Solar System Tests versus Cosmological Constraints for *f(G)* models

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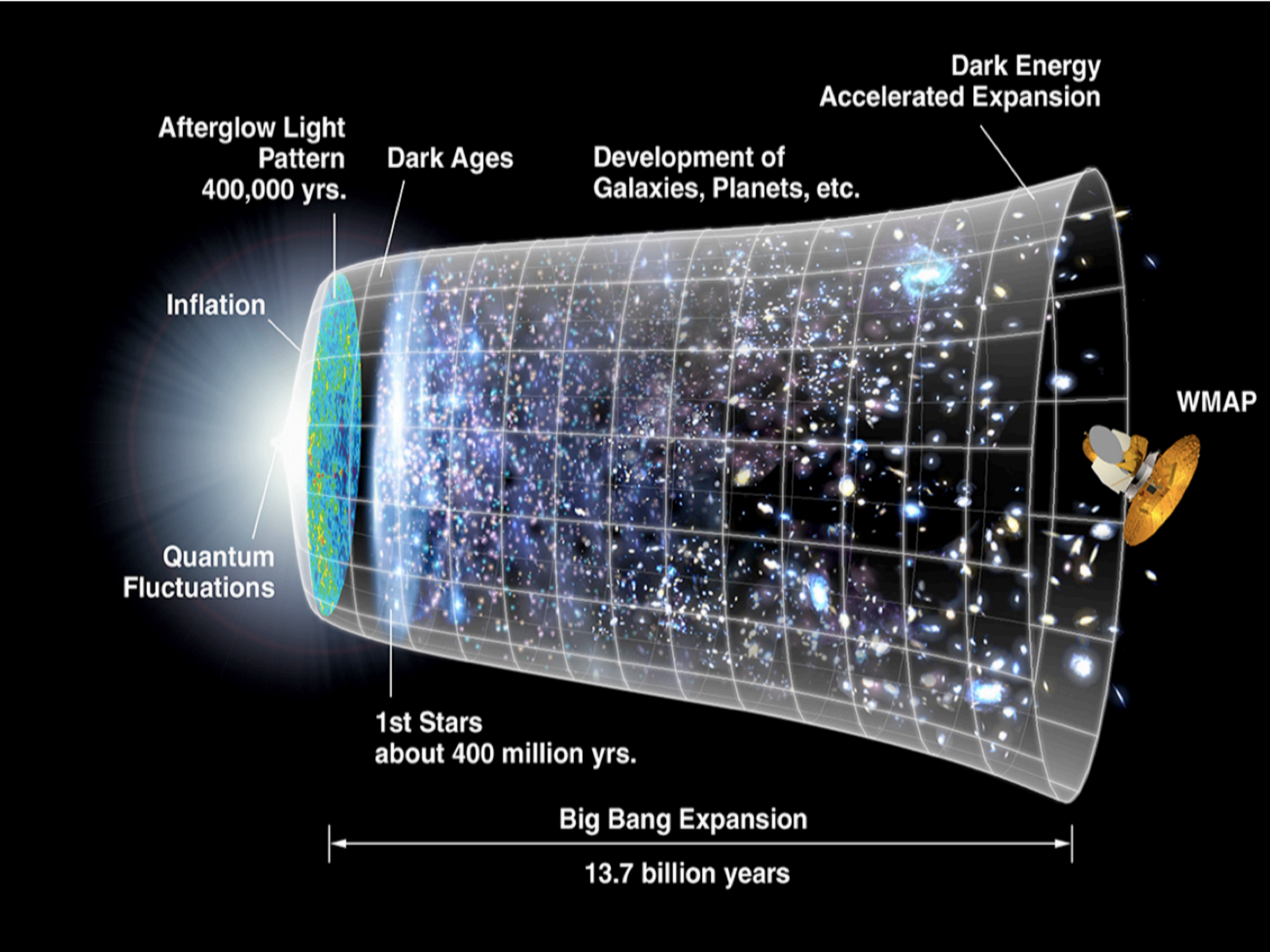
SESAPS 10/21/2011

