CMB Windows on Dark Energy

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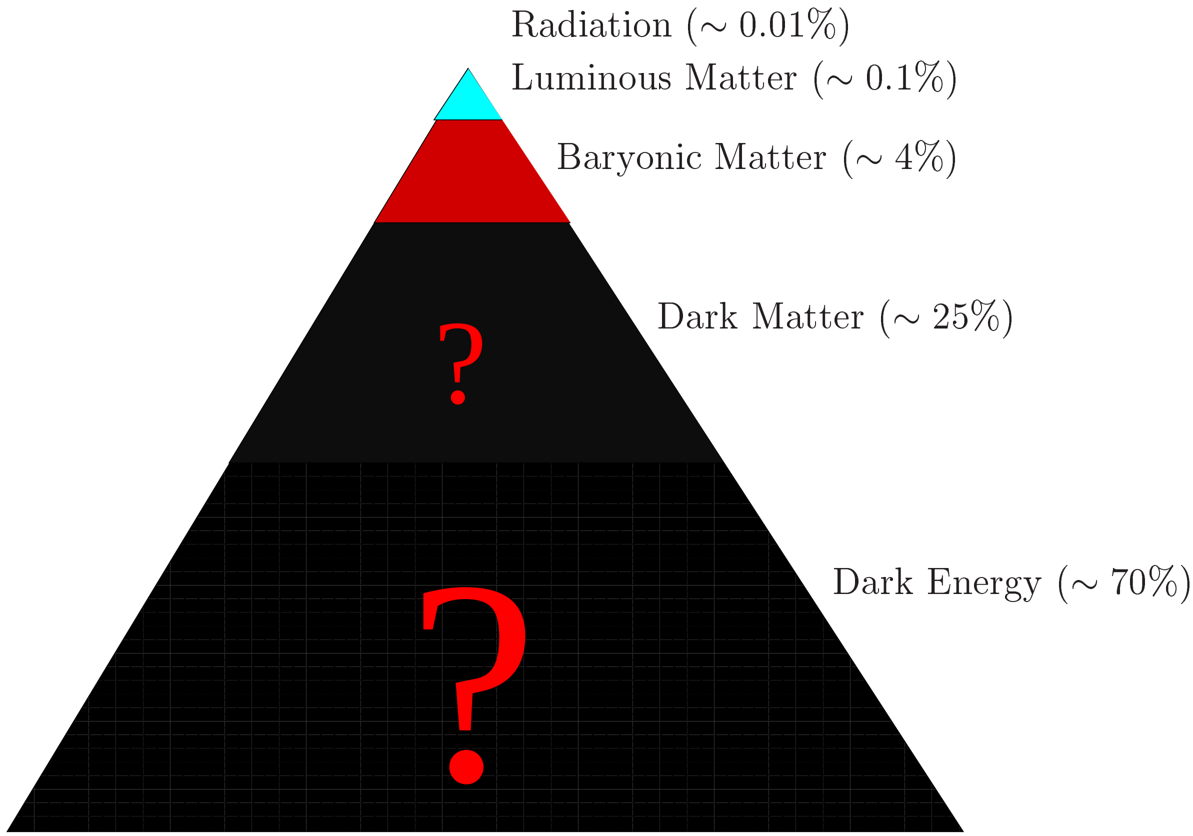
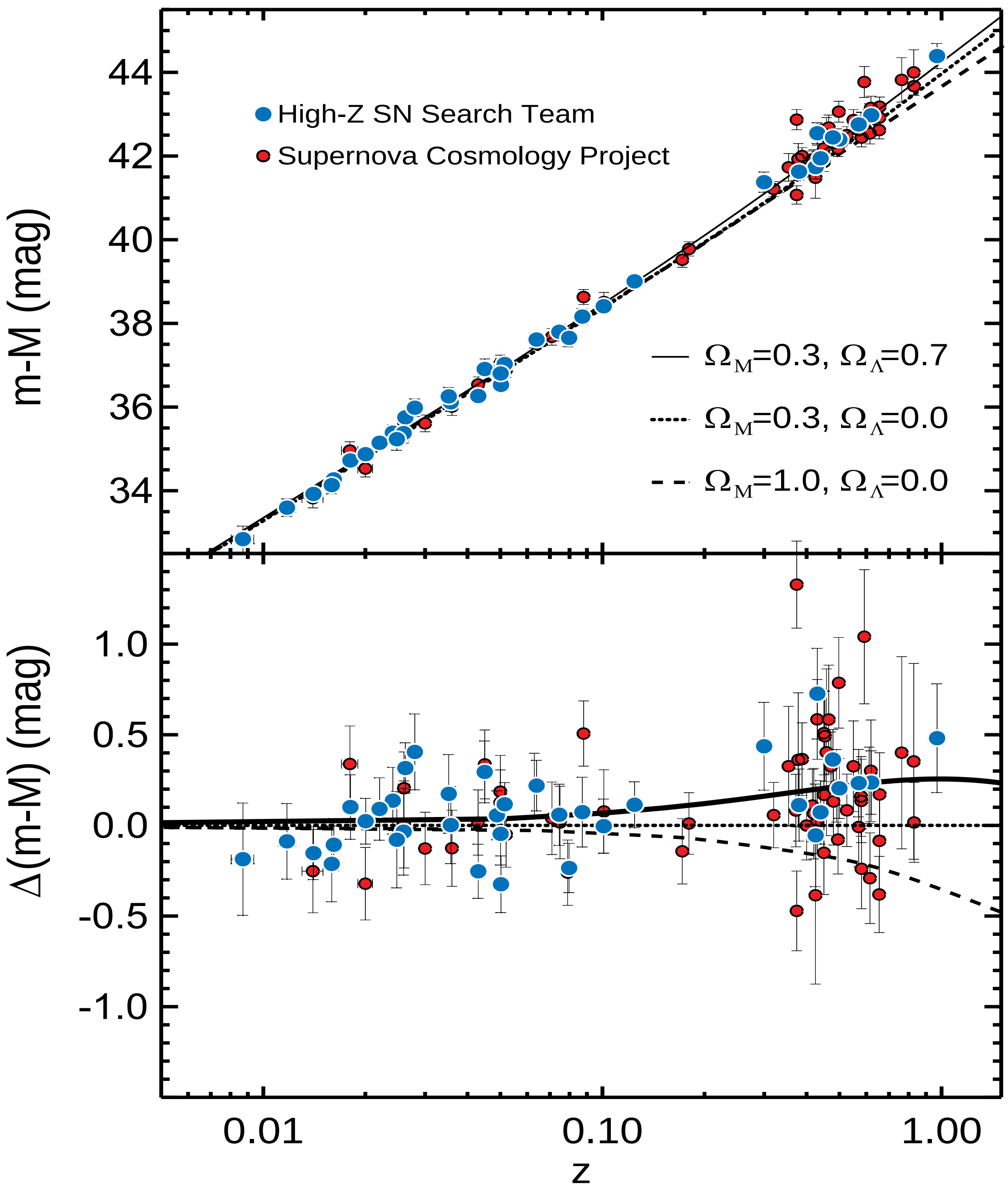
LeBron James



Radiation (∼ 0.01%)
Luminous Matter (∼ 0.1%)
Baryonic Matter (∼ 4%)
Dark Matter (∼ 25%)
?
Dark Energy (∼ 70%)
?

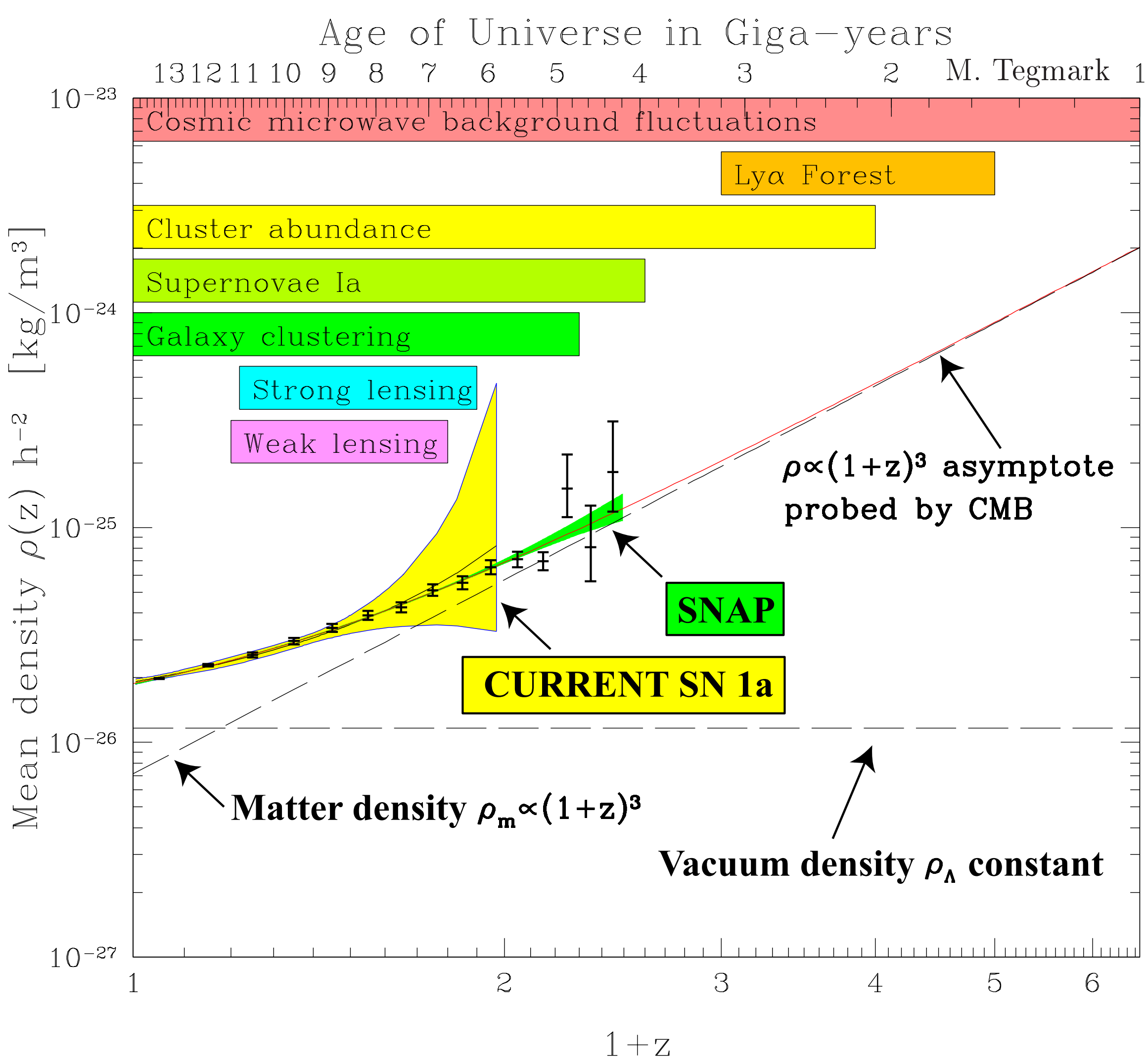


Describe dark energy by (Turner & White 1999)

