Neutrino masses and dark forces

Zach Weiner • Perimeter Institute

GGI, September 5, 2025

based on work with Marilena Loverde (2410.00090) and forthcoming

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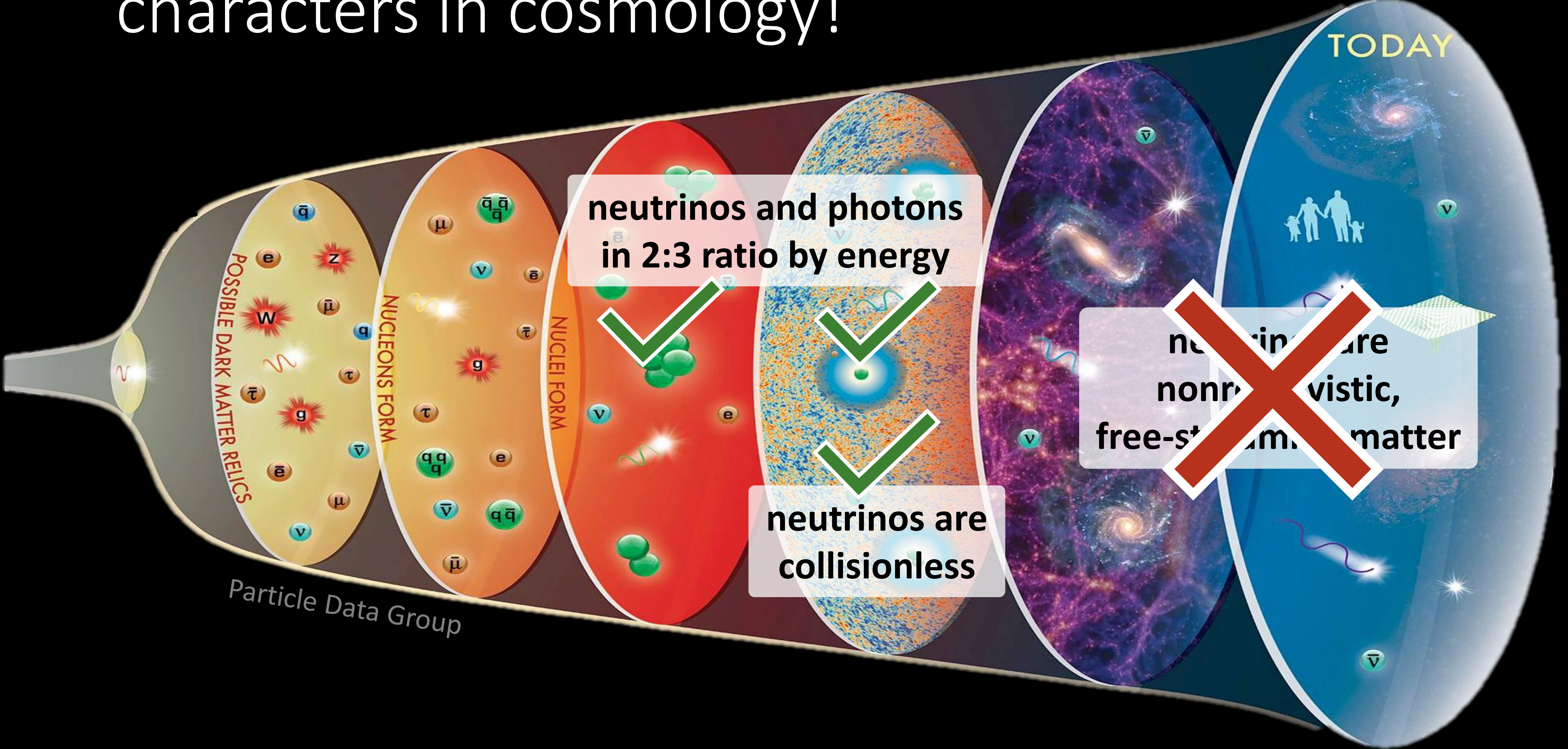
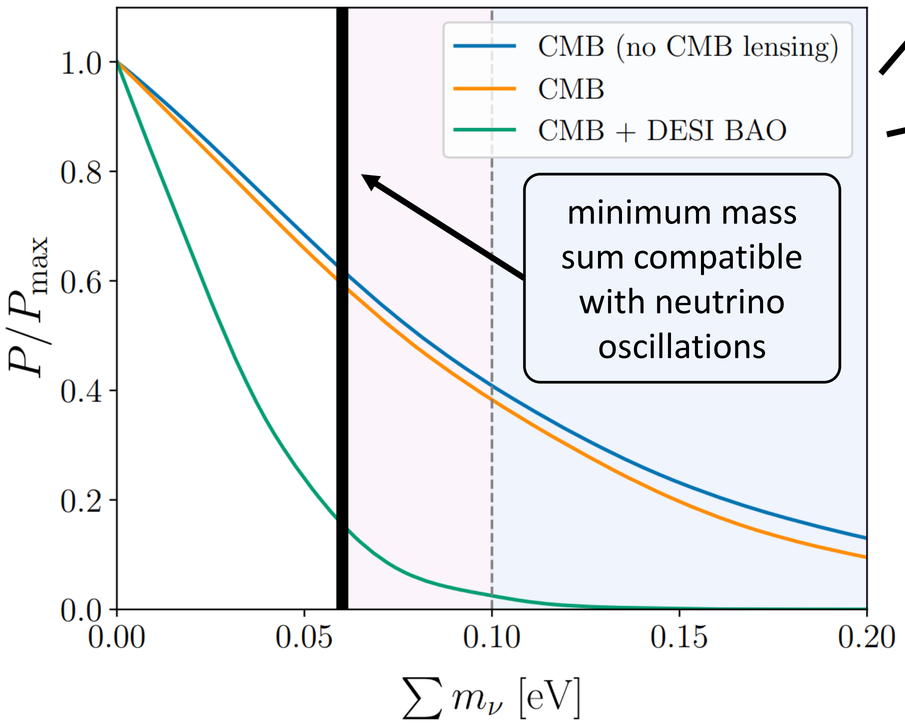
Neutrinos are main characters in cosmology!



Are neutrinos massive?

DESI's first data release (2404.03002)



where are the cosmological signatures of neutrino masses?

do neutrinos have "negative mass?"

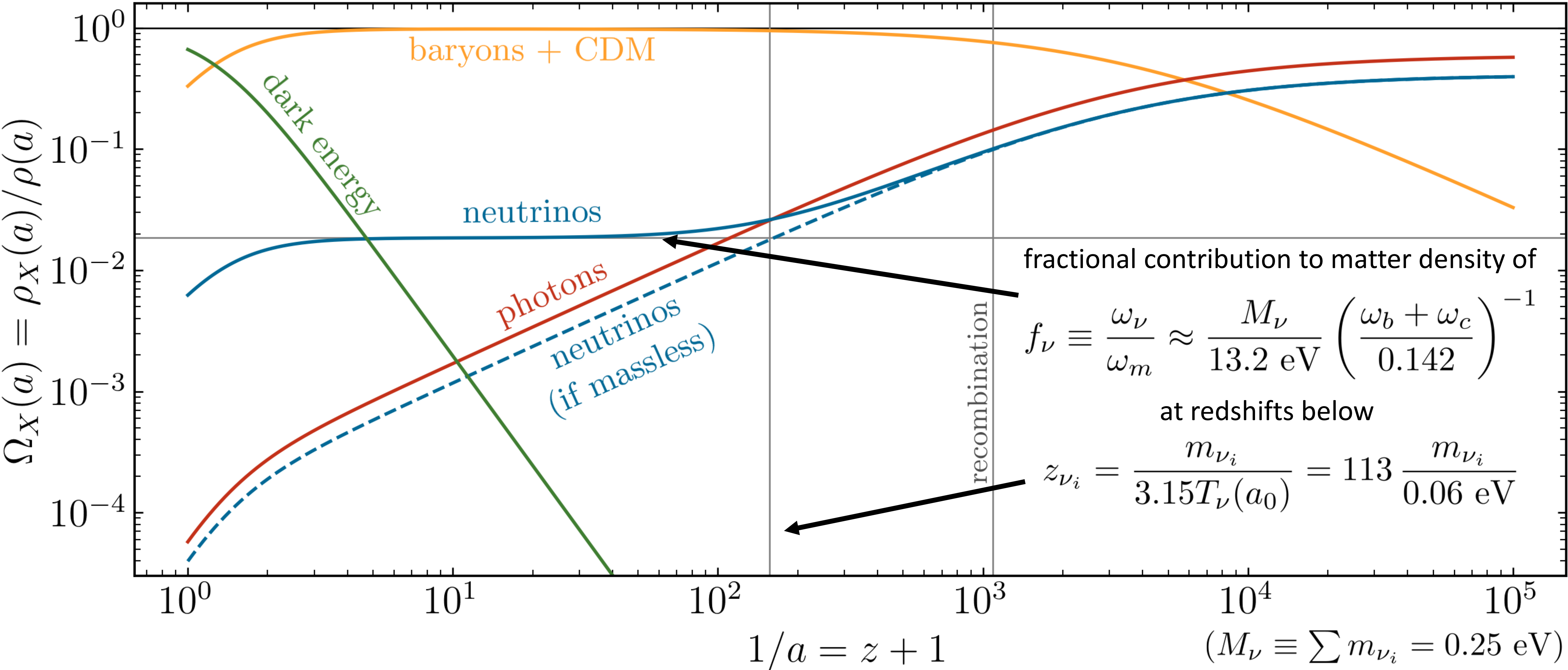
Critical to understand all physical effects of massive neutrinos

- Impact on expansion history not negligible, is as important as suppression of structure
- Distances and LSS jointly measure mass by constraining effects on structure *and* geometry

Every challenge is an opportunity

- Something unknown in either fundamental physics or observational systematics

Massive neutrinos are "late-time" physics



fractional contribution to matter density of

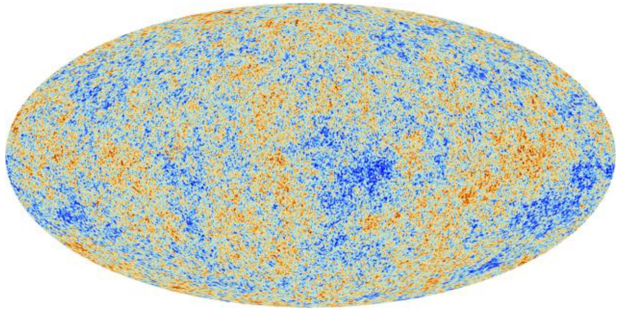
$$f_\nu \equiv \frac{\omega_\nu}{\omega_m} \approx \frac{M_\nu}{13.2\ \text{eV}} \left(\frac{\omega_b + \omega_c}{0.142}\right)^{-1}$$

at redshifts below

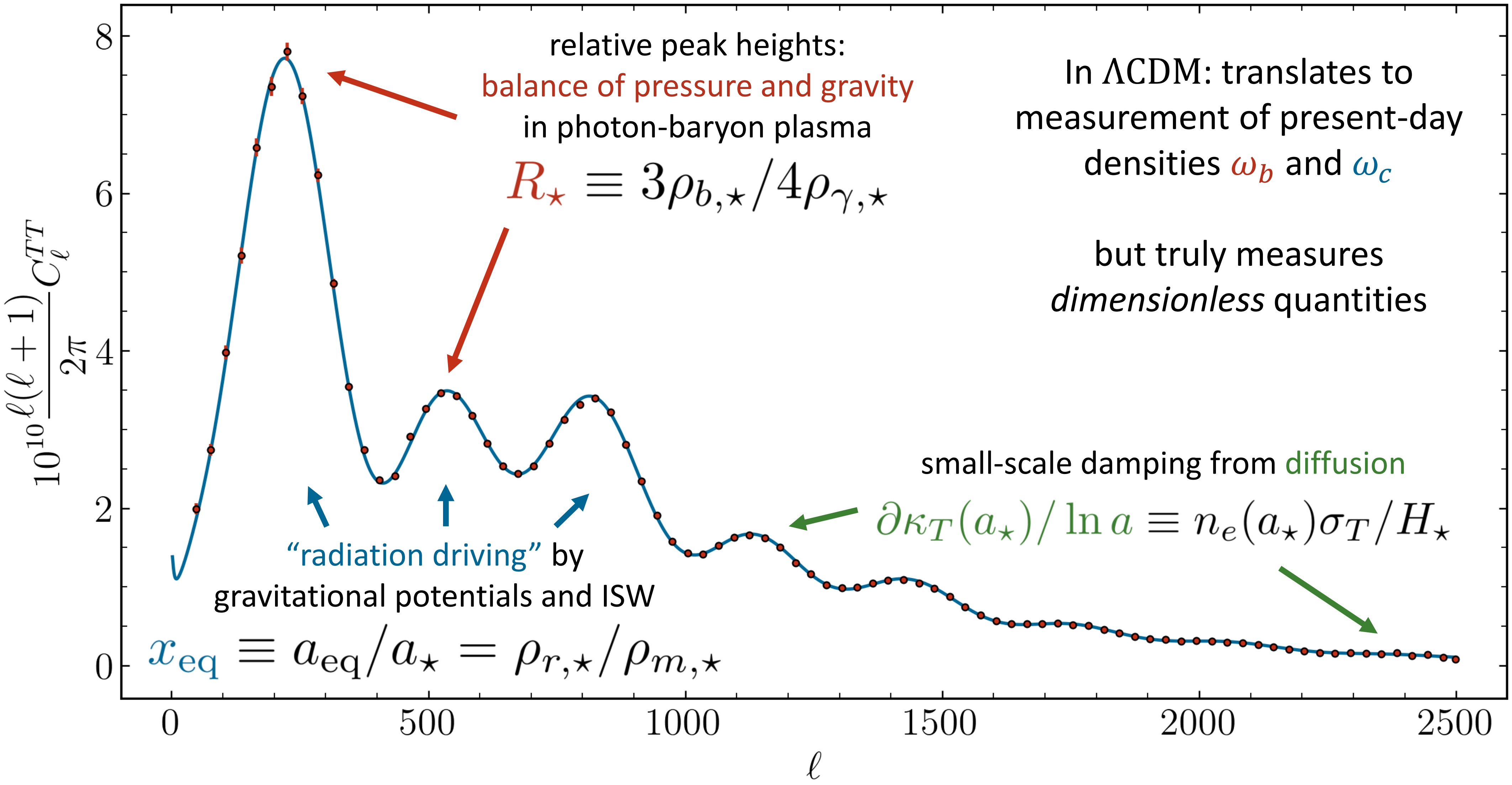
$$z_{\nu_i} = \frac{m_{\nu_i}}{3.15 T_\nu(a_0)} = 113\ \frac{m_{\nu_i}}{0.06\ \text{eV}}$$

Steps to neutrino masses

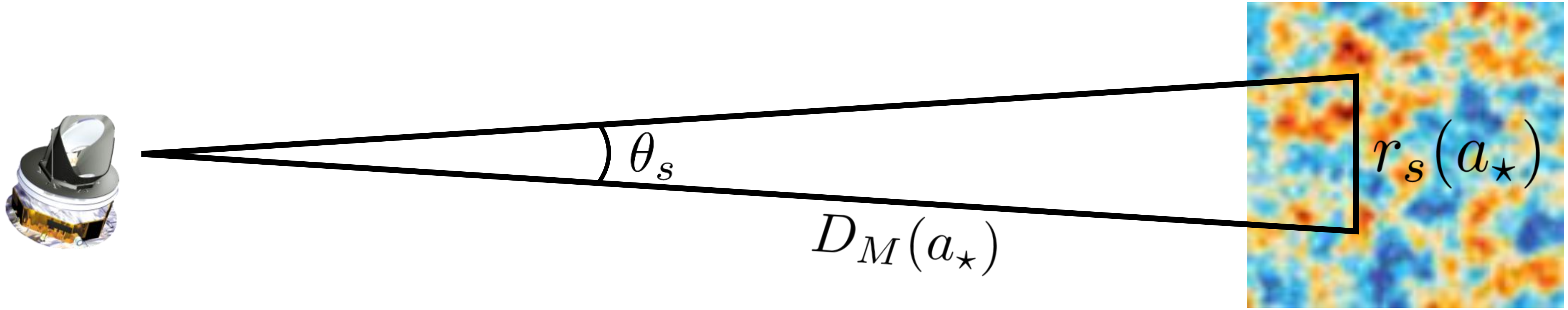
1. Calibrate the initial conditions and densities at recombination with CMB temperature and polarization



