Modern Cosmology

Ed Copeland -- Nottingham University

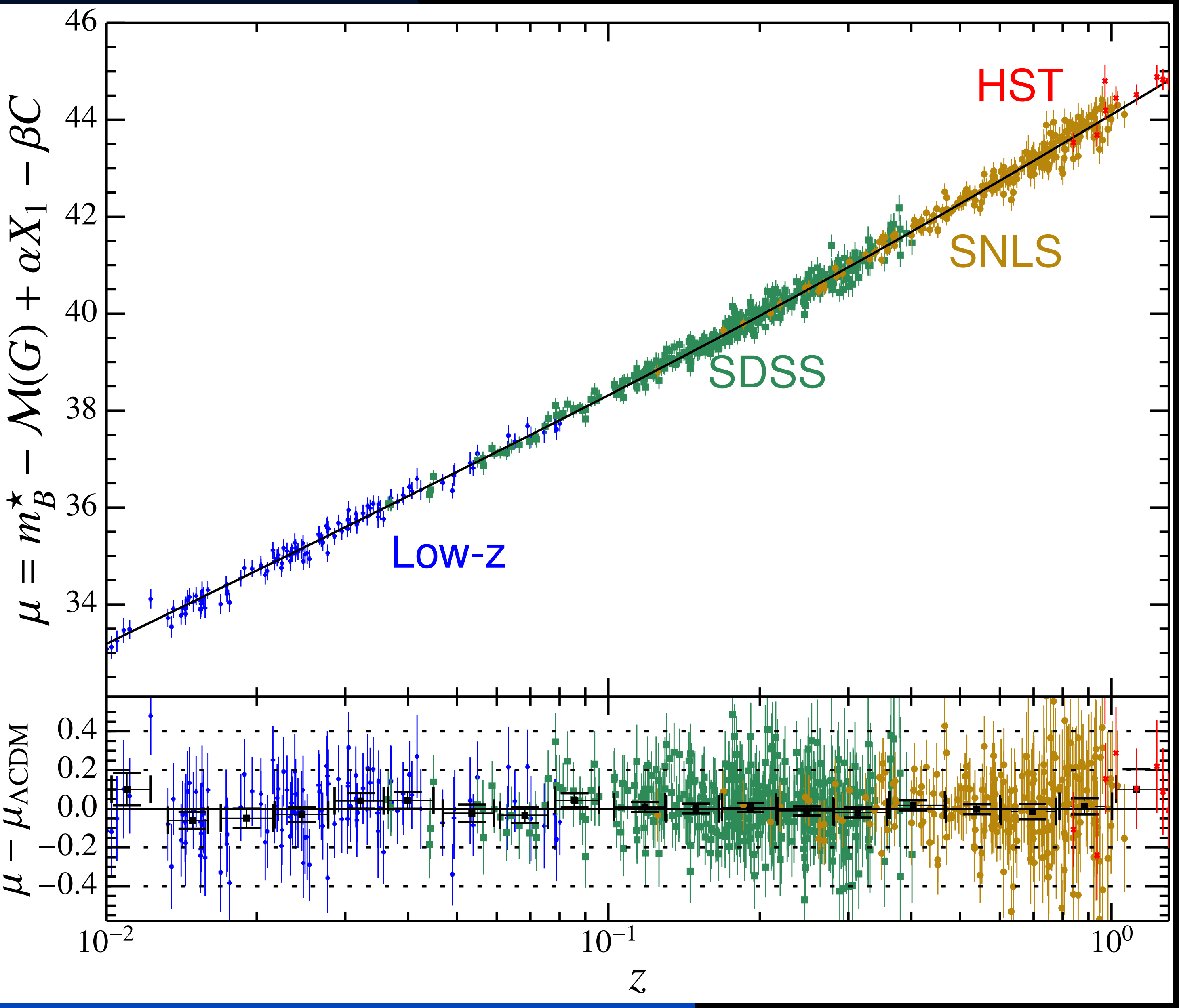
1. The general picture, evolution of the universe: assumptions and evidence supporting them.
2. Dark Energy - Dark Matter - Modified Gravity
3. Theory - Inflation, CCP, Dark Energy.
4. Future - Euclid, GW, ELTs, SKA

June 21st 2016 -- NAM-- Nottingham

1. The Big Bang – (1sec → today)

The cosmological principle -- isotropy and homogeneity on large scales

Test 1



Betoule et al 2014

- **The expansion of the Universe**

$v=H_0d$

H_0=73.02±1.79 km s^{-1} Mpc^{-1}

(Riess et al, 2016)

H_0=67.3±0.7 km s^{-1} Mpc^{-1}

(Planck, 2015)

Is there a local v global difference emerging in **H_0** ?

$$\text{Redshift } 1 + z = \frac{a_0}{a} \qquad H = \frac{\dot{a}}{a}$$

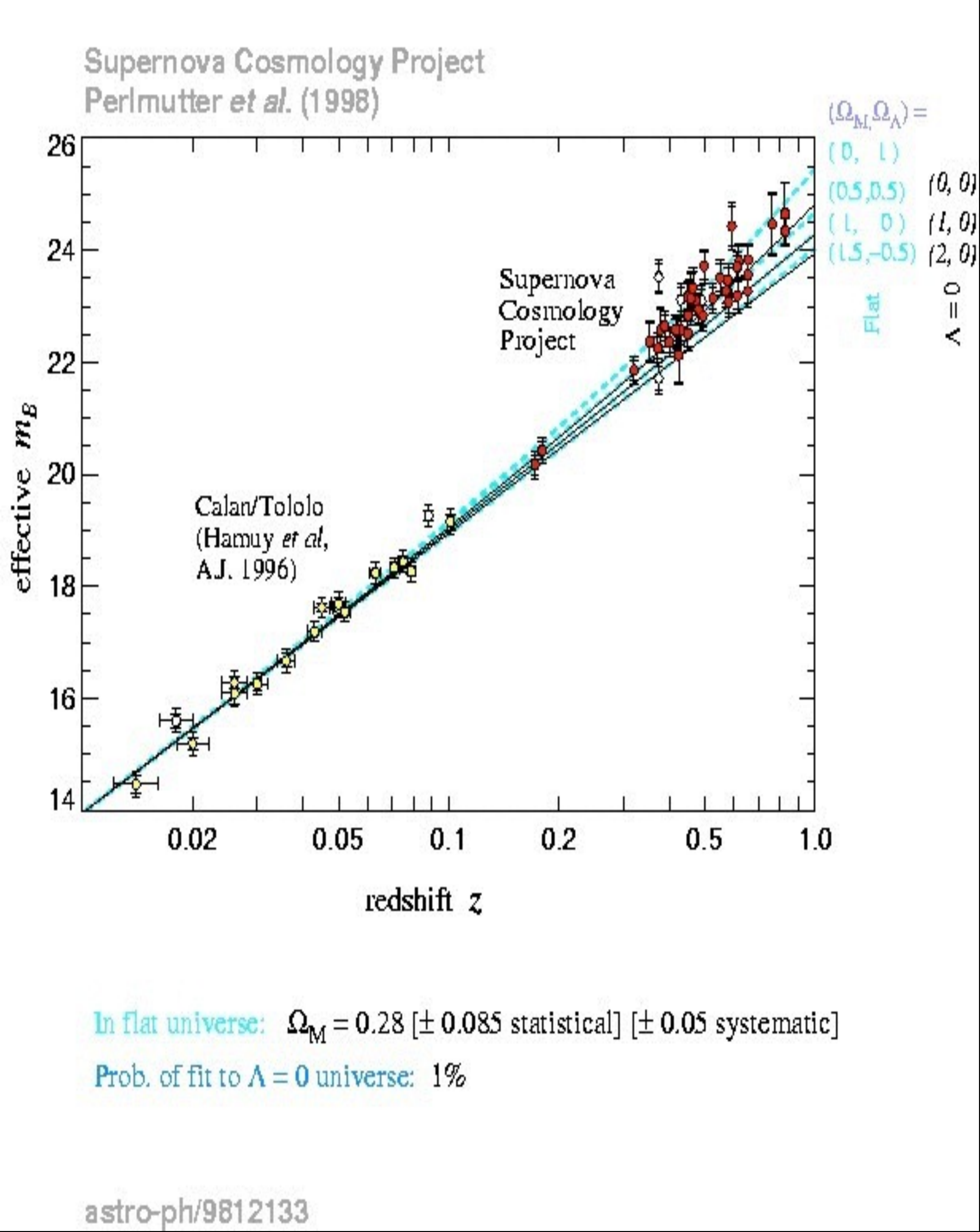
In fact the universe is accelerating !

Observations of distant supernova in galaxies indicate that the rate of expansion is increasing !

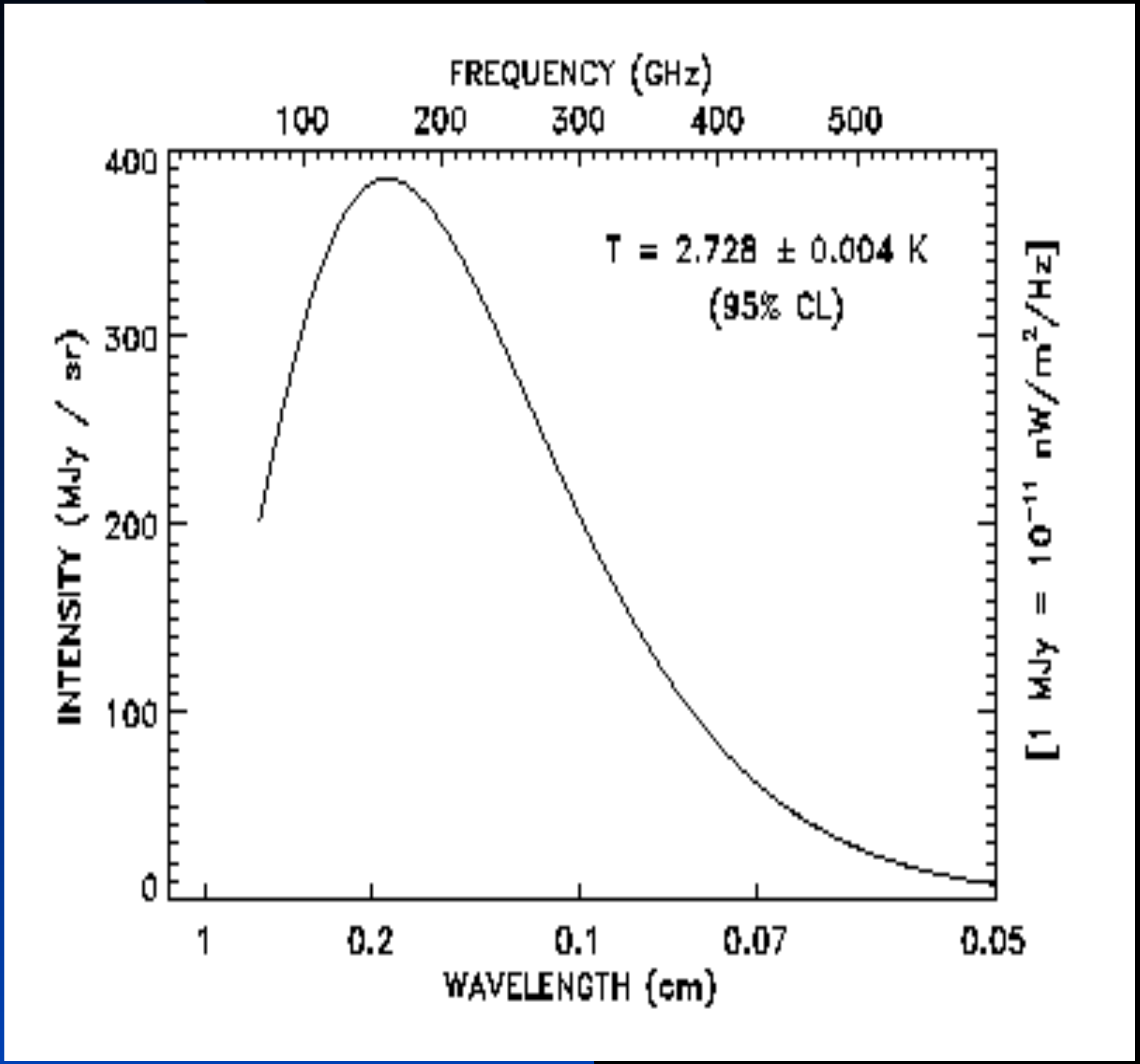
Huge issue in cosmology -- what is the fuel driving this acceleration?

We call it Dark Energy -- emphasises our ignorance!

Makes up 70% of the energy content of the Universe



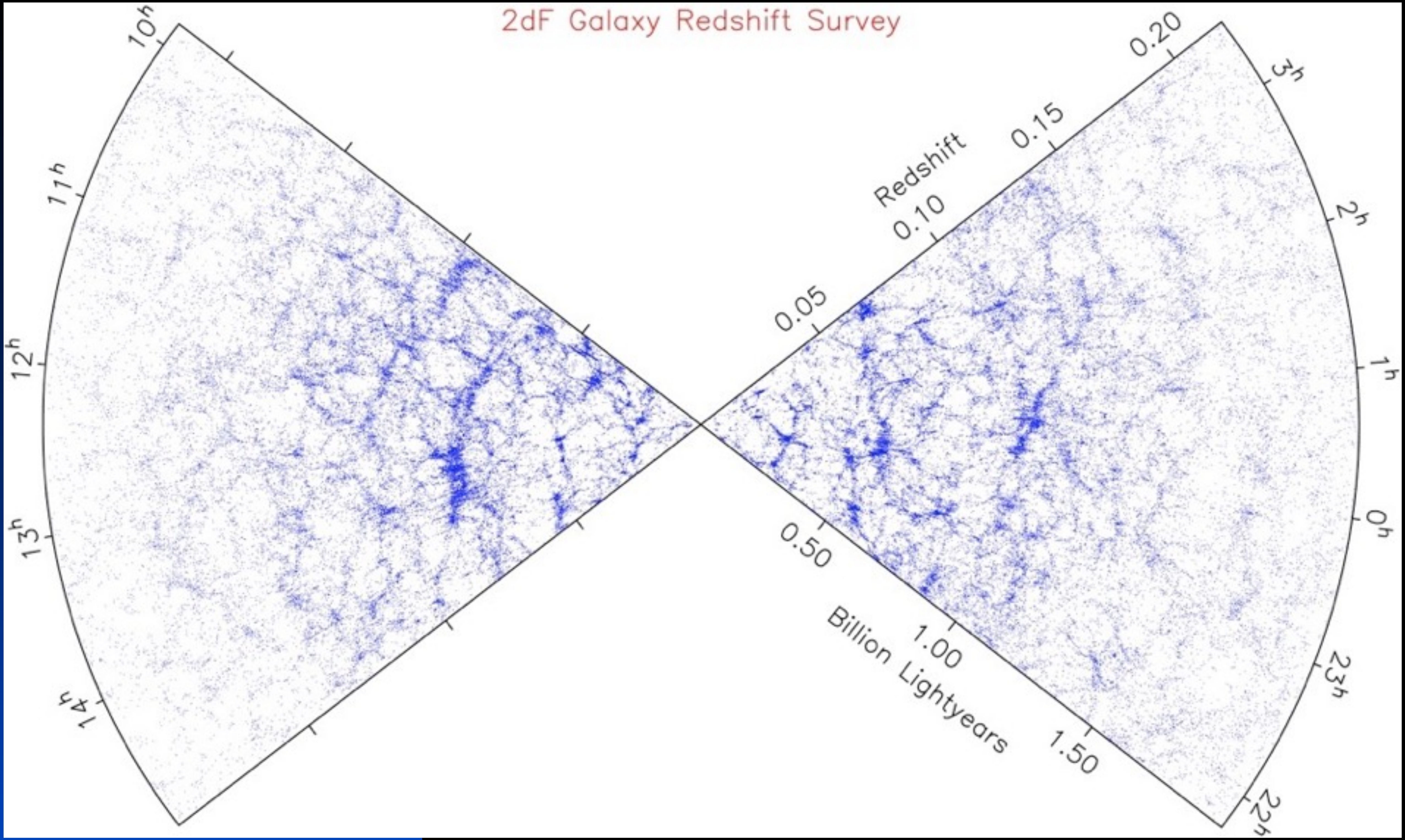
The Big Bang – (1sec → today)



Test 2

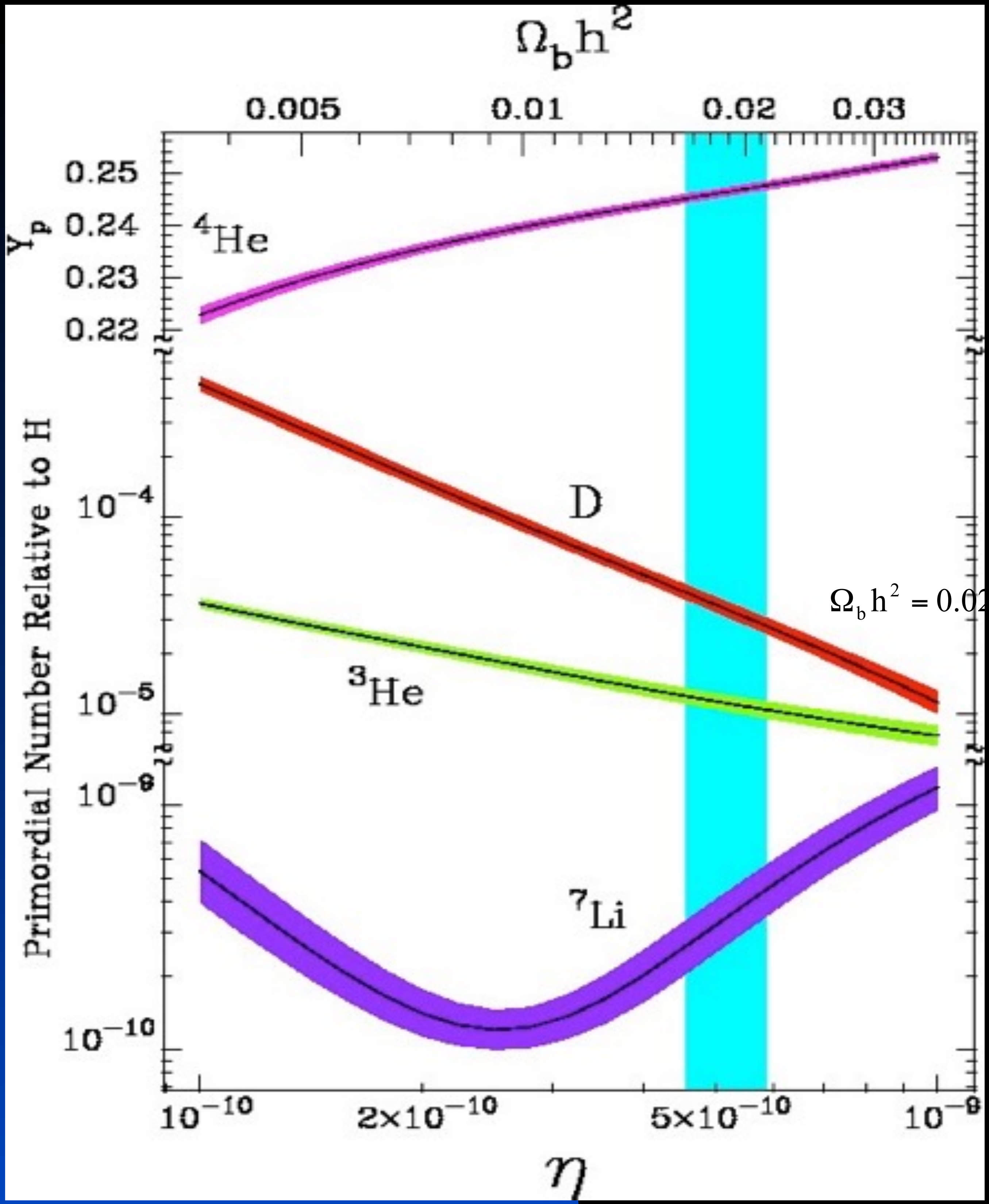
- **The existence and spectrum of the CMBR**
- **T_0=2.728 ± 0.004 K**
- Evidence of isotropy -- detected by COBE to such incredible precision in 1992
- Nobel prize for John Mather 2006

2dF Galaxy Redshift Survey



Homogeneous on large scales?

