Neutrino Mass & Neutrino Number from Large Scale Structure

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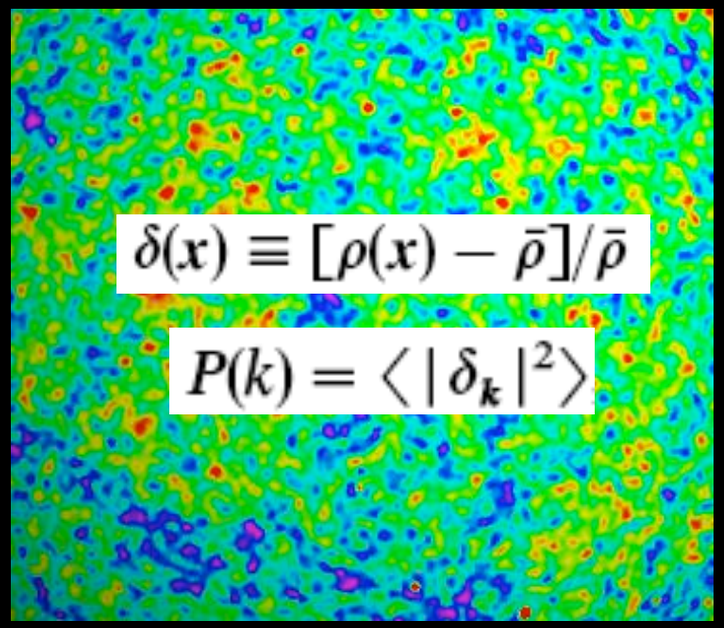
University of California, Irvine

Cosmic Frontier Snowmass 2013 Workshop - CF5
March 6, 2013

Dynamics: the cosmological density perturbation spectrum



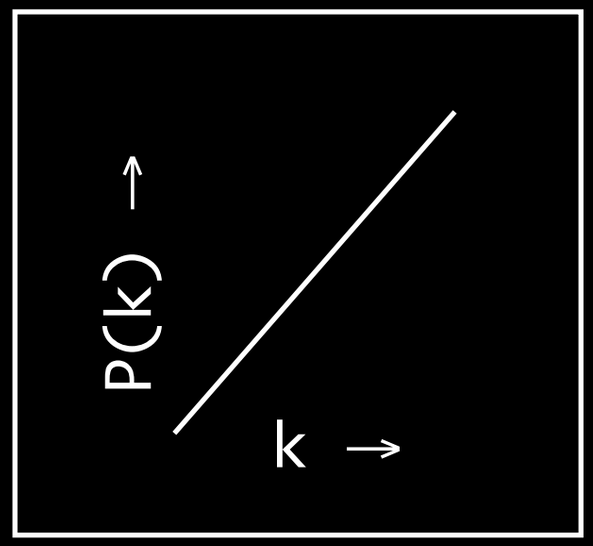
- Power spectrum of cosmological density fluctuations

$$P(k) = \langle |\delta_k|^2 \rangle$$

- Primordial Harrison-Zeldovich: from scale invariance

$$P(k) \propto k$$

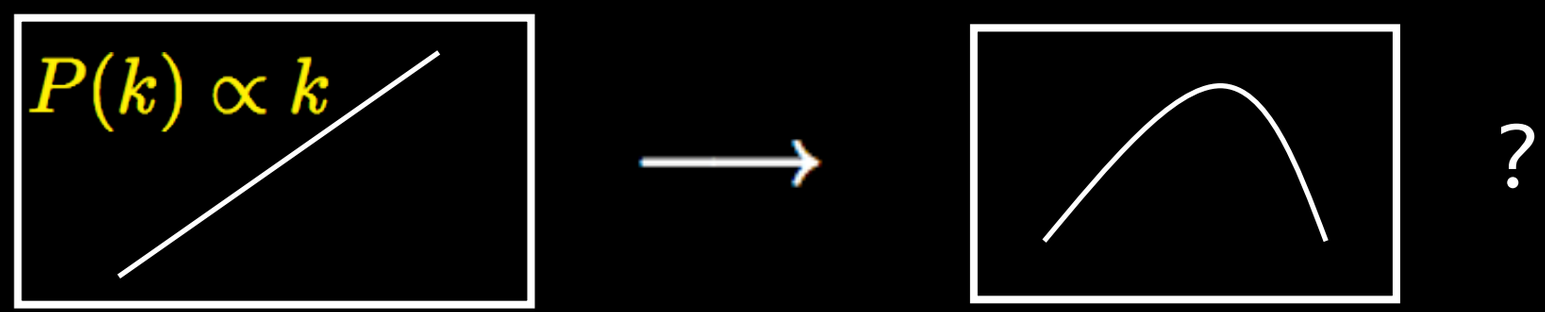
  – Natural solution to perturbation spectrum: self-similar evolution



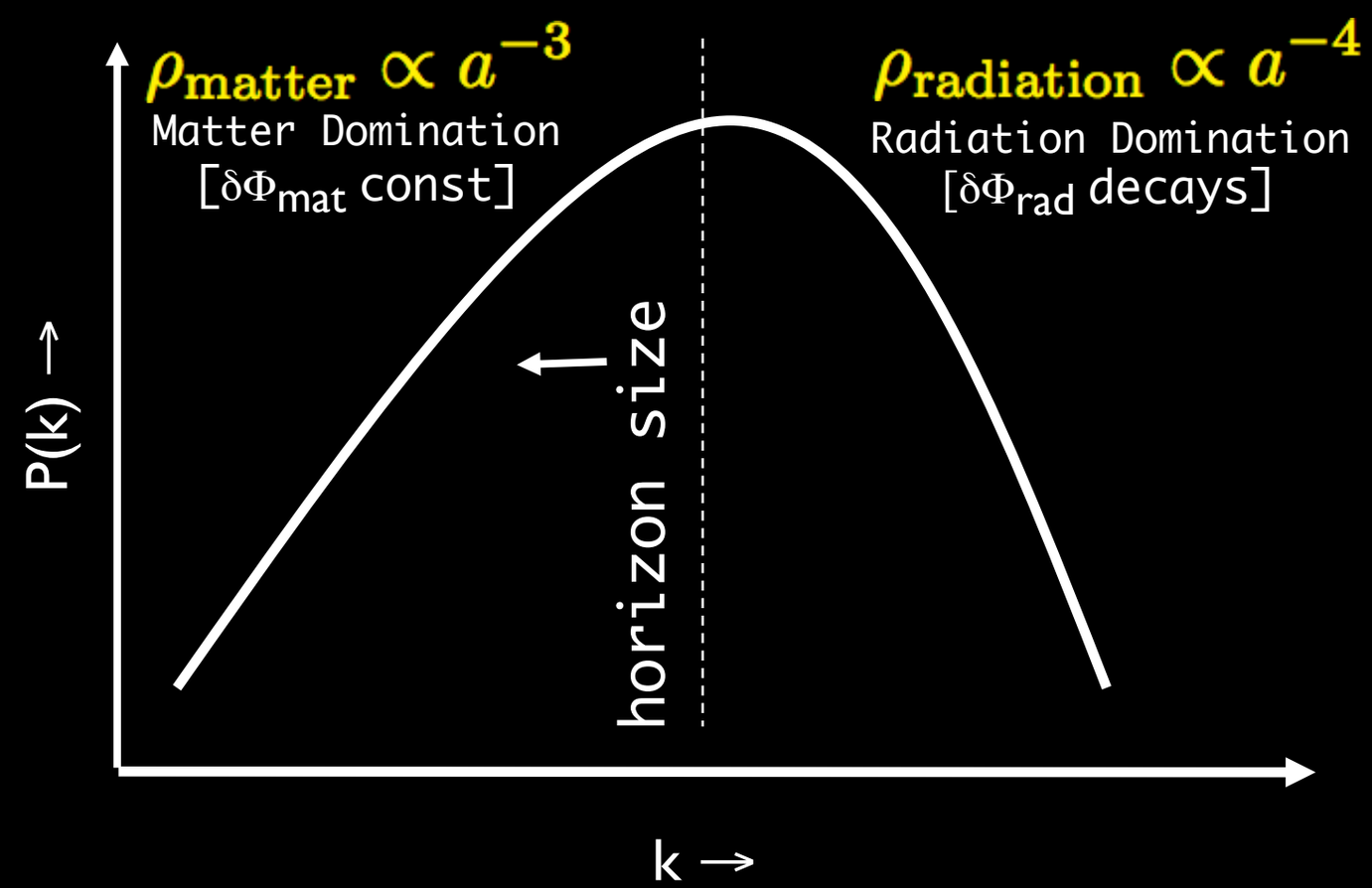
- Predicted by inflation

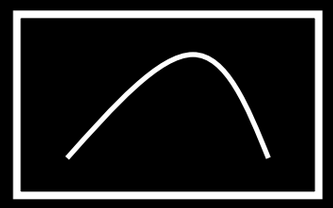
$$P(k) \propto k^n \qquad n \lesssim 1$$

The Cosmological Matter Power Spectrum



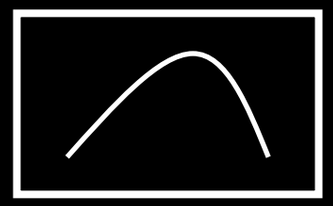
Perturbations enter horizon:



How does  probe neutrinos?

$$n_\nu = N_\nu \times \left(\frac{3}{11}\right) n_\gamma \approx 340\ \mathrm{cm}^{-3}$$

(Assuming thermal equilibrium)

How does  probe neutrinos?

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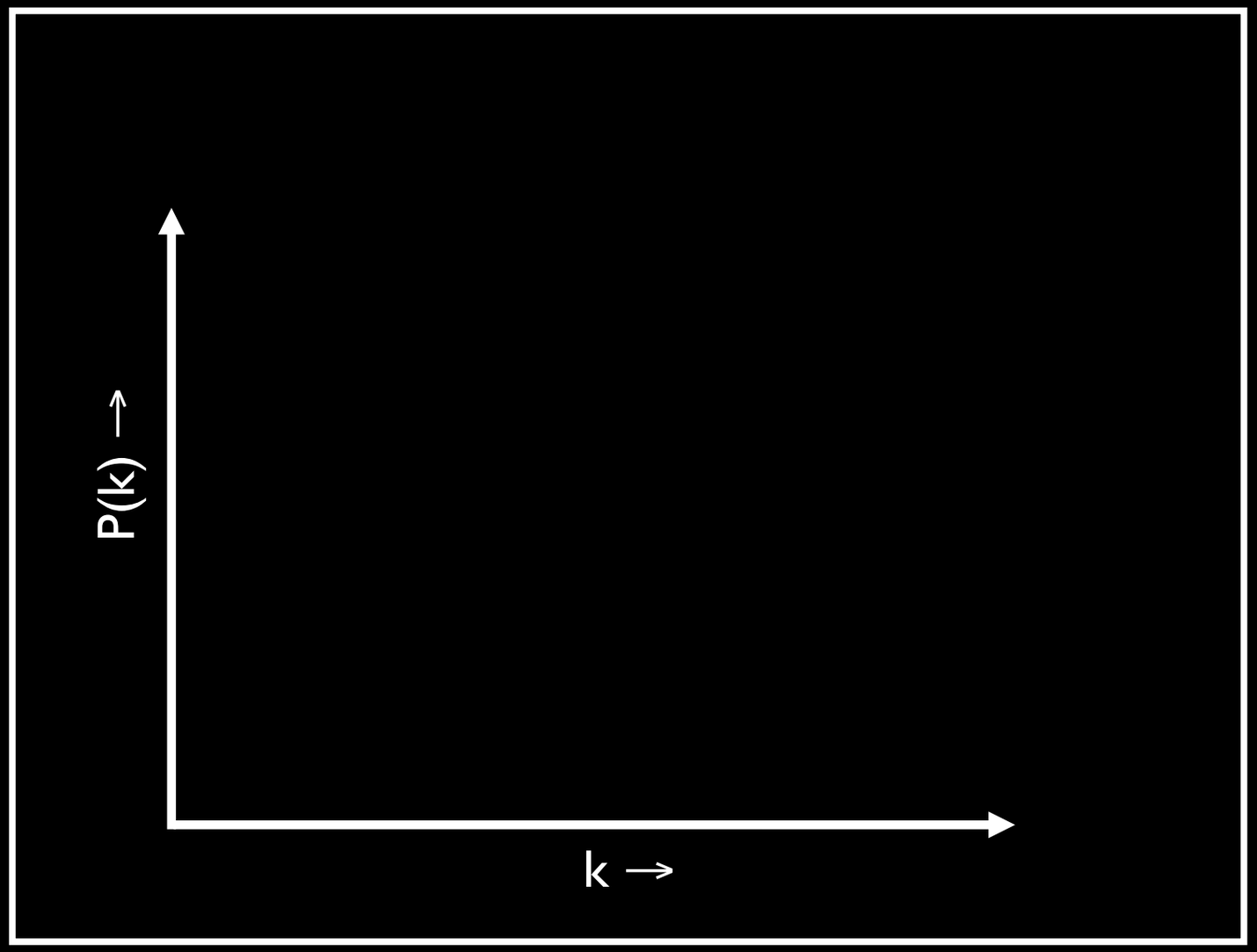
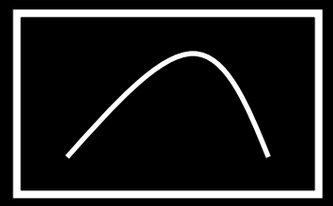


How does  probe neutrinos?

