Neutrino Physics from the CMB & Large Scale Structure
- Report -

Topical Conveners:
K.N. Abazajian, J.E. Carlstrom, A.T. Lee

Contributors:
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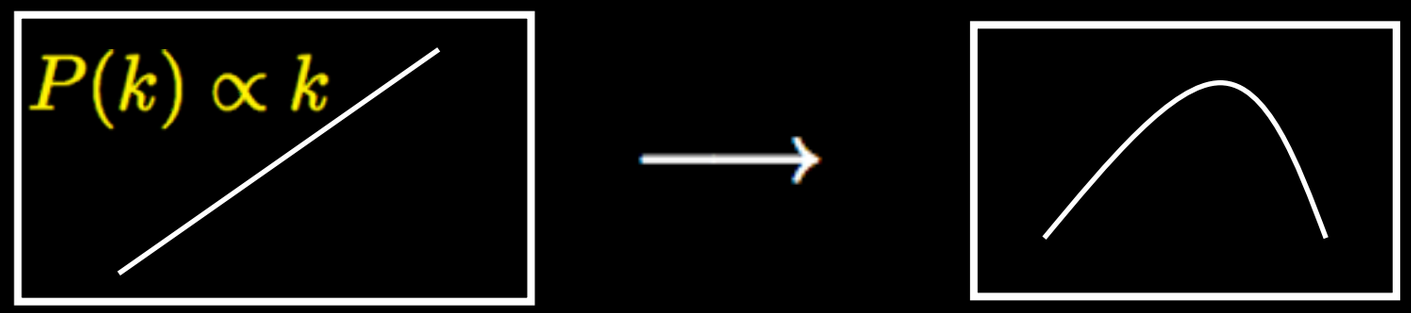
Paper: http://is.gd/AnSecR [arXiv on Friday (?)]

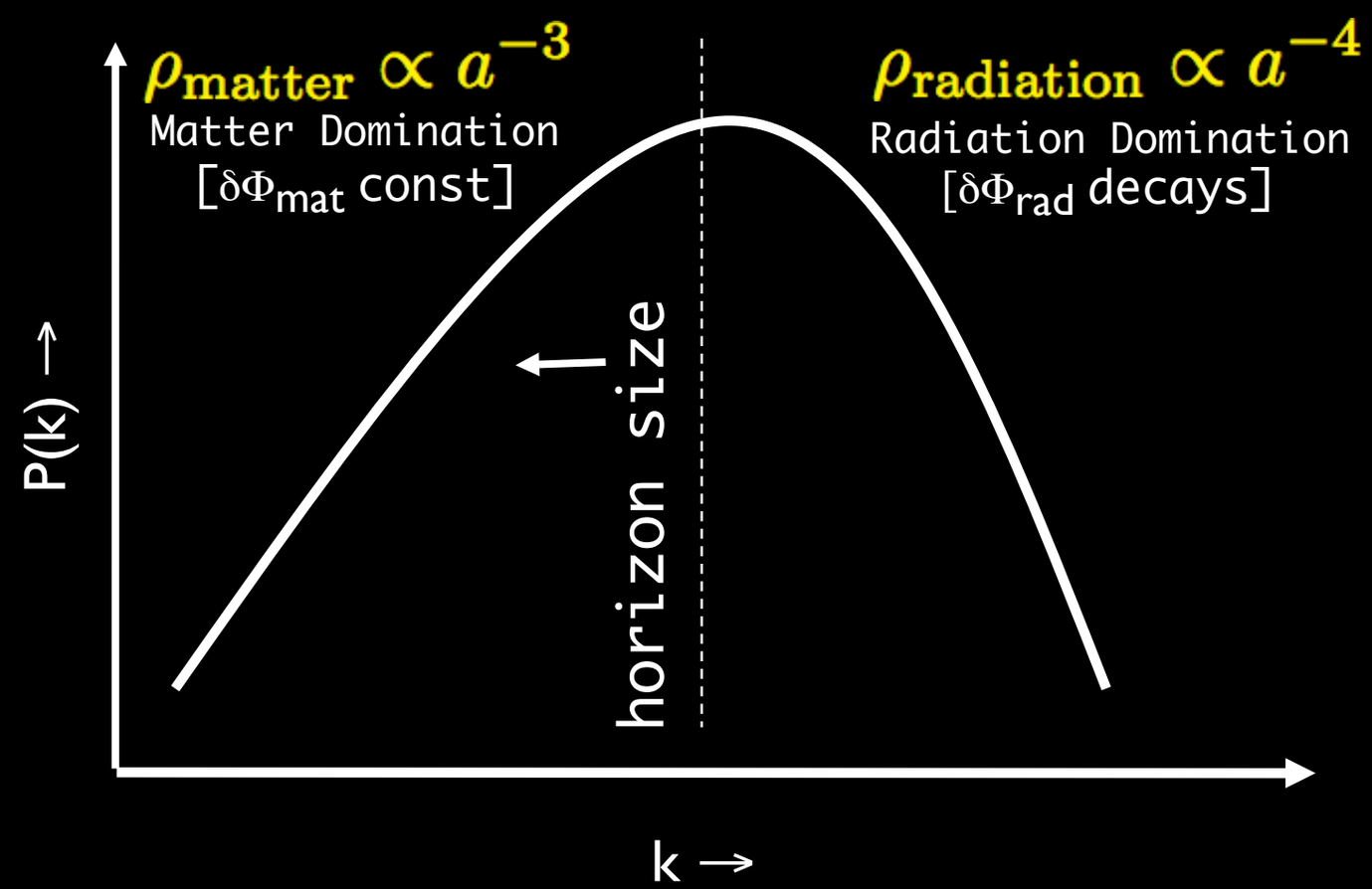
Cosmic Frontier Snowmass Community Summer Study 2013
August 1, 2013

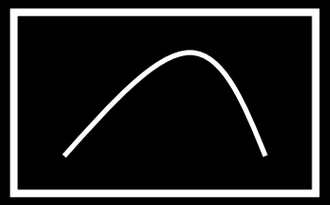
The Cosmological Matter Power Spectrum

Inflation:



<u>Perturbations enter horizon:</u>



How does  probe neutrinos?

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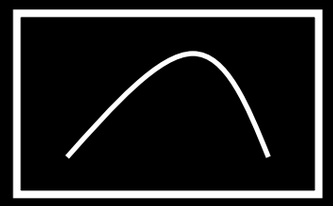
(Assuming thermal equilibrium)

How does  probe neutrinos?

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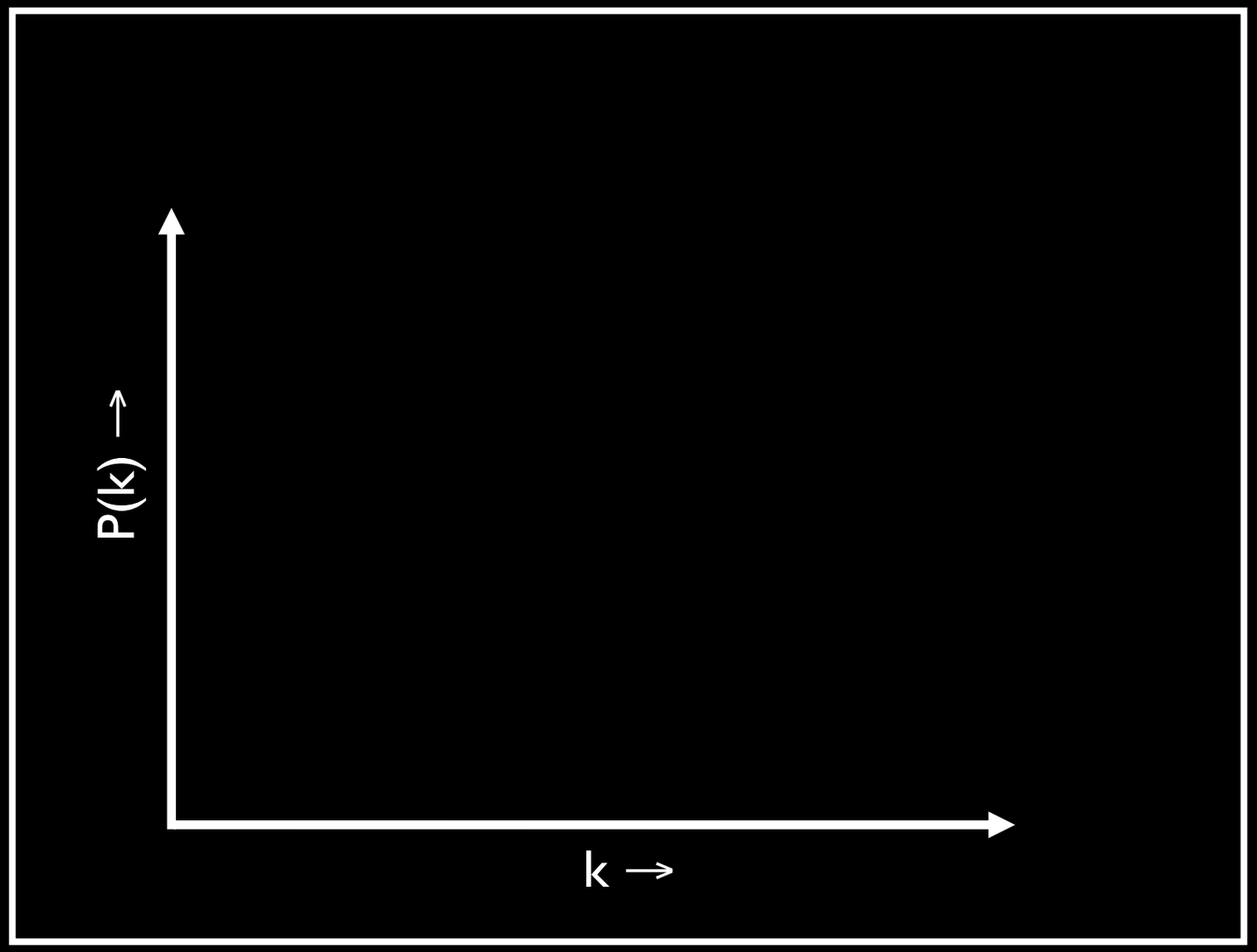
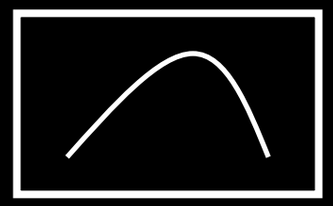


How does  probe neutrinos?

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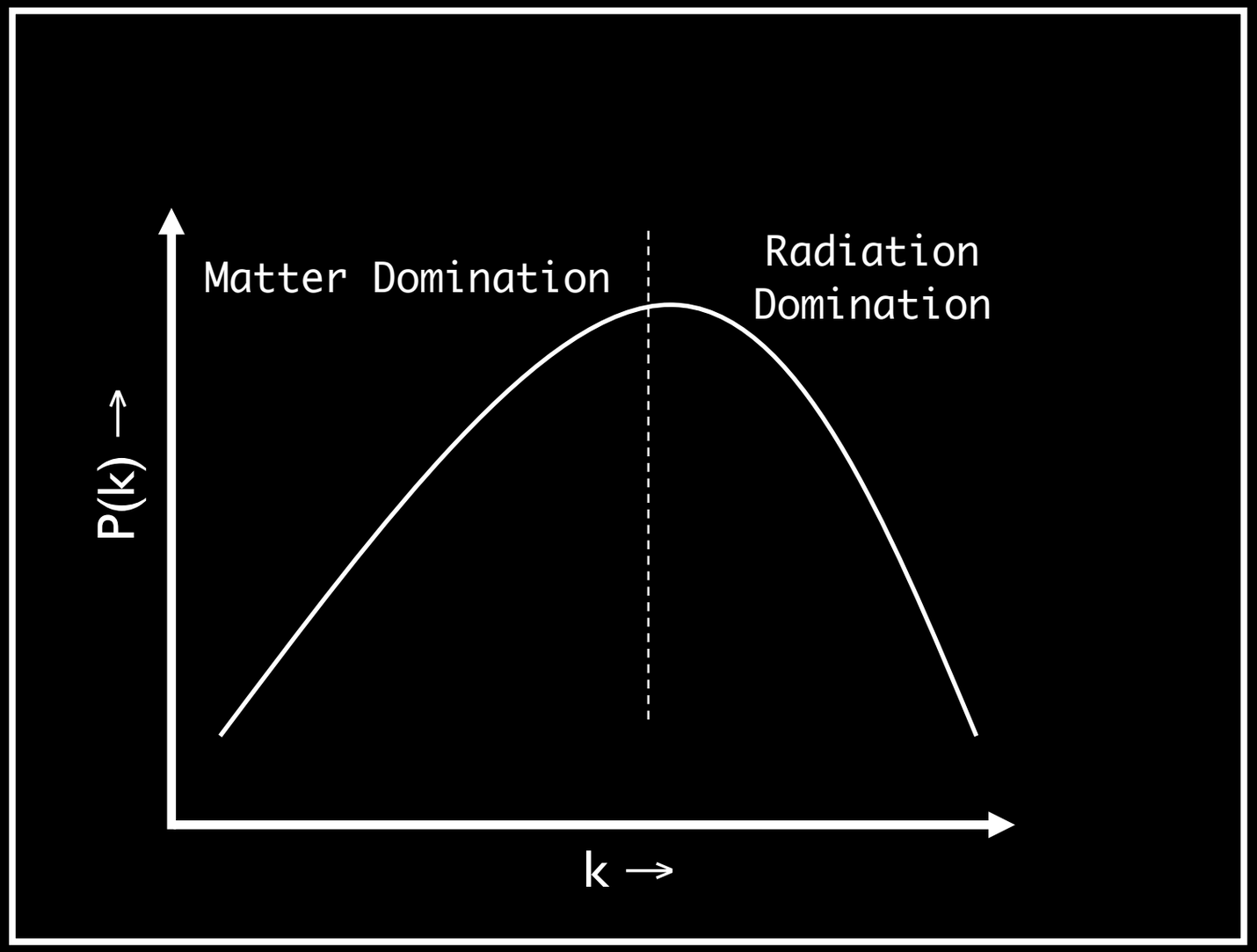
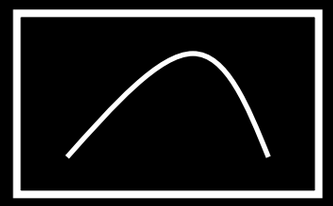


How does  probe neutrinos?

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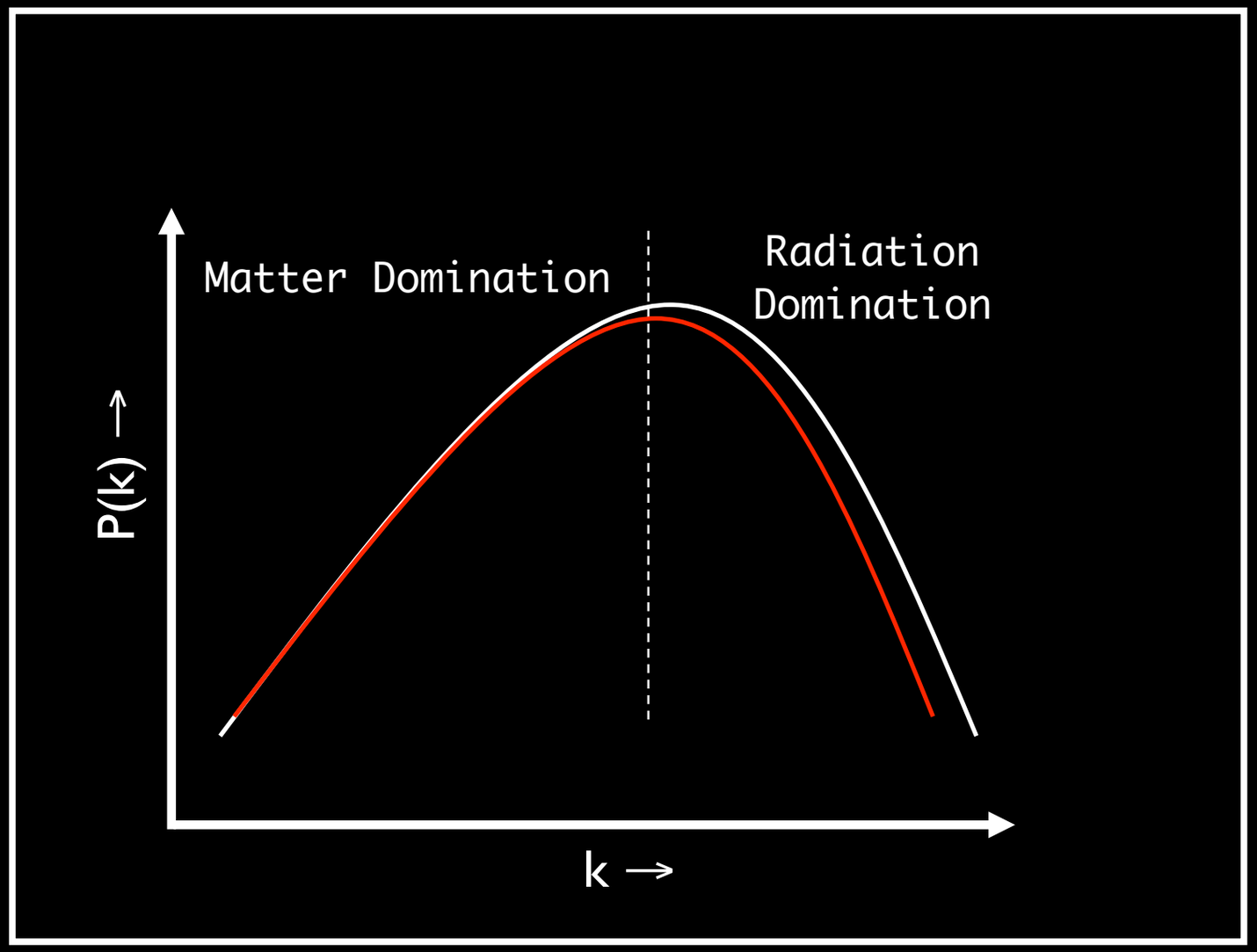
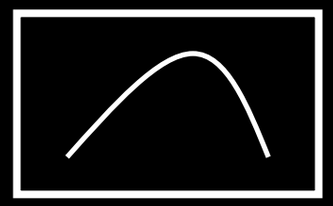


How does  probe neutrinos?

