DES, LSST, and other experiments will probe the nature of dark energy and determine if it is *just* the Cosmological Constant (Λ). What are the specific measurements that need to be made, and how precisely do such experiments need to be, before **you** will be convinced that dark energy is just Λ?

Rodolfo Capdevilla	University of Notre Dame
Benjamin Osherson	University of Illinois, Urbana-Champaign
Sebouh Paul	College of William and Mary
Ana Diaz Rivero	Harvard University
Arthur Constantino Scardua	Brazilian Center for Physical Research
Chun-Hao To	Stanford University
Liangtai Xing	Brown University
Ziang Yan	University of British Columbia
Xuji Zhao	Texas A&M University

$$G^{\mu\nu} = 8\pi T^{\mu\nu} \mid T^{\mu\nu} \supset \Lambda g^{\mu\nu} + \sum_i \underbrace{\left((\rho_i + P_i) u_i^\mu u_i^\nu + P_i g^{\mu\nu}\right)}_{perfect\ \ fluid\ \ in\ \ equilibrium}$$

perfect fluid contribution in equilibrium, in inertial frame
$(\mathbf{u} = (1,0,0,0),\ g^{\mu\nu} = \eta^{\mu\nu})$

$$T_i^{\mu\nu} = \begin{pmatrix} \rho & & & \\ & P & & \\ & & P & \\ & & & P \end{pmatrix}$$

	dust	radiation	Λ
$P = w\rho$	$w = 0$	$w = 1/3$	$w = -1$

$$G^{\mu\nu} = 8\pi T^{\mu\nu} \mid T^{\mu\nu} \supset \Lambda g^{\mu\nu} + \textstyle\sum_i \underbrace{\left((\rho_i + P_i) u_i^{\mu} u_i^{\nu} + P_i g^{\mu\nu}\right)}_{perfect\ \ fluid\ \ in\ \ equilibrium}$$

YOU'VE SEEN THIS

perfect fluid contribution in equilibrium, in inertial frame
$(\mathbf{u} = (1, 0, 0, 0),\ g^{\mu\nu} = \eta^{\mu\nu})$

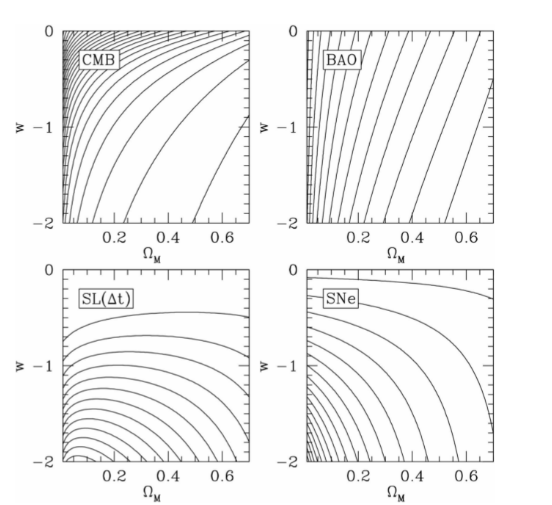
$$T_i^{\mu\nu} = \begin{pmatrix} \rho & & & \\ & P & & \\ & & P & \\ & & & P \end{pmatrix}$$

	dust	radiation	Λ
$P = w\rho$	$w = 0$	$w = 1/3$	$w = -1$

What are the specific measurements that need to be made?

