Image credit: Illustris Collaboration

Fundamental Physics with kSZ Tomography

Avery Tishue

Illinois Center for Advanced Studies of the Universe &
Department of Physics, University of Illinois Urbana-Champaign

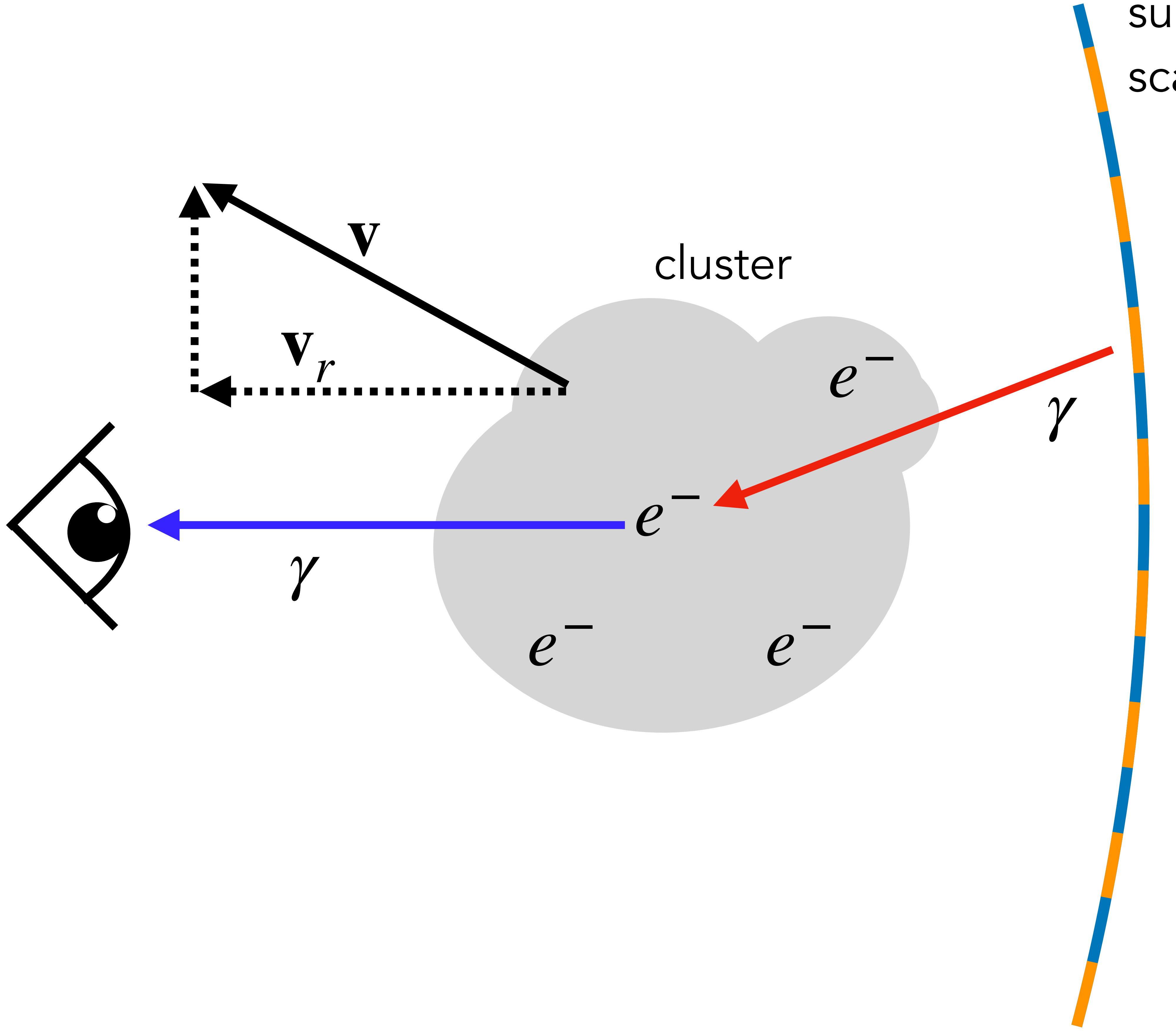
Based on 2407.21094 & 2502.05260 with:
S. Hotinli, P. Adshead, E. Kovetz, M. Madhavacheril

mm Universe 2025
University of Chicago, June 23-27, 2025

KSZ Tomography

Kinematic Sunyaev-Zeldovich (kSZ) Effect

- Inverse Compton scattering between CMB photons and free electrons moving with a bulk peculiar velocity [Y. Zeldovich & R. Sunyaev 1969]
- Induces correlations between large scale structure and CMB



KSZ Tomography

kSZ Tomography: Velocity Reconstruction

- kSZ temperature anisotropy:

$$\Theta_{\mathrm{kSZ}}(\vec{\theta}) = K(z_\star)\int_0^R dr\,\delta_e(\vec{x})v_r(\vec{x})$$

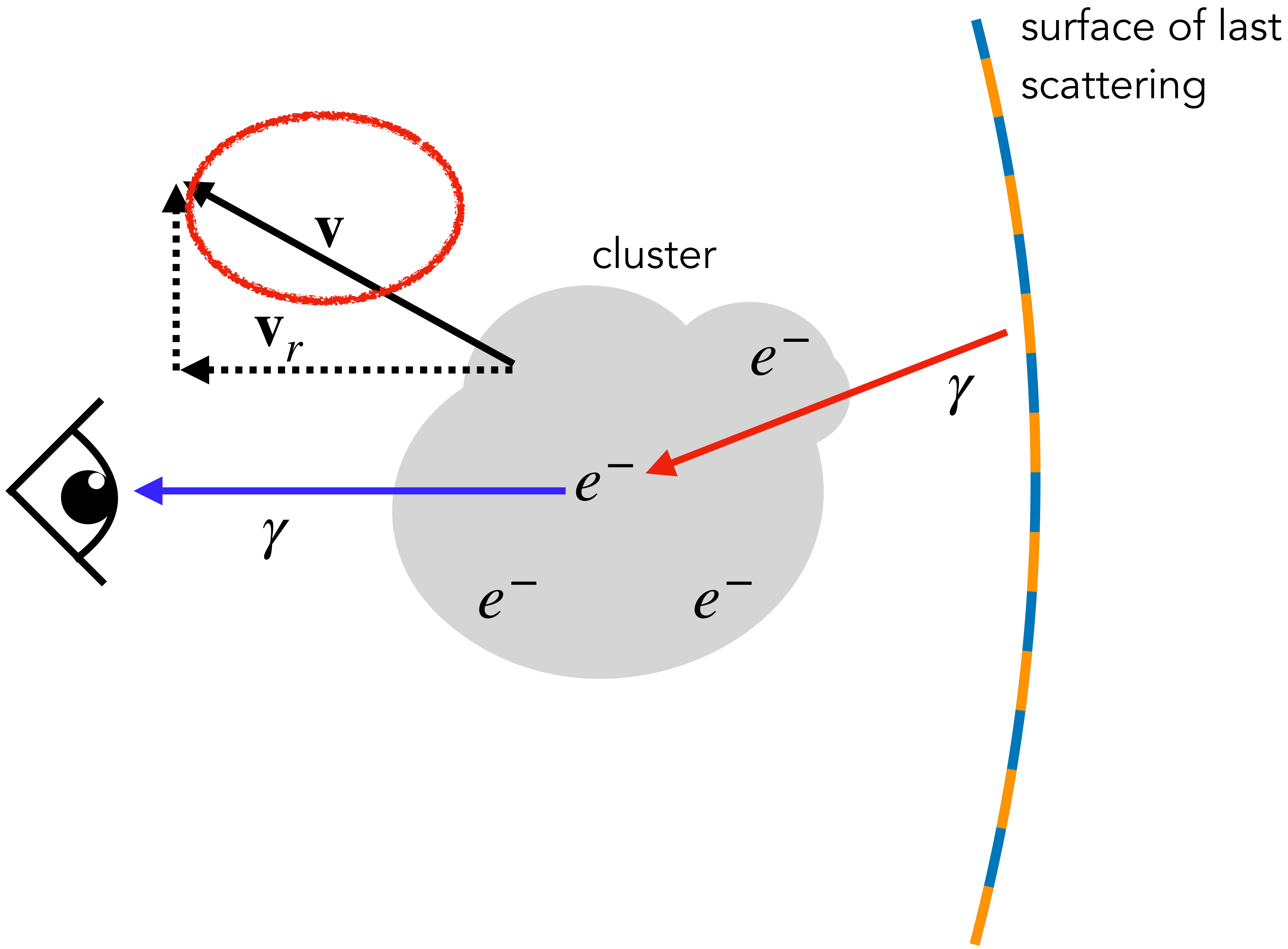
- **Temperature** fluctuation correlated with **velocity** of **large-scale structure**
  - minimum variance quadratic estimator: $\hat{v}_r \sim \langle gT \rangle$
  - reconstruct velocities:

    $$\hat{v}_r(k_L) \sim \int dk_S\, d\ell\, \delta_g(k_s)T(\ell)W(k_s,\ell)$$

    $W(k_s,\ell) \rightarrow$ minimize noise, unbiased $\hat{v}_r$

    [Smith et. al. 2018]

- do cosmology



KSZ Tomography

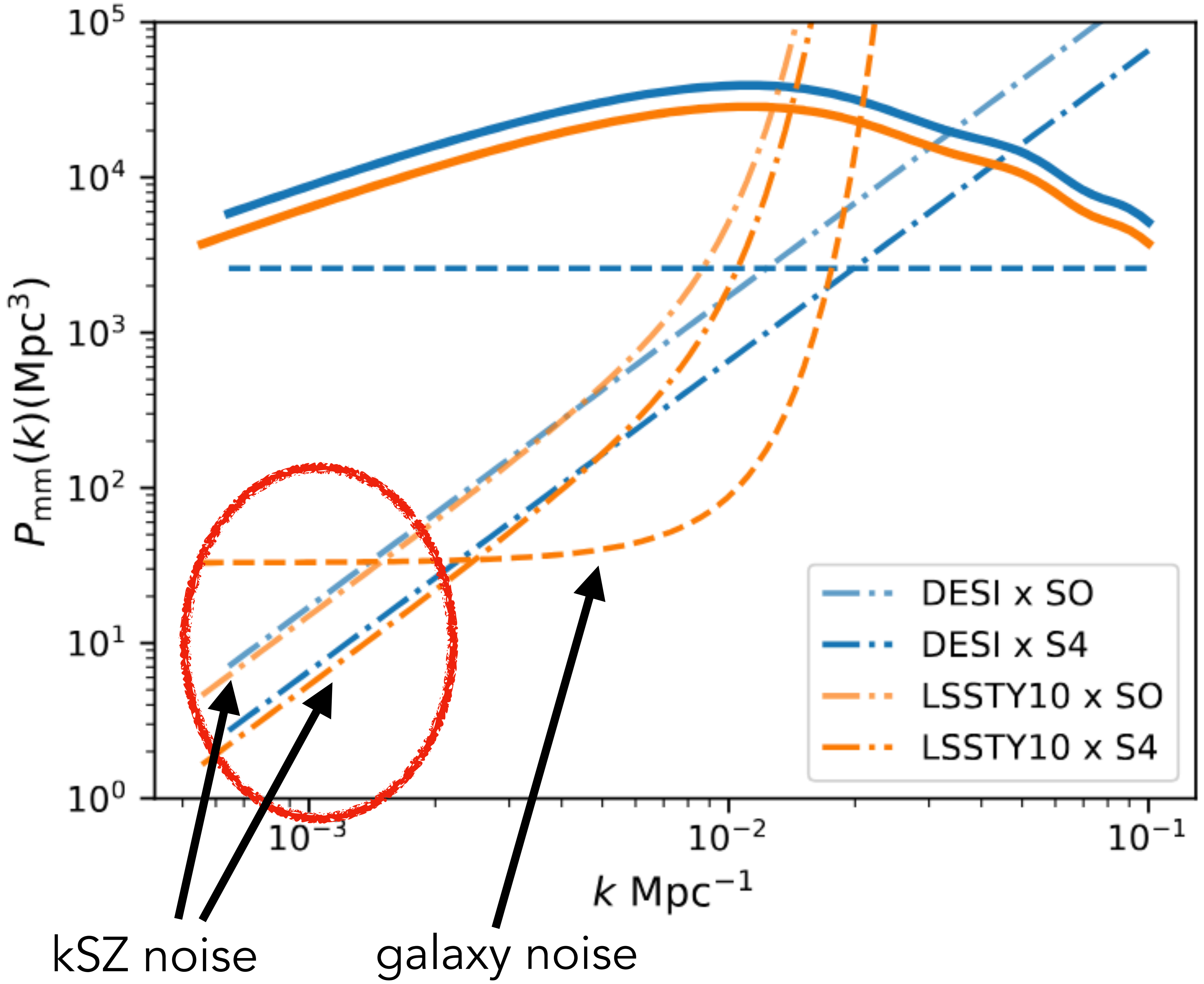
Cosmology with kSZ Velocities

- Velocity field traces **matter (clustering)** and **growth rate**:

$$v \sim \delta_m \frac{faH}{k}$$

  - $\langle \delta_m \delta_m \rangle \sim P_{mm}$
  - $f = \frac{d}{d \ln a}\left[\left(\frac{P_{mm}(k,a)}{P_{mm}(k,a=1)}\right)^{1/2}\right]$
  - growth rate can tell us about modified gravity, dark energy, massive neutrinos, etc.
- **Observables**: power and cross spectra
  - $P_{\hat{v}_r\hat{v}_r}(k,z) = \left[b_v(z)\mu\frac{f(k)aH}{k}\right]^2 P_{mm}(k,z)$
  - $P_{g\hat{v}_r}(k,z) = b_v(z)\mu\frac{f(k)aH}{k}b_g(k,z)P_{mm}(k,z)$
  - $v \sim 1/k$: **kSZ is a probe of matter power and cosmic growth with good signal to noise on large scales**

