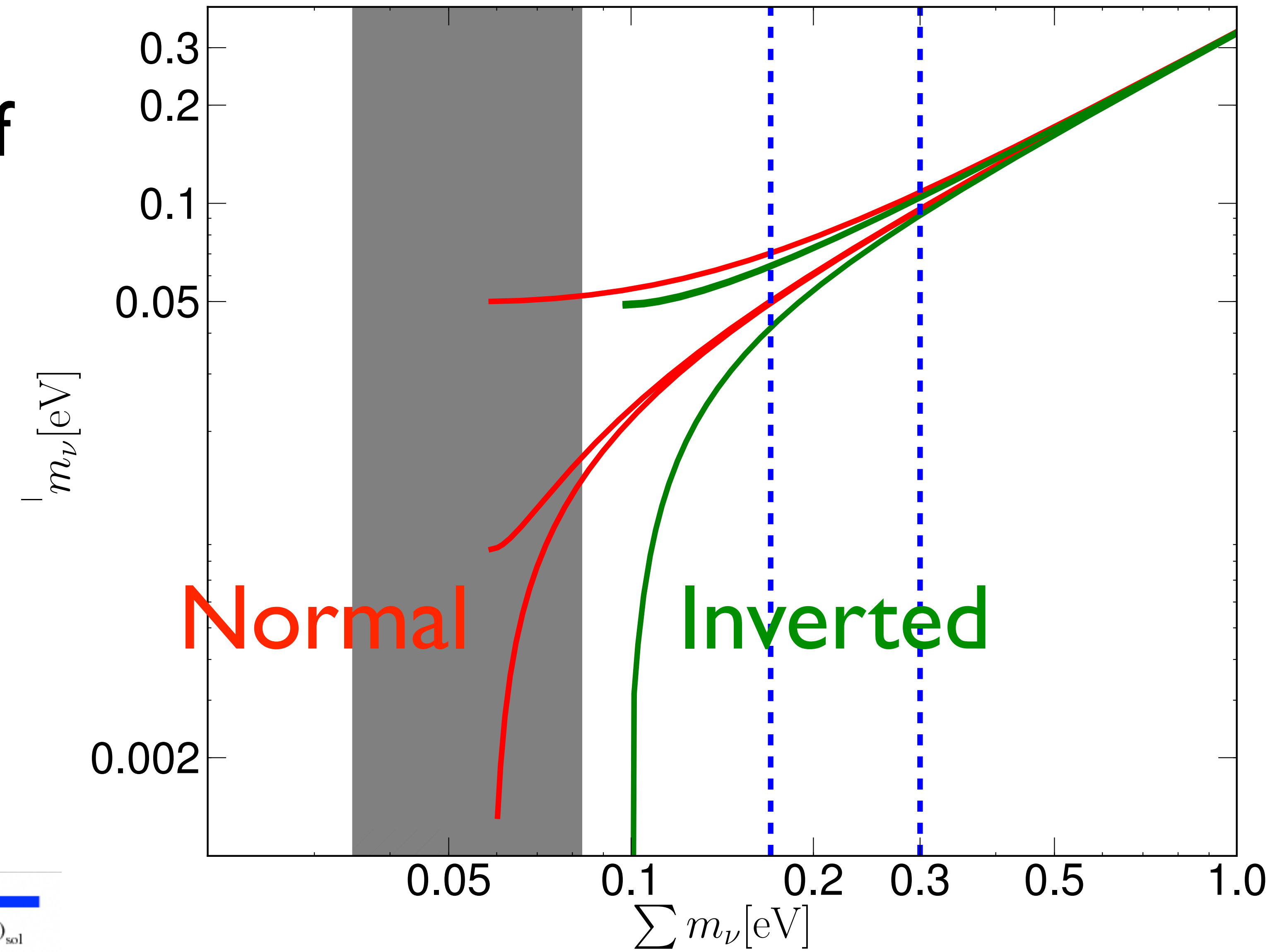
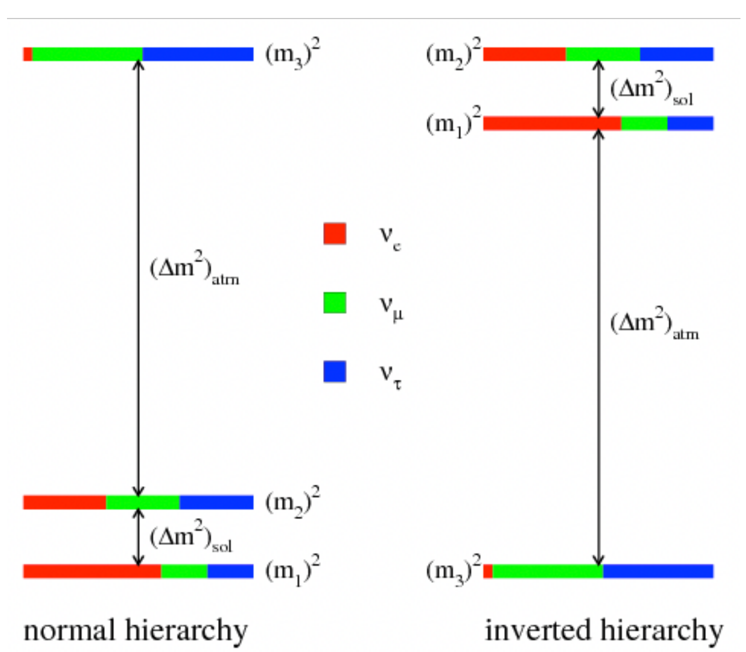
Sum of masses vs. hierarchy