$$\Omega_X = \frac{\rho_X}{\rho_{\text{crit}}},\ w = \frac{p_X}{\rho_X}$$

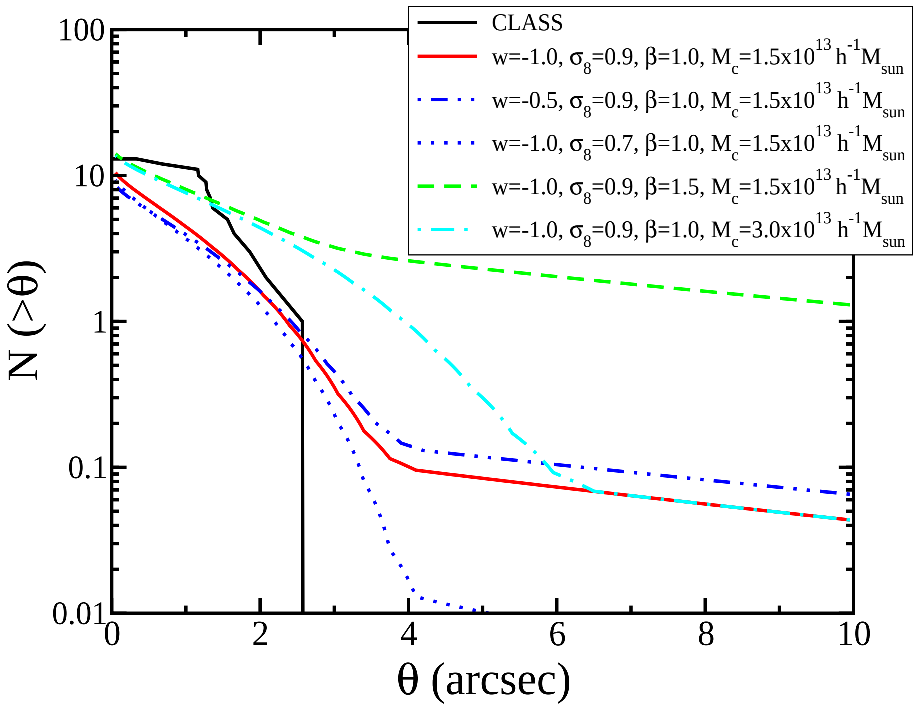
Cosmological tests of Dark Energy

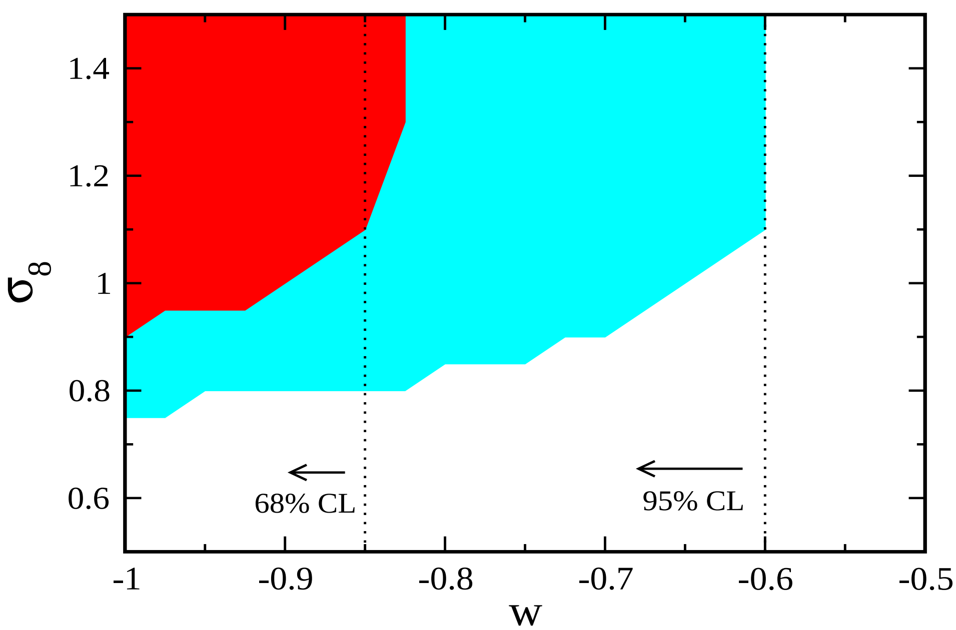
$$H^2(z) = H_0^2 \left[\Omega_M(1+z)^3 + \Omega_K(1+z)^2 + \Omega_{DE}(1+z)^{3(1+w)}\right]$$



(Huterer & Turner, Weller & Albrecht, Kujat et al.,
Linder, Hu, Tegmark, etc. etc.)

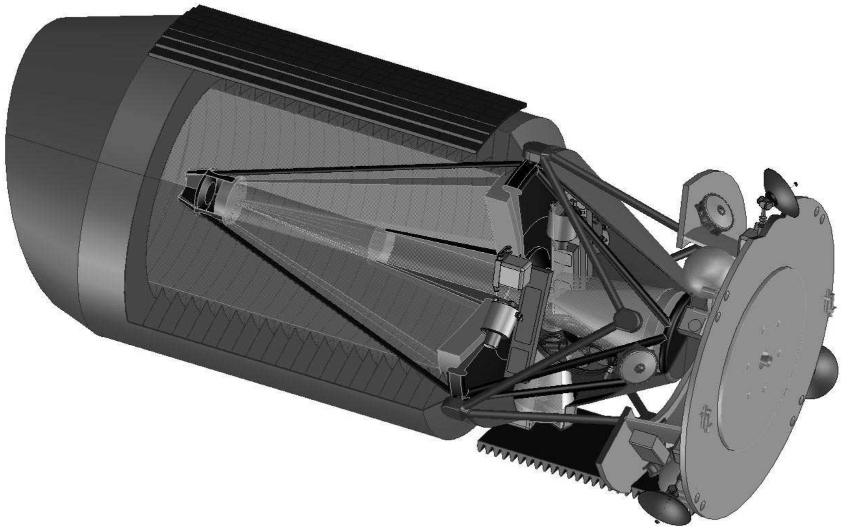
Strong Gravitational Lensing Statistics

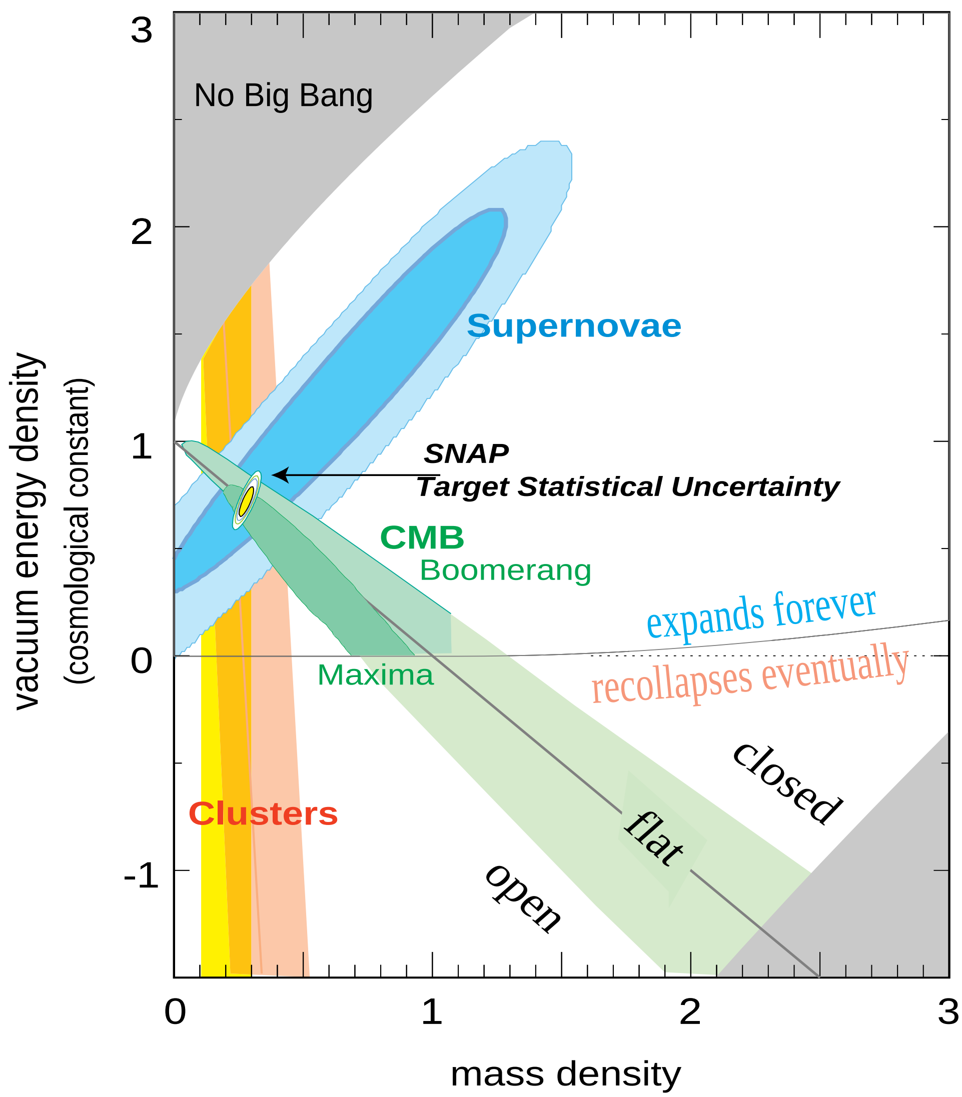




(Huterer & Ma 2003; also Chae et al. 2002)