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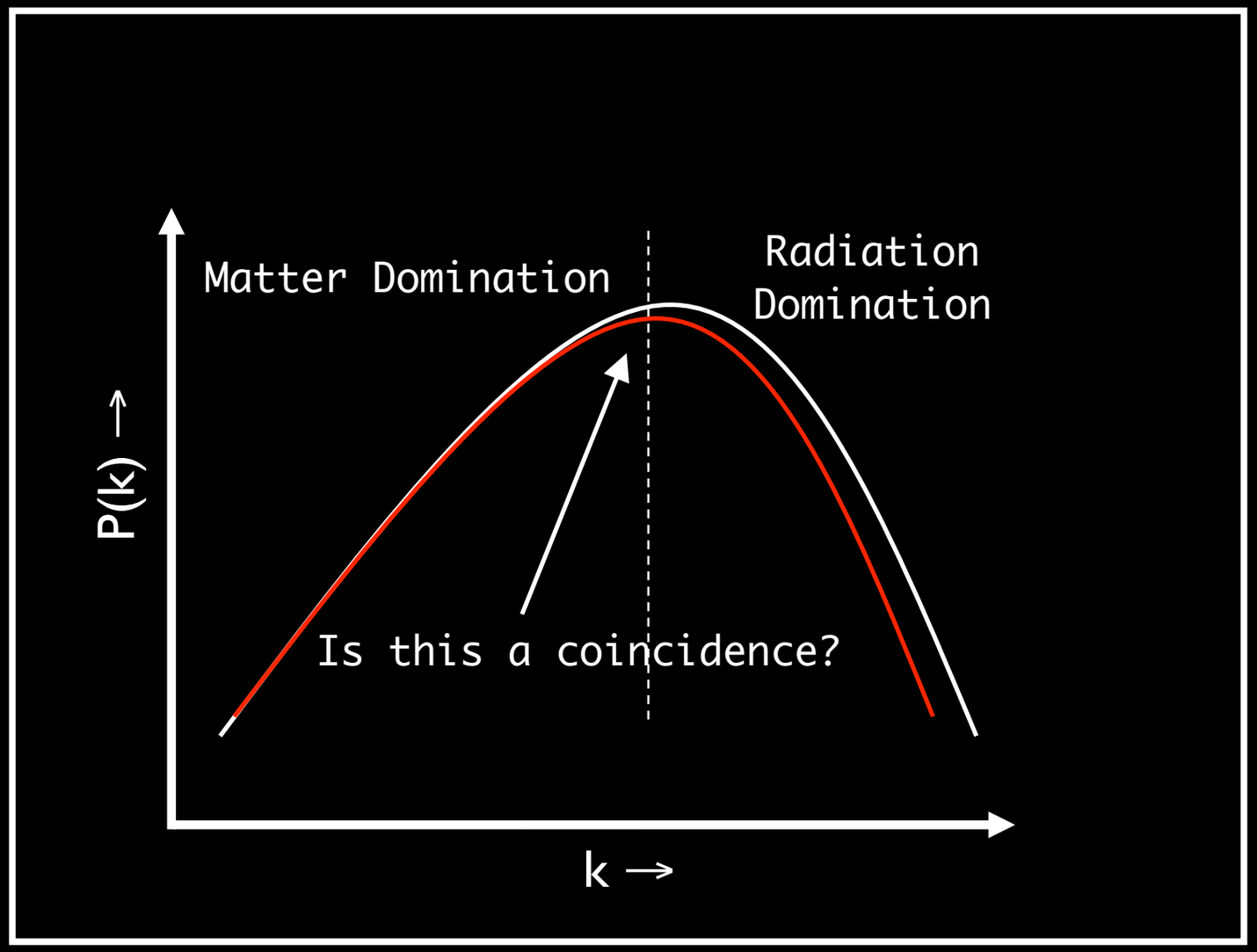
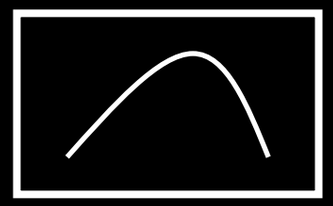


How does  probe neutrinos?

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(Assuming thermal equilibrium)

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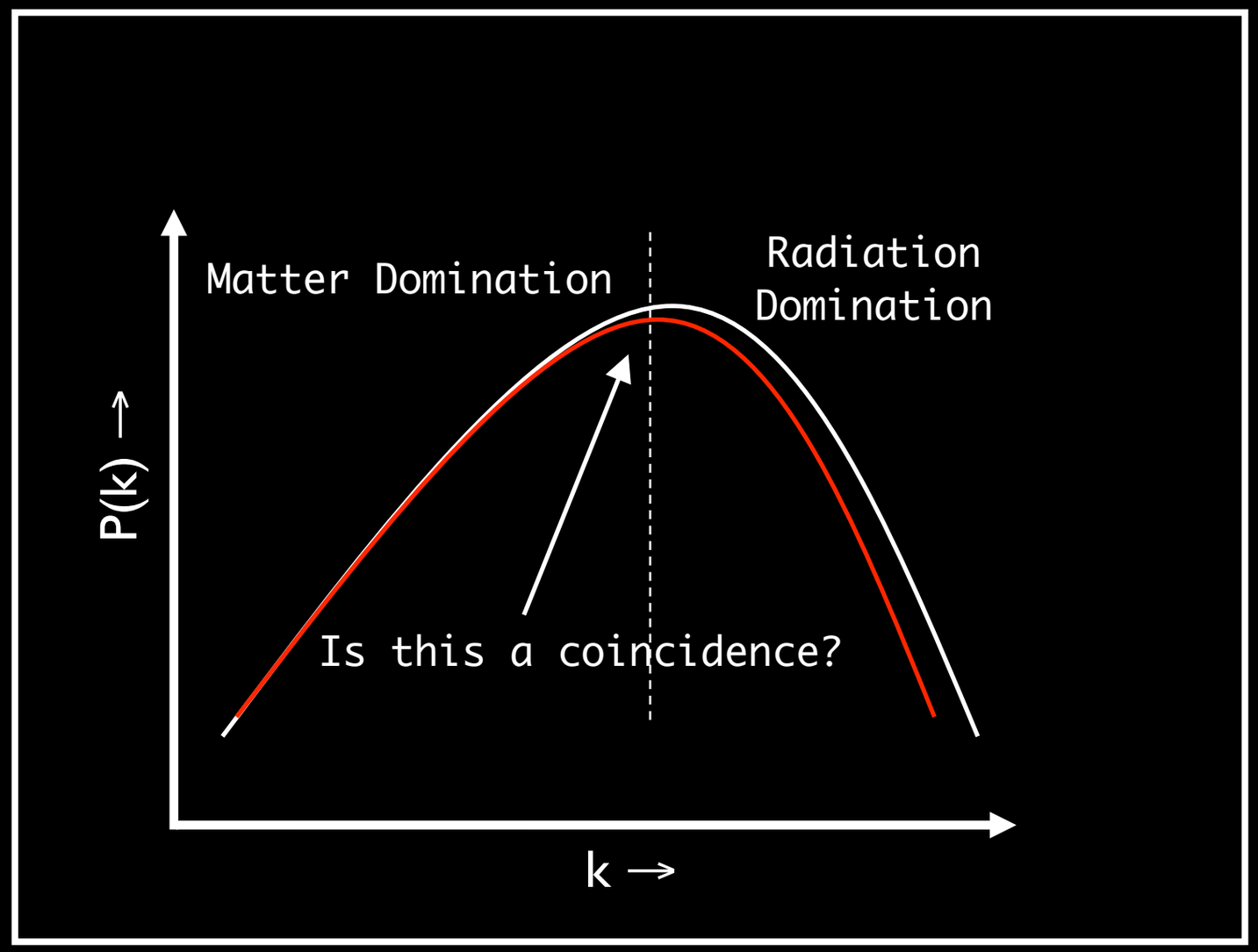
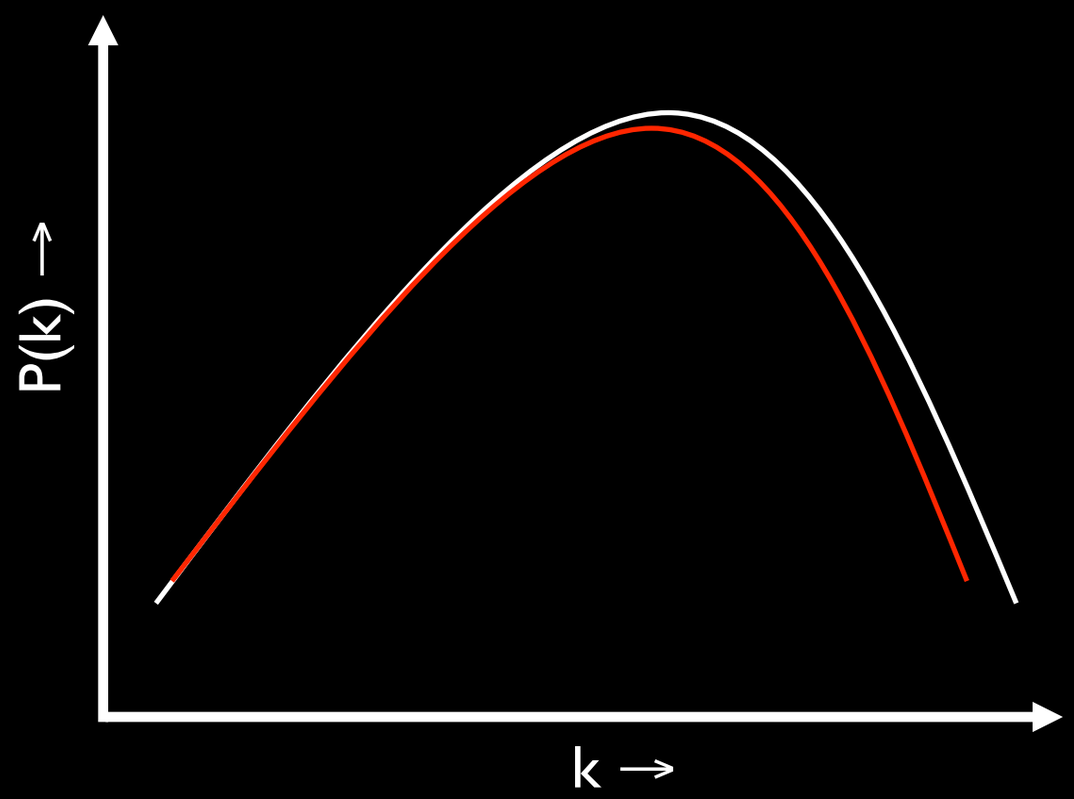
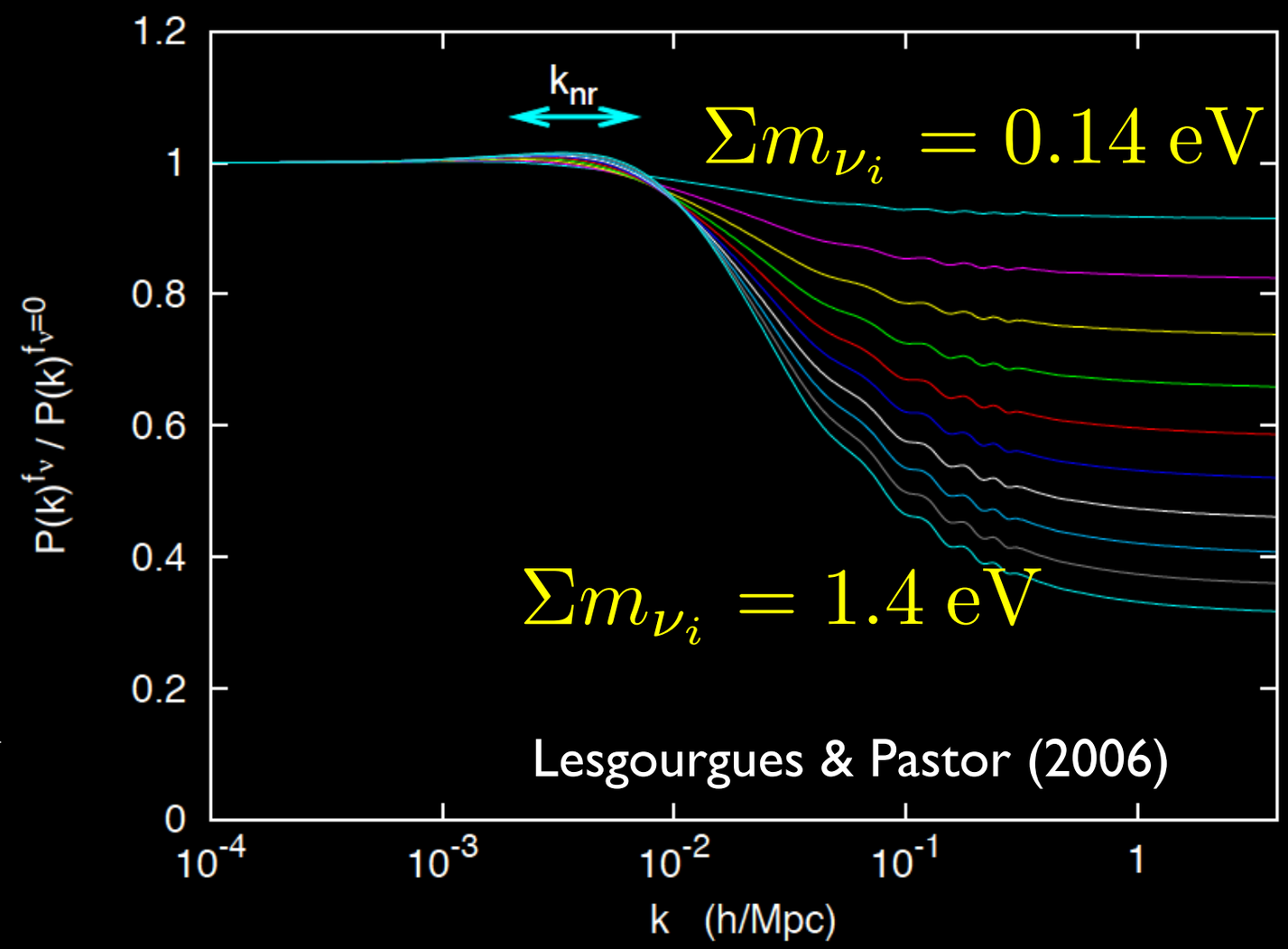
$$\Omega_\nu \approx \frac{\sum m_{\nu_i}}{93\ h^2 \text{ eV}}$$

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



Distinguishing Features in the Power Spectrum





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

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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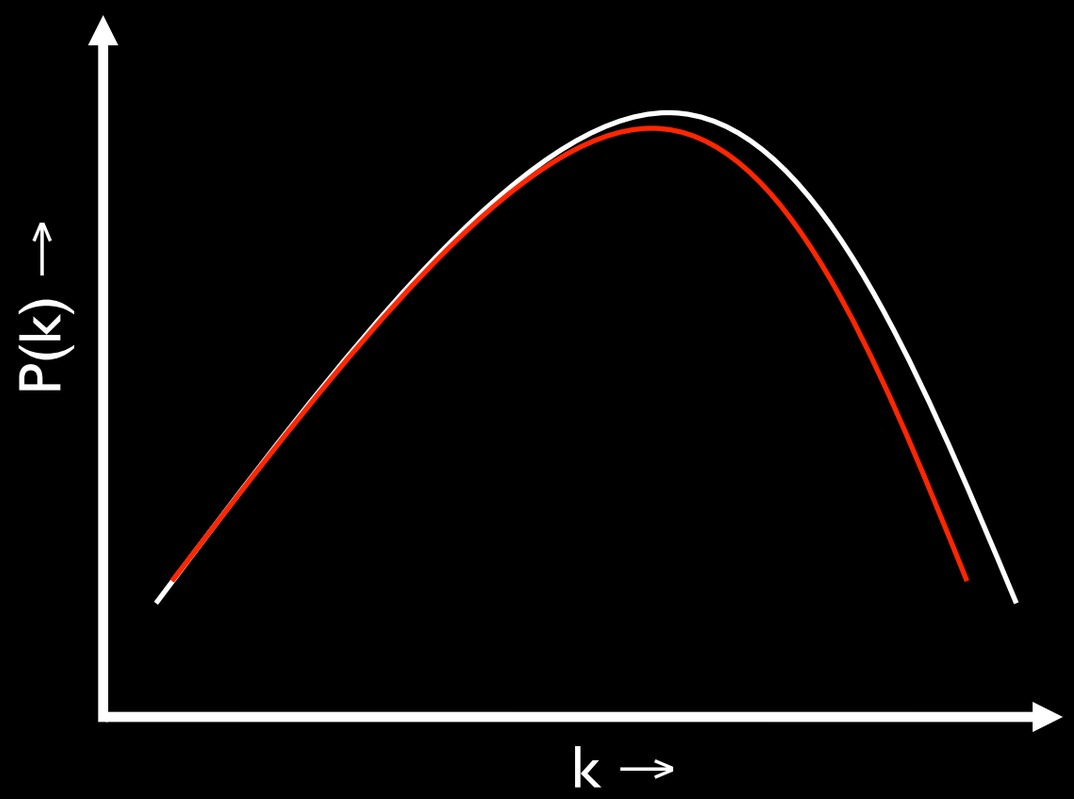

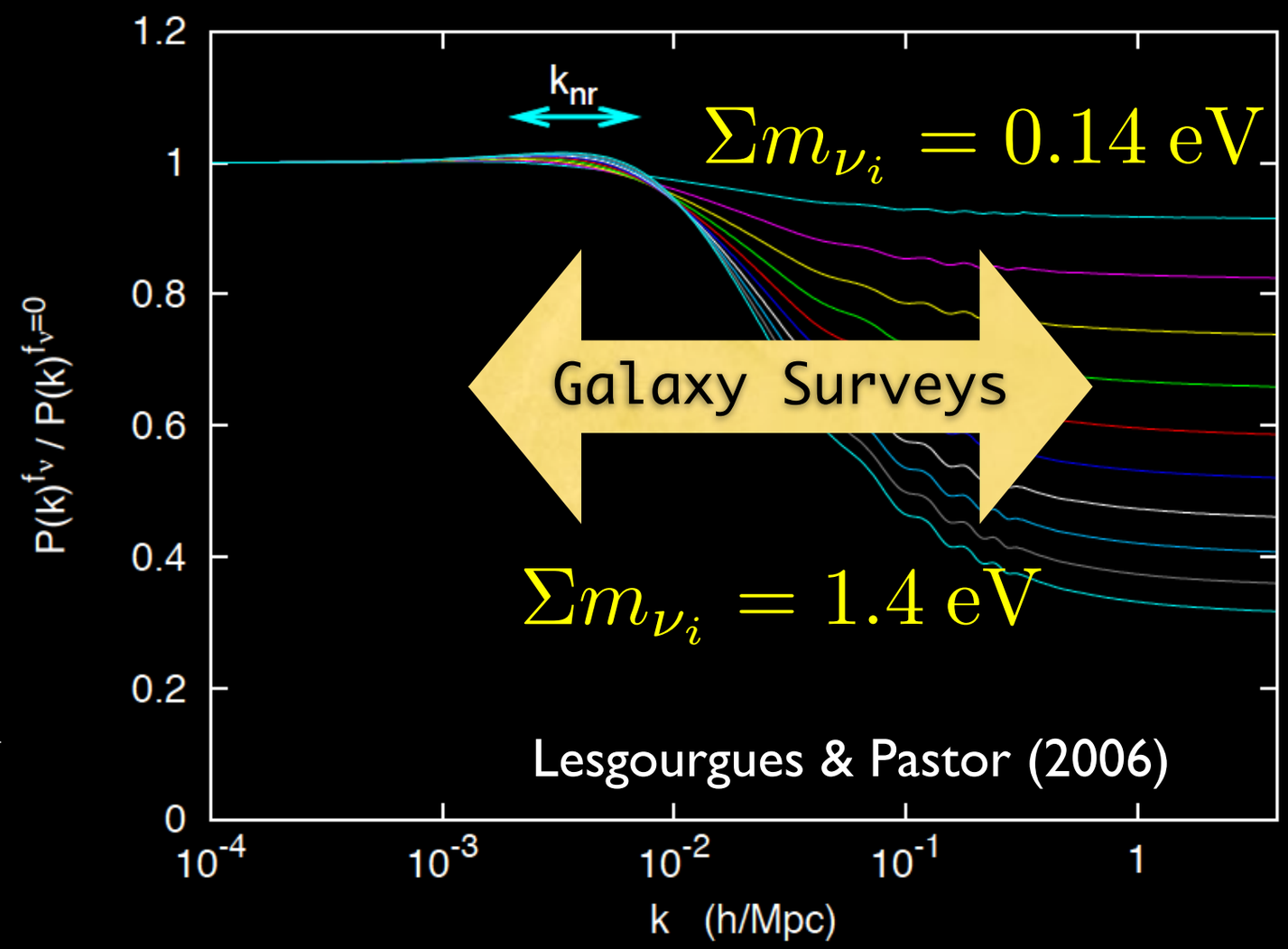

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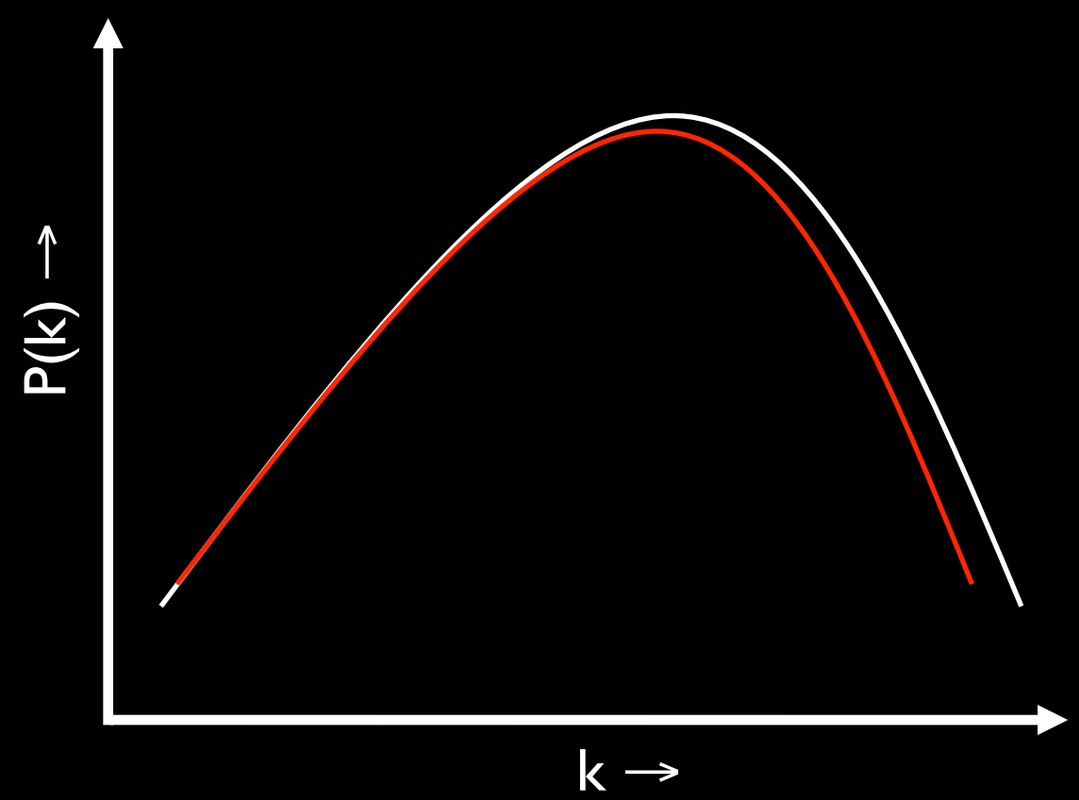