Density ratios from recombination

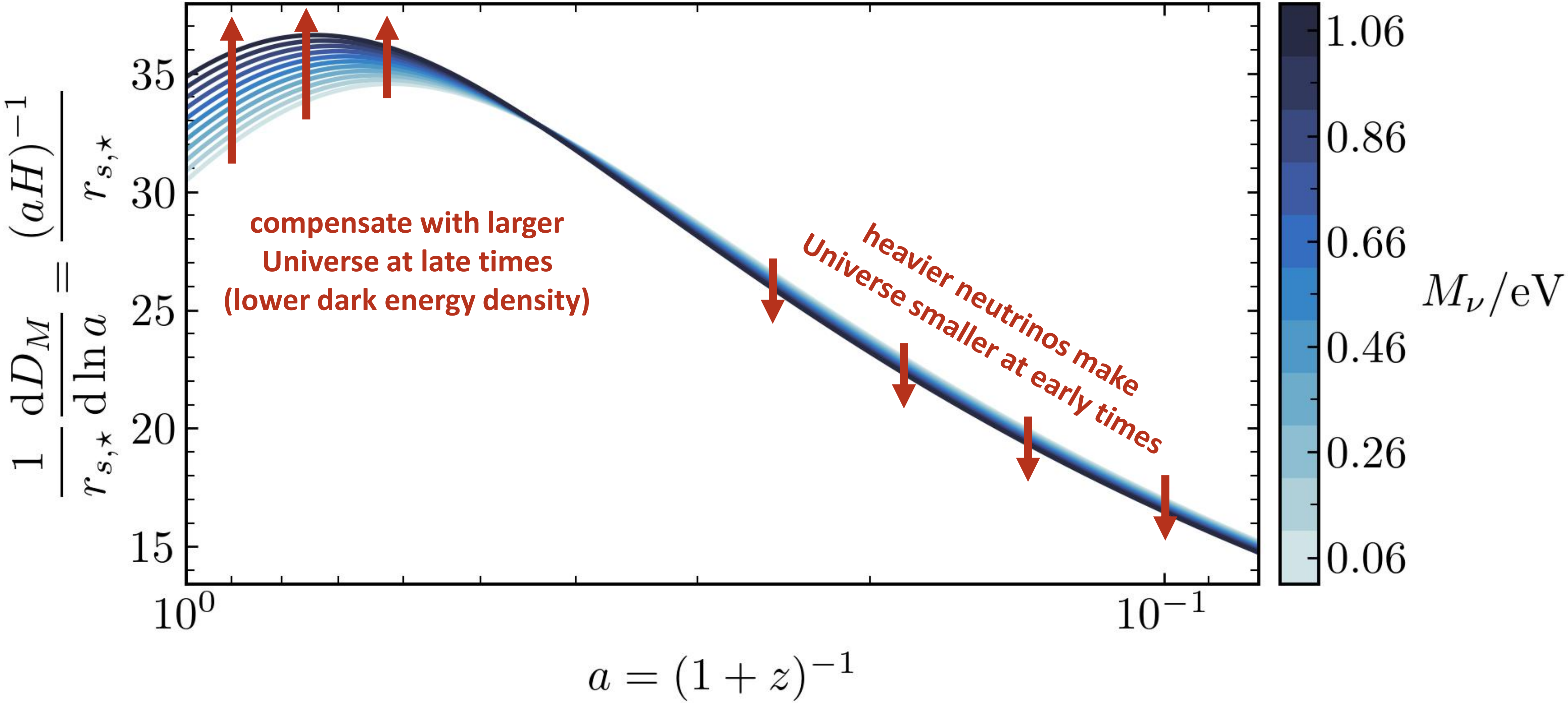


Second-best measured number in cosmology



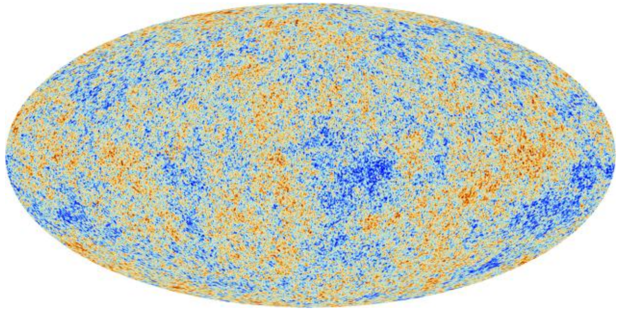
$$\theta_s \equiv \frac{\text{fixed by shape of primary CMB in } \Lambda\text{CDM}}{\text{must fix with remaining parameter freedom: } \Lambda} = \frac{r_s(a_\star)}{D_M(a_\star)}$$

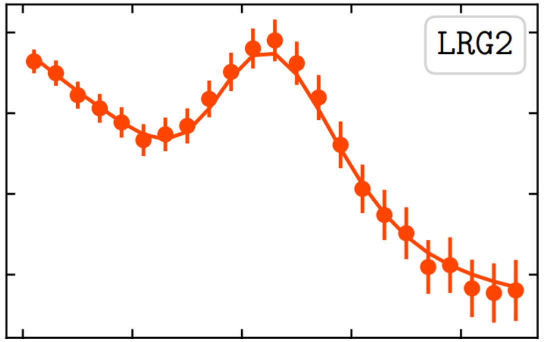
Fixing the distance to last scattering



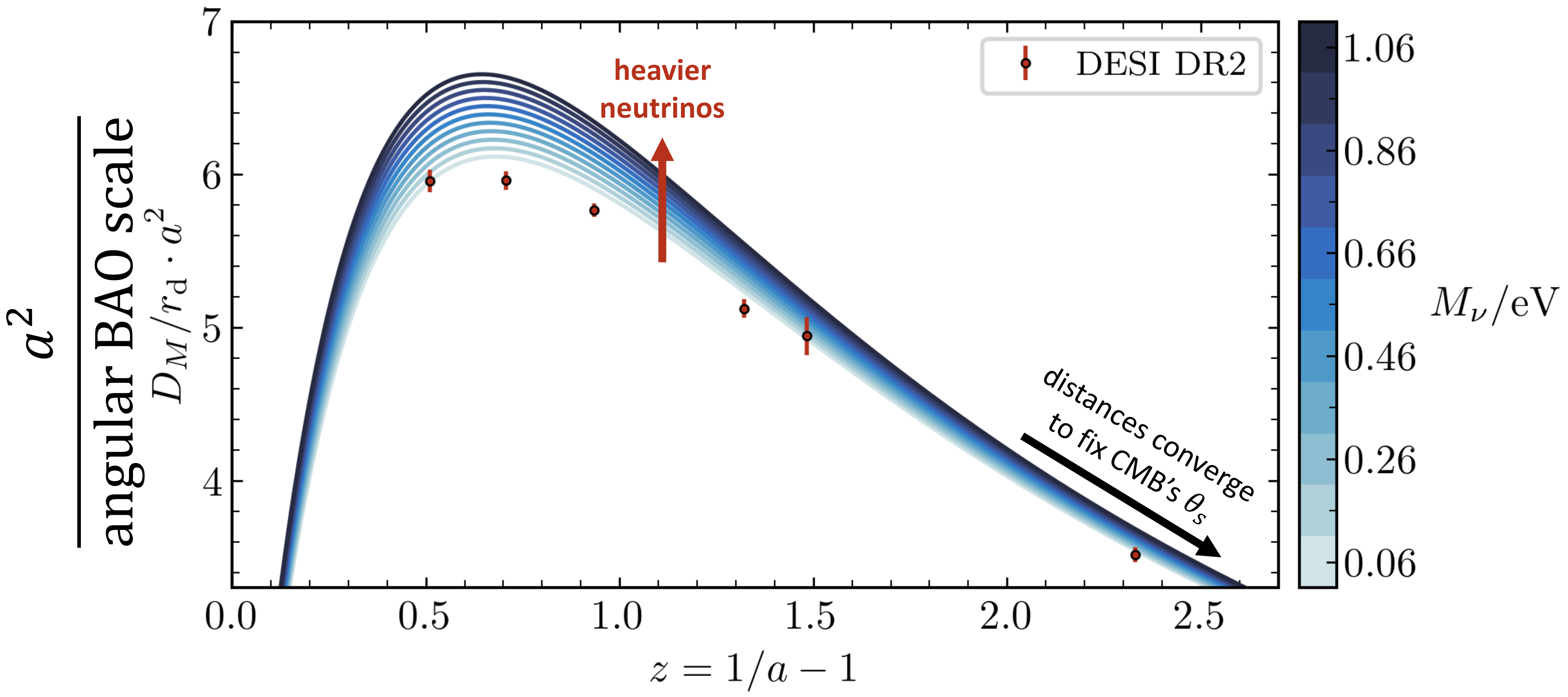
Steps to neutrino masses

1. Calibrate the initial conditions and densities at recombination with CMB temperature and polarization
2. Extrapolate late-time dynamics
   a) Relative distances as a function of redshift





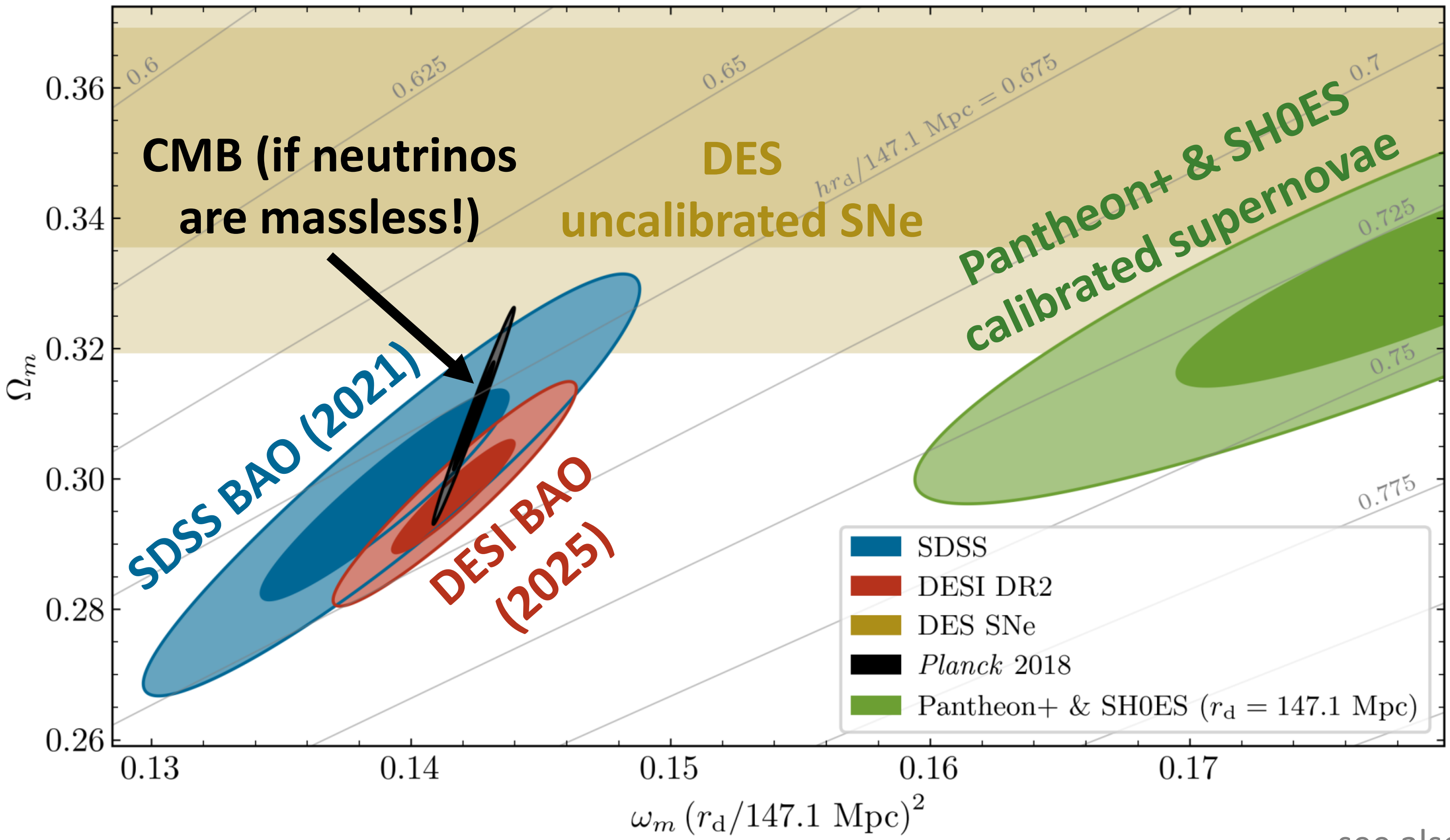
Massive neutrinos distort distances



Late-time extrapolation and measurements

matter *fraction*

$$\Omega_m = \frac{\rho_{m,0}}{\rho_0}$$



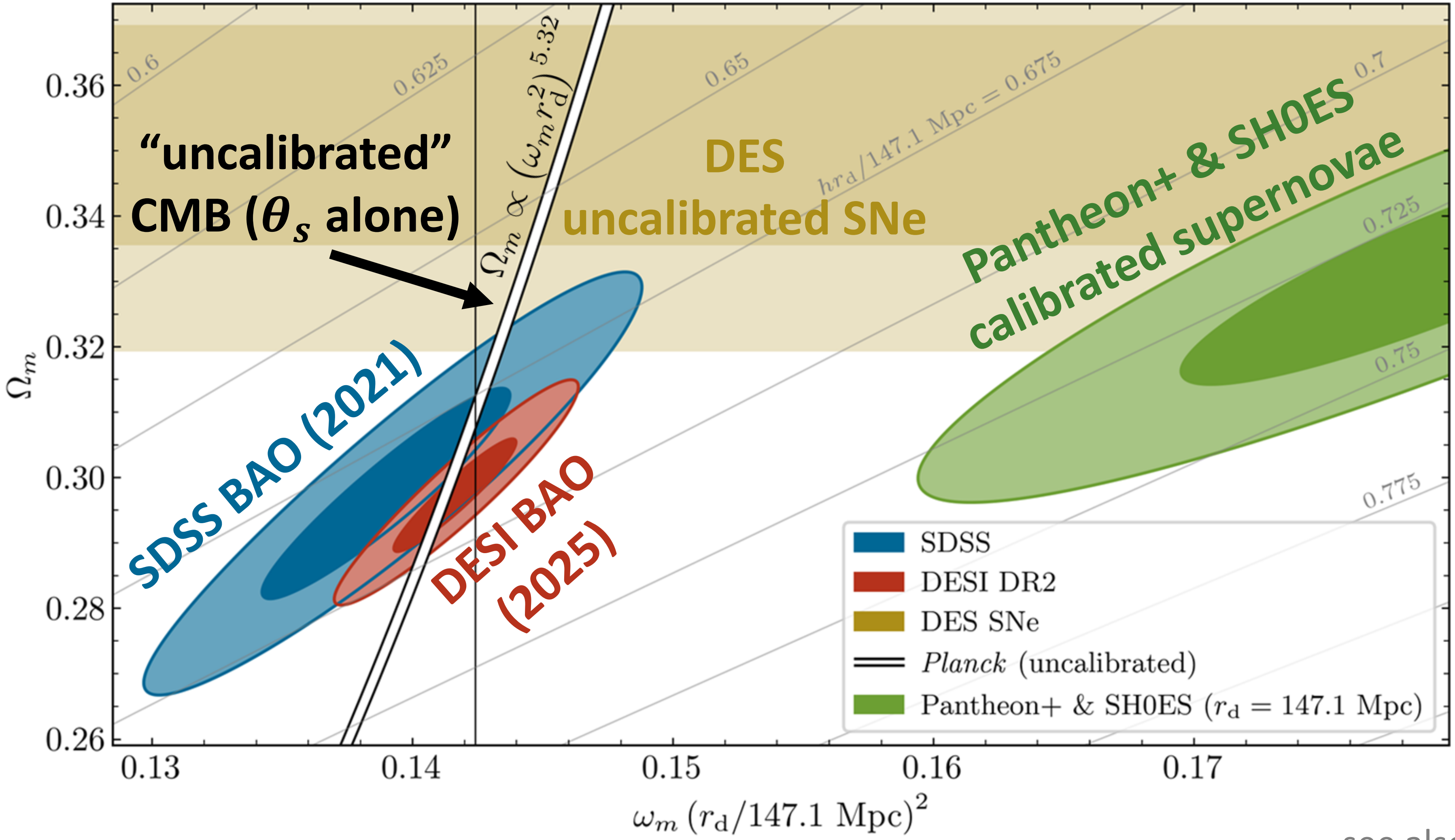
matter *density* relative to sound horizon

2410.00090
see also Eisenstein & White (astro-ph/0407539)

Decalibrated extrapolation

matter *fraction*

$\Omega_m = \frac{\rho_{m,0}}{\rho_0}$



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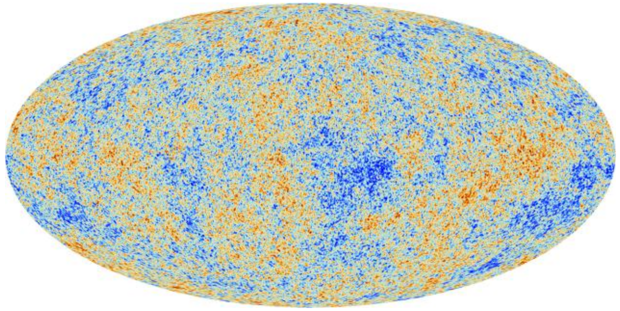
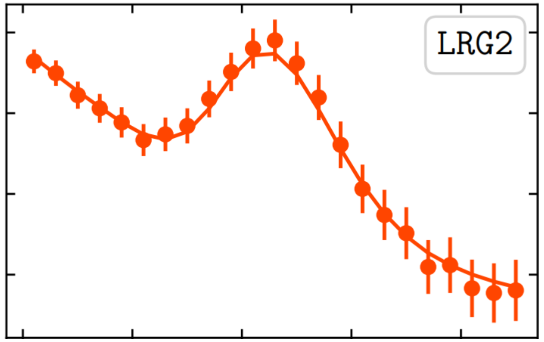
Steps to neutrino masses

1. Calibrate the initial conditions and densities at recombination with CMB temperature and polarization
2. Extrapolate late-time dynamics
   a) Relative distances as a function of redshift
3. Infer neutrino mass that explains…
   a) Increase in abundance of nonrelativistic matter

