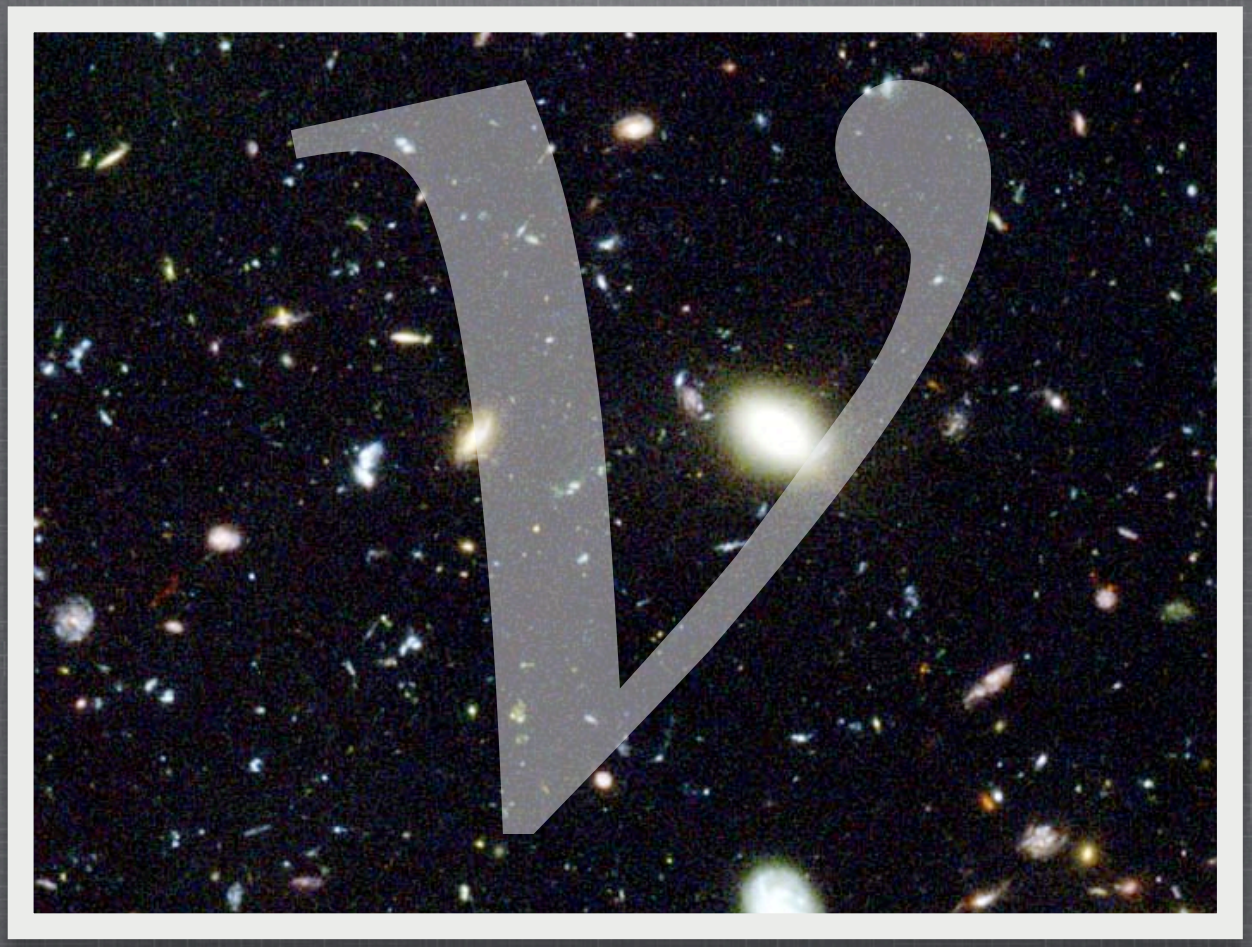
NEUTRINOS AND FUTURE CONCORDANCE COSMOLOGIES



Neutrino 2008 / Richard Easther (Yale)

INTRODUCTION...

- Integrated History of the Universe...
- Probes:
  - CMB
  - Large scale structure
  - 21 cm
- Summary...

