Cluster cosmology and the status of ΛCDM

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In collaboration with

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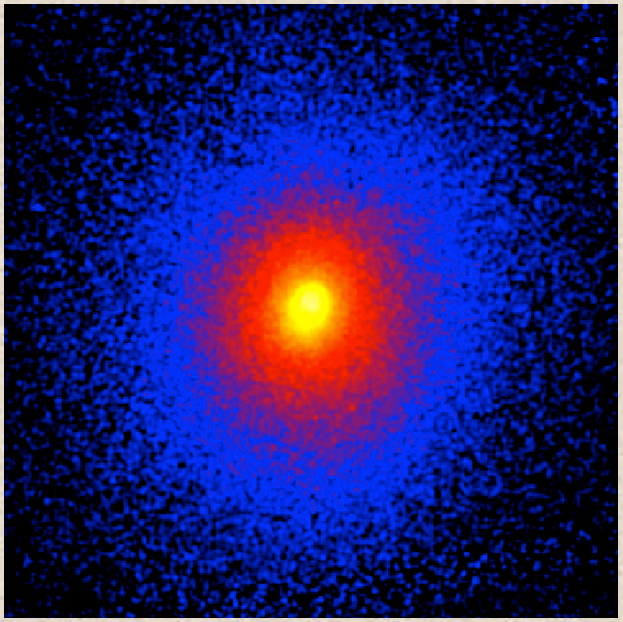
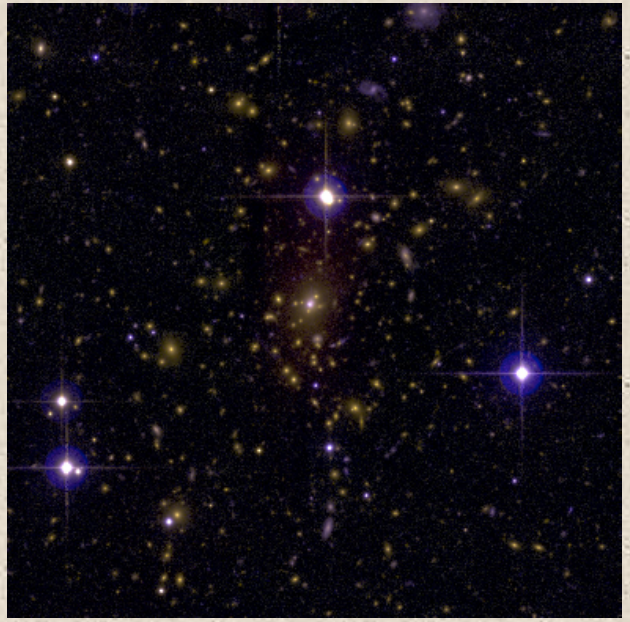
Short introduction

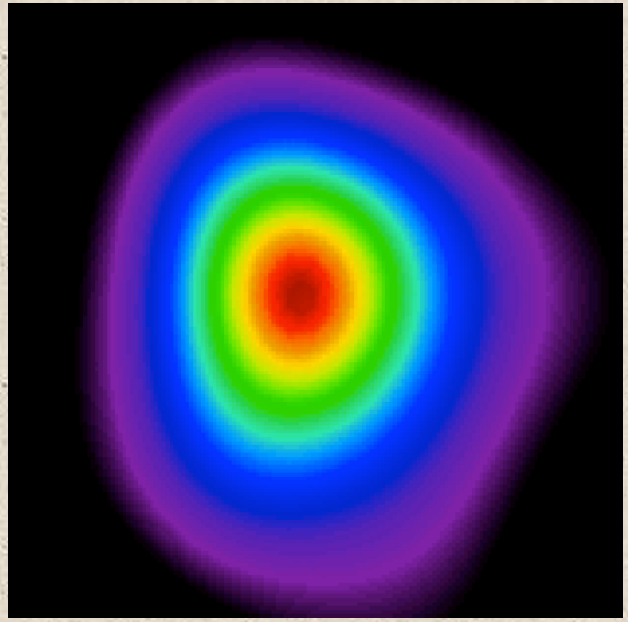
Figure from Allen, Evrard & Mantz 11 (credits X-ray/Mantz; Optical/von der Linden et al; SZ/Marrone)



X-ray



Optical



Millimeter (SZ)

- Images of galaxy cluster Abell 1835 in different wavelength
- Cosmology with galaxy clusters using X-ray observations:
  - Abundance of clusters and their observable-mass relations
  - Gas mass fraction

Outline and keywords

1. Simultaneous measurements of cosmic growth and expansion.

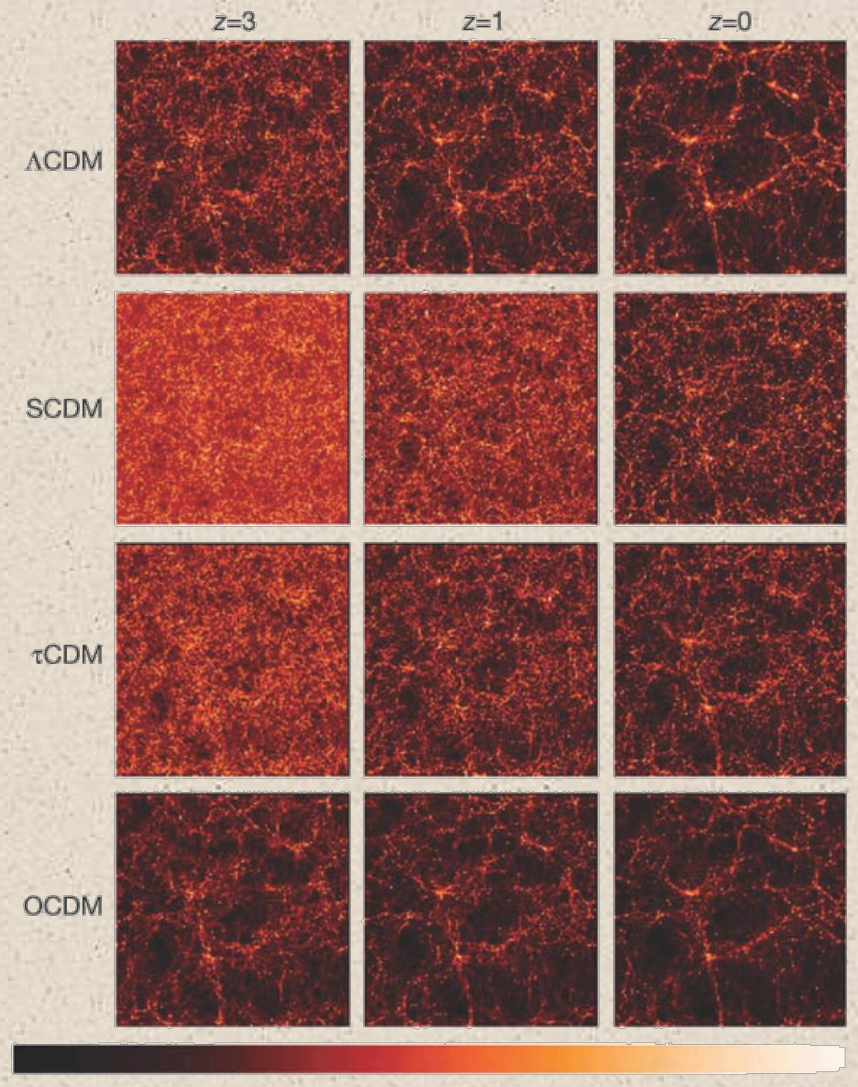
2. Combination of independent experiments with very different systematics: galaxy clusters, CMB, galaxy clustering, SNIa, BAO.

3. Include all the covariances between parameters and break their degeneracies with complementary data.

4. Given cosmic acceleration: consistency test of the current standard model, ΛCDM + General Relativity on all scales (GR has been very well tested from small to Solar system scales but less at cosmic scales).

5. Testing the Gaussianity of the primordial density fluctuations of the inflation paradigm.

Theory: Growth of structure

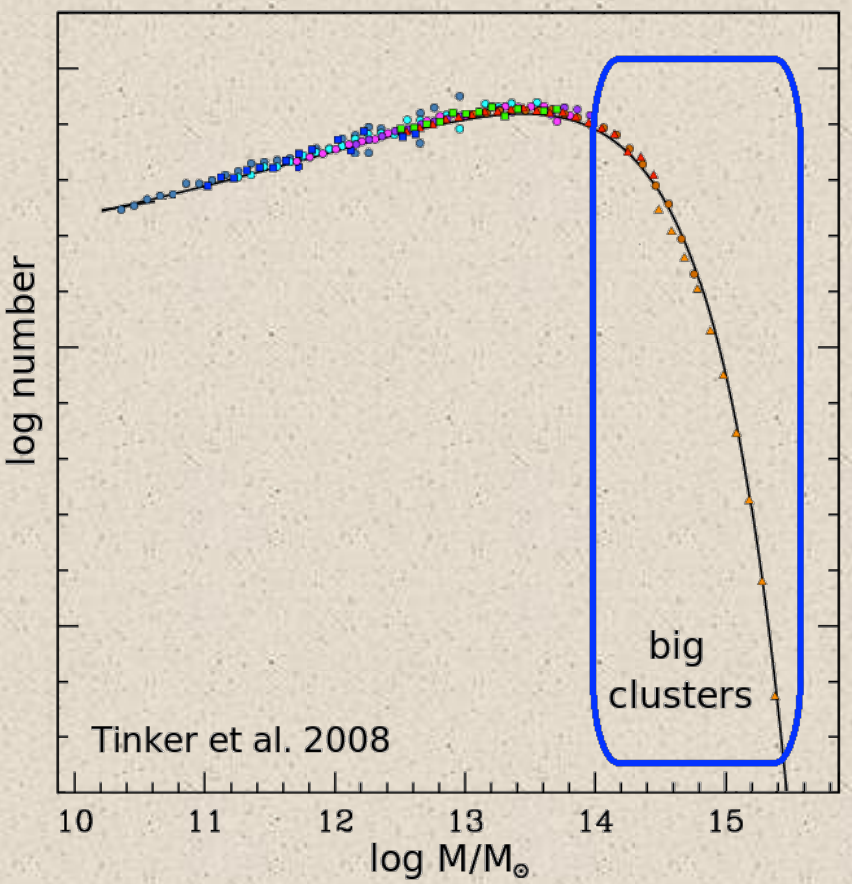


- Simulated cosmologies to model the non-linear growth of structure.

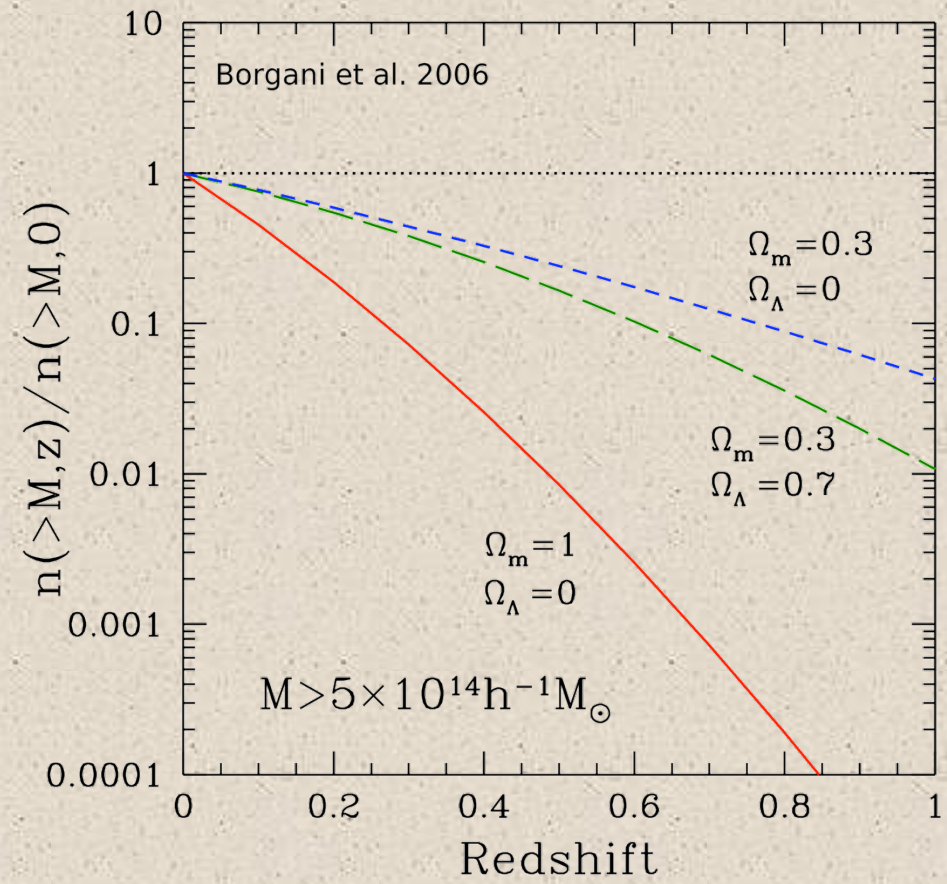
- Even looking so apparently different can be conveniently related with the linear growth calculations through a fitting formula. (See e.g. Jenkins et al 2001, Tinker et al 2008, etc.)

Cole et al 2005

Cluster abundance as a function of mass and redshift

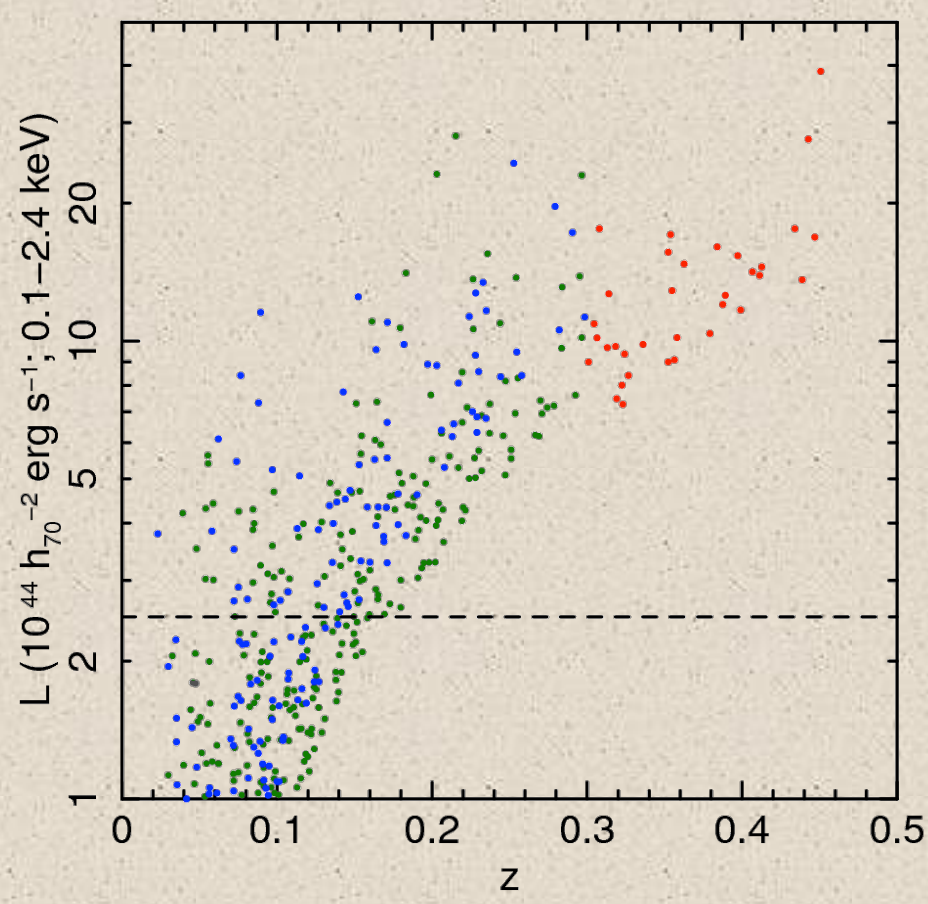


N-body simulations



Linear theory

Cluster survey data



$L > 2.55 \times 10^{44}\ h_{70}^{-2}$ erg s^{-1} (dashed line).
Cuts leave 224 massive clusters

Low redshift (z<0.3)

