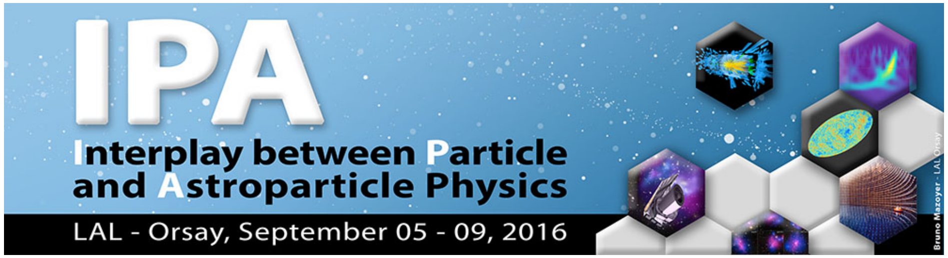
# The ΛCDM model (successes and) tensions

Stéphane Ilić
CPT (Marseille) / IRAP (Toulouse)



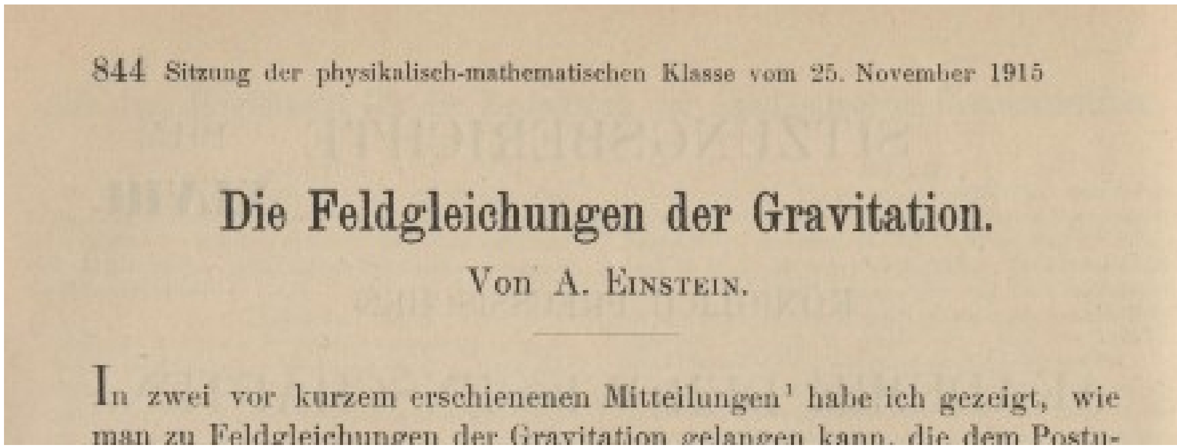
# I – The ΛCDM model

Emerged in its current form in 1990s…

...but originates back to 1910s

# A bit of history

1915 : General relativity (GR)

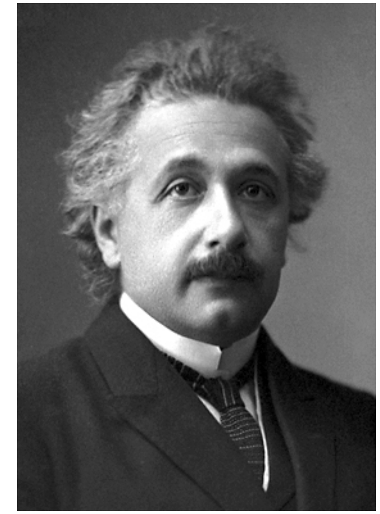


844 Sitzung der physikalisch-mathematischen Klasse vom 25. November 1915

Die Feldgleichungen der Gravitation.

Von A. Einstein.

In zwei vor kurzem erschienenen Mitteilungen[1] habe ich gezeigt, wie man zu Feldgleichungen der Gravitation gelangen kann, die dem Postu-



Explains/predicts many phenomena :

- advance of Mercury's perihelion
- deflection of starlight by sun (1919)
- …
- ...
- gravitational waves (2016)

# A bit of history

But : tested up to relatively “small” scales (~Solar system, <10^9 km)

Einstein, as soon as 1917 : “Why not apply it to the whole Universe ?”
=> ~birth of cosmology

At that time : Universe==Milky way (10^18 km)

Now : Observable Universe ~ 10^23 km

**Validity of GR at these scales still discussed to this day…..**

# Basis of the model

Einstein equations :

$$R_{\mu\nu} - \frac{1}{2} R g_{\mu\nu} + \Lambda g_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}$$

- complicated to solve (10 non-linear diff. eq.)
- first cosmological models : **homogeneous** & **isotropic** (FRW metric)
- Einstein (& co.) => static, Lemaître (& co.) => dynamic
- Hubble (1929) : **expansion** confirmed…
- ...but still depends on Universe content

# 50 years of developments

- <u>1965 :</u> discovery of CMB, consolidates BB picture
- <u>1970s :</u> ~pure baryonic models, pbs with galaxy formation
- <u>Early 1980s :</u> dom. CDM could solve it (+ hints from rotation curves)
- <u>1980s :</u> CDM (95%) and baryons (5%), pbs with H0 and gal. clustering
- <u>1992 :</u> also pb with CMB by COBE ; some models add HDM, Λ/DE
- <u>1998 :</u> acceleration of expansion, ΛCDM becomes leading model

# The ingredients of $\Lambda$CDM

“A few” assumptions :

- Homogeneity
- Isotropy
- GR (& standard physics)
- Small, Gaussian, initial fluctuations generated at early times with power-law power spectrum

“Only” six parameters :

- baryon density
- CDM density
- Age of the Universe/H0
- Reionisation “optical depth”
- Amplitude…
- ...and slope of initial fluctuations power spectrum

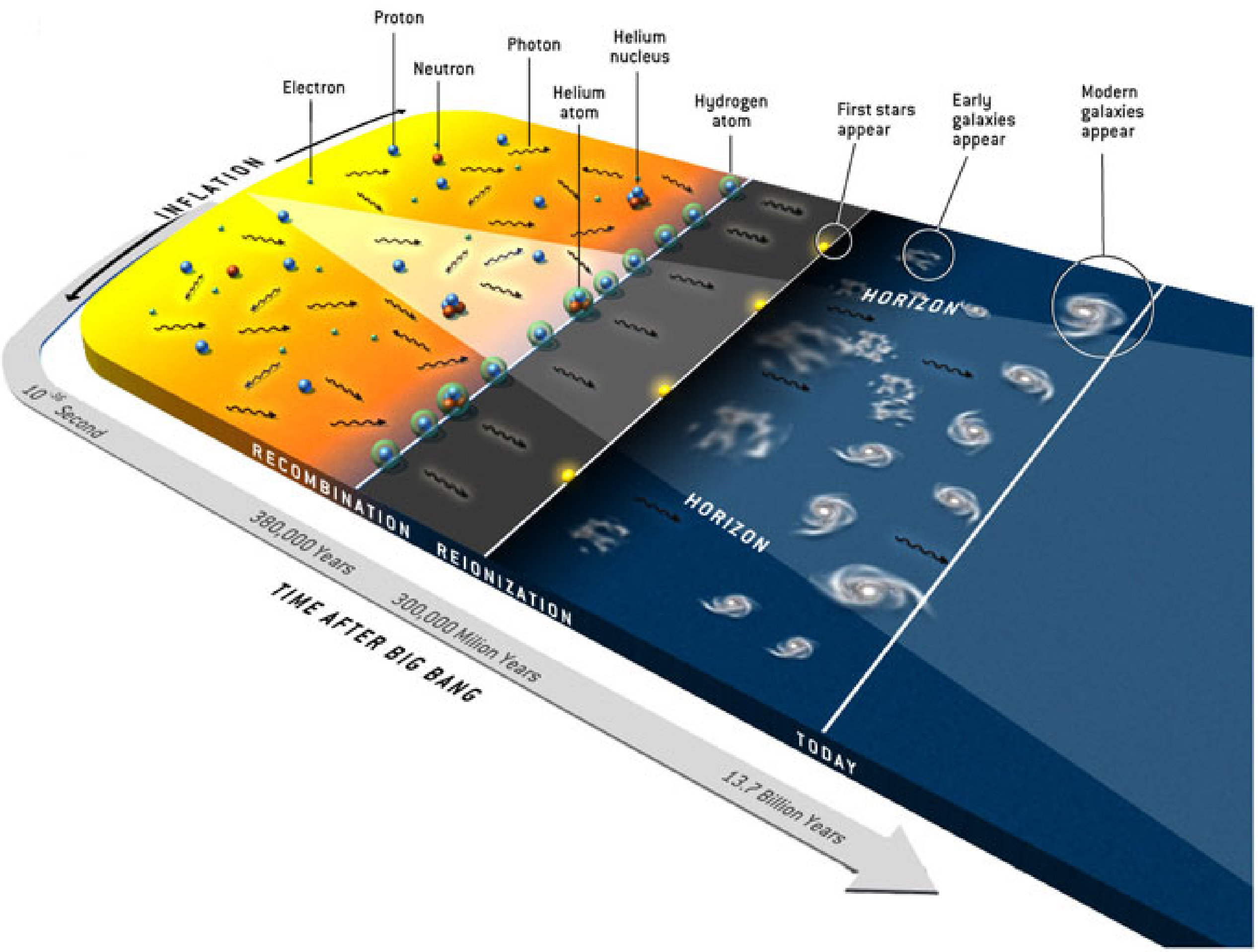
# A few “hidden” ingredients

- Total density : critical density, i.e. Universe is flat
- Equation of state of dark energy = −1, i.e. it's Λ
- Sum of three neutrino masses = 0.06 eV/$c^2$ (“minimal neutrino”)
- Effective number of relativistic degrees of freedom = 3.046
- No primordial gravitational waves
- Initial power spectra is strictly a power law

