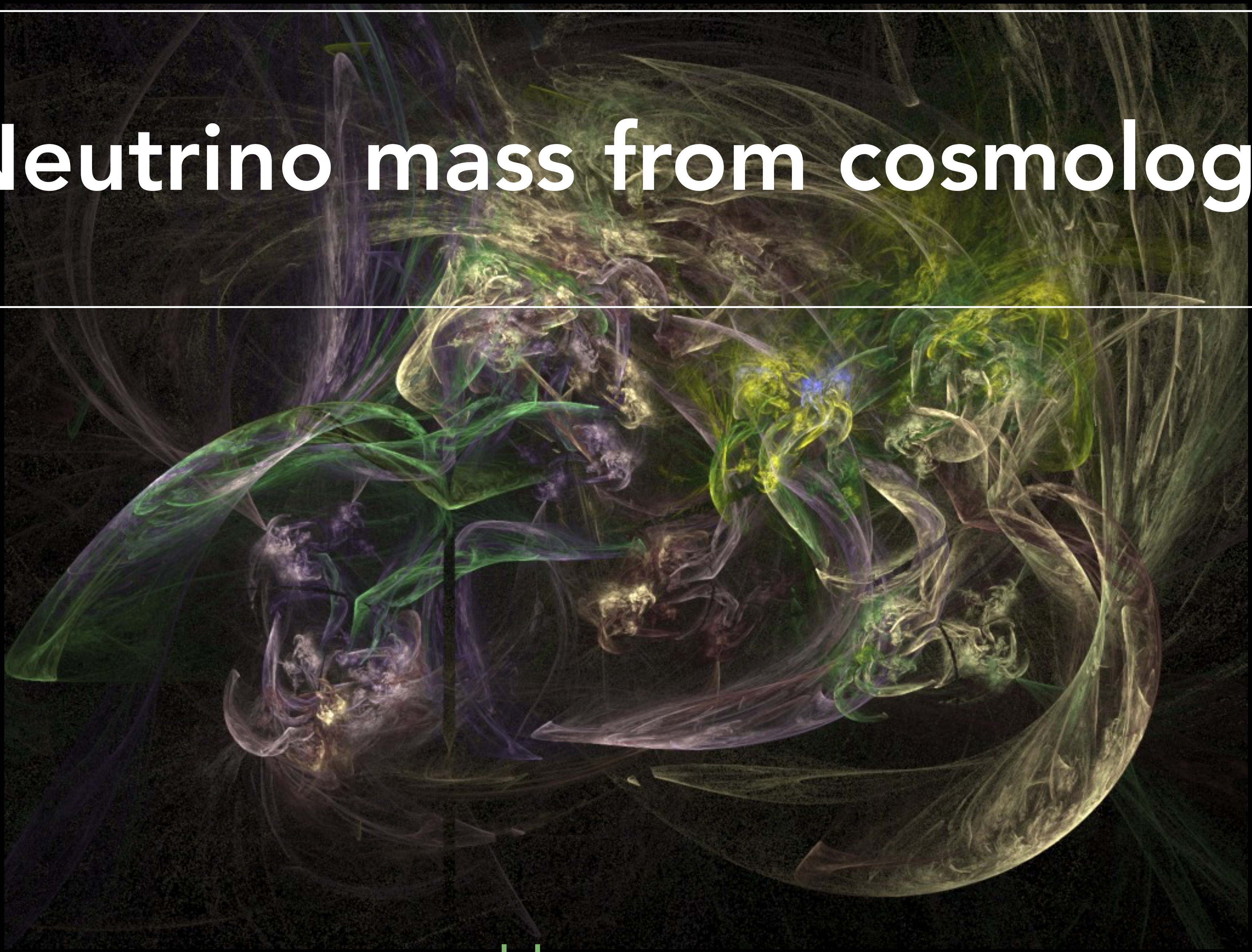
CoSyne, IAP, Paris, 10.12.2019

Neutrino mass from cosmology



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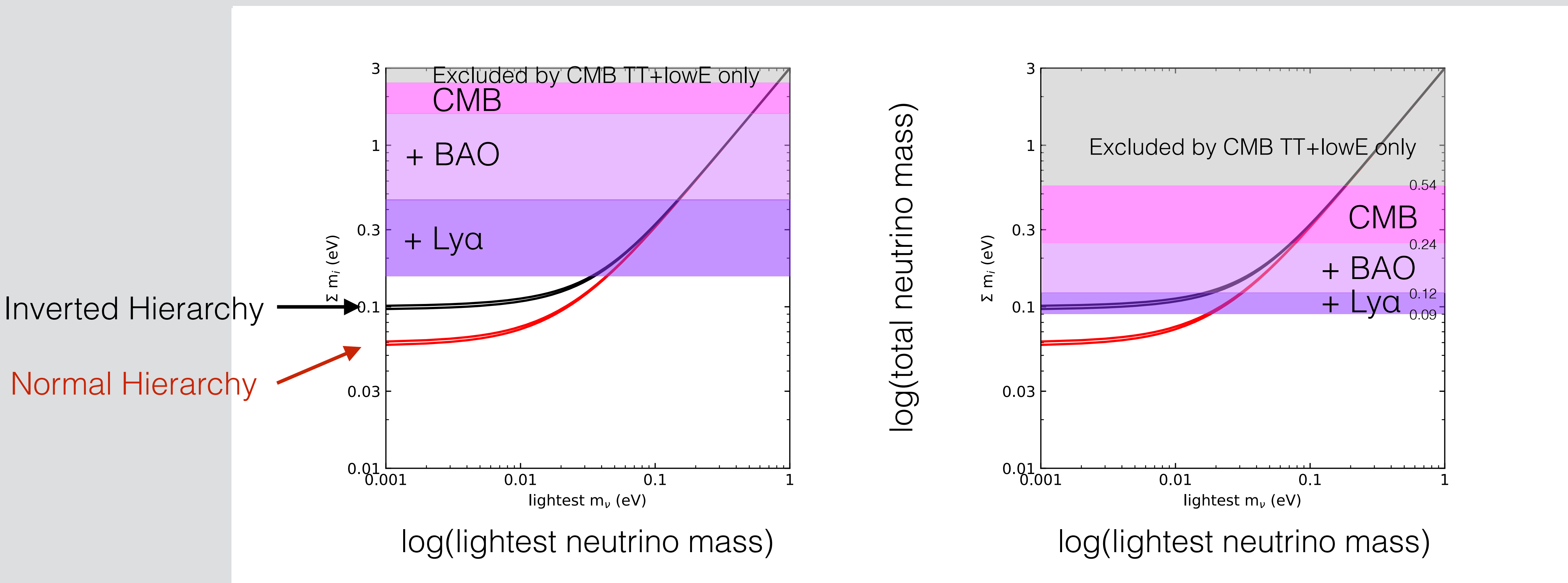
Current bounds

After Planck: strong bounds on total neutrino mass, about to rule out Inverted Hierarchy

For 7-param $\Lambda\text{CDM} + M_\nu$, 95%CL:

2006 (post-WMAP) 2019 (post-Planck)



Planck 2018 VI, 1807.06209

Palanque-Delabrouille et al. 1911.09073

Future bounds

We are excluding ~100 meV at 2 sigma…

… but detecting 60 meV at several sigmas will be very difficult!

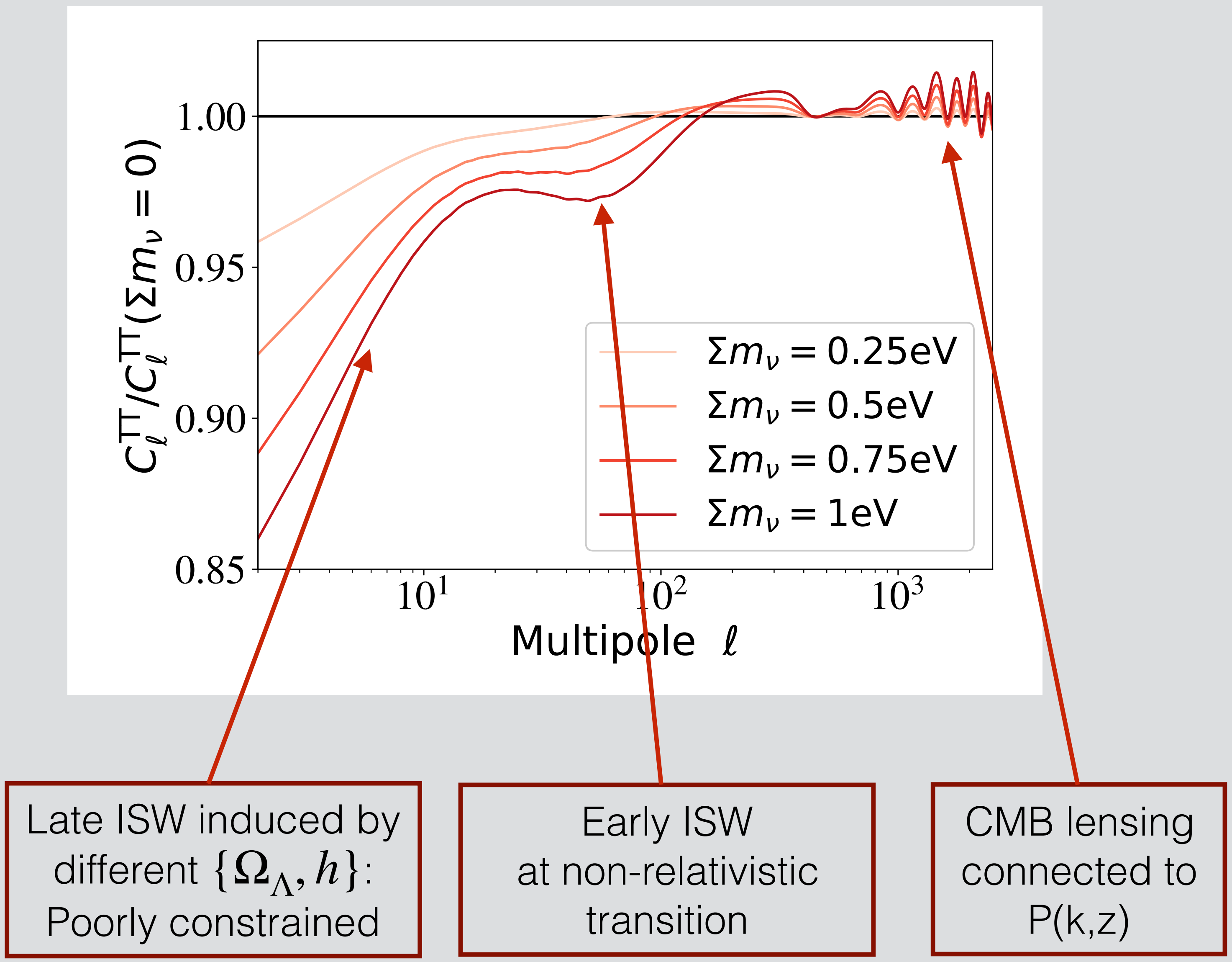
Enemy: not non-linear effects (non-linear growth, baryonic feedback, …) ,

