A dark matter solution to cosmic tensions and the ISW-void anomaly

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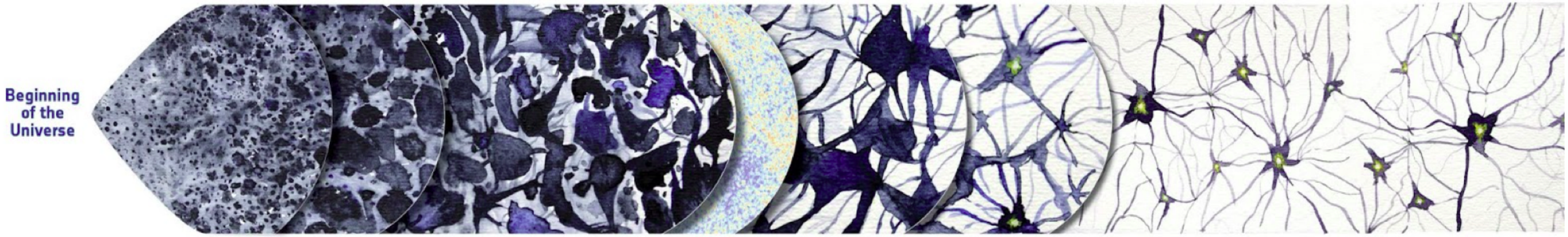
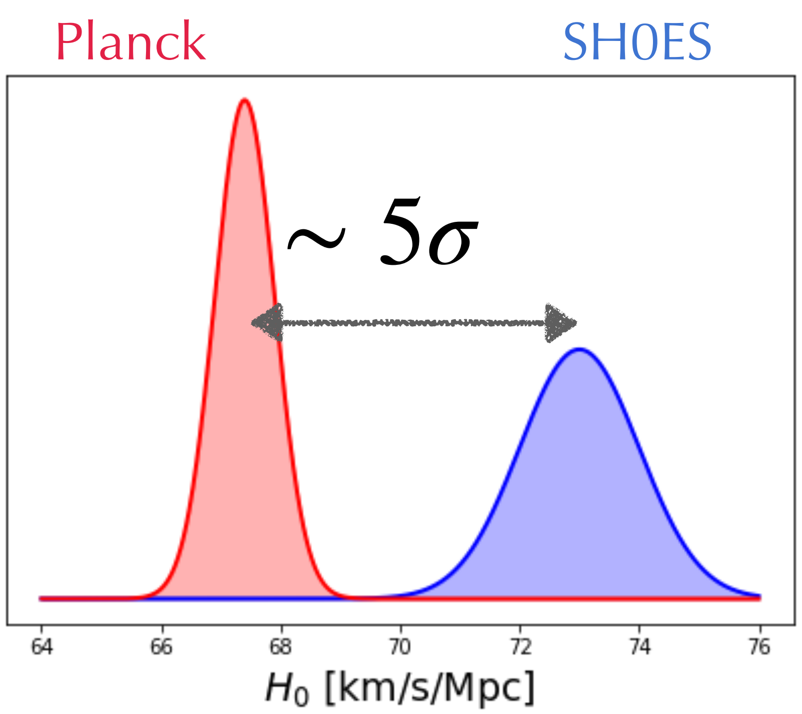
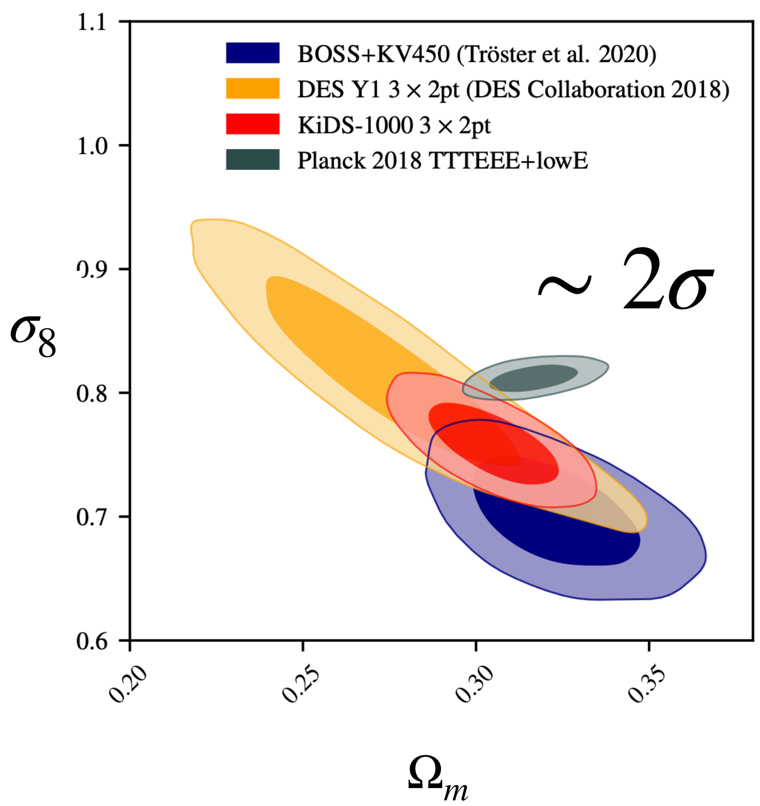
The *incomplete* Cosmological Model: ΛCDM



ΛCDM: Remarkable success across a plethora of observations

Physical nature of the **dark sector**?

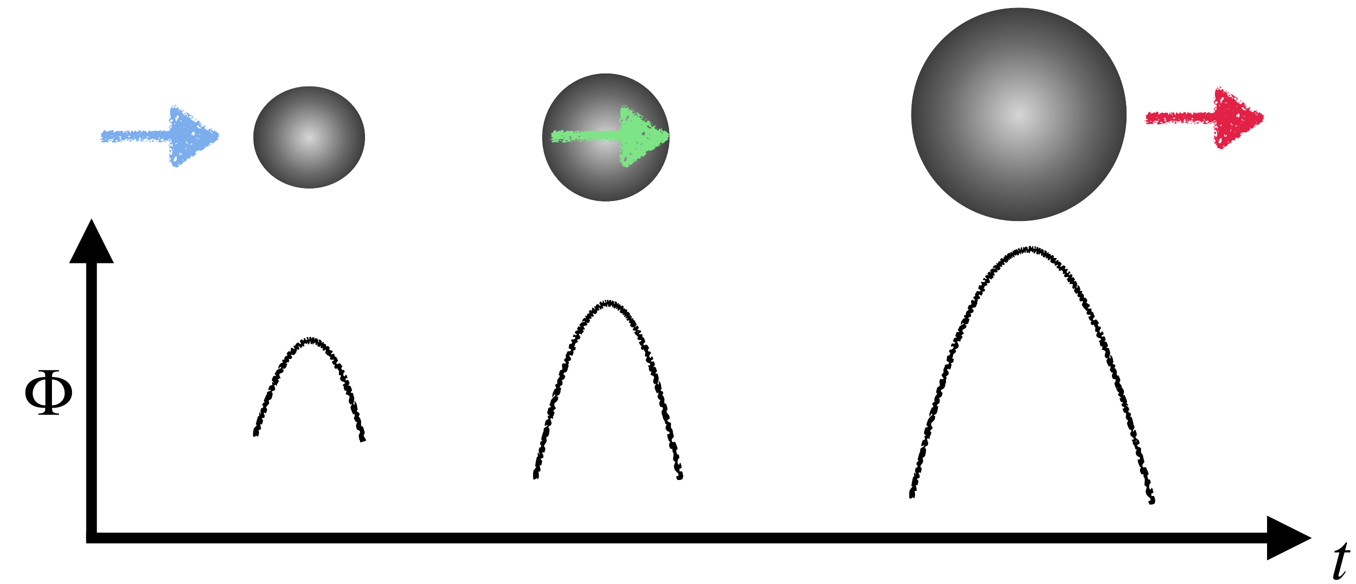


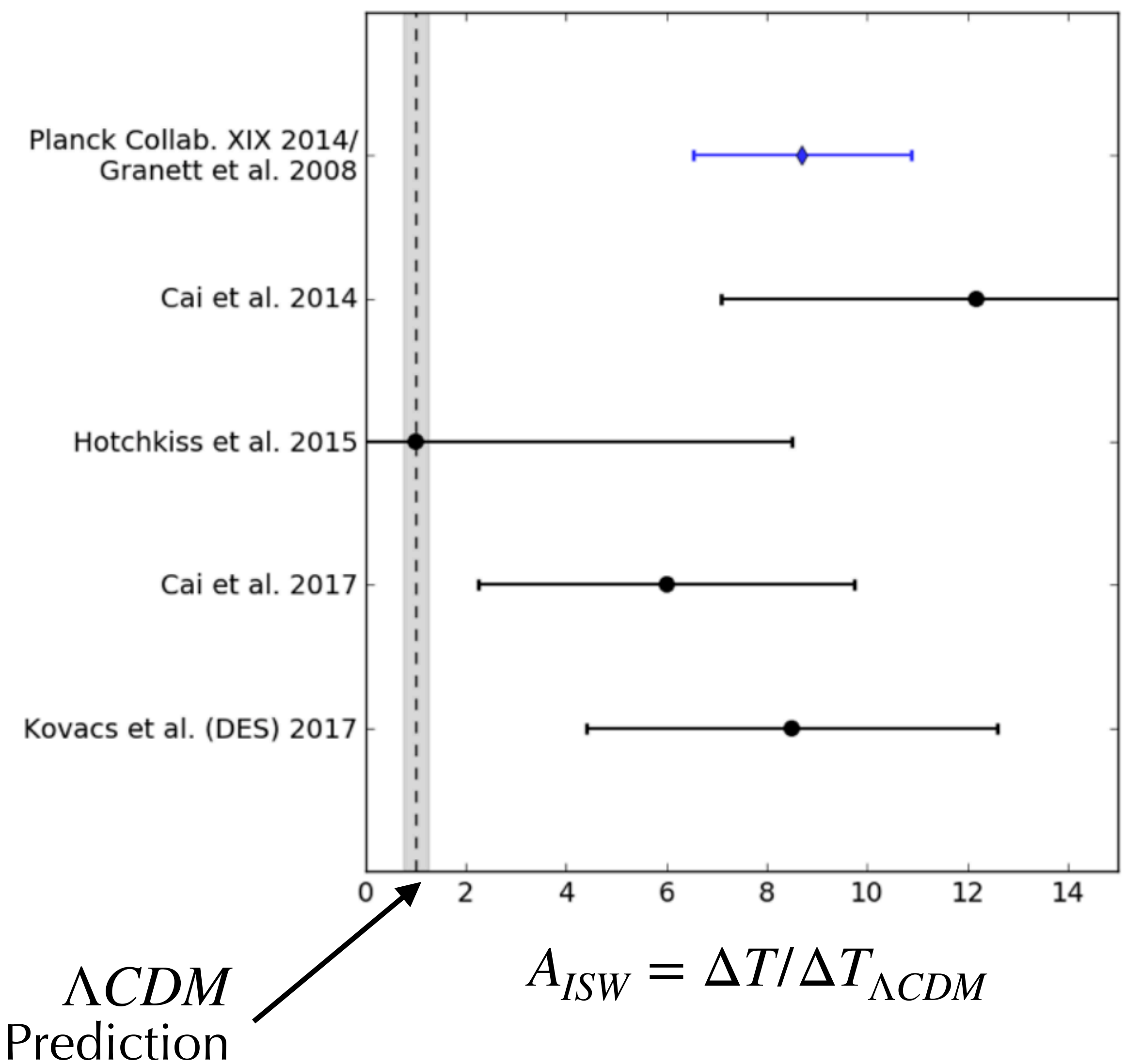


- H_0 tension: $\sim 5\sigma$ [DiValentino + (2021a), Verde +(2024)].*
- σ_8 tension: $\sim 2\sigma$ [DiValentino + (2021b)] to 4.5σ [Chen+(2024)].

Current tensions & anomalies

- $$\frac{\Delta T_{ISW}}{\bar{T}}(\hat{n}) \propto \int \dot{\Phi}(\hat{n}, z)dz$$
- **Cosmic voids**: Photons loose energy entering and regain less energy upon exiting due to cosmic expansion
- Net cooling effect of CMB photons.