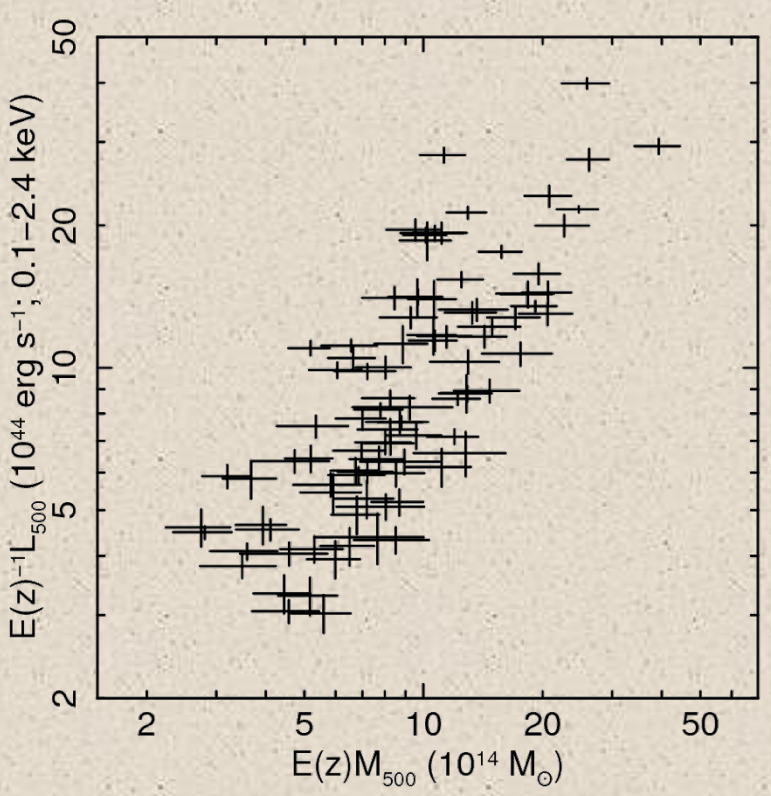
- BCS (Ebeling et al 98, 00)
  $F > 5 \times 10^{-12}$ erg s^{-1} cm^{-2}
  ~33% sky coverage
- REFLEX (Böhringer et al 04)
  $F > 3.0 \times 10^{-12}$ erg s^{-1} cm^{-2}
  ~33% sky coverage

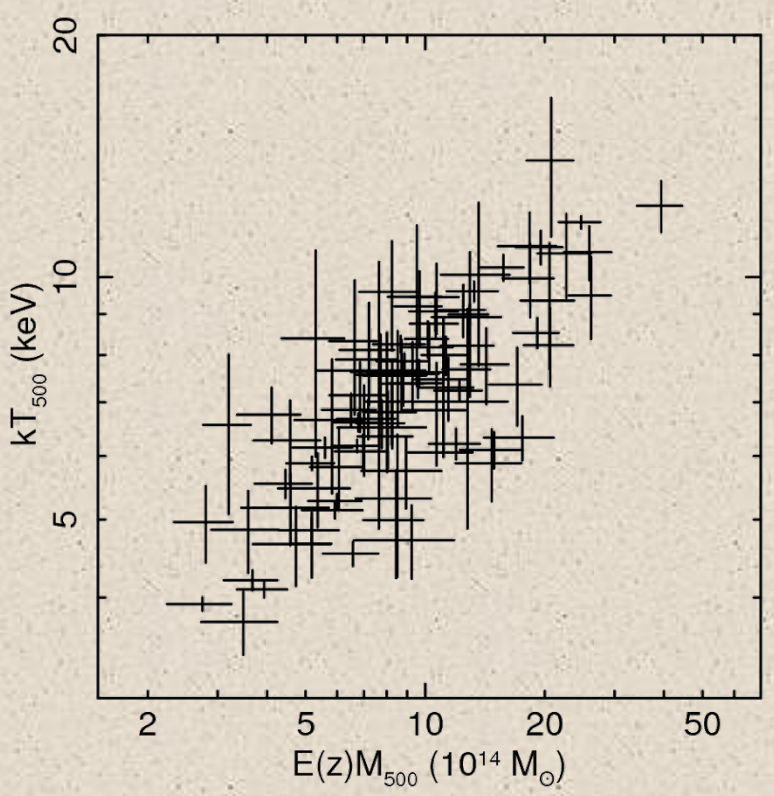
Intermediate redshifts (0.3<z<0.5)

- Bright MACS (Ebeling et al 01, 10)
  $F > 2.0 \times 10^{-12}$ erg s^{-1} cm^{-2}
  ~55% sky coverage

All based on RASS detections. Continuous and all 100% redshift complete.

Scaling relations data: X-ray follow-up for 94 clusters

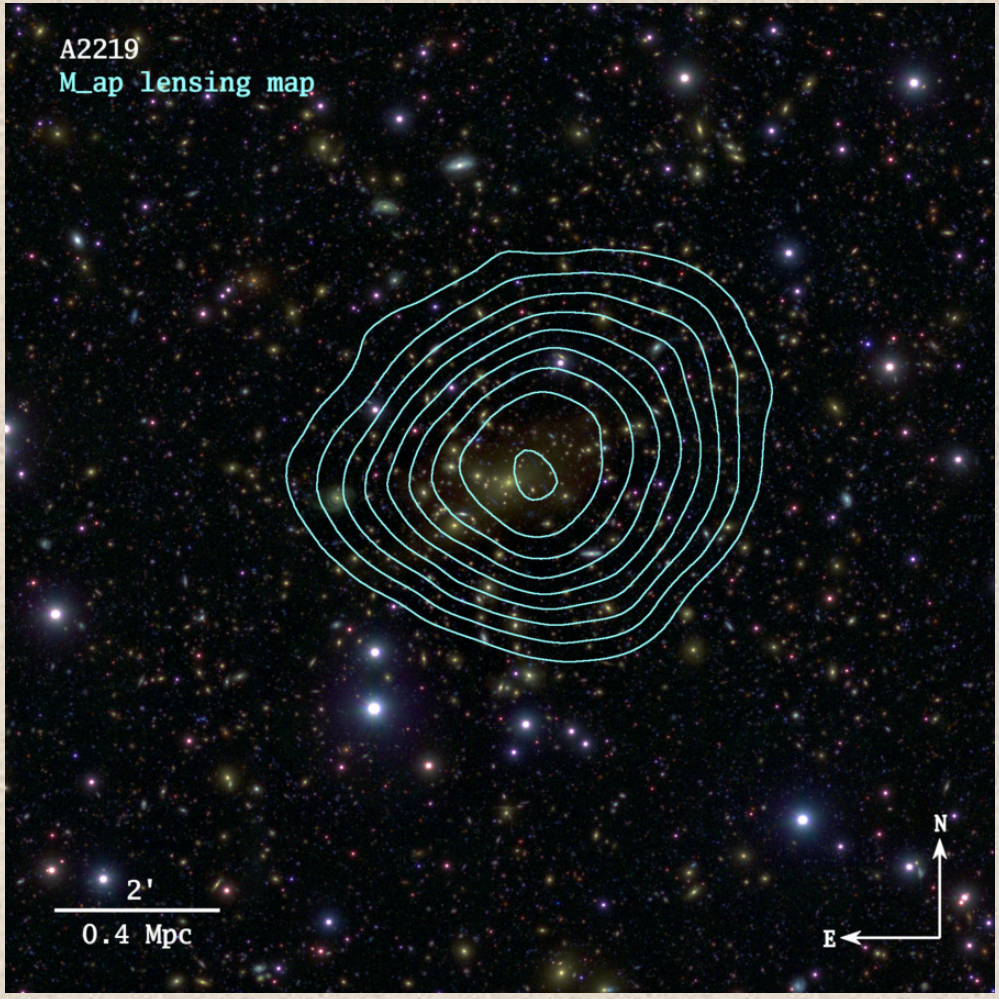




Both, power law, self-similar, constant log-normal scatter.

* Crucial: self-consistent and simultaneous analysis of survey+follow-up data, accounting for selection biases, degeneracies, covariances, and systematic uncertainties.
* Data does not require additional evolution beyond self-similar (see tests in Mantz et al 10b).
* Important cluster astrophysics conclusions (see Mantz et al 10b).

Mass calibration data

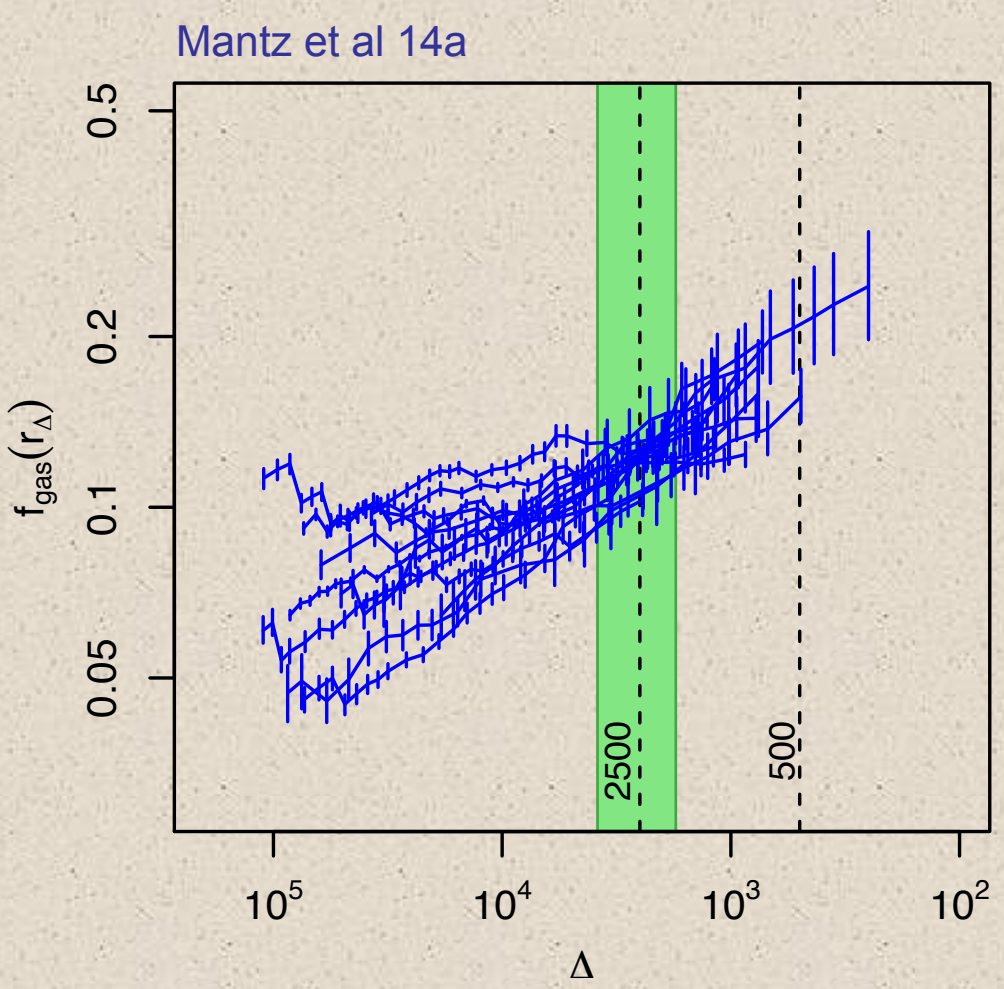


Weighing the Giants (WtG) project.

Subaru/CFHT optical, weak lensing data for 50 clusters to measure the total mass.

High quality data with a robust treatment of the systematic uncertainties.

Gas mass fraction data



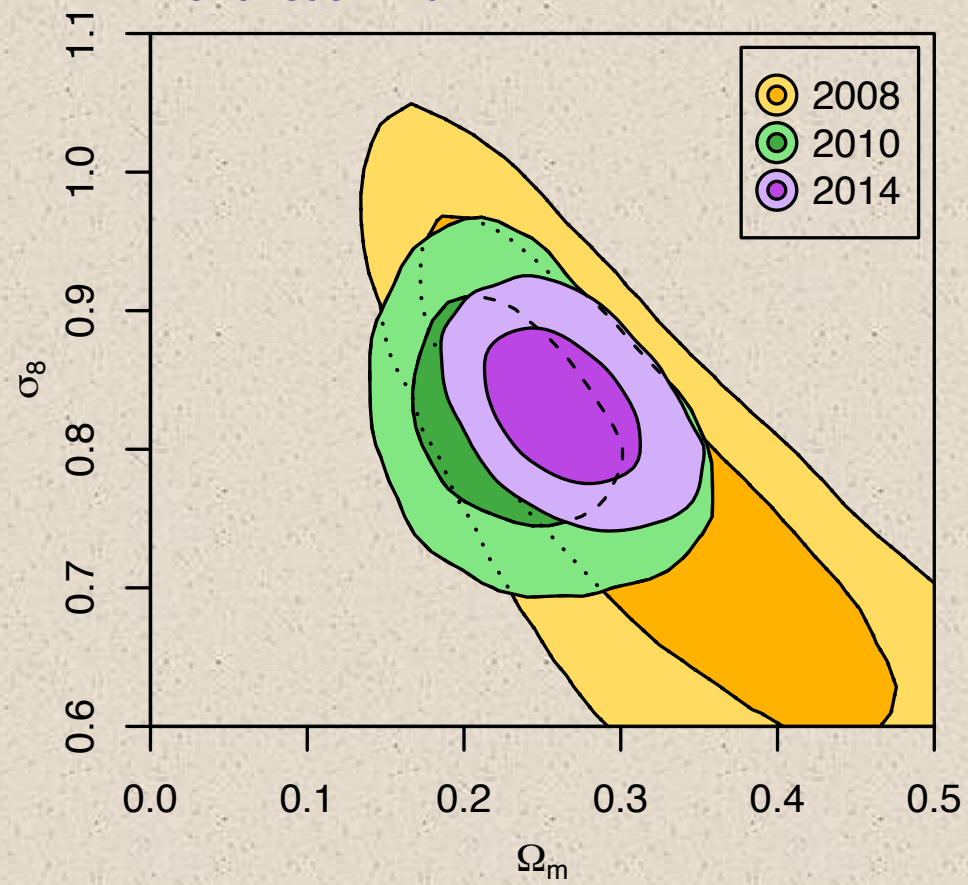
fgas experiment: Chandra measurements of the hottest, most luminous, dynamically relaxed galaxy clusters

Mantz et al 14a: 40 clusters spanning a redshift range $0.07 < z < 1.1$

Independent constraints on Ω_m and additional constraining power on dark energy.

Flat ΛCDM constraints: comparisons

Mantz et al 14b



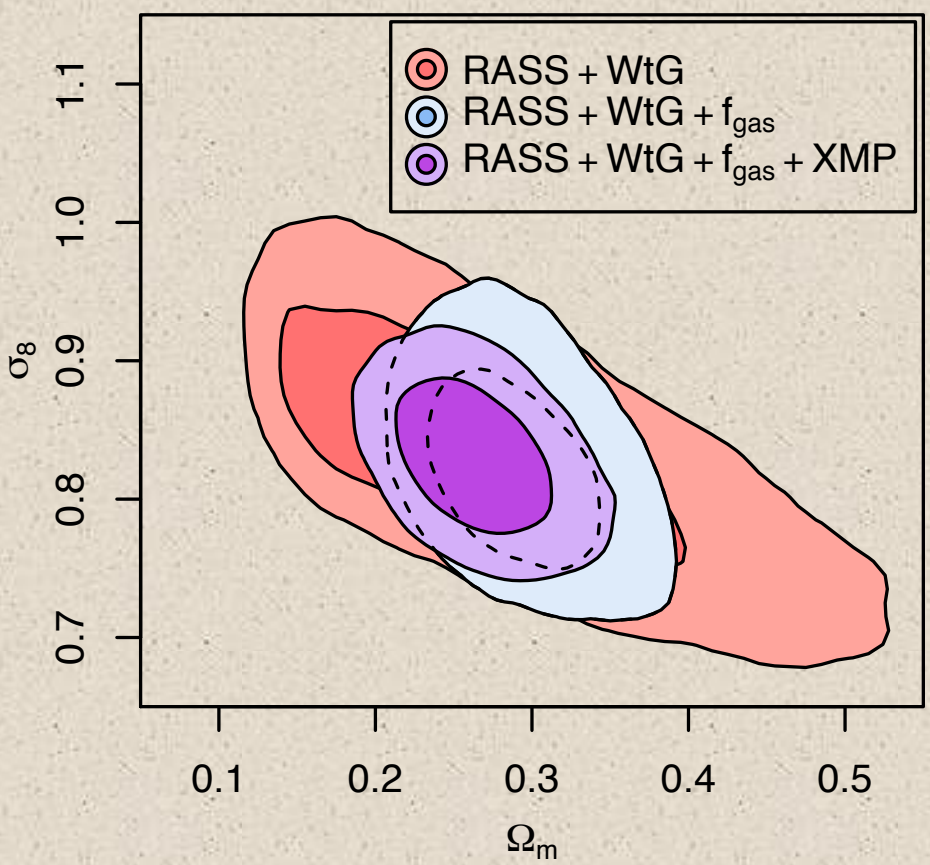
Clusters: counts (survey + X-ray follow-up + WtG) + fgas (M14a) data: BCS +REFLEX+MACS (Mantz et al 14b).

Including systematics and standard priors on $\Omega_b h^2$ and h (when using only clusters but not when combining them with CMB data).

