Gravity or Dark Matter models as solutions to CMB-LSS tensions

Julien Lesgourgues (TTK, RWTH Aachen University)

Gravity at the Largest scales, Heidelberg, 27.10.2015

CMB vs LSS tensions

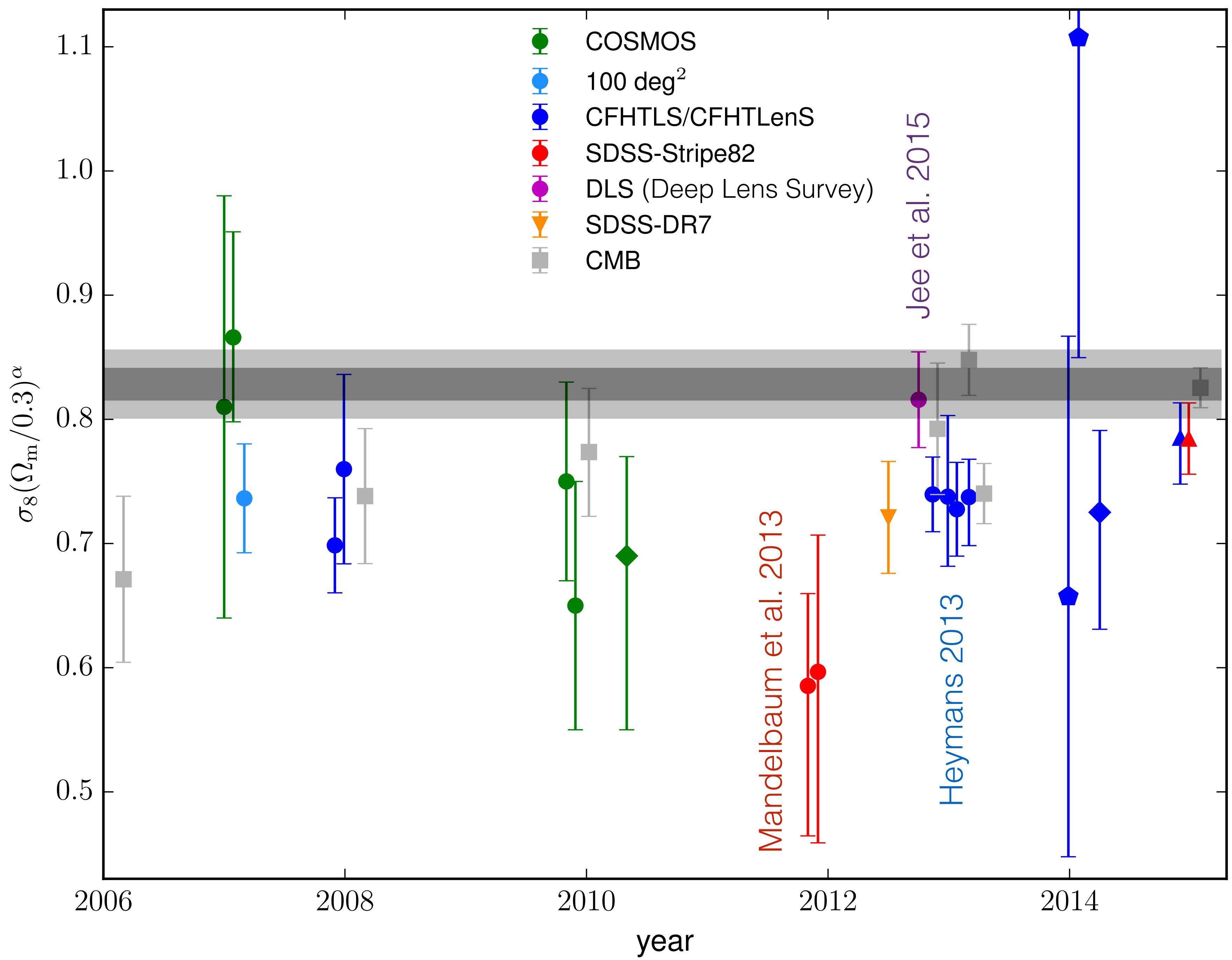
- ΛCDM best-fit to Planck 2015: σ_8 given by extrapolation of perturbations amplitude to z=0 (for given A_s, n_s, H_0, Ω_m)

data	σ_8	Ω_m
TT + lowTEB	0.829 ± 0.014	0.315 ± 0.013
+ BAO	0.829 ± 0.014	0.310 ± 0.008
+ JLA	0.829 ± 0.014	0.312 ± 0.012
+ H_0 (conservative)	0.829 ± 0.014	0.312 ± 0.013
TTTEEE + lowTEB	0.831 ± 0.013	0.316 ± 0.009
+ BAO	0.831 ± 0.013	0.312 ± 0.006
+ JLA	0.831 ± 0.013	0.314 ± 0.009
+ H_0 (conservative)	0.831 ± 0.013	0.314 ± 0.009

- several LSS experiments measure directly $\sigma_8(z^*)$, i.e. $(\Omega_m)^\alpha\, \sigma_8(z=0)$

Weak lensing observations

- From review of Kilbinger 2014 (68% CL)



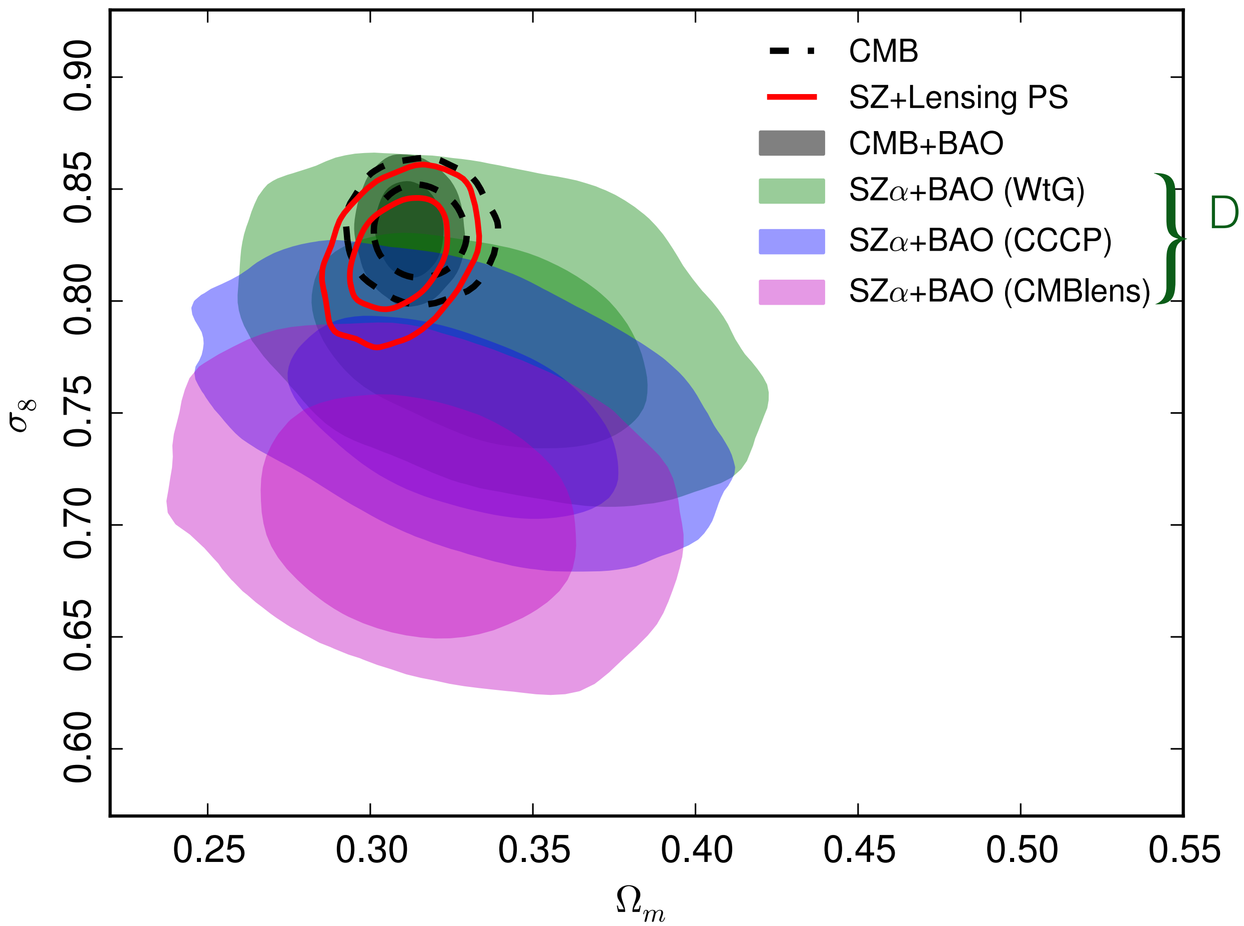
2σ-3σ tensions
12% offset in σ_8
24% offset in P(k)

