What's going on with Dark Energy?

Bill Carithers

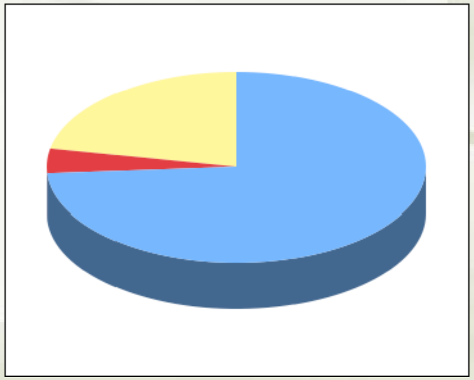
Aspen 2008

I assume you all know:

Expansion of the universe is accelerating

Dark energy
Λ?

Off by 10^{60}
“worst prediction in the history of science”



Why now?

GR on a slide

$$R_{\mu\nu} - \frac{1}{2}Rg_{\mu\nu} = 8\pi\frac{G}{c^4}T_{\mu\nu} - \Lambda g_{\mu\nu}$$

Simplify, simplify… homogeneous, isotropic, perfect fluid
(stress-energy tensor becomes diagonal)

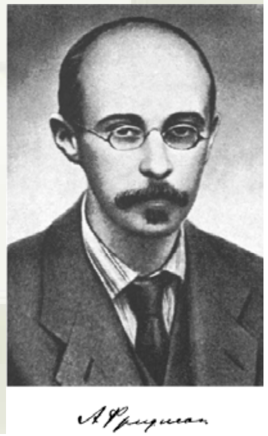
then

$$H^2 \equiv \left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G}{3}\rho - K\frac{c^2}{a^2}$$

← curvature term

$$3\,\frac{\ddot{a}}{a} = -4\pi G\left(\rho + \frac{3p}{c^2}\right)$$

a is the (expansion) scale factor = 1/(1+ z)
H is Hubble factor



OK, two slides

$$H^2 \equiv \left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G}{3}\rho \cdot$$

Define: $\rho_c = 3\,H_0^2\,/8\pi G$ where H_0 is the current value of Hubble const
$\Omega = \rho/\rho_c$ for each component (I.e., baryons, dark matter, dark energy, radiation)

In a flat universe, $\sum_i \Omega_i = 1$

Define: equation of state, $w = \frac{p}{\rho}$

$$3\,\frac{\ddot{a}}{a} = -4\pi G\left(\rho + \frac{3p}{c^2}\right)$$

$$= -4\pi G\rho(1+3w)$$

For acceleration, $w < -1/3$, cosmological constant implies $w = -1$

$$H(a) = H_0\sqrt{\Omega_m a^3 + \Omega_{de} a^{3(1+w)} + \Omega_k a^2}$$

Caution about astro-speak
H_0 = (100 km/s/Mpc) h

What is it that we actually measure?

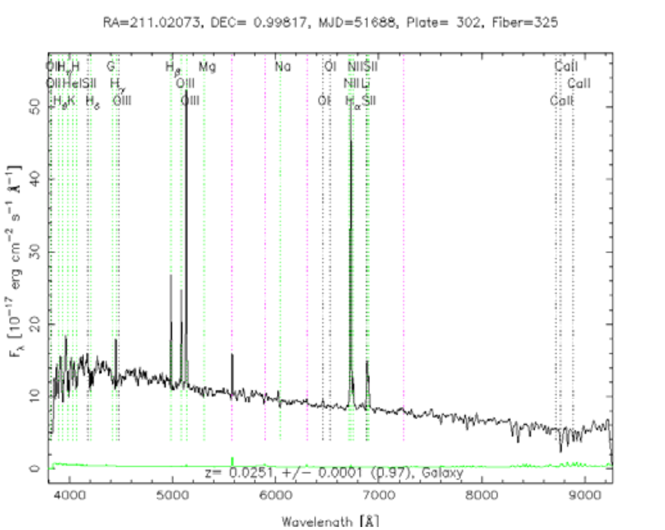
- Answer: detailed expansion history of the universe.
- Need two ingredients
  - Distance (equivalent to time=age)
  - Red shift

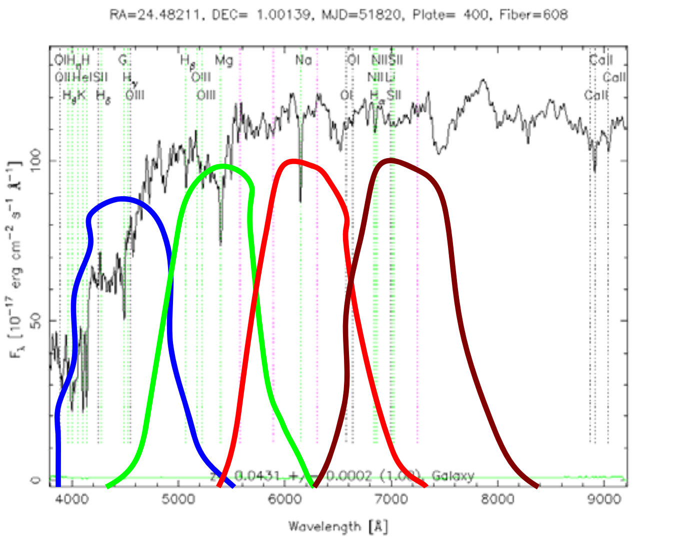
The program

- Measure a(t) with standard rulers, candles
- Strategy 1: Assume GR and extract dark energy equation of state
  - Is it -1 ?
  - Does it vary? $w = w_0 + w_a\,(1- a)$?
  - Need multiple techniques to sort out the degeneracies
- Strategy 2: Measure growth of structure
- Compare the results of the two strategies as a consistency check on GR