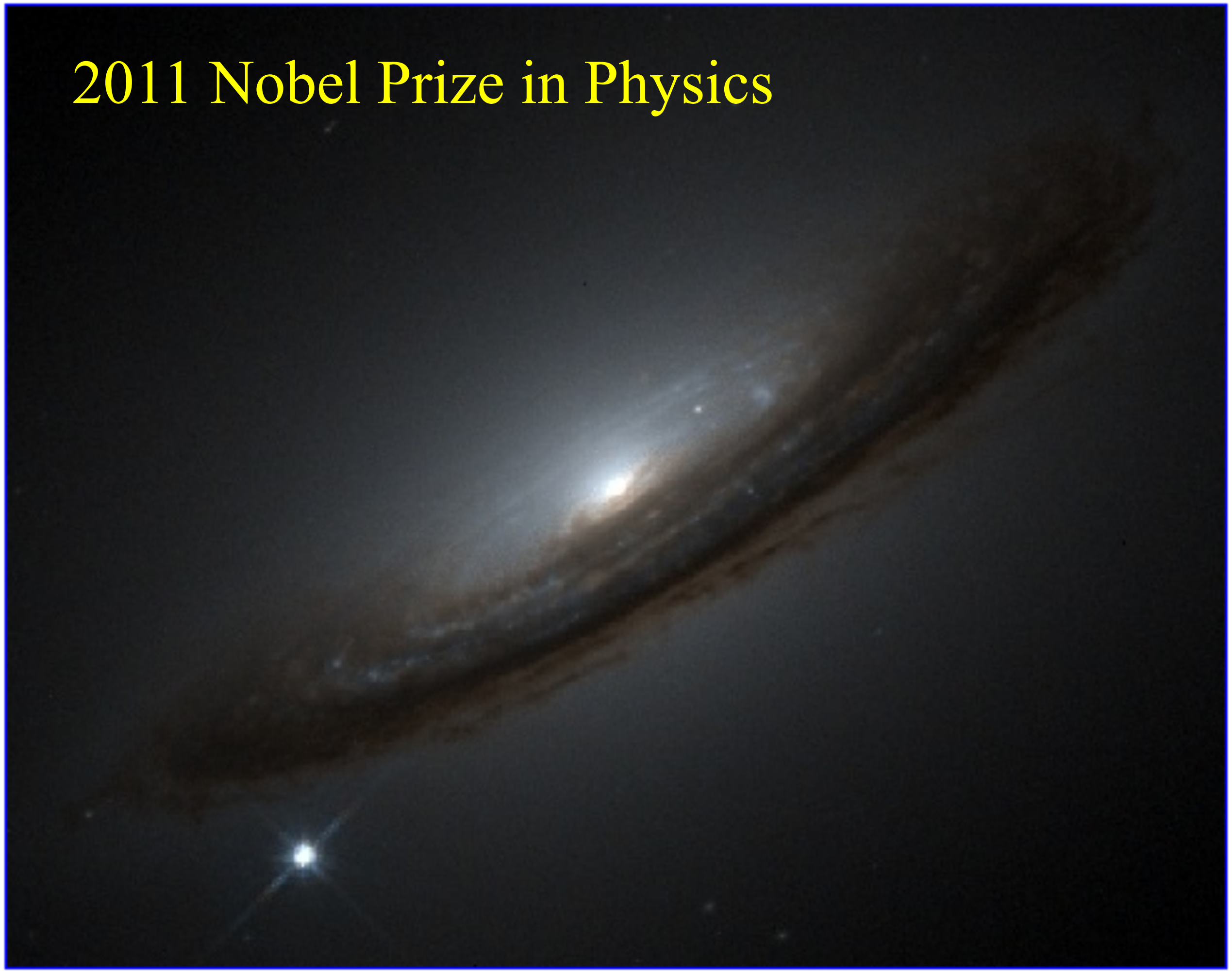


Dark Energy
Accelerated Expansion
Afterglow Light
Pattern
400,000 yrs.
Dark Ages
Development of
Galaxies, Planets, etc.
Inflation
WMAP
Quantum
Fluctuations
1st Stars
about 400 million yrs.
Big Bang Expansion
13.7 billion years

Cosmic acceleration and Dark Energy
Evidence from distances to Supernovae Type Ia
(since 1998! About 557 supernovae now!)