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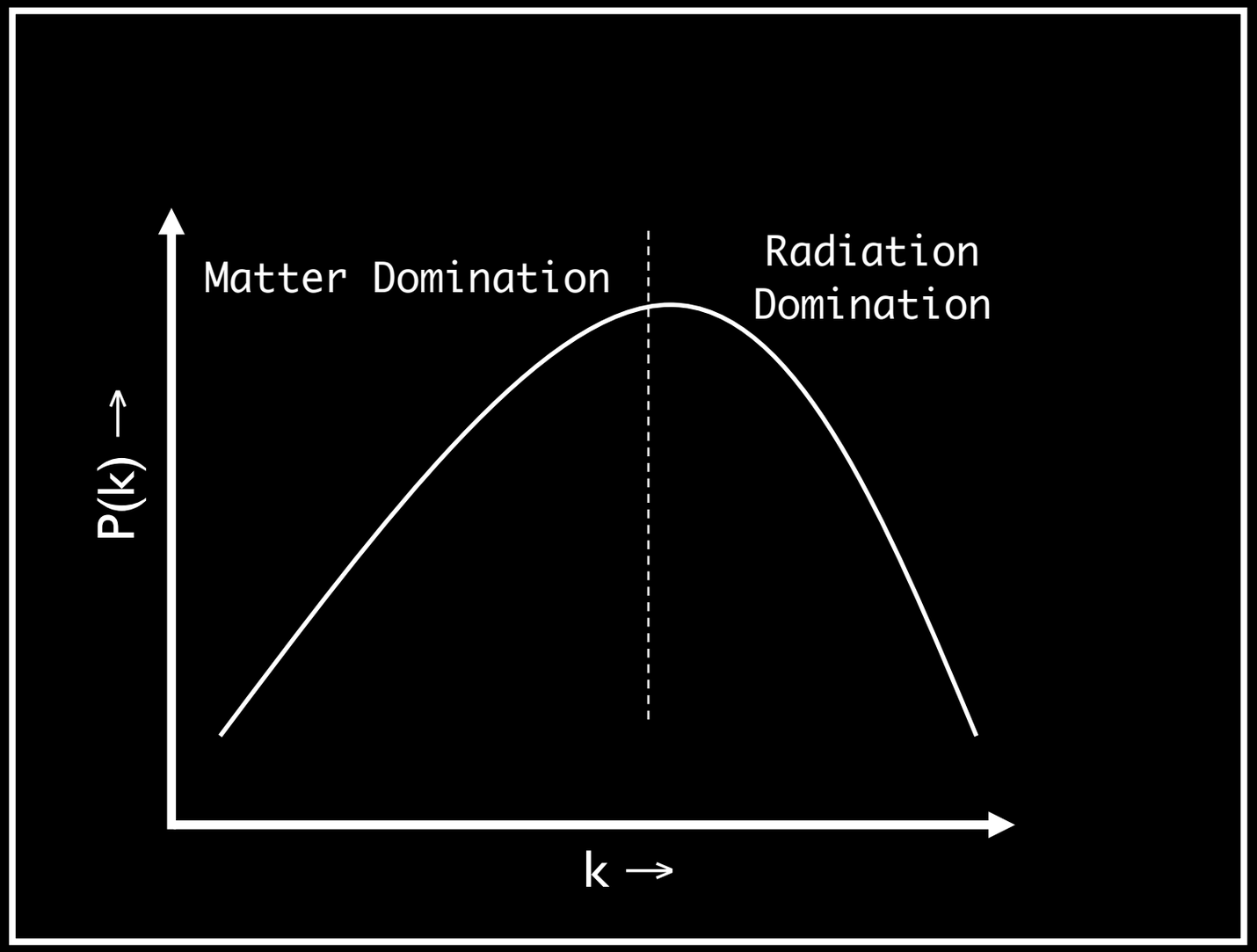
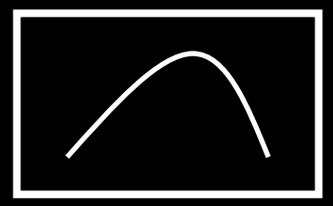


How does  probe neutrinos?

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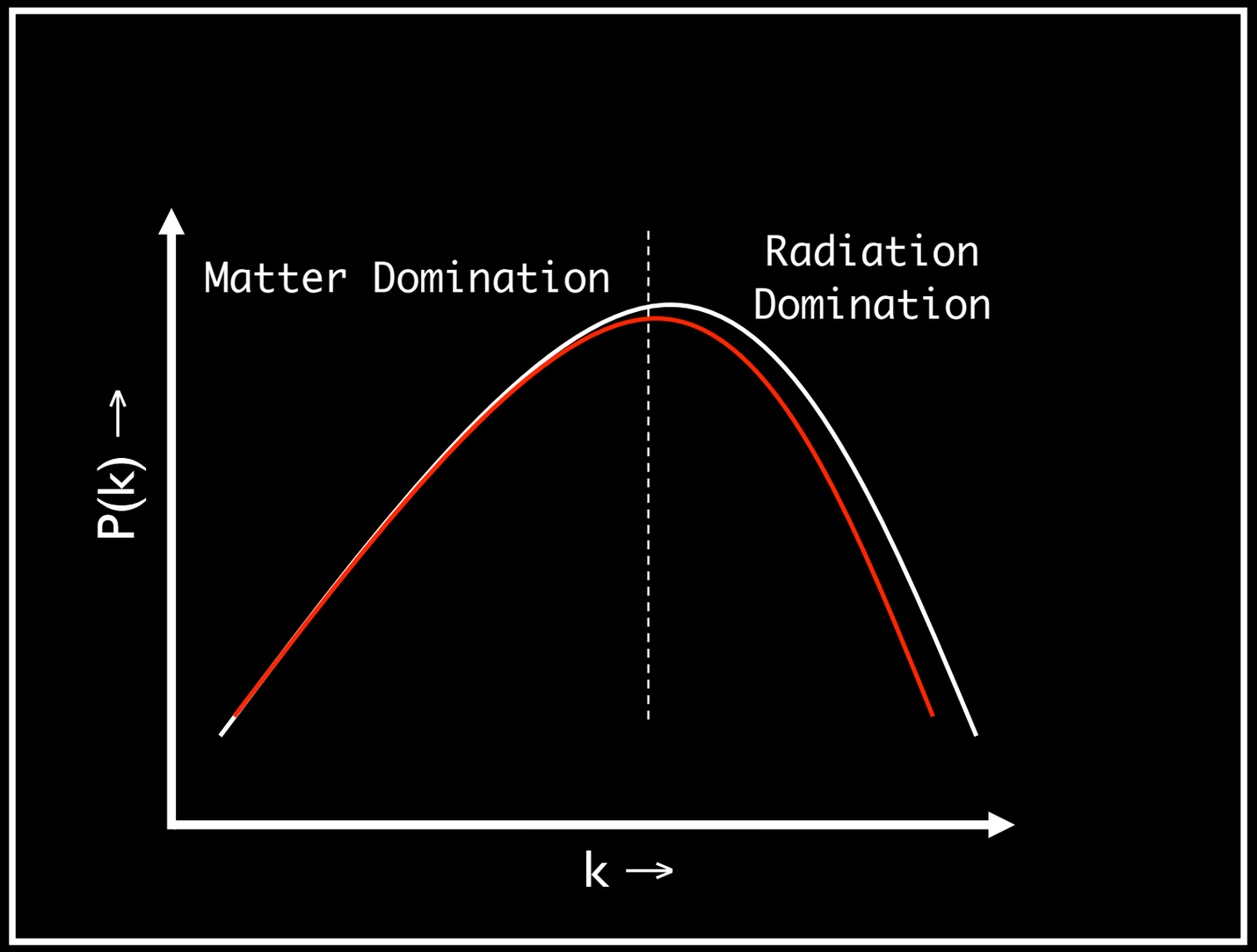
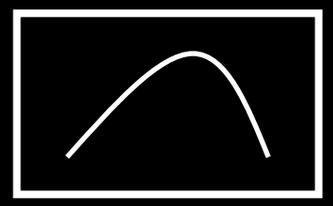


How does  probe neutrinos?

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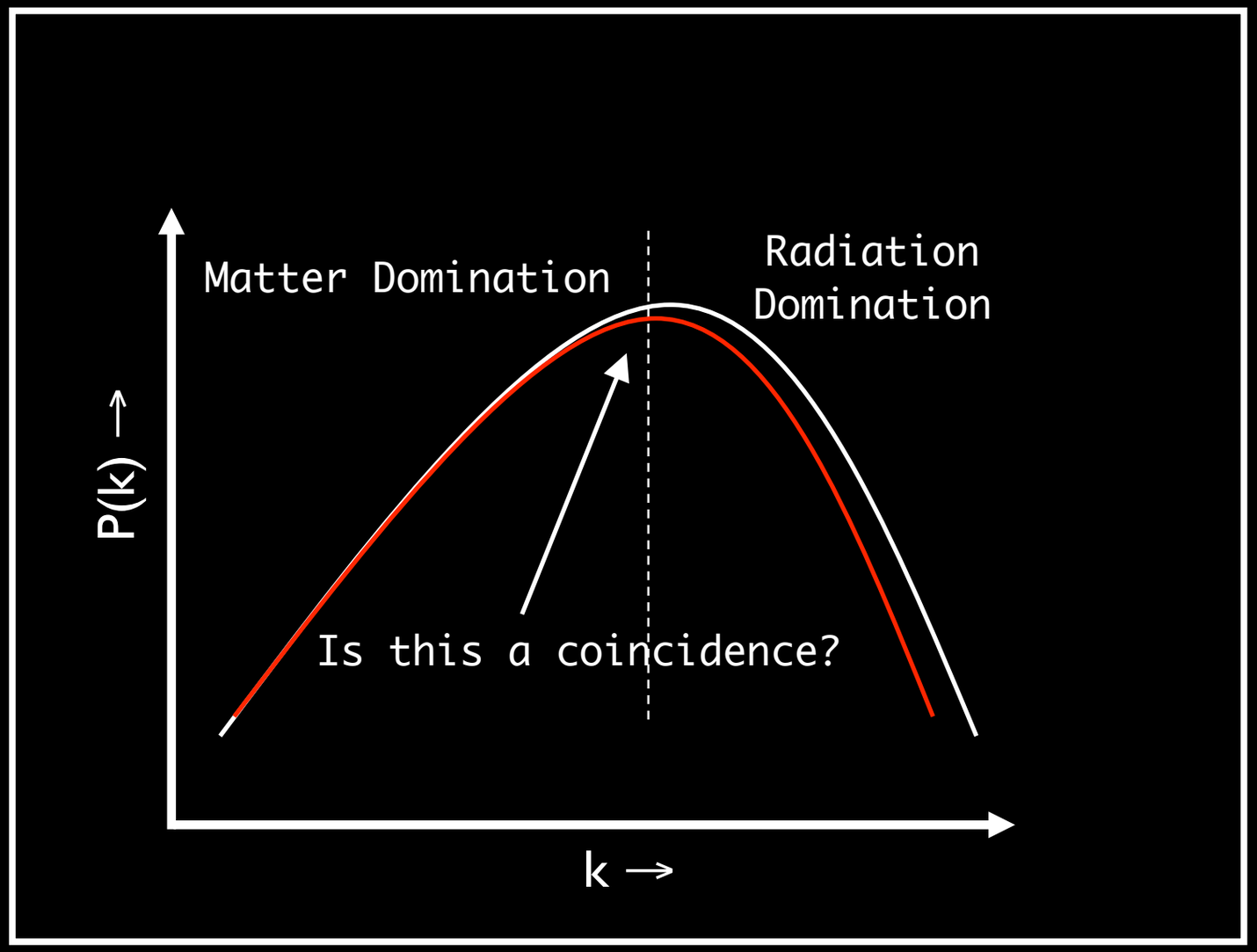
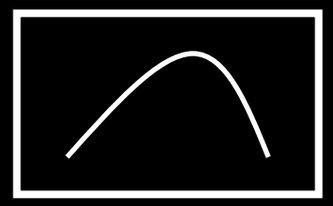


How does  probe neutrinos?

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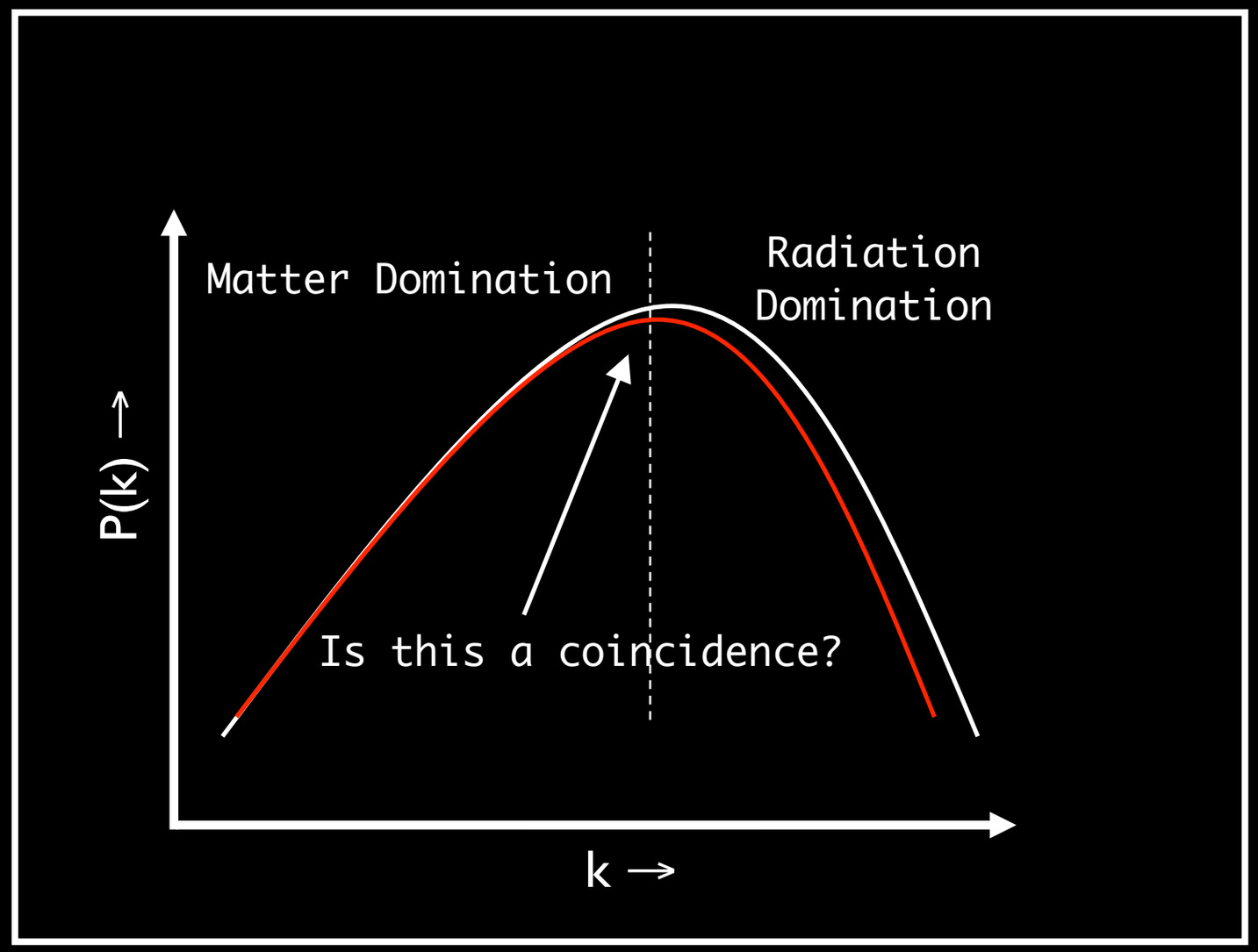
(Assuming thermal equilibrium)

