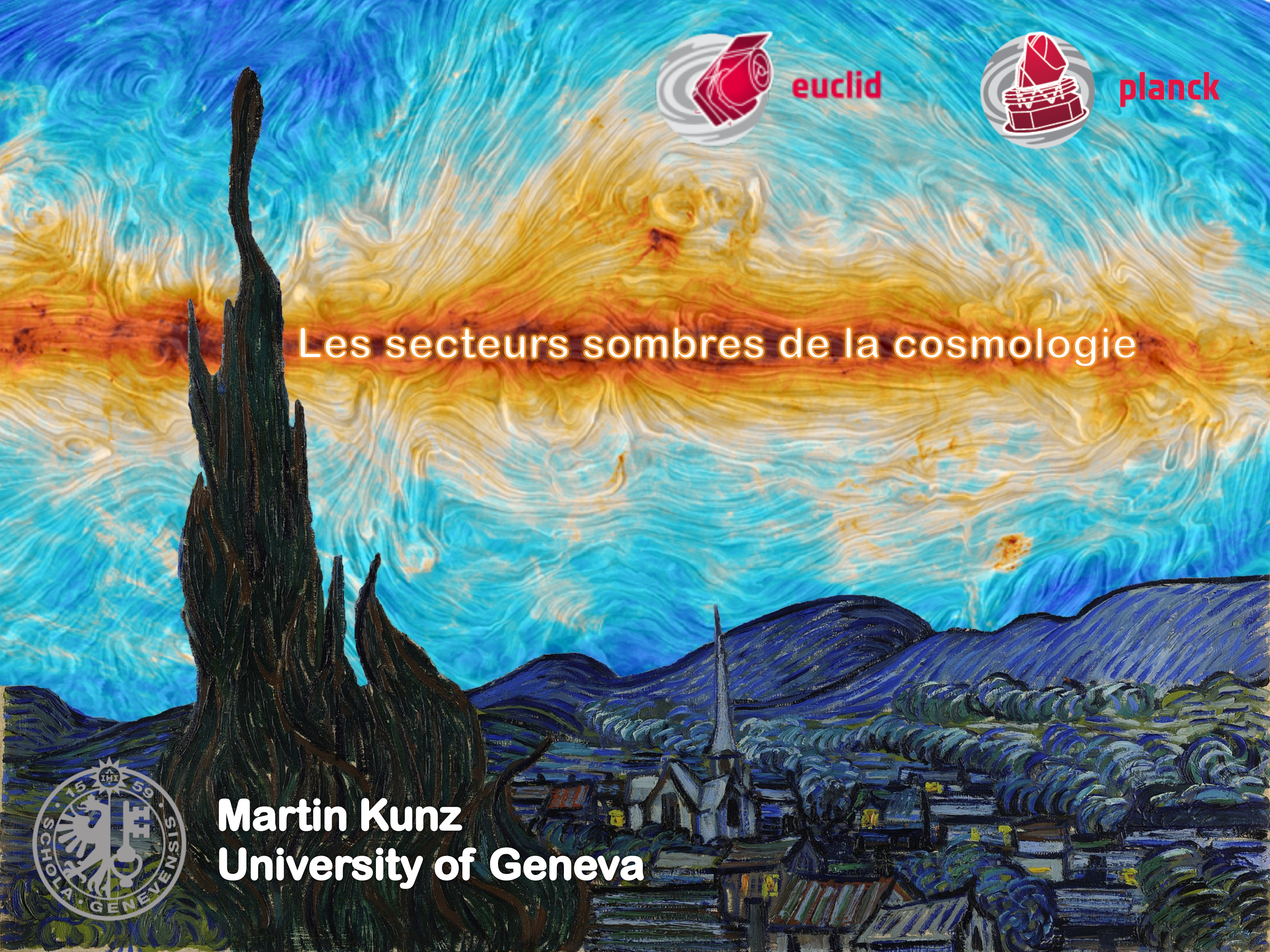

euclid
planck
Les secteurs sombres de la cosmologie
Martin Kunz
University of Geneva

les secteurs sombres de la cosmologie

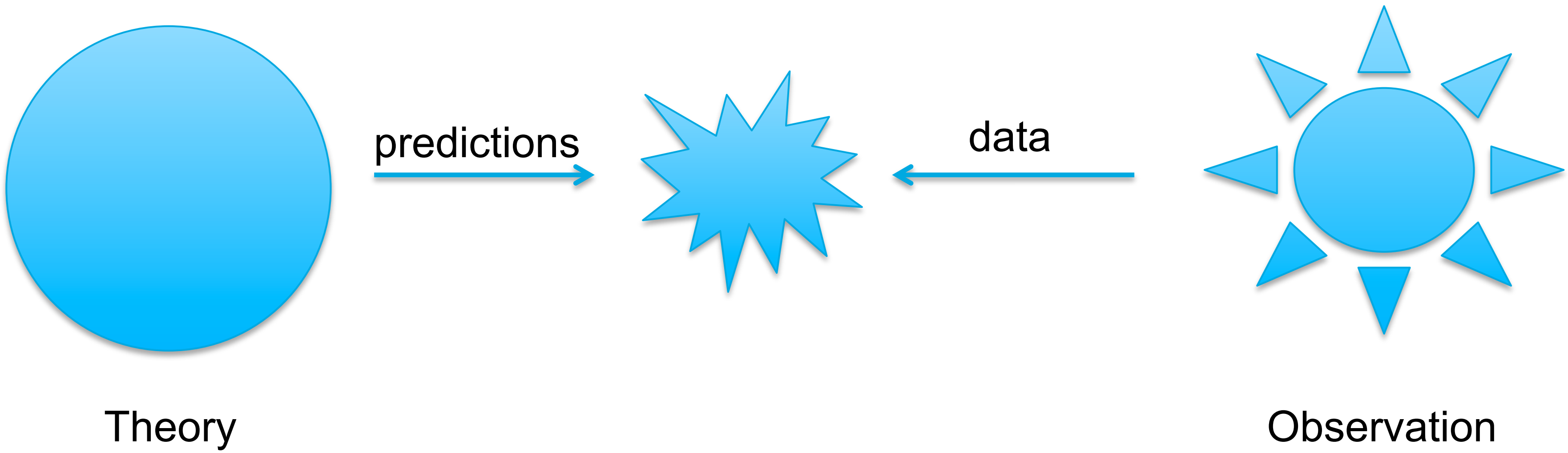
Dark questions for bright minds?

1. **Where are we coming from?**
    - what do we know about the early Universe?
2. **What is around us?**
    - what is the large-scale structure of the Universe?
    - what is the stuff around us (especially the 95% we haven't seen at CERN)?
3. **Where are we going to?**
    - what is the future of the Universe?

What are the links between these questions? And what are the hidden assumptions and missing questions?

finding answers

text book approach:



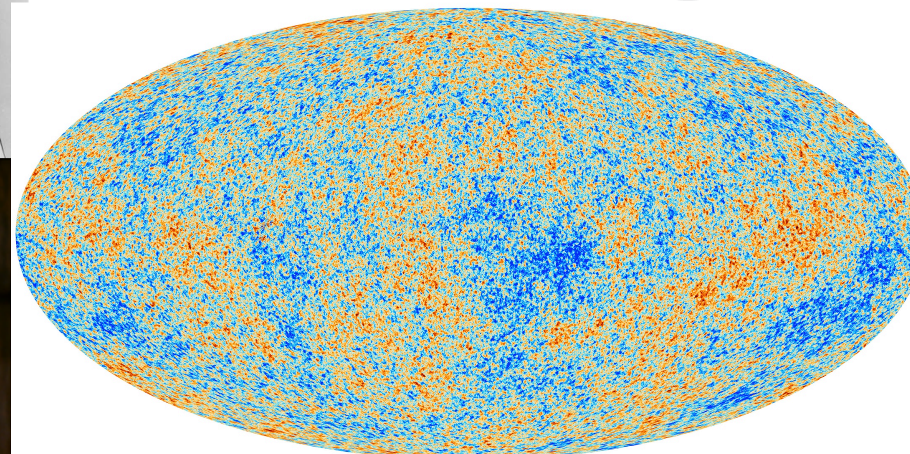
This obviously needs

a) data (preferably correct)

b) a framework within which we can interpret the data

cosmologie sombre? lumineuse!

Penzias & Wilson 1965

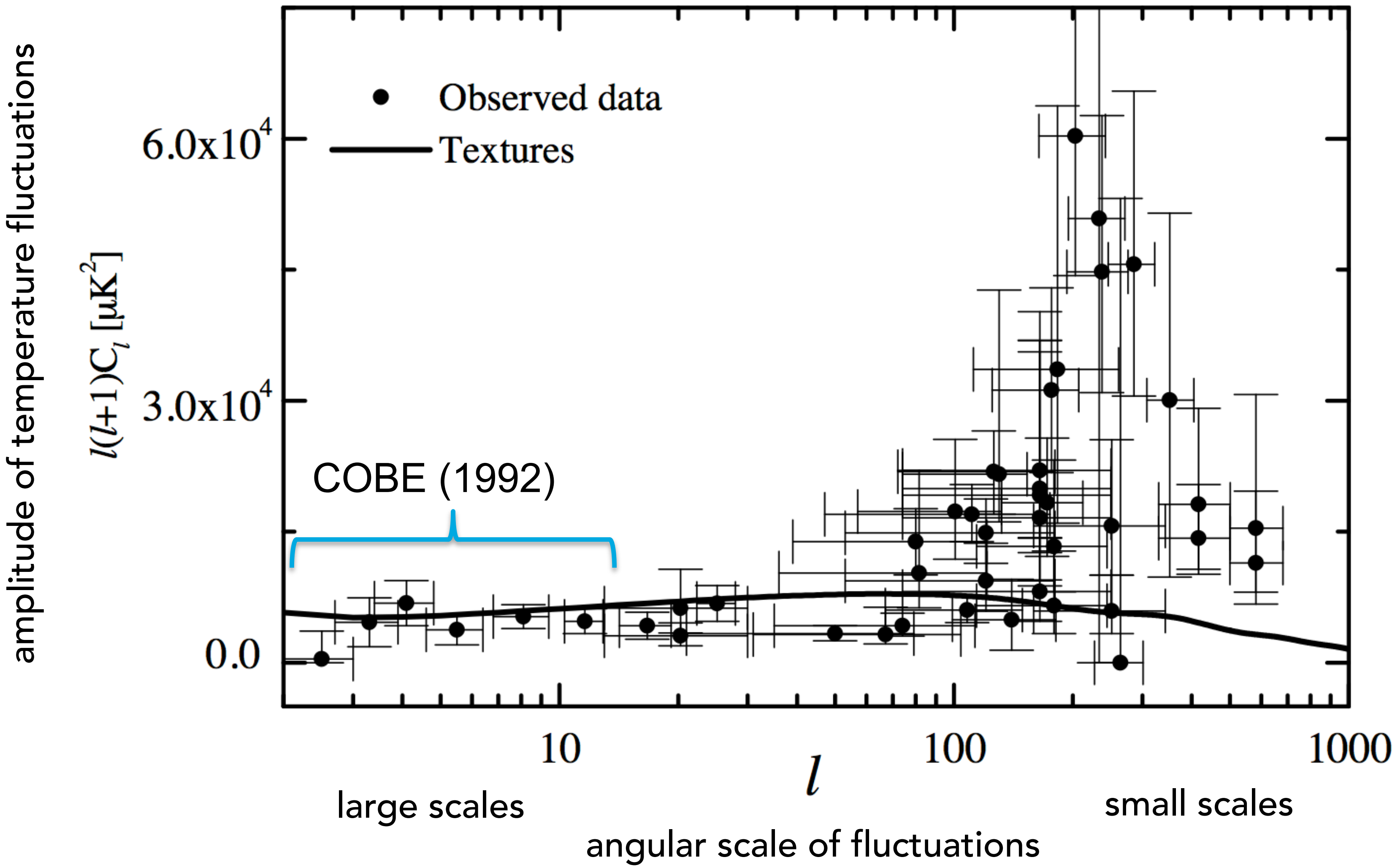


Planck 2015
(what a difference 50 years make!)

This mysterious noise in the antenna is a relic from a time when the Universe was 1000 times smaller!

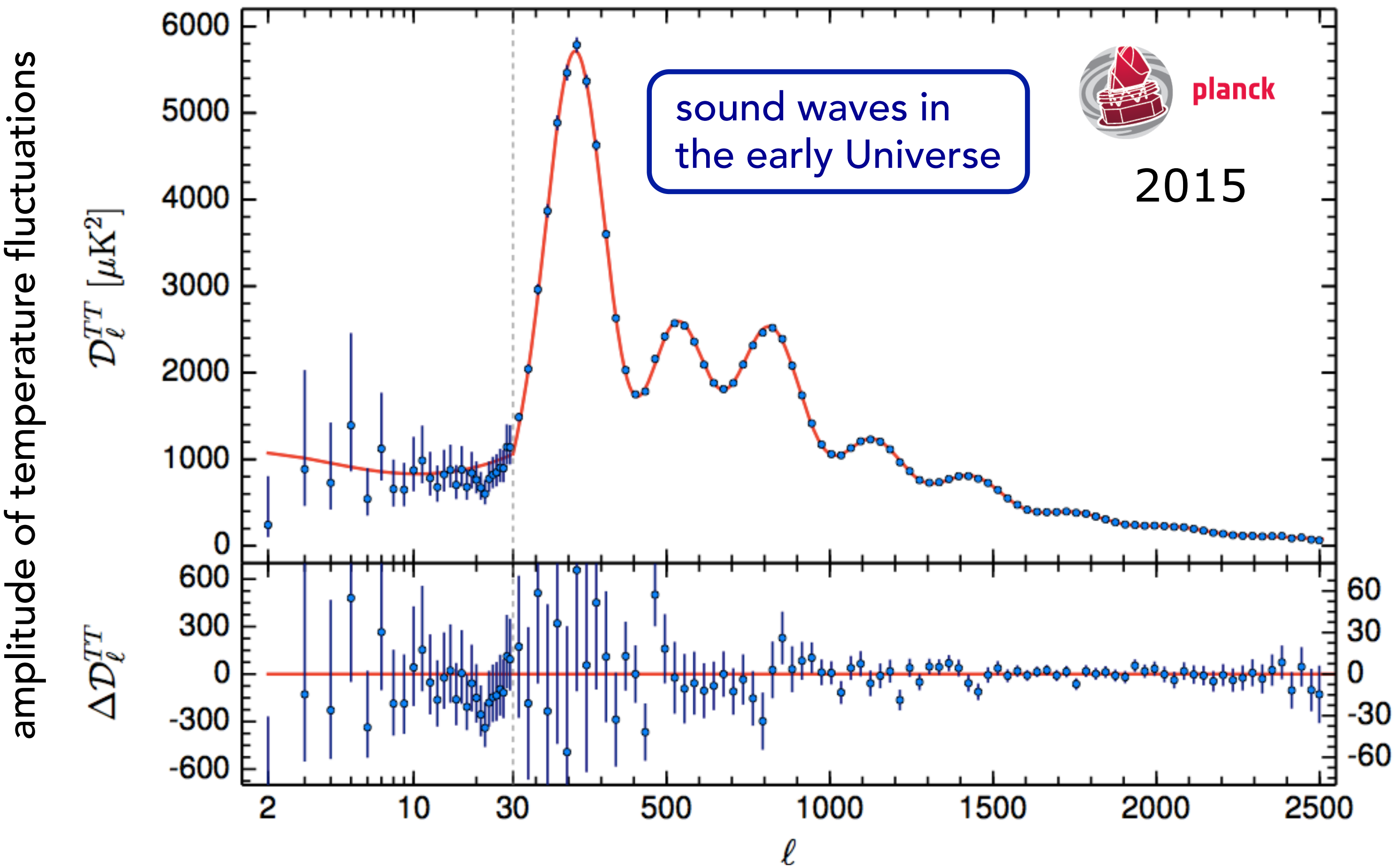
the cosmic microwave background

angular fluctuation spectrum in CMB ca 1998:



the cosmic microwave background

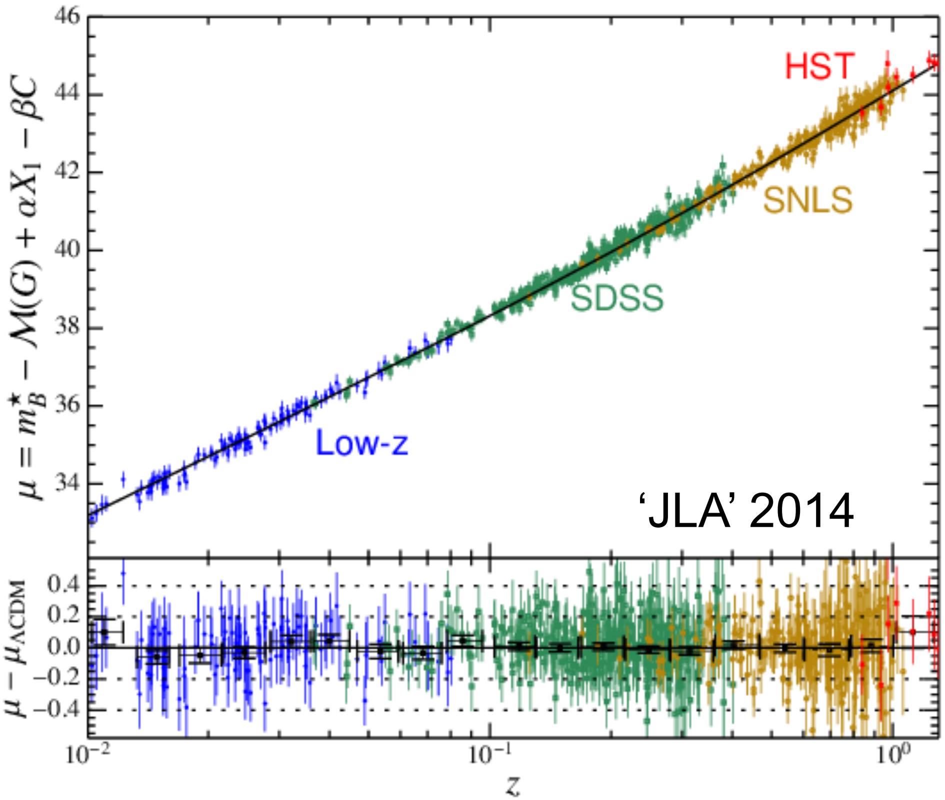
planck

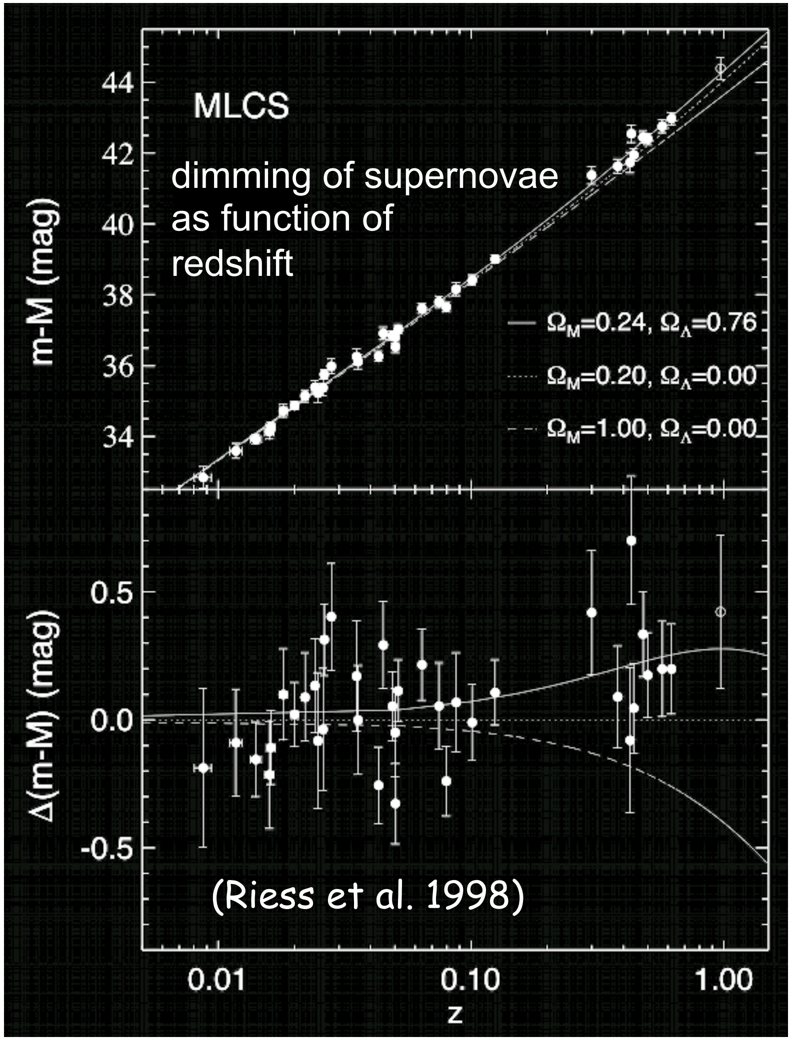


red curve:
best fit 6-parameter ΛCDM ('standard') model
→ fits thousands of C_l / millions of pixels

Planck 2015 TT combined:
ell range 30 – 2508
$X^2 = 2546.67$; $N_{dof} = 2479$
probability 16.8%

more data





Not to mention:

- cosmic shear (WL): ~ 2000
- RSD: ~ 2002
- BAO: ~ 2005

also theory has evolved… ?

Leiden 1995 – error bars have decreased, but has our understanding improved?

also theory has evolved… ?

	RD	PL	JM	BR	GS	LV	AH	Beyond LCDM
Dimensions	3+1	3+1	2 in UV	4	4	e^(4-x) x>=4	3+1	3+1
FRW	y	y	n	y	n	y	y	n
Inflation?	y or n	y	n	y	maybe	y	y	y
Dark Matter	CDM	CDM+	none	CDM+	Strange	CDM-like	IDM	Split
Gravity Theory	MG	GRish	Not GR	GR	nearly GR	GR++	GR++	Split
Acceleration: Λ/DE/MG/BR	MG	DE	MG	DE	Λ	Degenerate w/ Λ	Λ	MG
Anomalies =New Physics	n	y	y	n	y	not yet	n	Split

outline

- Introduction (done ☺)
- Some things we have learned
  (assuming the LCDM standard scenario)
- Beyond the standard model
  (using phenomenology)
- A closer look at weak lensing
- Future surveys, Euclid
  (more from Valeria, Yannick and others)
- Conclusions

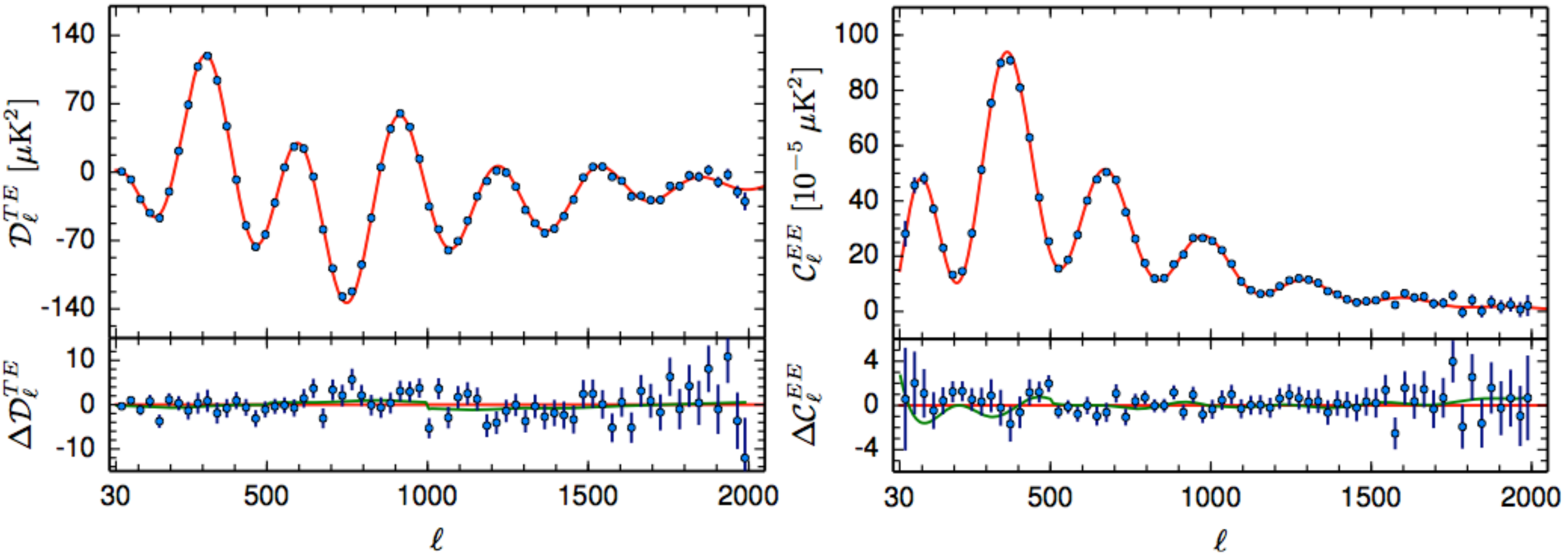
(I will focus on standard cosmological probes, but don't forget other tests!)

The scientific results that we present today are a product of the Planck Collaboration, including individuals from more than 100 scientific institutes in Europe, the USA and Canada

Planck is a project of the European Space Agency, with instruments provided by two scientific Consortia funded by ESA member states (in particular the lead countries: France and Italy) with contributions from NASA (USA), and telescope reflectors provided in a collaboration between ESA and a scientific Consortium led and funded by Denmark.

where are we coming from?

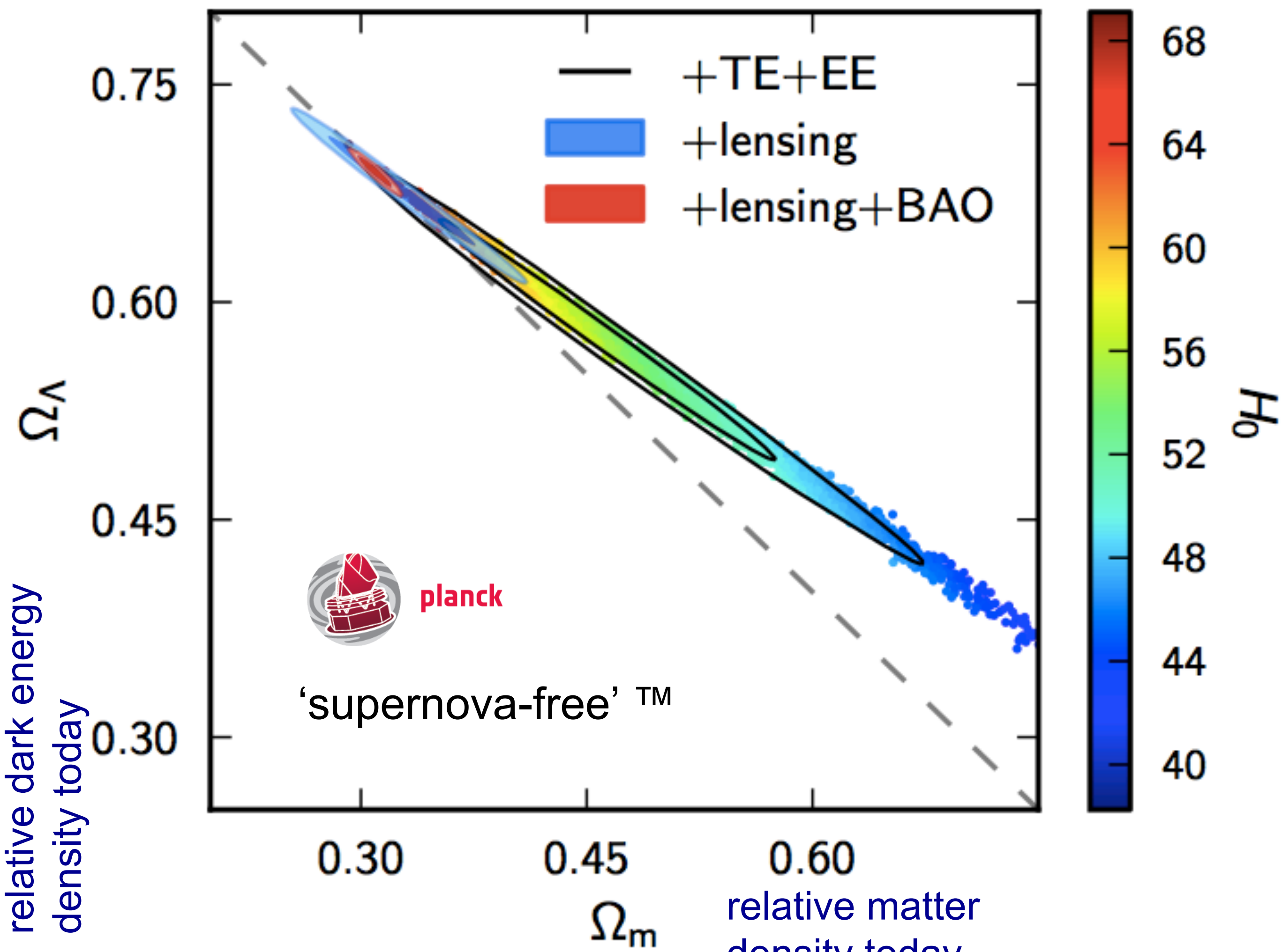
planck



- first peak in polarisation: something created super-horizon correlations
- $n_s \neq 1$: `super-early dark energy' evolution $n_s - 1 = -3(1+w) + d\ln(1+w)/dN$

what is in the Universe?

spatial curvature: Ω_k=0.000±0.005 (95%)

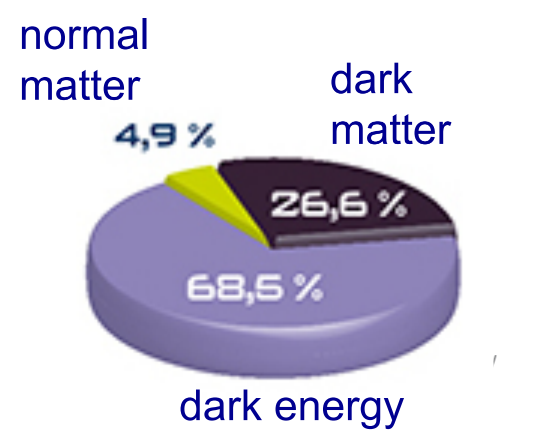


We clearly need dark energy and dark matter (?)

But this assumes LCDM and FLRW

Needs testing!