Supernova 1994D and the Unexpected Universe

30.12.1998



Credit: High-Z Supernova Search Team, HST, NASA

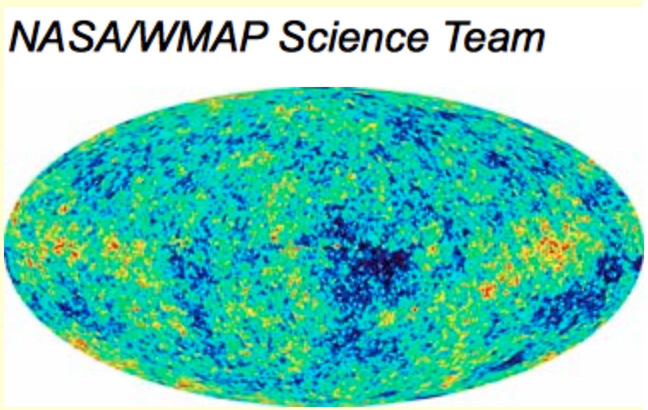
The acceleration of the expansion of the Universe is one of the most challenging and important problems in cosmology

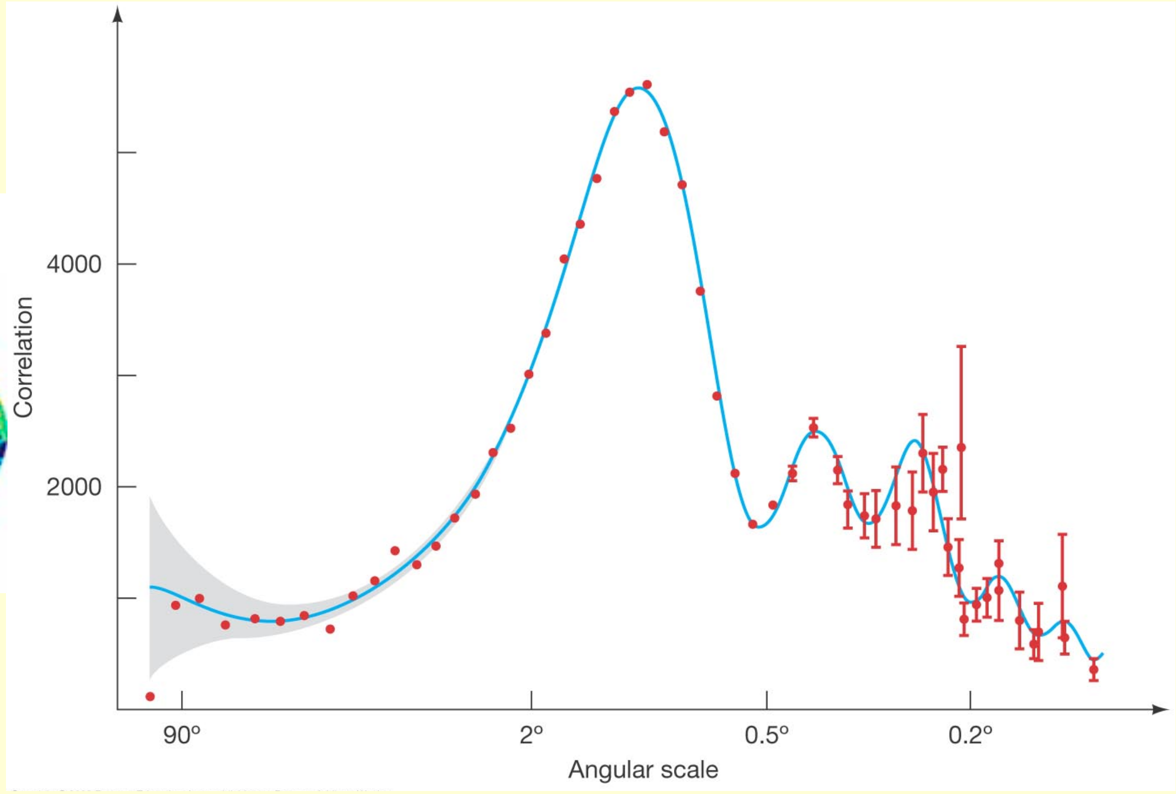
- The observational evidence for cosmic acceleration has continued to grow for the last 12 years
- IMPORTANT: The evidence comes from several independent and complementary cosmological observations.
- Possible explanations:
  - A new form of energy in the universe called Dark Energy, i.e. the Cosmological Constant.
  - A modification or extension of the gravitational theory at cosmological scales of distances

CMB from the Wilkinson Microwave Anisotropy Probe (WMAP)