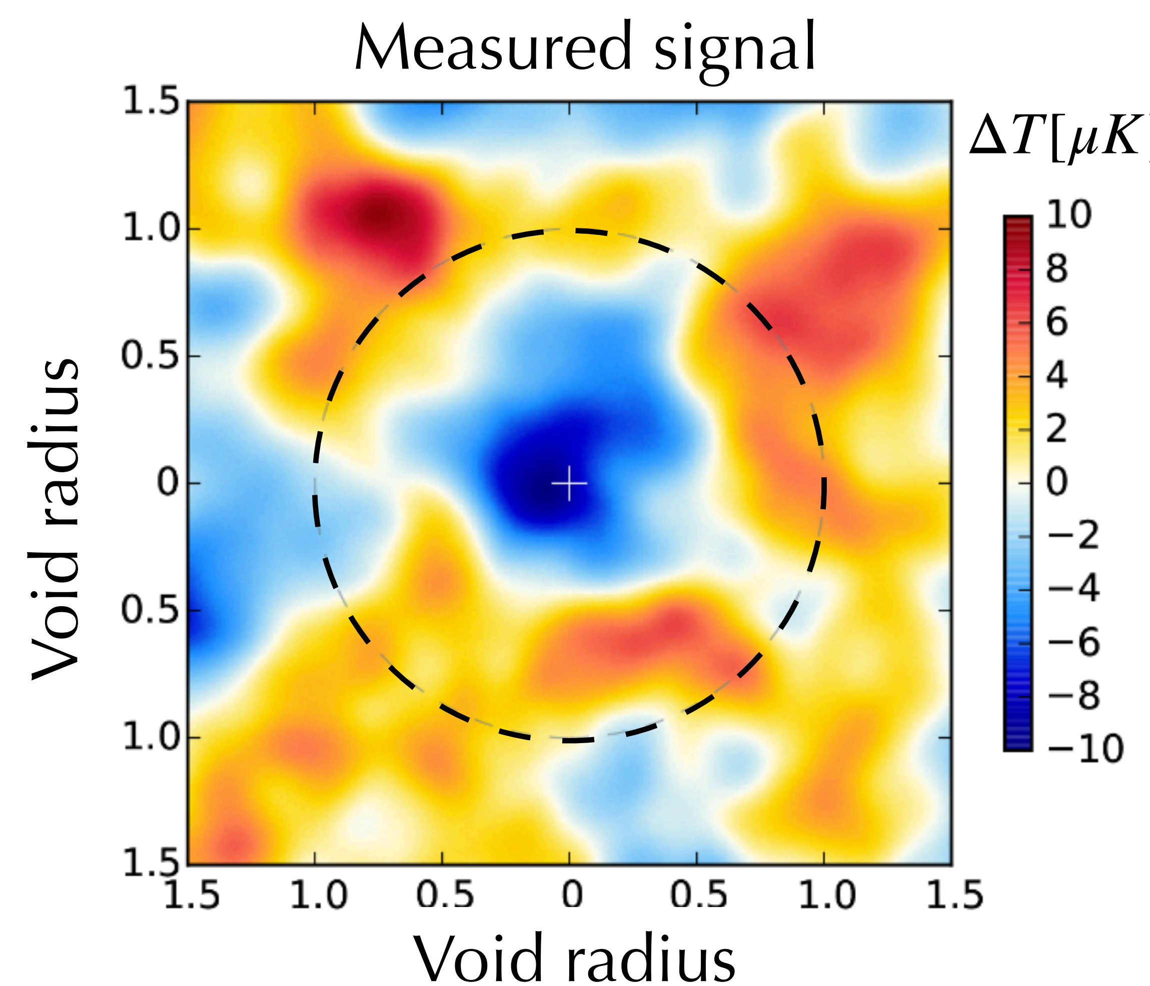
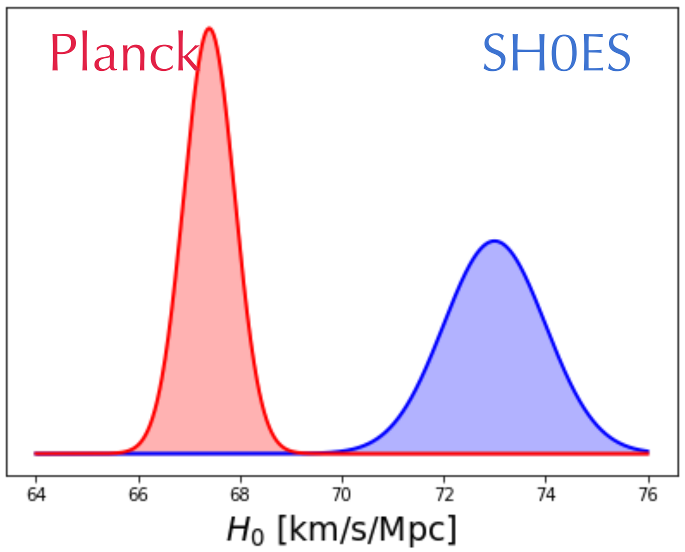
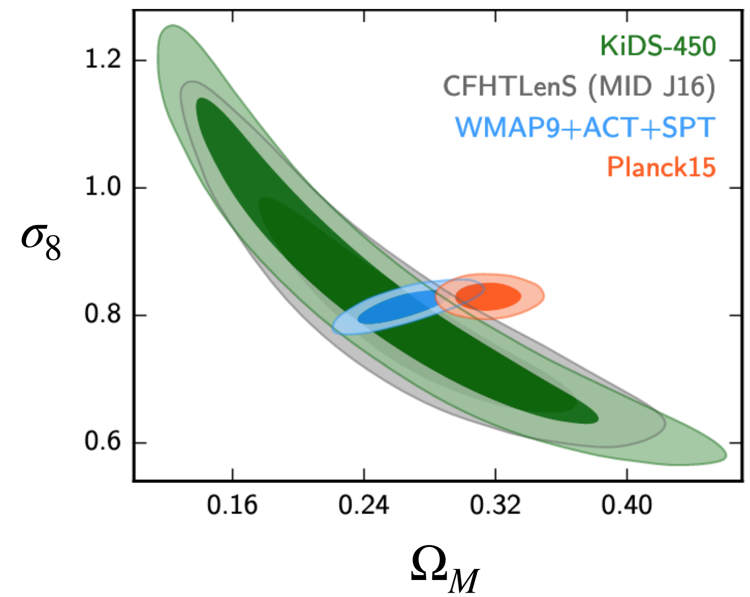
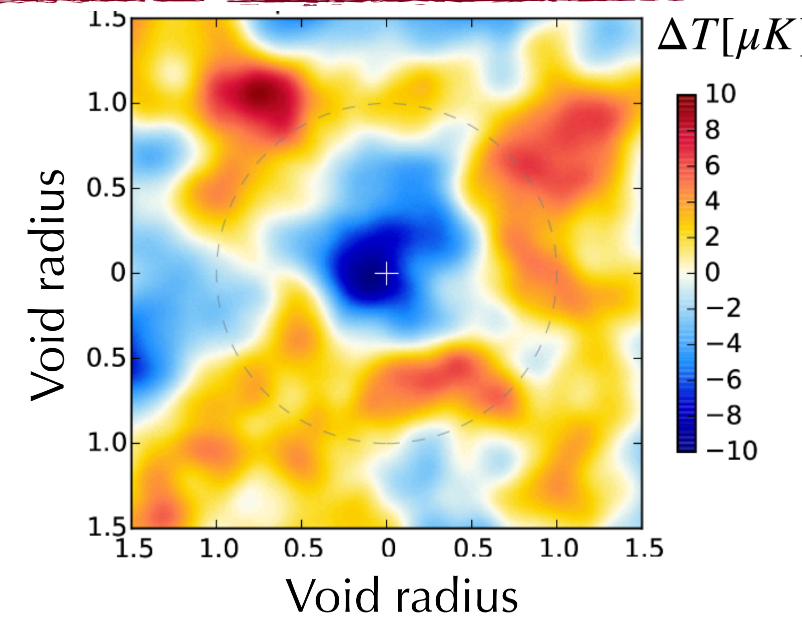


Fig. adapted from Kovacs (2017) [ArXiv: 1701.08583]

ΛeDM simultaneously alleviates these tensions







- Phenomenological extension to ΛCDM.
- Based on W. Hu's generalised dark matter model [Hu (1998)]
- No viscosity terms.
- Null adiabatic speed of sound.
- Fix $a_{nz} = 0.5 \ \ (z = 1)$.
- $\omega_{dm,0}$ free parameter.

$$\rho_{dm}(a) = \rho_{dm,0} W(a),$$

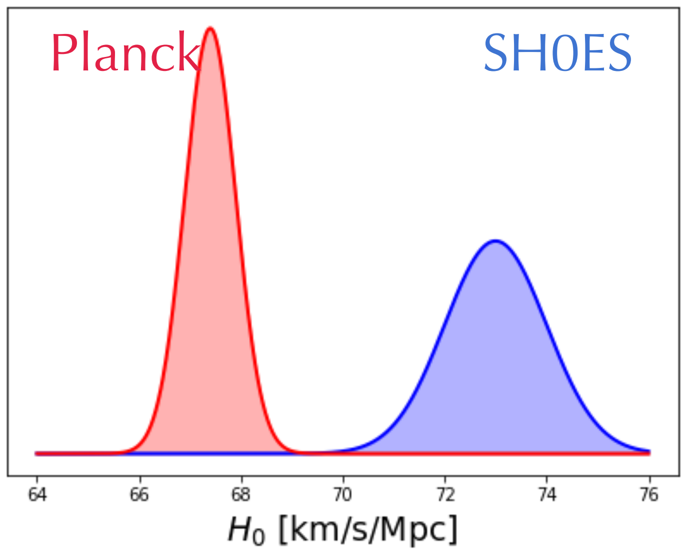
$$W(a) = \exp\left(3\int_a^1 \frac{\omega(a')da'}{a'}\right),$$

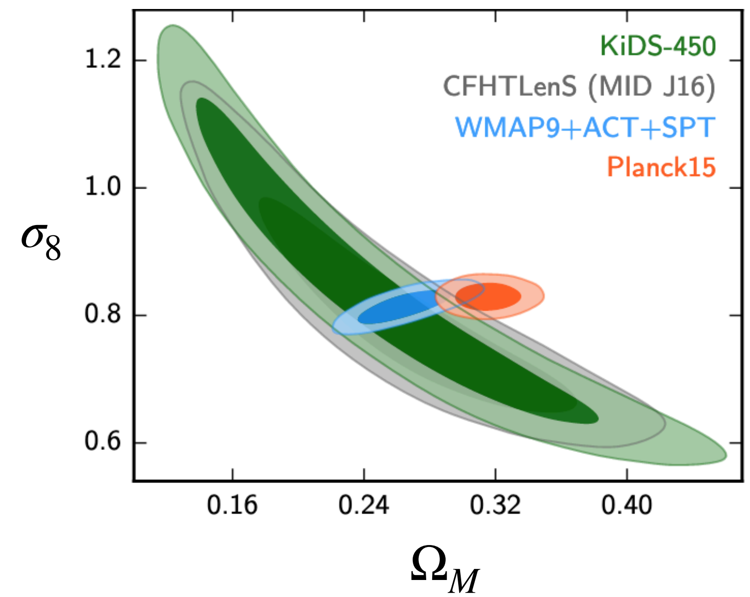
$$\omega_{dm}(a) = w_{dm,0}\left(\frac{a - a_{nz}}{1 - a_{nz}}\right), \quad \text{for } a \geq a_{nz}$$

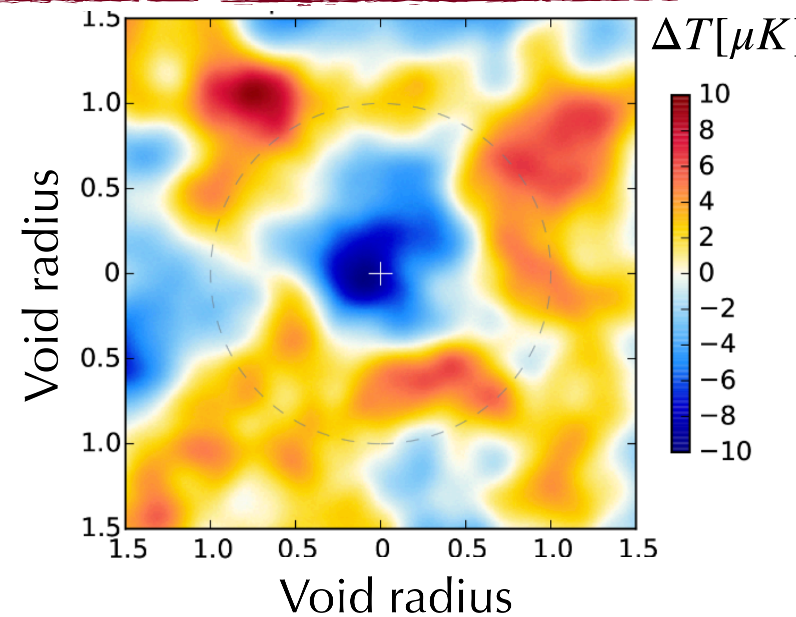
$$\omega_{dm}(a) = 0 \text{ for } a < a_{nz}$$