- most conservative guess: systematics at highest k (which dominate)

Cluster count observations

- From Planck 2015 XXIV (Planck SZ clusters)

(Conservative marginalisation over slope α of SZ-mass scaling relation)



Different ways to constrain SZ-mass bias with lensing observations

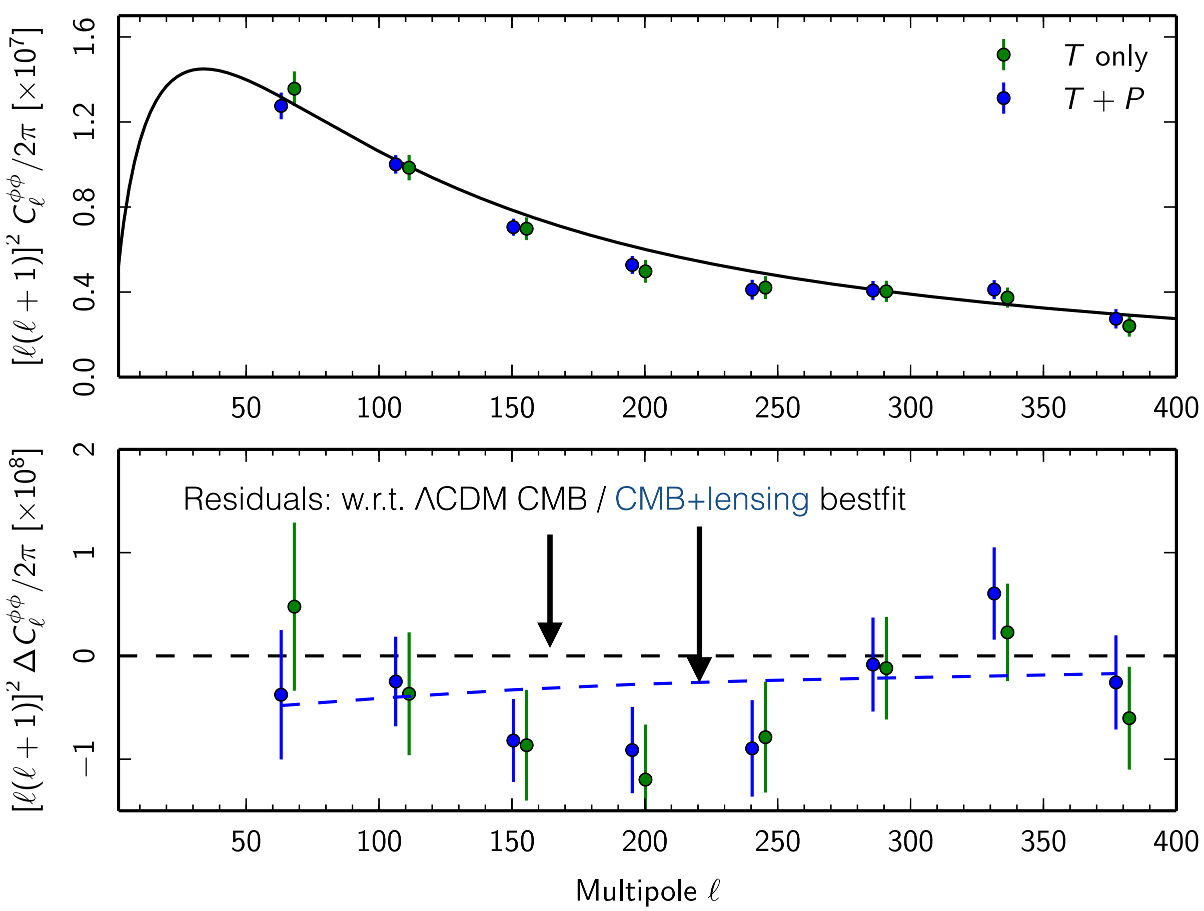
- most conservative guess: systematics in determination of mass bias

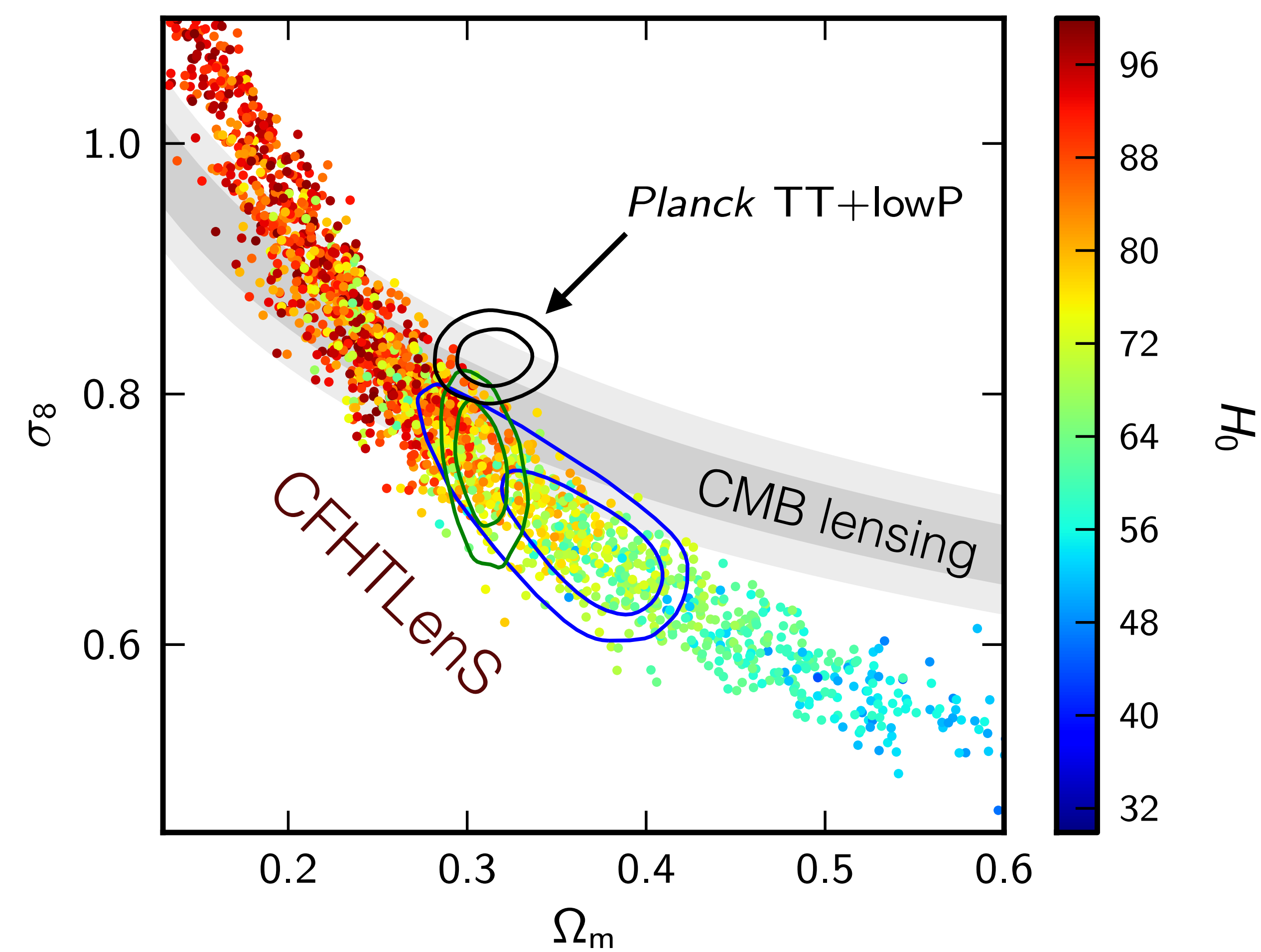
- tensions disappears when looking at recent constraints from X-ray cluster (Mantz et al. 2015), due to their new measurement of SZ-mass bias with weak lensing (WtG)