Homogeneous and isotropic on large scales

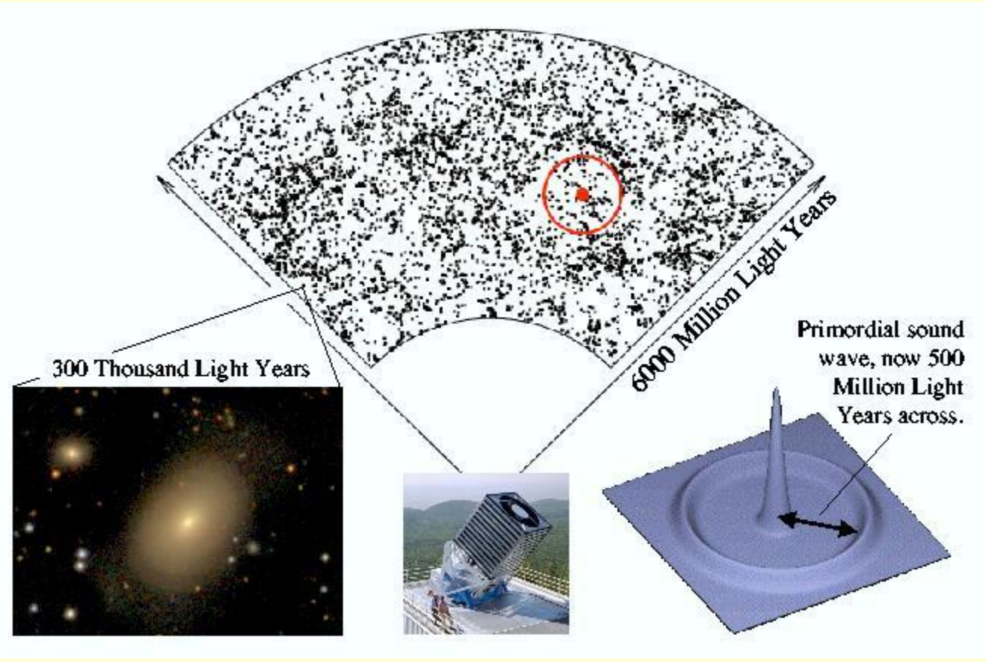
$$\Delta T = 10^{-5} K$$

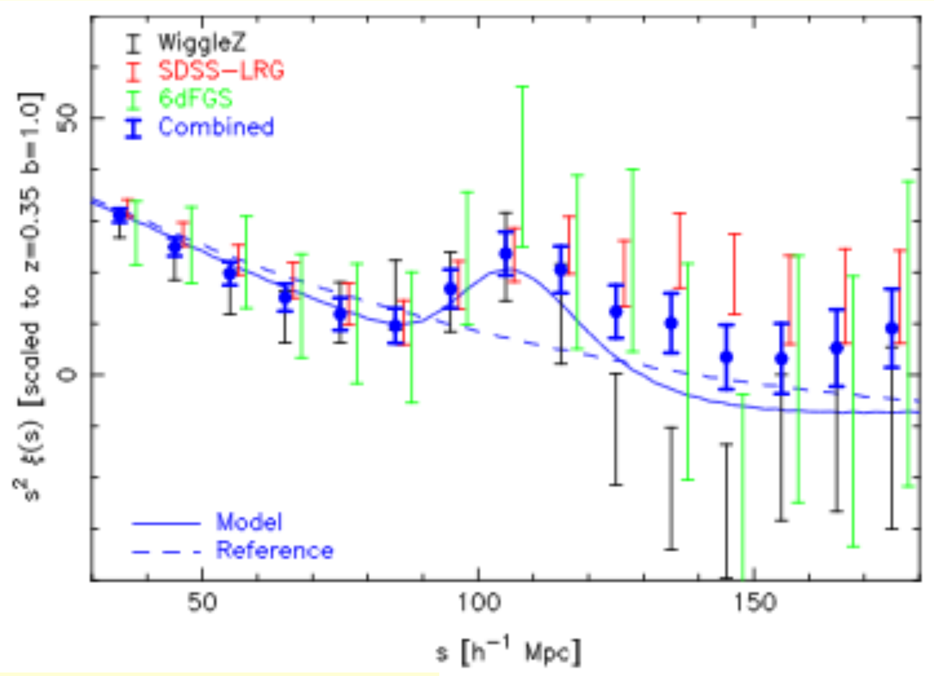