**No significant deviation found (yet !) when relaxing those**

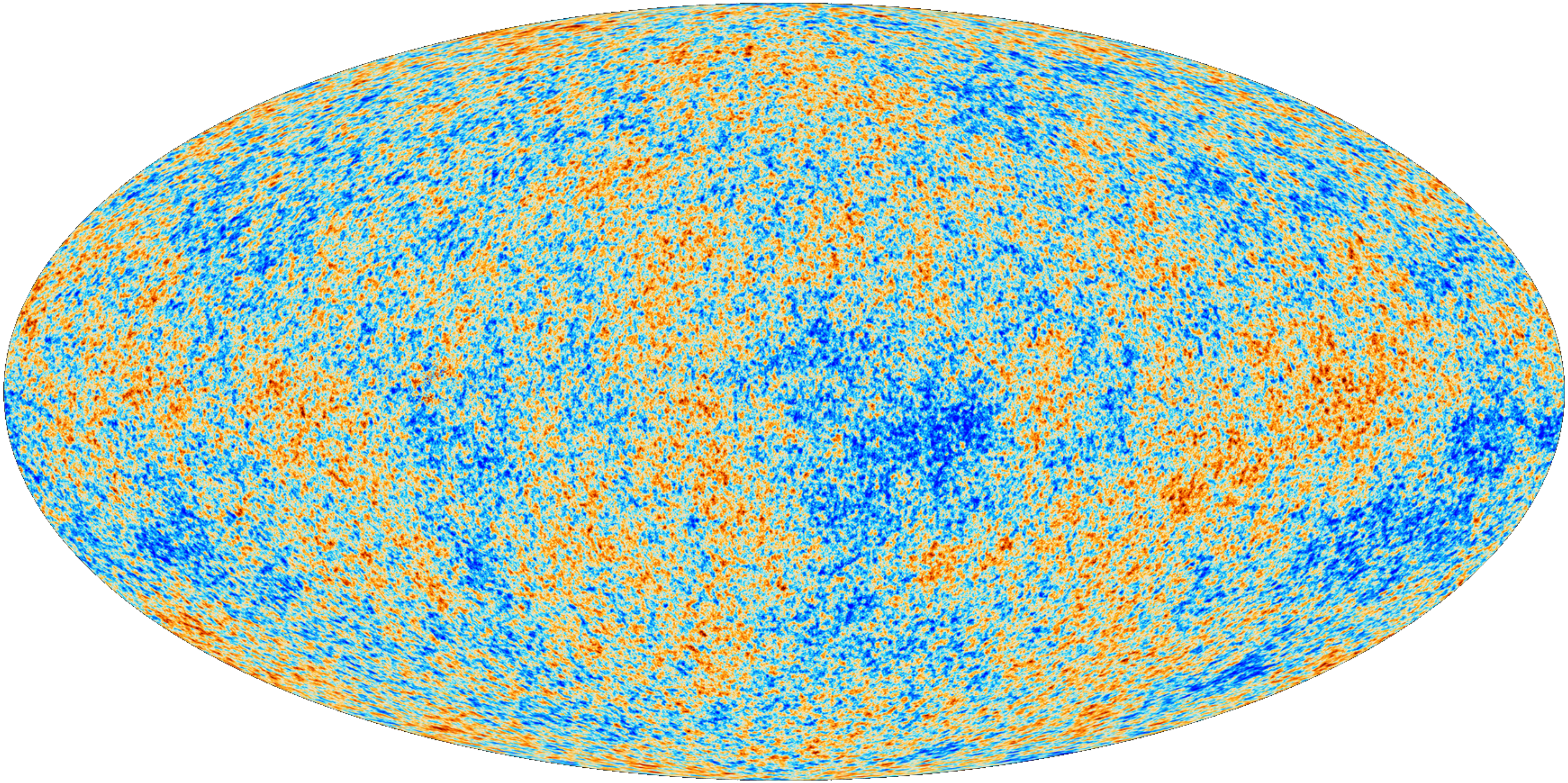
# II – The successes

# A coherent picture

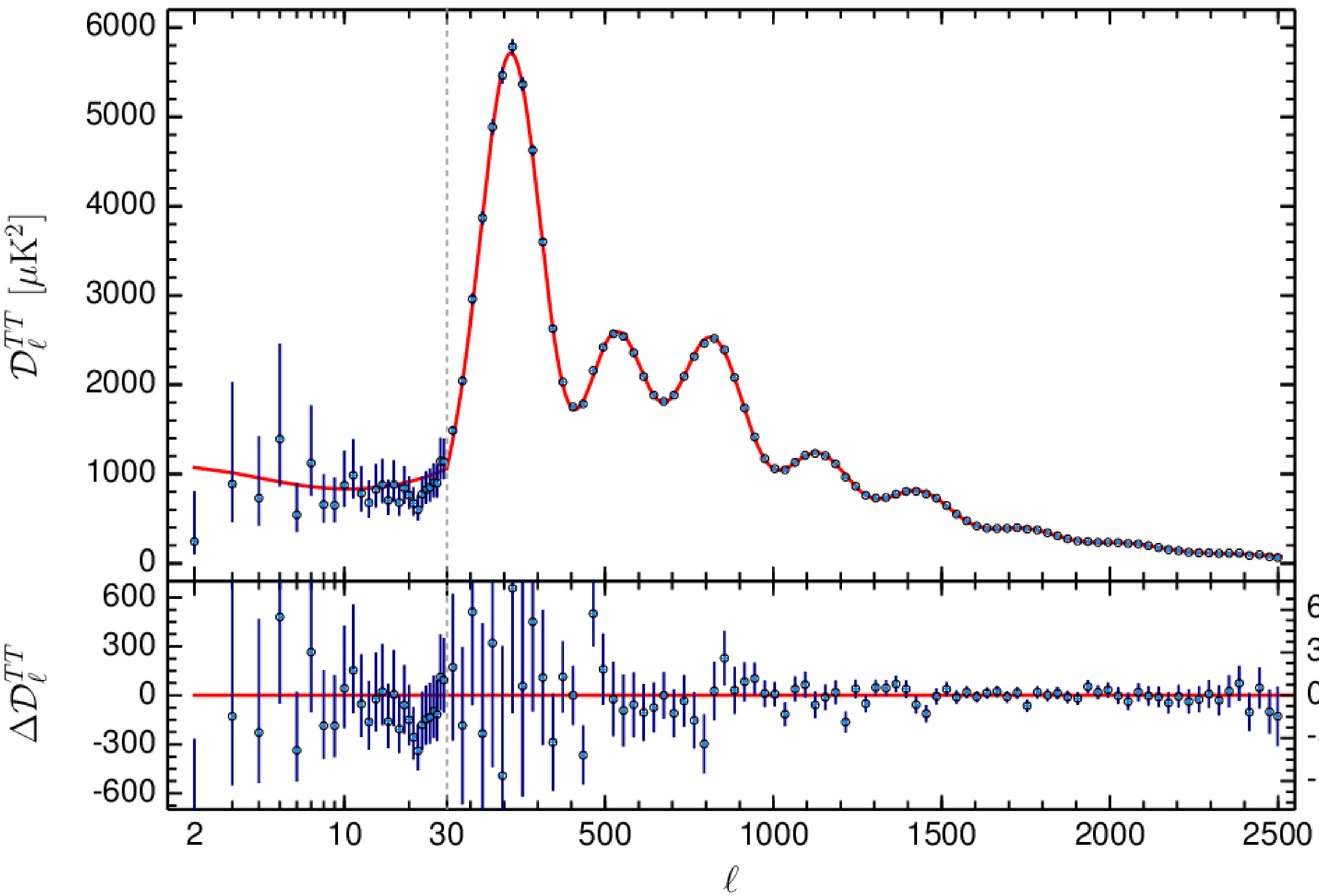



<u>Explains :</u> abundance of light elements, large scale structures, accelerated expansion…..