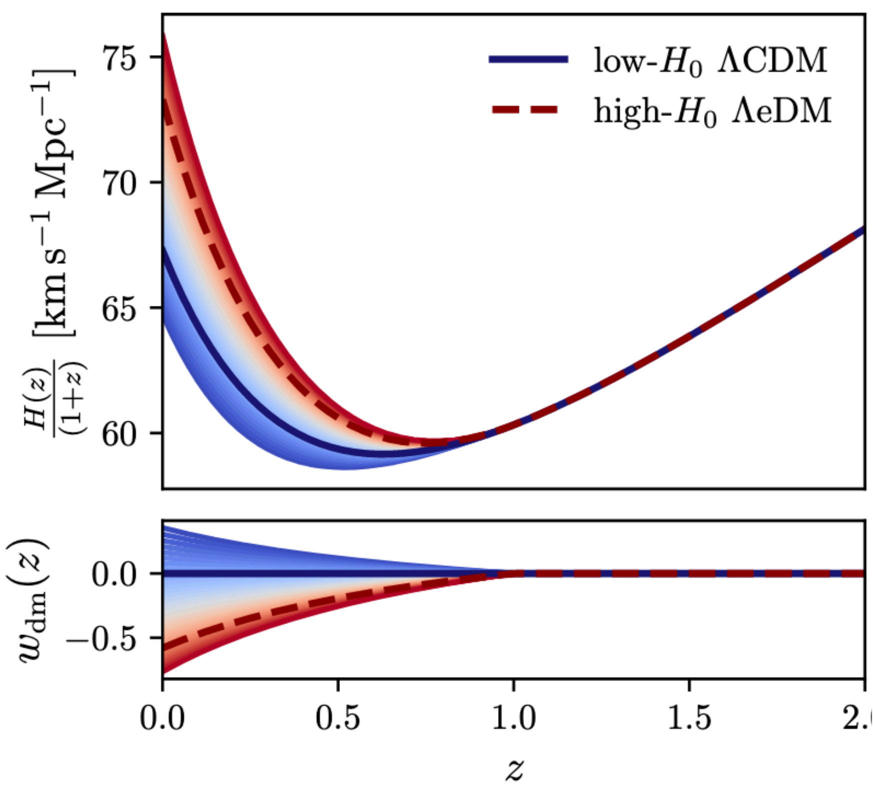
[Naidoo, **MJ**,+ PRD (2024), arXiv:2209.08102]

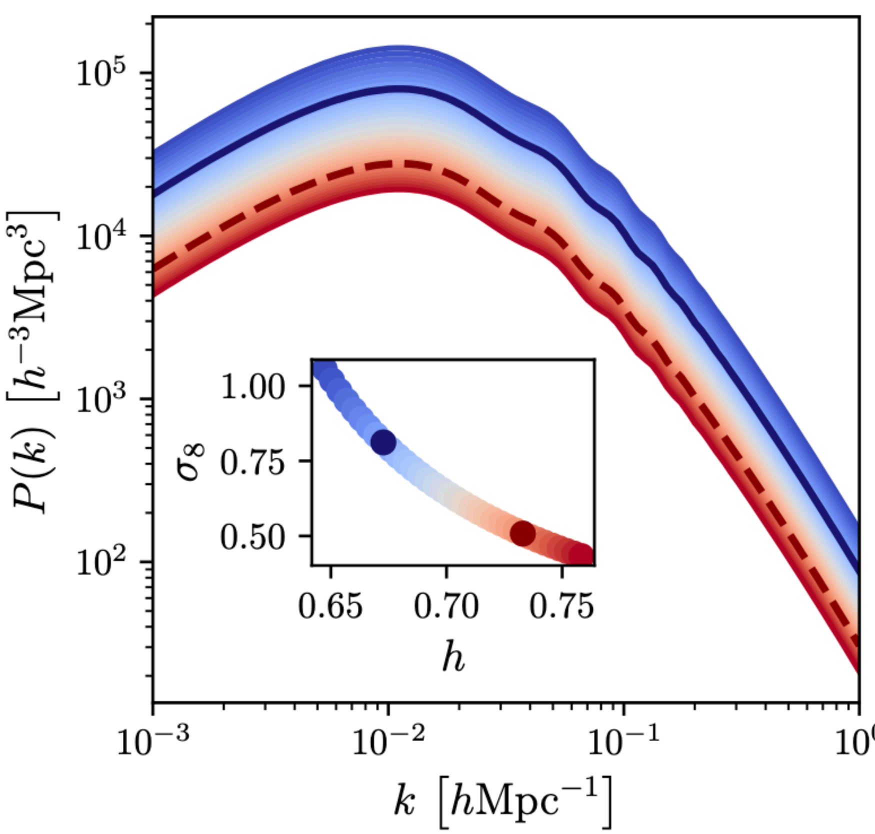
ΛeDM simultaneously alleviates these tensions

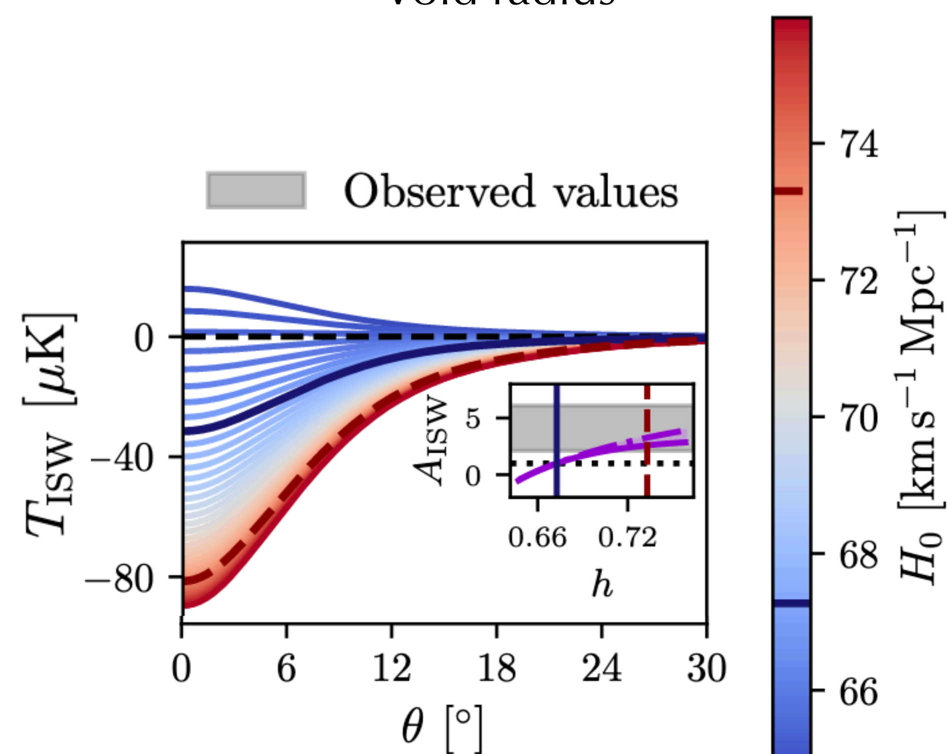












Allowing ω_{dm} to vary links these tensions and anomalies.

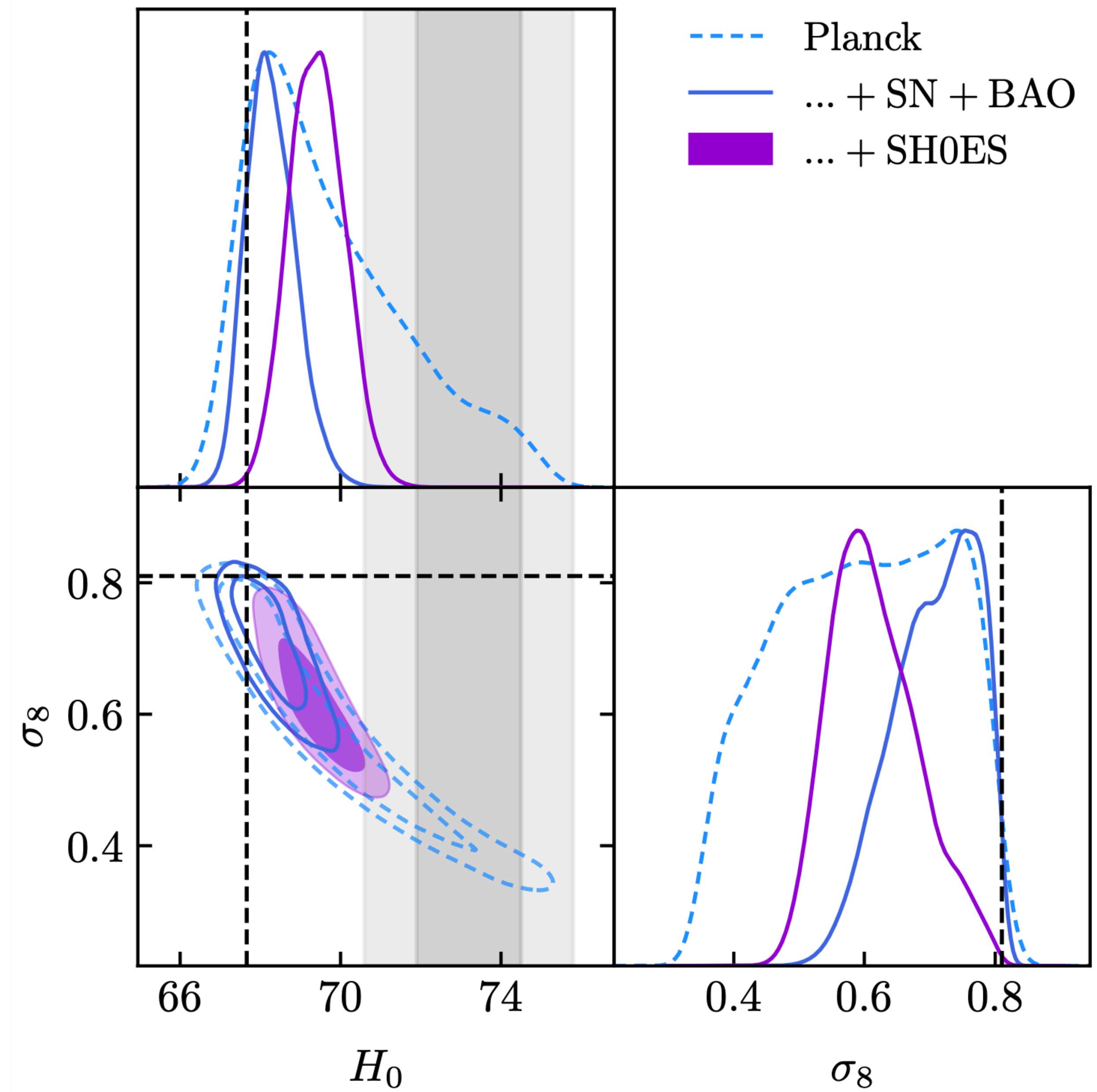
[Naidoo, **MJ**,+ PRD (2024), arXiv:2209.08102]

Constraining ΛeDM

- H_0 tension is reduced to $\sim 3.5\sigma$
- σ_8 tension is reduced to $\sim 1\sigma$
- Non-zero value for $w_{dm,0}$

  $$w_{dm,0} = -0.31^{+0.30}_{-0.25}$$

- Better fit (smaller χ^2) but penalised by AIC.



Caveats:

- Negative equation of state for dark matter

  $$c_s^2 = \left(\frac{\partial P}{\partial \rho}\right)_s \neq 0$$

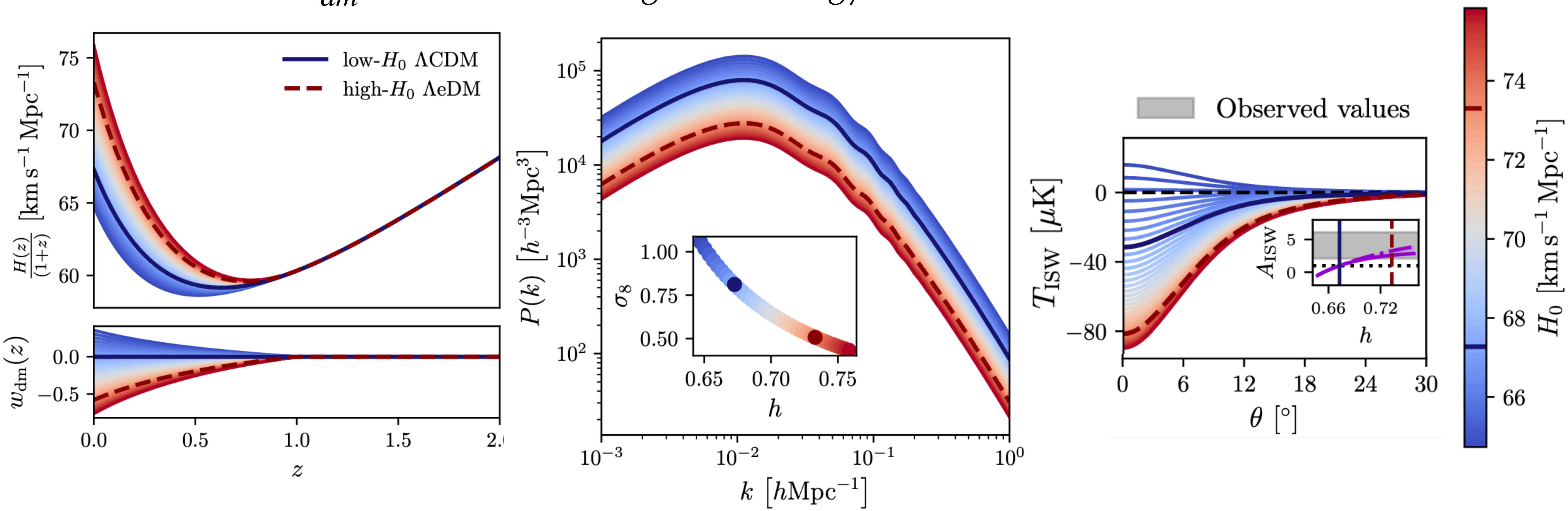
  Impact on structure formation.