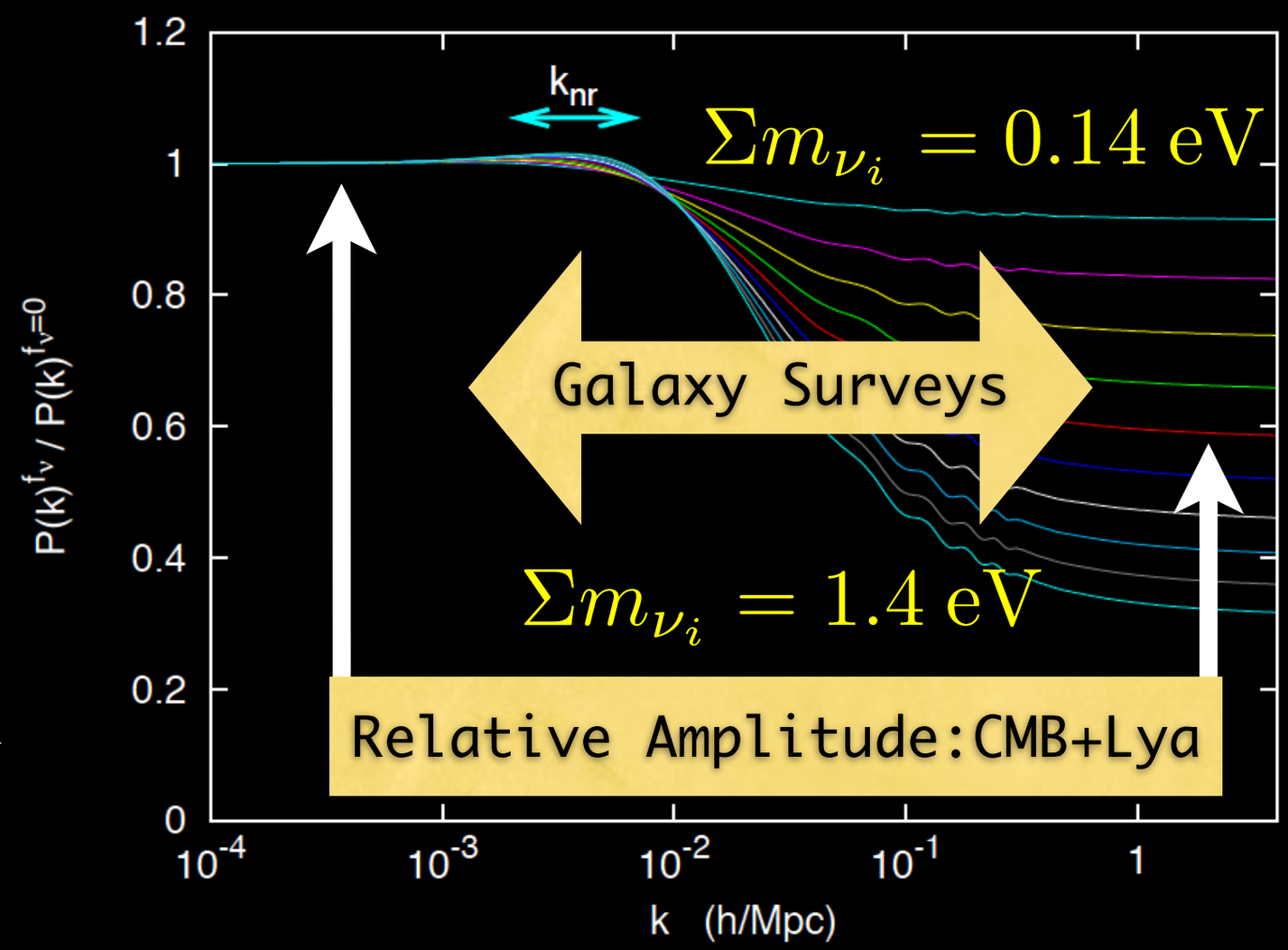

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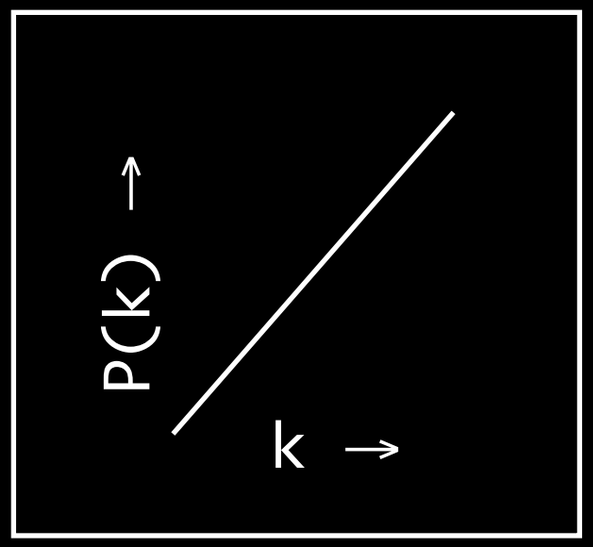
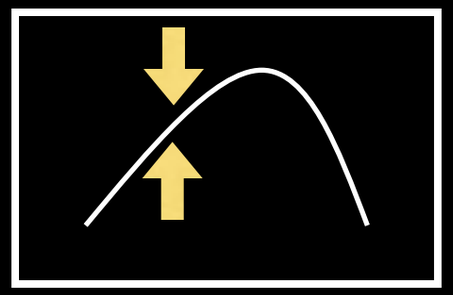


The Primordial Spectrum: Precision Determination at Large Scales

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

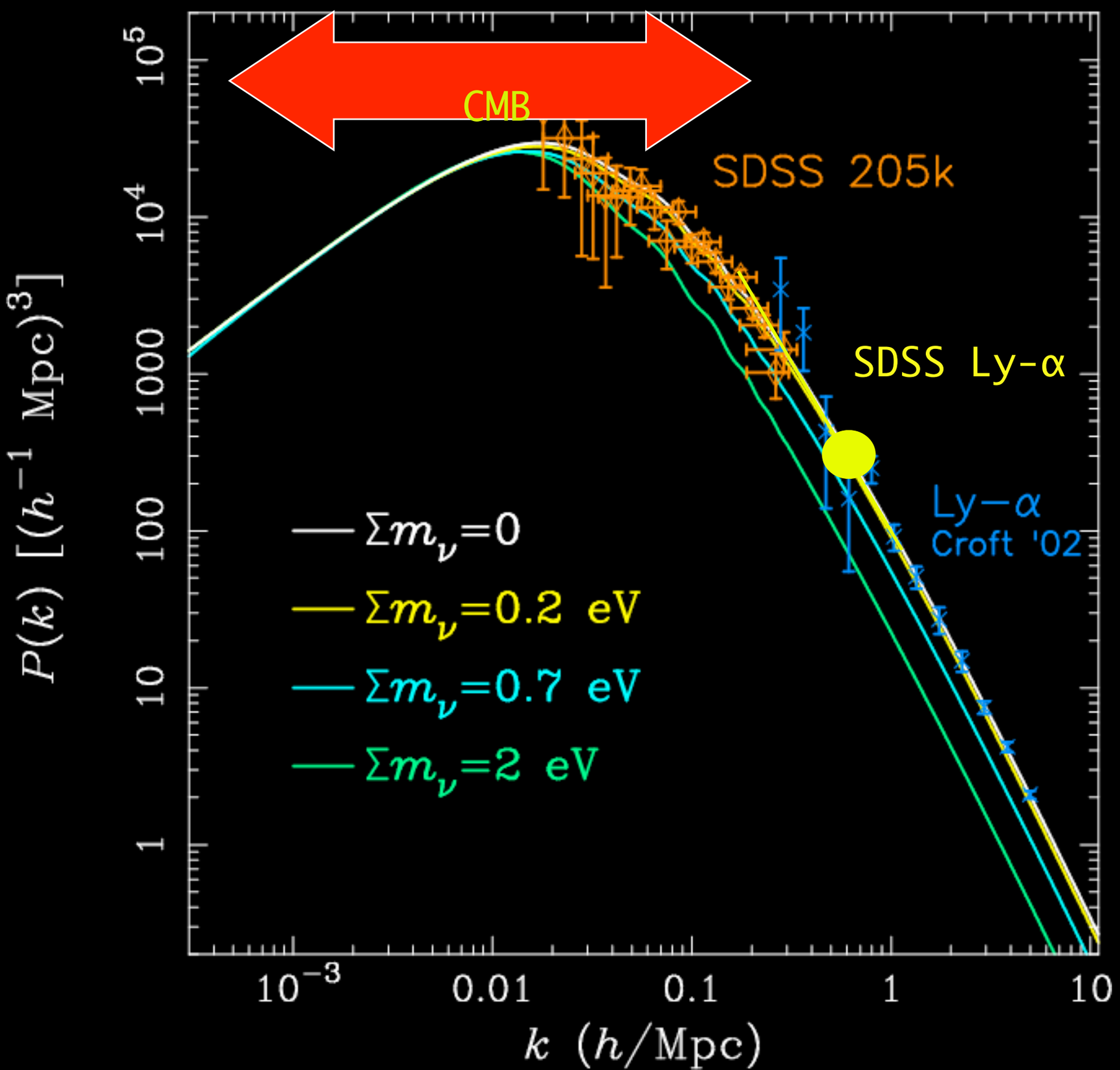
Planck 1-Year + WMAP Pol.: (Planck Collab. 2013)



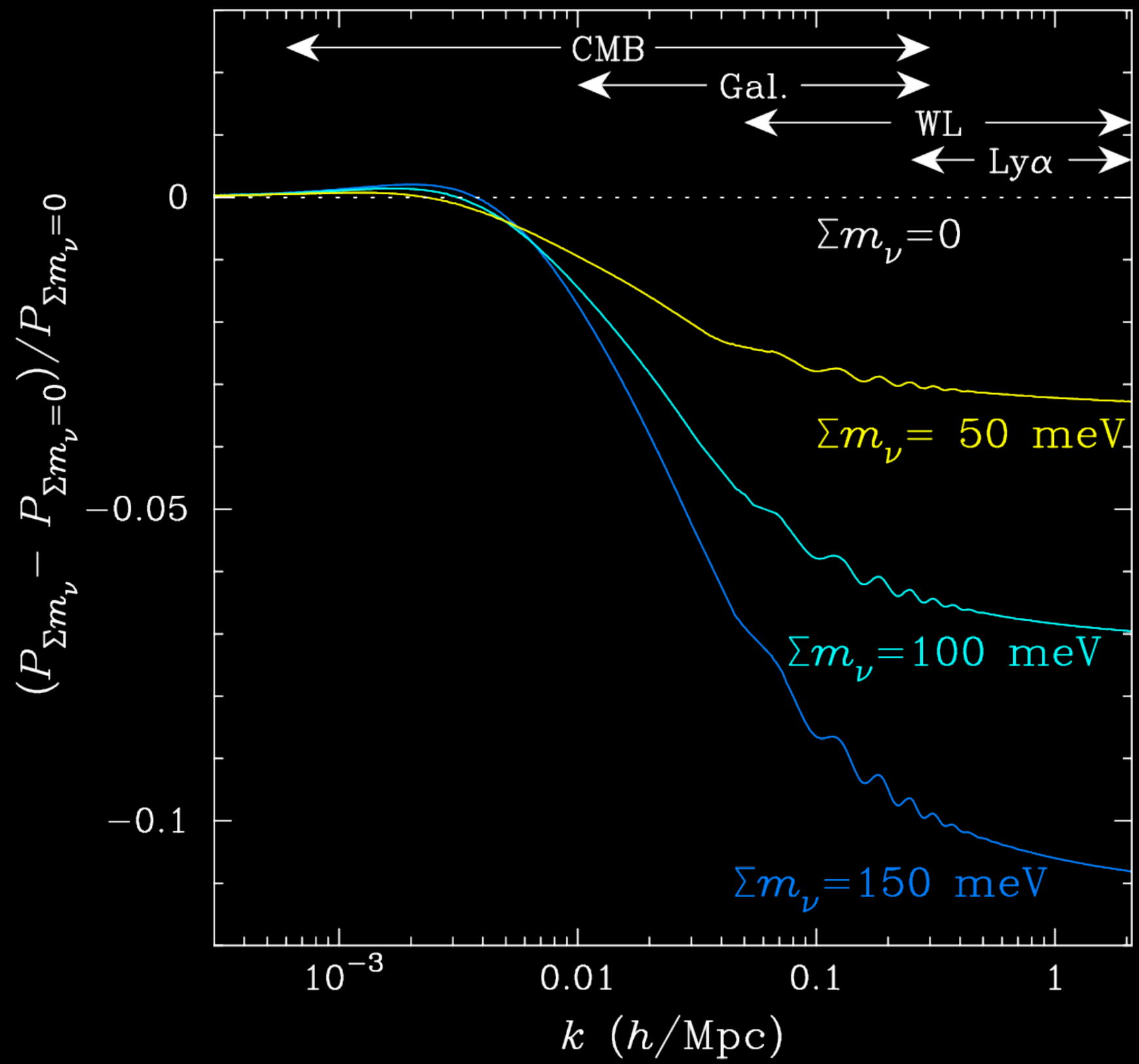
$$A = 2.196^{+0.051}_{-0.060} \qquad (3\%)$$

$$n = 0.9603 \pm 0.0073 \qquad (0.8\%)$$

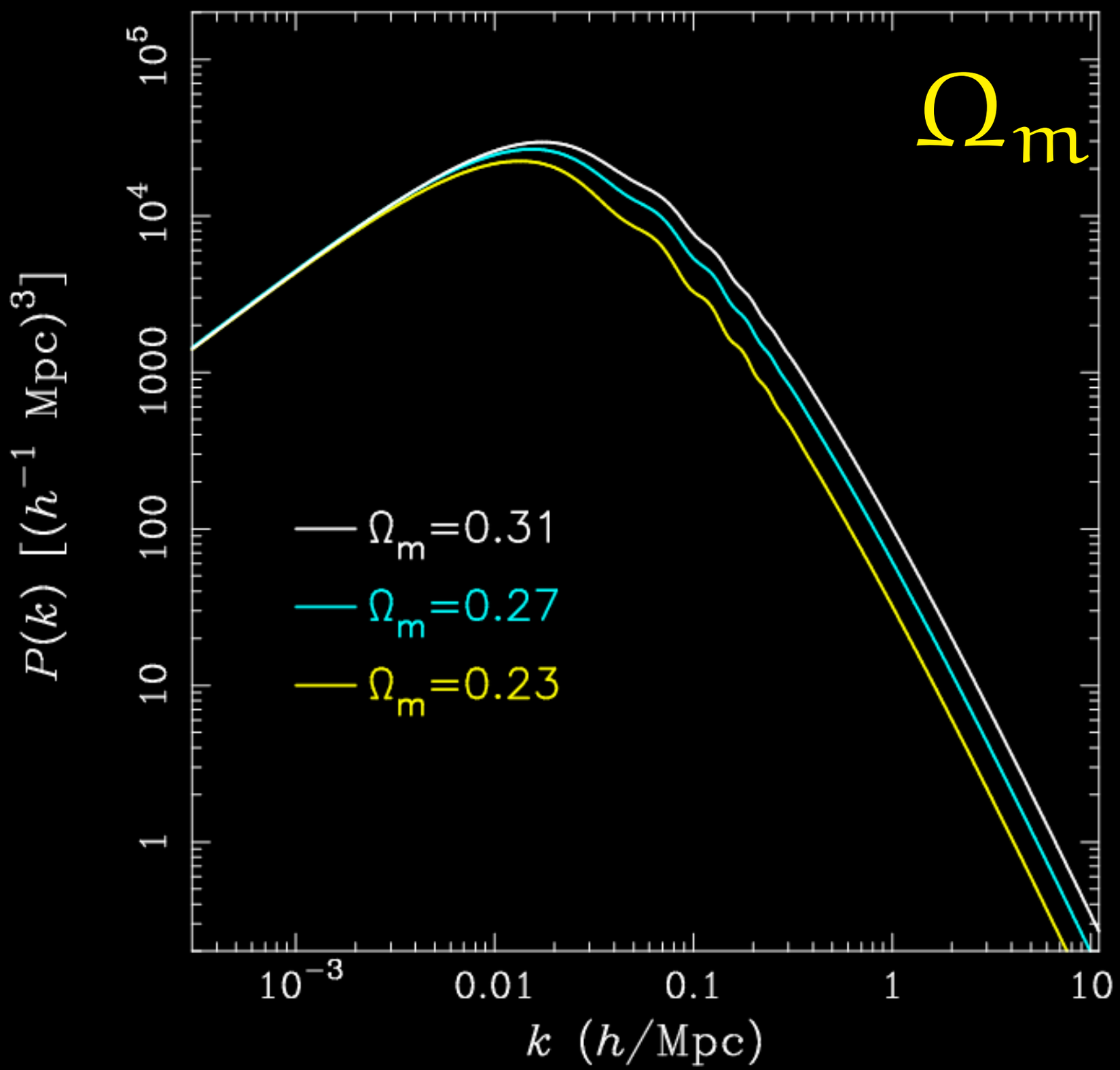
Measuring $P(k)$: from largest to smallest scales