but parameter degeneracies.

M_ν effects on CMB

Neutrino mass effects on lensed C_l^{TT} with fixed $\{\ \omega_b\ , \omega_c\ , \theta_s\ , \tau_{reio}\ , A_s\ , n_s\ \}$ $(\Rightarrow z_{eq})$

Large mass



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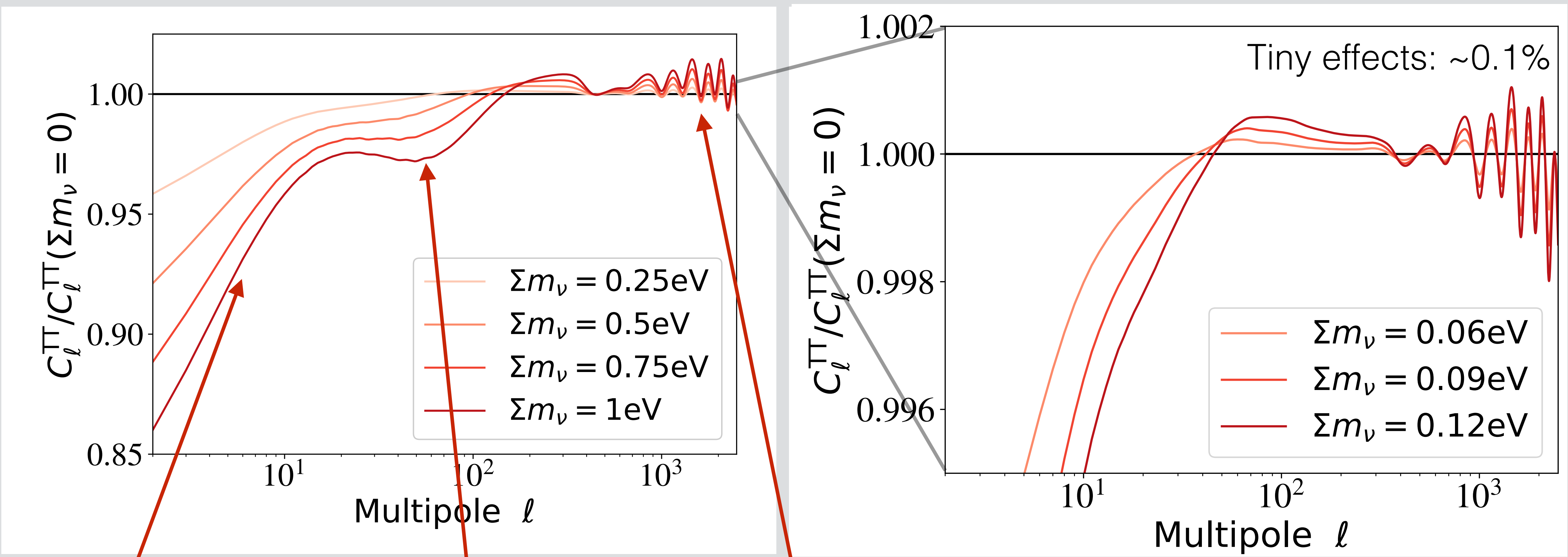
M_ν effects on CMB

Neutrino mass effects on lensed C_l^{TT} with fixed { ω_b , ω_c , θ_s , τ_{reio} , A_s , n_s } ($\Rightarrow z_{eq}$)

Large mass

Small mass



Late ISW induced by different $\{\Omega_\Lambda, h\}$: Poorly constrained

Early ISW at non-relativistic transition

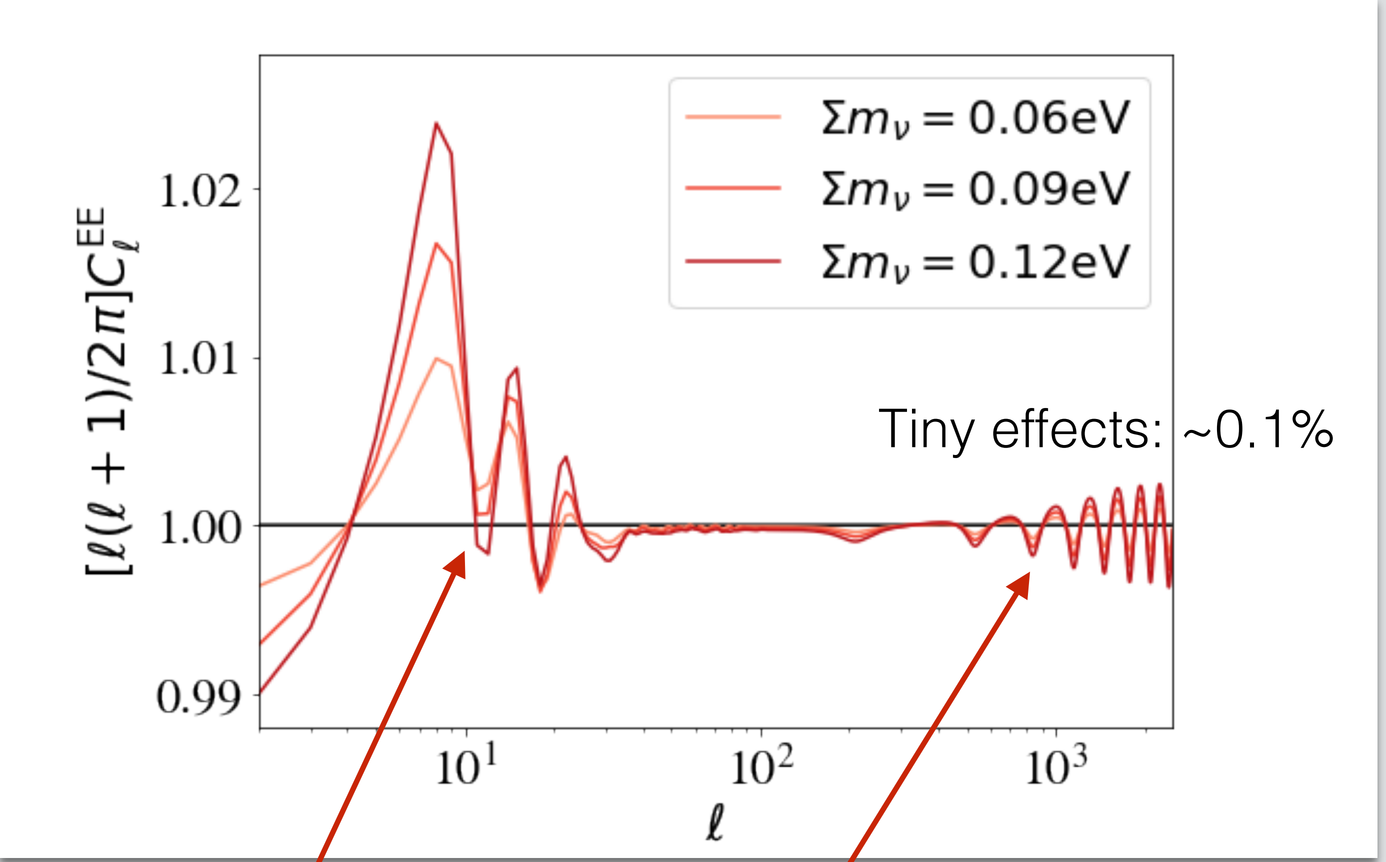
CMB lensing connected to P(k,z)

Is this below noise / cosmic variance?