- without this, all other X-ray, optical or SZ cluster counts return low σ_8 (e.g. Böhringer et al. 2014)

CMB lensing observations

- From Planck 2015: in $C_l^{\phi\phi}$, mild tension near l~200, pushing for smaller σ_8

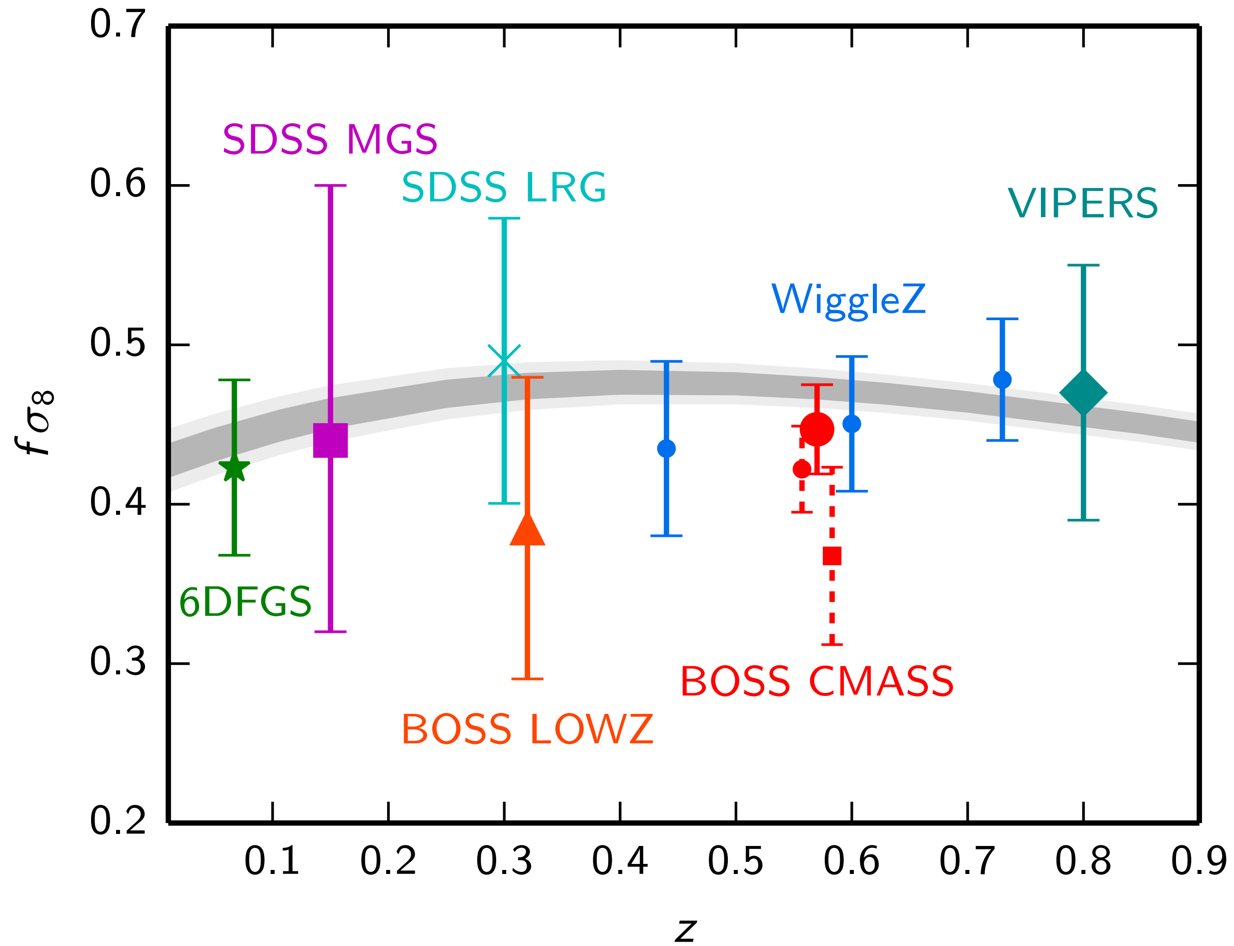




- on the other hand the lensing effect is strong in C_l^{TT}. Suggests that a P(k) suppressed only at small scales, not all scales, could be a slightly better fit.

Redshift space distorsions

- No significant tensions between f σ_8 measurements and Planck ΛCDM best-fit



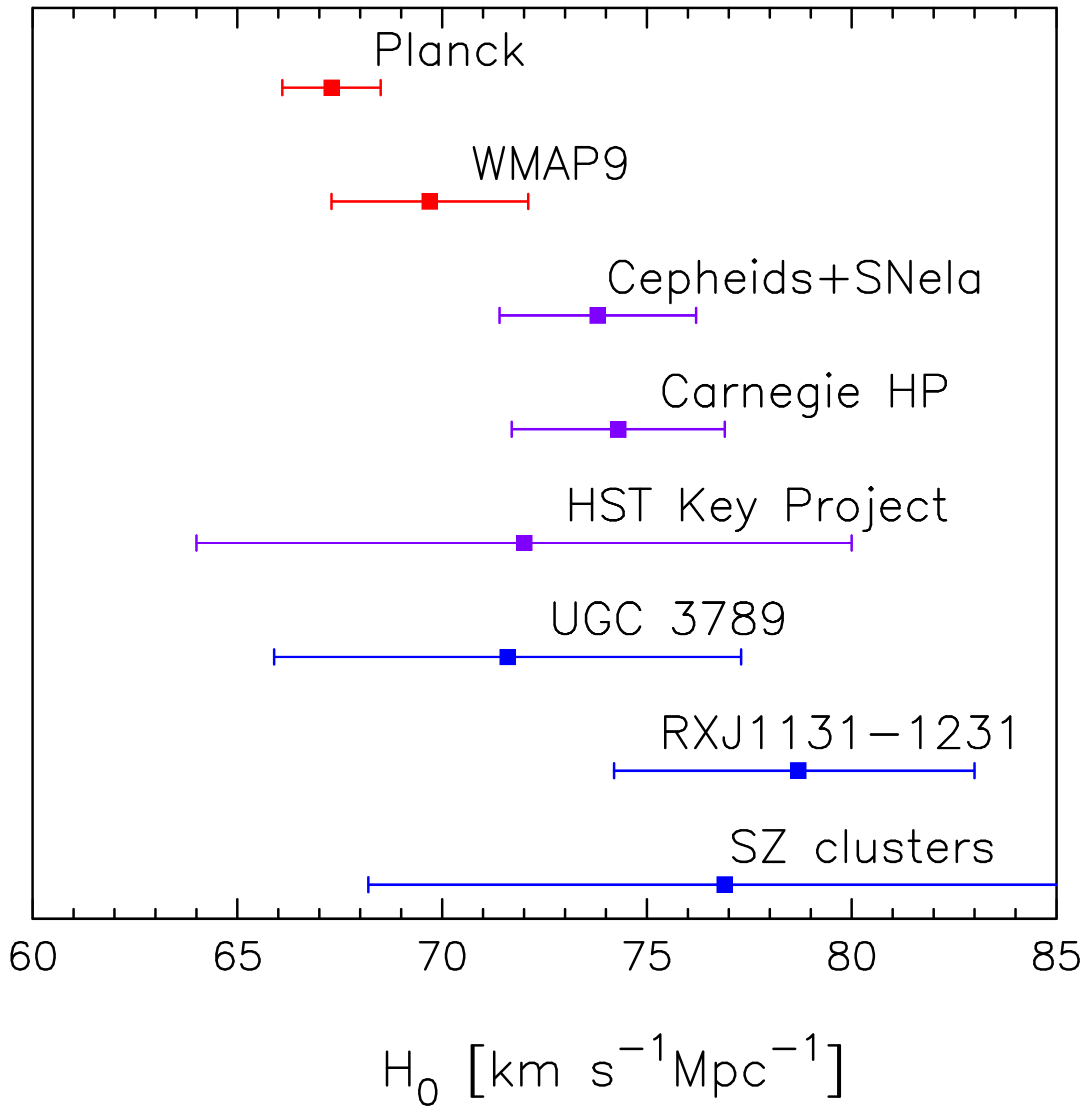
- still, 2σ tension with a few points from BOSS. Depends on analysis details…