	Expansion	**Growth rate of structure**
Observable	$H(z)$, d_L, d_A	σ_8, S_8, $f\sigma_8$, γ_L Matter Power Spectrum
Experiments	SN Ia Galaxy BAO peak Ly-α/Quasar BAO peak Strong Lensing Voids* Gravitational waves*	RSD CMB (kSZ, tSZ) Weak Gravitational Leasing Clusters of galaxies

*Soon

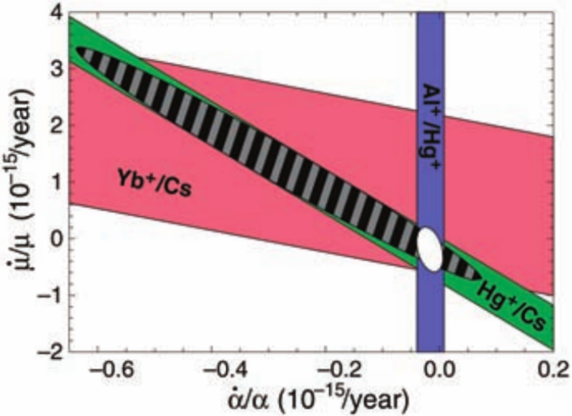


[1]

[1] LSST Science book

To what precision do these measurements need to be made?

Λ just happens to have some 'fine tuned' value, but it's as constant as the fine-structure constant α.

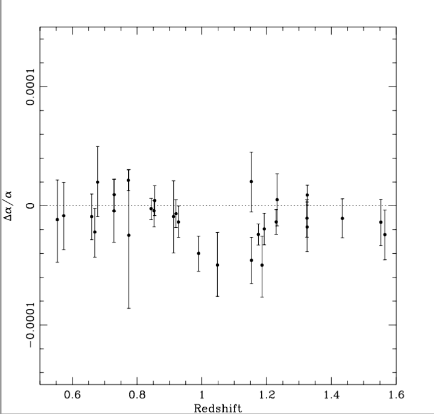


Ratio of frequencies of dissimilar atomic clocks depends on α! Seventeen decimal places of measured α did not change over a year.[2]

[2] T. Rosenband et al. (2008)

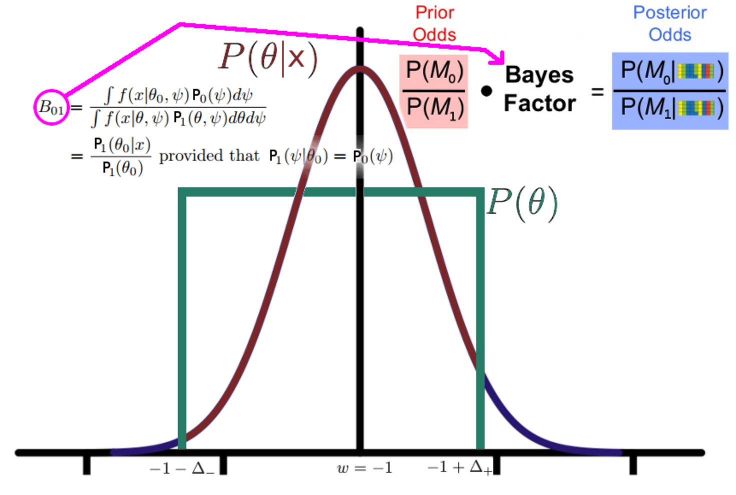
$2 \cdot 10^9$ years ago, a pocket in the Earth naturally formed a *Ur* fission reactor, reacting for $2.3 \cdot 10^5$ years. The abundance ratio of ${}^{149}_{62}Sm/{}^{150}_{62}Sm$ constrains $|\Delta\alpha/\alpha| < 10^{-5}$, the coolest experiment ever.[3]

[3] J-P Uzan (2002)



Quasar measurements constrain $\alpha(z)$ by things like comparing spectral lines for *MgII* and *FeII* as a function of redshift. [4]

[4] J. Webb et al. (1998)


$P(\theta|x)$
$B_{01} = \frac{\int f(x|\theta_0,\psi)\,P_0(\psi)d\psi}{\int f(x|\theta,\psi)\,P_1(\theta,\psi)d\theta d\psi}$
$= \frac{P_1(\theta_0|x)}{P_1(\theta_0)}$ provided that $P_1(\psi|\theta_0) = P_0(\psi)$
Prior Odds
$\frac{P(M_0)}{P(M_1)}$
• Bayes Factor =
Posterior Odds
$P(M_0|$ $)$
$P(M_1|$ $)$
$P(\theta)$
$-1-\Delta_-$
$w=-1$
$-1+\Delta_+$

