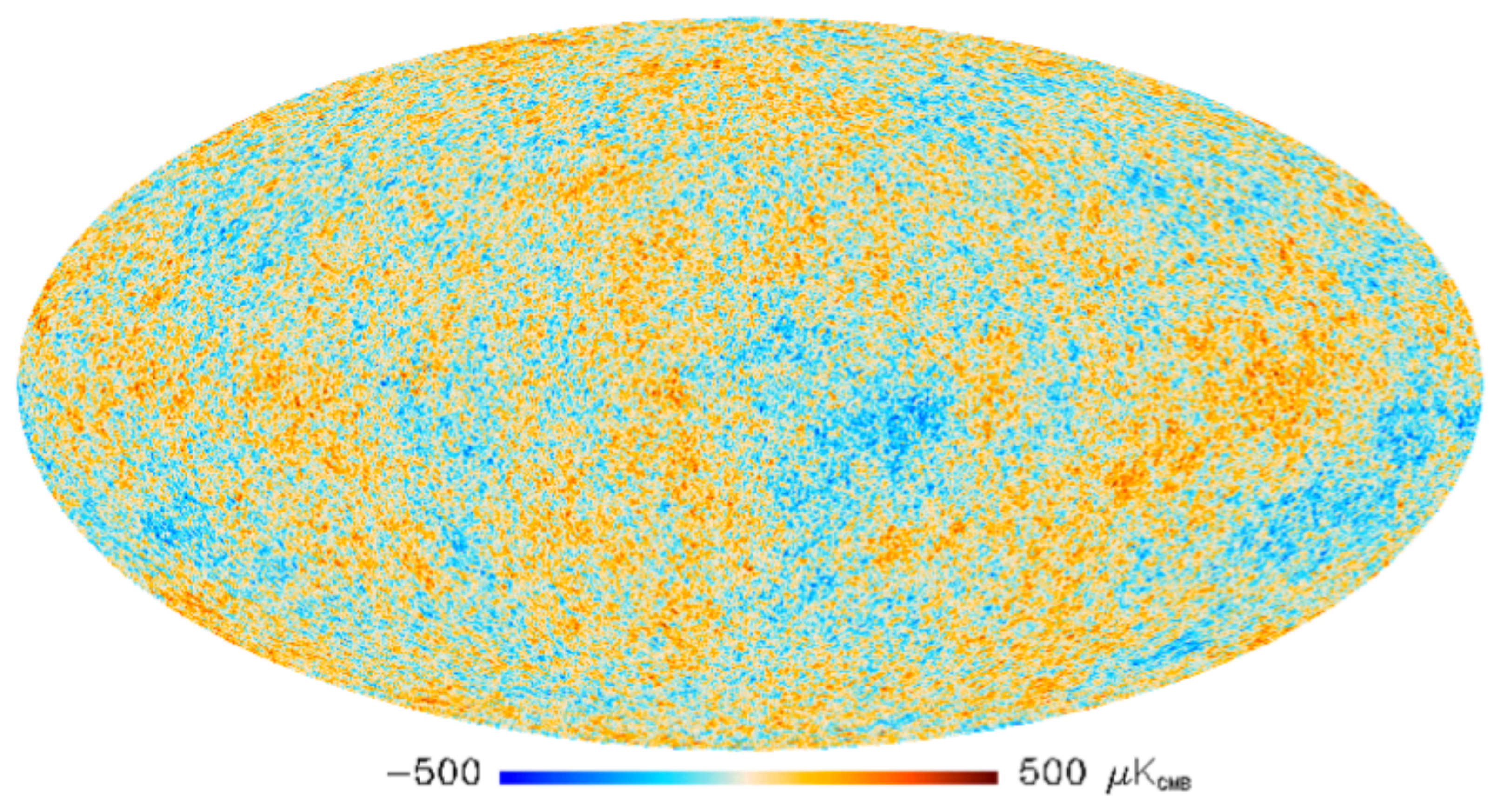
Cosmology after 50 years of Texas meetings

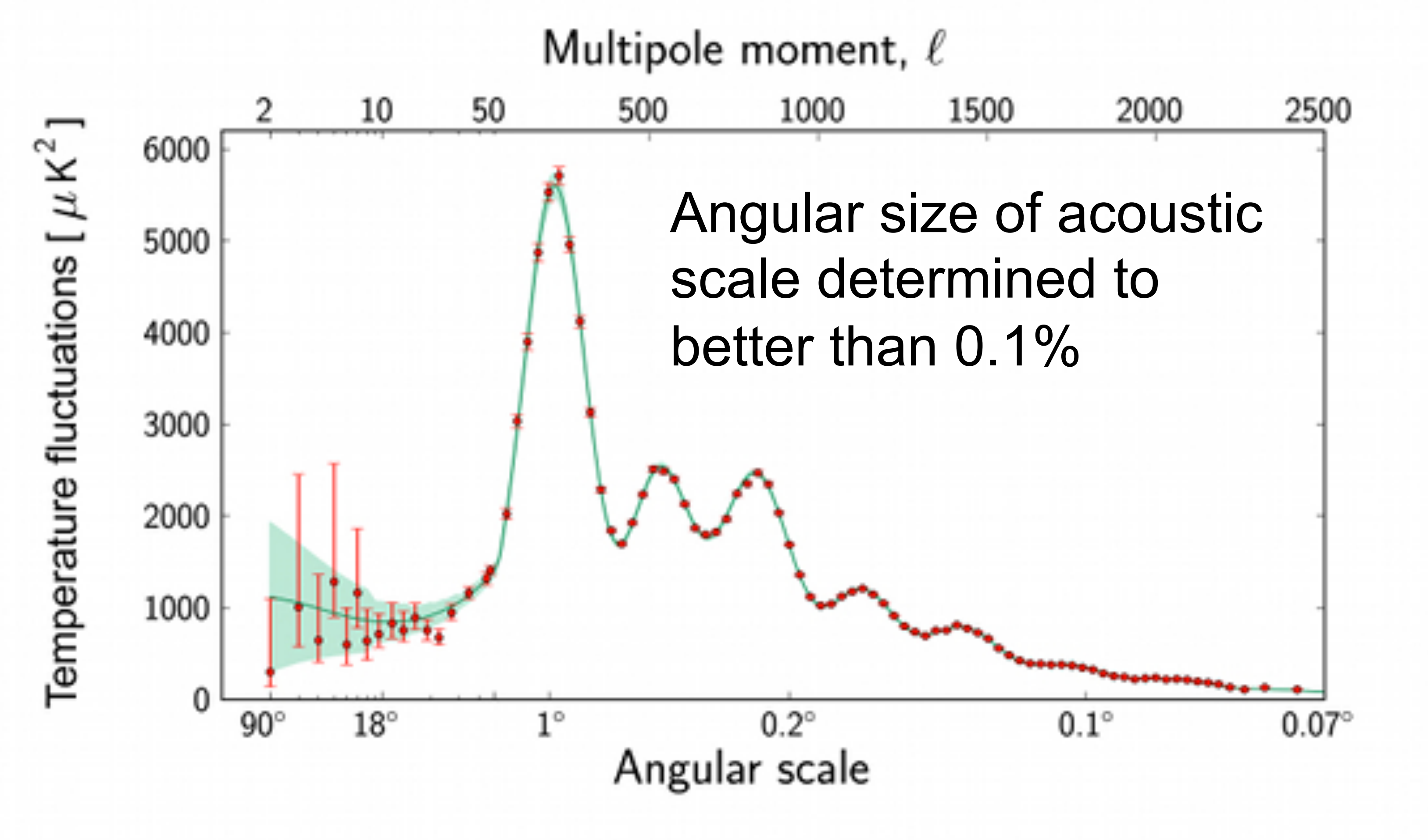
- Where are we now?
- Experimental Tensions
- Theoretical Tensions
- What are the missing pieces? Dark matter and dark energy