Tests need a framework



Possible explanations for ä>0

1. It is a cosmological constant, and there is no problem ('anthropic principle' , 'string landscape') – unsatisfactory but agrees with data
2. The (supernova) data is wrong – unlikely
3. We are making a mistake with GR (aka 'backreaction') or the Copernican principle is violated ('LTB') – unlikely
4. It is something evolving, e.g. a scalar field ('dark energy')
5. GR is wrong and needs to be modified ('modified gravity')

ISW cross-corr.
(paper XXI)

(there is a funny issue when stacking CMB anisotropies at locations of known structures)

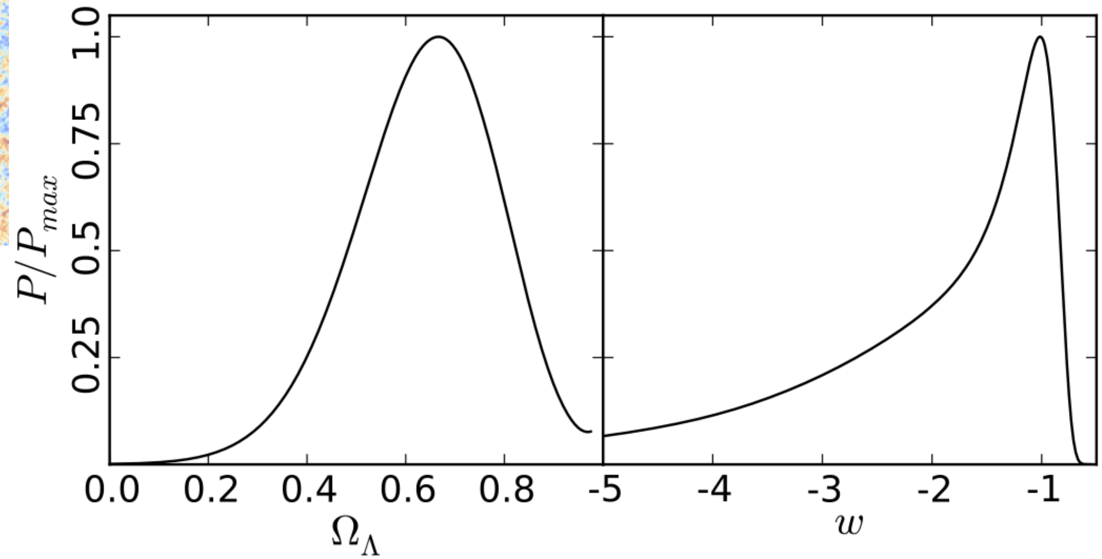


Table 2. ISW amplitudes A, errors σ_A, and significance levels S/N = A/σ_A of the CMB-LSS cross-correlation (survey-by-survey and for different combinations). These values are reported for the four *Planck* CMB maps: COMMANDER, NILC, SEVEM, and SMICA. The last column stands for the expected S/N within the fiducial ΛCDM model.

LSS data	COMMANDER		NILC		SEVEM		SMICA		Expected
	$A \pm \sigma_A$	S/N	$A \pm \sigma_A$	S/N	$A \pm \sigma_A$	S/N	$A \pm \sigma_A$	S/N	S/N
NVSS	0.95 ± 0.36	2.61	0.94 ± 0.36	2.59	0.95 ± 0.36	2.62	0.95 ± 0.36	2.61	2.78
WISE-AGN ($\ell_{\min} \geq 9$)	0.95 ± 0.60	1.58	0.96 ± 0.60	1.59	0.95 ± 0.60	1.58	1.00 ± 0.60	1.66	1.67
WISE-GAL ($\ell_{\min} \geq 9$)	0.73 ± 0.53	1.37	0.72 ± 0.53	1.35	0.74 ± 0.53	1.38	0.77 ± 0.53	1.44	1.89
SDSS-CMASS/LOWZ	1.37 ± 0.56	2.42	1.36 ± 0.56	2.40	1.37 ± 0.56	2.43	1.37 ± 0.56	2.44	1.79
SDSS-MphG	1.60 ± 0.68	2.34	1.59 ± 0.68	2.34	1.61 ± 0.68	2.36	1.62 ± 0.68	2.38	1.47
Kappa ($\ell_{\min} \geq 8$)	1.04 ± 0.33	3.15	1.04 ± 0.33	3.16	1.05 ± 0.33	3.17	1.06 ± 0.33	3.20	3.03
NVSS and Kappa	1.04 ± 0.28	3.79	1.04 ± 0.28	3.78	1.05 ± 0.28	3.81	1.05 ± 0.28	3.81	3.57
WISE	0.84 ± 0.45	1.88	0.84 ± 0.45	1.88	0.84 ± 0.45	1.88	0.88 ± 0.45	1.97	2.22
SDSS	1.49 ± 0.55	2.73	1.48 ± 0.55	2.70	1.50 ± 0.55	2.74	1.50 ± 0.55	2.74	1.82
NVSS and WISE and SDSS	0.89 ± 0.31	2.87	0.89 ± 0.31	2.87	0.89 ± 0.31	2.87	0.90 ± 0.31	2.90	3.22
All	1.00 ± 0.25	4.00	0.99 ± 0.25	3.96	1.00 ± 0.25	4.00	1.00 ± 0.25	4.00	4.00

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1. It is a cosmological constant, and there is no problem ('anthropic principle', 'string landscape') – unsatisfactory but agrees with data
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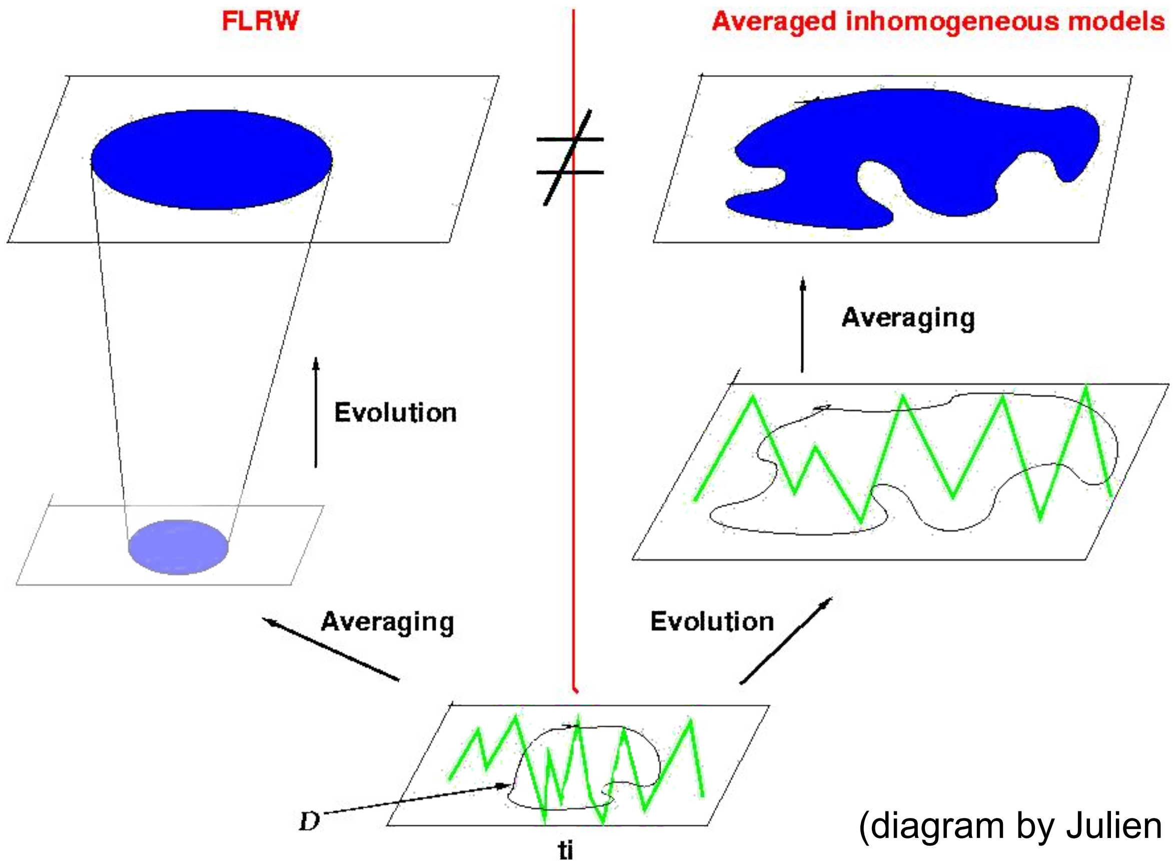
average and evolution

the average of the evolved universe is in general not the evolution of the averaged universe!

(this is a true statement – but is it important?)



(diagram by Julien Larena)

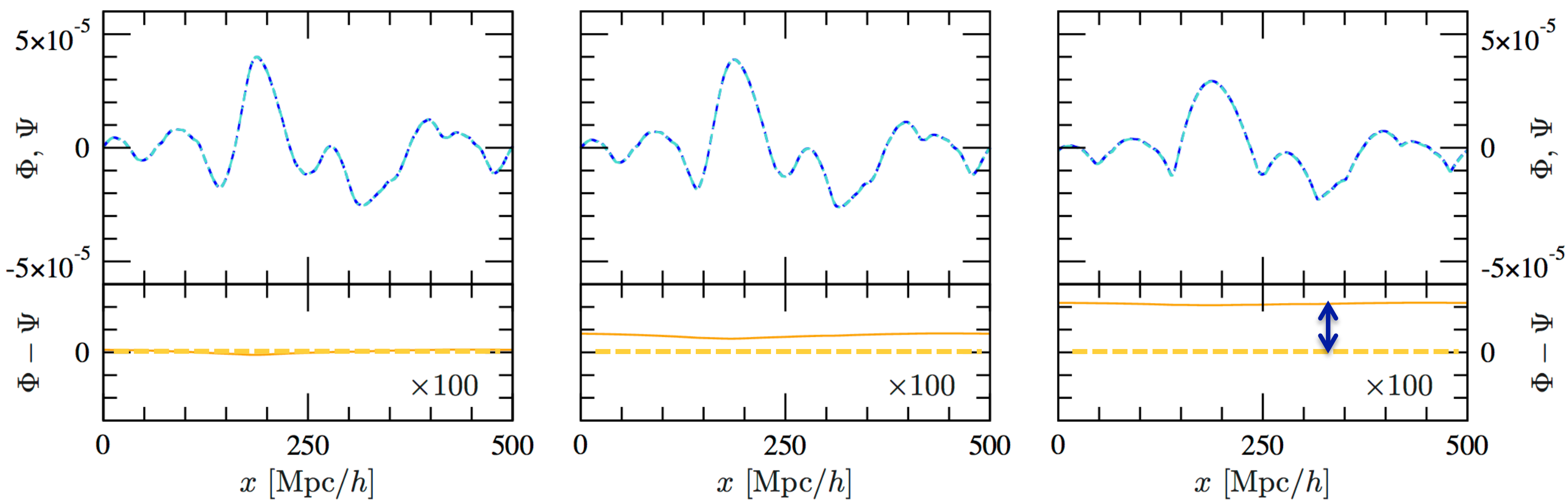
deviation from FLRW background in *gevolution*

$$ds^2 = -(1+2\psi)dt^2 + a^2(1-2\phi)dx^2$$

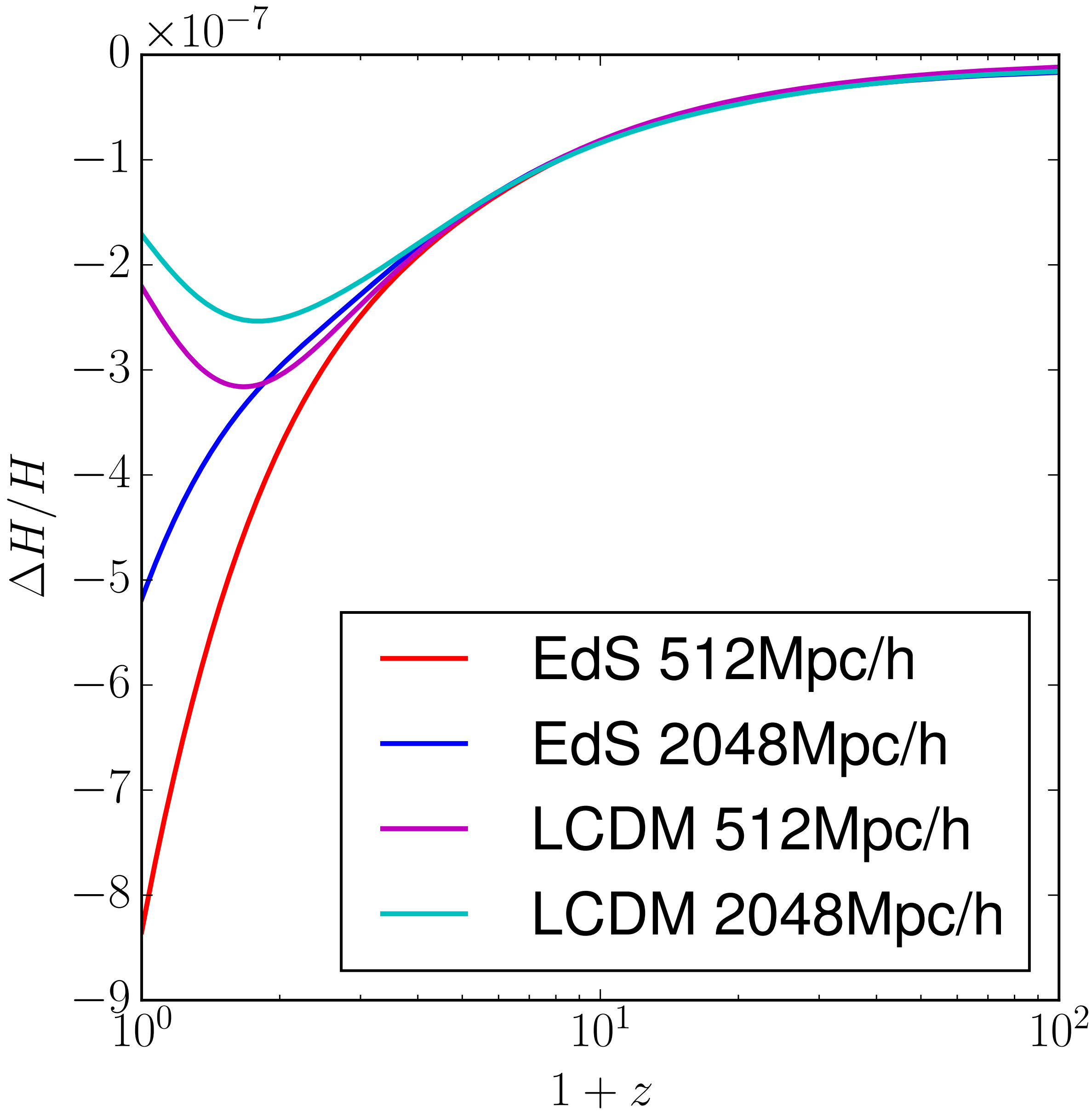
weak-field GR

arXiv:1408.2741
arXiv:1604.06065
arXiv:1706.09309

- absorb Ψ zero mode into time redefinition
- interpret Φ zero mode as correction to chosen background evolution a(t)
- can check if background evolves differently than in FLRW → not possible in Newtonian simulations!



'geometric' backreaction



Change in average expansion of simulation box:

- small: $<10^{-6}$
- negative: slows down expansion

BUT:

1. Our simulation box is a flat periodic torus
   - boundary conditions impact ΔH/H
   - inside box dispersion $O(10^{-4})$ around this
   - gauge dependent
2. In any case, we need to obtain `observations', eg. with raytracing.