These results are essentially identical in non-flat ΛCDM and flat wCDM.

Flat ΛCDM constraints: comparisons

Mantz et al 14b



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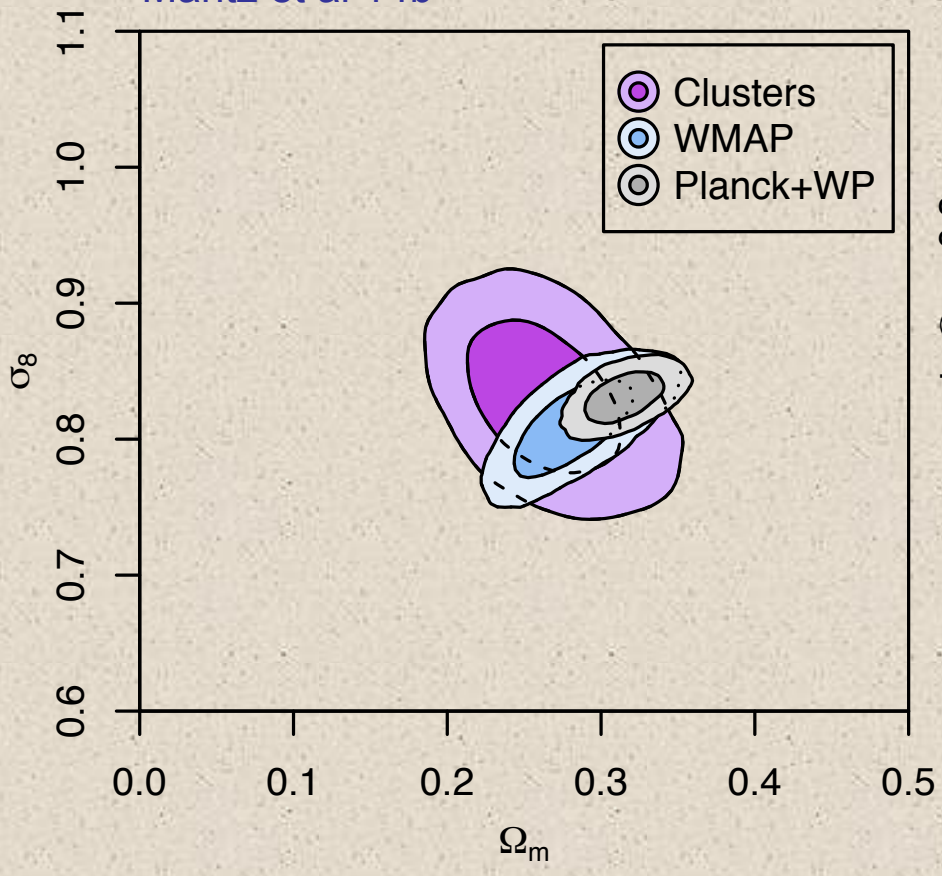
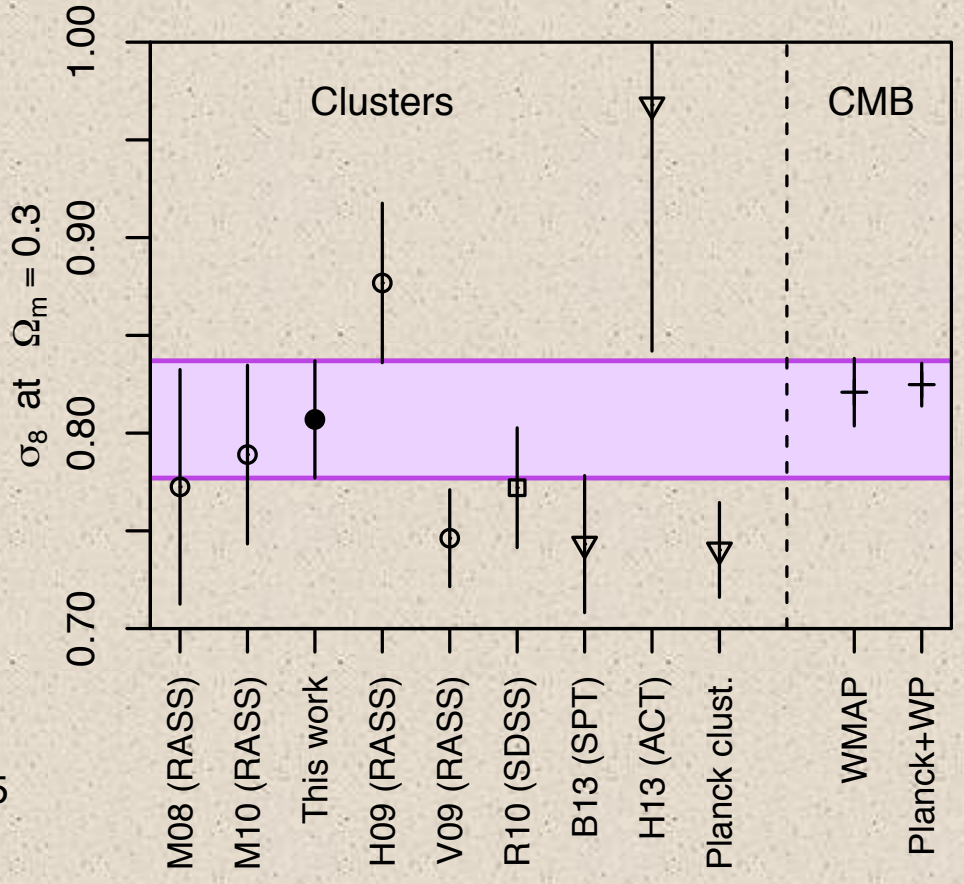
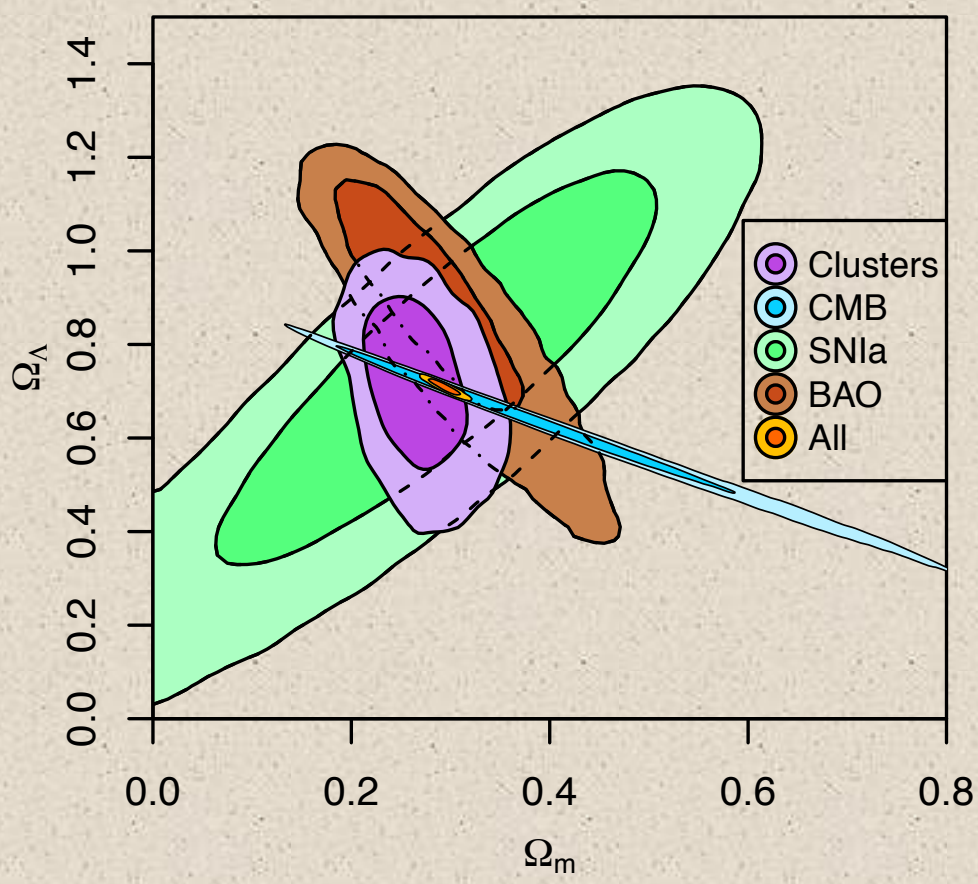




Using our blinded weak lensing mass calibration our results agree with those from the CMB.

Non-flat ΛCDM constraints

Mantz et al 14b



Green: SNIa (Suzuki et al 12, Union 2.1)

Blue: CMB (WMAP9+ACT+SPT)

Brown: BAO (Beutler et al 11, Padmanabhan et al 12, Anderson et al 14)

Gold: Clusters+CMB+SNIa+BAO

Clusters: counts (survey + X-ray follow-up + WtG) + fgas (M14a) data: BCS +REFLEX+MACS (Mantz et al 14b). Including systematics.

$\Omega_m = 0.261 \pm 0.032$
$\sigma_8 = 0.830 \pm 0.035$
$\Omega_\Lambda = 0.728 \pm 0.115$

WtG mass calibration

Constraints on dark energy

All data sets

1. Abundance of massive clusters (cluster counts) to measure cosmic expansion and growth of matter fluctuations with respect to the mean density.

$$D(z) \equiv \frac{\delta(z)}{\delta(z_{\rm t})} = \frac{\sigma(M,z)}{\sigma(M,z_{\rm t})} \qquad \delta = (\rho_{\rm m} - \bar{\rho}_{\rm m})/\bar{\rho}_{\rm m}$$

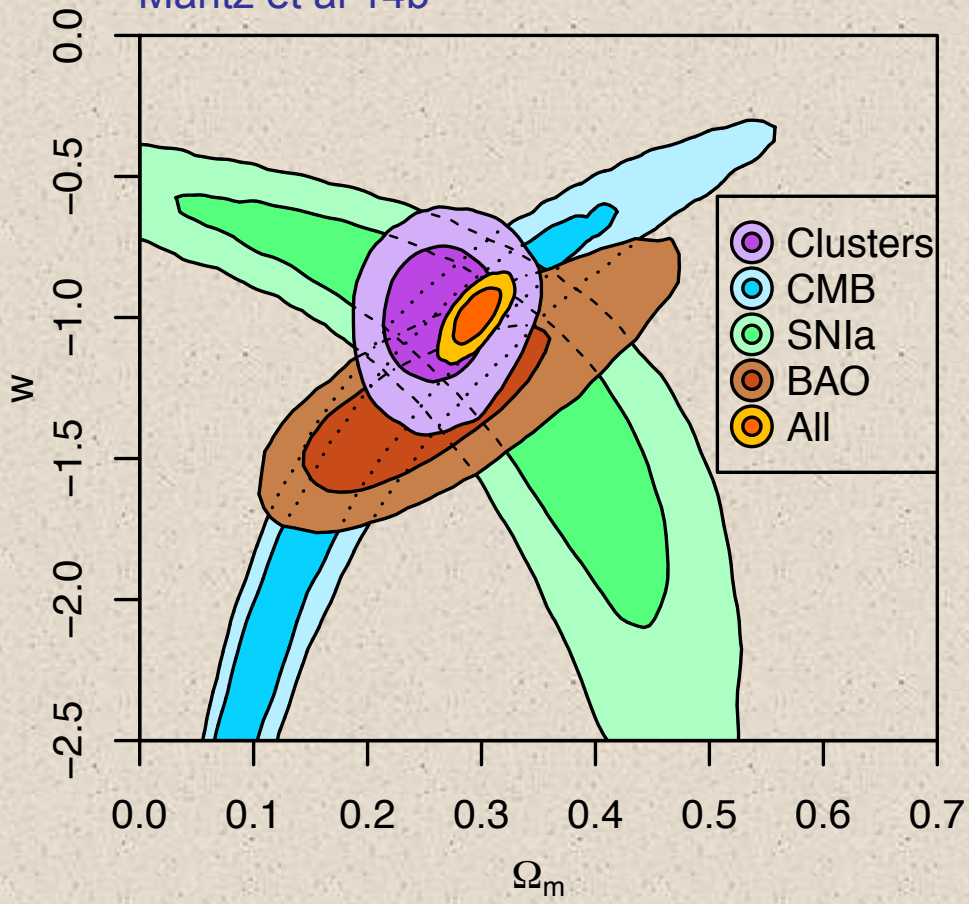
2. SNIa, f_{gas}, cluster counts, CMB, BAO to measure the cosmic expansion of the background density. We use three expansion histories well fitted by these data sets.

$$E(a) = \left[\Omega_{\rm m}\, a^{-3} + \Omega_{\rm de}\, a^{-3(1+w)} + \Omega_{\rm k}\, a^{-2}\right]^{1/2}$$

i) flat ΛCDM w=-1, Ω_k=0
ii) flat *w*CDM w constant, Ω_k=0
iii) non-flat ΛCDM w=-1, Ω_k constant

Dark Energy results: flat wCDM

Mantz et al 14b



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$\Omega_m = 0.261 \pm 0.031$
$\sigma_8 = 0.831 \pm 0.036$
$w = -0.98 \pm 0.15$

WtG mass calibration

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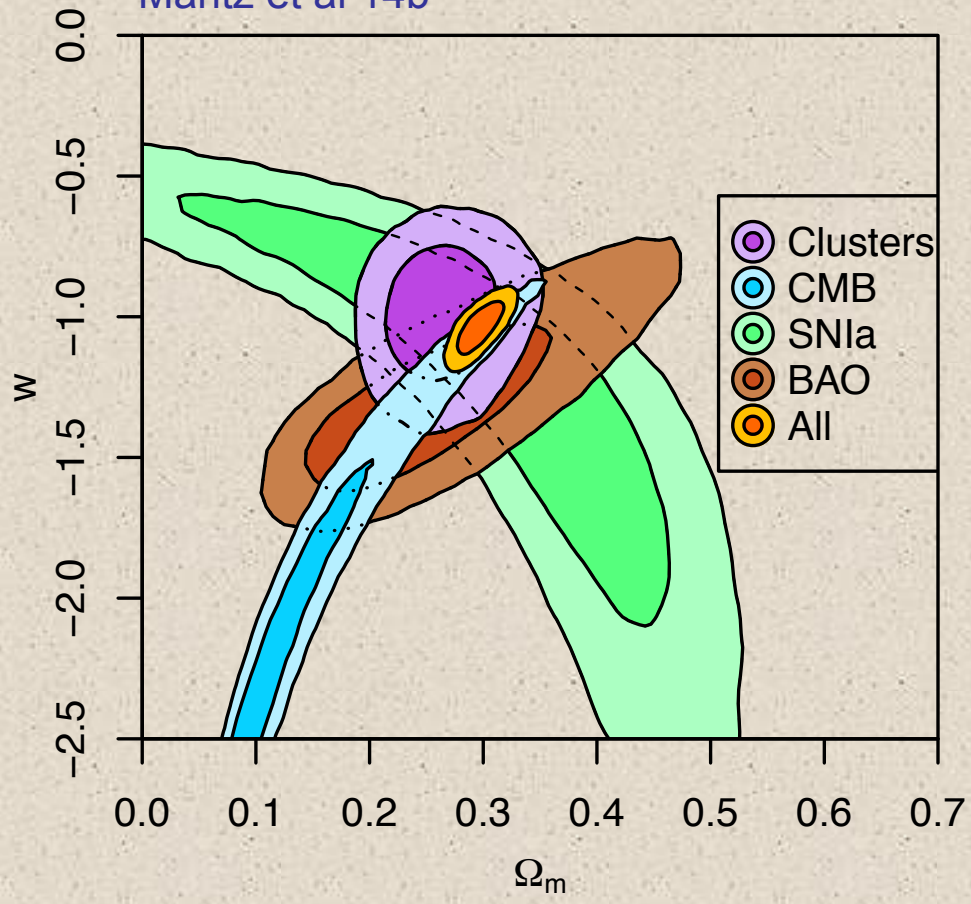