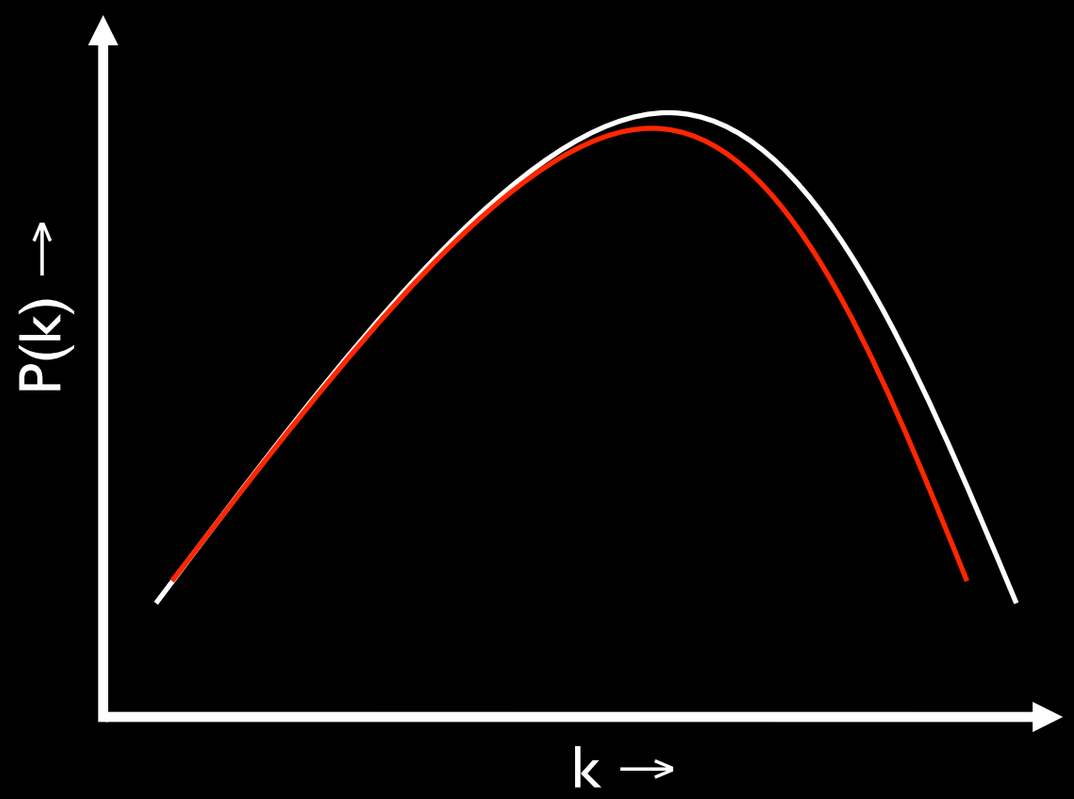
$$\rho_\nu = \sum m_i n_{\nu_i}$$

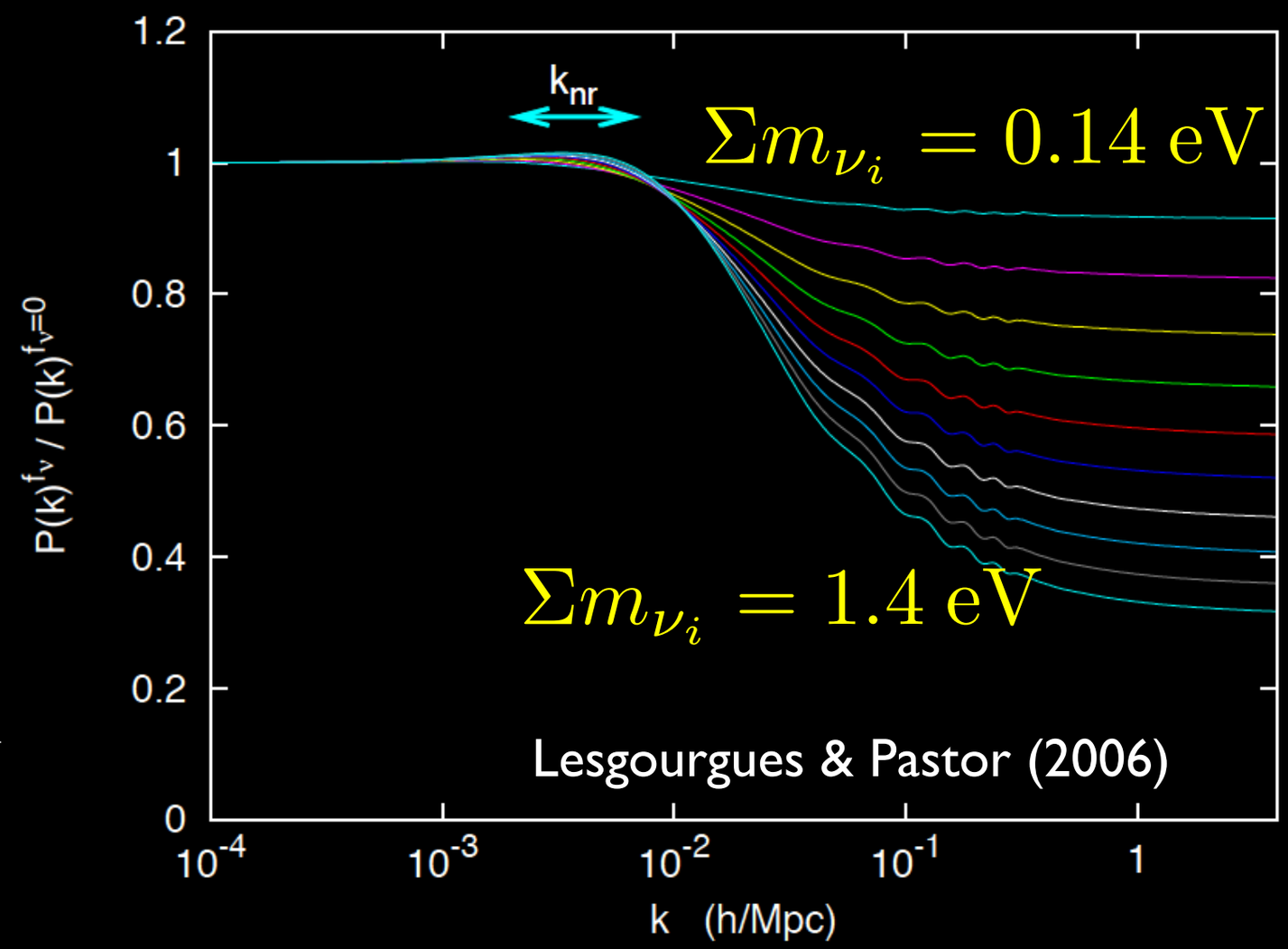
$$\Omega_\nu \approx \frac{\sum m_{\nu_i}}{93\ h^2 \text{ eV}}$$

$$E^2 = p^2 + m^2$$



Distinguishing Features in the Power Spectrum





1. Shape Information:
   Galaxy Surveys (Future: Weak Lensing Surveys)

2. Relative Amplitude Information:
   CMB plus Lyman-alpha Forest, Galaxy Bias $\frac{\Delta P(k)}{P(k)} = -8\frac{\Omega_\nu}{\Omega_m}$

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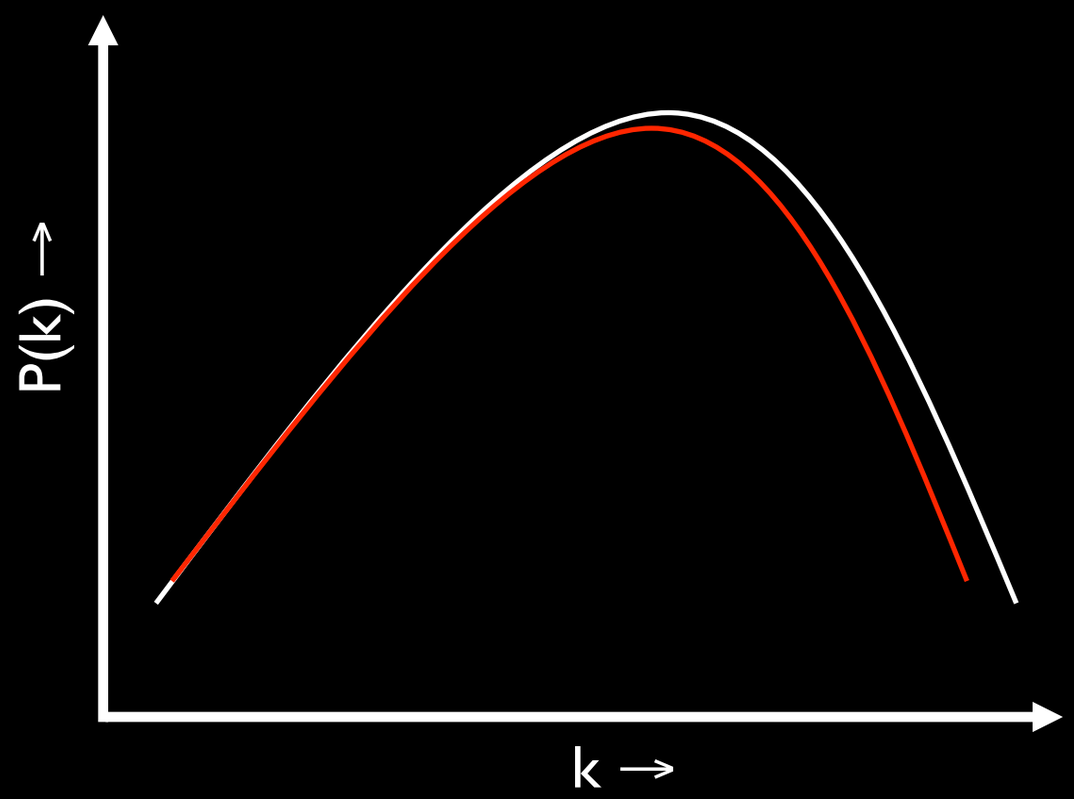