The Big Bang – (1sec → today)



$\Omega_b h^2 = 0.0$

Test 3

- **The abundance of light elements in the Universe.**
- **Most of the visible matter just hydrogen and helium.**

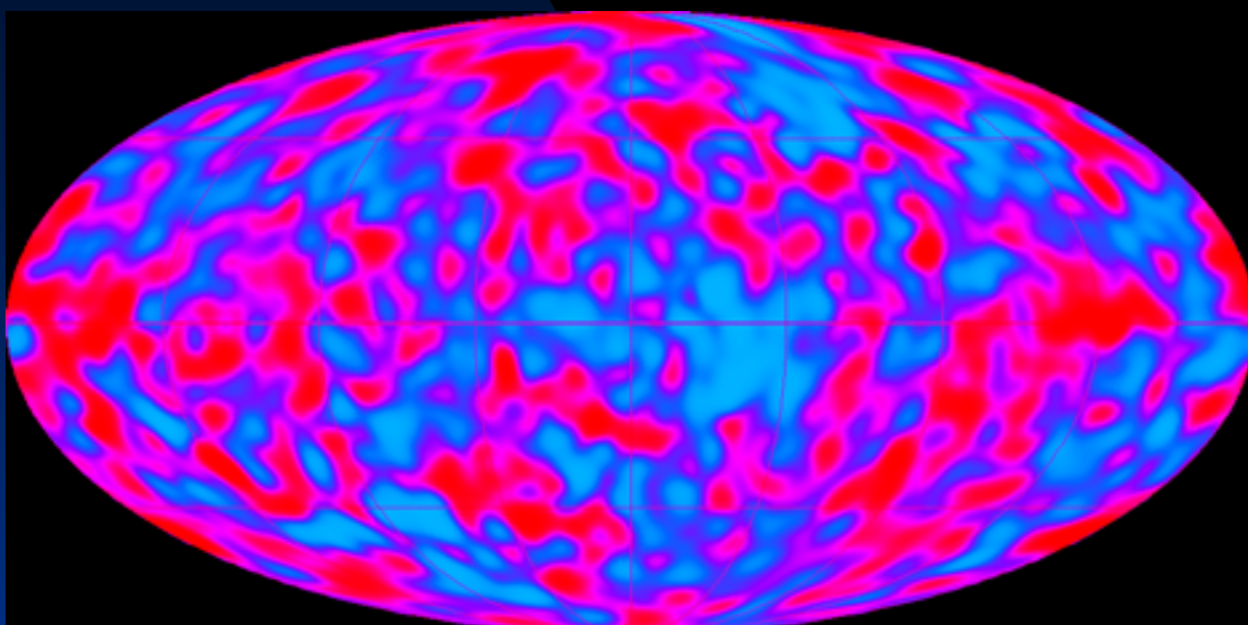
$$\Omega_b h^2 = 0.02207 \pm 0.00033 \ (68\% \ \mathrm{CL})$$

Planck 2013

The Big Bang – (1sec → today)

Test 4

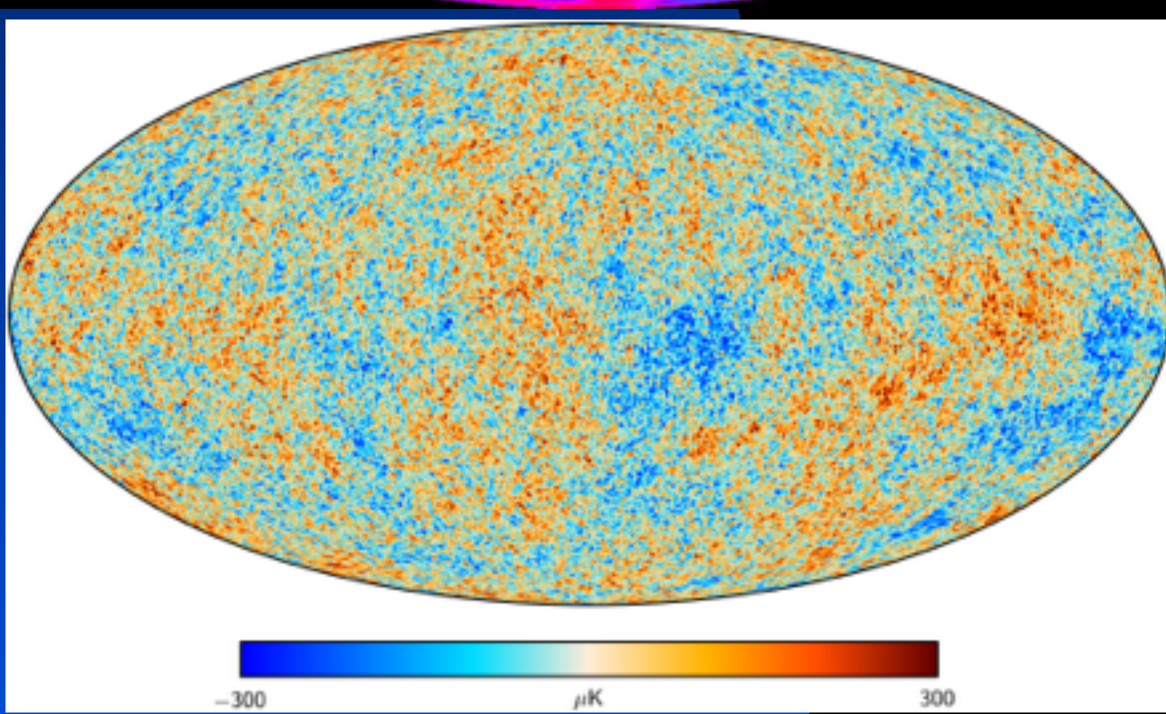
- Given the irregularities seen in the CMBR, the development of structure can be explained through gravitational collapse.



COBE - 1992, 2006

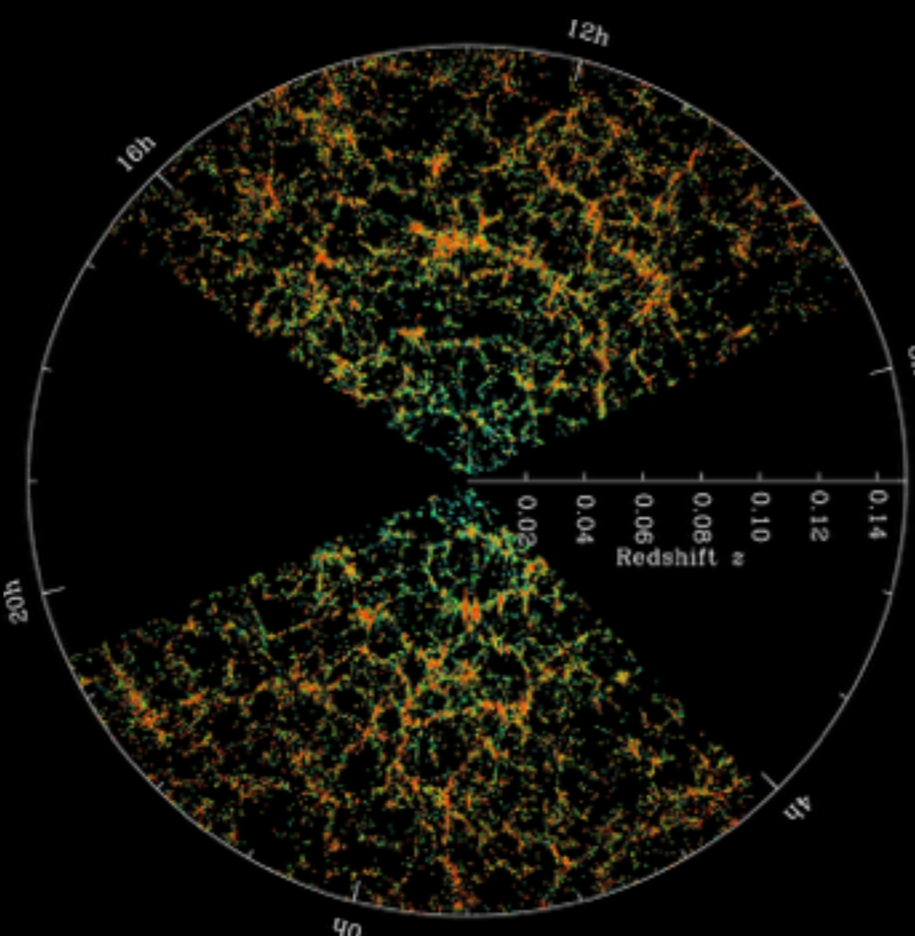
Nobel prize for

George Smoot



PLANCK-2015

SDSS



$$G_{\mu\nu} = 8\pi G T_{\mu\nu} - \Lambda g_{\mu\nu}$$ applied to cosmology

Friedmann:

$$H^2 \equiv \frac{\dot{a}^2}{a^2} = \frac{8\pi}{3} G\rho - \frac{k}{a^2} + \frac{\Lambda}{3}$$

a(t) depends on matter, $\rho(t)=\Sigma_i \rho_i$ -- sum of all matter contributions, rad, dust, scalar fields ...

$$\text{Energy density } \rho(t): \quad \text{Pressure } p(t)$$

$$\text{Related through}: p = w\rho$$

Eqn of state parameters: w=1/3 – Rad dom: w=0 – Mat dom: w=-1– Vac dom

Eqns (Λ=0):

Friedmann + Fluid energy conservation

$$H^2 \equiv \frac{\dot{a}^2}{a^2} = \frac{8\pi}{3} G\rho - \frac{k}{a^2}$$

$$\dot{\rho} + 3(\rho + p)\frac{\dot{a}}{a} = 0$$

$$\nabla^\mu T_{\mu\nu} = 0$$

Combine Friedmann and fluid equation to obtain Acceleration equation:

$$\boxed{\frac{\ddot{a}}{a} = -\frac{8\pi}{3} G\left(\rho + 3p\right) - - - Accn}$$

$$\boxed{If\ \ \rho + 3p < 0 \Rightarrow \ddot{a} > 0}$$

Inflation condition -- true today !

$$H^2 \equiv \frac{\dot{a}^2}{a^2} = \frac{8\pi}{3} G\rho - \frac{k}{a^2}$$

$$\dot{\rho} + 3(\rho + p)\frac{\dot{a}}{a} = 0$$

$$\rho(t) = \rho_0 \left(\frac{a}{a_0}\right)^{-3(1+w)} \quad ; a(t) = a_0 \left(\frac{t}{t_0}\right)^{\frac{2}{3(1+w)}}$$

$$\mathrm{RD} \quad : \quad w = \frac{1}{3} : \rho(t) = \rho_0 \left(\frac{a}{a_0}\right)^{-4} \quad ; \ a(t) = a_0 \left(\frac{t}{t_0}\right)^{\frac{1}{2}}$$

$$\mathrm{MD} \quad : \quad w = 0 : \rho(t) = \rho_0 \left(\frac{a}{a_0}\right)^{-3} \quad ; \ a(t) = a_0 \left(\frac{t}{t_0}\right)^{\frac{2}{3}}$$

$$\mathrm{VD} \quad : \quad w = -1 : \rho(t) = \rho_0 \ \ ; \ a(t) \propto e^{Ht}$$

A neat equation

$$\rho_c(t) \equiv \frac{3H^2}{8\pi G} \quad ; \quad \Omega(t) \equiv \frac{\rho}{\rho_c}$$

$$\Omega > 1 \leftrightarrow k = +1$$

$$\Omega = 1 \leftrightarrow k = 0$$

$$\Omega < 1 \leftrightarrow k = -1$$

Friedmann eqn

$$\Omega_m + \Omega_\Lambda + \Omega_k = 1$$

Ω_m - baryons, dark matter, neutrinos, electrons, radiation ...

Ω_Λ - dark energy ; Ω_k - spatial curvature

$$\rho_c(t_0) \equiv 1.88h^2 * 10^{-29}\,\mathrm{gcm}^{-3}$$

Critical density

Bounds on H(z) -- Planck 2015 - (+BAO+lensing+lowP)

$$\mathbf{H^2(z) = H_0^2\left(\Omega_r(1+z)^4 + \Omega_m(1+z)^3 + \Omega_k(1+z)^2 + \Omega_{\rm de}\exp\left(3\int_0^z \frac{1+w(z')}{1+z'}dz'\right)\right)}$$

(Expansion rate) -- H_0=67.8 ± 0.9 km/s/Mpc

(radiation) -- Ω_r = (8.5 ± 0.3) x 10^{-5} - (WMAP)

(baryons) -- $\Omega_b h^2$= 0.02226 ± 0.00023

(dark matter) -- $\Omega_c h^2$= 0.1186 ± 0.0020 —-(matter) - Ω_m = 0.308 ± 0.0013

(curvature) -- Ω_k =0.000 ± 0.005 (95%CL)

(dark energy) -- Ω_{de} = 0.692 ± 0.012 -- Implying univ accelerating today

(de eqn of state) -- 1+w = 0.006 ± 0.045 -- looks like a cosm const.

If allow variation of form : $w(z) = w_0 + w' z/(1+z)$ then
w_0=-0.93 ±0.12 and w'=-0.38 ± 0.65 (68% CL) — (WMAP)

Important because distance measurements often rely on assumptions made about the background cosmology.

Weighing the Universe

$$\Omega_m + \Omega_\Lambda + \Omega_k = 1$$

$1.\ \Omega_m$

a. Cluster baryon abundance using X-ray measurements of intracluster gas, or SZ measurements.

b. Weak grav lensing and large scale peculiar velocities.

c. Large scale structure distribution.

d. Numerical simulations of cluster formation.

e. Cosmic Microwave Background Anisotropies

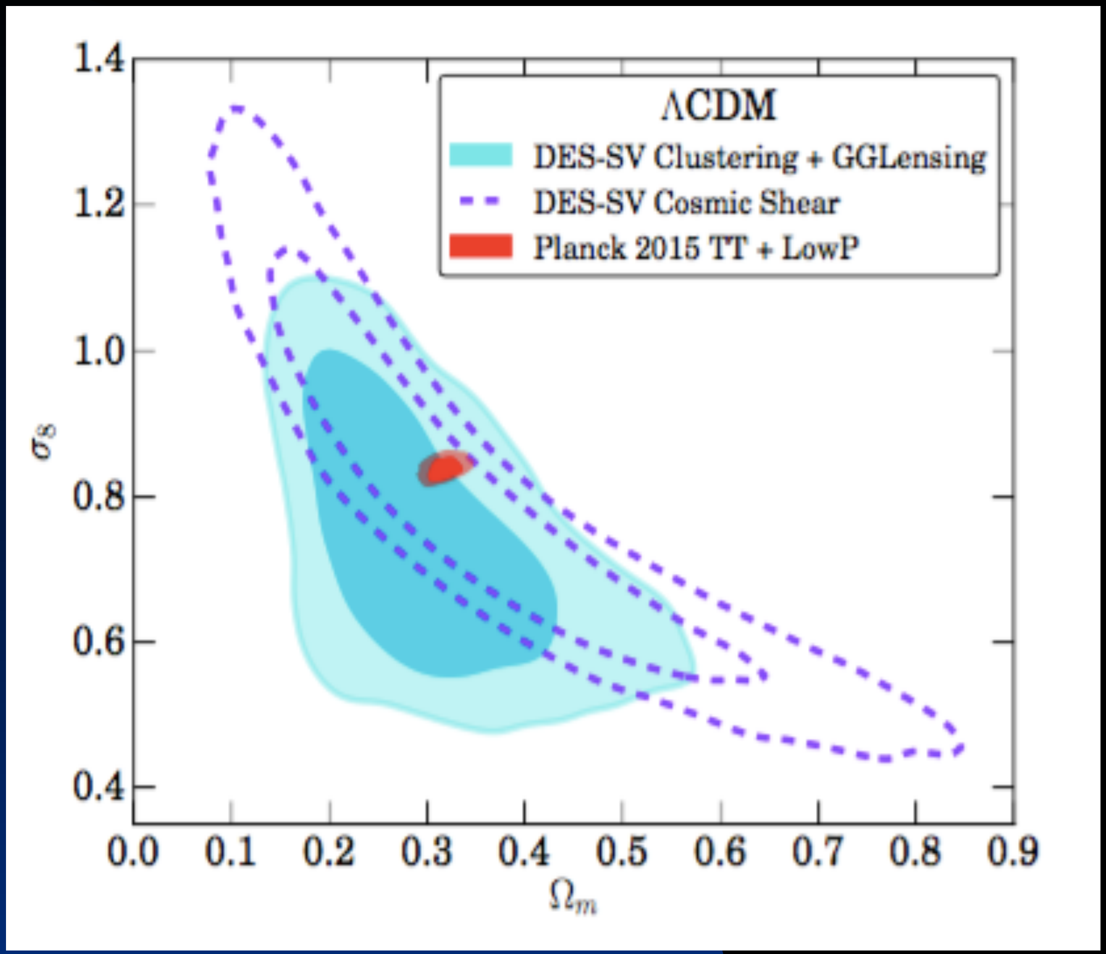
$\Omega_m = 0.308 \pm 0.0013$

(Planck 2015)

$\Omega_m << 1$

$H_0 = 67.8 \pm 0.9$ km s^{-1} Mpc^{-1}

Testing ΛCDM with DES

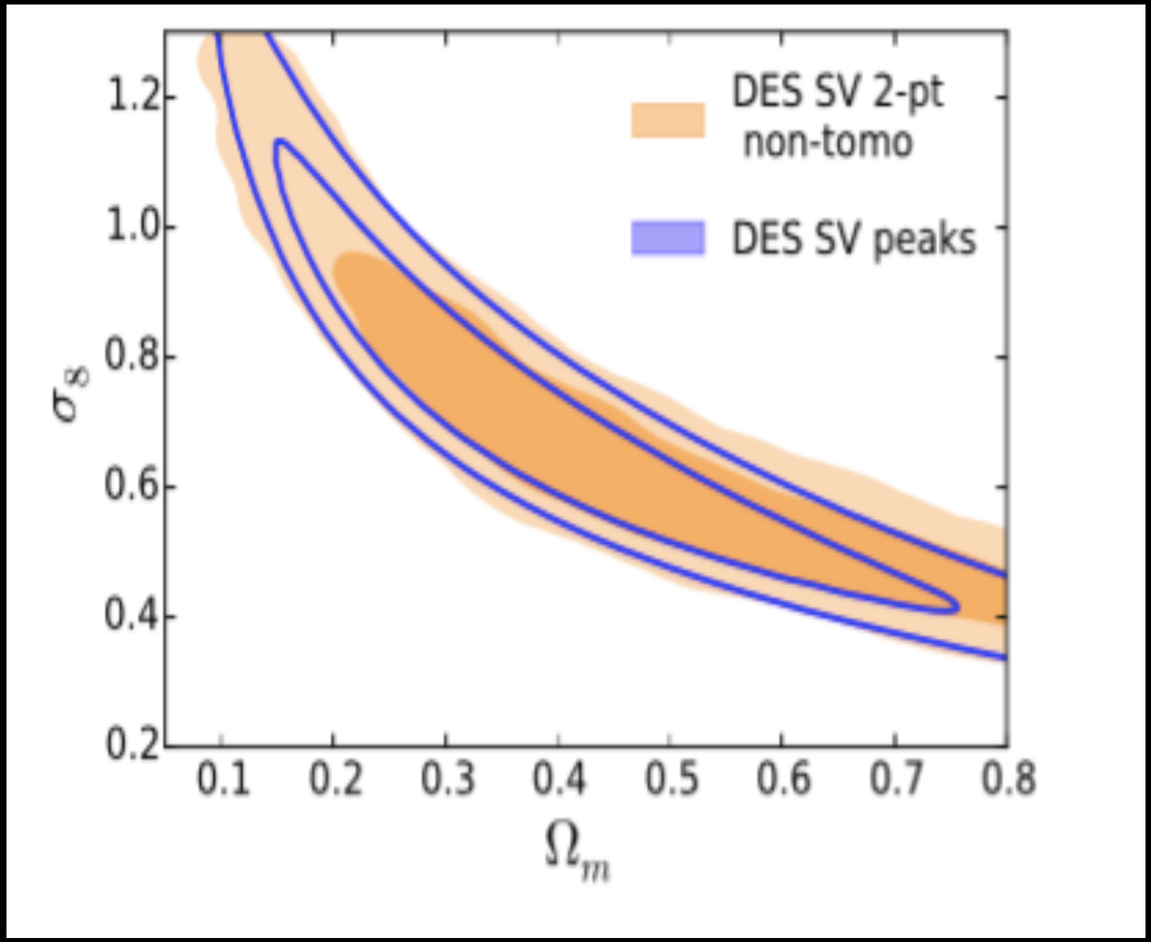


Kwan et al. 1604.07871
DES Collaboration 1507.05552 - Dashed line

Combined analysis of angular clustering of red galaxies and their cross-correlation with weak gravitational lensing of bgd galaxies.