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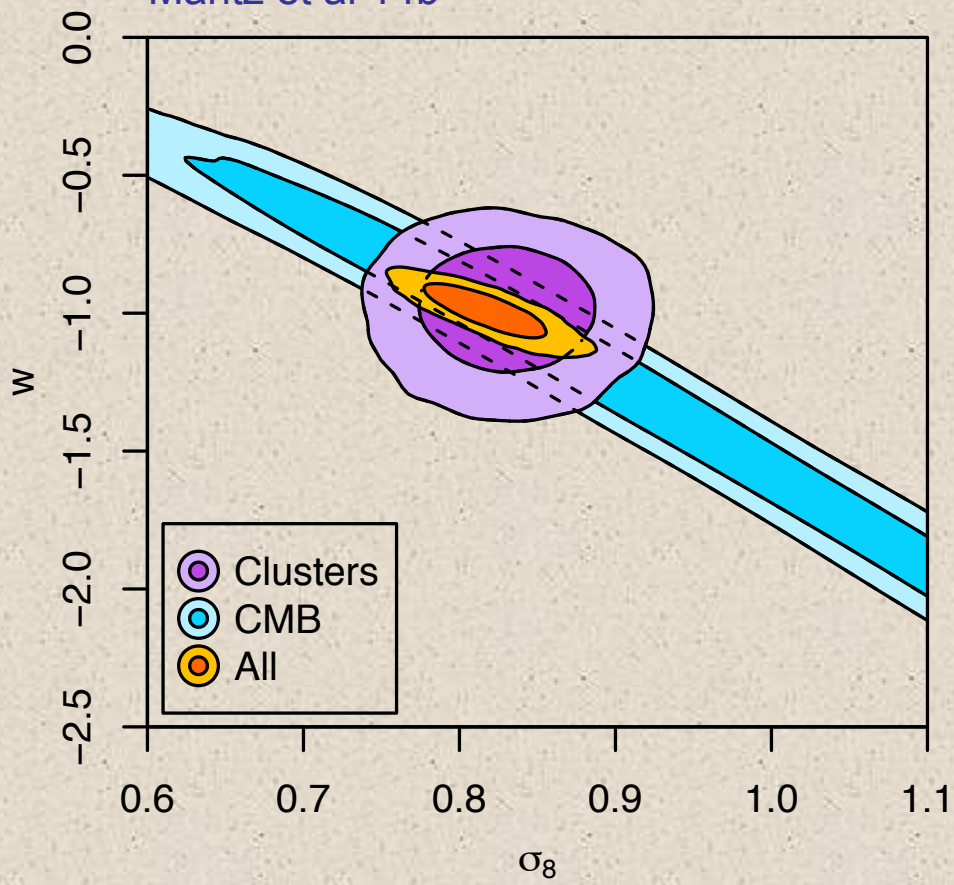


Blue: CMB (WMAP9+ACT+SPT)

Gold: Clusters+CMB+SNIa+BAO

Ω_m = 0.295 ± 0.013
σ_8 = 0.819 ± 0.026
w = −0.99 ± 0.06

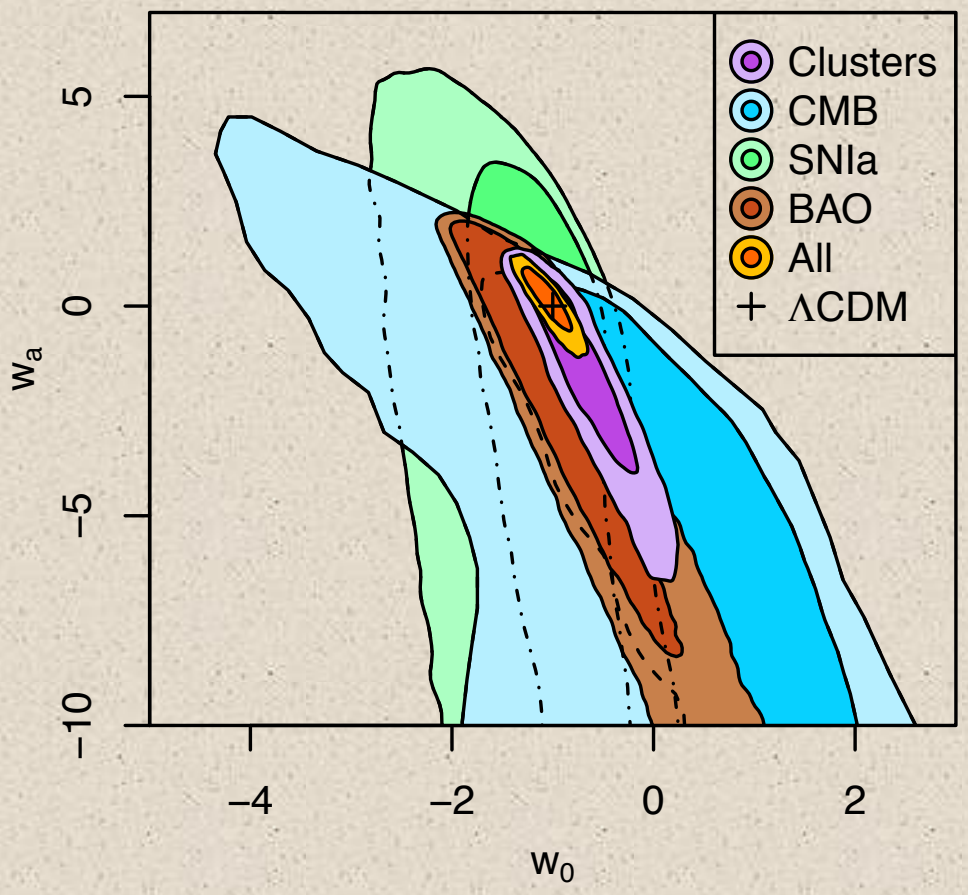
Clusters: counts (survey + X-ray follow-up + WtG) + fgas (M14a) data: BCS +REFLEX+MACS (Mantz et al 14b). Including systematics.

Ω_m = 0.261 ± 0.031
σ_8 = 0.831 ± 0.036
w = −0.98 ± 0.15

Testing ΛCDM: Evolving dark energy w(z)

Constraints on evolving w(z): w_0, w_a

Mantz et al 14b



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Gold: Clusters+CMB+SNIa+BAO

$w_0 = -1.04 + 0.13 - 0.18$

$w_a = 0.3 + 0.4 - 0.6$

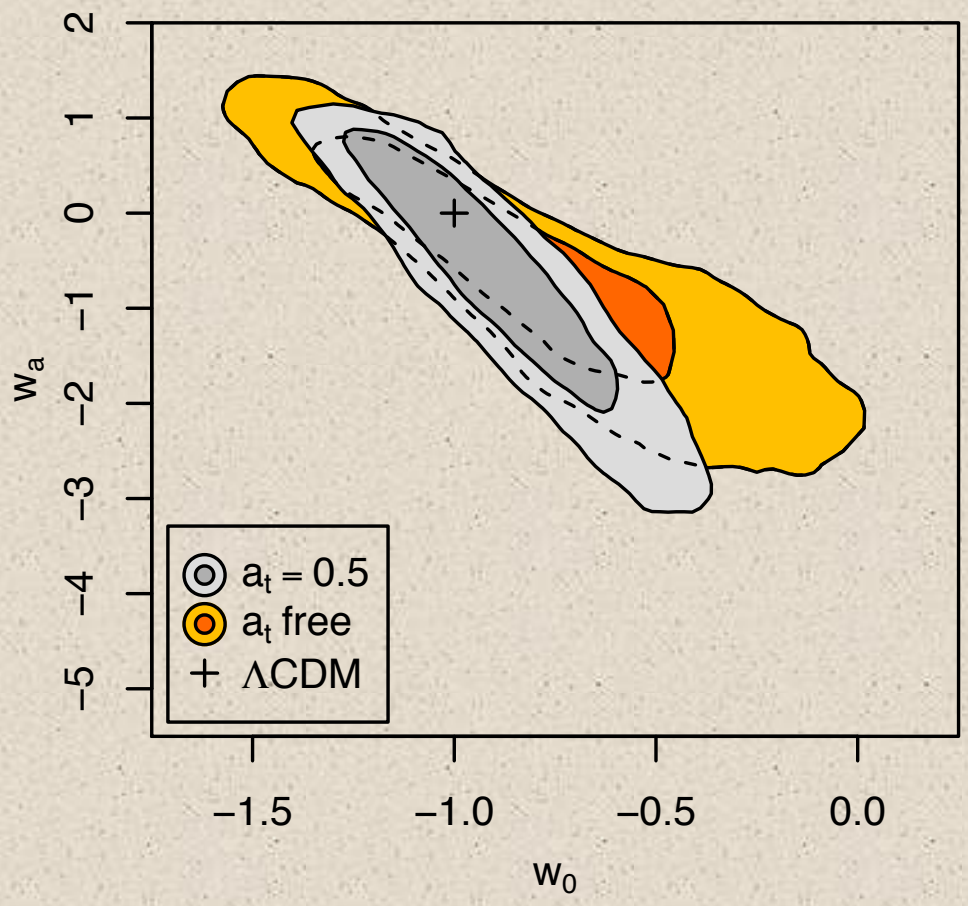
$w_{et} = -0.8 + 0.3 - 0.4$

Two parameters:

$w=w_0+w_a(1-a)$ fix transition at $z_t=1$ between w_0 (present) and $w_{et}=w_0+w_a$ (early times).

Constraints on w_0, w_a marginalizing over a_t

Mantz et al 14b



Gold: combined constraints; free curvature and marginalized over $0.05<a_t<0.95$

w_0 = -0.97 + 0.40 – 0.22

w_a = -0.1 + 0.6 – 1.2

Two parameters:

$w=w_0+w_a(1-a)$ fix transition at $z_t=1$ between w_0 (present) and $w_{et}=w_0+w_a$ (early times).

Three parameters:

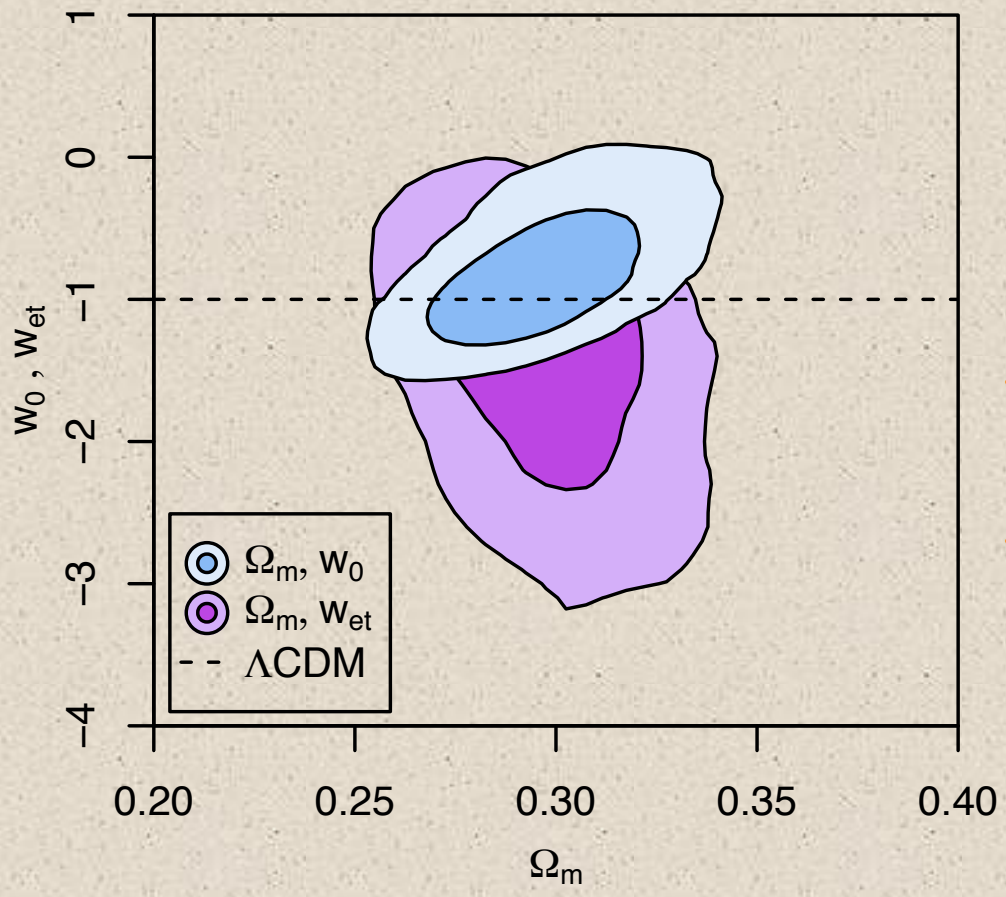
free transition a_t between w_0 and w_{et}:

$$w = \frac{w_{\rm et} z + w_0 z_{\rm t}}{z + z_{\rm t}} = \frac{w_{\rm et}(1-a)a_{\rm t} + w_0(1-a_{\rm t})a}{a(1-2a_{\rm t}) + a_{\rm t}}$$

Rapetti et al 05

Constraints on w_0, w_{et} marginalizing over a_t

Mantz et al 14b



Combined constraints; free curvature and marginalized over $0.05<a_t<0.95$

$w_0 = -0.97 + 0.40 - 0.22$

$w_{et} = -1.1 + 0.5 - 0.7$

Two parameters:

$w=w_0+w_a(1-a)$ fix transition at $z_t=1$ between w_0 (present) and $w_{et}=w_0+w_a$ (early times).

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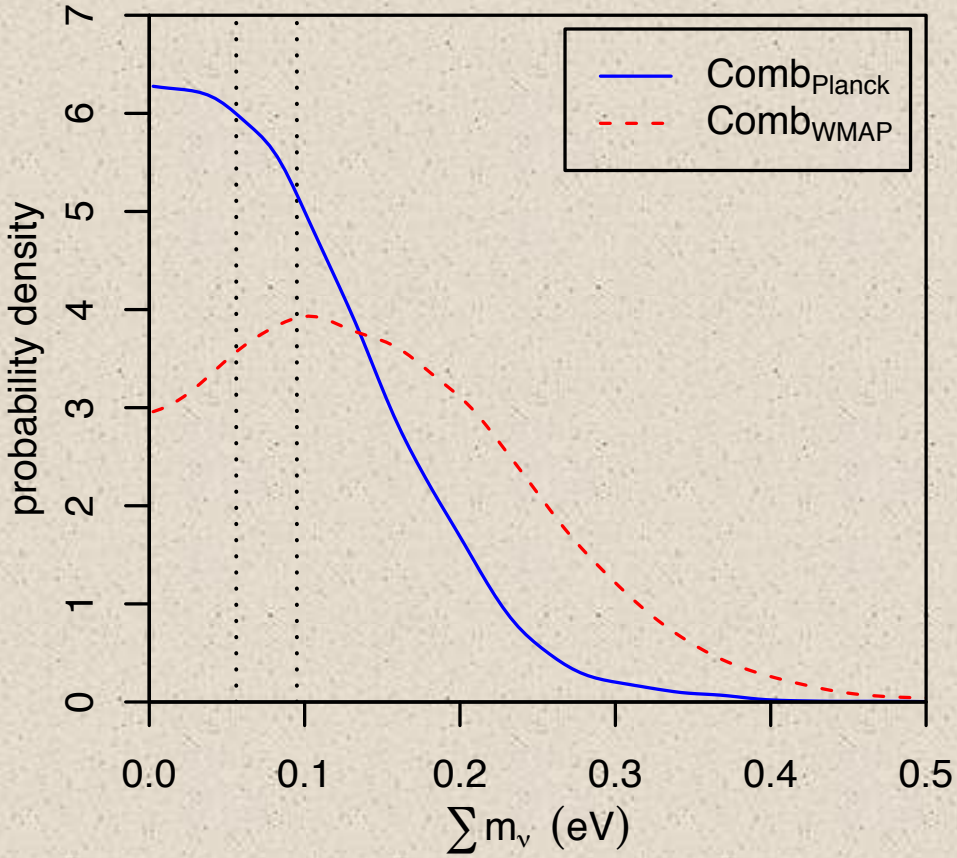
Rapetti et al 05

Testing ΛCDM: Neutrino properties

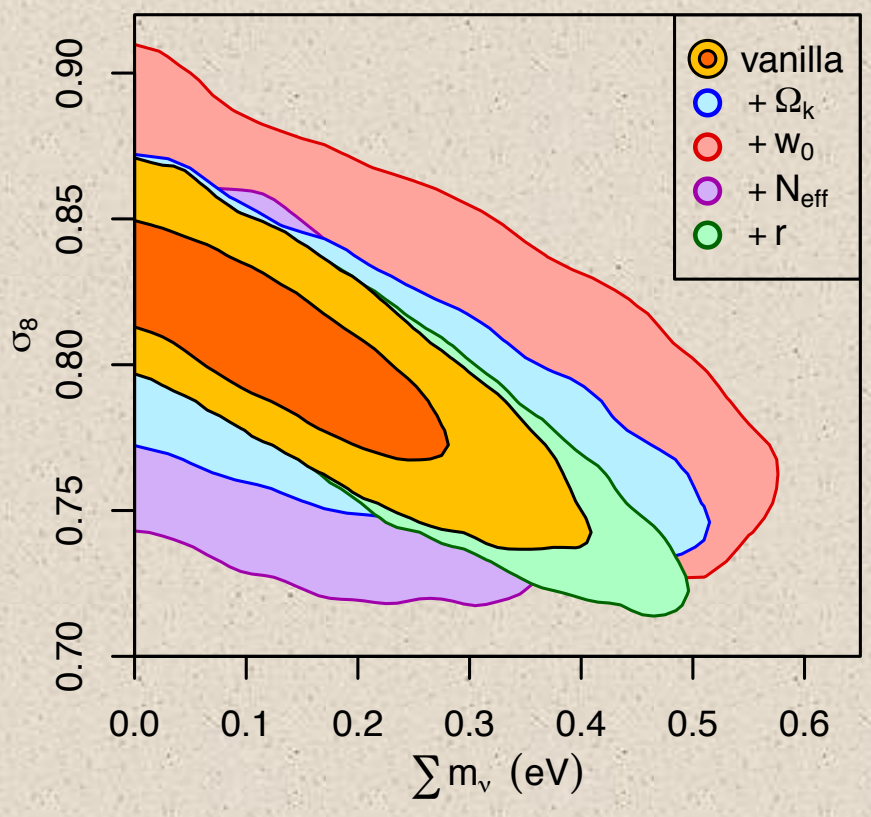
Robust constraints on neutrino properties

