



Universiteit
Leiden



Shape of CMB lensing in EDE

arXiv:2305.18873,

Gen Ye, Jun-Qian Jiang, Yun-Song Piao

Cosmological Tensions

Hubble tension

SHOES

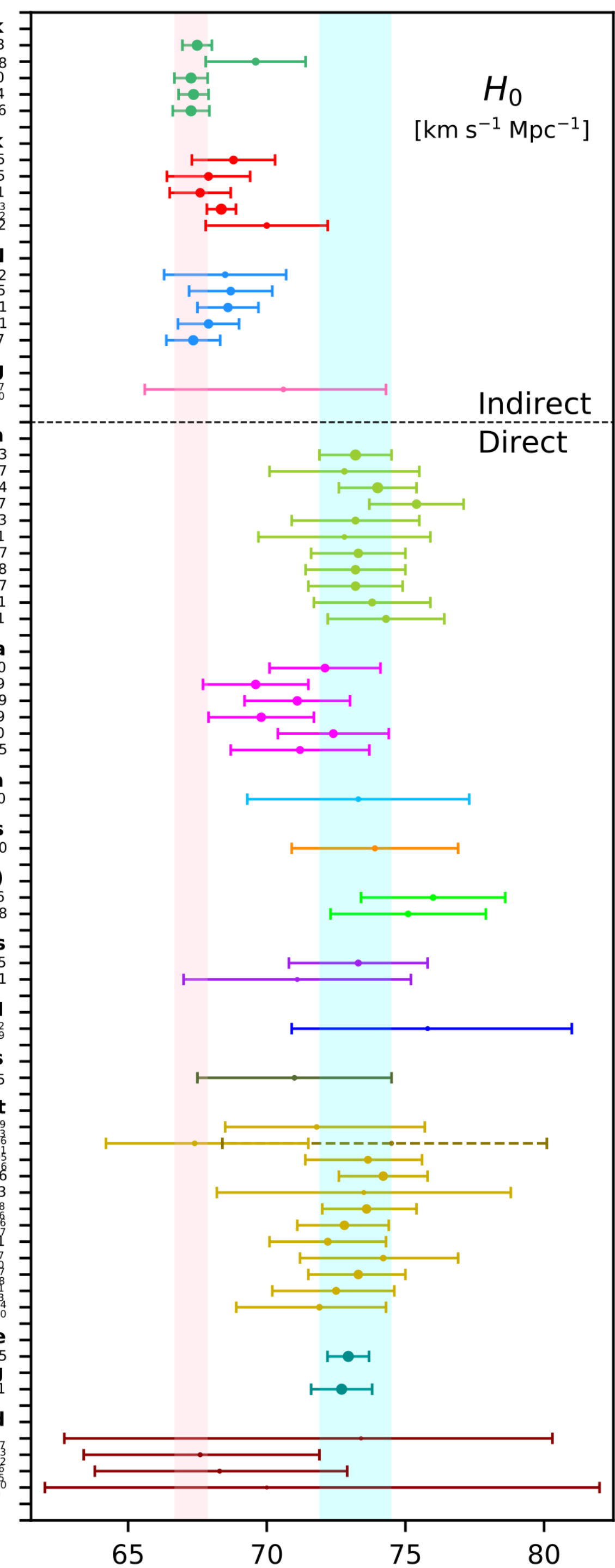
$$H_0 = 73.04 \pm 1.04 \text{ km/s/Mpc}$$

V.S.

CMB

$$H_0 = 67.49 \pm 0.52 \text{ km/s/Mpc}$$

- CMB with Planck**
 Balckenhol et al. (2021), Planck 2018+SPT+ACT : 67.49 ± 0.53
 Pogosian et al. (2020), eBOSS+Planck $\Omega_m H^2$: 69.6 ± 1.8
 Aghanim et al. (2020), Planck 2018: 67.27 ± 0.60
 Aghanim et al. (2020), Planck 2018+CMB lensing: 67.36 ± 0.54
 Ade et al. (2016), Planck 2015, $H_0 = 67.27 \pm 0.66$
- CMB without Planck**
 Dutcher et al. (2021), SPT: 68.8 ± 1.5
 Aiola et al. (2020), ACT: 67.9 ± 1.5
 Aiola et al. (2020), WMAP9+ACT: 67.6 ± 1.1
 Zhang, Huang (2019), WMAP9+BAO: $68.36^{+0.53}_{-0.52}$
 Hinshaw et al. (2013), WMAP9: 70.0 ± 2.2
- No CMB, with BBN**
 D'Amico et al. (2020), BOSS DR12+BBN: 68.5 ± 2.2
 Colas et al. (2020), BOSS DR12+BBN: 68.7 ± 1.5
 Philcox et al. (2020), P_r +BAO+BBN: 68.6 ± 1.1
 Ivanov et al. (2020), BOSS+BBN: 67.9 ± 1.1
 Alam et al. (2020), BOSS+eBOSS+BBN: 67.35 ± 0.97
- $P_l(k)$ + CMB lensing**
 Philcox et al. (2020), $P_l(k)$ +CMB lensing: $70.6^{+3.7}_{-3.0}$
- Cepheids – SNIa**
 Riess et al. (2020), R20: 73.2 ± 1.3
 Breuval et al. (2020): 72.8 ± 2.7
 Riess et al. (2019), R19: 74.0 ± 1.4
 Camarena, Marra (2019): 75.4 ± 1.7
 Burns et al. (2018): 73.2 ± 2.3
 Dhawan, Jha, Leibundgut (2017), NIR: 72.8 ± 3.1
 Follin, Knox (2017): 73.3 ± 1.7
 Feeney, Mortlock, Dalmasso (2017): 73.2 ± 1.8
 Riess et al. (2016), R16: 73.2 ± 1.7
 Cardona, Kunz, Pettorino (2016), HPs: 73.8 ± 2.1
 Freedman et al. (2012): 74.3 ± 2.1
- TRGB – SNIa**
 Soltis, Casertano, Riess (2020): 72.1 ± 2.0
 Freedman et al. (2020): 69.6 ± 1.9
 Reid, Pesce, Riess (2019), SHOES: 71.1 ± 1.9
 Freedman et al. (2019): 69.8 ± 1.9
 Yuan et al. (2019): 72.4 ± 2.0
 Jang, Lee (2017): 71.2 ± 2.5
- Miras – SNIa**
 Huang et al. (2019): 73.3 ± 4.0
- Masers**
 Pesce et al. (2020): 73.9 ± 3.0
- Tully – Fisher Relation (TFR)**
 Kourkchi et al. (2020): 76.0 ± 2.6
 Schombert, McGaugh, Lelli (2020): 75.1 ± 2.8
- Surface Brightness Fluctuations**
 Blakeslee et al. (2021) IR-SBF w/ HST: 73.3 ± 2.5
 Khetan et al. (2020) w/ LMC DEB: 71.1 ± 4.1
- SNIi**
 de Jaeger et al. (2020): $75.8^{+4.3}_{-3.3}$
- HII galaxies**
 Fernández Arenas et al. (2018): 71.0 ± 3.5
- Lensing related, mass model – dependent**
 Denzel et al. (2021): $71.8^{+3.9}_{-3.9}$
 Birrer et al. (2020), TDCOSMO+SLACS: $67.4^{+4.1}_{-3.2}$, TDCOSMO: $74.5^{+3.6}_{-3.6}$
 Yang, Birrer, Hu (2020): $H_0 = 73.65^{+3.26}_{-3.26}$
 Millon et al. (2020), TDCOSMO: 74.2 ± 1.6
 Baxter et al. (2020): 73.5 ± 5.3
 Qi et al. (2020): $73.6^{+1.8}_{-1.6}$
 Liao et al. (2020): $72.8^{+1.7}_{-1.7}$
 Liao et al. (2019): 72.2 ± 2.1
 Shajib et al. (2019), STRIDES: $74.2^{+2.7}_{-1.9}$
 Wong et al. (2019), H0LiCOW 2019: $73.3^{+1.9}_{-1.6}$
 Birrer et al. (2018), H0LiCOW 2018: $72.5^{+2.3}_{-2.3}$
 Bonvin et al. (2016), H0LiCOW 2016: $71.9^{+3.4}_{-3.0}$
- Optimistic average**
 Di Valentino (2021): 72.94 ± 0.75
- Ultra – conservative, no Cepheids, no lensing**
 Di Valentino (2021): 72.7 ± 1.1
- GW related**
 Gayathri et al. (2020), GW190521+GW170817: $73.4^{+6.9}_{-10.7}$
 Mukherjee et al. (2020), GW170817+ZTF: $67.6^{+4.3}_{-4.3}$
 Mukherjee et al. (2019), GW170817+VLBI: $68.3^{+4.6}_{-4.6}$
 Abbott et al. (2017), GW170817: $70.0^{+12.0}_{-8.0}$