Cosmology: Overview

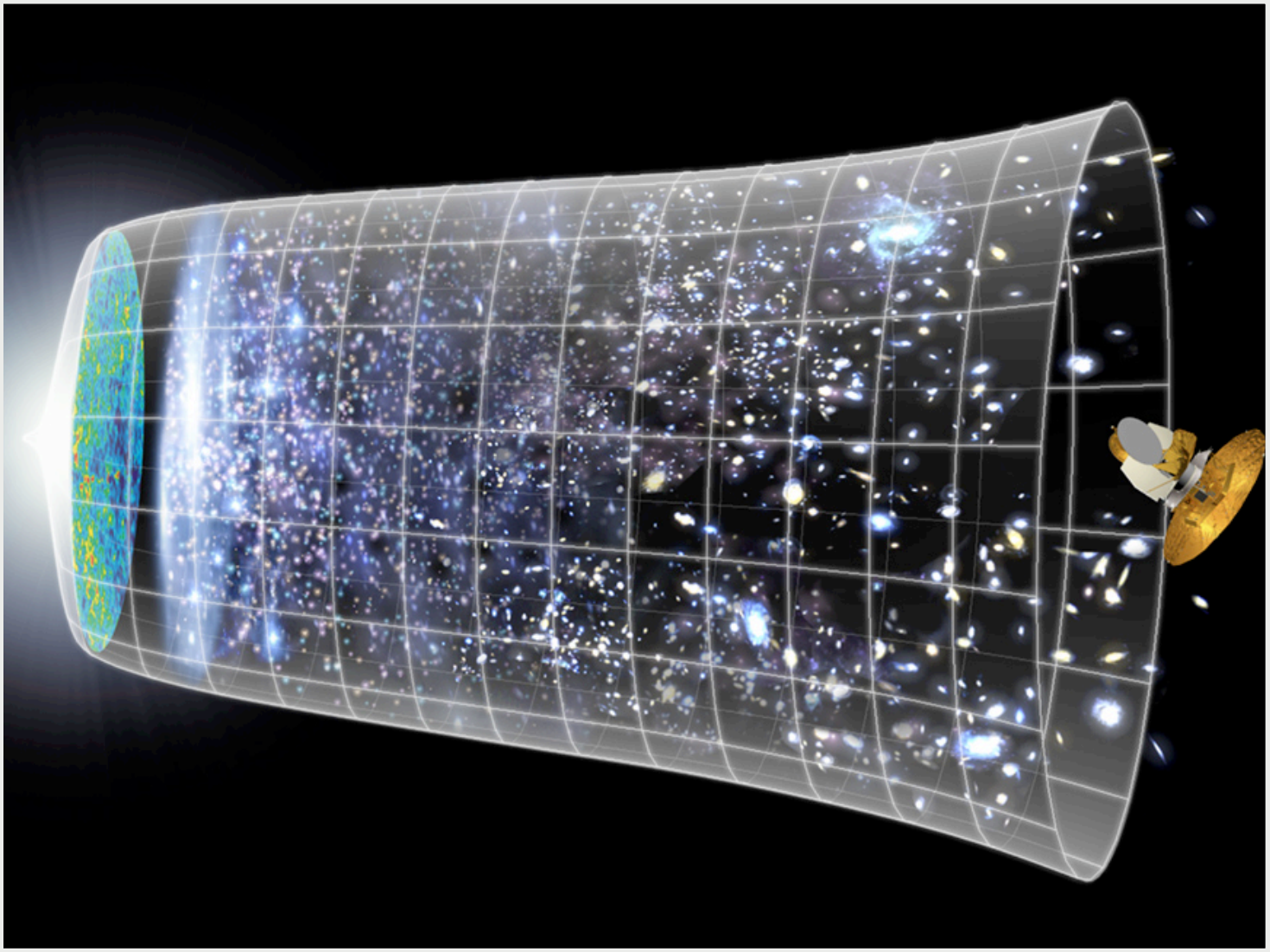


Image: NASA

Cosmology: Overview

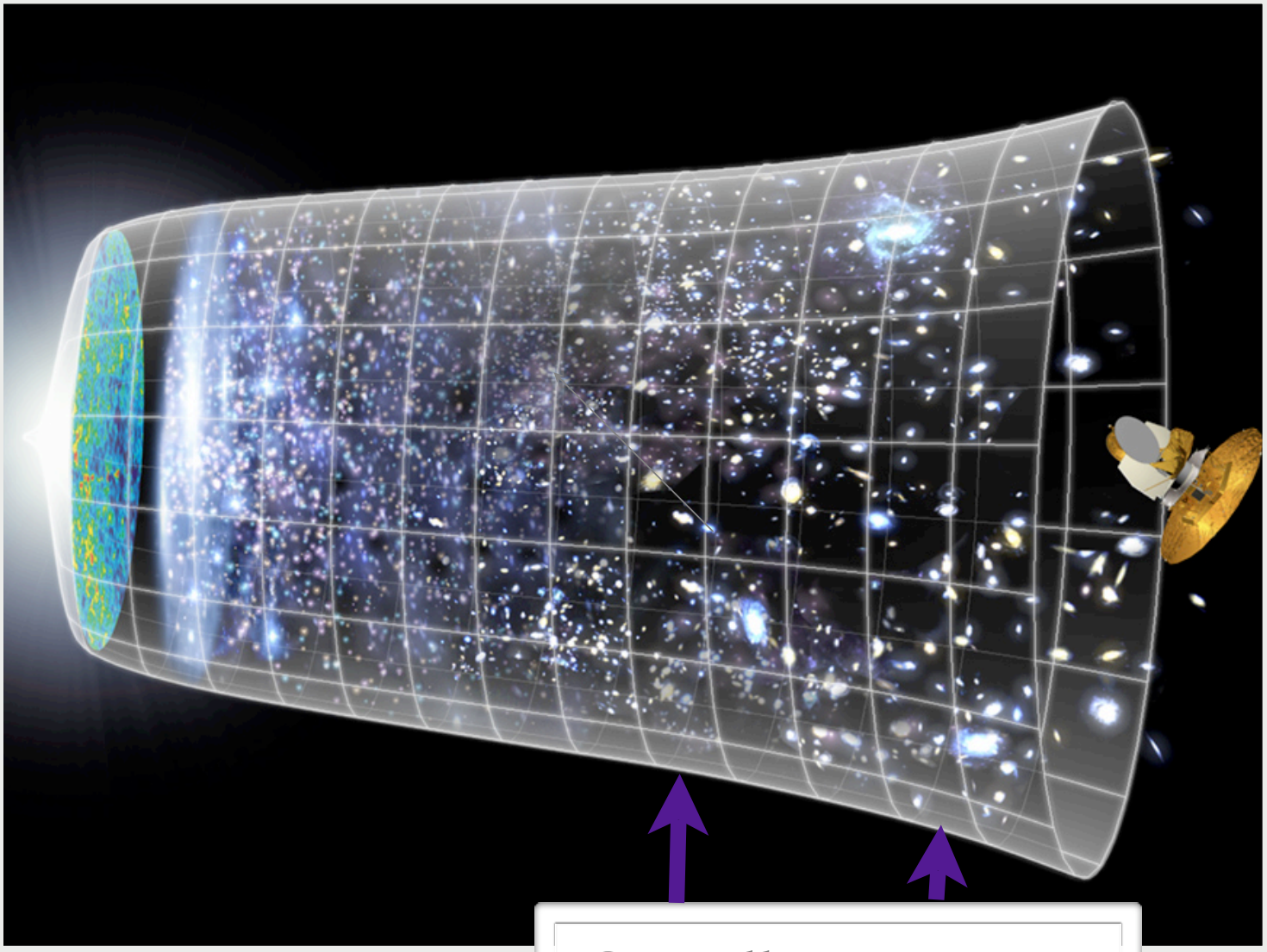


Image: NASA

Cosmology: Overview

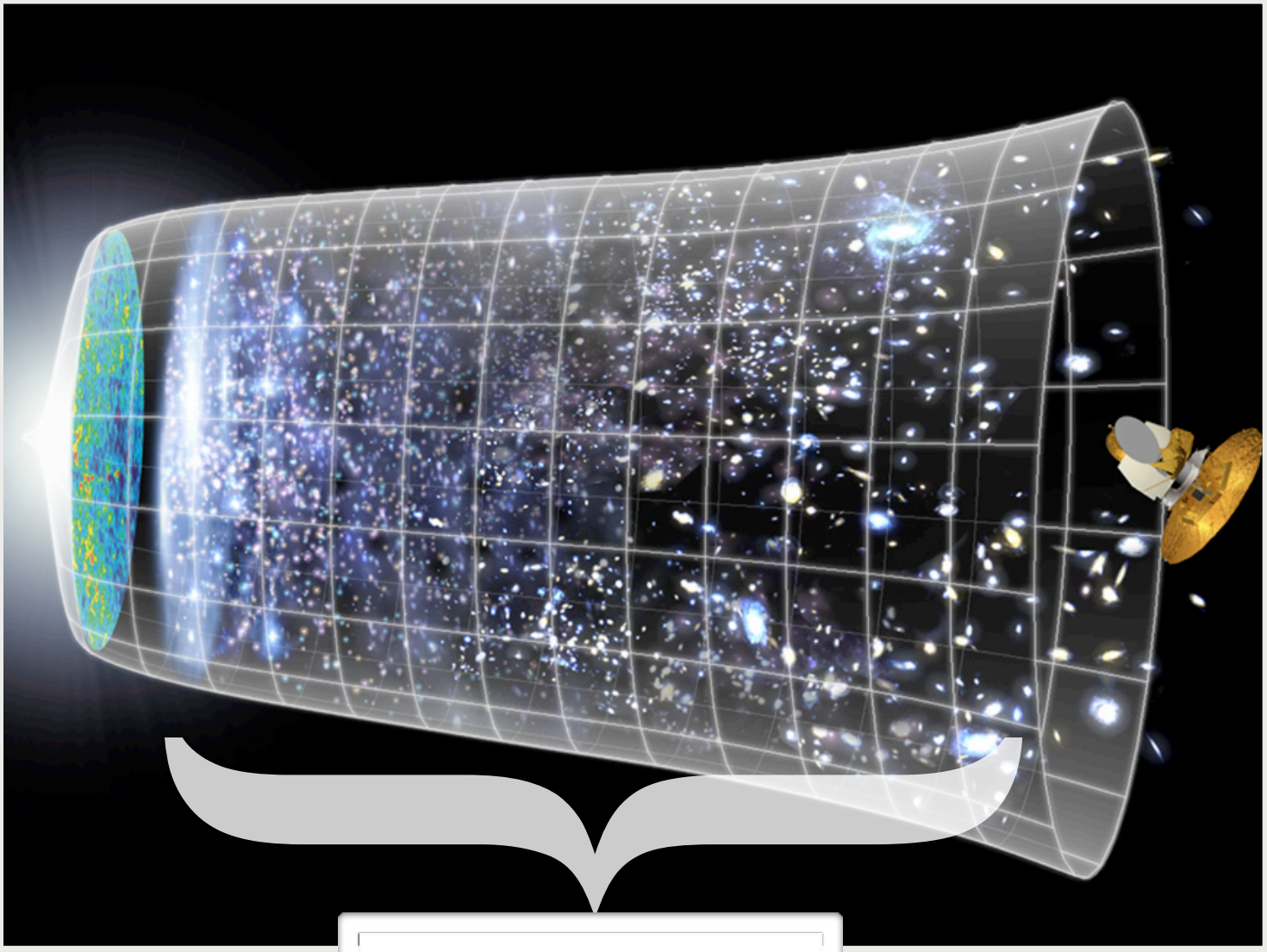
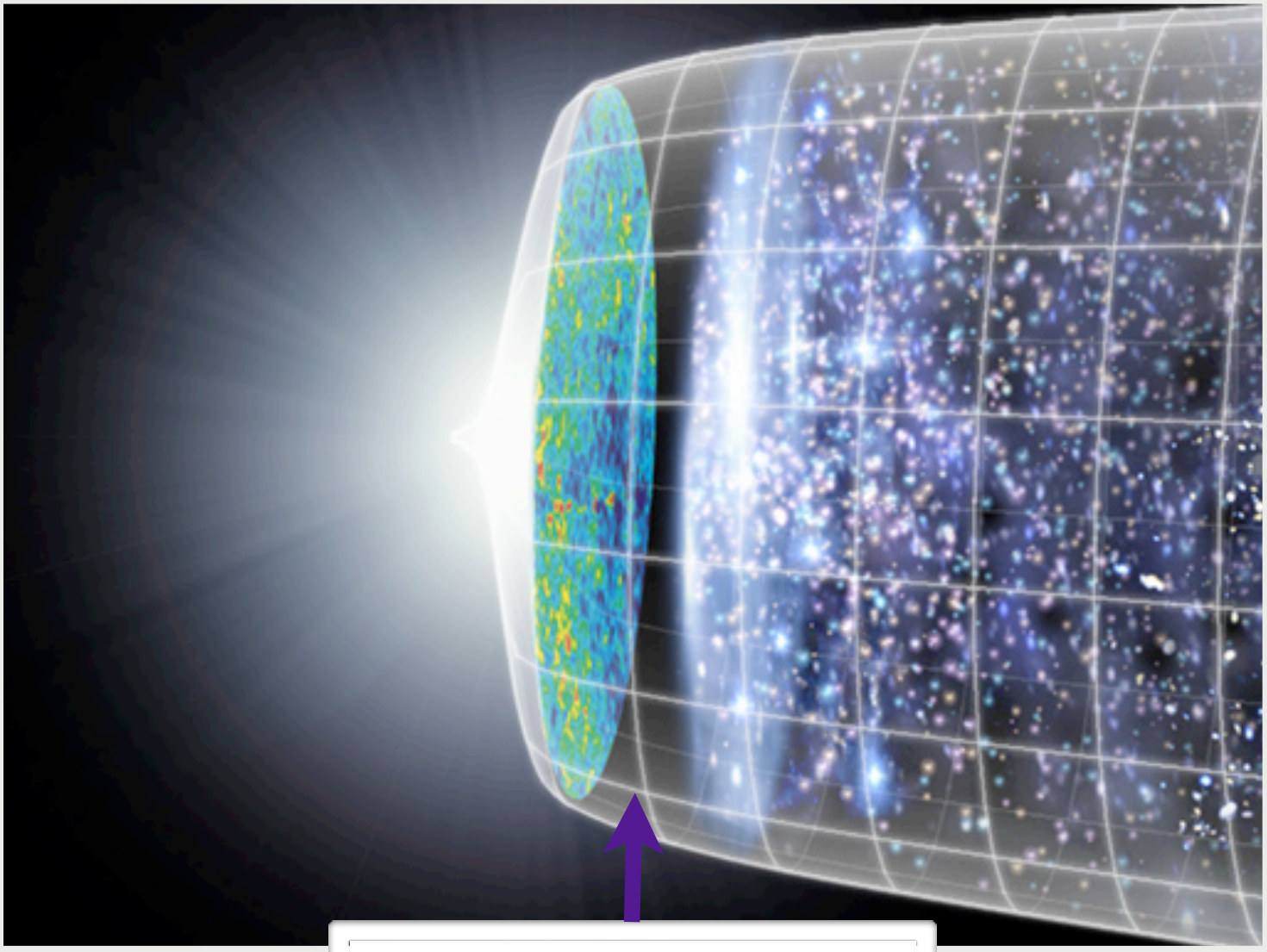


Image: NASA

Cosmology: Overview



Dark Ages...