Clusters+CMB+SNIa+BAO
WMAP: neutrino mass < 0.33eV
Planck+WP: neutrino mass < 0.22eV



Vanilla: ΛCDM+Σm_ν

CMB (WMAP+)+SNIa+BAO+Clusters



Mantz et al 14b

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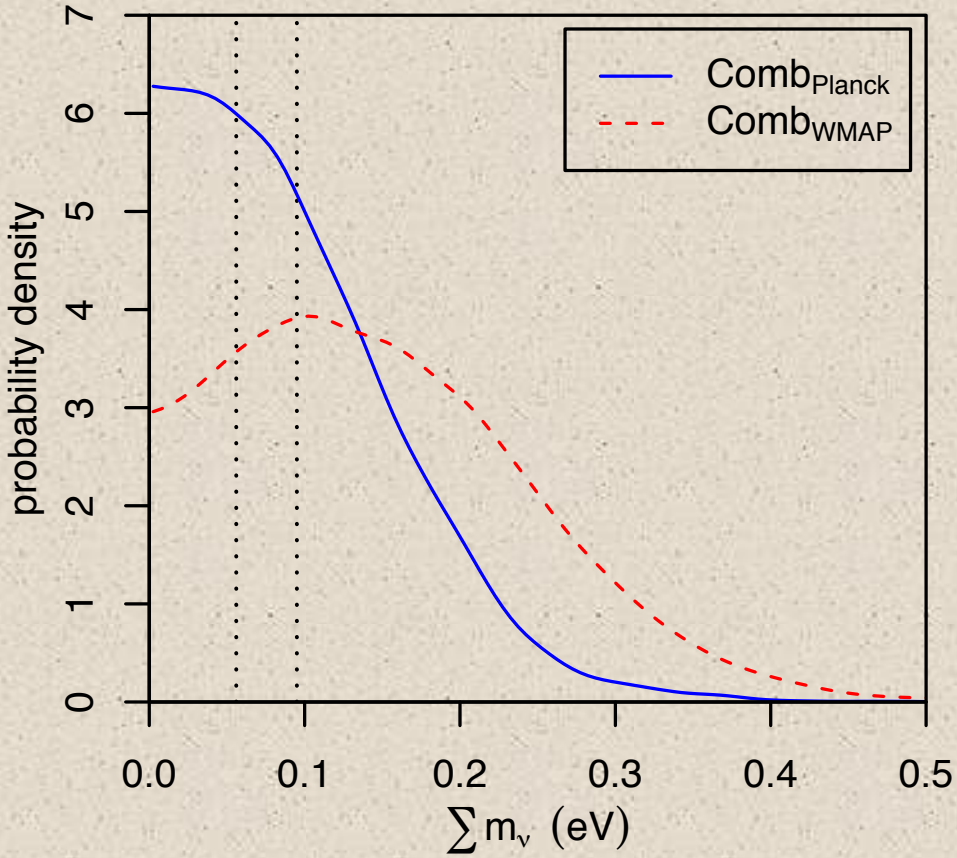

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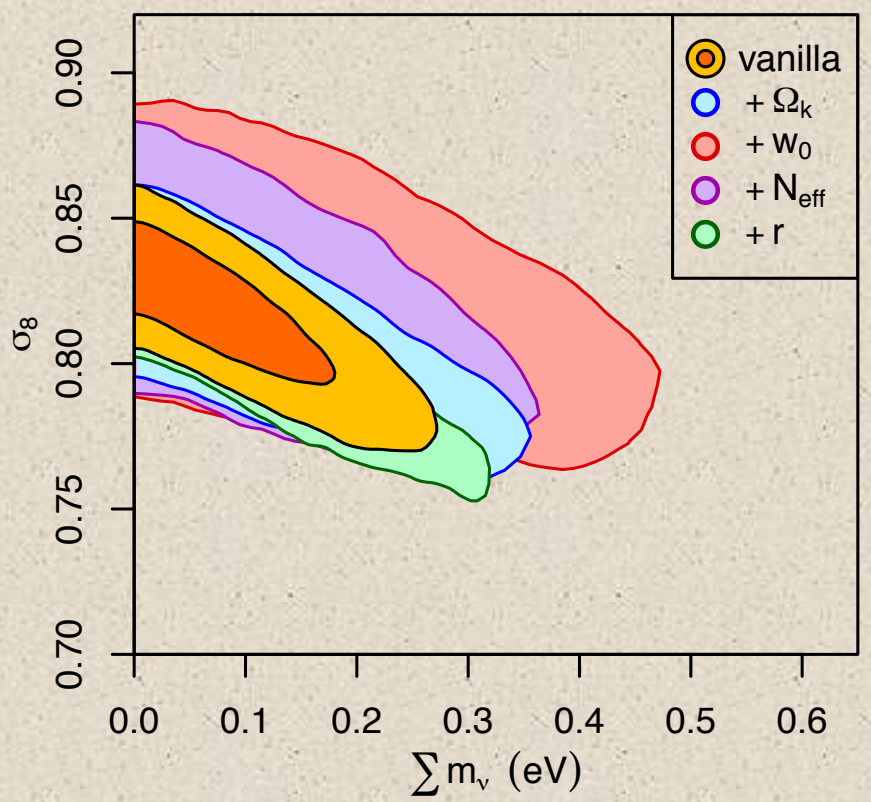


Mantz et al 14b

Testing ΛCDM: Gravity at large scales

Modeling linear, time-dependent cosmic growth (departing from GR)

$$P(k, z) \propto k^{n_s} T^2(k, z_t) D(z)^2$$

Linear power spectrum

$$D(z) \equiv \delta(z)/\delta(z_t)$$

Growth factor

$$f(a) \equiv \frac{\mathrm{d}\ln\delta}{\mathrm{d}\ln a} = \Omega_m(a)^\gamma$$

Growth rate; power law description

$$\Omega_m(a) = \Omega_m a^{-3} E(a)^{-2}$$

Evolving mean matter density

$$\ddot{\delta} + 2\frac{\dot{a}}{a}\dot{\delta} = 4G\pi\bar{\rho}_m\delta$$

Scale independent in the synchronous gauge

General relativity (γ~0.55)

$$\gamma = \ln f(z)/\ln \Omega_m(z)$$

To measure γ we need measurements of growth, f(z), and expansion, $\Omega_m(z)$.

Consistency test of the growth rate of General Relativity

1. We use a phenomenological time-dependent parameterization of the growth rate and of the expansion history.

2. We assume the same scale-dependence as GR.

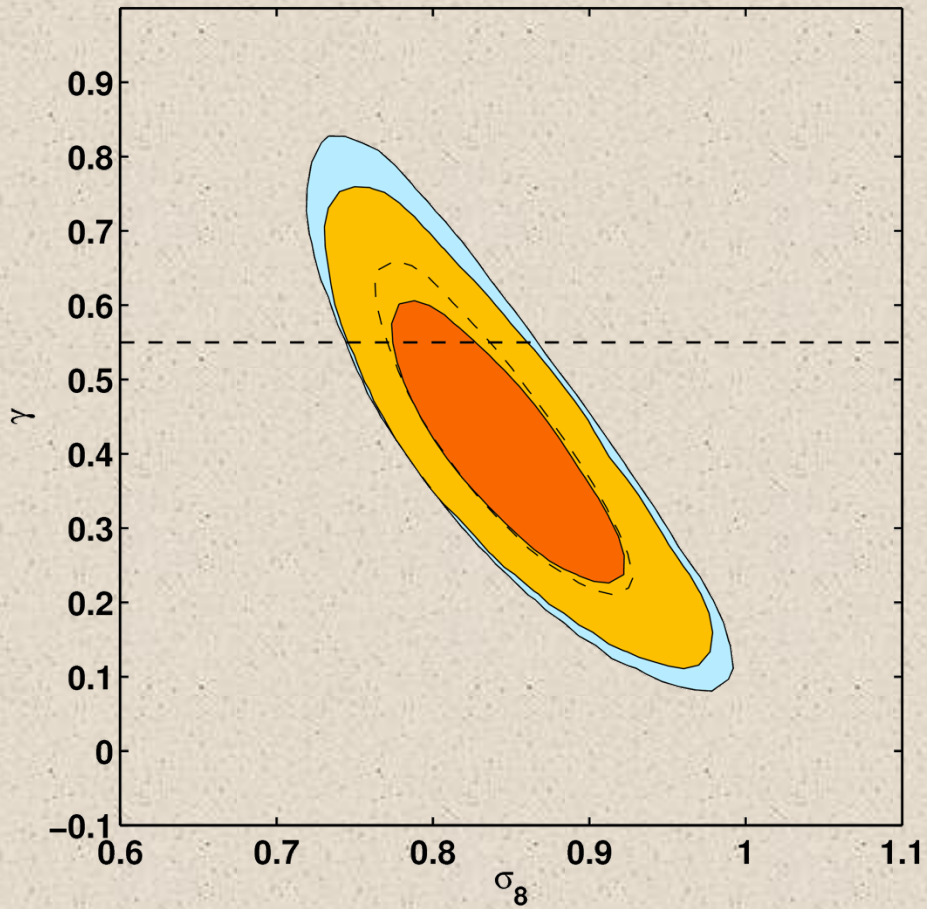
3. We test only for linear effects (not for non-linear effects). We use the "universal" dark matter halo mass function (Tinker et al 2008). Note that the relevant scales for the cluster abundance experiment are at the low end of the linear regime.

4. We match GR at early times and small scales.

5. We assume 3 species of massless neutrinos.

flat ΛCDM + growth index γ

Rapetti et al 10



XLF: BCS+REFLEX+MACS (z<0.5)

238 survey with 94 X-ray follow-up

CMB (WMAP5)

SNIa (Kowalski et al 2008, UNION)

cluster f_{gas} (Allen et al 2008)

For General Relativity γ~0.55

Gold: Self-similar evolution and constant scatter

Blue: Marginalizing over β^{lm}_2 and σ'_{lm}

$$\gamma\left(\frac{\sigma_8}{0.8}\right)^{6.8} = 0.55^{+0.13}_{-0.10}$$

Tight correlation between σ_8 and γ:

$$\rho = -0.87$$

Redshift space distortions and Alcock-Paczynski effect

e.g. Blake et al 11; Beutler et al 12; Reid et al 12

Anisotropic galaxy clustering: RSD and AP effect

Sources of anisotropy in the distribution of galaxies (2-point statistics) used to constrain the cosmological model:

- Redshift space distortions: due to velocity patterns of galaxies infalling into gravitational potential wells

$$f\sigma_8(z)$$

f(z) is the linear growth rate and $\sigma_8(z)$ the variance in the density field at $8h^{-1}$Mpc

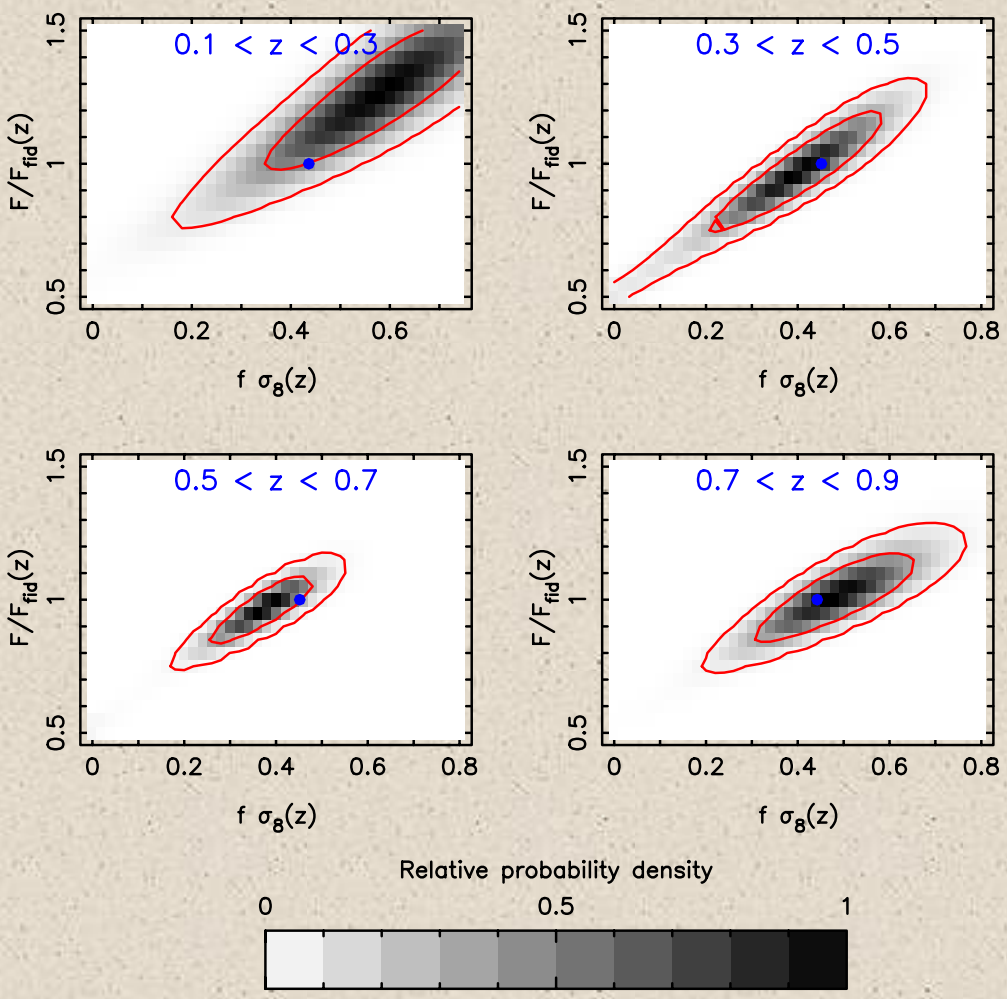
- Alcock-Paczynski distortion: between the tangential and radial dimensions of objects or patterns when the correct cosmological model is assumed to be isotropic

$$F(z) = (1+z)D_A(z)H(z)/c$$

$D_A(z)$ is the angular diameter distance and $H(z)=H_0E(z)$ is the Hubble parameter

WiggleZ and 6dFGS constraints on RSD and AP effect

Blake et al 11



For WiggleZ (Blake et al 11):
- We use a bivariate Gaussian likelihood on $f\sigma_8(z)$ and F(z) (good approximation):

z = (0.22, 0.41, 0.60, 0.78)

$f\sigma_8(z)$ = (0.53±0.14, 0.40±0.13, 0.37±0.08, 0.49±0.12)

F(z) = (0.28±0.04, 0.44±0.07, 0.68±0.06, 0.97±0.12)

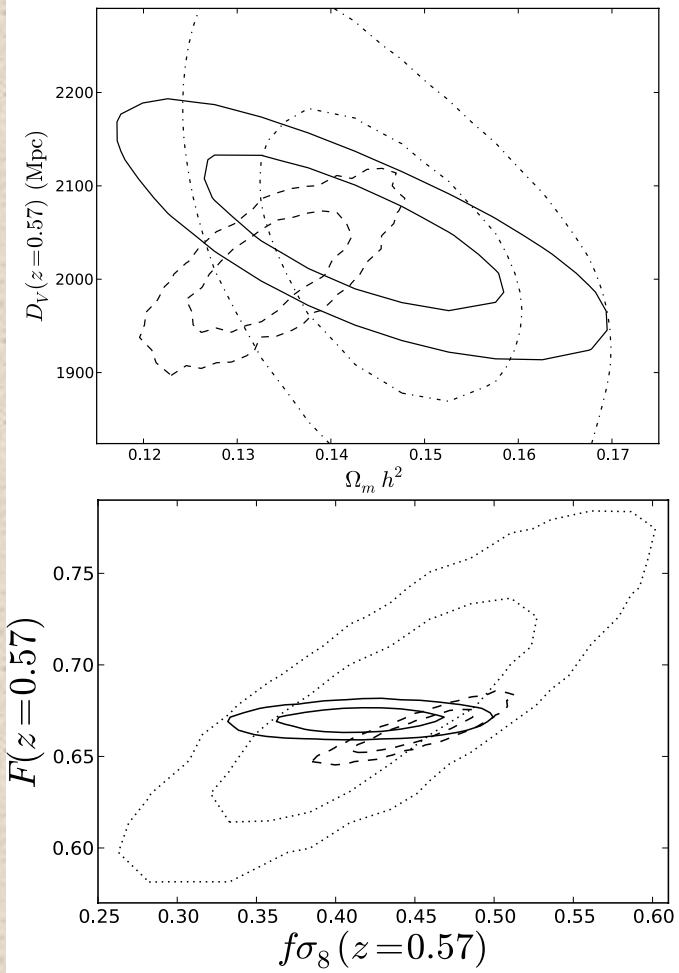
r=(0.83, 0.94, 0.89, 0.84)