# ...and the CMB



# CMB temperature fluctuations

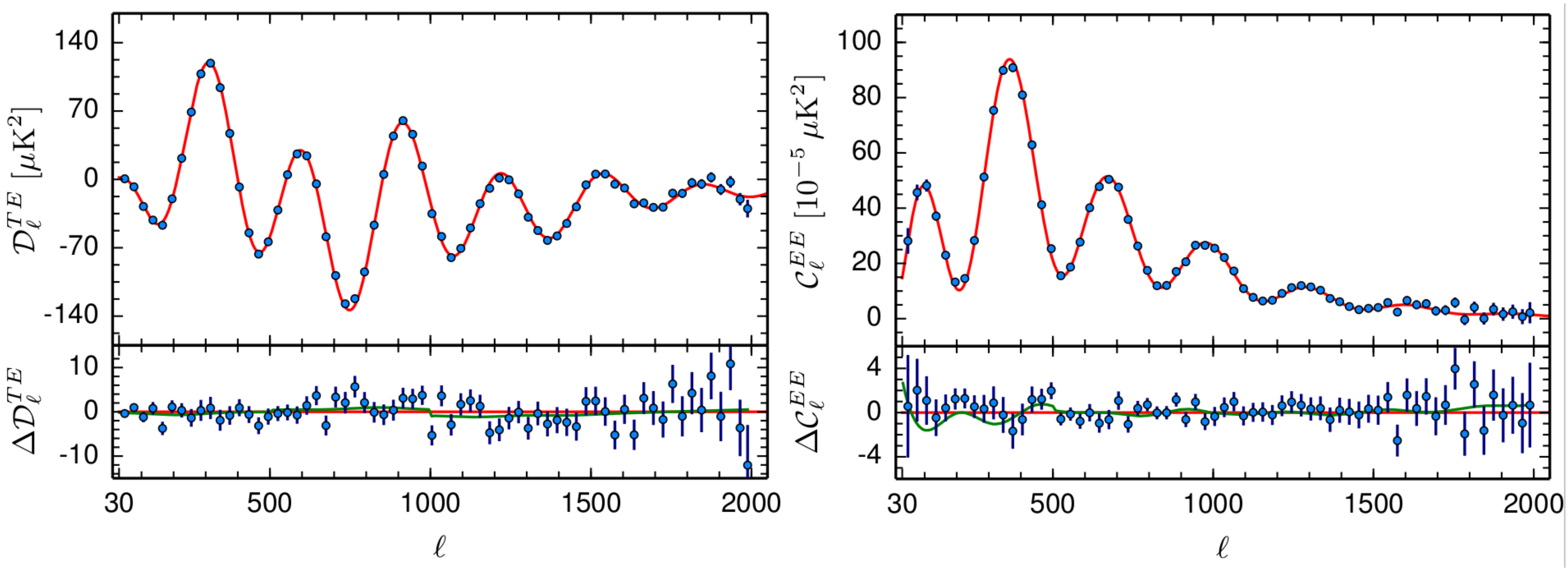


# Cosmological parameters

Planck 2015 results

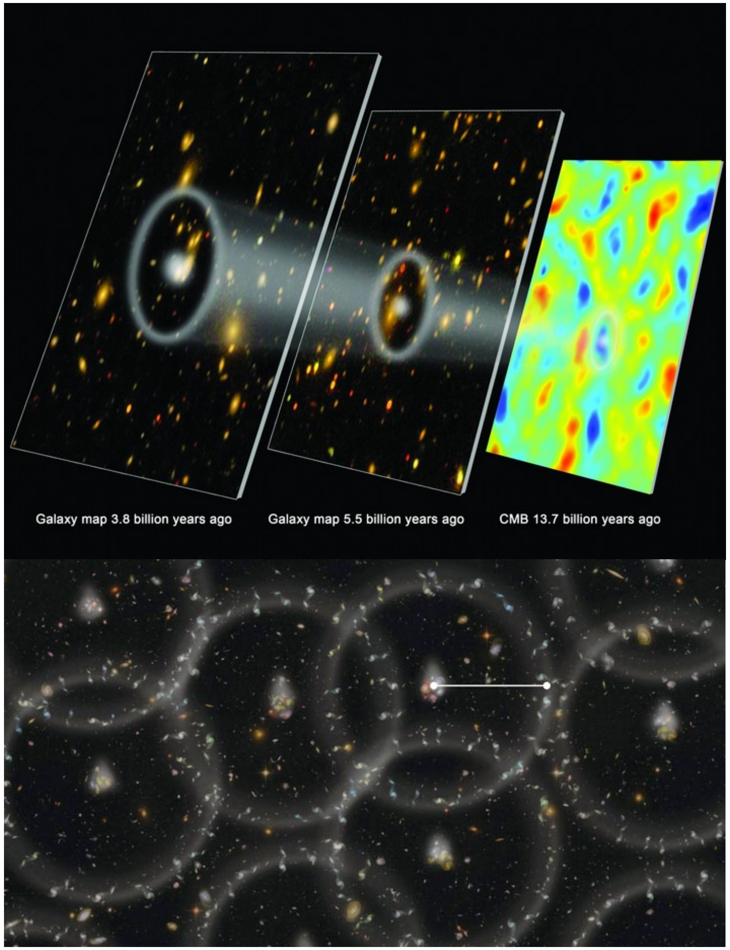
| Parameter | TT+lowP 68 % limits | TT+lowP+lensing 68 % limits |
|---|---|---|
| $\Omega_b h^2$ . . . . . . . . . . . . . | $0.02222 \pm 0.00023$ | $0.02226 \pm 0.00023$ |
| $\Omega_c h^2$ . . . . . . . . . . . . . | $0.1197 \pm 0.0022$ | $0.1186 \pm 0.0020$ |
| $100\theta_{MC}$ . . . . . . . . . . | $1.04085 \pm 0.00047$ | $1.04103 \pm 0.00046$ |
| $\tau$ . . . . . . . . . . . . . . . | $0.078 \pm 0.019$ | $0.066 \pm 0.016$ |
| $\ln(10^{10} A_s)$ . . . . . . . . . | $3.089 \pm 0.036$ | $3.062 \pm 0.029$ |
| $n_s$ . . . . . . . . . . . . . . | $0.9655 \pm 0.0062$ | $0.9677 \pm 0.0060$ |

# CMB polarisation

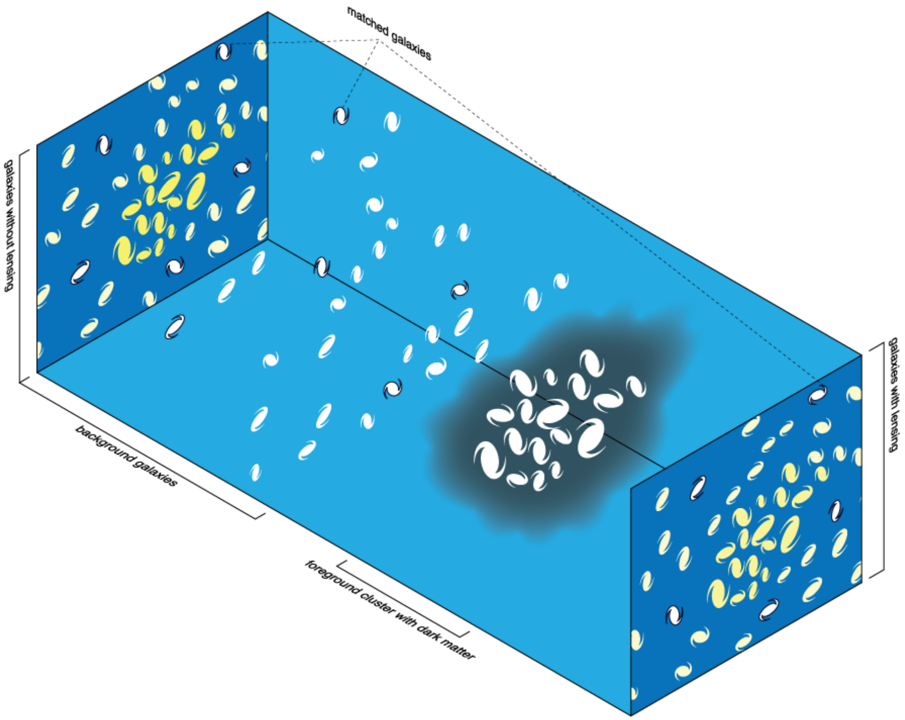



(N.B. : Red curve => not a fit !)

# Verified predictions of ΛCDM




Baryon acoustic oscillations
(2005)




Weak gravitational lensing
(~2000)

# III – The problems

# 1) It's most likely incomplete

GR : Most likely not complete (link to QFT)

Primordial universe :

- Baryon asymmetry ?
- Origin of initial fluctuations ? Are they really Gaussian ? Generated by inflation ? If yes, what kind of inflation ? (cf. next 3 talks)
- Big Bang or something else ?
- ...

Small scale problems (simulations vs. observations) :

- Density profile of galaxies
- Missing “satellites”
- Angular momentum of galaxies
- “Nasty baryon physics”
- ...

# 2) Not sure what is in it

*There are only two things wrong with ΛCDM: Λ; and CDM."* (T. Shanks, Durham)