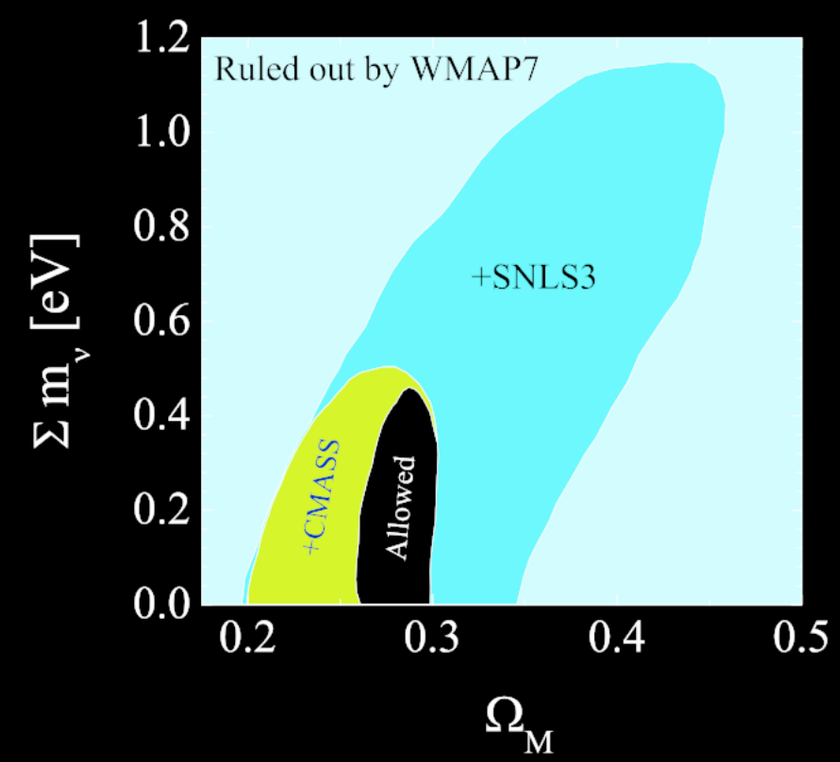


Upcoming High-Precision Era: Relative Change to $P(k)$



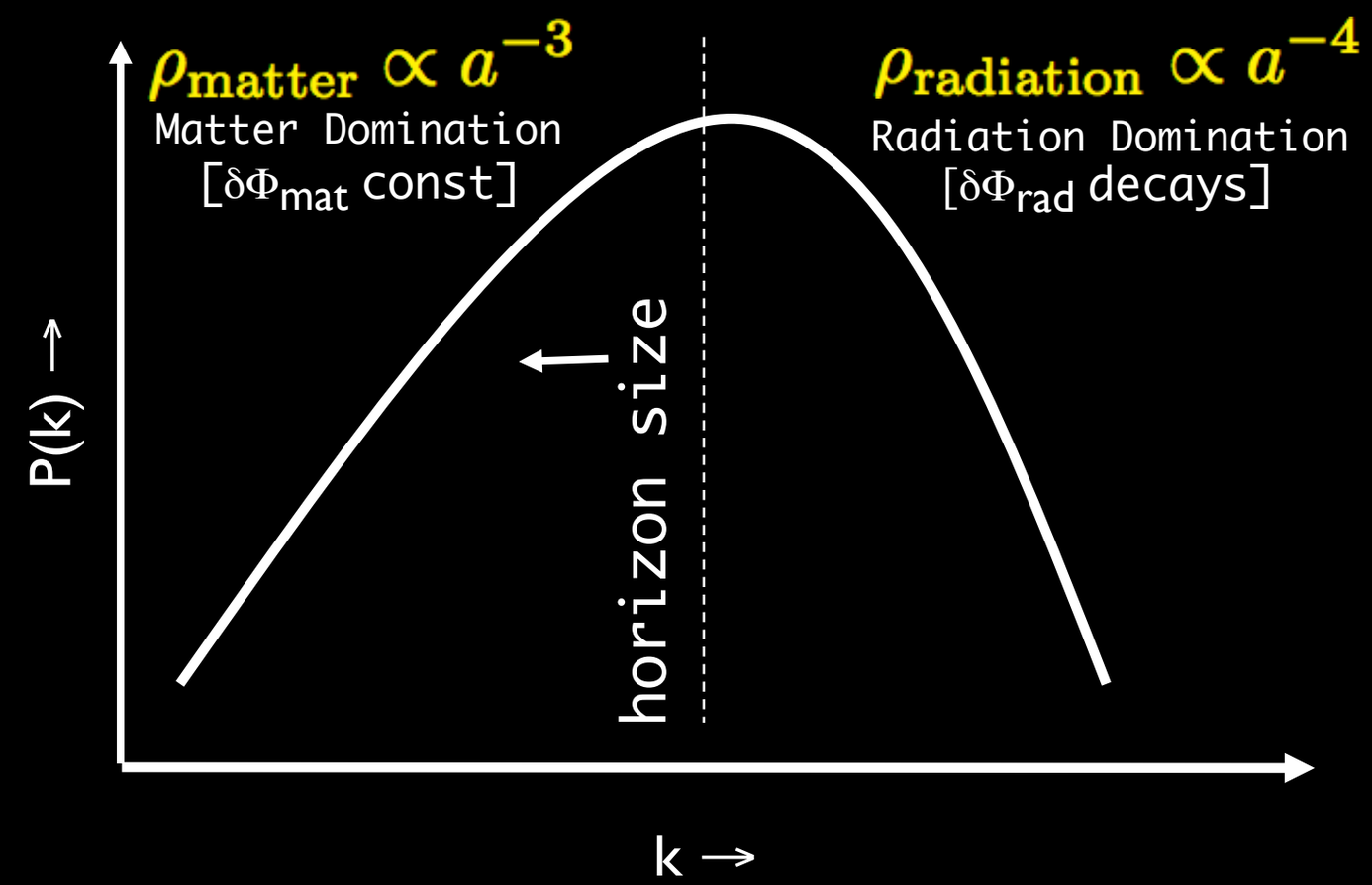
Ω_m & Other Parameter Degeneracy





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

For LSS: Perturbations enter horizon at M/R equality



For BAO: Extra radiation changes expansion rate from perturbation evolution through baryon decoupling

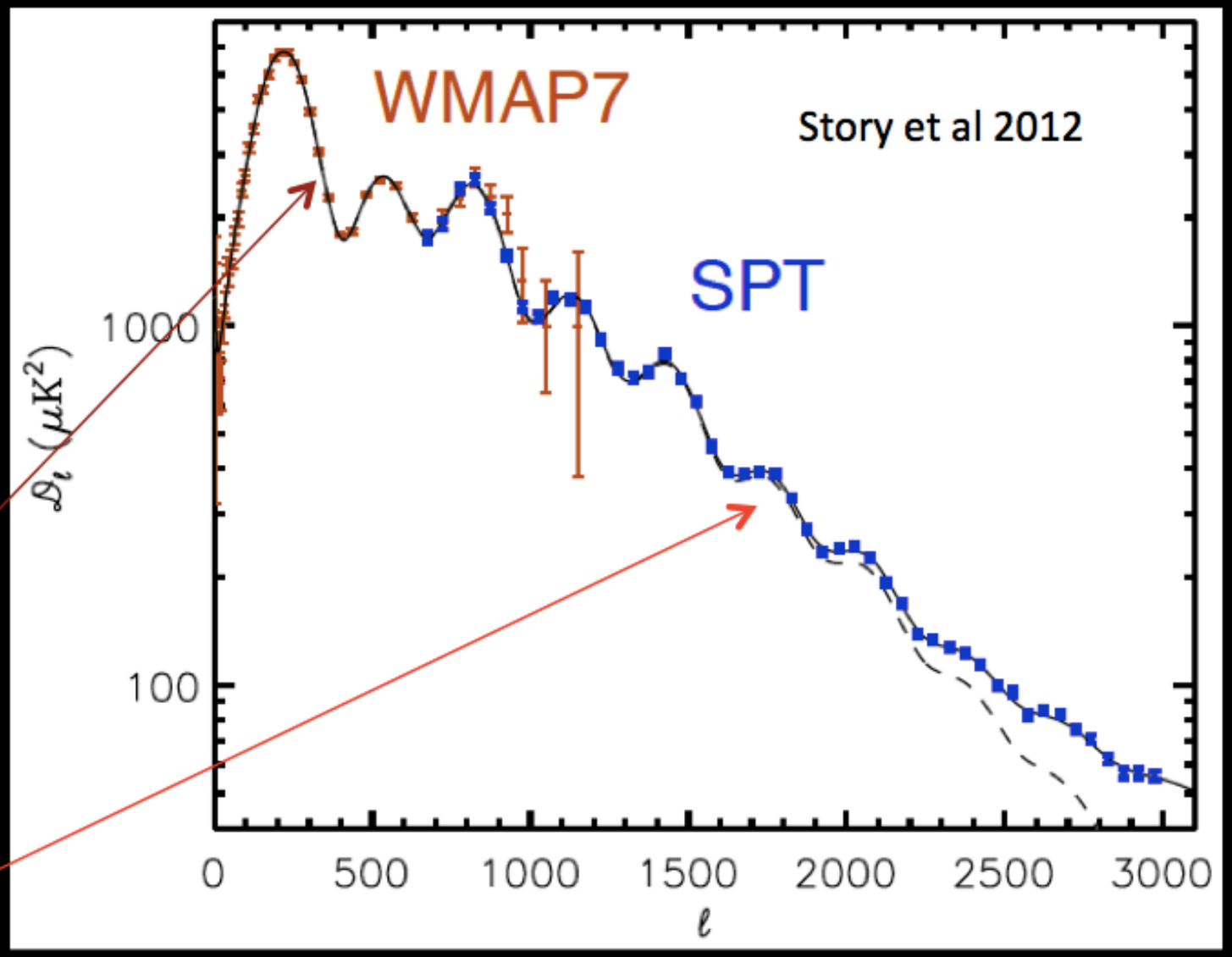
CMB Spectrum & N_{eff}

$$\frac{r_d}{D} \propto H^{1/2}$$

Larger N_{eff} leads to more damping

Angular scale of acoustic peaks (r_s/D) is known precisely

Angular scale of damping (r_d/D) measured recently



[Dodelson (SLAC Cosmic Frontiers)]

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

68% CL

⋮

WMAP7

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

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

- 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*)

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

Planck

- Planck + high-l CMB + WMAP P + BAO (Planck Collab. 2013)

$$N_{\rm eff} = 3.30 \pm 0.27$$

Estimating Upcoming Cosmological Neutrino Mass Constraints

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Hu, Eisenstein & Tegmark 1998

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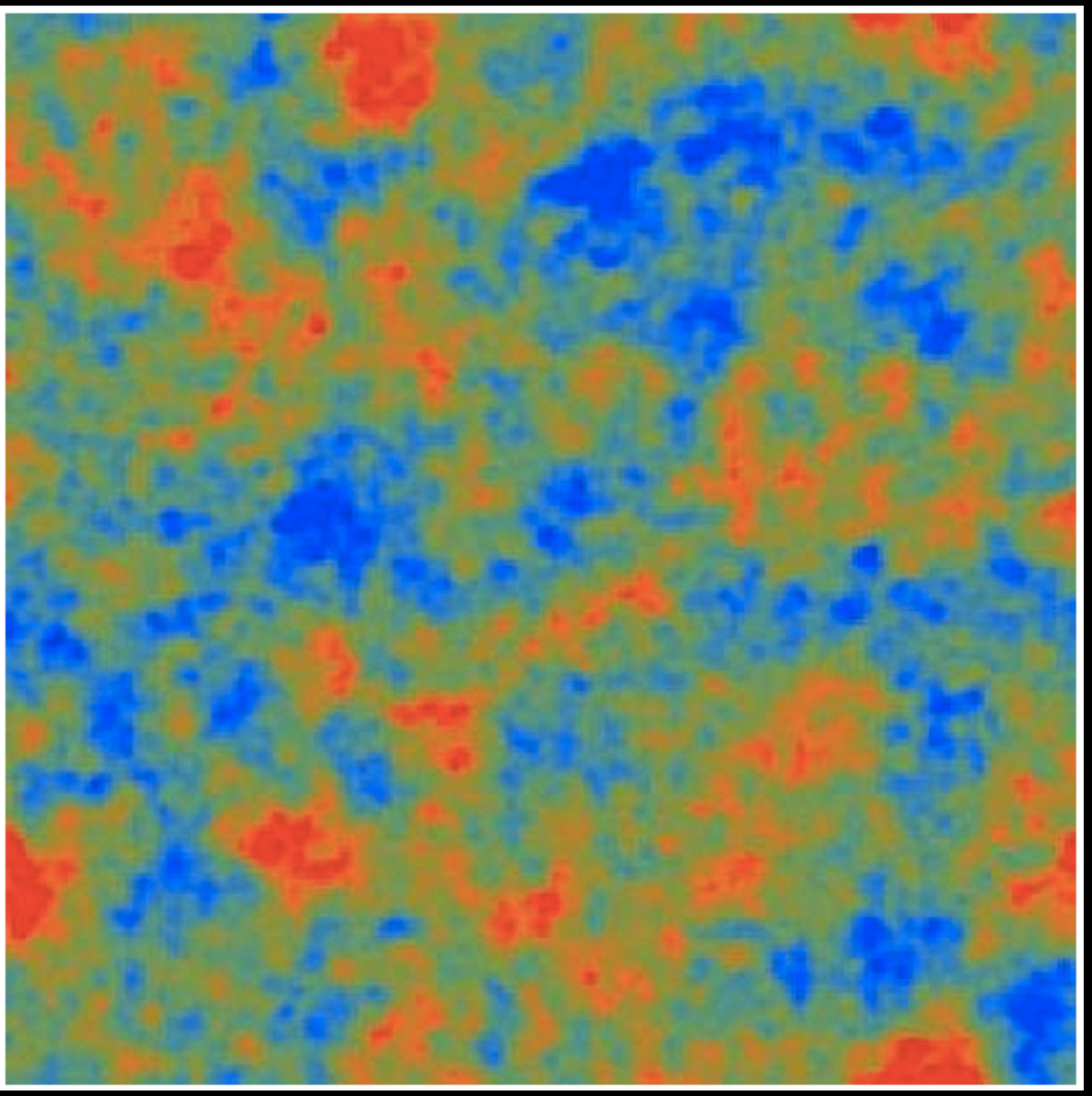
Kaplinghat et al PRL 2003 (CMB WL)
Wang et al PRL 2005 (WL Clusters)
De Bernardis et al. 2009 (Opt. WL)
Joudaki & Kaplinghat 2011 (LSST)
Basse et al. 2013 (Euclid)
CF5 Neutrino Report 2013

Lensing of the CMB



Hu & Okamoto 2001

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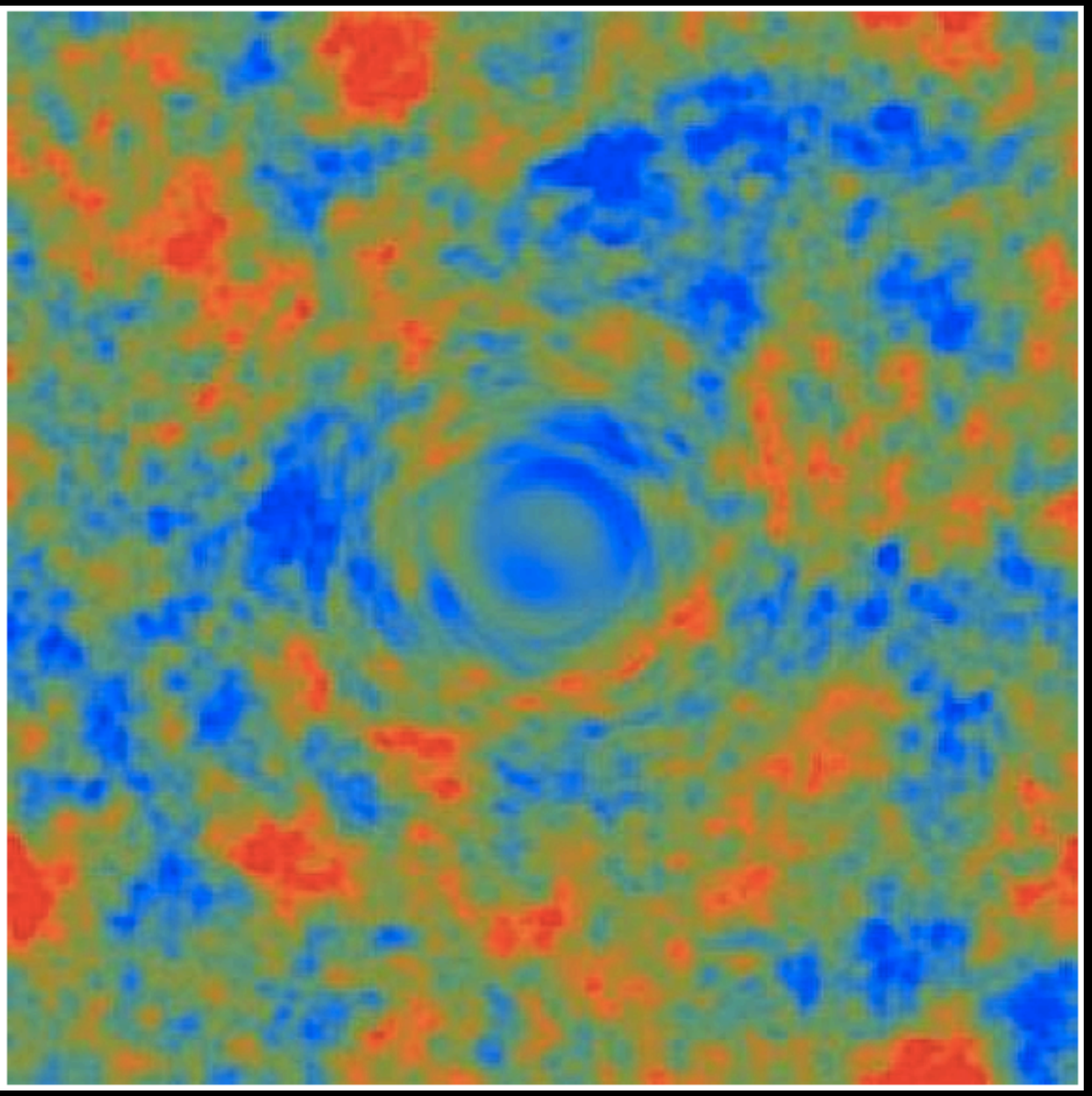

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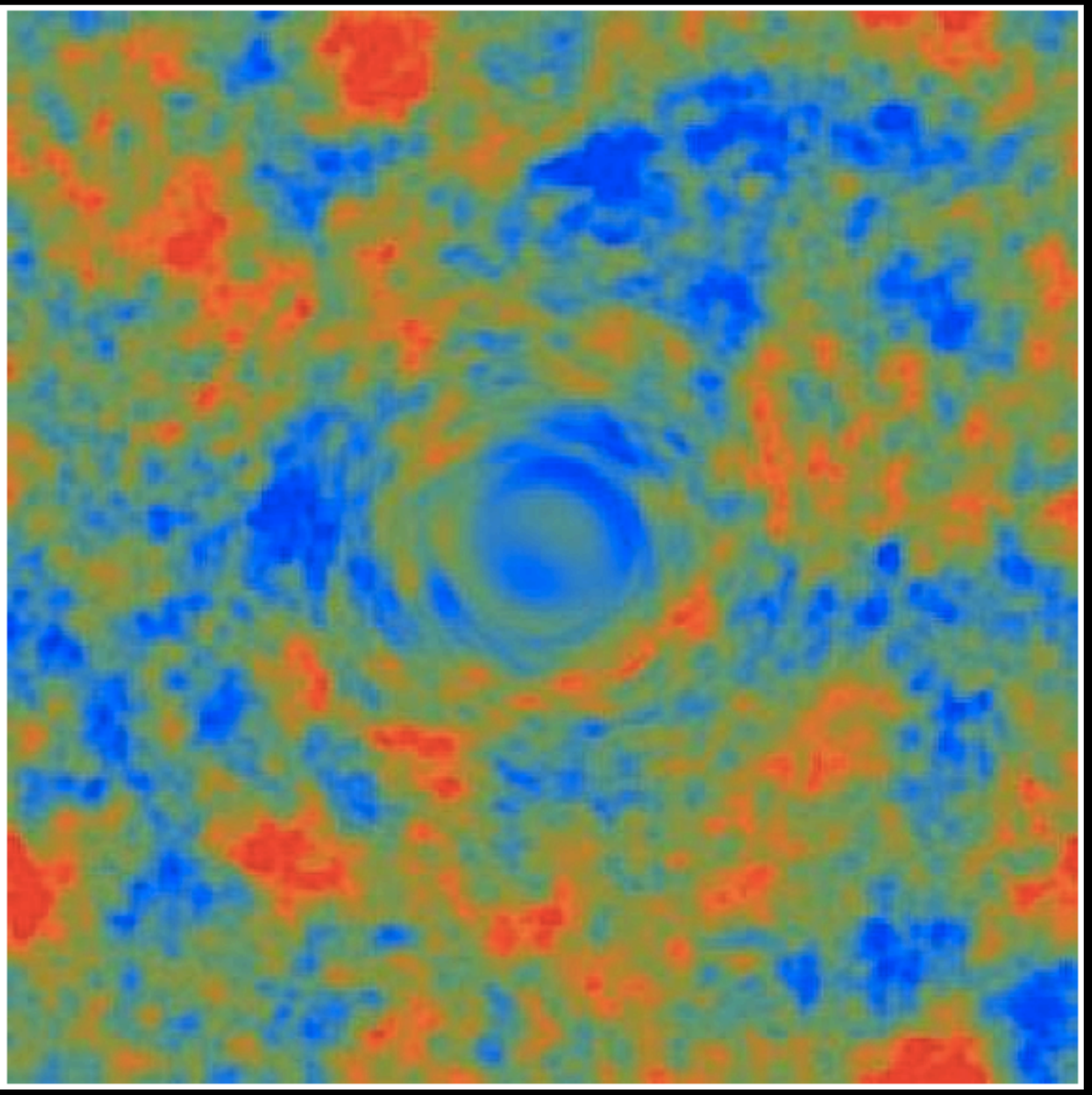