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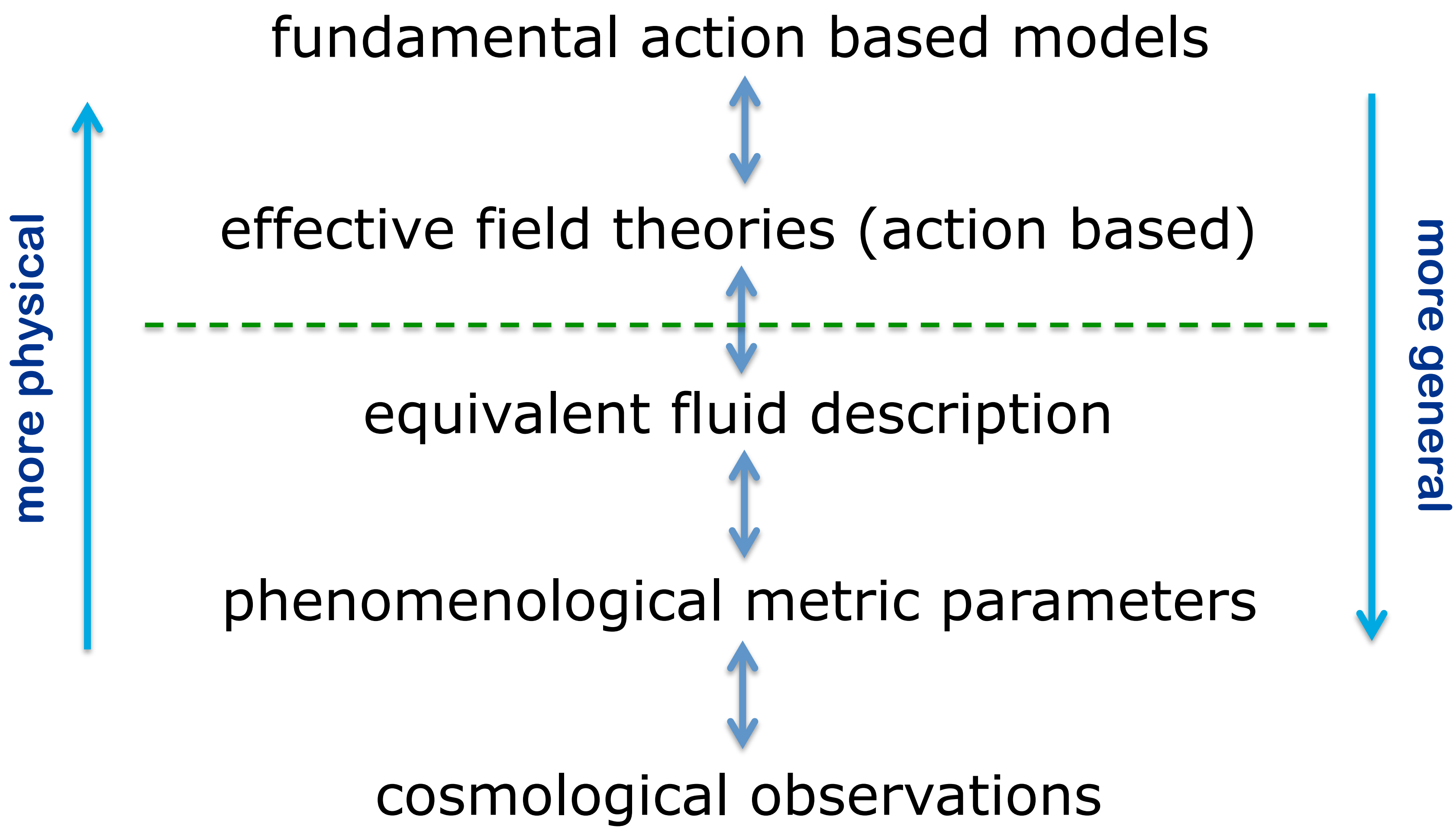
how to characterize?

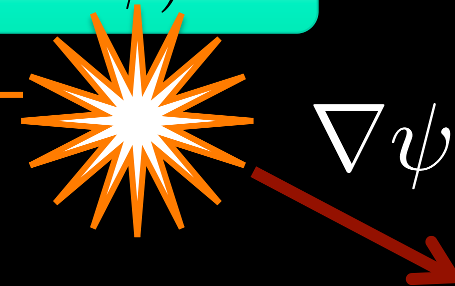
a hierarchy of DE modelling



phenomenological parameters

$$ds^2 = -(1+2\psi)dt^2 + a(t)^2(1-2\phi)dx^2$$

a(t)



$\nabla\psi$

$\nabla_\perp(\phi+\psi)$

(lensing)

(velocity field)

observations probe space-time geometry
→ characterize geometry

deviations from "standard clustering":

$$-k^2\Psi \equiv 4\pi G a^2 \mu(a,\mathbf{k})\rho\Delta$$

$$\Phi \equiv \eta(a,\mathbf{k})\Psi$$

- extra clustering
- G_{eff}/G
- something else

We expect
μ = 1
η = 1
at low z

(many equivalent parametrisations cf e.g. MK 2012)

geometry vs effective fluid

metric "template"

$$ds^2 = -dt^2 + a(t)^2 dx^2$$

observations:

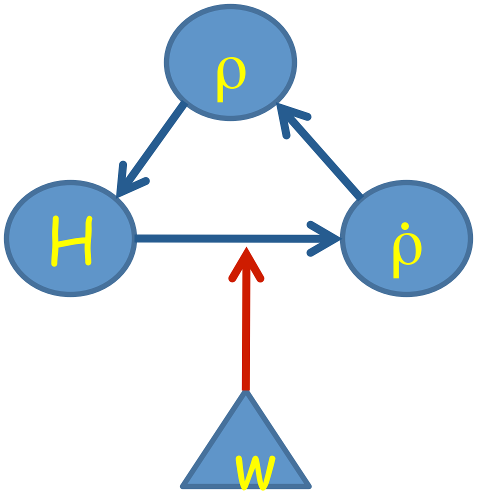
$$d_L = (1+z)\int_0^z \frac{du}{H(u)}$$

Einstein eq'n $$H^2 = \left(\frac{\dot a}{a}\right)^2 = \frac{8\pi G}{3}(\rho_1 + \rho_2 + \ldots + \rho_n)$$

conservation $$\dot\rho_i = -3H(\rho_i + p_i) = -3H(1+w_i)\rho_i \qquad i = 1,\ldots,n$$

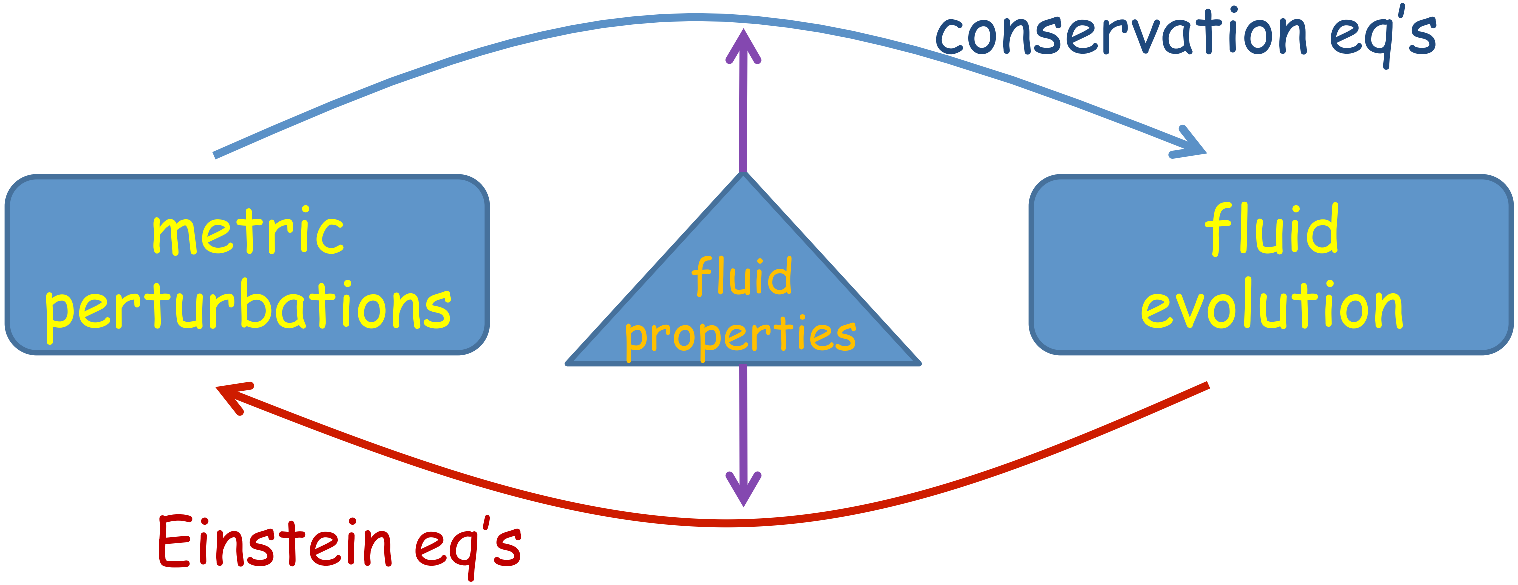
- w_i describe the fluids
- (>1 fluid: dark degeneracy)

- H|a describe observables (distances, ages, etc)



perturbations

$$ds^2 = -(1+2\psi)dt^2 + a^2(1-2\phi)dx^2$$ metric (gauge fixed, scalar dof)



$$k^2\phi = -4\pi G a^2 \sum_i \rho_i \left(\delta_i + 3Ha\frac{V_i}{k^2}\right), k^2(\phi-\psi) = 12\pi G a^2 \sum_i (1+w_i)\rho_i\sigma_i$$

$$\delta_i' = 3(1+w_i)\phi' - \frac{V_i}{Ha^2} - \frac{3}{a}\left(\frac{\delta p_i}{\rho_i} - w_i\delta_i\right)$$

$$V_i' = -(1-3w_i)\frac{V_i}{a} + \frac{k^2}{Ha}\left(\frac{\delta p_i}{\rho_i} + (1+w_i)(\psi-\sigma_i)\right)$$

modeling dark matters

fluid: EMT conservation equations (+ Einstein) $T^{\nu}{}_{\mu;\nu}=0$ -- one set for each type (matter, radiation, DE, …)

$$\delta_i' = 3(1+w_i)\phi' - \frac{V_i}{Ha^2} - \frac{3}{a}\left(\frac{\delta p_i}{\rho_i} - w_i\delta_i\right)$$
$$V_i' = -(1-3w_i)\frac{V_i}{a} + \frac{k^2}{Ha}\left(\frac{\delta p_i}{\rho_i} + (1+w_i)(\psi - \sigma_i)\right)$$

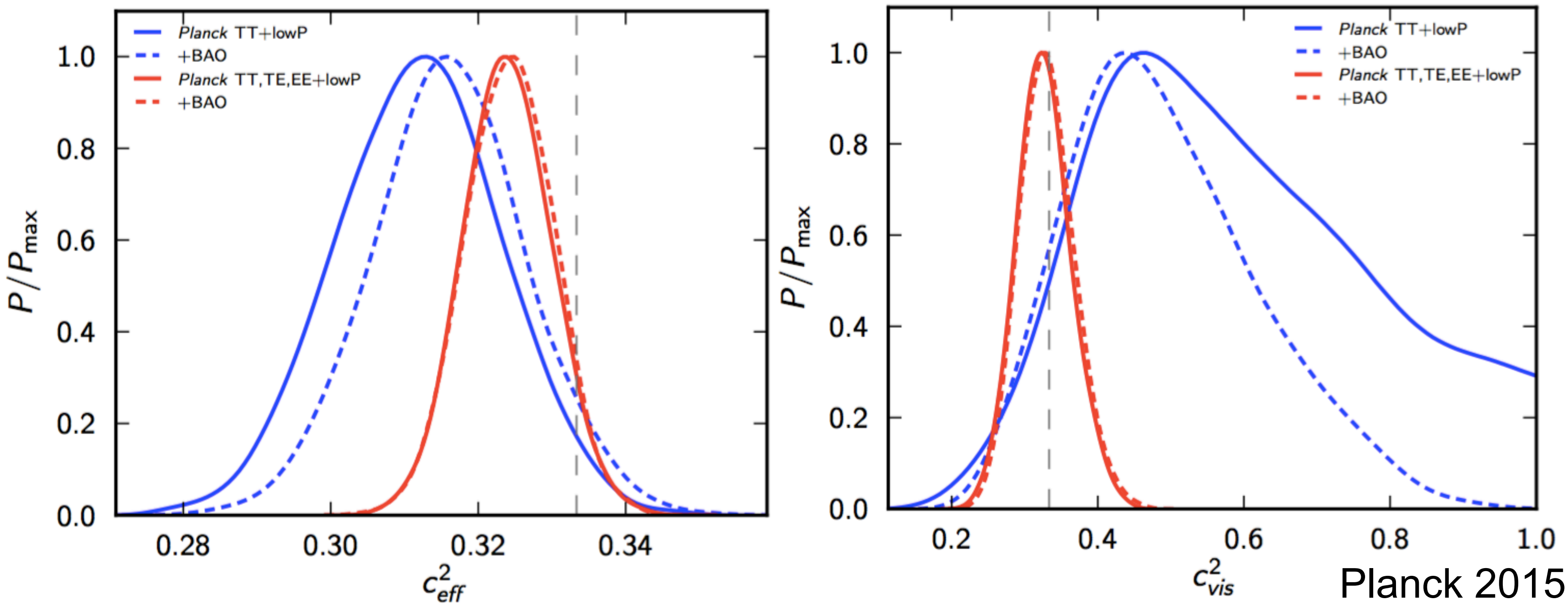
$w=p/\rho$, δp [~ $c_{eff}^2\,\delta\rho$], σ [<-> c_{vis}^2]: determines physical nature of fluid

Take-home message here:

- If you have a model, you can predict what the phenomenological parameters are
- If you don't have a model, you can try to measure them from the data to get hopefully some inspiration
- At the very least, they provide a way to combine multiple observations in a coherent, general `theory-agnostic' framework

this really works (for neutrinos)

Planck 2015 paper XIII



Planck 2015

Parameter	TT+lowP	TT+lowP+BAO	TT,TE,EE+lowP	TT,TE,EE+lowP+BAO
σ : c^2_{vis}	$0.47^{+0.26}_{-0.12}$	$0.44^{+0.15}_{-0.10}$	0.327 ± 0.037	0.331 ± 0.037
δp : c^2_{eff}	0.312 ± 0.011	0.316 ± 0.010	0.3240 ± 0.0060	0.3242 ± 0.0059

- significant detection of "primordial neutrino anisotropies"
- agrees well with expected values

European Space Agency

results for generalized DM

arXiv:1604.05701

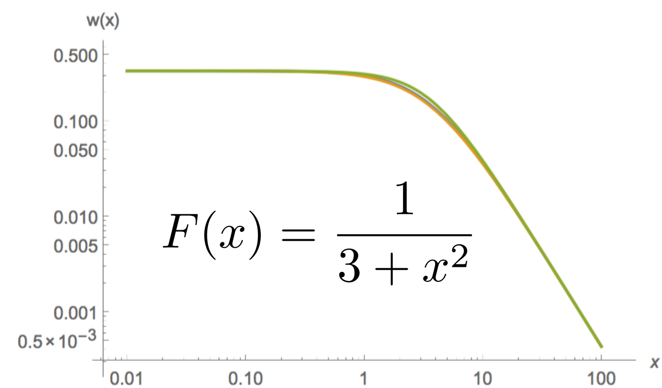
1. Just include w, c_s^2 and c_{vis}^2 as free DM parameters, using Planck+ext
   - $w = (-0.26 \pm 0.68) \times 10^{-3}$
   - $\log_{10} c_s^2 < -5.9$, $\log_{10} c_{vis}^2 < -5.7$ at 99%

     (consistent with Thomas+ arXiv:1601.05097)

   using ‘linearized’ weak lensing (CFHTLenS) does not change much

2. Physically expect a $1/a^2$ redshifting behaviour in non-relativistic regime
   - strong suppression at late times
   - today $\log_{10}[w, c_s^2, c_{vis}^2] <\sim -10$!
   - implies DM non-relativistic at decoupling