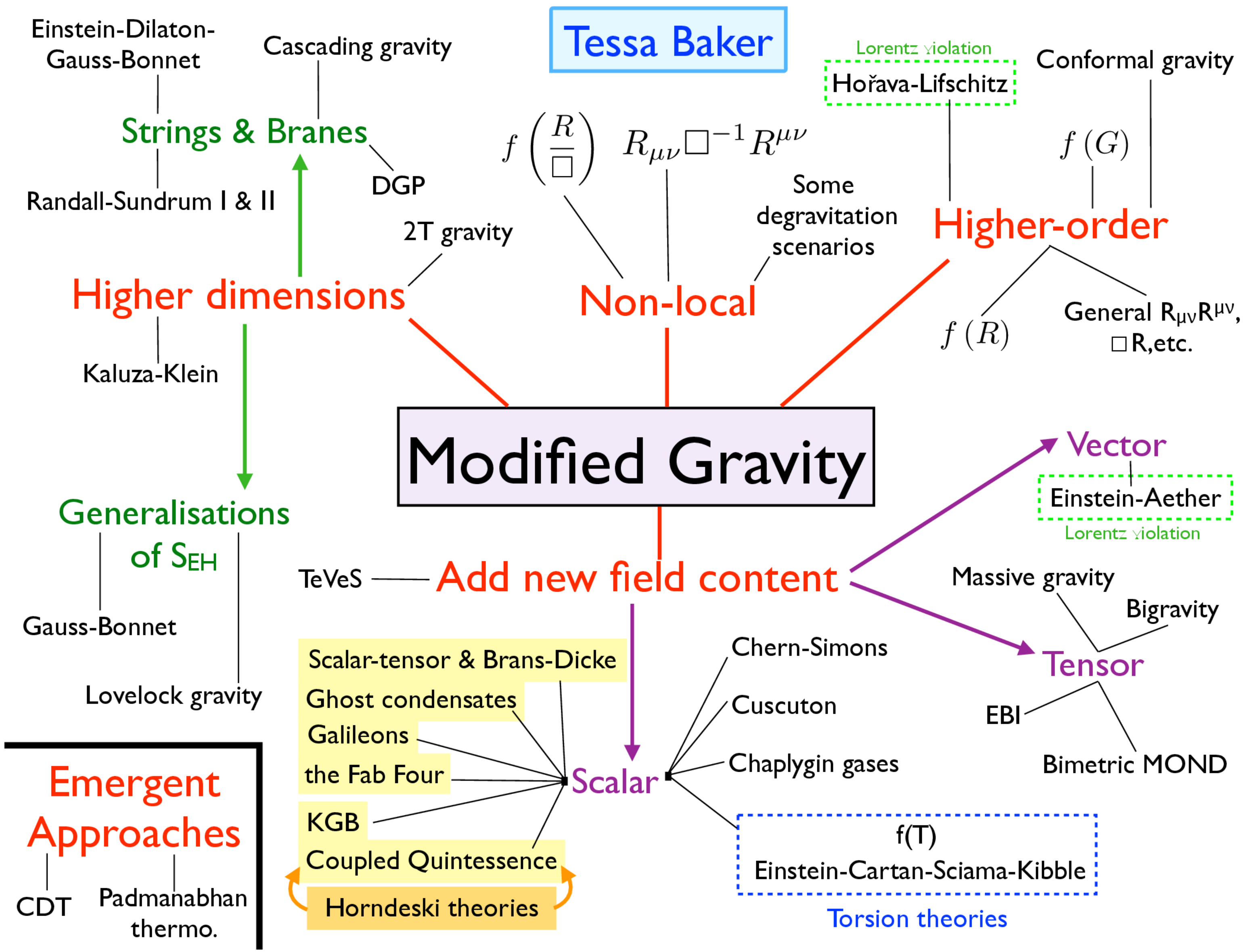
Dark Matter :

- Does it really exist ? (cf. MOND & Modified Gravity)
- If it does, what kind of "stuff" is it ? New particle ? Old particle ? Something else ?
- Cold or not ? Mixture ?

Dark Energy :

- Some (undeserved) prejudices against Λ, but it works (for now !)
- Many (many !) theoretical developments for alternatives
- Examples : scalar fields, modified gravity…
- More drastic : inhomogeneous Universe, "back-reaction"….

# 2) Not sure what is in it




(cf. P. Brax talk tomorrow)

# 3) Tensions between probes/datasets

# 3) Tensions between probes/datasets

Probes of $\Lambda$CDM :

| | **"Background" evolution (i.e. expansion)** | **"Perturbed" sector (i.e. linear growth of structures)** |
|---|---|---|
| **Early Universe** | | |
| **Late Universe** | | |

# 3) Tensions between probes/datasets

<u>Probes of ΛCDM :</u>

| | **"Background" evolution (i.e. expansion)** | **"Perturbed" sector (i.e. linear growth of structures)** |
|---|---|---|
| **Early Universe** | CMB (T & P) | CMB (T & P) |
| **Late Universe** | Standard candles (BAO, SN, Cepheids) | Weak lensing, galaxy clustering +CMB lensing |

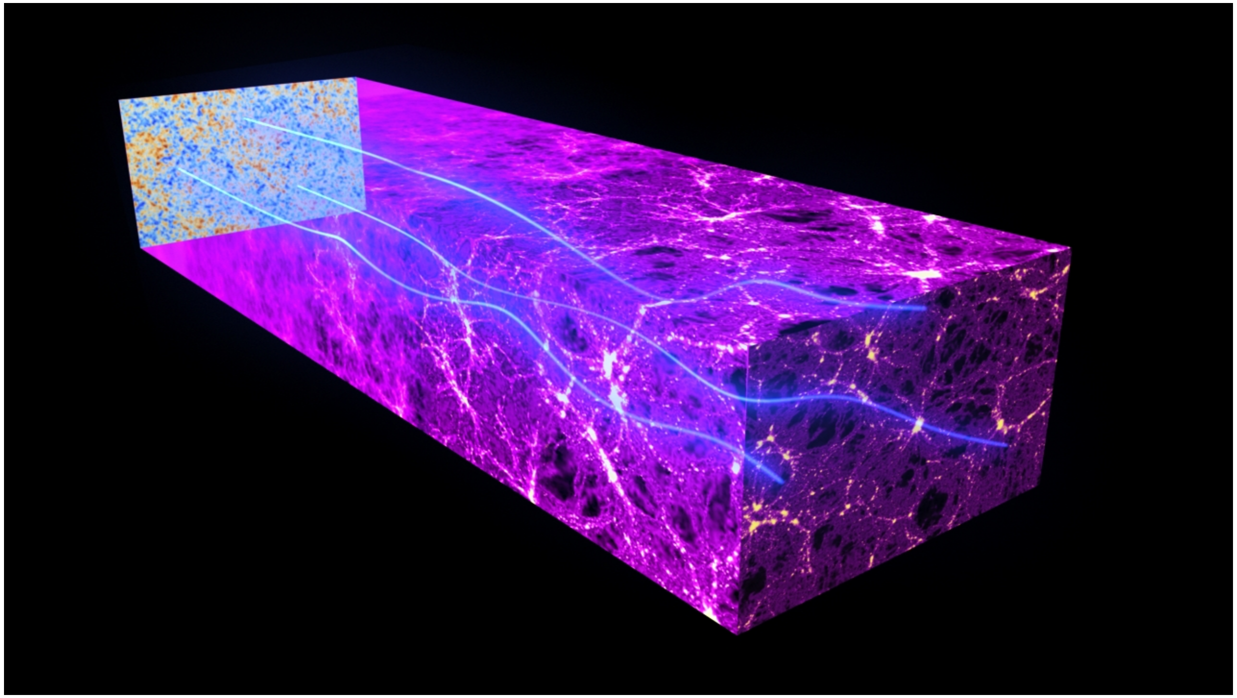
# 3) Tensions between probes/datasets

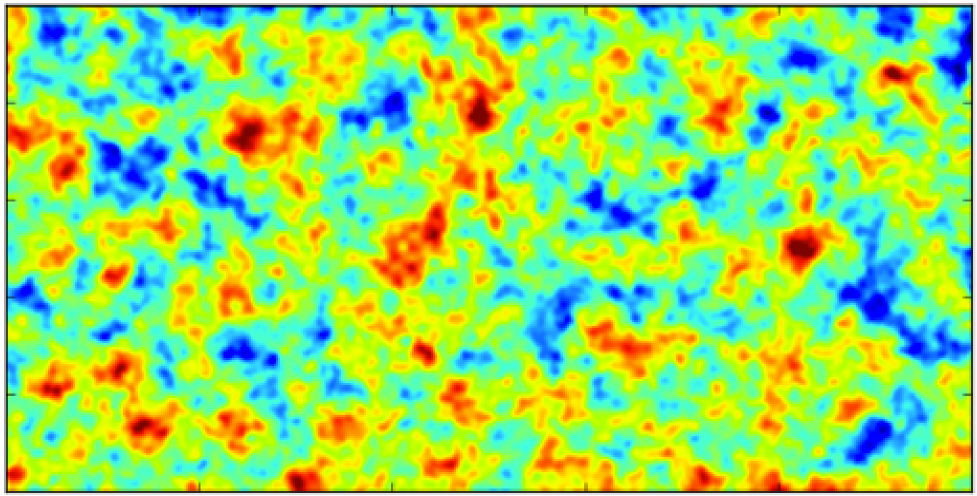
Probes of ΛCDM :

| | **"Background evolution" (i.e. expansion)** | **"Perturbed sector" (i.e. linear growth of structures)** |
|---|---|---|
| **Early Universe** | CMB (T & P) | CMB (T & P) |
| **Late Universe** | Standard candles (BAO, SN, Cepheids) | Weak lensing, galaxy clustering +CMB lensing |