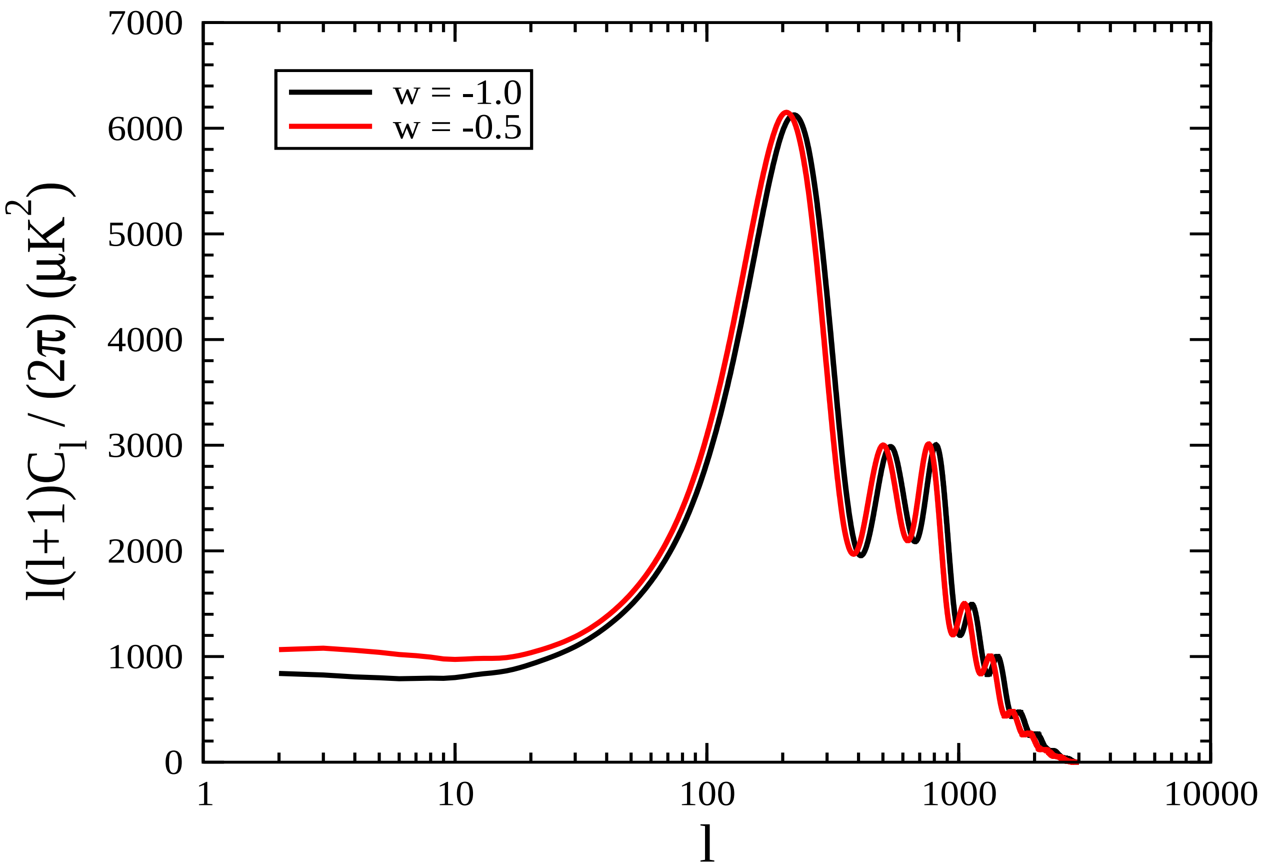
SNAP





No Big Bang
Supernovae
SNAP
Target Statistical Uncertainty
CMB
Boomerang
Maxima
expands forever
recollapses eventually
closed
flat
open
Clusters
vacuum energy density
(cosmological constant)
mass density
3
2
1
0
-1
0
1
2
3

CMB and Dark Energy



- **peak locations** are sensitive to dark energy (but not much):

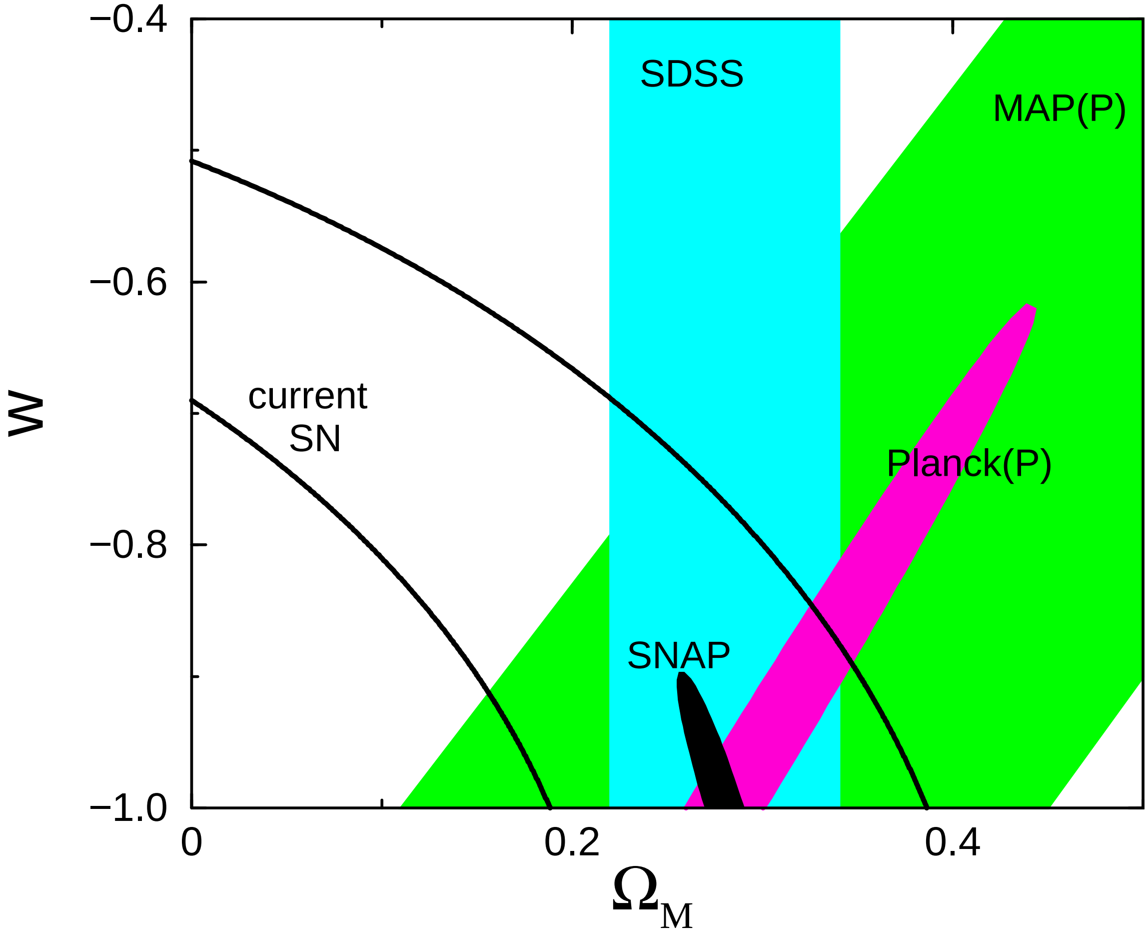
$$\frac{\Delta l_1}{l_1} = -0.084\Delta w - 0.23\frac{\Delta\Omega_M h^2}{\Omega_M h^2} + 0.09\frac{\Delta\Omega_B h^2}{\Omega_B h^2} + 0.089\frac{\Delta\Omega_M}{\Omega_M} - 1.25\frac{\Delta\Omega_{\rm TOT}}{\Omega_{\rm TOT}}$$

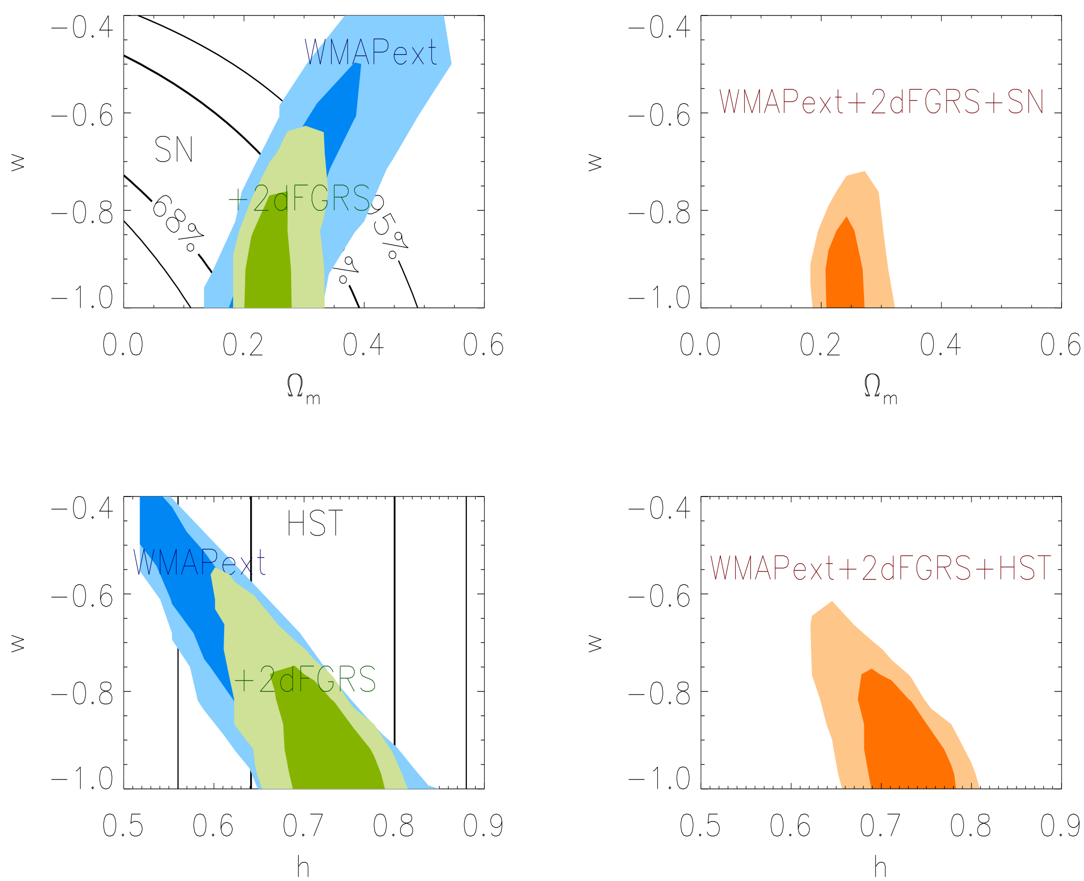
- Same as a measurement of angular diameter distance to $z \sim 1000$ *with $\Omega_M h^2$ fixed*