M_ν effects on CMB

Neutrino mass effects on lensed C_l^{EE} with fixed { ω_b , ω_c , θ_s , τ_{reio} , A_s , n_s } ($\Rightarrow z_{eq}$)

Small mass



Tiny effects: ~0.1%

Late background effect: different relation $\tau_{\rm reio} \leftrightarrow z_{\rm reio}$

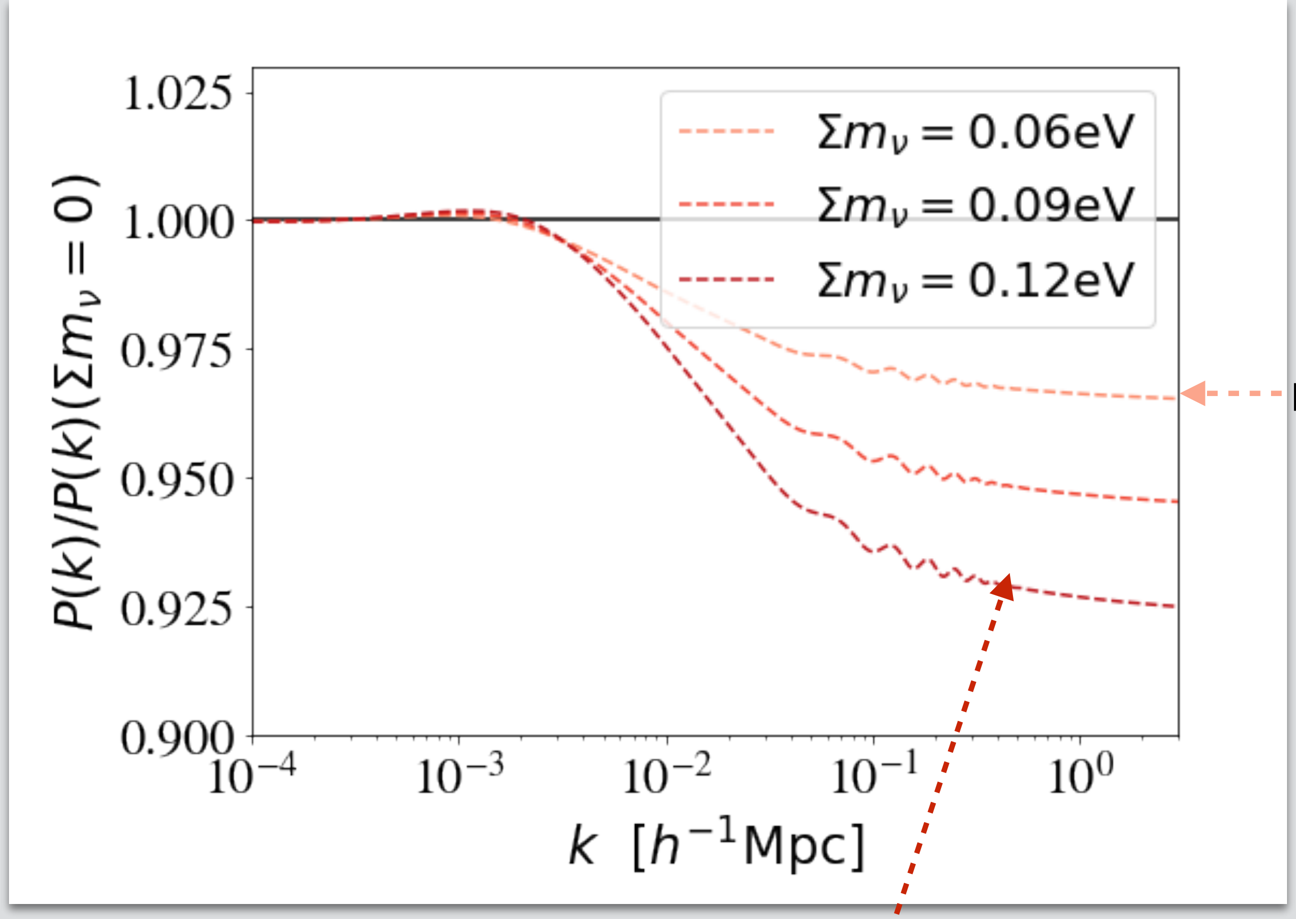
CMB lensing connected to P(k,z)

Is this below noise / cosmic variance?

M_ν effects on LSS

Neutrino mass effects on lensed $P(k, z=0)$ with fixed { ω_b , ω_c , θ_s , τ_{reio} , A_s , n_s } ($\Rightarrow z_{eq}$)

Small mass



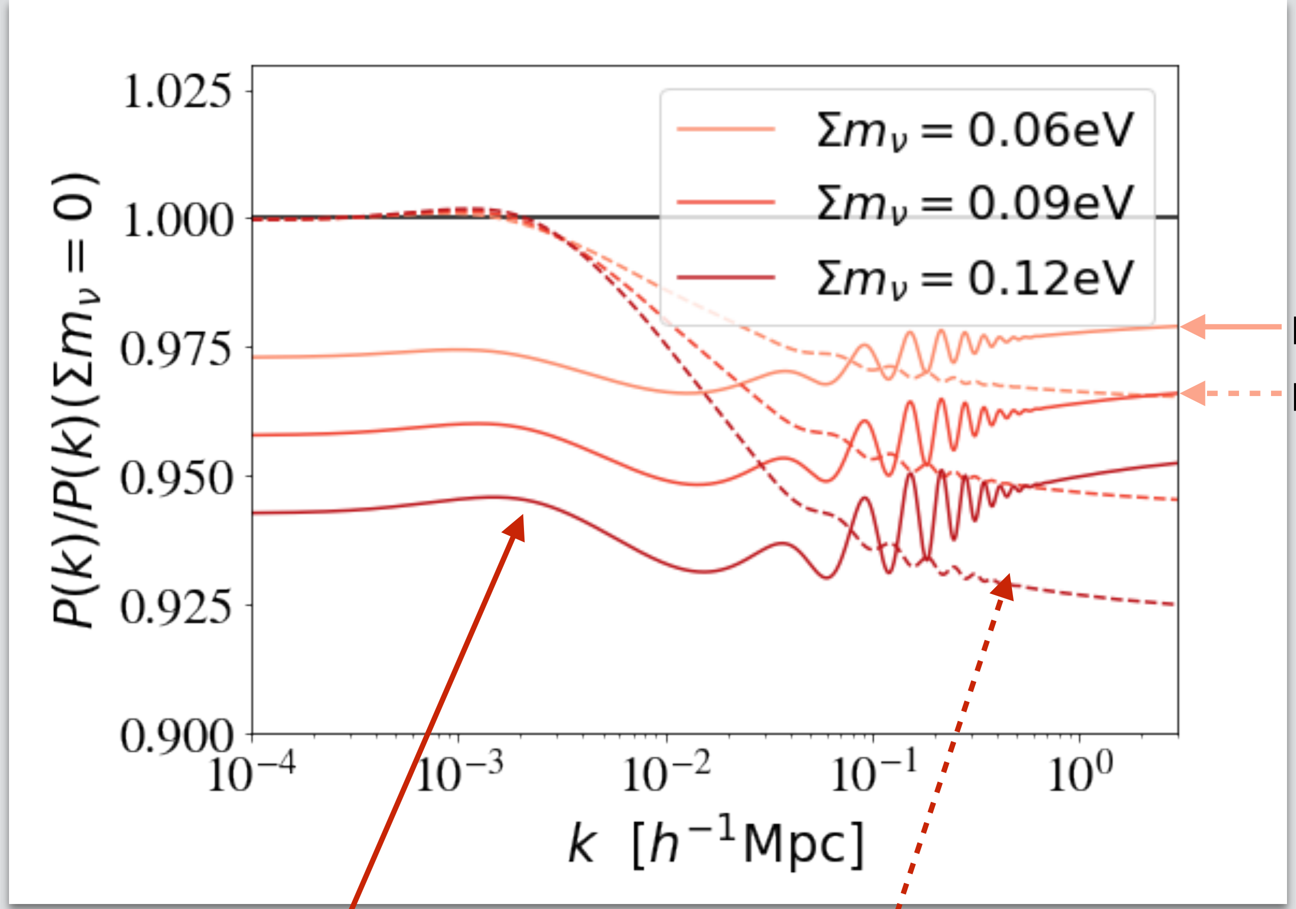
min 4% in $P_m(k, z=0)$ (3% in P_{cb})

Neutrino free-streaming slowing down growth of δ_{cb}

M_ν effects on LSS

Neutrino mass effects on lensed $P(k, z=0)$ with fixed { ω_b , ω_c , θ_s , τ_{reio} , A_s , n_s } ($\Rightarrow z_{eq}$)

Small mass



min 3% in $P_m(k, z=0)$ (2% in P_{cb})
min 4% in $P_m(k, z=0)$ (3% in P_{cb})