$$\Omega_{\rm m} = 0.31 \pm 0.09$$

$$\sigma_8 = 0.74 \pm 0.13$$

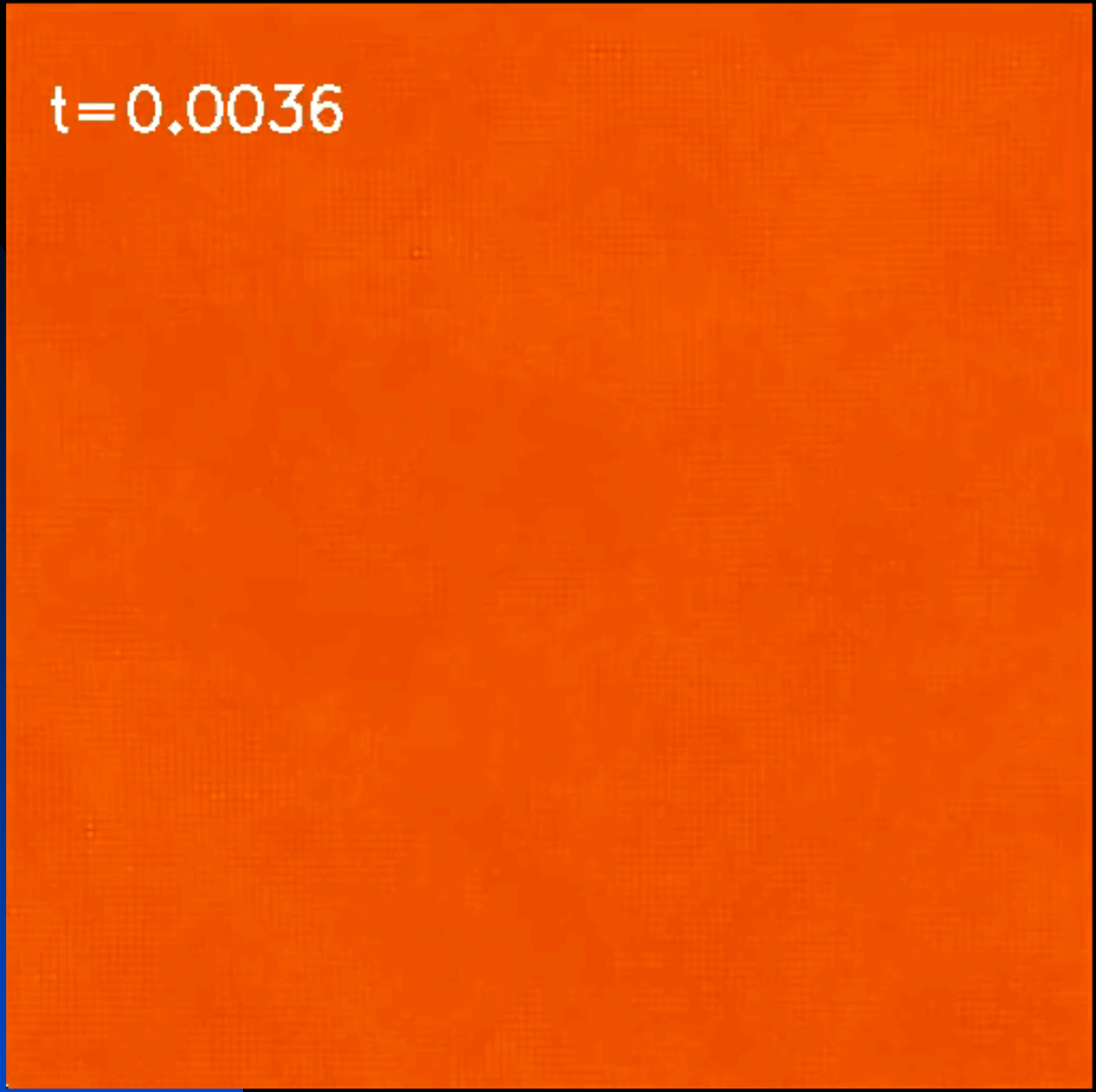


Kacprzak et al. 1603.05040

Shear peak statistics analysis of DES (SV) data, using weak gravitational lensing measurements from a 139 deg field. Compare to predicted peak counts as a function of cosmological parameters from suite of N-body simulations spanning 158 models with varying Ω_m and σ_8 fixing w=-1, h=0.7, Ω_b=0.04 and n_s=1.

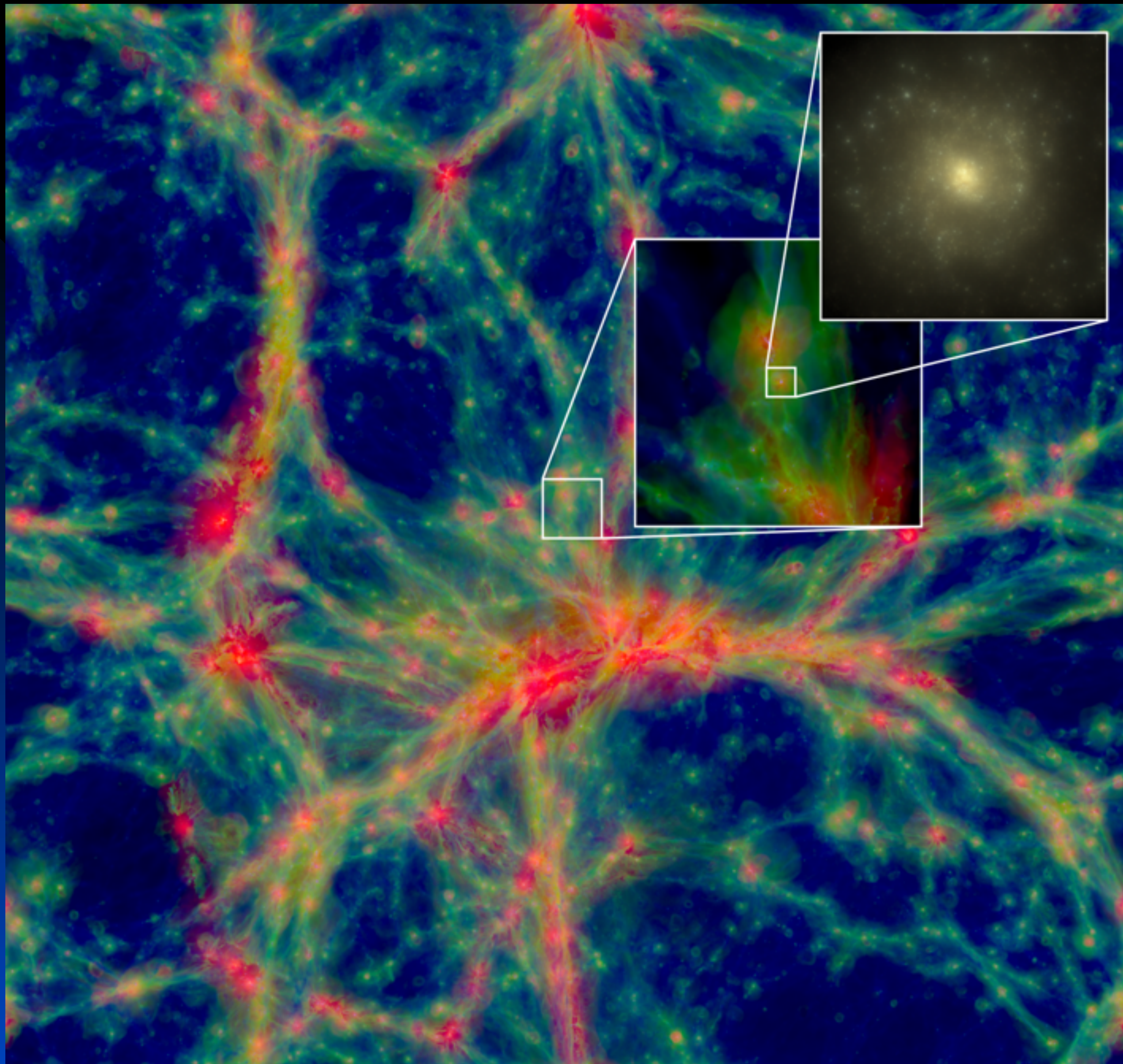
$$\sigma_8(\Omega_{\rm m}/0.3)^{0.6} = 0.77 \pm 0.07$$

Simulations are key elements in our ability to determine cosmologies



Virgo Consortium

The evolution of a 50 Mpc ΛCDM cube showing the formation of two cluster sized dark matter halos



EAGLE Project
Virgo Consortium

Simulation aimed at understanding how Galaxies form and evolve. Models formation of structure in volume 100Mpc on a side, over 10,000 Milky Way size galaxies enabling comparison with Hubble Deep Field Distribution.

$2. \Omega_b$ $\xrightarrow{\text{BBN}}$ $\Omega_b h^2 = 0.02226 \pm 0.00023$

Majority of baryonic matter dark.

$\Omega_b << \Omega_m$ → **Require Dark matter !!**

Candidates: WIMPS (Neutralinos, Kaluza Klein Particles, Universal Extra Dimensions...)

Axinos, Axions, Axion-like light bosons, Sterile neutrinos, Q-balls, WIMPzillas, Elementary Black Holes...

Search for them is on:

1. Direct detection -- 20 expts worldwide

2. Indirect detection -- i.e. Bullet Cluster !

3. LHC -- i.e. missing momentum and energy

Summary of current status:

Various 'hints':

excesses above expected backgrounds (CoGeNT, CDMS-Si)

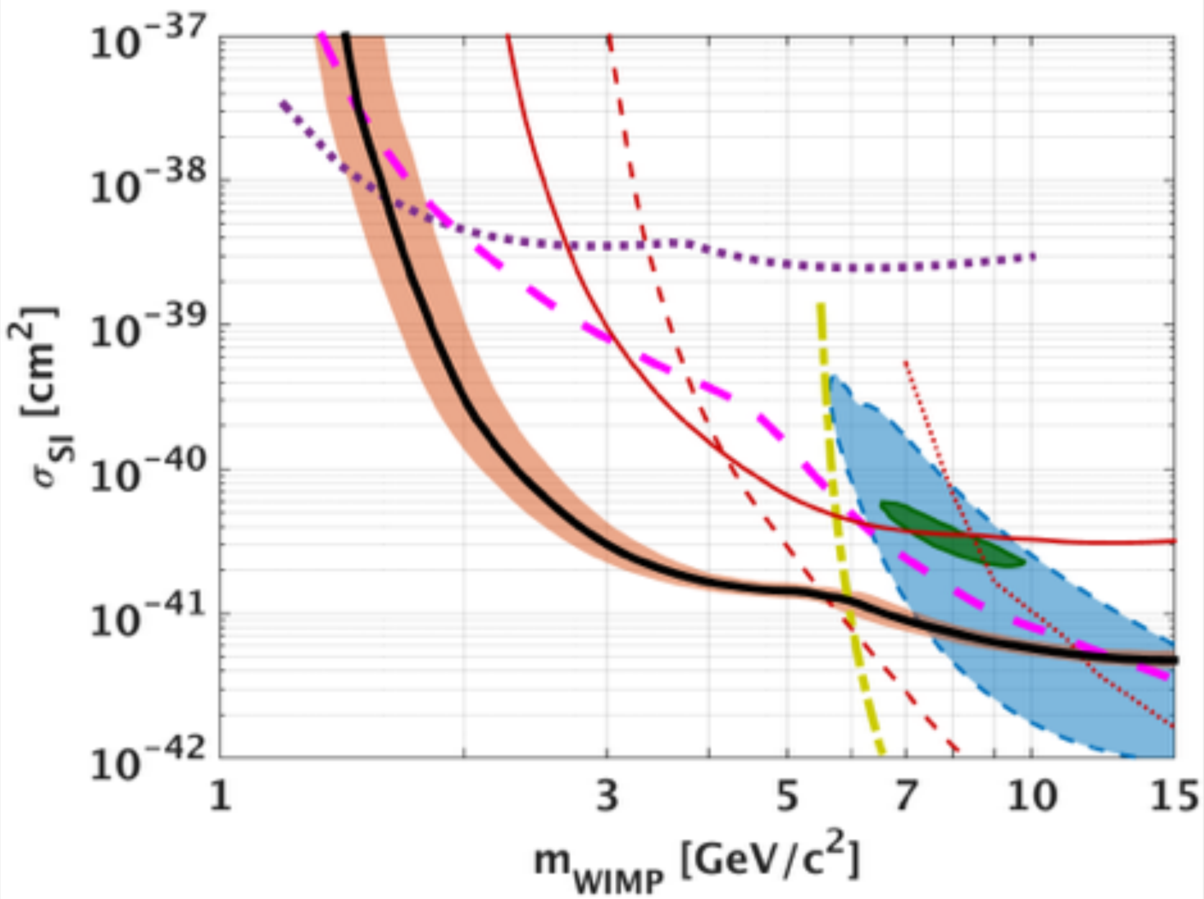
annual modulations (DAMA-LIBRA, CoGeNT)

which can individually be interpreted in terms of light (~10 GeV) WIMPs.

BUT

Hints are incompatible with each other and also null results from CDMSlite, CRESST (- -), LUX (- - -), SuperCDMS (- - - -).

WIMP-proton cross-section (cm^2)

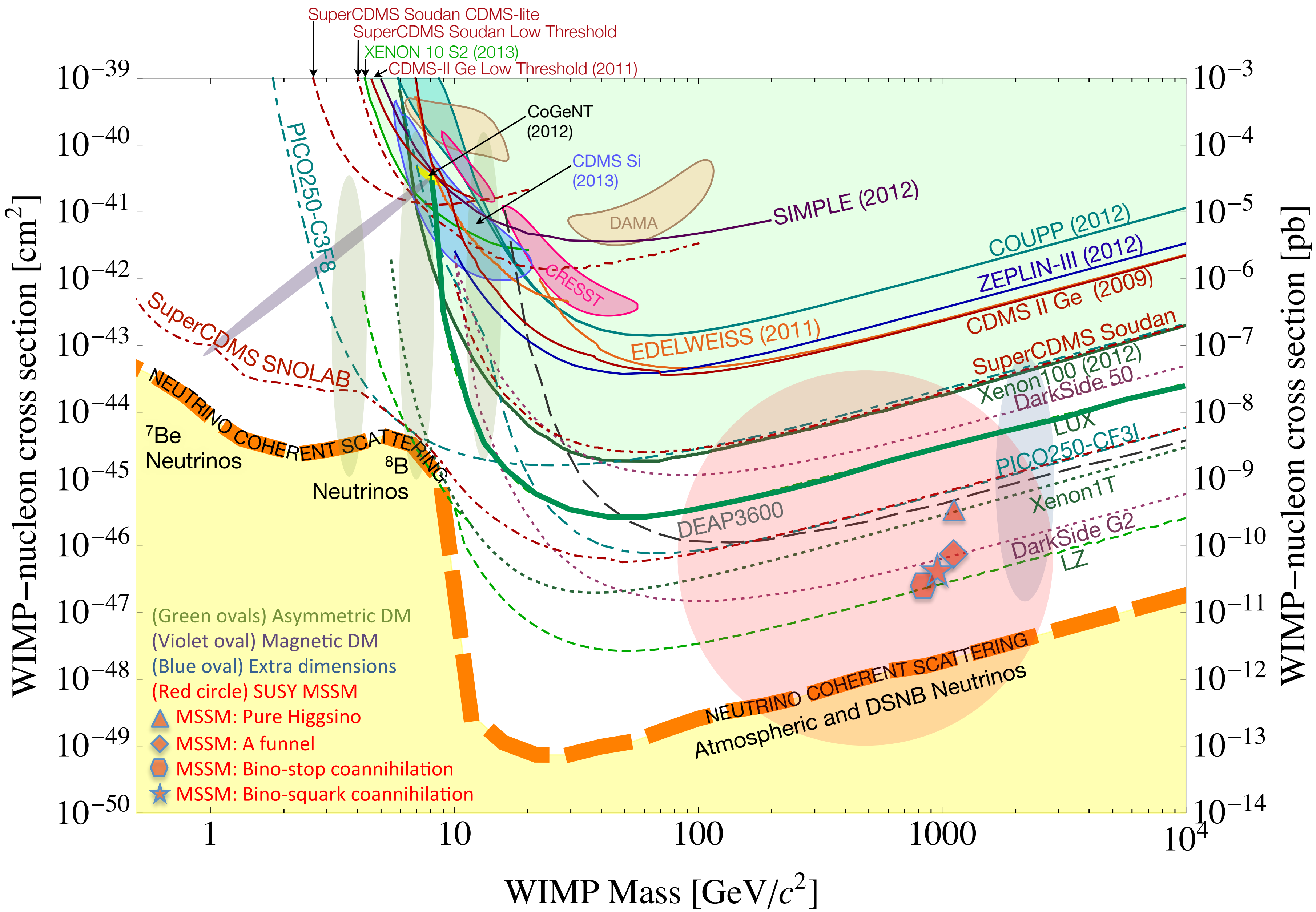


WIMP mass (GeV)

[CDMSlite]

Future prospects:

Upgrades of current experiments to the multi-tonne scale, improving sensitivity by up to 3 orders of magnitude.
(e.g. DARWIN, EURECA, LUX-Zeplin, SuperCDMS)



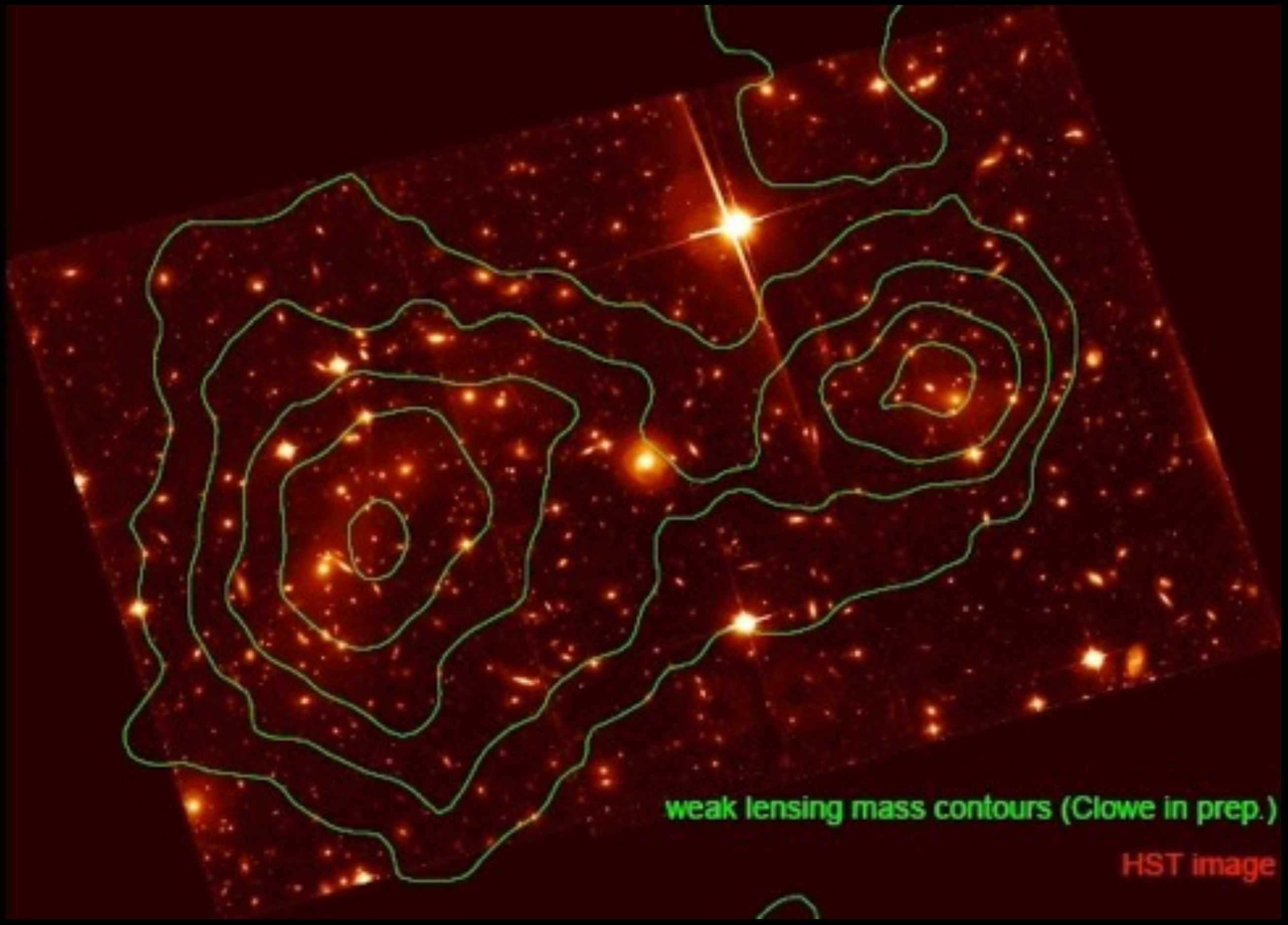
[Snowmass CF1 WG]

Indirect evidence for Dark Matter -- Bullet Cluster

Two clusters of galaxies colliding.