Katherine Freese, Univ. of Michigan

The Universe according to Planck



Planck Data

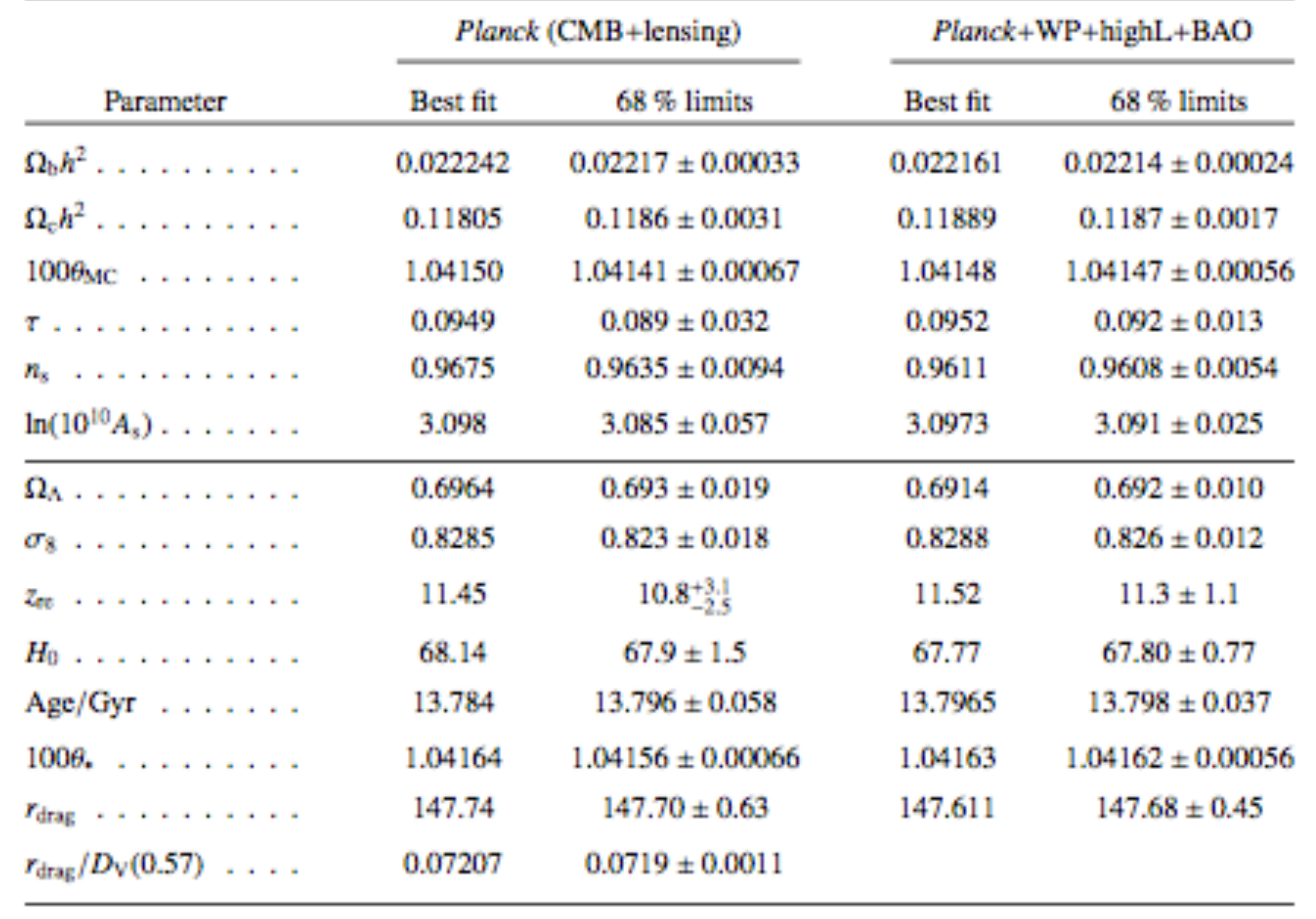


Angular size of acoustic scale determined to better than 0.1%

Seven acoustic peaks

LAMDA CDM FITS THE DATA

Cosmological Parameters from Planck



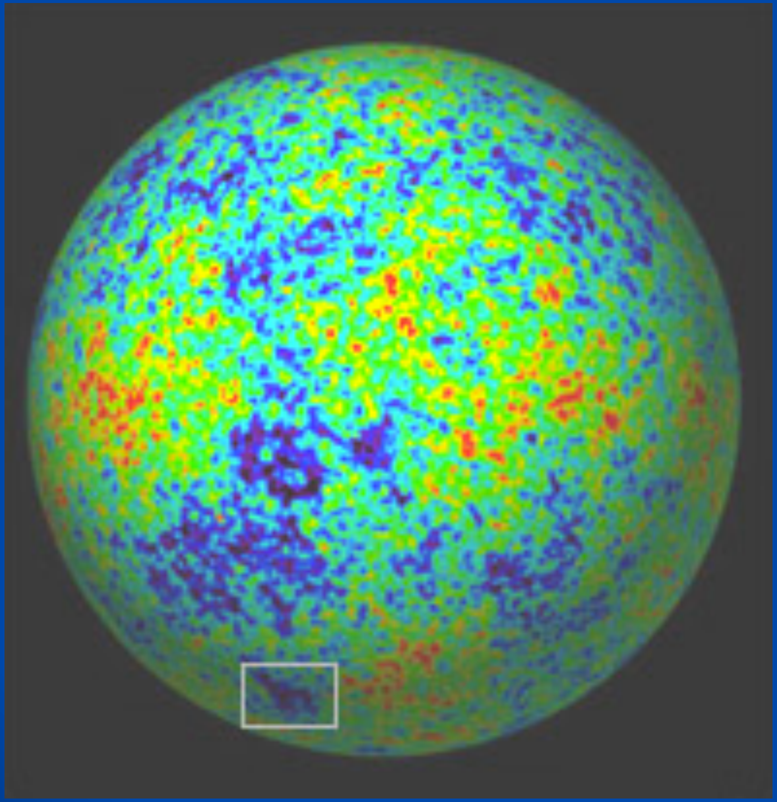
	Planck (CMB+lensing)		*Planck*+WP+highL+BAO	
Parameter	Best fit	68 % limits	Best fit	68 % limits
$\Omega_b h^2$	0.022242	0.02217 ± 0.00033	0.022161	0.02214 ± 0.00024
$\Omega_c h^2$	0.11805	0.1186 ± 0.0031	0.11889	0.1187 ± 0.0017
$100\theta_{MC}$	1.04150	1.04141 ± 0.00067	1.04148	1.04147 ± 0.00056
τ	0.0949	0.089 ± 0.032	0.0952	0.092 ± 0.013
n_s	0.9675	0.9635 ± 0.0094	0.9611	0.9608 ± 0.0054
$\ln(10^{10} A_s)$	3.098	3.085 ± 0.057	3.0973	3.091 ± 0.025
Ω_Λ	0.6964	0.693 ± 0.019	0.6914	0.692 ± 0.010
σ_8	0.8285	0.823 ± 0.018	0.8288	0.826 ± 0.012
z_{re}	11.45	$10.8^{+3.1}_{-2.5}$	11.52	11.3 ± 1.1
H_0	68.14	67.9 ± 1.5	67.77	67.80 ± 0.77
Age/Gyr	13.784	13.796 ± 0.058	13.7965	13.798 ± 0.037
$100\theta_*$	1.04164	1.04156 ± 0.00066	1.04163	1.04162 ± 0.00056
r_{drag}	147.74	147.70 ± 0.63	147.611	147.68 ± 0.45
$r_{drag}/D_V(0.57)$	0.07207	0.0719 ± 0.0011		

Weird Anomalies of WMAP hold up

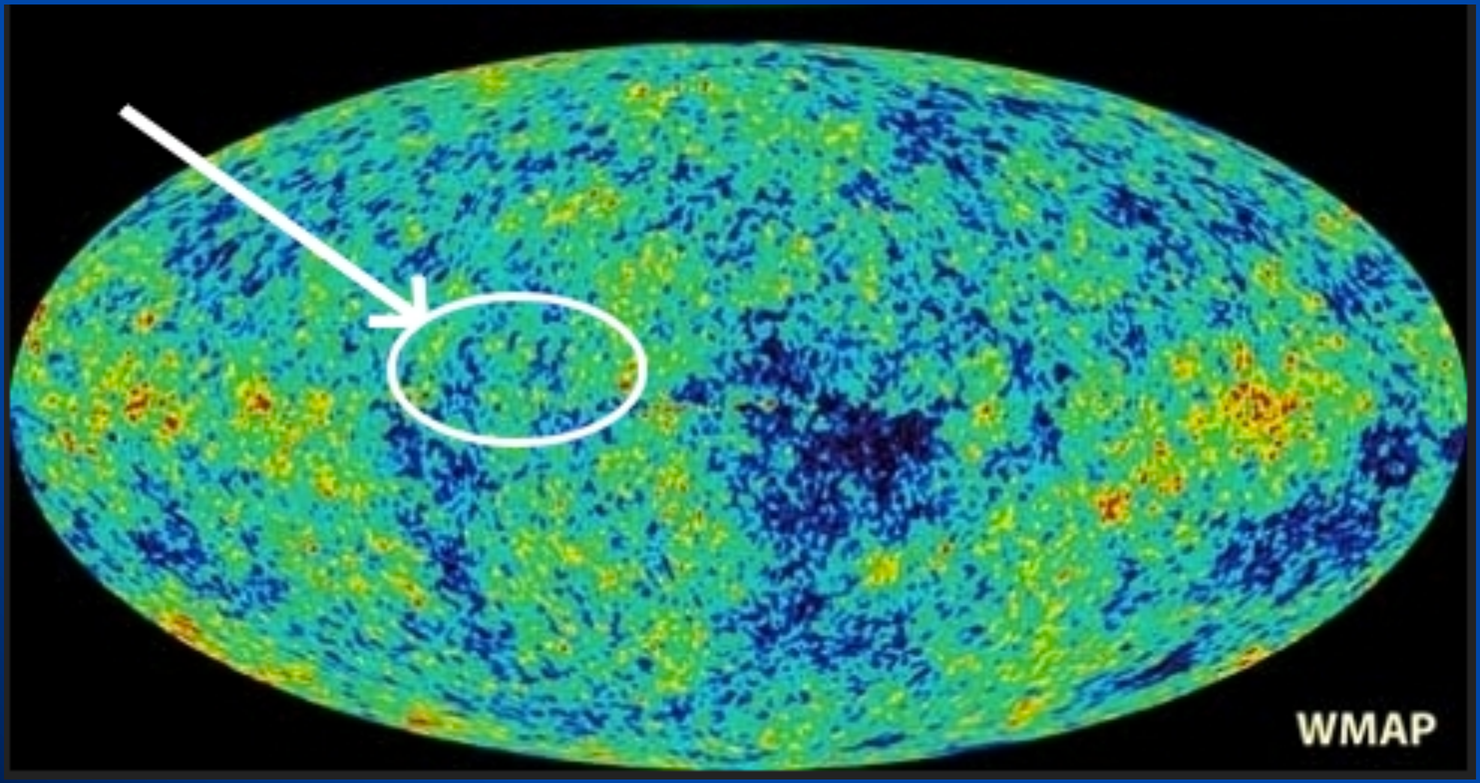
- Alignment between quadrupole and octopole moments (axis of evil)
- Asymmetry of power between two hemispheres
- The Cold Spot
- Deficit of power in low-l modes (below l=30)

- All confirmed to 3 sigma
- Cosmological origin favored (consistency between different CMB maps)

WMAP cold spot (also in Planck)



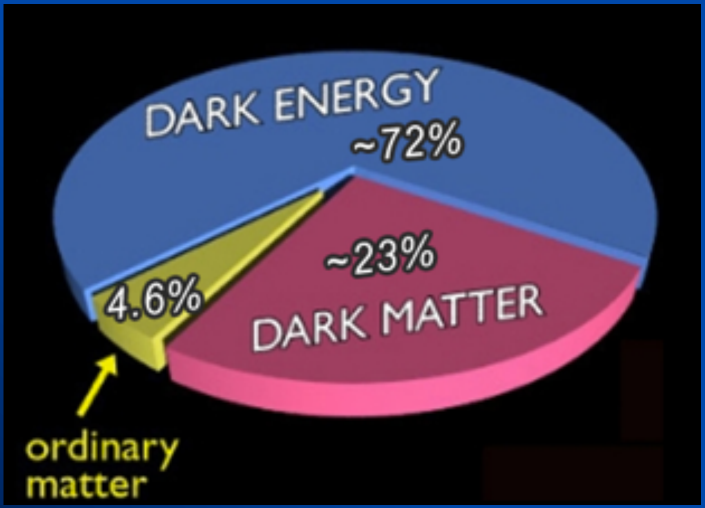
SH initials in WMAP satellite data

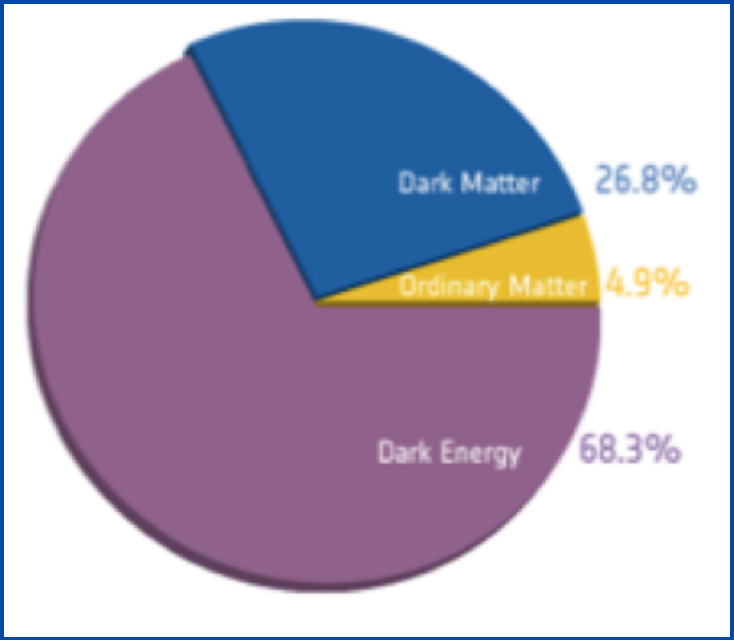


Experimental Tensions

More dark matter

- WMAP: 4.7% baryons, 23% DM, 72% dark energy
- PLANCK: 4.9% baryons, 26% DM, 69% dark energy