- End up constraining: $\mathcal{D} \equiv \Omega_M - 0.28(1 + w) \approx 0.3$
(Planck: $\mathcal{D}$ to $\sim 10\%$) (Frieman et al. 2003)

CMB provides a *single* measurement of the distance to LSS, therefore

- Degeneracy in parameter estimation
- Only $w_{\rm eff}$ is probed

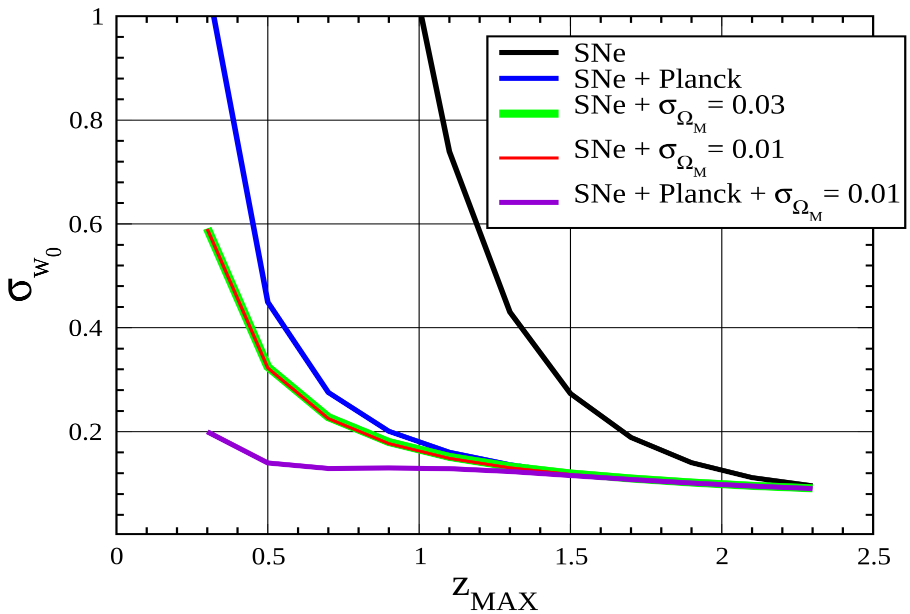


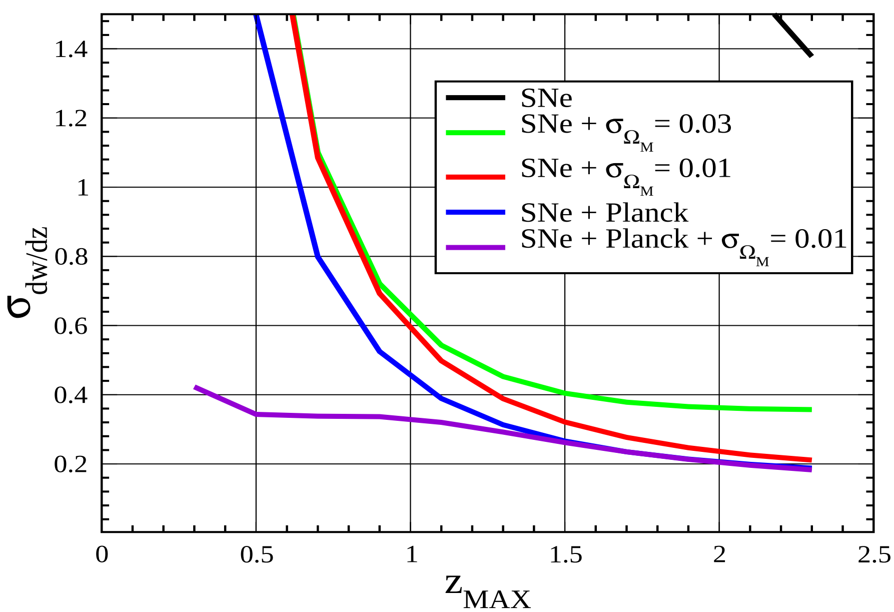


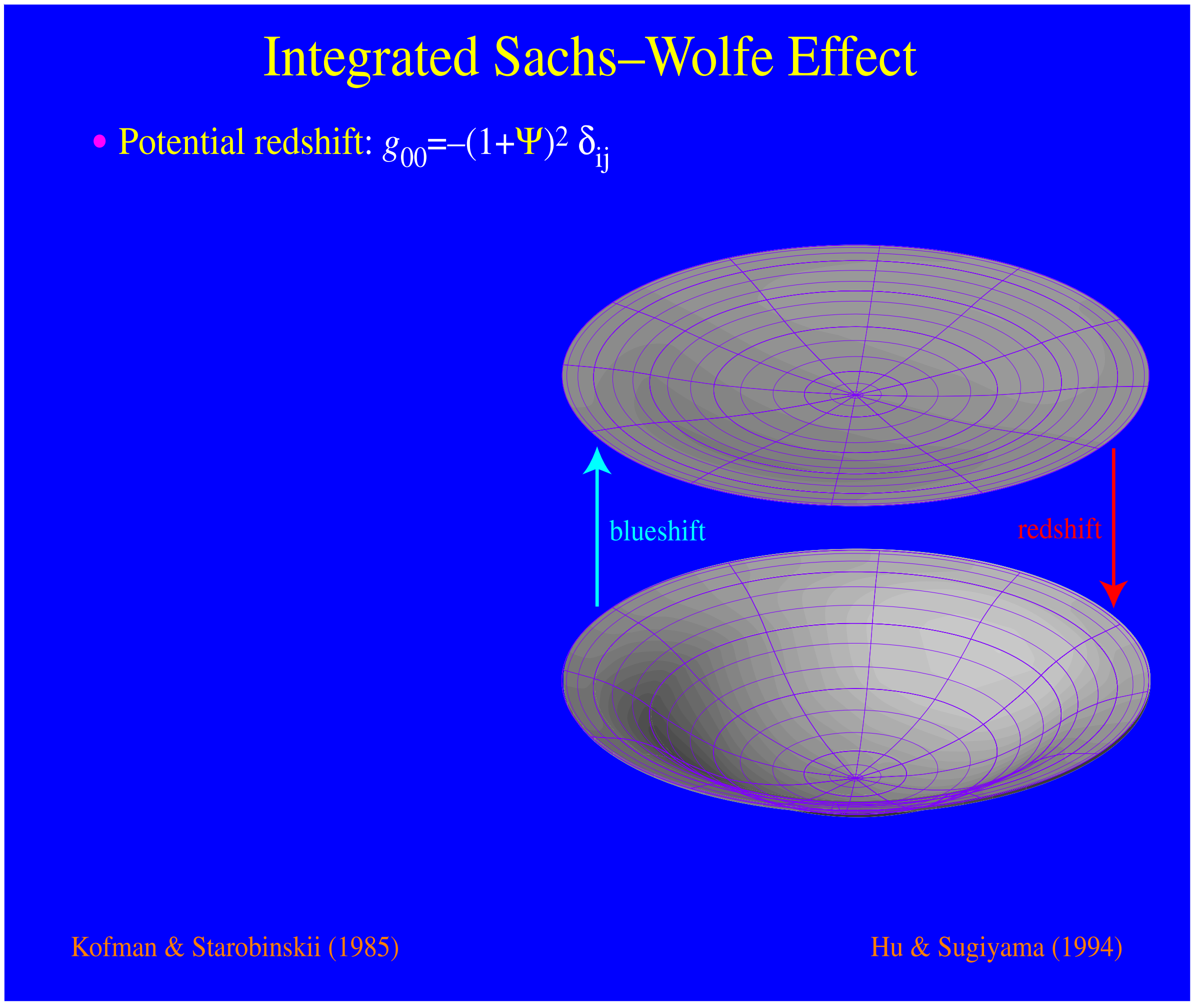
(Spergel et al. 2003)

Assuming $w(z) = w_0 + w_1\, z$:

Frieman et al. 2003







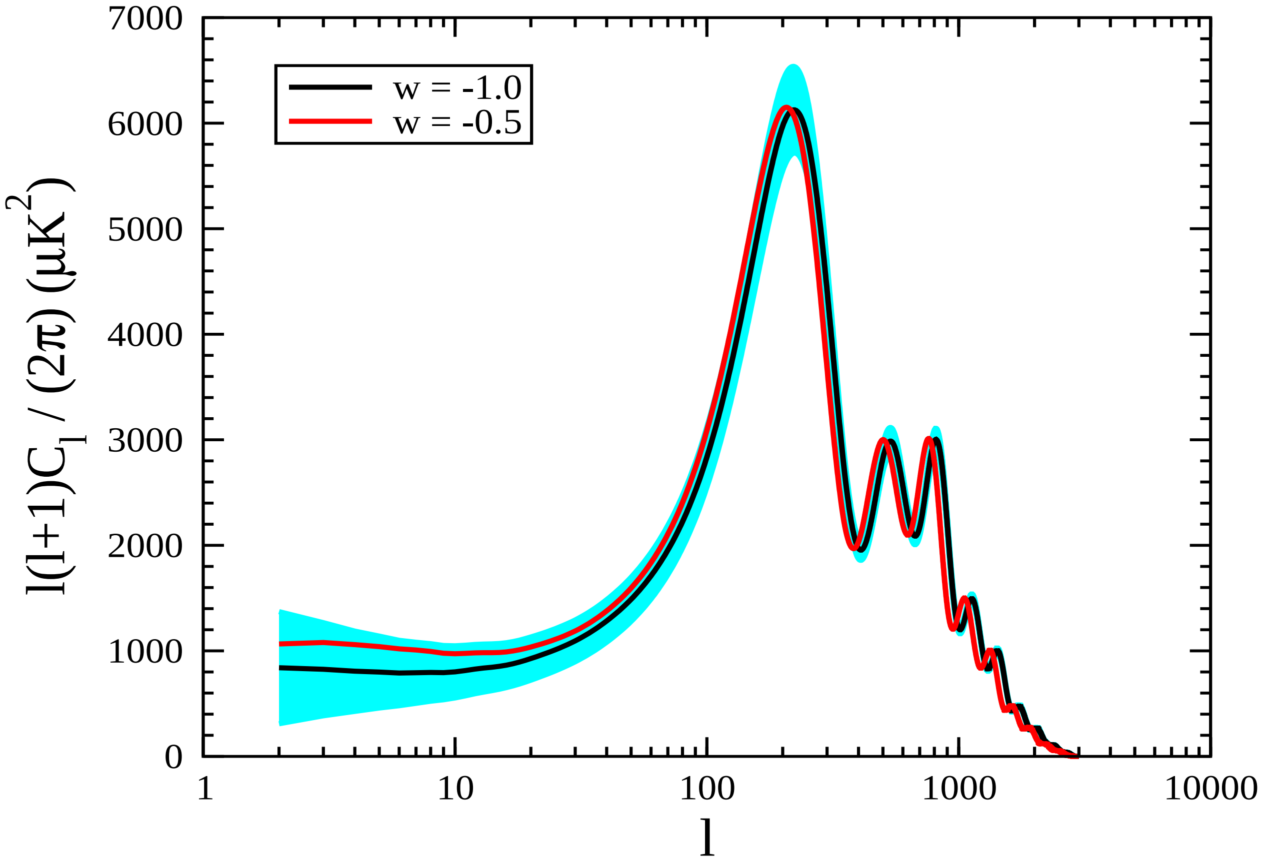
$$\Delta T^{\rm ISW}(\hat{\mathbf{n}}) = -2\int_0^{\eta_{\rm rec}} d\eta'\,\frac{d\Phi(\eta')}{d\eta'}$$

Recall, Poisson eq. $\nabla^2\Phi = 3/2\, H_0^2\, \Omega_{\rm M}\, (\delta/\mathbf{a})$

$$C_2^{\rm SW} = \frac{4\pi}{9}\int_0^\infty \frac{dk}{k}\Delta^2_{\Phi\Phi}(k, r_{\rm rec}) j_2^2[kr_{\rm rec}]$$

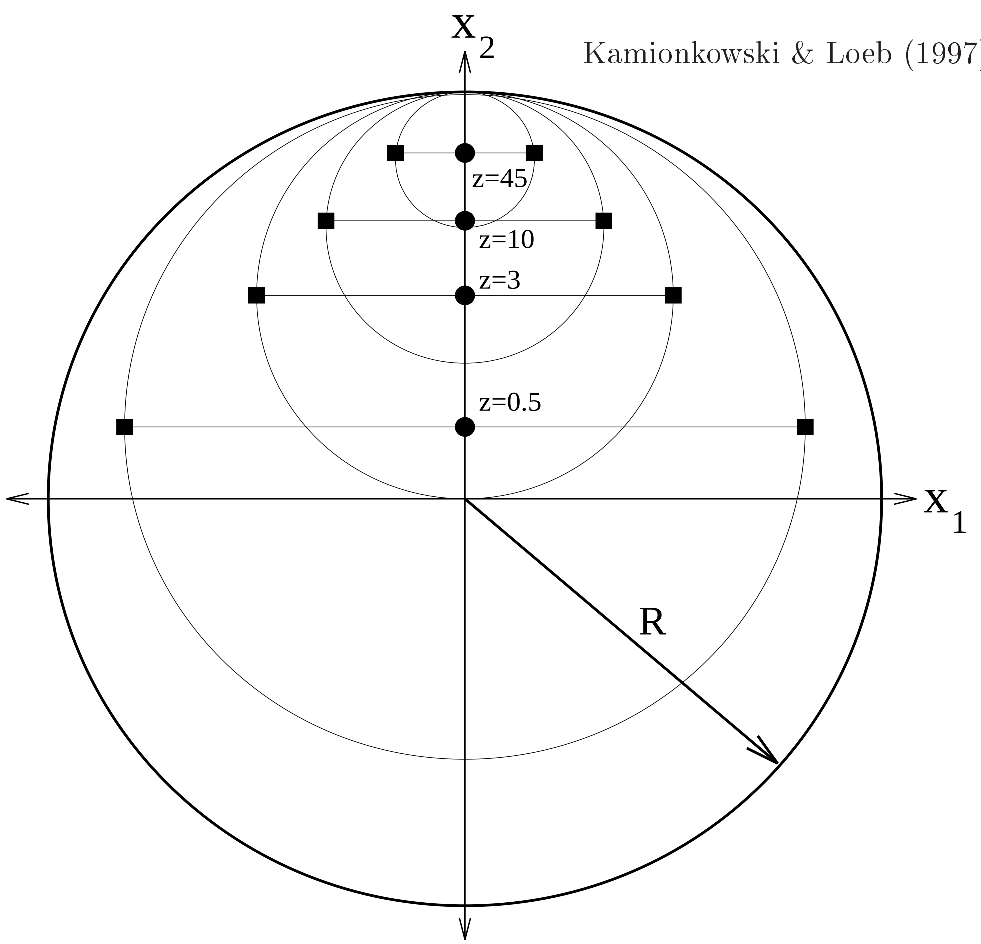
$$C_2^{\rm ISW} = 16\pi\int_0^\infty \frac{dk}{k}\Delta^2_{\Phi\Phi}(k, r_{\rm rec}) \times \left[\int_0^{r_{rec}} dr'\frac{1}{g(z_{\rm rec})}\frac{d}{dr'}g(z')\ j_2(kr')\right]^2$$

But cosmic variance rules...



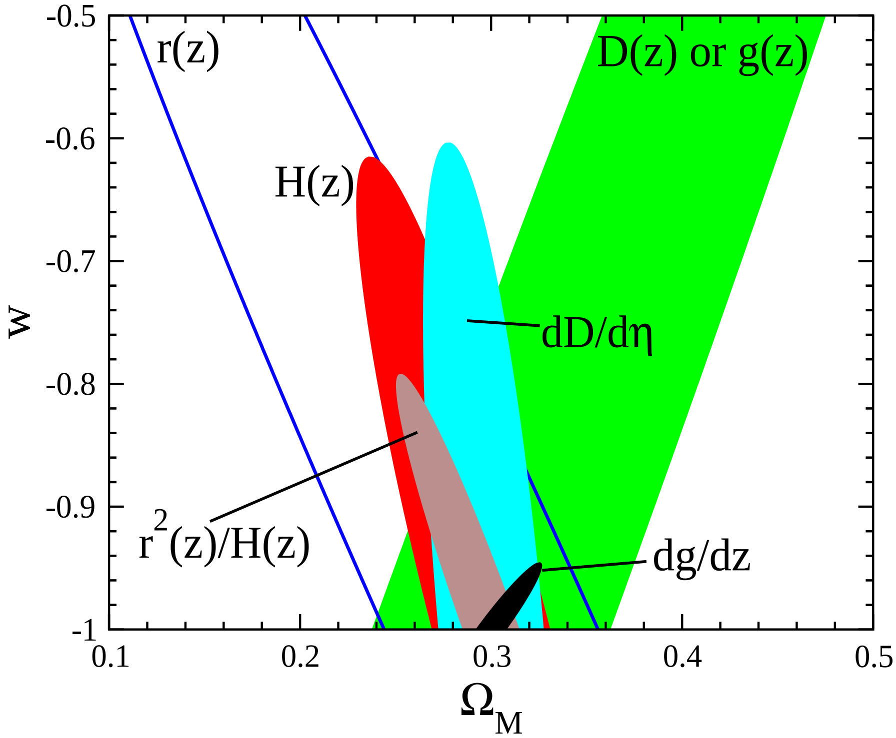
Getting Around Cosmic Variance!