- Higher-order statistics in CMB T maps can reconstruct the lensing potential. (detected by SPT, ACT, Planck)

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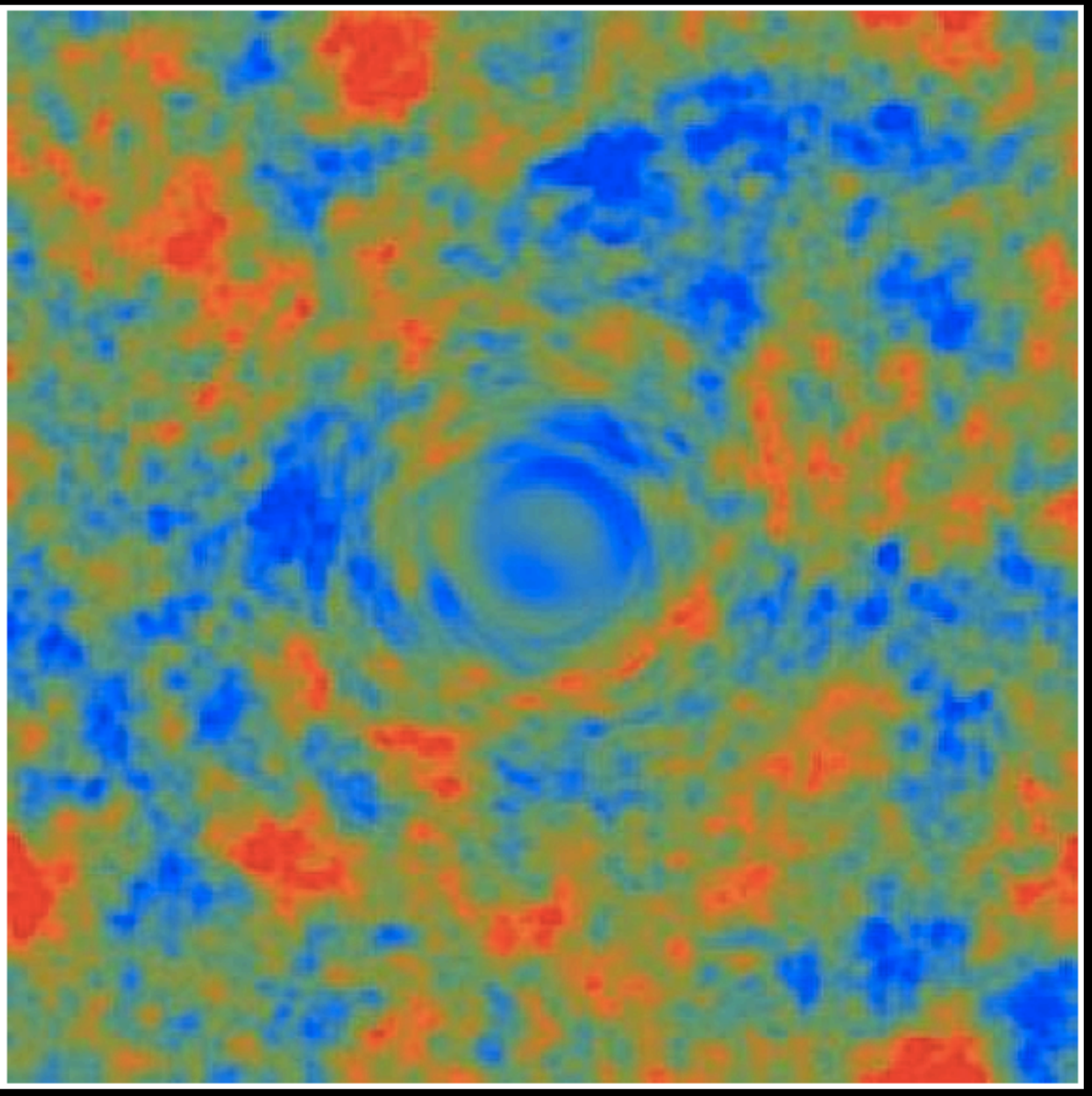

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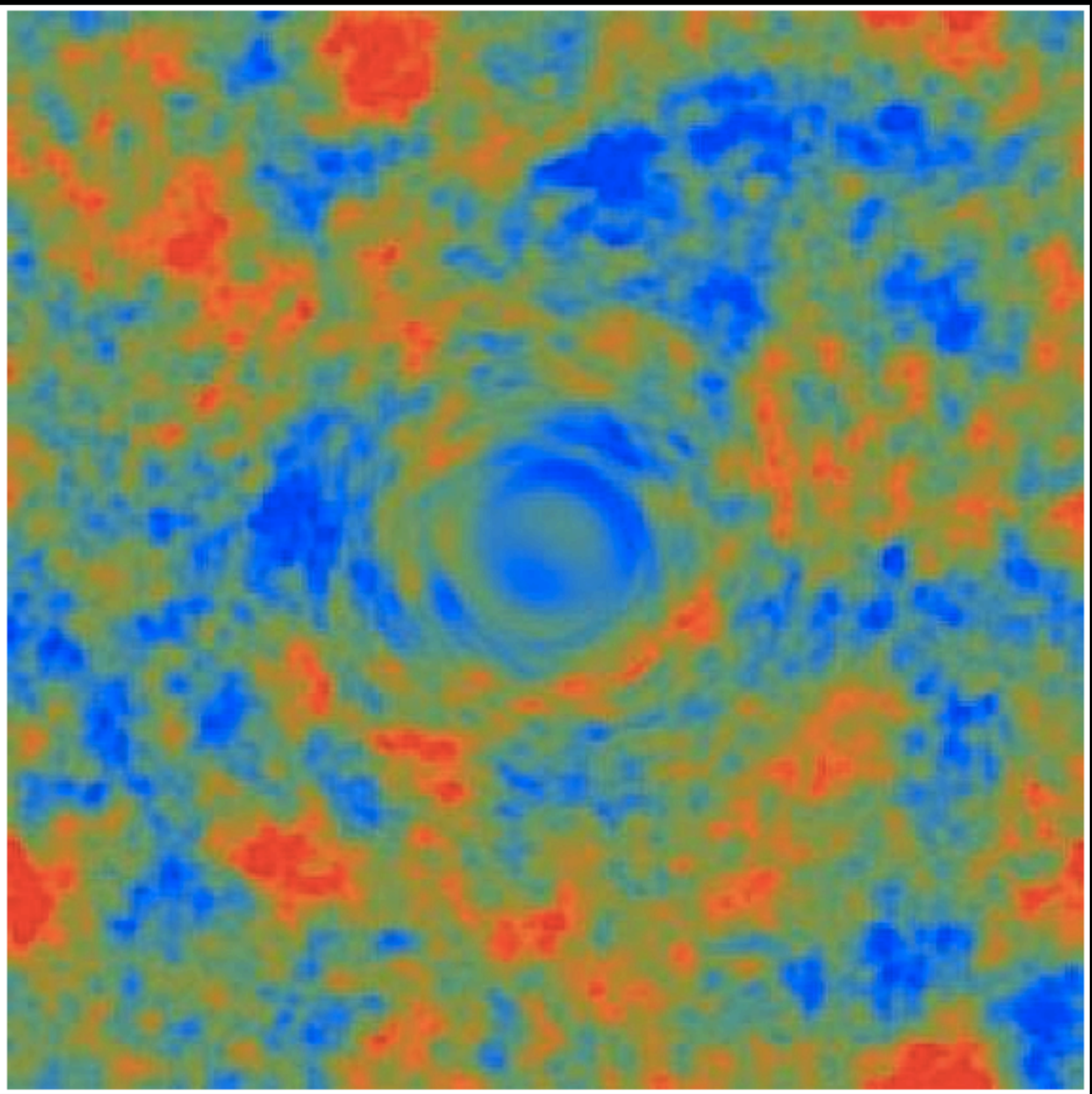

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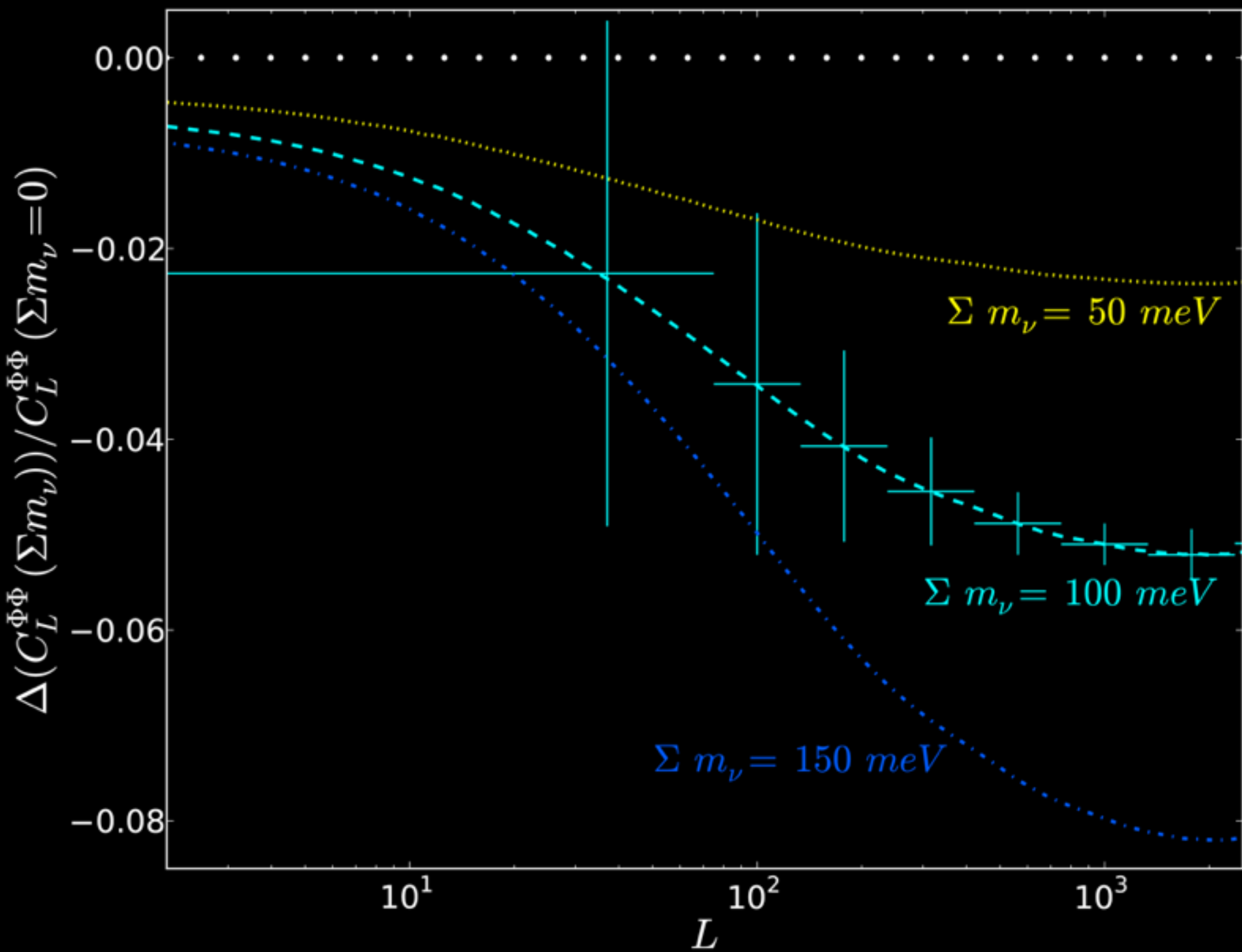
- Detailed, high signal-to-noise measurements of arcminute polarization can therefore be used to reconstruct the lensing potential $C_L^{\phi\phi}$

Lensing Potential Power: Relative Change over an Integrated $P(k)$



Σm_ν: The March of Time

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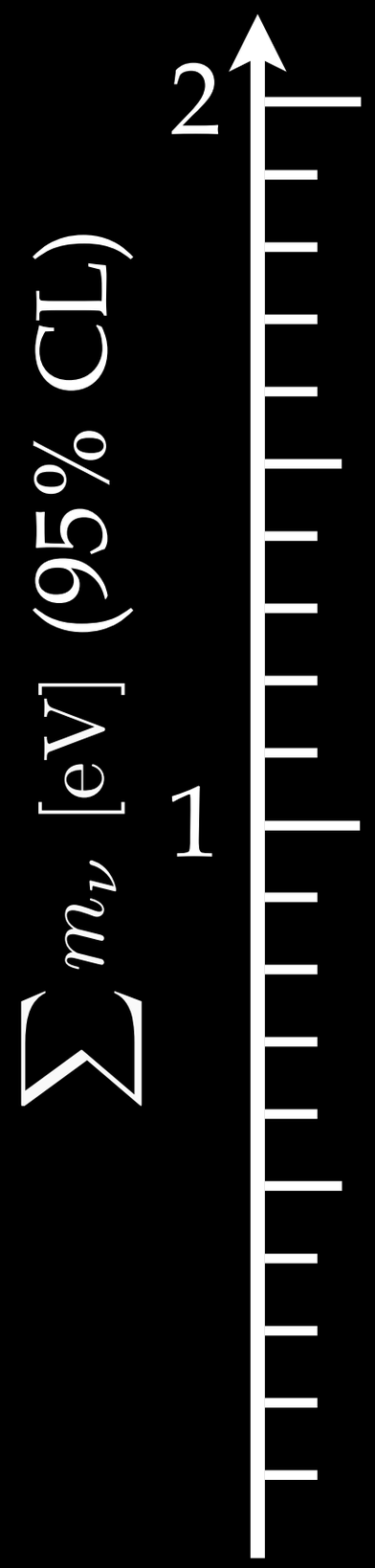

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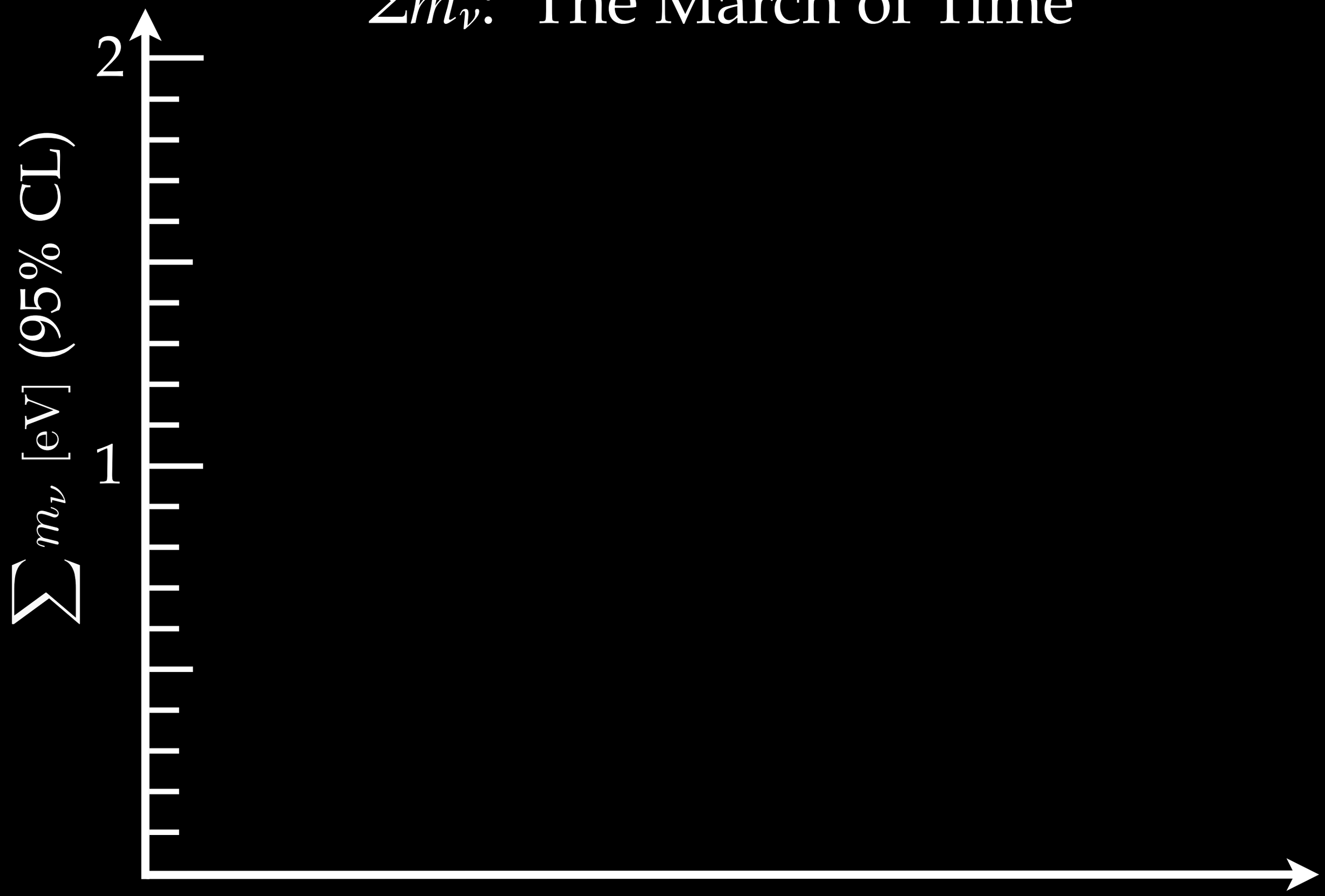