Computing the Bayes Factor

$$P(\theta|x) = \frac{1}{N} e^{-\frac{1}{2}\left(\frac{w-1}{\sigma}\right)^2} \quad | \quad -1 - \Delta_- \leq w \leq -1 + \Delta_+$$

$$N = \frac{\sigma\sqrt{\pi}}{\sqrt{2}} \left(erfc\left(\frac{-\Delta_-}{\sigma\sqrt{2}}\right) - erfc\left(\frac{\Delta_+}{\sigma\sqrt{2}}\right)\right)$$

$$P(w = -1) = \frac{dw}{\Delta_+ + \Delta_-} \qquad P(w = -1|x) = \frac{dw}{N}$$

$$B_{01} = \frac{\sqrt{2}(\Delta_+ + \Delta_-)}{\sigma\sqrt{\pi}} \left(erfc\left(\frac{-\Delta_+}{\sigma\sqrt{2}}\right) - erfc\left(\frac{\Delta_-}{\sigma\sqrt{2}}\right)\right)^{-1}$$

Can do this for any (multidimensional) parametrization of w, as long as $(D.E. = \Lambda)$ is a nested model.

Computing the Bayes Factor

$$B_{01} = \frac{\sqrt{2}(\Delta_+ + \Delta_-)}{\sigma\sqrt{\pi}}\left(erfc\left(\frac{-\Delta_+}{\sigma\sqrt{2}}\right) - erfc\left(\frac{\Delta_-}{\sigma\sqrt{2}}\right)\right)^{-1}$$

If your theory allows for $-1.00 < w < -0.99$, you need to measure $w = -1.000 \pm .0016$ at one σ for $\ln(B_{01}) = 5$.

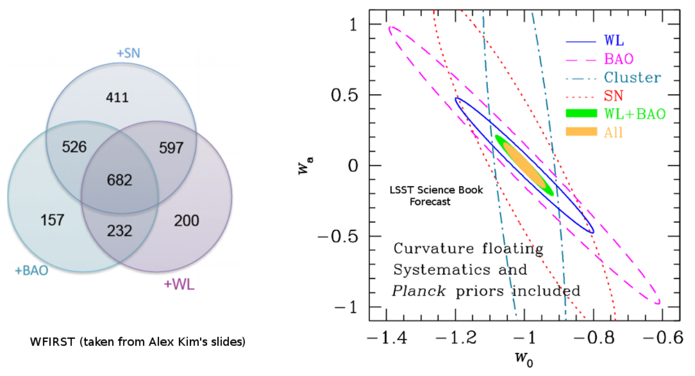
If your theory allows for $-1.000 < w < -0.999$, you need to measure $w = -1.0000 \pm .0004$ at one σ for $\ln(B_{01}) = 5$.

Model	(Δ_+, Δ_-)	Required σ for odds $> 20:1$	$> 150:1$	$\ln B$ today ($\sigma = 0.1$)
Phantom	$(0, 10)$	0.4	$5 \cdot 10^{-2}$	4.4 (strongly disfavoured)
Fluid–like	$(2/3, 0)$	$3 \cdot 10^{-2}$	$3 \cdot 10^{-3}$	1.7 (slightly disfavoured)
Small departures	$(0.01, 0.01)$	$4 \cdot 10^{-4}$	$5 \cdot 10^{-5}$	0.0 (inconclusive)

[5]

[5] Amendola et al. (2012)