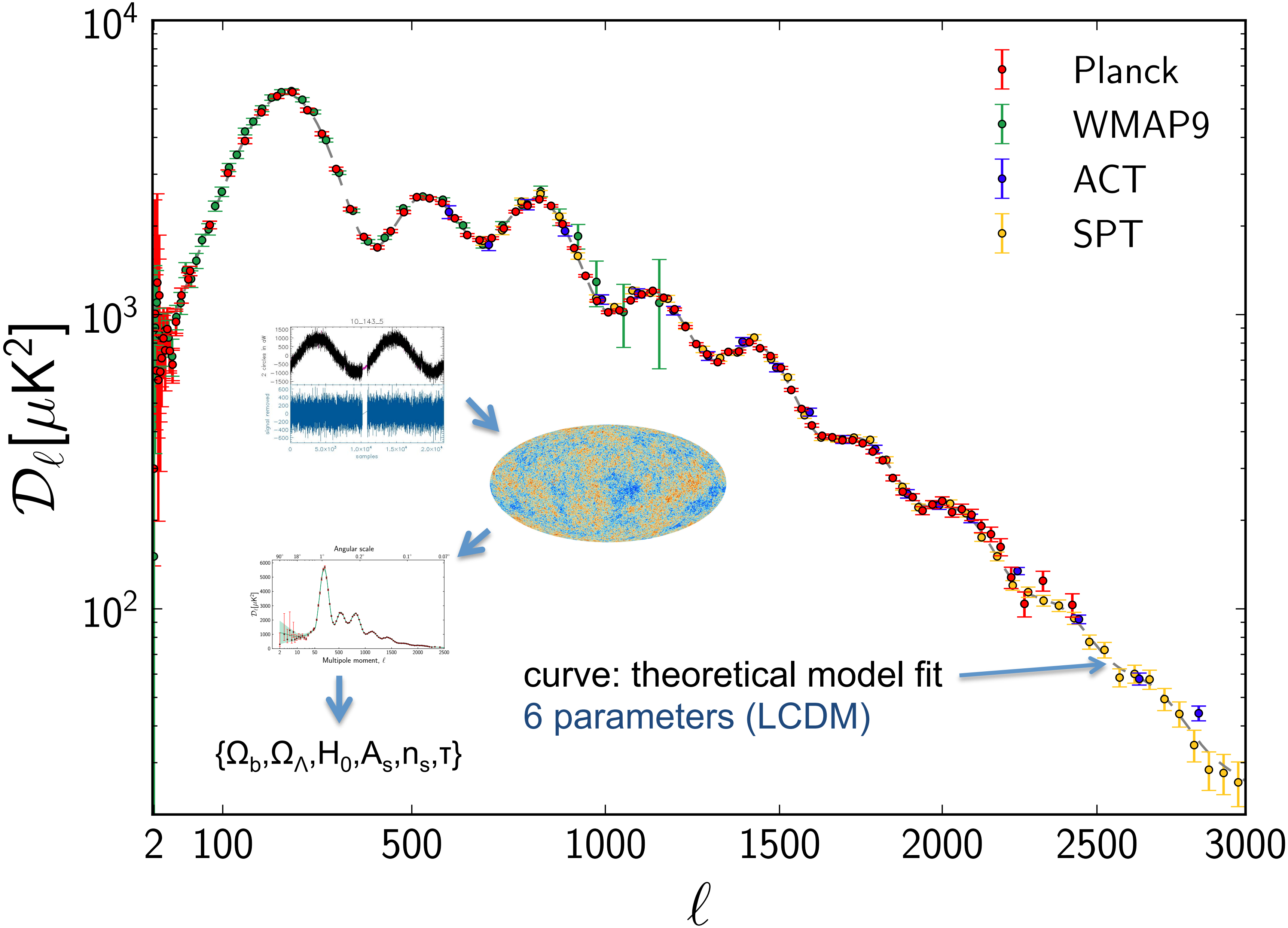
     $w(z_{rec}) \sim 10^{-3}$ (same for c_s^2, c_{vis}^2)
   - CMB lensing gives $c_s^2 < 10^{-6}$ at low-z
   - these are model-independent constraints
   - Weak lensing more powerful, but more systematics, should see non-linear velocity dispersion soon



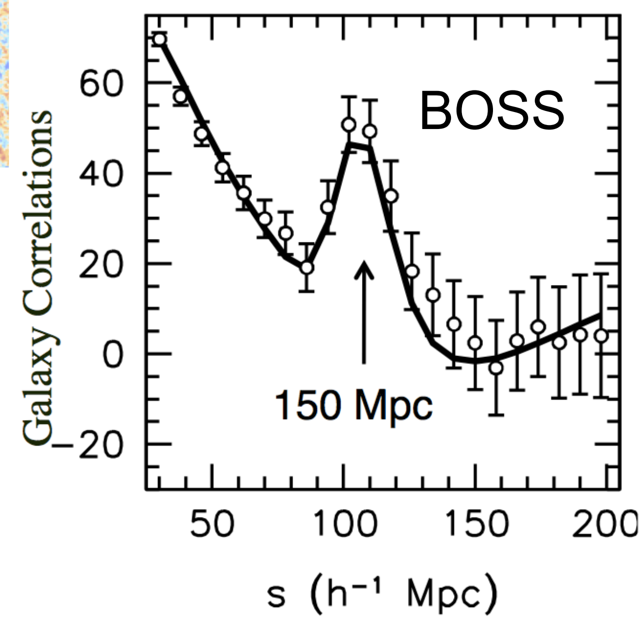
DE/MG constraints w/ current data
(Planck 2015 paper XIV)

- **Planck CMB data** (temperature + polarization)
- **'background'** (BSH): constrain **H(z) ↔ w(z)**
  - supernovae: JLA
  - Baryon acoustic oscillations (BAO): SDSS, BOSS LOWZ & CMASS, 6dFGS
  - H_0: (70.6 ± 3.3) km/s/Mpc [Efstathiou 2014]
- **redshift space distortions** (BAO/RSD)
  - sensitive to velocities from gravitational infall
  - acceleration of test-particles (galaxies) come from **grad ψ**
  - usually given as limit on $f\sigma_8$ (continuity eq.)
  - we use BOSS CMASS
- **gravitational lensing** (WL and CMB lensing)
  - deflection of light governed by **φ+ψ**
  - galaxy weak lensing: CFHTLenS with 'ultraconservative cut'
  - CMB lensing: lensing of Planck CMB map
    - extracted from map trispectrum
    - power spectrum is also lensed!

the CMB power spectrum

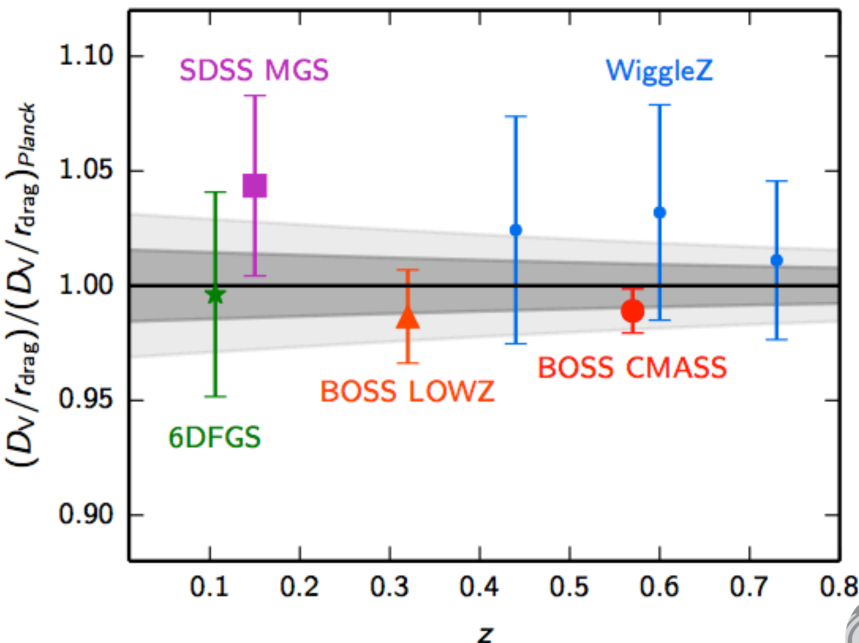


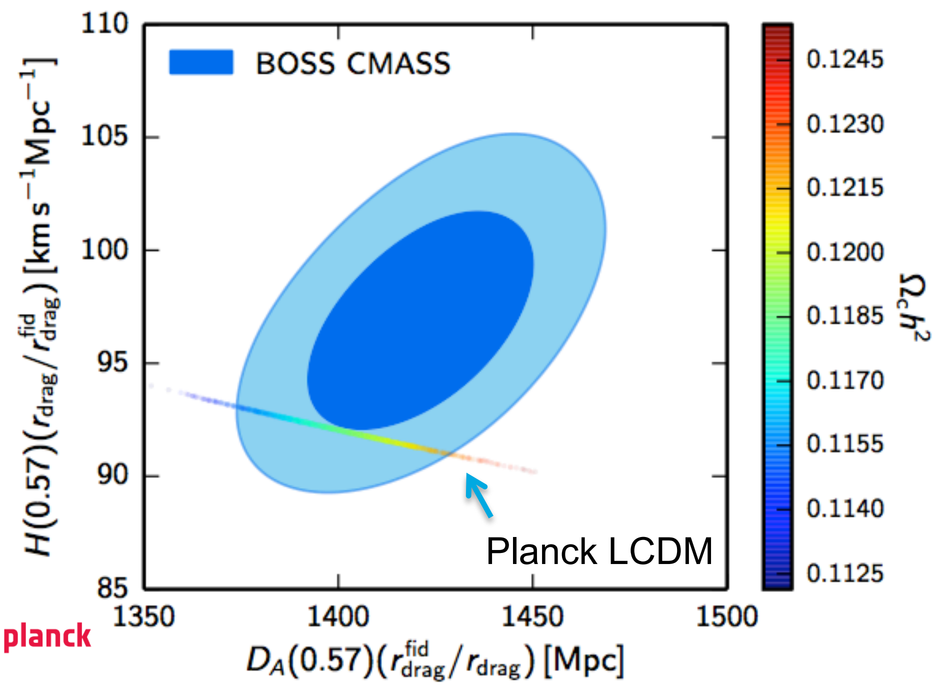
BAO distances



a standard ruler of ~150 comoving Mpc gives us an angular diameter distance (linked to same scale as CMB peak position!)

Planck 2015 + LCDM

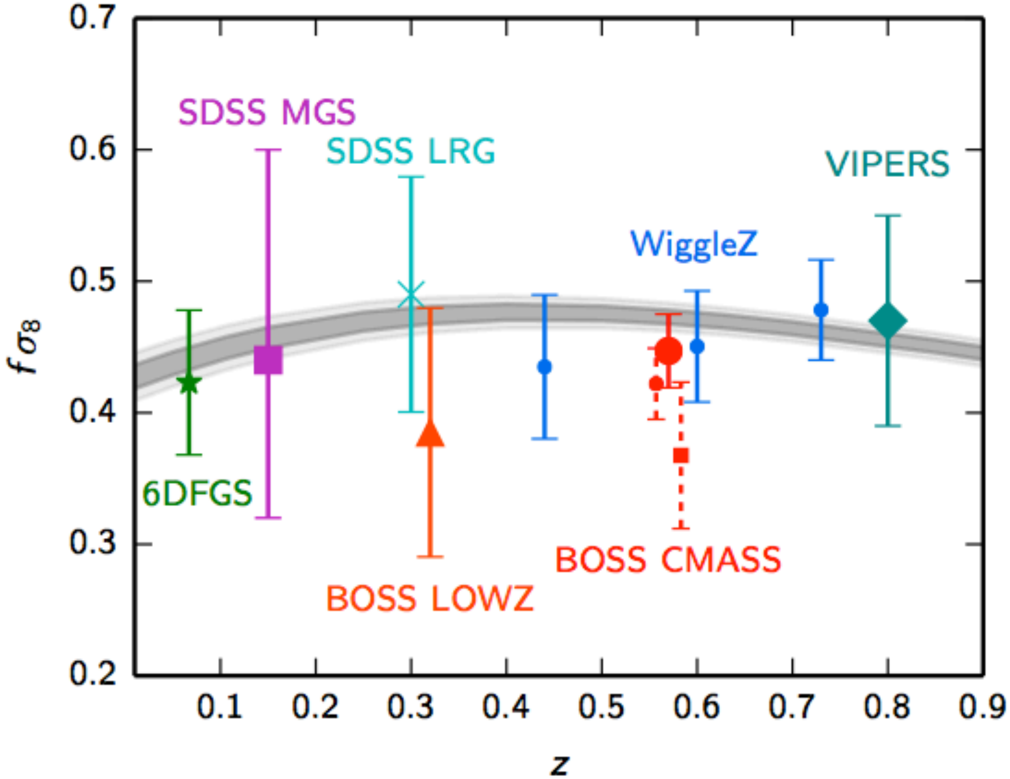


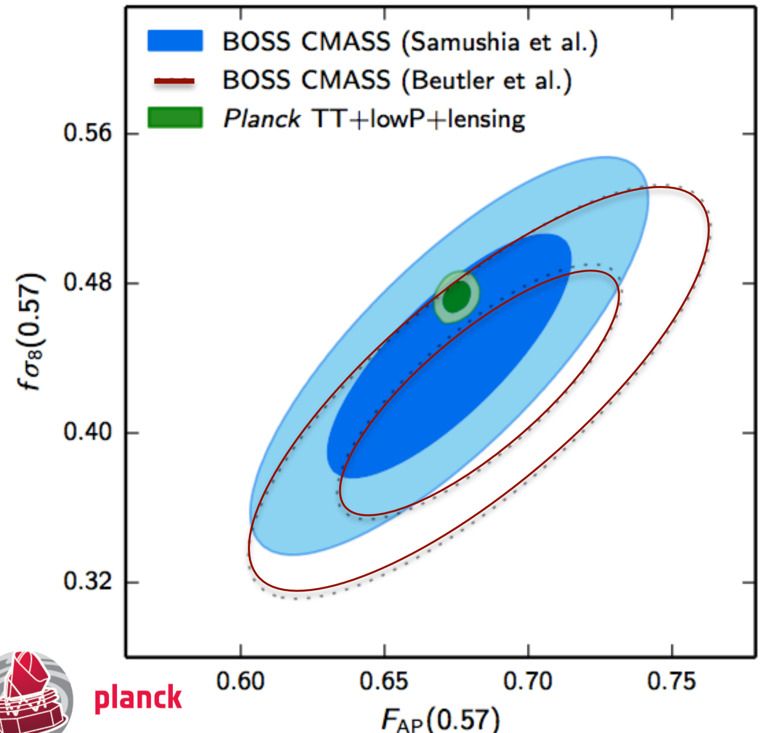


redshift space distortions

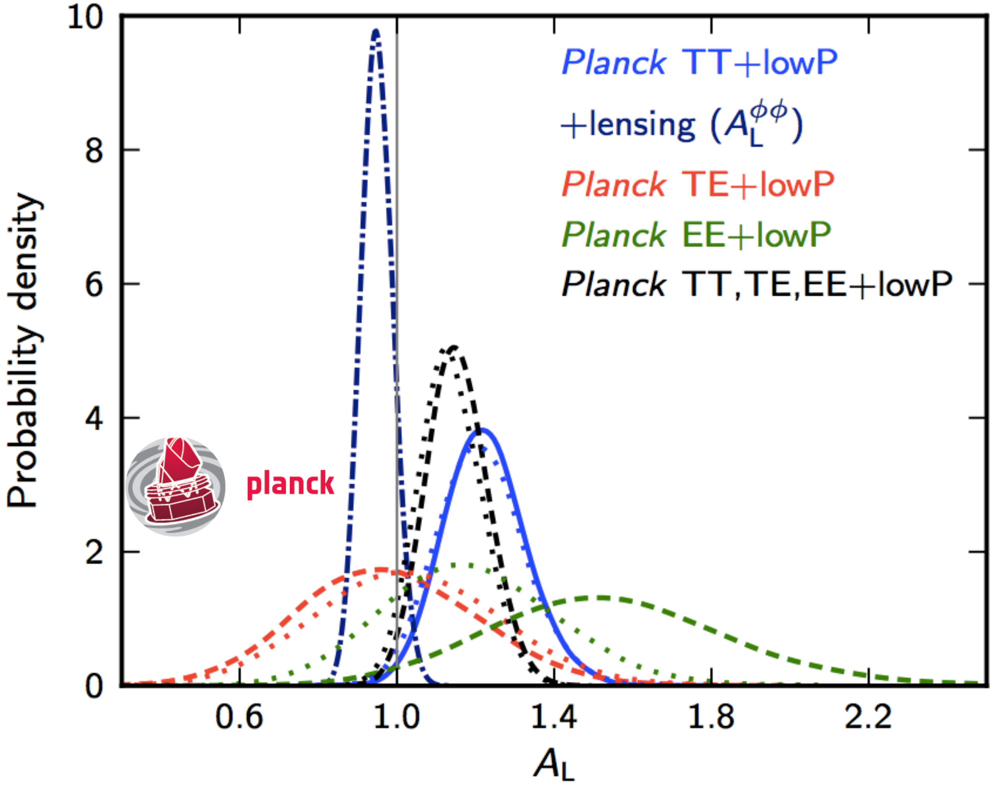
- particle conservation: velocities → growth
  → RSD measure combination $f\sigma_8$, $f = d\ln D/d\ln a$
- particle acceleration ~ grad Ψ