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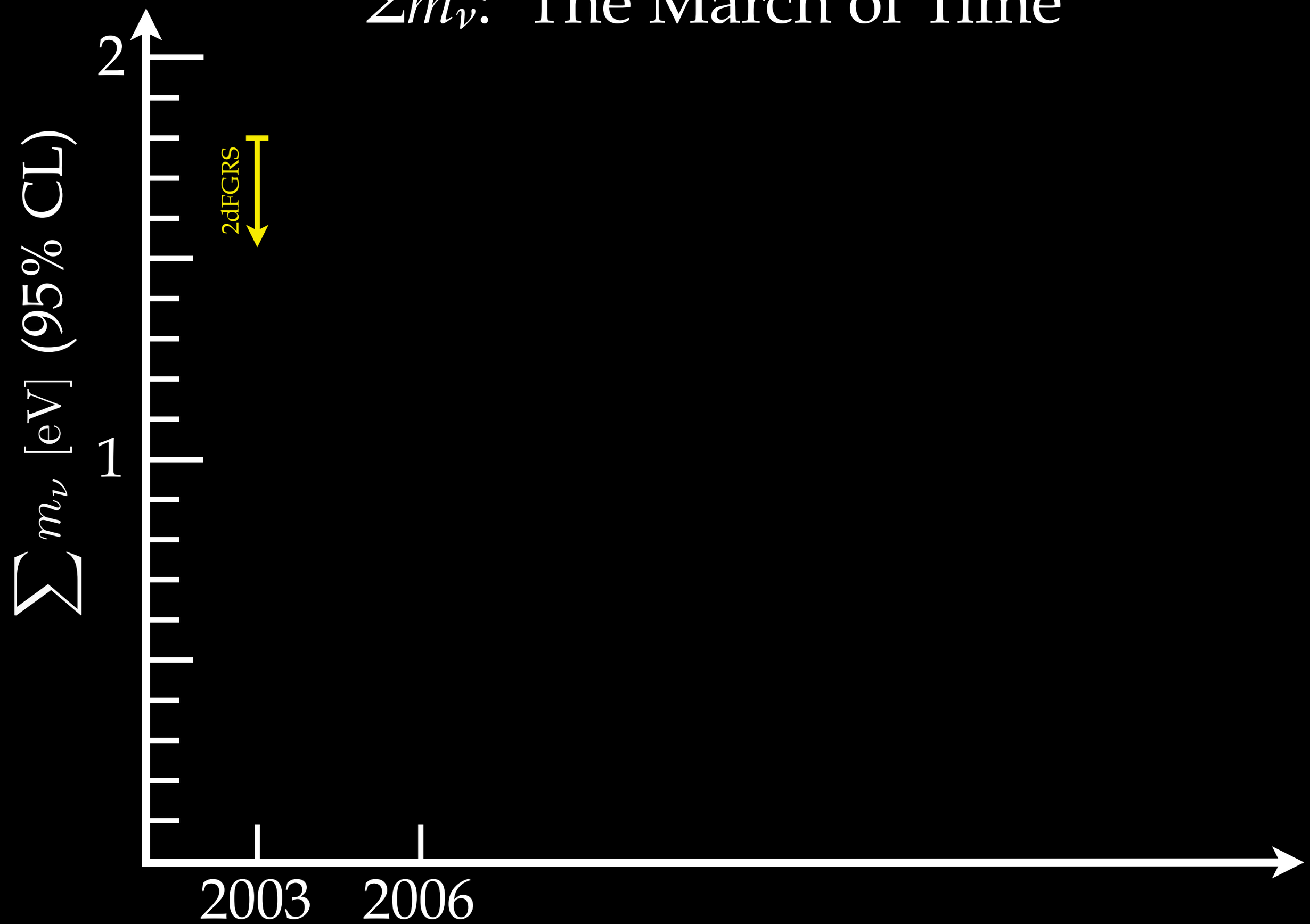

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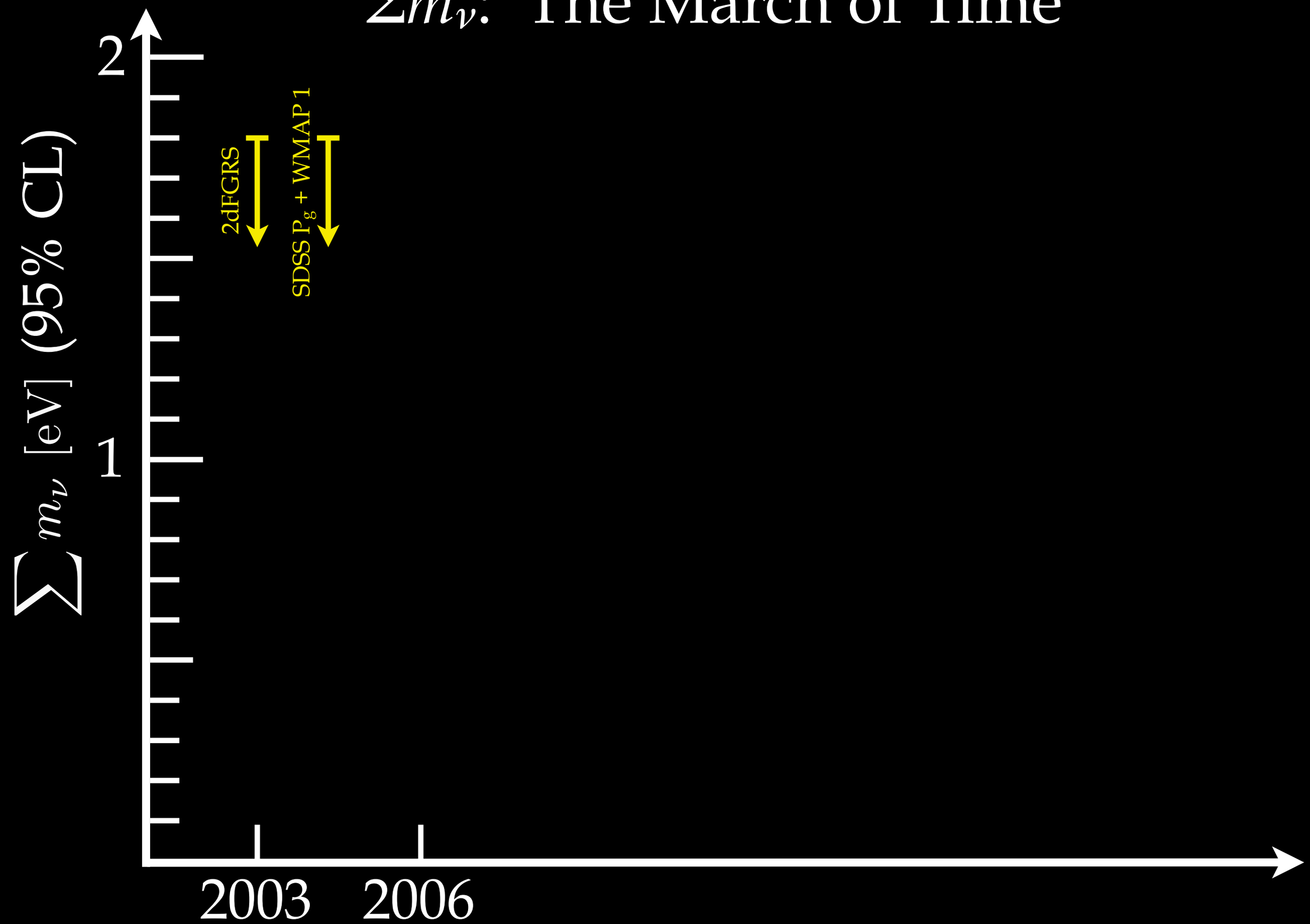

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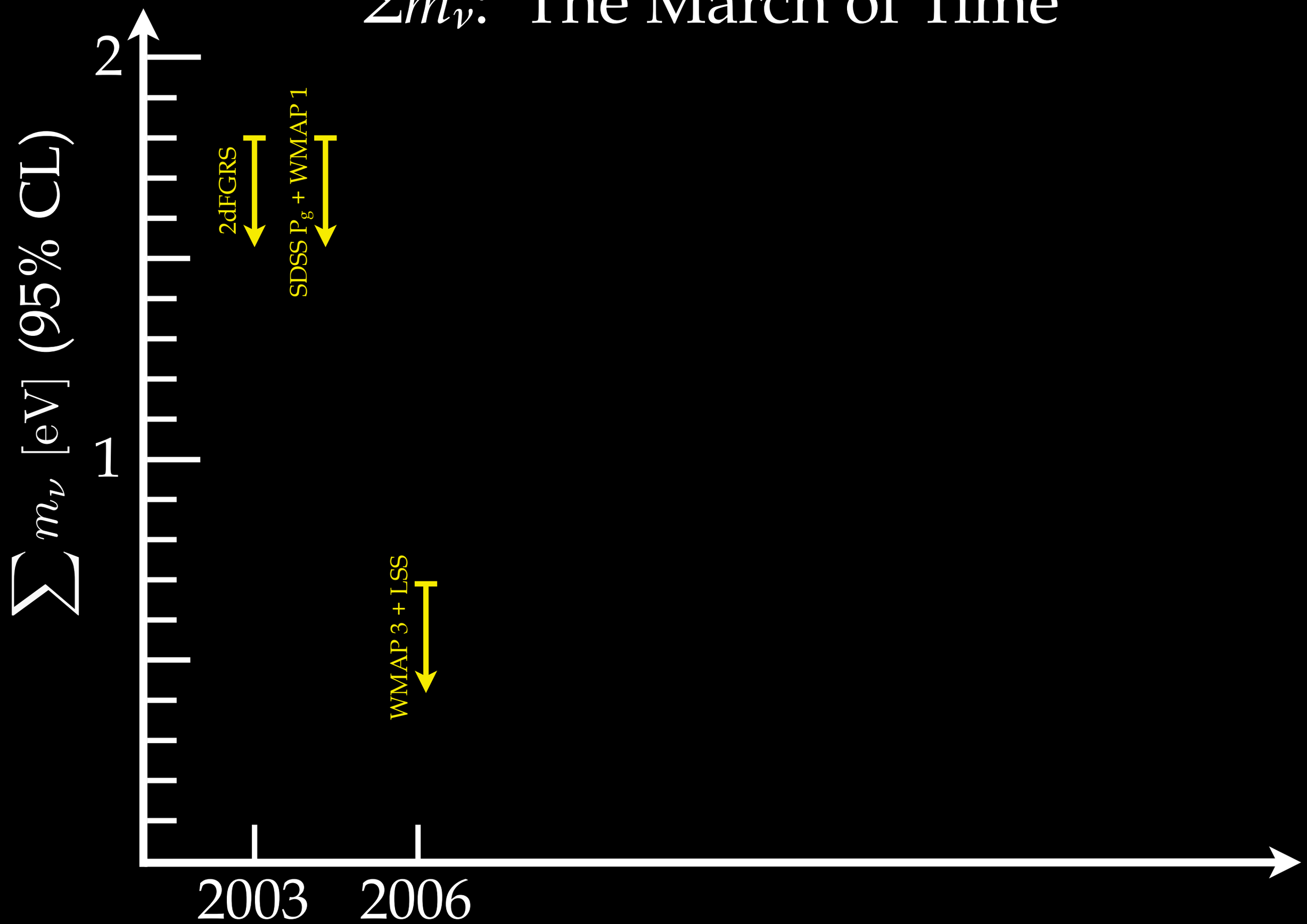

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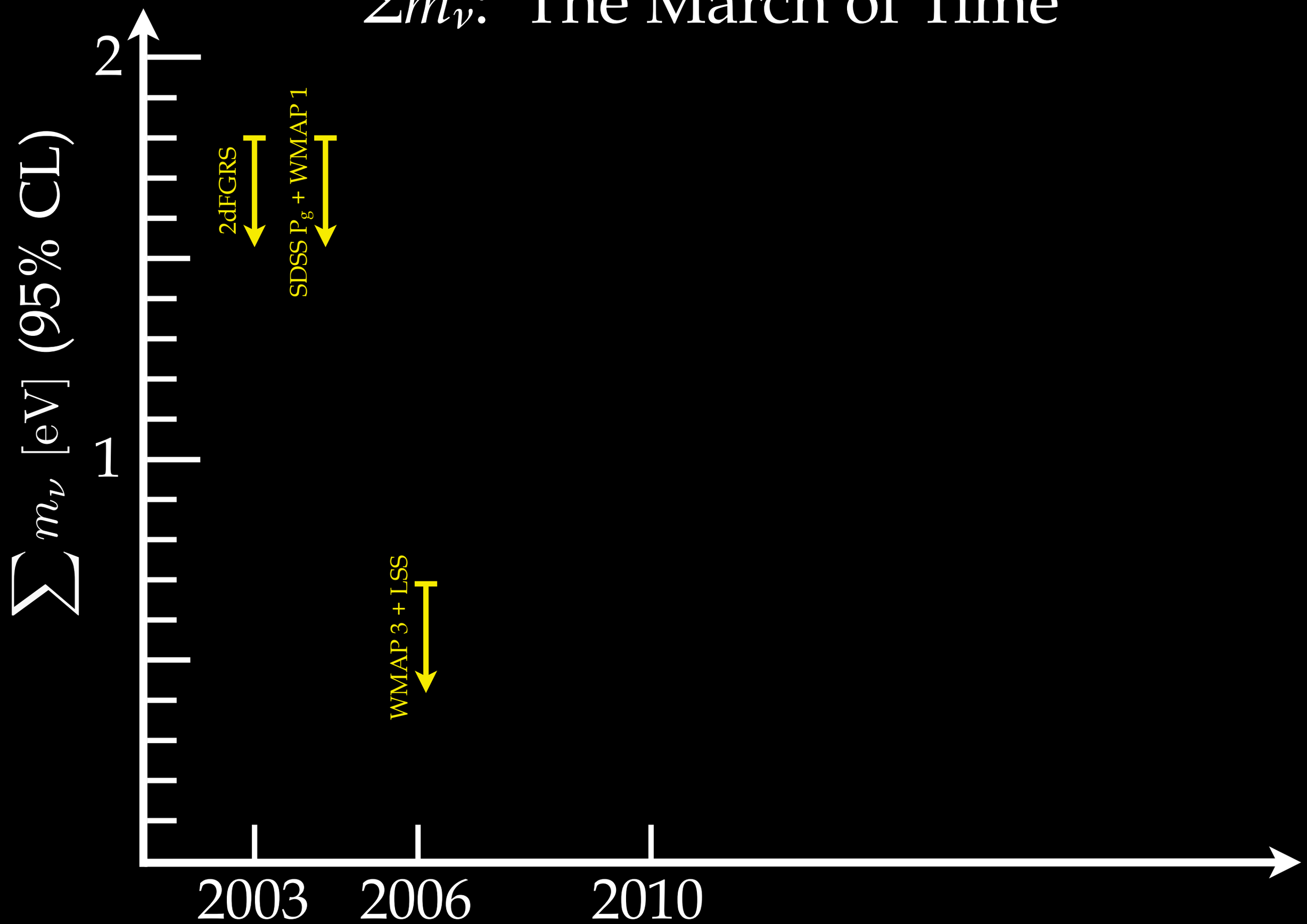

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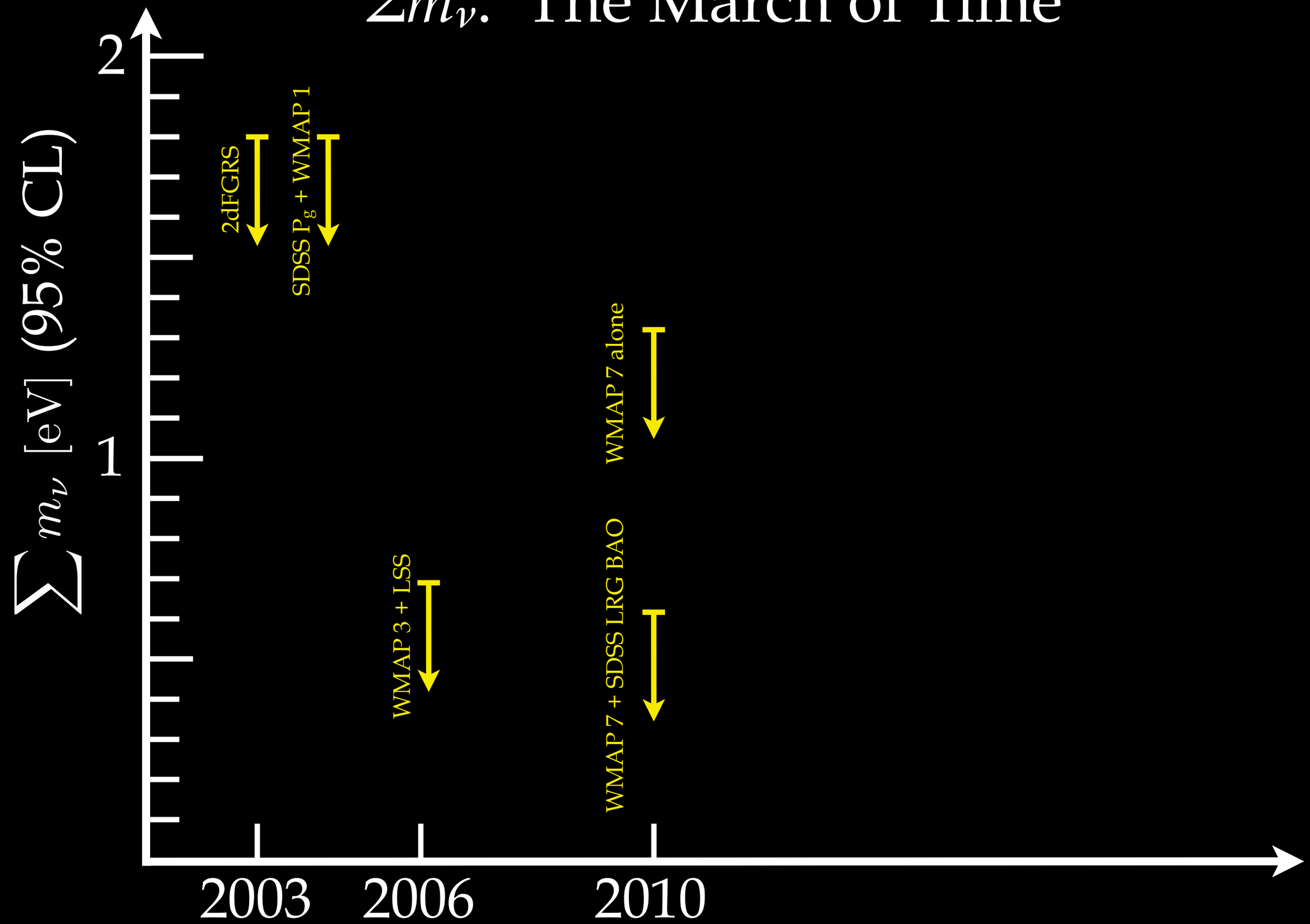

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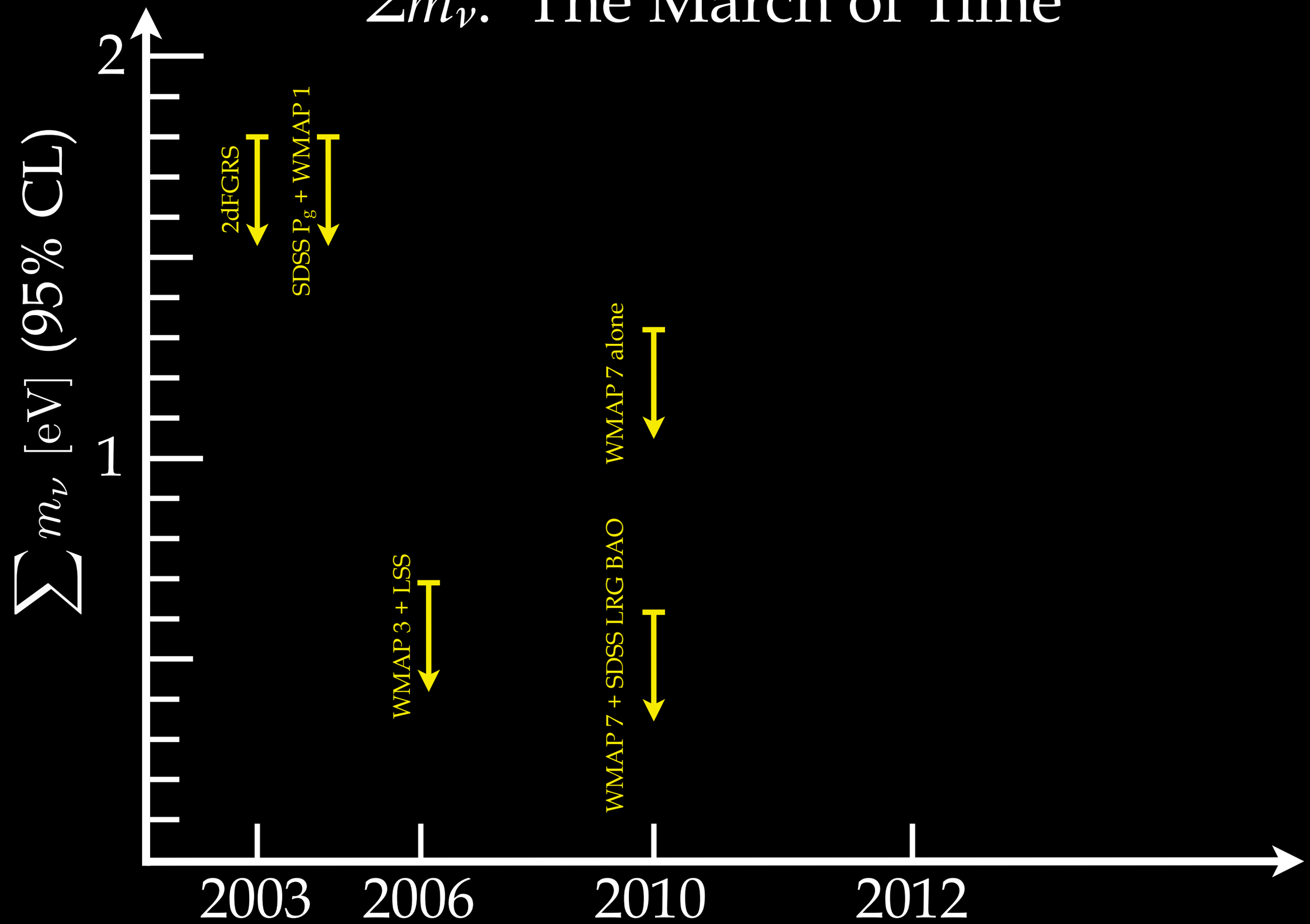