- **Key fact:** LSS basically only measures the sum of neutrino masses.
- Minimum sum of masses:
  - -normal: 59 meV
  - -inverted: 100 meV
- LSS *might* be able to identify a minimal mass normal hierarchy.

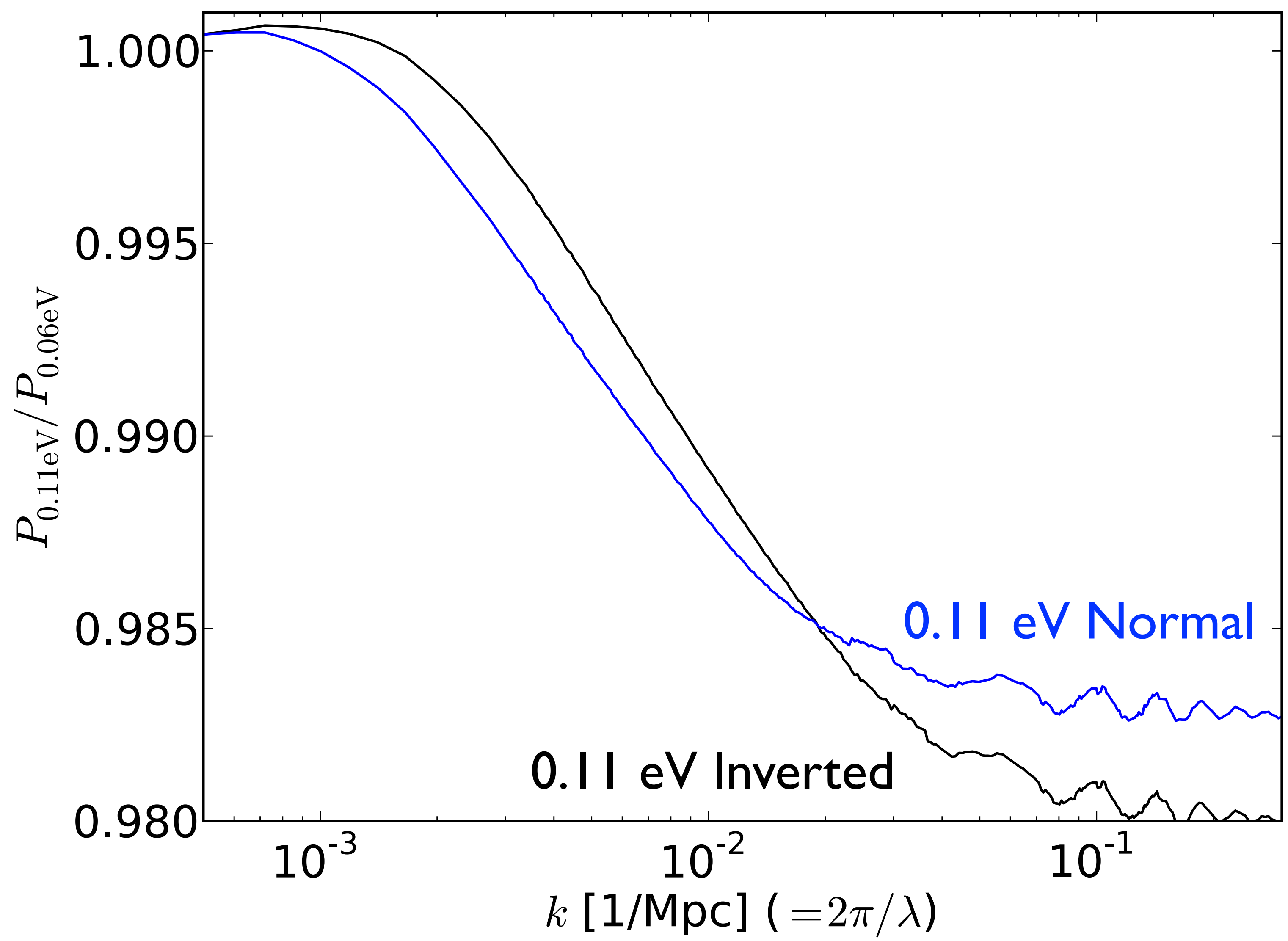




Neutrino suppression of power

$$v_{\rm rms} \simeq 3173\,(1{+}z)\,(0.057\,{\rm eV}/m_\nu)\;{\rm km\ s^{-1}}$$

- Only at z~100 does a 50 meV neutrino finally become non-relativistic.
- Contribute to the subsequent background evolution as if they were dark matter.
- Don't cluster except on very large scales.
- Mass perturbations are "underweight" and don't grow as fast as they would for pure CDM.



$$P(k) \propto \left\langle |\delta_{\mathbf{k}}|^2 \right\rangle \propto {\rm FT}\left[\langle \delta(\mathbf{x})\delta(\mathbf{x}+\mathbf{r})\rangle\right]$$

CMB optical depth degeneracy

The best measurement of neutrino mass comes from comparing the power measured by the CMB to low z power.

Scattering of CMB by electrons after reionization at z~7 suppresses observed CMB power, limiting this comparison.

The scattering optical depth is determined by messy astrophysics but can be measured using large-scale CMB polarization.

CMB measures $A_s e^{-2\tau}$ very precisely. $\sigma_{\ln A_s} = 2\sigma_\tau$

Projections

Current constraint from Planck + BOSS: $\Sigma m_\nu < 120$ meV (95%)

TABLE II. Projected error on Σm_ν, in meV.