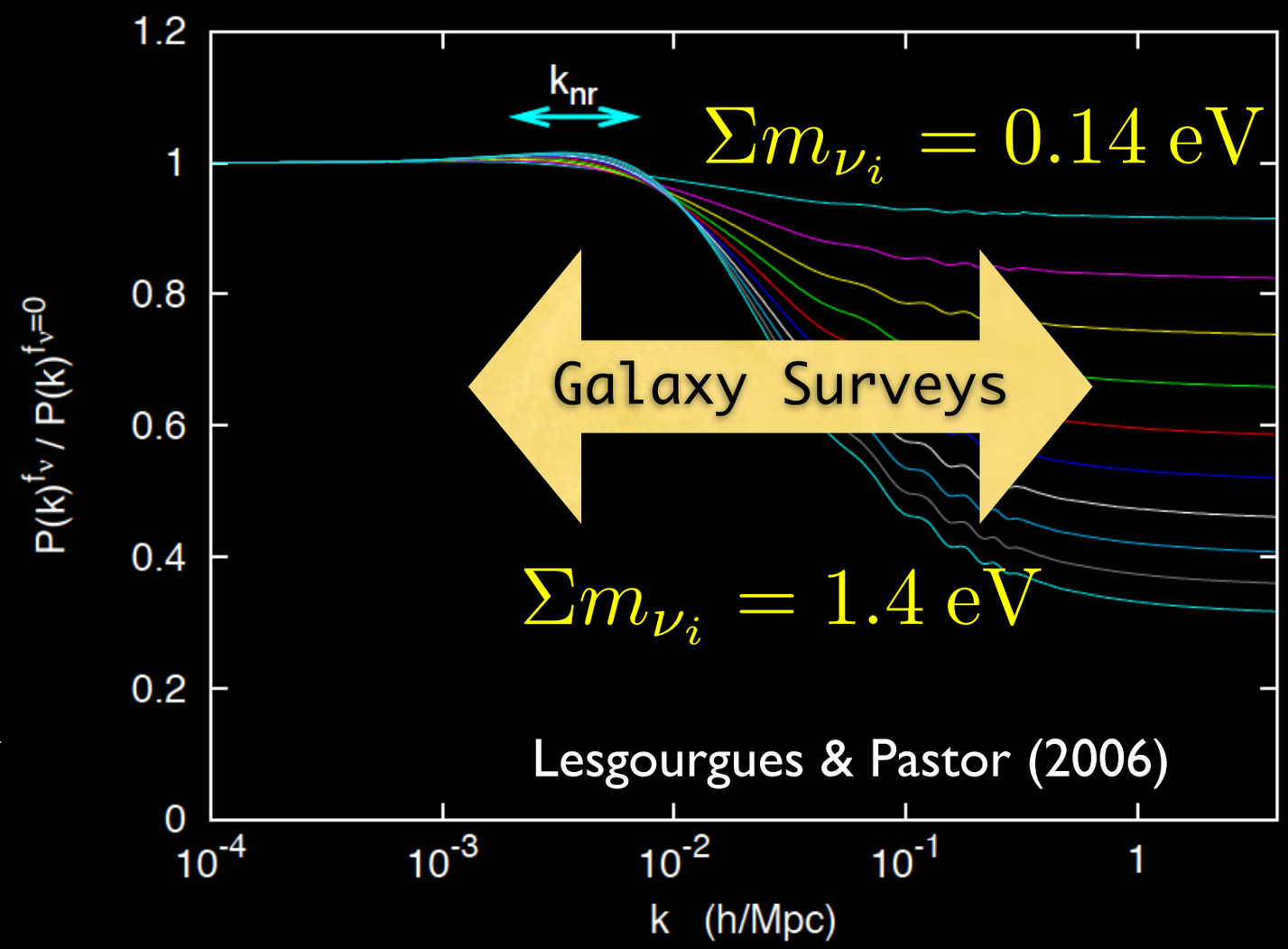

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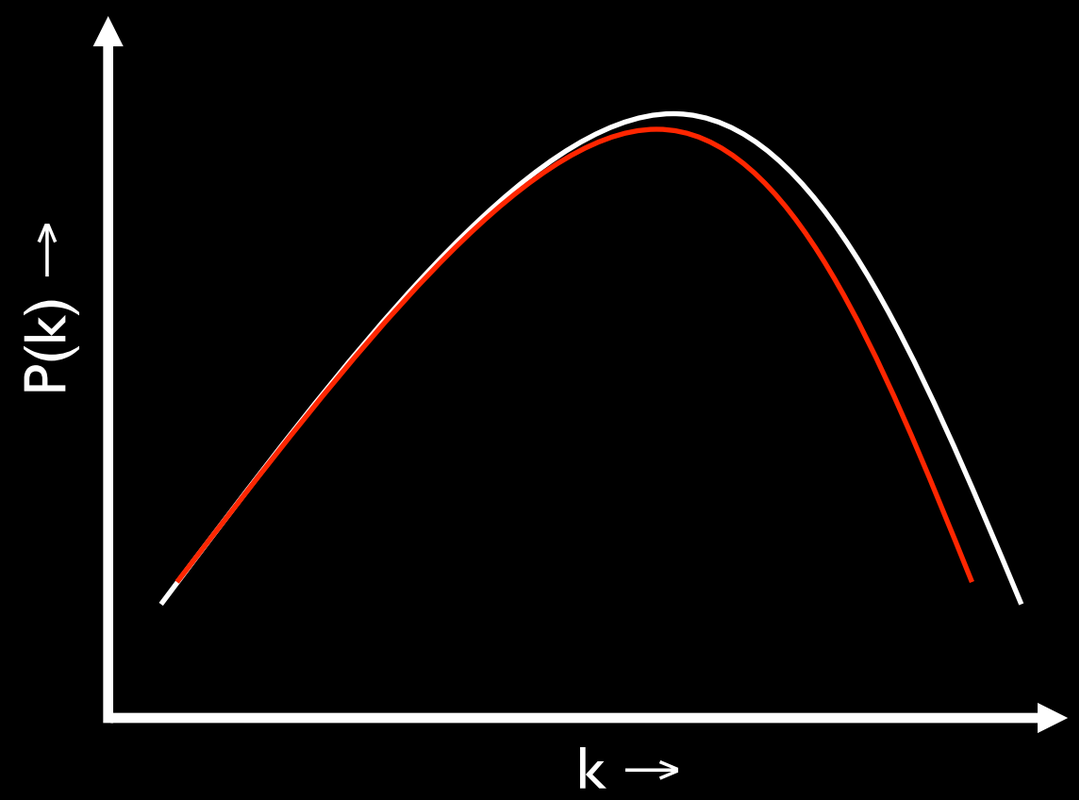

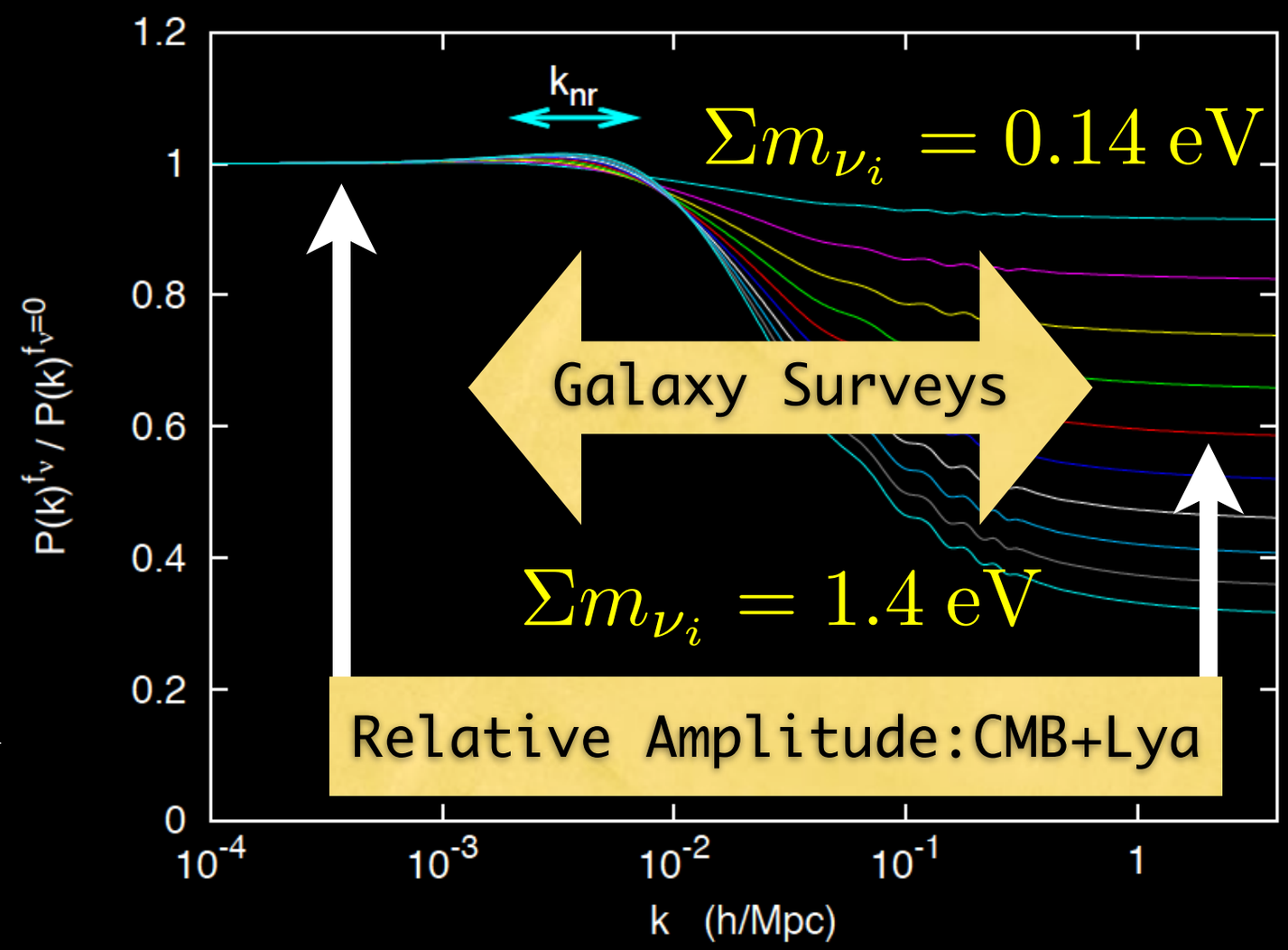

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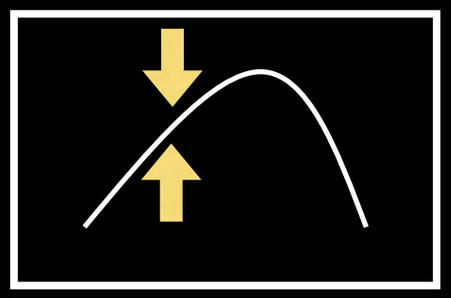
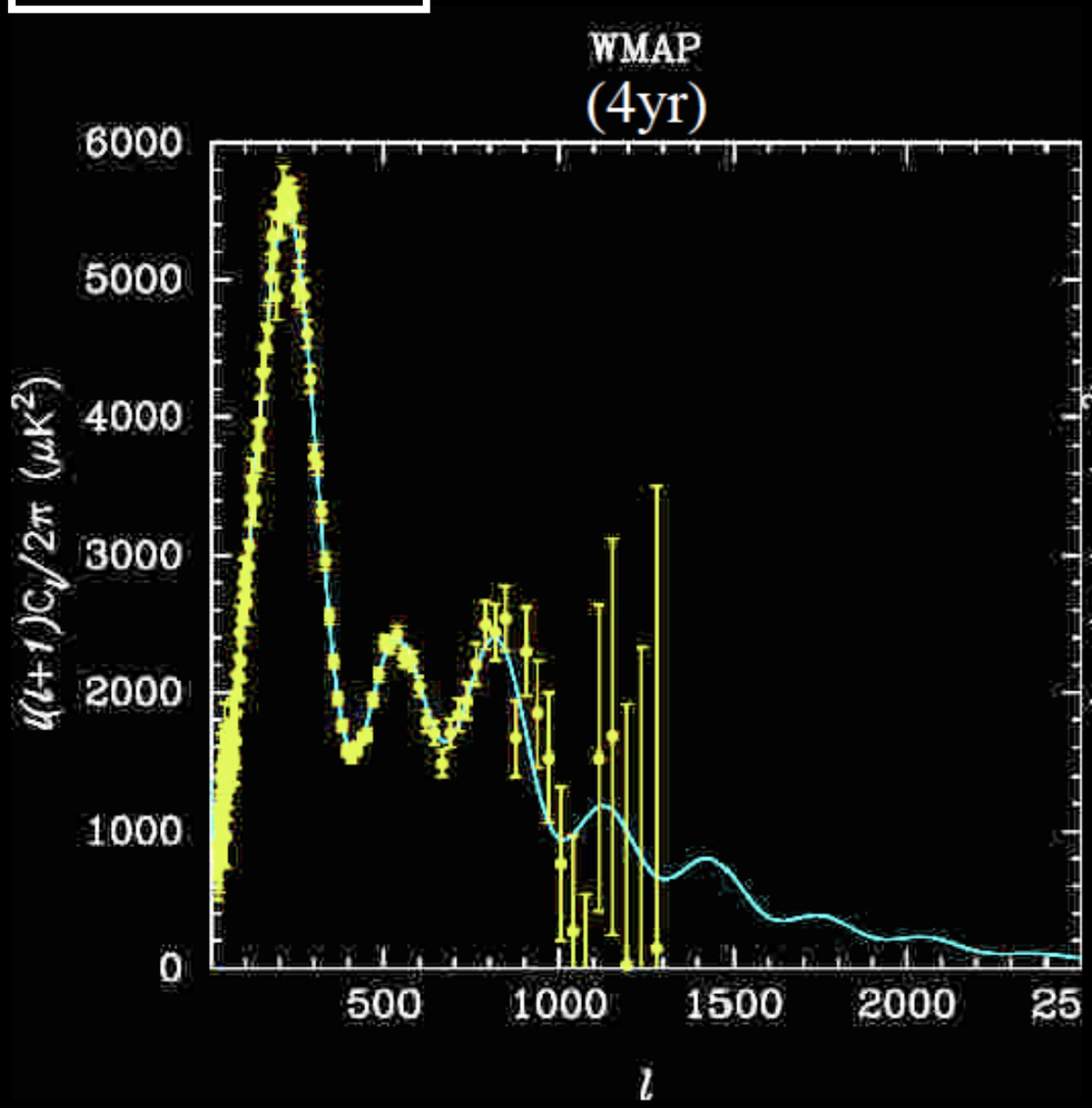
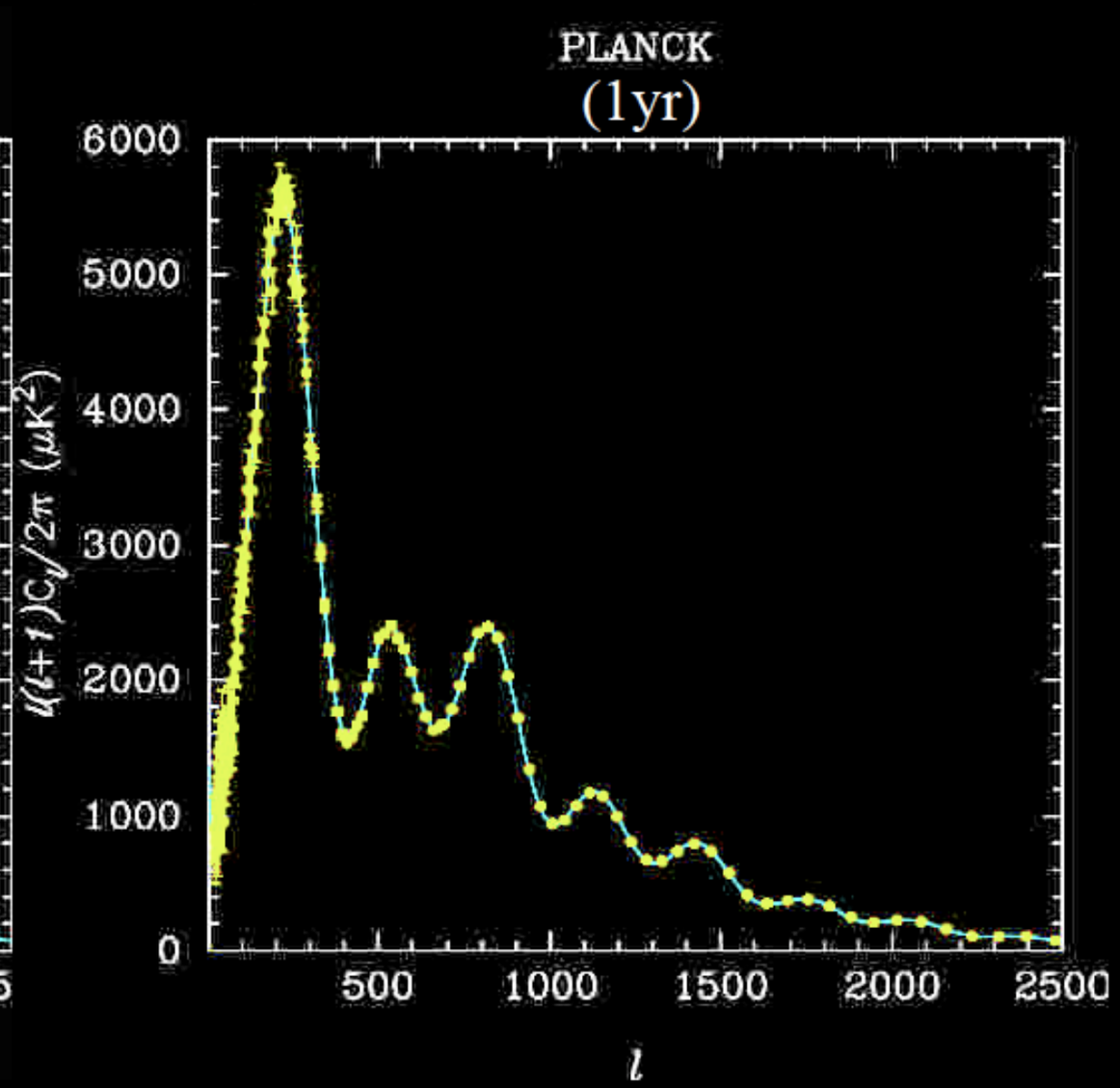
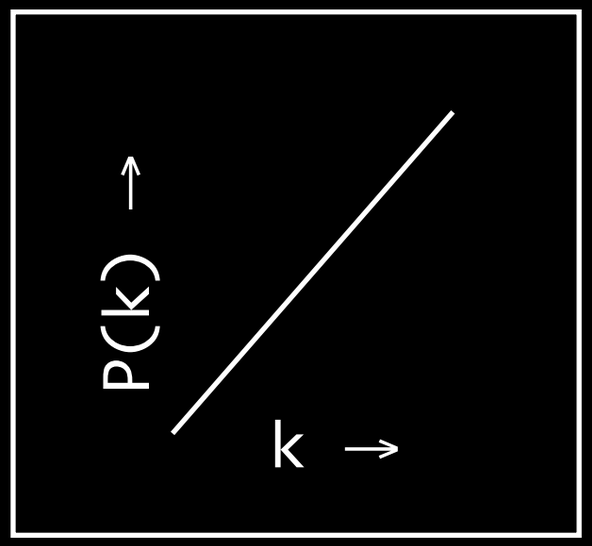
Relative Large Scale Amplitude:
PLANCK