Early Dark Energy (EDE)

$$\theta_s = \frac{r_s}{D_A} \sim \frac{1}{\Delta l}$$

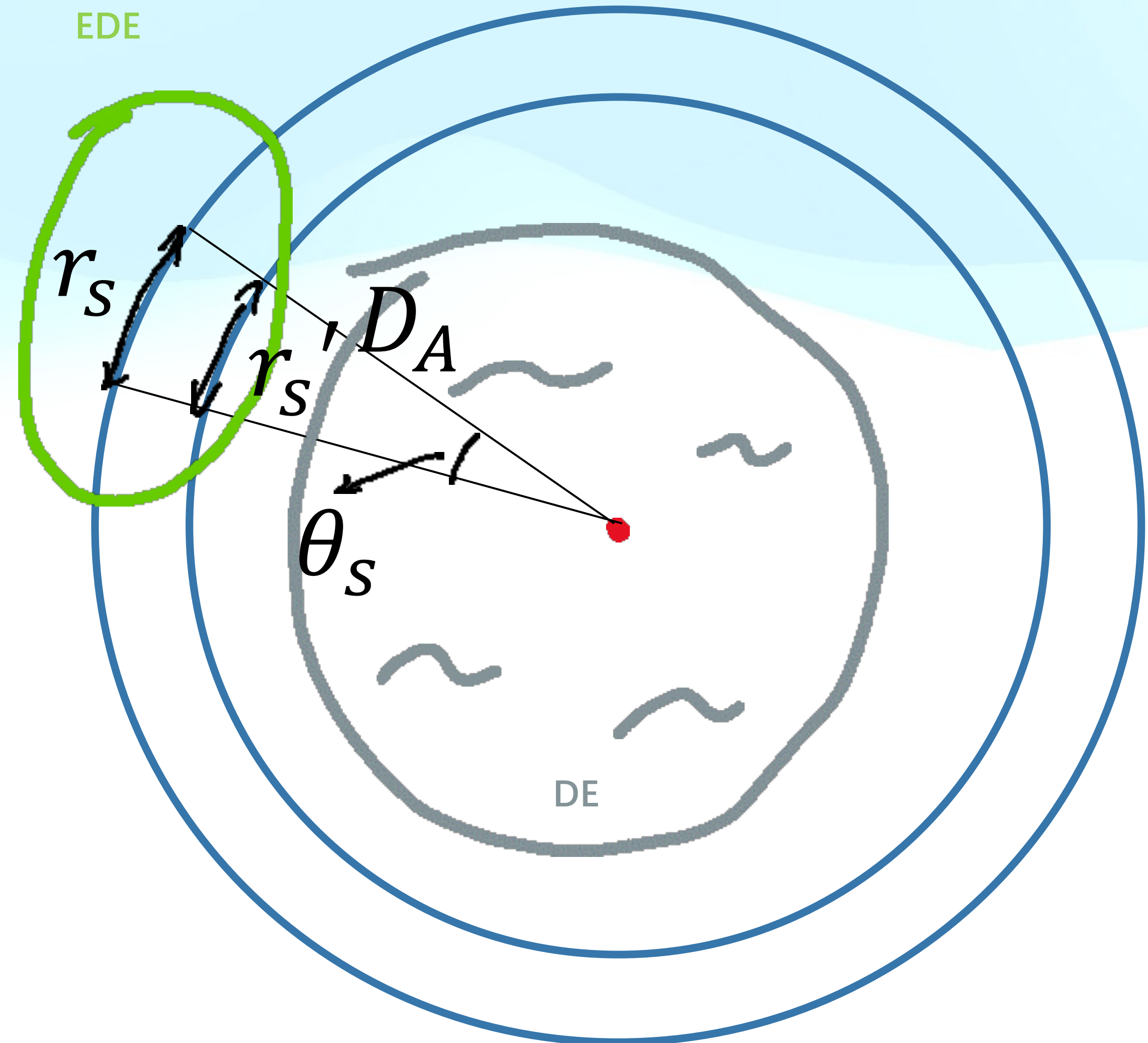
Tanvi Karwal, Marc Kamionkowski, PhysRevD.94.103523
Vivian Poulin, Tristan L. Smith, Tanvi Karwal, Marc Kamionkowski, PhysRevLett.122.221301

$$r_s = \int_{z_*}^{\infty} \frac{c_s}{H(z)} dz$$

Early Dark Energy

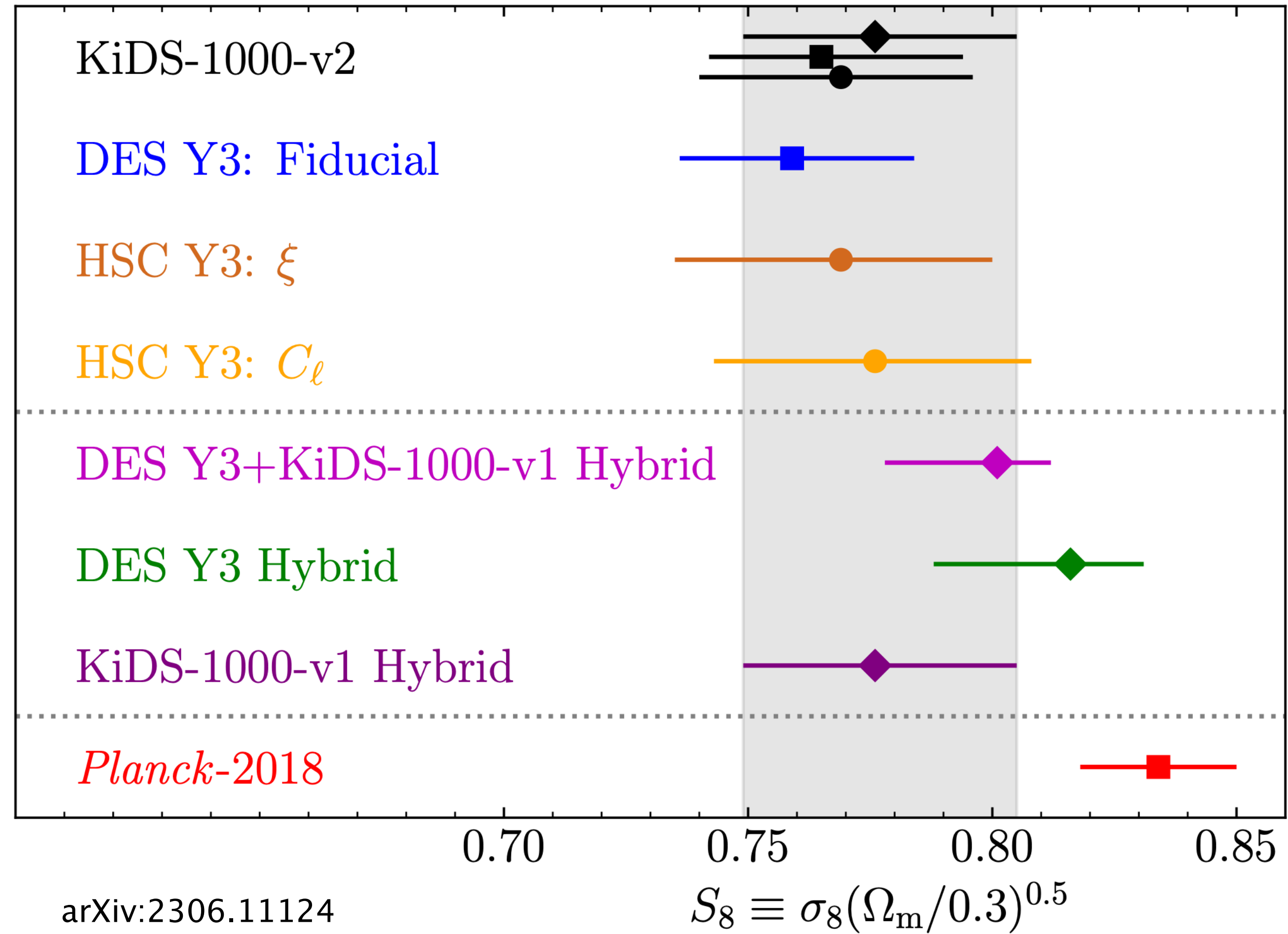
$$D_A = H_0^{-1} \int_0^{z_*} \frac{dz}{E(z)}$$