[Smith et. al. 2018]



Two Applications of kSZ Tomography

1. PNG: "Beyond Local Type"

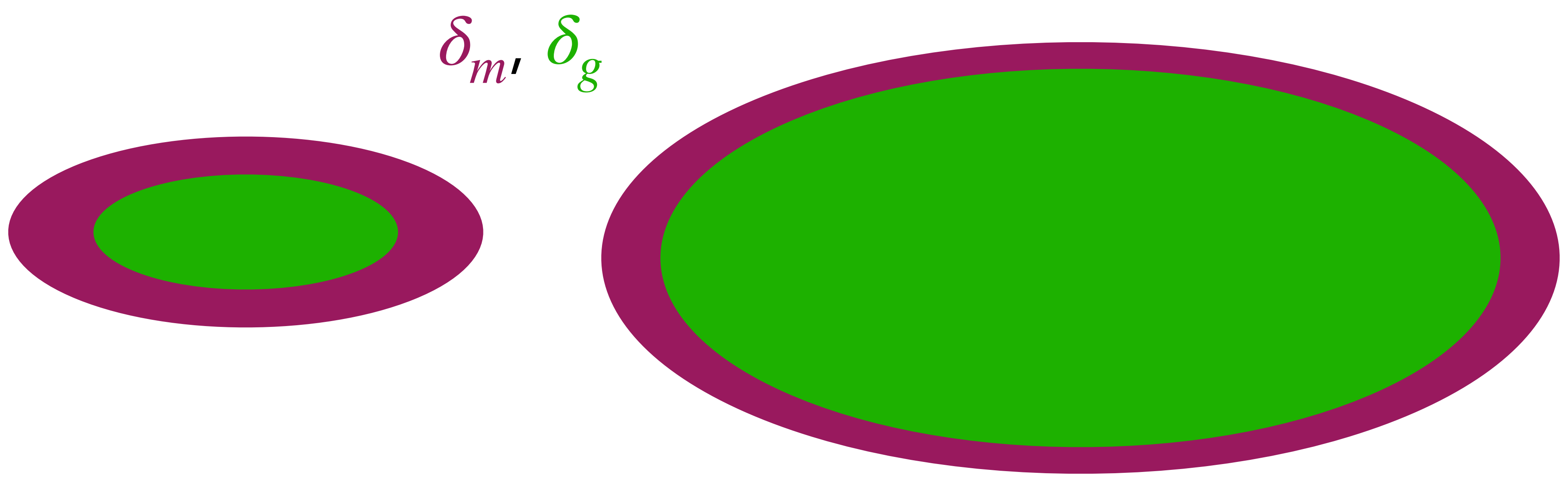
- *Specific scenario*: light fields during inflation $m \lesssim H$
- *More generally*: large scale galaxy bias beyond $\Delta b(k) \propto 1/k^2$ (from $f_{NL}^{\rm loc}$)

Beyond-Local Primordial Non-Gaussianity with kSZ

Scale-dependent galaxy bias and PNG

- Familiar "local-type": $\zeta_{NG} = \zeta_g(\mathbf{x}) + f_{NL}^{\rm loc}\left[\zeta_g^2(\mathbf{x}) - \langle \zeta_g^2 \rangle\right]$
- **signal: scale-dependent galaxy bias** [e.g. N. Dalal et. al. 2008, M. LoVerde et. al. 2008]
  - $\delta_g = (b_1 + \Delta b(k))\delta_m$, $\quad \Delta b(k) \propto \dfrac{f_{NL}^{\rm loc}}{T(k)D(z)k^2}$
- *Where does kSZ come in?*
  - galaxy survey in isolation suffers degeneracies, large-scale cosmic variance: $P_{gg}(k,z) = b_g^2(k,z)P_{mm}(k,z)$
    - use additional tracers! [U. Seljak 2009, M. Münchmeyer et. al. 2018]

      $\implies P_{gg}/P_{\hat{v}_r\hat{v}_r} \sim b_g^2/b_v^2$
- **But! many sources of primordial non-Gaussianity** (multi-field scenarios, excited initial states, etc.)
  - **beyond local type** [D. Baumann 2009]
  - this can work for non-Gaussianity **beyond local-type, too**



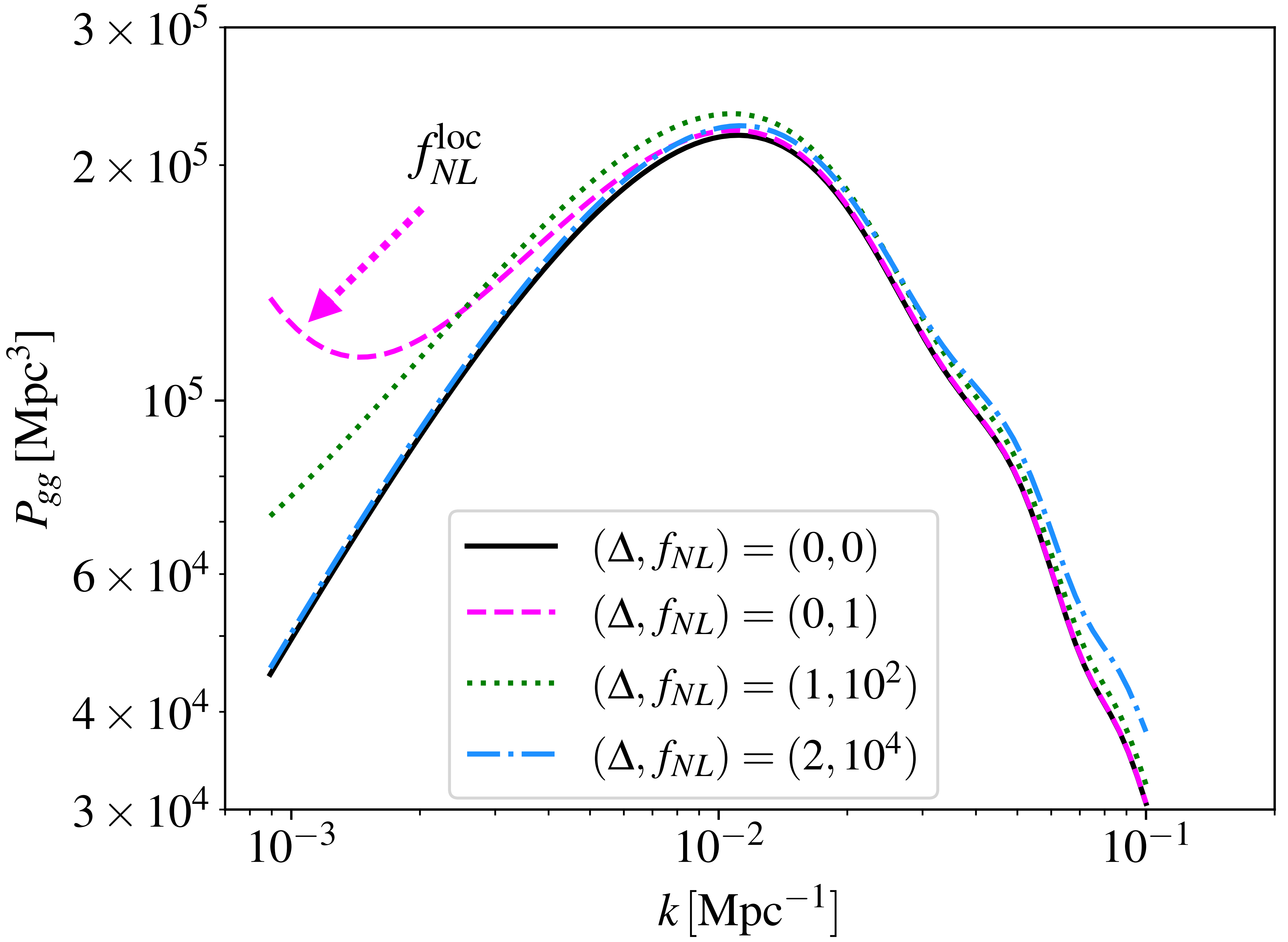
various early universe scenarios $\implies$ primordial non-Gaussianity $\Downarrow$ scale-dep. galaxy bias on large scales $\implies$ kSZ tomography

Beyond-Local Primordial Non-Gaussianity with kSZ

Primordial Signals in Galaxy Bias: beyond local PNG

- **scenario**: inflaton ϕ, & light spectator χ (mass $m \lesssim H$) [D. Baumann et. al. 2013, SPHEREx collab. 2015, D. Green et. al. 2023]
  - "Scaling exponent" $\Delta = \frac{3}{2} - \sqrt{9/4 - m^2/H^2}$
  - PNG $\implies$ Scale-dependent bias **beyond local-type**
    - **local type**: $\Delta b(k) \propto \frac{f_{NL}^{\mathrm{loc}}}{T(k)D(z)k^2}$, $(m = 0)$
    - **generally:** $\Delta b_{NG}(k,z) \propto 3 f_{NL}^{(\Delta)} \frac{b_\phi(z)}{k^2 T(k) D(z)} (kR_\star)^\Delta$

use kSZ to look for this!

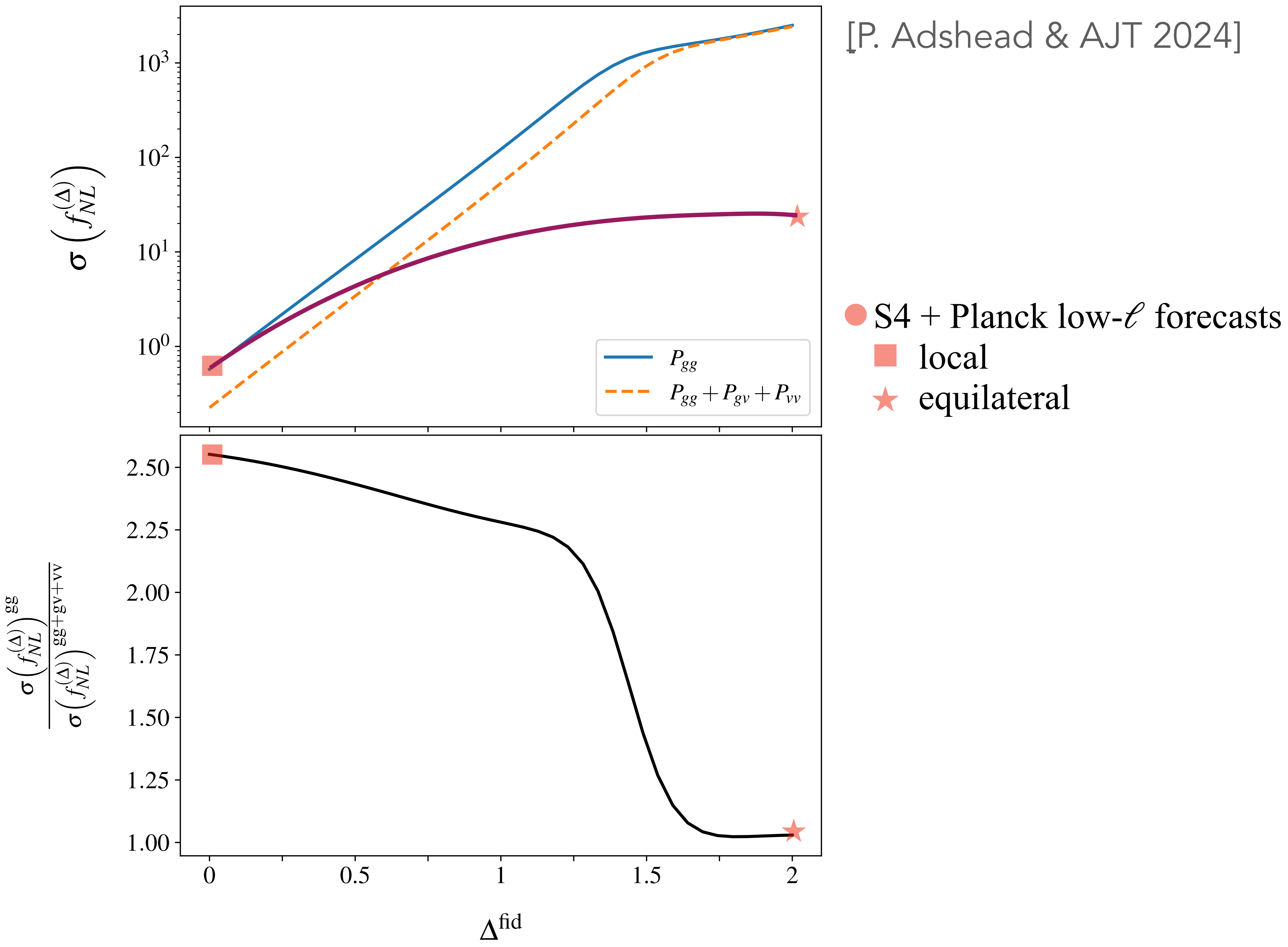


Beyond-Local Primordial Non-Gaussianity with kSZ

Probing beyond local-type ($\Delta = 0$) PNG with kSZ

- Fisher Forecast: CMB S4 + LSST
- Improved constraints around $f_{NL} = 0$ from kSZ + galaxies compared to:
  - galaxies alone, P_{gg}
    - Constraints 2× tighter!
  - Projected CMB bispectrum constraints
    - kSZ outperforms CMB for range of Δ

kSZ may be the best probe of primordial non-Gaussianity for various interesting early Universe scenarios!