$$\frac{\dot{a}}{a} = H_0\sqrt{\Omega_m a^3 + (1-\Omega_m)a^{3(1+w)}}$$

Measuring red shift





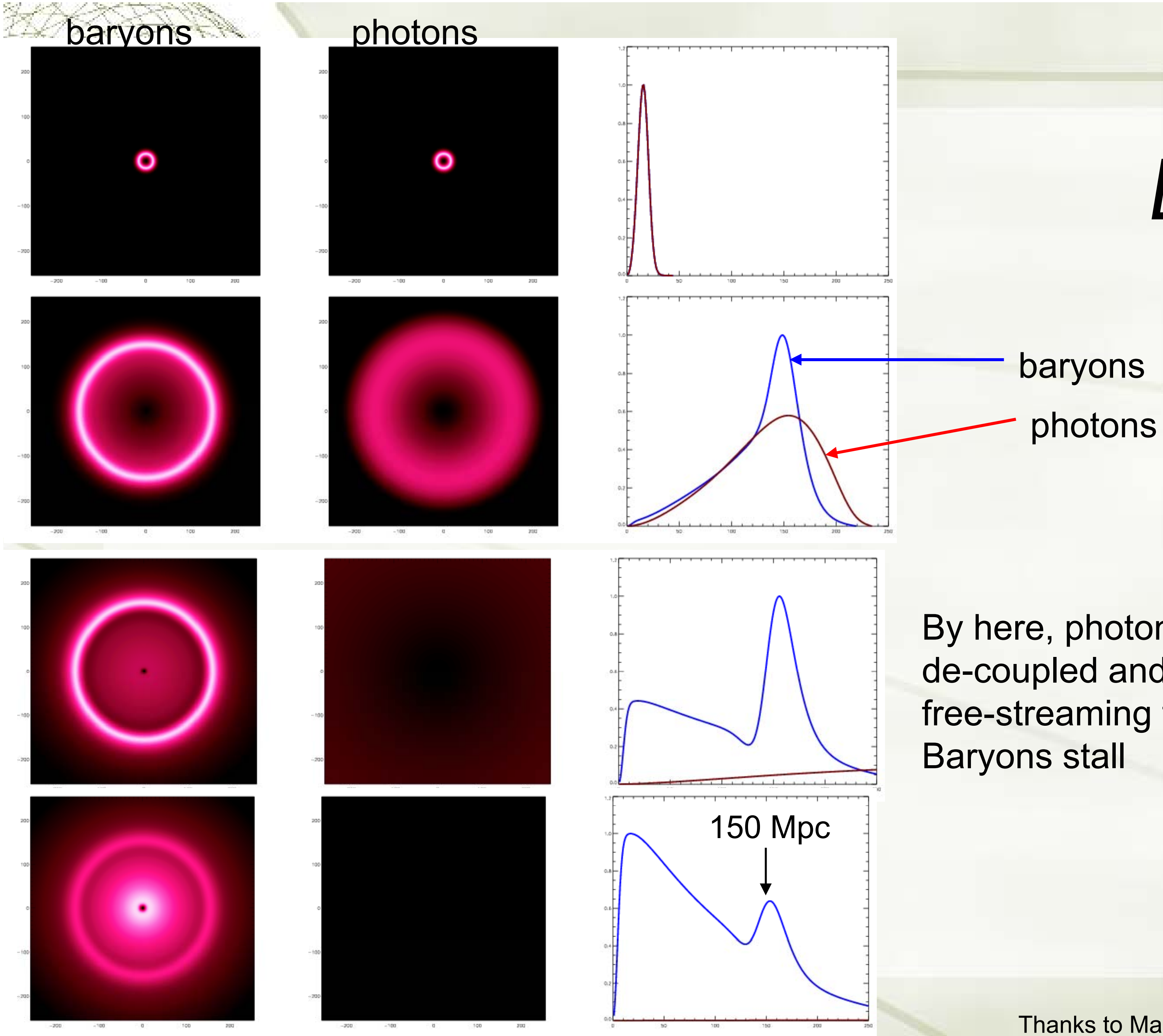
The precise way--spectral lines

But… takes a <u>long</u> time!

Photometric redshifts

Quick but accuracy limited to $\delta z > .03$

BAO

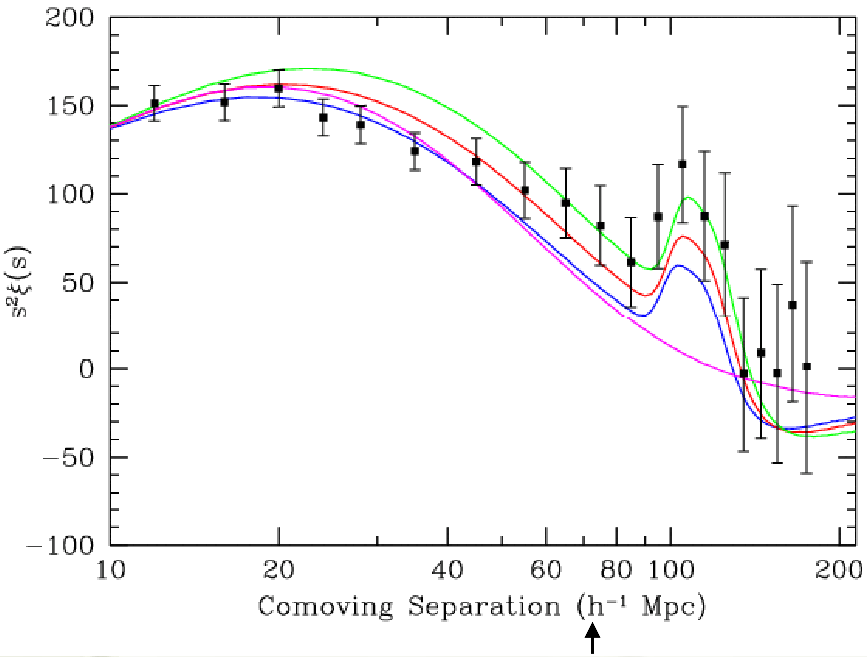


By here, photons have de-coupled and are free-streaming to become CMB
Baryons stall

Thanks to Martin White for graphics

BAO first measurement

Scaled correlation



Spectroscopic survey of 55000 LRG's from SDSS, <z> = 0.35 (Eisenstein, et al. 2005)

BAO is same physics as CMB but much smaller effect and harder to measure so what's the point?

The point is that it is at very different redshift, z<3 (CMB is z=1100)

- Stake through the heart of curvature (or discovery!)
- Relevant region for emergence of dark energy and relatively free of astrophysical complications (galaxy counting exeriment)
- Need sub-percent (spectrographic) accuracy on redshift-- photo-z not good enough

BAO future

QuickTime™ and a
decompressor
are needed to see this picture.