Image: NASA

Cosmology: Overview

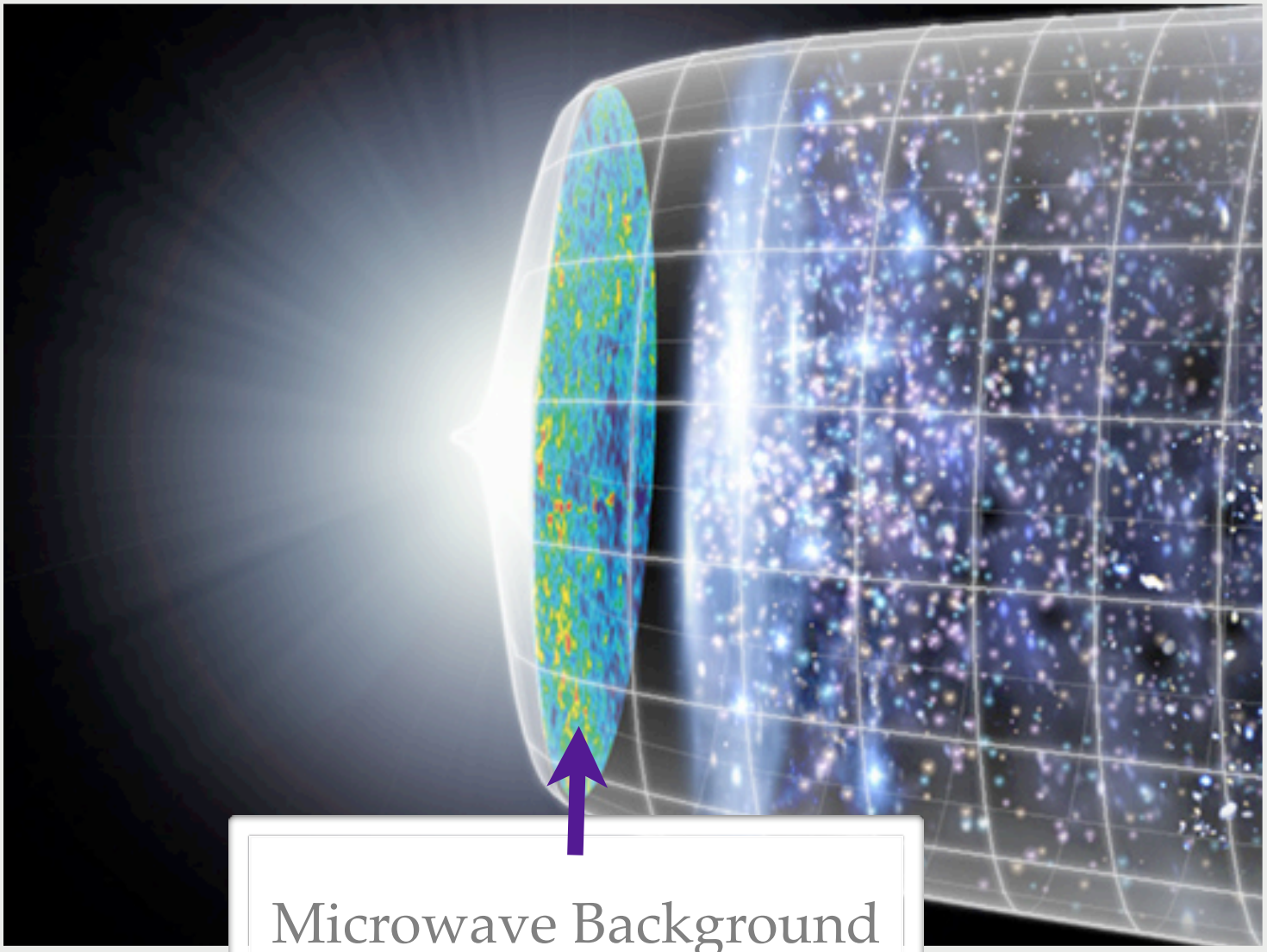


Image: NASA

Cosmology: Overview

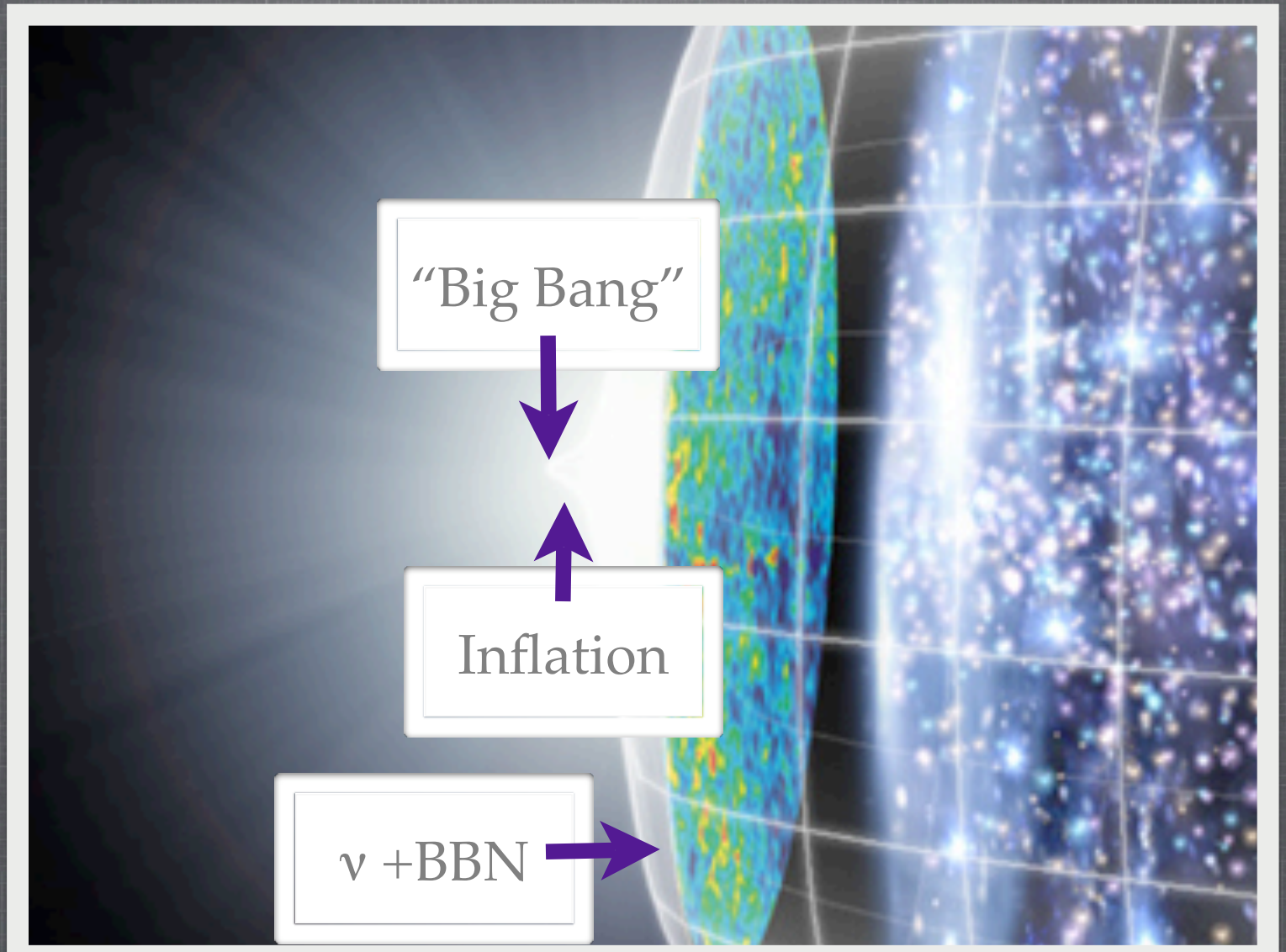


Image: NASA

CONCORDANCE COSMOLOGY

Ω_b	Baryon fraction (Mass known, #??)	Baryogenesis (? - GUT, Electroweak?)
Ω_{CDM}	Dark matter (Mass ??, #??)	TeV Scale physics?? Supersymmetry? LHC?
Ω_Λ	Cosmological constant	Quantum Gravity Tooth fairy?
τ	Reionization	First stars (gastrophysics, nuclear physics)
h	Hubble's "constant"	When we are looking
A_s, n_s	Primordial Perturbations	Inflation GUT/string physics?