BAO from SDSS LRG, 6dFGS and WiggleZ

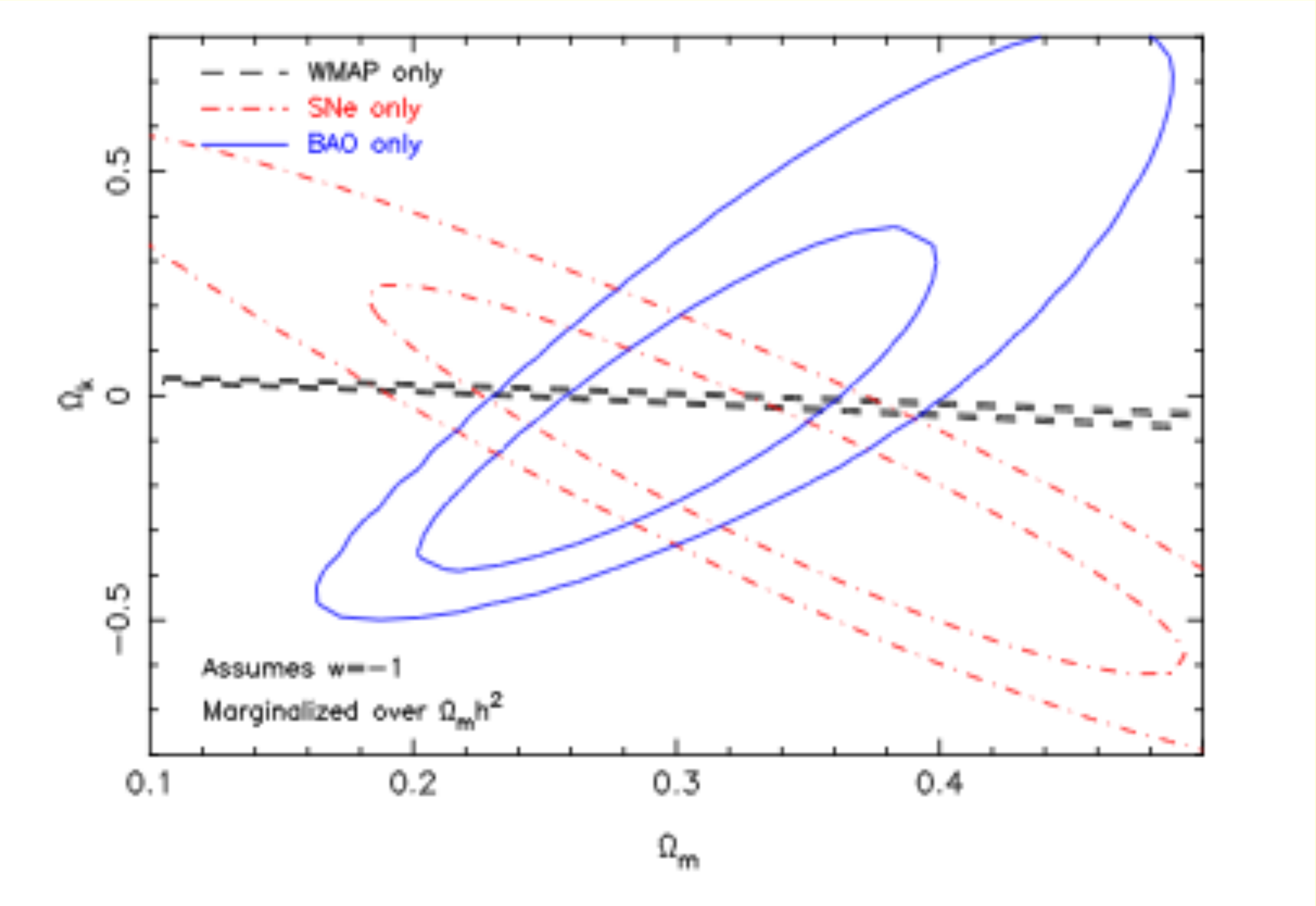
Standard rulers for measuring the cosmic acceleration from structures of galaxies.