- in summary, most noteworthy CMB-LSS tensions are with weak lensing data, and cluster data with “standard” assumption on mass bias

One non-LSS tension: direct H0 measurements

- H_0 not directly constrained by CMB, but indirectly by comparing $\Omega_m h^2$ (matter density) and Ω_Λ (late ISW, scale of the peak, lensing…), and even better with H_0 + BAO

From Planck 2013



- Situation unclear, conservative analyses (like Efstathiou 2014) get larger errors but always higher best-fit value

Can we find models reconciling the σ_8 tension?

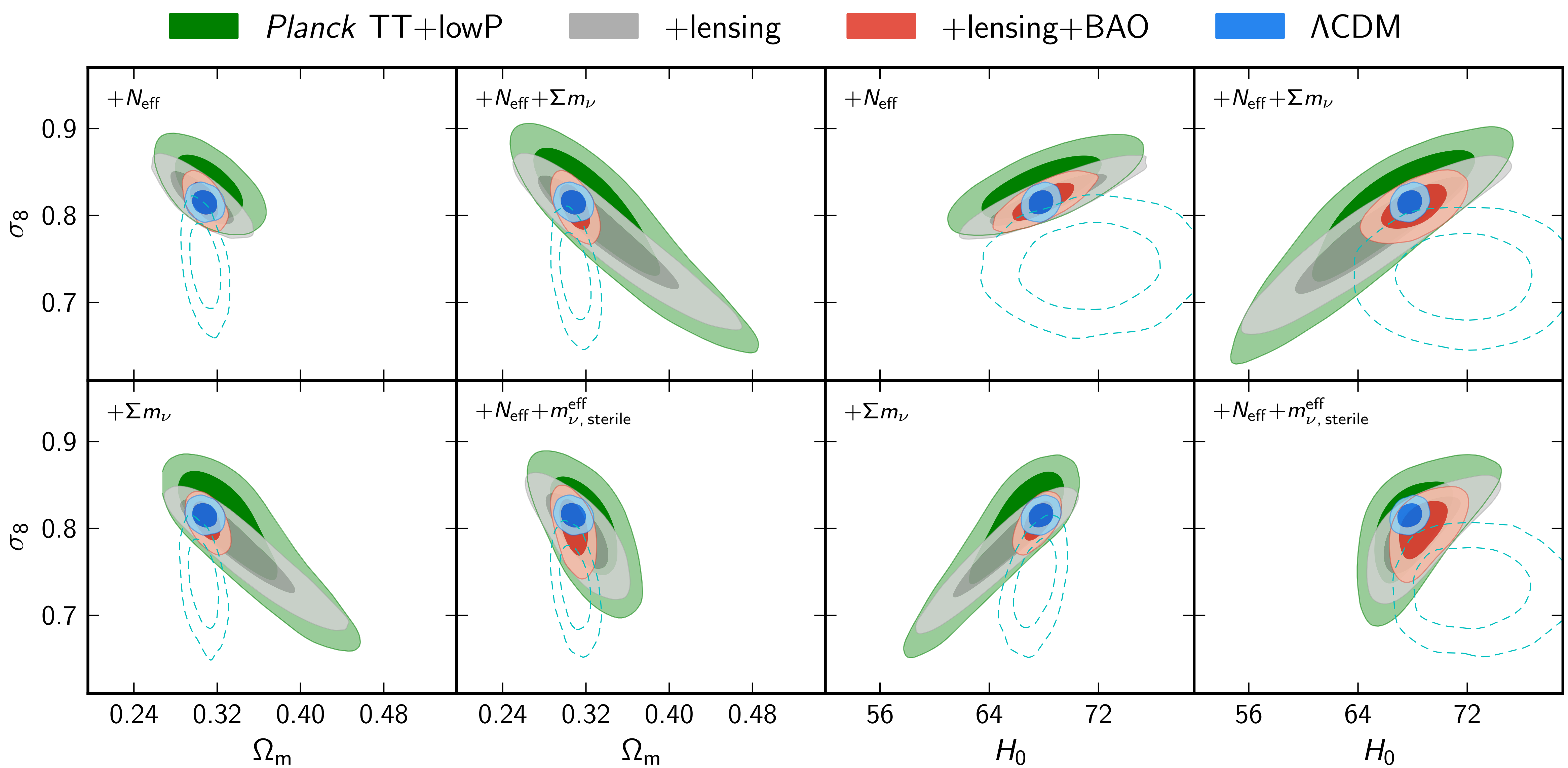
- seems to be a trivial exercises
- expectations: many models should be able to do that (neutrino sector, dark matter sector, modified gravity, dark energy) and it will be difficult to discriminate

Attempts with neutrinos

- Increasing total neutrino mass cannot work:
  - -12% in σ_8 requires $M_\nu \sim 0.5$ eV
  - effect on CMB lensing spectrum: OK
  - effect on shape of C_l^{TT} (dip at $50 < l < 200$ due to eISW and less “lensing smoothing”): problematic
  - effect on peak scale compensated by shift of H_0 by ~ 5 km/s/Mpc: problematic
- Decreasing N_{eff} with same z_{eq} cannot work either:
  - requires significantly smaller H_0 : problematic
- Complicated games with both, or with eV-mass sterile neutrinos… (e.g. Wyman et al. 2014; Battye & Moss 2014; Hamann & Hasenkamp 2013; Leistedt et al. 2014; Bergstroöm et al. 2014; MacCrann et al. 2014)

Attempts with neutrinos

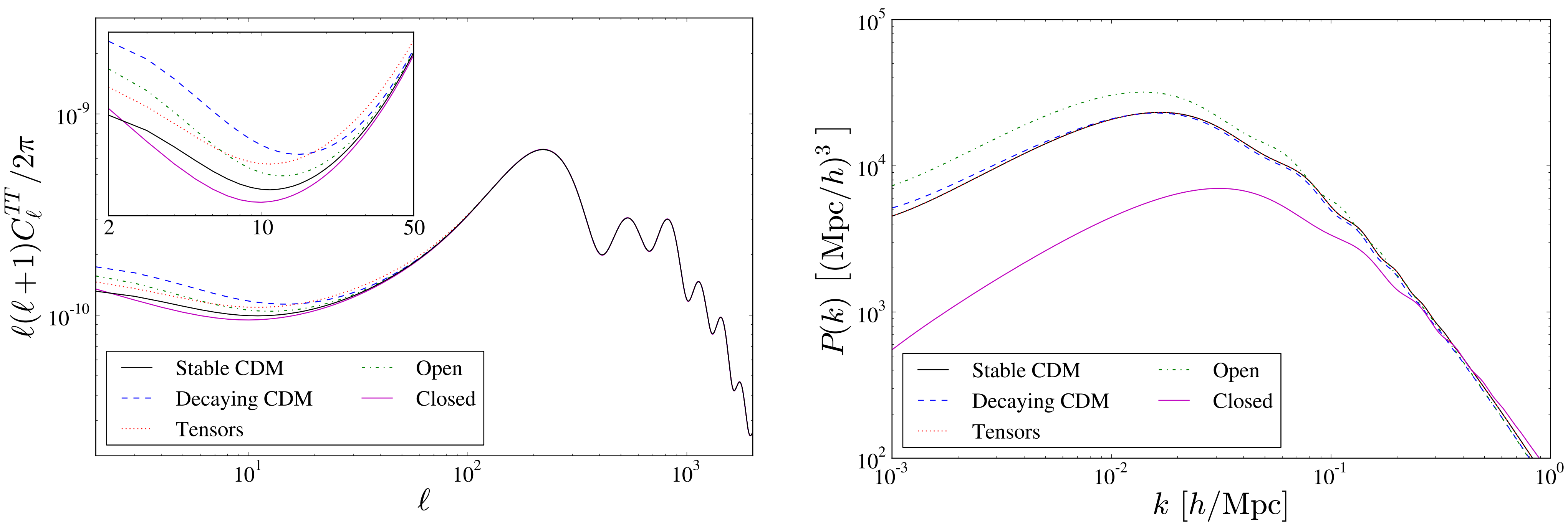
- Complicated games with both, or with eV-mass sterile neutrinos…