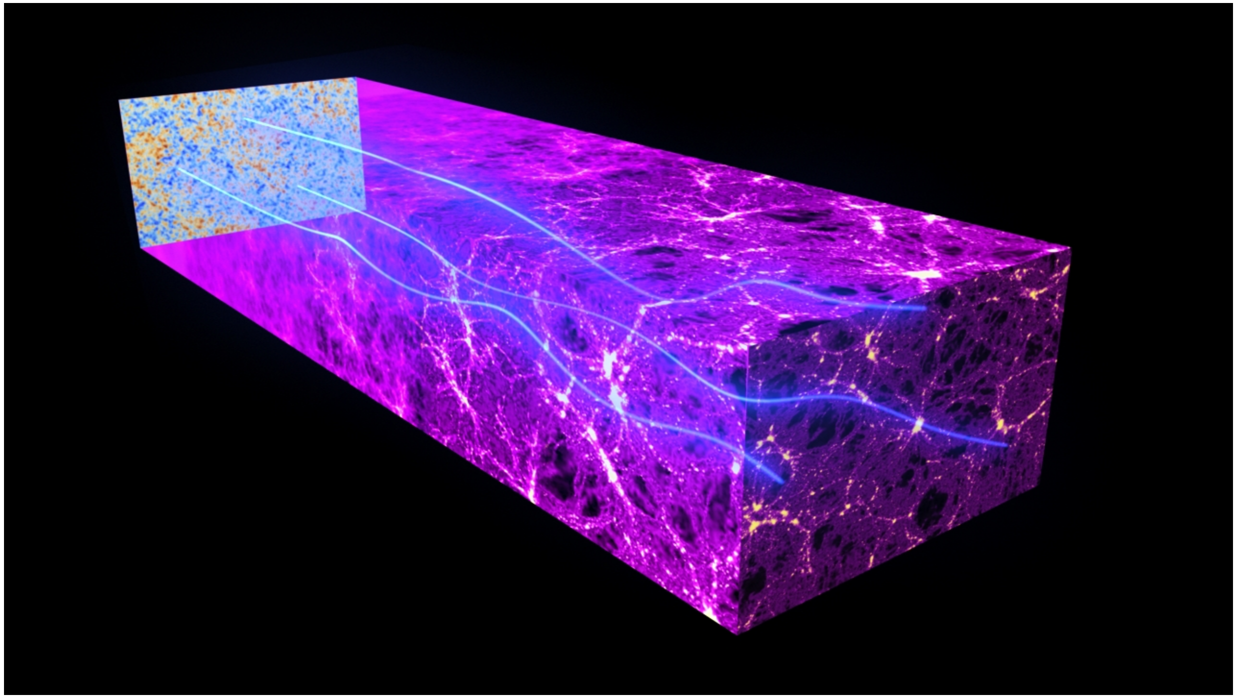
Physics at the CMB time (380,000 yr after BB) may not be still valid at late times (~10,000,000 yr after BB)

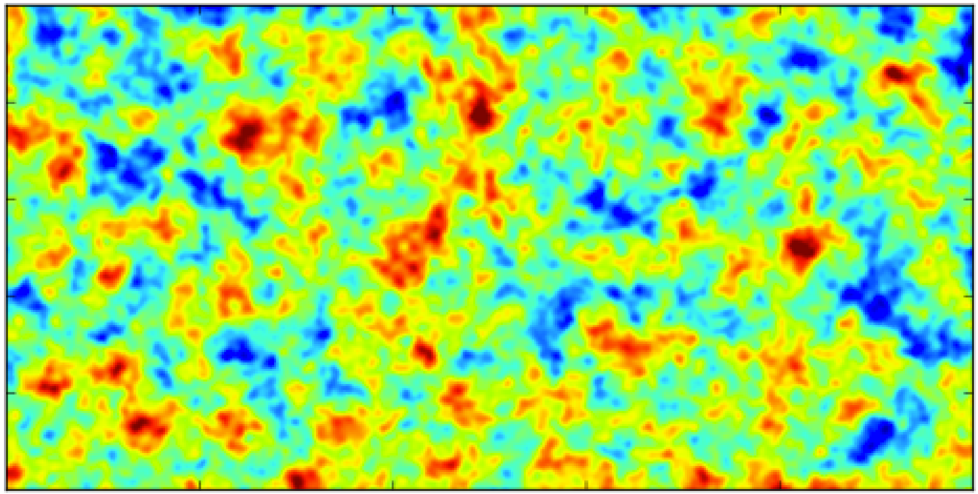
# Lensing in the CMB



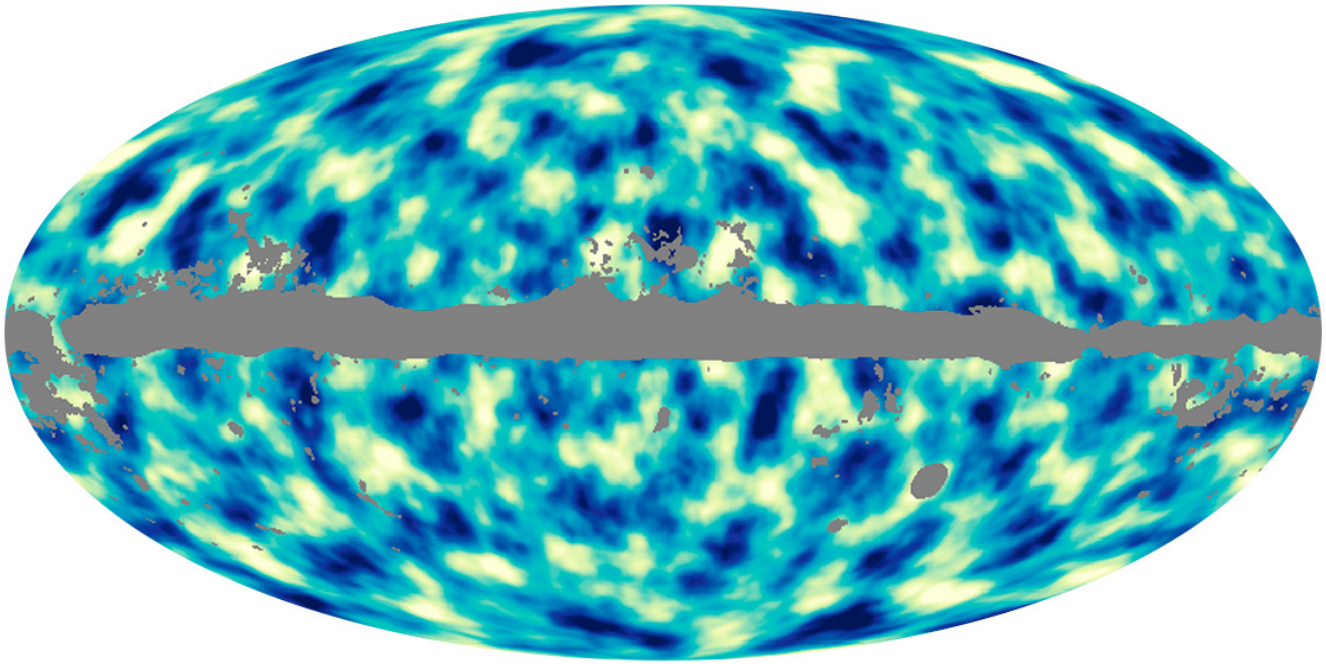


# Lensing in the CMB





# Lensing in the CMB



Planck data : tension with predicted amount of lensing

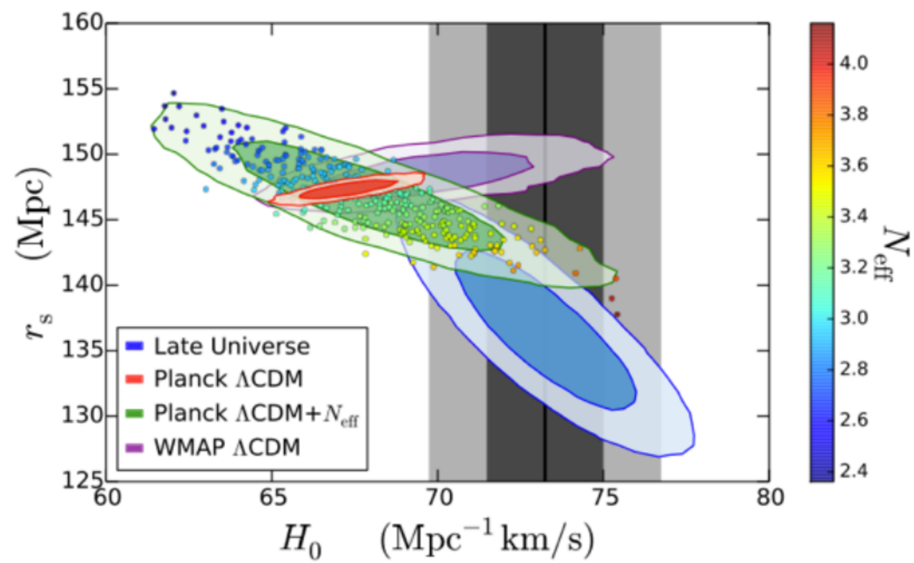
- Mostly relieved when adding small scale CMB data (Couchot et al. 2015)
- Hints at non-trivial correlation with foregrounds
- Room for new physics ? WIP (cf. Martha's talk)

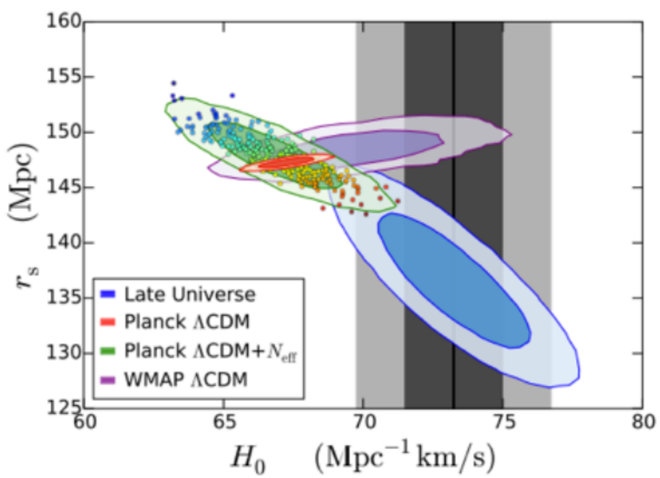
# H0 (from SN & Cepheids)