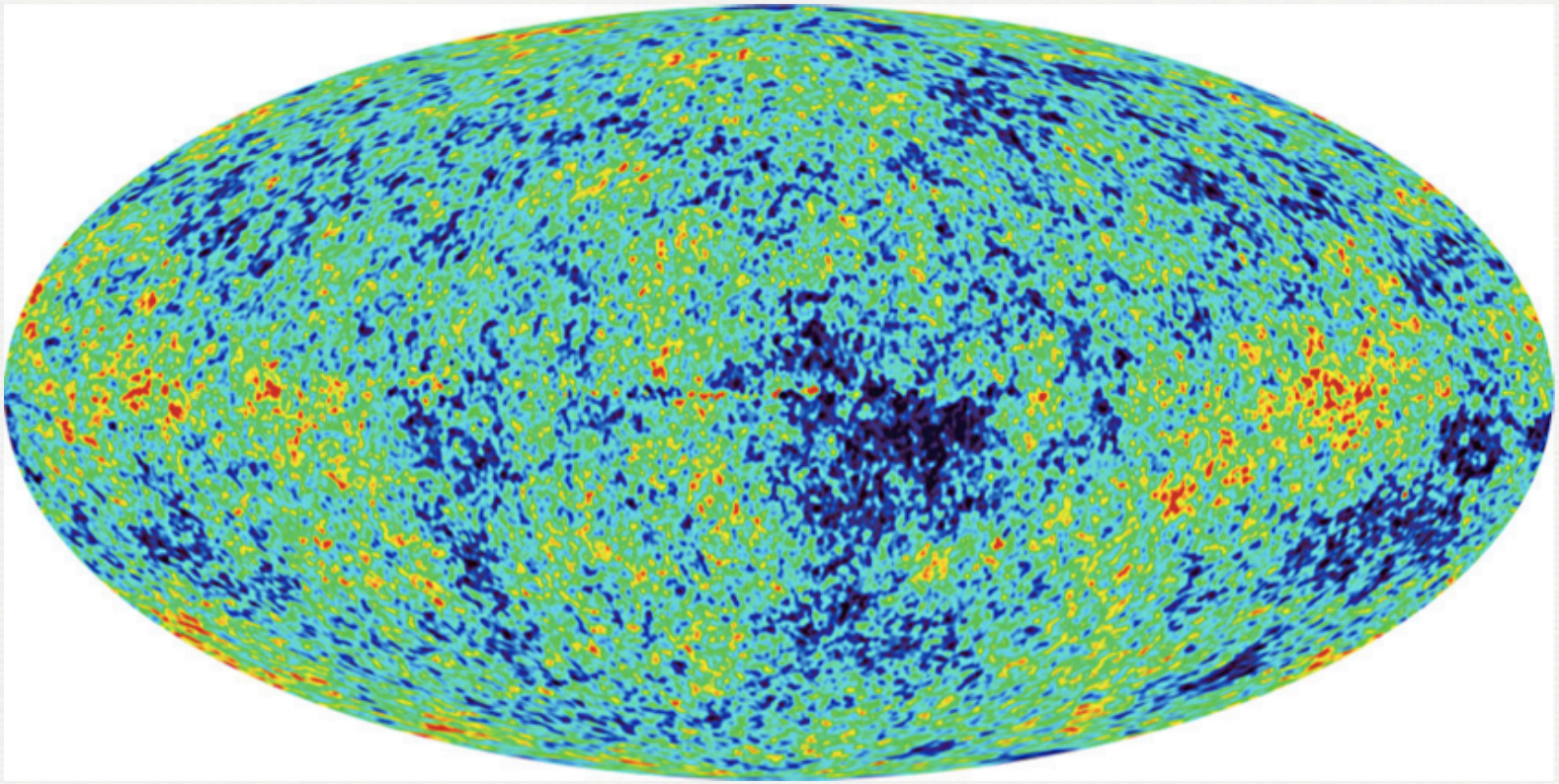
THE FUTURE...

- Parameter set will *expand*
  - Neutrino sector! Scale dependence of n? Dark energy parameters? Tensor modes? Helium fraction? Curvature? Secondary anisotropies?
- Parameter set will *shrink*
  - Neutrino masses from experiments?
  - Recombination observed directly in 21cm?
  - Specific *models* of inflation?

NUMBERS…

- Photons: $T_\gamma = 2.726\ K = 2.35\ 10^{-4}\ eV$ (measured)
  - Massless ν: $T_\nu \sim 1.9K = 1.7\ 10^{-4}\ eV$ (inferred)
- Photons at z = 1,089: $T_\gamma = 2.97\ 10^3\ K = 0.255\ eV$
  - Massless ν: $T_\nu \sim 2.07\ 10^3\ K = .17\ eV$
- Minimum $\Sigma m_\nu \sim 0.05$ eV (normal hierarchy)
- Change in equation of state as universe expands!

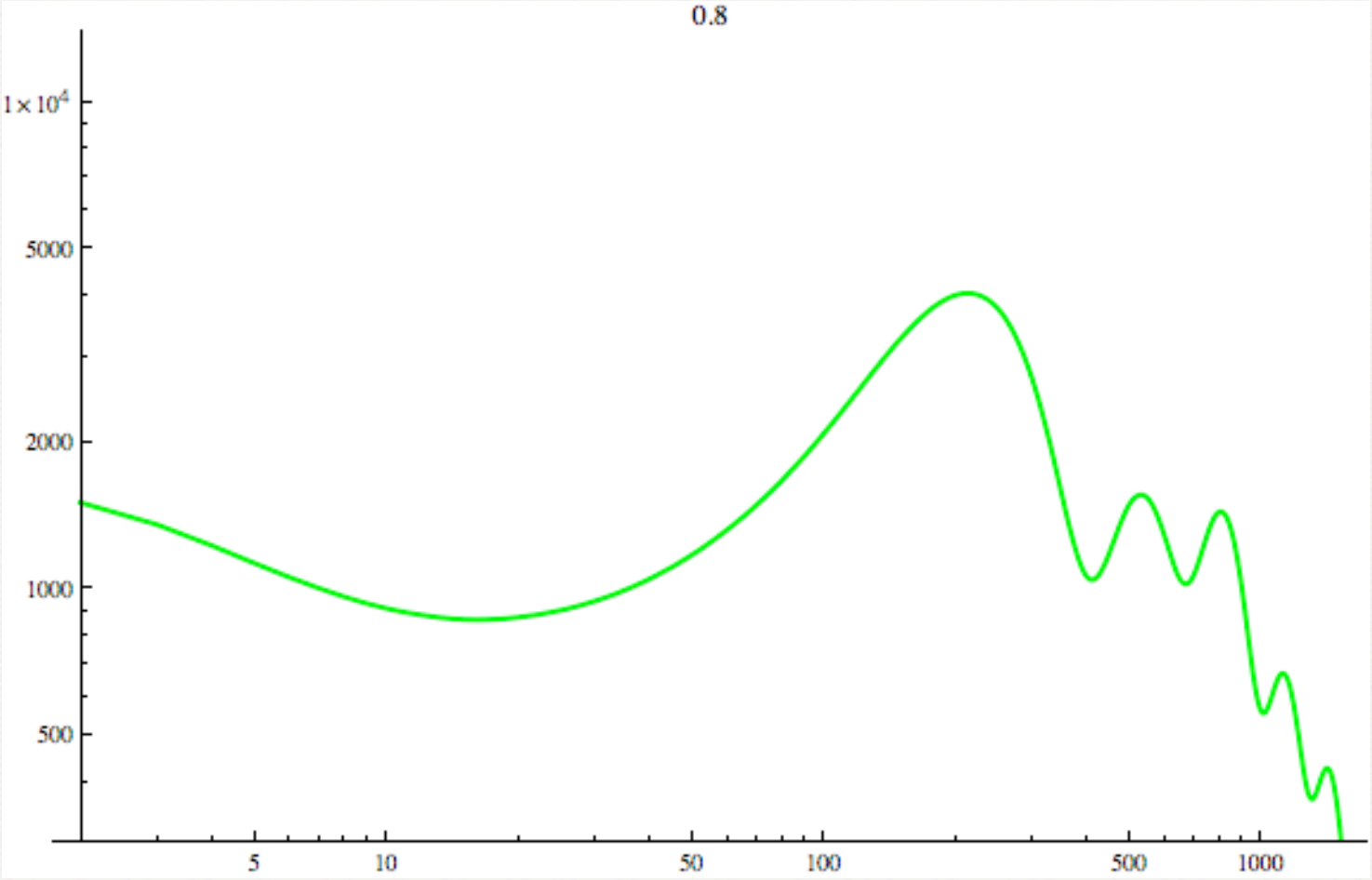
CMB: WMAP



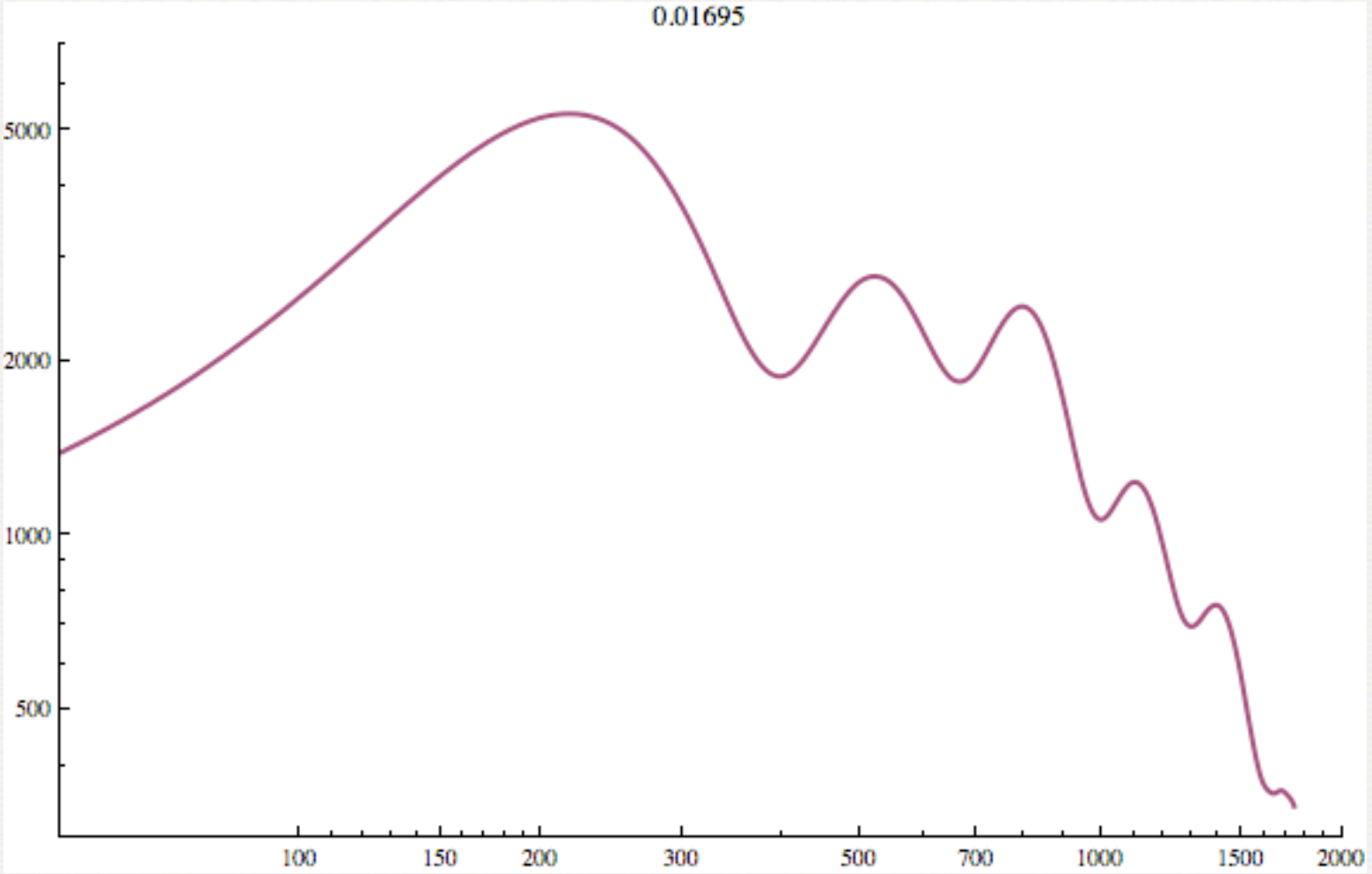
BEST FIT

- Early universe is a *simple* system
  - General relativity and *small* inhomogeneities
  - e^-, p, He nuclei, dark matter, ν, γ, also Λ, H_o and k
- Boltzmann equations
  - Beautiful and largely classical classical physics
  - Compute C_l & polarization (E and B mode)