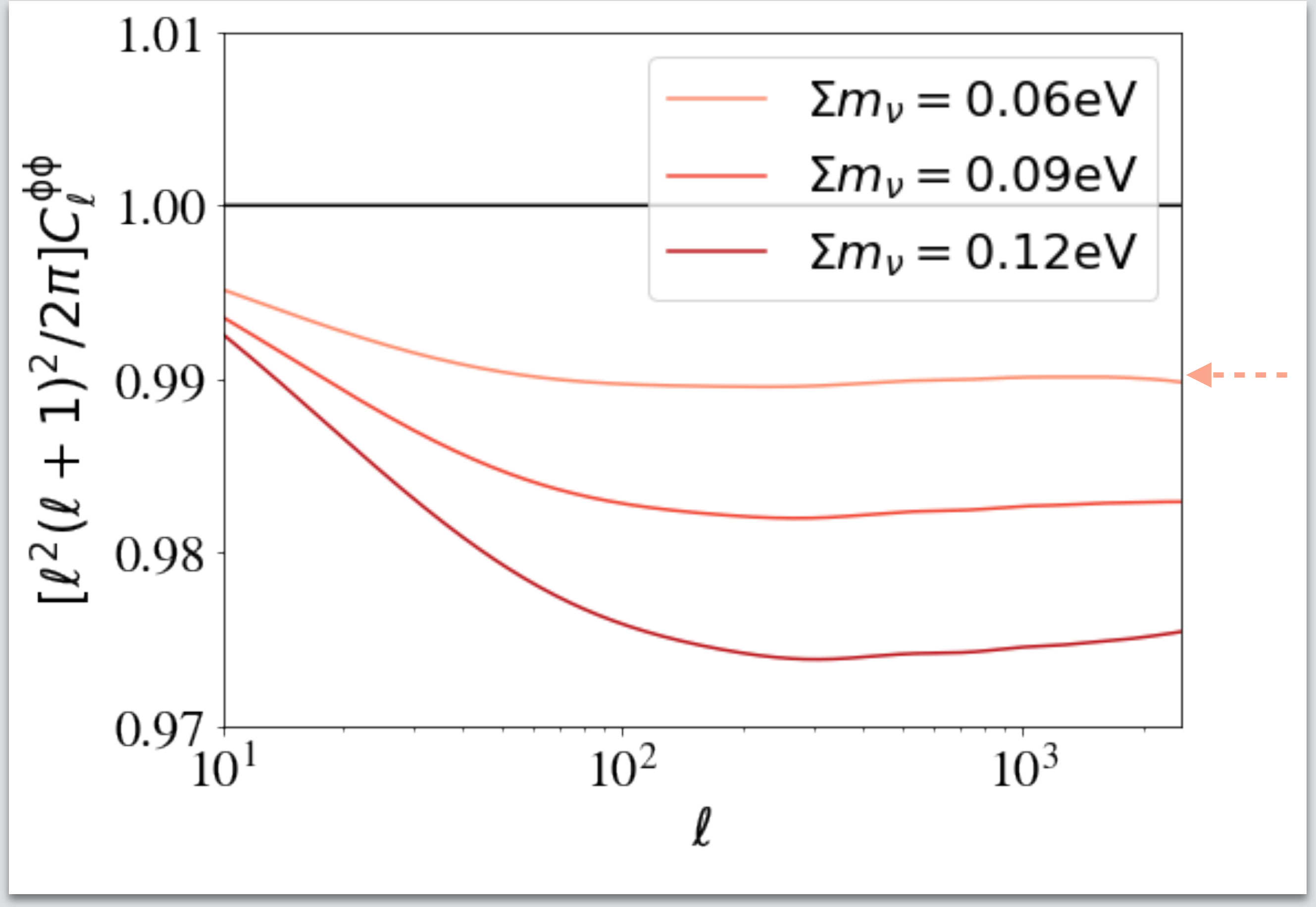
Additional Background effect (change in H_0 , BAO scale)

Neutrino free-streaming slowing down growth of δ_{cb}

M_ν effects on LSS

Neutrino mass effects on lensed $C_l^{\phi\phi}$ with fixed { ω_b , ω_c , θ_s , τ_{reio} , A_s , n_s } ($\Rightarrow z_{eq}$)

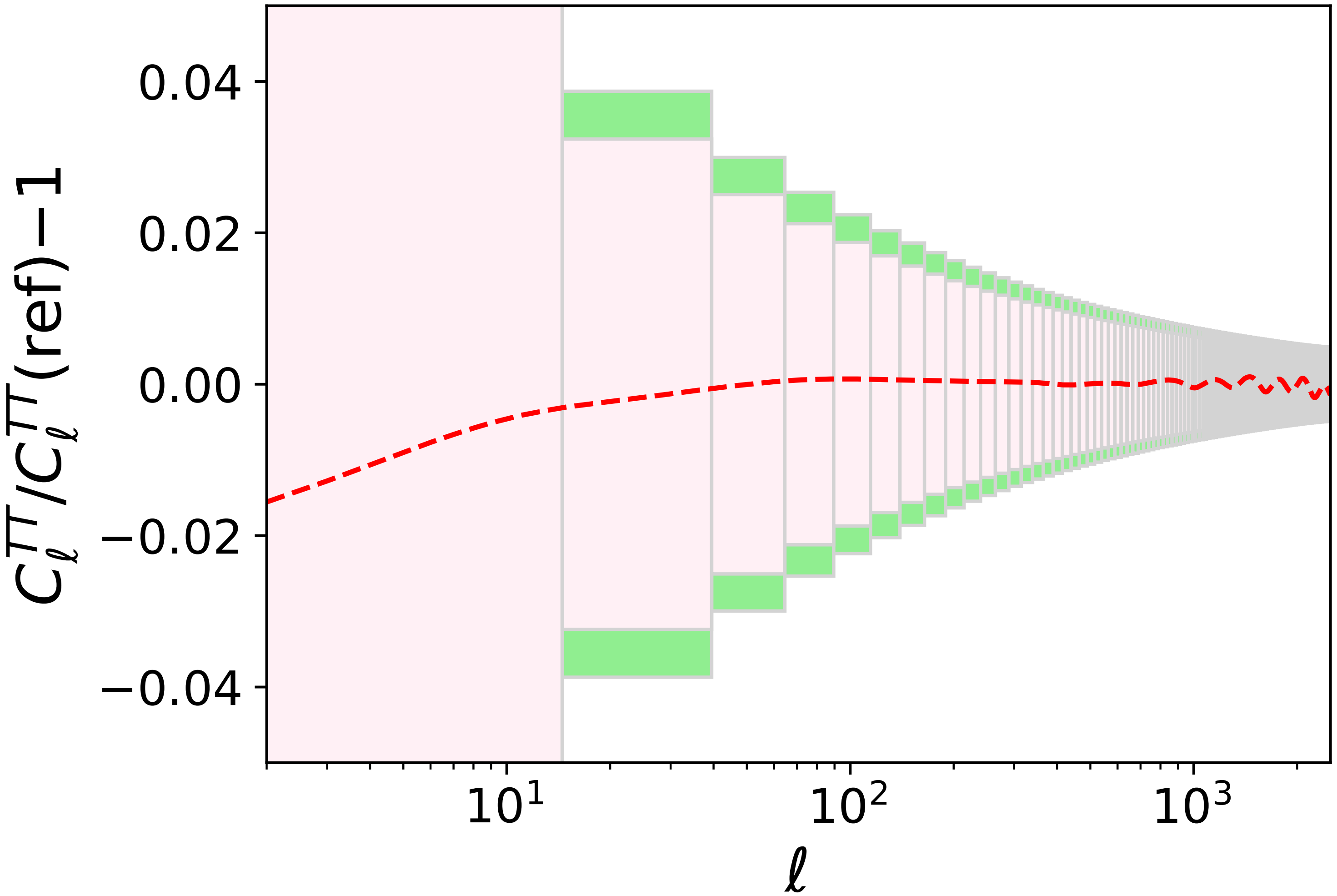
Small mass



min 1%

Detectability and degeneracies with CMB alone

Trying to differentiate 50 meV from 150 meV with fixed $\{ \omega_b , \omega_c , \theta_s , \tau_{reio} , A_s , n_s \}$ $(\Rightarrow z_{eq})$
Pink = cosmic variance
Green = CORE



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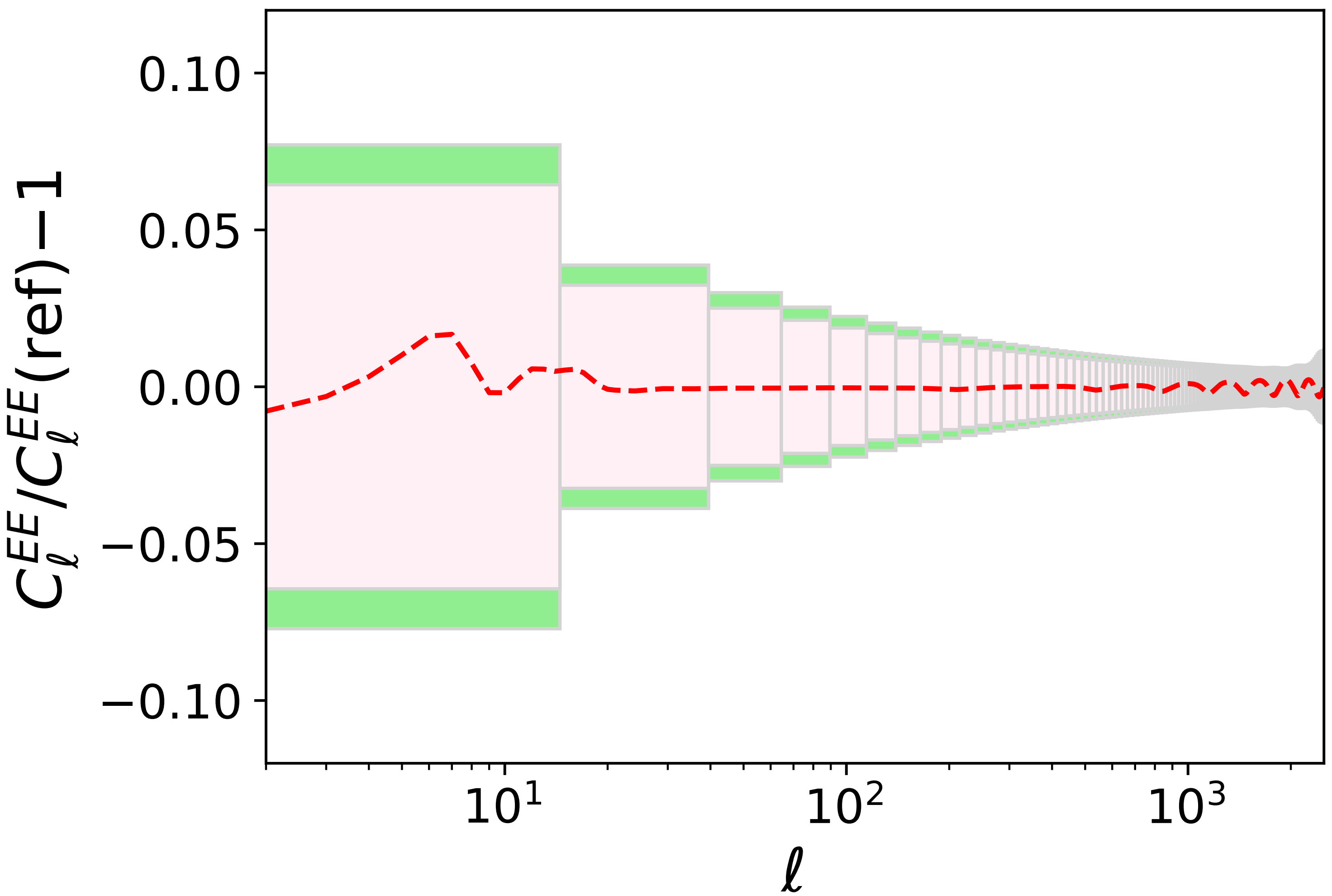
TT: below cosmic variance