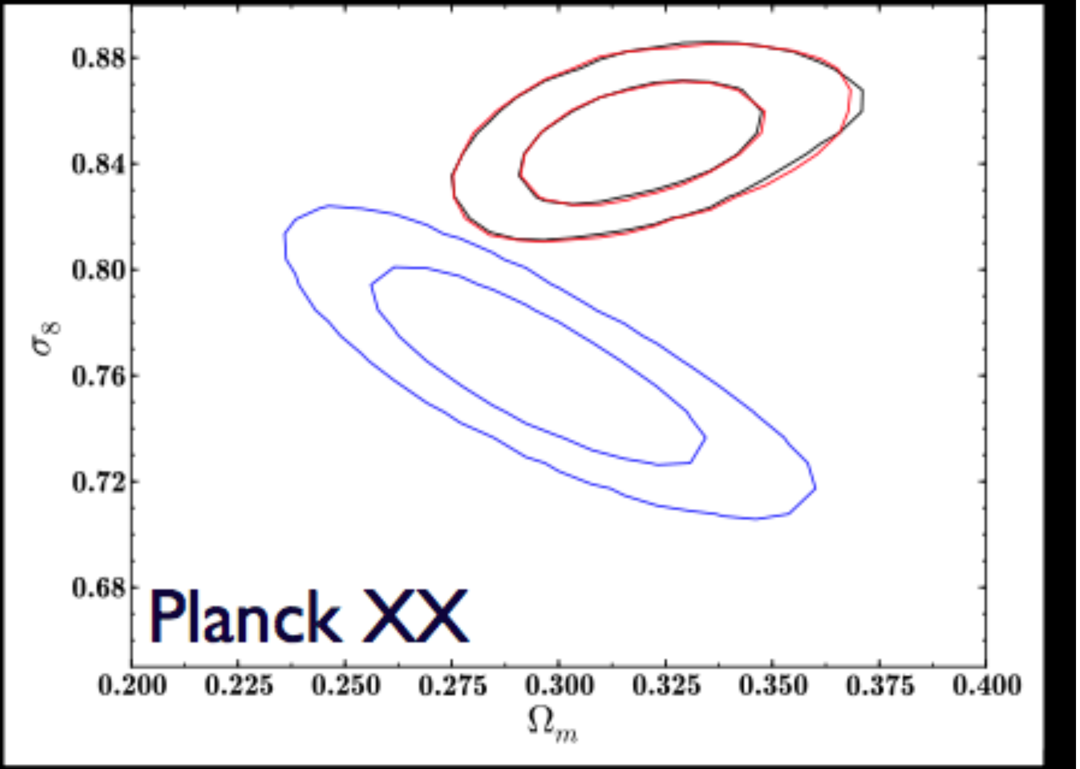




For discussion: is the difference due to instrumental effects? Is it due to 217 X 217 GHz spectra?

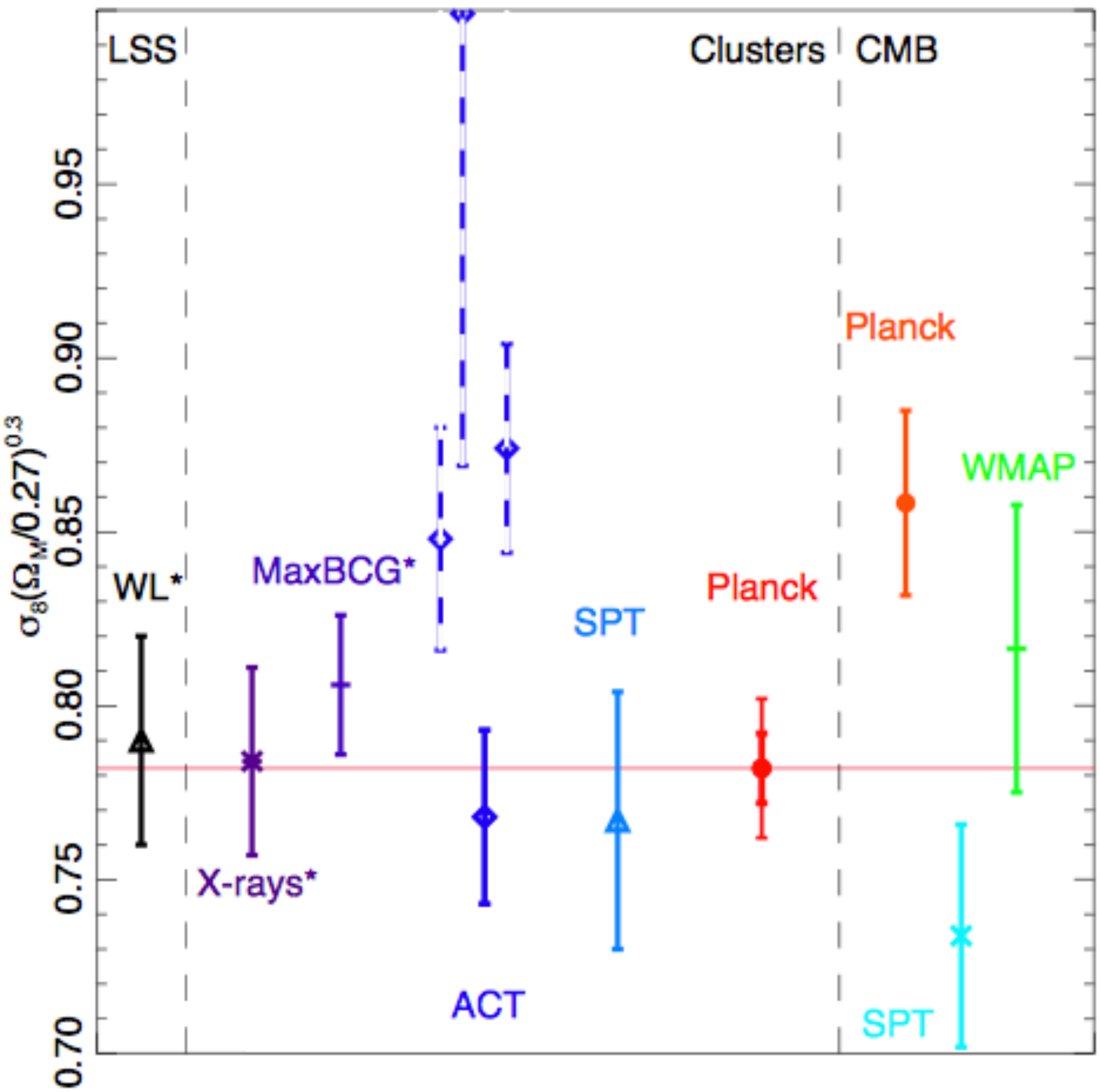
Parameter Concerns

- High matter density seems 2-3 σ higher than cluster and lensing estimates
- Low Hubble Constant deviates from most recent measurements
- High amplitude of density fluctuations



New physics or systematics in multiple data sets or systematics in Planck?

Sigma8 measures the amplitude of the (linear) power spectrum on the scale of 8 h^{-1} Mpc



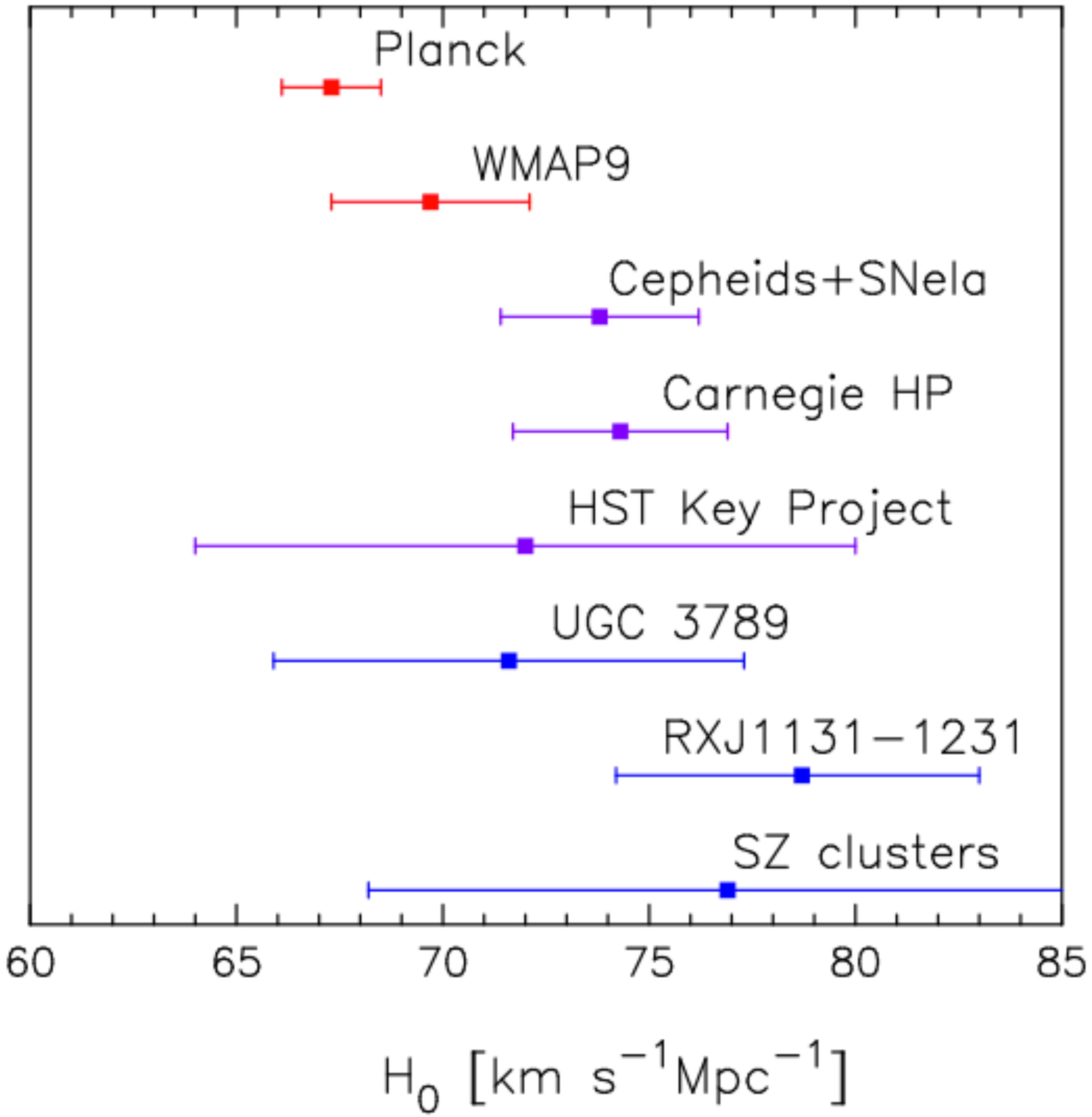
a crucial cosmological parameter which has a big influence over growth of fluctuations in the early universe