- Physical model for this type of dark matter?

[Naidoo, **MJ**,+ PRD (2024), arXiv:2209.08102]

Conclusions

- A dynamical ω_{dm} links known tensions and anomalies.
  - Reduces cosmic tensions: H_0 ($5\sigma \rightarrow 3.5\sigma$) and σ_8 ($2\sigma \rightarrow 1\sigma$).
  - Recovers A_{ISW} consistent with observations from large stacked voids.
- ISW from voids 'smoking gun' for DM solution to tensions.
  - More precise measurements with future/ongoing surveys (DESI, Euclid, LSST)
- Instead of $\omega_{dm} < 0$: *Interacting dark energy-dark matter* model?

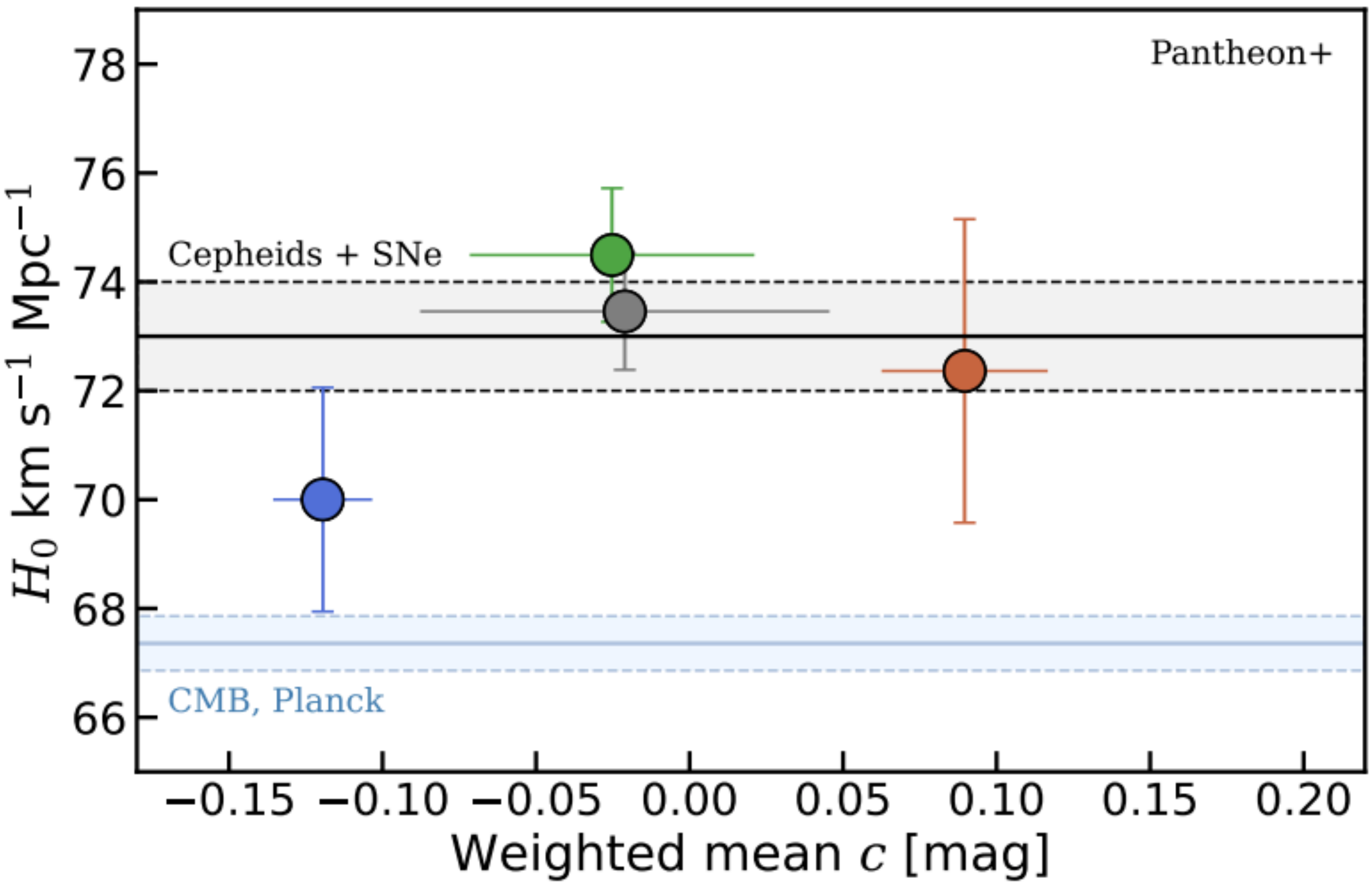


[Naidoo, **MJ**,+ PRD (2024), arXiv:2209.08102]

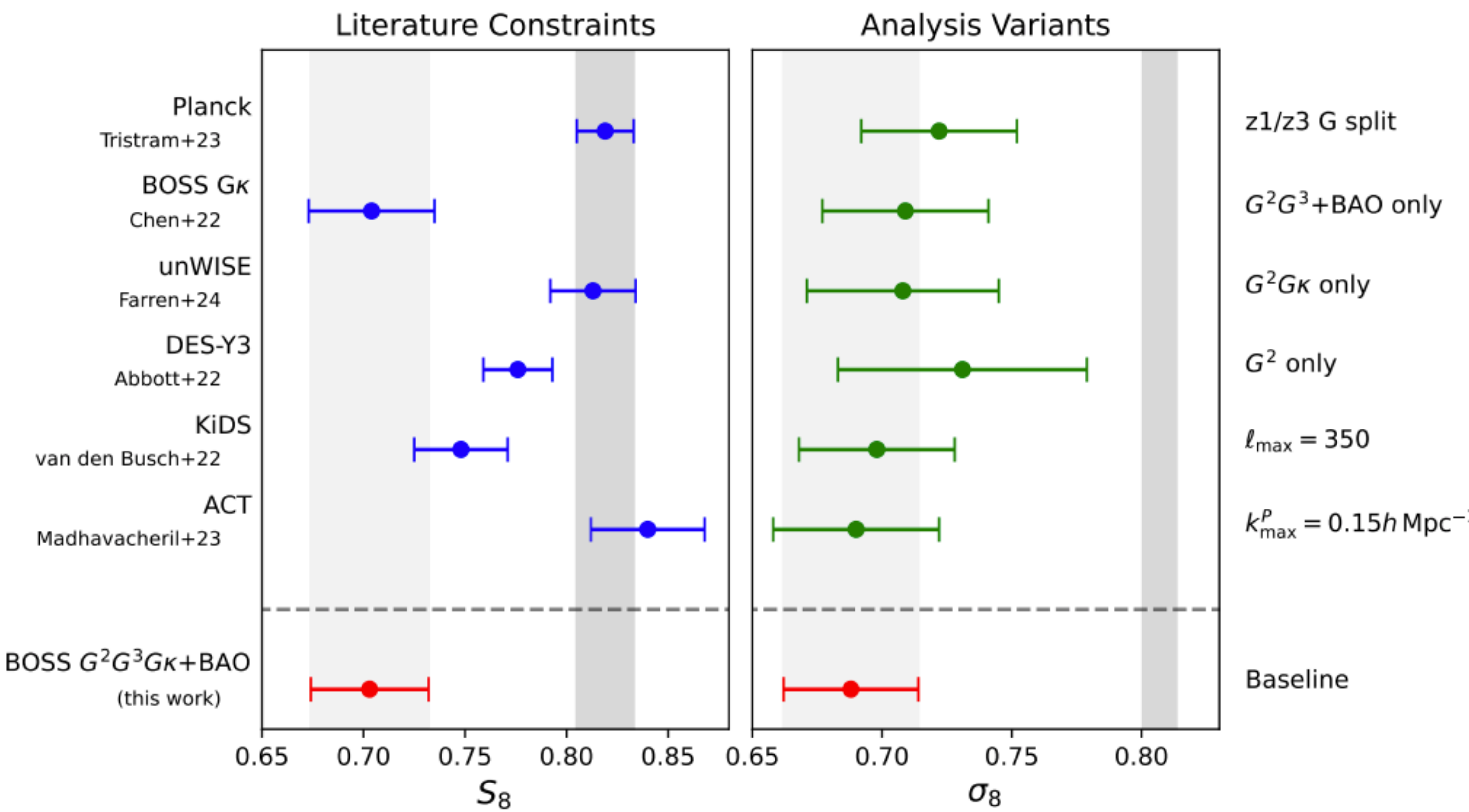
Extra Slides

Current tensions & anomalies

[Fig. from arXiv:2411.05642]



Current tensions & anomalies



- Structure formation in the late universe (BOSS galaxies) is substantially suppressed compared to CMB (Planck): ~4.5σ [Chen+(2024), arXiv:2406.13388].

ΛeDM explains Tensions

- Convergence:

$$\kappa(\hat{\eta}) = \frac{3H_0^2}{2c^2}\,\Omega_{\rm m} \int_0^{\chi_{\rm s}} \frac{\chi}{\chi_{\rm s}}\,(\chi_{\rm s}-\chi)\,\frac{D(\chi)}{a(\chi)}\,\Gamma(\chi)\,\delta(\chi)\,{\rm d}\chi$$

Extra eDM term

- Integrated Sachs-Wolf effect:

$$\frac{T_{\rm ISW}(\hat{\eta})}{T} = \frac{2}{c^3}\int_0^{\chi_{\rm LS}} \dot{\Phi}\left[\chi\hat{\eta}, t(\chi)\right]\,a(\chi)\,{\rm d}\chi$$

$$\dot{\Phi}(x,t) = H(t)\left[f(t) - 1 + \Upsilon(t)\right]\Phi(x,t)$$

$$\Phi(x,t) = \frac{3}{2}H_0^2\,\Omega_{\rm m}\,\Gamma(t)\,\frac{D(t)}{a(t)}\,\nabla^{-2}\delta(x,0)$$