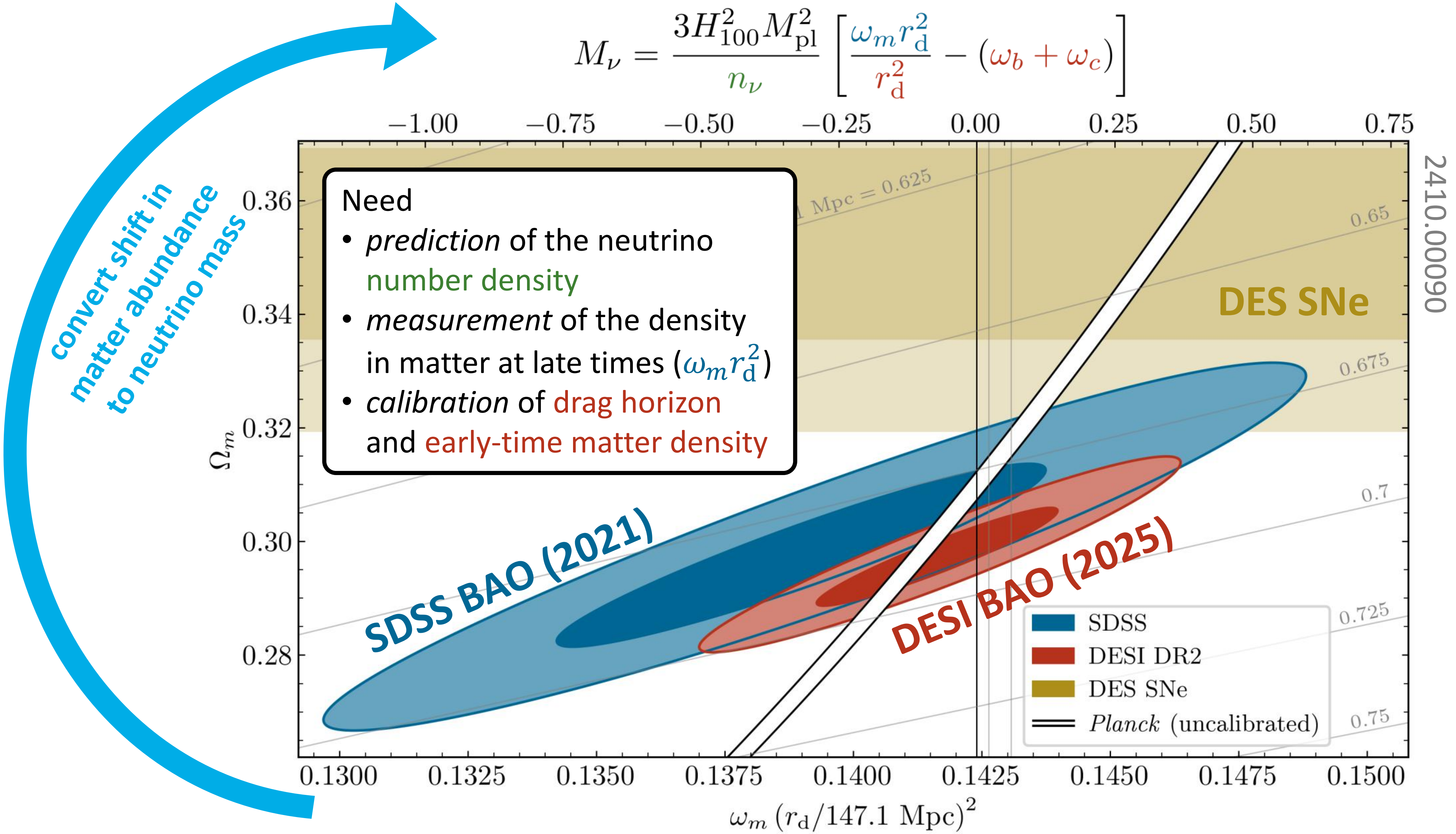




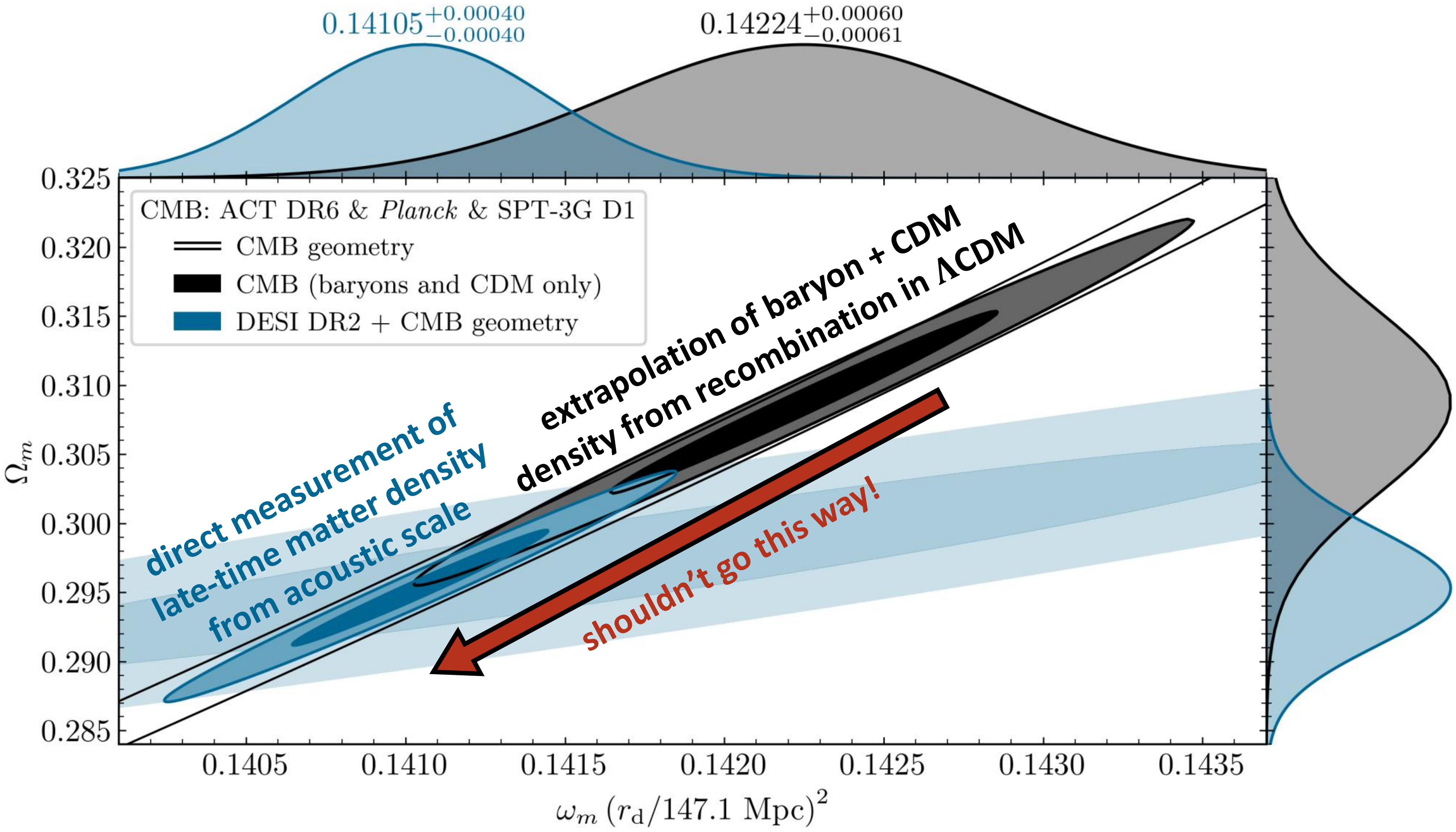
Neutrino mass from the acoustic scale

$$M_\nu = \frac{3H_{100}^2 M_{\rm pl}^2}{n_\nu}\left[\frac{\omega_m r_{\rm d}^2}{r_{\rm d}^2} - (\omega_b + \omega_c)\right]$$

Need
- *prediction* of the neutrino number density
- *measurement* of the density in matter at late times ($\omega_m r_{\rm d}^2$)
- *calibration* of drag horizon and early-time matter density

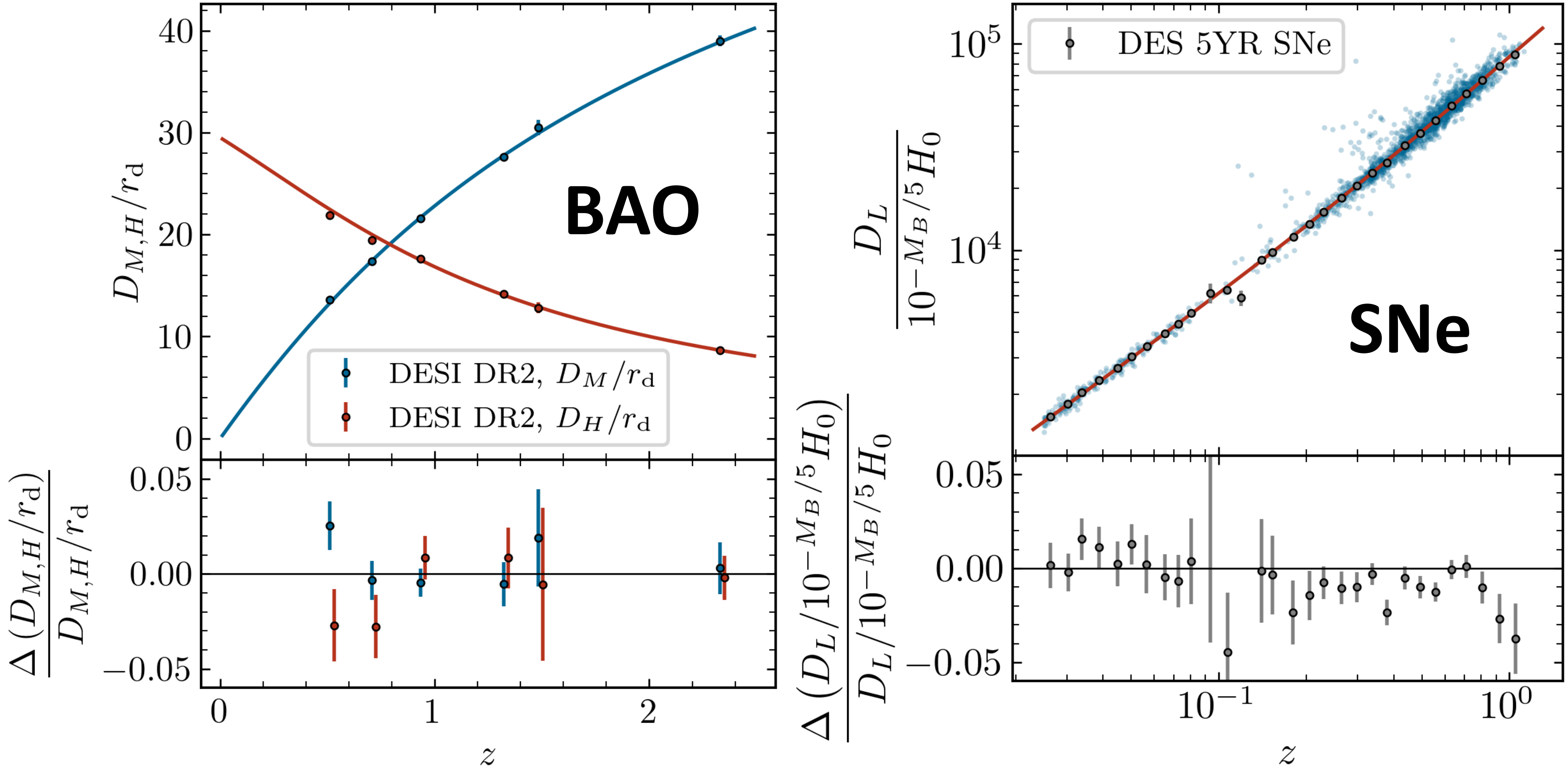


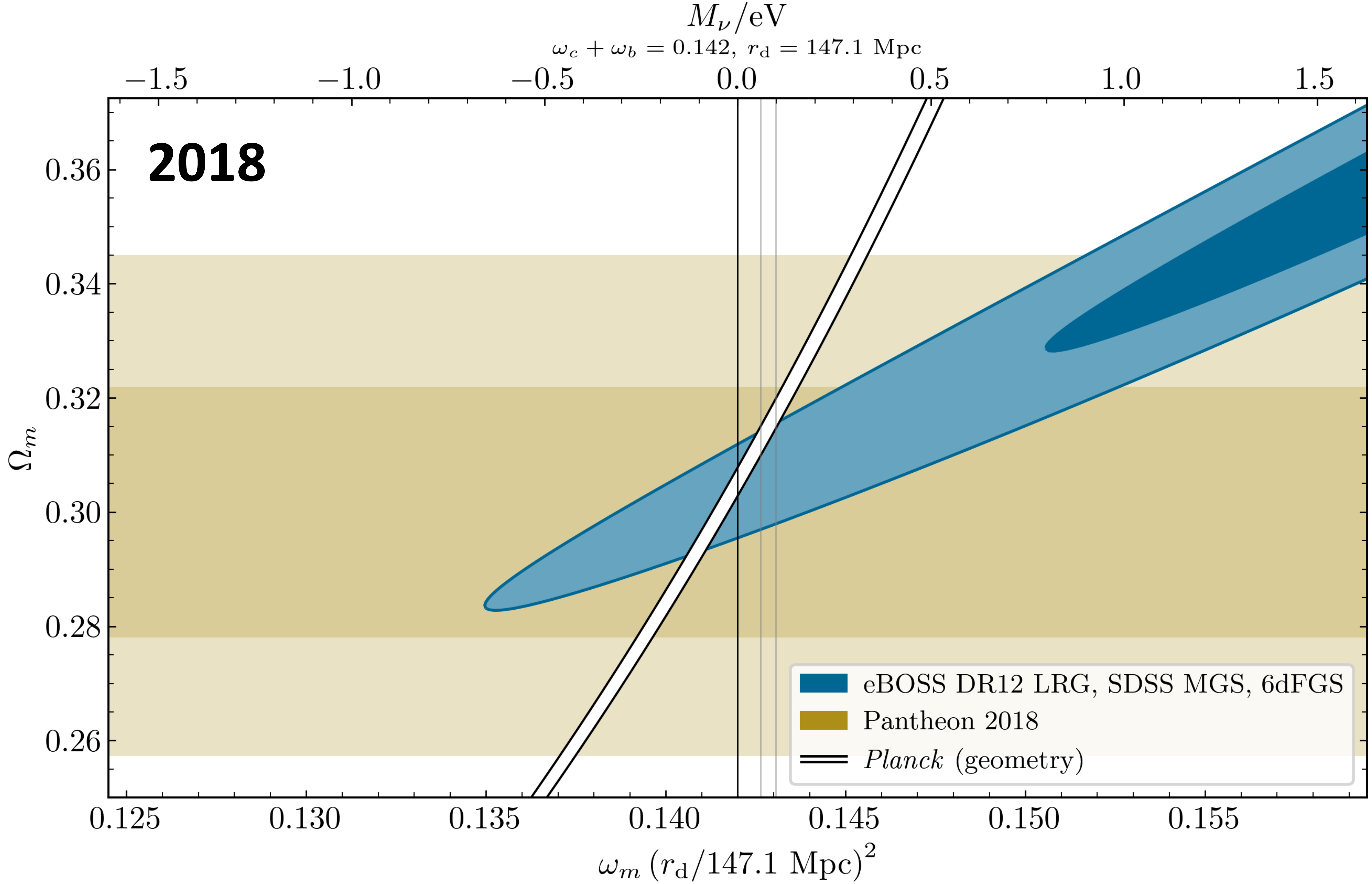
Matter density deficit



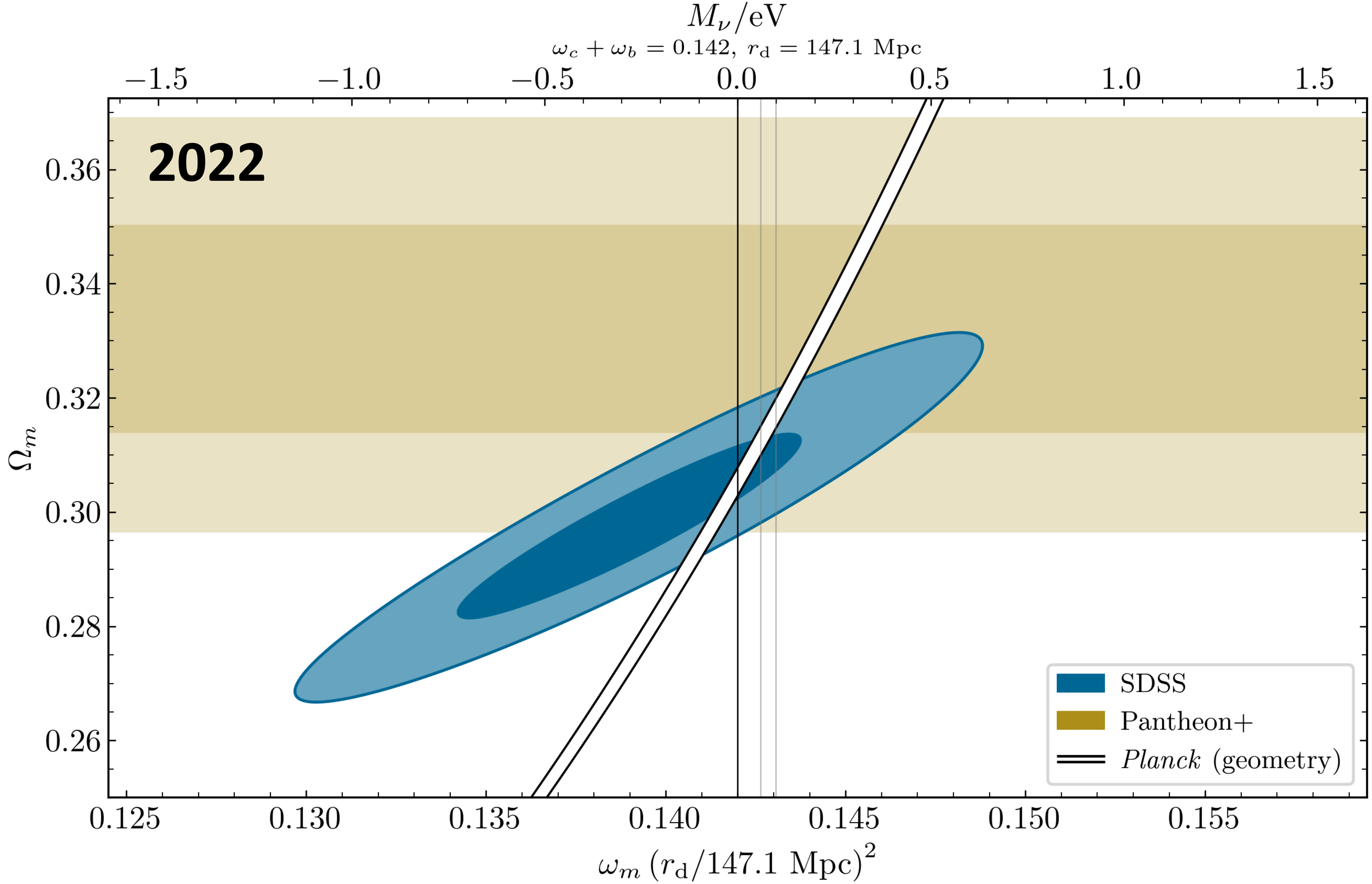
see 2410.00090
(phrase coined by Lloyd Knox and Gabe Lynch, 2503.14470)

Supernovae measure distances, too!