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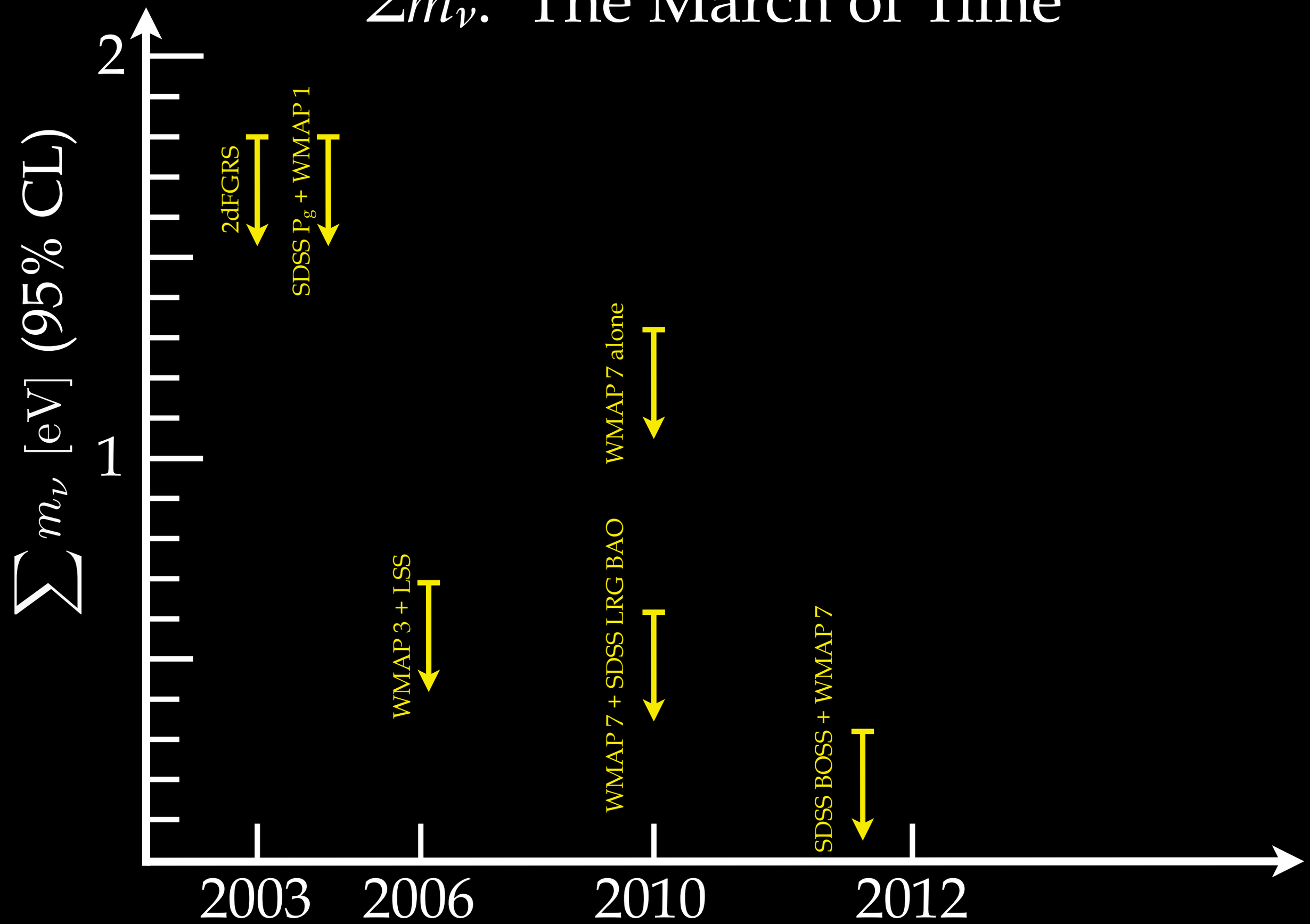

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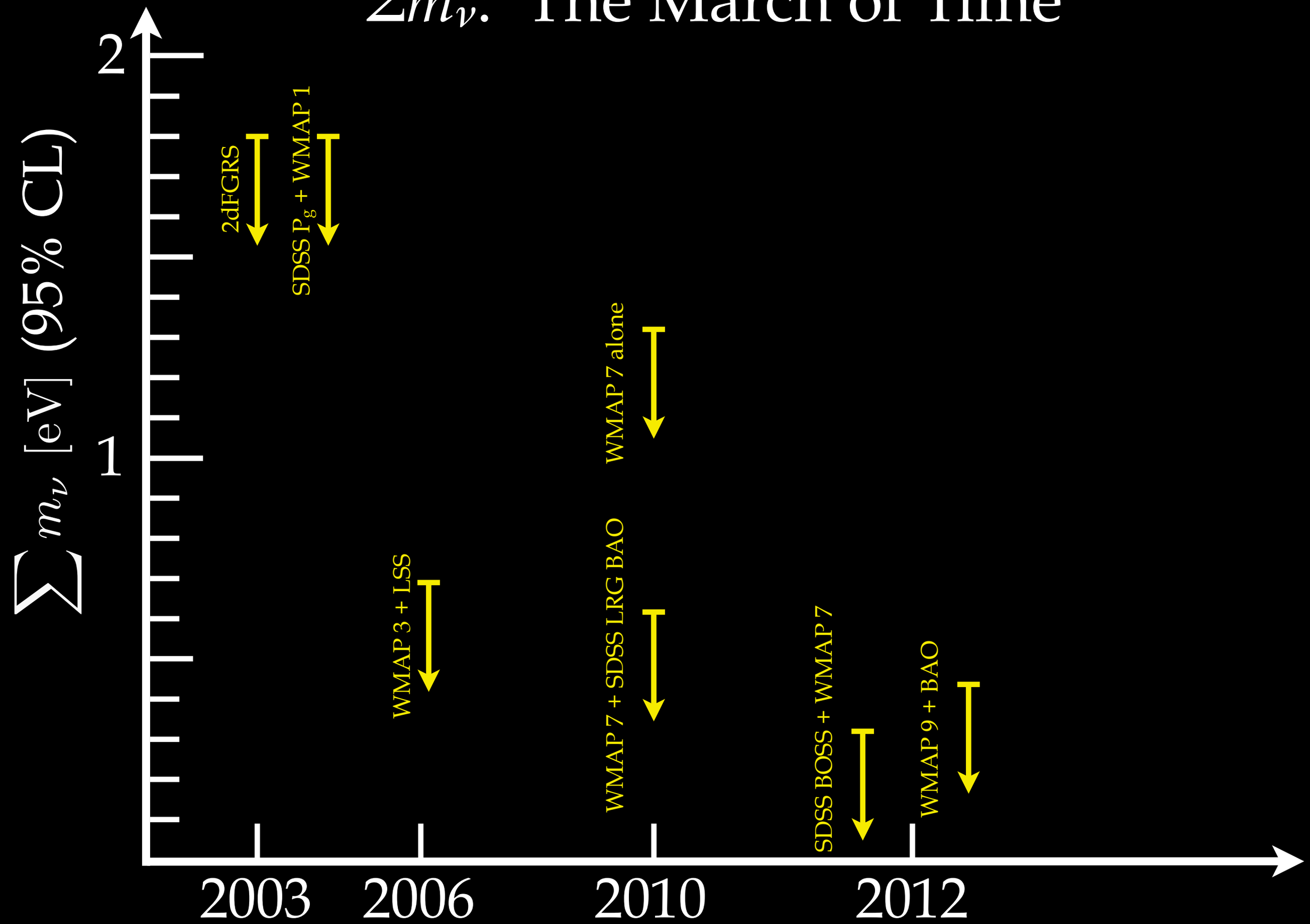

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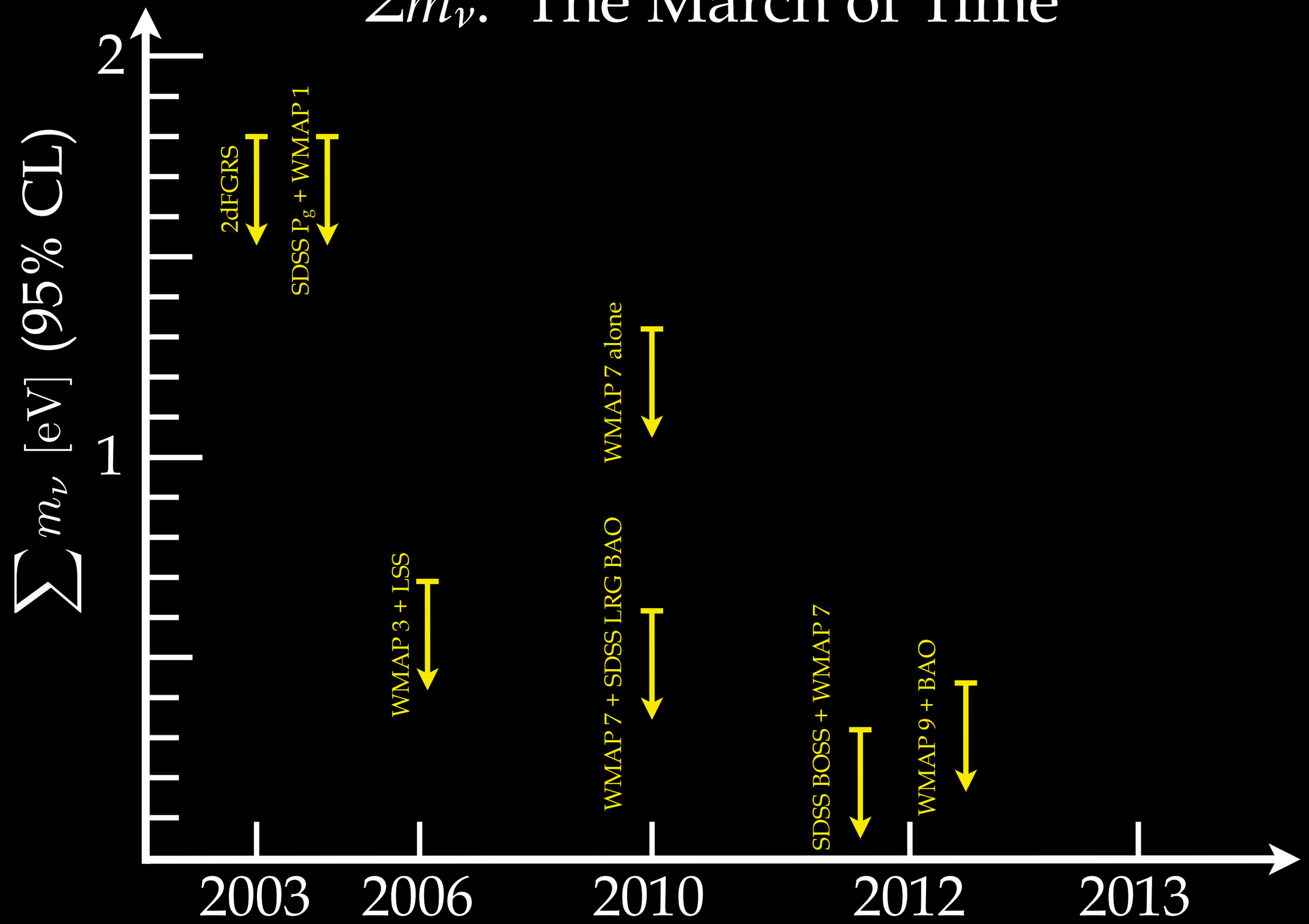

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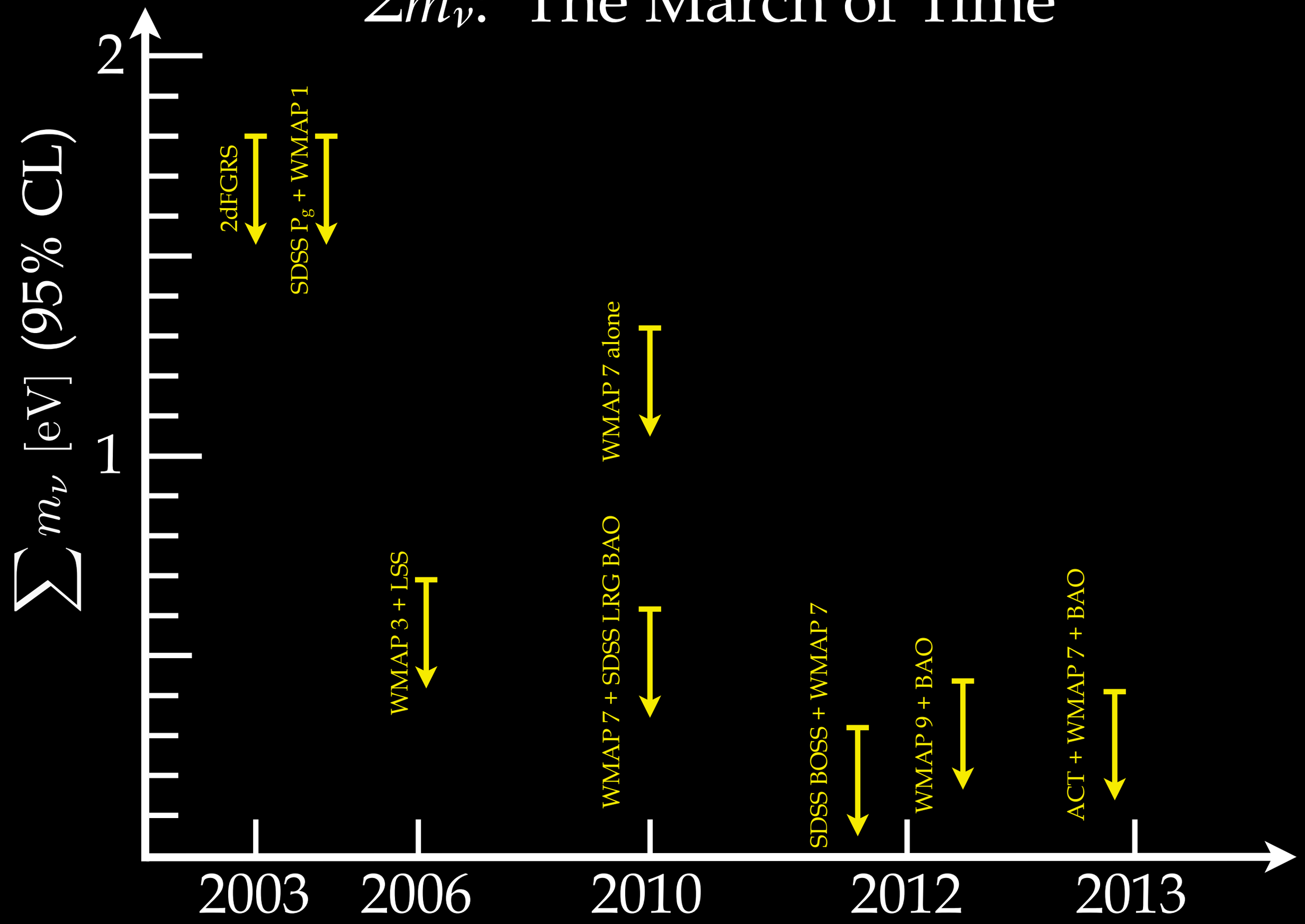

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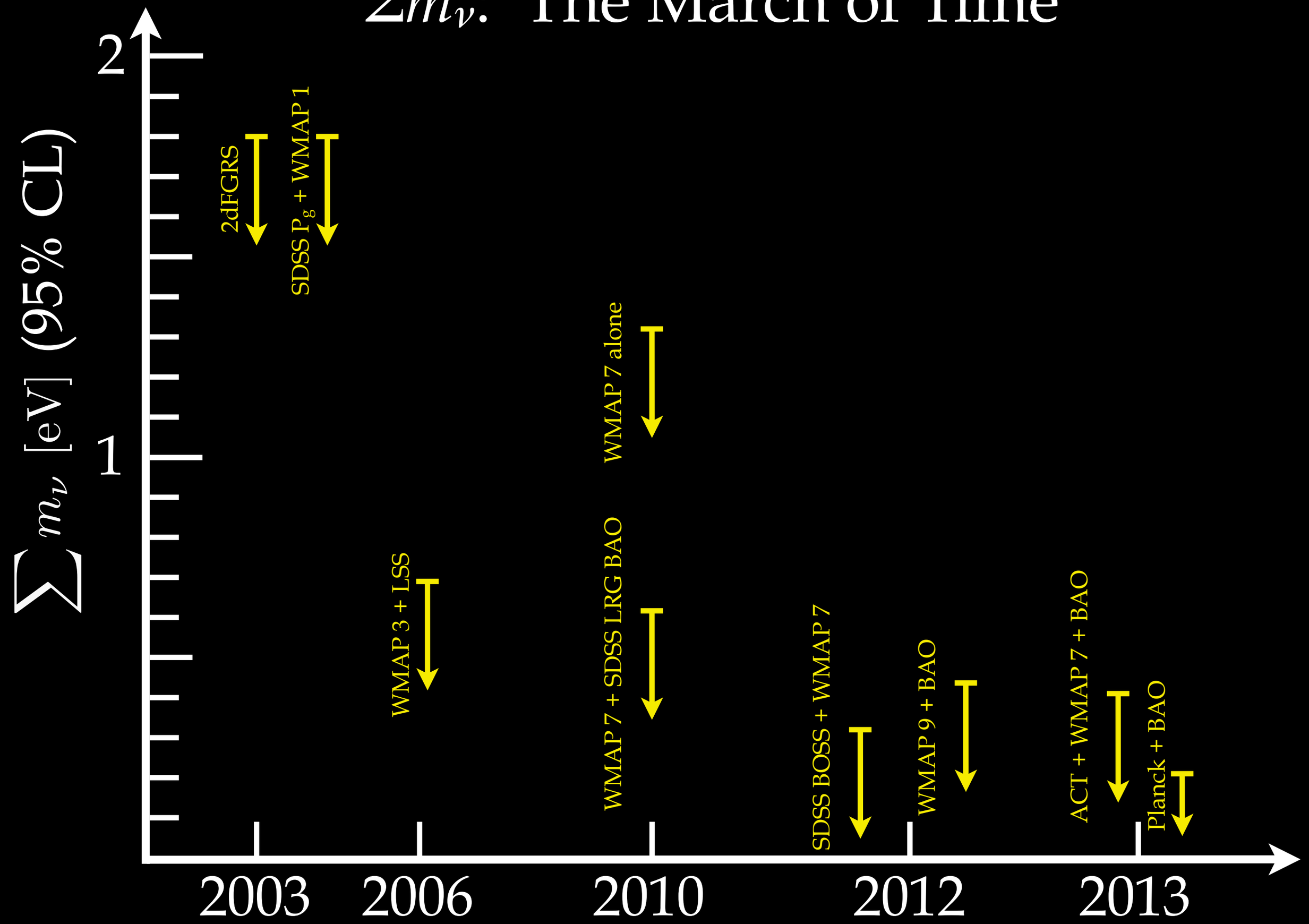