Kamionkowski & Loeb (1997)



Growth Rate of fluctuations

$$\begin{aligned} \delta(z) &= \delta(0)\, D(z) \\ \ddot{\delta} + 2(\dot{a}/a)\dot{\delta} - 4\pi G \rho_{\rm M} \delta &= 0 \\ g(a) &\equiv D(a)/a \end{aligned}$$



(Cooray, Huterer & Baumann 2003)

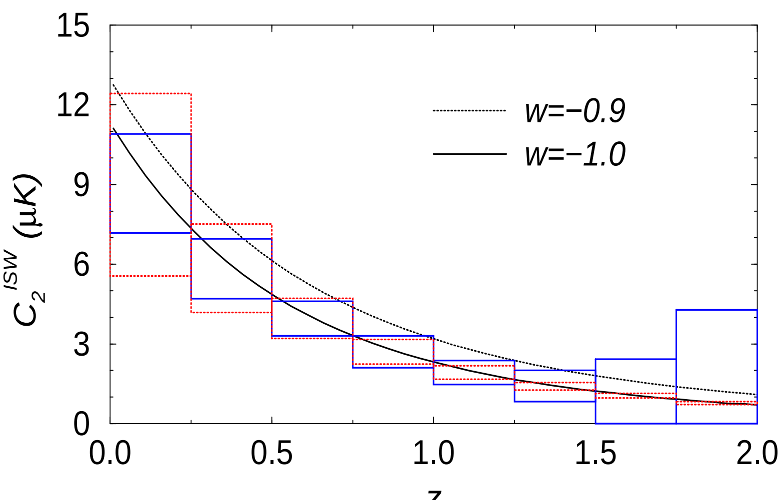
Polarization measurements from clusters

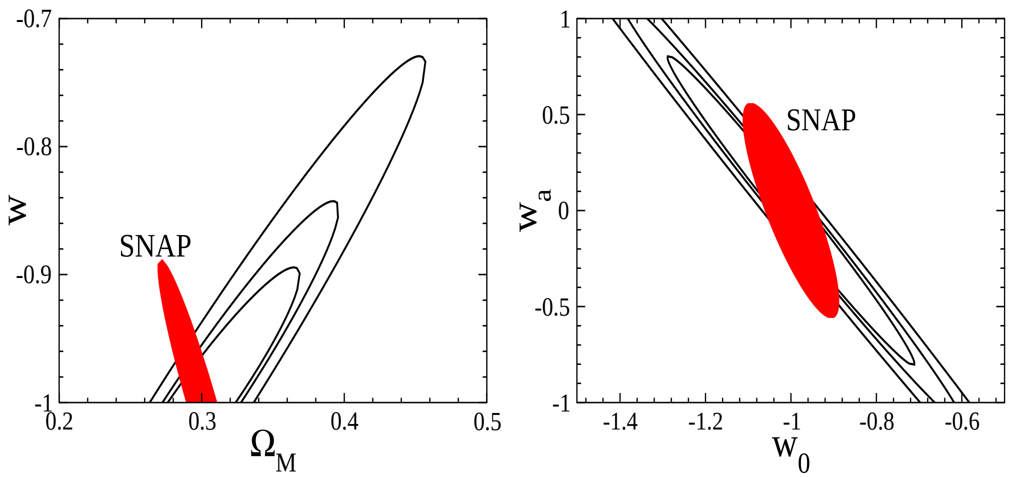
$$P^{\rm prim} = \frac{\sqrt{6}}{10} \langle \tau \rangle \frac{Q^{\rm rms}(z)}{T_{\rm CMB}}$$

$$P^{\rm kin} = \frac{1}{10} g(x) \langle \tau \rangle \langle \beta^2 \rangle$$

(Sazonov & Sunyaev 1999, Challinor et al. 2000,
Cooray & Baumann 2003)

- Maximum signal: $0.1(\tau/0.02)\,\mu K$.
- Other effects: $\propto \frac{kT_e}{m_e c^2} \tau^2$, $\beta\tau^2$
- Frequency separation possible; $P^{\rm prim}$ dominates





Most optimistic ellipses assume:

- 3 arcmin resolution $\rightarrow \sim$ 2 meter dish
- a few $\mu K\sqrt{\rm sec}$ resolution per detector with $\sim$ 100 detectors

so that $\sim$ 10,000 sq. deg. can be covered in about 1/2 year at $\sim 0.1\mu K$ sensitivity.

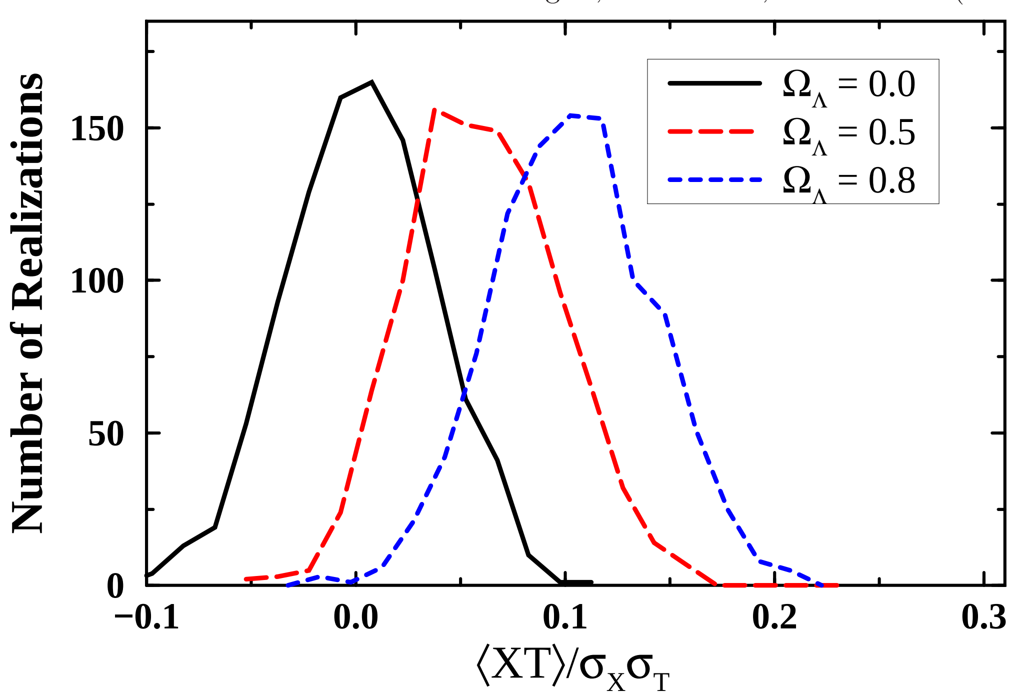
or, in several years of running, a few tens of nK sensitivity.

CMB-LSS Cross-Correlation

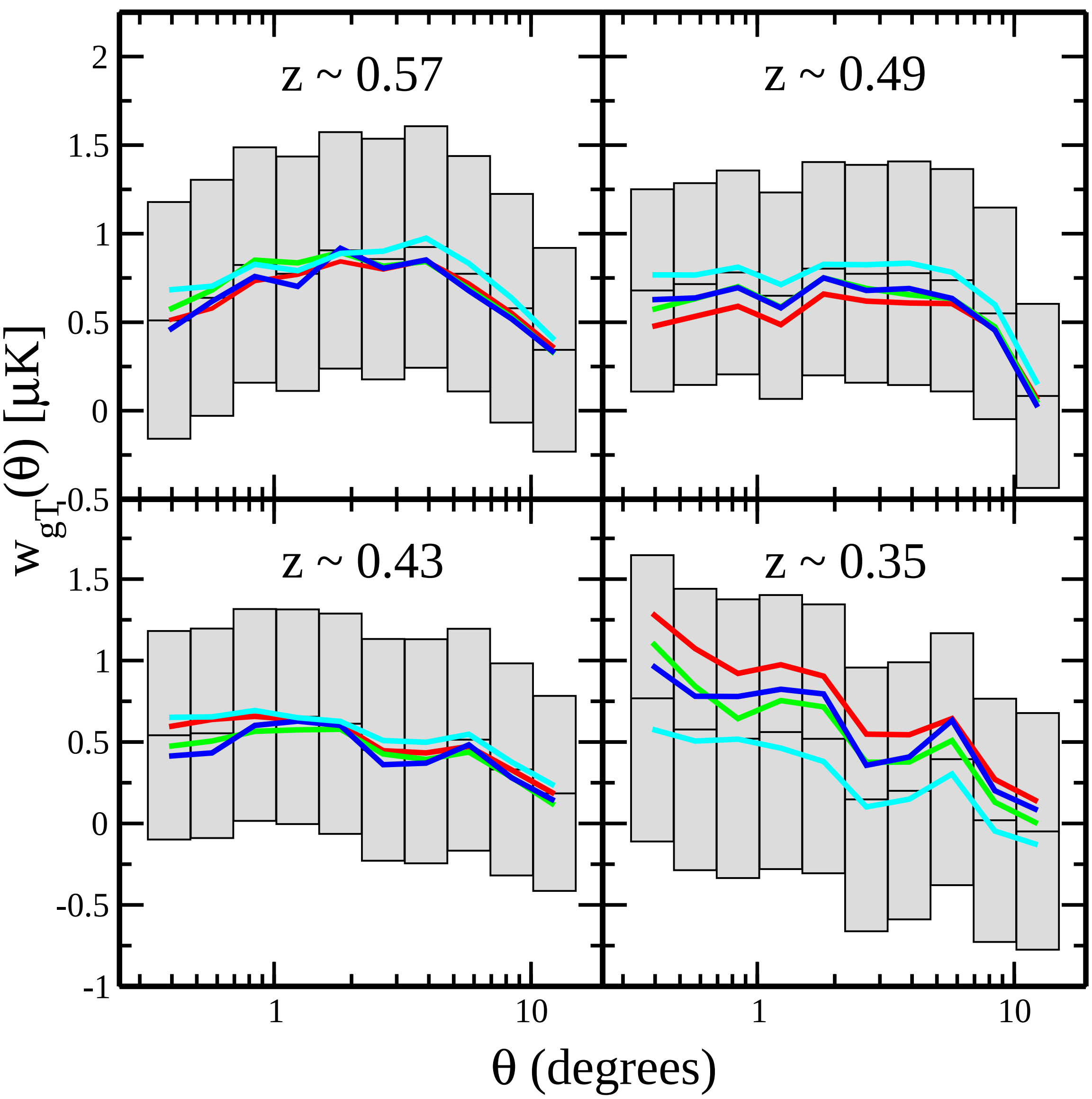
$$\langle TX(\theta)\rangle = \frac{\sum_{\theta_{ij}=\theta} X_i T_j \, \mathrm{w}_i \mathrm{w}_j}{\sum_{\theta_{ij}=\theta} \mathrm{w}_i \mathrm{w}_j}$$

Non-zero correlation would be a signature of ISW and, therefore, dark energy!

Boughn, Crittenden, Turok et al. (1997)



Scranton et al. (2003)



Will it work even better with $C_2(z)$?