Strange H0 discrepancy

- FROM CMB MEASUREMENTS:
- Planck: 67 +- 1.2
- WMAP9: 69.7+- 2.4

- vs.
- Freedman etal (2012, HST + Spitzer): 74.3 +-1.5+2.1
- Riess etal (2011): 73.8 +- 2.4

- Is this indicative of real physics? Did H0 change between z=1000 and z=1?


Planck
WMAP9
Cepheids+SNeIa
Carnegie HP
HST Key Project
UGC 3789
RXJ1131−1231
SZ clusters
60
65
70
75
80
85
H_0 [km s^{-1}Mpc^{-1}]

- THE 217× 217 POWER SPECTRUM: A FLY IN THE OINTMENT?

- arXiv:1312:3313
- Spergel, Flauger, Hlozek

- “The 217×217 detector set spectra are responsible for a significant amount of the shift in cosmological parameters”

Minimal inflation:

- 1) a single weakly-coupled neutral scalar field, the inflaton, drives the inflation and generates the curvature perturbation
- 2) with canonical kinetic term
- 3) slowly rolling down featureless potential
- 4) initially lying in a Bunch-Davies vacuum state

- If any one of these conditions is violated, detectable amplitudes of nonGaussianity should have been seen.

$$\langle \Phi(\boldsymbol{k}_1)\Phi(\boldsymbol{k}_2)\Phi(\boldsymbol{k}_3)\rangle = (2\pi)^3\delta^{(3)}(\boldsymbol{k}_1+\boldsymbol{k}_2+\boldsymbol{k}_3)B_\Phi(k_1,k_2,k_3).$$

$$B_\Phi(k_1,k_2,k_3) = f_{\rm NL}F(k_1,k_2,k_3)\,.$$

Primordial nonGaussianities

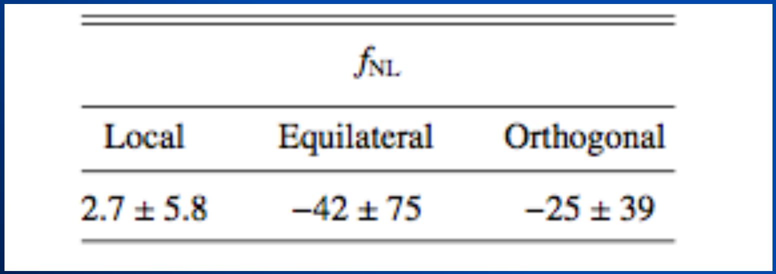
- If primordial fluctuations are Gaussian distributed, then they are completely characterized by their two-point function, or equivalently by the power spectrum. All odd-point functions are zero.
- If nonGaussian, there is additional info in the higher order correlation functions
- The lowest order statistic that can differentiate is the 3-point function, or bispectrum in Fourier space:

$$\langle \Phi(\mathbf{k}_1)\Phi(\mathbf{k}_2)\Phi(\mathbf{k}_3)\rangle = (2\pi)^3\delta^{(3)}(\mathbf{k}_1+\mathbf{k}_2+\mathbf{k}_3)B_\Phi(k_1,k_2,k_3).$$

- Here Phi is comoving curvature perturbation (density pert)

No primordial nonGaussianities in Planck

- Single field models: so small as to be undetectable
- Other models: three shapes (configurations of triangles formed by the three wavevectors)
- Any detection of nonGaussianity would have thrown out all single field models
- Data show no evidence of nonGaussianity, implying single field models work



$f_{\rm NL}$		
Local	Equilateral	Orthogonal
2.7 ± 5.8	-42 ± 75	-25 ± 39

- Data bound the speed of sound c_s>0.02

Models with NG: f_NL>>1

- Local NG: squeezed triangles, k1<<k2 = k3,
  e.g. multifield models, curvaton
- Equilateral NG, k1=k2=k3, e.g. non-canonical kinetic terms as in k-inflation or DBI inflation, models with general higher-derivative interactions of the inflaton field such as ghost inflation, and models arising from effective field theories
- Folded NG, e.g. single-field models w non-Bunch-Davies vacuum, and modesl with general higher derivative interactions.
- Orthogonal NG, e.g. non-canonical kinetic terms.

No evidence for any of these nonGaussianities in Planck.
Disfavored: EKPYROTIC with exponential potential

Predictions of Single Field Models

- 1) no nonGaussianities
- 2) no running of spectral index of scalar perturbations

- Scalar
- modes
- Tensor
  modes

$$\mathcal{P}_{\mathcal{R}}(k) = A_{\mathrm{s}}\left(\frac{k}{k_*}\right)^{n_{\mathrm{s}}-1+\frac{1}{2}\,\mathrm{d}n_{\mathrm{s}}/\mathrm{d}\ln k\,\ln(k/k_*)+\frac{1}{6}\,\mathrm{d}^2 n_{\mathrm{s}}/\mathrm{d}\ln k^2(\ln(k/k_*))^2+\ldots}$$

$$\mathcal{P}_{\mathrm{t}}(k) = A_{\mathrm{t}}\left(\frac{k}{k_*}\right)^{n_{\mathrm{t}}+\frac{1}{2}\,\mathrm{d}n_{\mathrm{t}}/\mathrm{d}\ln k\,\ln(k/k_*)+\ldots},$$

- Both predictions proven true by Planck

- “With these results, the paradigm of standard single-field inflation has survived its most stringent tests to date”

Four parameters from inflationary perturbations:

I. Scalar perturbations:

amplitude $(\delta\rho/\rho)\big|_s$ spectral index n_s

II. Tensor (gravitational wave) modes:

amplitude $(\delta\rho/\rho)\big|_T$ spectral index n_T

Expressed as $r \equiv \dfrac{P_T^{1/2}}{P_S^{1/2}}$

Inflationary consistency condition: $r = -8n_T$

Plot in r-n plane (two parameters)

Inflation after Planck (Planck paper XXII)

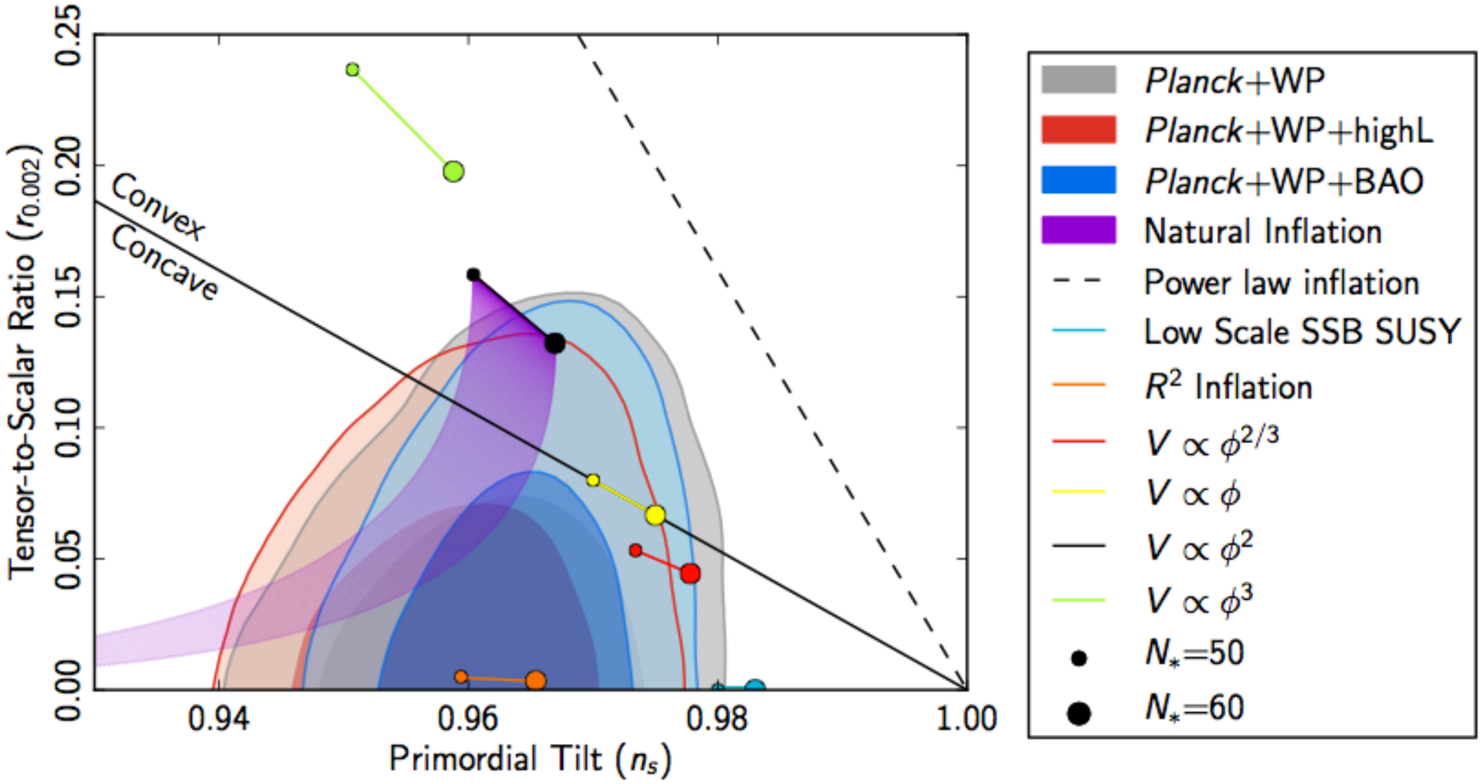


Fig. 1. Marginalized joint 68% and 95% CL regions for n_s and $r_{0.002}$ from *Planck* in combination with other data sets compared to the theoretical predictions of selected inflationary models.