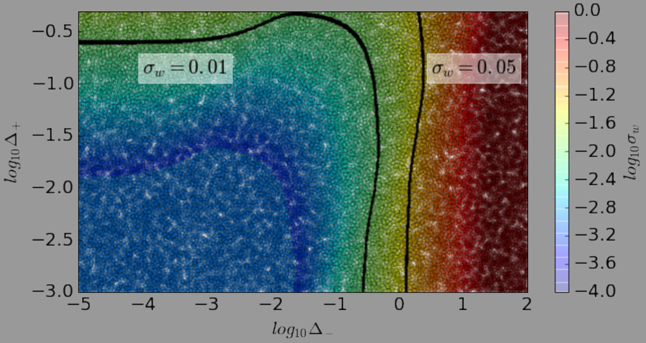
Figures of Merit



$$B_{01} = \frac{\Delta w_a \Delta w_0 \mathrm{FoM}}{\pi}$$

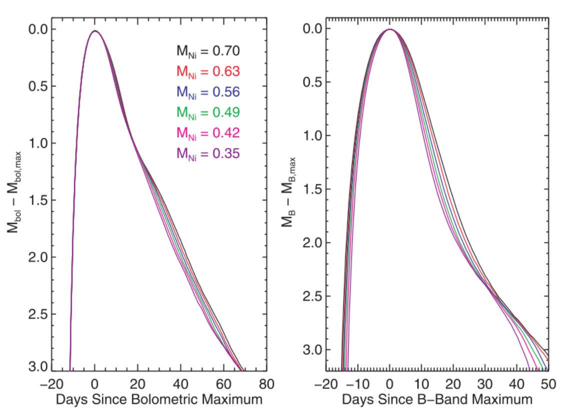
Normally constained: FoM $>\simeq 350$
Very constrained: FoM $>\simeq 10000$

$$B_{01} = \frac{\sqrt{2}(\Delta_+ + \Delta_-)}{\sigma\sqrt{\pi}} \left(erfc\left(\frac{-\Delta_+}{\sigma\sqrt{2}}\right) - erfc\left(\frac{\Delta_-}{\sigma\sqrt{2}}\right)\right)^{-1}$$



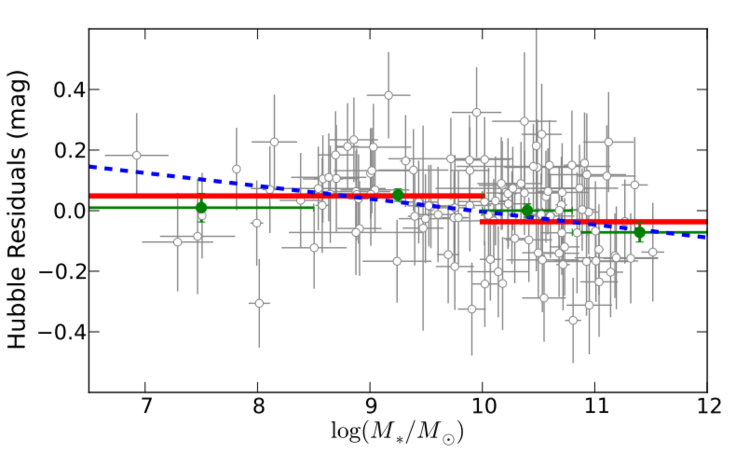
Plot for $B_{01} = constant$ [6]

[6] Amendola et al. (2012), recreated by Chun-Hao To



Phillips relationship of luminosity vs. duration explained by non-equilibrium dynamics and metallicity ratios? [7]

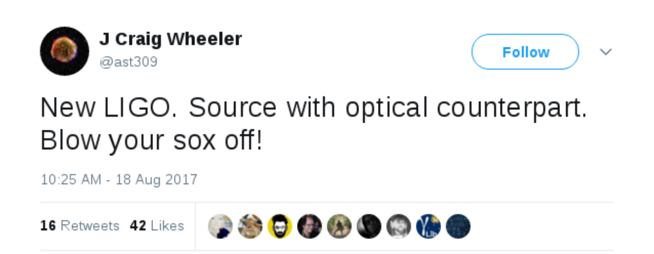
[7] D. Kasen & S. E. Woosley. (2007)