Dark Energy

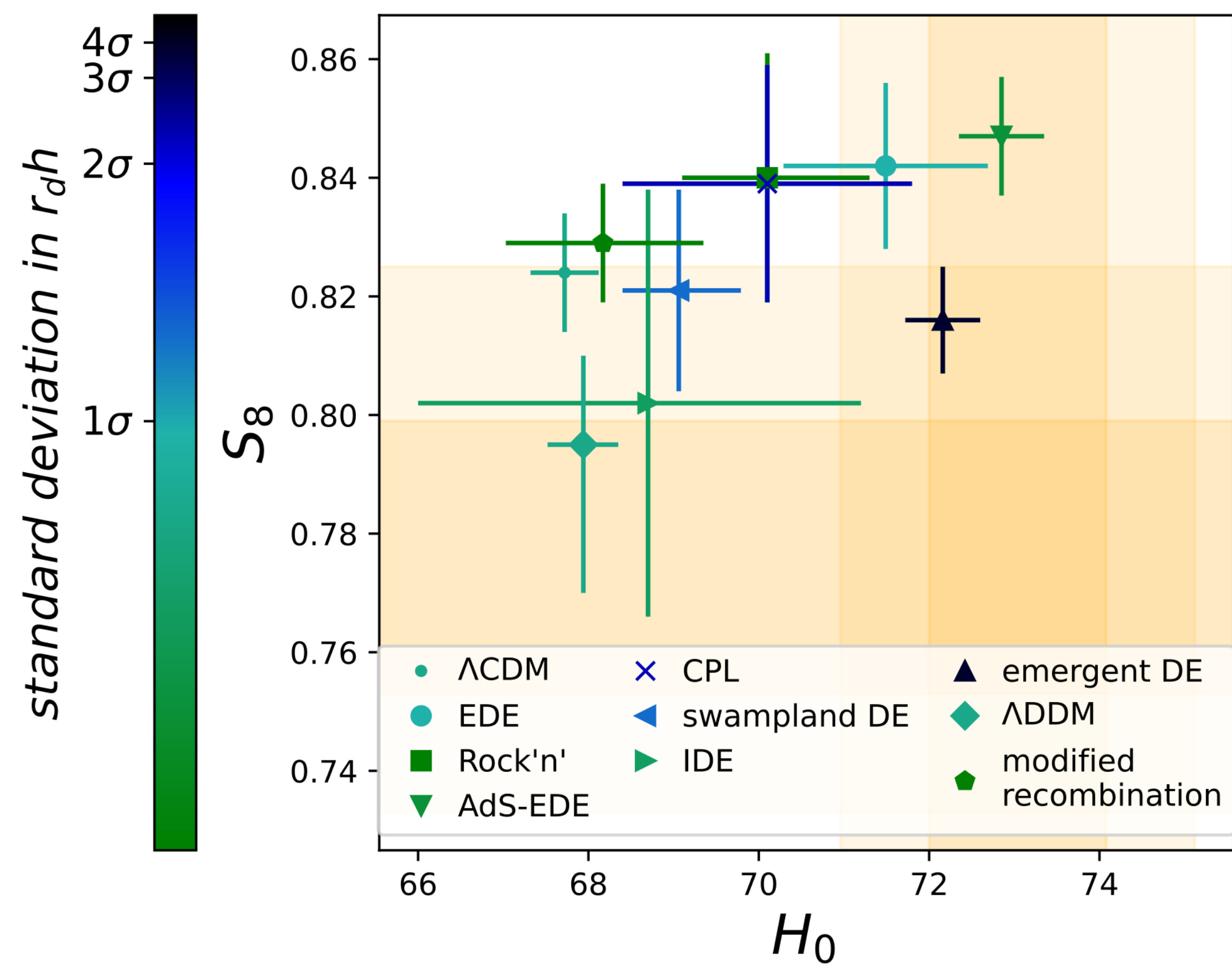
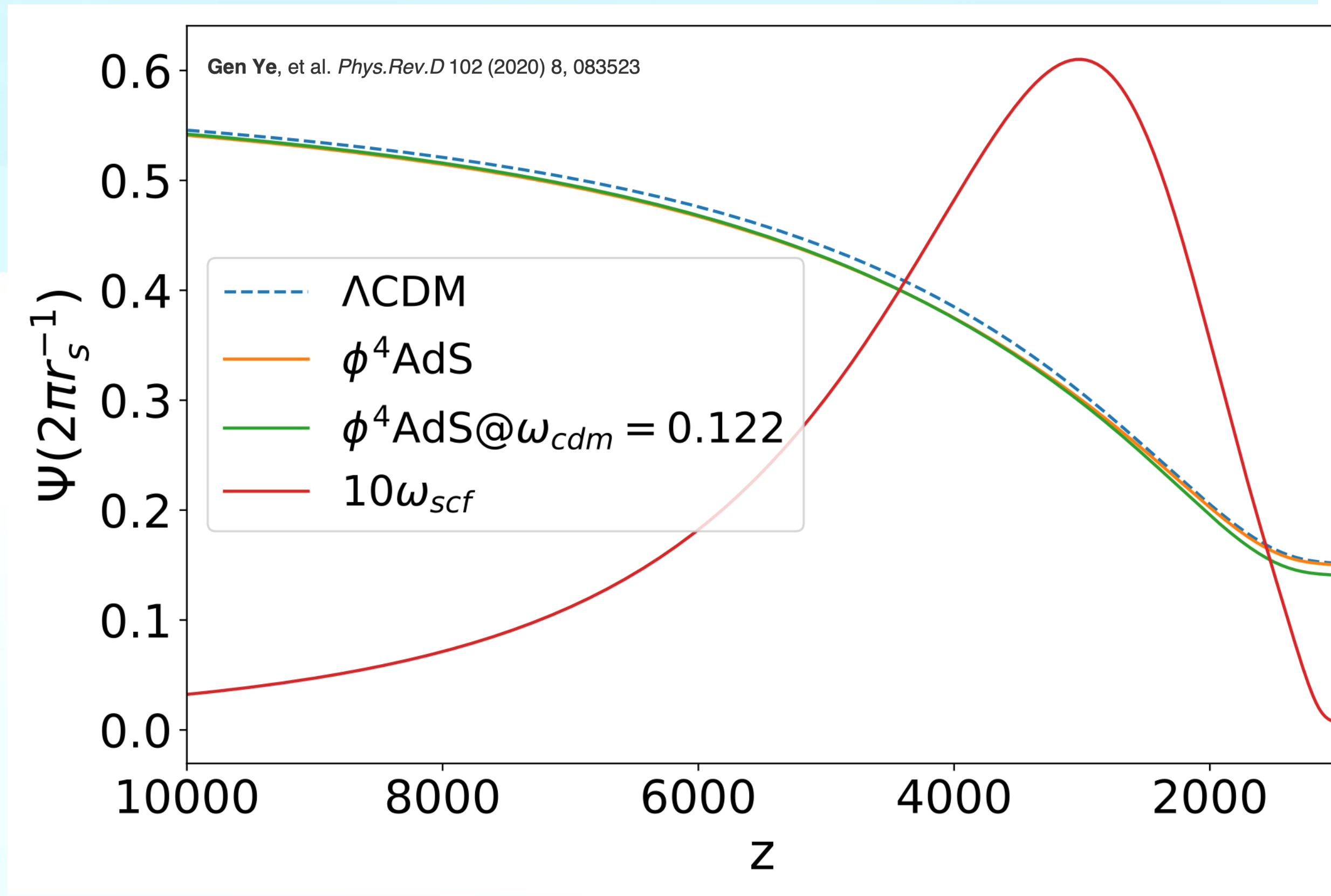


Tensions in the model?