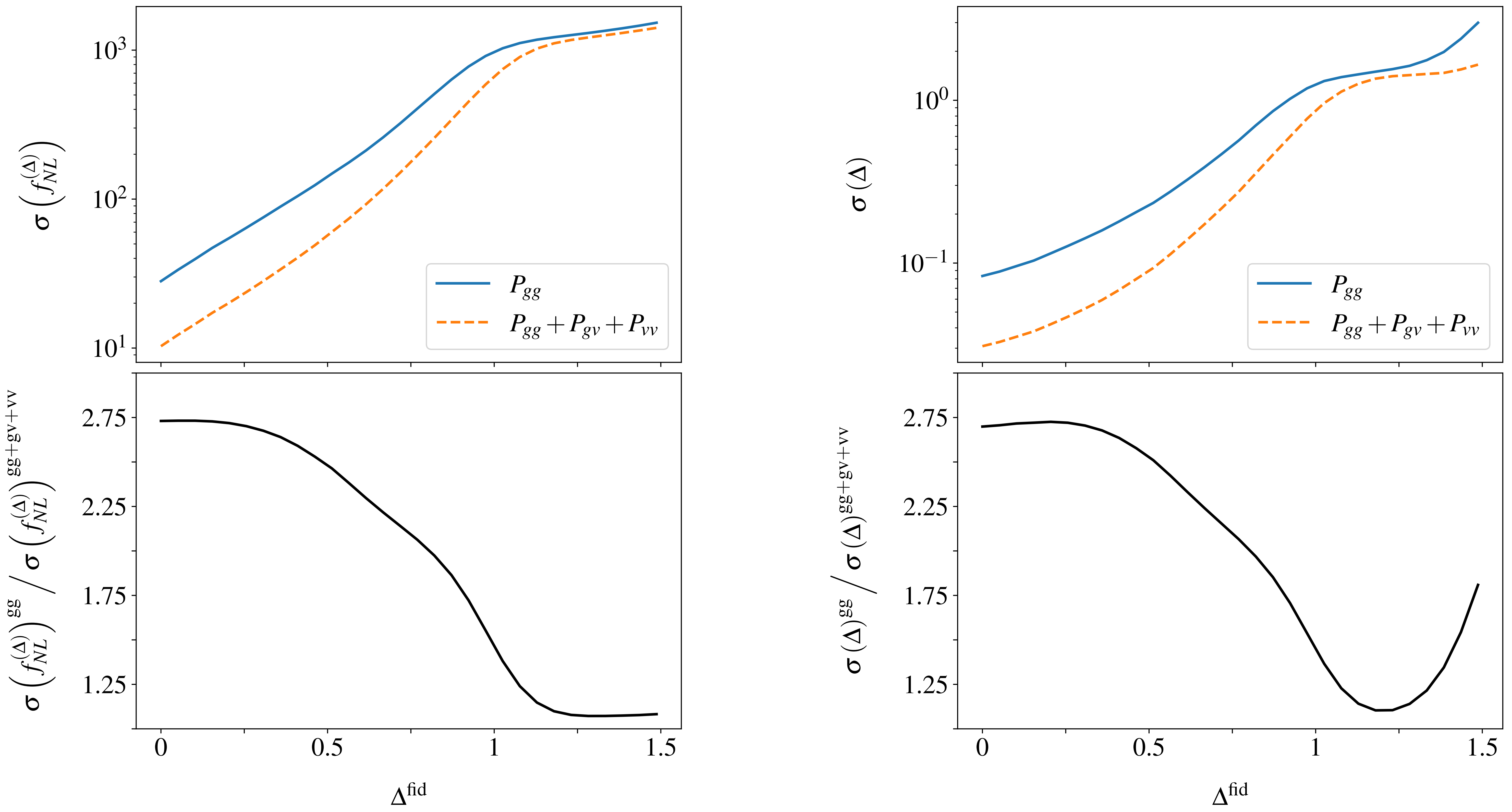


Beyond-Local Primordial Non-Gaussianity with kSZ

Detecting beyond local-type non-Gaussianity with kSZ

[P. Adshead & AJT 2024]

- Assume we detect nonzero f_{NL} — now what?
  - We need to know the shape! Δ
    - Significantly degrades constraints from galaxies and kSZ
    - 'apples to apples' comparison with pure CMB is non-trivial
    - kSZ can reinforce CMB results on non-zero f_{NL}
    - kSZ improves shape constraints significantly — information about primordial scenarios!



Two Applications of kSZ Tomography

1. PNG: "Beyond Local Type"

- *Specific scenario*: light fields during inflation $m \lesssim H$
- *More generally*: large scale galaxy bias beyond $\Delta b(k) \propto 1/k^2$ (from $f_{NL}^{\rm loc}$)

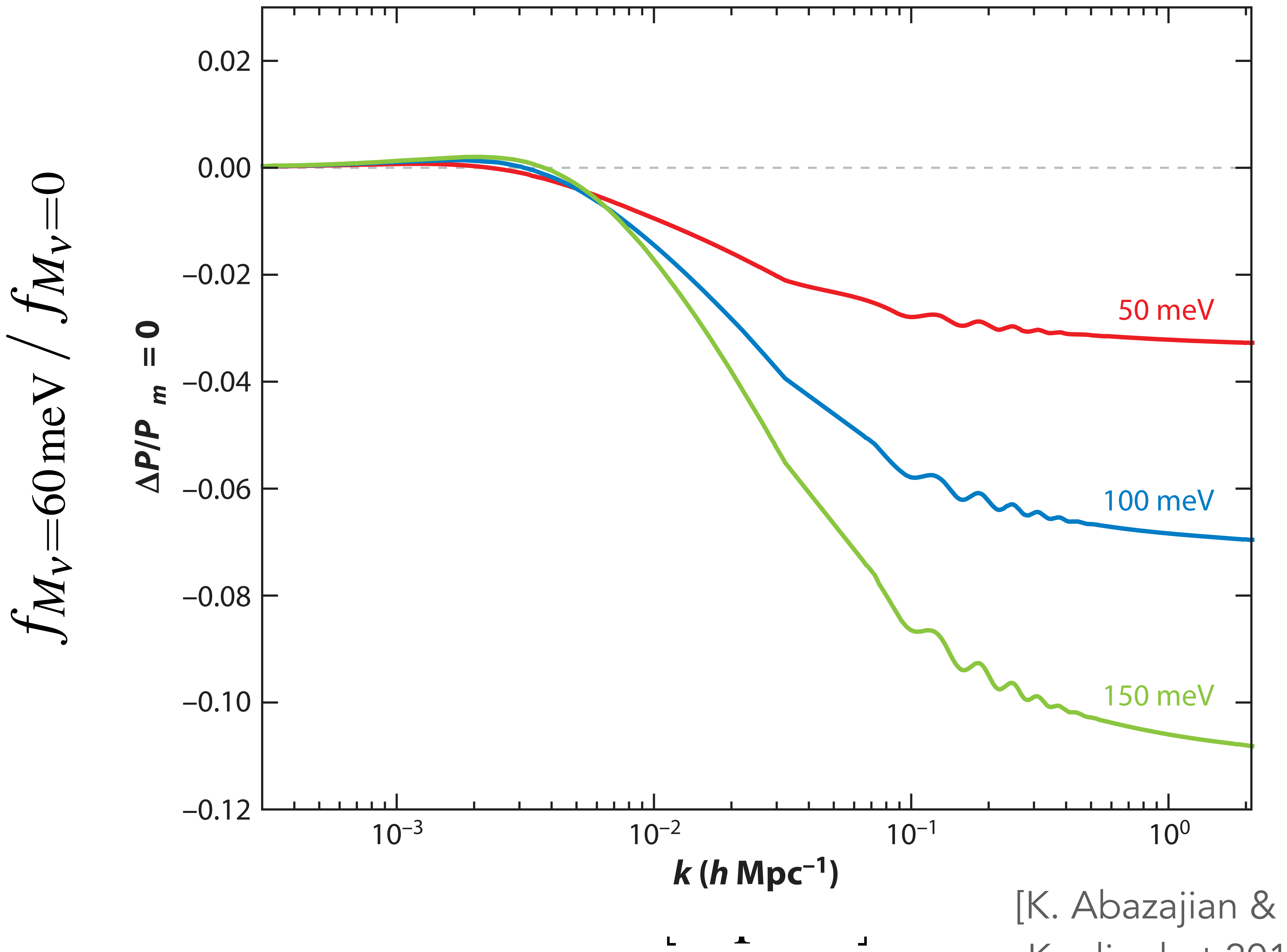
2. Massive Neutrinos

- Improve constraints on $\sum m_\nu$?
- Matter clustering, **cosmic growth**

Neutrino Mass Constraints from kSZ Tomography

Why might kSZ be useful here?

- Velocity field traces **matter (clustering)** and **growth rate**: $v \sim \delta_m \frac{faH}{k}$
  - $f = \frac{d}{d\ln a}\left[\left(\frac{P_{mm}(k,a)}{P_{mm}(k,a=1)}\right)^{1/2}\right]$
  - $P_{g\hat{v}_r}(k,z) = b_v(z)\mu\frac{f(k)aH}{k}b_g(k,z)P_{mm}(k,z)$

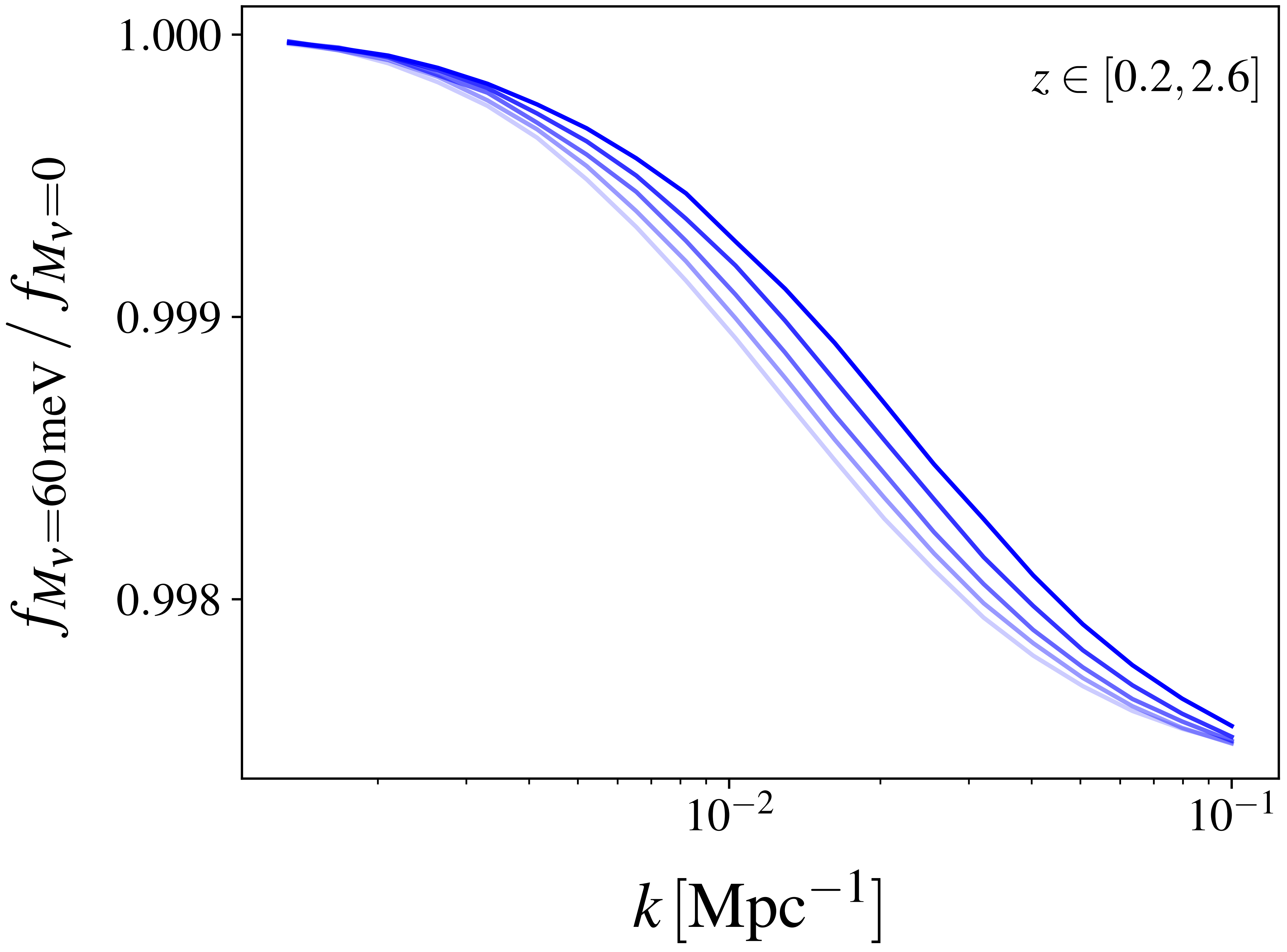


[K. Abazajian & M. Kaplinghat 2016]

Neutrino Mass Constraints from kSZ Tomography

Why might kSZ be useful here?