(Martin White)



The Primordial Spectrum: Precision Determination at Large Scales

$$P(k) = Ak^n$$

WMAP 9 + eCMB BAO + H_0: (Hinshaw et al. 2012)

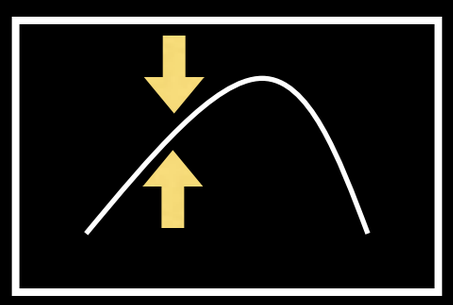
$$A = 2.464 \pm 0.072 \qquad (2.9\%)$$

$$n = 0.9608 \pm 0.0080 \qquad (0.8\%)$$

PLANCK + SDSS LRG: (Eisenstein, Hu, Tegmark 1998)

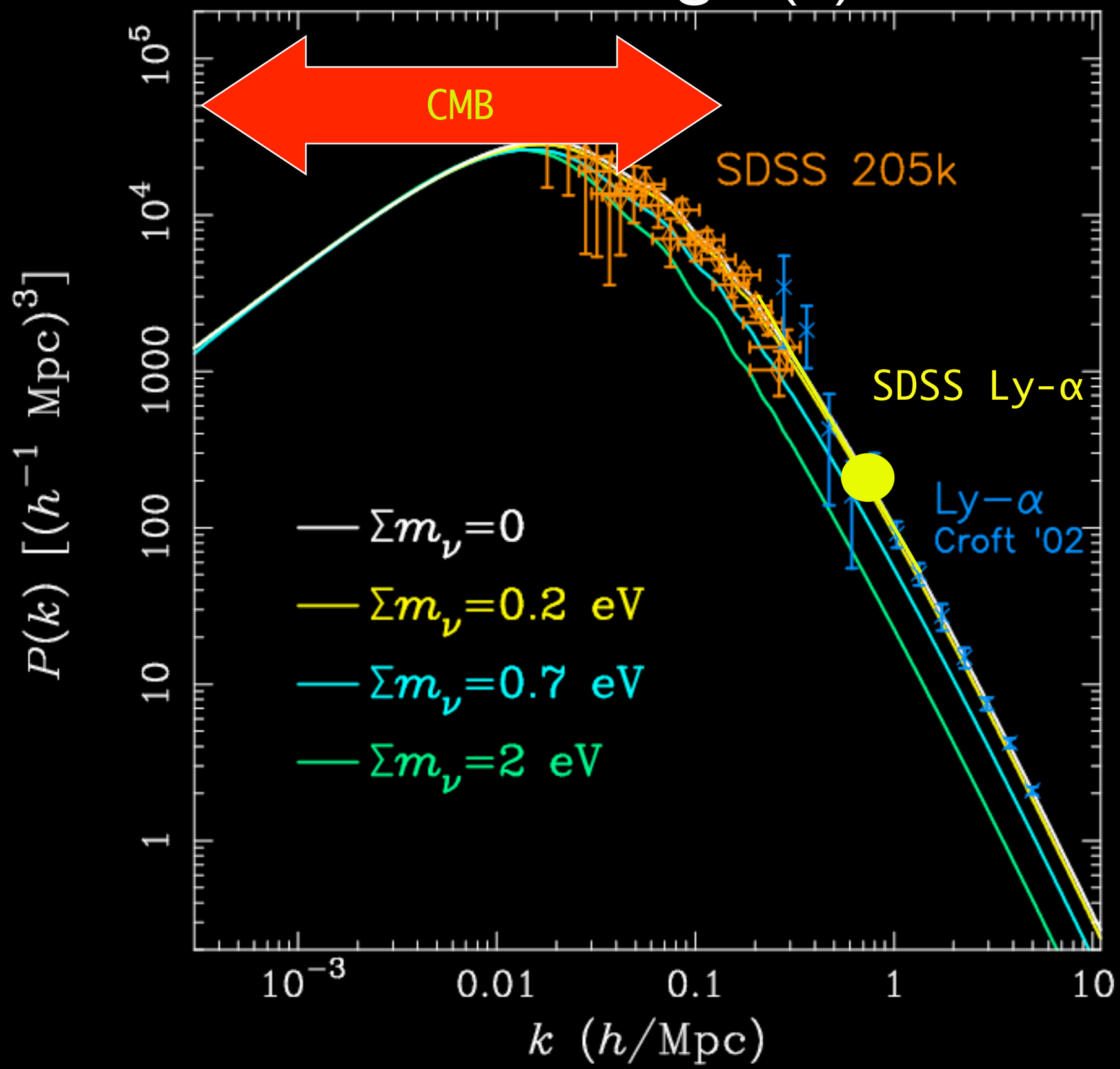
$$A = 2.4450 \pm 0.0085 \quad (0.35\%)$$

$$n = 0.9600 \pm 0.0077 \quad (0.8\%)$$

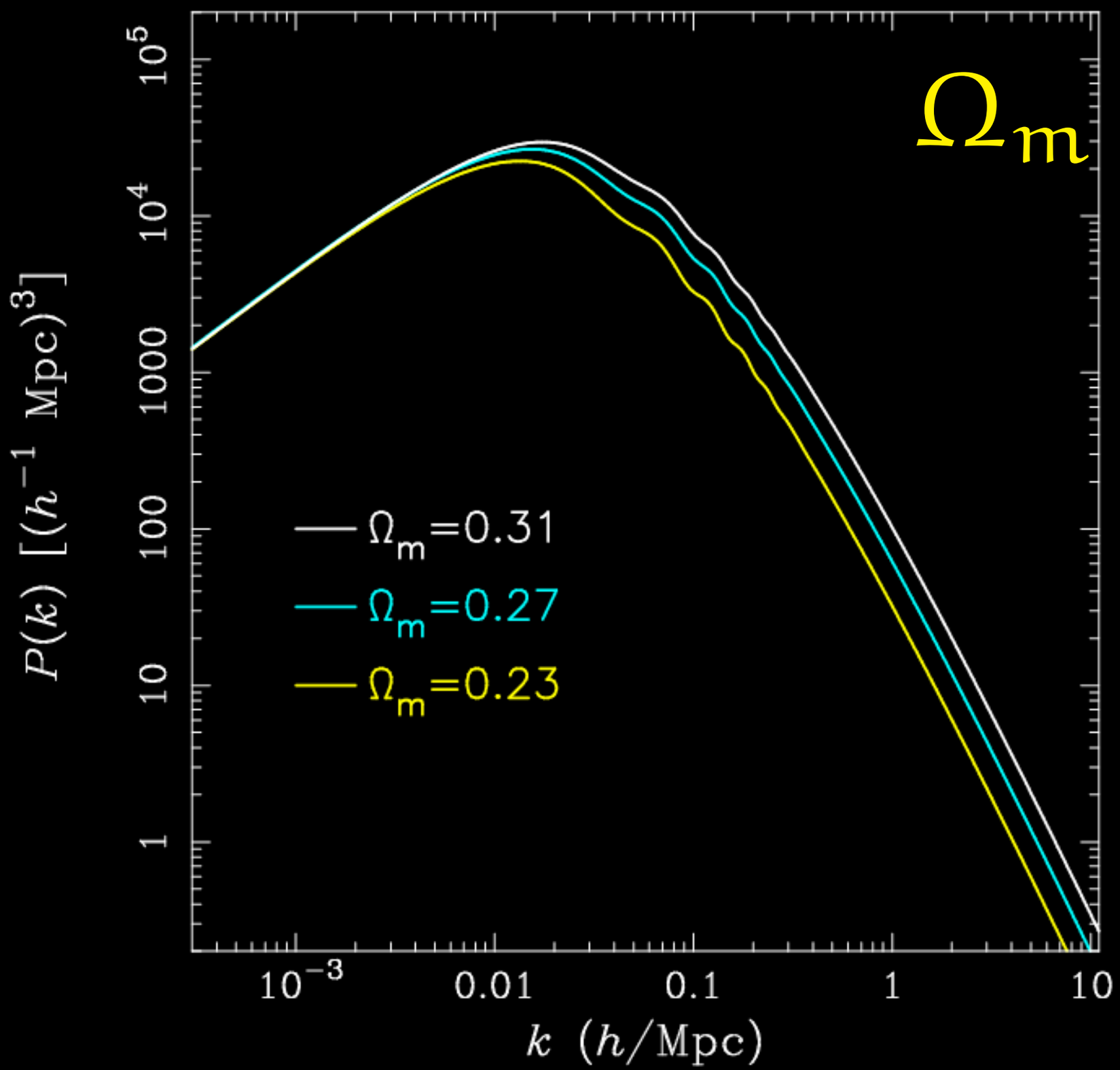


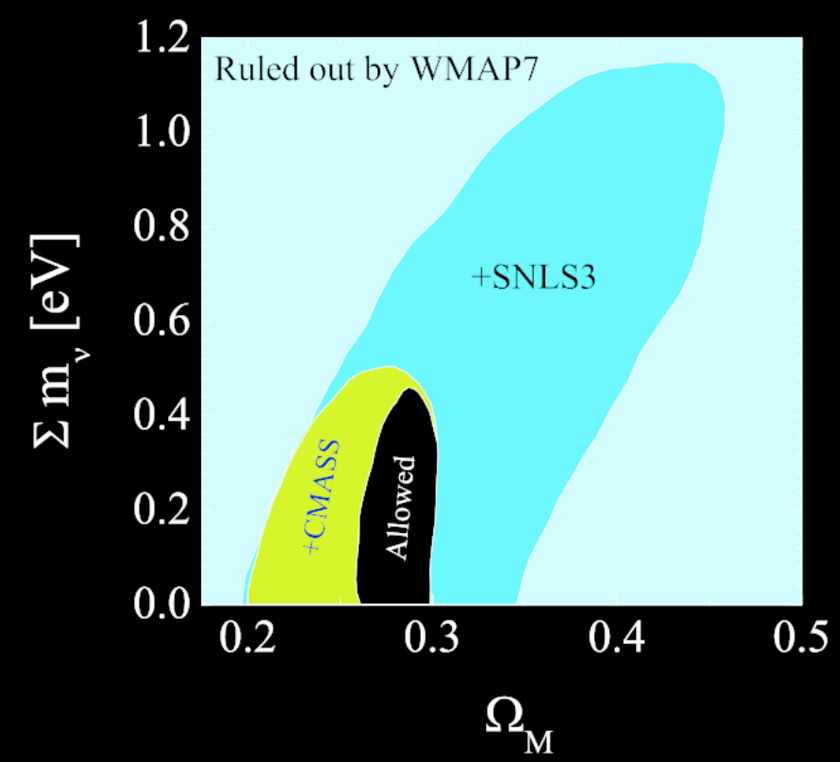
forecast!