For 6dFGS (Beutler et al 2012):
- We use a Gaussian likelihood on $f\sigma_8(z)$ only (since at low-z the AP effect is negligible):

$f\sigma_8(z=0.067) = 0.423 \pm 0.055$

SDSS-III CMASS BOSS constraints

Reid et al 12



For CMASS BOSS (Reid et al 2012):

- We use either a bivariate (growth) or a trivariate (BAO) Gaussian likelihood on $f\sigma_8(z)$, $F(z)$ and $\alpha(z)$ (good approximation):

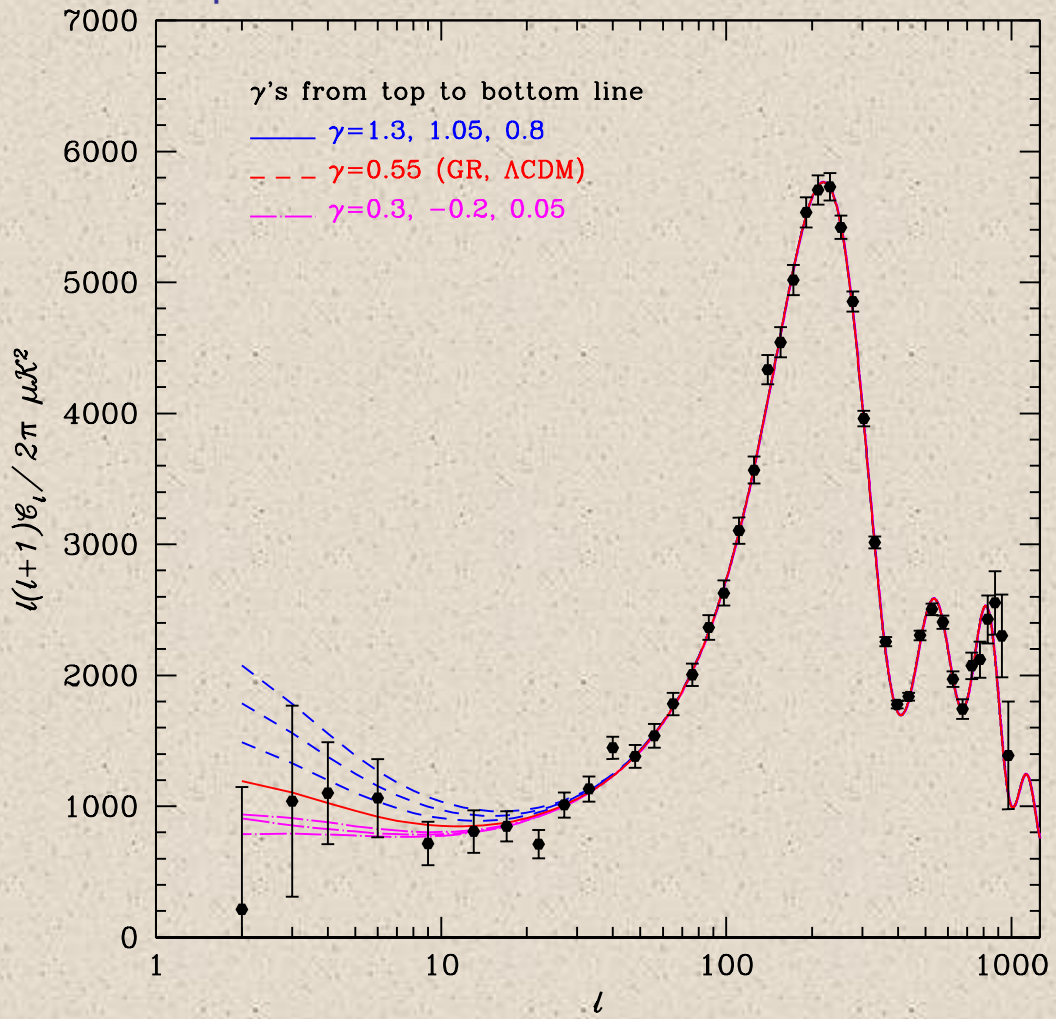
$f\sigma_8(z=0.57) = 0.43 \pm 0.07$
$F(z=0.57) = 0.68 \pm 0.04$
$\alpha(z=0.57) = 1.023 \pm 0.019$

$r_{f\sigma F} = 0.87$
$r_{f\sigma\alpha} = -0.0086$
$r_{F\alpha} = -0.080$

$$\alpha \equiv [d_z]_{\rm fiducial}/d_z \quad d_z \equiv r_s(z_d)/D_v(z)$$
$$D_v(z) \equiv [(1+z)^2 D_A(z)^2 c\, z/H(z)]^{1/3}$$

CMB constraints and the Integrated Sachs-Wolfe effect

Rapetti et al 09



The ISW effect changes for different growth rates.

$$\Delta_l^{\mathrm{ISW}}(k) = 2\int \mathrm{d}t\, \mathrm{e}^{-\tau(t)}\phi'\, j_l\,[k(t-t_0)]$$

$$\phi' = 4\pi G a^2 k^{-2}\,\mathcal{H}\,\delta\rho_{\mathrm{m}}\,[1-\Omega_{\mathrm{m}}(a)^{\gamma}]$$

Plus constraints on energy density content, reionization and background expansion:

$$\Omega_{\mathrm{b}}h^2 \quad \Omega_{\mathrm{c}}h^2 \quad \tau \quad \ln(A_{\mathrm{s}}) \quad n_{\mathrm{s}} \quad \theta$$

Summary: physics of the observables

$$\sigma_8(z) = \sigma_8 e^{-g(z)}$$ Density field variance

$$\Omega_{\rm m}(a) = \Omega_{\rm m} a^{-3} E(a)^{-2}$$ Mean matter density

Galaxy clusters

$$f\sigma_8(z)$$ RSD

$$F(z) = (1+z) D_{\rm A}(z) H(z)/c$$ AP effect

Galaxy clustering

$$\phi' = 4\pi G a^2 k^{-2} \mathcal{H}\, \delta\rho_{\rm m} \left[1 - \Omega_{\rm m}(a)^{\gamma}\right]$$ ISW

$$\Omega_{\rm b} h^2\, \Omega_{\rm c} h^2\, \tau\, \ln(A_{\rm s})\, n_{\rm s}\, \theta$$ Anisotropies

CMB

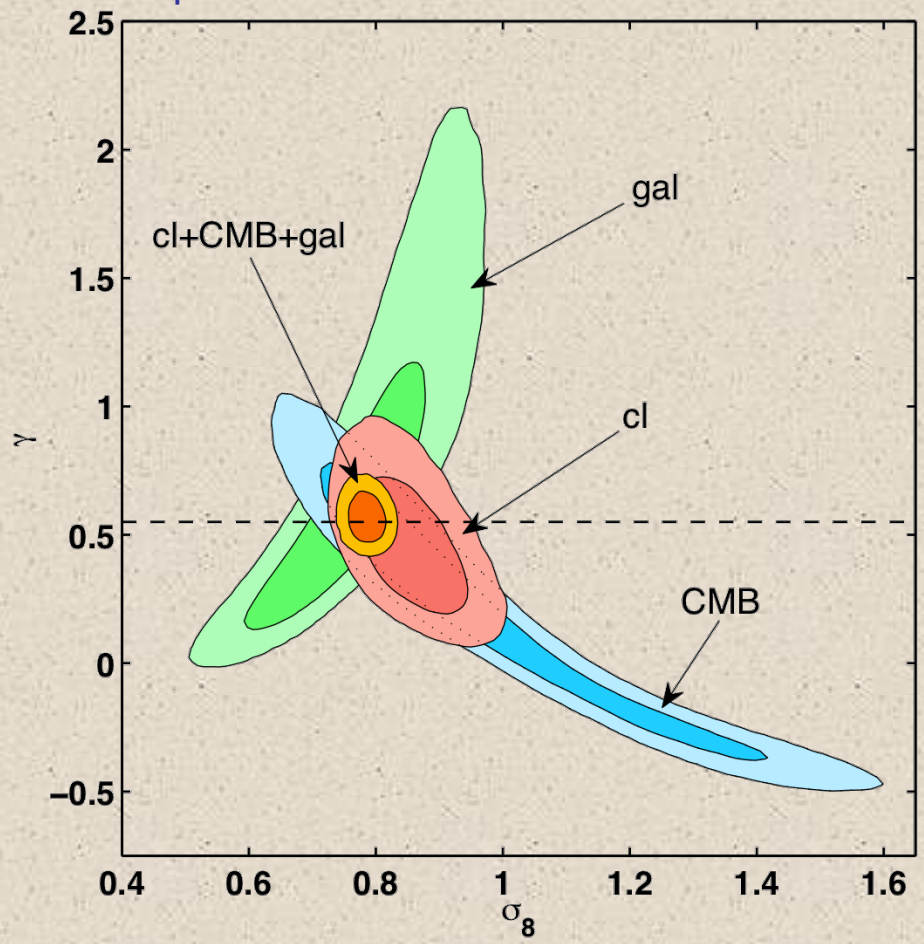
Combined constraints on growth and expansion: breaking degeneracies

"A combined measurement of cosmic growth and expansion from clusters of galaxies, the CMB and galaxy clustering",
MNRAS 2013, 432, 973
David Rapetti, Chris Blake, Steven Allen, Adam Mantz, David Parkinson, Florian Beutler (R13)

"Weighing the Giants IV: Constraints on Cosmology and Neutrino Mass",
Mantz et al 2014 (M14, WtG4), arXiv:1407.4516

Flat ΛCDM + growth index γ

Rapetti et al 13



clusters (XLF+f_{gas}): BCS+REFLEX +MACS

CMB (ISW): WMAP5

galaxies (RSD+AP): WiggleZ +6dFGS+BOSS

clusters+CMB+galaxies

(+BAO+SNIa+SH0ES)

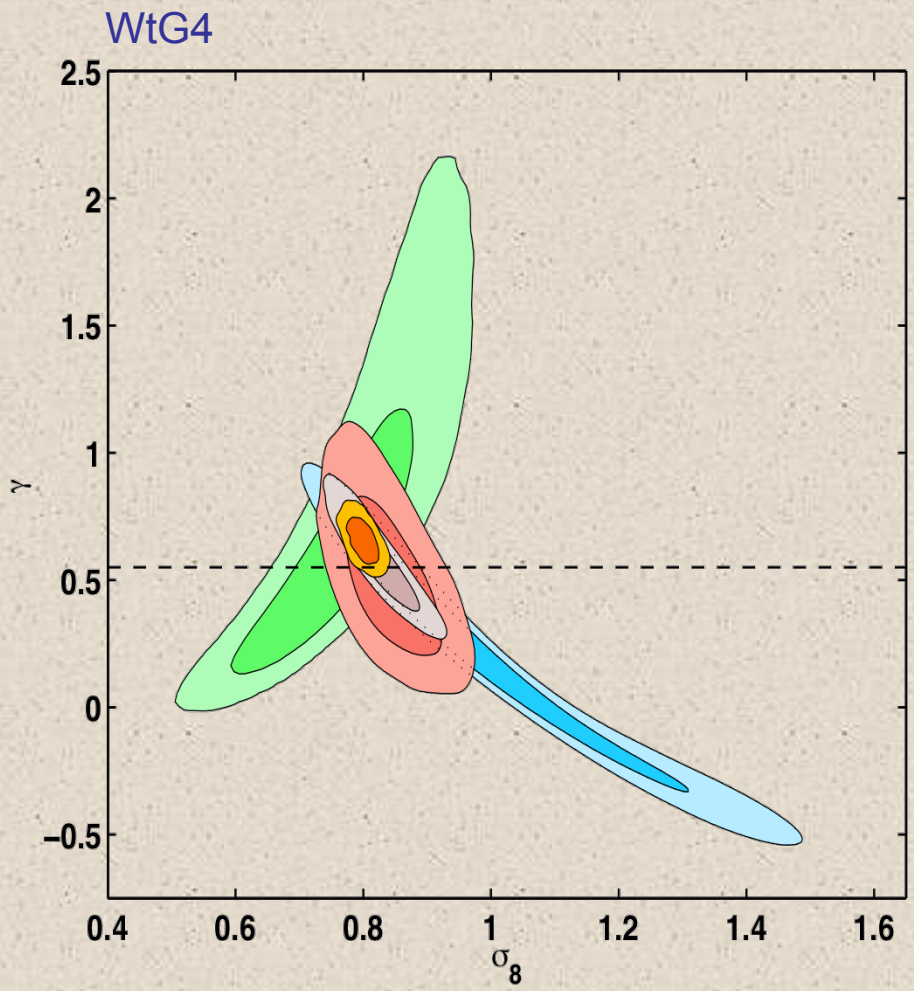
$$\gamma = 0.616 \pm 0.061$$

$$\sigma_8 = 0.791 \pm 0.019$$

$$\Omega_m = 0.277 \pm 0.011$$

$$H_0 = 70.2 \pm 1.0$$

Flat ΛCDM + growth index γ



clusters (XLF+f_{gas}): BCS+REFLEX +MACS (WtG4)

CMB (ISW, len.): WMAP9+SPT+ACT

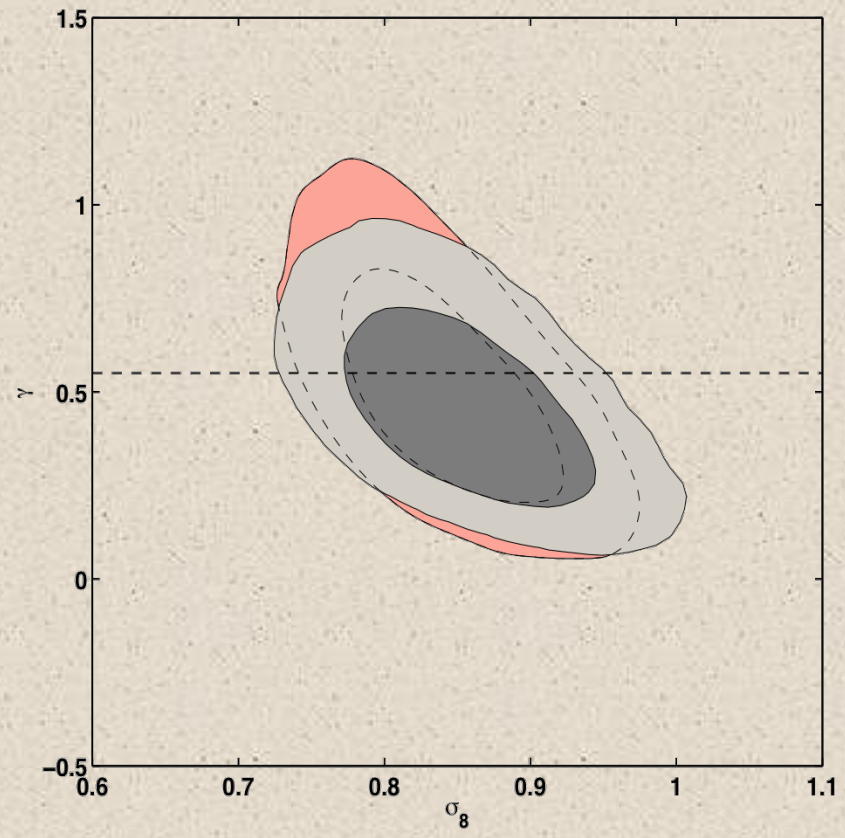
galaxies (RSD+AP): WiggleZ+6dFGS +BOSS

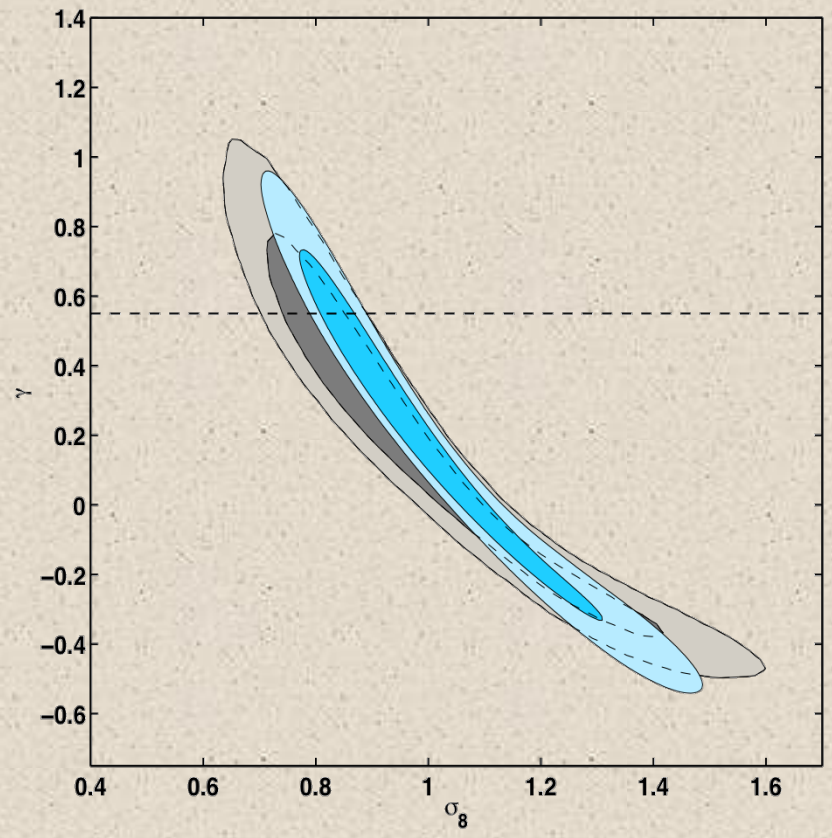
clusters+CMB

clusters+CMB+galaxies

As in the previous analysis, this includes only massless neutrinos.