- Velocity field traces **matter (clustering)** and **growth rate**: $v \sim \delta_m \frac{faH}{k}$
  - $f = \frac{d}{d \ln a}\left[\left(\frac{P_{mm}(k,a)}{P_{mm}(k,a=1)}\right)^{1/2}\right]$
  - $P_{g\hat{v}_r}(k,z) = b_v(z)\mu\frac{f(k)aH}{k}b_g(k,z)P_{mm}(k,z)$



Neutrino Mass Constraints from kSZ Tomography

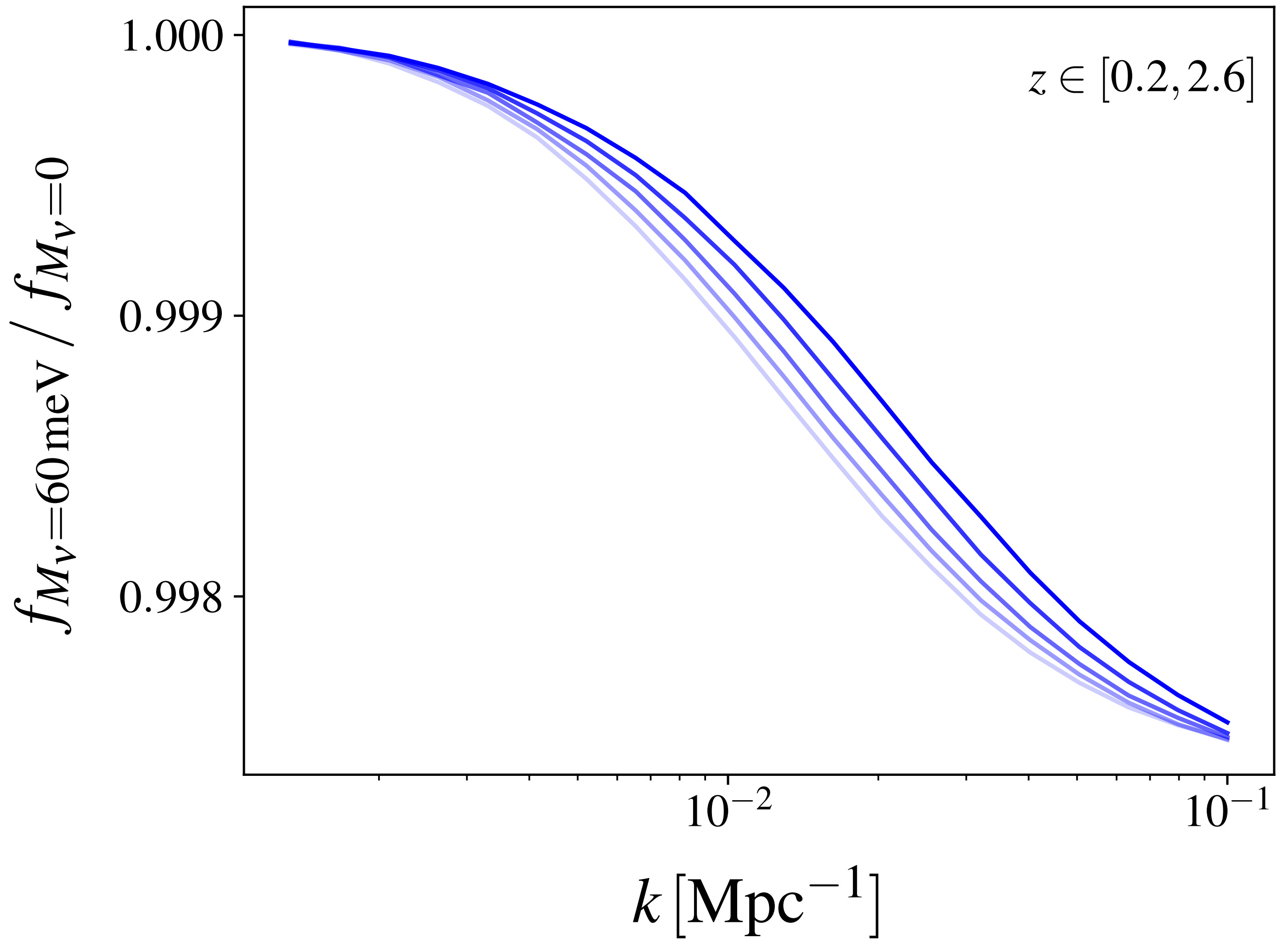
The Role of kSZ in Probing Massive Neutrinos

- important early work [E. M. Mueller et. al., 2014]
- kSZ $\Longrightarrow$ additional, differently biased tracer of matter power
  - break degeneracy between cosmology and astrophysics

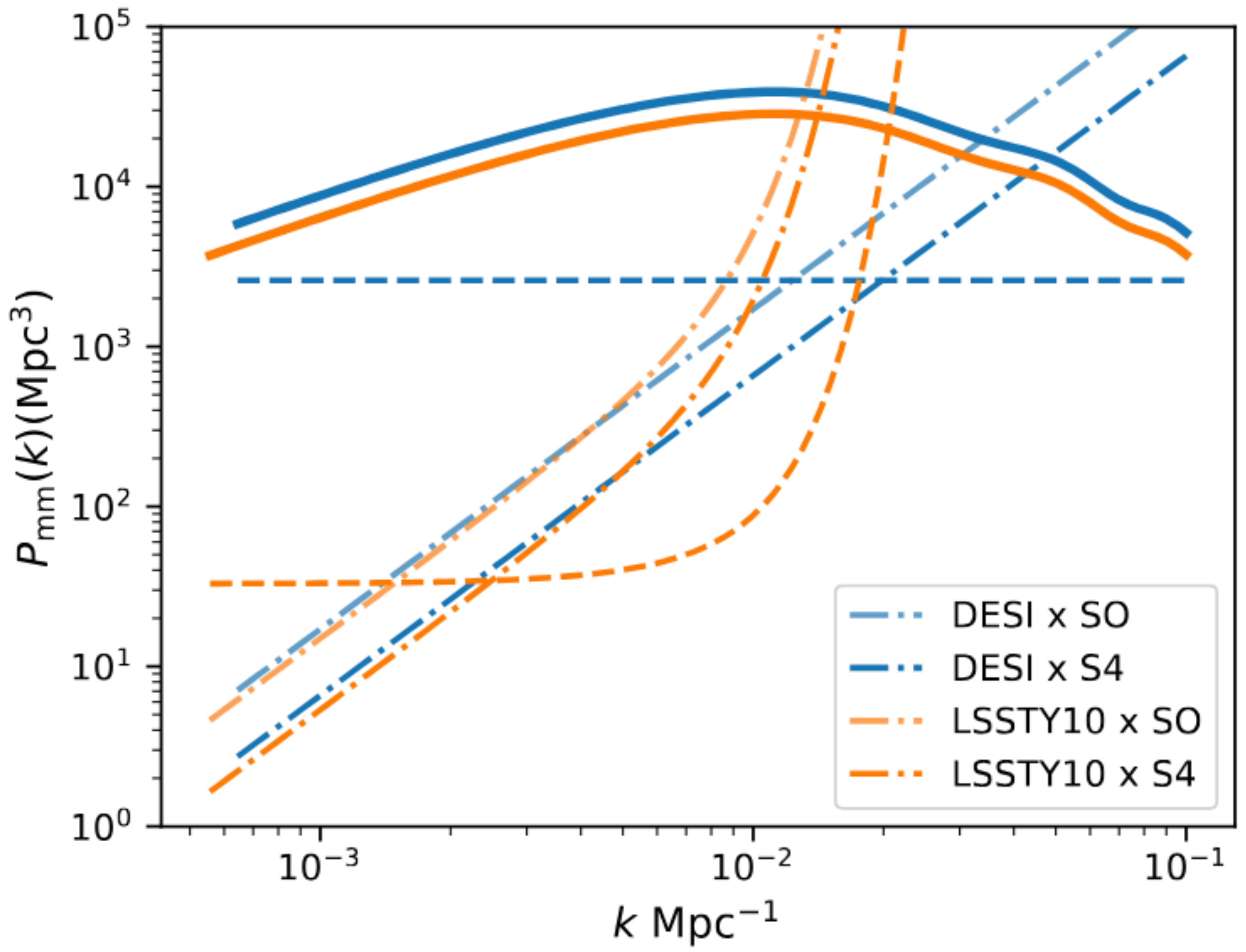
$$P_{gg}(k,z) = b_g(k,z)^2 P_{mm}(k,z)$$

$$P_{\hat{v}_r\hat{v}_r}(k,z) = \left[b_v(z)\mu\frac{f(k)aH}{k}\right]^2 P_{mm}(k,z)$$

- "Anchor" the galaxies $\Longrightarrow$ improved small scale sensitivity
- **Independent probe of cosmic growth**



[Smith et. al. 2018]



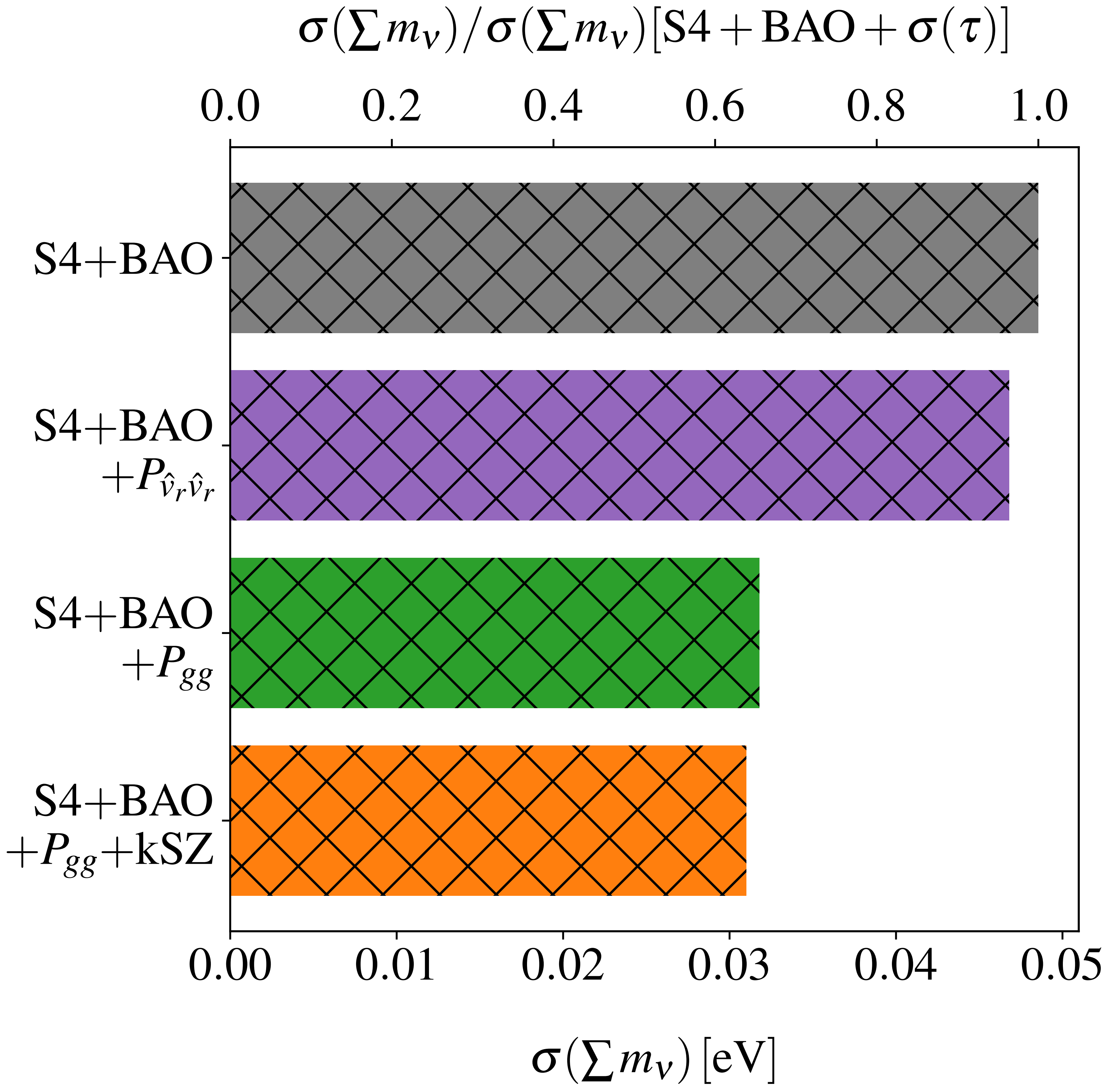
Neutrino Mass Constraints from kSZ Tomography