Measuring P(k)



Ω_m & Other Parameter Degeneracy





Summary of Cosmological Neutrino Mass Constraints: 2010

WMAP1

- 2dFGRS Shape (conservative but very important limits on Ω_m)
  [Elgaroy et al 2002]:

$$\Sigma m_{\nu_i} \leq 1.8 \text{ eV}$$

95% CL

- SDSS 3D $P_g(k)$ shape + WMAP I
  [Tegmark et al, 2003]:

$$\Sigma m_{\nu_i} \leq 1.8 \text{ eV}$$

⋮

- CMB + SDSS 2-point correlation function (*nonlinear modeling*):
  [Abazajian et al 2005]:

$$\Sigma m_{\nu_i} \leq 0.69 \text{ eV}$$

WMAP7

- WMAP 7 alone
  [Komatsu et al 2010]:

$$\Sigma m_{\nu_i} < 1.3 \text{ eV}$$

- SDSS Ly-alpha forest + WMAP 3-year
  [Seljak et al., 2006]:

$$\Sigma m_{\nu_i} \leq 0.17 \text{ eV}$$

- WMAP 7 + SDSS LRG BAO + H_0 [Komatsu et al, 2010]:

$$\Sigma m_{\nu_i} < 0.58 \text{ eV}$$

Summary of Cosmological Neutrino Mass Constraints: today

WMAP7

- SDSS BOSS Galaxy Clustering + BAO + WMAP 7 + SNe + H_0 (Zhao et. al 2012)

$$\Sigma m_{\nu_i} \leq 0.34 \text{ eV}$$

95% CL

⋮

- SPT + WMAP 7 + H_0 + SPT_{CL} (Hou et al. 2012)
  ⇒ See, however, Rozo et al 2012

$$0.10 \text{ eV} \leq \Sigma m_{\nu_i} \leq 0.54 \text{ eV}$$

- ACT + WMAP 7 + BAO + H_0 (Sievers et. al 2013)

$$\Sigma m_{\nu_i} \leq 0.39 \text{ eV}$$

WMAP9

- WMAP 9 + eCMB + BAO + H_0 (Hinshaw et al. 2012)

$$\Sigma m_{\nu_i} \leq 0.44 \text{ eV}$$

Estimating Upcoming Cosmological Neutrino Mass Constraints

$$\frac{\Delta P(k)}{P(k)} \approx 1\% \approx -8\frac{\Omega_\nu}{\Omega_m}$$

Hu, Eisenstein & Tegmark 1998;
Abazajian & Dodelson 2003

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Kaplinghat et al PRL 2003 (CMB WL)
Wang et al PRL 2005 (WL Clusters)
De Bernardis et al. 2009 (Opt. WL)

Forecast Sensitivities

Probe	Current $\sum m_\nu$ (eV)	Forecast $\sum m_\nu$ (eV)	Key Systematics	Current Surveys	Future Surveys
CMB Primordial	1.3	0.6	Recombination	WMAP, Planck	None
CMB Primordial + Distance	0.58	0.35	Distance measurements	WMAP, Planck	None
Lensing of CMB	∞	$0.2 - 0.05$	NG of Secondary anisotropies	Planck, ACT [39], SPT [96]	EBEX [57], ACTPol, SPTPol, POLARBEAR [5], CMBPol [6]
Galaxy Distribution	0.6	0.1	Nonlinearities, Bias	SDSS [58, 59], BOSS [82]	DES [84], BigBOSS [81], DESpec [85], LSST [92], Subaru PFS [97], HETDEX [35]
Lensing of Galaxies	0.6	0.07	Baryons, NL, Photometric redshifts	CFHT-LS [23], COSMOS [50]	DES [84], Hyper SuprimeCam, LSST [92], Euclid [88], WFIRST[100]
Lyman α	0.2	0.1	Bias, Metals, QSO continuum	SDSS, BOSS, Keck	BigBOSS[81], TMT[99], GMT[89]
21 cm	∞	$0.1 - 0.006$	Foregrounds, Astrophysical modeling	GBT [11], LOFAR [91], PAPER [53], GMRT [86]	MWA [93], SKA [95], FFTT [49]
Galaxy Clusters	0.3	0.1	Mass Function, Mass Calibration	SDSS, SPT, ACT, XMM [101] Chandra [83]	DES, eRosita [87], LSST
Core-Collapse Supernovae	∞	$\theta_{13} > 0.001^*$	Emergent ν spectra	SuperK [98], ICECube[90]	Noble Liquids, Gadzooks [7]

Abazajian et al. 2011

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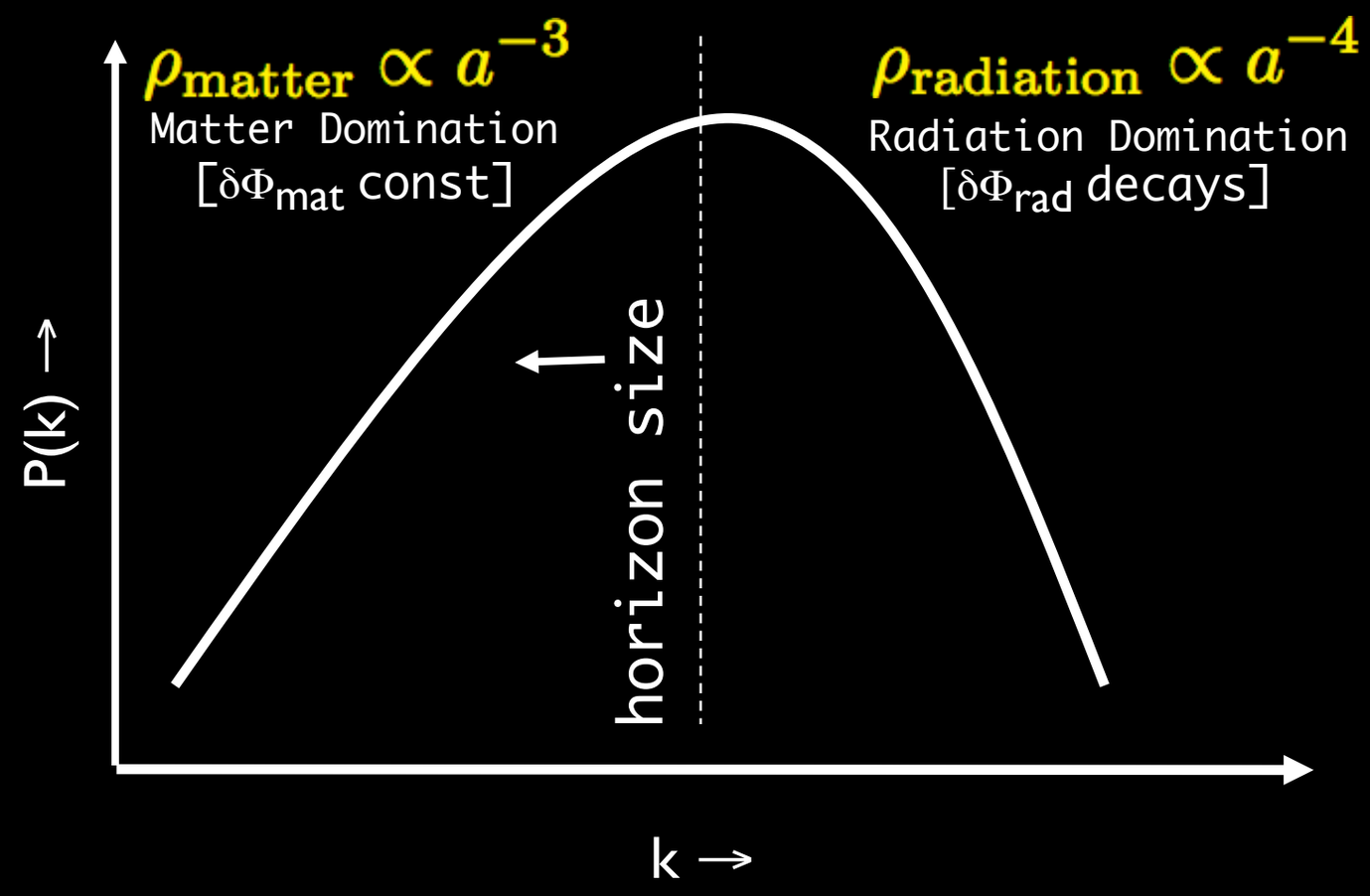
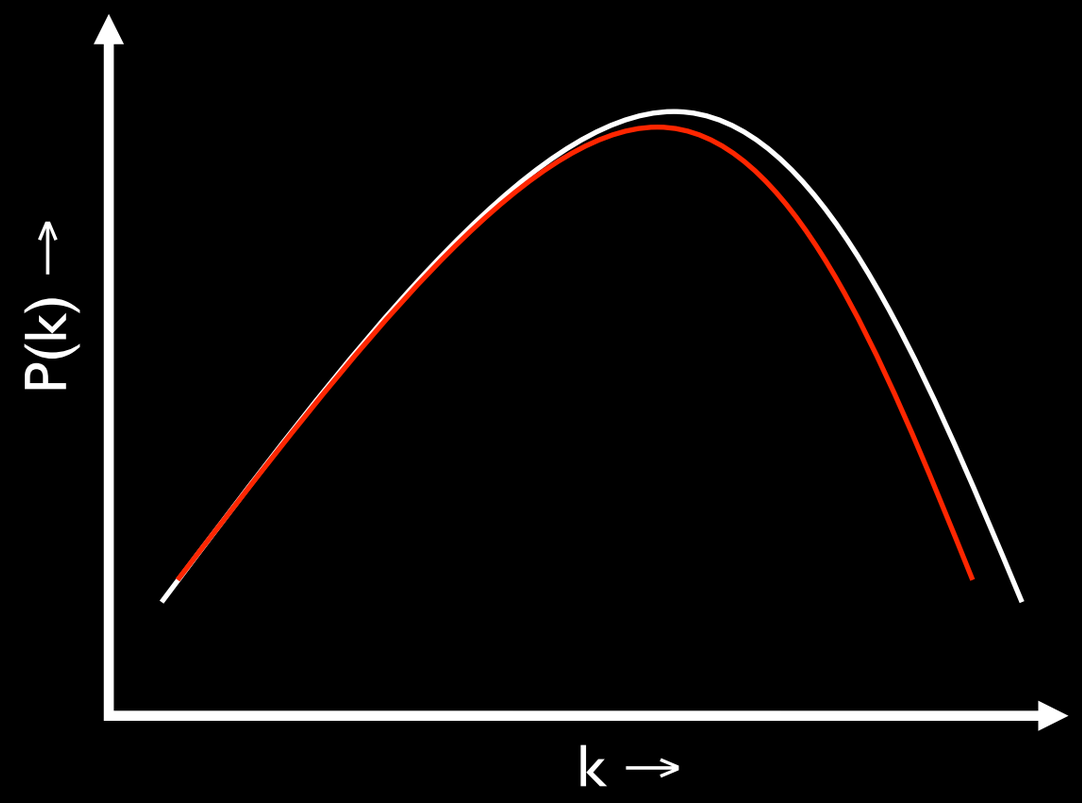
Cosmological Matter Power Spectrum & CMB Constraints on N_{eff}

Perturbations enter horizon:



SDSS+WMAP3 Lyman-alpha Constraints (Seljak et al 2006)



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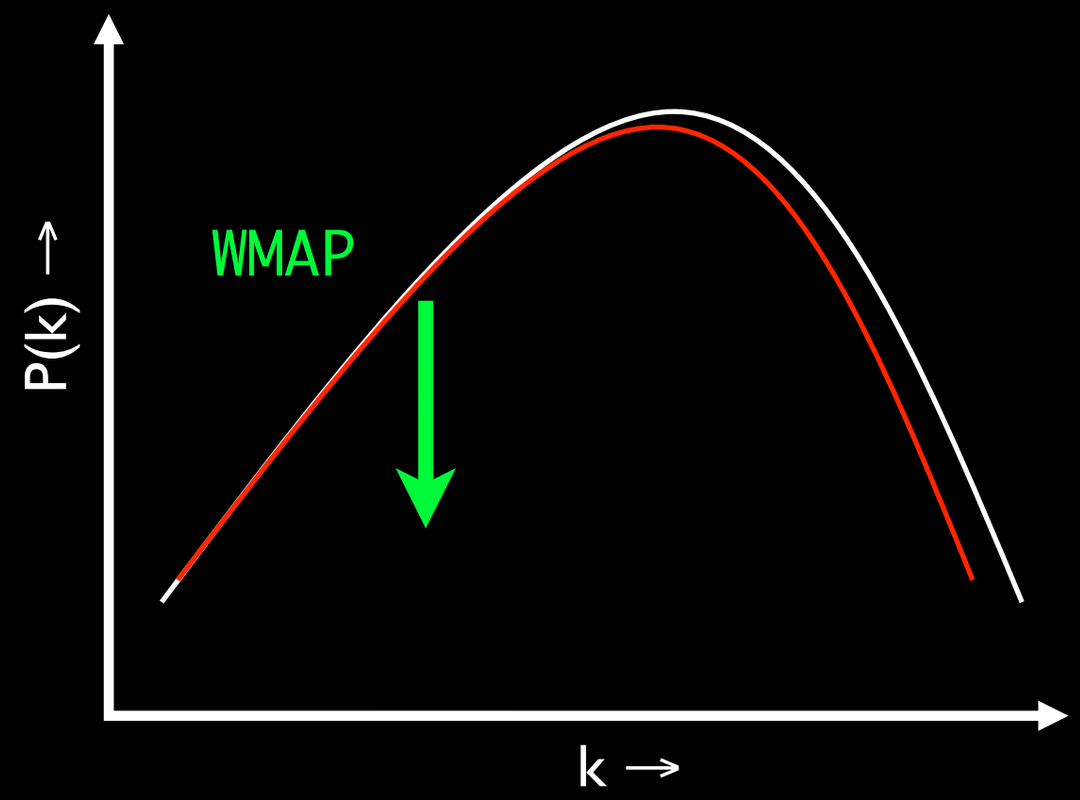
WMAP3:

$$\sigma_8 = 0.74^{+0.05}_{-0.04}$$



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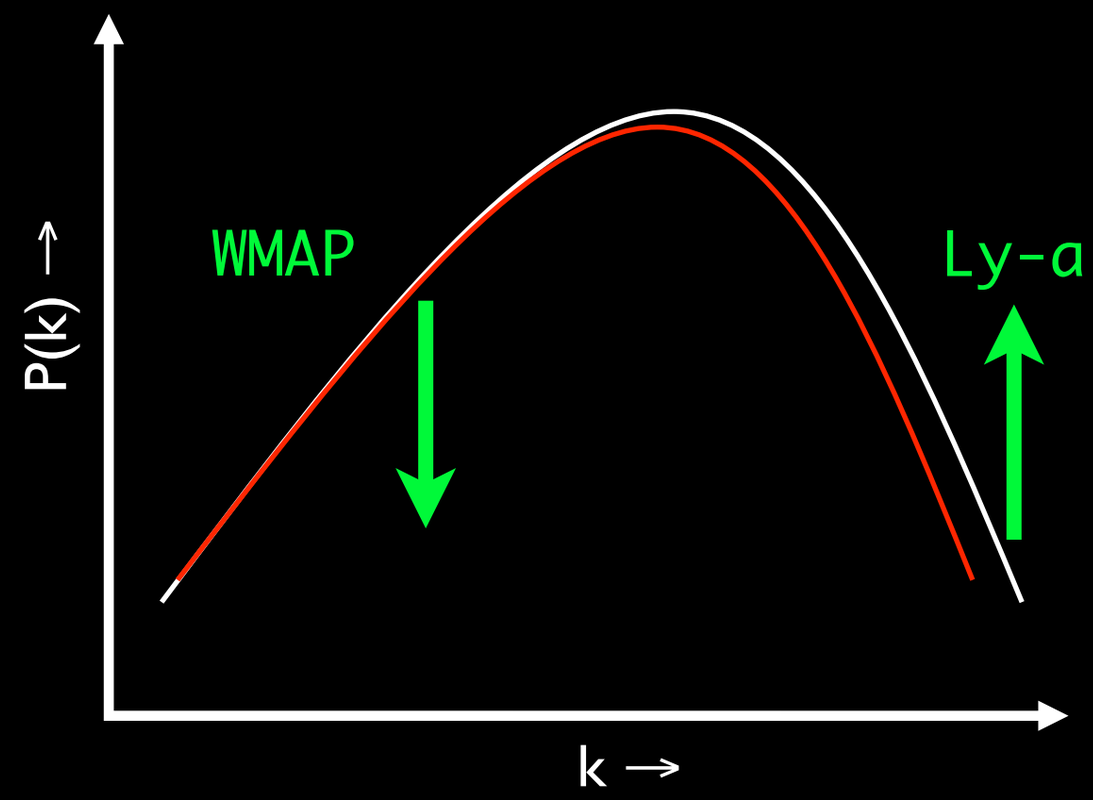