	σ_τ		
surveys	0.008	0.004	0.002
Planck+DESI BAO	78	77	77
Planck+DESI	29	20	18
CMB-S4+DESI	26	17	13
CMB-S4+DESI+LSST	23	15	11
CMB-S4+MegaMapper	23	14	11
CMB-S4+LSST+MegaMapper	21	13	9.9

Caveat

- Quoted constraint estimates generally assume there is no *other* new physics affecting LSS, e.g., time-dependent Dark Energy equation of state instead of a cosmological constant.
- (one avenue for improvements may be to work on doing better even when allowing for this kind of uncertainty)

Questions and things to do?

- LBL is broadly leading already, leading DESI, leading CMB-S4, and (less obviously) leading theory/analysis developments.

- What do we expect for tau, and is there anything we can do to improve it?

- What can we do to make sure the main large-scale galaxy clustering & lensing measurements are as powerful as possible?

- Are there other surveys/analyses that could realistically improve the bottom line measurement?

(backup slide, 2019)
Optical depth improvements?

- CMB measurement comes from low-l polarization, hard to do from ground.

- CLASS is a ground-based experiment aimed at this, which is running and hopes to achieve better than 0.004 (Watts et al. 2018)

- BFORE balloon hopes to do something similar flying in 2021 (Bryan et al. 2018)

- LiteBIRD satellite could achieve cosmic variance limit ~0.002, launching in ~2028 (see also COrE, PICO)