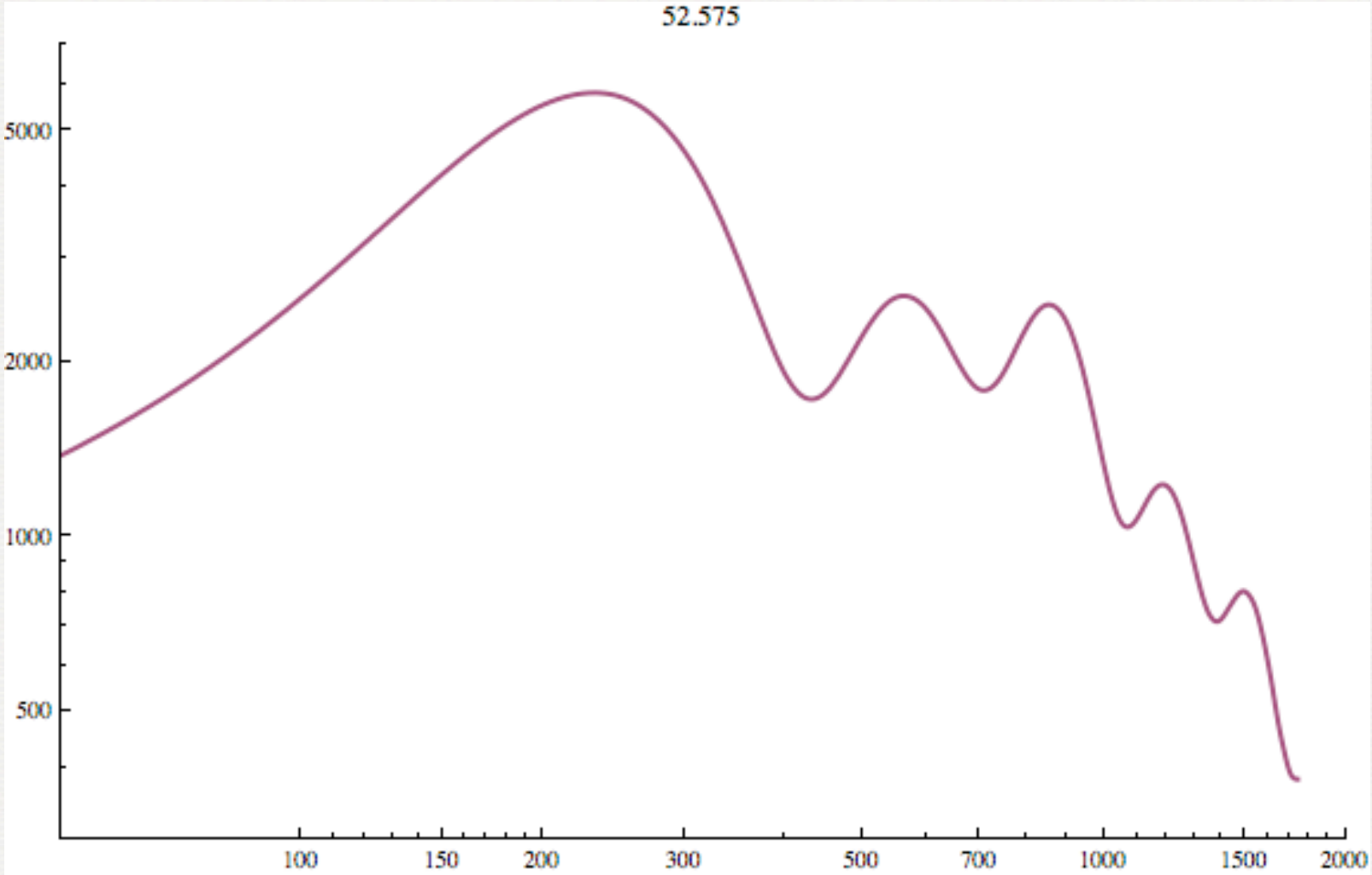
THE SPECTRAL INDEX



THE BARYON FRACTION



HUBBLE PARAMETER



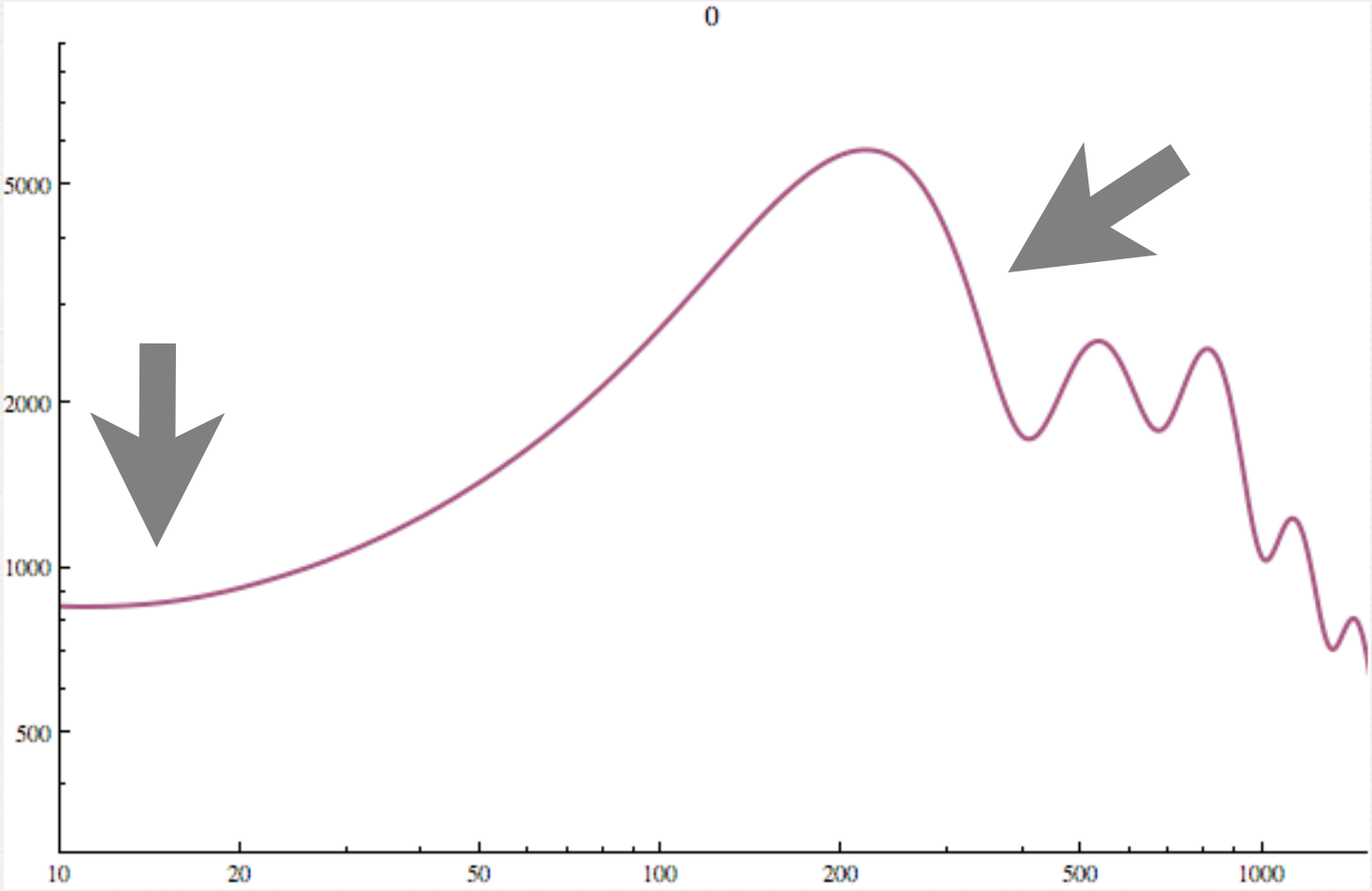
WHAT DO WE LEARN?