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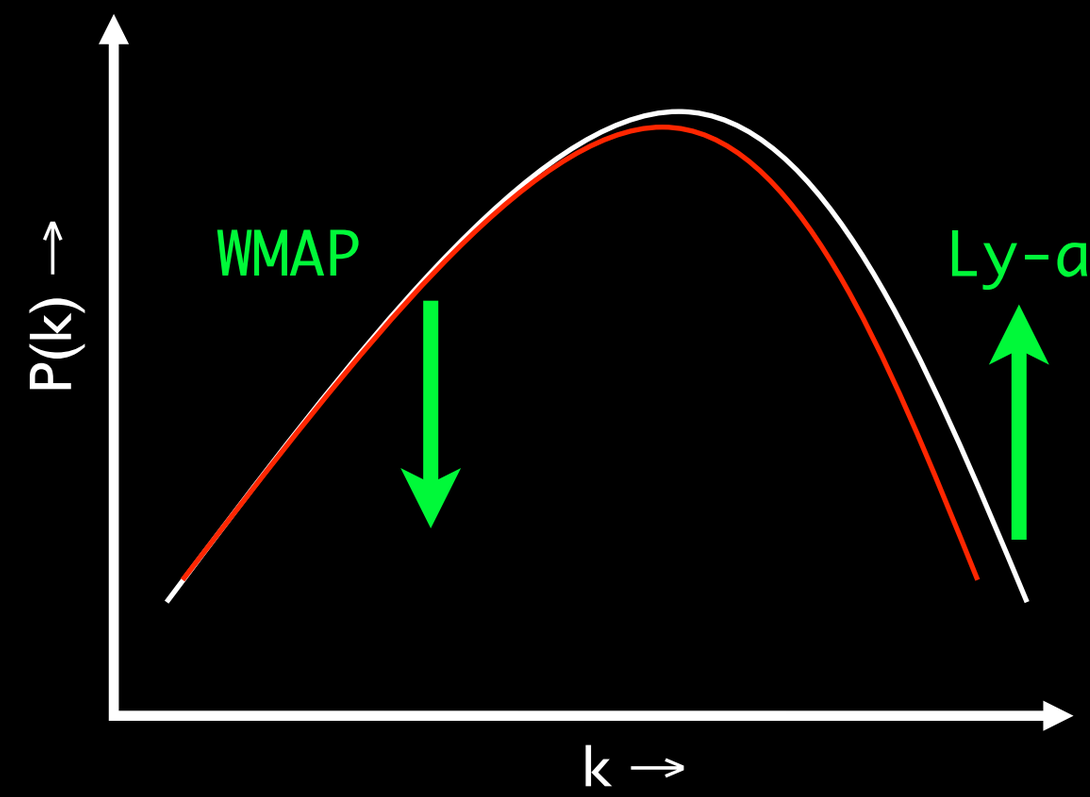

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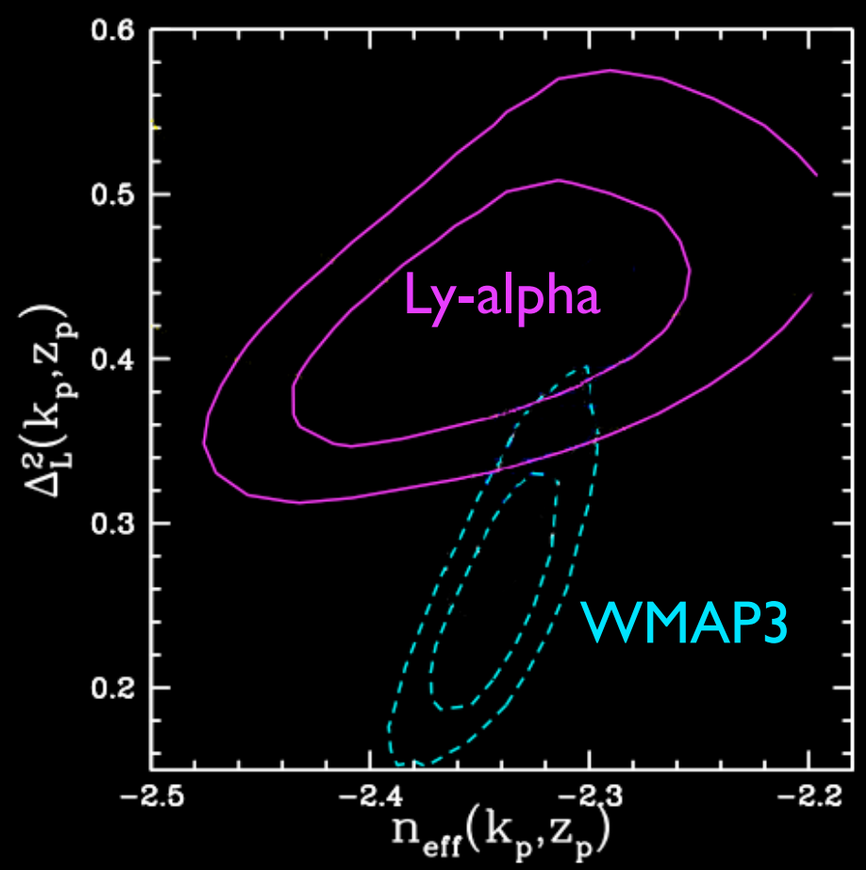

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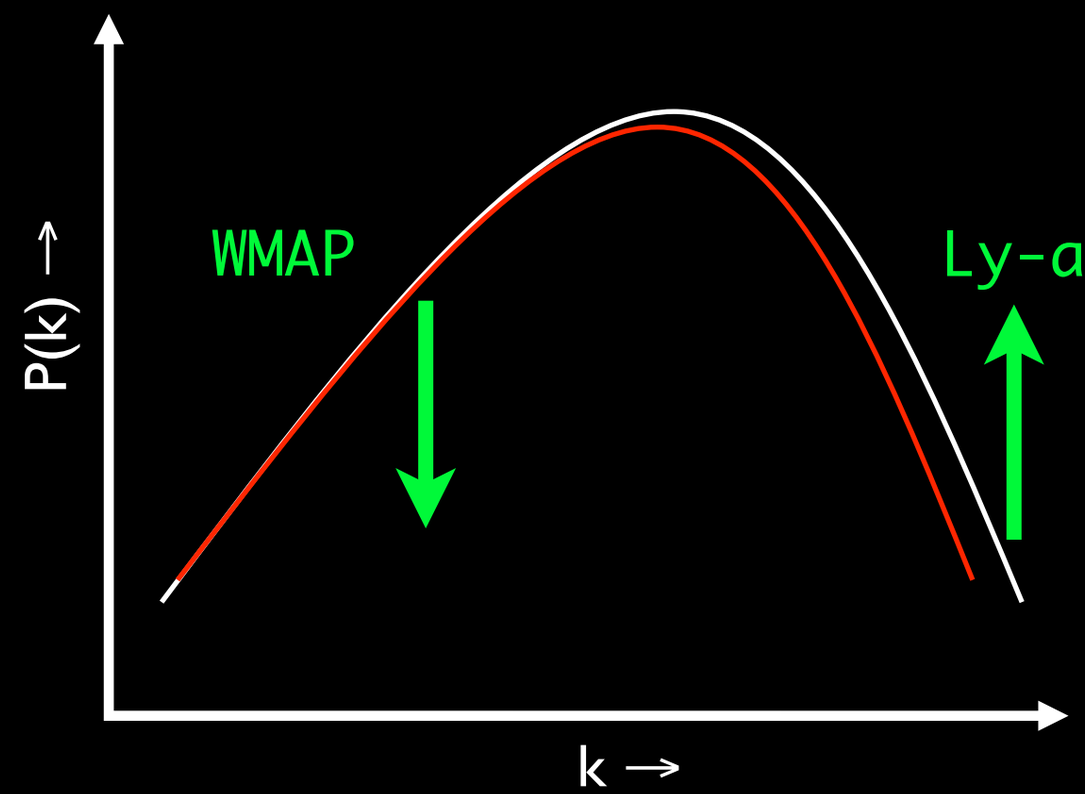
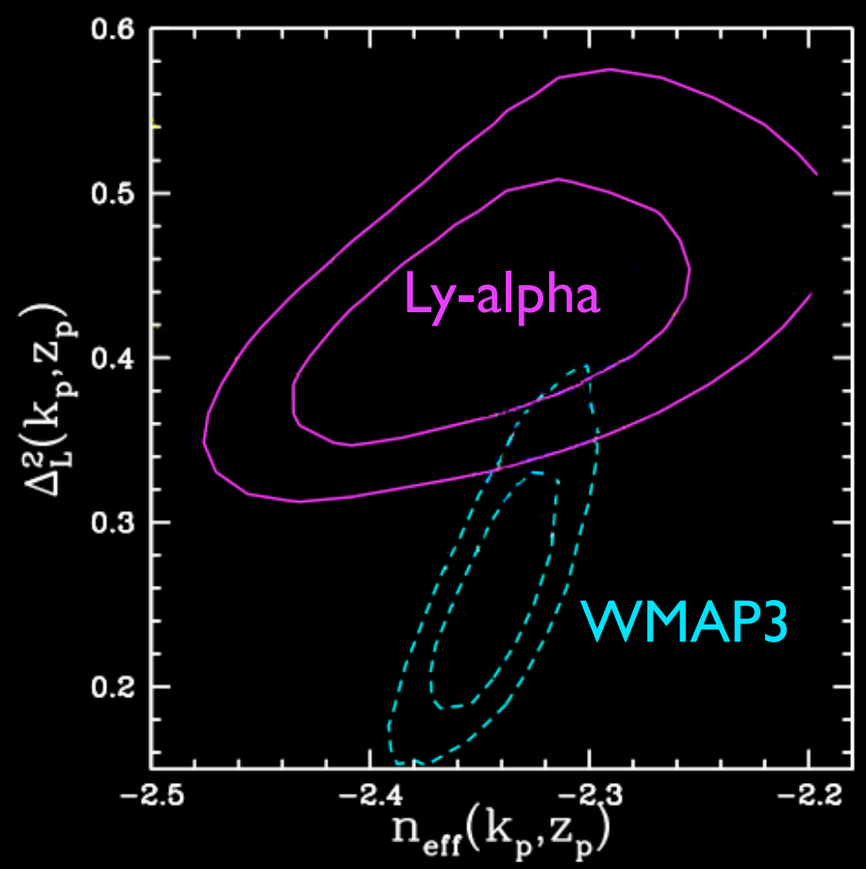
WMAP3:

$$\sigma_8 = 0.74^{+0.05}_{-0.04}$$



SDSS Ly-alpha (Seljak et al 2003):

$$\sigma_8 = 0.9^{+0.03}_{-0.03}$$



$N_\nu = 5.4^{+0.4}_{-0.6}$ Seljak et al. Lyα

$N_\nu = 3.08^{+0.74}_{-0.68}$

BBN, Cyburt et al. 2004

$N_\nu = 3.04$ (standard model)

Summary of Cosmological $N_{\rm eff}$ Constraints

WMAP7

- SDSS BOSS Galaxy Clustering + BAO + WMAP 7 + SNe + H_0 (Zhao et. al 2012)

$$N_{\rm eff} = 4.308 \pm 0.794$$

68% CL

⋮

- SPT + WMAP 7 + H_0 (Hou et al. 2012)

$$N_{\rm eff} = 3.71 \pm 0.35$$

- ACT + WMAP 7 + BAO + H_0 (Sievers et. al 2013)

$$N_{\rm eff} = 2.78 \pm 0.55$$

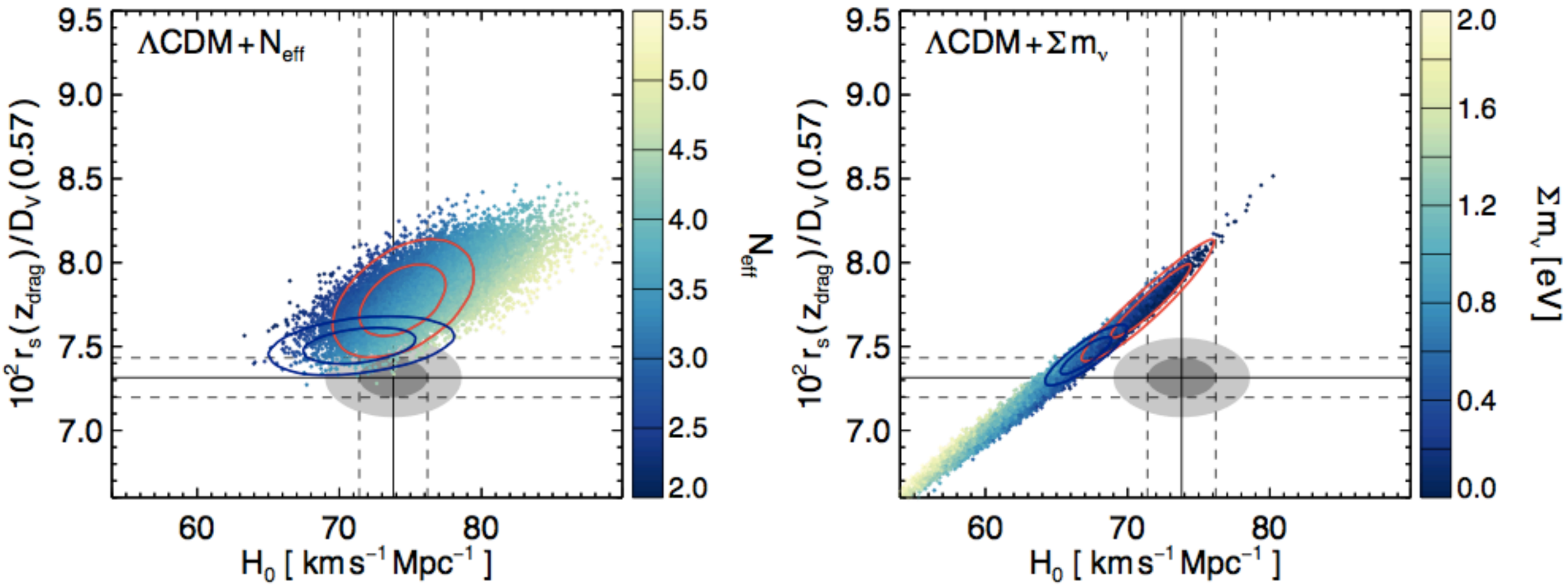
WMAP9

- WMAP 9 + eCMB + BAO + H_0 (Hinshaw et al. 2012 *v2*)