Planck 2015 + LCDM

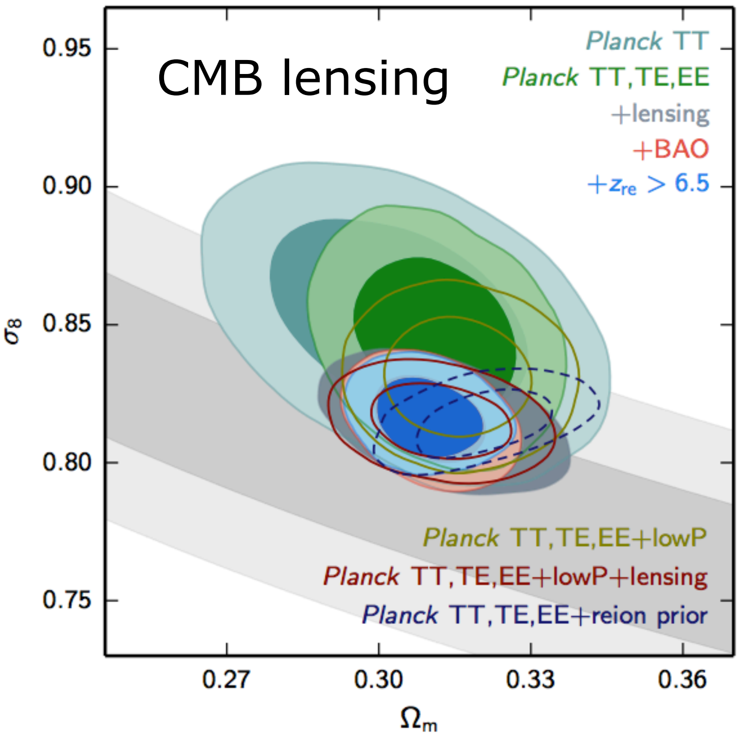




weak / CMB lensing



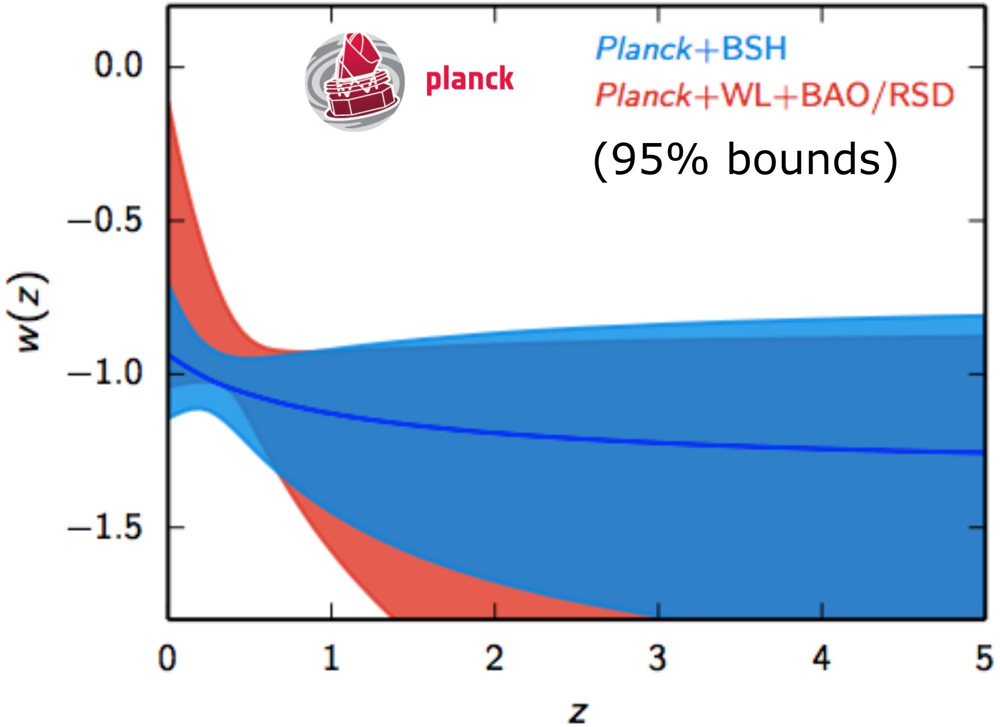
- WL still young technique
- CFHTLenS analyses marginally compatible with each other
- region ~Planck needs high H_0
- we use 'ultraconservative' cut

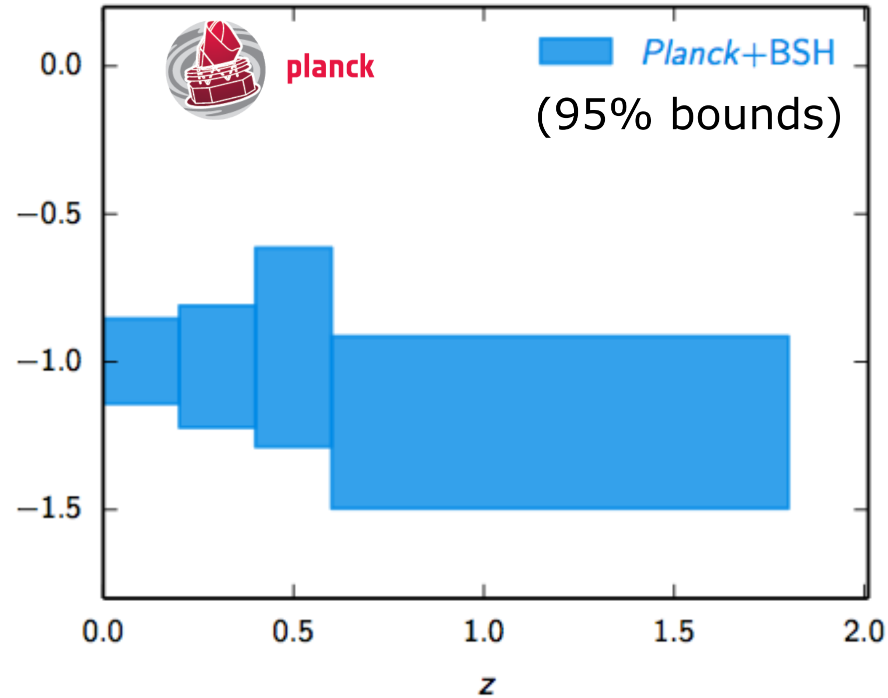


- CMB lensing now quite mature
- relatively good agreement with primary CMB
- (still a slight 'lensing excess' in power spectrum)

ncy

w(z) reconstruction





from ensemble of
$w_0+(1-a)w_a$ curves
(we also tried cubic in a)

PCA
(we also tried more bins)

no deviation from w=-1

European Space Agency

phenomenological approach

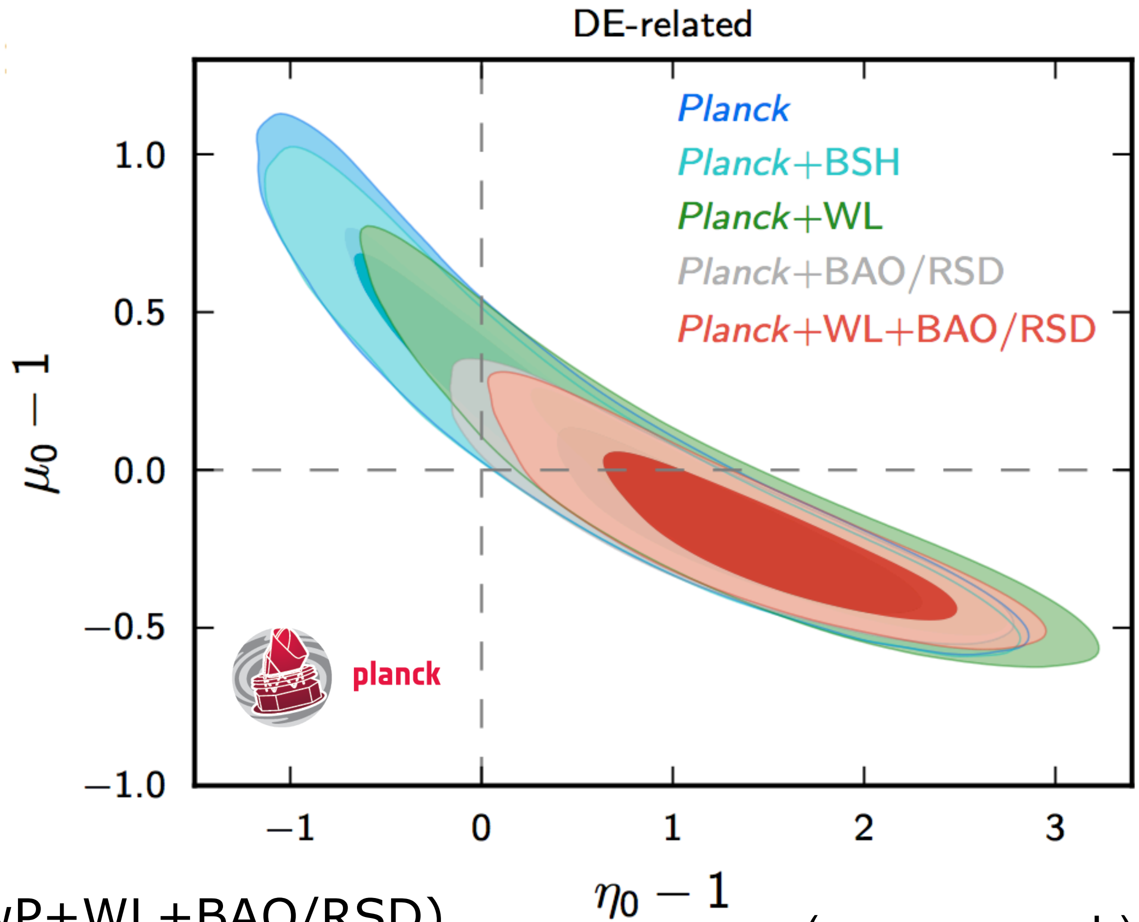
parameterisation of
late-time perturbations:

$$-k^2\Psi \equiv 4\pi G a^2 \mu(a,\boldsymbol{k})\rho\Delta$$

$$\eta(a,\boldsymbol{k}) \equiv \Phi/\Psi$$

functions ~ $\Omega_{DE}(a)$
ΛCDM background

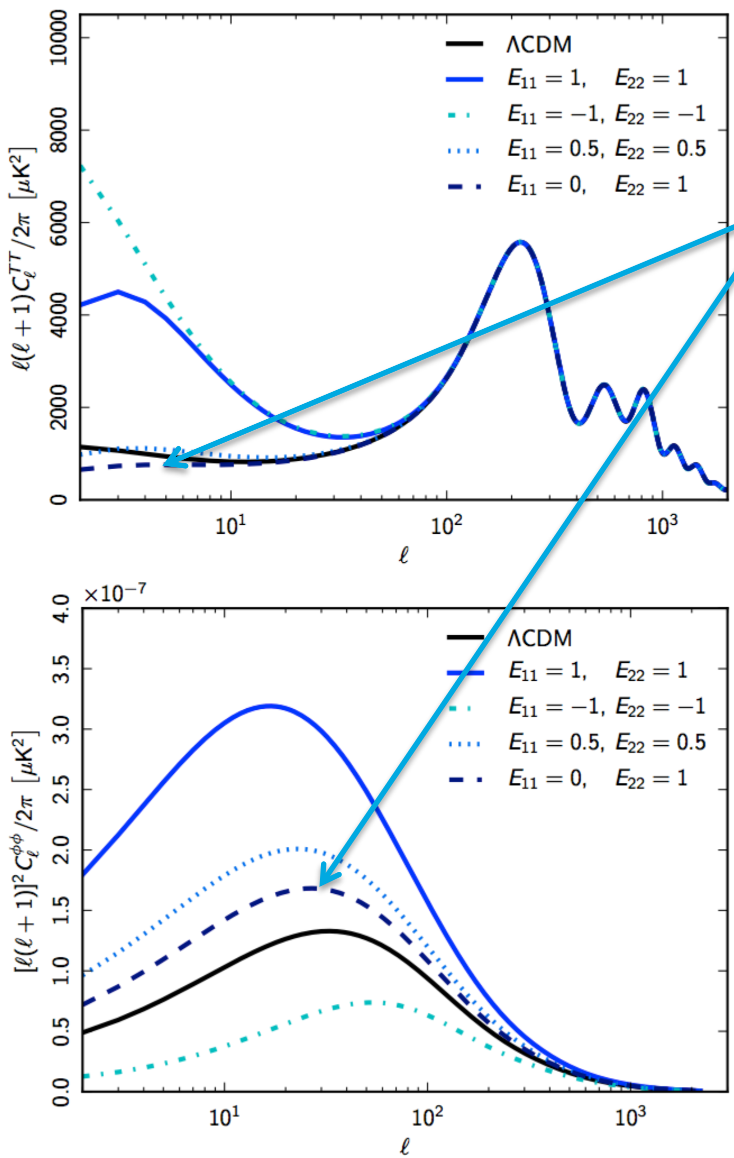
- no scale dependence detected
- deviation driven by CMB and WL



$\Delta\chi^2$ = -10.8 (Planck TT+lowP+WL+BAO/RSD)

(uses mgcamb)

MG impact on observables

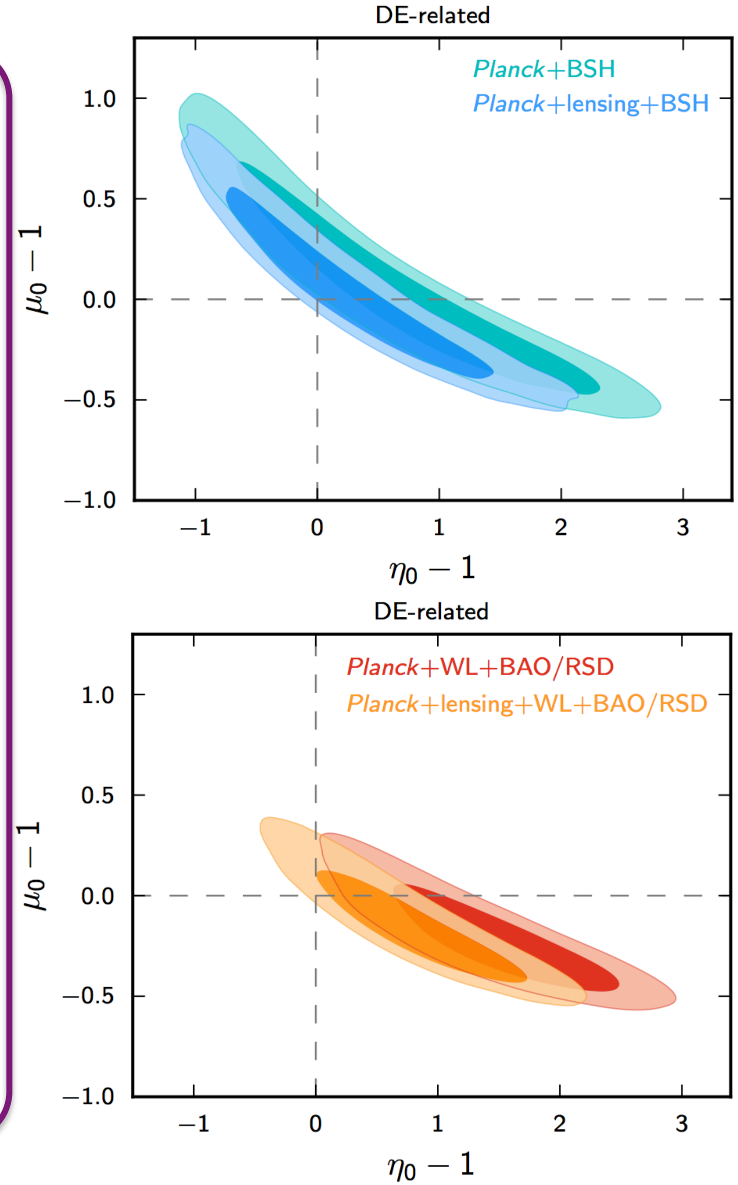


best-fit model is similar to -- model

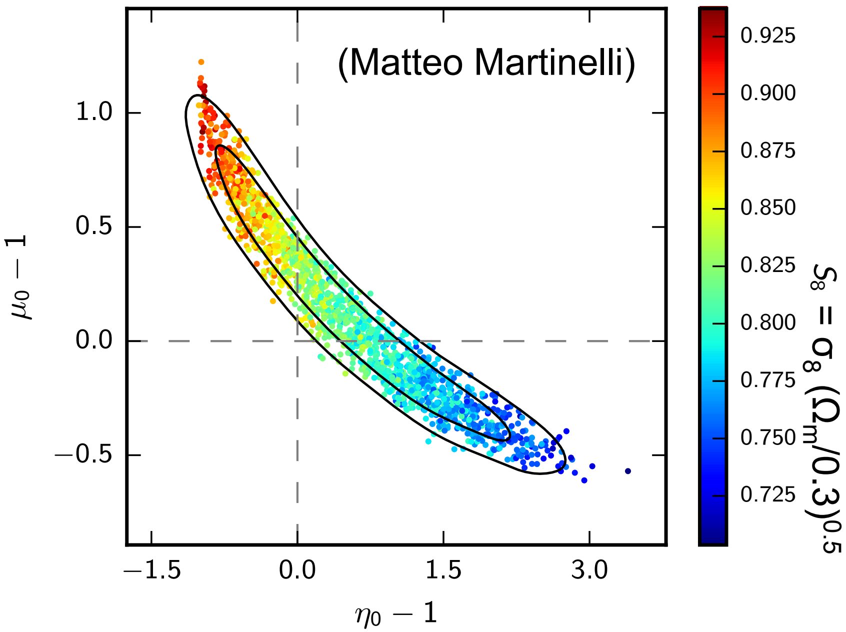
CMB data prefers lower low-l value and higher lensing in TT

BUT NOT in the 4-point lensing → CMB lensing prefers LCDM!