S_8 tension



EDE and S_8



S_8 tension exacerbated by EDE

Phys. Rev. D 102, 043507 (2020)
 Phys. Rev. D 102, 103502 (2020)
 JCAP 05, 072 (2021)

ω_{cdm} is increased to compensate for EDE's effect on radiation driving and ISW

Gen Ye, et al. *Phys.Rev.D* 102 (2020) 8, 083523

Astrophys. J. Lett. 904, L17 (2020)

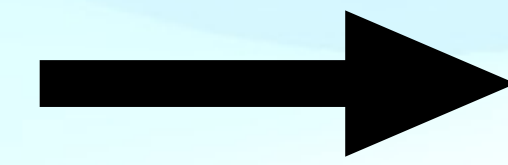
Phys. Rev. D 104, 063524 (2021)

EDE?

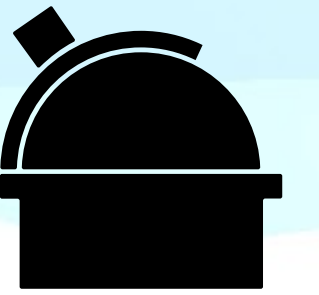
Λ CDM



Recombination



Λ CDM



Decaying DM?

ULA DM?

DE/MG?

Interacting DM?

...

Phys. Rev. D 104, L081303 (2021)

Phys. Lett. B 839, 137770 (2023)

Phys. Rev. D 107, 083527 (2023)

Mon. Not. Roy. Astron. Soc. 520, 3688 (2023)

Phys. Rev. D 104, 12533 (2021)

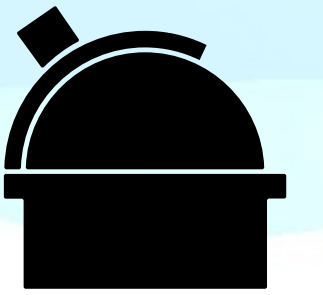
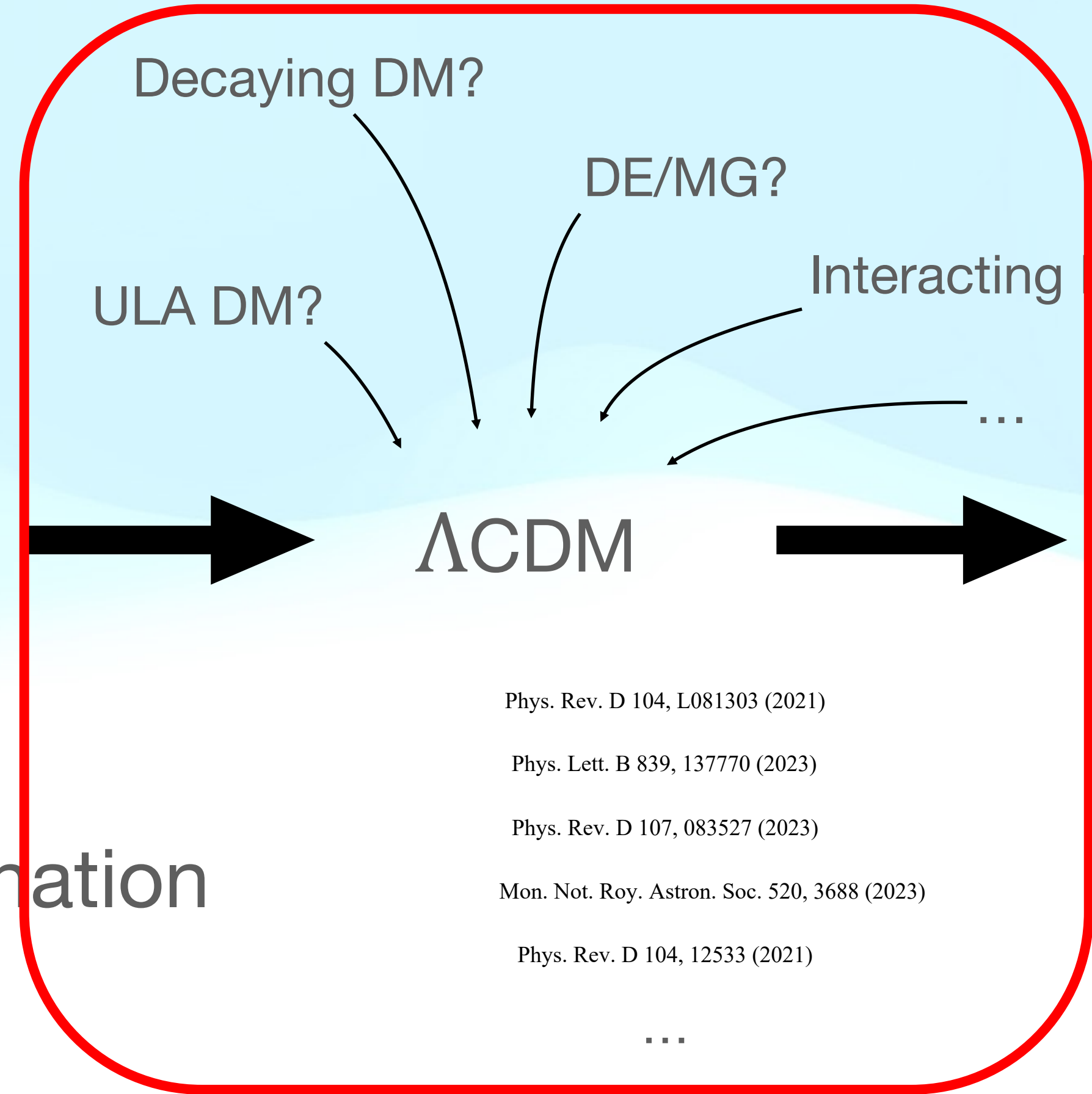
...

EDE?

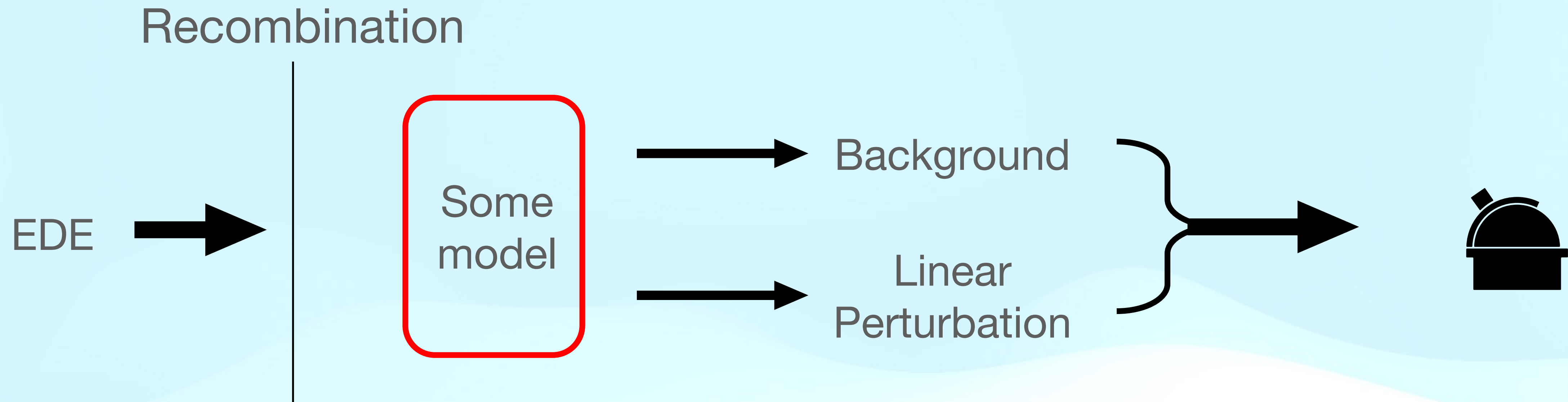
Λ CDM



Recombination



Marginalization



Background?