Purple swath is natural inflation model of Freese, Frieman, and Olinto 1990

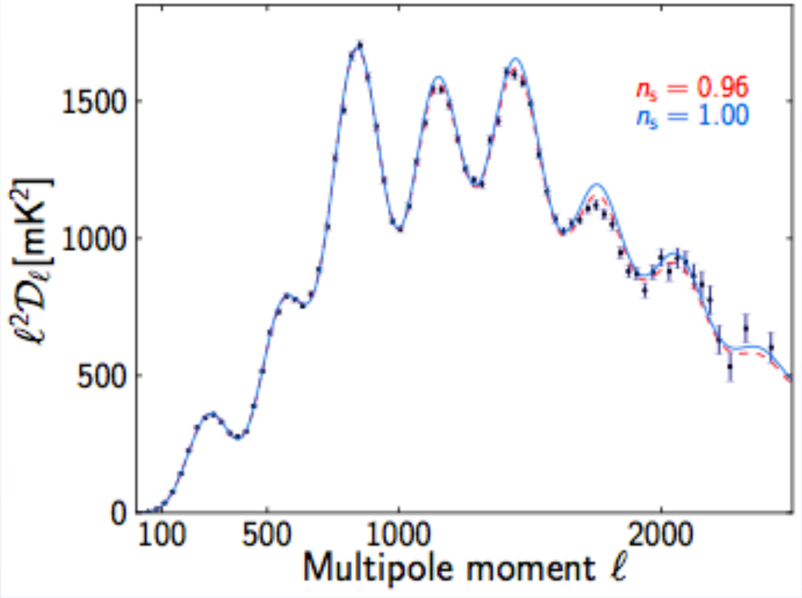
Natural Inflation:
Shift Symmetries

- Shift symmetries (e.g. axionic) protect flatness of inflaton potential

  $\Phi \rightarrow \Phi + \mathrm{constant}$ (e.g. inflaton is Goldstone boson)
- Additional explicit breaking allows field to roll.
- This mechanism, known as natural inflation, was first proposed in

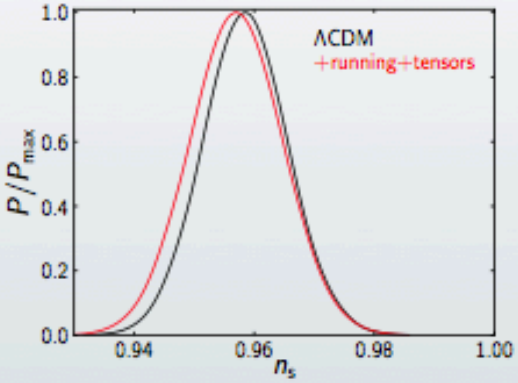
Freese, Frieman, and Olinto 1990;
Adams, Bond, Freese, Frieman and Olinto 1993

Extensions to ΛCDM model
Early-Universe physics: ns, dn_s/dk and r



6σ departure from scale invariance

$$n_s = 0.9603 \pm 0.0073$$

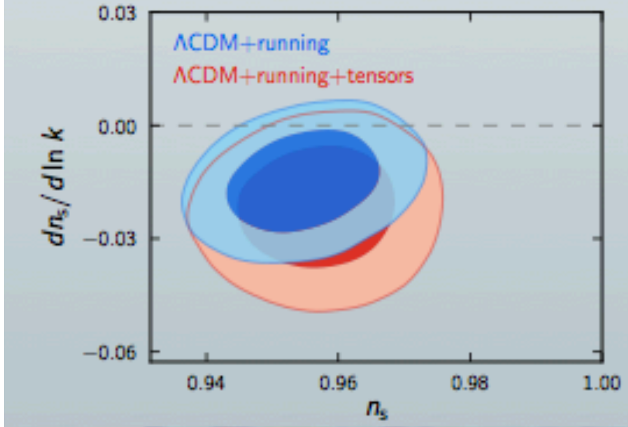


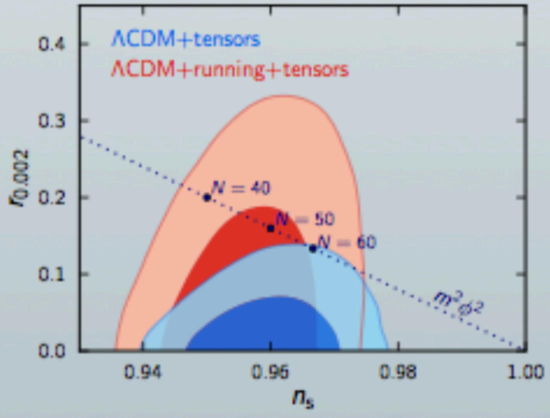
l<50

$$dn_s / d\ln k = -0.0134 \pm 0.0090$$

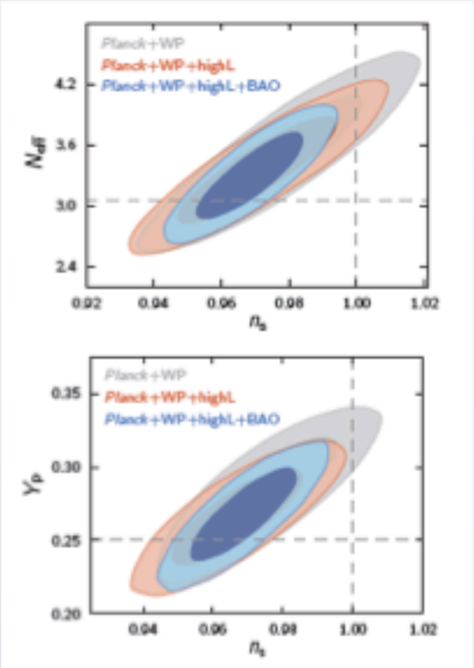
$$r < 0.11 \qquad V_*$$

$$V = (1.94\times10^{16} GeV)^4 (r_{0.02}/0.12)$$





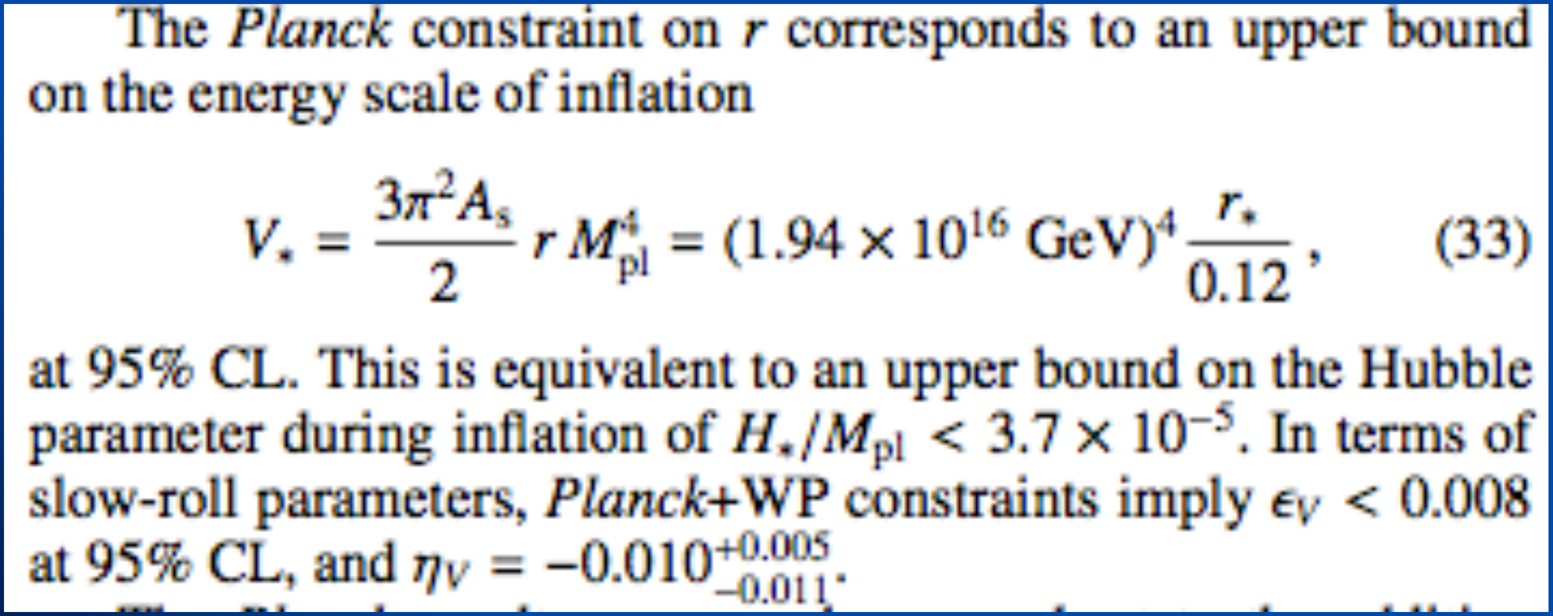
3σ



Slide from Graca Rocha

We eagerly await Planck polarization data

- To date: r<0.12 (k=0.002Mpc^-1) at 95% C.L.