- Planck 2015 XIII : $\Delta\chi^2$ ~ 3 at most…

Decaying Dark Matter

- idea that $[\rho_{DM}\, a^3]$ decreases between z~1000 and z~0 and reduces P(k,z) cannot work:
  - decay into SM particles: very strong cosmic ray bounds
  - decay into DR: allowed by particle physics bounds. P(k,z) changes on all scales due to combined background effect + modified perturbation growth rate at late times.
  - strong CMB constraints due to late ISW. No significant effect in P(k) remains. No significant improvement when fitting CMB+BAO+LSS



from Audren et al. 2014;
see also
Enqvist et al. 2015

- true for any model changing linear growth rate on cluster scales.

Modified Gravity

- need to reduce dark matter growth rate on scales contributing to $\sigma 8$
- (already challenging? many models tend to increase it, e.g. f(R), Einstein-aether, khronometric…)
- photon/baryon dynamics should not be affected till z~1000 (primary CMB)
- need to avoid significant enhancement of late ISW…
- similar challenge for dark energy models…

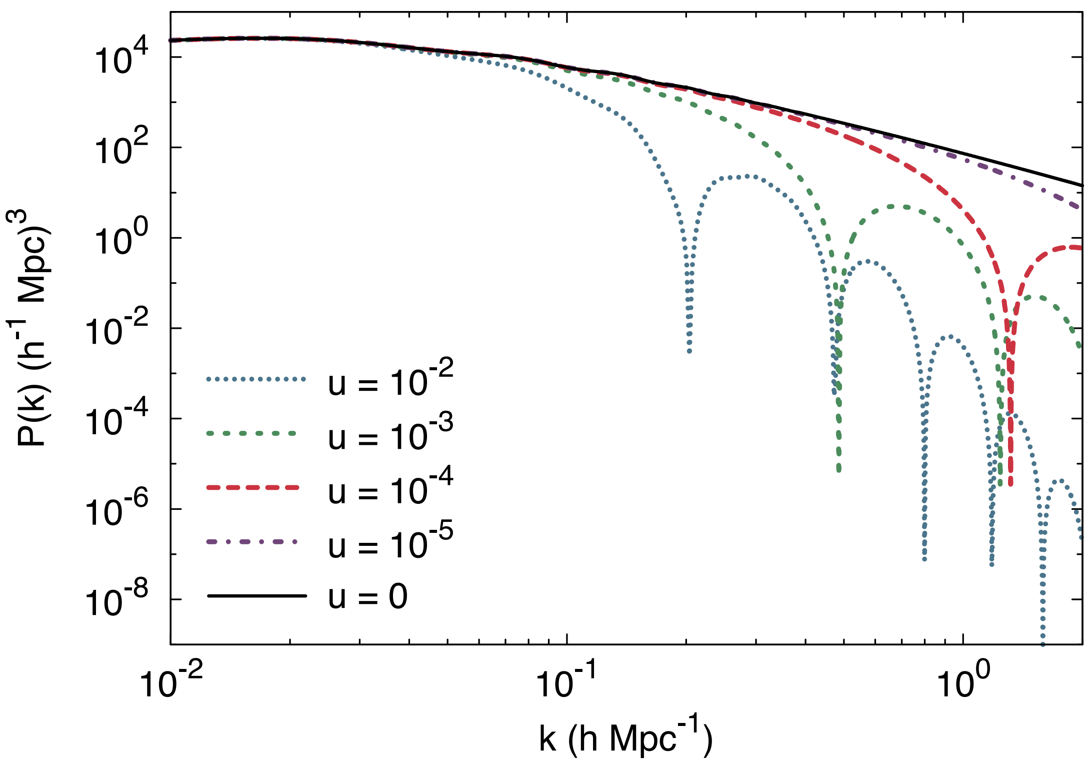
Interacting Dark Matter

- Dark Matter can have interactions:
  - with baryons and photons (< electromagnetic for CMB, + accelerator / direct / indirect detection constraints)
  - possibly larger ones with neutrinos, DR, DE, or with itself
- rate of momentum transfer $\Gamma_{DM} \sim T^n$; particle physics models motivate different values of n ; rich phenomenology :
  - interaction can be important at early / intermediate / late time
  - many effects: (Silk) damping, drag, dark oscillation…

Interacting Dark Matter

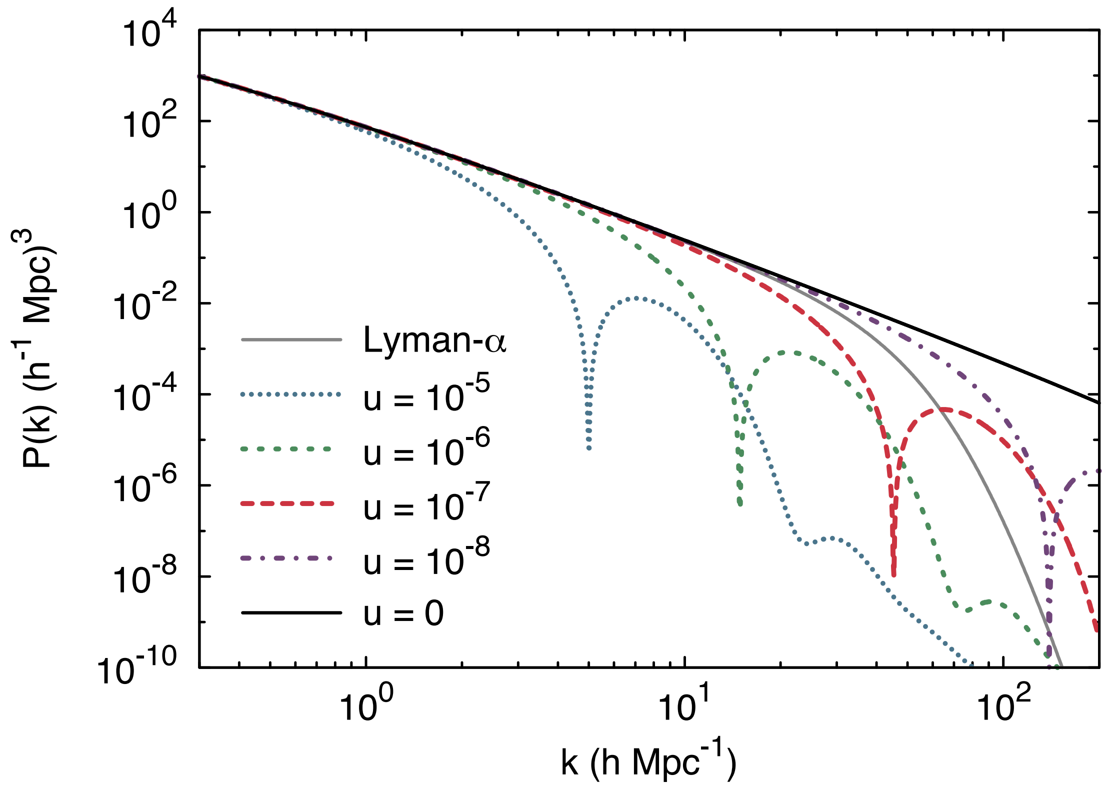
DM-γ (Wilkinson et al. 2013)

σ ~ constant (Thomson-like), $\Gamma_{DM} = 1/t_c \sim T^4$



DM-ν (Wilkinson et al. 2014)