Detectability and degeneracies with CMB alone

Trying to differentiate 50 meV from 150 meV with fixed $\{\ \omega_b\ ,\omega_c\ ,\theta_s\ ,\tau_{reio}\ ,A_s\ ,n_s\ \}\ \ (\Rightarrow z_{eq}\ )$

Pink = cosmic variance

Green = CORE



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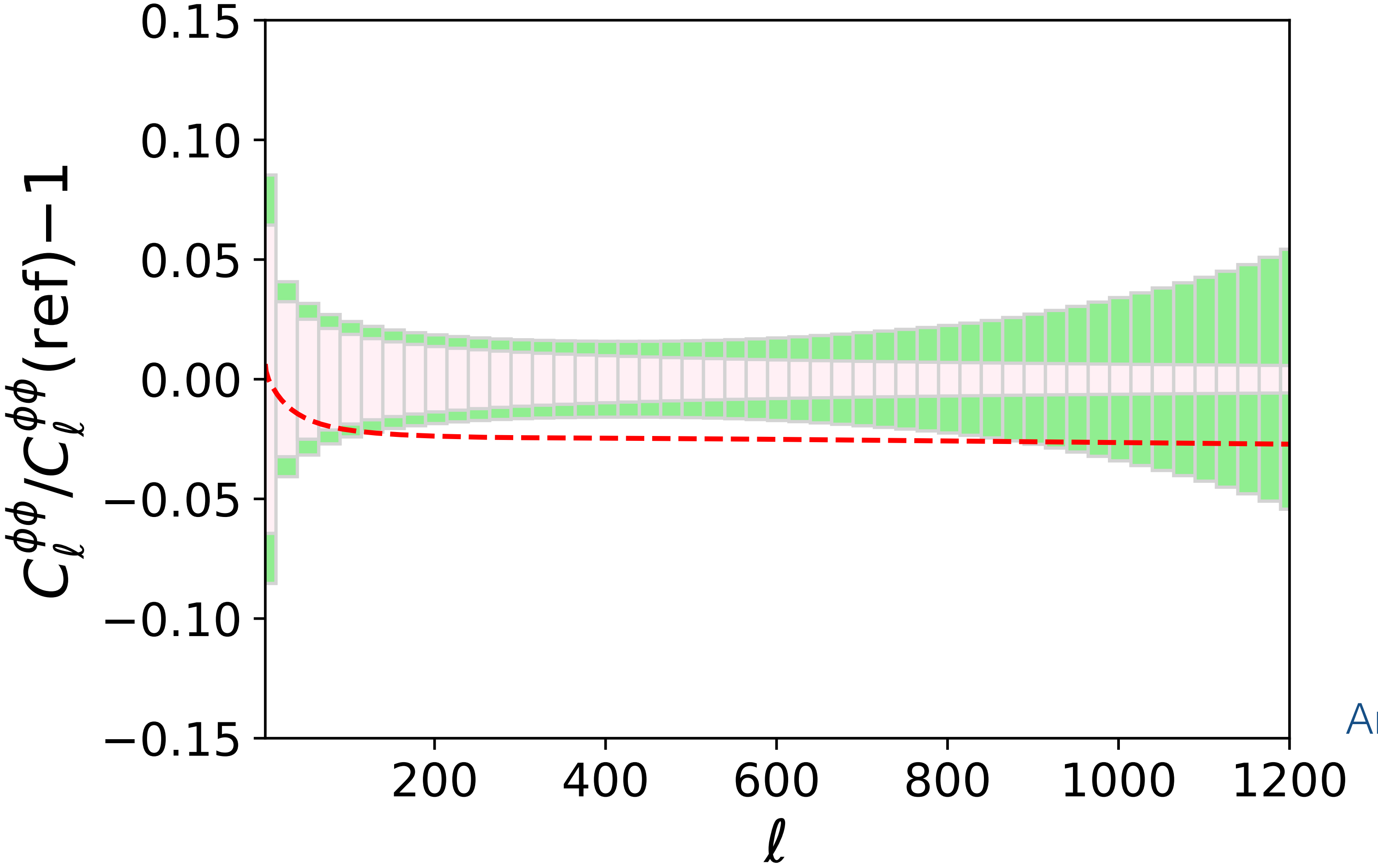
EE: below cosmic variance

Detectability and degeneracies with CMB alone

Trying to differentiate 50 meV from 150 meV with fixed $\{ \omega_b , \omega_c , \theta_s , \tau_{reio} , A_s , n_s \}$ $(\Rightarrow z_{eq})$

Pink = cosmic variance

Green = CORE



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$\phi\phi$: above cosmic variance over a wide range of multipoles

Could be detectable *if* not degenerate with other parameters…

Detectability and degeneracies with CMB alone

Is it possible to increase the overall amplitude of $C_l^{\phi\phi}$ by ~3% without spoiling the good fit to $C_l^{TT,TE,EE}$?

$$\ell^4 C_\ell^{\phi\phi} \propto A_s \omega_m^{3/2} h^{-1/2} M_\nu^{-\alpha}$$

1. *Increase A_s by 3% and decrease $\tau_{\rm reio}$ by $\frac{1}{2}\ln 1.03 = 0.015$ to keep $A_s e^{-2\tau_{\rm reio}}$ constant ?*

   NO: $\sigma(\tau_{\rm reio}) = 0.008$ (Planck) or 0.002 (LiteBird/CORE).

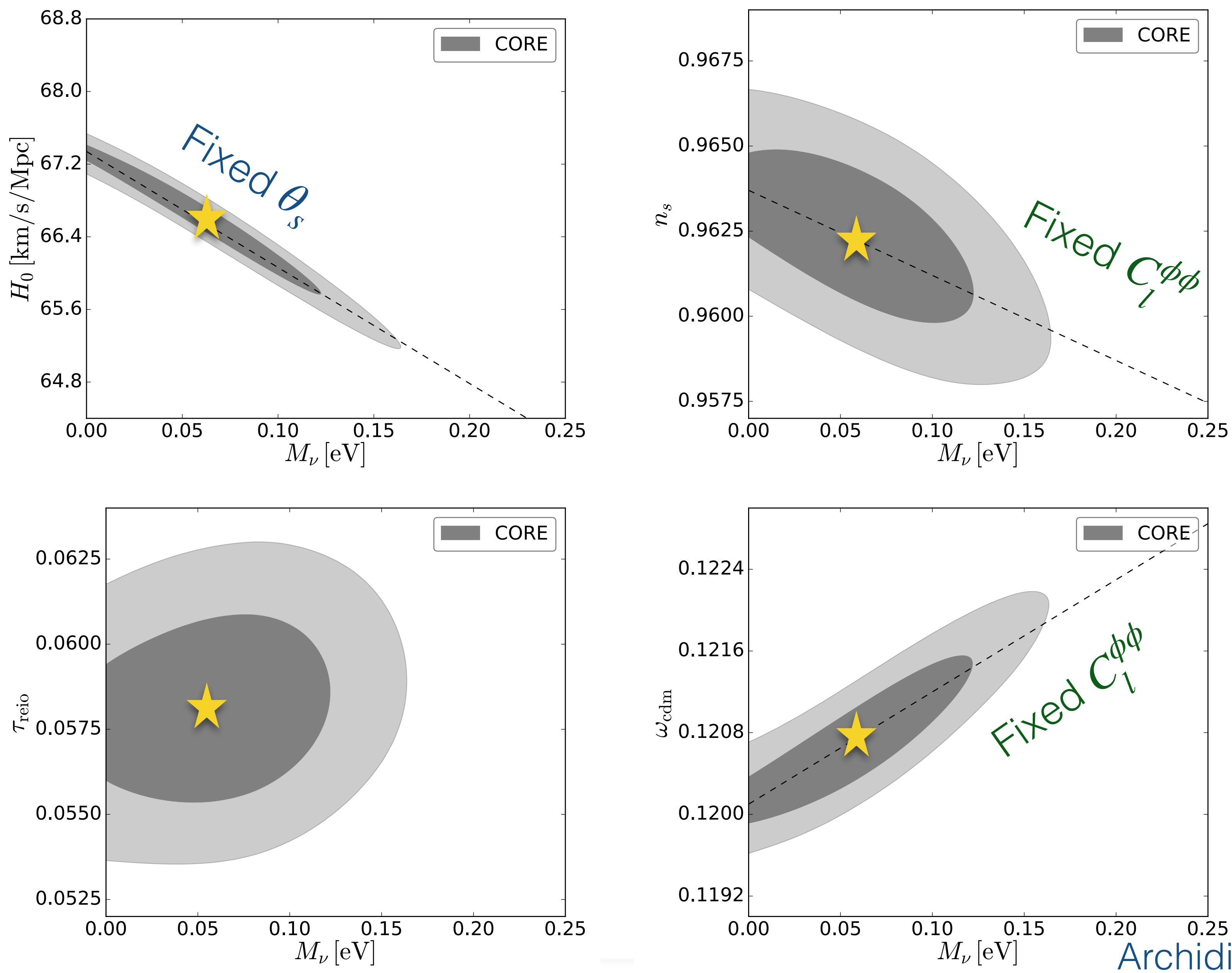
   So CMB alone can probe M_ν , but accuracy potentially limited by correlation $M_\nu \leftrightarrow \tau_{\rm reio}$.