M_ν/eV
$\omega_c + \omega_b = 0.142,\ r_d = 147.1$ Mpc
−1.5
−1.0
−0.5
0.0
0.5
1.0
1.5
2018
0.36
0.34
0.32
0.30
0.28
0.26
Ω_m
eBOSS DR12 LRG, SDSS MGS, 6dFGS
Pantheon 2018
Planck (geometry)
0.125
0.130
0.135
0.140
0.145
0.150
0.155
$\omega_m\,(r_d/147.1\ \mathrm{Mpc})^2$



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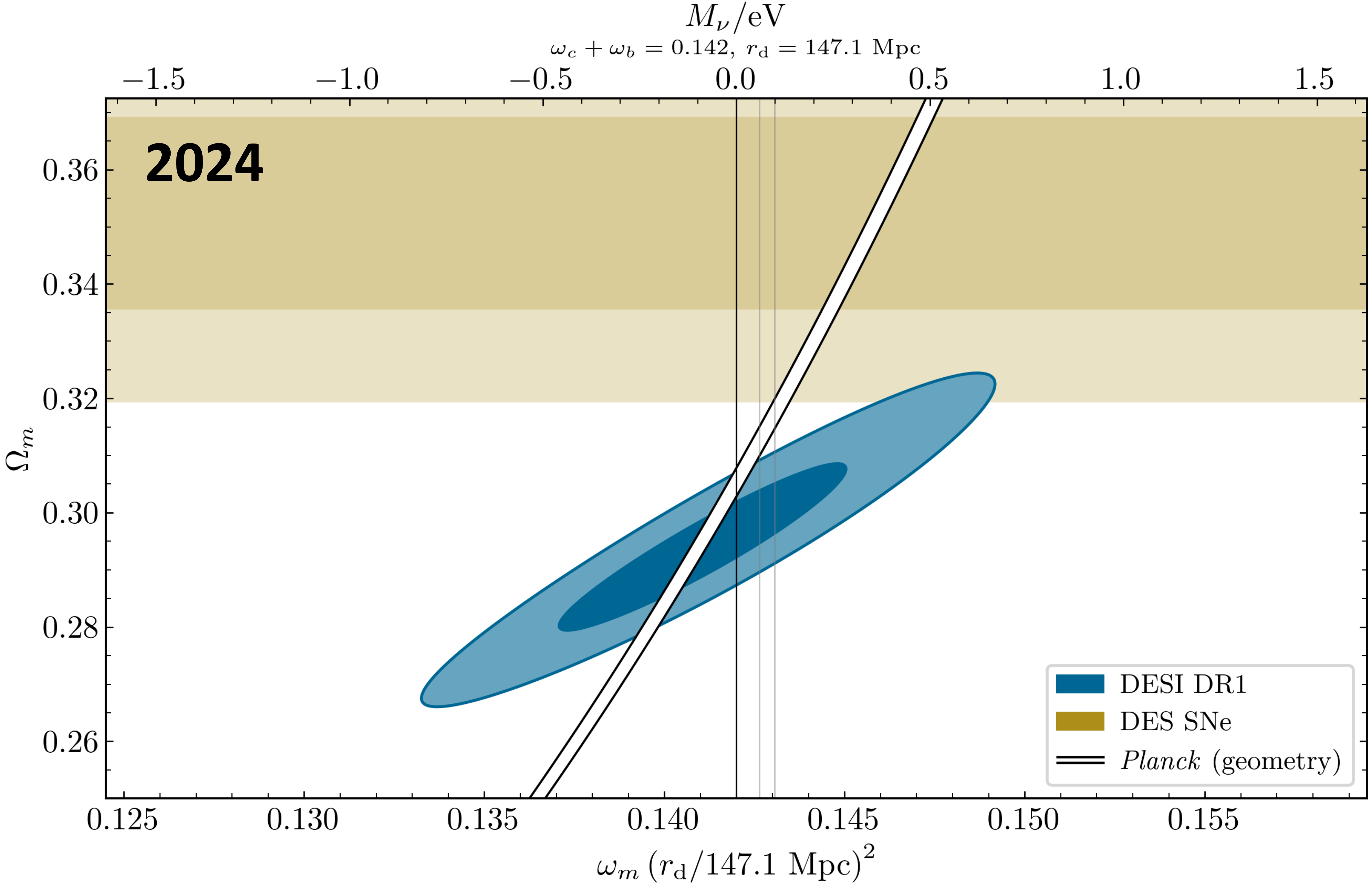
SDSS
Pantheon+
Planck (geometry)



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−1.5
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2024
0.36
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0.30
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0.26
Ω_m
DESI DR1
DES SNe
Planck (geometry)
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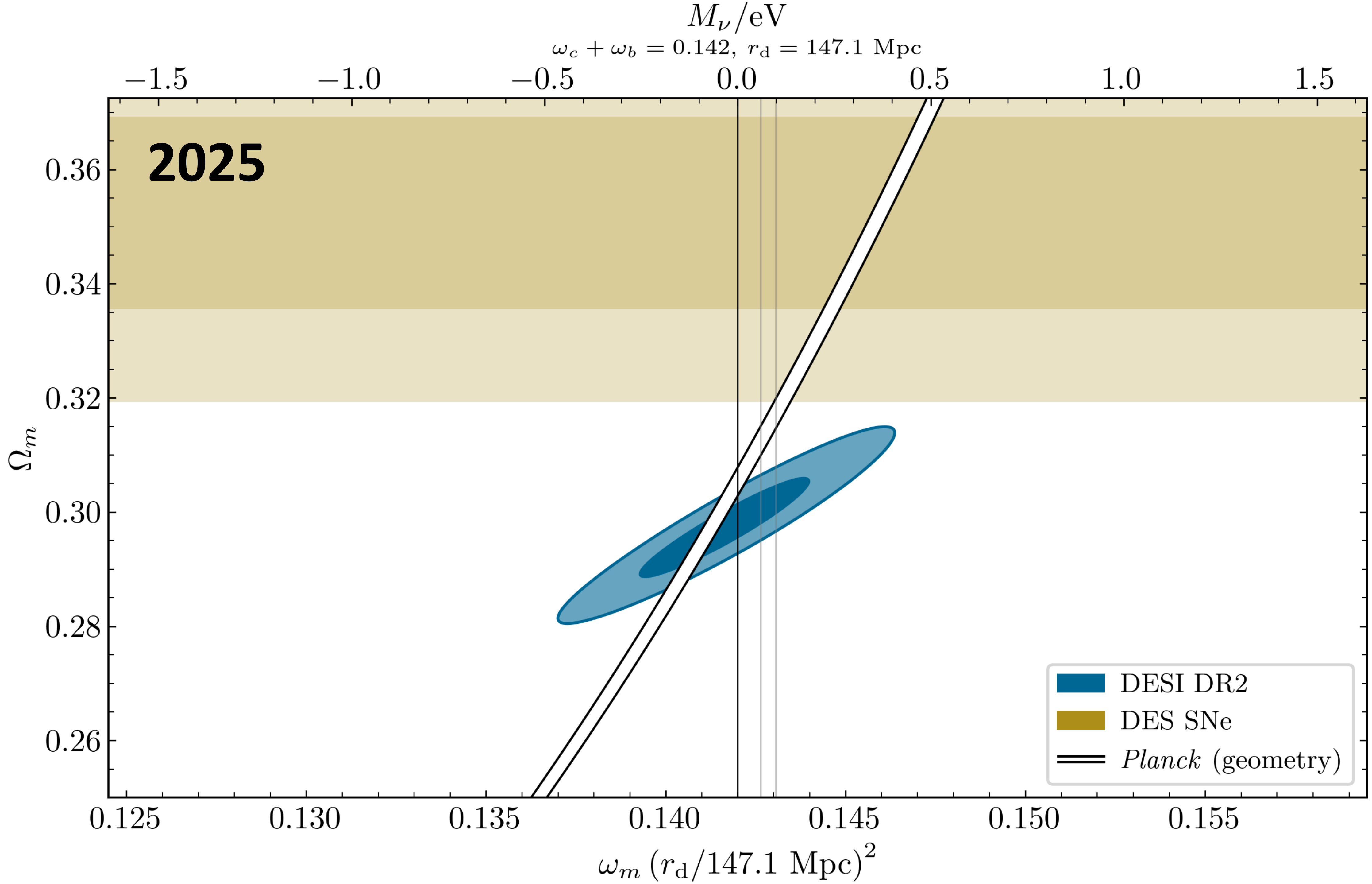
$\omega_m\,(r_d/147.1\ \mathrm{Mpc})^2$



M_ν/eV
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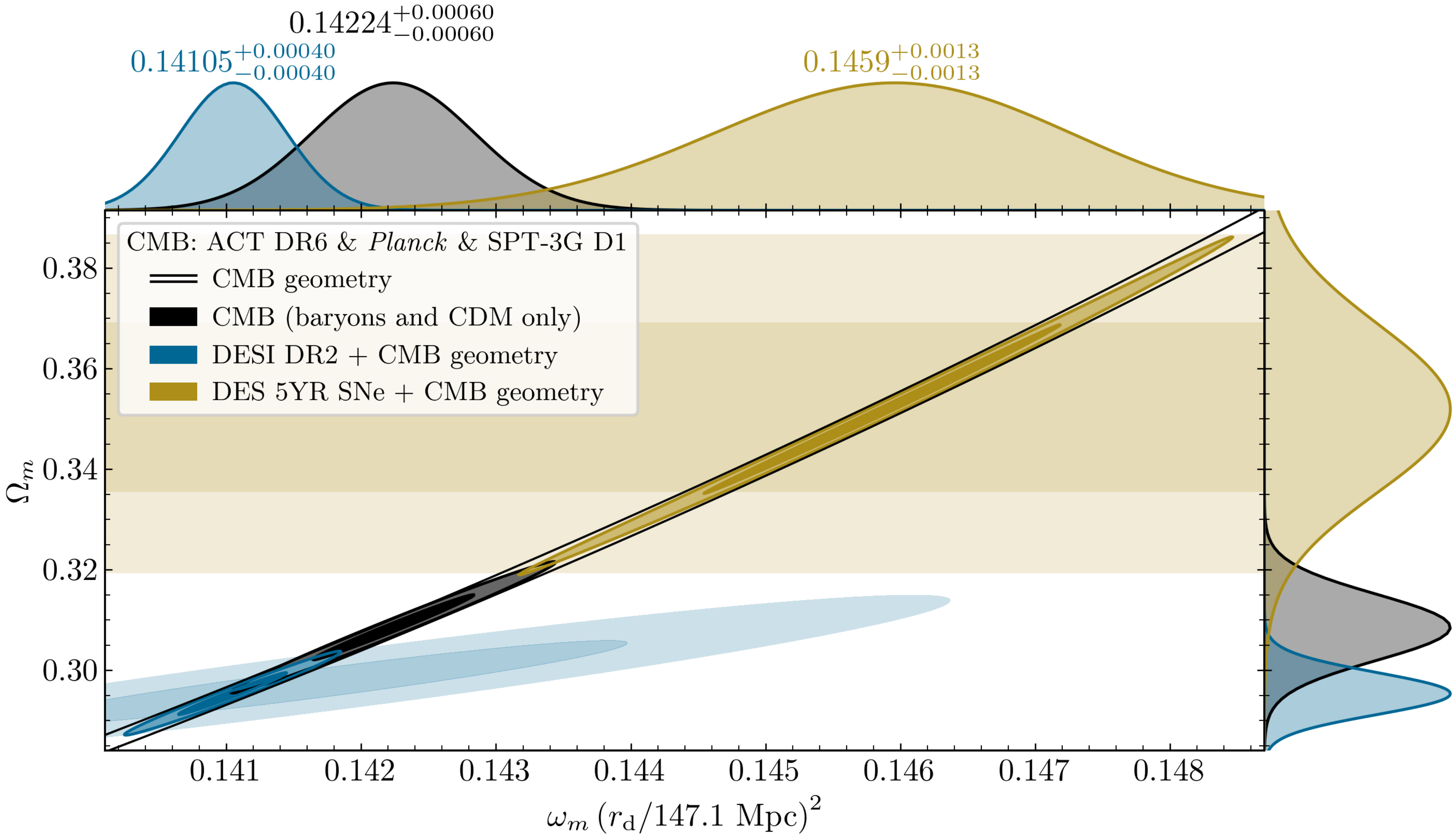
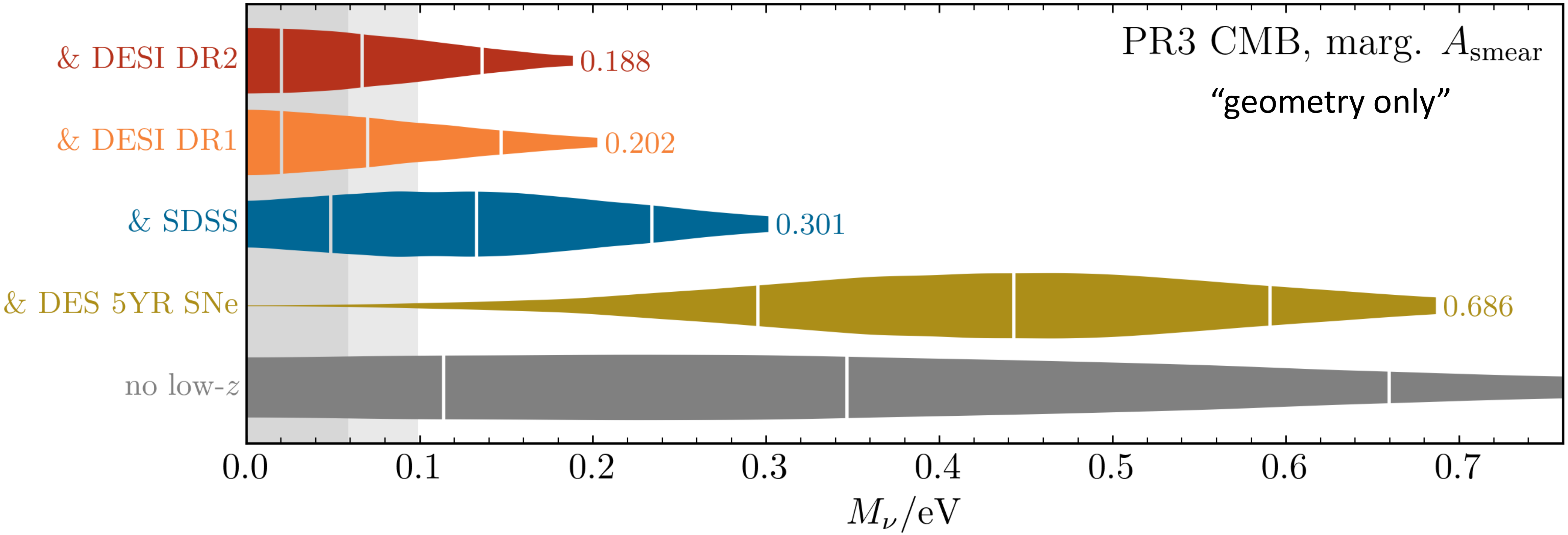
$\omega_m\,(r_d/147.1\ \mathrm{Mpc})^2$