σ ~ constant (Thomson-like), $\Gamma_{DM} \sim T^4$

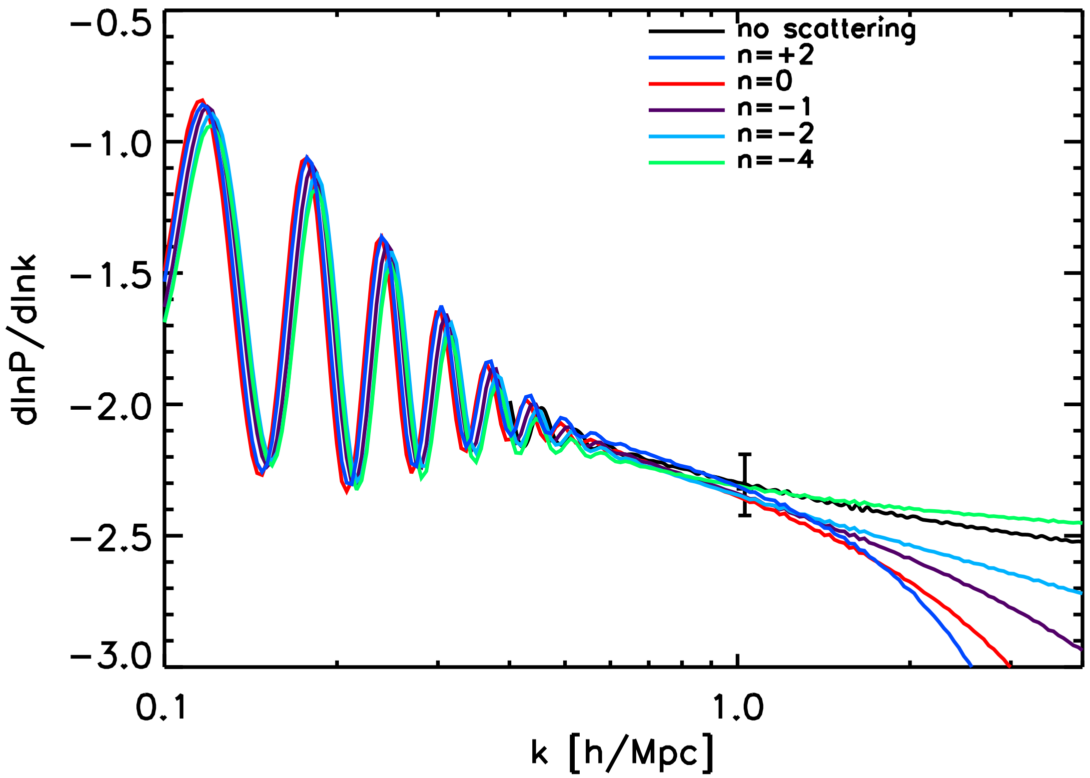


- similar to WDM (exponential cut-off at scale given by k=aH when H~Γ). Models compatible with Lyman-α data are identical to ΛCDM on larger scales.
- constraints also from CMB (effects on recombination time, sound speed, collisional damping of photons, photon-neutrino gravitational interactions…)
- small differences when assuming $\sigma \sim T^2$ - still the story is similar…

Interacting Dark Matter

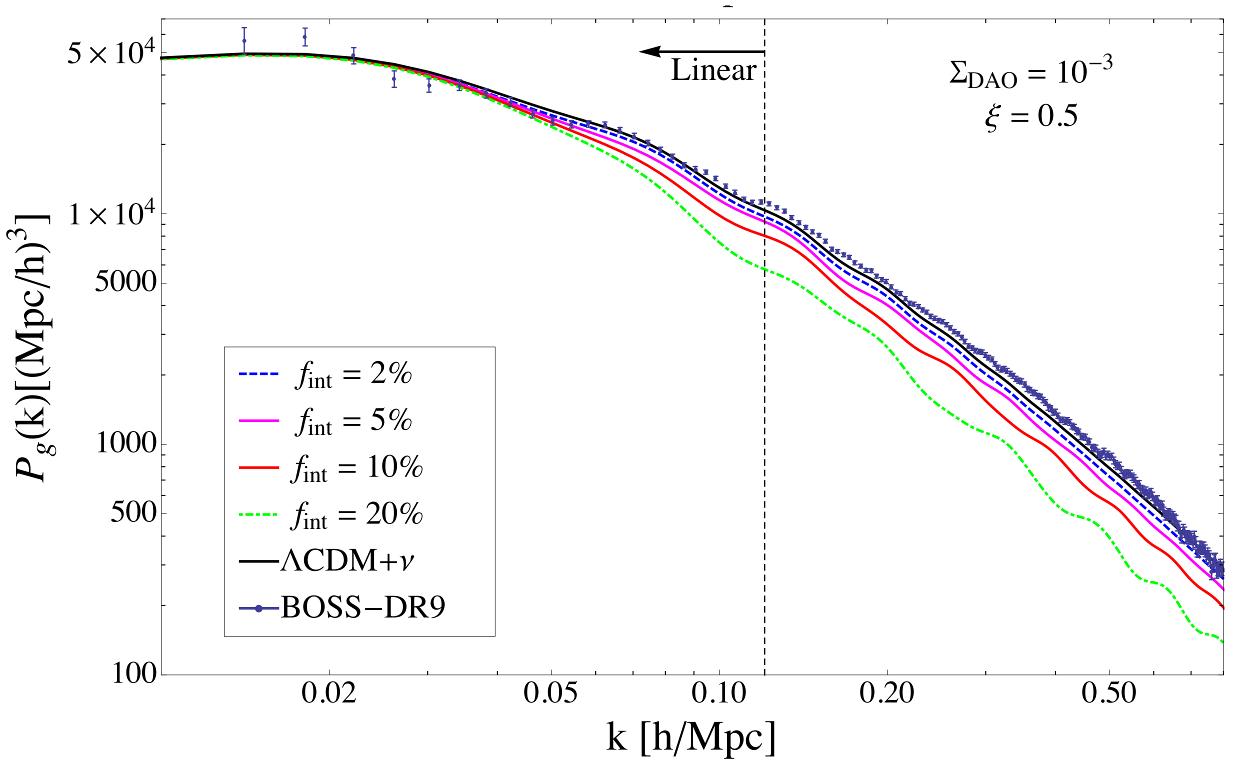
DM-baryons (Dvorkin et al. 2013)

$\sigma \sim v^n \sim T^{n/2}$, $\Gamma_{DM} \sim T^{n/2+3}$



DM-DR (Cyr-Racine et al. 2013)

before *dark recombination*: $\Gamma_{DM} \sim T^4$



- similar to WDM (exponential cut-off). Models compatible with Lyman-α data are identical to ΛCDM on larger scales.
- DM-baryons: weaker/stronger constraints from CMB, depending on n; DM-DR: dark oscillations impact CMB (*fast modes* in fast/slow decomposition)

Interacting Dark Matter

- $H \sim T^2$ during RD, $T^{3/2}$ during MD
- if $\Gamma_{DM} = 1/t_c \sim T^2$:
  - during RD: Γ/H small and constant; no dark oscillations, but small DR drag effect on DM; small impact on all modes crossing during RD; slow mode: CMB unaffected
  - during MD: Γ/H -> 0, no impact on modes crossing during MD, $\delta_{DM} \sim a$ for all scales: no extra late ISW
- such scaling not natural with photons (Compton-like), electrons (Coulomb-like) and neutrinos (Weak-like)
- many interesting non-SUSY-based Dark Matter models have dark gauge groups with:
  - dark photons (abelian),
  - dark gluons (non-abelian),
  - new charged fermions
- may behave as Dark Radiation coupled to Dark Matter with appropriate scaling