Baseline Results: kSZ Neutrino Mass Constraints

Key Questions:

- "How effective is kSZ as a sole, independent probe of growth?"
  - Remove *all* CMB lensing info
  - Marginalize over RSD bias, $b_g \ni b_{\rm rsd} f \mu^2$
- "What does kSZ add that isn't already in the galaxy and CMB survey used to facilitate the velocity reconstruction?"
  - Compare $[\mathrm{S4} + \mathrm{P_{gg}}]$ to $[\mathrm{S4} + \mathrm{P_{gg}} + \mathrm{kSZ}]$

[AJT et. al. 2025]



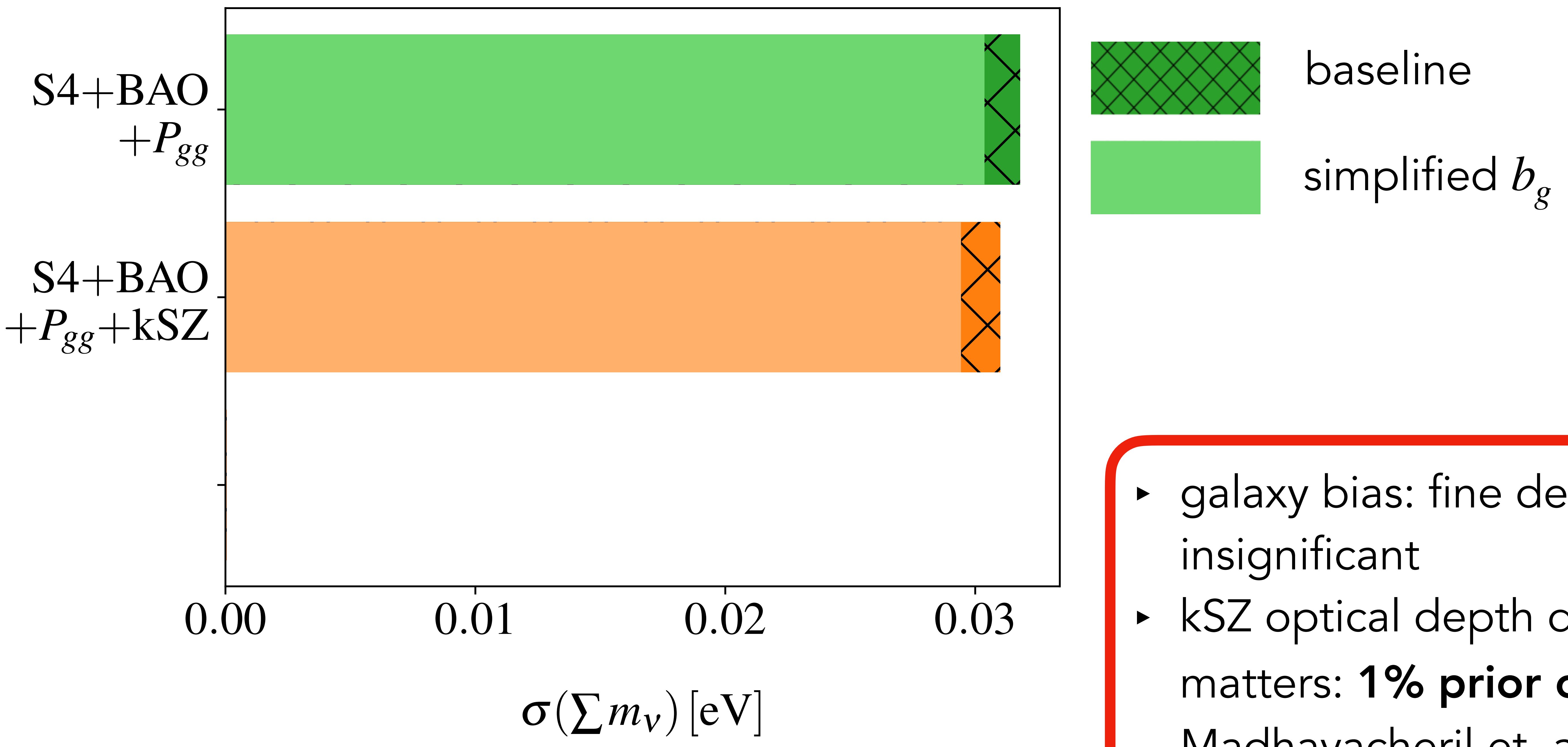
kSZ offers about 3% reduction in $\sigma(\Sigma m_\nu)$

Neutrino Mass Constraints from kSZ Tomography

Modeling Details: Bias Assumptions

- **simpler galaxy bias model?** (redshift- and scale-dependent information) — **minimal impact**
- **kSZ optical depth degeneracy**
  - how do electrons trace LSS? $P^{\text{true}}_{ge}(k_S) \neq P^{\text{fid}}_{ge}(k_S) \rightarrow \hat{v}_r = b_v v_r$
    - **biased velocity reconstruction!**
  - Uncertainty in small scale astrophysics $\iff$ uncertainty in cosmological inference
  - Marginalize over b_v (analogous to linear galaxy bias b_1)

[AJT et. al. 2025]

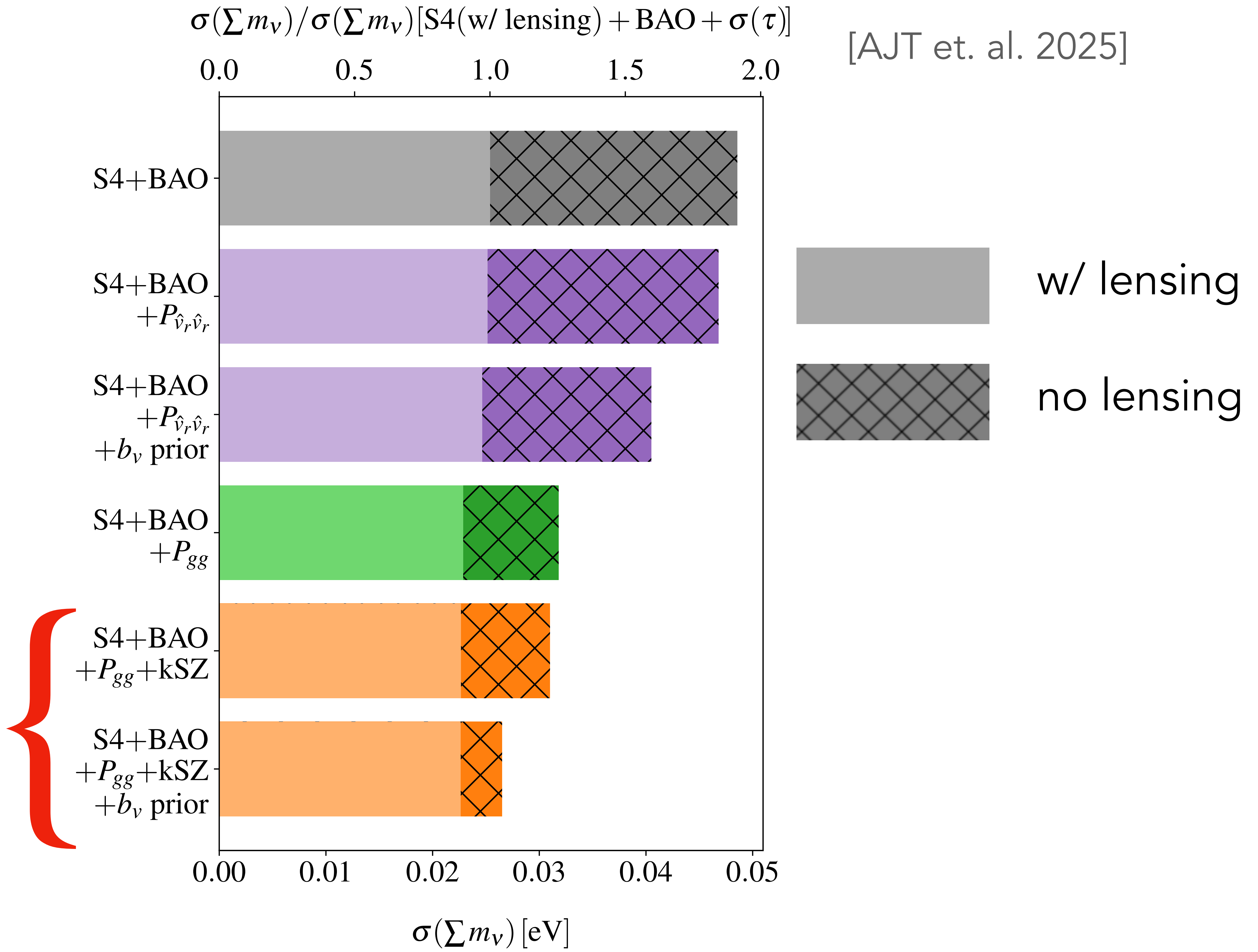


- galaxy bias: fine details are insignificant
- kSZ optical depth degen. matters: **1% prior on** b_v [M. Madhavacheril et. al. 2019] $\implies \gtrsim 15\,\%$ **improvement!**

Neutrino Mass Constraints from kSZ Tomography

What about CMB Lensing?

- Observed CMB temperature, polarization are necessarily lensed; extra information from $C_\ell^{\phi\phi}$
- **CMB lensing is a powerful probe of cosmic growth, massive neutrinos**
- **gains from breaking kSZ optical depth degeneracy are overshadowed by CMB lensing info**



Neutrino Mass Constraints from kSZ Tomography

Looking (Way) Ahead

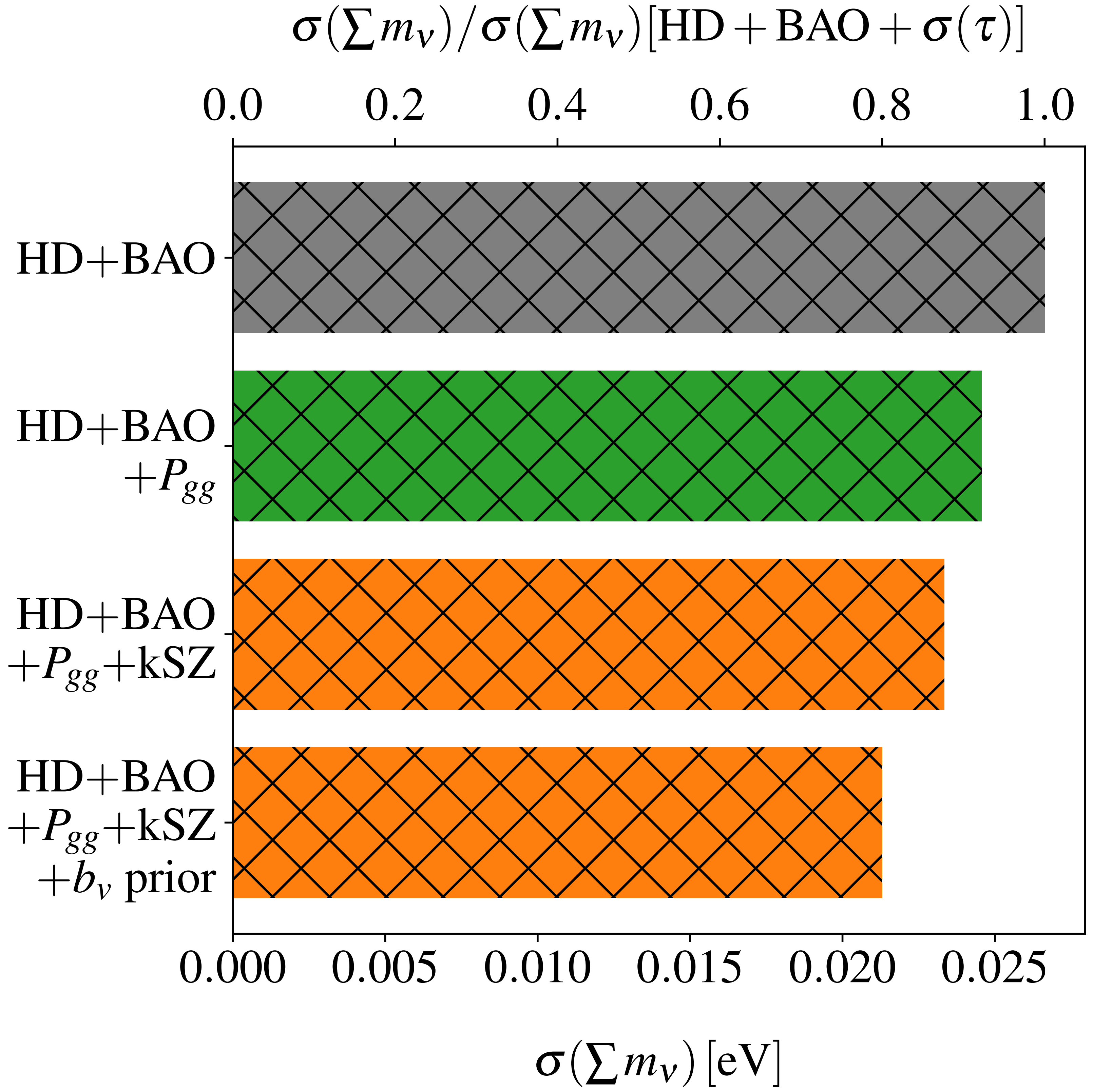
CMB HD:

- no lensing info
- similar to baseline (S4+LSST) results
- HD + "spec-z LSST" $\Longrightarrow \sim 25\,\%$ tighter constraints on $\sum m_\nu$ **without** b_ν prior

Other non-kSZ probes:

- KSZ & neutrino-induced galaxy bias? [Chiang et. al. 2018, AJT et. al. (in prep)]
- "neutrino winds" [C. Nascimento & M. Loverde, 2023]
- line intensity mapping [Shmueli et. al. 2024]
- etc.

[AJT et. al. 2025]



Summary and Outlook

- **kSZ** can help us search for **new physics from the early universe**, e.g. light particles present during an inflationary epoch, with **scale-dependent bias from primordial non-Gaussianity beyond the local limit**

- **In principle, kSZ may shed light on massive neutrinos**, but *in practice* its use case will likely be more complementary than it will be distinctive

- futuristic prospects look very bright!

Extra Slides

KSZ Tomography

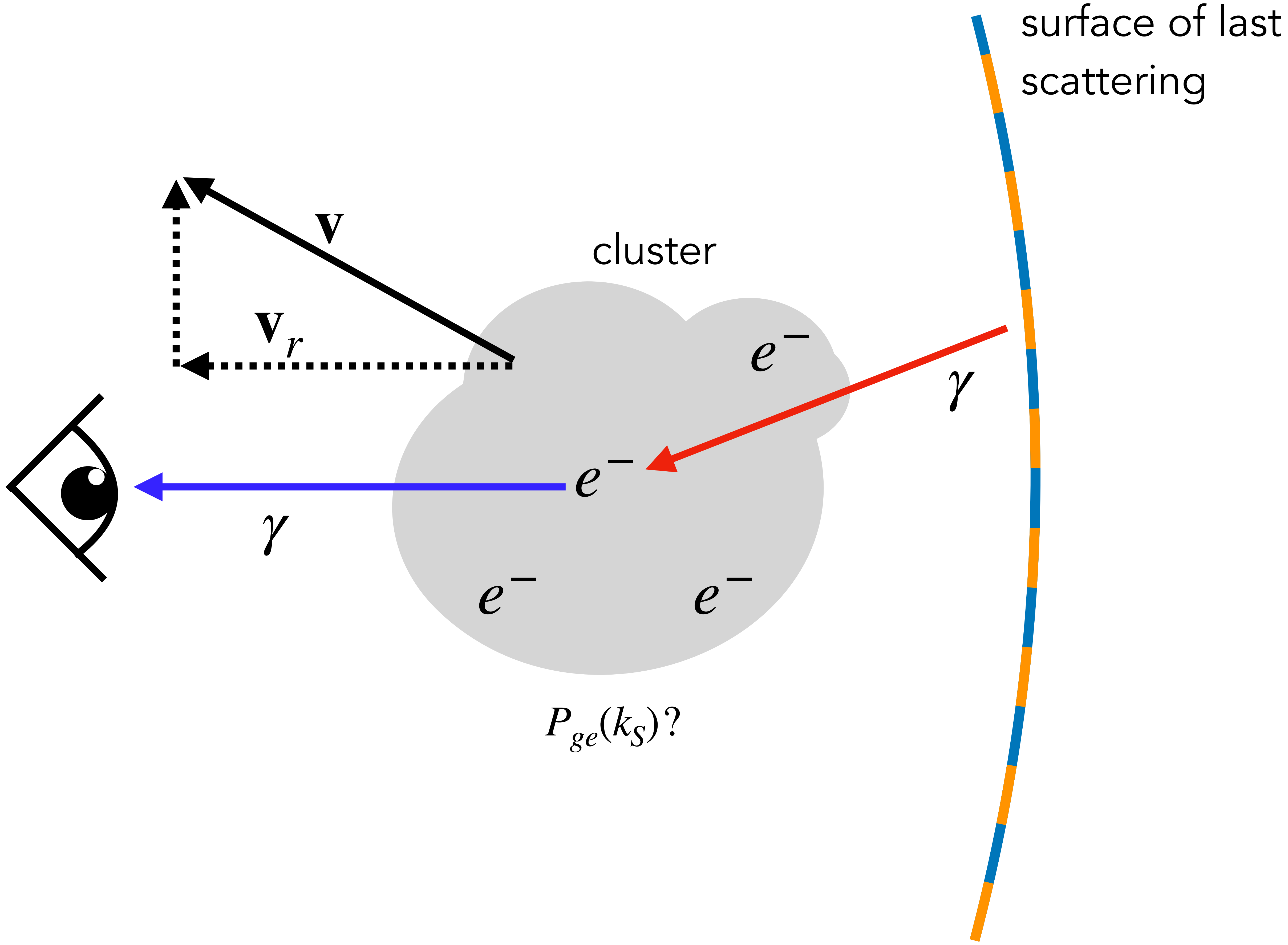
kSZ 'Optical Depth' Degeneracy

- kSZ tomography: underlying signal is a squeezed bispectrum [Smith et. al. 2018]
  - $P_{gv}? \rightarrow \langle \delta_g \delta_g T \rangle \propto P_{ge}(k_S) P_{gv}(k_L)$

uncertainty in small-scale astrophysics

cosmological inference

- Biased velocity reconstruction $P_{ge}^{\text{true}}(k_S) \neq P_{ge}^{\text{fid}}(k_S) \rightarrow \hat{v}_r = b_v v_r$
  - marginalize over b_v (scale-independent, analogous to linear galaxy bias b_1)

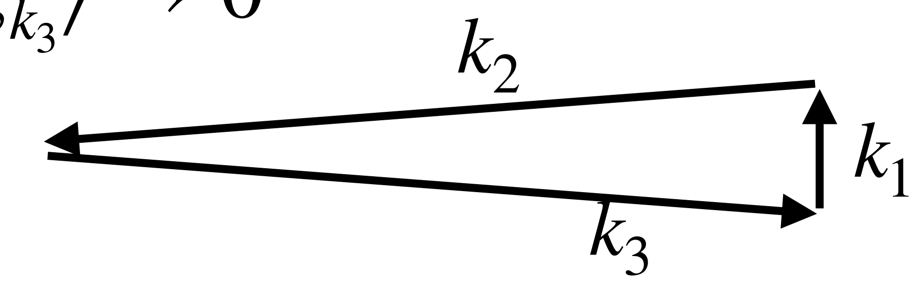


Primordial Non-Gaussianity with kSZ: Overview

Primordial non-Gaussianity: Basics

- inflation: quantum fluctuations seeds large scale structure, $\delta\phi \sim \zeta$
  - 'generically' Gaussian (single field, slow roll)
    - Observable squeezed bispectrum is small!

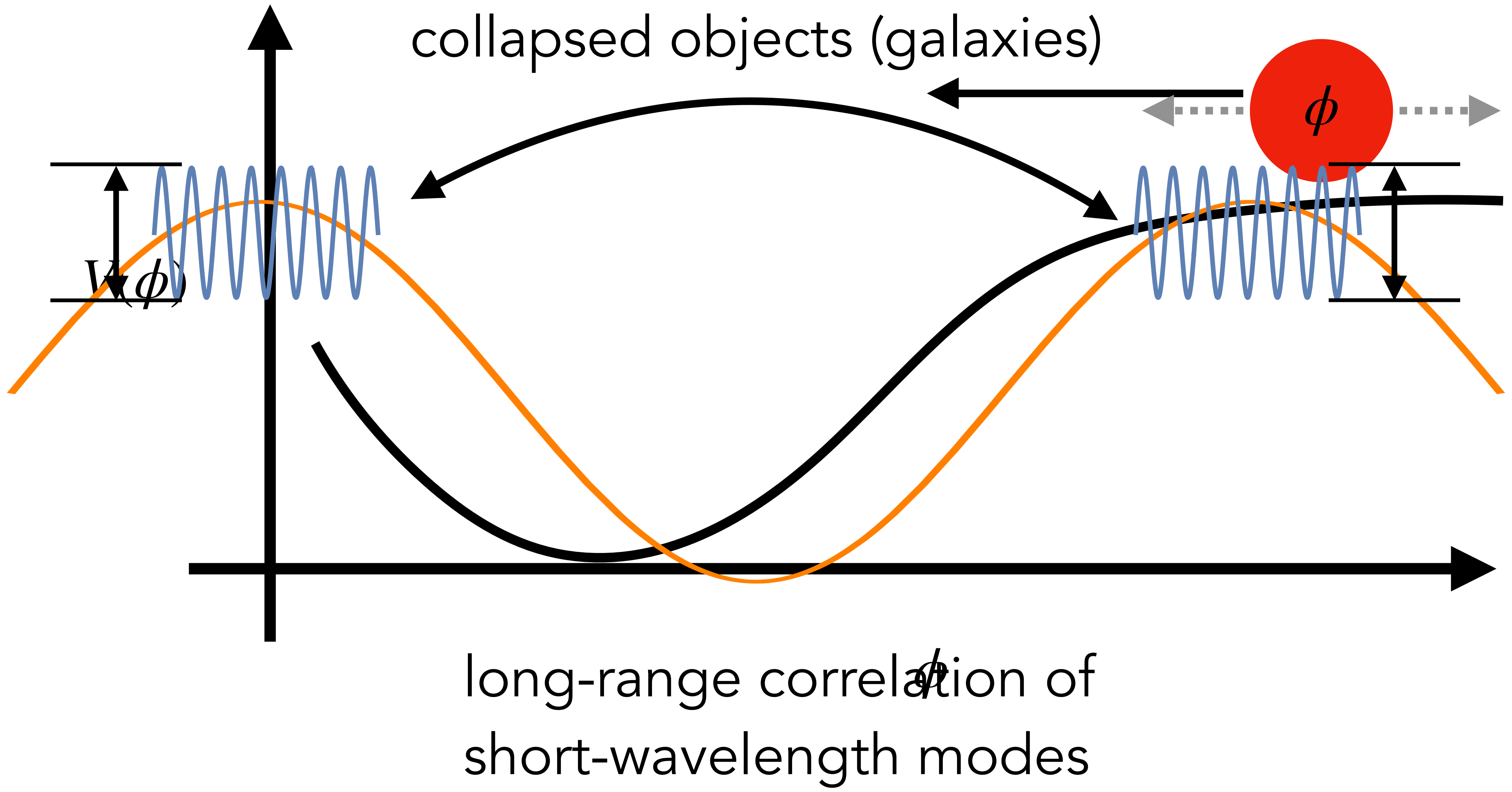
$$\lim_{k_1 \to 0} \langle \zeta_{k_1} \zeta_{k_2} \zeta_{k_3} \rangle \to 0$$



[J. Maldacena 2003]
[P. Creminelli & M. Zaldarriaga 2004]
[E. Pajer et. al., 2013, P. Creminelli et. al. 2014]

- "Local-type": $\zeta_{NG} = \zeta_g(\mathbf{x}) + f_{NL}^{\text{loc}} \left[\zeta_g^2(\mathbf{x}) - \langle \zeta_g^2 \rangle \right]$
- Many sources of primordial non-Gaussianity (multi-field scenarios, excited initial states, etc.)
  - **beyond local type**!