Extra eDM terms

$$\rho_{\rm m}(a) = \frac{\rho_{\rm m,0}}{a^3}\,\Gamma(a)$$

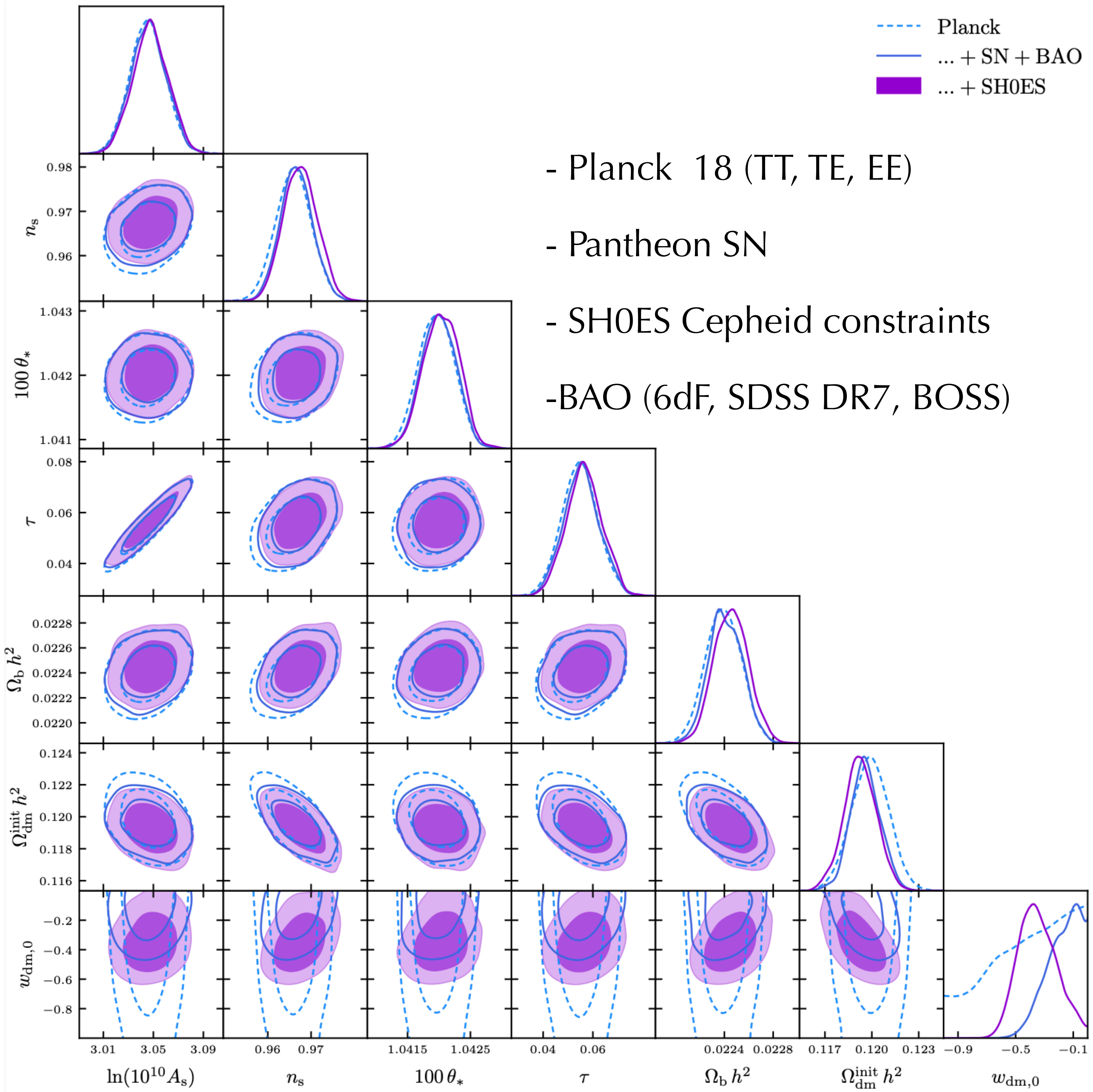
$$\Gamma(a) = f_{\rm b} + f_\nu + f_{\rm dm}\,W(a)$$

$$\Upsilon(a) = \frac{{\rm d}\,\Gamma(a)}{{\rm d}\ln a} = 3\,f_{\rm dm}\,\frac{w_{\rm dm}(a)\,W(a)}{\Gamma(a)}$$

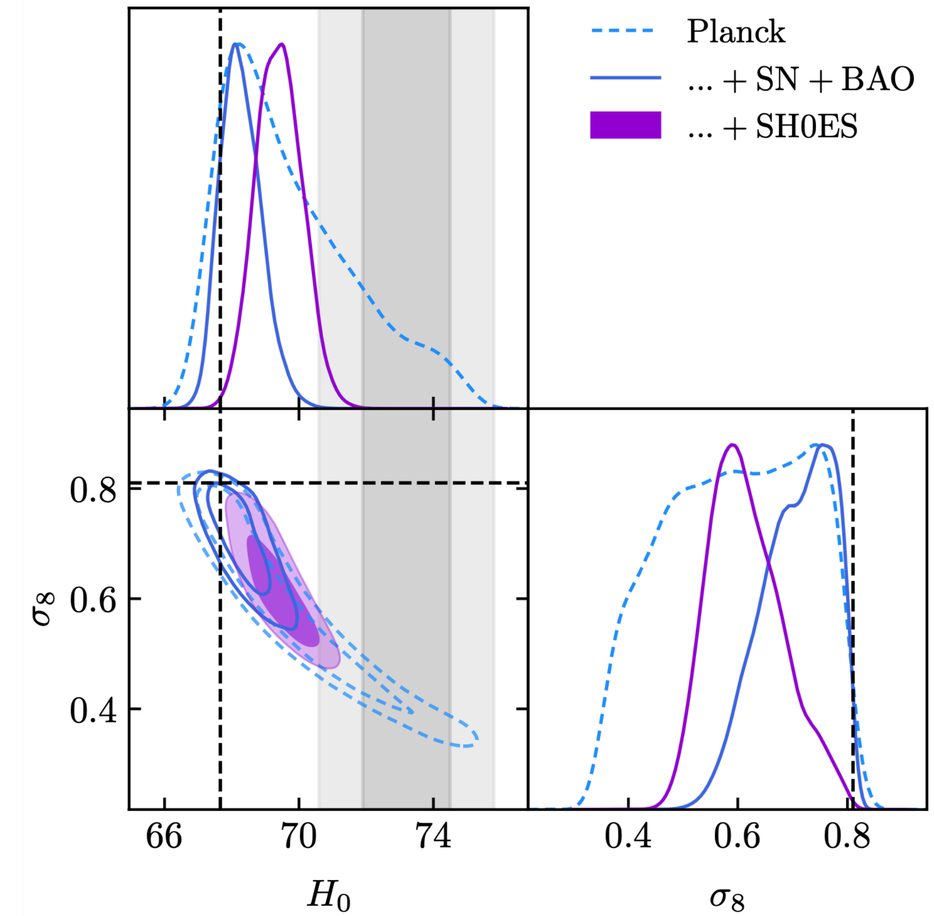
[Naidoo, **MJ**,+ PRD (2024), arXiv:2209.08102]

Constraining ΛeDM

Free parameter: $w_{dm,0}$



- Planck 18 (TT, TE, EE)
- Pantheon SN
- SH0ES Cepheid constraints
- BAO (6dF, SDSS DR7, BOSS)



$$w_{dm,0} = -0.31^{+0.30}_{-0.25}$$

Modified Boltzmann Solver

CLASS

Cobaya MCMC sampler

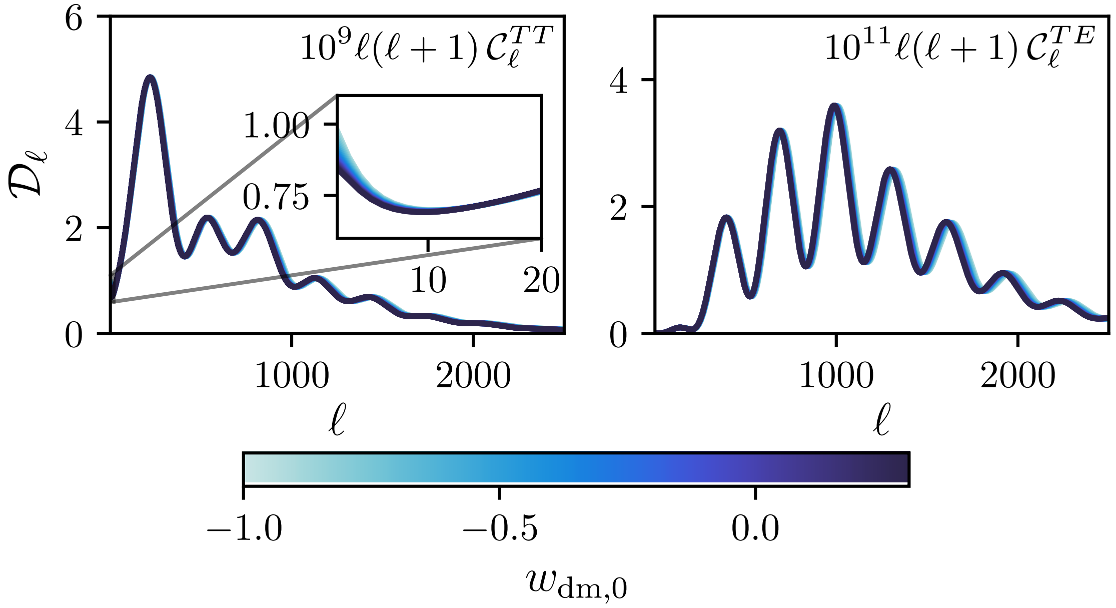
[Naidoo, **MJ**,+ PRD (2024), arXiv:2209.08102]

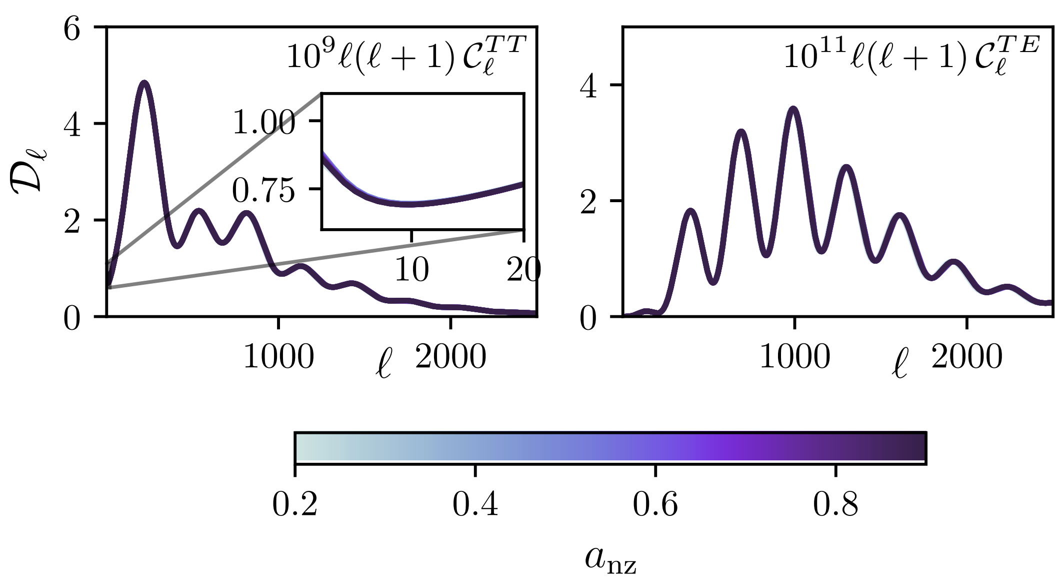
Constraining ΛeDM

	P18		… + SN		… + M_B		… + BAO	
	ΛCDM	ΛeDM	ΛCDM	ΛeDM	ΛCDM	ΛeDM	ΛCDM	ΛeDM
$\ln(10^{10}A_s)$	$3.045^{+0.029}_{-0.028}$	$3.045^{+0.030}_{-0.028}$	3.045 ± 0.028	$3.046^{+0.029}_{-0.028}$	$3.048^{+0.030}_{-0.028}$	$3.050^{+0.031}_{-0.028}$	$3.048^{+0.029}_{-0.027}$	$3.051^{+0.030}_{-0.028}$
n_s	$0.9659^{+0.0080}_{-0.0079}$	0.9660 ± 0.0082	$0.9658^{+0.0078}_{-0.0079}$	$0.9665^{+0.0082}_{-0.0080}$	$0.9672^{+0.0082}_{-0.0081}$	$0.9688^{+0.0080}_{-0.0081}$	0.9675 ± 0.0075	$0.9692^{+0.0071}_{-0.0074}$
$100\theta_*$	1.04196 ± 0.00056	$1.04196^{+0.00057}_{-0.00060}$	1.04196 ± 0.00055	1.04198 ± 0.00056	$1.04203^{+0.00058}_{-0.00057}$	$1.04210^{+0.00057}_{-0.00058}$	$1.04204^{+0.00057}_{-0.00056}$	$1.04212^{+0.00055}_{-0.00056}$
τ	$0.055^{+0.015}_{-0.014}$	$0.055^{+0.016}_{-0.014}$	$0.055^{+0.015}_{-0.014}$	$0.055^{+0.015}_{-0.014}$	$0.056^{+0.016}_{-0.014}$	$0.058^{+0.016}_{-0.015}$	$0.057^{+0.015}_{-0.014}$	$0.059^{+0.015}_{-0.014}$
$\Omega_b h^2$	0.02239 ± 0.00029	0.02240 ± 0.00029	0.02239 ± 0.00028	$0.02241^{+0.00029}_{-0.00028}$	$0.02245^{+0.00029}_{-0.00028}$	0.02250 ± 0.00028	$0.02245^{+0.00028}_{-0.00027}$	$0.02251^{+0.00027}_{-0.00026}$
$\Omega_{dm}^{init} h^2$	$0.1199^{+0.0023}_{-0.0024}$	$0.1198^{+0.0024}_{-0.0025}$	0.1199 ± 0.0023	$0.1196^{+0.0022}_{-0.0023}$	$0.1194^{+0.0023}_{-0.0024}$	$0.1187^{+0.0023}_{-0.0022}$	0.1193 ± 0.0020	$0.1185^{+0.0018}_{-0.0017}$
$w_{dm,0}$	n/a	—	n/a	> -0.439	n/a	$-0.31^{+0.30}_{-0.25}$	n/a	> -0.462
M_B	n/a	n/a	n/a	n/a	-19.411 ± 0.028	$-19.386^{+0.039}_{-0.038}$	$-19.409^{+0.023}_{-0.022}$	$-19.393^{+0.030}_{-0.028}$
Derived								
H_0	67.4 ± 1.1	$69.7^{+4.3}_{-3.0}$	$67.5^{+1.0}_{-0.99}$	$68.3^{+1.6}_{-1.5}$	67.9 ± 1.0	$69.2^{+1.8}_{-1.7}$	$67.99^{+0.81}_{-0.80}$	$68.8^{+1.3}_{-1.2}$
σ_8	0.811 ± 0.012	$0.59^{+0.21}_{-0.22}$	0.810 ± 0.012	$0.69^{+0.12}_{-0.13}$	0.809 ± 0.012	$0.64^{+0.15}_{-0.14}$	0.809 ± 0.012	0.67 ± 0.13
S_8	$0.829^{+0.025}_{-0.026}$	$0.59^{+0.23}_{-0.25}$	0.827 ± 0.024	$0.70^{+0.13}_{-0.14}$	0.818 ± 0.024	$0.63^{+0.16}_{-0.15}$	0.816 ± 0.020	$0.67^{+0.14}_{-0.13}$
Tensions								
H_0	5.04σ	1.73σ	5.02σ	3.86σ	n/a	n/a	n/a	n/a
S_8	2.94σ	1.13σ	2.93σ	0.83σ	2.5σ	1.53σ	2.54σ	1.21σ
	(1.89σ)	(1.28σ)	(1.85σ)	(1.12σ)	(1.4σ)	(1.8σ)	(1.38σ)	(1.52σ)
Model Selection								
χ^2	1012.02	1012.24	2047.35	2046.87	2057.42	2054.85	2063.32	2062
$\Delta\chi^2$	0	0.22	0	−0.48	0	−2.57	0	−1.32
AIC	1013.15	1015.34	2048.35	2049.95	2061.88	2062.18	2067.69	2068.42
ΔAIC	0	2.19	0	1.6	0	0.31	0	0.72