Dark matter in each pass straight through and doesn't interact -- seen through weak lensing in right image.

Ordinary matter in each interacts in collision and heats up -- seen through infra red image on left.



Clowe et al 2006

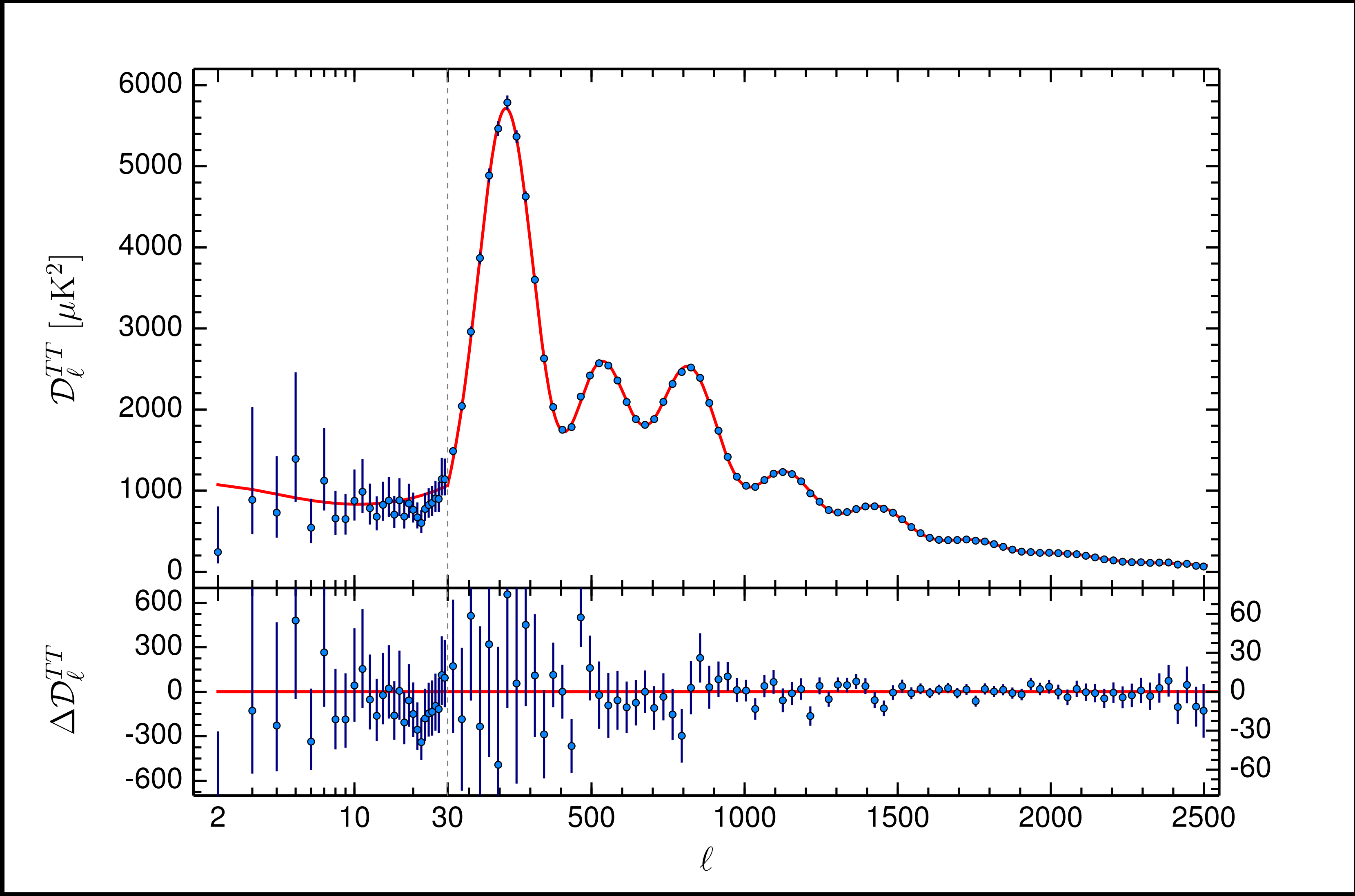
Evidence for Dark Energy?

Enter CMBR:

$$3. \Omega_0 = \Omega_m + \Omega_\Lambda$$

Provides clue. 1st angular peak in power spectrum.

$$l_{\text{peak}} \approx \frac{220}{\sqrt{\Omega_0}}$$



Planck TT spectrum (2015)

$$\Omega_k = 0.000 \pm 0.005 \text{ (95\% CL)}$$

Planck + Lensing+ BAO consortium 2015

Dark Energy

Parameterise eos: $$w(a) \equiv \frac{p}{\rho} = w_0 + (1-a)w_a$$

Planck alone weak constraints on DE because of degeneracy of w with H_0:

Break with other probes including lensing, SN, BAO ...

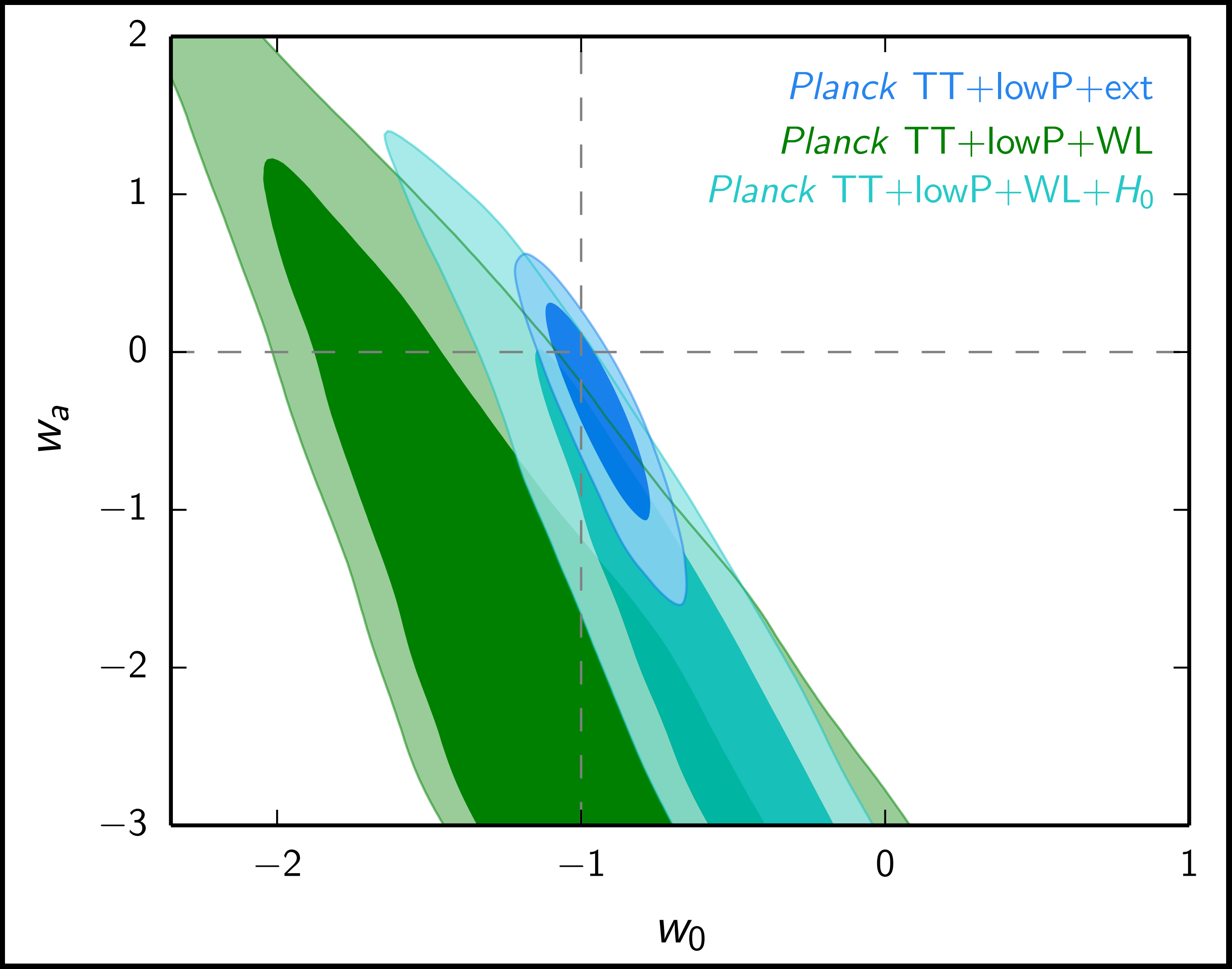
Example - if assume $w_a = 0$, 95% CL

$$w = -1.023^{+0.091}_{-0.096} \quad \textit{Planck}\ \mathrm{TT{+}lowP{+}ext}\,; \qquad ($$

$$w = -1.006^{+0.085}_{-0.091} \quad \textit{Planck}\ \mathrm{TT{+}lowP{+}lensing{+}ext}\,; \qquad ($$

$$w = -1.019^{+0.075}_{-0.080} \quad \textit{Planck}\ \mathrm{TT, TE, EE{+}lowP{+}lensing{+}ext}$$

Planck 2015:



How should we parameterise w?

What is making the Universe accelerate?

Dark energy -- a weird form of energy that exists in empty space and pervades the universe -- also known as vacuum energy or cosmological constant.

Smoothly distributed, doesn't cluster.

Constant density or very slowly varying

Doesn't interact with ordinary matter -- only with gravity

Big problem though. When you estimate how much you expect there to be, from the Quantum world, the observed amount is far less than expected.

Theoretical prediction = 10^{120} times observation

Different approaches to Dark Energy include amongst many:

A true cosmological constant -- but why this value?

Time dependent solutions arising out of evolving scalar fields -- Quintessence/K-essence.

Modifications of Einstein gravity leading to acceleration today.

Anthropic arguments.

Perhaps GR but Universe is inhomogeneous.

Hiding the cosmological constant -- its there all the time but just doesn't gravitate

Yet to be proposed ...

Early evidence for a cosmological constant type term.

1987: Weinberg argued that anthropically ρ_{vac} could not be too large and positive otherwise galaxies and stars would not form. It should not be very different from the mean of the values suitable for life which is positive, and he obtained $\Omega_{vac} \sim 0.6$

1990: Observations of LSS begin to kick in showing the standard $\Omega_{CDM} = 1$ struggling to fit clustering data on large scales, first through IRAS survey then through APM (Efstathiou et al).

1990: Efstathiou, Sutherland and Maddox - Nature (238) -- explicitly suggest a cosmology dominated today by a cosmological constant with $\Omega_{vac} < 0.8$!

1998: Type Ia SN show striking evidence of cosm const and the field takes off.

The String Landscape approach

Type IIB String theory compactified from 10 dimensions to 4.

Internal dimensions stabilised by fluxes. Assumes natural AdS vacuum uplifted to de Sitter vacuum through additional fluxes !

Many many vacua ~ 10^{500} ! Typical separation ~ $10^{-500}\ \Lambda_{pl}$

Assume randomly distributed, tunnelling allowed between vacua --> separate universes .

Anthropic : Galaxies require vacua < $10^{-118}\ \Lambda_{pl}$ [Weinberg] Most likely to find values not equal to zero!

Landscape gives a realisation of the multiverse picture.

There isn't one true vacuum but many so that makes it almost impossible to find our vacuum in such a Universe which is really a multiverse.

So how can we hope to understand or predict why we have our particular particle content and couplings when there are so many choices in different parts of the universe, none of them special ?

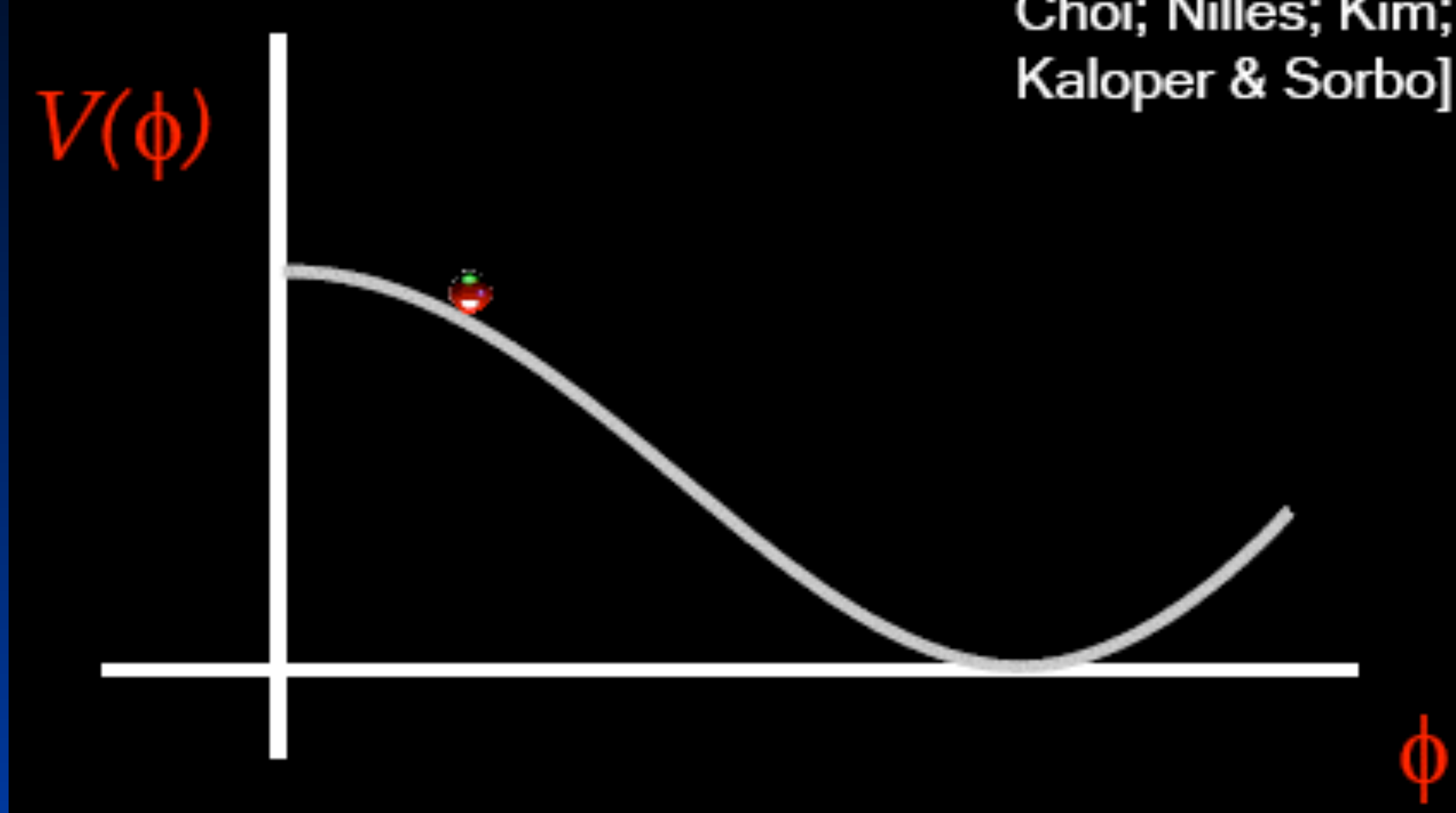
Particle physics inspired models?

Pseudo-Goldstone Bosons -- approx sym ϕ --> ϕ + const.

Leads to naturally small masses, naturally small couplings

[Hill, Freiman, et al; Choi; Nilles; Kim; Kaloper & Sorbo]

Barbieri et al

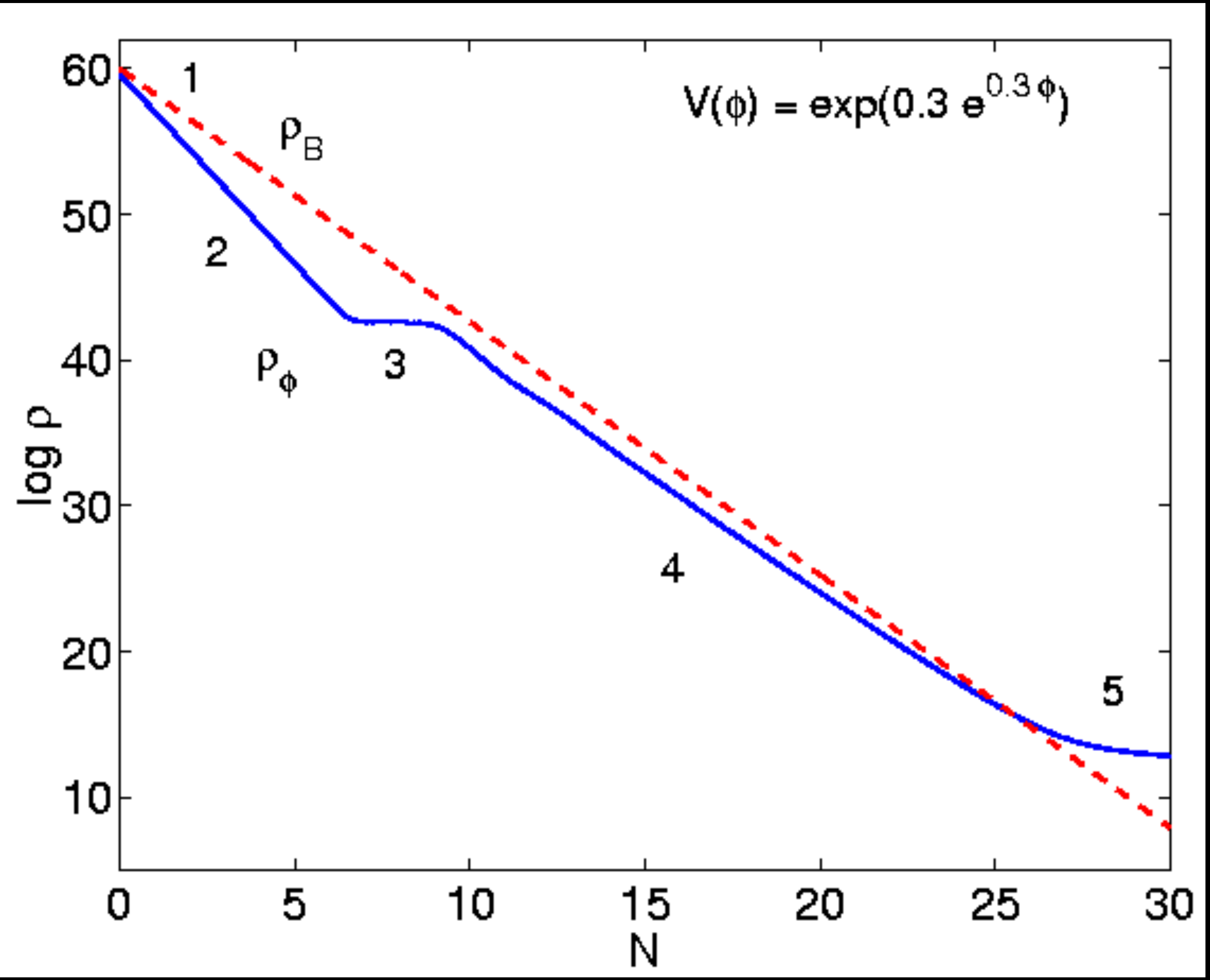


$$V(\phi) = \lambda^4 (1 + \cos(\phi/F_a))$$

Axions could be useful for strong CP problem, dark matter and dark energy — Quintessential Axion.