The *Planck* constraint on r corresponds to an upper bound on the energy scale of inflation

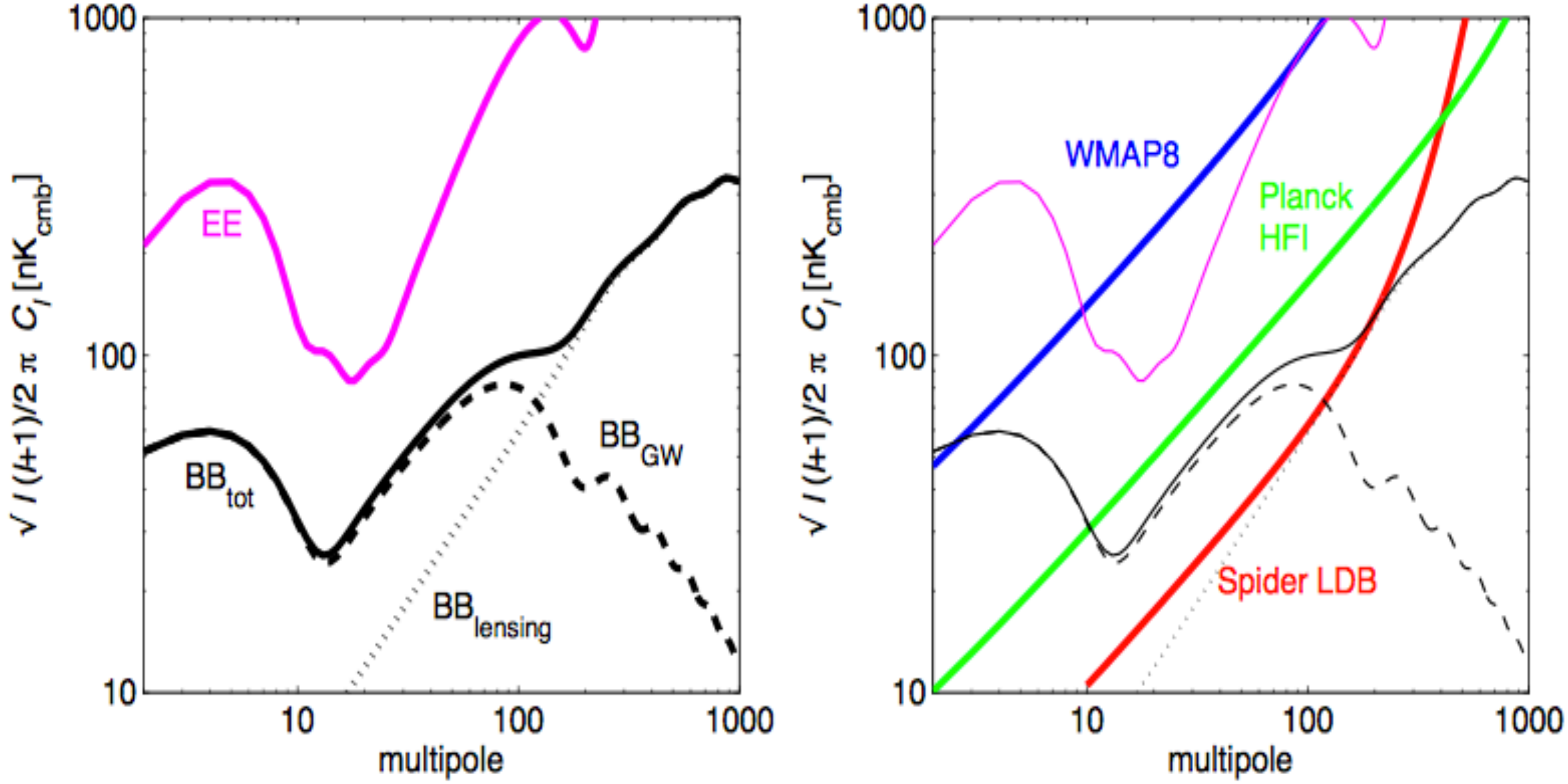
$$V_* = \frac{3\pi^2 A_s}{2} r M_{\rm pl}^4 = (1.94 \times 10^{16}\ {\rm GeV})^4 \frac{r_*}{0.12}, \qquad (33)$$

at 95% CL. This is equivalent to an upper bound on the Hubble parameter during inflation of $H_*/M_{\rm pl} < 3.7 \times 10^{-5}$. In terms of slow-roll parameters, *Planck*+WP constraints imply $\epsilon_V < 0.008$ at 95% CL, and $\eta_V = -0.010^{+0.005}_{-0.011}$.

- If cosine (original variant of natural inflation) is right, then r >0.02 is predicted (given bounds on n_s)

What's next for inflation? Polarization: SPIDER, ACT, SPT

- (talk of Aurelien Fraisse)

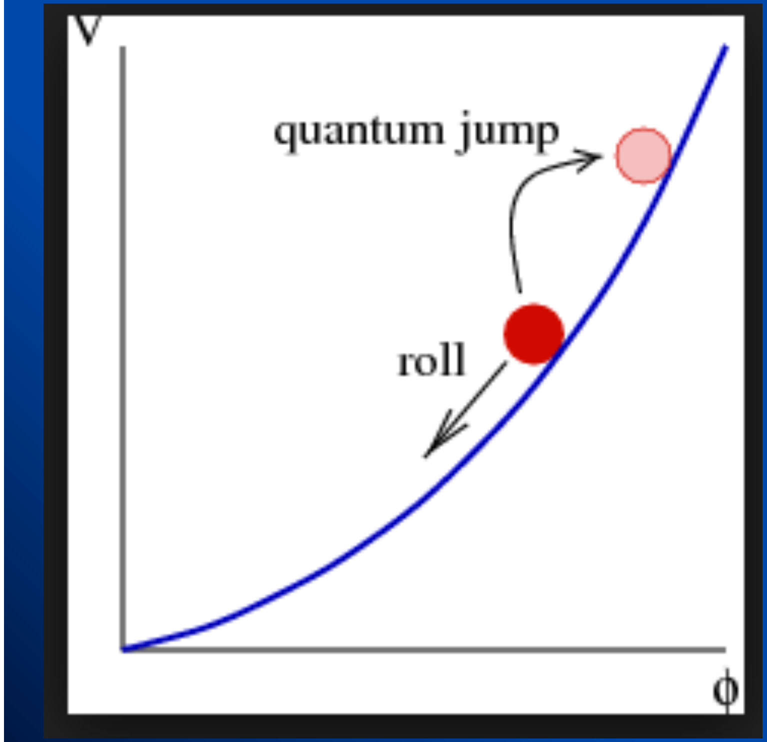


Large Scale Structure

- Provides complementary and/or competing info w/ CMB
- Different temporal (later) and spatial (smaller) scales
- LSS has more modes and in principle more info:
    - CMB is 2D
    - LSS is 3D
- Yet: can systematic errors be controlled?
- LSS has great potential: can it be tapped?