Naidoo, MJ,+ ArXiv:2209.08102

Degeneracies: Fixing the transition time



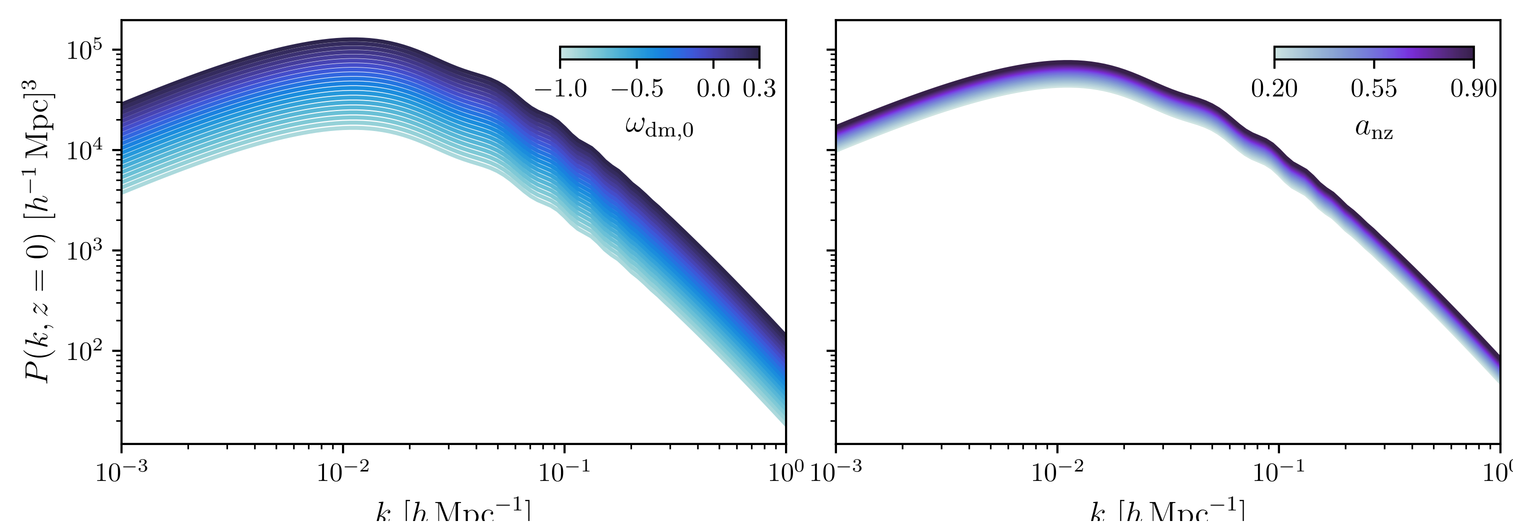


eDM EoS – zero at early times and then linearly increases/ decreases

(a_{NZ} = 0.5 → z = 1)

Redshift - Scale factor

$$\frac{a}{a_0} = \frac{1}{1+z}$$



[Naidoo, **MJ**,+ PRD (2024), arXiv:2209.08102]

Speed of propagation of perturbations

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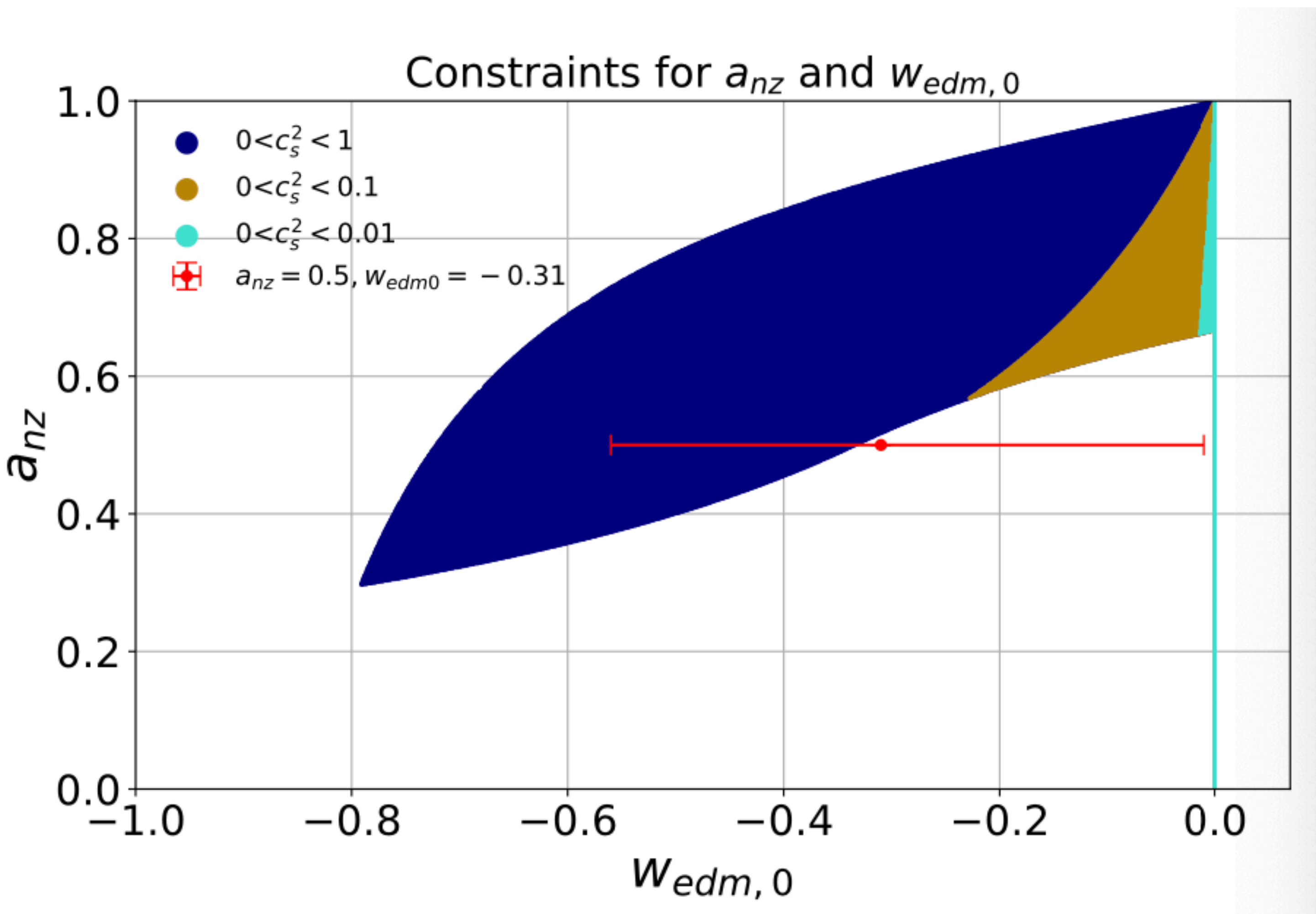
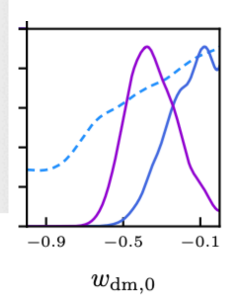
Can we relax this assumption?

For a strictly adiabatic case:

$$c_s^2 = \left(\frac{\partial P}{\partial \rho}\right)_s \quad \text{which gives us:} \quad c_s^2 = w_{eDM,0}\frac{a - a_{nz}}{1 - a_{nz}} - \frac{1}{3}\frac{a w_{eDM,0}}{1 - a_{nz} + (a - a_{nz})w_{eDM,0}}$$



Imposing positive and non-superluminous values for c_s^2 we can further constraint the values of the free parameters



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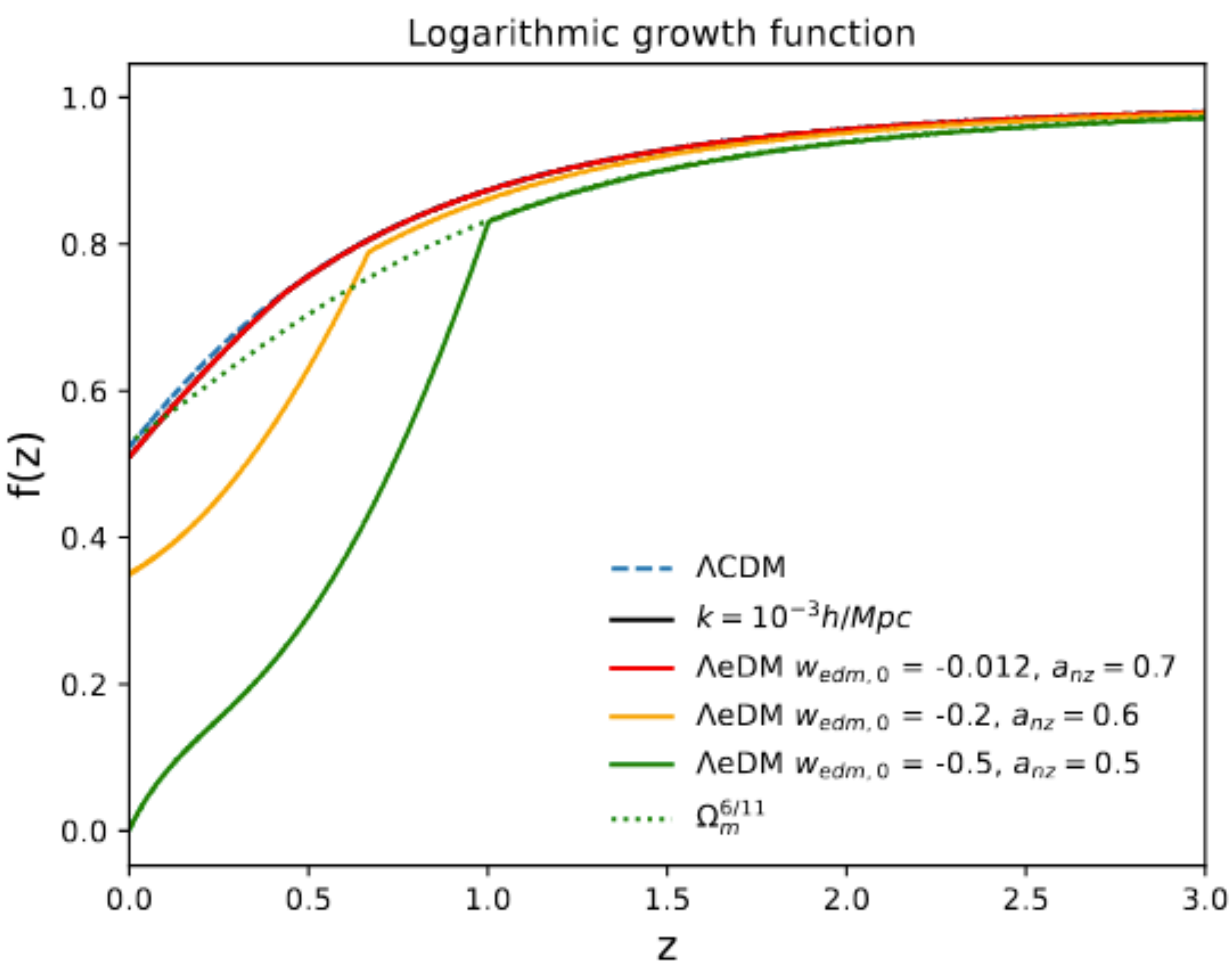