Shameless plug

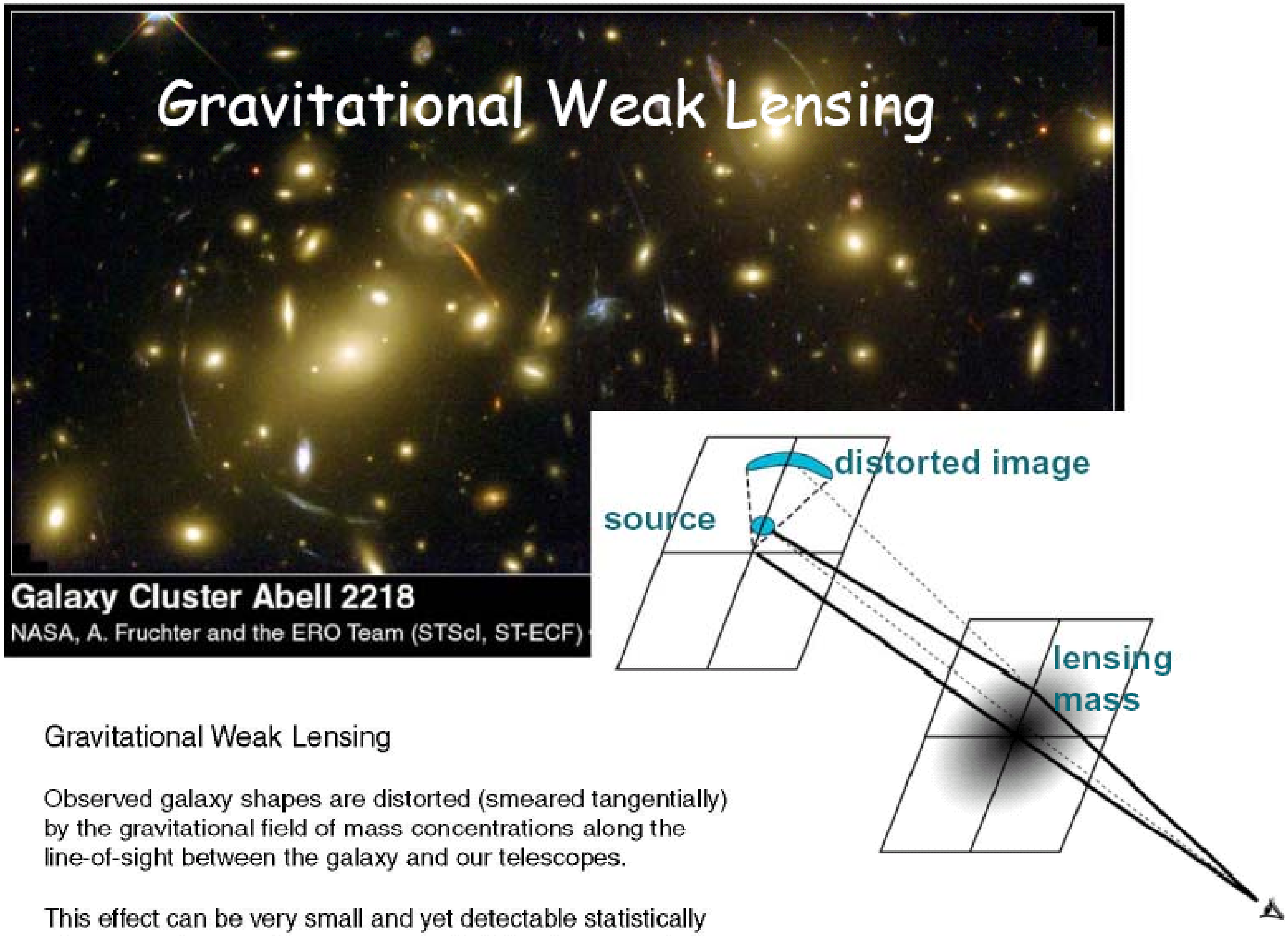
Baryon Oscillation Spectrographic Survey (BOSS)

- Next step in SDSS
- Big collaboration led by LBNL (David Schlegel)

QuickTime™ and a
decompressor
are needed to see this picture.

Stage IV: ADEPT (a JDEM proposal) $1<z<2$, 30,000 sq deg

Weak gravitational lensing

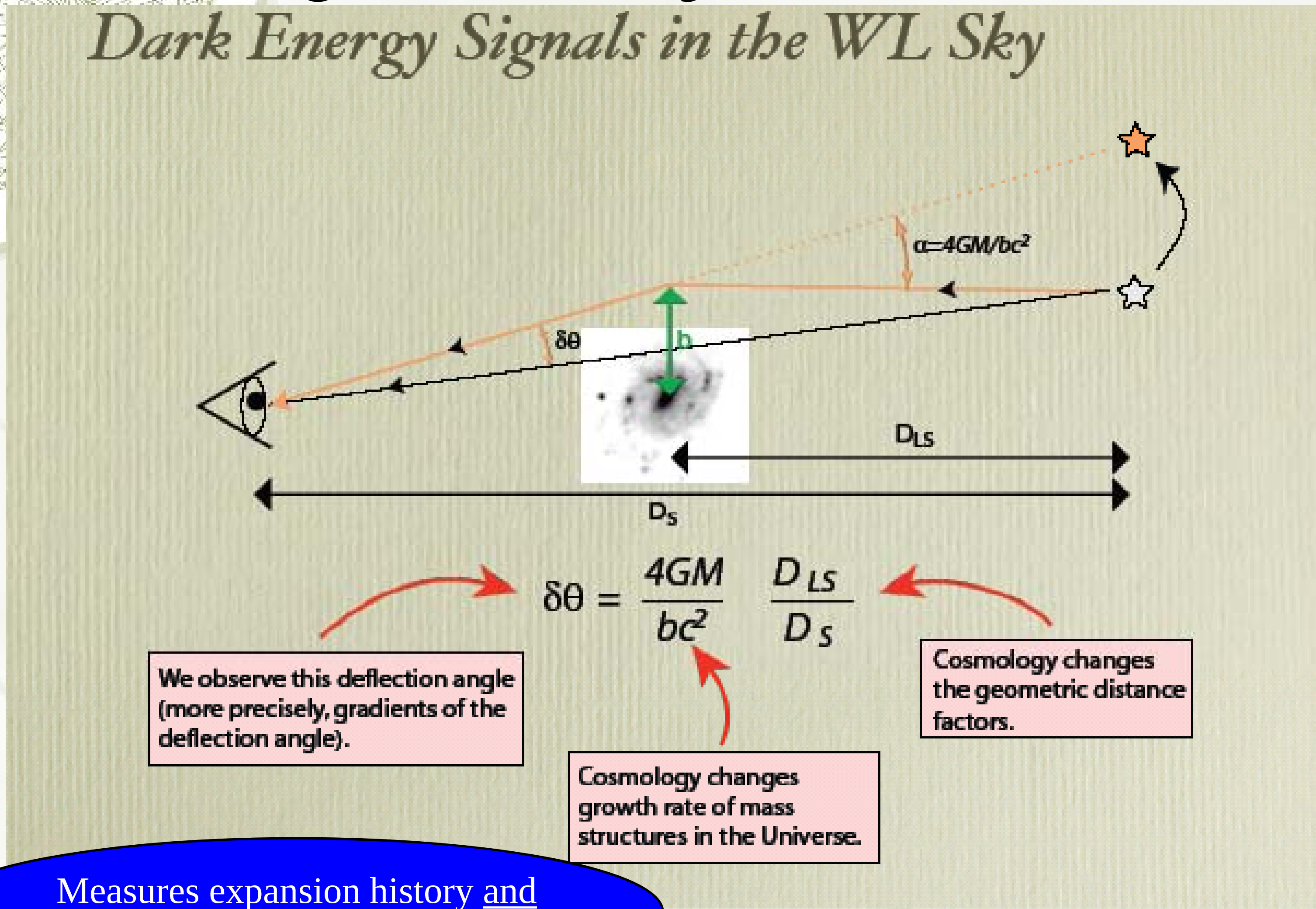


Gravitational Weak Lensing

Observed galaxy shapes are distorted (smeared tangentially) by the gravitational field of mass concentrations along the line-of-sight between the galaxy and our telescopes.

This effect can be very small and yet detectable statistically after averaging over the measured ellipticity of many galaxies.