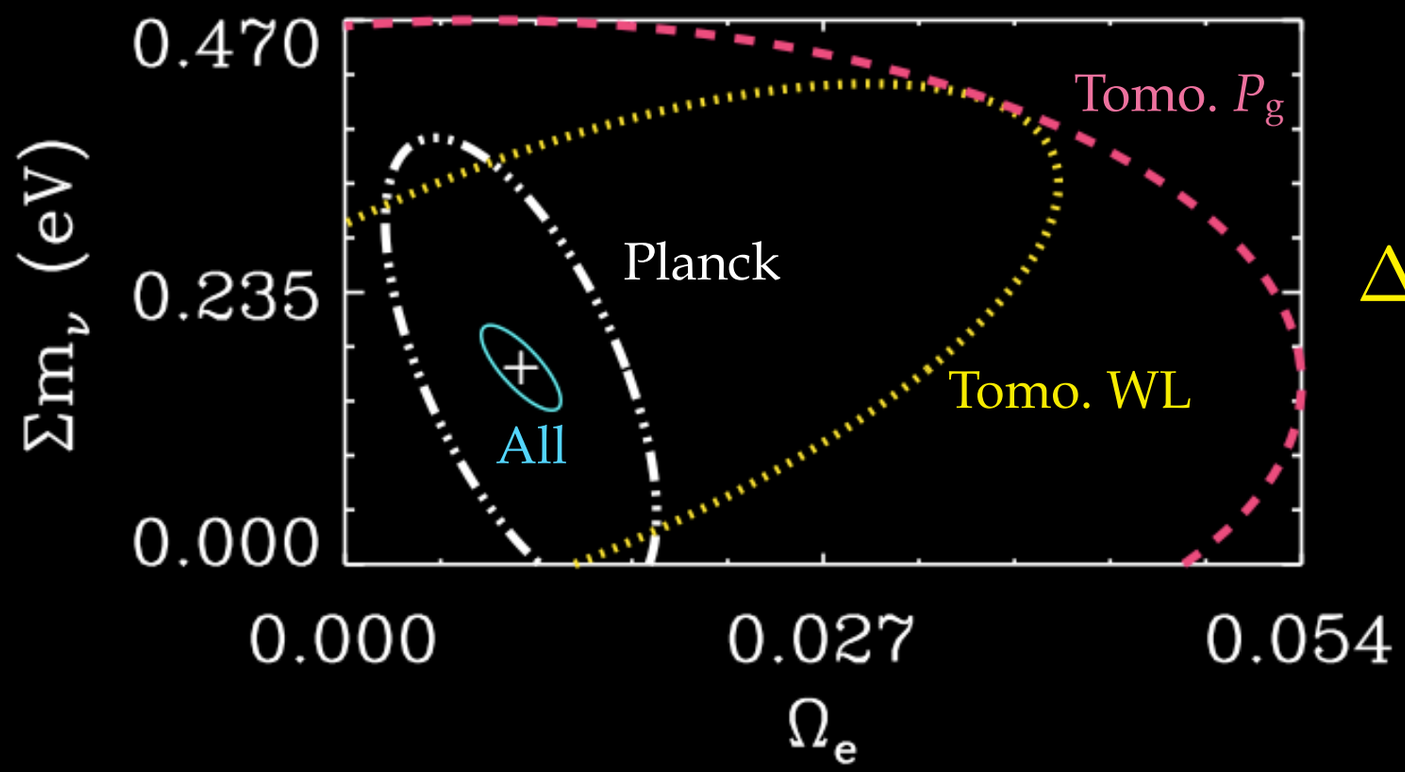
$$N_{\rm eff} = 3.84 \pm 0.40$$

but, see Verde et al. 2011: shape of priors

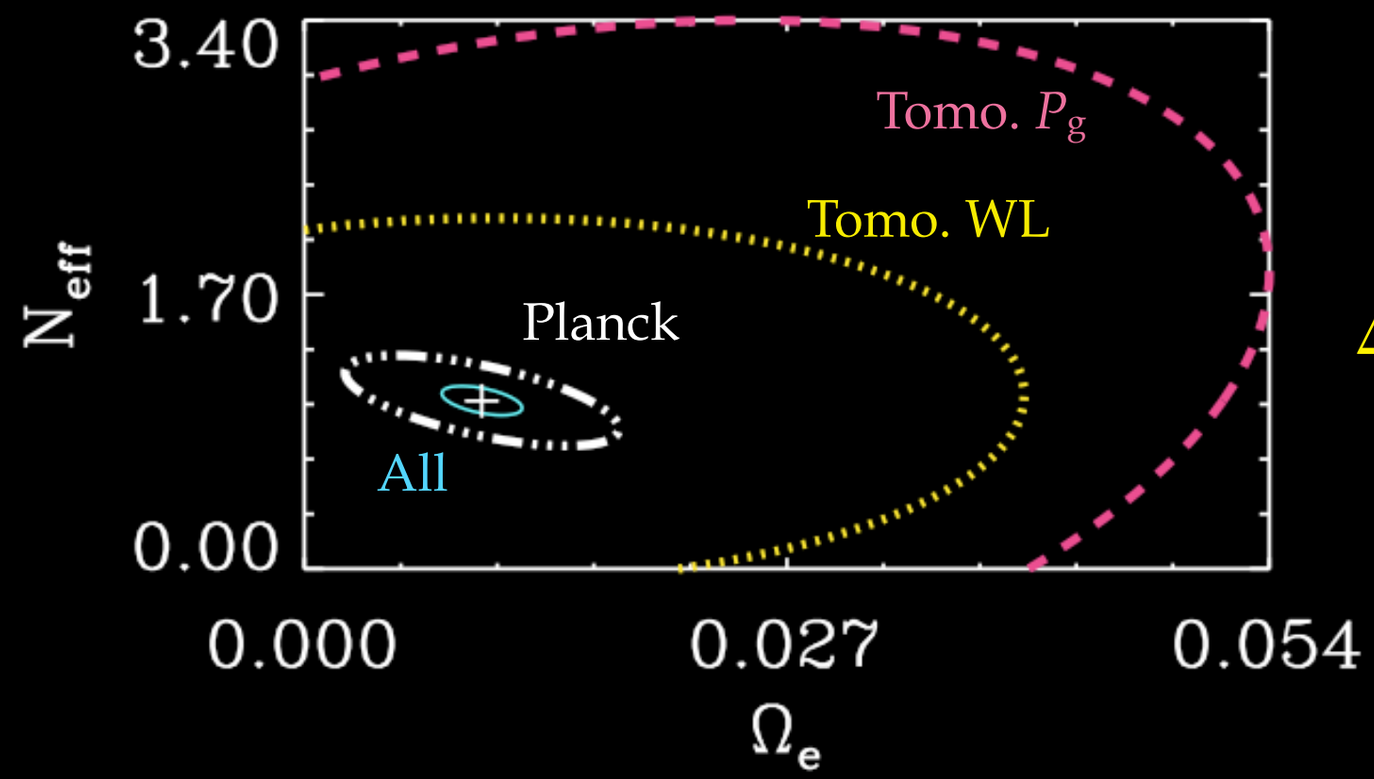
Tension in CMB + BAO leading to neutrino "anomalies"? (Hou et al. 2012)



Forecast sensitivities: Planck + LSST



$$\Delta(\Sigma m_{\nu_i}) = 0.023 \quad (68\% \text{ CL})$$

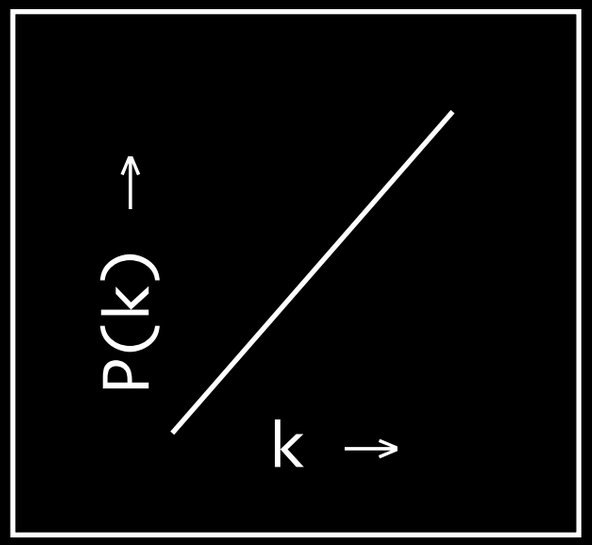


$$\Delta N_{\rm eff} = 0.078 \quad (68\% \text{ CL})$$

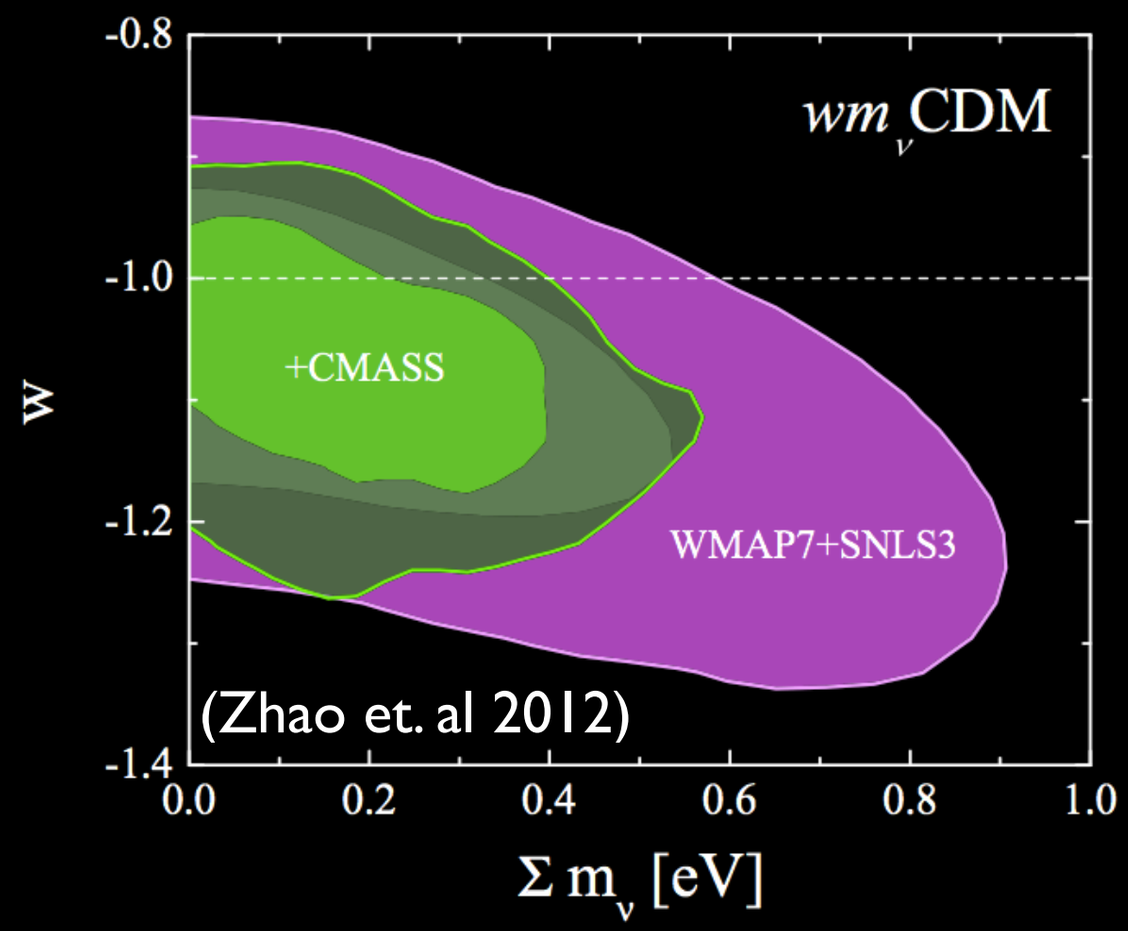
Joudaki & Kaplinghat 2011

Neutrino Mass from Cosmology: Beware Hidden Assumptions!

1. Uniform primordial scale invariance



2. No other prevalent "non-vanilla" cosmological parameters



Summary

- Cosmology has the strongest inferred constraints on the total neutrino mass.
- The constraints rely on an underlying set of assumptions [scale invariance, flatness, w = -1, etc.]. While simplifying, they introduce a large level of systematic uncertainty.
- Evidence for extra relativistic degrees of freedom persists, though *may be* becoming less significant.