## Neff and H0

- Planck H0 *vs.* local H0 (3 sigma)
- BAO and SNIa constrain rs-h
- Can Neff help in solving this tension?

$$\Delta N_{\mathrm{eff}} \sim 0.4$$



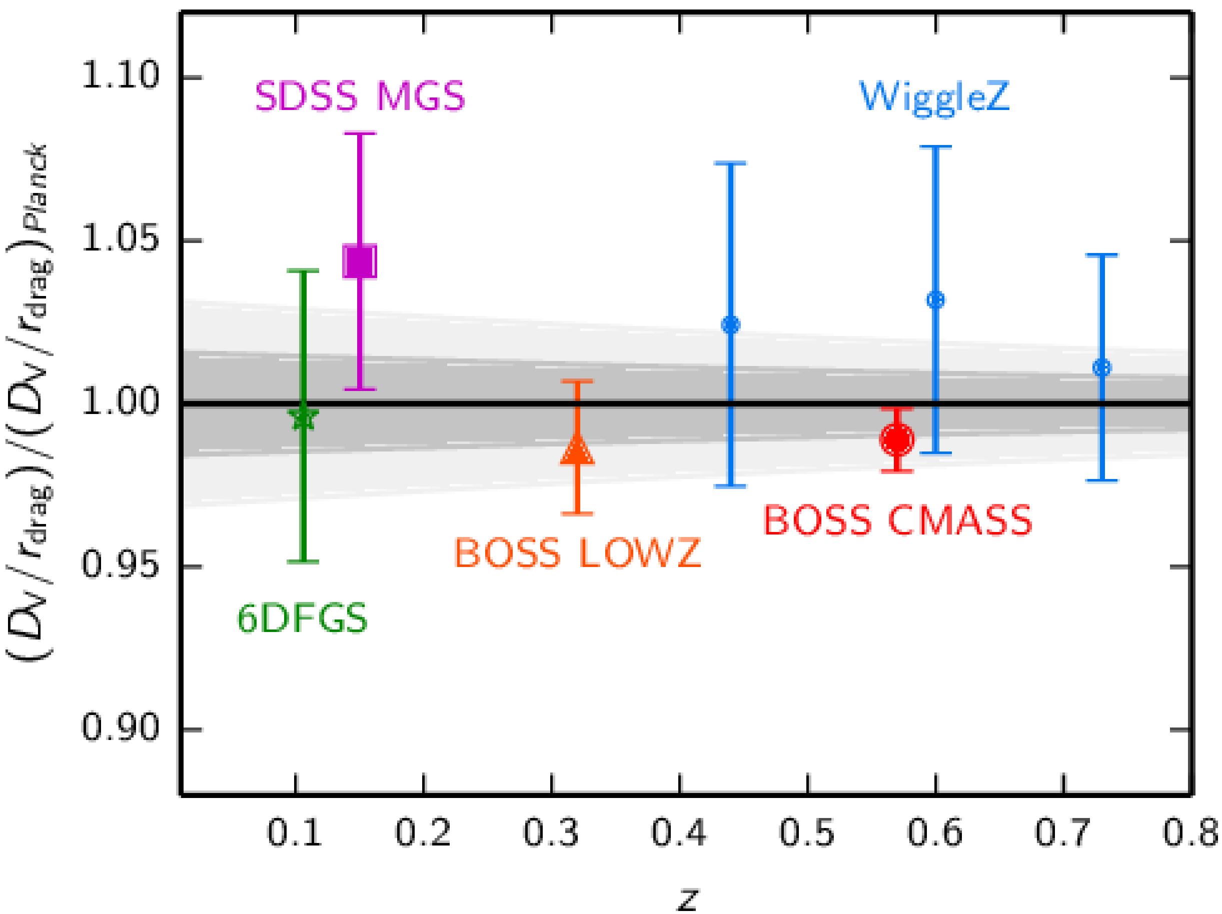

- NOT true anymore if Planck polarisation is included

Bernal et al 2016 (arXiv:1607.05617)