Flat ΛCDM + growth index γ





Clusters (M14, WtG4)

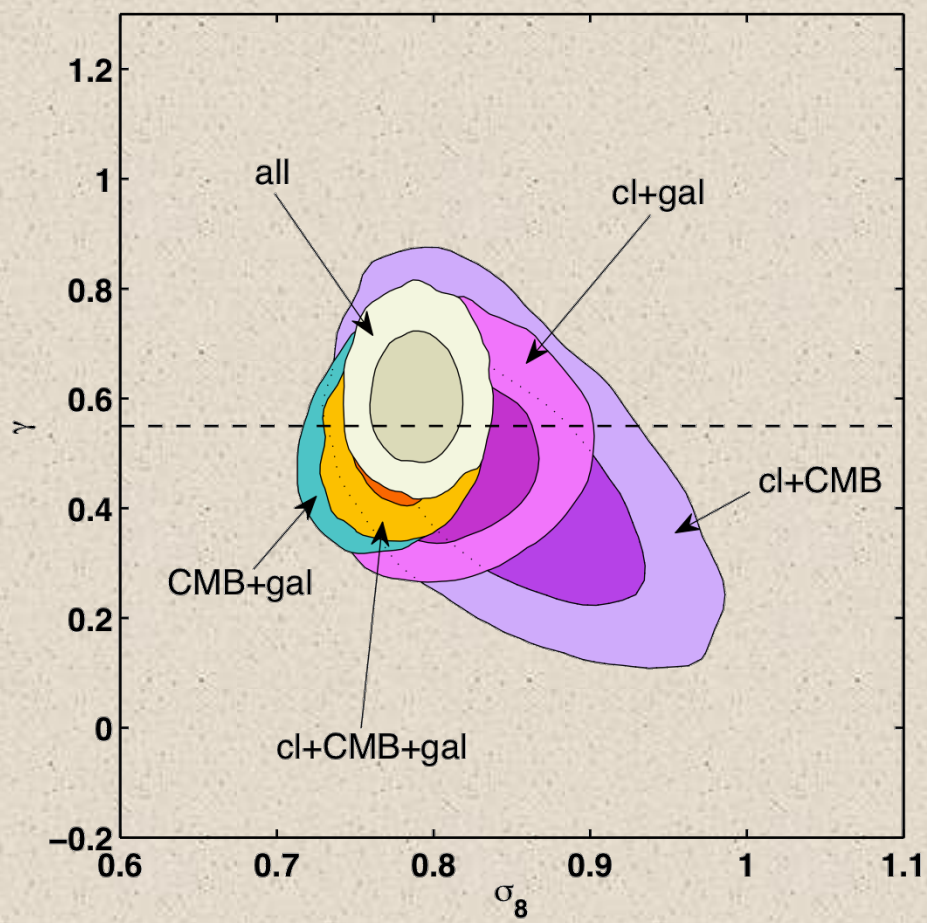
Clusters (R13)

CMB (WMAP9+SPT+ACT)

CMB (WMAP5)

Flat wCDM + growth index γ: growth plane

Rapetti et al 13



For General Relativity γ~0.55

Magenta: clusters+galaxies

Purple: clusters+CMB

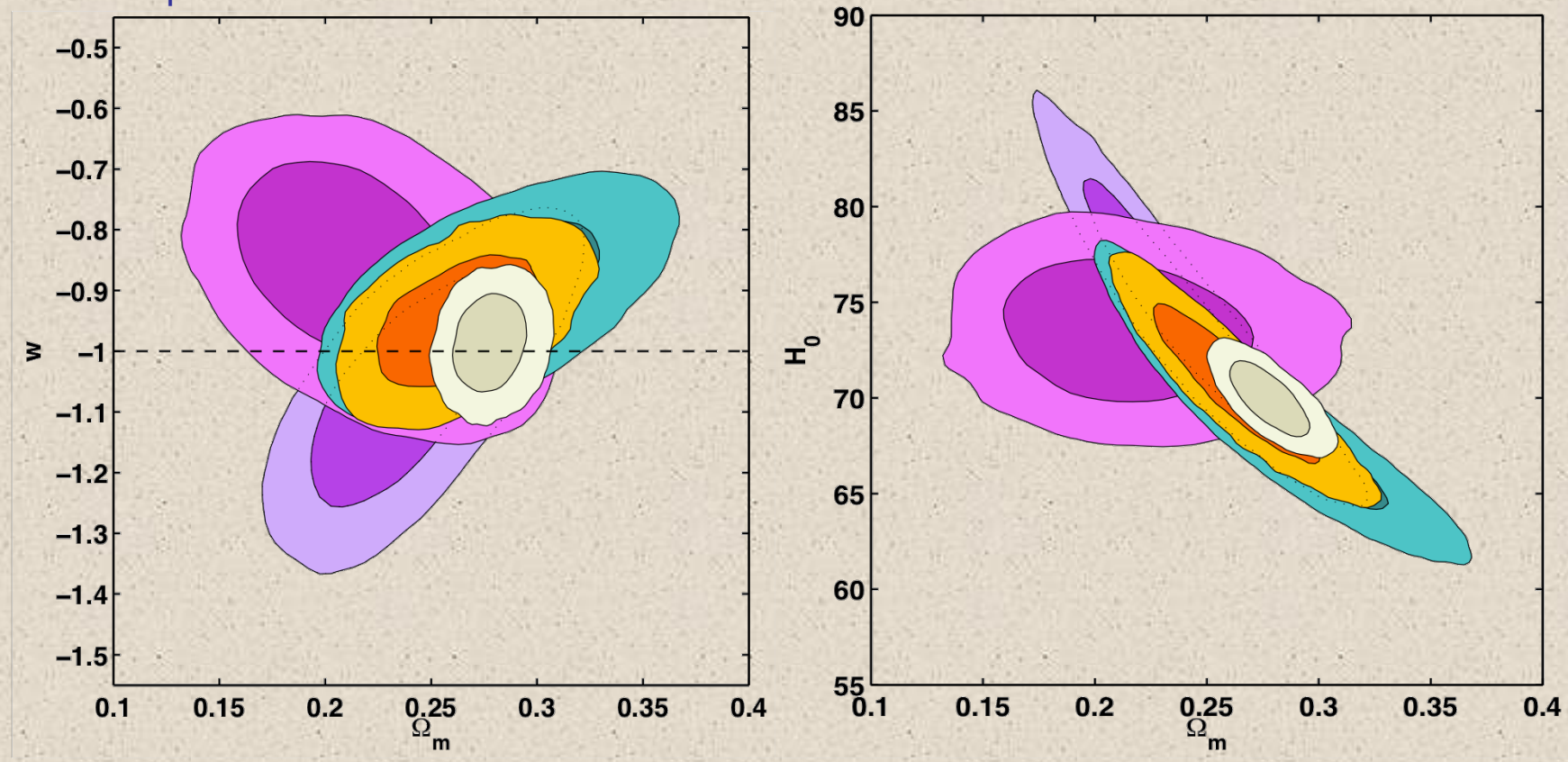
Turquoise: CMB+galaxies

Gold: clusters+CMB+galaxies

Platinum: clusters+CMB+galaxies +BAO (Reid et al 12; Percival et al 10)+SNIa (Suzuki et al 12) +SH0ES (Riess et al 11)

Flat wCDM + growth index γ: expansion planes

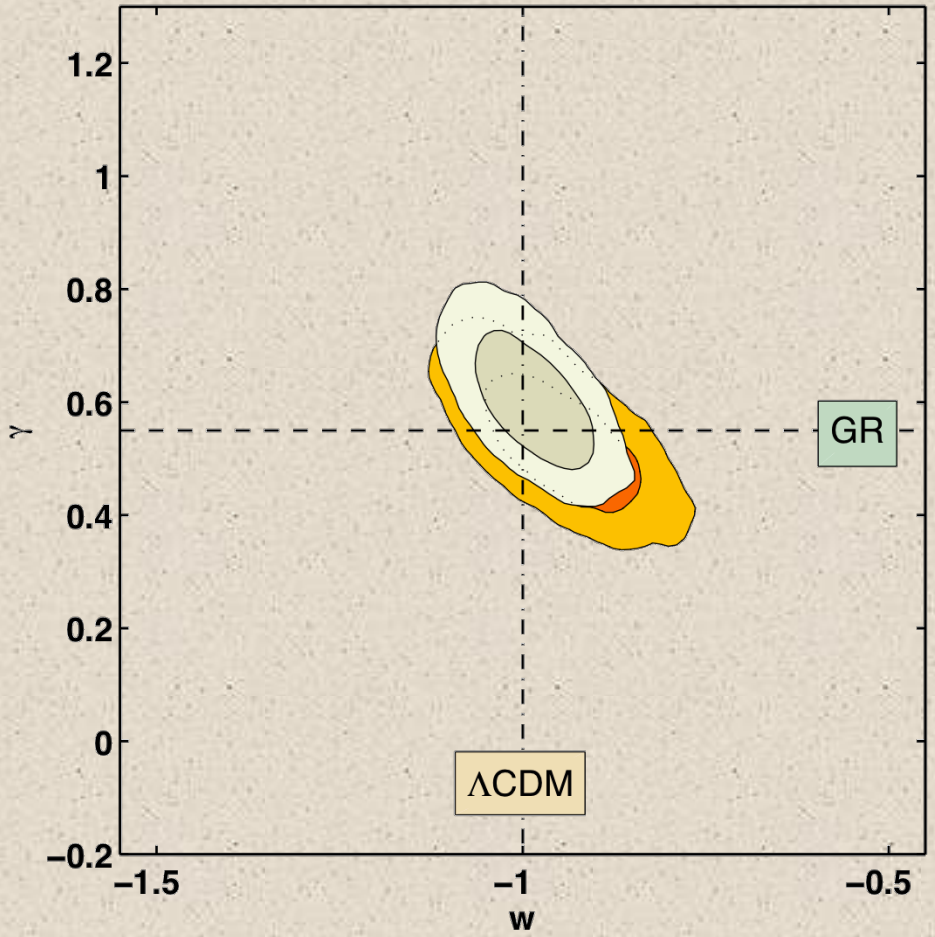
Rapetti et al 13



Platinum: clusters + CMB + galaxies + BAO (Reid et al 12; Percival et al 10) + SNIa (Suzuki et al 12) + SH0ES (Riess et al 11)