Discordant neutrino mass measurements



2410.00090

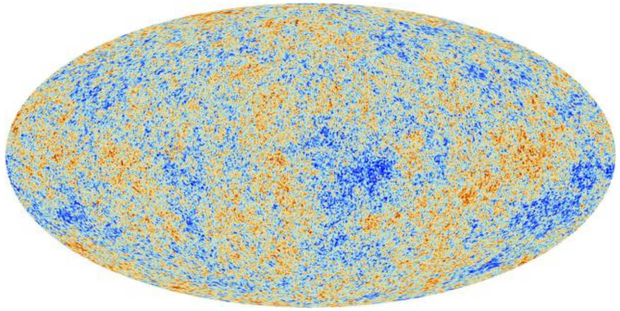
Discordant neutrino mass measurements

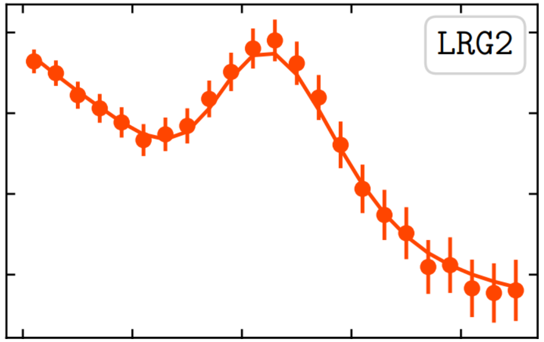


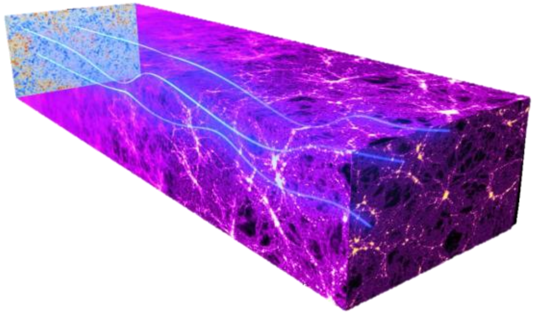
2410.00090

Steps to neutrino masses

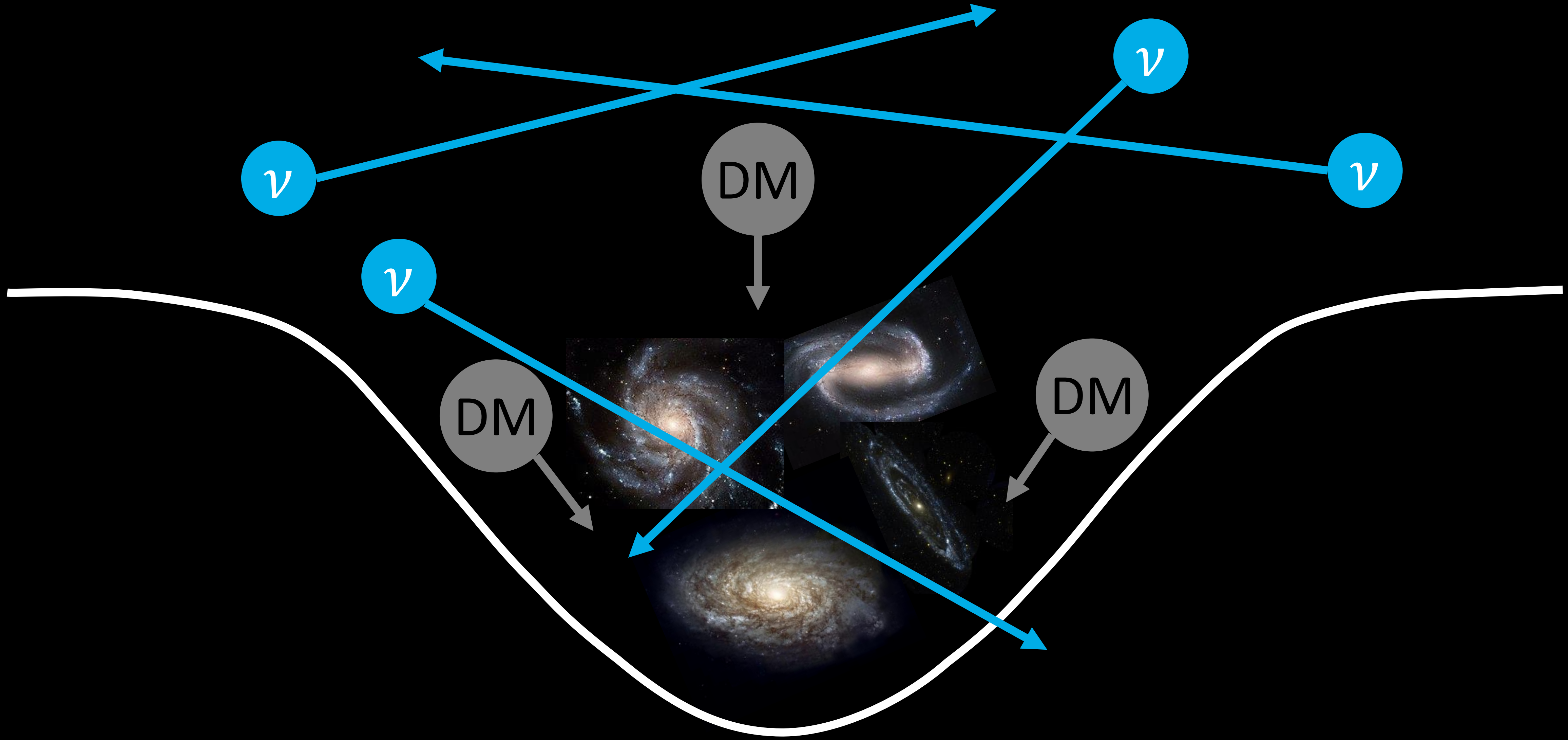
1. Calibrate the initial conditions and densities at recombination with CMB temperature and polarization
2. Extrapolate late-time dynamics
   a) Relative distances as a function of redshift
   b) Growth of structure



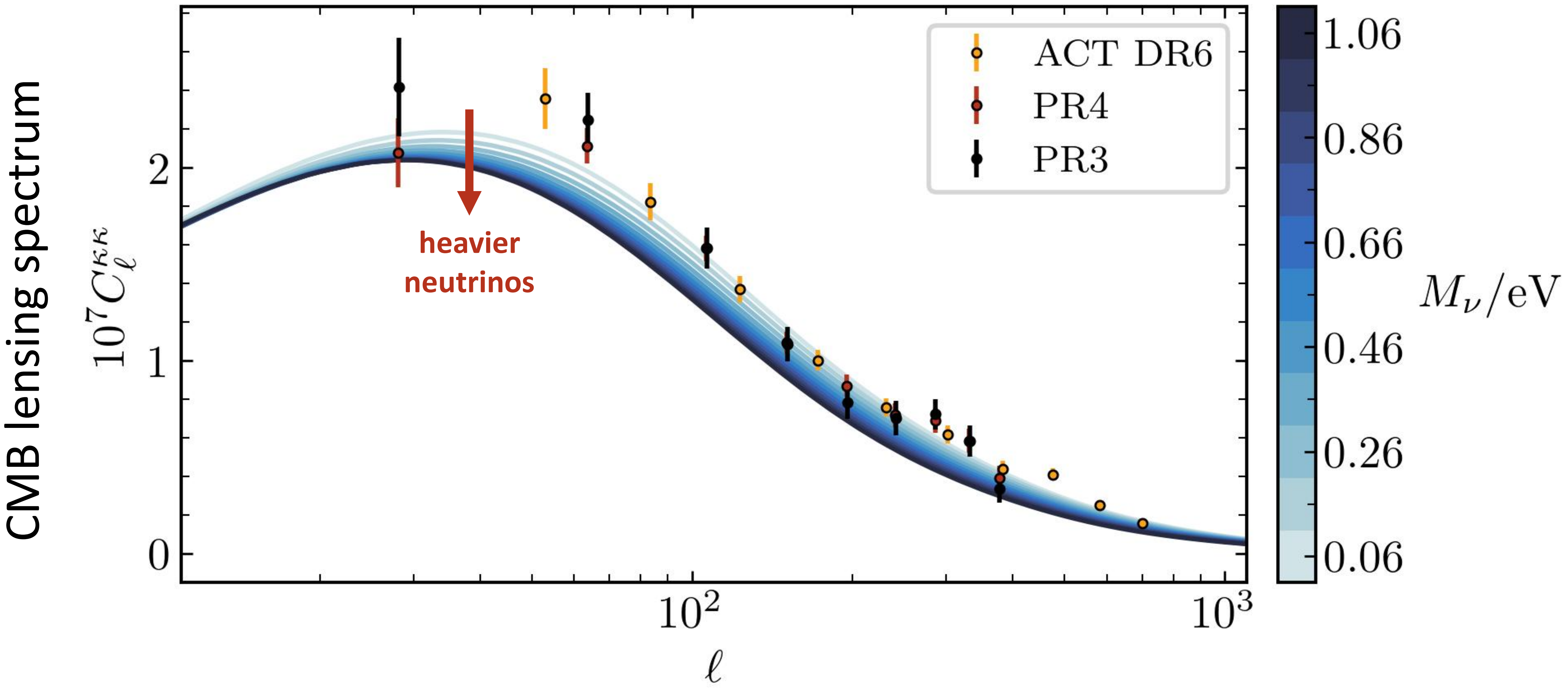




Neutrinos are fast



Massive neutrinos suppress structure



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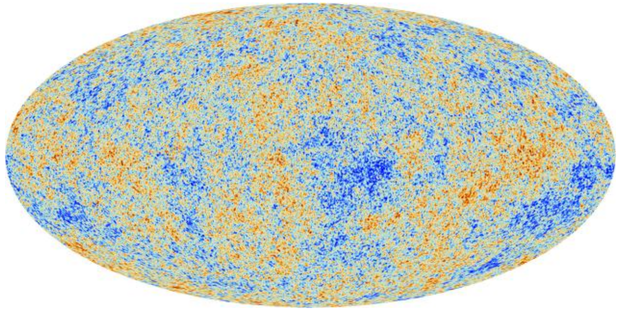
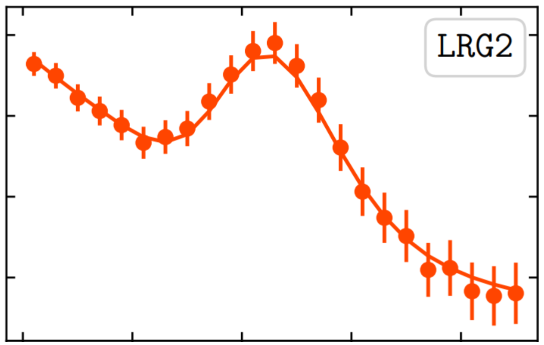
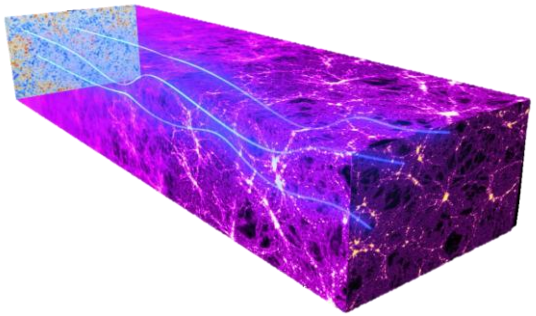


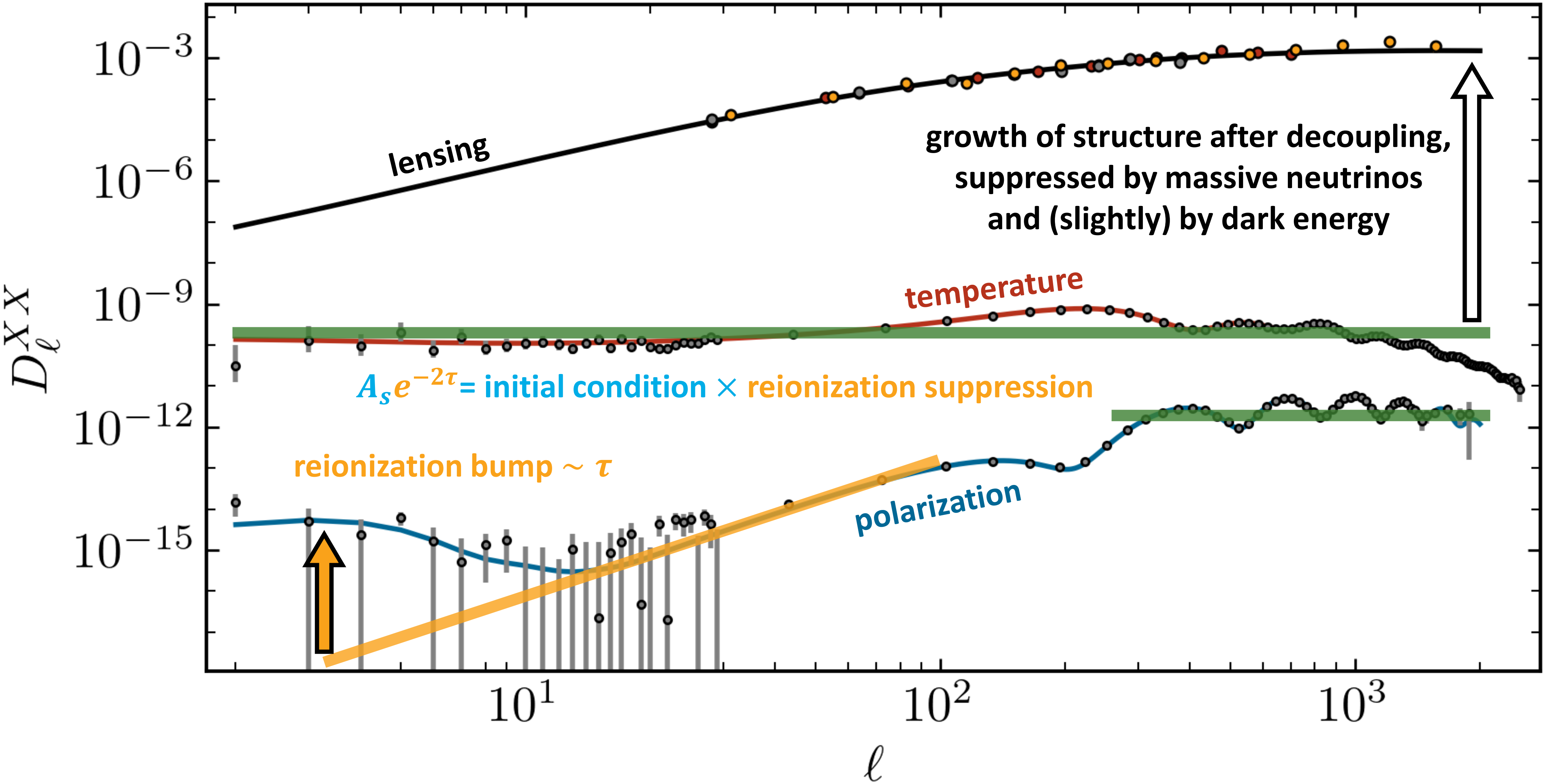
2. Extrapolate late-time dynamics
   a) Relative distances as a function of redshift
   b) Growth of structure



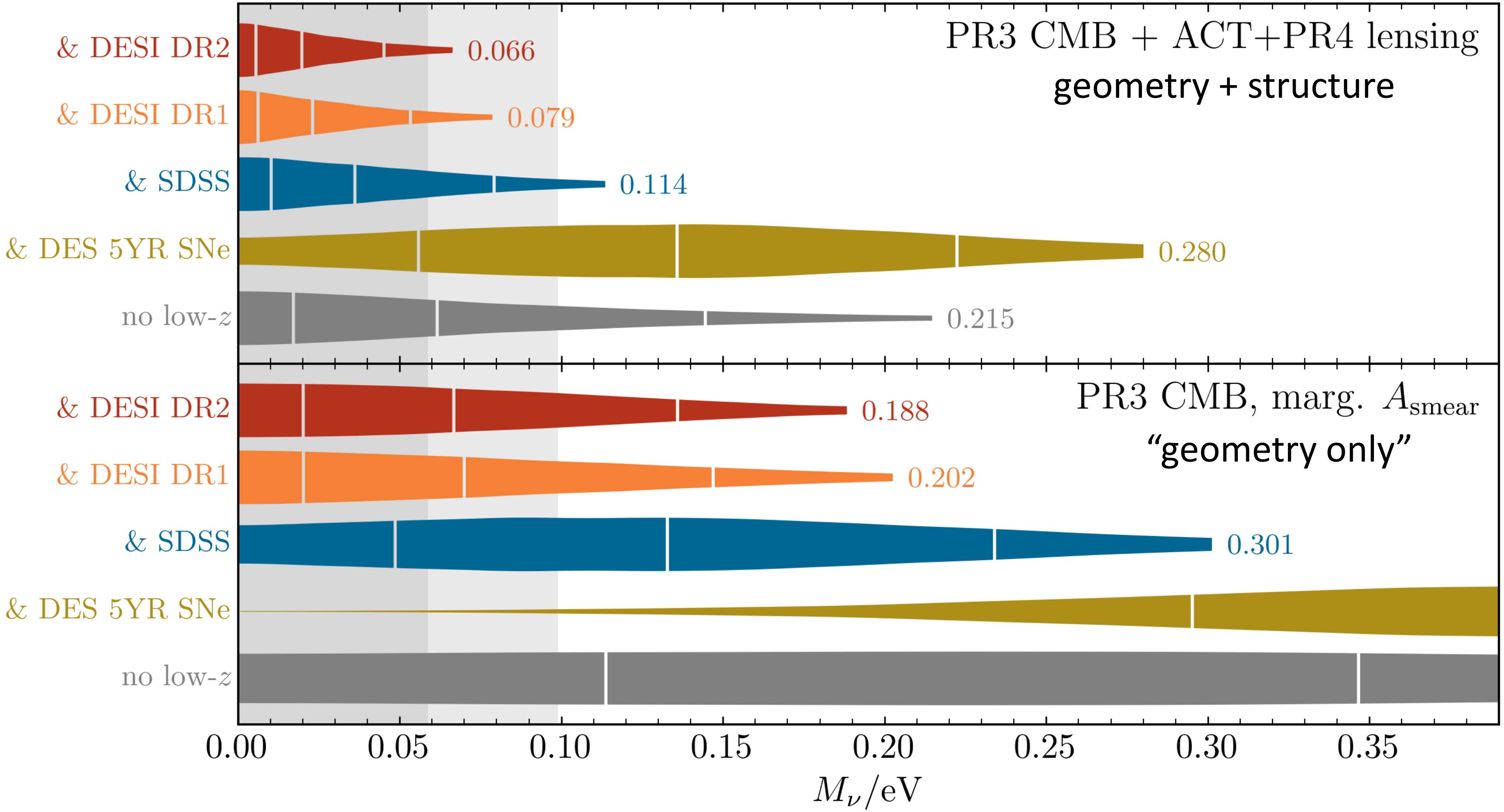
3. Infer neutrino mass that explains…
   a) Increase in abundance of nonrelativistic matter
   b) Decrease in accumulated structure growth