Dependence on host galaxies too? [8]

[8] M. Childressi et al. (2013)

Standard sirens



- Interferometry alone can not measure redshift!
  - But it is an independent measurement of d_L.
- Need a complimentary E&M measurement to break redshift & mass degeneracy.
- Mergers could then be detected to at least $z \sim 5 - 10$, possibly beyond. [9]

[9] D. E. Holz & S. A. Hughes (2005)

Weak gravitational lensing: Systematics

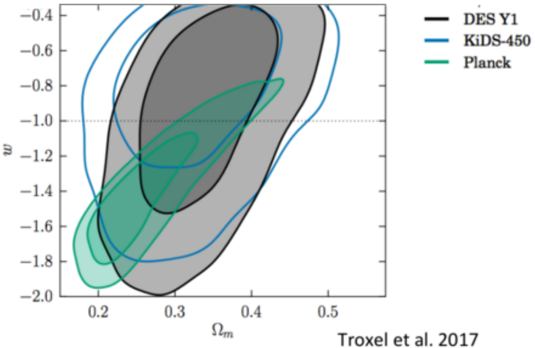
- Error in photoZ
- PSF model error
- instrinsic alignment

Systematics in terms of shear-shear power spectrum

$$\tilde{(}C)_{ij}^{\gamma\gamma}(l) = \underbrace{(1+f_i)(1+f_i)C_{ij}^{\gamma\gamma}(l)}_{multiplicative} + \underbrace{C_{ij}^{add}(l)}_{additive}$$

Additive error will not be overly important for LSST from Image simulation (C. Change et al., 2012)
Multiplicative error has to be less than 0.4% (Masset et al. 2011)

Weak gravitational lensing: Current status

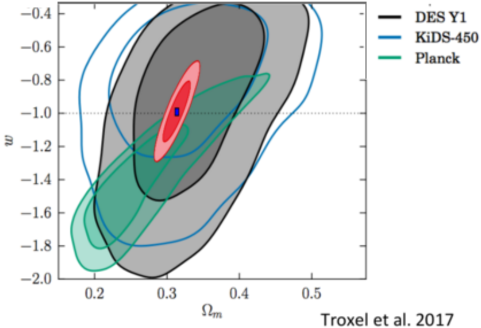


Troxel et al. 2017

- 2 shape measurement (im3shape/metacalibration)
- 2 independent way to measure photoZ

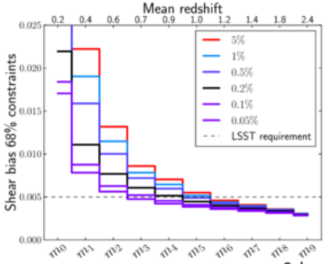
Multiplicative error: 1%

Weak gravitational lensing: Future experiment



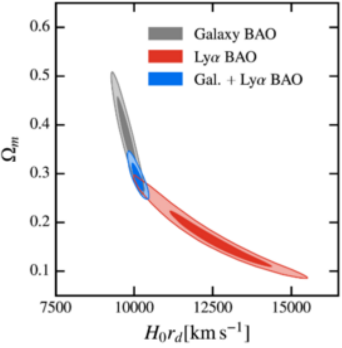
Troxel et al. 2017

Simulation shows by combing CMB S4 lensing, multiplicative error can be less than 0.4% (Schaan et al 2017).