2. *Decrease ω_c and compensate small changes in $C_l^{TT,TE,EE}$ with other parameters like n_s ?*

   Works better: correlation $M_\nu \leftrightarrow \omega_c$ much stronger than $M_\nu \leftrightarrow \tau_{\rm reio}$ with CMB alone.

Conclusions: CMB alone can detect small masses, but sensitivity limited by partial degeneracies: first $M_\nu \leftrightarrow \omega_c$, second by $M_\nu \leftrightarrow \tau_{\rm reio}$

Detectability and degeneracies with CMB alone



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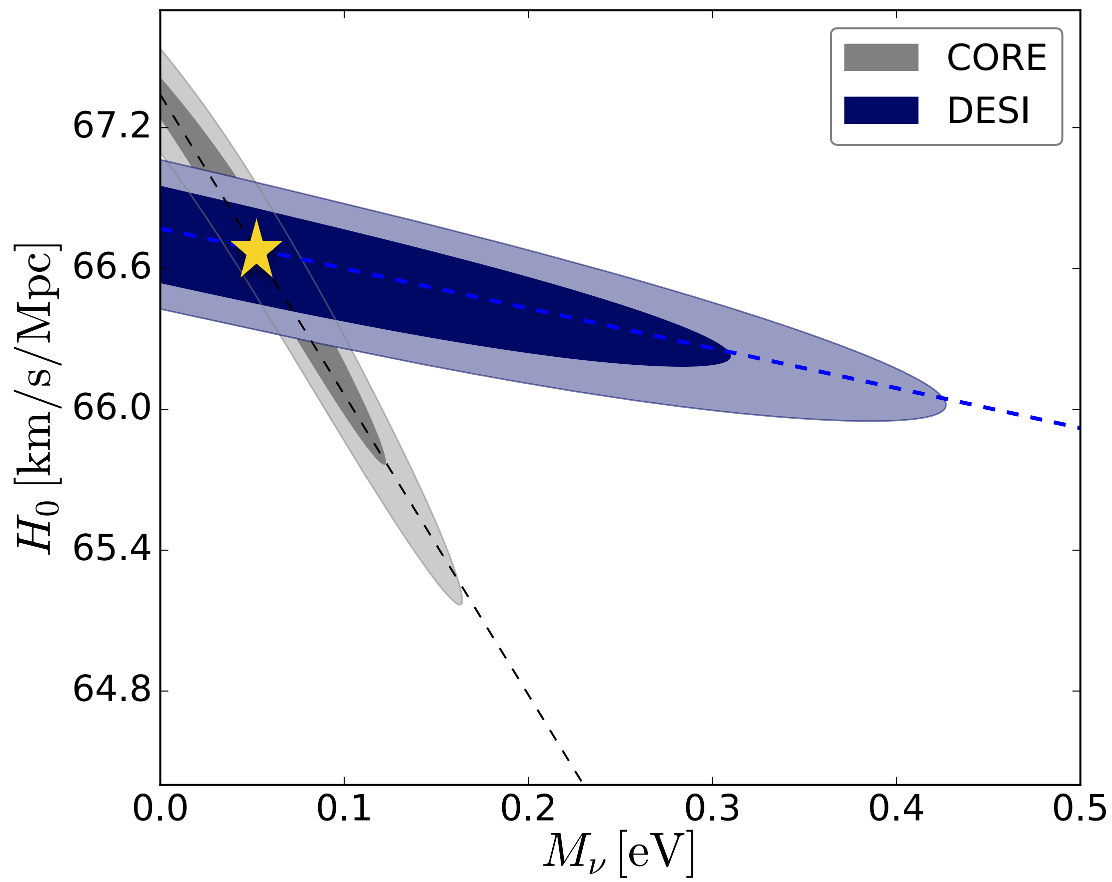
Main correlations:

$$M_\nu \leftrightarrow H_0, \quad M_\nu \leftrightarrow \omega_c \text{ and } n_s, \quad (M_\nu \leftrightarrow \tau_{\rm reio} \text{ and } A_s)$$

Detectability and degeneracies with CMB + BAO

BAO probe different direction in { M_ν , H_0 }space : much better M_ν determination



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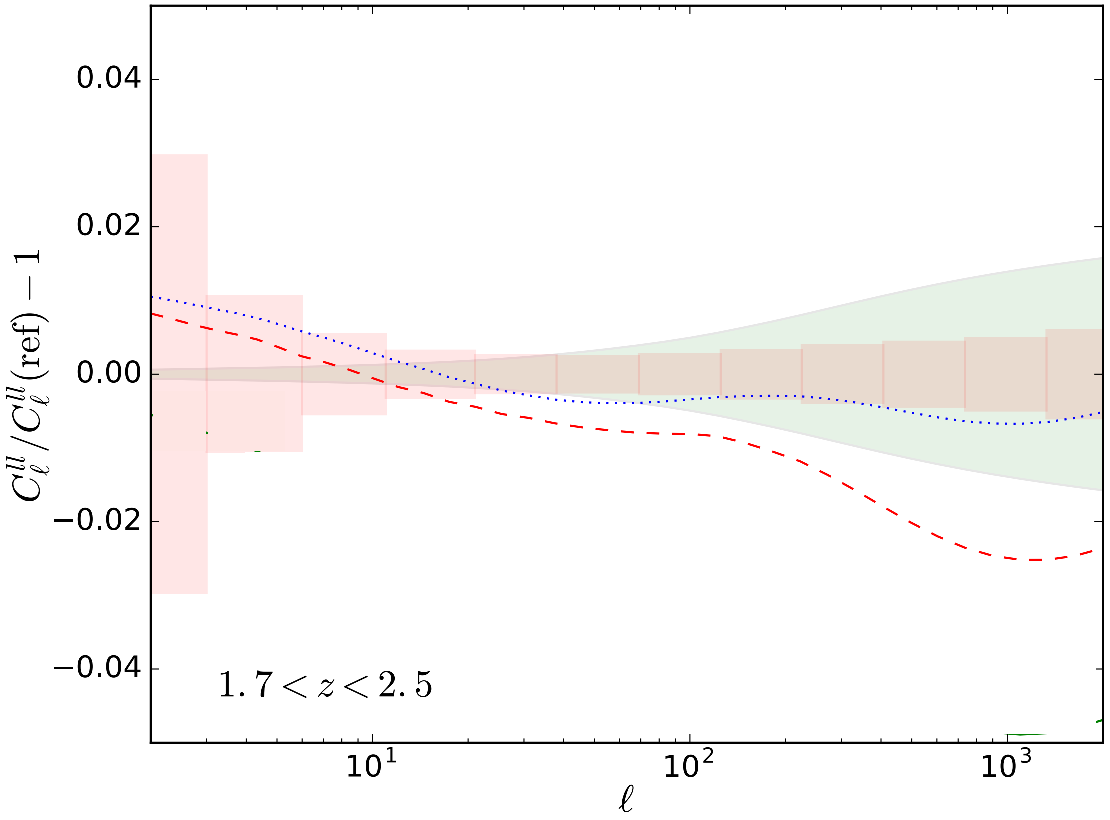
Sensitivity to M_ν still limited by small correlations:

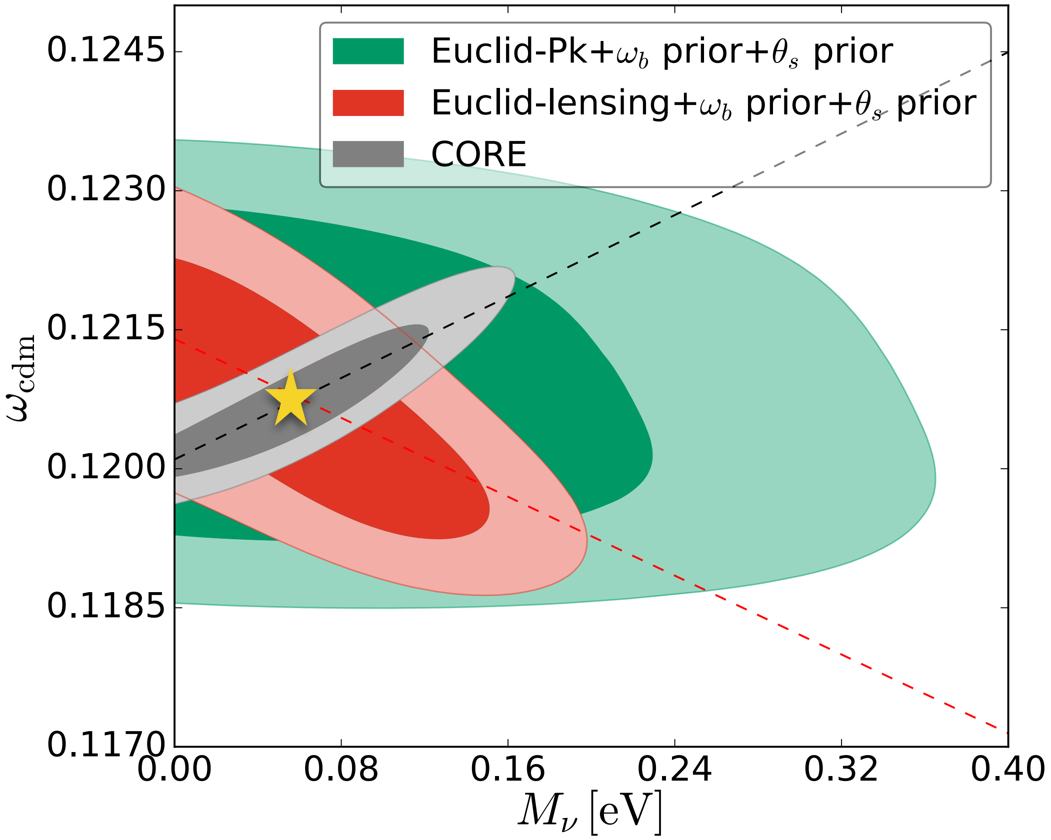
$$M_\nu \leftrightarrow H_0, \quad M_\nu \leftrightarrow \omega_c \; and \; n_s, \quad M_\nu \leftrightarrow \tau_{\rm reio} \; and \; A_s$$

Detectability and degeneracies with CMB + BAO + cosmic shear surveys

Cosmic shear surveys add sensitivity to M_ν at different z that reduces $M_\nu \leftrightarrow H_0$, $M_\nu \leftrightarrow \omega_c$ *and* n_s

Comparison of 60 meV to 150 meV
(dashed red line)
Pink = Euclid CS uncertainty
Green = additional theoretical error





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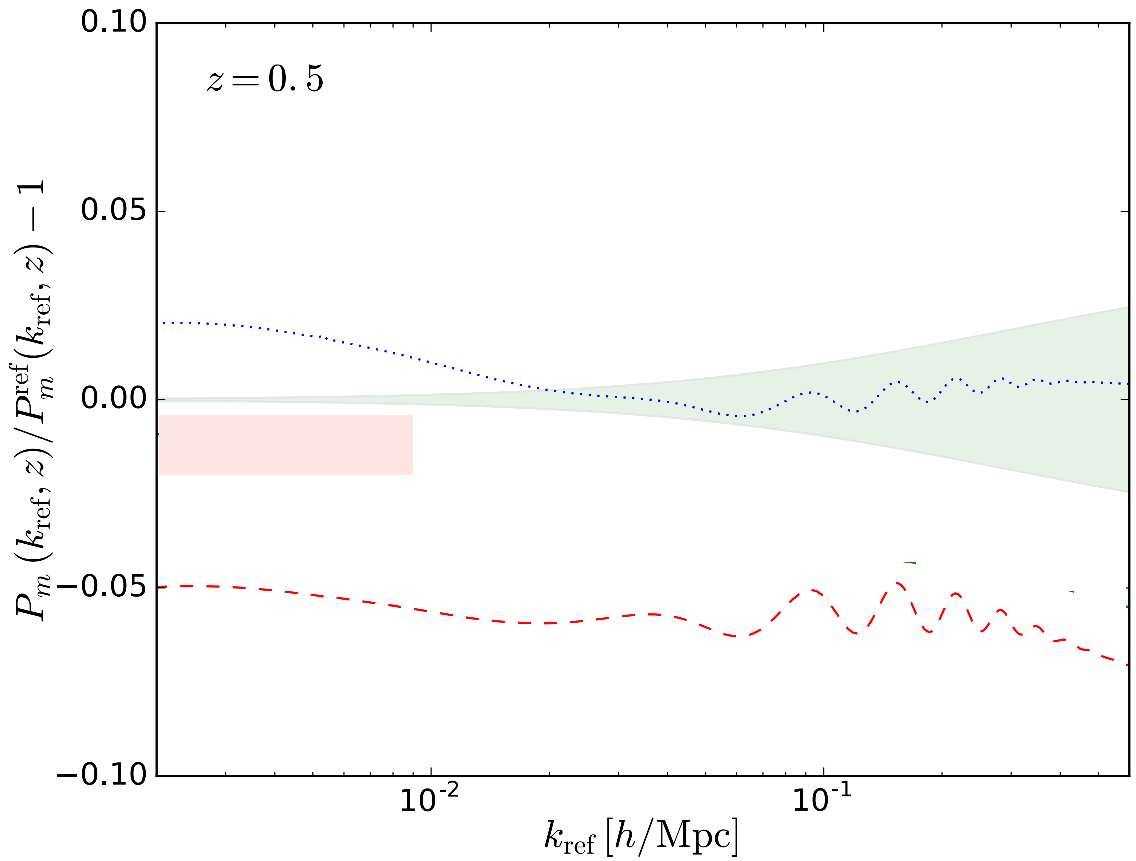
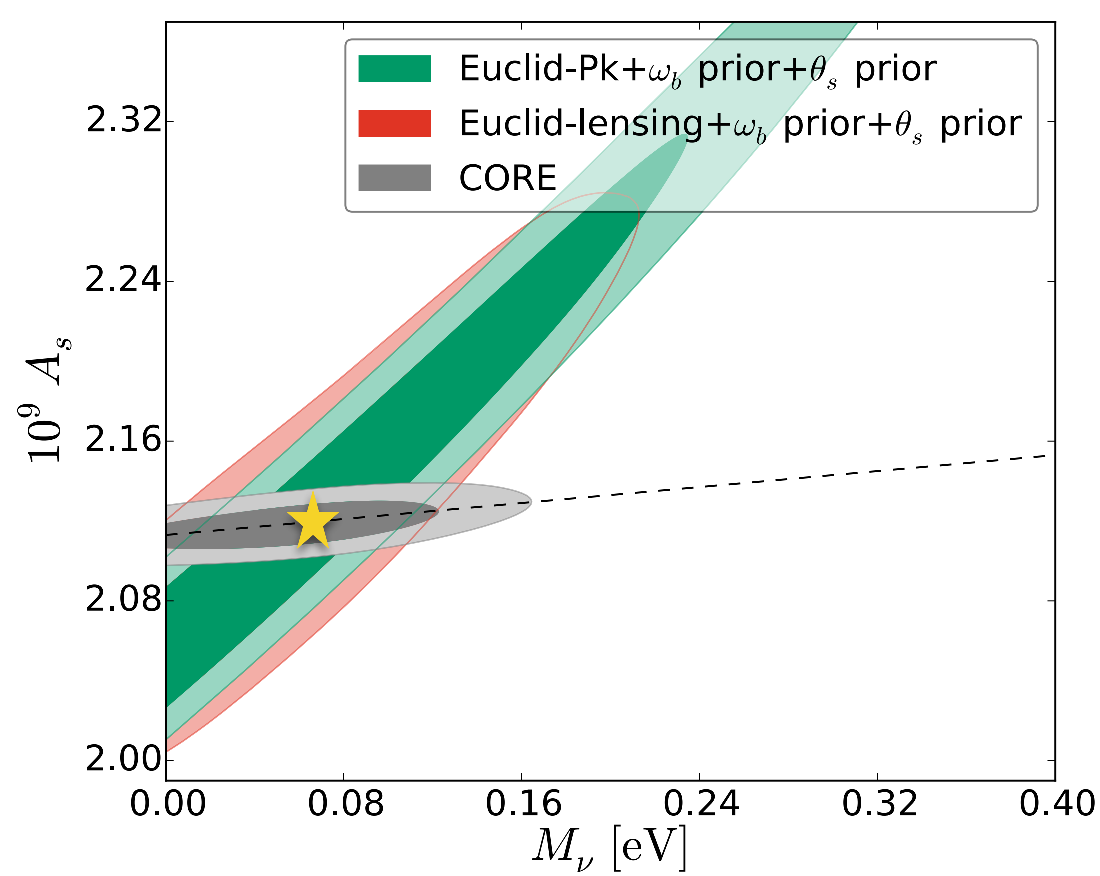
Detectability and degeneracies with CMB + BAO + cosmic shear/galaxy surveys

Galaxy surveys adds a lot of sensitivity to A_s, M_ν at different z and reduces $M_\nu \leftrightarrow \tau_{\rm reio}$ *and* A_s

Comparison of 60 meV to 150 meV
(dashed red line)
Pink = Euclid CS uncertainty
Green = additional theoretical error





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First conclusions

First conclusions: we need to combine CMB, BAO, and shear / galaxy / 21cm surveys!