Class	Parameter	*WMAP* 5-year ML[a]	*WMAP*+BAO+SN ML	*WMAP* 5-year Mean[b]	*WMAP*+BAO+SN Mean
Primary	$100\Omega_b h^2$	2.268	2.263	2.273 ± 0.062	2.265 ± 0.059
	$\Omega_c h^2$	0.1081	0.1136	0.1099 ± 0.0062	0.1143 ± 0.0034
	Ω_Λ	0.751	0.724	0.742 ± 0.030	0.721 ± 0.015
	n_s	0.961	0.961	$0.963^{+0.014}_{-0.015}$	$0.960^{+0.014}_{-0.013}$
	τ	0.089	0.080	0.087 ± 0.017	0.084 ± 0.016
	$\Delta^2_{\mathcal{R}}(k_0{}^e)$	2.41×10^{-9}	2.42×10^{-9}	$(2.41 \pm 0.11) \times 10^{-9}$	$(2.457^{+0.092}_{-0.093}) \times 10^{-9}$
Derived	σ_8	0.787	0.811	0.796 ± 0.036	0.817 ± 0.026
	H_0	72.4 km/s/Mpc	70.3 km/s/Mpc	$71.9^{+2.6}_{-2.7}$ km/s/Mpc	70.1 ± 1.3 km/s/Mpc
	Ω_b	0.0432	0.0458	0.0441 ± 0.0030	0.0462 ± 0.0015
	Ω_c	0.206	0.230	0.214 ± 0.027	0.233 ± 0.013
	$\Omega_m h^2$	0.1308	0.1363	0.1326 ± 0.0063	0.1369 ± 0.0037
	$z_{\rm reion}{}^f$	11.2	10.5	11.0 ± 1.4	10.8 ± 1.4
	$t_0{}^g$	13.69 Gyr	13.72 Gyr	13.69 ± 0.13 Gyr	13.73 ± 0.12 Gyr

WMAP 5 +

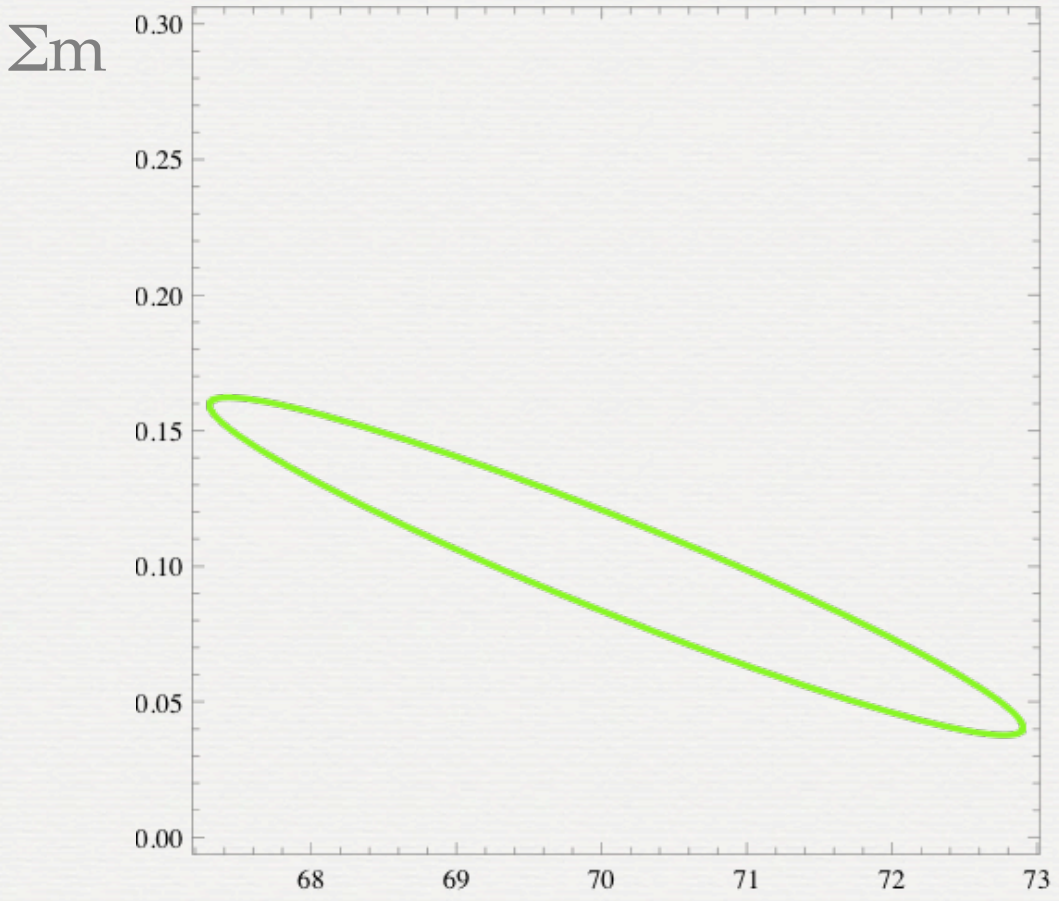
- Count the significant figures...
  - Cosmology graduated from back of the envelope!

TOTAL NEUTRINO MASS



ERROR FORECASTS

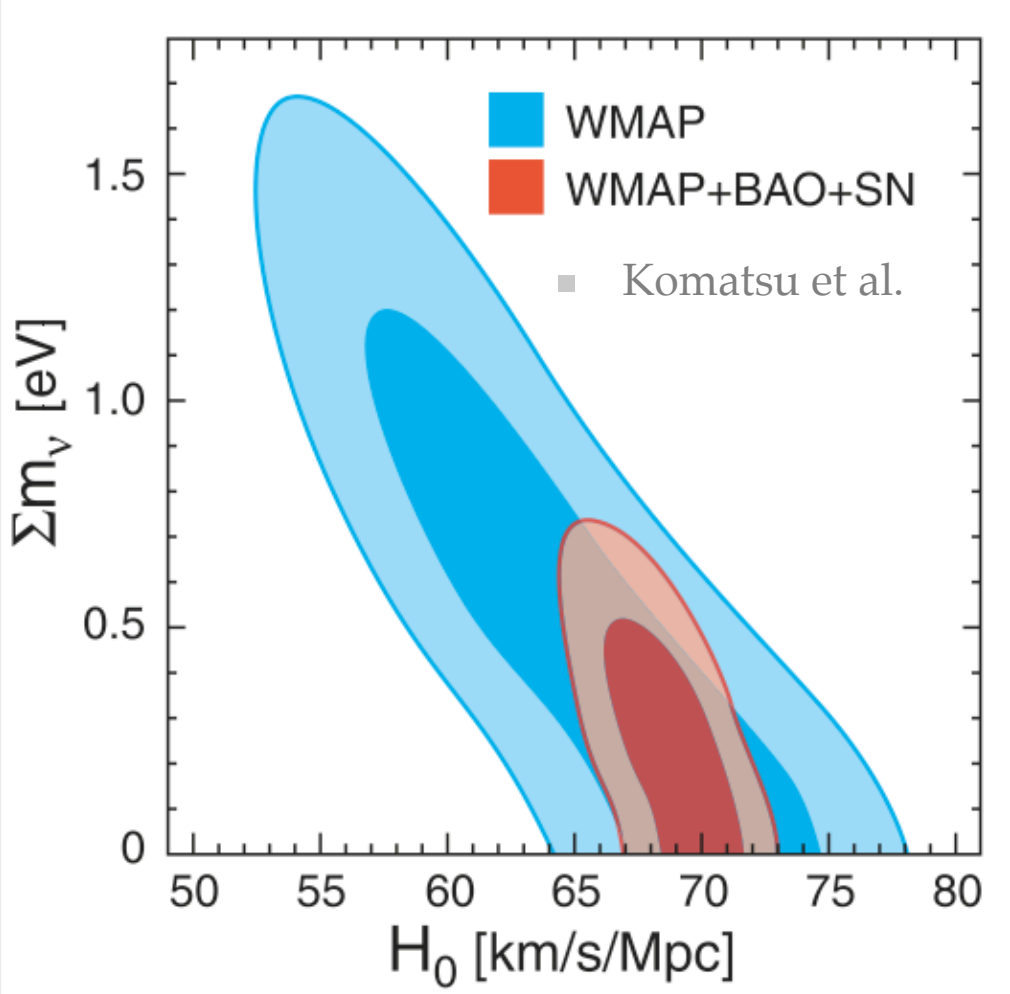
(Rough & Overly Optimistic)