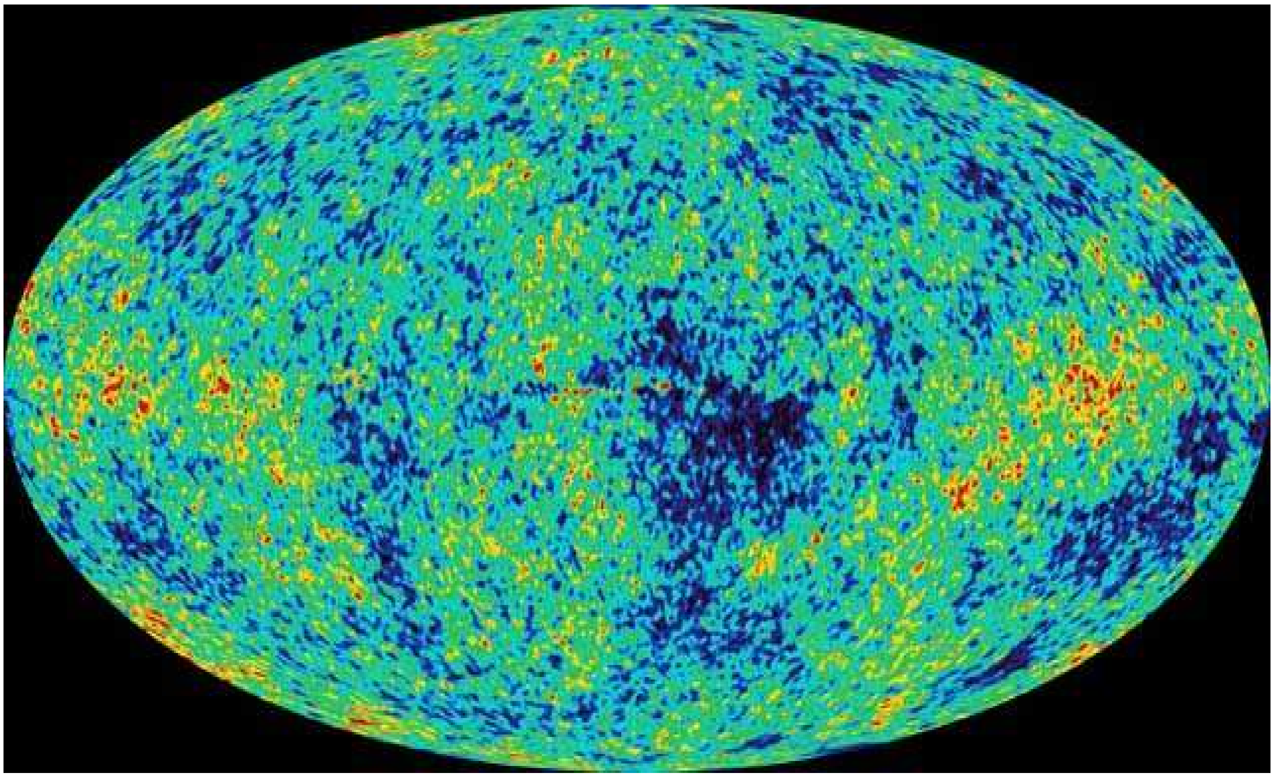
Polarization from clusters recap:

- Observationally challenging.
- Provides $C_2(z)$
- Which leads to $\frac{dg}{dz}(z)$
- Decreases cosmic variance on C_2
- Probes different scales of $P(k)$

“Multipole Vectors”!

(Copi, Huterer & Starkman 2003)

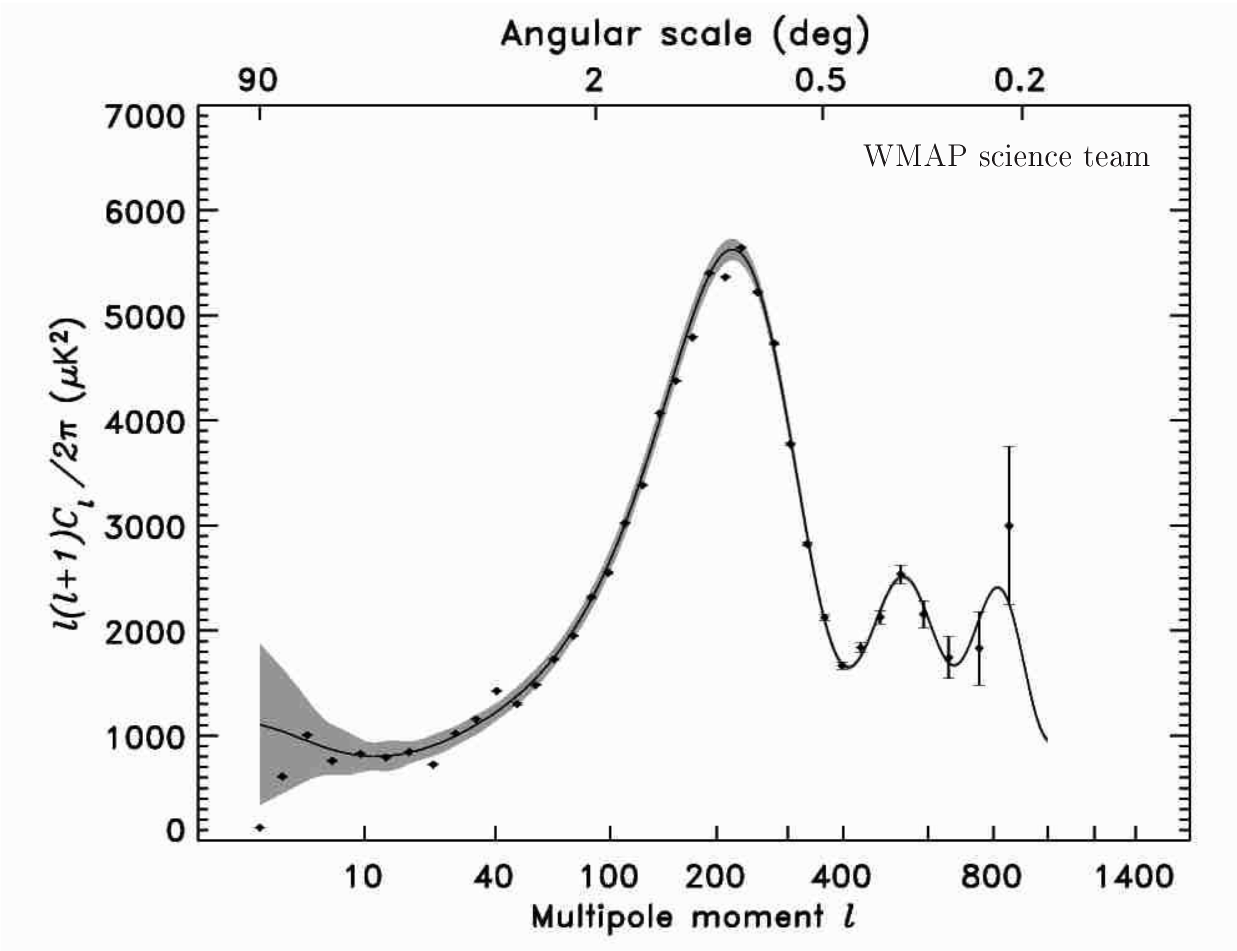
WMAP science team



$$\frac{\delta T}{T}(\theta,\phi) = \sum_{l,m} a_{lm} Y_{lm}(\theta,\phi)$$

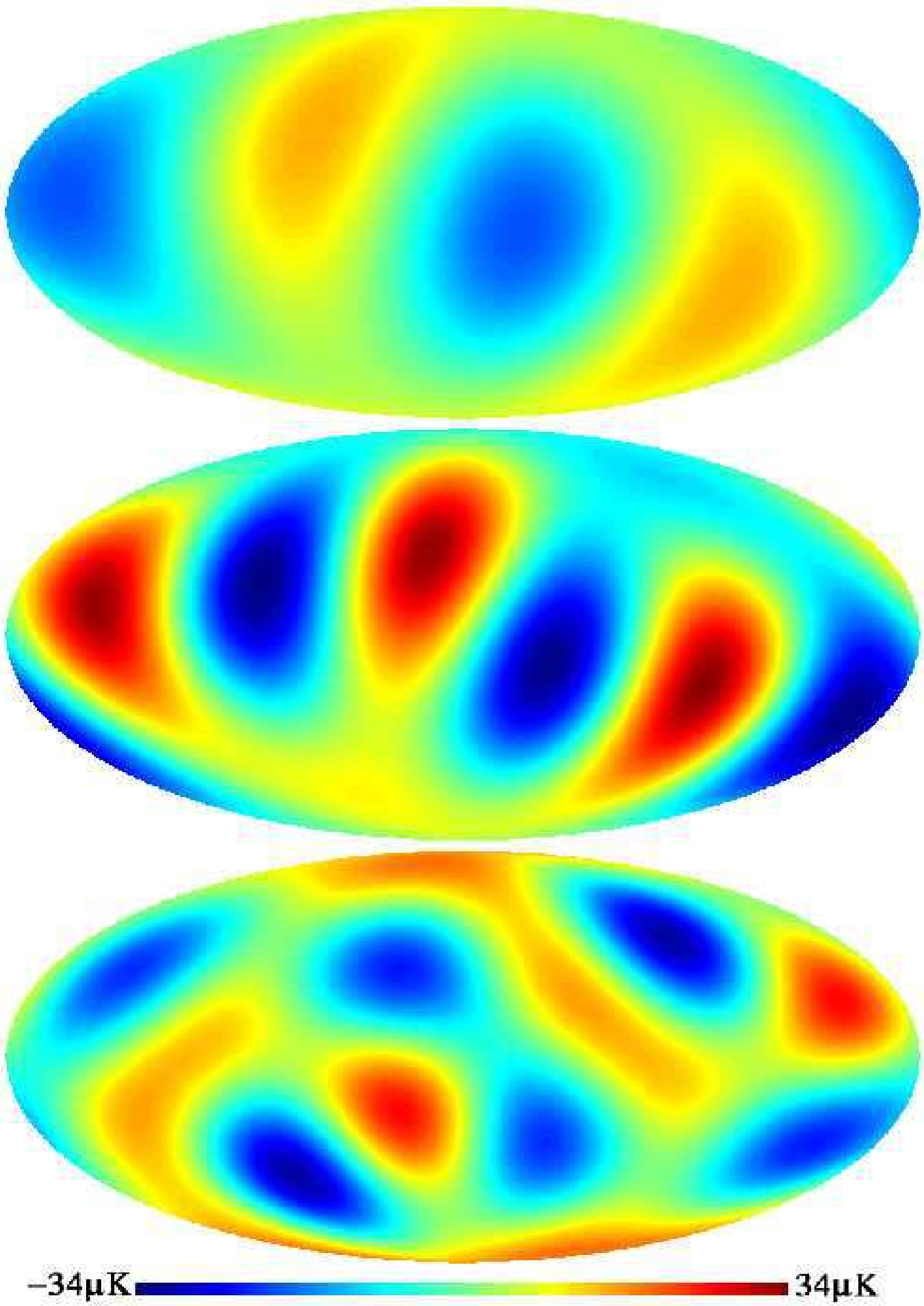
$$a_{lm} = \int \frac{\delta T}{T}(\Omega)\, Y^*_{lm}(\Omega)\, d\Omega$$

$$C_l = \frac{1}{2l+1} \sum_m |a_{lm}|^2$$



Angular scale (deg)
90
2
0.5
0.2
WMAP science team
7000
6000
5000
4000
3000
2000
1000
0
$l(l+1)C_l\,/2\pi$ (μK^2)
10
40
100
200
400
800
1400
Multipole moment l