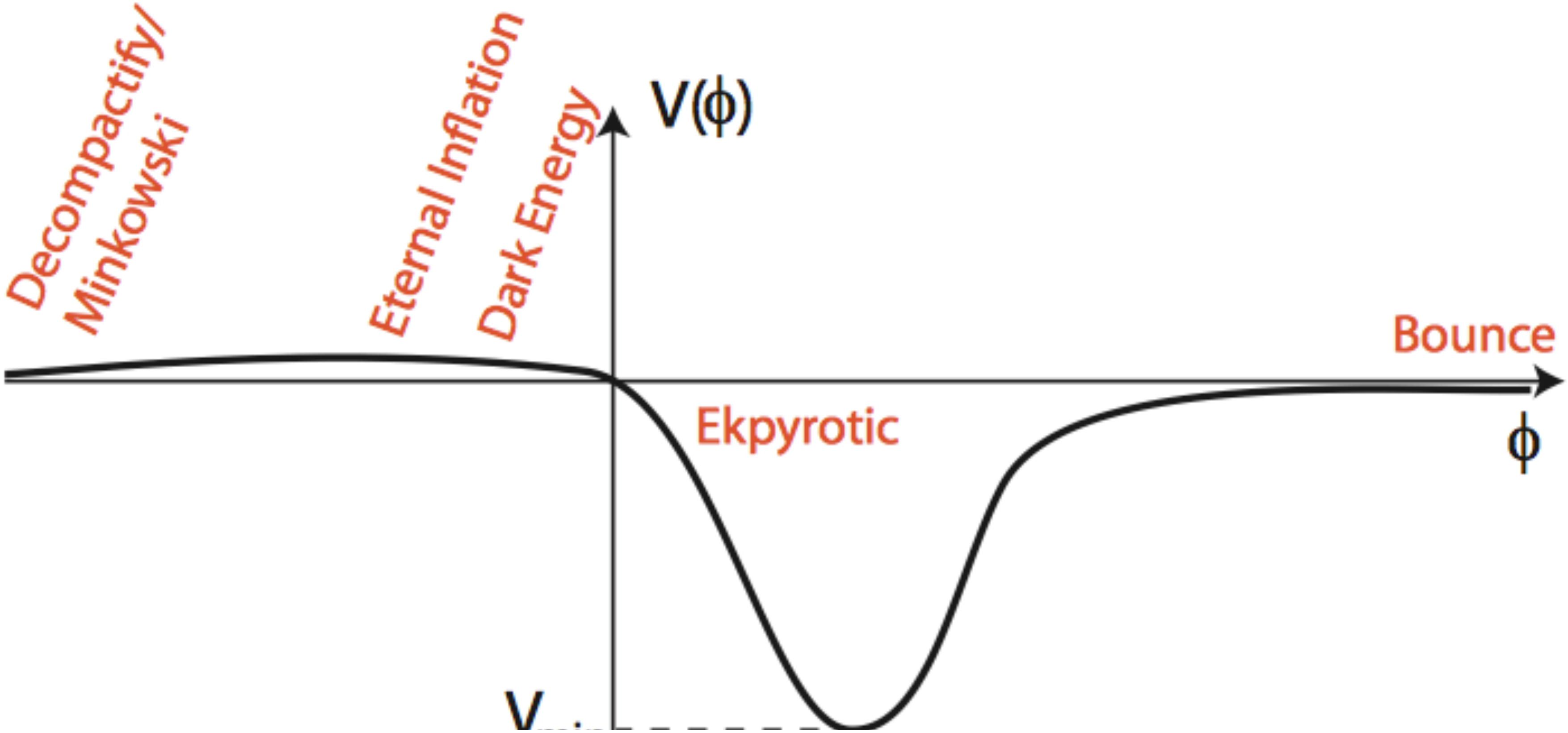
Theoretical Tension

Eternal Inflation

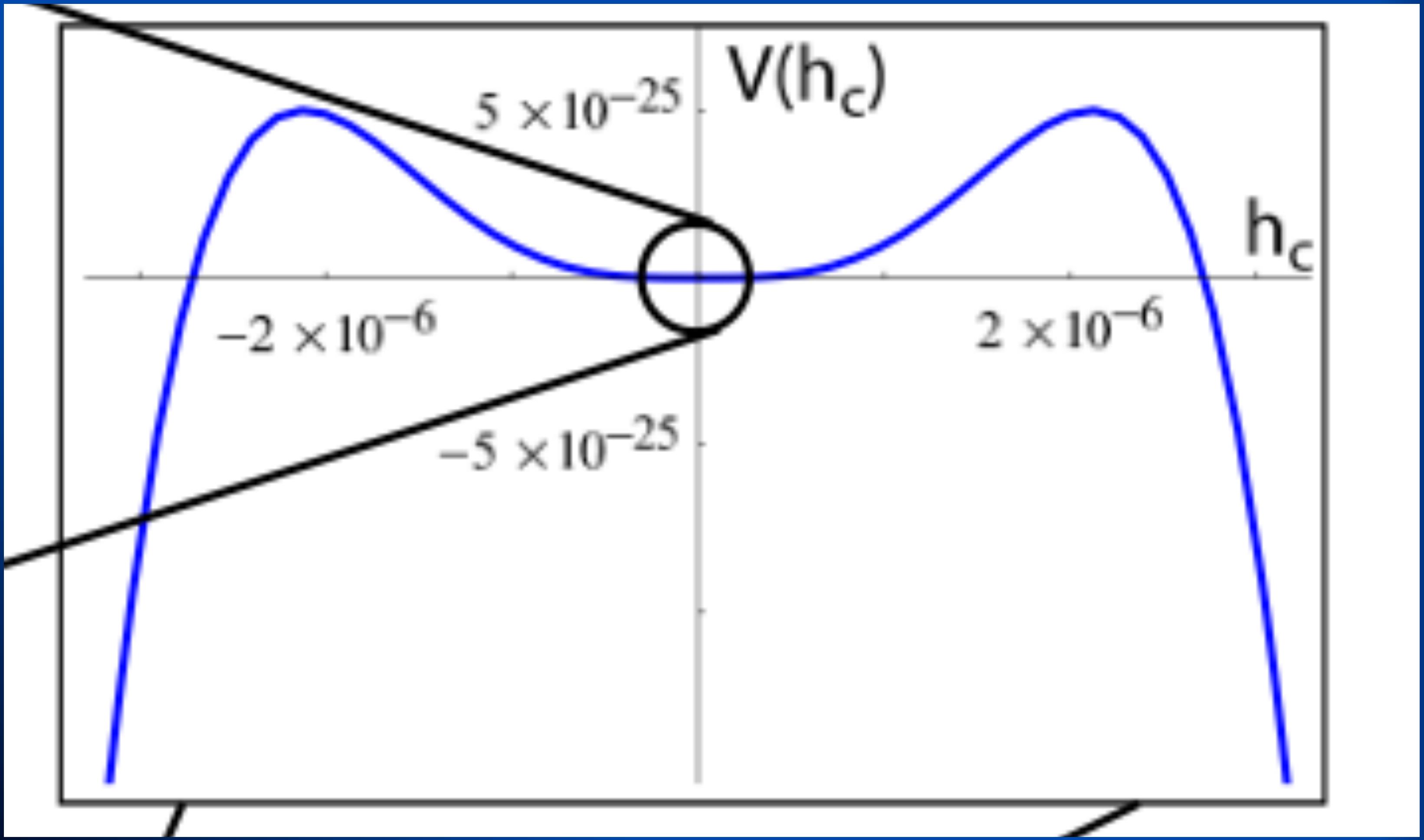


Alternatives

- Penrose: Conformal Cyclic Cosmology predicts circles in the CMB sky
- Expyrotic/Cyclic Models (Steinhardt)



New variant uses metastability of the Higgs



What are the missing pieces?
Dark matter and Dark energy

The WIMP Miracle

Weakly Interacting Massive Particles are the best motivated dark matter candidates, e.g.: Lightest Supersymmetric Particles (such as neutralino) are their own antipartners. Annihilation rate in the early universe determines the density today.

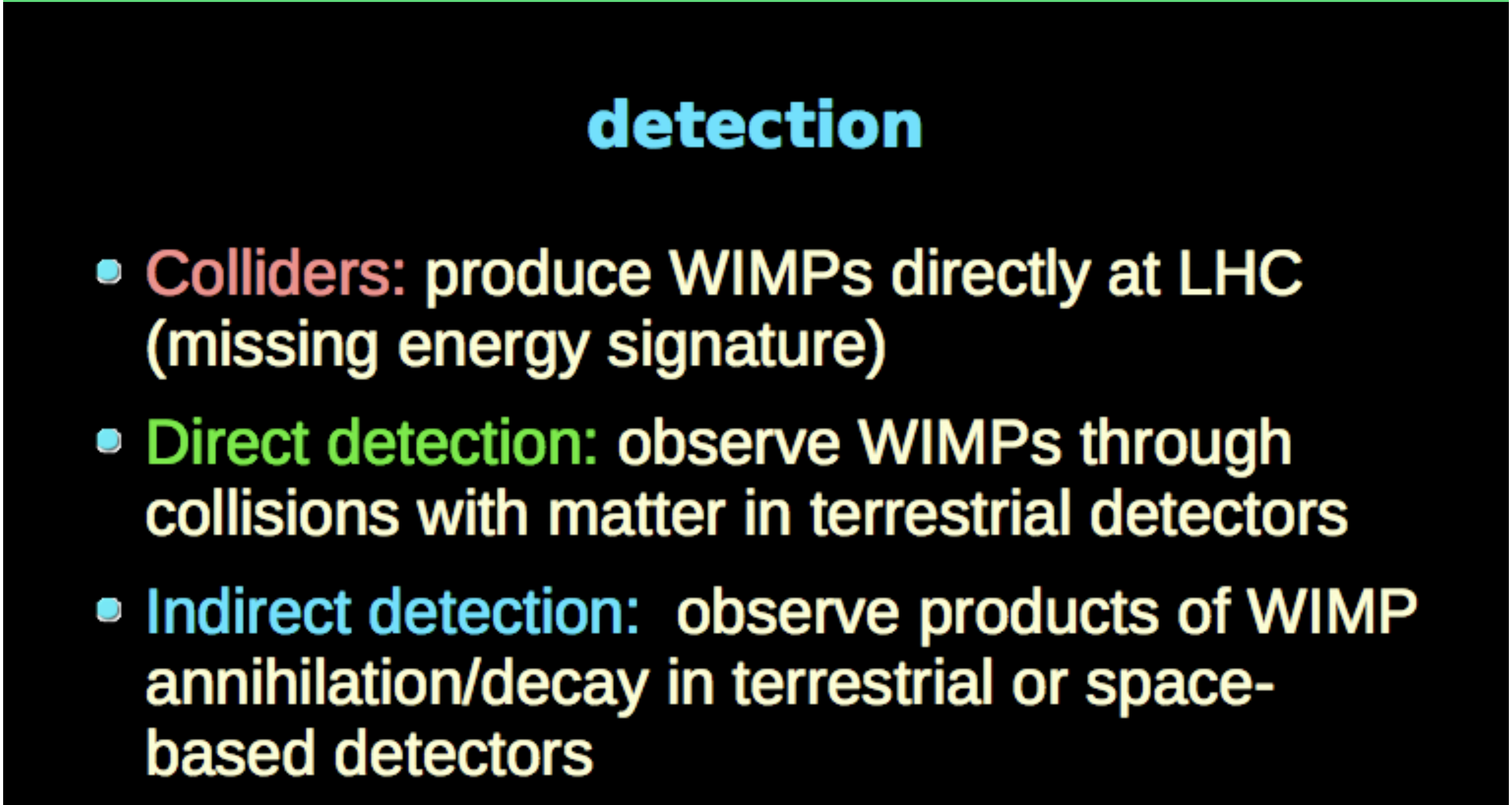
- The annihilation rate comes purely from particle physics and automatically gives the right answer for the relic density!

$$\Omega_\chi h^2 = \frac{3\times 10^{-27}\ cm^3/\mathrm{sec}}{<\sigma v>_{ann}}$$

This is the mass fraction of WIMPs today, and gives the right answer (23%) if the dark matter is weakly interacting

WIMP mass: GeV – 10 TeV

Three Pronged Approach to WIMP detecton

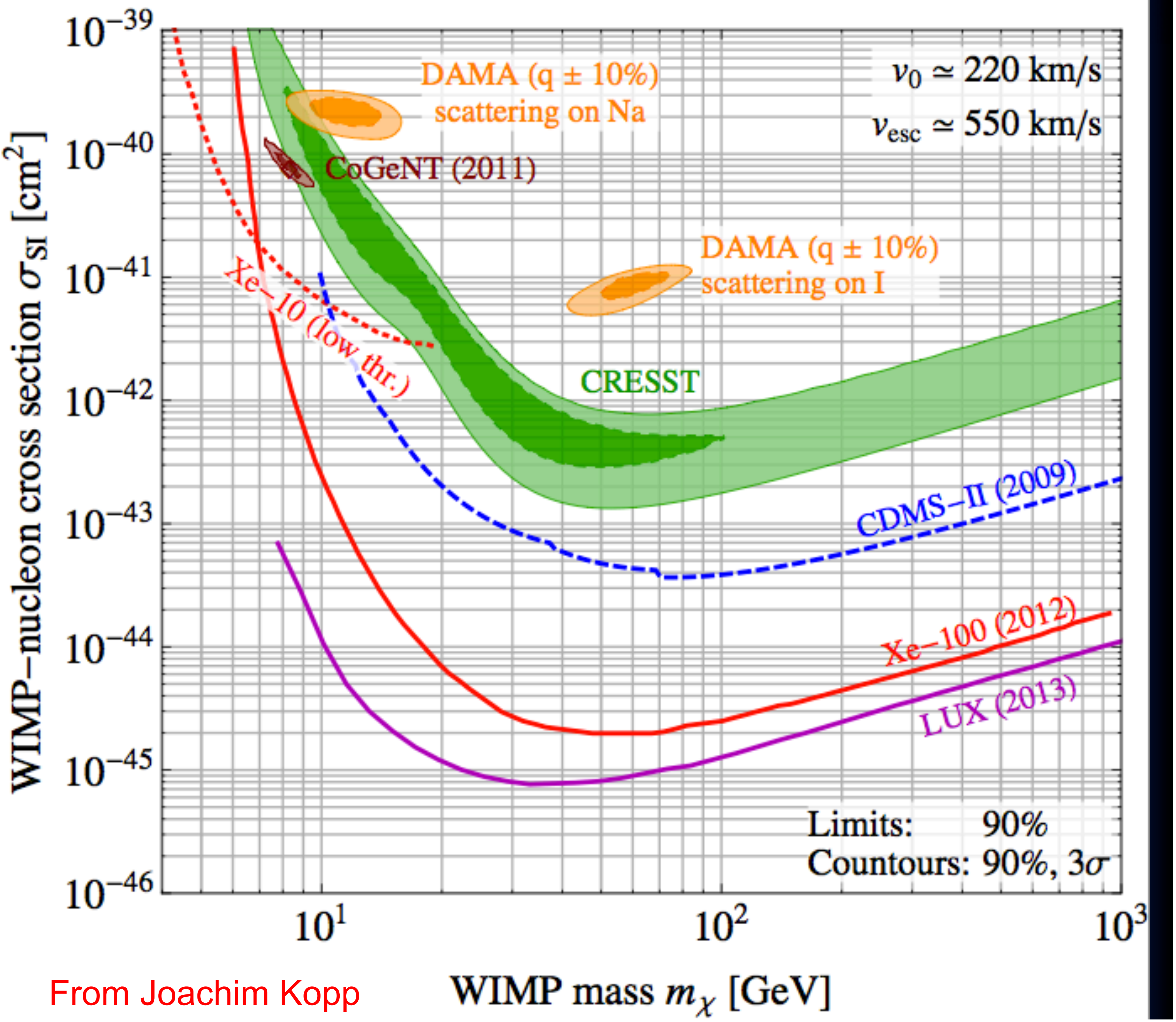


detection

- **Colliders:** produce WIMPs directly at LHC (missing energy signature)
- **Direct detection:** observe WIMPs through collisions with matter in terrestrial detectors
- **Indirect detection:** observe products of WIMP annihilation/decay in terrestrial or space-based detectors