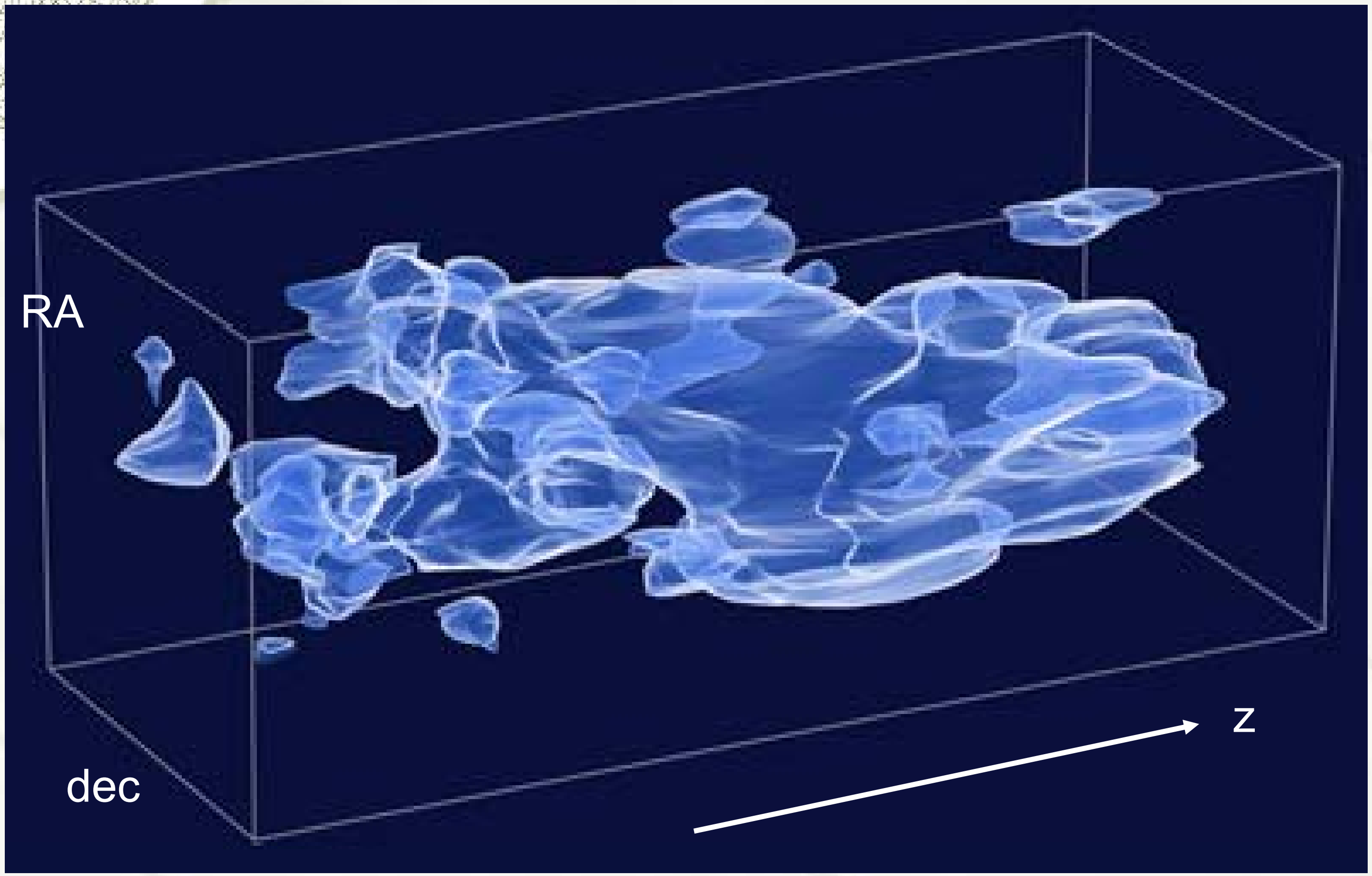
WL--geometry and structure



Measures expansion history and growth of structure

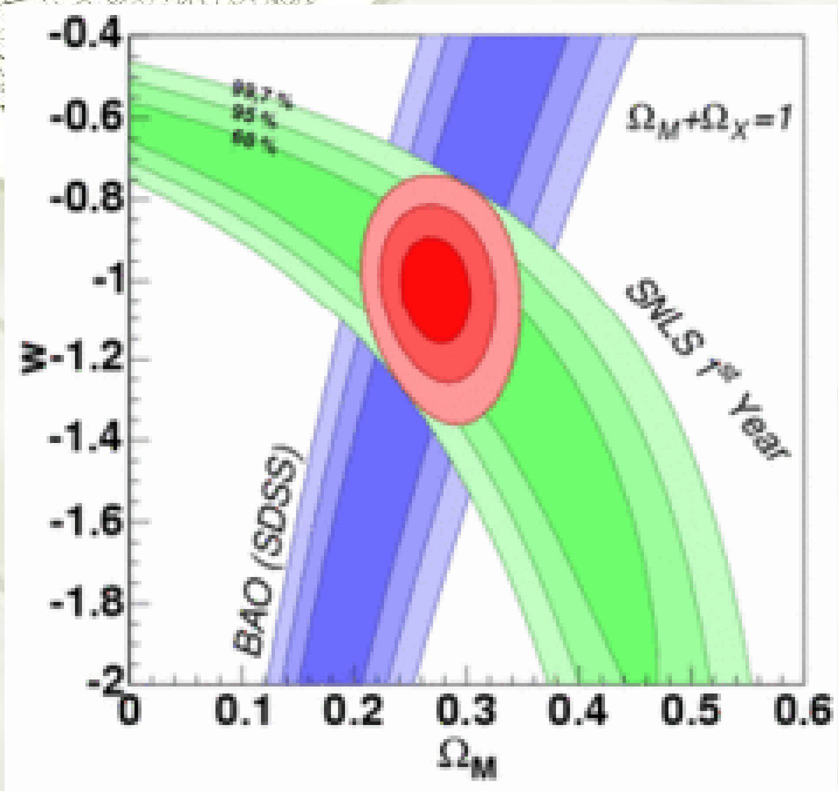
Thanks to Gary Bernstein

WL tomography



From HST COSMOS field, Massey et al., 2007

Dark energy current status

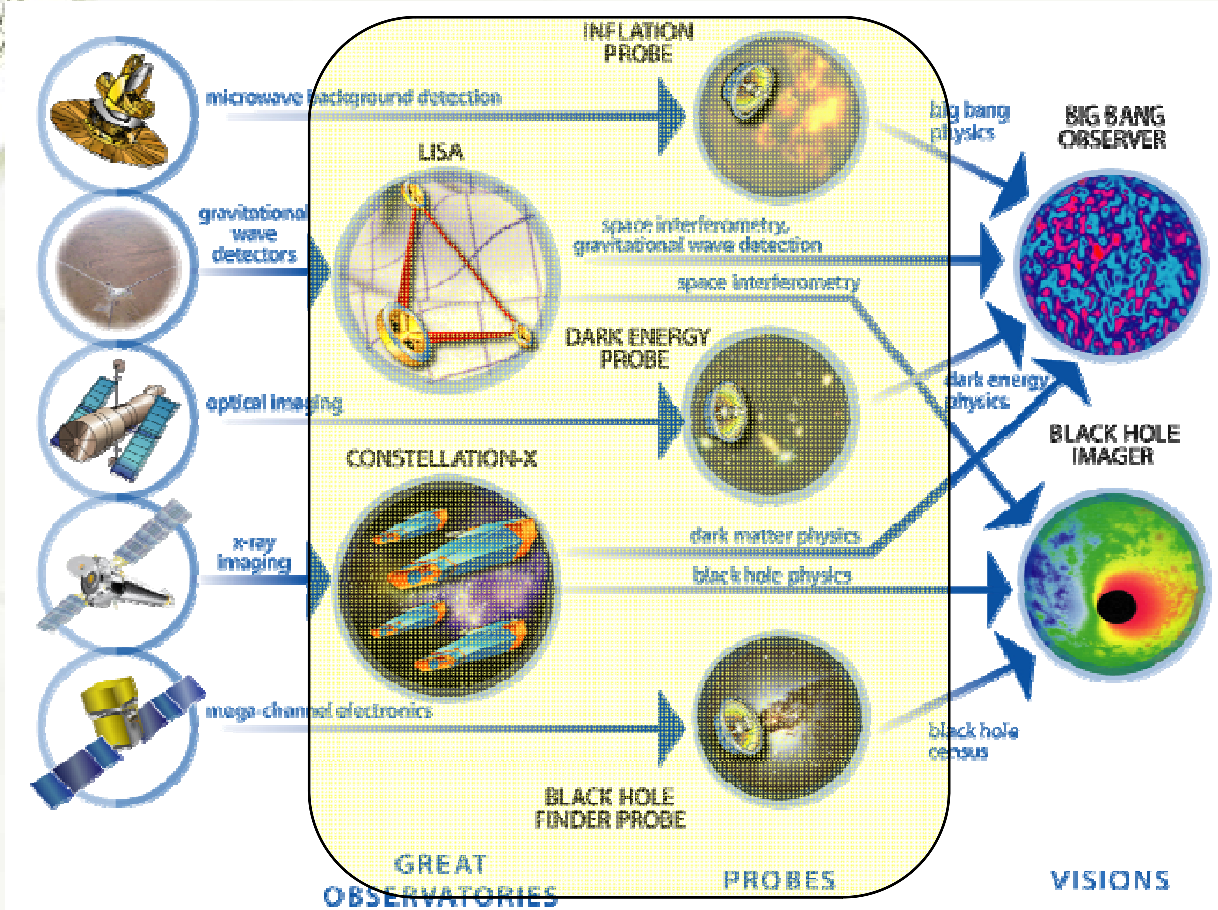


Adding “all” the data:
w_0 = -1.04 $\pm$ 0.06

Still Λ after all those years

Assumes flat universe and constant w