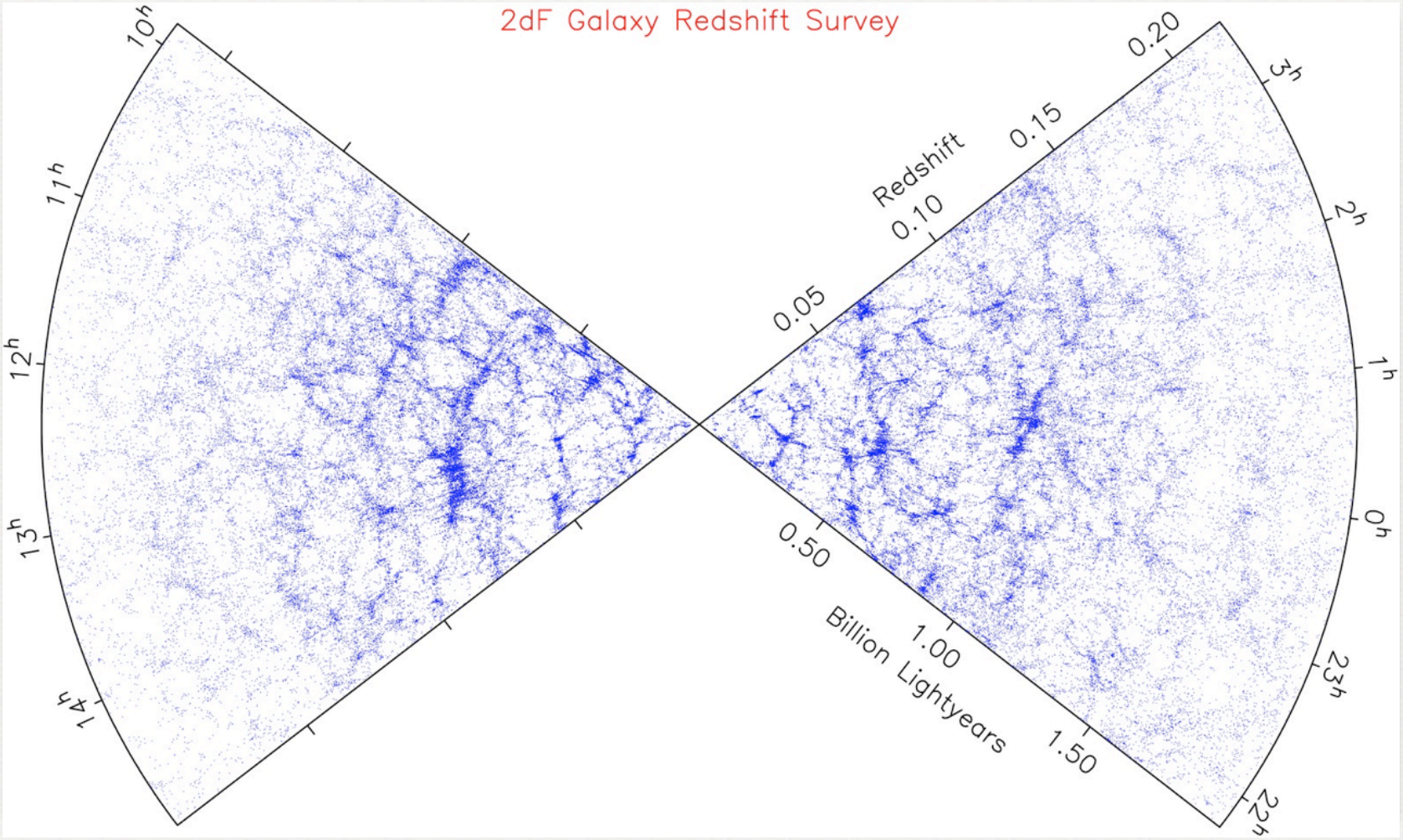
Planck'
"Ideal"
Perfect

CURRENT CONSTRAINTS

- WMAP5 + All
  - Care needed
  - Priors
- Systematics between datasets
- $\Sigma m_\nu < \sim 1eV$



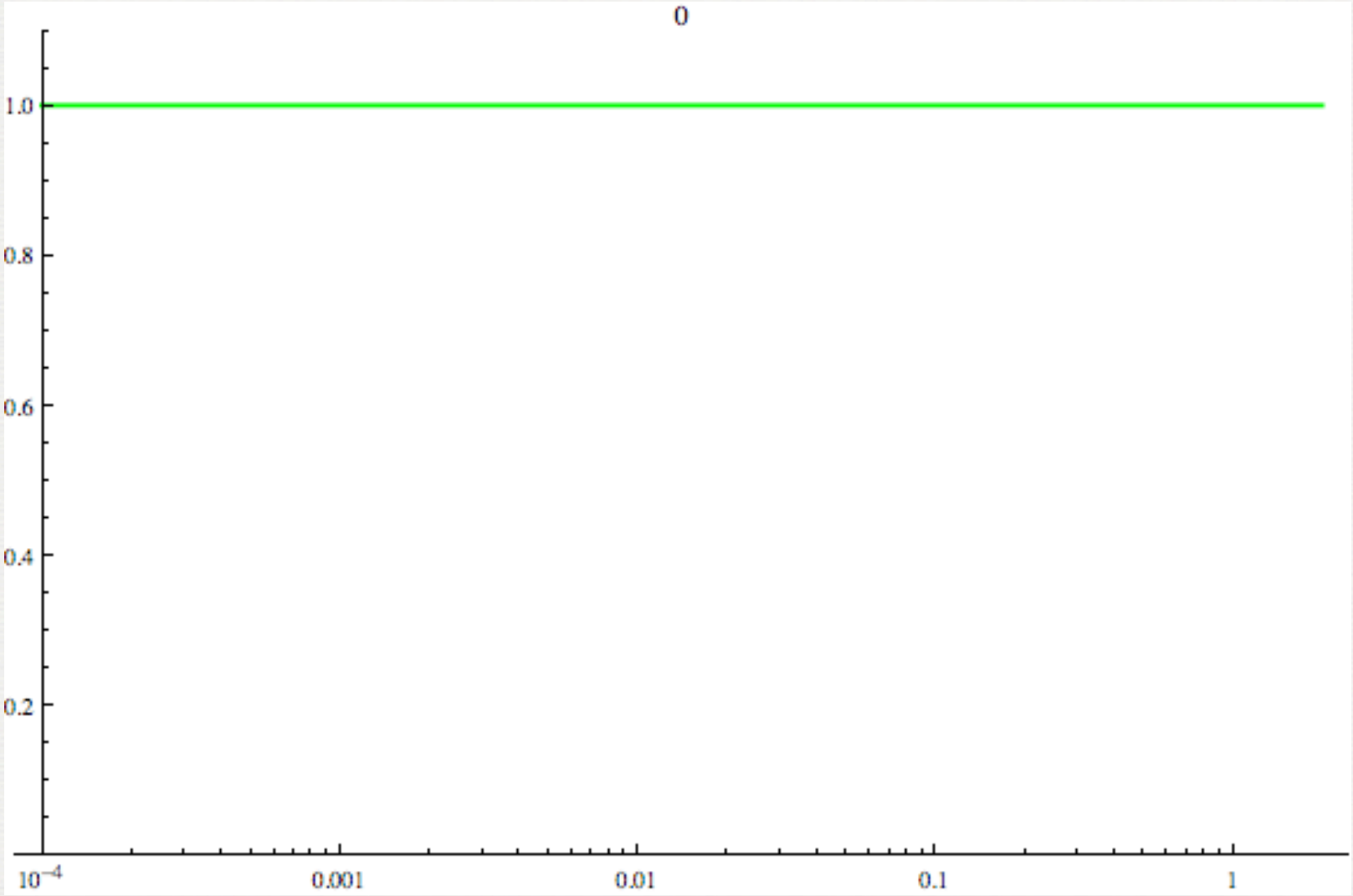
LARGE SCALE STRUCTURE



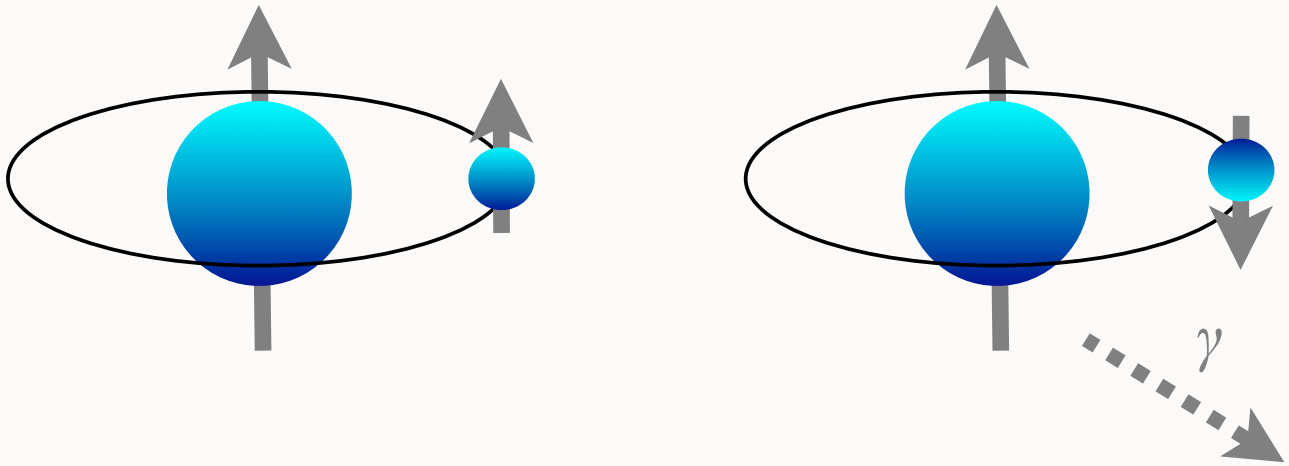
LARGE SCALE STRUCTURE & LENSING

- Galaxies clustered in space
  - Bubbles and voids
  - Orthogonal information to microwave background
- Large scale structure
  - Get power spectrum *P(k)*
  - Break degeneracies
- Nonlinear at short scales (function of redshift)

MATTER POWER...