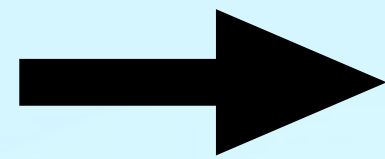
- $D_A(z) = H_0^{-1} \int_0^z \frac{dz'}{E(z')}$
 - Cosmological parameters: H_0, Ω_m
 - Dark energy EoS $w(z)$
- Phys. Lett. B 832, 137244 (2022)
 arXiv:2302.07333 } $w \equiv -1$

Perturbation?

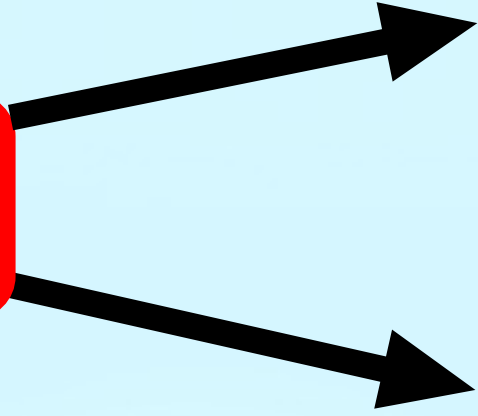
- Reionization
 - High ℓ optical depth $A_s e^{-2\tau}$
 - Low ℓ E polarization
- Integrated Sachs-Wolfe
 Phys. Rev. D, 107 103505
- Gravitational Lensing $P(k)$
This work arXiv:2305.18873

Recombination

EDE



Marginalization

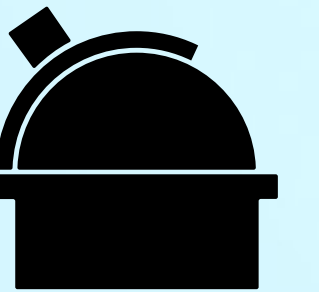
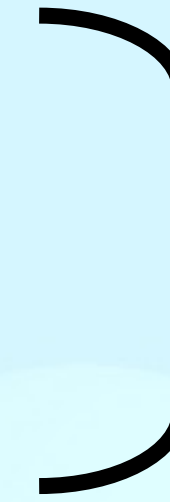


$$w_{DE} = -1$$

$$\tau$$

$$A_{ISW} = 1$$

$$C_L^{\phi\phi}$$

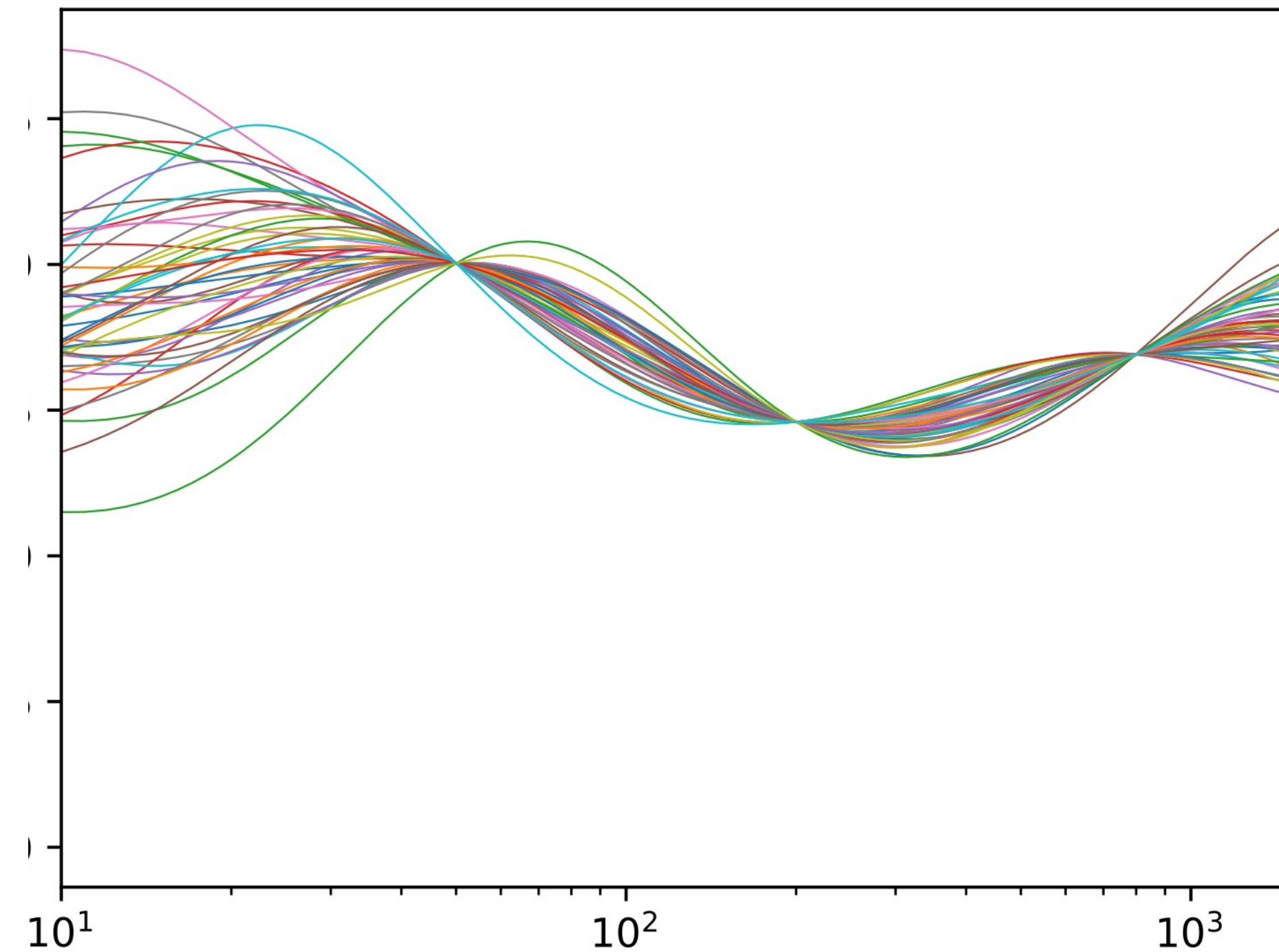


Gaussian Process (GP)