Slowly rolling scalar fields
Quintessence - Generic behaviour

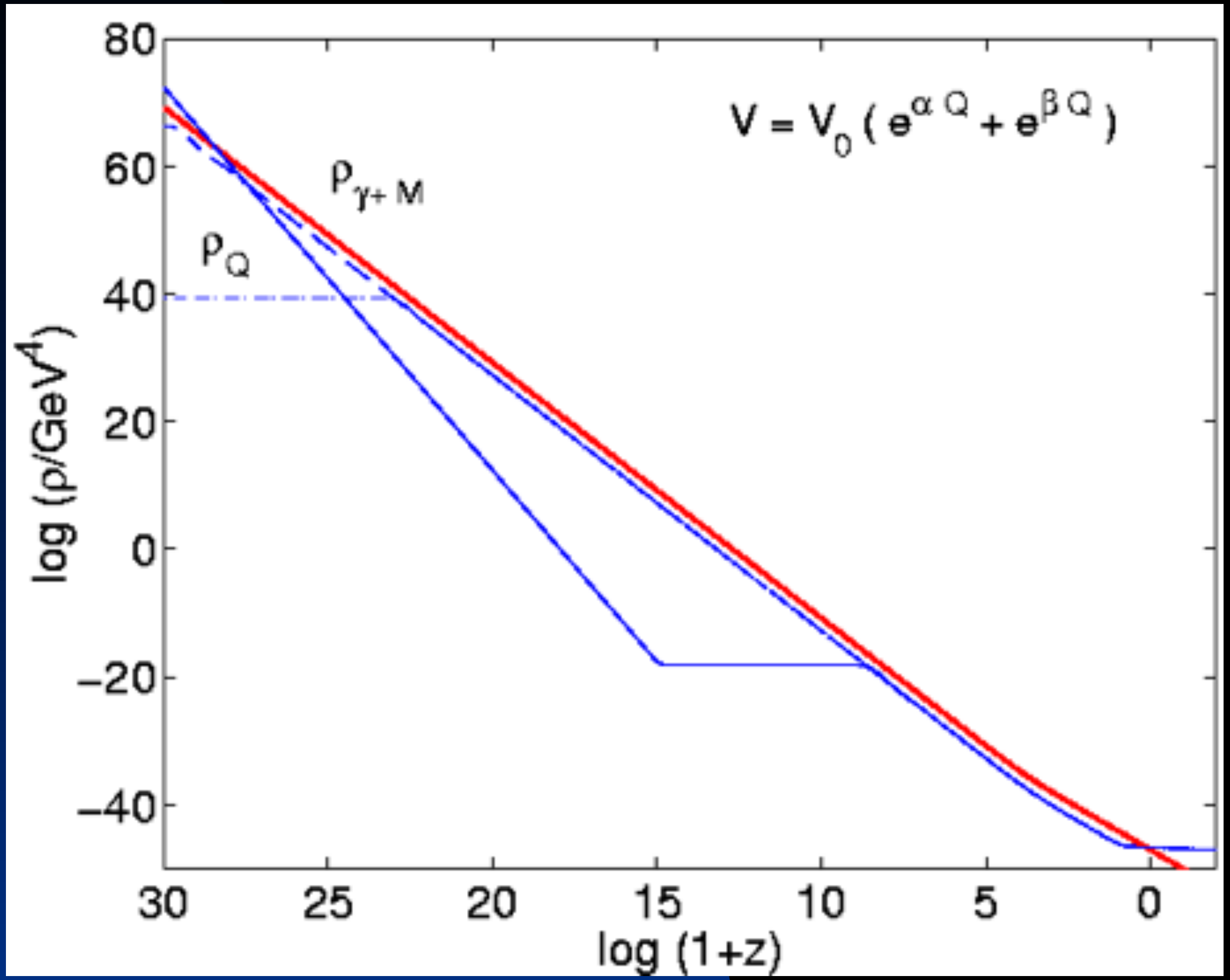
1. **PE → KE**
2. **KE dom scalar field energy den.**
3. **Const field.**
4. **Attractor solution: almost const ratio KE/ PE.**
5. **PE dom.**

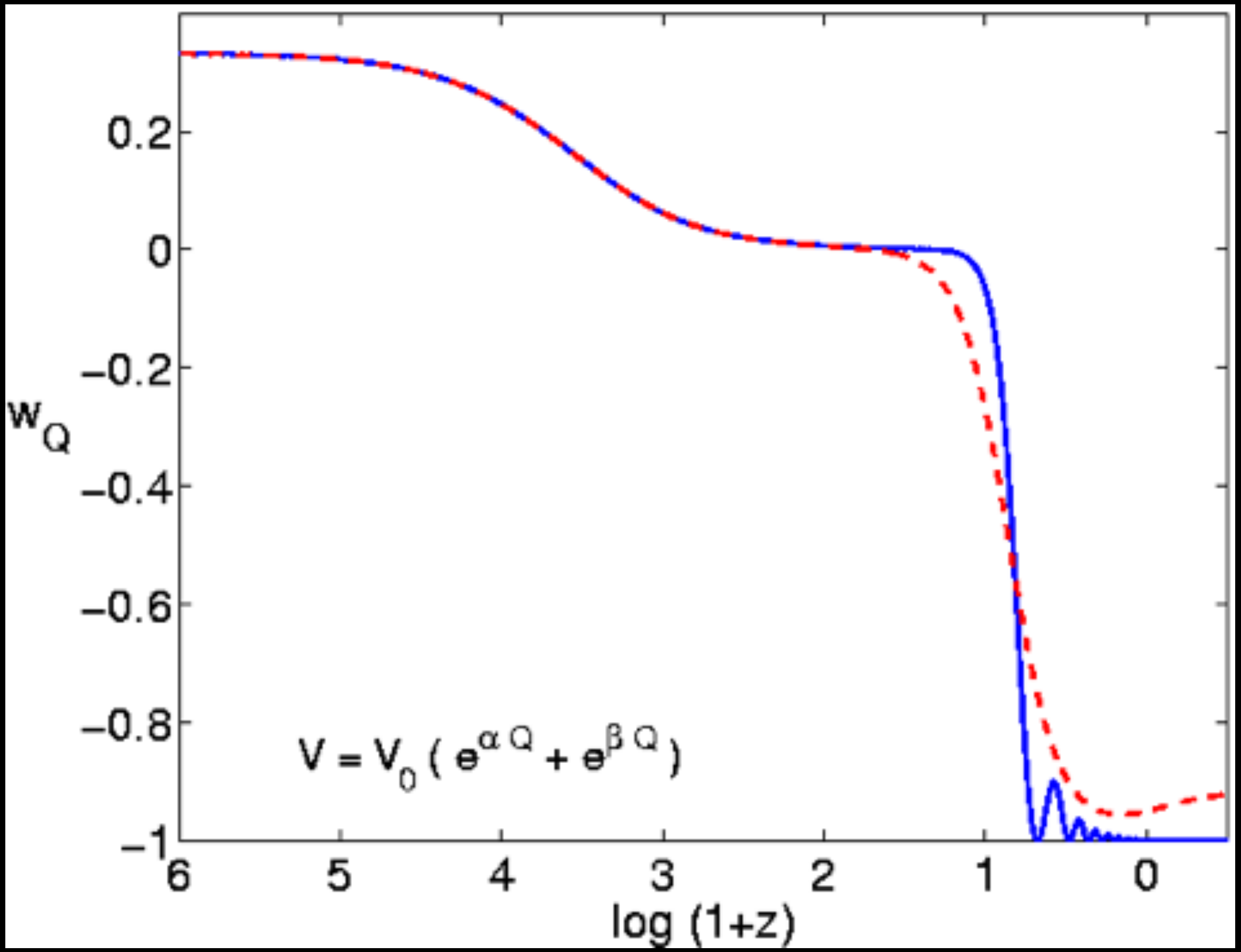


Nunes

Attractors make initial conditions less important

$$V(\phi) = V_1 + V_2$$
$$= V_{01}e^{-\kappa\lambda_1\phi} + V_{02}e^{-\kappa\lambda_2\phi}$$





$\alpha = 20; \beta = 0.5$

Scaling for wide range of i.c.

Fine tuning: $V_0 \approx \rho_\phi \approx 10^{-47}\ \text{GeV}^4 \approx (10^{-3}\ \text{eV})^4$

Mass: $m \approx \sqrt{\frac{V_0}{M_{pl}^2}} \approx 10^{-33}\ \text{eV}$

Generic issue Fifth force - require screening mechanism!

Screening mechanisms

1. Chameleon fields [Khoury and Weltman (2003) ...]

Non-minimal coupling of scalar to matter in order to avoid fifth force type constraints on Quintessence models: the effective mass of the field depends on the local matter density, so it is massive in high density regions and light (m~H) in low density regions (cosmological scales).

2. K-essence [Armendariz-Picon et al ...]

Scalar fields with non-canonical kinetic terms. Includes models with derivative self-couplings which become important in vicinity of massive sources. The strong coupling boosts the kinetic terms so after canonical normalisation the coupling of fluctuations to matter is weakened -- screening via Vainshtein mechanism

Similar fine tuning to Quintessence -- vital in brane-world modifications of gravity, massive gravity, degravitation models, DBI model, Gallileons, ...

3. Symmetron fields [Hinterbichler and Khoury 2010 ...]

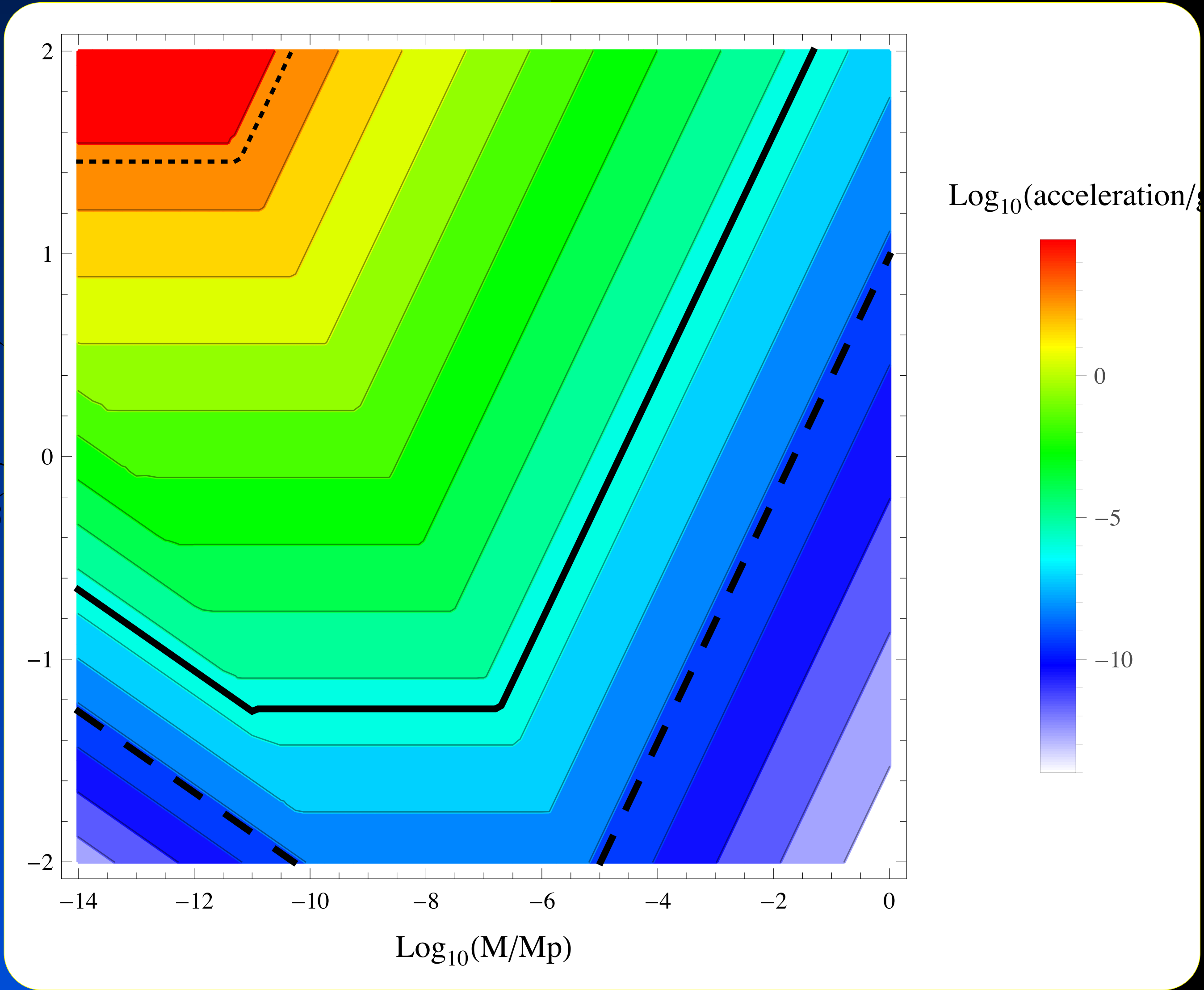
vev of scalar field depends on local mass density: vev large in low density regions and small in high density regions. Also coupling of scalar to matter is prop to vev, so couples with grav strength in low density regions but decoupled and screened in high density regions.

Dark Energy Direct Detection Experiment [Burrage, EC, Hinds 2015,Hamilton et al 2015]

Atom Interferometry

Idea: Individual atoms in a high vacuum chamber are too small to screen the chameleon field and so are very sensitive to it - can detect it with high sensitivity. Can use atom interferometry to measure the chameleon force - or more likely constrain the parameters !

$$\nabla^2\phi = -\frac{\Lambda^2}{\phi^2} + \frac{\rho}{M}$$



$$F_r = \frac{GM_AM_B}{r^2}\left[1 + 2\lambda_A\lambda_B\left(\frac{M_P}{M}\right)^2\right]$$

$$\lambda_i = 1 \text{ for } \rho_i R_i^2 < 3M\phi_{bg}$$

$$\lambda_i = \frac{3M\phi_{bg}}{\rho_i R_i^2} \text{ for } \rho_i R_i^2 > 3M\phi_{bg}$$

Sph source A and test object B near middle of chamber experience force between them - usually ƛ<<1 in cosmology but for atom ƛ=1 - reduced suppression

The problem of coupling DE and DM directly with scalars

Generate loop corrections to the DE mass.

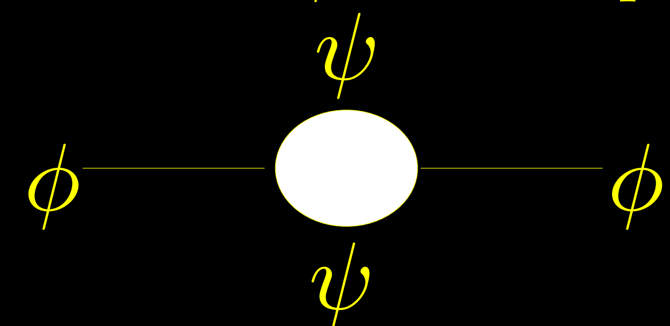
Consider Yukawa type coupling between DE scalar and DM fermion $g\phi\bar{\psi}\psi$

Now since it is DE: $m_\phi \simeq H \sim 10^{-33} eV$

Very light so long range attractive 5th force: $Pot : \Phi(r) \sim g^2/r$

Must be less than grav attraction of DM particles by say factor 10 $g < m_\psi/(10 m_{\rm pl})$

Loop correction to DE mass from DM



$$\delta m_\phi^2 \simeq g^2 m_\psi^2 < m_\psi^4/(10 m_{\rm pl})^2$$

Require: $\delta m_\phi^2 < H_0^2$ implying : $m_\psi < 10^{-3} eV$

But then the required light DM isn't cold - or go for an axion with a protected mass or a different coupling between DM and DE

Modifying Gravity rather than looking for Dark Energy - non trivial

Any theory deviating from GR must do so at late times yet remain consistent with Solar System tests. Potential examples include:

•f(R), f(G) gravity -- coupled to higher curv terms, changes the dynamical eqns for the spacetime metric. Need chameleon mechanism [Starobinski 1980, Carroll et al 2003, ...]

- Modified source gravity -- gravity depends on nonlinear function of the energy.
- Gravity based on the existence of extra dimensions -- DGP gravity

We live on a brane in an infinite extra dimension. Gravity is stronger in the bulk, and therefore wants to stick close to the brane -- looks locally four-dimensional.

Tightly constrained -- both from theory [ghosts] and observations

- Scalar-tensor theories including higher order scalar-tensor lagrangians -- recent examples being Galileon models
- Massive gravity - single massive graviton bounds m>O(1meV) from demand perturbative down to O(1)mm - too large to conform with GR at large distances

[Burrage et al 2013]

Baryon Acoustic Oscillations (BAO) - seeing modified gravity?

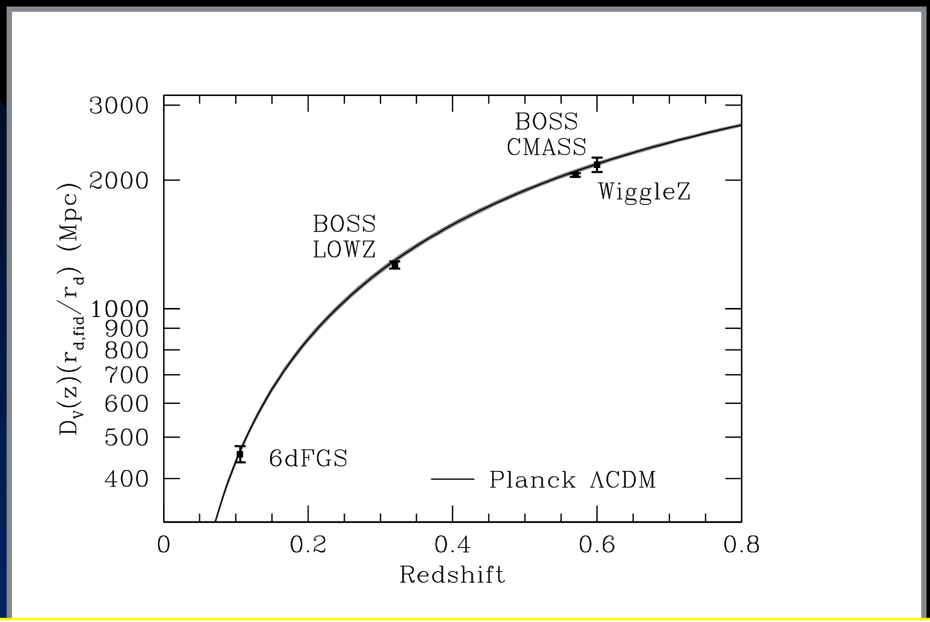
Periodic feature in the clustering of galaxies

Allows us to have a new standard ruler, measures the sound horizon (hence the angular diameter distance and Hubble parameter) at different redshifts.