JDEM and BEPAC



NASA to NRC: “Which of these should go first(FY09)?”

NRC to NASA: “JDEM” (with LISA 2nd)

BEPAC considered 3 JDEM candidates

ADEPT

BAO for 1< z <2, 30000 sq deg

DESTINY

Ia SN using slitless spectrometer

Weak lensing over 1000 sq deg

SNAP

2000 well-measured Ia SN (imaging + spectro)

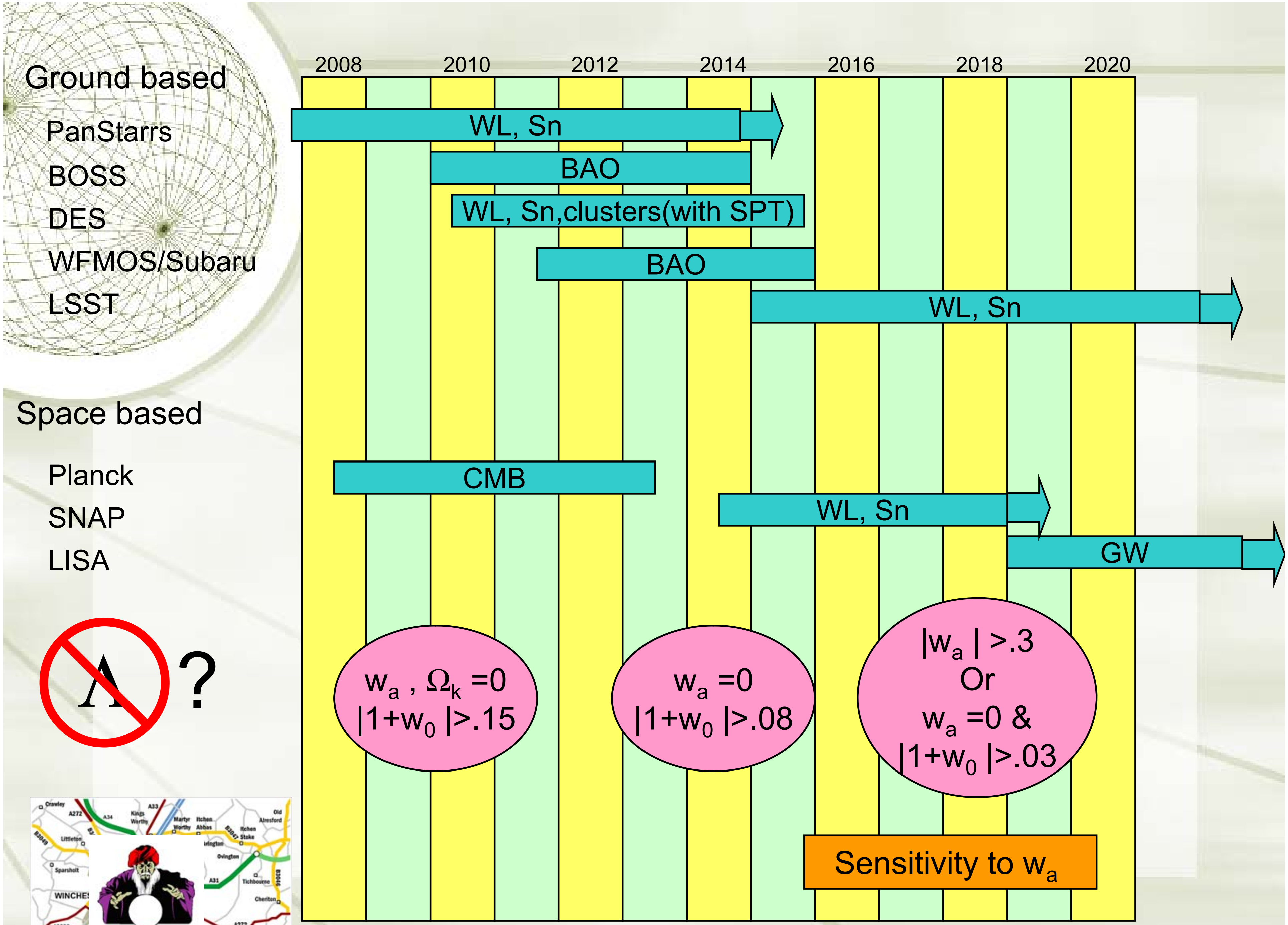
Weak lensing over 4000 sq deg

BEPAC: importance of “other science”