Reionization and large-scale polarization

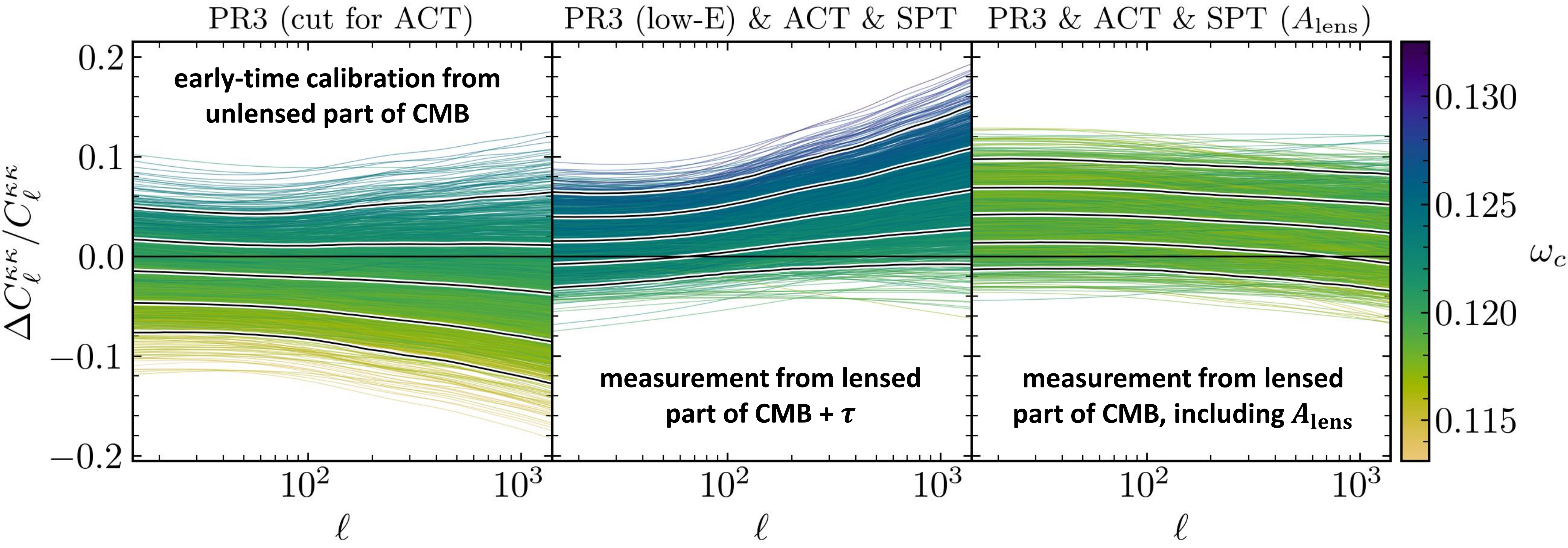


Discordant neutrino mass measurements

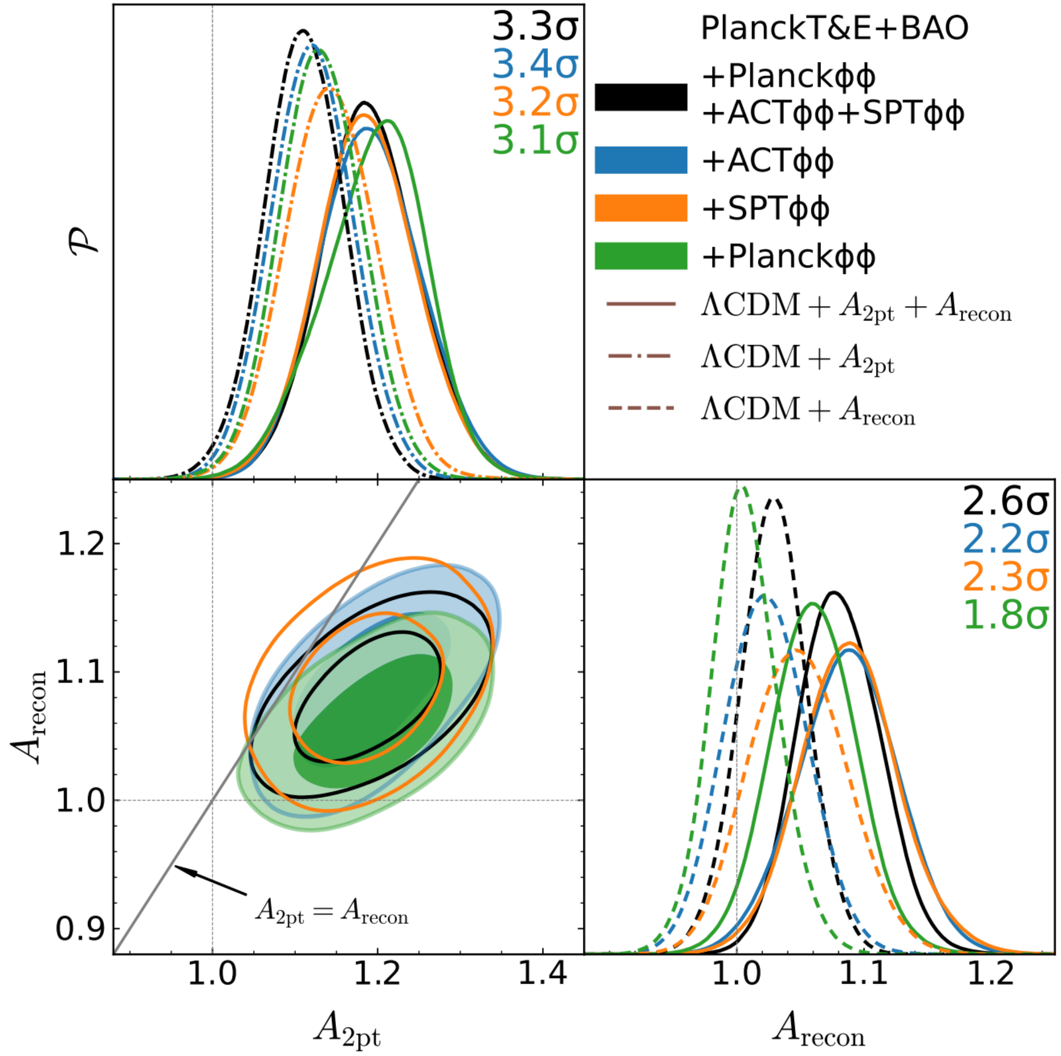


2410.00090

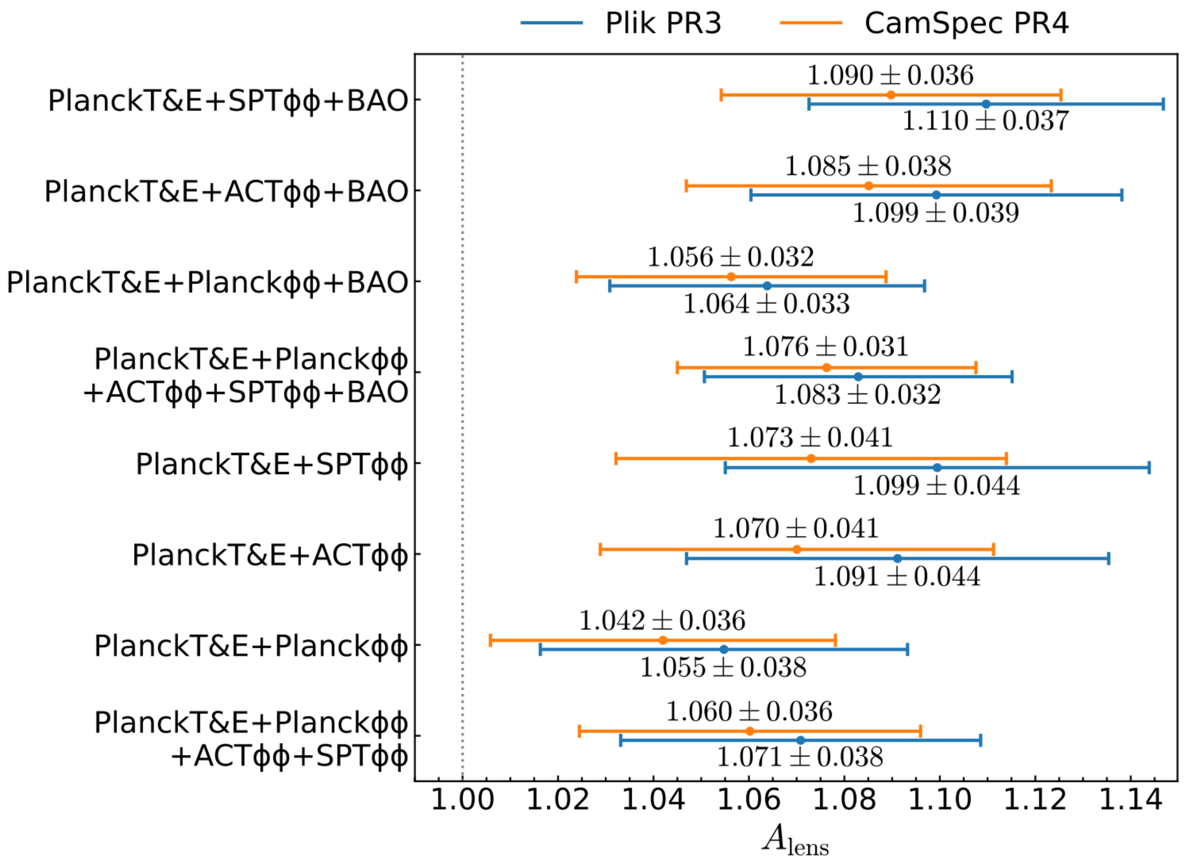
What is the CMB lensing excess?



The lensing excess



SPT-3G (2411.06000)

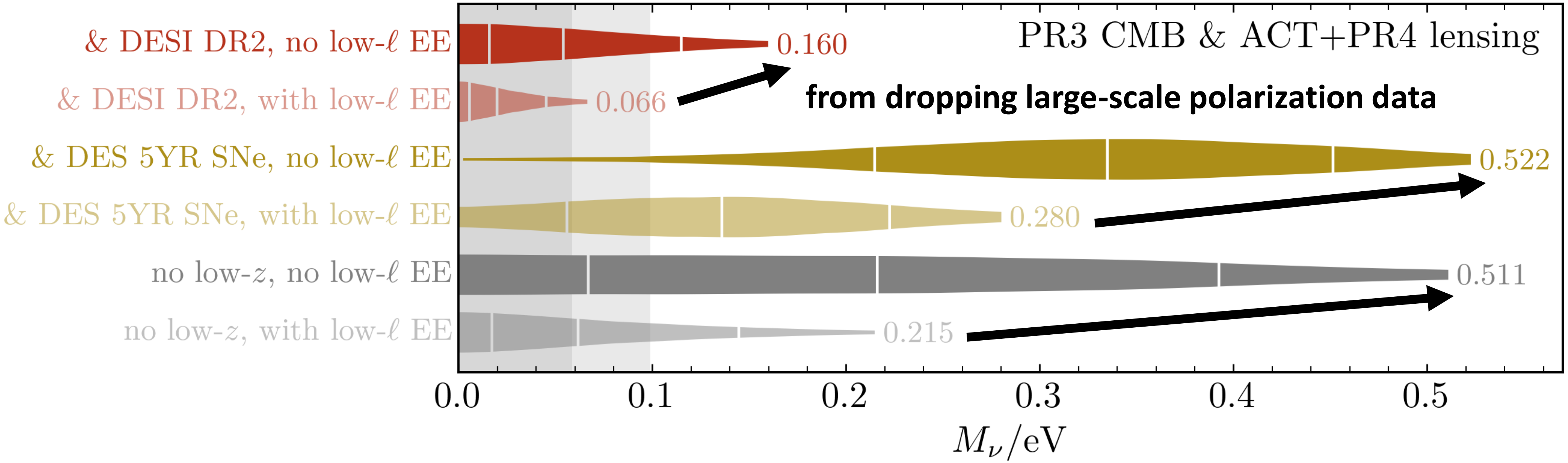


Reionization and large-scale polarization

CMB lensing measures neutrino suppression via

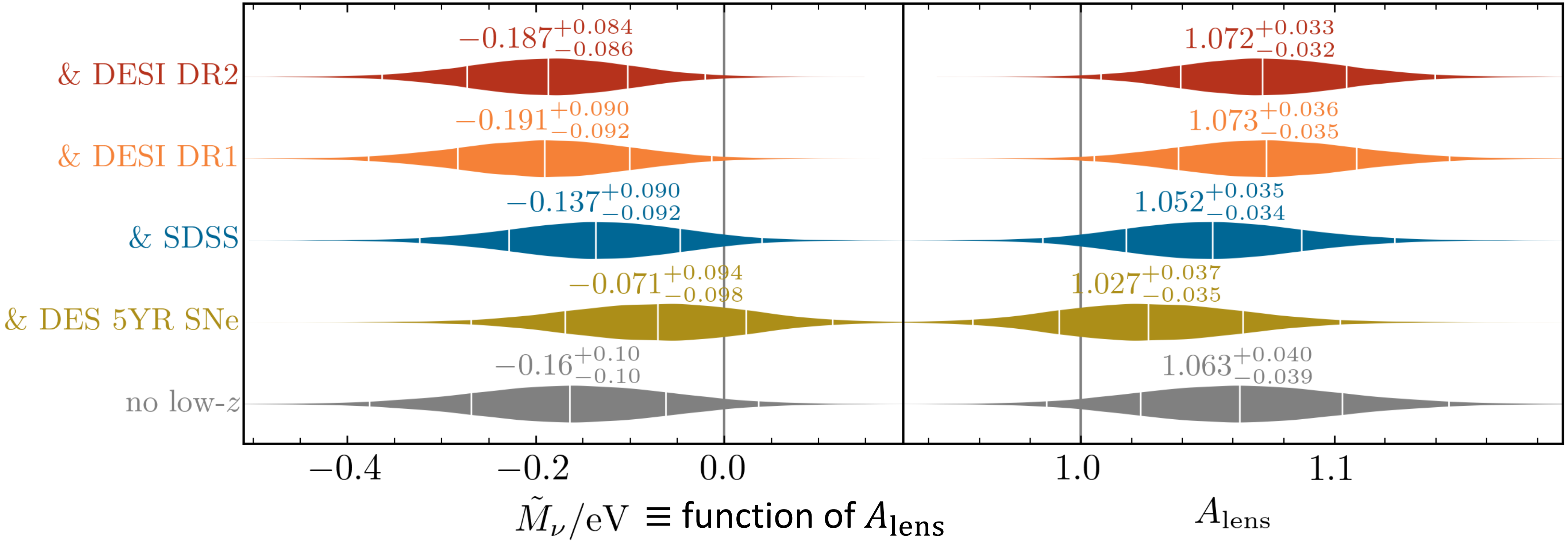
inferred from large-scale polarization data

$$\frac{\text{late-time structure}}{\text{initial condition}} \sim \frac{\text{amplitude of } C_\ell^{\phi\phi}}{\text{amplitude of } C_\ell^{TT}/\text{reionization suppression}} \sim \frac{C_\ell^{\phi\phi}}{\left[A_s e^{-2\tau_{\rm reio}}\right]/e^{-2\tau_{\rm reio}}}$$



2410.00090

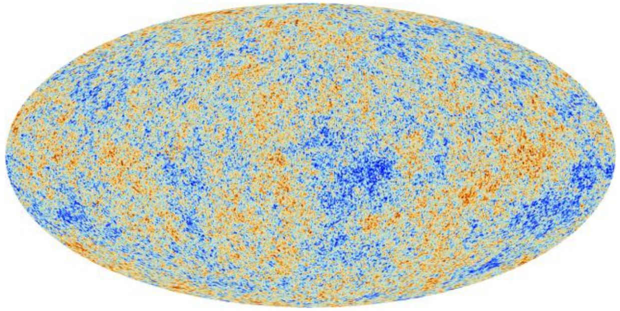
Pretending neutrinos don't affect expansion

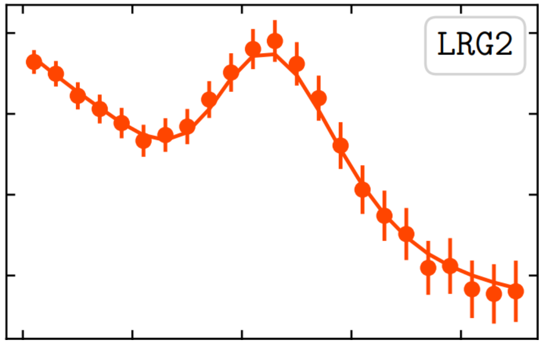


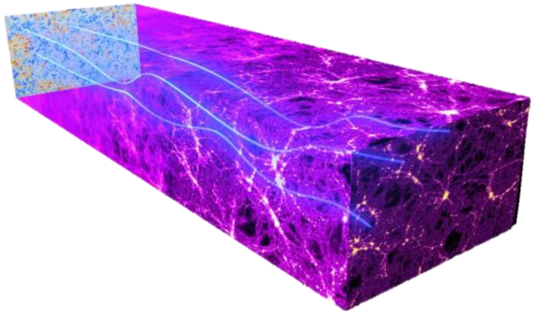
low-redshift distances needed *only*
because of neutrinos' geometric effects!