$$C_L^{\phi\phi} = A(L)C_{L, fid}^{\phi\phi}$$

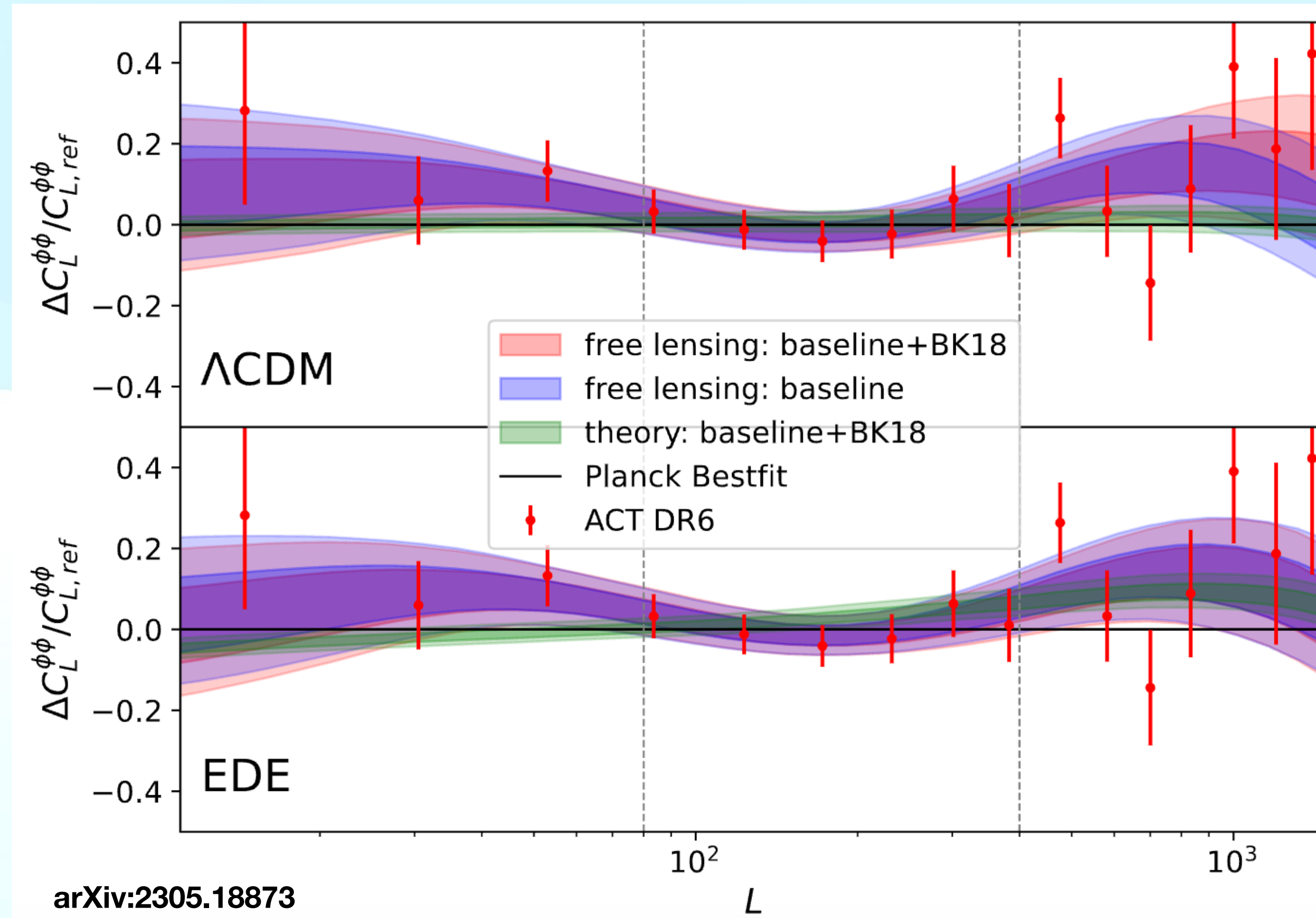
$$A(L) \sim GP[\bar{f}(L), K]$$

3 Nodes: $\{A_{L=50}, A_{L=200}, A_{L=800}\}$



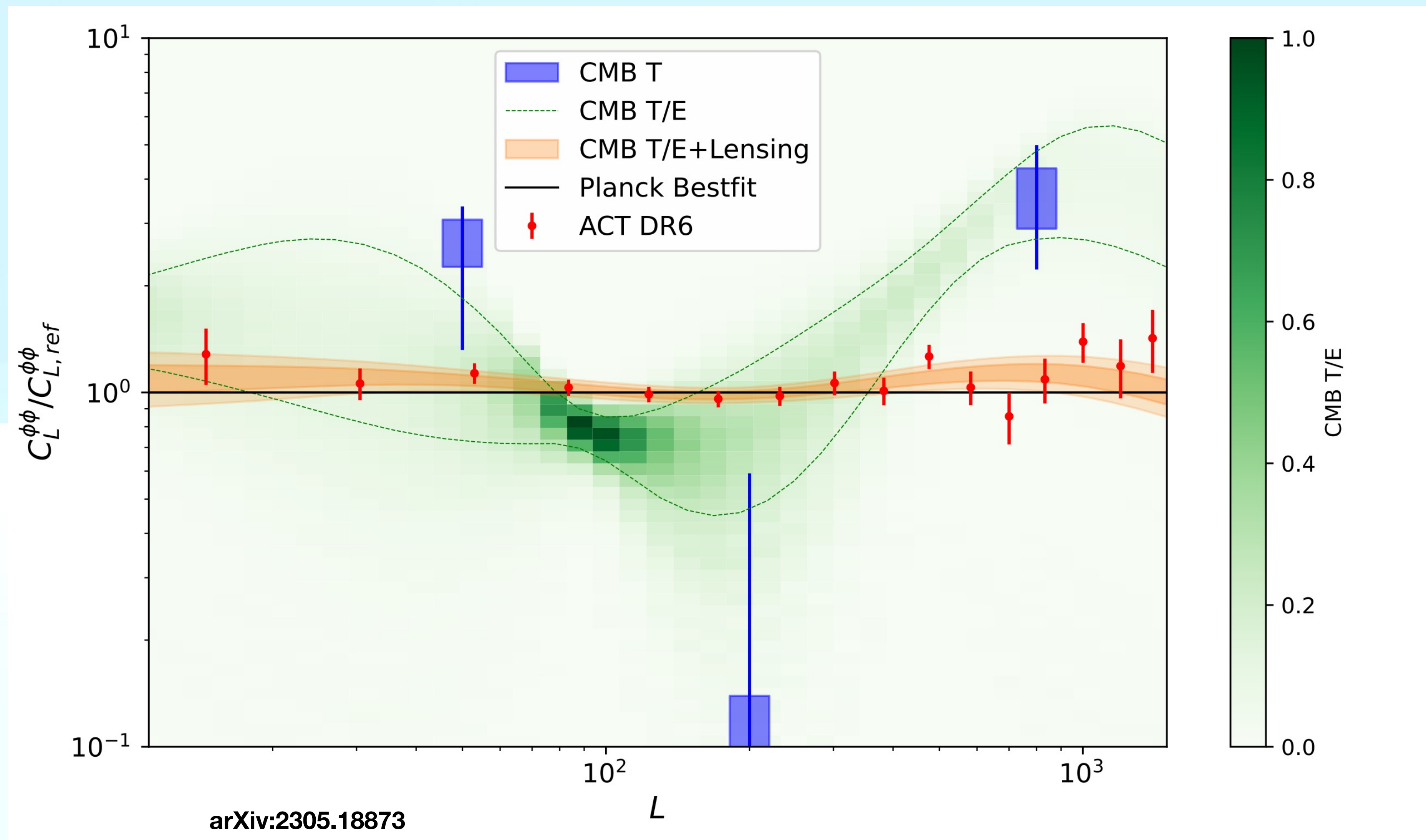
Results

CMB TTTEE + Lensing reconstruction (+ CMB B mode)

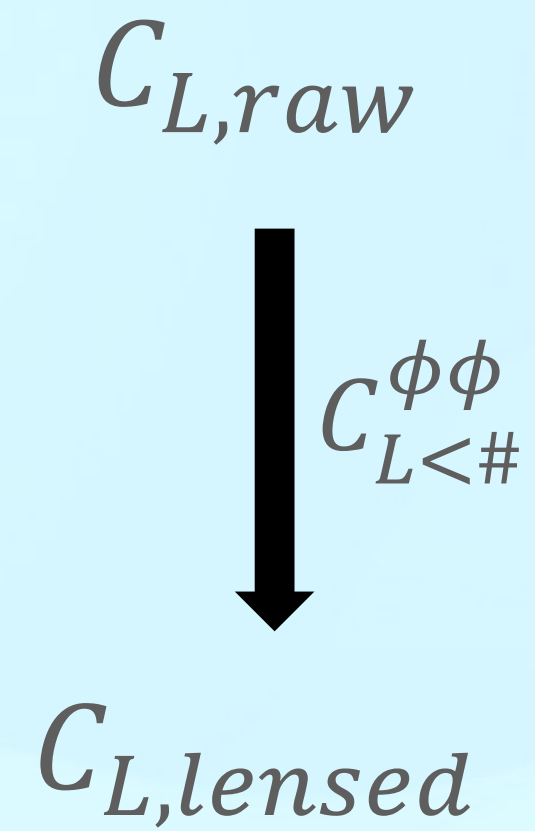


- Similar constraints for different EDE
- Compatible with LCDM in (80,400)
- Enhanced amplitude at high and low L
- B mode constraint at high L