LABORATOIRE DE L'ACCÉLÉRATEUR LINÉAIRE

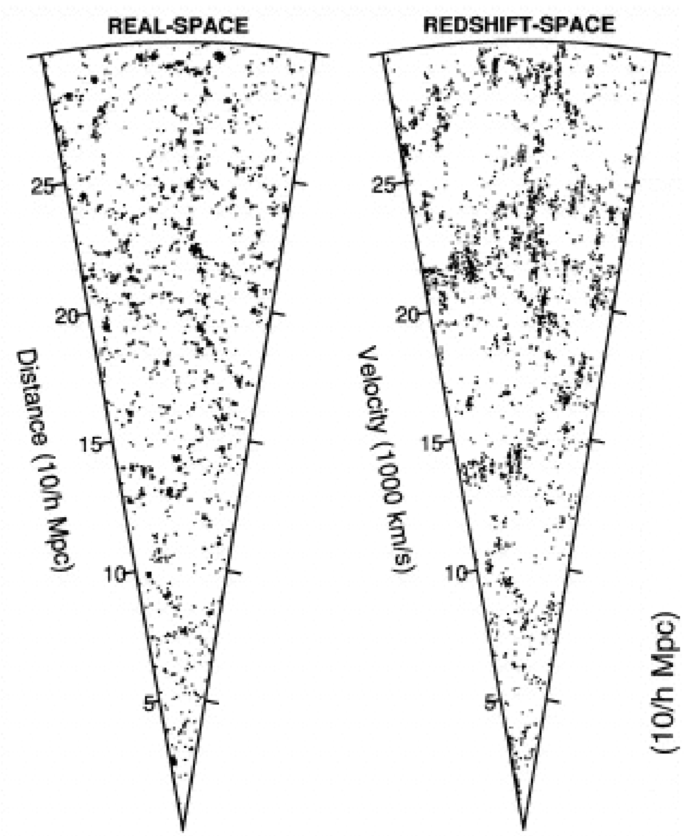
Marta Spinelli

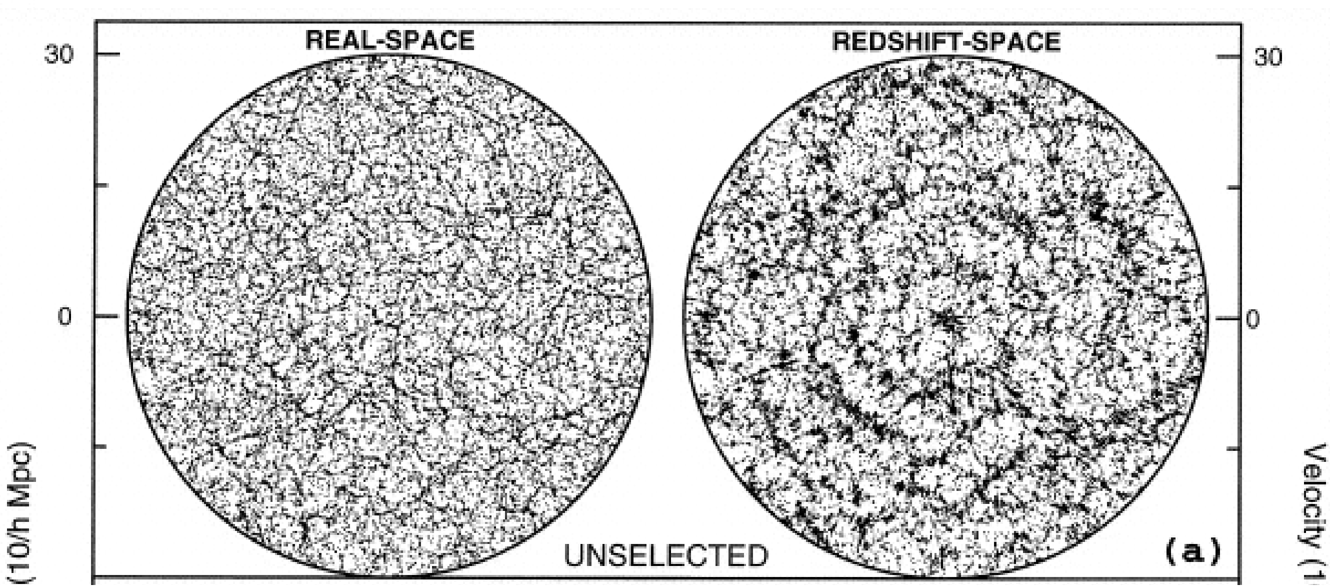
# BAO



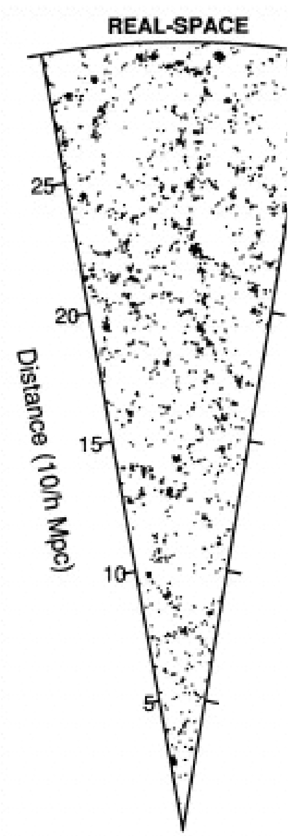

<u>Mostly OK !</u>

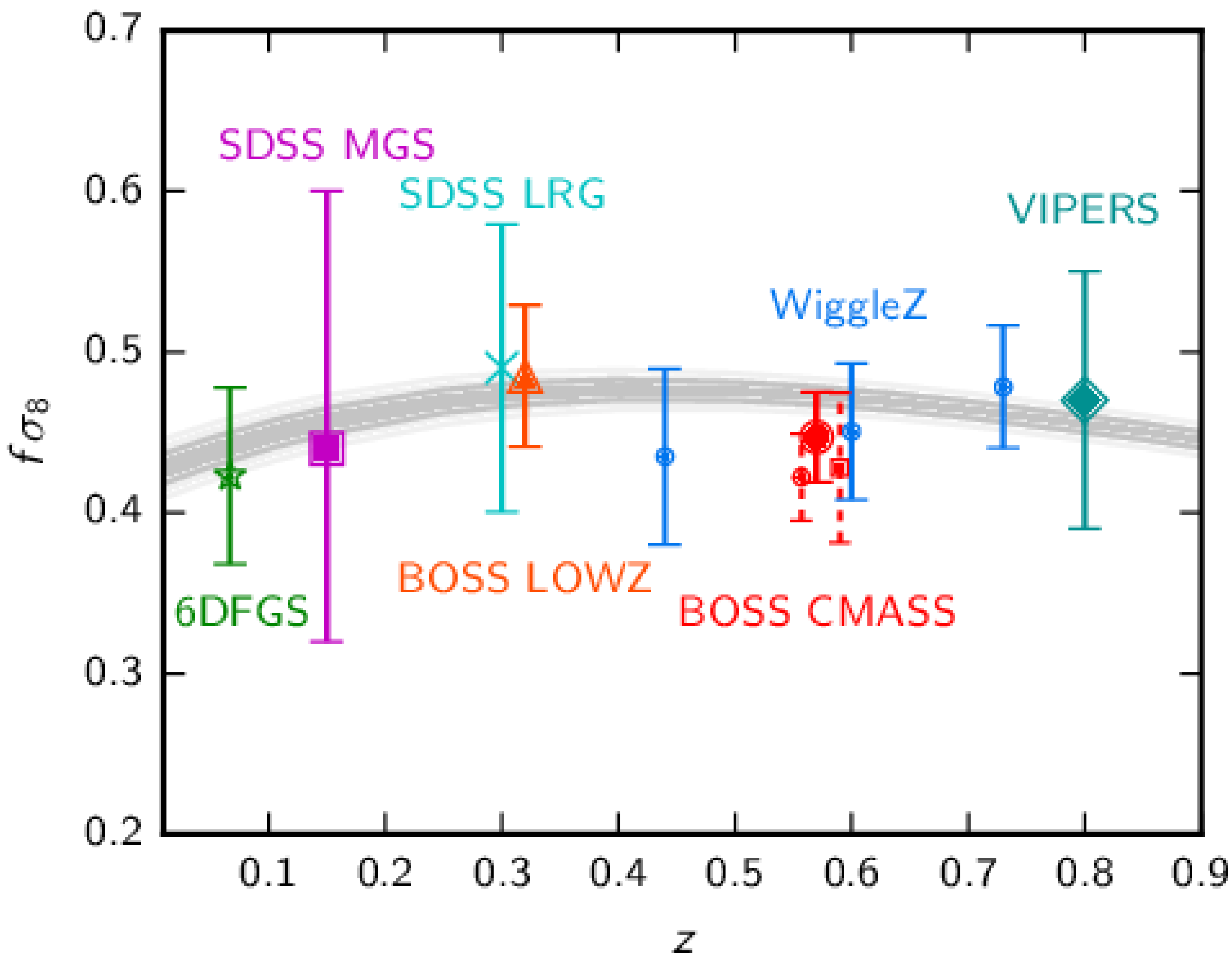
# Gal. clustering/Redshift Space Dist.

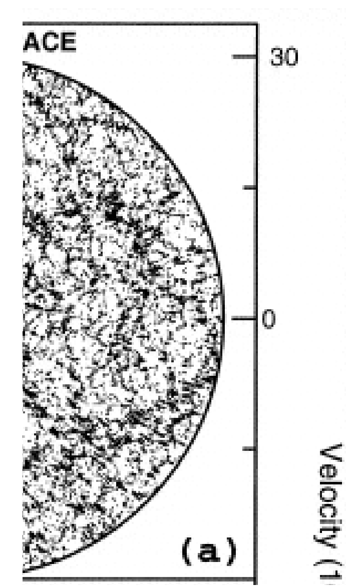


# Gal. clustering/Redshift Space Dist.



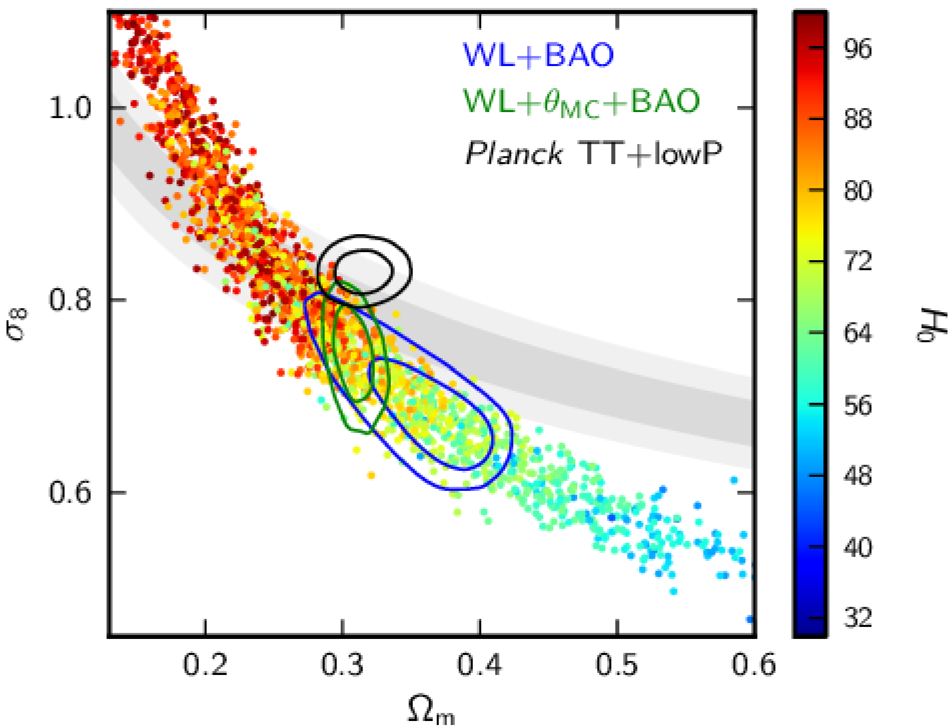




<u>Mostly OK !</u>

# Gravitational weak lensing

CFHTLens data




<u>New physics ?</u>

- Maybe !
- Need something that reduces growth of structures in late Universe
- Ex. : DE/MG models w/o modifying background evolution **(cf. EFT of DE)**

<u>However : many systematic effects</u>

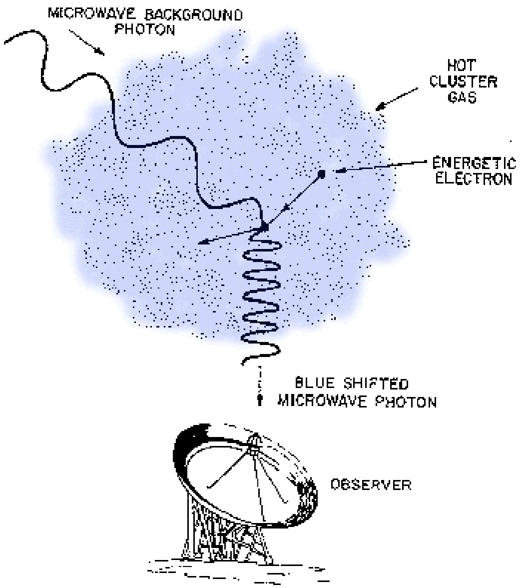
- intrinsic galaxy alignments
- baryonic effects
- redshift uncertainties.

# Galaxy clusters

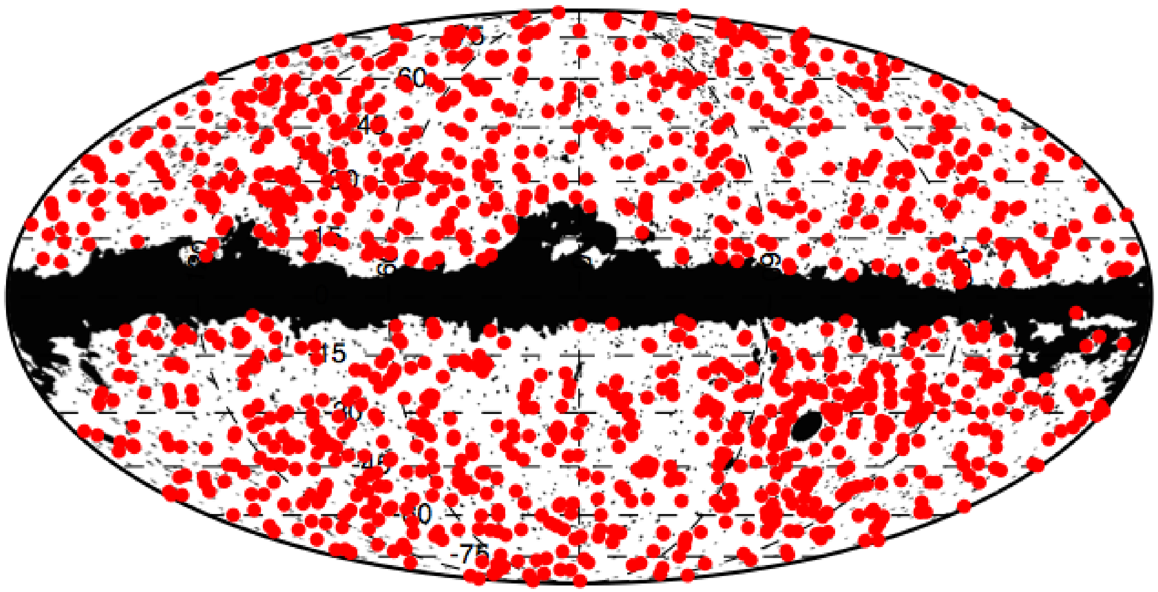
Galaxy clusters :