Flat wCDM + growth index γ: expansion+growth

Rapetti et al 13



For General Relativity γ~0.55

For ΛCDM w=-1

Gold: clusters+CMB+galaxies

Platinum: clusters+CMB+galaxies +BAO+SNIa+SH0ES

$$\gamma = 0.604 \pm 0.078$$

$$\sigma_8 = 0.789 \pm 0.019$$

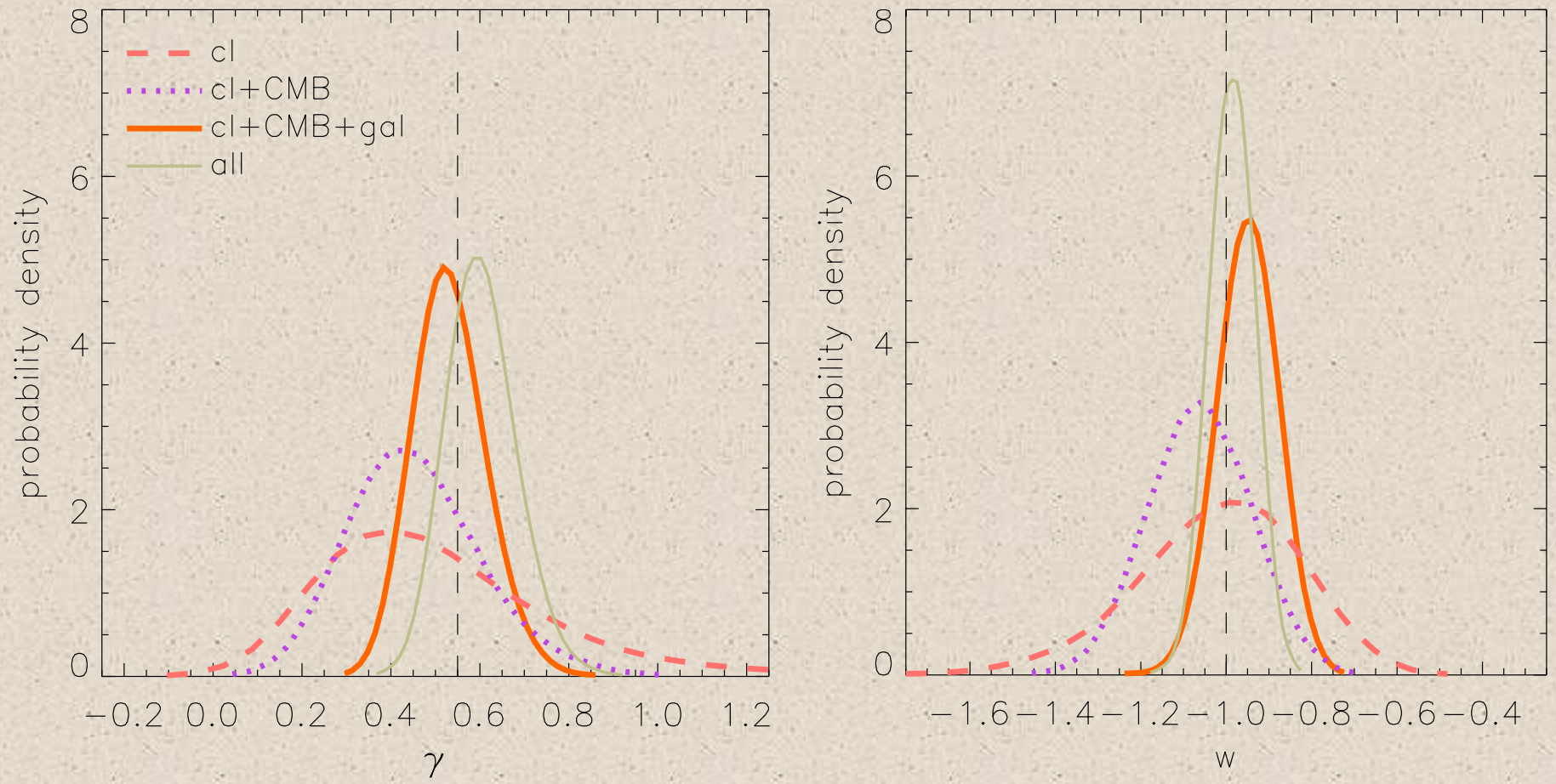
$$w = -0.967^{+0.054}_{-0.053}$$

$$\Omega_m = 0.278^{+0.012}_{-0.011}$$

$$H_0 = 70.0 \pm 1.3$$

Flat wCDM + γ: full pdf's

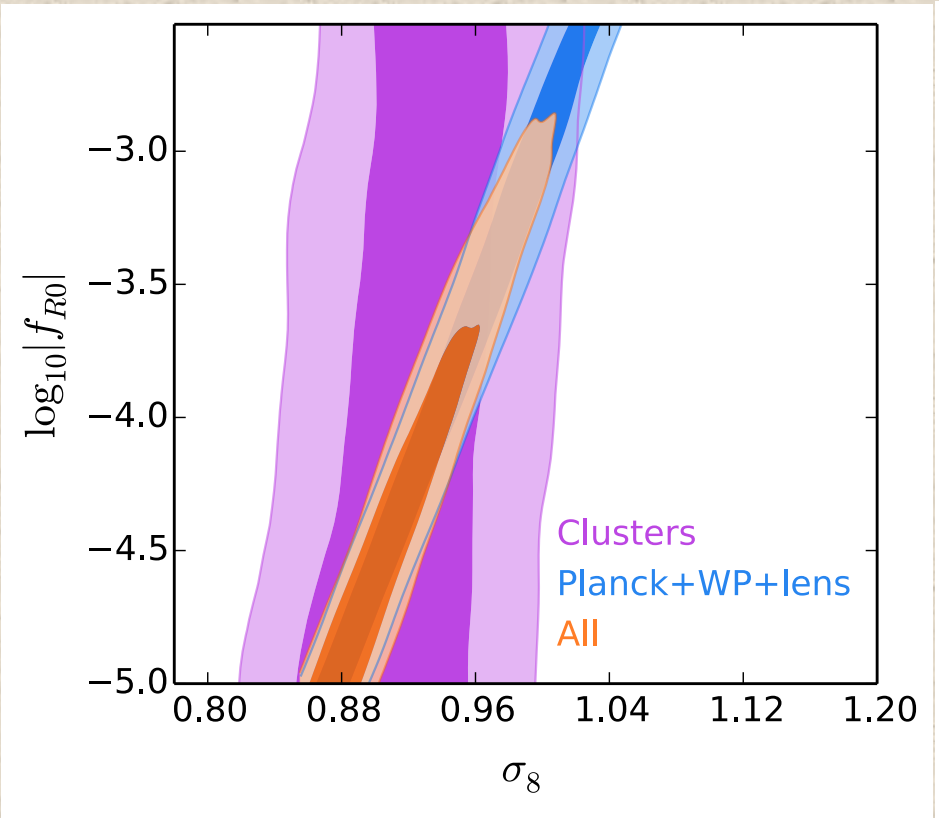
Rapetti et al 13

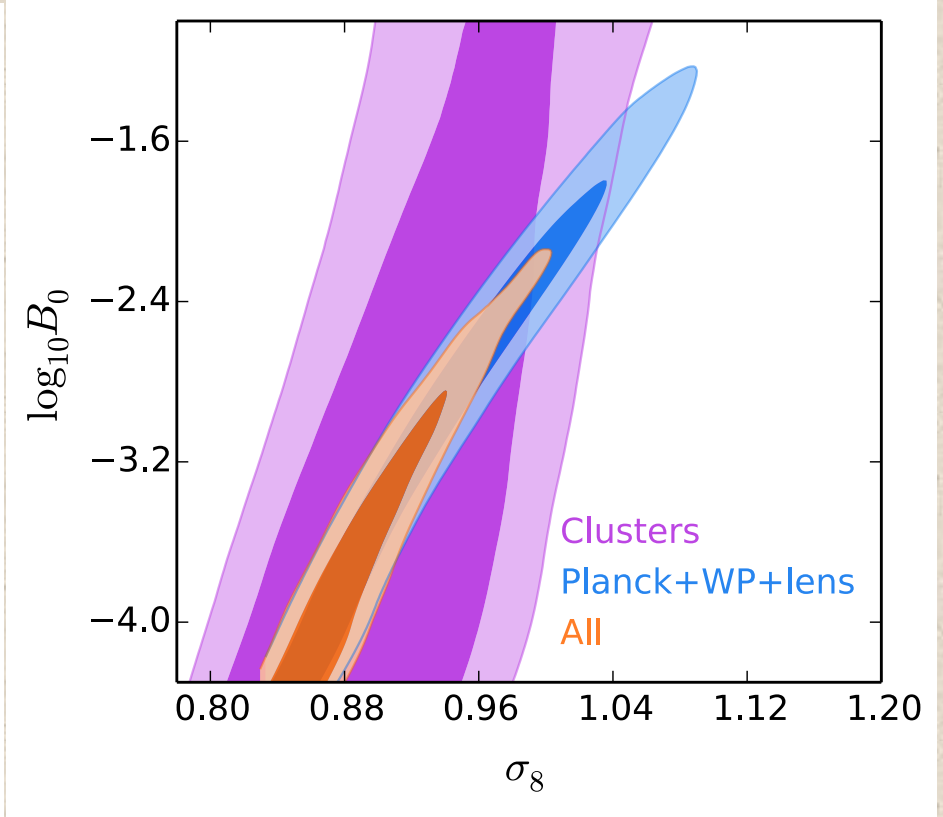


Red, dashed line: clusters; Purple, dotted line: clusters+CMB; Gold, solid line: clusters+CMB+galaxies; Platinum, long-dashed line: all

Constraints on f(R) gravity

Cataneo et al 14, in preparation





Preliminary results

Red: Clusters+CMB (degeneracy break)

Testing ΛCDM: Primordial non-Gaussianity

"X-ray cluster constraints on non-Gaussianity",
JCAP 2013, 8, 004
Sarah Shandera, Adam Mantz, David Rapetti, Steven Allen

"Weighing the Giants IV: Constraints on Cosmology and Neutrino Mass",
Mantz et al 2014b, arXiv:1407.4516

Testing the Gaussianity of the primordial fluctuations

1. When cumulants beyond skewness (correlations beyond the bispectrum) are important, if we can only properly describe the non-Gaussianity with a one-parameter model we can use this parameter to specify the amplitude of all the correlations.

2. We assume two different ways to scale higher moments with the skewness based on particle physics models of inflation.

3. Cluster counts probe smaller scales (0.1-0.5h/Mpc) than the CMB and the galaxy bias.

4. Cluster counts are sensitive to any non-Gaussianity and to higher order moments of the probability distribution of primordial fluctuations.

Testing the Gaussianity of the primordial fluctuations

$$\langle \delta_R^3 \rangle = \int \frac{d^3\vec{k}_1}{(2\pi)^3} \int \frac{d^3\vec{k}_2}{(2\pi)^3} \int \frac{d^3\vec{k}_3}{(2\pi)^3} M(k_1, R, z) M(k_2, R, z) M(k_3, R, z) \langle \Phi(\vec{k}_1)\Phi(\vec{k}_2)\Phi(\vec{k}_3)\rangle_c$$

Integrated moments of the smoothed density fluctuations

$$\left\langle \Phi(\vec{k}_1)\Phi(\vec{k}_2)\Phi(\vec{k}_3) \right\rangle_c = (2\pi)^3 \delta_D^3(\vec{k}_1 + \vec{k}_2 + \vec{k}_3)\ B(k_1, k_2, k_3)$$

Generic homogeneous and isotropic bispectrum of the potential

$$\mathcal{M}_{n,R} = \frac{\langle \delta_R^n \rangle_c}{\langle \delta_R^2 \rangle^{n/2}}$$

Dimensionless ratios of the cumulants of the density field

$$\left(\frac{dn}{dM}\right)_{\rm NG} = \left(\frac{dn}{dM}\right)_{{\rm T}, M_{300}} \left(\frac{n_{\rm NG}}{n_{\rm G}} \bigg|_{\rm Edgeworth} \right)$$

Non-Gaussian mass function

$$\mathcal{M}_n^h \approx 2^{n-3} n! \left(\frac{1.58\mathcal{M}_3}{8}\right)^{n-2}$$

Hierarchical scaling (local)

$$\mathcal{M}_{n,M}^f \approx 2^{n-1}(n-1)! \left(\frac{1.32\mathcal{M}_3}{8}\right)^{n/3}$$

Feeder scaling (two field model)

Non-Gaussian mass function modifications
(matched recently to simulations)

$$\left.\frac{n_{\rm NG}}{n_{\rm G}}\right|_{\rm Edgeworth} \approx 1 + \frac{F_1^{\rm h,f\prime}(M)}{F_0'(M)} + \frac{F_2^{\rm h,f\prime}(M)}{F_0'(M)} + \ldots$$

Edgeworth expansion

$$F_0'(M) = -\frac{\nu_c'(M)}{\sqrt{2\pi}} e^{-\frac{1}{2}\nu_c(M)^2}$$

Press-Schechter normalization

$$f_1(M) = \frac{F_{0,nG}'(M)}{F_{0,G}'(M)} = \frac{\nu_{c,nG}'(M)}{\nu_{c,G}'(M)} e^{-\frac{1}{2}\left(\nu_{c,nG}^2 - \nu_{c,G}^2\right)}$$

Mass/scale dependent correction
(typically close to 1; Adhikari et al 2014)

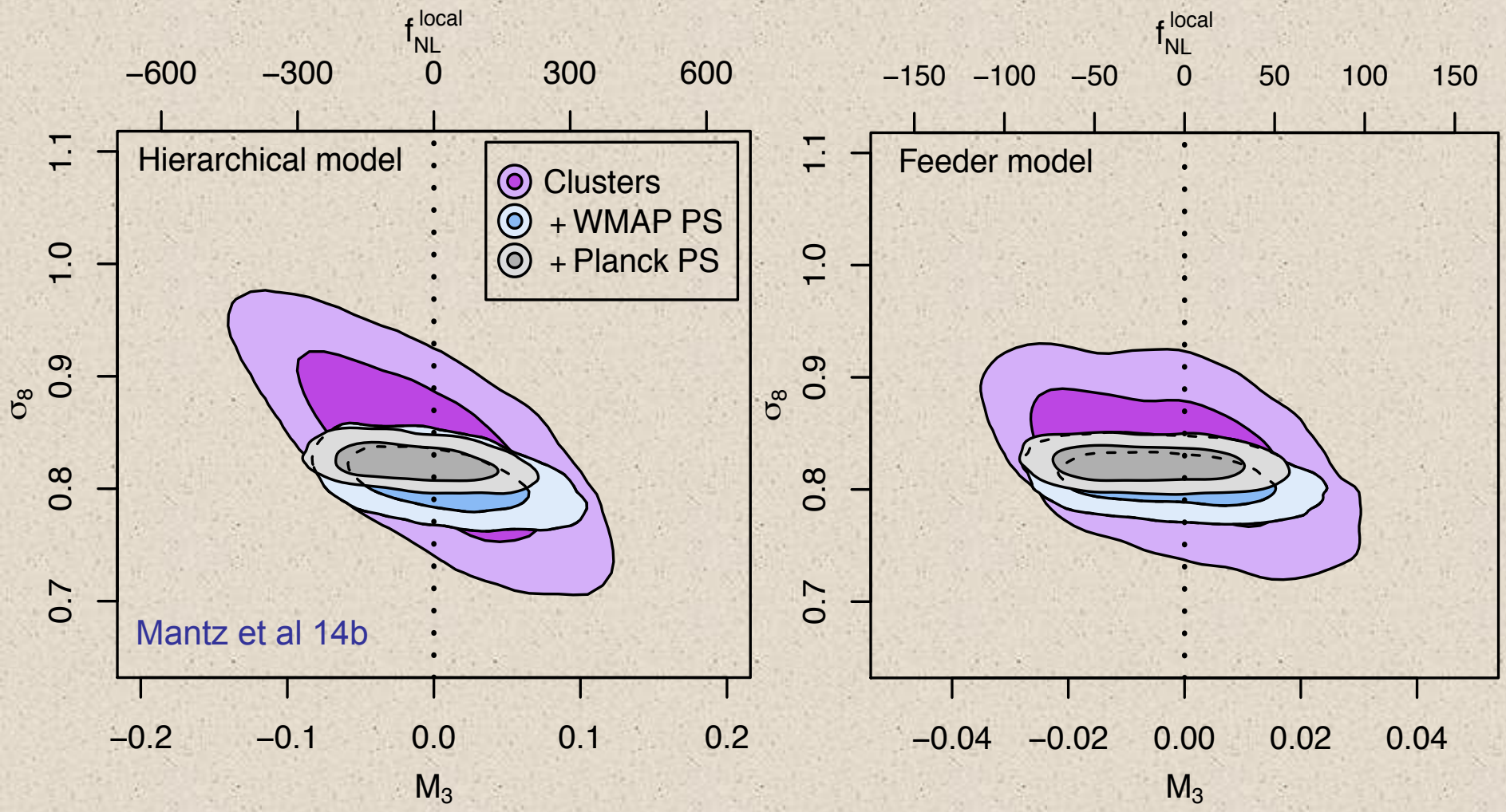
$$F_s^{\rm h\,\prime}(\nu) = F_0' \sum_{\{k_m\}_h} \left\{ H_{s+2r} \prod_{m=1}^{s} \frac{1}{k_m!} \left(\frac{\mathcal{M}_{m+2,R}}{(m+2)!} \right)^{k_m} + H_{s+2r-1} \frac{\sigma}{\nu} \frac{d}{d\sigma} \left[\prod_{m=1}^{s} \frac{1}{k_m!} \left(\frac{\mathcal{M}_{m+2,R}}{(m+2)!} \right)^{k_m} \right] \right\}$$

Hierarchical scaling

$$F_s^{\rm f\,\prime}(\nu) = F_0' \sum_{\{k_m\}_f} \left\{ H_{s+2} \prod_{m=1}^{s} \frac{1}{k_m!} \left(\frac{\mathcal{M}_{m+2,R}}{(m+2)!} \right)^{k_m} + H_{s+1} \frac{\sigma}{\nu} \frac{d}{d\sigma} \left[\prod_{m=1}^{s} \frac{1}{k_m!} \left(\frac{\mathcal{M}_{m+2,R}}{(m+2)!} \right)^{k_m} \right] \right\}$$

Feeder scaling

Flat ΛCDM + beyond skewness



Gaussian distribution M_3=0

For the CMB, only the CMB power spectra (not bispectra or trispectra) are used

Converting the constraints on skewness to those on the amplitude of bispetrum

Mantz et al 14b $\quad$ Tinker $+ f_{\mathrm{LMSV,many\,terms}}$

Model	Data	σ_8	$10^3\mathcal{M}_3$	$f_{\mathrm{NL}}^{\mathrm{local}}$	$f_{\mathrm{NL}}^{\mathrm{equil}}$	$f_{\mathrm{NL}}^{\mathrm{orthog}}$
H	Clusters	0.835 ± 0.053	8^{+40}_{-65}	24^{+129}_{-210}	88^{+471}_{-765}	-123^{+1066}_{-656}
H	Clusters+WMAP	0.808 ± 0.019	-1^{+42}_{-36}	-3^{+135}_{-116}	-12^{+494}_{-424}	16^{+590}_{-689}
H	Clusters+*Planck*+WP	0.823 ± 0.011	-29^{+46}_{-24}	-94^{+148}_{-77}	-341^{+541}_{-282}	475^{+393}_{-754}
F	Clusters	0.830 ± 0.041	4^{+8}_{-21}	11^{+26}_{-68}	41^{+94}_{-247}	-57^{+344}_{-131}
F	Clusters+WMAP	0.810 ± 0.017	-7^{+16}_{-9}	-23^{+50}_{-27}	-85^{+182}_{-100}	119^{+139}_{-254}
F	Clusters+*Planck*+WP	0.823 ± 0.011	-15^{+19}_{-4}	-48^{+60}_{-11}	-174^{+218}_{-41}	242^{+57}_{-303}

$f_{\mathrm{NL}}^{\mathrm{local}} = -192 \pm 310$ Benson et al 13 (SPT+CMB) Jenkins $+ f_{\mathrm{Dalal}}$

$f_{\mathrm{NL}}^{\mathrm{local}} = 20 \pm 450$ Williamson et al 11 (SPT+CMB) Jenkins $+ f_{\mathrm{Dalal}}$

$f_{\mathrm{NL}}^{\mathrm{local}} = 282 \pm 317$ Mana et al 13 (MaXBCG) Tinker $+ f_{\mathrm{LMSV,skew\,only}}$

Summary

- We performed a consistency test of General Relativity (growth rate) at large scales using cluster growth data+f_{gas}, Tinker et al 2008 mass function, with X-ray and lensing follow-up observations as well as other cosmological data.

- Combining clusters (ROSAT+Chandra+WtG), CMB (WMAP or Planck) and galaxy clustering (WiggleZ, 6dFGS, CMASS BOSS) data we break key degeneracies in this test and obtain robust and tight constraints on cosmic growth and expansion rate.

- Simultaneously fitting γ and w, we find that current data is consistent with GR+ΛCDM.

- Our results highlight the importance of combining X-ray cluster data, CMB and galaxy clustering data to test dark energy and modified gravity with current and future missions (SPTpol, ACTpol, XMM-Newton surveys, Planck, DES, eROSITA, BOSS/Big BOSS, Euclid, LSST, WFIRST, etc.).

- More gravity tests using our full analysis including e.g. all the covariances between parameters are coming soon (M. Cataneo et al 2014 in prep., etc.).

- Cluster counts are sensitive to any primordial non-Gaussianity and can be used to distinguish models of inflation with different NG levels but identical bispectra.