Tensions and Anomalies in ΛCDM

2. The σ_8 tension

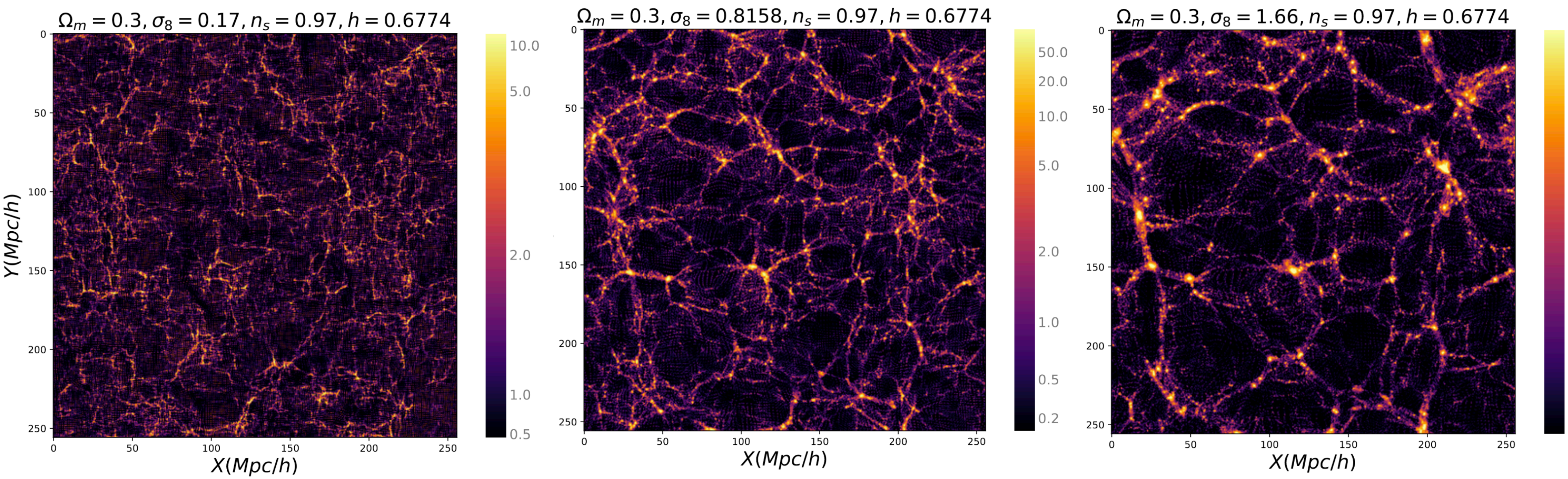
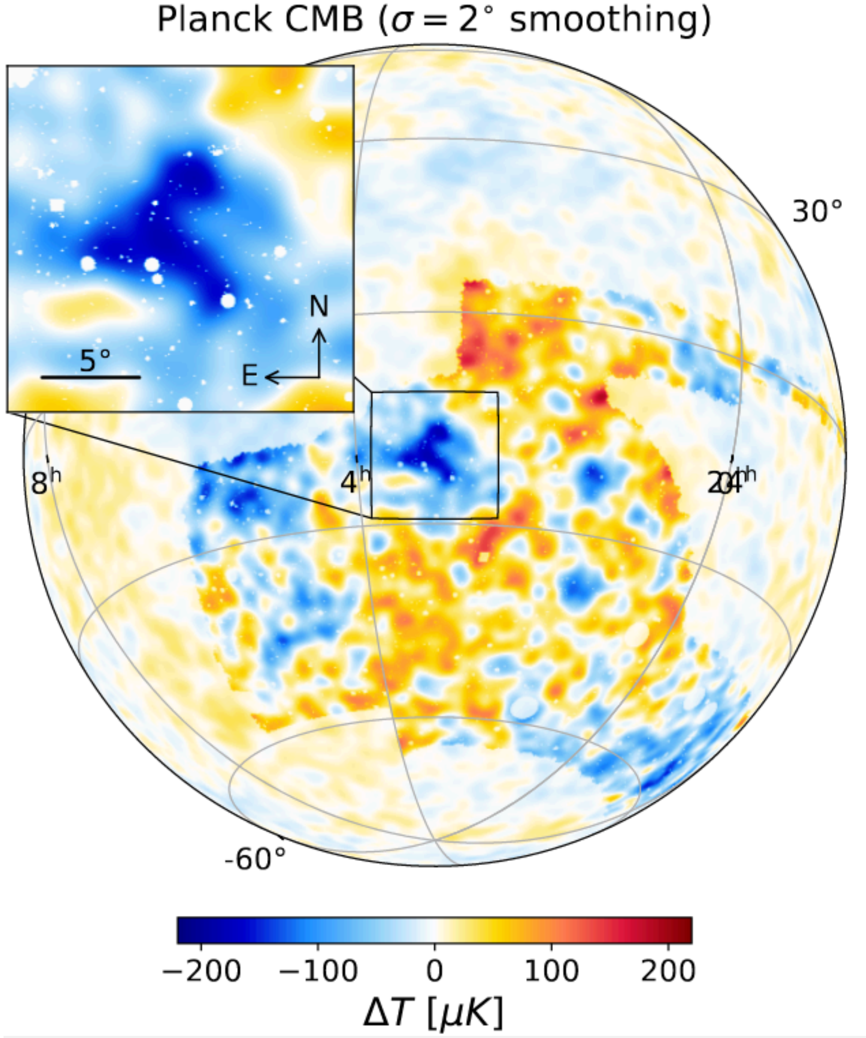


Fig. adapted from arXiv:2402.15712

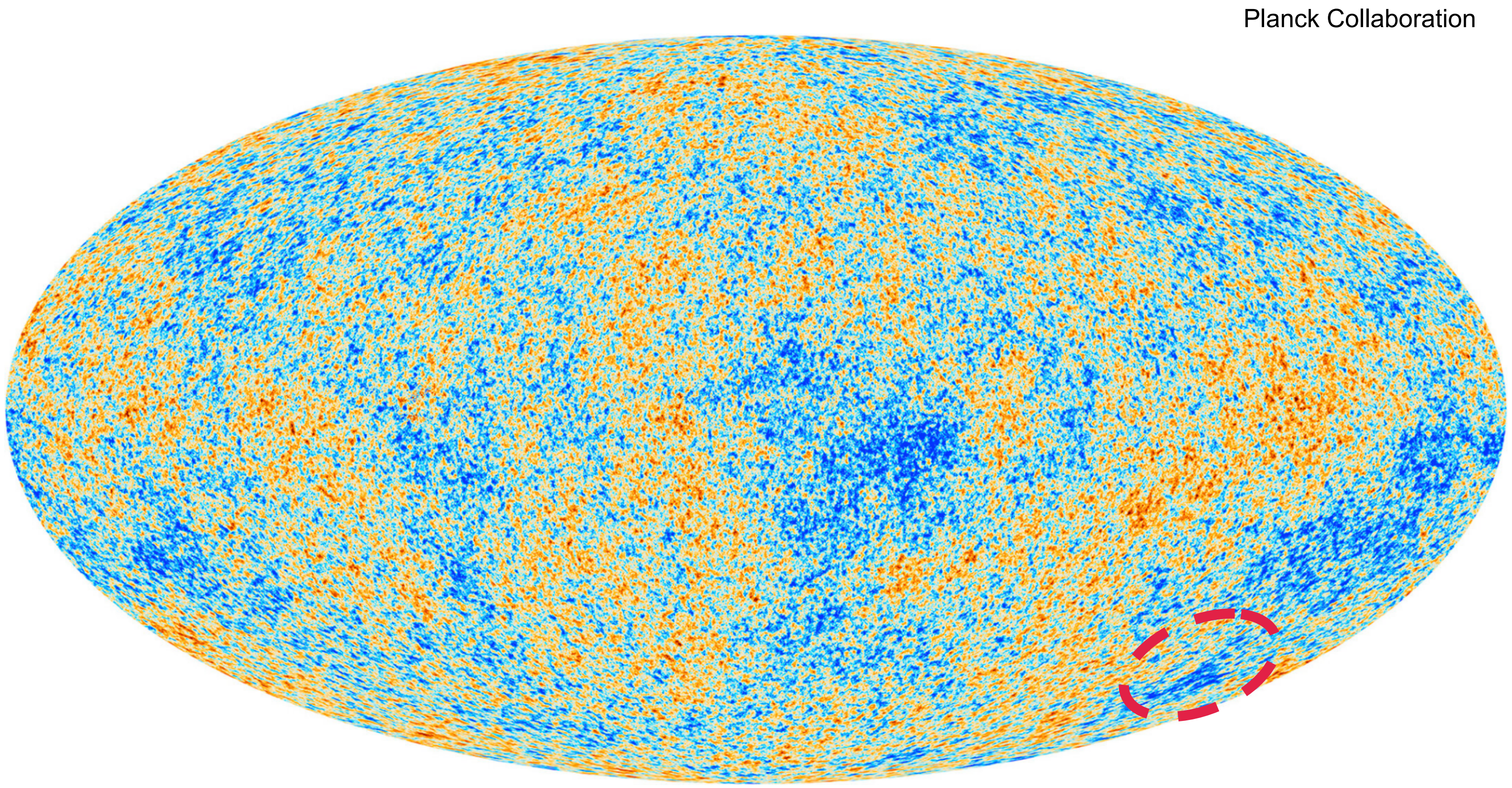
- $\sigma_R^2 = \int_0^\infty \frac{dk}{k} W_R^2(k)\Delta^2(k)$, the RMS of matter density fluctuations on spheres of radius 8Mpc/h.
- $S_8 = \sigma_8\sqrt{\Omega_m/0.3}$, combines information about the amplitude of matter fluctuations (σ_8) with the total matter content of the universe (Ω_m). This makes it a sensitive probe of cosmic structure formation and growth.

Tensions and Anomalies in ΛCDM

3. The ISW-void lensing anomaly



Kovács et al. (2022) [ArXiv: 2112.07699]



The cold spot

- A region of unusually low temperature that has been linked to the **Eridanus supervoid**.

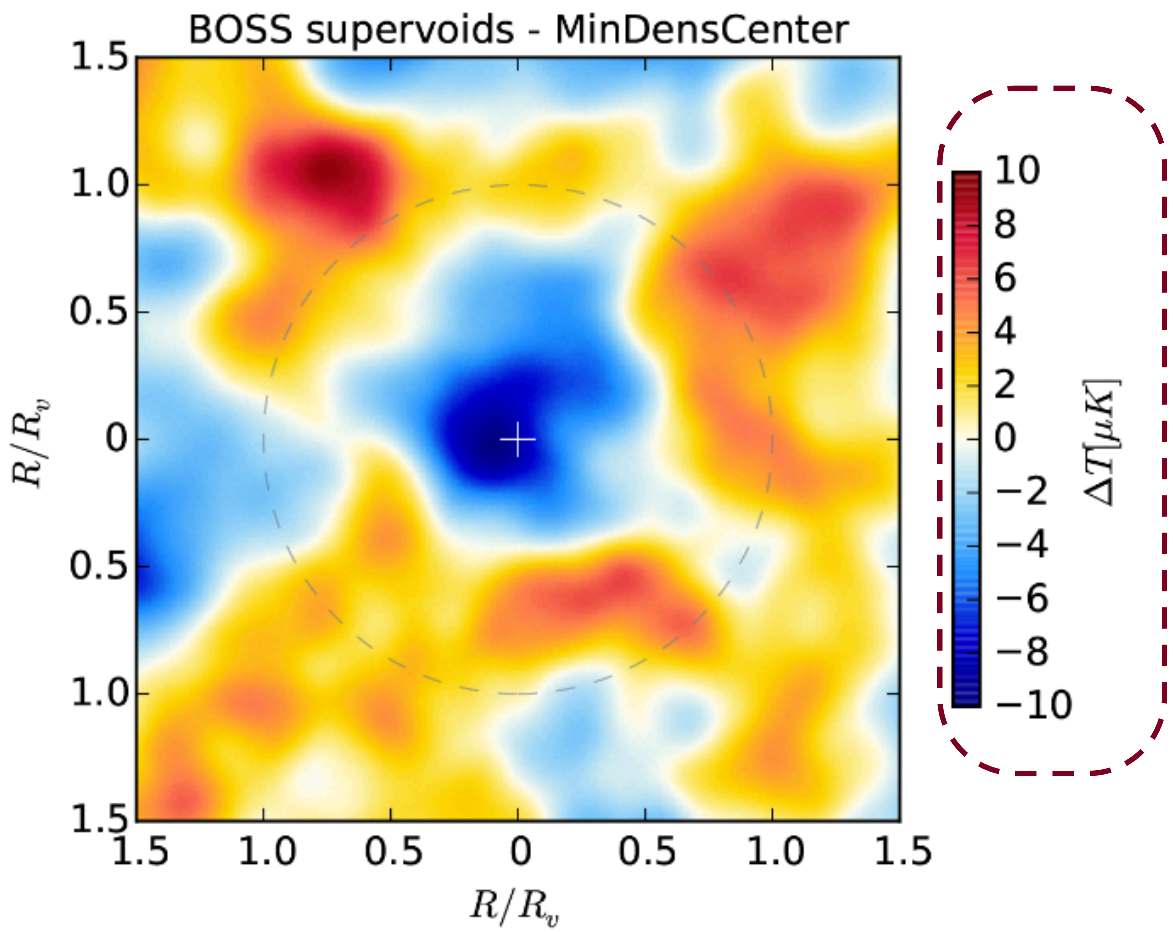
- Discovered on WMAP (Cruz et al. 2005) ~ 4.5σ when compared to the rest of the map.