DARK STARS: WIMP annihilation powers the first stars

Assumes Spin-Independend. Scattering i.e. scales as A^2



From Joachim Kopp

Possible evidence for WIMP detection already now:

- Direct Detection:
  - DAMA annual modulation
  - COGENT, CRESST, CMDS-Si (but XENON, LUX)
- Indirect Detection:
  - The HEAT/PAMELA/FERMI positron excess
  - 130 GeV gamma ray line in FERMI
  - FERMI bubble near galactic center
- Theorists are looking for models in which some of these results are consistent with one another (given an interpretation in terms of WIMPs)

Dark Energy

- Experimental: Talk of Bob Kirshner
- Theory: What is it?
- Talk of George Ellis on inhomogeneous Universe as alternative to vacuum energy. Do we live in a 300 Mpc void at a distance of 15 Mpc from the center? Do CMB and kSZ data allow this option to survive?

Looks easy now!

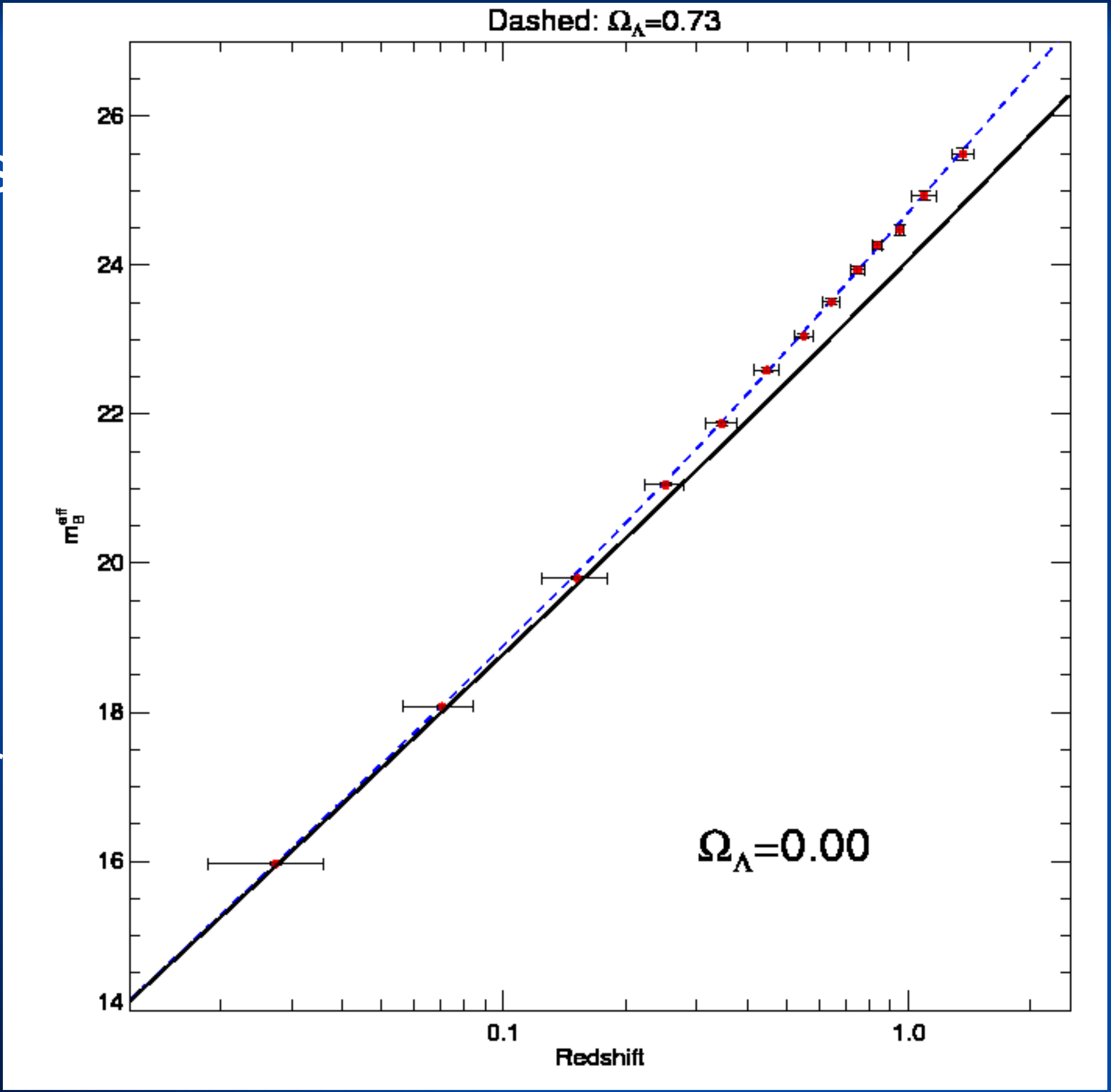
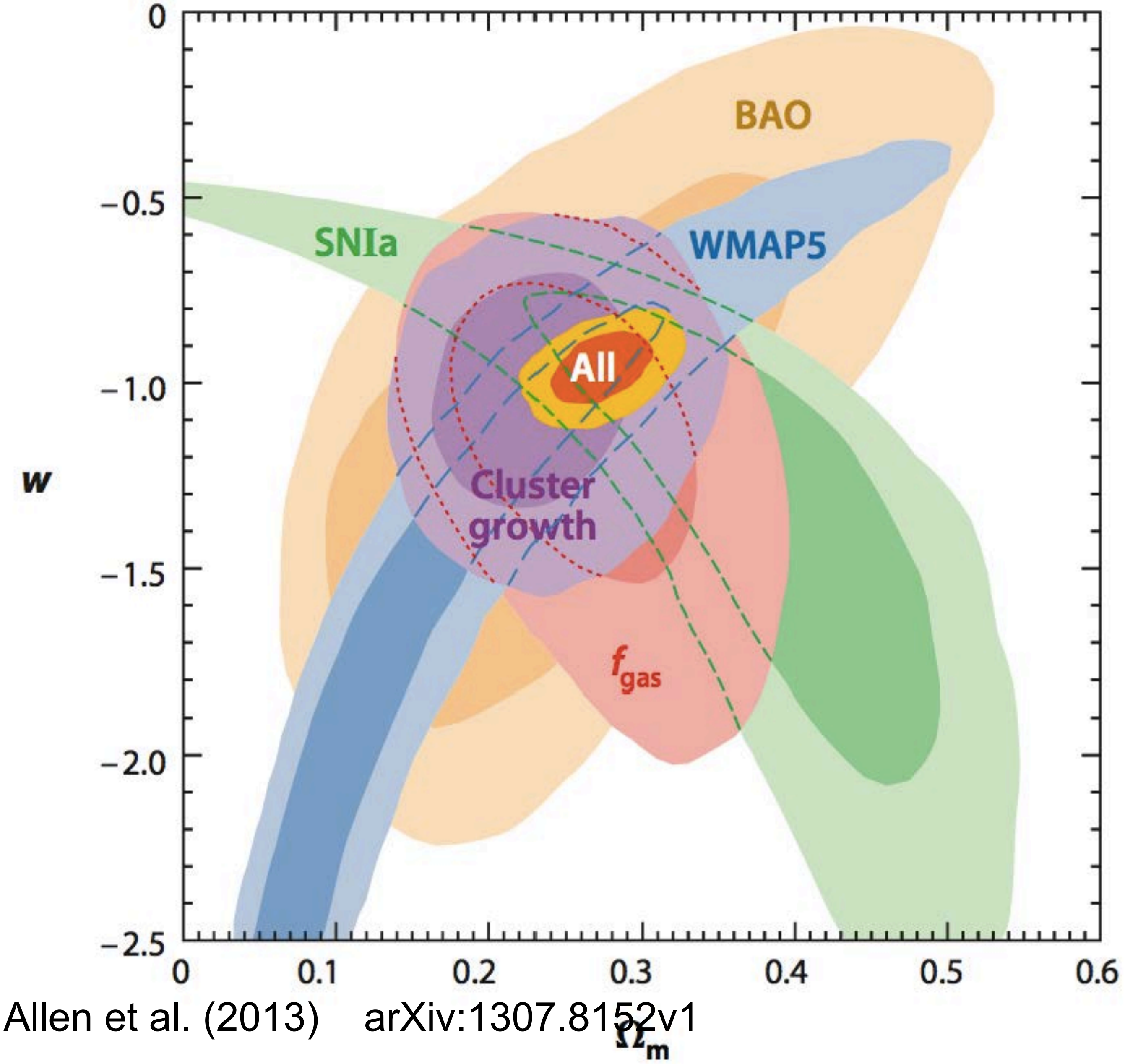


Figure from Ariel Goobar



Allen et al. (2013) arXiv:1307.8152v1

Current and Future missions that will teach us about DE

- DES
- PANSTARRS
- RAISIN (use IR Camera on HST)
- JWST
- EUCLID
- LSST
- GMT
- AFTA/WFIRST

The Role of Texas Relativistic Astrophysics meetings

- Major collaborations between the many types of physicists here can solve these problems:
- The experimental tensions
- The theoretical tensions
- What are the dark matter and dark energy

LOOK FORWARD TO THE NEXT 50 YEARS!!!!