- CMB constrains several directions in $\{\omega_b, \omega_c, \theta_s, \tau_{reio}, A_s, n_s\}$ space and bounds $\{A_s, \tau_{\rm reio}\}$: large scales for $\tau_{\rm reio}$ (LiteBird/CORE), small scales for lensing and A_s (Stage4/Sim.Obs.)
- BAO removes $M_\nu \leftrightarrow H_0$ degeneracy
- shear / galaxy / 21cm surveys measure overall $P(k,z)$ amplitude (on all scales: non-linear scales not so crucial)

Then neutrino mass explains apparent mismatch between $C_l^{TT,TE,EE}$ amplitude: $A_s e^{-2\tau_{\rm reio}}$ and $P(k,z)$ amplitude: $A_s(1-\alpha(z)M_\nu)$

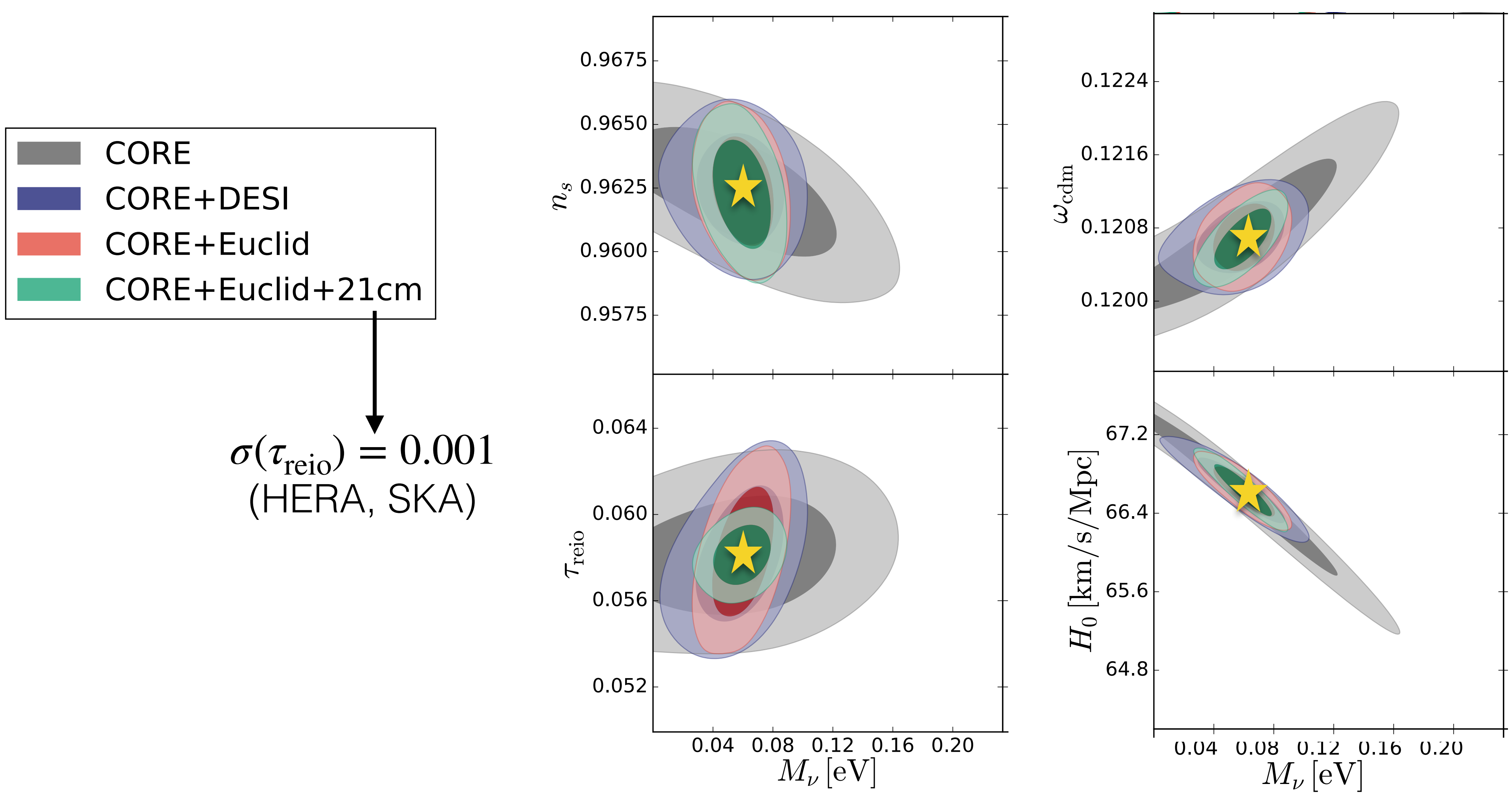
What could ruin this?

- $> \mathcal{O}(1\%)$ uncertainty on global amplitude of $P(k,z)$ (Euclid: 2.5% uncertainty on linear bias and its redshift dependence index, correlated across the bins)

What could improve it?

- Independent measurement of H_0 or $\tau_{\rm reio}$

First conclusions



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What could improve it?

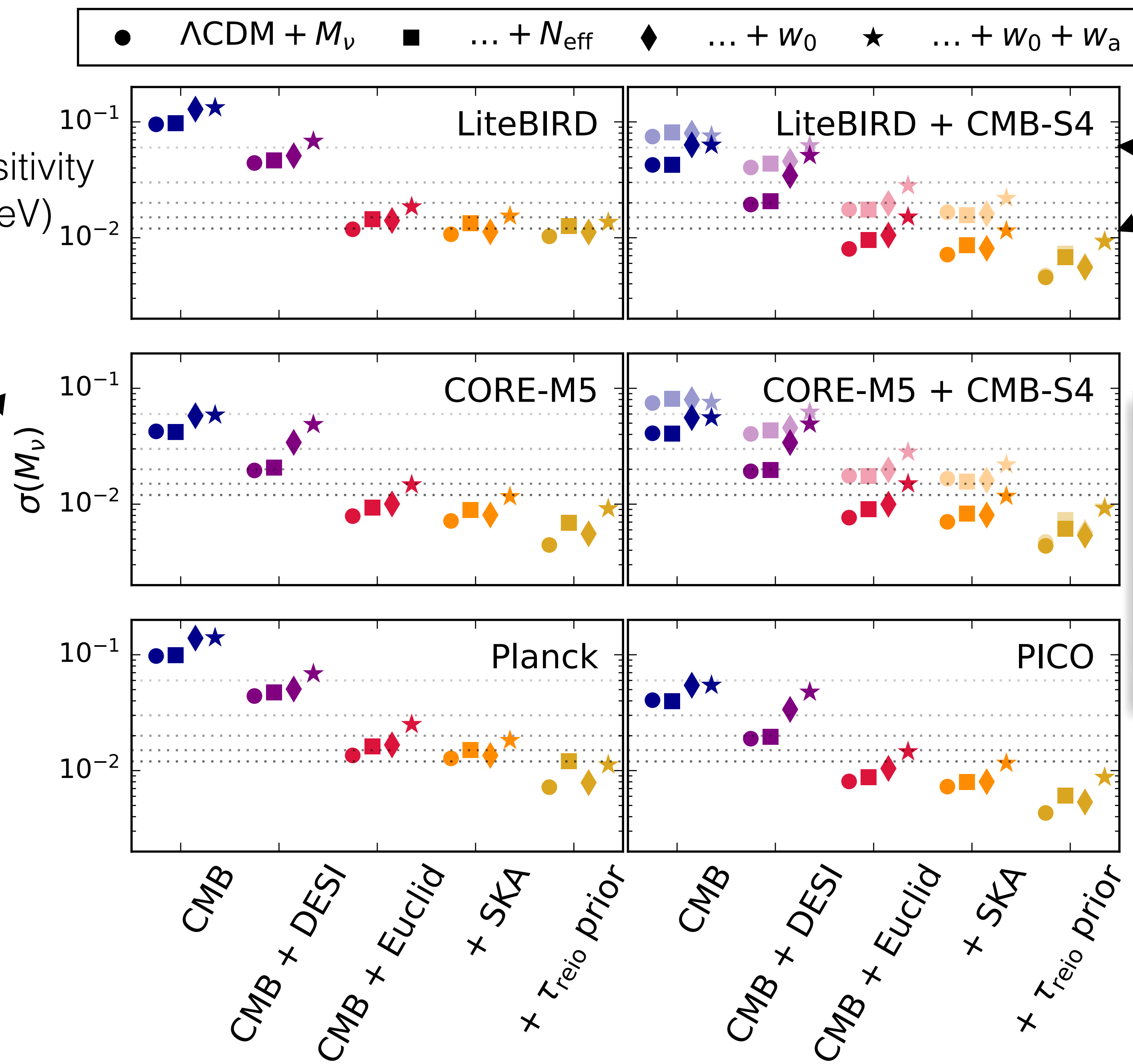
- Independent measurement of H_0 or $\tau_{\rm reio}$

Conservative MCMC forecasts

- Conservative MCMC forecasts with theoretical error bar (assuming M_ν=0.06eV):

Sprenger et al. 1804.07261, Brinckmann et al. 1808.05955

1σ sensitivity to M_ν (eV)



1σ to 5σ detection levels assuming fiducial M_ν=0.06eV

>5σ detection is a safe bet with e.g.
LiteBird+CMB-S4+EUCLID
or
Planck+SKA+τ_{prior}

$\sigma(\tau_{reio})$ ~ 0.001 from SKA/HERA to resolve M_ν - τ_{reio} degeneracy in CMB+BAO data

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