JDEM next steps

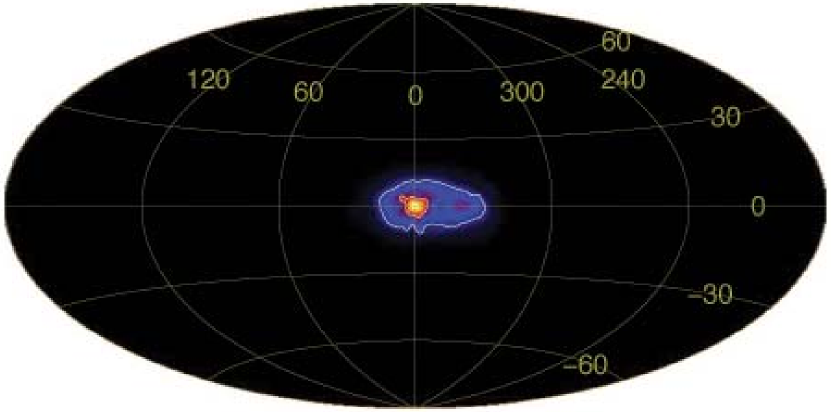
- DOE and NASA working to formulate a call for proposals (Announcement of Opportunity[AO] in NASA-speak)
- AO released in 2008
- Selection in 2009
- Launch in 2014

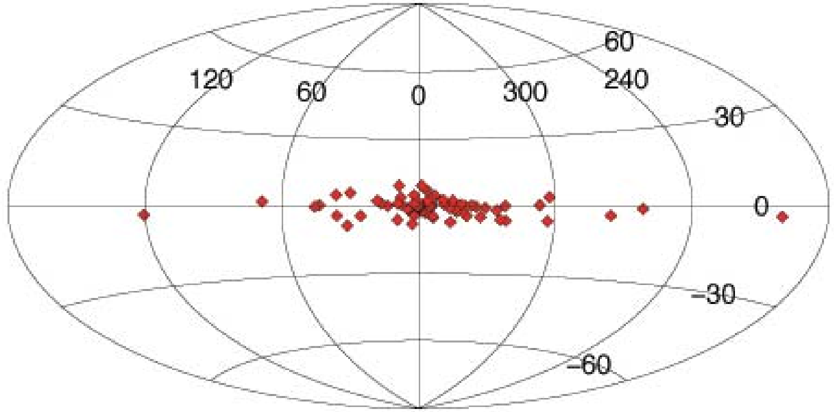
... and in conclusion

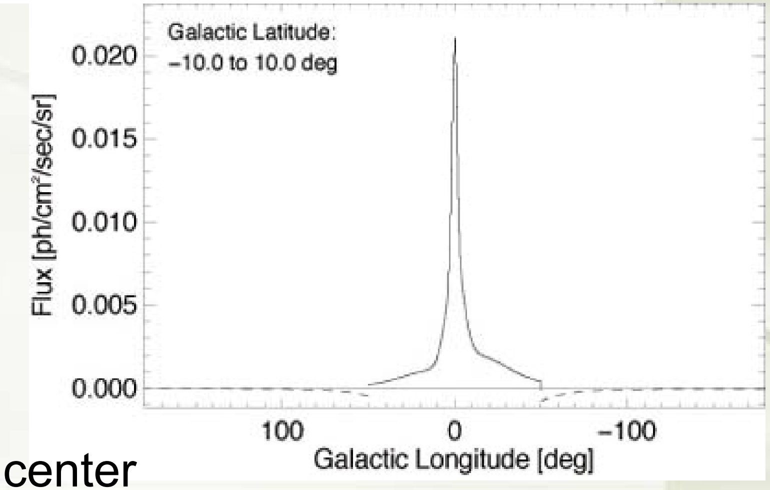


Bill's crystal ball roadmap

Breaking news







INTEGRAL 511 KeV high resolution map of galactic center
Doesn’t look good for dark matter annihilation, but seems to correlate with low mass X-ray binaries