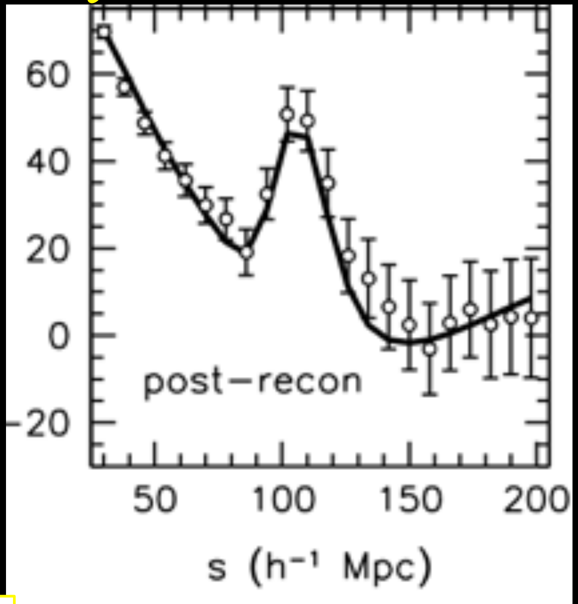
Lots of galaxy surveys : SDSS, 6dFGS, BOSS, WiggleZ

Distance-Redshift relation

Anderson et al, BOSS

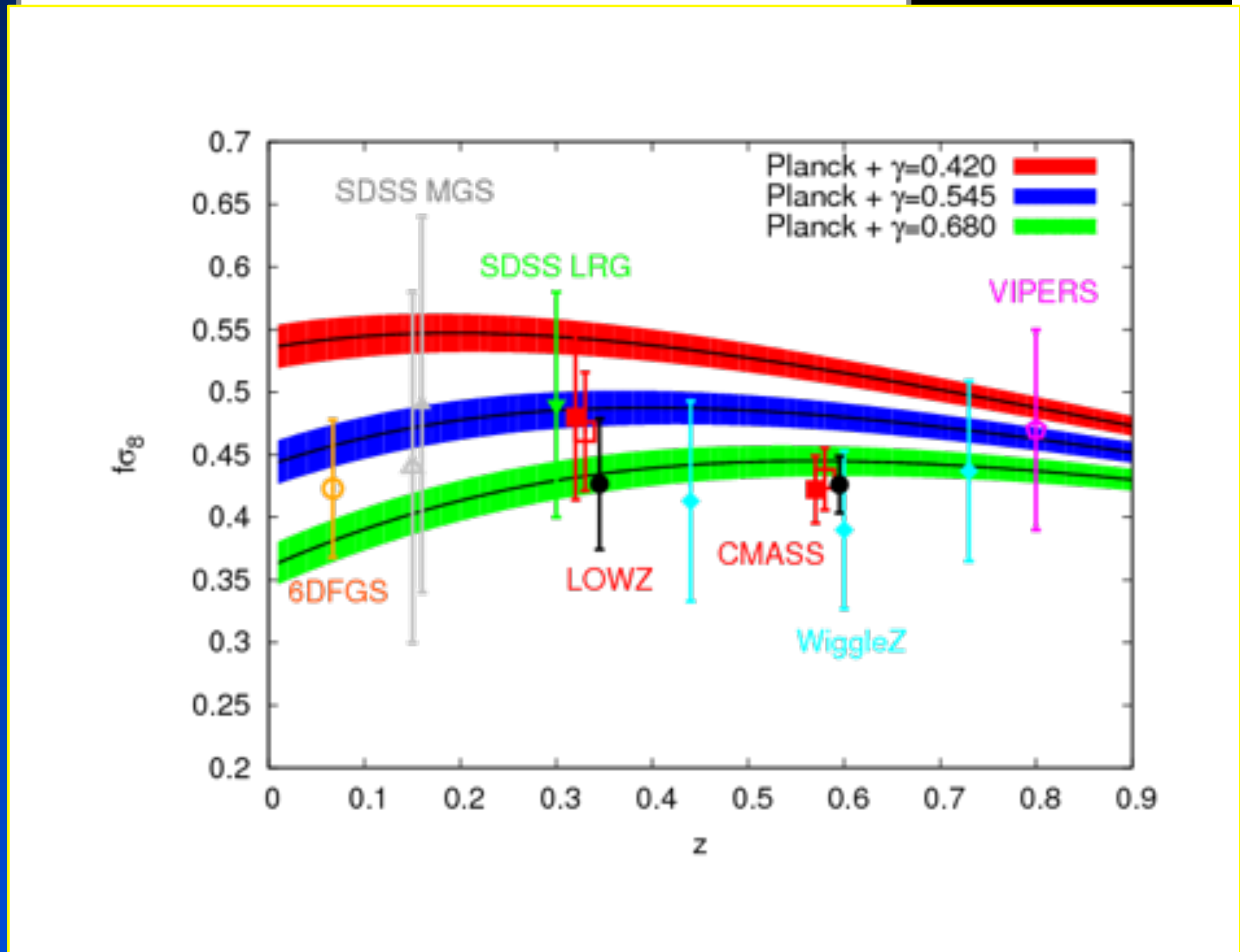


Galaxy correlation function



Clustering of galaxies

Gil-Marin et al 2016



f - growth rate of structure.

In ΛCDM

$$f(z) = \Omega_m^{\gamma}(z)$$

σ_8 - amplitude of dark matter density fluctuations

$\gamma_{GR} = 0.55 \qquad \gamma_{BOSS} = 0.719^{+0.080}_{-0.072}$

2.5σ tension with GR - new physics ?

Return to the beginning -- Inflation

A period of accelerated expansion in the early Universe

Small smooth and coherent patch of Universe size less than (1/H) grows to size greater than the comoving volume that becomes entire observable Universe today.

Explains the homogeneity and spatial flatness of the Universe

and also explains why no massive relic particles predicted in say GUT theories

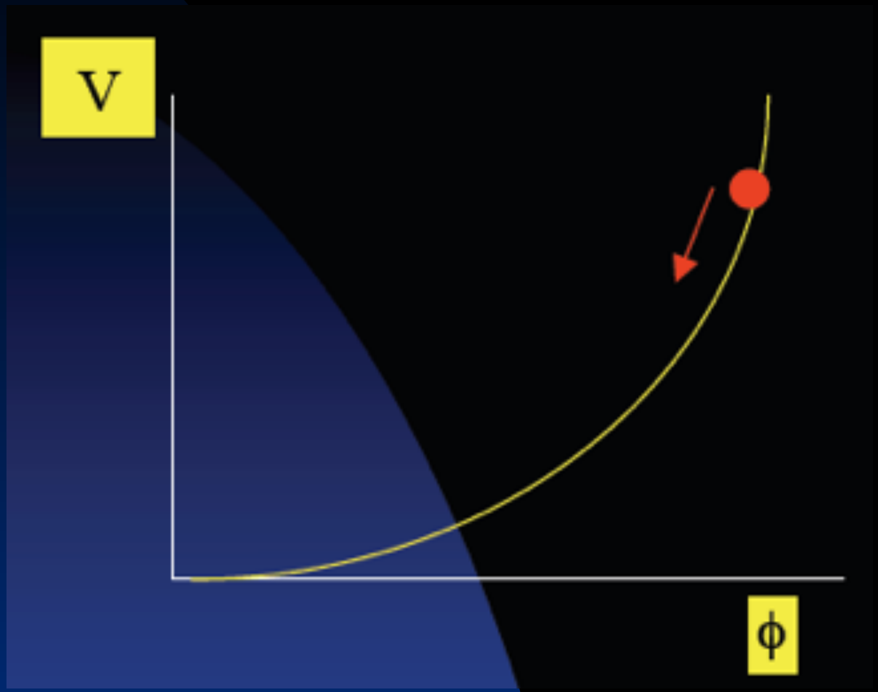
Leading way to explain observed inhomogeneities in the Universe

$$\boxed{\frac{\ddot{a}}{a} = -\frac{8\pi}{3} G(\rho + 3p) - - - Accn}$$

$$\boxed{If \;\; \rho + 3p < 0 \Rightarrow \ddot{a} > 0}$$

Intro fundamental scalar field -- like Higgs

If Universe is dominated by the potential of the field, it will accelerate!



$$\rho = \frac{1}{2}\dot{\phi}^2 + V(\phi)$$
$$p = \frac{1}{2}\dot{\phi}^2 - V(\phi)$$

We aim to constrain potential from observations.

During inflation as field slowly rolls down its potential, it undergoes quantum fluctuations which are imprinted in the Universe. Also leads to gravitational wave production.

Prediction -- potential determines important quantities

Slow roll parameters [Liddle & Lyth 1992]

$$\epsilon = \frac{1}{16\pi G}\left[\frac{V'(\phi)}{V(\phi)}\right]^2$$

$$\eta = \frac{1}{8\pi G}\left[\frac{V''(\phi)}{V(\phi)}\right]$$

Inflation occurs when both of these are << 1

Density perturbations

$$\delta_H^2(k) \simeq \delta_H^2(k_0)\left(\frac{k}{k_0}\right)^{n-1}$$

$$\delta_H^2(k_0) \simeq \frac{32}{75}\frac{VG^2}{\epsilon}, \quad n-1 = 6\epsilon - 2\eta$$

Gravitational waves

$$\delta_g^2(k) \simeq \delta_g^2(k_0)\left(\frac{k}{k_0}\right)^{n_G}$$

$$r \equiv \frac{\delta_g^2(k_0)}{\delta_H^2(k_0)} = 16\epsilon, \quad n_G = -2\epsilon = -\frac{r}{8}$$

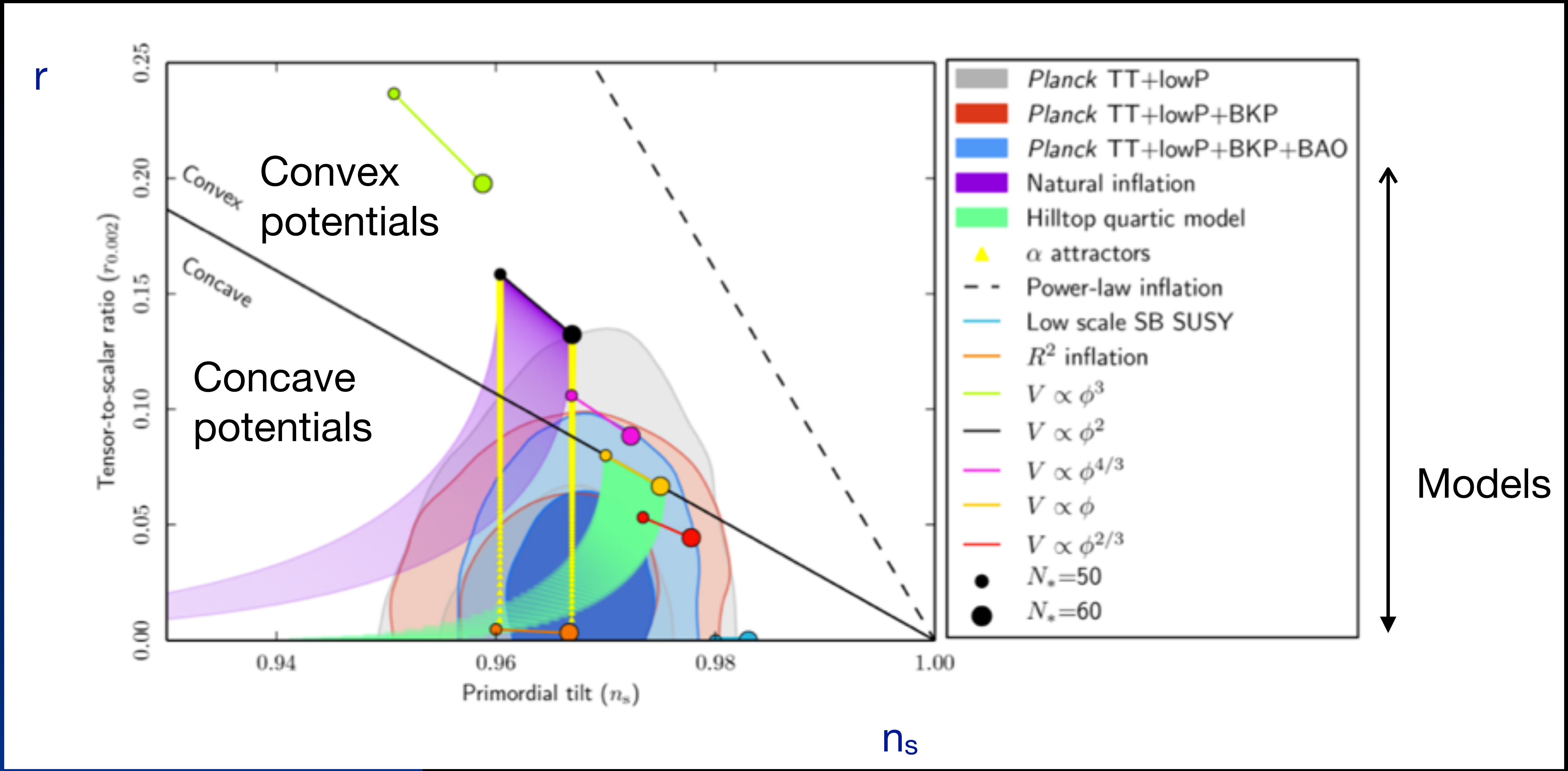
End of inflation.

•Inflaton is coupled to other matter fields and as it rolls down to the minima it produces particles –perturbatively or through parametric resonance where the field produces many particles in a few oscillations.

•Dramatic consequences. Universe reheats, can restore previously broken symmetries, create defects again, lead to Higgs windings and sphaleron effects, generation of baryon asymmetry at ewk scale at end of a period of inflation.

•Important constraints: e.g.: gravitino production means : $T_{rh} < 10^9$ GeV -- often a problem!

Planck 2015 and Inflation



$$n_s = 0.968 \pm 0.006, \quad r < 0.11$$

Still no evidence of primordial non-gaussianty, running of the spectral index or tensor modes in the polarisation of the CMB (Keck-Bicep-Planck). Time will tell if they are there.

Inflation model building -- big industry

Multi-field inflation

Inflation in string theory and braneworlds

Inflation in extensions of the standard model

Cosmic strings formed at the end of inflation

The idea is clear though:

Use a combination of data (CMB, LSS, SN, BAO ...) to try and constrain models of the early universe through to models explaining the nature of dark energy today.

Planck claims - single field inflation appears to be all we need:

No evidence of primordial non-gaussanity

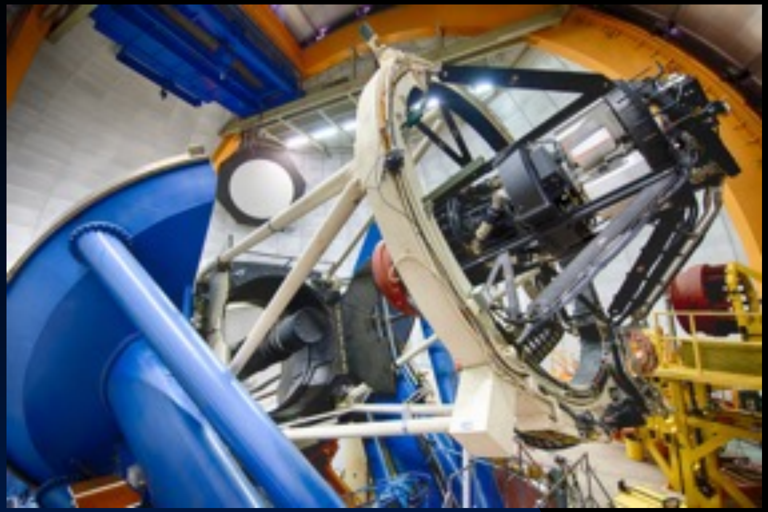
Reheating/flatness constraints - $50 < N_* < 60$ - efoldings

$$\text{Power law}: V(\phi) = V_0\phi^n, \quad n = 3, 4 \text{ ruled out}$$

$$V(\phi) = V_0 \exp(\lambda\phi) \text{ ruled out}$$

$$\text{Chaotic inflation } V(\phi) = V_0\phi^2, \quad \text{in tension}$$

The Future is Bright



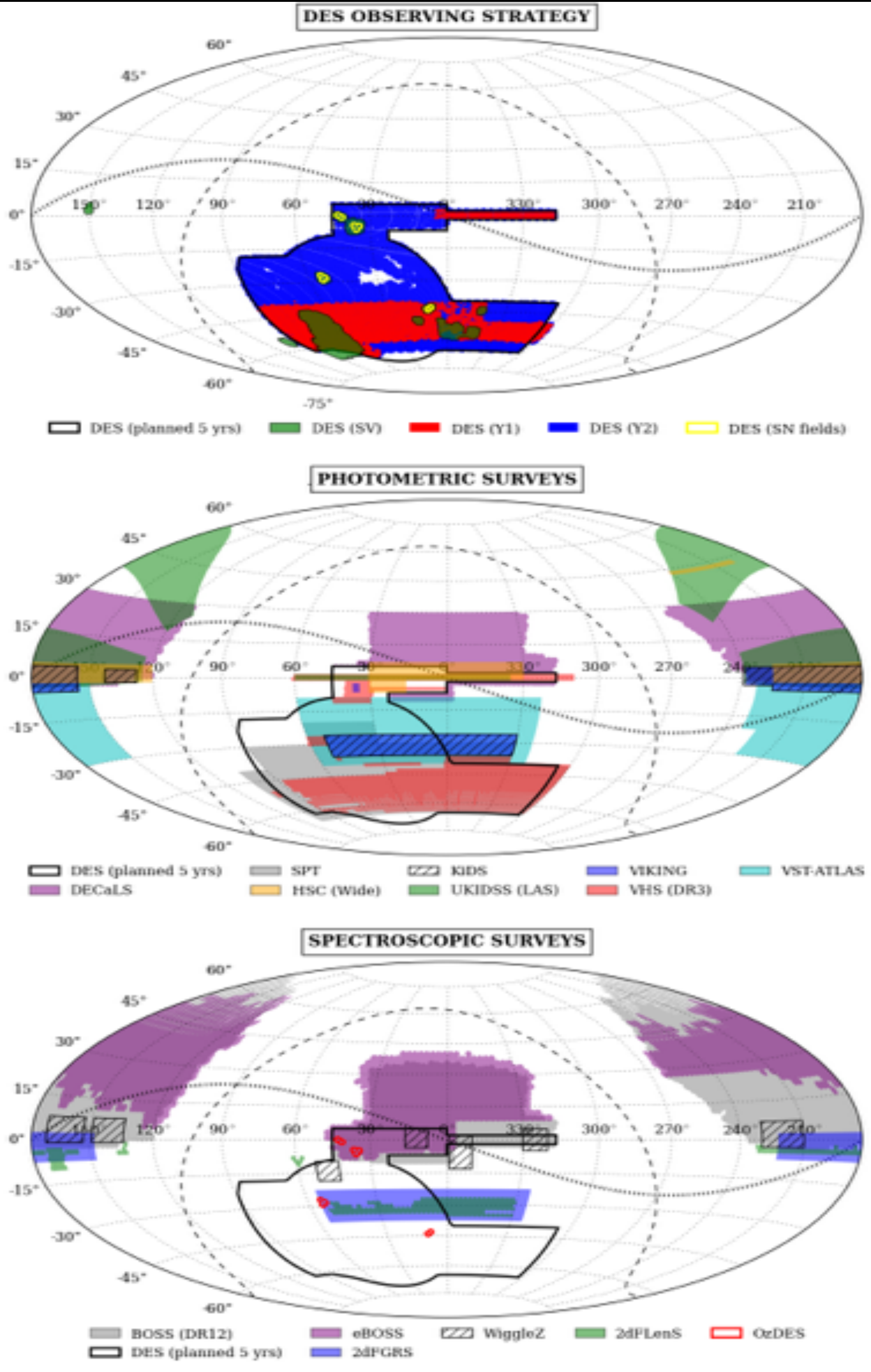
Dark Energy Survey

Credit: Reidar Hahn Fermilab

68 DES papers in total
21 of them since Oct 2015
(in reverse chronological order as on the arXiv)

- Lognormality of LSS and kappa maps (L. Clerkin et al.)
- LSS+ gg lensing (J. Kwan et al.)
- Galaxy populations in clusters (C. Hennig et al.)
- gg lensing (J. Clampitt et al.)
- Shear peaks (T. Kacprzak et al.)
- Kinetic SZ (B. Soergel et al.)
- Lensing-galaxy correlations (Baxter et al.)
- LIGO: EM follow up (B. Abbott et al.)
- LIGO: DES search in the LMC (J. Annis et al.)
- LIGO: DES search for an optical counterpart (M. Soares-Santos et al.)
- RedMaPPer cluster catalog (Rykoff et al.)
- Stellar mass in DES/CLASH cluster (A. Palmese et al.)
- Biasing from LSS and WL maps (C. Chang et al.)
- Non-DE Overview (DES collaboration)
- Chromatic errors (T. Li et al.)
- Superluminous SN (M. Smith et al.)
- Cross correlation DES-CMB lensing (D. Kirk et al.)
- Six SL systems (B. Nord et al.)
- Star clusters in the LMC (A. Pieres et al.)
- Crowdsourcing (P. Melchior et al.)
- Search for gamma ray emission from dwarfs (S. Li et al.)