- The existence of this supervoid suggests that it could be responsible for this cooling effect observed in CMB data.

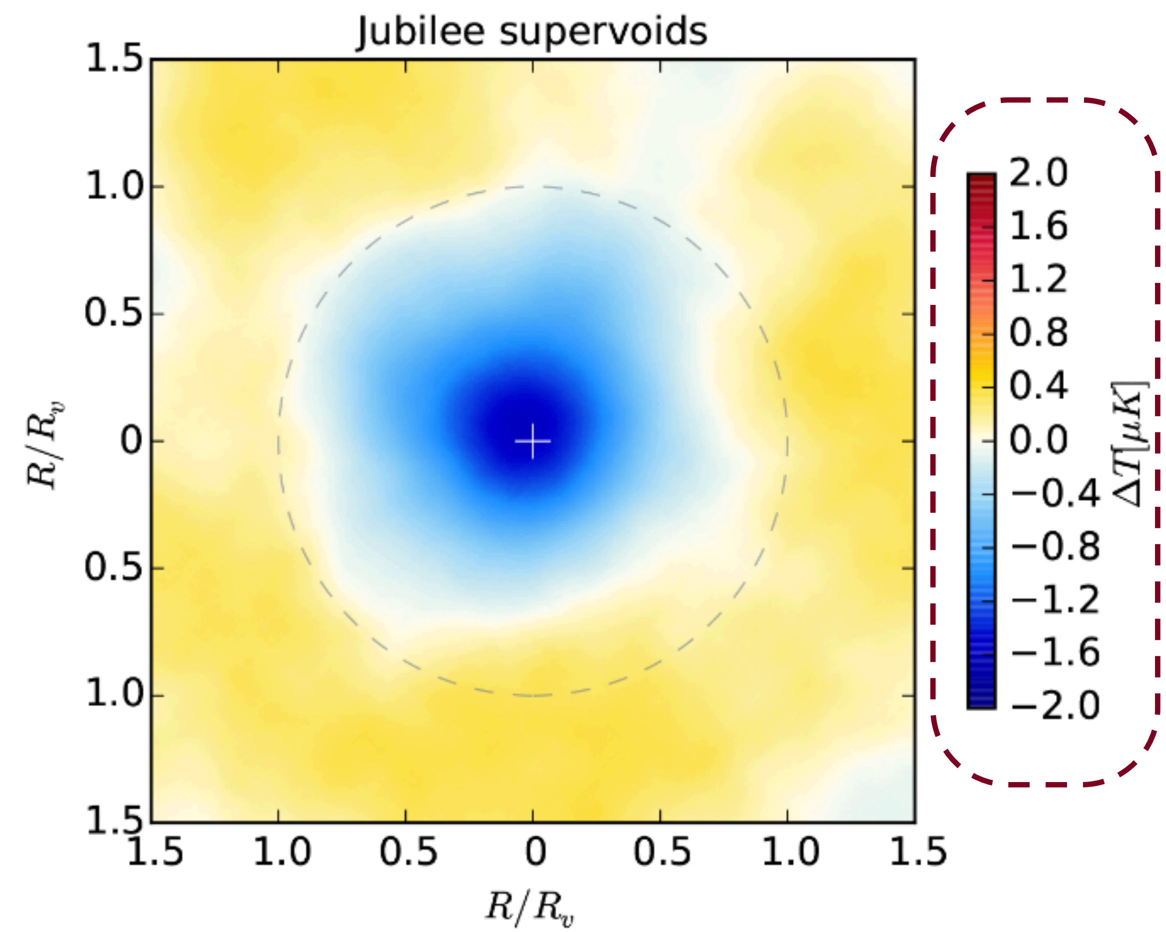
Tensions and Anomalies in ΛCDM

3. The ISW void lensing **anomaly**

Measurement



Theory



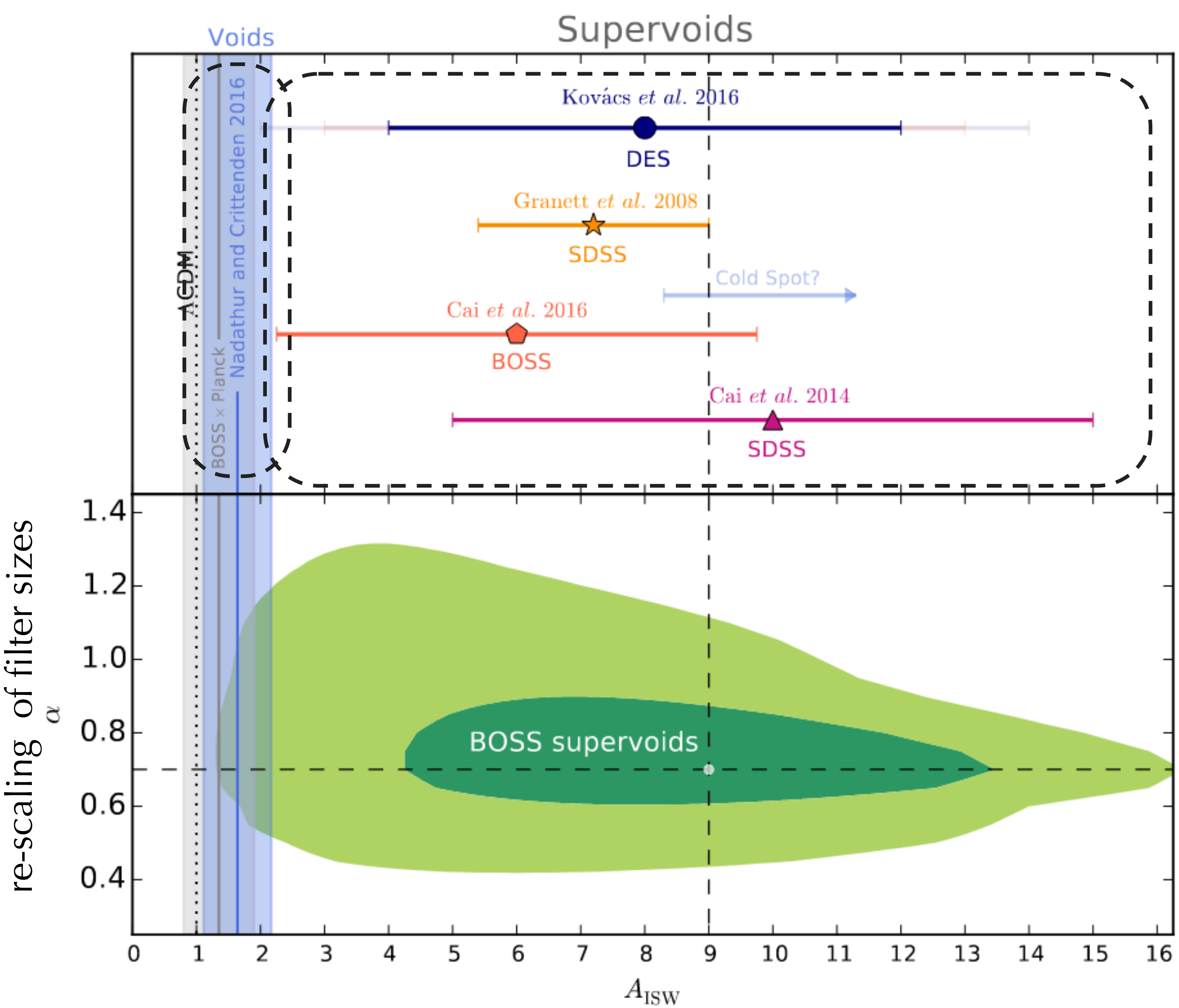
Identifying voids and then stacking CMB temperatures.

As a result: a higher signal than expected.

Kovacs (2018) [ArXiv: 1701.08583]

Tensions and Anomalies in ΛCDM

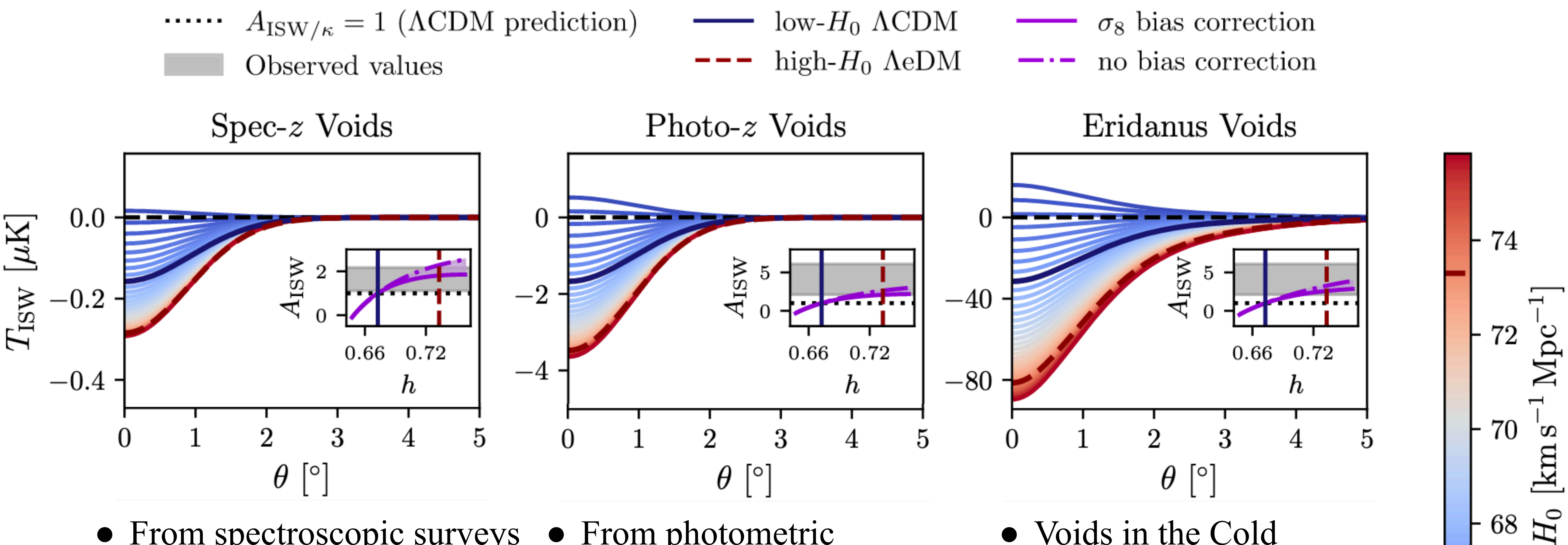
3. The ISW void lensing **anomaly**



Amplitude of ISW: $A_{ISW} = \Delta T / \Delta T_{LCDM}$

- Observations have indicated that the amplitude parameter, A_{ISW}, which quantifies the ISW signal strength, is significantly higher than predictions from standard cosmological models
- Voids identified in spectroscopic (small and spherical) vs photometric surveys (large and elongated along the LOS)

ΛeDM explains Tensions



- From spectroscopic surveys
- Spherical and smaller
- ISW excess is smaller and consistent with ΛCDM

- From photometric surveys
- Elongated along LOS and larger
- ISW excess is significantly larger than ΛCDM

- Voids in the Cold Spot direction

Amplitude of ISW: $A_{ISW} = \Delta T / \Delta T_{LCDM}$

Naidoo, MJ,+ ArXiv:2209.08102, PRD 109, 083511 (2024)