→ doesn't look very significant after all?



another look at lensing

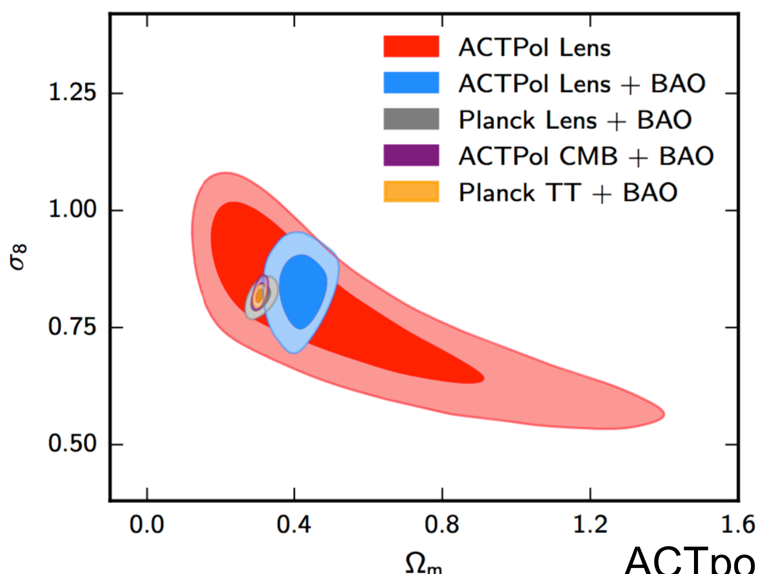


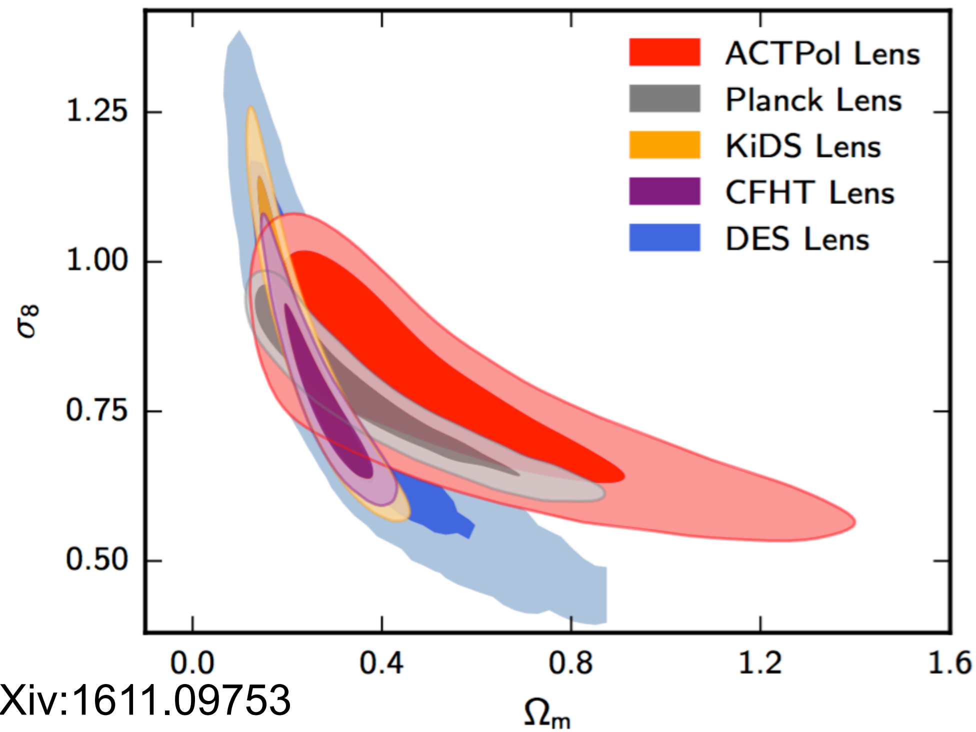
dark energy can suppress power

- at late times (evolving w)
- on small scales (sound horizon)

ex: S_8 varies across (μ,η) plane

CMB (early, large scales) seems to see more power than WL

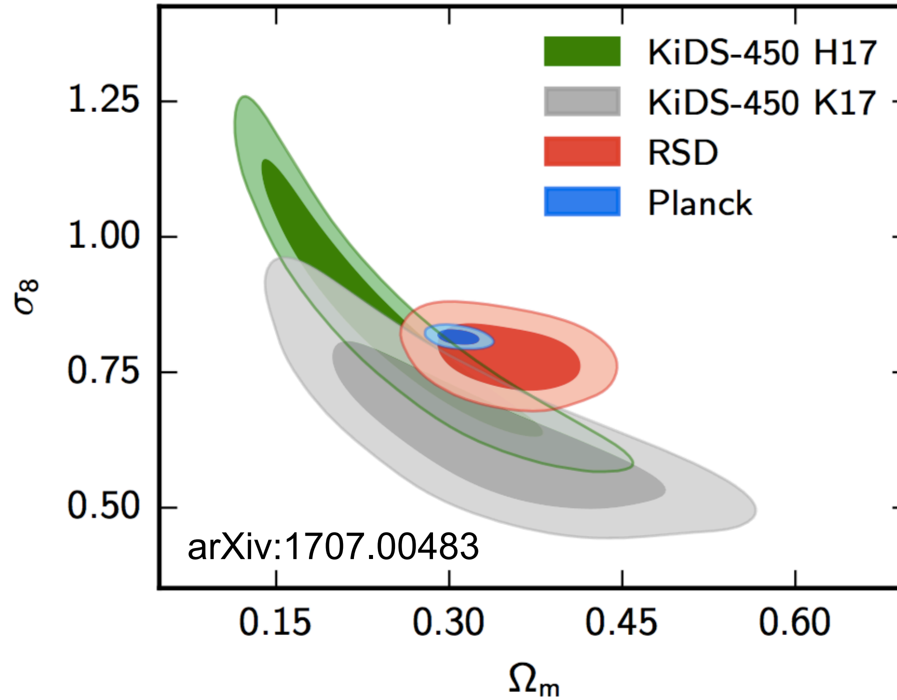


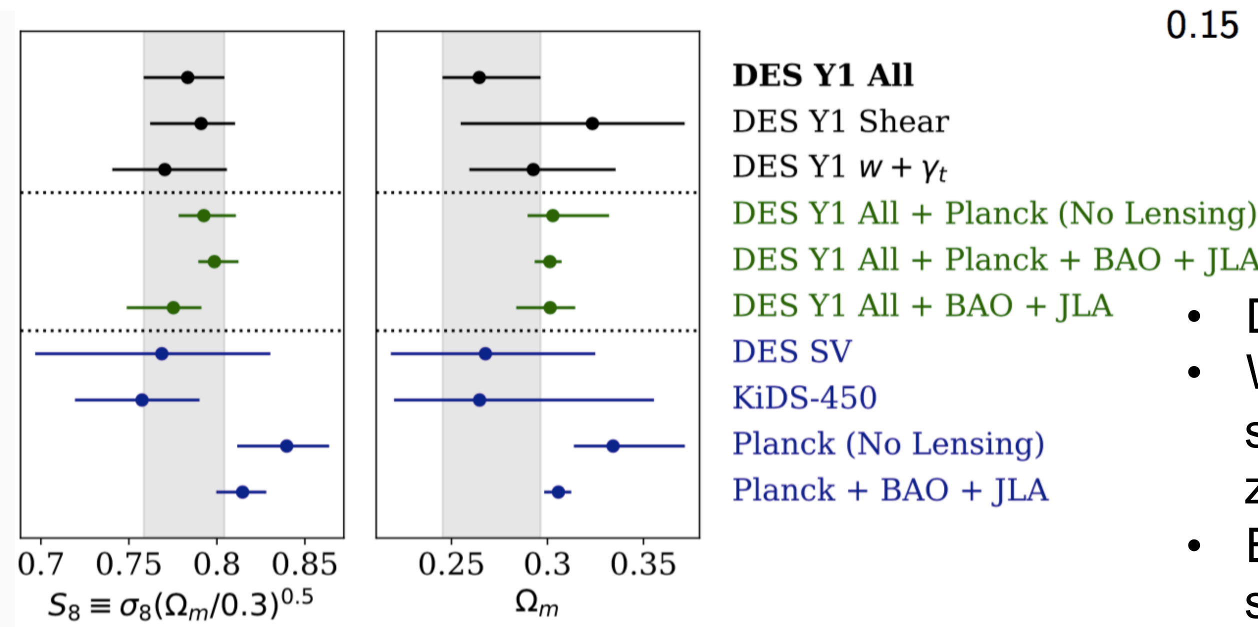


ACTpol, arXiv:1611.09753

a lensing crisis for LCDM?

- Hildebrandt (H17) KiDS analysis seems to have (too?) large internal scatter of data.
- Different KiDS analyses find quite different posteriors, some (eg when adding GAMA data) consistent with CMB.
- RSD also consistent with CMB.





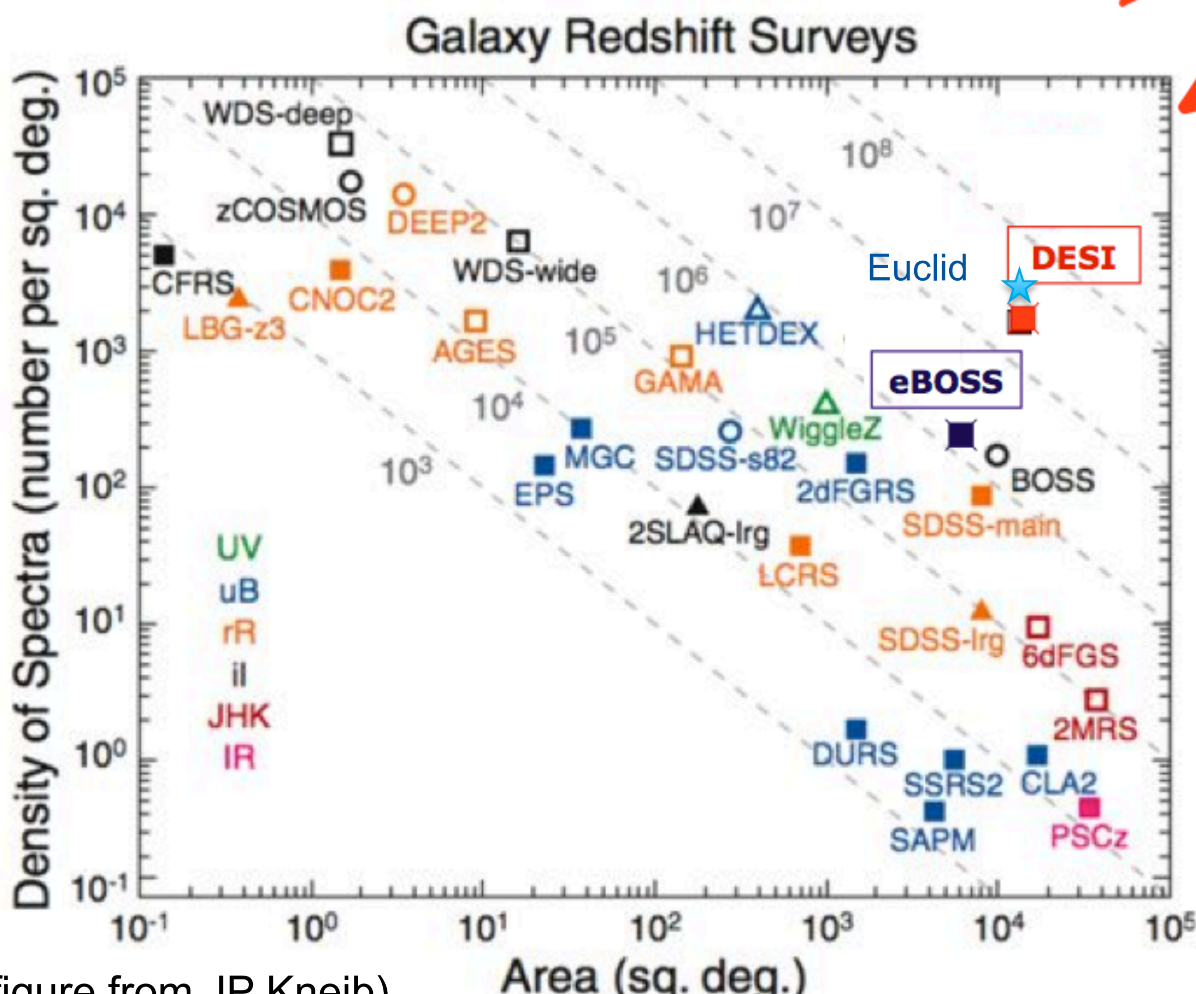
- DES Y1 sits in the middle
- WL is relatively young, systematic effects (eg photo-z) not yet well understood?
- Best to adopt a ‘wait and see’ attitude?