Blake et al. (2011) MNRAS

Observational Tests of Cosmological Models



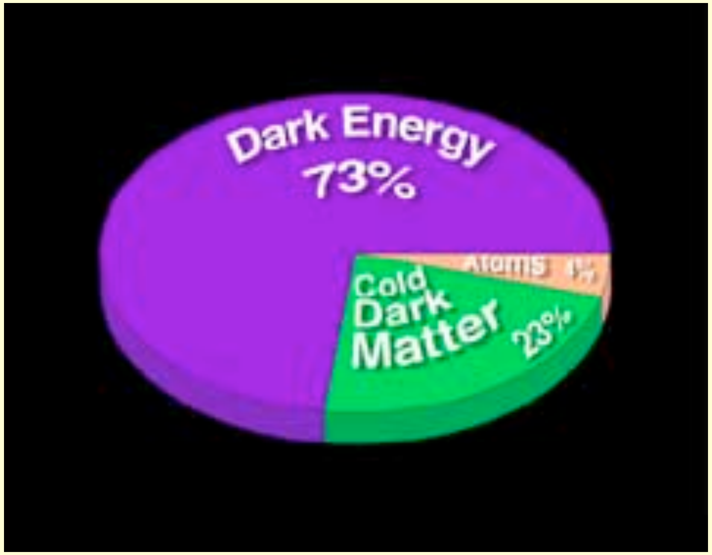
Blake et al. (2011) MNRAS

Combined constraints from SN, BAO, CMB give support to the standard model in cosmology:

Lambda Cold Dark Matter (LCDM) model

Observational Tests of Cosmological Models

LCDM model as **the Standard Model of Cosmology**.



Other explanations for the cosmic expansion need to be tested.

Let's try some **modified gravity models.**

Higher Order Gravity (HOG) models

- Einstein-Hilbert action with additional term

$$I = \int d^4x\sqrt{-g}\left[\frac{1}{2}R + f(G)\right] + \int d^4x\sqrt{-g}L^{\mathrm{sources}}$$

- Gauss Bonnet term:

$$G = R^2 - 4R^{\alpha\beta}R_{\alpha\beta} + R^{\alpha\beta\gamma\delta}R_{\alpha\beta\gamma\delta}$$

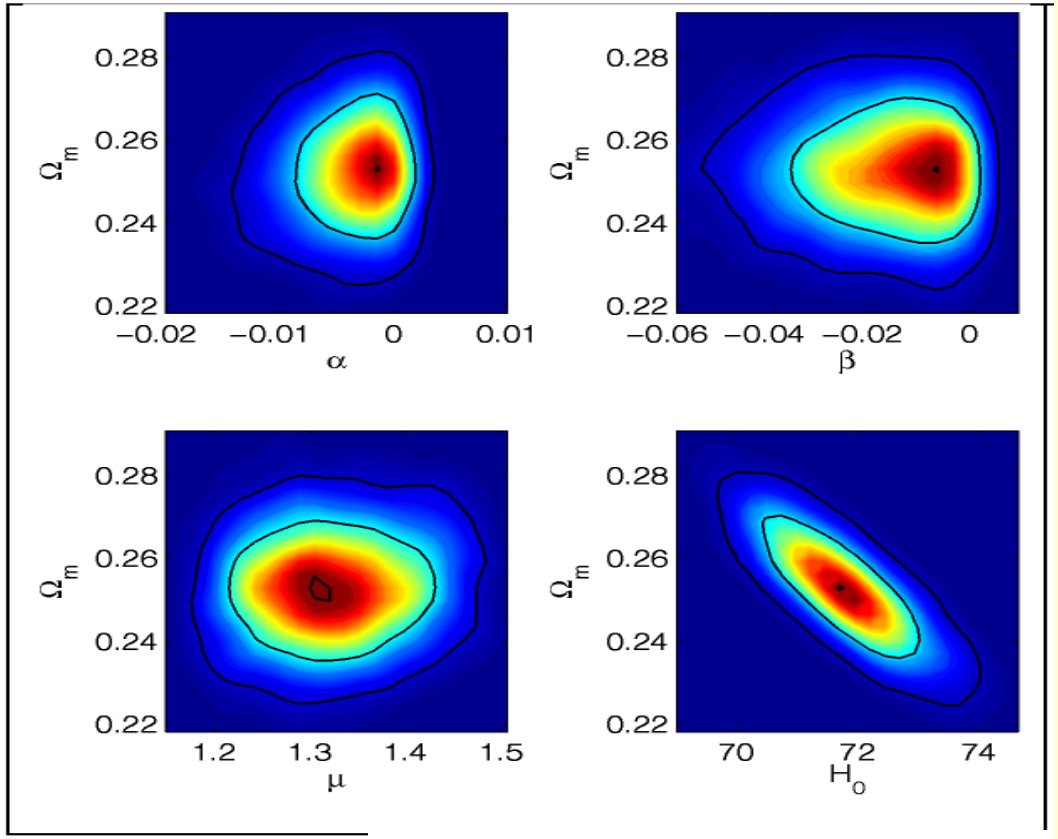
- New field equations:

$$8[R_{\alpha\gamma\beta\delta} + R_{\gamma\beta}g_{\delta\alpha} - R_{\gamma\delta}g_{\beta\alpha} - R_{\alpha\beta}g_{\delta\gamma} + R_{\alpha\delta}g_{\beta\gamma} + \frac{1}{2}R(g_{\alpha\beta}g_{\delta\gamma} - g_{\alpha\delta}g_{\beta\gamma})]\nabla^{\gamma}\nabla^{\delta}f_G$$

$$+(Gf_G - f)g_{\alpha\beta} + R_{\alpha\beta} - \frac{1}{2}g_{\alpha\beta}R = T^{\mathrm{sources}}_{\alpha\beta},$$

Gauss Bonnet Models

Model ZCS-A: $f(G) = \alpha\sqrt{G} + \beta\sqrt[4]{G},$



J. Moldenhauer, et. al., PRD (2010)

Solve and test with expansion history for FLRW spacetime

Cosmological parameters are constrained within physical limits.

Constraints on Cosmological Models

J. Moldenhauer, et. al., PRD (2010)

Constraints from Observations	χ^2	χ^2/dof	Ω_m	H_0	$\hat{\mu}$	G_0	α	λ	β
$DFT-A$	329.1	1.0754	$0.254939^{+0.049835}_{-0.025707}$	$71.2827^{+11.8991}_{-17.8981}$	$1.4424^{+0.356636}_{-0.309619}$	$-$	$26.6096^{+48.3636}_{-21.5027}$	$0.136131^{+1.75928}_{-0.111111}$	$-$
$DFT-A$	329.0	1.0751	$0.253516^{+0.0607013}_{-0.0231282}$	$68.1122^{+11.3855}_{-16.2845}$	$-$	$.214908^{+0.194690}_{-0.114864}$	$54.3437^{+20.6530}_{-44.9701}$	$0.0832318^{+1.81255}_{-0.058080}$	$-$
$DFT-B$	329.4	1.0764	$0.251225^{+0.0537648}_{-0.0218609}$	$70.6107^{+8.94104}_{-17.1149}$	$-$	$.253771^{+0.155822}_{-0.149289}$	$9.99891^{+39.9510}_{-6.78136}$	$0.313781^{+1.49185}_{-0.288712}$	$-$
$DFT-C$	328.9	1.0748	$0.253603^{+0.049532}_{-0.023303}$	$69.6979^{+9.64599}_{-16.0135}$	$-$	$.238717^{+0.170843}_{-0.135459}$	$13.9569^{+36.0160}_{-4.56533}$	$0.529189^{+1.36409}_{-0.473996}$	$-$
$ZCS-A$	328.2	1.0725	$0.25047^{+0.02857}_{-0.02093}$	$72.066^{+1.6351}_{-2.1441}$	$1.35273^{+0.13186}_{-0.18860}$	$-$	$0.00084^{+0.00016}_{-0.01632}$	$-$	$-0.03498^{+0.03595}_{-0.02399}$
$ZCS-B$	362.4	1.1843	$0.254855^{+0.018011}_{-0.025755}$	$71.1289^{+1.81457}_{-1.37513}$	$1.30822^{+0.0448309}_{-0.0363830}$	$-$	$-0.00014^{+0.000083}_{-0.001439}$	$-$	$0.00031^{+0.03288}_{-0.76993}$
$ZCS-C$	332.4	1.0862	$0.27302^{+0.02810}_{-0.01934}$	$81.511^{+1.8530}_{-1.7468}$	$1.7754^{+0.10141}_{-0.07048}$	$-$	$-0.00012^{+0.000004}_{-0.00295}$	$-$	$-0.0000017^{+0.00012}_{-0.00142}$