Interacting DM-DR with $\Gamma \sim T^2$

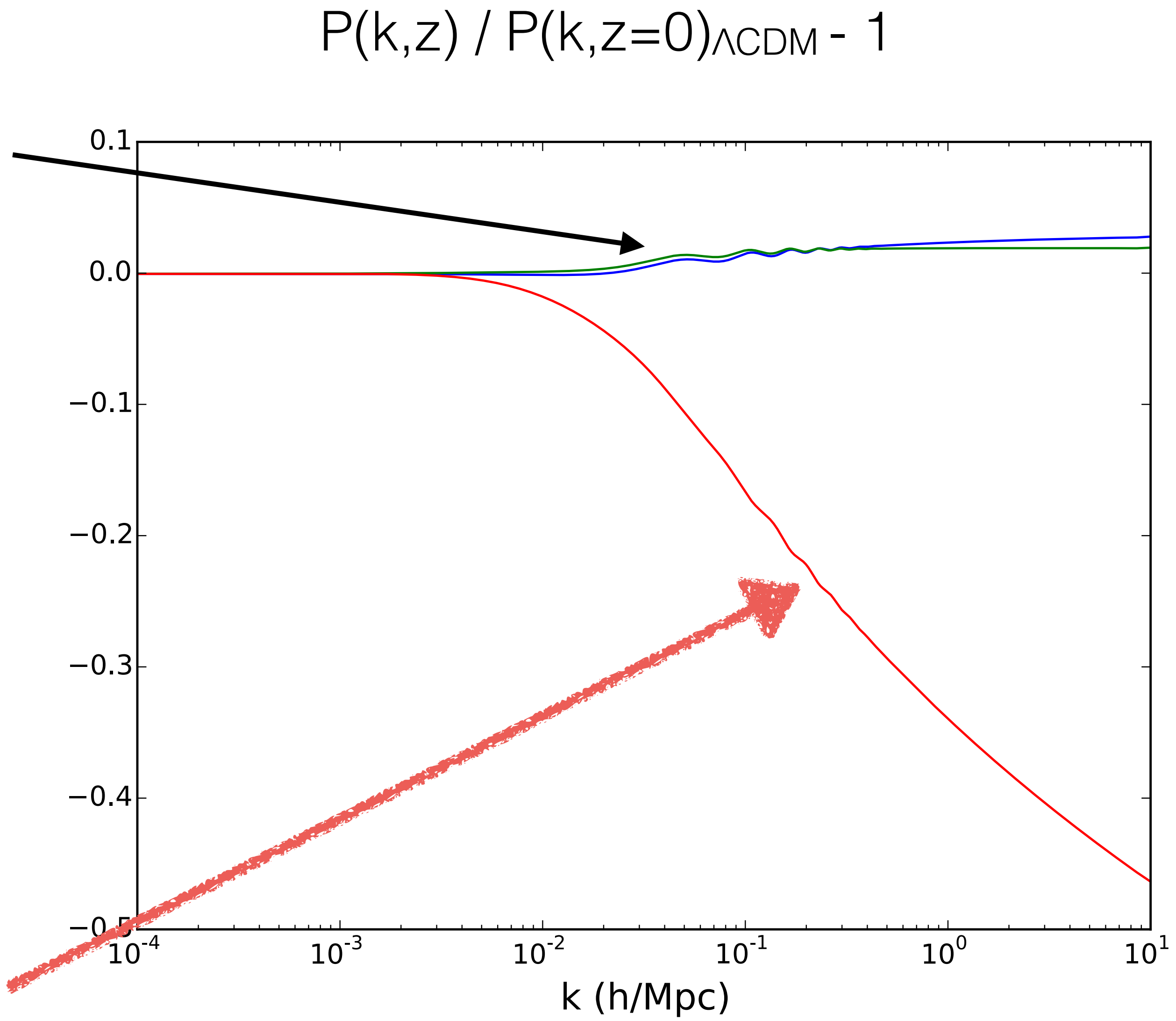
$$\dot{\delta}_{\rm dm} = -\theta_{\rm dm} + 3\dot{\phi}$$
$$\dot{\theta}_{\rm dm} = -\frac{\dot{a}}{a}\theta_{\rm dm} + a\Gamma(\theta_{\rm dr} - \theta_{\rm dm}) + k^2\psi$$

$$\Gamma = \Gamma_0 \left(\frac{T}{T_0}\right)^2$$

- Buen-Abad, Marques-Tamares, Schmaltz 2015:
    - dark gauge groupe SU(N)
    - DM has weak and dark interactions
    - DR = dark gluons, self-interacting, tiny mean free path, no viscosity
    - DM relic density value imposes $\Delta N_{eff}(N) = 0.21$, …
- JL, Marques-Tamares, Schmaltz 2015:
    - dark gauge group U(1)
    - DM has weak and dark interactions
    - DR = dark photon + massless fermions with dark charge, also self-interacting

Interacting DM-DR with $\Gamma \sim T^2$

- non-trivial effect of extra relativistic perfect fluid, mainly on CMB (see Audren et al. 2014, Planck 2015 XIII), small for P(k,z)
- extra effect of DM-DR interaction:
  - tiny for CMB (photon-DM forces irrelevant, photon-DR forces relevant but weakly affected)
  - ~10 to 15 times larger for P(k,z): slow-down of DM growth during Radiation Domination (Dark Radiation drag)



Interacting DM-DR with Γ ~ T^2

w.r.t. ΛCDM :

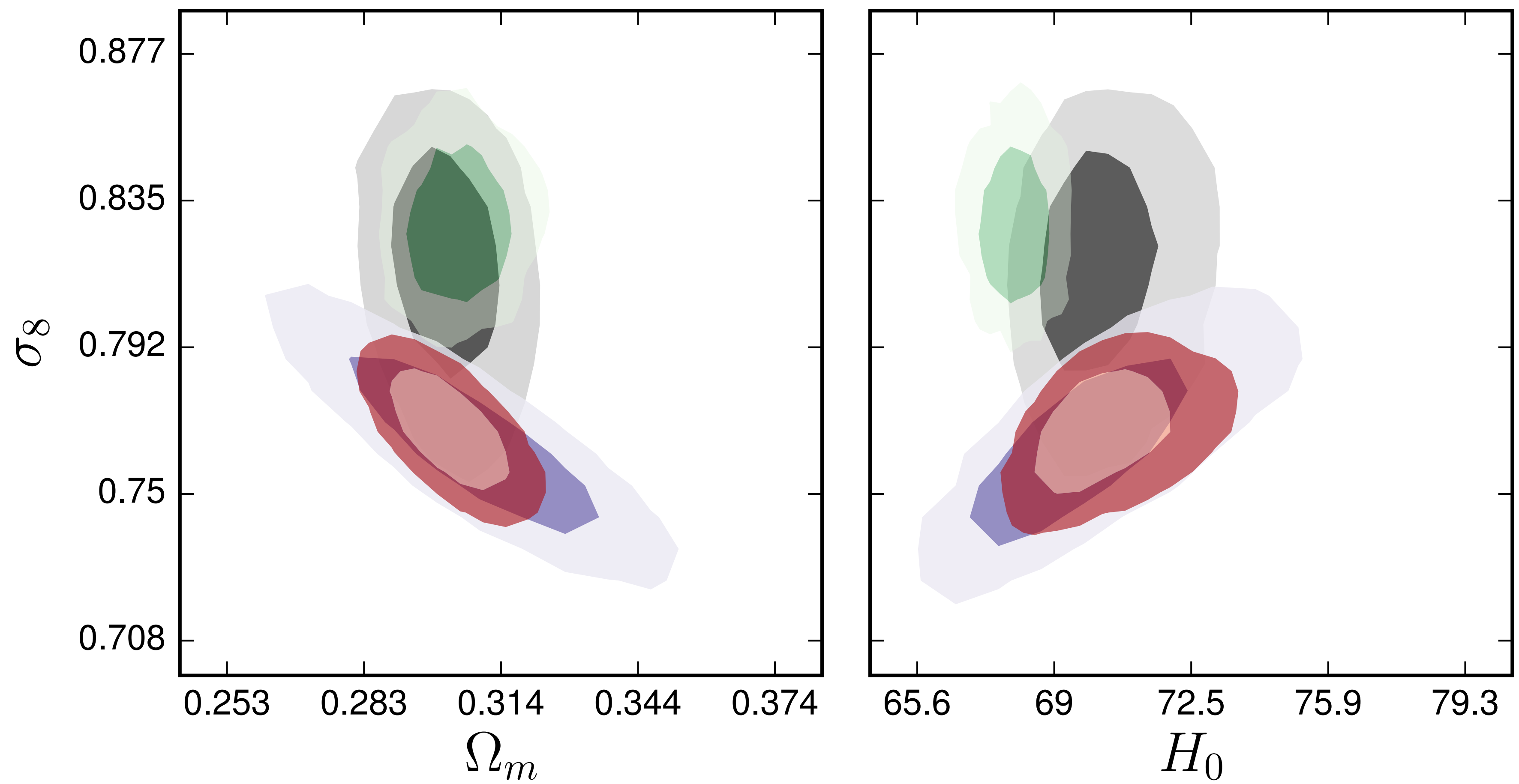
model is compatible with significantly smaller σ_8, with same Ω_m and equal or larger H_0