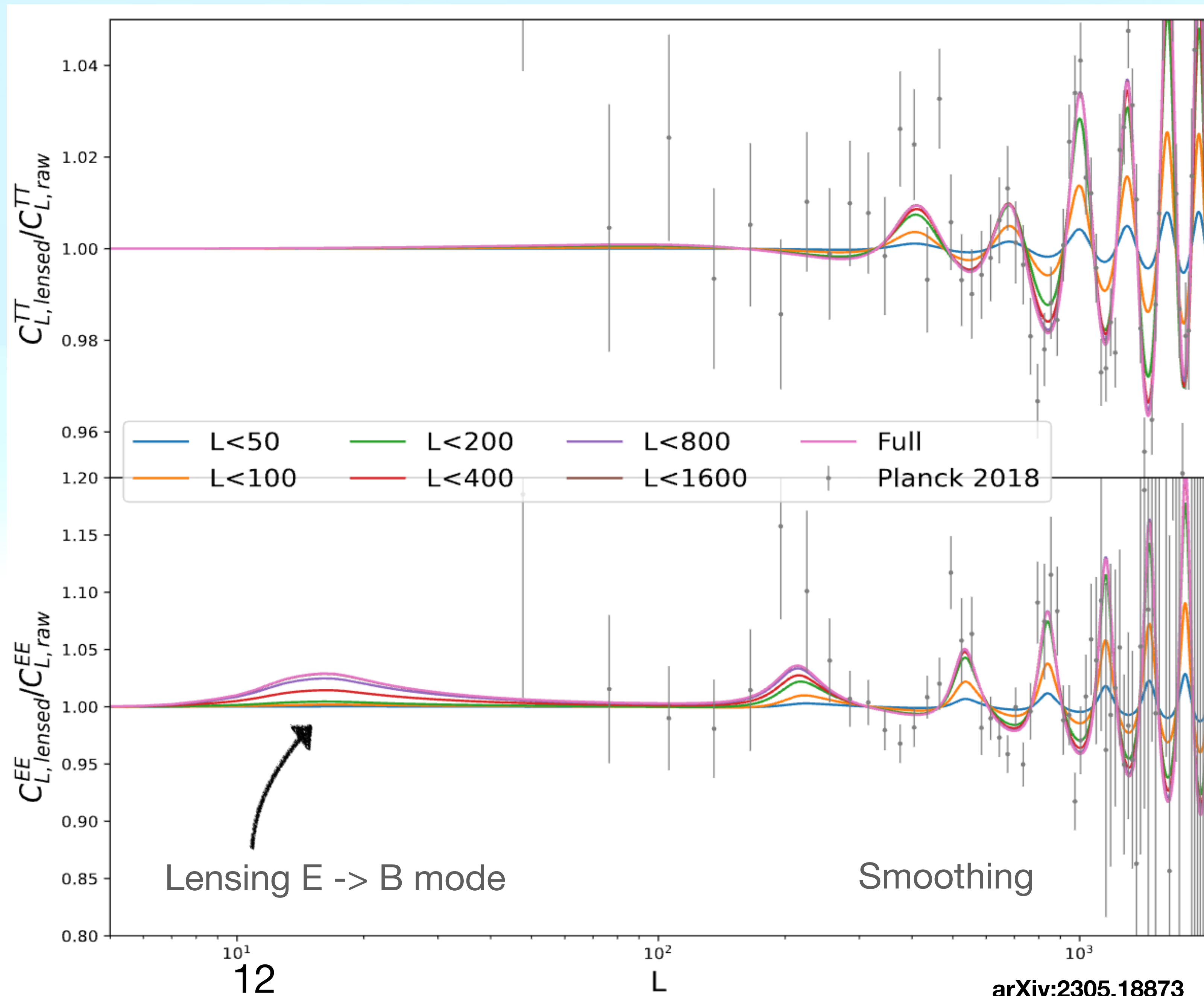
Results



Results

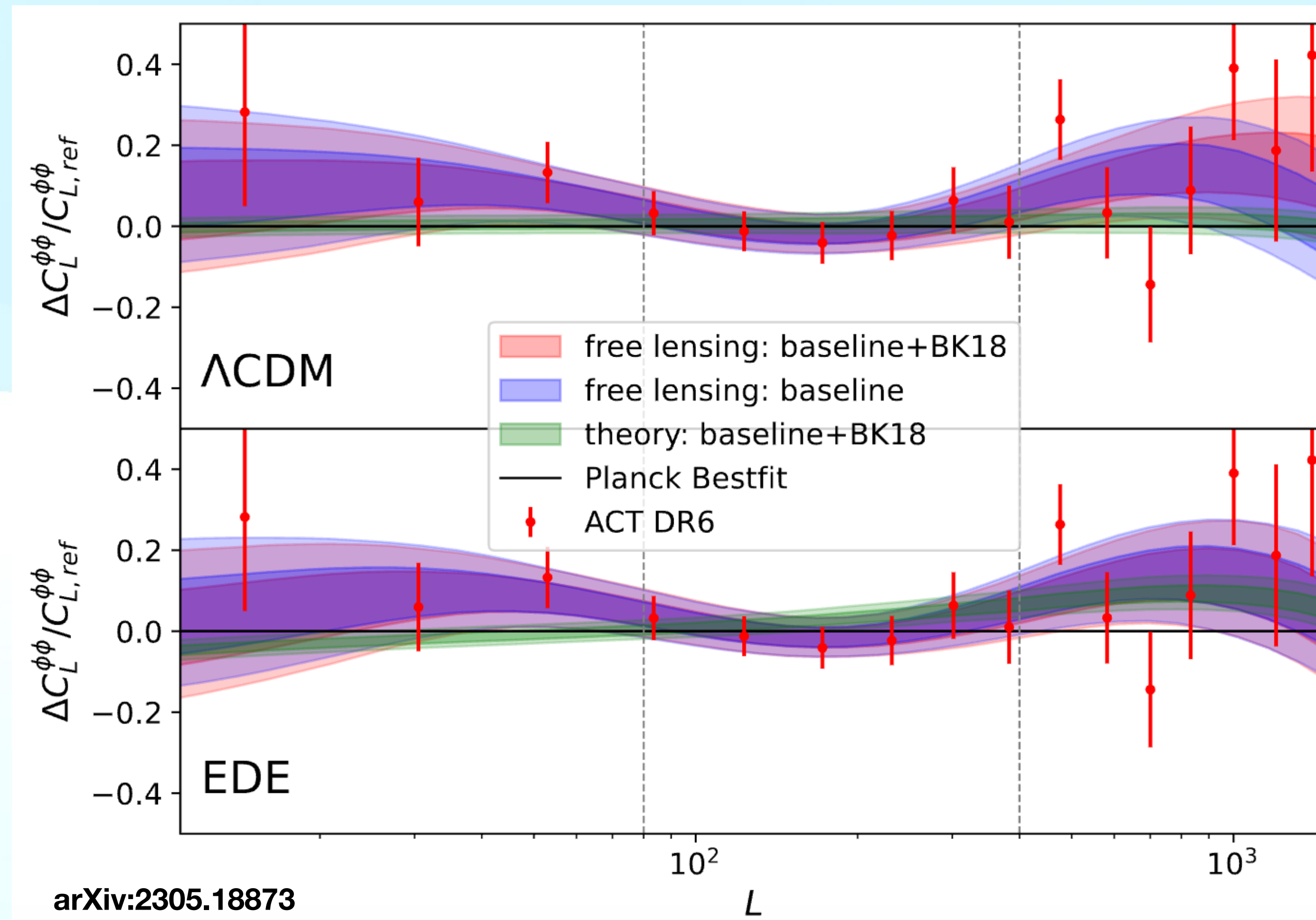


B mode constrains $L > 400$



Results

CMB TTTEE + Lensing reconstruction (+ CMB B mode)



- Similar constraints for different EDE
- Compatible with LCDM in (80,400)
- Enhanced amplitude at high and low L
- B mode constraint at high L