Galaxy redshift survey "history"

- 1986 CfA 3500
- 1996 LCRS 23000

Fractional error in the amplitude of the fluctuation spectrum

1970	x100
1990	x2
1995	±0.4
1998	±0.2
1999	±0.1
2002	±0.05
2003	±0.03
2009	±0.01
2012	±0.002

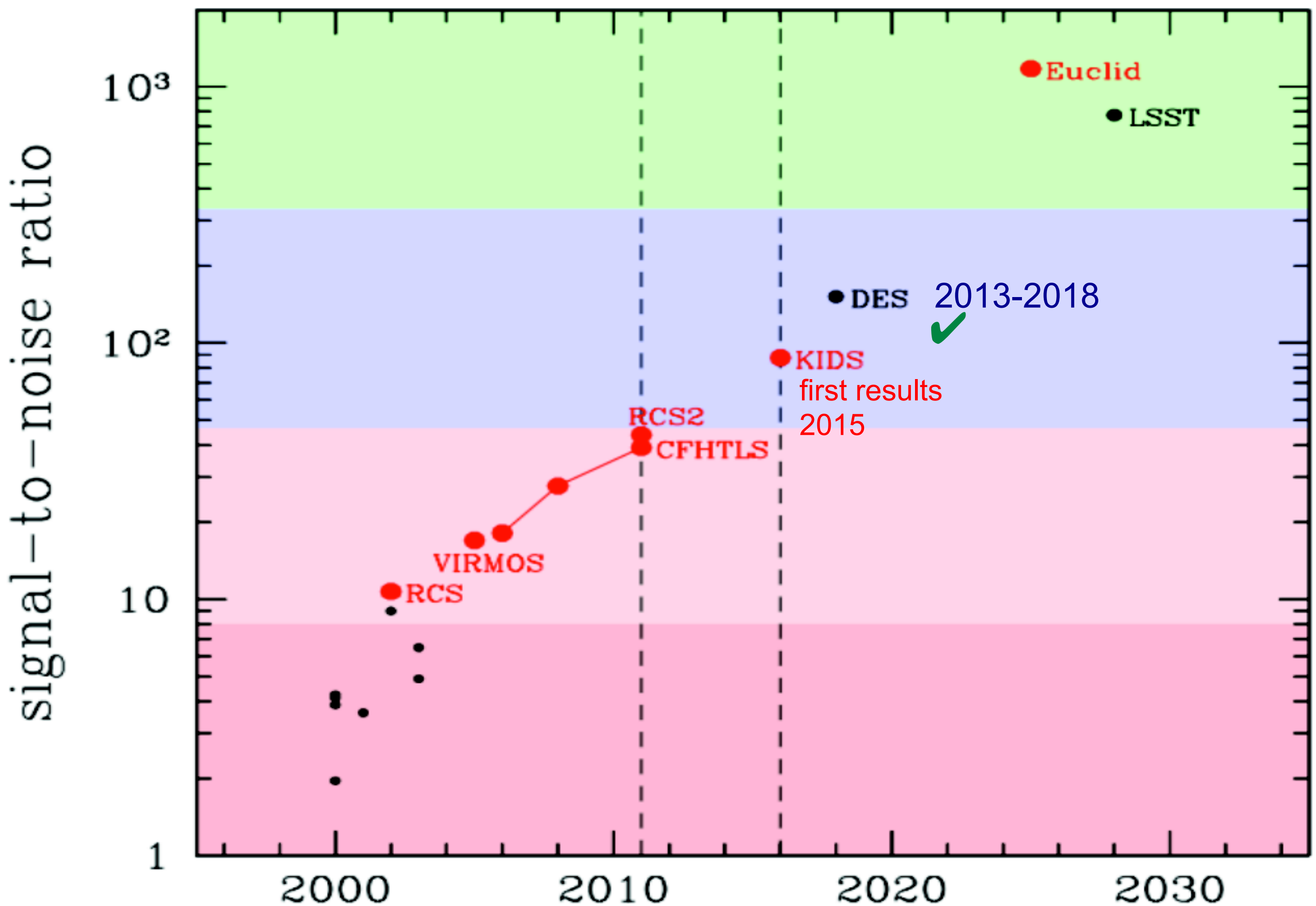


(figure from JP Kneib)

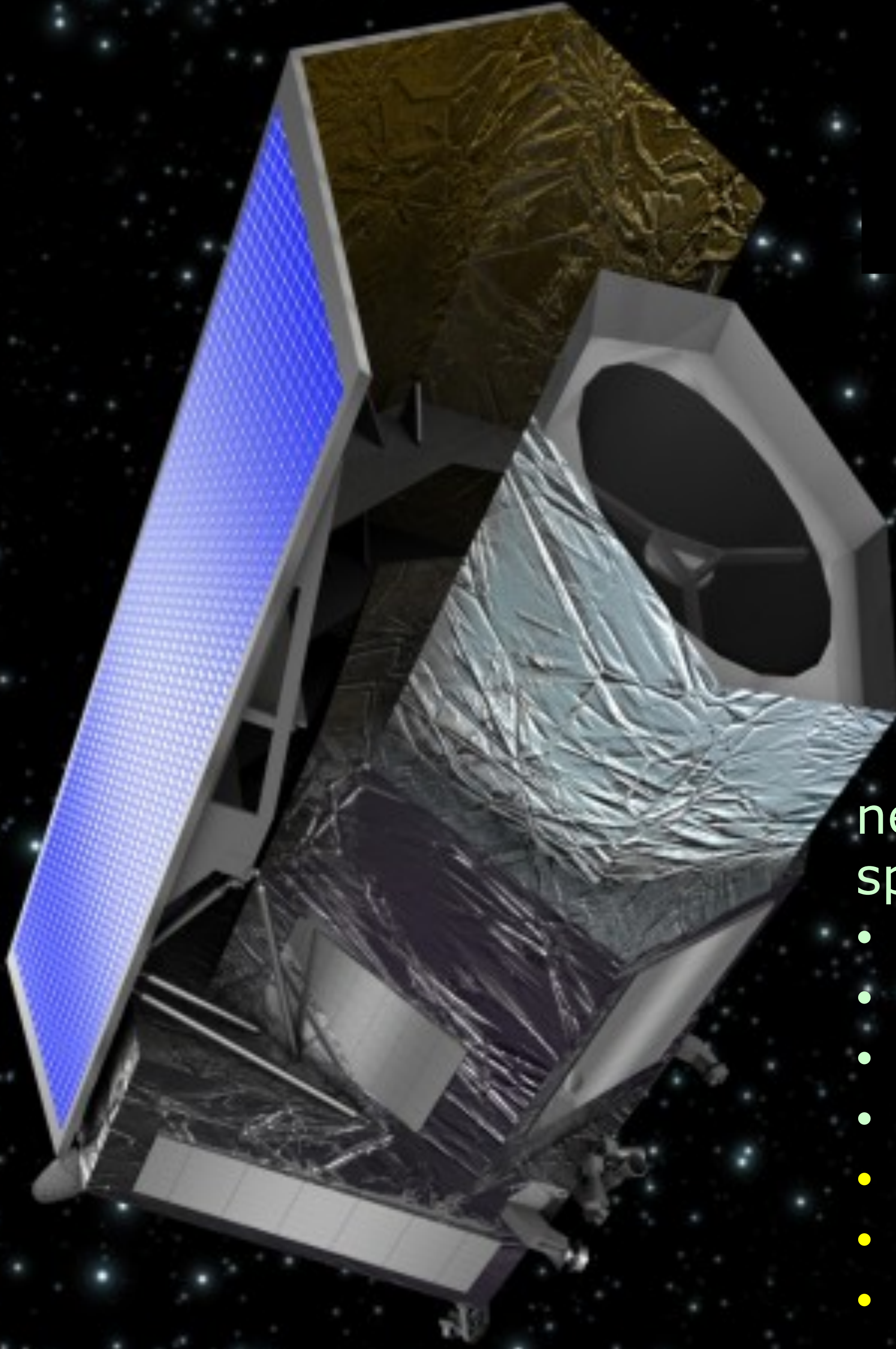
Driven by the development of instrumentation

(slide from Will Percival)

weak lensing surveys (wide-field cosmic shear)



CFHTLS: www.cfhtlens.org, KiDS: kids.strw.leidenuniv.nl, DES: www.darkenergysurvey.org



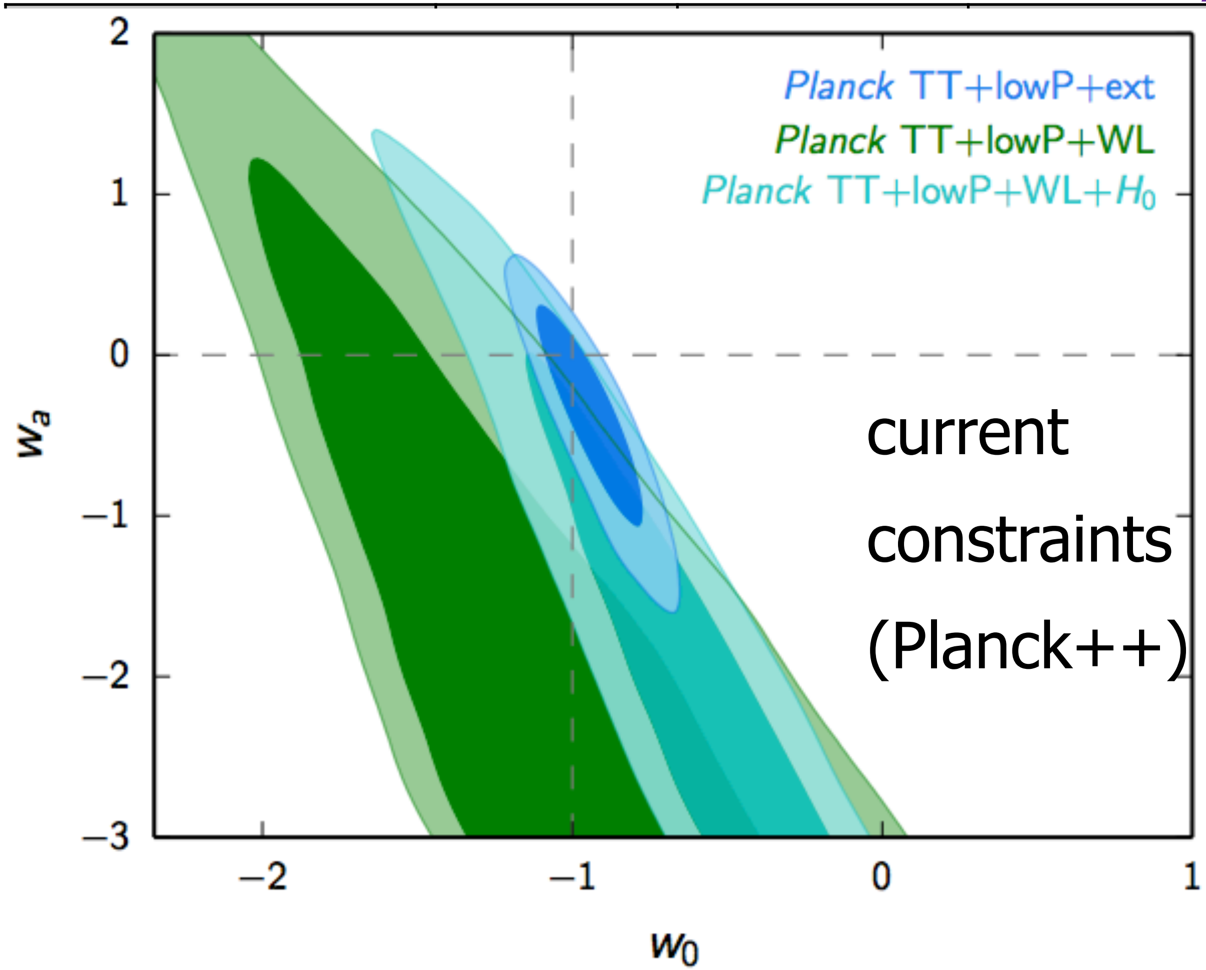
Euclid
ca 2021

near-infrared and optical space telescope

- 15’000 square degrees
- 1 million+ images
- data rate ~1Tb/day
- ~100 Pb data (inc grnd)
- 12 billion sources
- 1.5 billion shapes
- 30 million redshifts

Euclid Post-Planck Forecast for the Primary Program

Assume systematic errors are under control



	Dark Energy		
	w_p	w_a	FoM $= 1/(\Delta w_0 \times \Delta w_a)$
	0.015	0.150	430
	0.013	**0.048**	**1540**
	0.007	0.035	**6000**
	0.100	**1.500**	**~10**
	>10	**>40**	**>400**

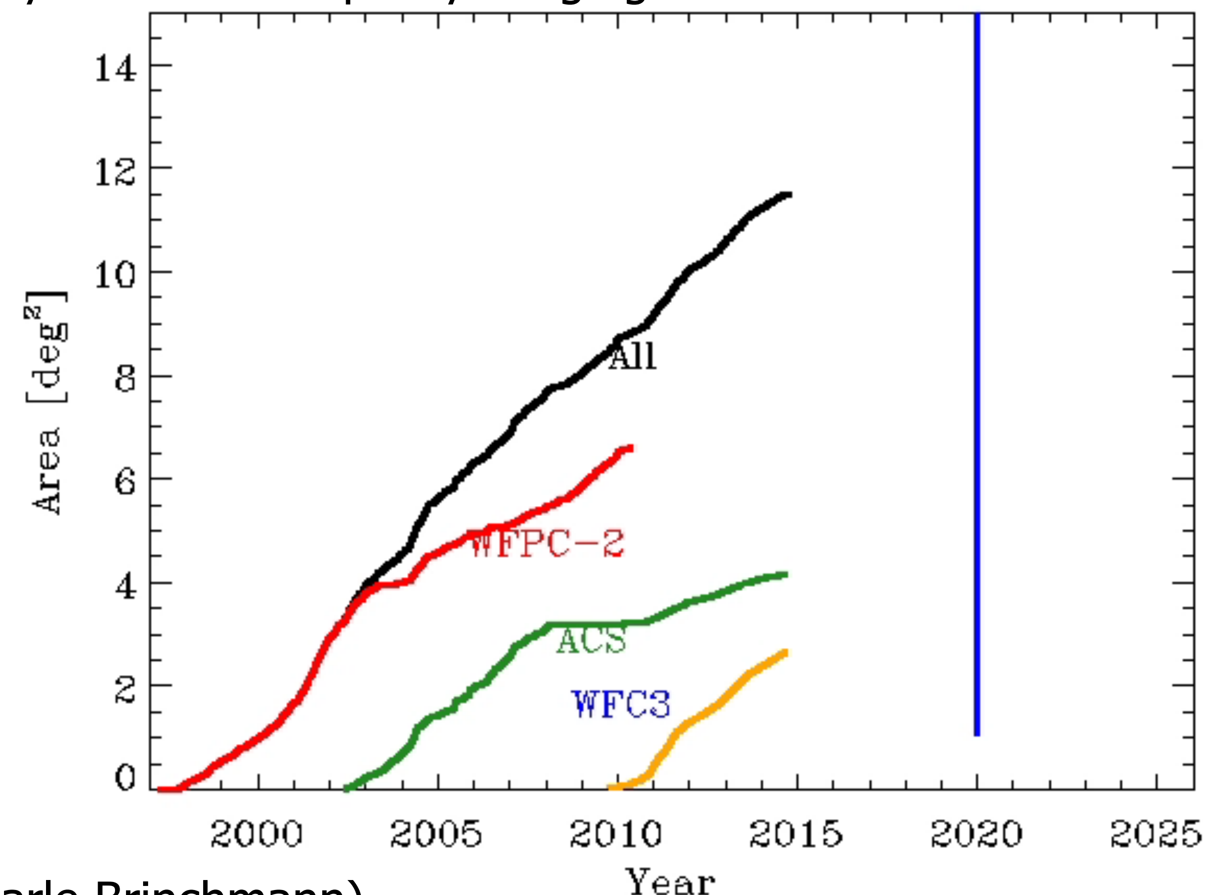
$w_a(a_p\text{-}a)$

- From Euclid data alone, get FoM=1/(Δw_a x Δw_p) > 400→ ~1% precision on w's.
- **Notice neutrino constraints -> minimal mass possible ~ 0.06 eV!**

Euclid does much more than DE!

- 12 billion sources, 3-σ

sky area of HST quality imaging



(Jarle Brinchmann)

Objects	Euclid	Before Euclid
	$\sim 2 \times 10^8$	$\sim 5 \times 10^6$
	Few hundreds	Few tenss
	$\sim 4 \times 10^7 / 10^4$	$\sim 10^4 / \sim 10^2$?
	$\sim 2 \times 10^4$	$\sim 10^3$?
	$\sim 10^4$	$< 10^3$
	$\sim 10^5$	
	~few 10^2	<10
	~300,000	~10-100
	~30	None

les secteurs sombres des secteurs sombres

- dark energy still looks compatible with flat ΛCDM

  (but keep eye on σ_8, H_0, large-scale anomalies, … and keep an open mind for other possibilities!)
- up to linear perturbations we have good schemes to test for deviations from the standard model (EFT, phenomenology)
- upcoming large surveys combined with Planck will decrease parameter uncertainties by another one to two orders of magnitude, but …
- systematic effects are becoming the dominant issue
  - modeling of non-linear scales
  - determination of (co-)variances, likelihood shape
  - photo-z, baryons
  - other observational effects
- Néanmoins, un brillant avenir pour les secteurs sombres! ☺


Thank you