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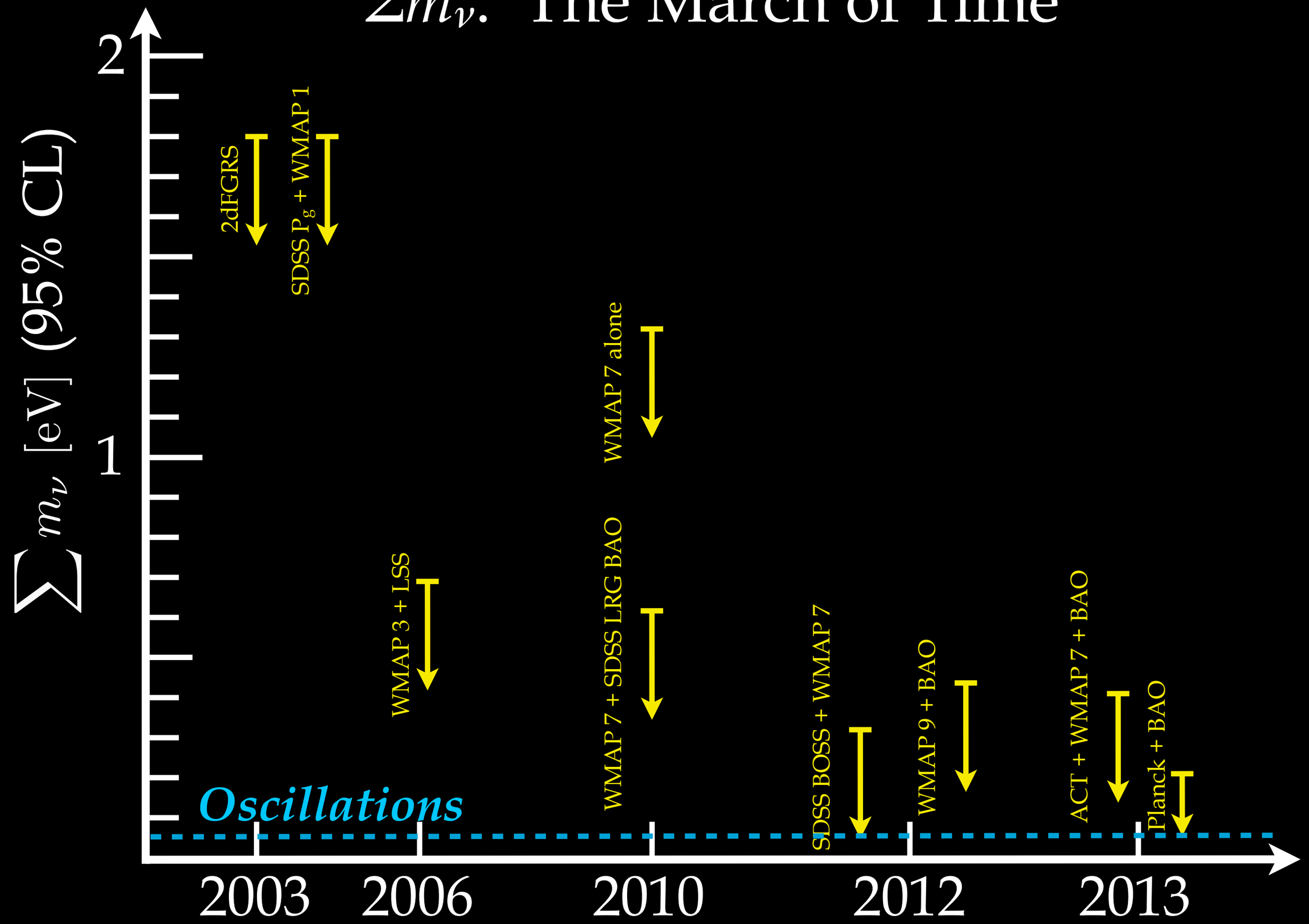
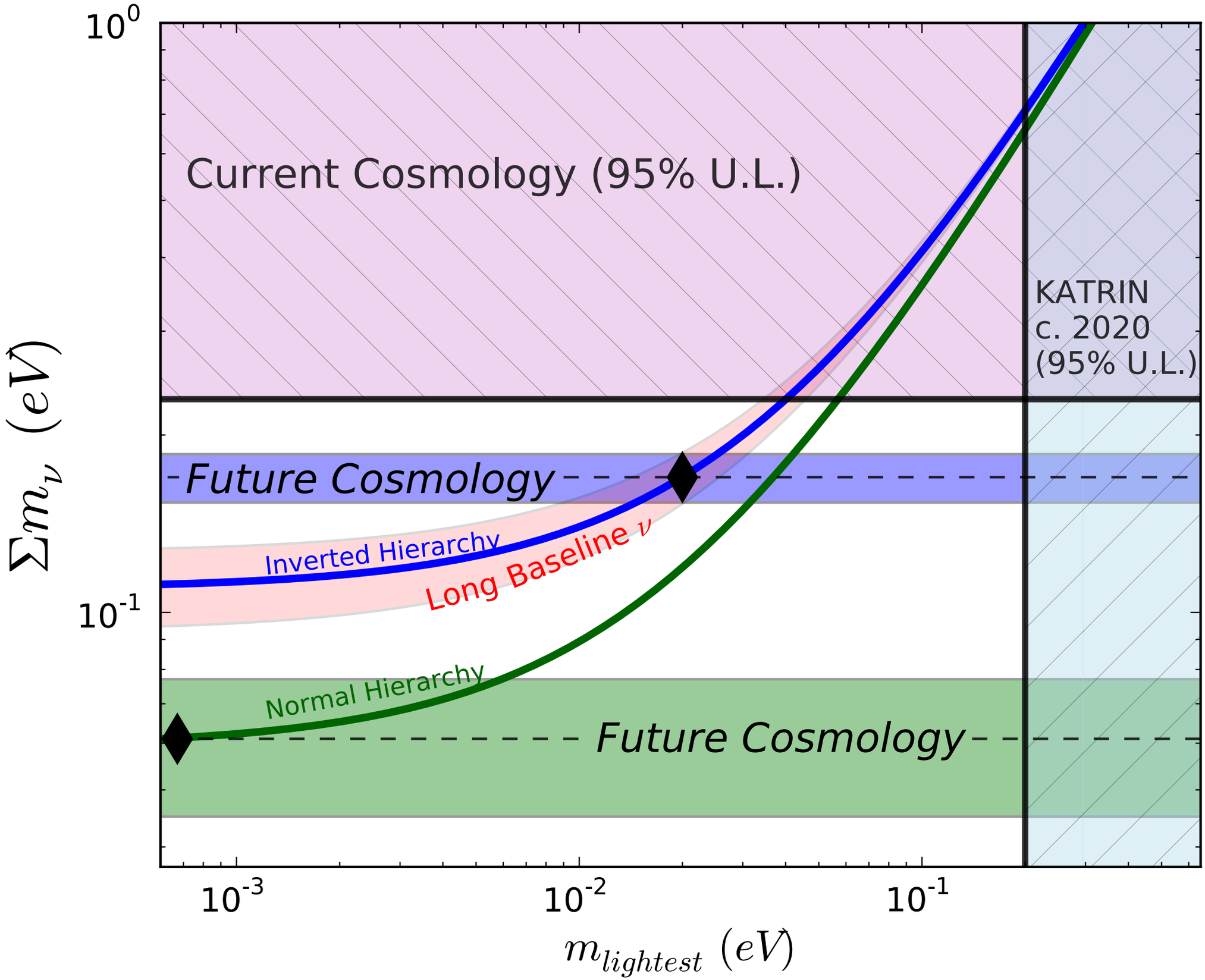
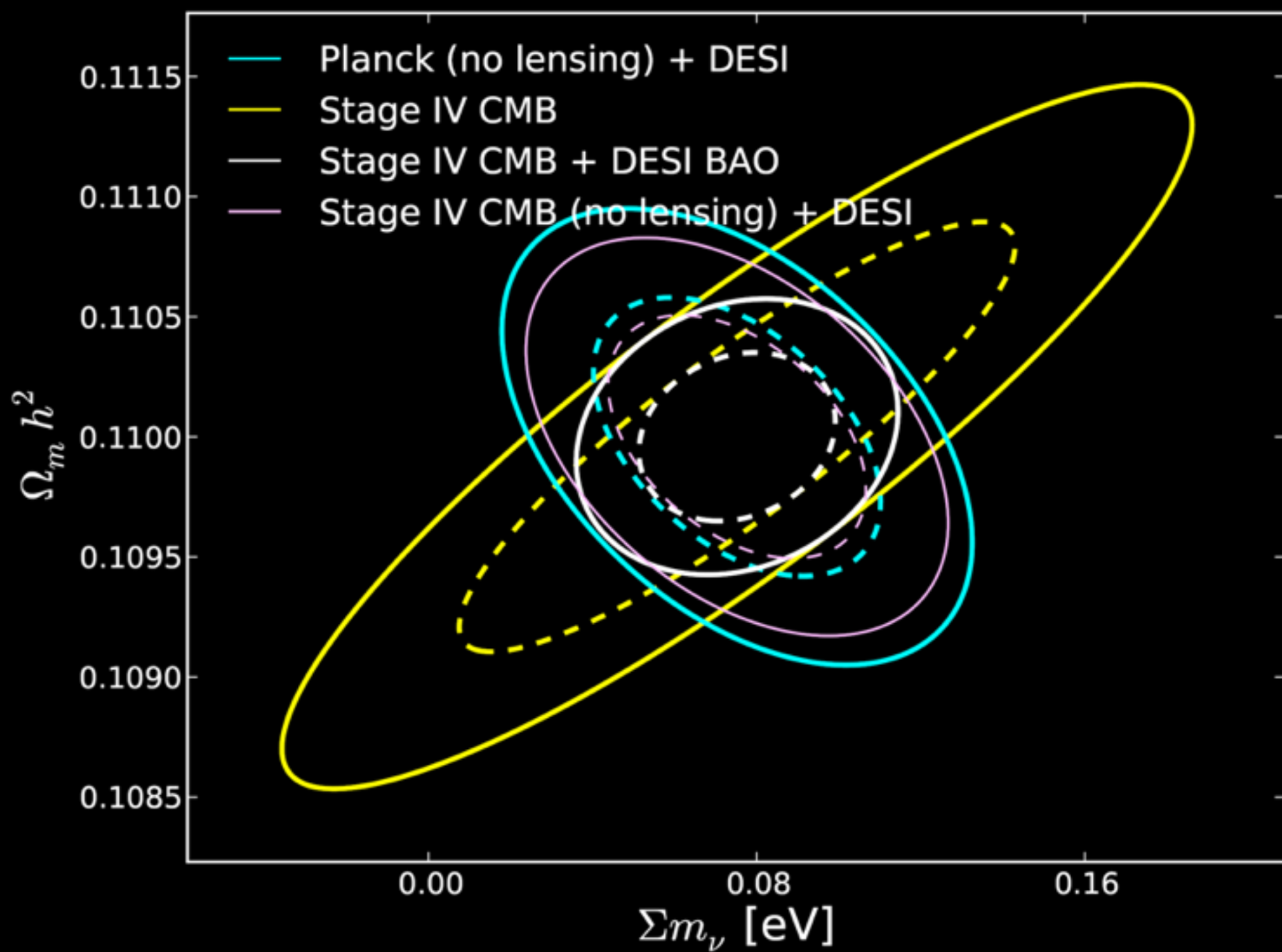


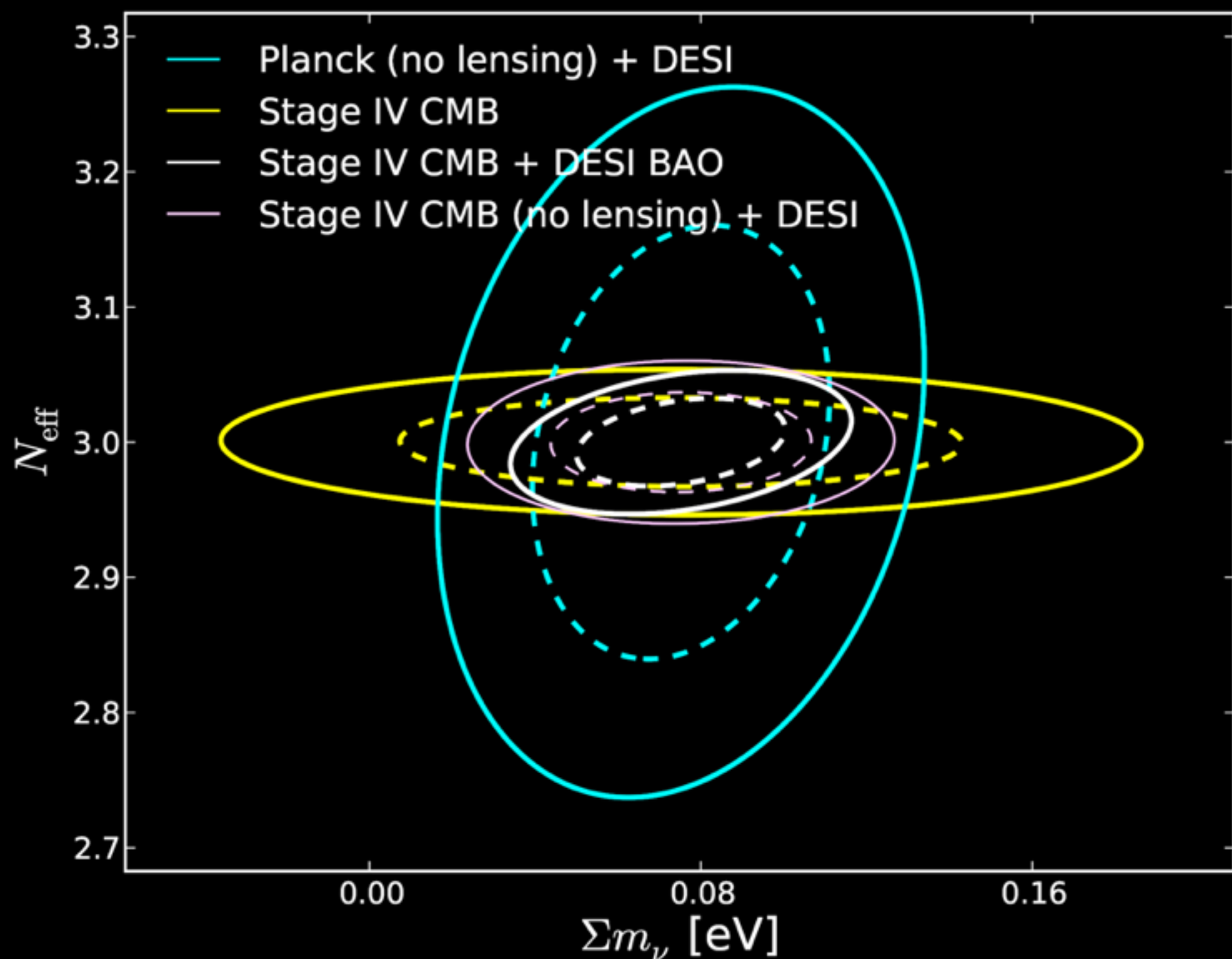
Cosmological & Laboratory Complementarity



CMB & LSS Complementarity: Parameter Degeneracy



Stage IV CMB + DESI: Σm_ν vs. $N_{\rm eff}$



Forecast Sensitivities

	$\sigma(\Sigma m_\nu)$	$\sigma(N_{\rm eff})$
Galaxy Clustering (current CMB):		
Planck + BOSS BAO	100	0.18
Planck + BOSS galaxy clustering	46/68	0.14/0.17
Planck + eBOSS BAO	97	0.18
Planck + eBOSS galaxy clustering	36/52	0.13/0.16
Planck + DESI BAO	91	0.18
Planck + DESI galaxy clustering	**17/24**	0.08/0.12
CMB Lensing (current galaxy clustering):		
Stage-IV CMB	45	**0.021**
Stage-IV CMB + BOSS BAO	**25**	0.021
CMB Lensing + Galaxy clustering:		
Stage-IV CMB + eBOSS BAO	23	0.021
Stage-IV CMB + DESI BAO	**16**	0.020
Stage-IV CMB no lensing + DESI galaxy clustering	15/20	0.022/0.024
Galaxy Weak Lensing:		
Planck + LSST	23	0.07
Planck + Euclid	25	NA†

CF5 Neutrino Paper

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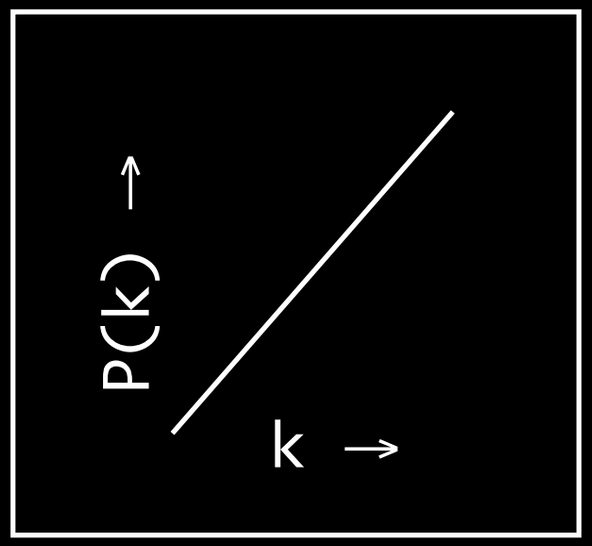
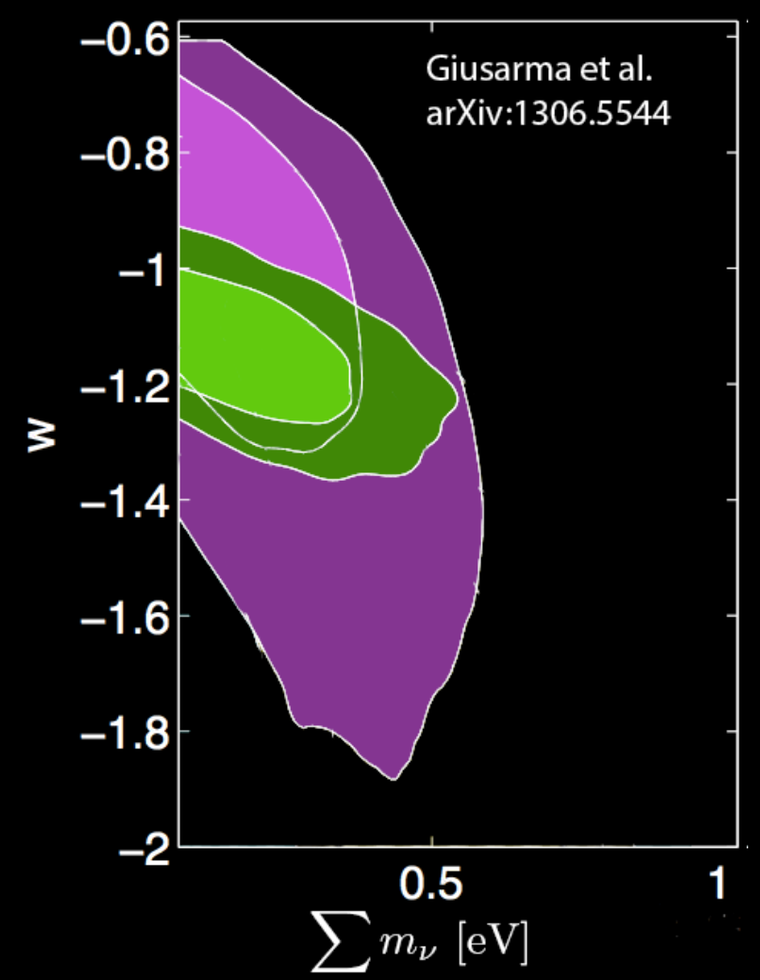
CF5 Neutrino Paper

Neutrino Mass from Cosmology: What would break if cosmology and neutrino experiment disagree?

1. Primordial power spectrum $P(k)$ is a simple power law



2. No other prevalent "non-vanilla" cosmological parameters and physics: w, N_{eff}, modified gravity...



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- **What if we do not detect the minimal model?**
  If the minimal neutrino sector, with Σm_ν = 58 meV and N_{eff} = 3.046, is ***not*** *robustly detected, it would imply something is "broken" in another aspect or aspects of cosmology, including possibly:* non-constant dark energy, a non-power-law primordial perturbation spectrum, extra particle or radiation species, non-zero curvature, as well as other possibilities, e.g., a nonthermal cosmological neutrino background.

Backups

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)

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