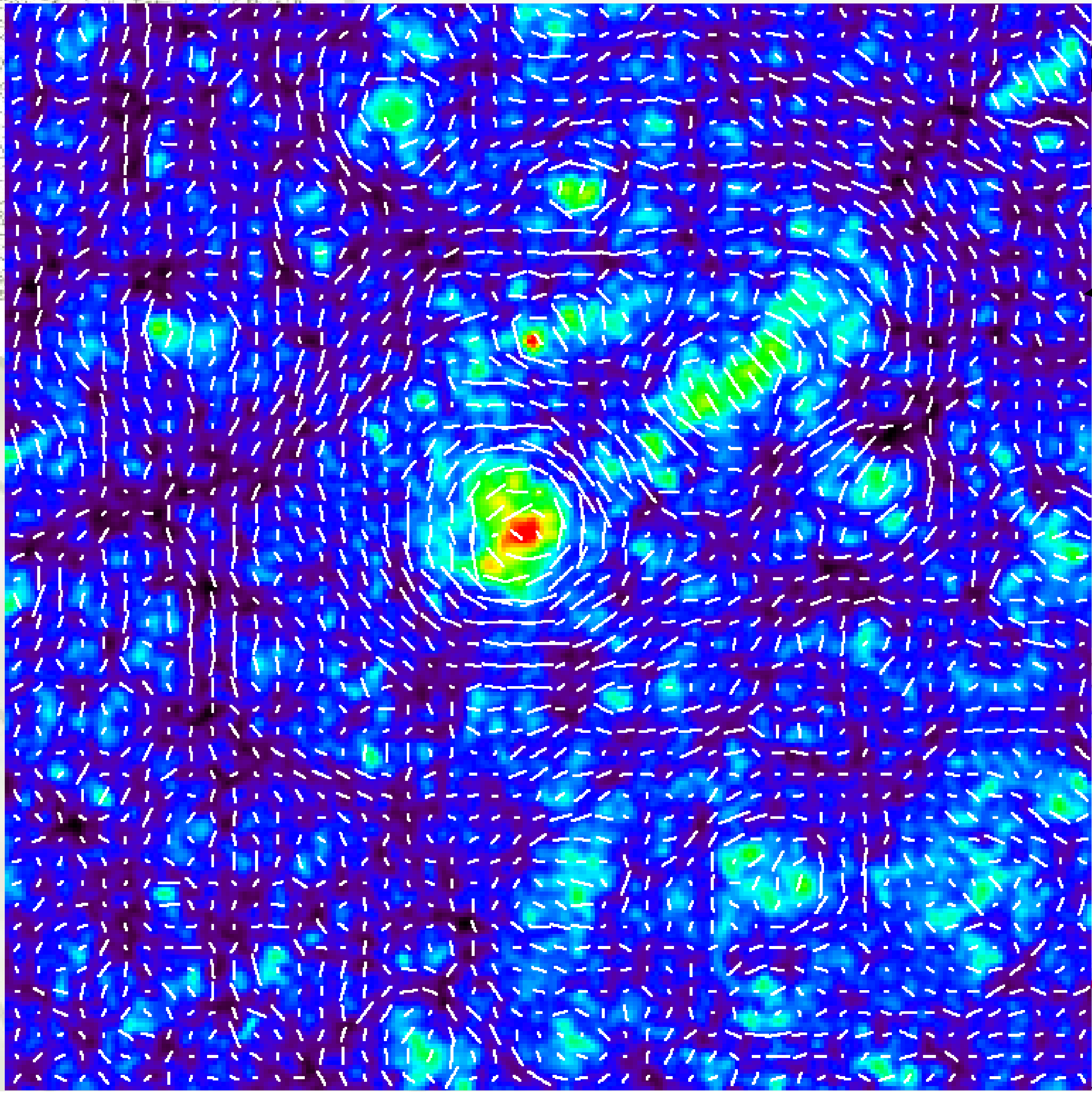
But wait, there's more

- Last week at the AAS meeting, NASA administrator Michael Griffin gave a speech where he revealed that, in response to the language in the Congressional Omnibus bill, he has asked BEPAC to rank JDEM against AMS

Toolbox for surveying the expansion history

- Red shift
- Standard candle (luminosity distance) from Type Ia SN
- Standard ruler (CMB and Baryon Acoustic Oscillations)
- Weak gravitational lensing
- Standard siren (if I have time)

osmology



Each “whisker” is an averaged measured galaxy ellipticity

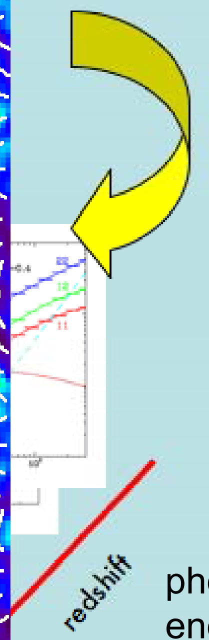
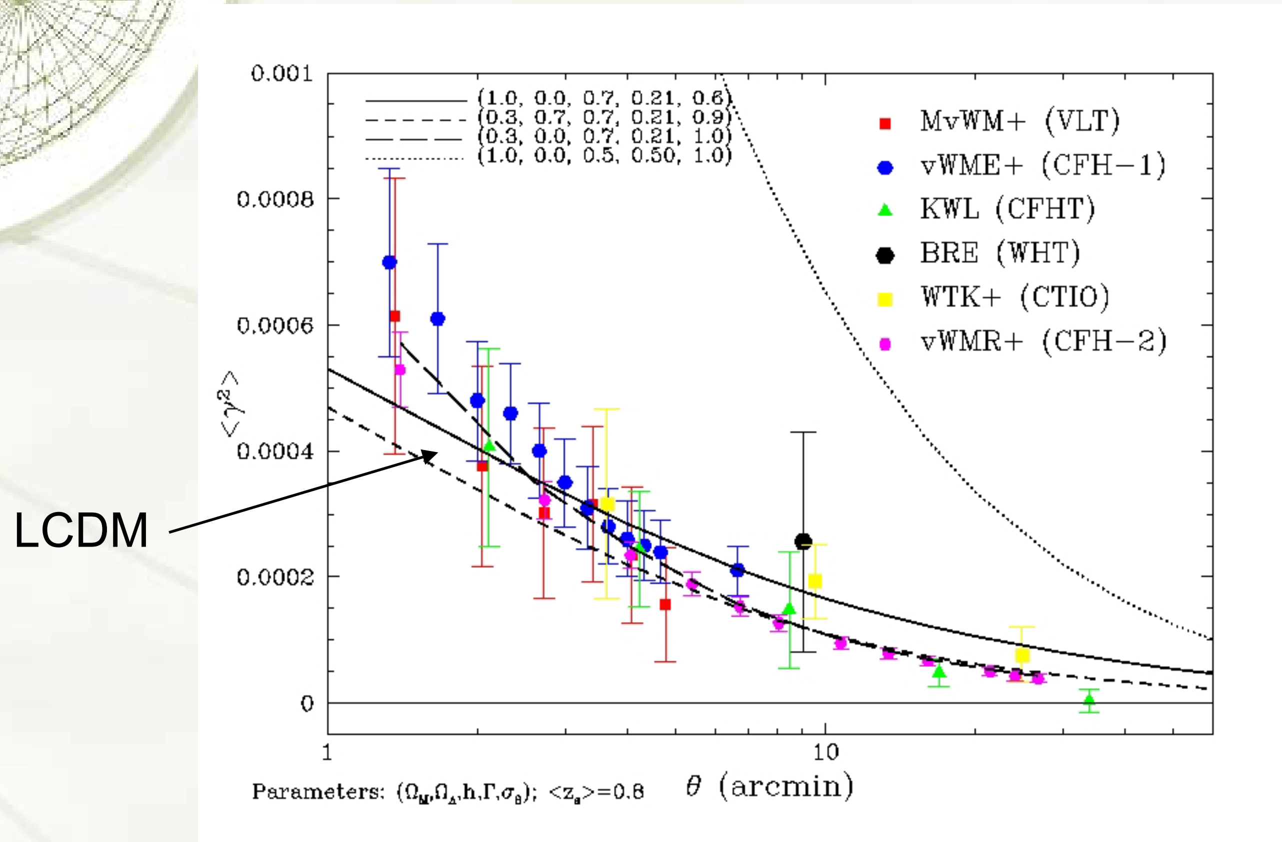


photo-z good enough

WL --current status



Really just getting started. Not a huge impact on cosmology yet
Long-term could be *the* most powerful technique