Conclusion

- New GP sampling method, fewer nodes required
- Late universe marginalized over
 - Insensitive to early Universe model (Λ CDM vs EDE)
 - $80 < l < 400$ dominated by lensing reconstruction
 - High and low l pushed up by lensed T/E
 - New constraint from B mode
- Work in progress: crossing with galaxy weak lensing

$$K(x_1, x_2) = \sigma^2 \exp\left(-\frac{|x_1 - x_2|^2}{2l^2}\right)$$

$$l = 1.0, \sigma = 0.1$$

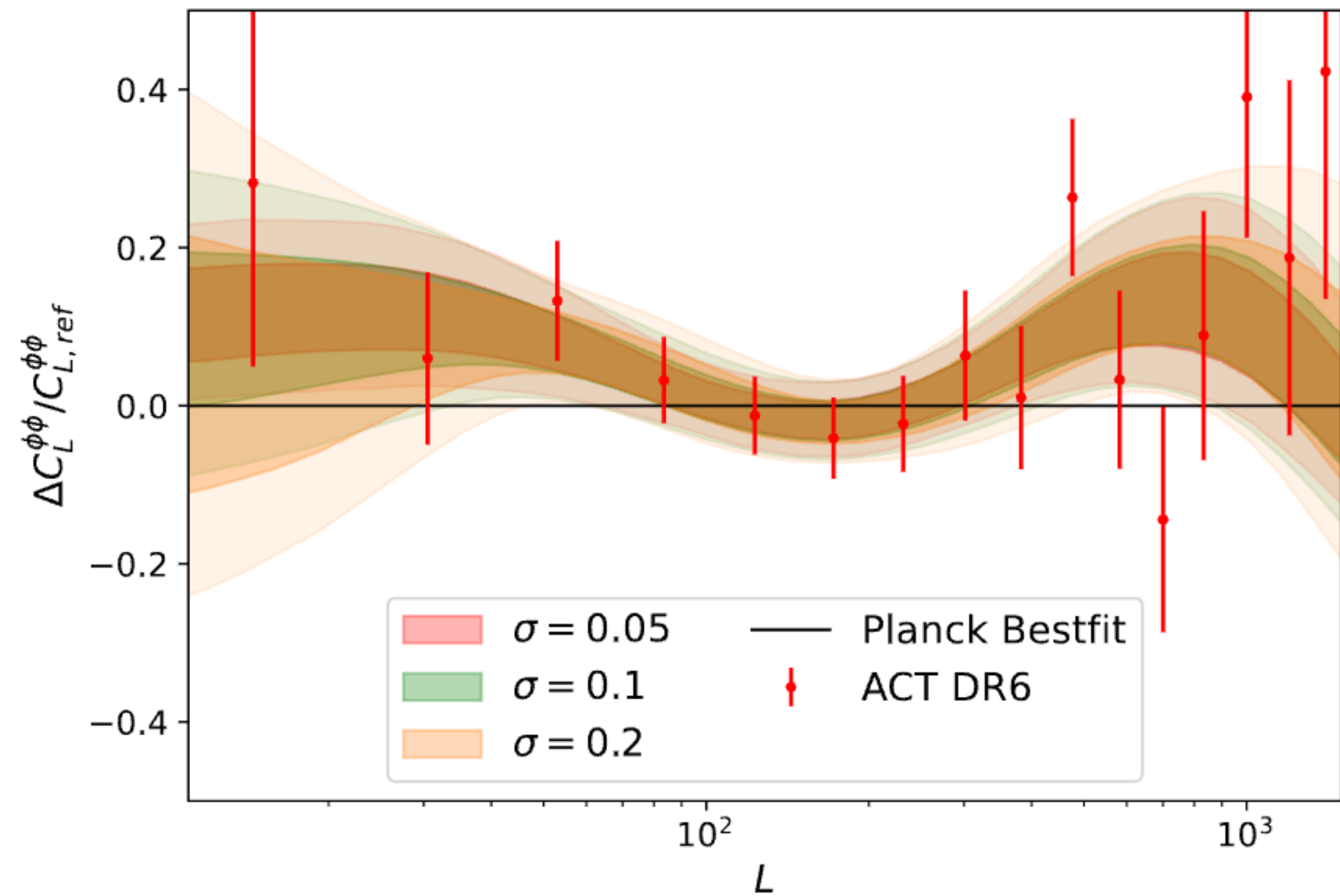
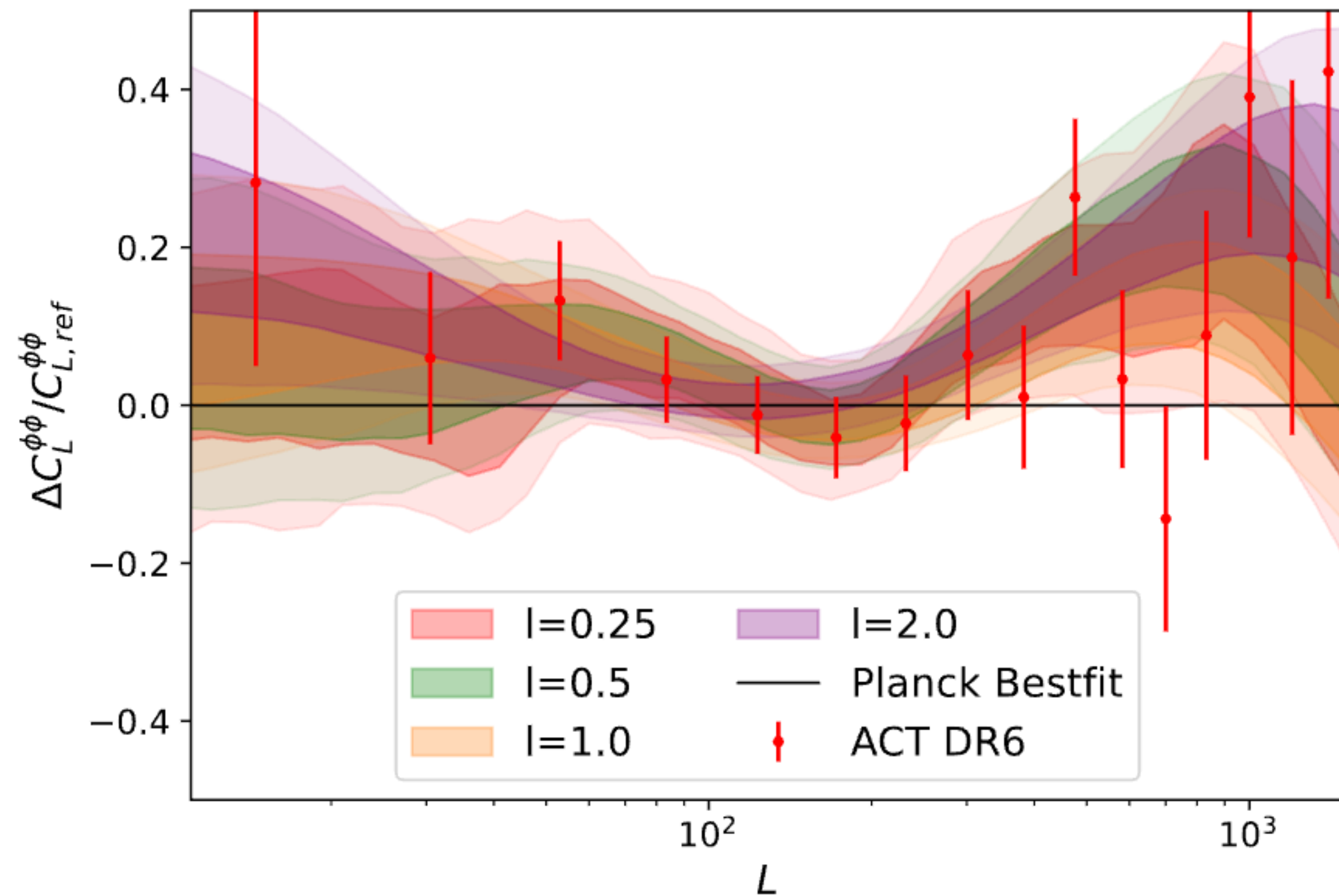


FIG. 10: Lensing shape constraints in Λ CDM with different GP parameters. *Left panel:* $l = \{0.25, 0.5, 1.0, 2.0\}$, $\sigma = 0.1$. *Right panel:* $l = 1.0$, $\sigma = \{0.05, 0.1, 0.2\}$.

$$A_{ISW} = 1$$

