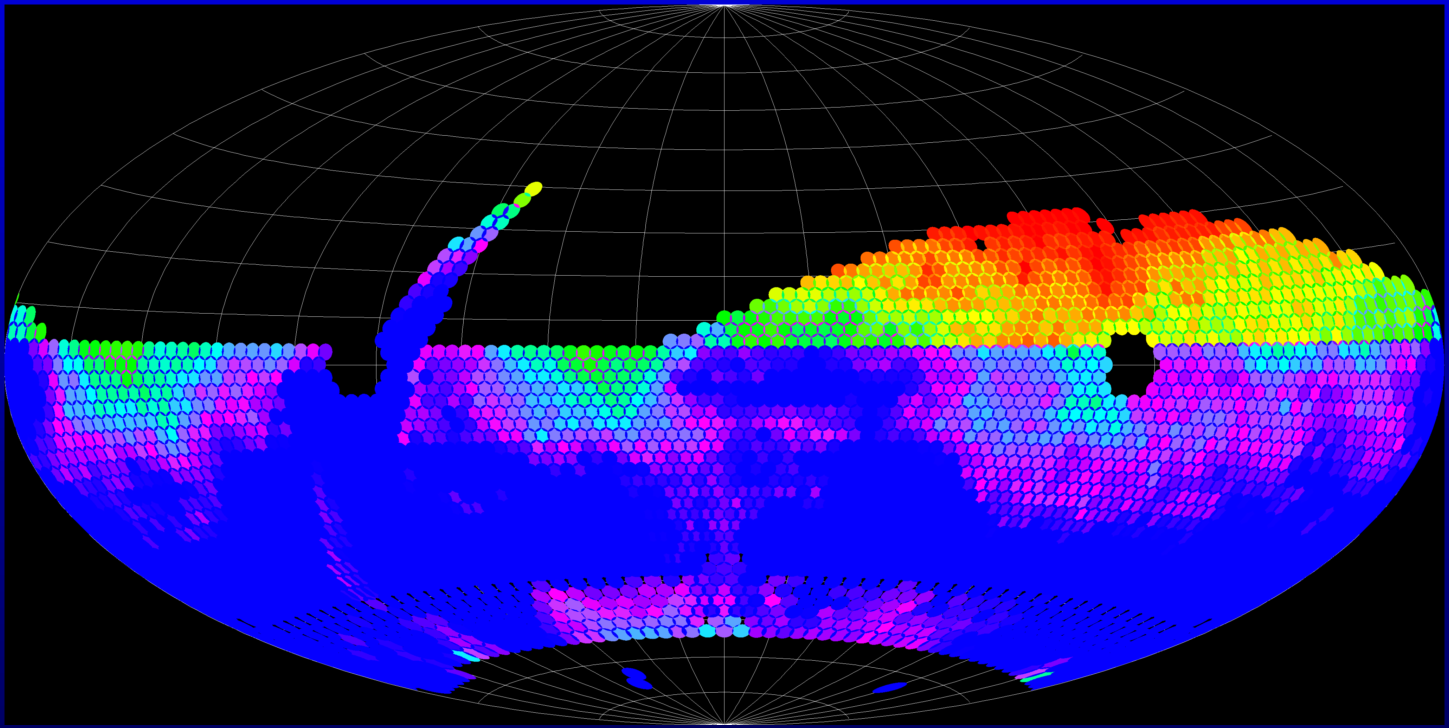
STOMP: Space and Time Ordered Mapping Package

http://nvogre.phyast.pitt.edu/gestalt/

- All cosmological statistics are measurements of spatial properties (area, angular distance, density)
- Describe complex geometries on the sphere and possibly spatial variations
- Find unions, intersections, and overlaps between large numbers of observations
- It has to be fast



STOMP: Space and Time Ordered Mapping Package



- Pixelize arbitrary survey footprints with 1” resolution
- Hierarchical scheme: extremely rapid localization & angular statistics
- Spatial information (completeness, flux, temperature, etc) & geometry

Lingua Franca – A World of Applications & Results

- Angular Correlations
  - ⋆ Integrated Sachs-Wolfe Effect
  - ⋆ $w(\theta)$ (Scranton et al., 2007)
  - ⋆ Higher Order (Ross et al., 2006)
- Survey Simulations
  - ⋆ Dark Energy Survey (DES)
  - ⋆ LSST
- Galaxy Evolution
  - ⋆ Galaxy Environment (Welikala et al., 2007)
  - ⋆ LRG luminosity function (Loh et al., 2007)
- Weak Lensing
  - ⋆ Magnification & Extinction
  - ⋆ Shear Lensing (Sheldon et al., 2004; Mandelbaum et al., 2005)
- Spectroscopic Surveys
  - ⋆ BAO (Eisenstein et al., 2005)
  - ⋆ Halo Multiplicity Function (Berlind et al., 2005)
- Galaxy Clusters
  - ⋆ MaxBCG (Koester et al., 2007)
  - ⋆ Optical/X-ray Counterparts (Miller et al., *in preparation)*

About that Google thing, I can neither confirm nor deny that something very, very cool is about to come out that will change the way that you do astronomy...

Summary

- The current generation of surveys has succeeded in solving the central questions in cosmology from a decade ago.
- Along the way, the richness of the data gathered drove new scientific results that were largely unanticipated prior to the beginning of these surveys.
- The next generation of surveys has the potential to tell us a great deal about the nature of dark energy, but the unavoidable size & complexity of these surveys will be a problem for outside users.
- By unifying the data and analysis sides into a common framework, STOMP surmounts these obstacles, allowing astronomers to easily move within and between surveys and measurements.
- Keep your eyes open for the next couple months. Something very interesting is on the way...