Schaan et al. 2017

BAO: Current status

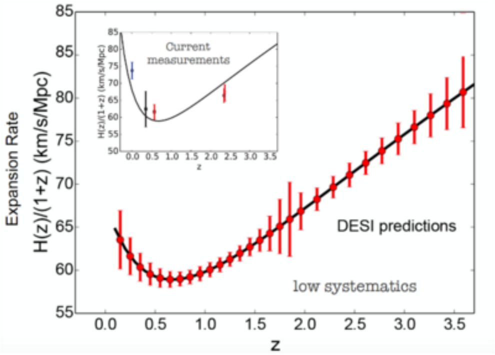


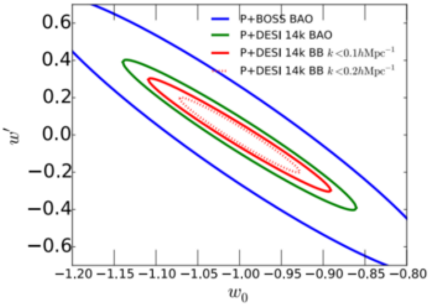
2.4σ tension between galaxy and Ly-α BAO (comparable to 2.5σ tension between Ly-α BAO and *Planck*)

- Will have to understand the systematic caused by different samples.

Addison et al.
astro-ph 1707.06547

BAO: Future experiment (DESI)

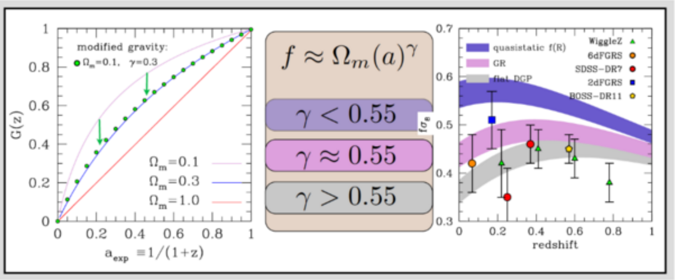




Risa Wechsler talk

RSD: Current status

Probe the growth of structure: $f = \frac{dlnG(a)}{dlna} = \Omega_m(z)^\gamma$

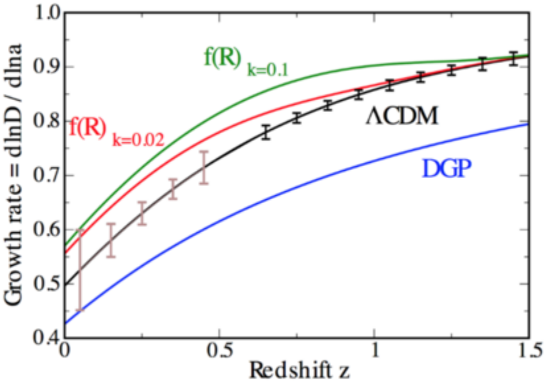


Only limit to k<0.05-0.1 h/Mpc

Will need better bias model and simulations

Risa Wechsler talk

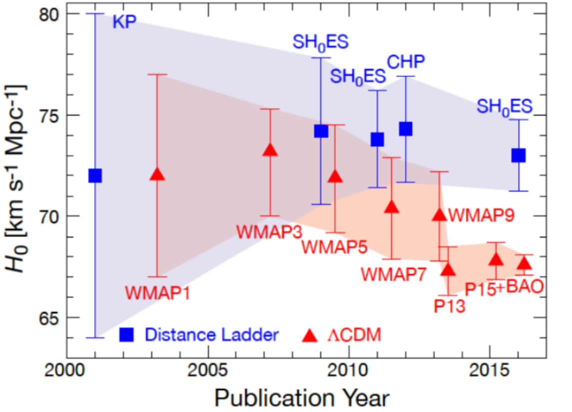
RSD: Future experiment (DESI)



For k down to 0.2 h/Mpc

Risa Wechsler talk

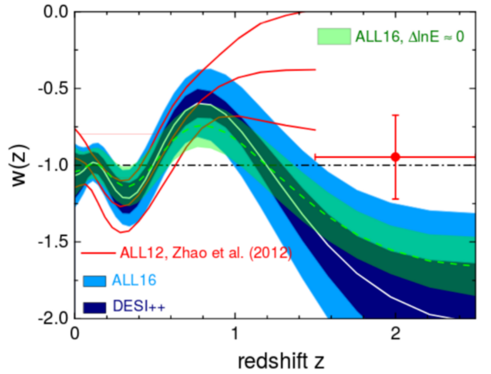
Hubble tension doesn't inspire confidence