Gravitational waves as standard sirens

LISA

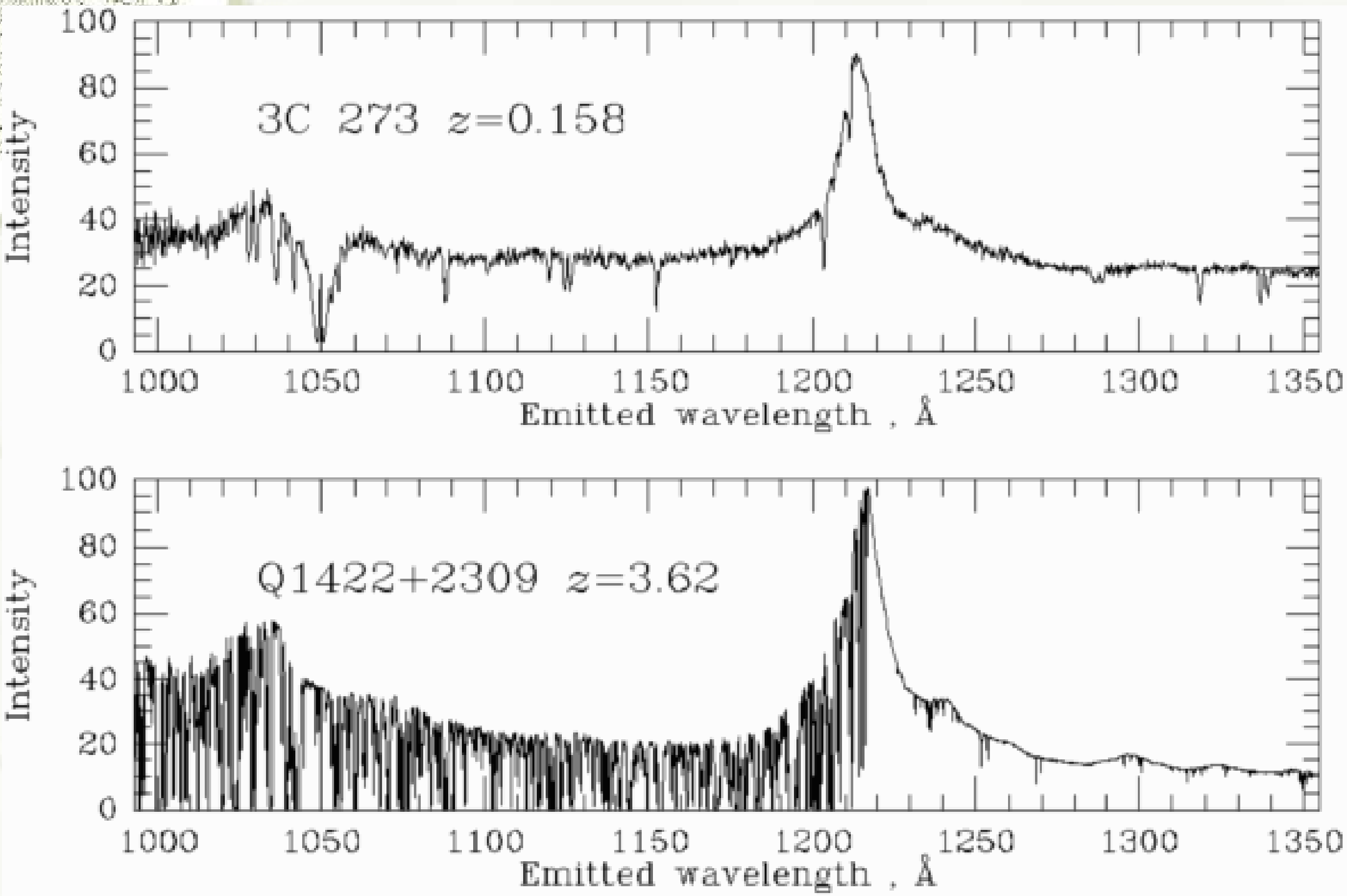
Problem for redshift
Pointing accuracy is poor
10^5 galaxies in error box

QuickTime™ and a
decompressor
are needed to see this picture.

≈ 1% distance

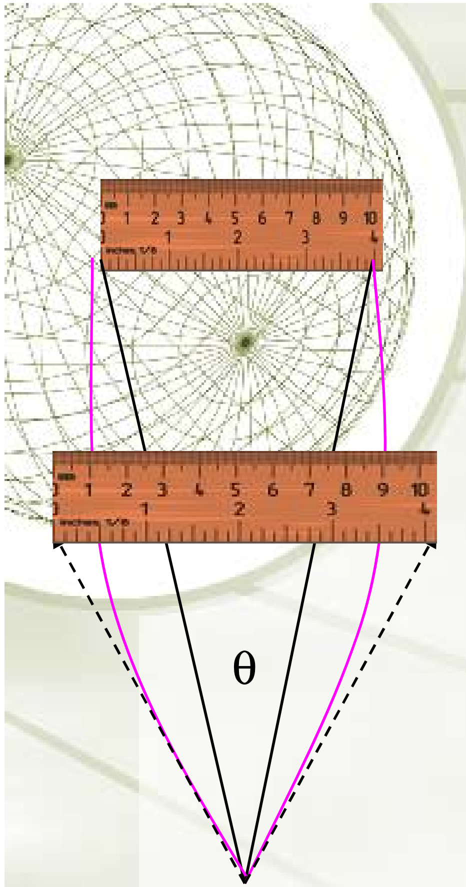
Binary black hole inspiral is
"absolutely calibrated"
source strength

BAO with neutral hydrogen

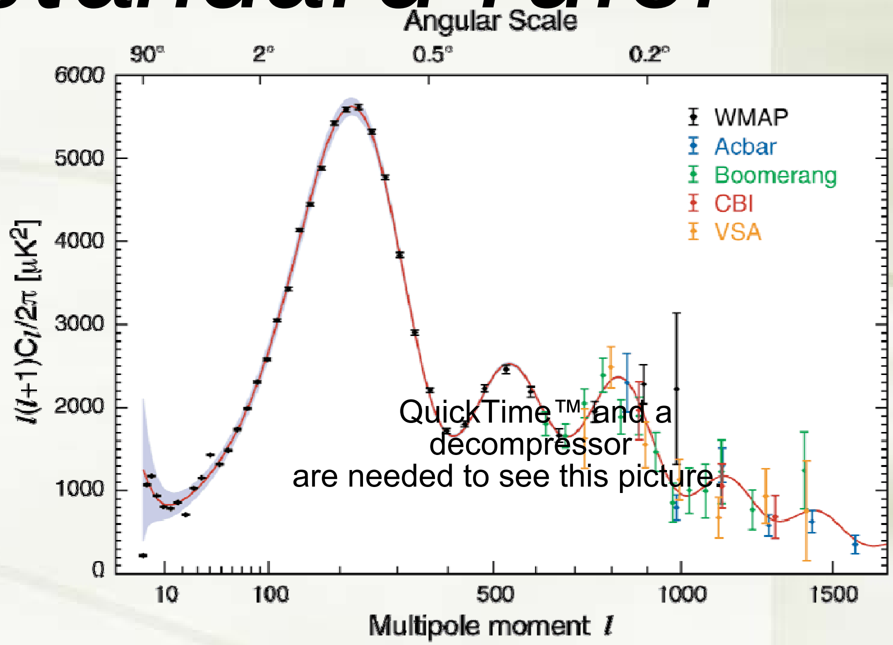


Or do a 21 cm survey

CMB, a standard ruler



Flat space?



$$D = \int_0^z \frac{c\,dz}{H(z)}$$

Moral: For CMB, there is a degeneracy between Curvature and knowledge of Hubble parameter

Moral 2: Unless you assume curvature is =0 on religious (read *inflation)* grounds, it is a complication so keep it in mind when you see results quoted

No sensitivity to w_a yet

QuickTime™ and a
decompressor
are needed to see this picture.

$$\frac{\dot{a}}{a} = H_0 \sqrt{\Omega_m a^3 + (1-\Omega_m) a^{3(1+w)}}$$