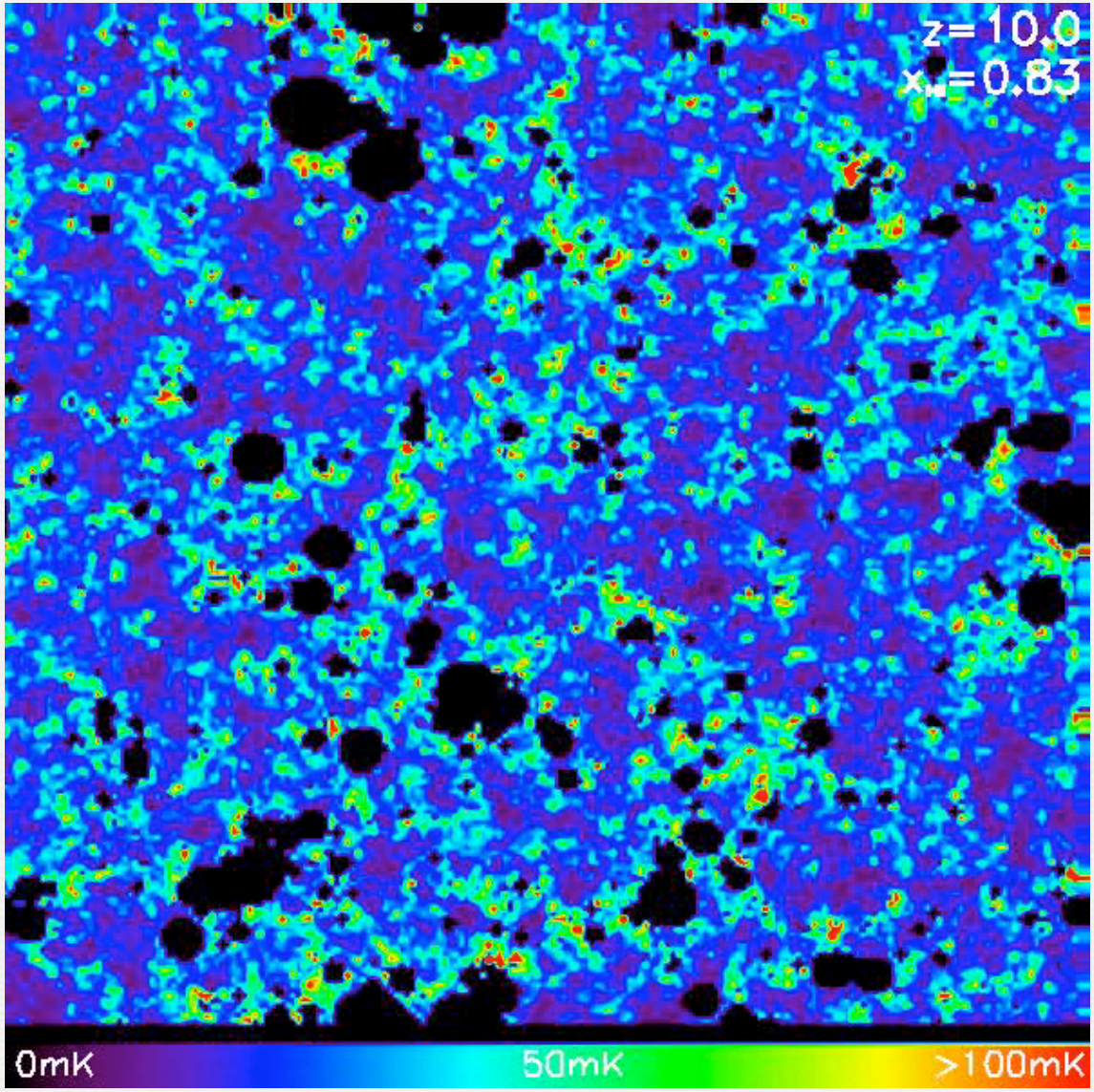
HIGH-REDSHIFT 21CM



- Before first stars, universe is mostly neutral H
  - Neutral hydrogen emits a 21cm *line*
  - Redshifted; H at redshift 10: 2.1 meters.

HIGH-REDSHIFT 21CM

- Observe sky at ~100 MHz
  - Remove foregrounds (!)
  - Map neutral hydrogen density as a function of z
- Needs radio-quiet location
- Get “slices” by tuning receiver



(Steve Furlanetto)

HIGH-REDSHIFT 21CM

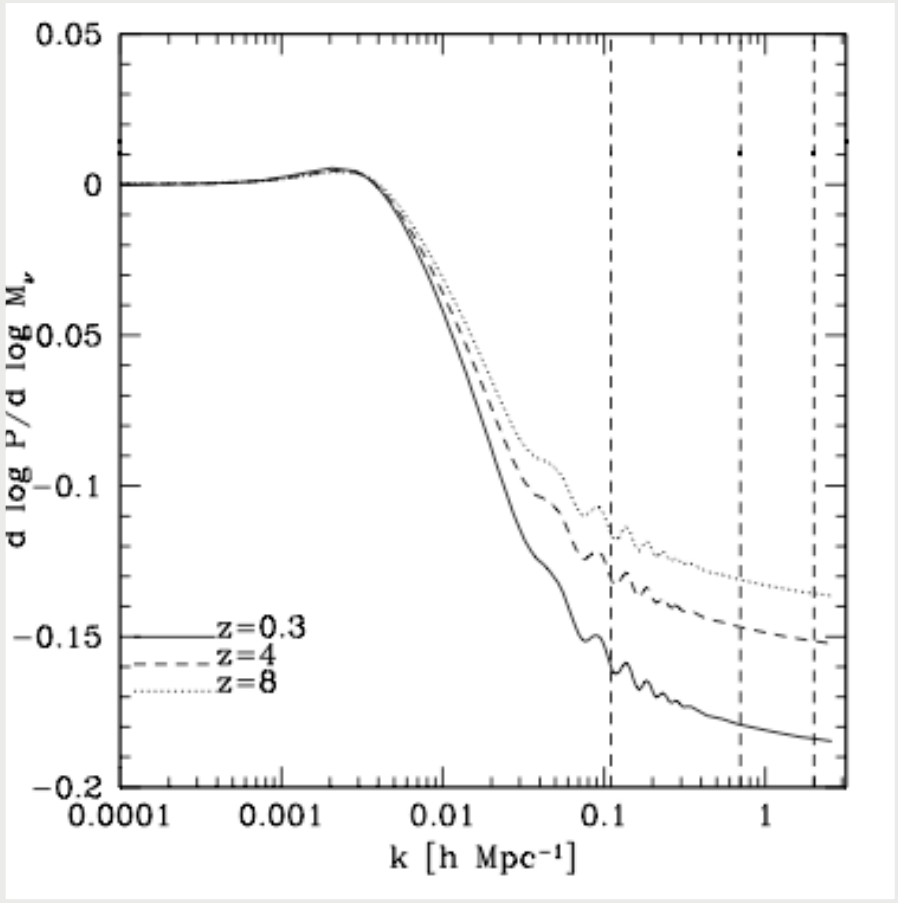
- Instruments
  - Mileura (Australia)
  - LOFAR (Belguim)
  - SKA (To be decided)
  - Lunar Array (Far side of the moon / vaporware!)

PROSPECT FOR NEUTRINOS

- First observations: “Low” redshift
  - Focus on reionization / first stars
- Longer term: High redshift
  - Weaker signal
  - Probe short wavelengths (uncollapsed)
  - Perturbations *small;* challenging experiments
- Foregrounds??? Terrestrial noise???

A BOLD PREDICTION?

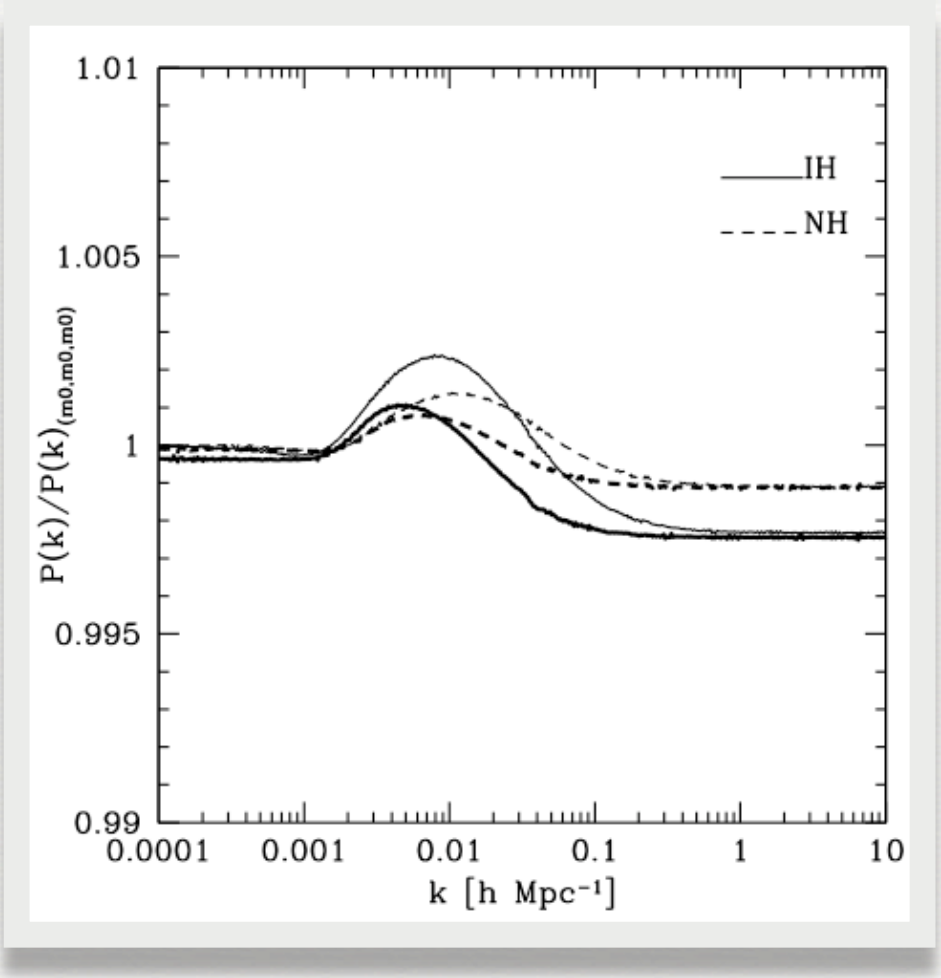
- Total mass: 0.3eV
- Nonlinear scales at z=0.3,4 and 8



Pritchard and Pierpaoli

A BOLD PREDICTION?

- Total mass 0.12eV
  - Both hierarchies
  - Solid z=8
- *Theoretically* distinguishable



Pritchard and Pierpaoli

COMMENTS AND CONCLUSIONS...

- Neutrinos provide definite target
  - Very good reason to believe they are there (WMAP)
  - We *know* their total mass is non-zero
  - Probe thermal history of very early universe
- Small effect: precision cosmology
  - Terrestrial measurements of neutrino mass constrain *other* cosmological parameters

COMMENTS AND CONCLUSIONS...

- Current bound ~10 times larger than minimum Σm
- Next few years: Planck, ACT, EBEX, DEC
  - Better SN1a bounds & BAO, first 21cm data
- Somewhat longer term: JDEM, LSST, CMBPol (?)
- Very long term: High precision high-z 21cm
- GUESS: A factor of 10 on Σm in 10 years??