DES Footprint



Overlapping Imaging Surveys

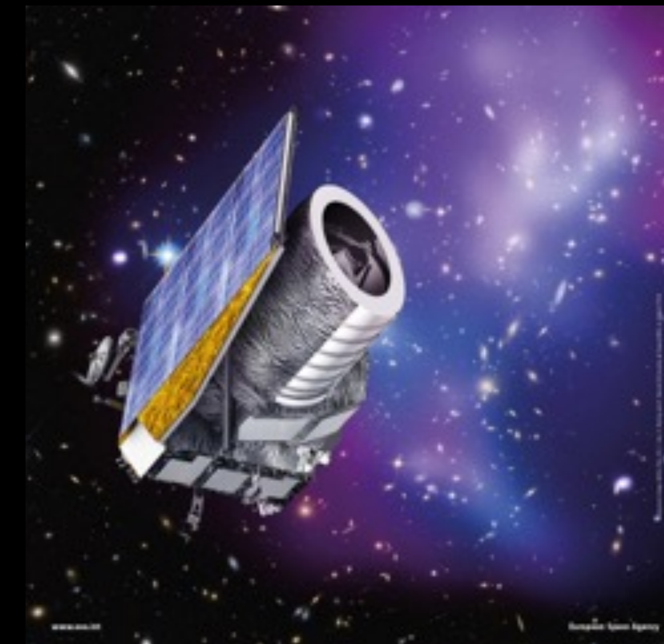
Overlapping Spectroscopic Surveys

Non-DE overview, arXiv: 1601.00329

Credit: Alex Merson (UCL)

EUCLID

ESA medium class mission due for launch in 2020.
Main goal understand origin of acceleration of the Universe.
Will explore expansion history and the evolution of cosmic structures by measuring shapes and red-shifts of galaxies as well as the distribution of clusters of galaxies over a large fraction of the sky.

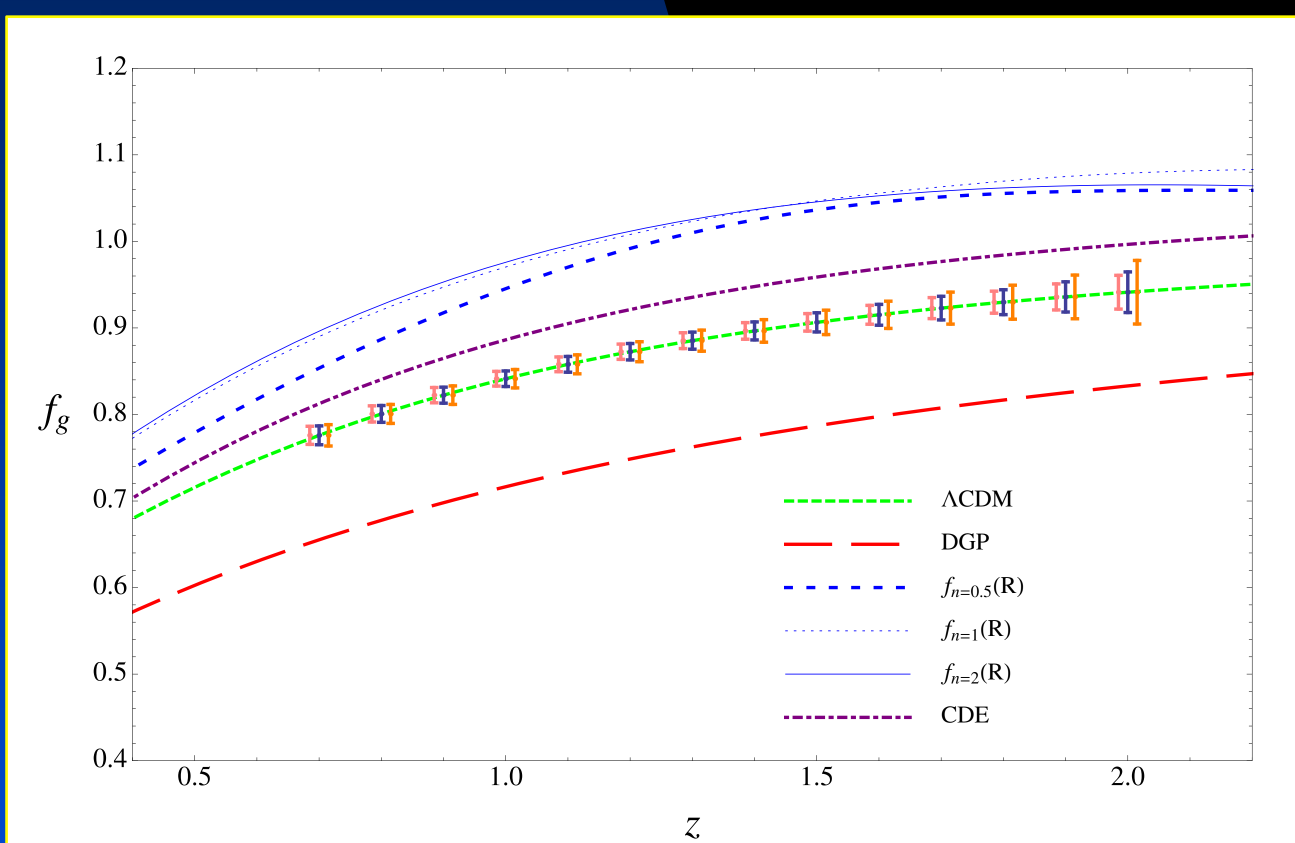


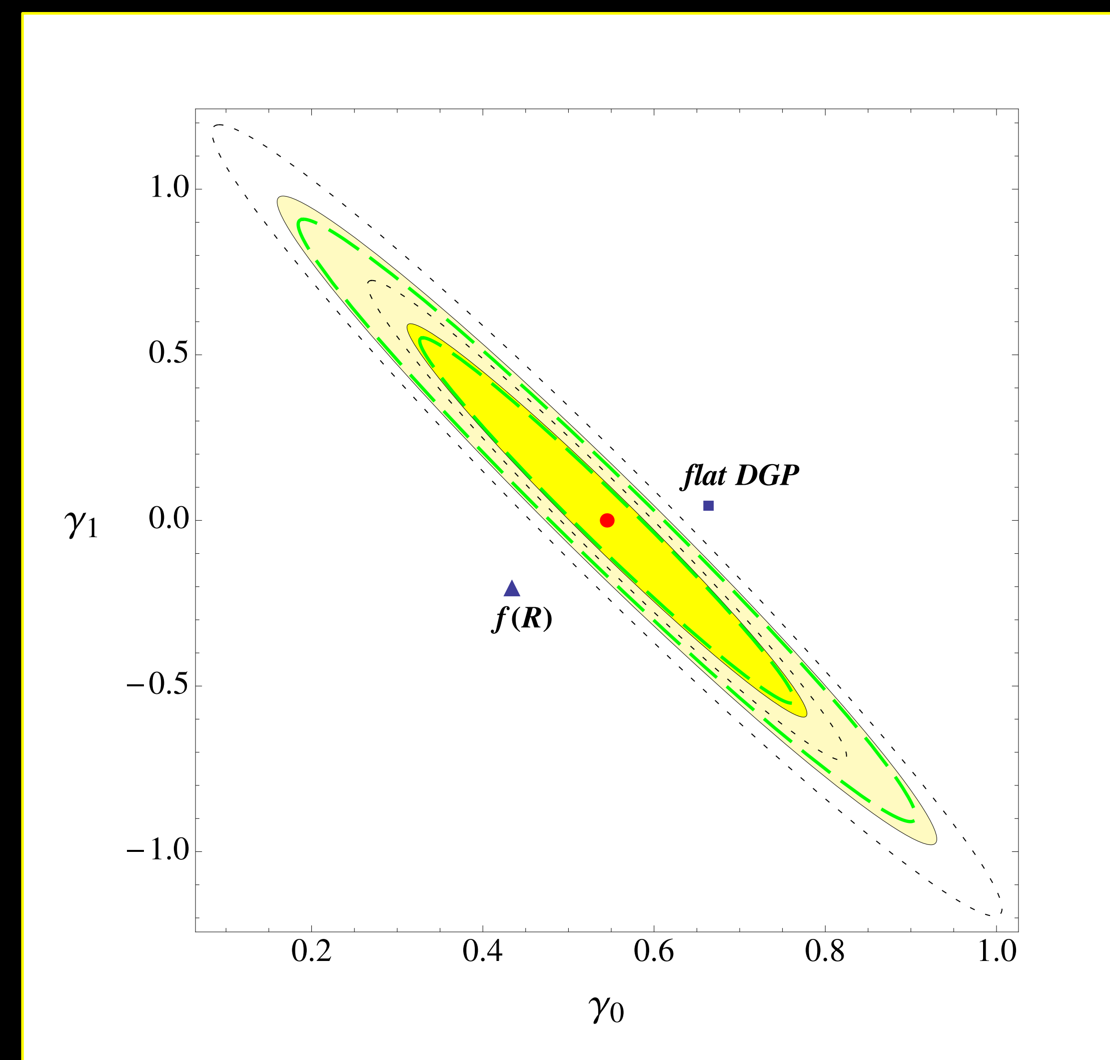
Example: consider growth rate and possible deviations form GR

$$f_g = \Omega_{\mathrm{m}}^{\gamma} \quad \gamma \sim 0.545 \text{ for } \Lambda\mathrm{CDM}$$

Consider parameterisation: $f_g \equiv \Omega_{\mathrm{m}}(z)^{\gamma(z)}$

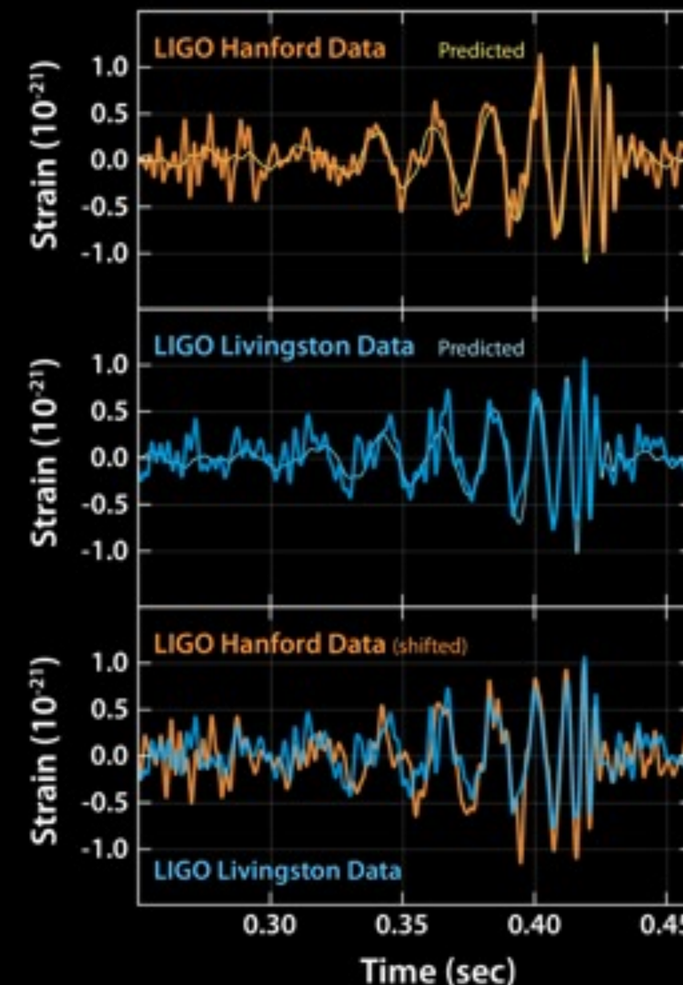
$$\text{where } \gamma(z) = \gamma_0 + \gamma_1 \frac{z}{1+z}$$





Amendola et al: 1606.00180

LIGO detection of GW from binary BH mergers not yet cosmology but wow !



Selected for a Viewpoint in *Physics*
PRL **116,** 061102 (2016) PHYSICAL REVIEW LETTERS week ending 12 FEBRUARY 2016

Observation of Gravitational Waves from a Binary Black Hole Merger

B. P. Abbott *et al.**
(LIGO Scientific Collaboration and Virgo Collaboration)
(Received 21 January 2016; published 11 February 2016)

LIGO

CARDIFF UNIVERSITY
PRIFYSGOL CAERDYDD

Primary black hole mass	$36^{+5}_{-4}\,M_\odot$
Secondary black hole mass	$29^{+4}_{-4}\,M_\odot$
Final black hole mass	$62^{+4}_{-4}\,M_\odot$
Final black hole spin	$0.67^{+0.05}_{-0.07}$
Luminosity distance	410^{+160}_{-180} Mpc
Source redshift, z	$0.09^{+0.03}_{-0.04}$

3 solar masses of energy were radiated

Peak luminosity was 3.6 x 10^{56} ergs.

Like waiting for buses -
nothing then a second pair show up !
Dec 26, 2015

$$M_1 = 14.2^{+8.3}_{-3.7} M_o$$

$$M_2 = 7.5^{+2.3}_{-2.3} M_o$$

$$M_{\rm Final} = 20.8^{+6.1}_{-1.7} M_o$$

$$d_L = 440^{+180}_{-190}\ \text{Mpc},\ \ z = 0.09^{+0.03}_{-0.04}$$

02/09/2010

Phys. Rev. Lett. **116**, 241103 – Published 15 June 2016

Stephen Fairhurst — LIGO

GW and Cosmology - LIGO has shown we can detect them directly.

Lisa Pathfinder:

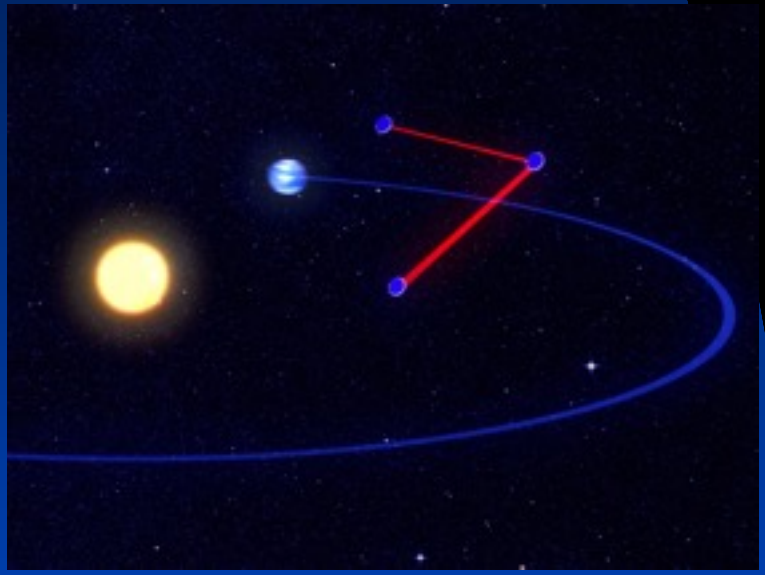
LISA Pathfinder operates from a vantage point in space about 1.5 million km from Earth towards the Sun, orbiting the first Sun–Earth Lagrangian point, L1. It successfully demonstrated the technology for a gravitational wave observatory in space such as LISA

Credit: ESA/ATG medialab ATG medialab

Pair of identical 2-kg, 46-mm gold-platinum cubes, separated by 38 cm, fly, surrounded, but untouched, by the spacecraft which adjusts its position constantly to avoid hitting them. Between the two test masses, is a laser interferometer which measures the test masses' positions and orientations relative to one another and to the satellite. The measurements done mean they can determine the distance of the two free falling test masses to less than the diameter of a single atom

Armano et al Phys.Rev.Lett. 116 (2016) no.23, 231101

eLisa:



credit AEI/MM/exozet

Three eLISA spacecraft will be placed in orbits that form a triangular formation with center 20° behind the Earth and side length 1 million km.

Each spacecraft will be in an individual Earth-like orbit around the Sun. will form a **high precision interferometer** that senses gravitational waves by monitoring the changes in distance between **free falling test masses** inside the spacecraft.

Compared to the Earth-bound gravitational wave observatories like LIGO and VIRGO, eLISA has a larger range of frequencies between 0.1 mHz and 1 Hz, which is **inaccessible on Earth** due to armlength limitations and terrestrial gravity gradient noise.

Could pick up GW from Early Universe effects such as bubble collisions, cosmic strings, massive BH mergers

Extremely Large Telescopes.

European Extremely Large Telescope (E-ELT) — 40 m aperture.

credit: ESO

Largest optical/near infrared telescope in the world.

Will correct for atm distortions from the start with images 16 times sharper than the HST.

Will allow study of planets around stars, first galaxies to form, supermassive BH and nature of the dark sector by finding the most distant Type 1aSN.

Will also measure Dark Energy by directly observing global dynamics by determining the tiny time-drift in the redshifts of distant objects.

Will search for evidence of time variations in the fundamental constants.

Other proposed Extremely Large Telescopes

Overwhelmingly Large Telescope (OWL) — 100 m aperture — ESO (Concept study completed)

Euro50 — 50 m aperture — Lund + collaborations in Spain, Finland, UK, Ireland (Concept study completed)

Thirty metre telescope (TMT) — 30m aperture - USA+Canada collaboration (Design study in progress)

Japan (J-ELT) — 30 m aperture — Japan (Design study in progress)

Giant Magellan Telescope (GMT) — 25m aperture — USA+Australia collaboration (Design study in progress)

Square Kilometre Arrary (SKA)

.

Largest multi radio telescope to be built in Australia and South Africa, with total collecting area of 1sq km.

Working over range of frequencies (50 MHz - 14 GHz) it will be 50 times more sensitive than any other radio instrument.

Highest resolution images with receiving stations out to distance of 3000km.

Headquarters at Jodrell Bank - chosen to balance out the weather !

Will test GR in extreme environments, using pulsars as GW detectors will probe spacetime in regions of extreme curvarture.

Use the sensitivity of SKA in the 21cm H line to map a billion galaxies out to the edge of the observable universe.

Use the LSS data revealed through imaging the H lines to help determine the processes behind galaxy formation and evolution, and to look for evidence of dark energy.

Probe the epoch of re-ionisation - the dark ages between 300,000 years or so and 1 billion years when first galaxies begin to form. How did the universe light up ?

Uncover the origin and evolution of cosmic magnetic fields.

Search for extraterrestrial life - protoplanetary discs in habitable zones.

credit: Swinburne Astronomy Productions

And so where are we today?

- Exciting time in cosmology -- Observations driving the way.
- Amazing exciting new prospects ahead - EUCLID, LIGO, eLISA, LSST, SKA, ELTs.
- Theory struggling a bit to keep up.
- What started the big bang ?
- How did inflation emerge – if at all ?
- Where is the inflaton field?
- How did the spacetime dimensions split up?
- Where did the particle masses come from?
- Why are there just three families of particles?
- Why is the Universe accelerating today?
- What is the dark matter ?
- Where is all the anti-matter?
- What is the dark energy?
- Do we need some form of modification of gravity ?

And finally

In preparing this talk it struck me quite how much we as a community of Astronomers, Cosmologists and Particle Physicists, all of whose work contributed to this talk, how much we rely on collaborations - often large International collaborations.

Our friends and colleagues across the world but in particular in Europe are probably even more confused and baffled than we are about what has just happened over the past few days.

We need to reassure them that with the support of our Universities we intend to continue playing a full part in all of our collaborations, the scientists of the UK intend to remain as leaders in our fields helping forge new directions through collaborations with our colleagues in Europe.

In science we are stronger together !

Thank you for listening

A few extra slides

Brief reminder why the cosmological constant is regarded as a problem?

The CC gravitates in General Relativity:

$$\mathcal{L} = \sqrt{-g}\left(\frac{R}{16\pi G} - \rho_{\rm vac}\right)$$

$$G_{\mu\nu} = -8\pi G \rho_{\rm vac} g_{\mu\nu}$$

Now: $\rho_{\rm vac}^{\rm obs} \ll \rho_{\rm vac}^{\rm theory}$

Just as well because anything much bigger than we have and the universe would have looked a lot different to what it does look like. In fact structures would not have formed in it.