- largest gravitationally bound objects
- abundance as function of mass : tight constraints on history of growth of structures
- … thus on dark energy

With Planck : detection through Sunyaev Zel'dovich (SZ) effect

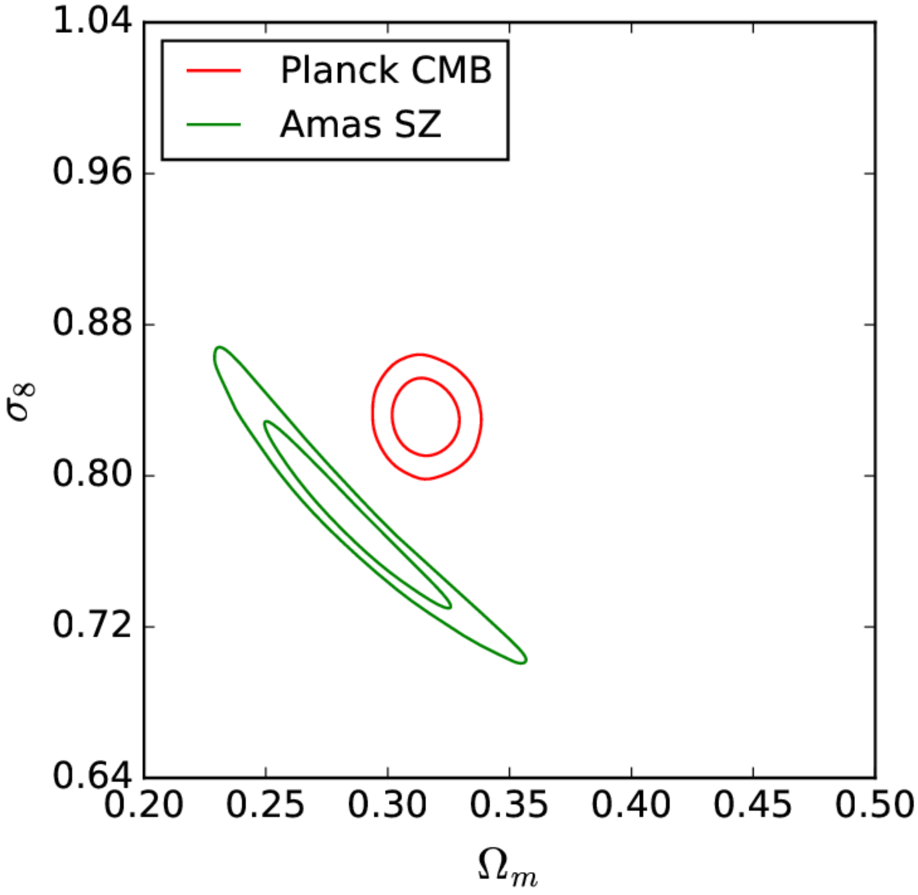



1227 clusters detected incl. 366 new ones



**Major obstacle : mass of a cluster is not an observable**
(here : derived from SZ signal + calibrations/simulations)

# Galaxy clusters




<u>Two possible solutions :</u>

- mass estimate is wrong (40% bias)
- Less growth in the late Universe (again !)

<u>Ilic et al 2015 :</u>

- not unique to SZ clusters
- if ΛCDM is to be trusted :

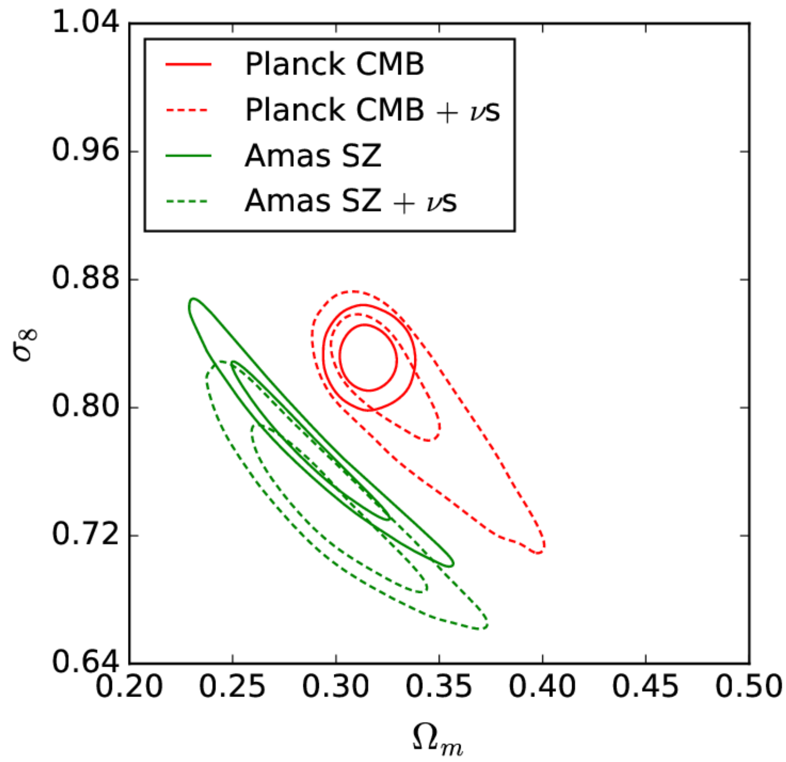
  **bias hypothesis is favored**

**Clear disagreement : CMB predicts more clusters than observed**

# Galaxy clusters

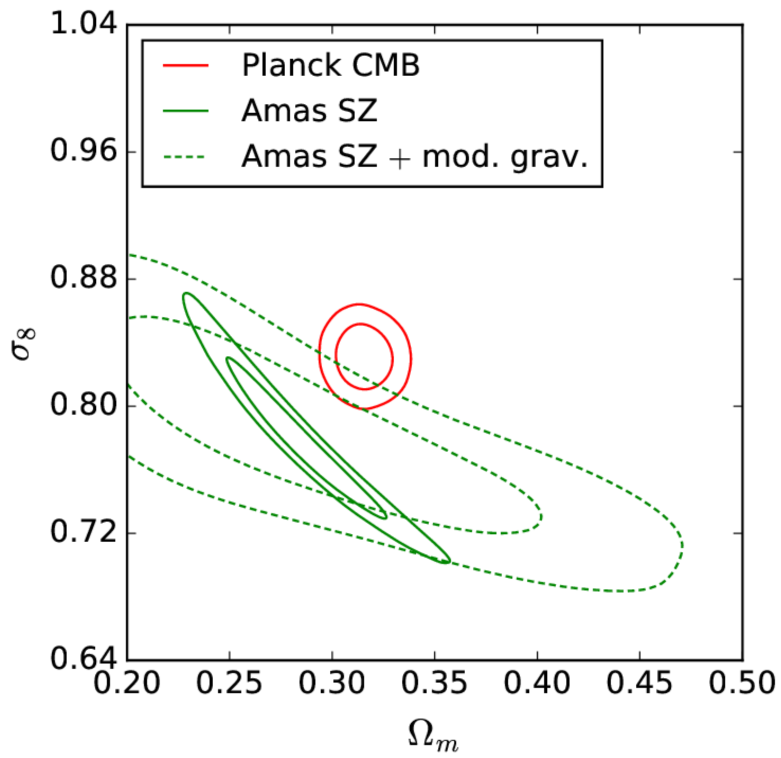
Ilic et al. 2016 (in prep) :

More massive neutrinos ?
=> suppress the growth of structures




**Does not solve the tension**

Modification of gravity ?




**Could help, but needs to be compatible with all others ΛCDM probes + struct. formation in MG ?**

# Conclusions

*“[…] from most cosmologists’ perspective, there is nothing wrong with it at all [...] Moving away from ΛCDM is also not trivial – the direction to take is not clear at all. ΛCDM is like Hotel California; it is very hard to leave, and most, if not all, efforts to do so have ended with some insurmountable obstacle.”* (A. Heavens, Imperial Coll. London)

- A extremely robust model…
- … but with a few persistent tensions !
- Great motivation to look further and further
- Warning : systematics and bias

What's next ?

- Next-gen CMB experiments : LiteBIRD, PIXIE, ESA M5
- Next-gen galaxy surveys : DES, LSST, Euclid

# Conclusions


Leiden 1995 : B. Jones, A. Blanchard, J. Peacock, P. Coles, V. Icke,
R. van de Weygaert, and P. Katgert

# Conclusions


"Beyond ΛCDM", Oslo, 2015 : R. Durrer, P. Lilje, J. Magueijo, B. Reid, G. Starkman, L. Verde, A. Heavens