Rescue neutrino masses by altering…

1. Calibration: modify prerecombination physics, relationship between sound horizon and matter densities
2. Extrapolation: modify postrecombination dynamics of matter components
3. Inference: modify low-redshift dynamics (e.g., of dark energy) that also affect distances, growth of structure







Modified extrapolation with dark forces

$$S = \int \mathrm{d}^4x\,\sqrt{-g}\,\left[-M_{\rm pl}^2\partial_\mu\varphi\partial^\mu\varphi - V_\varphi(\varphi)\right] - \sum_p \int \mathrm{d}\tau_p\, m_\chi\left(\varphi[x_p^\alpha(\tau_p)]\right)$$

$$\bar{\rho}_\chi(a) = \frac{m_\chi(a)}{m_\chi(a_i)}\,\frac{\bar{\rho}_\chi(a_i)}{(a/a_i)^3}$$

solves the matter density deficit?

$$\delta_{n_\chi}' + \partial_i\partial_i\delta u_\chi + \psi = 0$$

$$\delta u_\chi' + \left(\mathcal{H} + \frac{\mathrm{d}\ln m_\chi}{\mathrm{d}\tau}\right)\delta u_\chi = -\delta\ln m_\chi = -\frac{\partial \ln m_\chi}{\partial\varphi}\delta\varphi$$

solves the lensing excess?

see 2204.08484, 2309.11496, 2407.18252, …

$\delta_{n_\chi} \equiv n_\chi(x)/\bar{n}_\chi - 1$

Growth deviation with a massless mediator

subhorizon /quasistatic limit:

$$\delta''_{\chi b} + \left(\mathcal{H} + \frac{f_\chi \mathrm{d}\ln m_\chi/\mathrm{d}\tau}{1+(am_{\mathrm{eff}}/k)^2} \right) \delta'_{\chi b} \simeq \frac{a^2 \bar{\rho}_{\chi b}}{2M_{\mathrm{pl}}^2} \left(1 + \frac{f_\chi^2 \left(\partial \ln m_\chi/\partial\varphi\right)^2}{1+(am_{\mathrm{eff}}/k)^2} \right) \delta_{\chi b}$$

in matter domination, all coefficients slowly varying:

$$\frac{\mathrm{d}\ln\delta_{\chi b}}{\mathrm{d}\ln a} \approx 1 - \underbrace{\frac{2}{5} f_\chi \frac{\mathrm{d}\ln m_\chi}{\mathrm{d}\ln a}}_{\text{modified friction}} + \underbrace{\frac{3}{5}\left(f_\chi \frac{\partial \ln m_\chi}{\partial\varphi}\right)^2}_{\text{enhanced clustering}} + \underbrace{\frac{3}{5} w_\varphi f_\varphi}_{\text{modified expansion}} - \underbrace{\frac{3}{5} f_{\mathrm{ncl}}}_{\text{nonclustering matter}}$$

nonclustering matter: including mediator, massive neutrinos, …

Dynamics of a massless mediator

KG equation: $\bar{\varphi}''(\tau) + 2\,\mathcal{H}\,\bar{\varphi}'(\tau) = \frac{a(\tau)^2}{2\,M_{\rm pl}^2} \frac{\partial \ln m_\chi}{\partial \varphi}\ \bar{\rho}_\chi(\tau)$

linear coupling: $\frac{\partial \ln m_\chi}{\partial \varphi} = d_{m_\chi}^{(1)} = \sqrt{\beta}$

analytic solution: $\bar{\varphi}(a) = \ \bar{\varphi}_i - f_\chi d_{m_\chi}^{(1)} \ln \frac{a}{4a_{\rm eq}/e} + O(a_{\rm eq}/a)$

"mediator friction": $\frac{{\rm d} \ln m_\chi}{{\rm d} \ln a} \approx -\left(d_{m_\chi}^{(1)}\right)^2 f_\chi = -\beta f_\chi$

mediator fraction: $f_\varphi = \frac{1}{3}({\rm d}\varphi/{\rm d} \ln {\rm a})^2 = \frac{1}{3}\beta f_\chi^2$

2204.08484

Growth deviation with a massless mediator

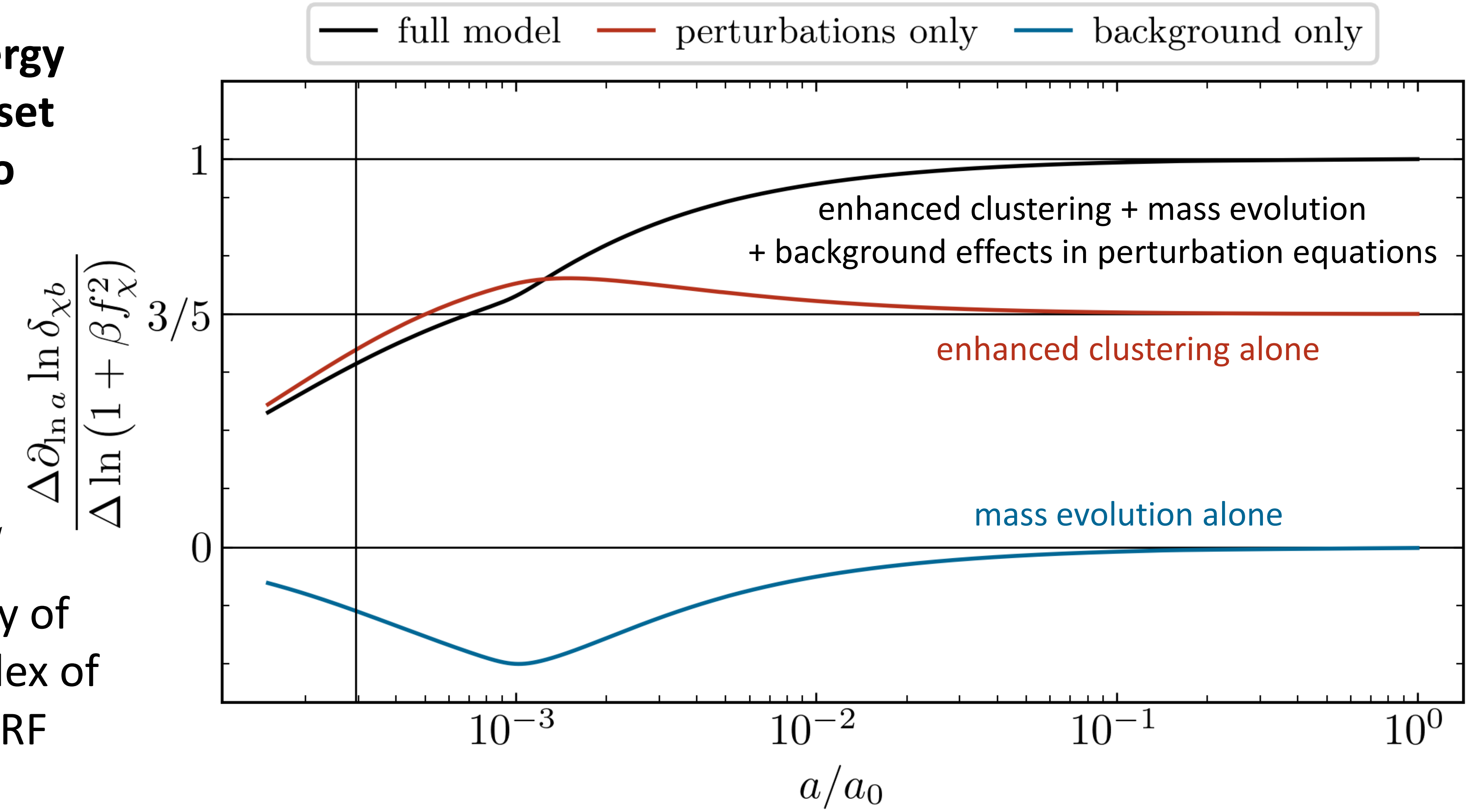
"mediator friction": $\frac{\mathrm{d}\ln m_\chi}{\mathrm{d}\ln a} \approx -\left(d^{(1)}_{m_\chi}\right)^2 f_\chi = -\beta f_\chi$

mediator fraction: $f_\varphi = \frac{1}{3}(\mathrm{d}\varphi/\mathrm{d}\ln \mathrm{a})^2 = \frac{1}{3}\beta f_\chi^2$

$$\frac{\mathrm{d}\ln\delta_{\chi b}}{\mathrm{d}\ln a} \approx 1 - \underbrace{\frac{2}{5}\times(-\beta f_\chi^2)}_{\text{modified friction}} + \underbrace{\frac{3}{5}\times\beta f_\chi^2}_{\text{enhanced clustering}} + \underbrace{\frac{3}{5}\times\frac{1}{3}\beta f_\chi^2}_{\text{modified expansion}} - \underbrace{\frac{3}{5}\times\frac{1}{3}\beta f_\chi^2}_{\text{nonclustering matter}} = \boxed{\beta f_\chi^2}$$

Growth deviation with a massless mediator

dark energy density set to zero



sensitivity of growth index of $\delta_{\chi b}$ to LRF

The density contrast is not the observable

$$\frac{\mathrm{d}\ln\Phi_{\mathrm{B}}}{\mathrm{d}\ln a} = \frac{\mathrm{d}\ln a^3\bar{\rho}_{\chi b}}{\mathrm{d}\ln a} + \frac{\mathrm{d}\ln\delta_{\chi b}/a}{\mathrm{d}\ln a}$$

$$\approx \underbrace{\frac{3}{5}f_\chi\frac{\mathrm{d}\ln m_\chi}{\mathrm{d}\ln a}}_{\text{background effects}} + \underbrace{\frac{3}{5}\left(f_\chi\frac{\partial\ln m_\chi}{\partial\varphi}\right)^2}_{\text{enhanced clustering}} + \underbrace{\frac{3}{5}w_\varphi f_\varphi}_{\text{modified expansion}} - \underbrace{\frac{3}{5}f_{\mathrm{ncl}}}_{\text{nonclustering matter}}$$

Growth deviation with a massless mediator

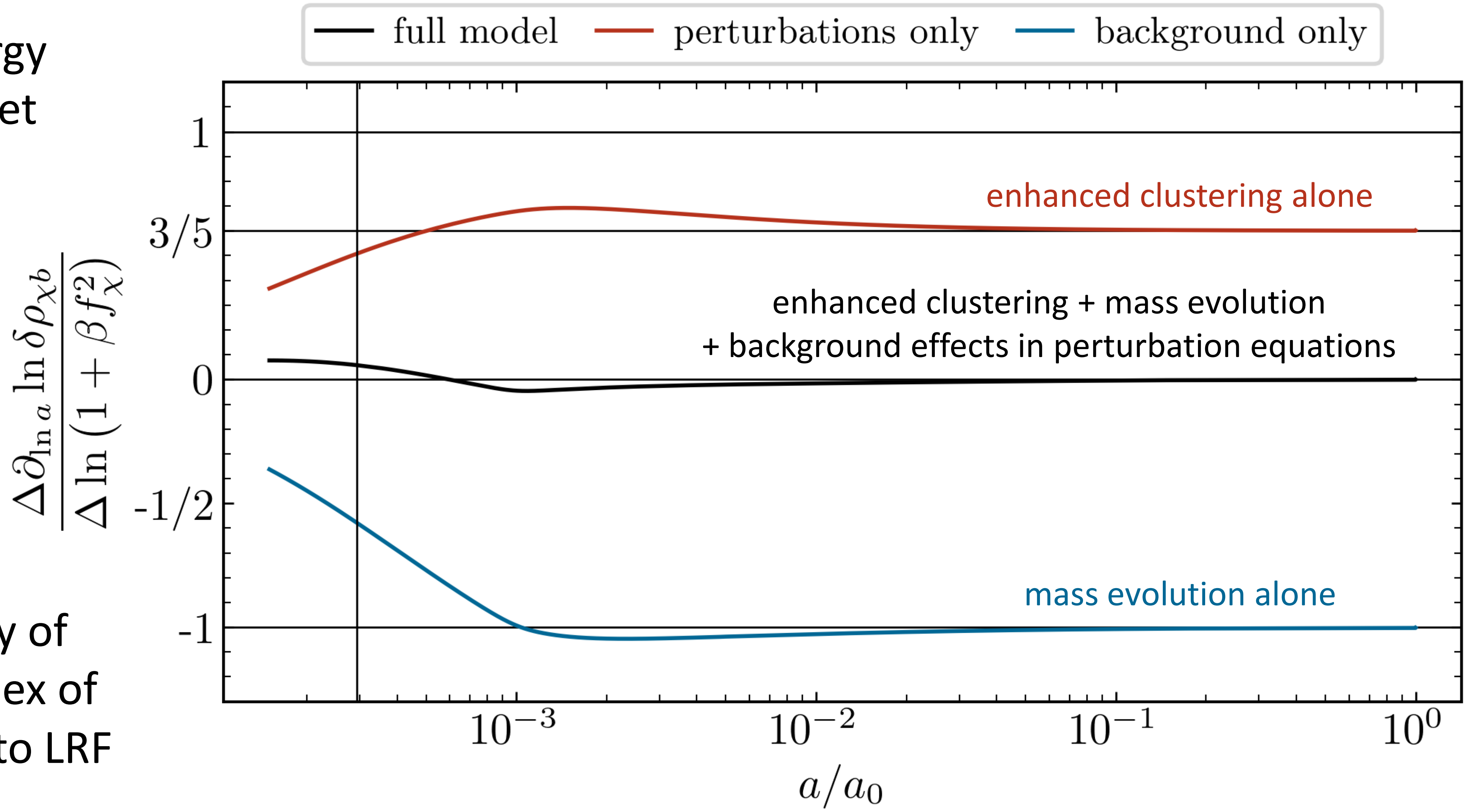
"mediator friction": $\frac{\mathrm{d}\ln m_\chi}{\mathrm{d}\ln a} \approx -\left(d^{(1)}_{m_\chi}\right)^2 f_\chi = -\beta f_\chi$

mediator fraction: $f_\varphi = \frac{1}{3}(\mathrm{d}\varphi/\mathrm{d}\ln \mathrm{a})^2 = \frac{1}{3}\beta f_\chi^2$

$$\frac{\mathrm{d}\ln\Phi_\mathrm{B}}{\mathrm{d}\ln a} \approx \underbrace{\frac{3}{5} f_\chi \times (-f_\chi\beta)}_{\text{background effects}} + \underbrace{\frac{3}{5}\beta f_\chi^2}_{\text{enhanced clustering}} = \boxed{0}$$