ΛCDM, CMB+BAO

DM-DR, CMB+BAO

DM-DR, CMB+LSS

DM-DR, CMB+BAO+LSS



CMB = Planck 2015 TT + lowTEB

BAO = same as in Planck 2015

LSS = Planck lensing + Planck SZ + CFHTLens

Interacting DM-DR with $\Gamma \sim T^2$

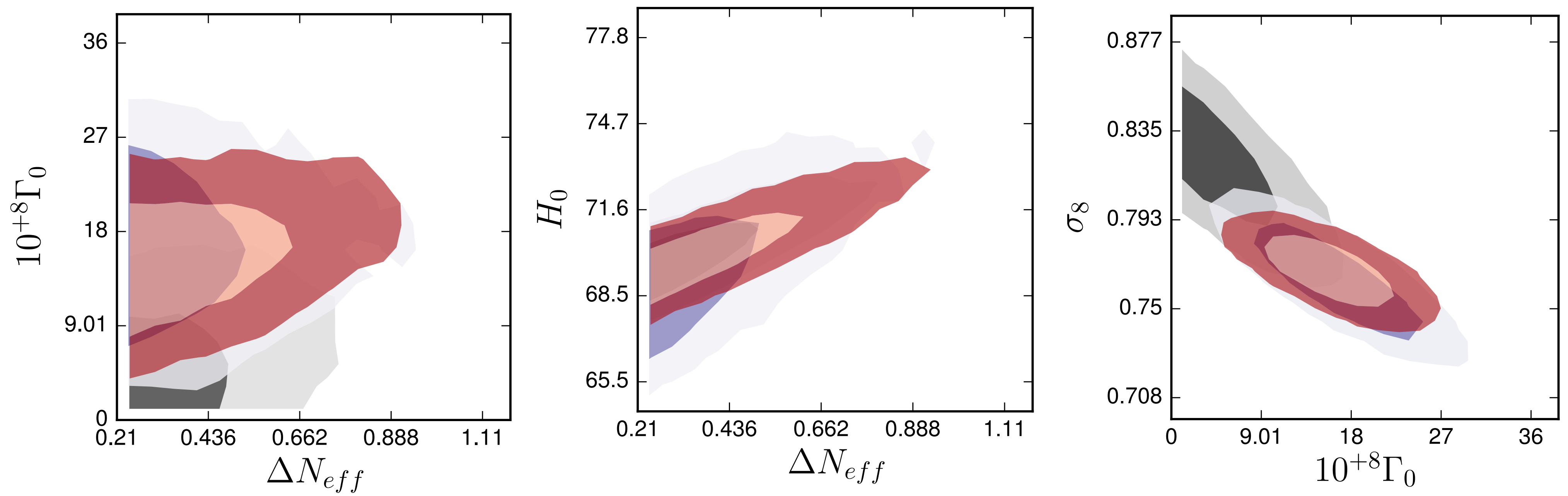
w.r.t. ΛCDM :

model is compatible with significantly smaller σ_8, with same Ω_m and equal or larger H_0

DM-DR, CMB+BAO

DM-DR, CMB+LSS

DM-DR, CMB+BAO+LSS



CMB = Planck 2015 TT + lowTEB

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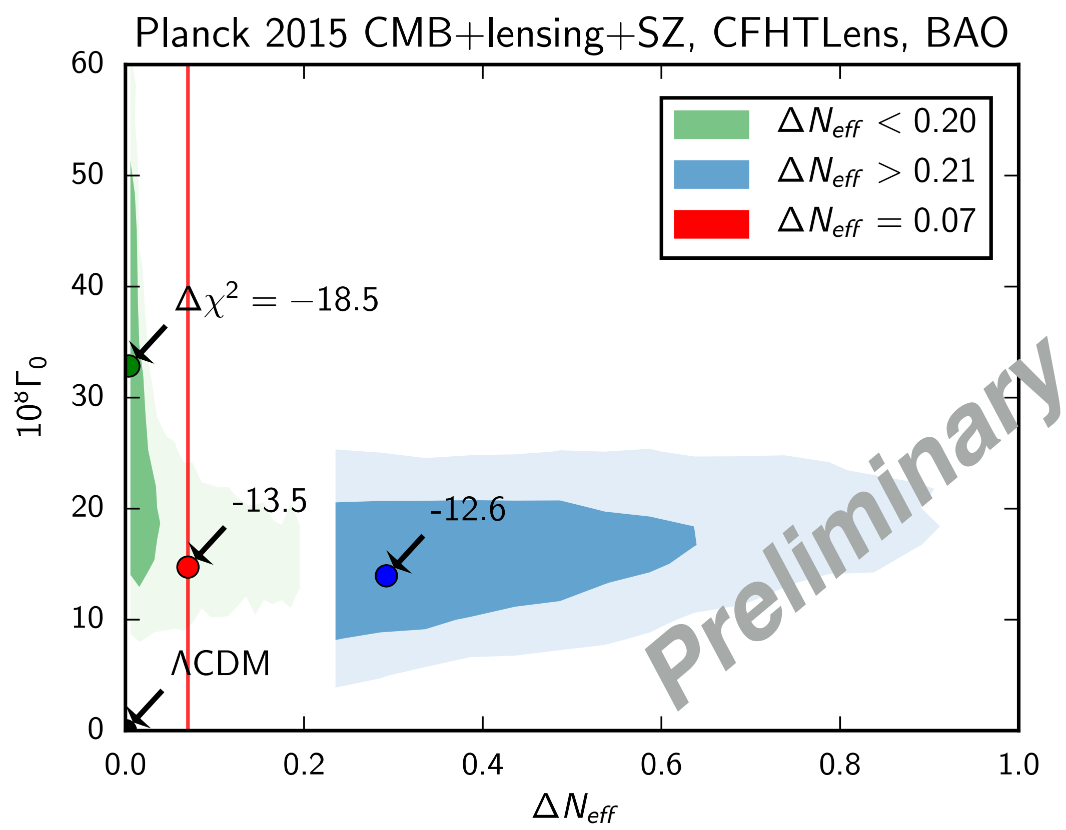
Interacting DM-DR with $\Gamma \sim T^2$

- 3-4σ evidence for DM-DR interaction
- ΔN_{eff} compatible with minimal value (unless H_0 from Riess et al. taken seriously)

Parameter	CMB+BAO	CMB+LSS	CMB+BAO +LSS
$\Delta N_{\rm eff}$	< 0.68	< 0.78	< 0.79
$10^7\Gamma_0$ [Mpc^{-1}]	< 1.45	$1.70^{+0.57}_{-0.58}$	$1.60^{+0.43}_{-0.44}$
$\Omega_{\rm m}$	$0.3018^{+0.0081}_{-0.0084}$	$0.308^{+0.020}_{-0.019}$	$0.3026^{+0.0085}_{-0.0087}$
σ_8	$0.8153^{+0.024}_{-0.020}$	$0.764^{+0.017}_{-0.019}$	$0.768^{+0.011}_{-0.011}$
$\Delta\chi^2$ / ΛCDM	0	-9.6	-12.6

Interacting DM-DR with $\Gamma \sim T^2$

- ongoing and future:
  - include P(k) from SDSS, full shape of CFHTLens, Lyman-α
  - … but to be fair we should also include the new DLS and WtG …
  - investigate small ΔN_{eff} regime (drag of DM on DR more relevant)



  - investigate case with free-streaming DR