- All models are within 95% confidence level (except ZCS-B)
- Models are competitive to standard LCDM model

- But, these alternative theories of gravity must also pass local tests of gravity

Solar System Tests

1. Gravitational redshift
2. Deflection of light
3. Time delay
4. Cassini effect
5. Perihelion shift of planets

Method

- Field equations for GB models with expansion parameter

$$G_{\alpha\beta} + \alpha H_{\alpha\beta} = 0,$$

- Contribution from expansion parameter term is small compared to Einstein term,

$$\alpha \ll 1$$

J. Moldenhauer, et. al., PRD (2010)

Approximation Method

- Spherically symmetric metric with expansion parameter for HOG contribution

$$ds^2 = -\left(1 - \frac{2G_N M}{r} + \Phi_{HOG}(r)\right) dt^2 + \left(1 - \frac{2G_N M}{r} + \Psi_{HOG}(r)\right)^{-1} dr^2 + r^2 d\Omega^2.$$

- Find contribution from GB model, so it will not rule out the model

- Example: Gravitational redshift measurement

$$\Delta\nu_{exp}/\Delta\nu_{GR} = 1 \pm 0.0002$$ *Vessot and Levine (1979) GRG*

Example

- Gravitational redshift

$$\frac{\rho_2\rho_1(\Phi_{HOG}(\rho_2)-\Phi_{HOG}(\rho_1))}{\rho_2-\rho_1} < 2\times 10^{-4}.$$

where we have used $\rho \equiv r/(2G_N M)$

- Contribution from expansion term

$$\Phi_{HOG} = 2\sqrt{2}\times 3^{3/4}\beta\rho^{3/2}$$

- Constraint on model parameter

$$\beta < 4.41\times 10^{-28}.$$

Results

Constraints from Observations	α Solar System	λ Solar System	β Solar System	Ω_m Cosmological	H_0 Cosmological	α Cosmological	λ Cosmological	β Cosmological
$ZCS-A$	$< 8.11 \times 10^{-8}$	–	$< 2.55 \times 10^{-29}$	$0.25^{+0.03}_{-0.02}$	$72.06^{+1.63}_{-2.14}$	$0.00084^{+0.00016}_{-0.01632}$	–	$-0.03498^{+0.03595}_{-0.02399}$
$ZCS-B$	$< 8.11 \times 10^{-8}$	–	$< 8.48 \times 10^{-56}$	$0.25^{+0.02}_{-0.02}$	$71.12^{+1.81}_{-1.37}$	$-0.00014^{+0.000083}_{-0.001439}$	–	$0.00031^{+0.03288}_{-0.76993}$
$ZCS-C$	$< 8.11 \times 10^{-8}$	–	$< 1.24 \times 10^{-96}$	$0.27^{+0.02}_{-0.02}$	$81.51^{+1.85}_{-1.74}$	$-0.00012^{+0.000004}_{-0.00295}$	–	$-0.0000017^{+0.00012}_{-0.00142}$
$DFT-A$	$> 0.65 \times 10^{-5}$ from $\alpha\lambda = 1$	$< 1.53 \times 10^{5}$	–	$0.25^{+0.06}_{-0.02}$	$68.11^{+11.38}_{-16.28}$	$54.3437^{+20.6530}_{-44.9701}$	$0.0832318^{+1.81255}_{-0.058080}$	–
$DFT-B$	$> 0.80 \times 10^{-14}$ from $\alpha\lambda = 1$	$< 1.25 \times 10^{14}$	–	$0.25^{+0.05}_{-0.02}$	$70.61^{+8.94}_{-17.11}$	$9.99891^{+39.9510}_{-6.78136}$	$0.313781^{+1.49185}_{-0.288712}$	–

TABLE I: Summary of solar system constraints and best-fit parameters for $f(G)$ models from cosmological constraints (supernovae, baryon acoustic oscillations, Hubble Space Telescope Key Project, and CMB surface) as derived in [19]. The solar system constraints are only listed for the strongest constraints from section IV. For the DFT-A and DFT-B the limit for α is derived from that of λ.

Conclusions

- The constraints on the parameters fit solar system tests and share overlapping parameter space with constraints to expansion history that are competitive fits to the standard LCDM model
- It is important to test modified gravity models with both local and cosmological observations