  [D. Baumann 2009]

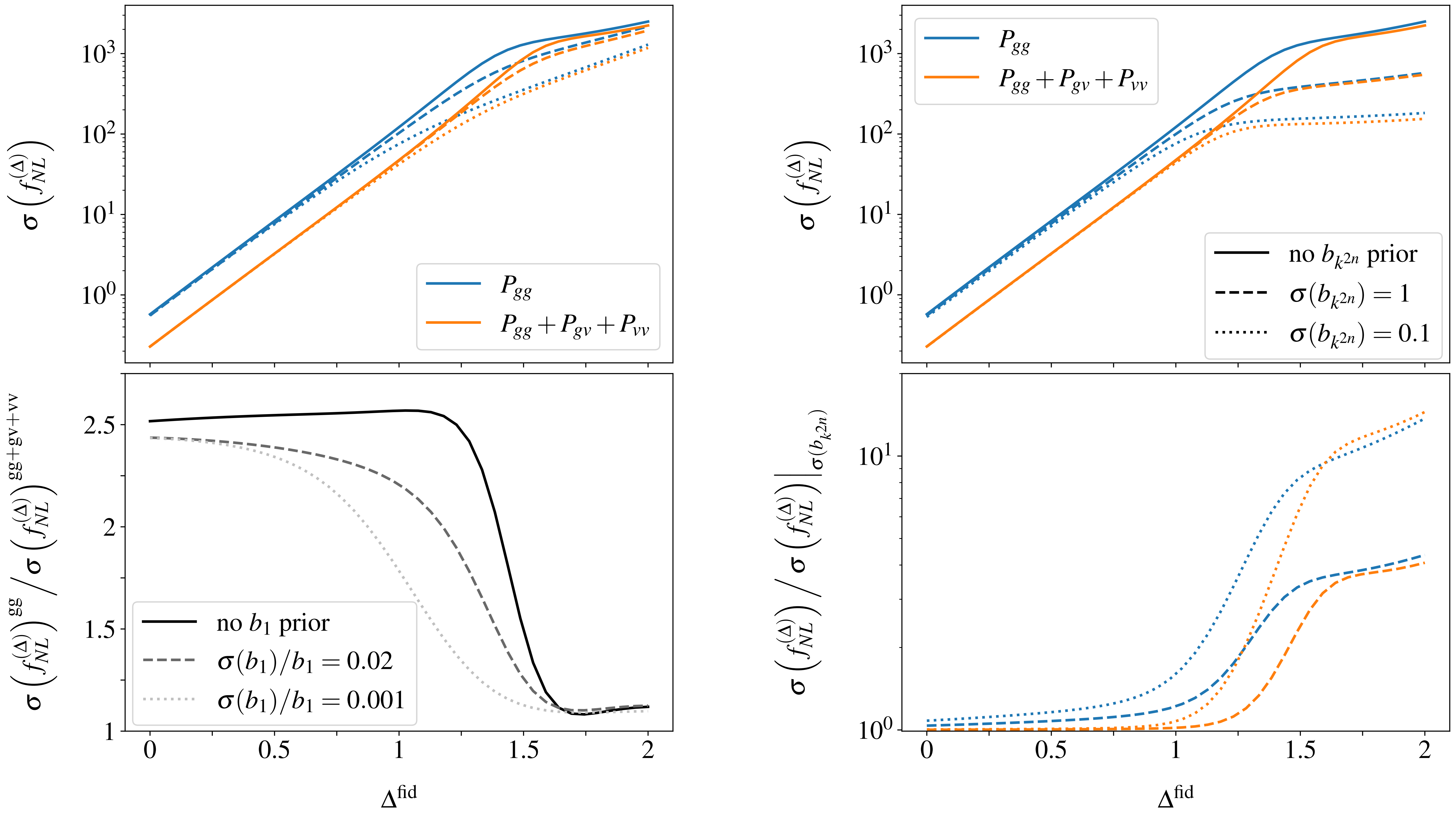


Primordial non-Gaussianity $\Longrightarrow$ different primordial scenarios

Primordial Non-Gaussianity with kSZ

Uncertainty in galaxy bias

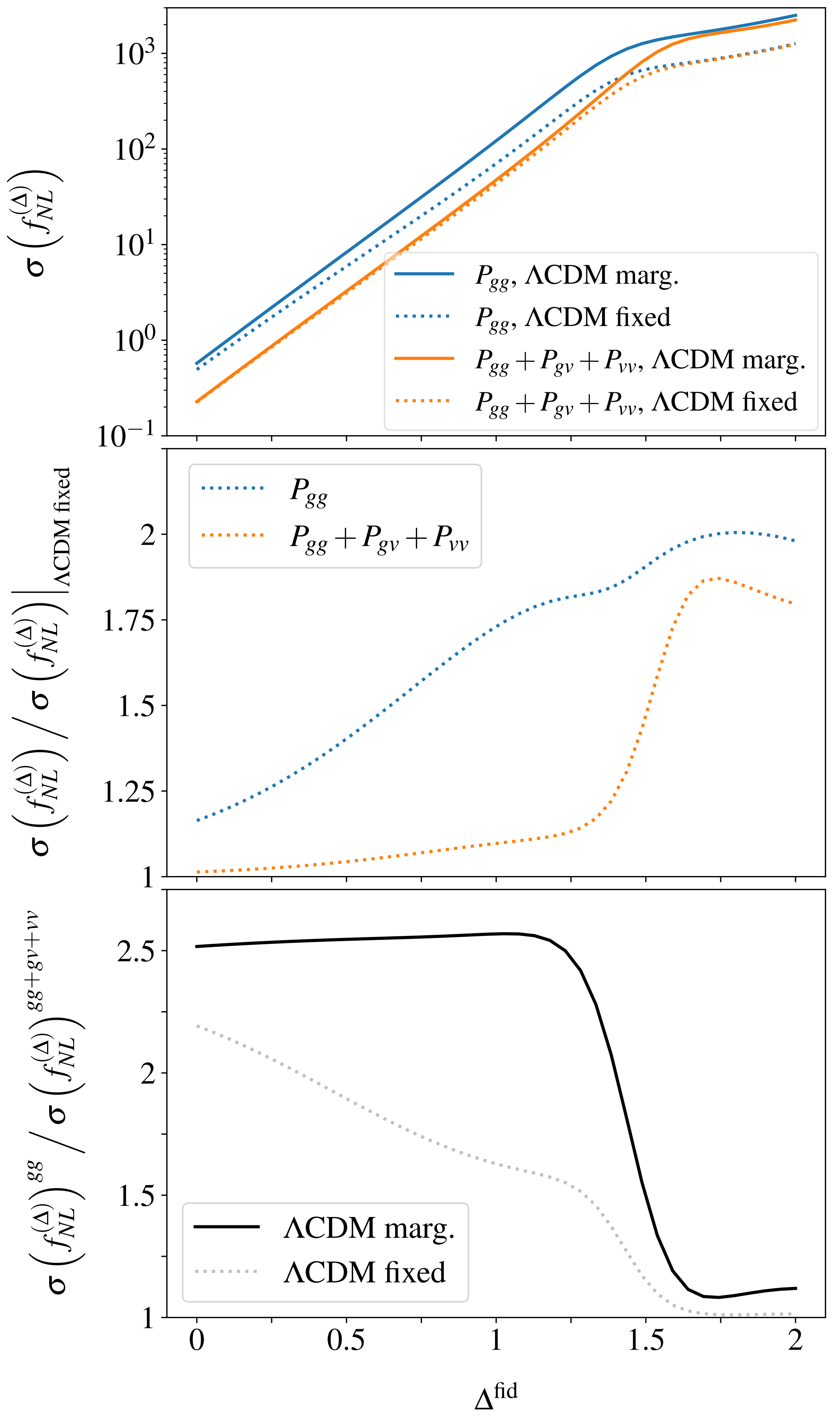
- kSZ mitigates loss of constraining power due to astrophysical uncertainties



Primordial Non-Gaussianity with kSZ

Uncertainties in ΛCDM parameters

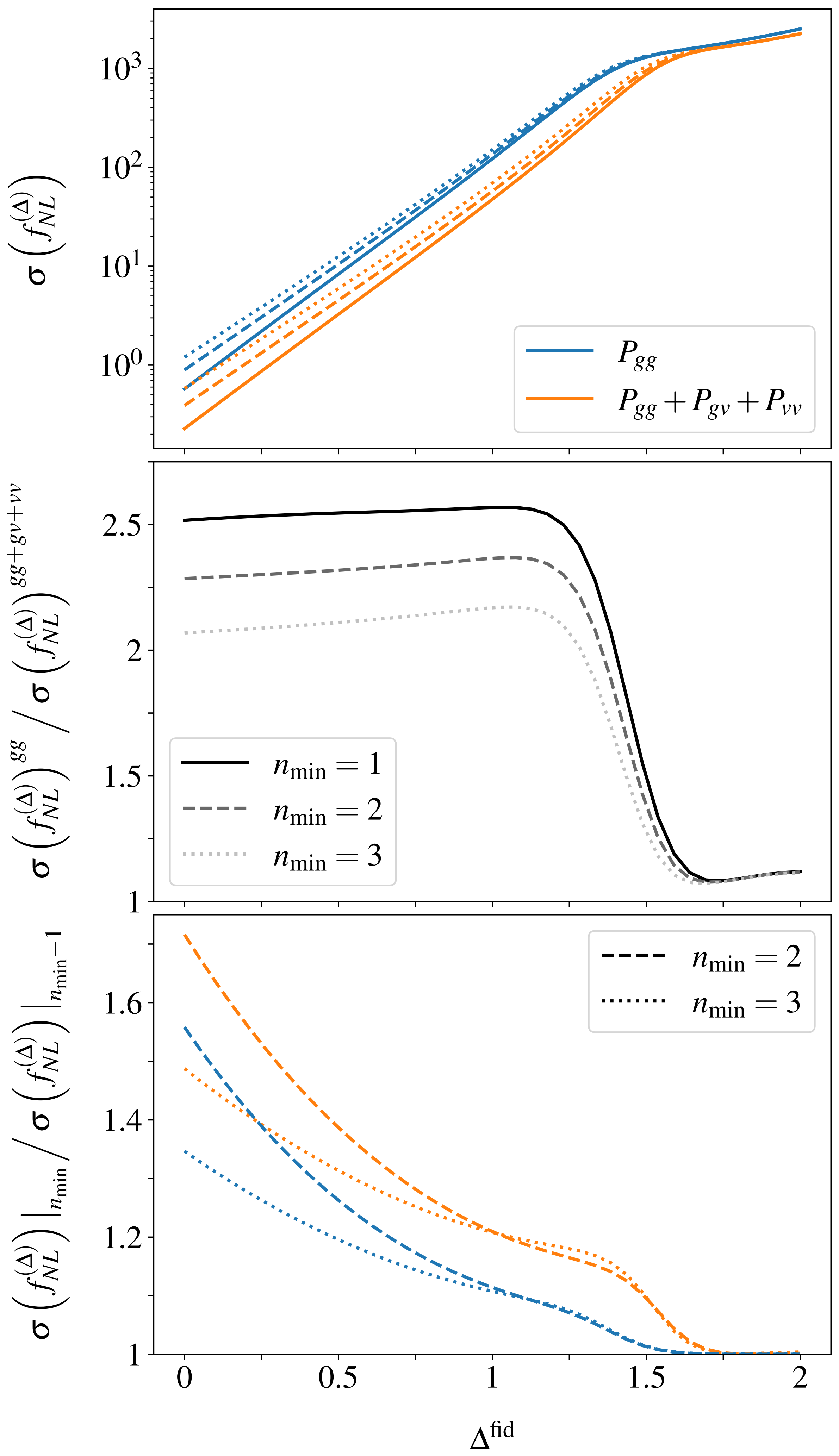
- kSZ helps measure cosmological parameters, break degeneracies
- CMB measurements pin down LCDM, slightly reduce efficacy of kSZ