Estimate what the vacuum energy should be :

$$\rho_{\text{vac}}^{\text{theory}} \sim \rho_{\text{vac}}^{\text{bare}}$$

$$+$$

zero point energies of each particle

$$+$$

contributions from phase transitions in the early universe

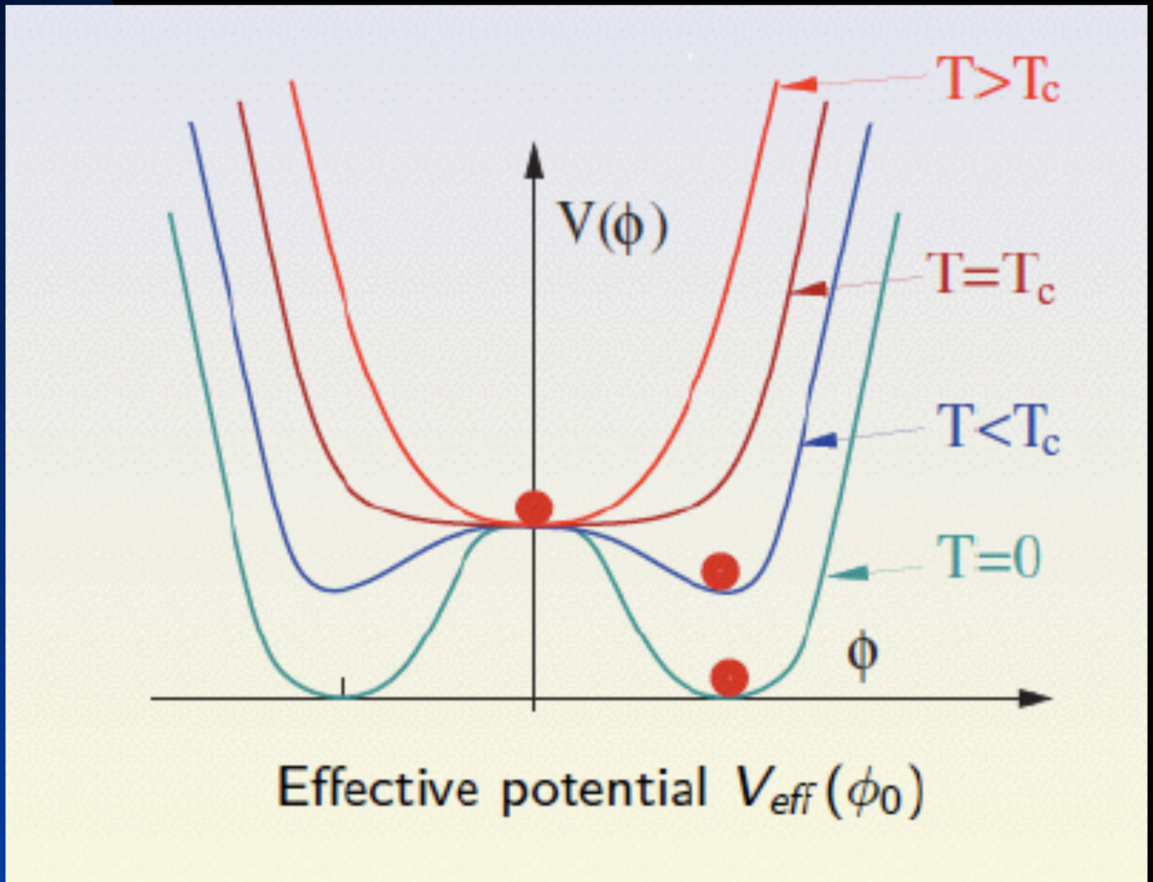
zero point energies of each particle

For many fields (i.e. leptons, quarks, gauge fields etc...):

$$< \rho > = \frac{1}{2} \sum_{\text{fields}} g_i \int_0^{\Lambda_i} \sqrt{k^2 + m^2} \frac{d^3k}{(2\pi)^3} \simeq \sum_{\text{fields}} \frac{g_i \Lambda_i^4}{16\pi^2}$$

where g_i are the dof of the field (+ for bosons, - for fermions).

contributions from phase transitions in the early universe



$$\Delta V_{\rm ewk} \sim (200\ {\rm GeV})^4$$

$$\Delta V_{\rm QCD} \sim (0.3\ {\rm GeV})^4$$

Quantum Gravity cut-off	$-(10^{18}\ \mathrm{GeV})^4$	fine tuning to 120 decimal places
SUSY cut-off	$-(\mathrm{TeV})^4$	fine tuning to 60 decimal places
EWK phase transition	$-(200\mathrm{GeV})^4$	fine tuning to 56 decimal places
QCD phase transition	$-(0.3\mathrm{GeV})^4$	fine tuning to 44 decimal places
Muon	$-(100\mathrm{MeV})^4$	
electron	$-(1\ \mathrm{MeV})^4$	fine tuning to 36 decimal places
	$-(\mathrm{meV})^4$	Observed value of the effective cosmological constant today !

4. Interacting Dark Energy

[Kodama & Sasaki (1985), Wetterich (1995), Amendola (2000) + many others…]

Ex: Including neutrinos -- 2 distinct DM families -- resolve coincidence problem

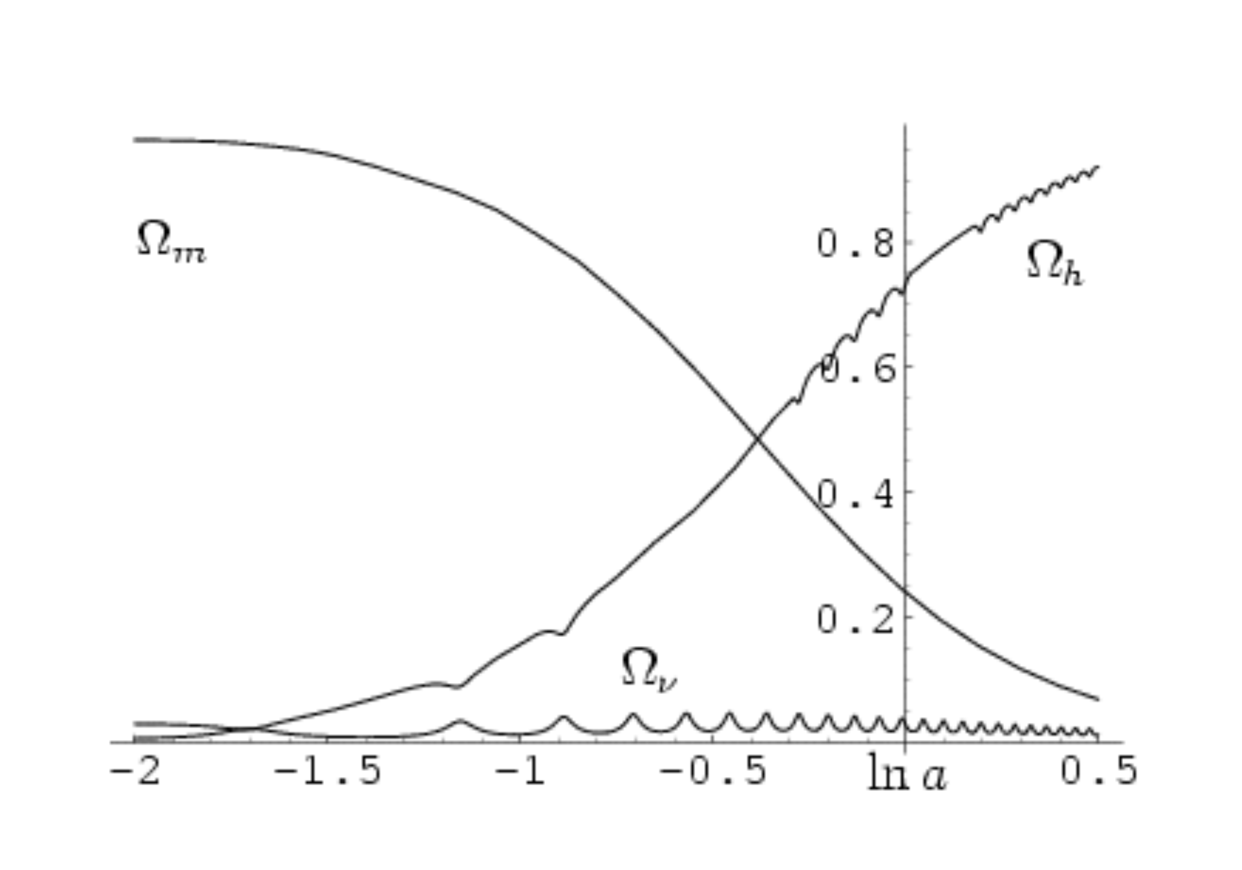
Amendola et al (2007)

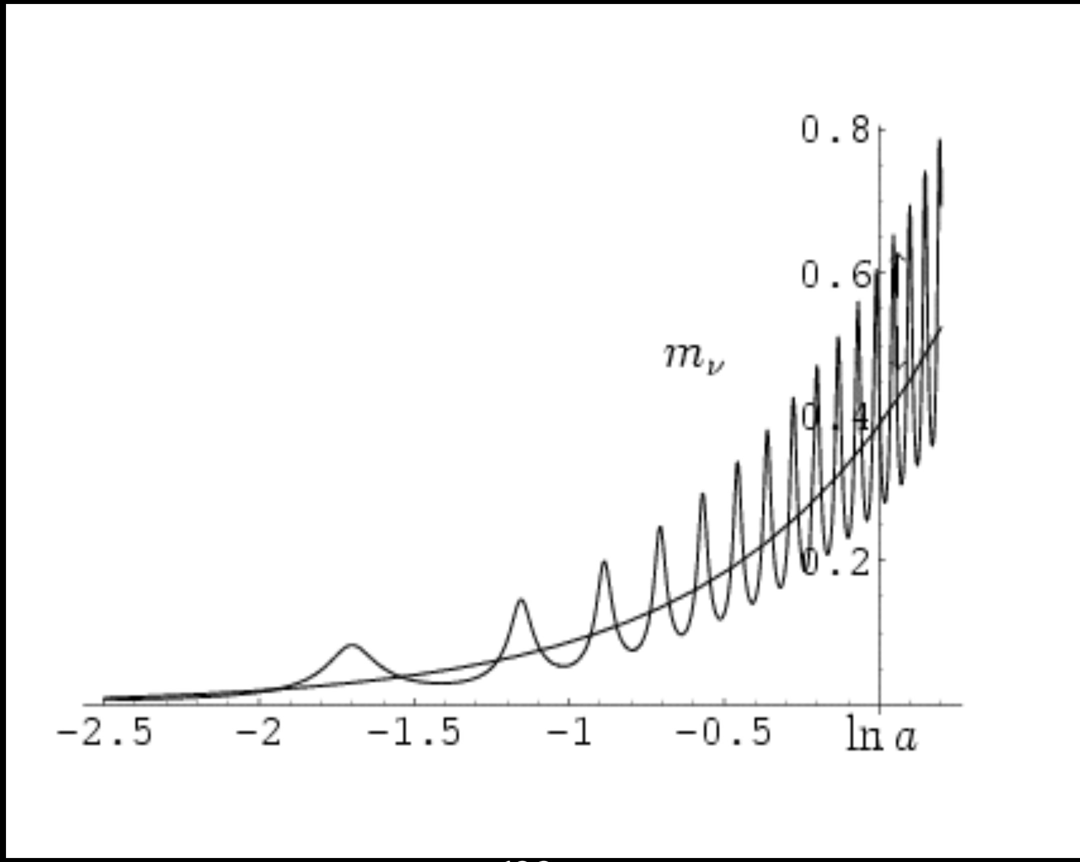
Depending on the coupling, find that the neutrino mass grows at late times and this triggers a transition to almost static dark energy.

Trigger scale set by time when neutrinos become non-rel

$$[\rho_h(t_0)]^{\frac{1}{4}} = 1.07 \left(\frac{\gamma m_\nu(t_0)}{eV}\right)^{\frac{1}{4}} 10^{-3} eV$$

$$w_0 \approx -1 + \frac{m_\nu(t_0)}{12\mathrm{eV}}$$





m_ν

Perturbations in Interacting Dark Energy Models [Baldi et al (2008), Tarrant et al (2010)]

Perturb everything linearly : Matter fluid example

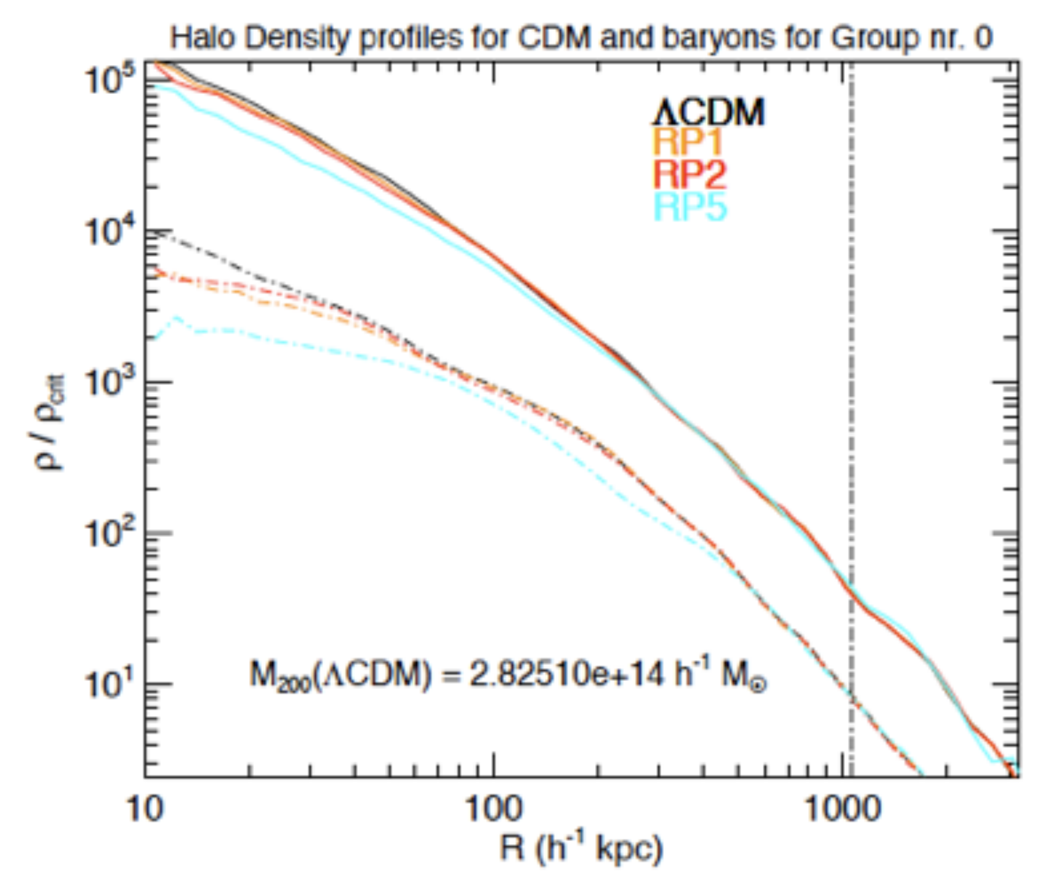
$$\ddot{\delta}_c + \left(2H - 2\beta\frac{\dot{\phi}}{M}\right)\dot{\delta}_c - \frac{3}{2}H^2[(1+2\beta^2)\Omega_c\delta_c + \Omega_b\delta_b] = 0$$

extra friction

modified grav interaction

vary DM particle mass

Include in simulations of structure formation : GADGET [Springel (2005)]



Density decreases as coupling β increases

Halo mass function modified.

Halos remain well fit by NFW profile.

Density decreases compared to ΛCDM as coupling β increases.

Scale dep bias develops from fifth force acting between CDM particles. enhanced as go from linear to smaller non-linear scales.

Still early days -- but this is where I think there should be a great deal of development (Puchwein et al 2013, Barreira et al 2014)

Dark Energy Effects

Interactions with standard model particles inevitable even if indirect.

Light scalar fields that interact with std model fields mediate fifth forces

but we dont see any long range fifth forces on earth or in the solar system.

Screening !

Dark energy changes the way photons propagate through B fields. The polarised photon can fluctuate into a DE scalar particle leading to a modification of apparent polarisation and luminosity of the sources.

Two tests Burrage, Davis Shaw, 2008,2009

Look for evidence of DE through changes in the scatter of luminosities of high energy sources.

Look for evidence of correlation between poln and freq of starlight .

More general f (R) models [Loads of people]

$$S = \int d^4x \sqrt{-g}\left[\frac{R + f(R)}{2\kappa^2} + \mathcal{L}_m\right]$$

No Λ

Usually f (R) struggles to satisfy both solar system bounds on deviations from GR and late time acceleration. It brings in extra light degree of freedom --> fifth force constraints.

Ans: Make scalar dof massive in high density solar vicinity and hidden from solar system tests by chameleon mechanism.

Requires form for f (R) where mass of scalar is large and positive at high curvature.

Issue over high freq oscillations in R and singularity in finite past.

In fact has to look like a standard cosmological constant [Song et al, Amendola et al]

What should we do to help determine the nature of DE ?

1. We need to define properly theoretically predicted observables, or determine optimum ways to parameterise consistency tests (i.e. how should we parameterise w(z)?)

2. Need to start including dynamical dark energy, interacting dark matter-dark energy and modified gravity models in large scale simulations -[Wyman et al 2013, Li et al 2013 Puchwein et al 2013, Jennings et al 2012, Barreira et al 2012, Brax et al 2013].

3. Include the gastrophysics + star formation especially when considering baryonic effects in the non-linear regimes - `mud wrestling'.

4. On the theoretical side, develop models that go beyond illustrative toy models. Extend Quintessential Axion models. Are there examples of actual Landscape predictions? De Sitter vaccua in string theory is non trivial.

5. Recently massive gravity and galileon models have been developed which have been shown to be free of ghosts. What are their self-acceleration and consistency properties?

6. Will we be able to reconstruct the underlying Quintessence potential from observation?

7. Will we ever be able to determine whether $w \neq -1$?

8. Look for alternatives, perhaps we can shield the CC from affecting the dynamics through self tuning-- The Fab Four, Sequestering

9. Given the complexity (baroque nature ?) of some of the models compared to that of say Λ, should we be using Bayesian model selection criterion to help determine the relevance of any one model.

10. We should be looking outside of cosmological scales and coming down to earth - after all DE is pervasive - it is everywhere.

Things are getting very exciting with DES beginning to take data and future Euclid missions, LSST, as well as proposed giant telescopes, GMT, ELT, SKA - travelling in new directions !

In the lab as we will see over the next two days there are some wonderful ideas out there to test models of DE in the lab.

Axions could be useful for strong CP problem, dark matter and dark energy.

Strong CP problem intro axion : $$m_a = \frac{\Lambda^2_{\rm QCD}}{F_a};\ F_a\ -\ \text{decay constant}$$

PQ axion ruled out but invisible axion still allowed:

$$10^9\ \text{GeV} \leq F_a \leq 10^{12}\ \text{GeV}$$

Sun stability CDM constraint

String theory has lots of antisymmetric tensor fields in 10d, hence many light axion candidates.

Can have $F_a \sim 10^{17}$-10^{18} GeV

Quintessential axion -- dark energy candidate [Kim & Nilles].

Requires $F_a \sim 10^{18}$ GeV which can give:

$$E_{\rm vac} = (10^{-3}\ \text{eV})^4 \rightarrow m_{\rm axion} \sim 10^{-33}\ \text{eV}$$

Because axion is pseudoscalar -- mass is protected, hence avoids fifth force constraints

Summary

1.Depending on your faith in the string landscape approach we have a solution to the CC problem. If not, its solution remains to be determined.

2. Quintessence type approaches require light scalars which bring with them fifth force constraints that need satisfying.

5. Need to screen this which leads to models such as axions, chameleons,non-canonical kinetic terms etc.. -- these have their own issues.

6. Alternatively could consider modified gravity such as massive gravity but this brings with it constraints.

7. Increased interest in coupled DE-DM models which can be analysed by PPF formalism and can include new couplings such as scalar field to velocity components.

8. New push emerging to test for DE more locally, in the lab and through colliders. It is going to be a challenge but initial calculations and experiments suggest it is possible at least for a class of screening DE models.

9. Very exciting time to be working in this field.

Things not explored - no time

1. Gravitational waves from pre-heating

2. Non-Gaussianity from multi-field inflation

3. Nature of perturbations (adiabatic v non-adiabatic)

4. Thermal inflation and warm inflation

5. Going beyond slow roll

6. Inflation model building -- how easy in string theory.

7. Where is the inflaton in particle physics ? How fine tuned is it?

8. Low energy inflation (i.e. TeV scale).

9. Singularity -- eternal inflation !

10. Impact of multiverse on inflation.

11. Alternatives: pre-big bang, cyclic/ekpyrotic, string cosmology, varying speed of light, quantum gravity ....