[10]

[10] W. L. Freedman (2017)

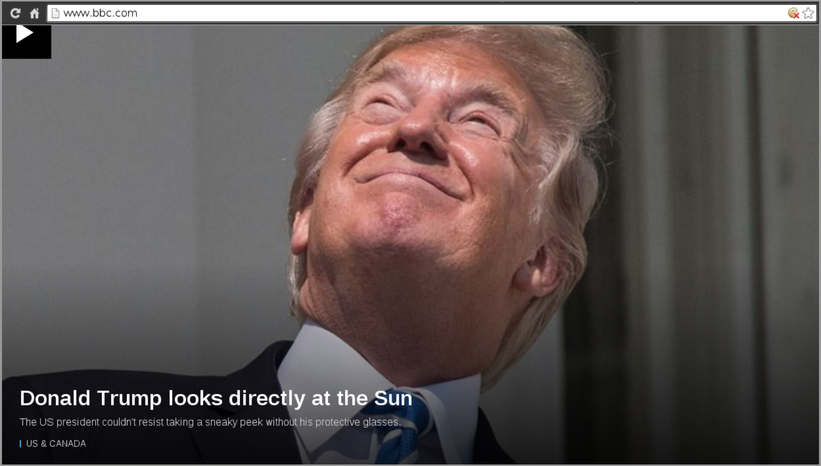
Alternative parametrizaion of w



Leave $w(z)$ completely unconstrained and resolve Hubble tension! [11]

[11] Gond-Bo Zhao et al. (2017)

- Models can be made such that they predict $|(w(z) - 1)| <$ very small.
  - ΛCDM will hold until something better comes along.
  - For these models, we need a correspondingly tiny σ on w measurements to have a Bayes factor that either comparatively favors or disfavors ΛCDM.
- If all systematics and tensions are resolved, then we may accept ΛCDM
  - SNe light curve discrepancies
  - Weak lensing photoZ error
  - Instrinsic alignment
  - Different BAO samples are inconsistent
  - Galaxy bias for RSB
  - Hubble tension between probes

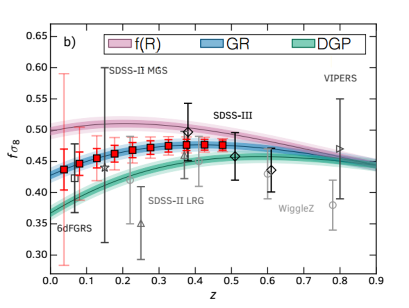

www.bbc.com
Donald Trump looks directly at the Sun
The US president couldn't resist taking a sneaky peek without his protective glasses.
US & CANADA

Triggers

Chameleon particle

$$S = \int d^4x\sqrt{-g}\left(-\frac{R}{16\pi G} + \frac{g_{\mu\nu}}{2}\partial_\mu\phi\partial_\nu\phi - V(\phi)\right) + S_{matter}$$

GammeV, CHASE, CERN Axion Solar Telescope



$$\frac{d\rho}{dt} = -3\frac{da/dt}{a}(\rho + P)$$

$$\frac{d\ln(\rho)}{d\ln(a)} = -3(1+w)$$

$$\rho(a) = \rho(a=1)a^{(-3-3w)}$$

$$H(a) = H_0\sqrt{a^{-3}\Omega_{matter,0} + a^{-4}\Omega_{rad,0} + \Omega_{\Lambda,0}} \quad | \quad \begin{array}{l} \Omega_X \equiv \rho_x/\rho_{crit} \\ X_0 = X(a=1) \end{array}$$