Primordial Non-Gaussianity with kSZ

Experimental details: galaxy survey

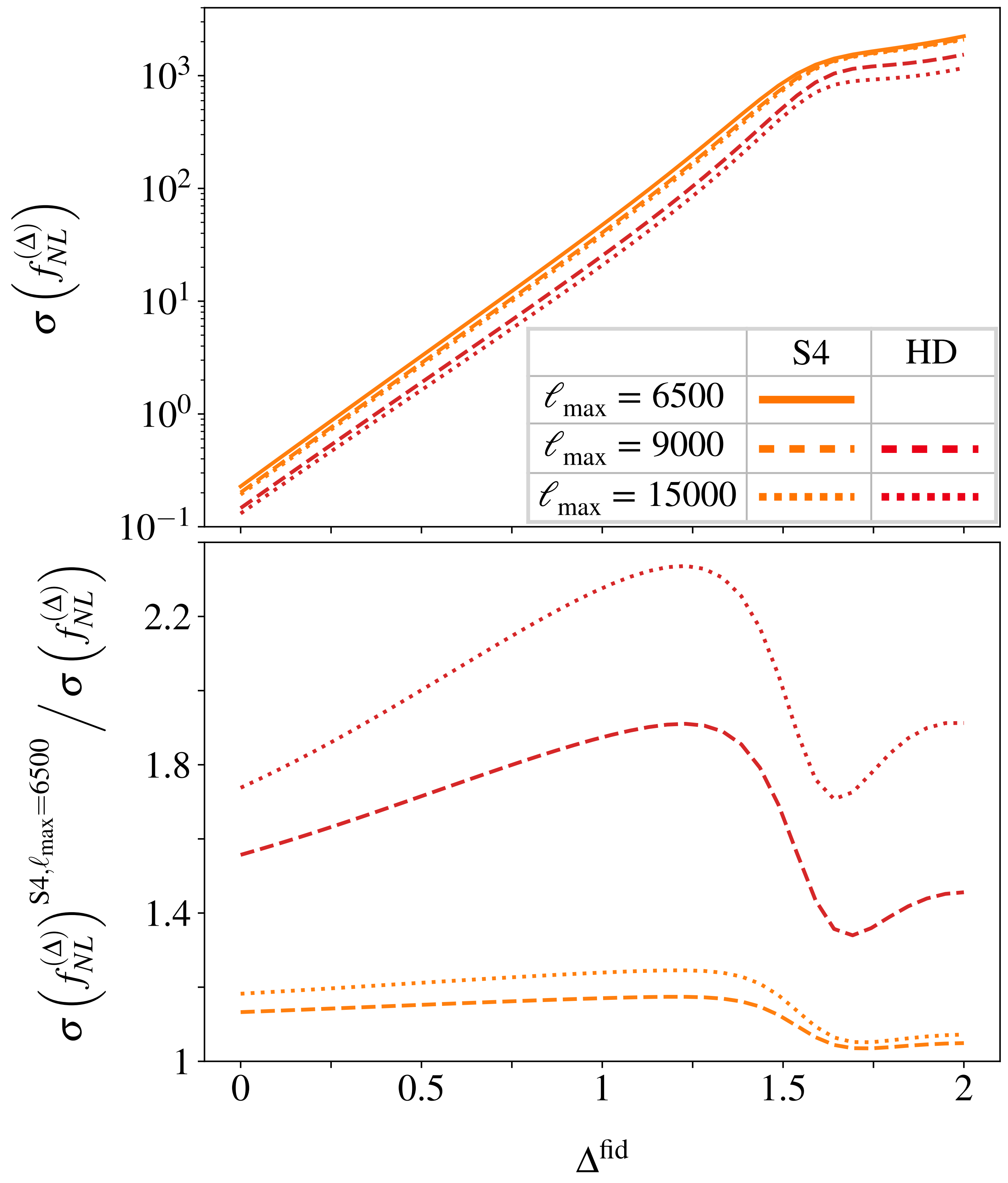
- Largest wavelengths (smallest k modes) are the most important



Primordial Non-Gaussianity with kSZ

Experimental details: CMB

- Higher resolution CMB experiment

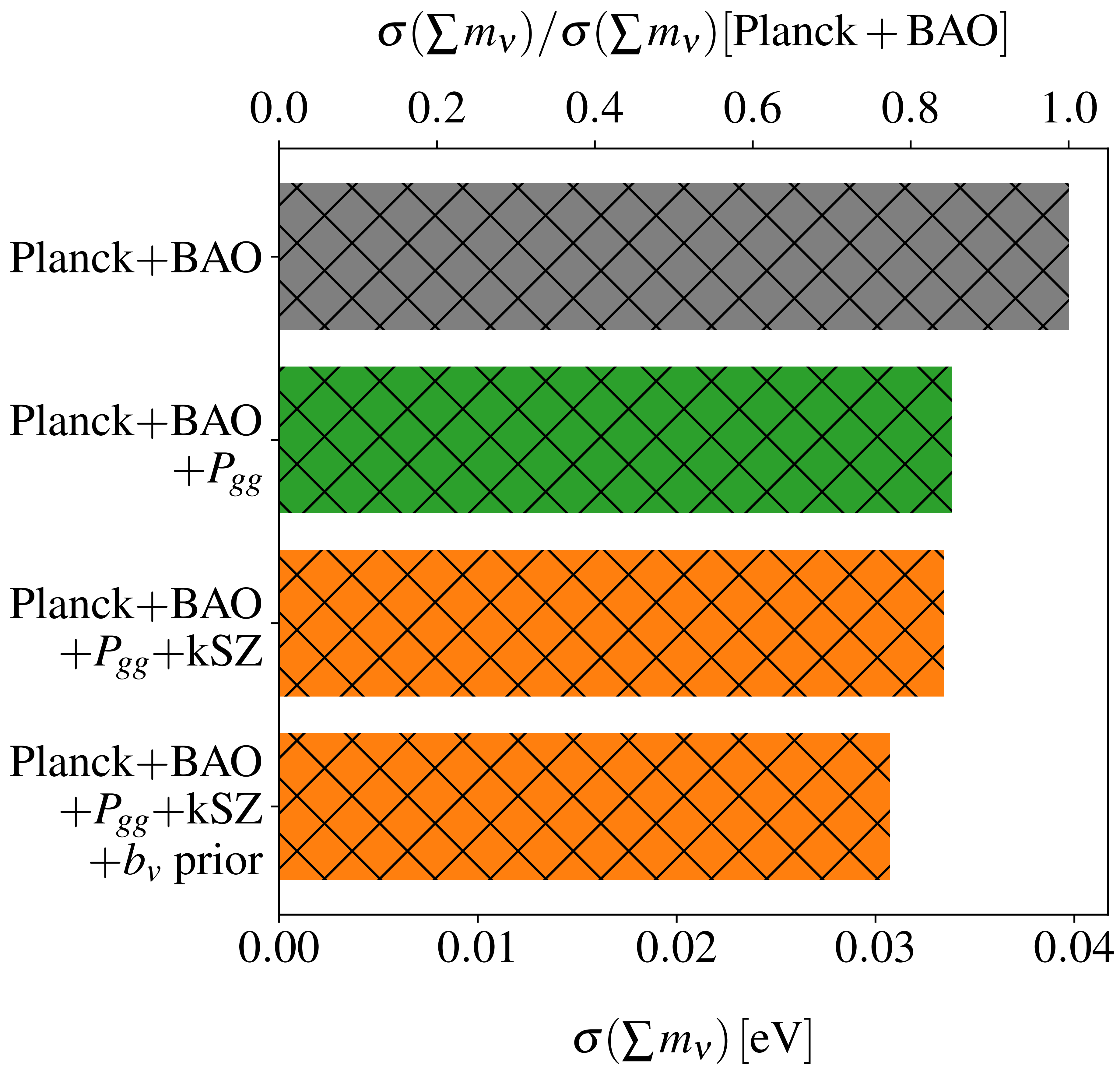


Neutrino Mass Constraints from kSZ Tomography

Past…

Planck PR3+BAO:

- necessarily lensed
- no lensing reconstruction
- similar to baseline (S4+LSST) results



[AJT et. al. 2025]

Neutrino Mass Constraints from kSZ Tomography

Baseline Forecasts

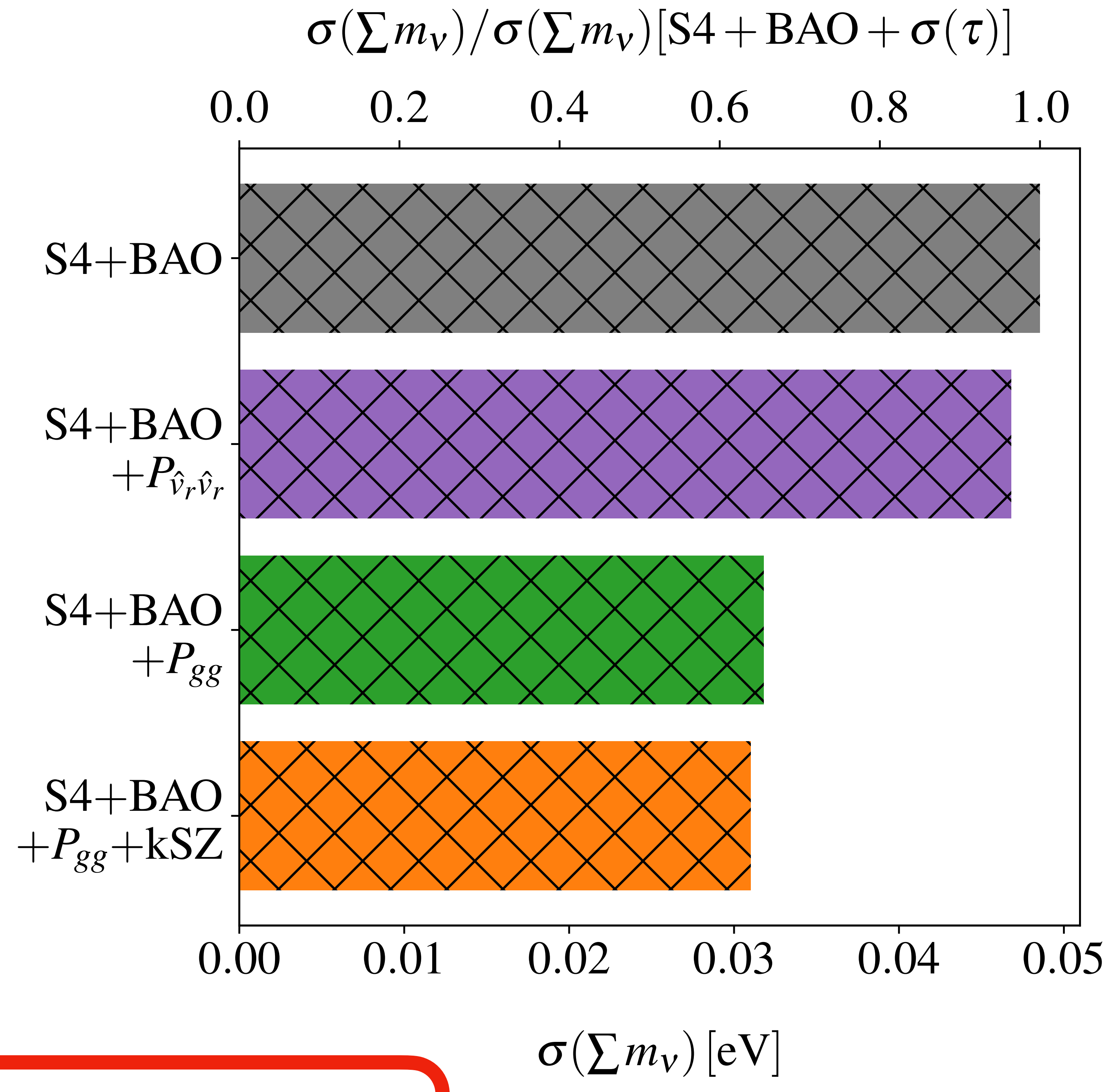
Details:

- LSSTY10 + CMBS4
- DESI BAO
- Include realistic effects (photo-z, RSD, galaxy bias model)
- CMB includes:
- White noise, moving lens and kSZ effects, tSZ, CIB, radio point sources
- Planck optical depth prior
- LSST bins:

z	V [Gpc^3]	n_g [Mpc^{-3}]	b_1
0.2	5.2	5×10^{-2}	1.05
0.7	43.6	2×10^{-2}	1.37
1.3	75.9	6×10^{-3}	1.79
1.9	89.3	1.5×10^{-3}	2.22
2.6	119.9	3×10^{-4}	2.74

Key Questions:

- "What does kSZ add that isn't already in the galaxy and CMB survey used to facilitate the velocity reconstruction?"
  - Compare $[\mathrm{S4} + \mathrm{P_{gg}}]$ to $[\mathrm{S4} + \mathrm{P_{gg}} + \mathrm{kSZ}]$
- "How effective is kSZ as a sole, independent probe of growth?"
  - Remove *all* CMB lensing info
  - Marginalize over RSD bias, $b_g \ni b_{\mathrm{rsd}} f \mu^2$



kSZ offers about 3% reduction in $\sigma(\Sigma\, m_\nu)$

Neutrino Mass Constraints from kSZ Tomography

"Minimal" Scenarios (Fewer Probes)

- Remove DESI BAO & τ prior
  - constraints degrade significantly
  - kSZ: 5% improvement
- Ignore CMB info — e.g. compare [galaxies] to [galaxies + kSZ]
  - "how complementary can kSZ be?"
  - weak constraints — $\mathcal{O}(10^2)$ meV
  - kSZ: 10% improvement over galaxies alone, mostly from $f(k)$

Upshot: appreciable neutrino mass information from kSZ, mostly from scale-dependent growth, but it is overshadowed by other probes.