Tegmark et al. 2003

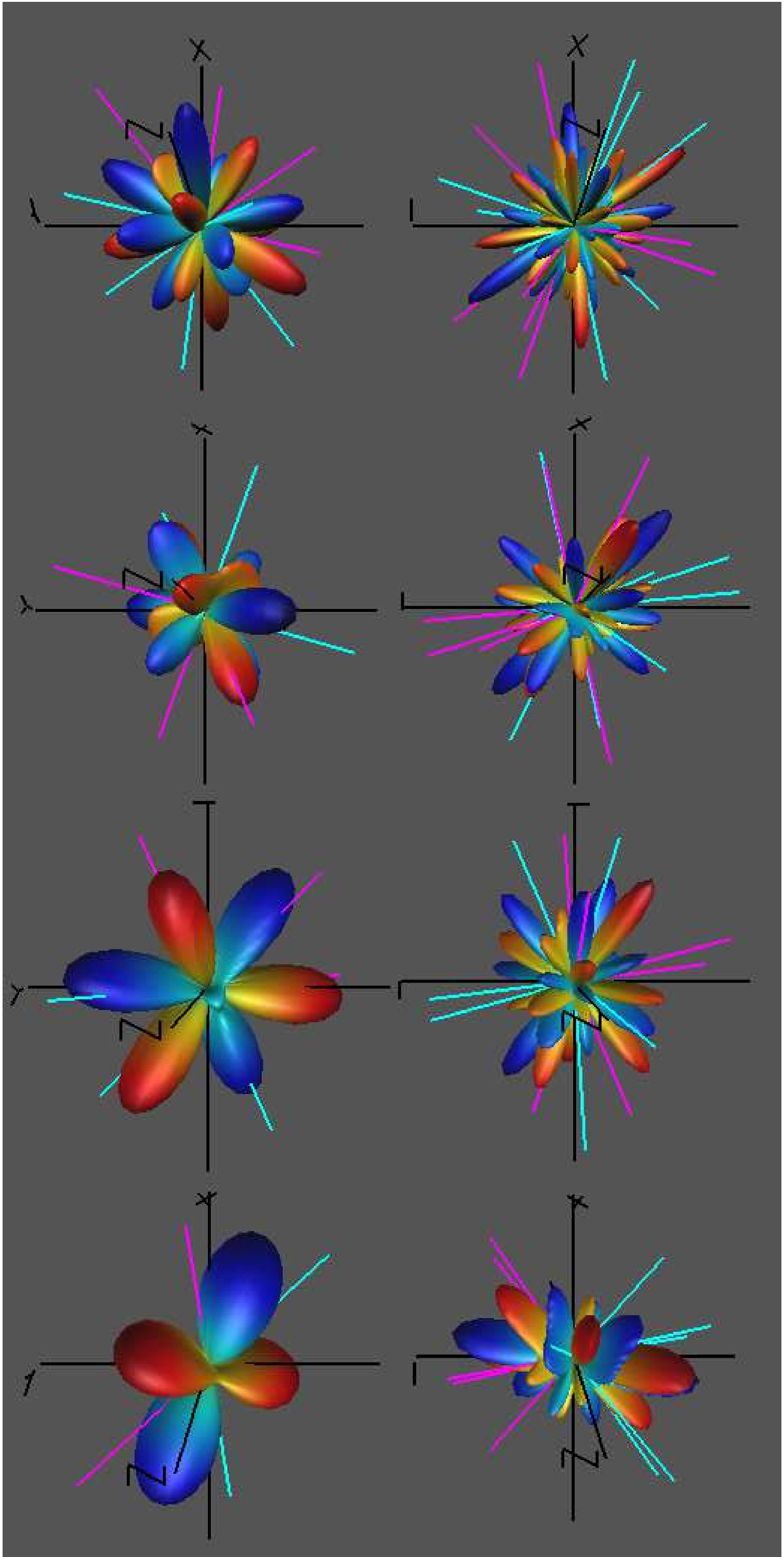


$$
\begin{aligned}
\frac{\delta T}{T}(\theta,\phi) &= \sum_{l,m} a_{lm} Y_{lm}(\theta,\phi) \\
&\equiv \sum_{l} \left\{ a_{l,0} Y_{l,0} + 2 \sum_{m=1}^{l} \left[a^{\mathrm{re}}_{l,m} Y^{\mathrm{re}}_{l,m} - a^{\mathrm{im}}_{l,m} Y^{\mathrm{im}}_{l,m} \right] \right\} \\
&= \sum_{l} \mathbf{A}^{(l)} \left[\hat{\mathbf{v}}^{(l)}_{\mathbf{1}} \otimes \hat{\mathbf{v}}^{(l)}_{\mathbf{2}} \otimes \ldots \hat{\mathbf{v}}^{(l)}_{\mathbf{l}} \right]
\end{aligned}
$$

To compute the vectors $\hat{v}_i^{(l)}$:

solve $3l$ coupled l^{th} order equations?!

Thankfully, no...



Tests of Non-Gaussianity with Multipole Vectors

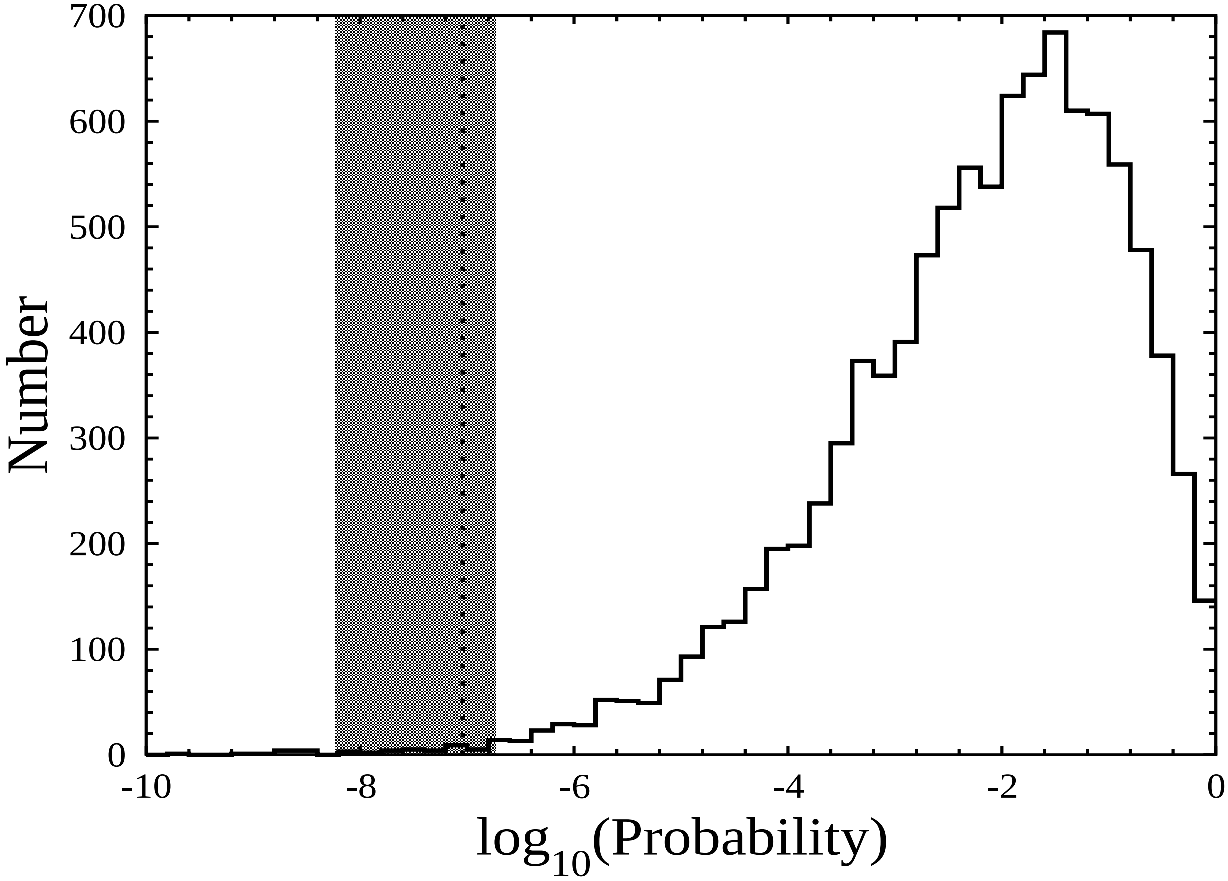
(PRELIMINARY!)

1. Bipolarity (for any multipole l_i)

$$T = \begin{pmatrix} \sum x_i^2 & \sum x_i y_i & \sum x_i z_i \\ \sum x_i y_i & \sum y_i^2 & \sum y_i z_i \\ \sum x_i z_i & \sum y_i z_i & \sum z_i^2 \end{pmatrix}$$

2. Dot products (for any l_i, l_j)

3. Dot products of cross products (for any l_i, l_j)



Probability of dot product of cross products for $[l_i, l_j] \in \{2, 3, \ldots., 8\}$:

4 parts in a thousand!

But: goes away when quadrupole, octupole are omitted.