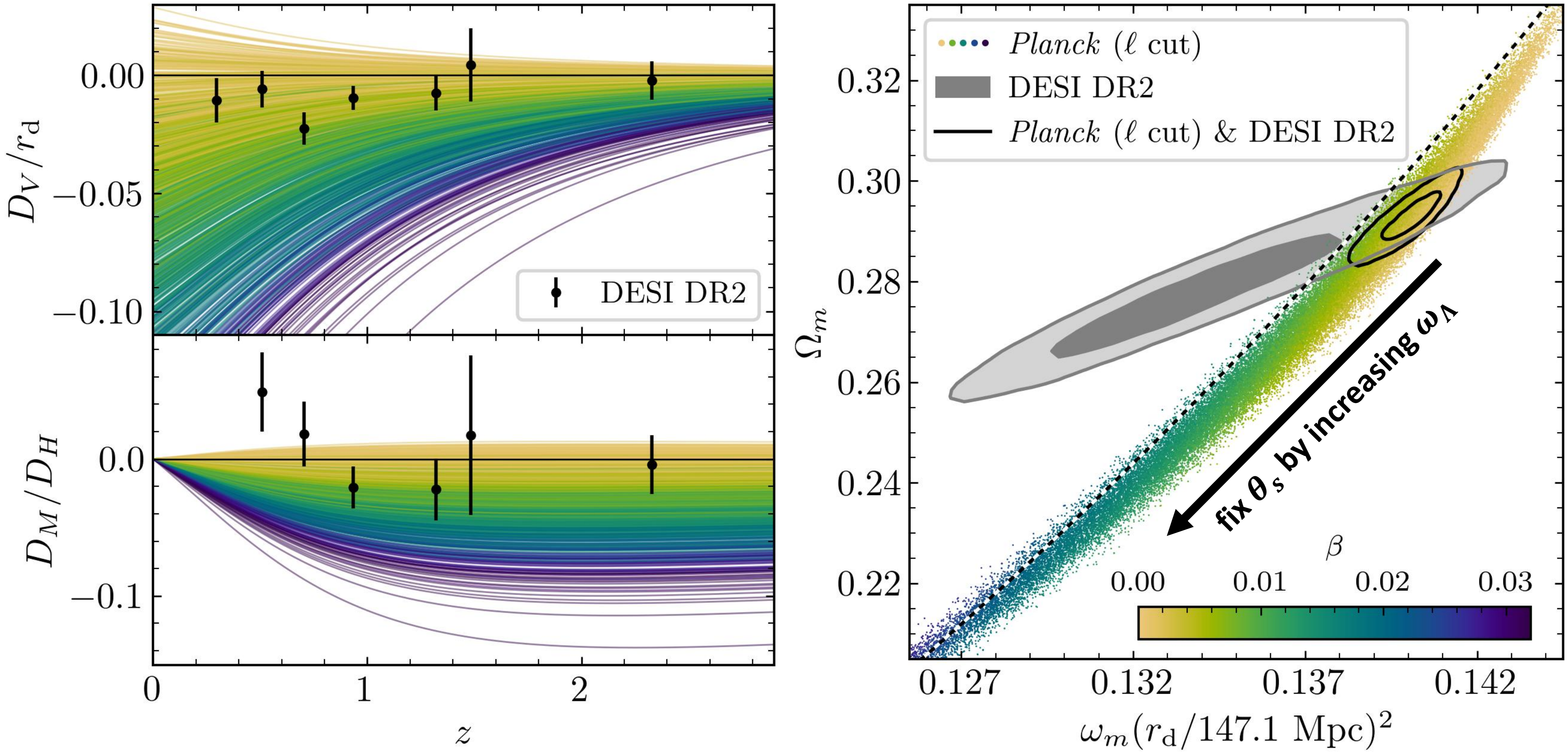
Growth deviation with a massless mediator

dark energy density set to zero

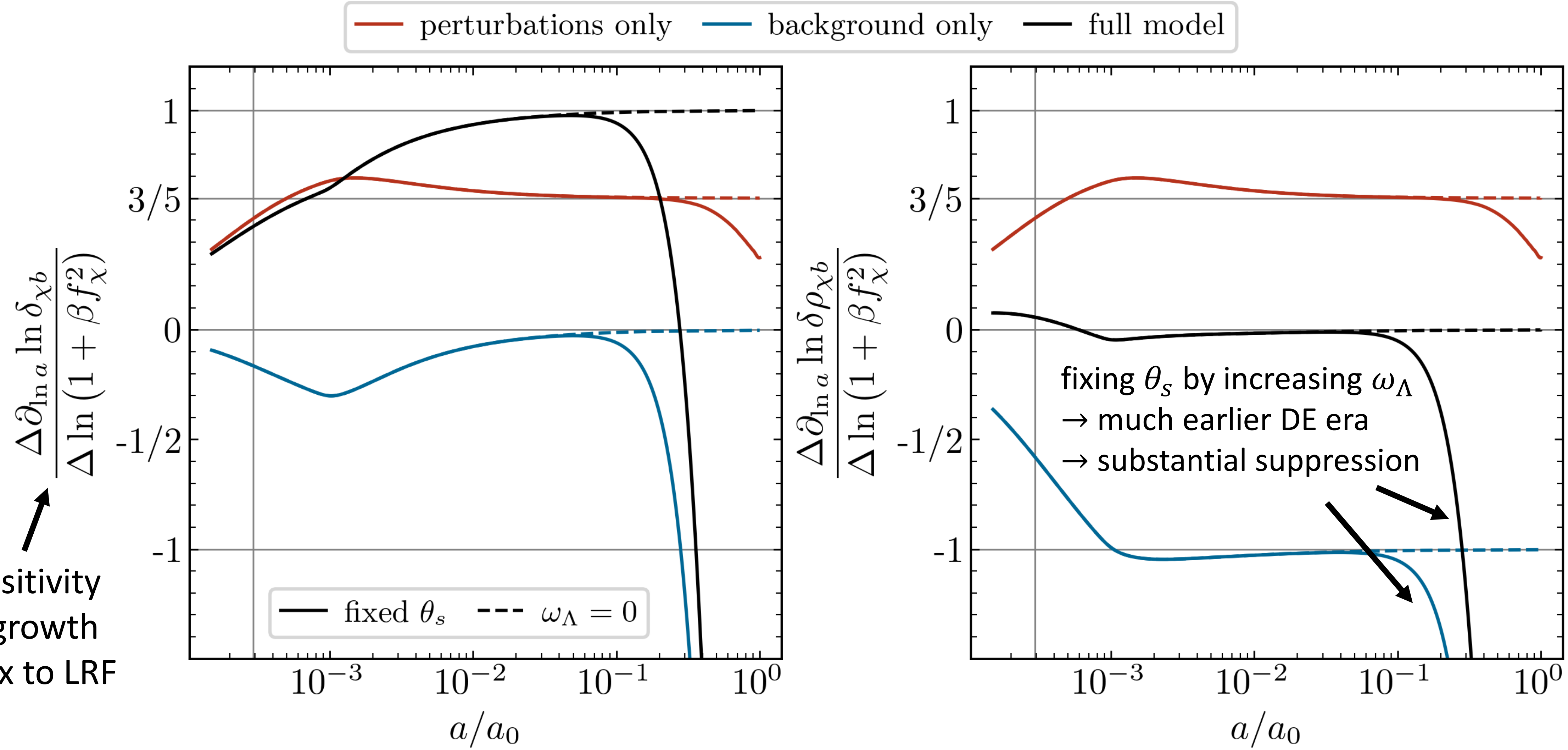


sensitivity of growth index of $\boldsymbol{\Phi \propto \delta\rho_{\chi b}}$ to LRF

Suppression of distances

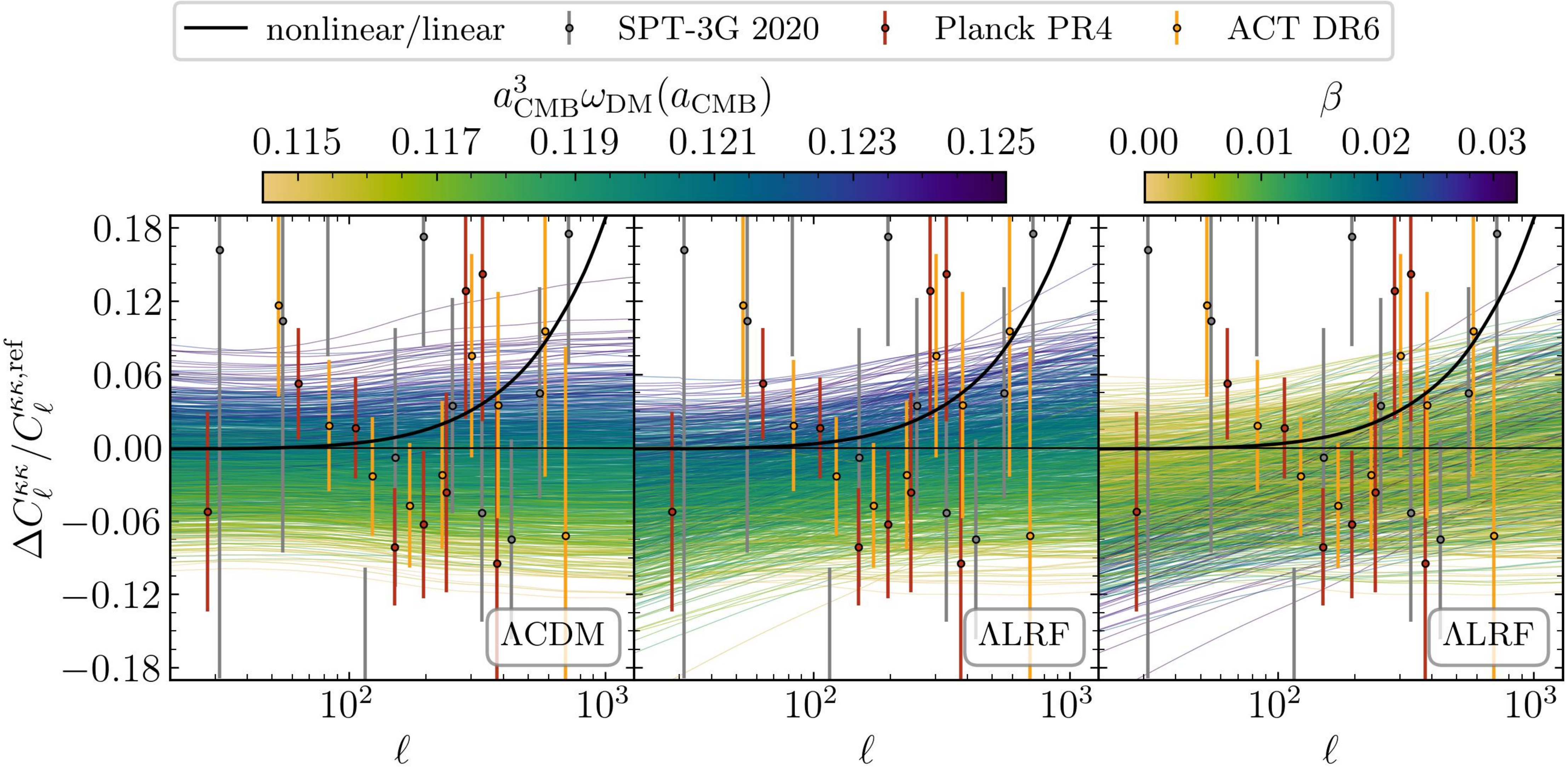


Suppression of structure



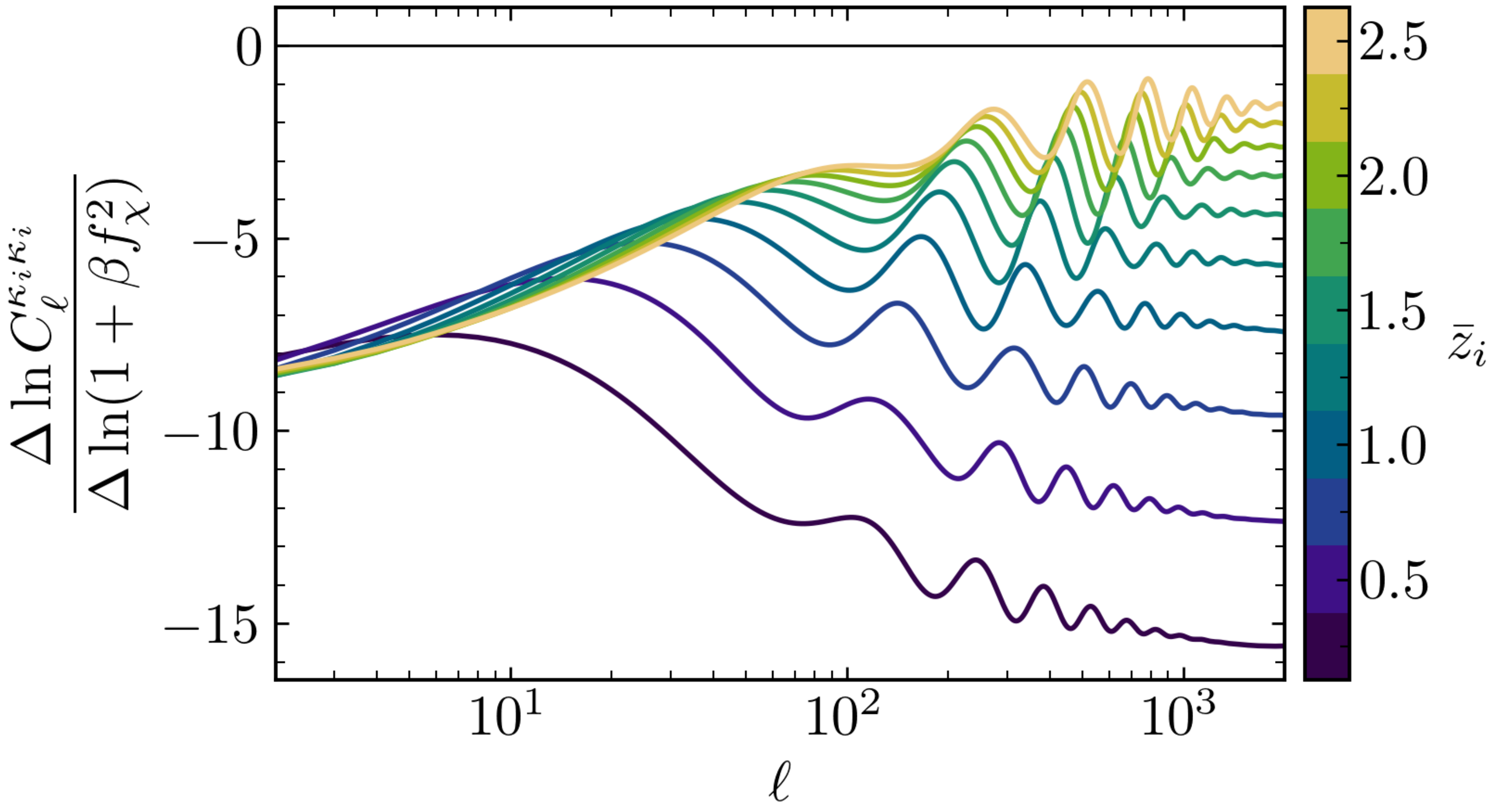
sensitivity of growth index to LRF

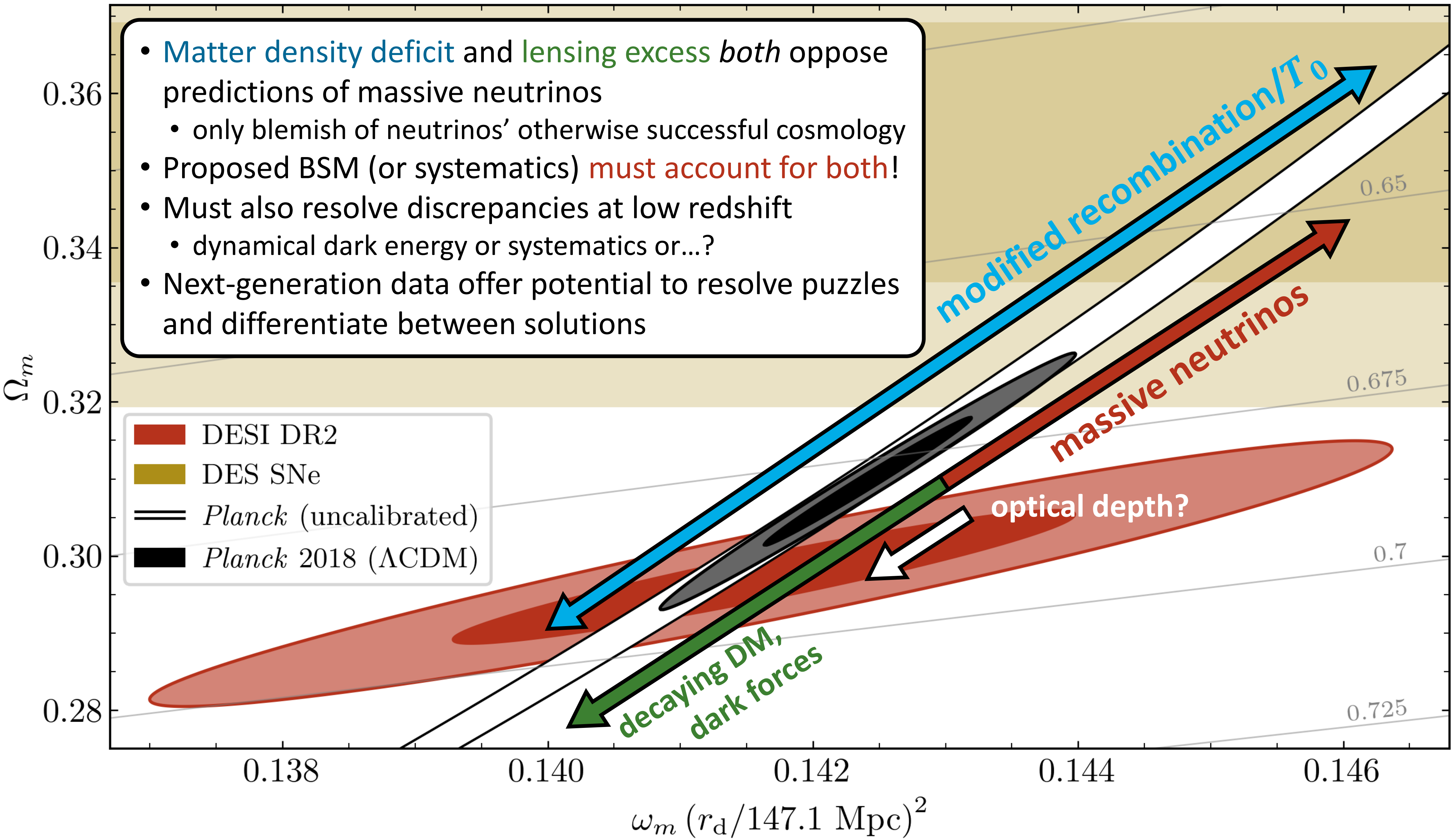
Suppression of structure



An amusing corollary: solving the "S_8" tension?

sensitivity coefficient of galaxy lensing to LRF strength




• Matter density deficit and lensing excess both oppose predictions of massive neutrinos
• only blemish of neutrinos' otherwise successful cosmology
• Proposed BSM (or systematics) must account for both!
• Must also resolve discrepancies at low redshift
• dynamical dark energy or systematics or…?
• Next-generation data offer potential to resolve puzzles and differentiate between solutions
modified recombination/T_0
massive neutrinos
optical depth?
decaying DM, dark forces
DESI DR2
DES SNe
Planck (uncalibrated)
Planck 2018 (ΛCDM)
0.65
0.675
0.7
0.725
Ω_m
0.36
0.34
0.32
0.30
0.28
0.138
0.140
0.142
0.144
0.146
$\omega_m \, (r_\mathrm{d}/147.1\ \mathrm{Mpc})^2$