Concordance Cosmology and Particle Physics

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Concordance Cosmology

- The "standard model" for cosmology
  - Simplest model that fits the data
  - Smallest number of free parameters
  - Smallest possible extension to currently *known* physics
- Like the particle physics Standard Model:
  - Does not explain *itself*
  - But explains the data

Outline

- Lecture 1: Concordance Cosmology
    - Quick Review: cosmological history & current data
    - Concordance cosmology and free parameters
    - Quick Review: CMB physics
    - Physics beyond standard model
    - Neutrino physics from cosmology

Outline

- Lecture 2: Inflationary Observables
  - Connecting inflation and the primordial power spectrum
  - Matching between inflation and astrophysical scales
  - Uncertainty in expansion rate of primordial universe
  - Consequences for inflationary observables
  - Consequences for particle physics beyond TeV scales

Cosmology: Overview

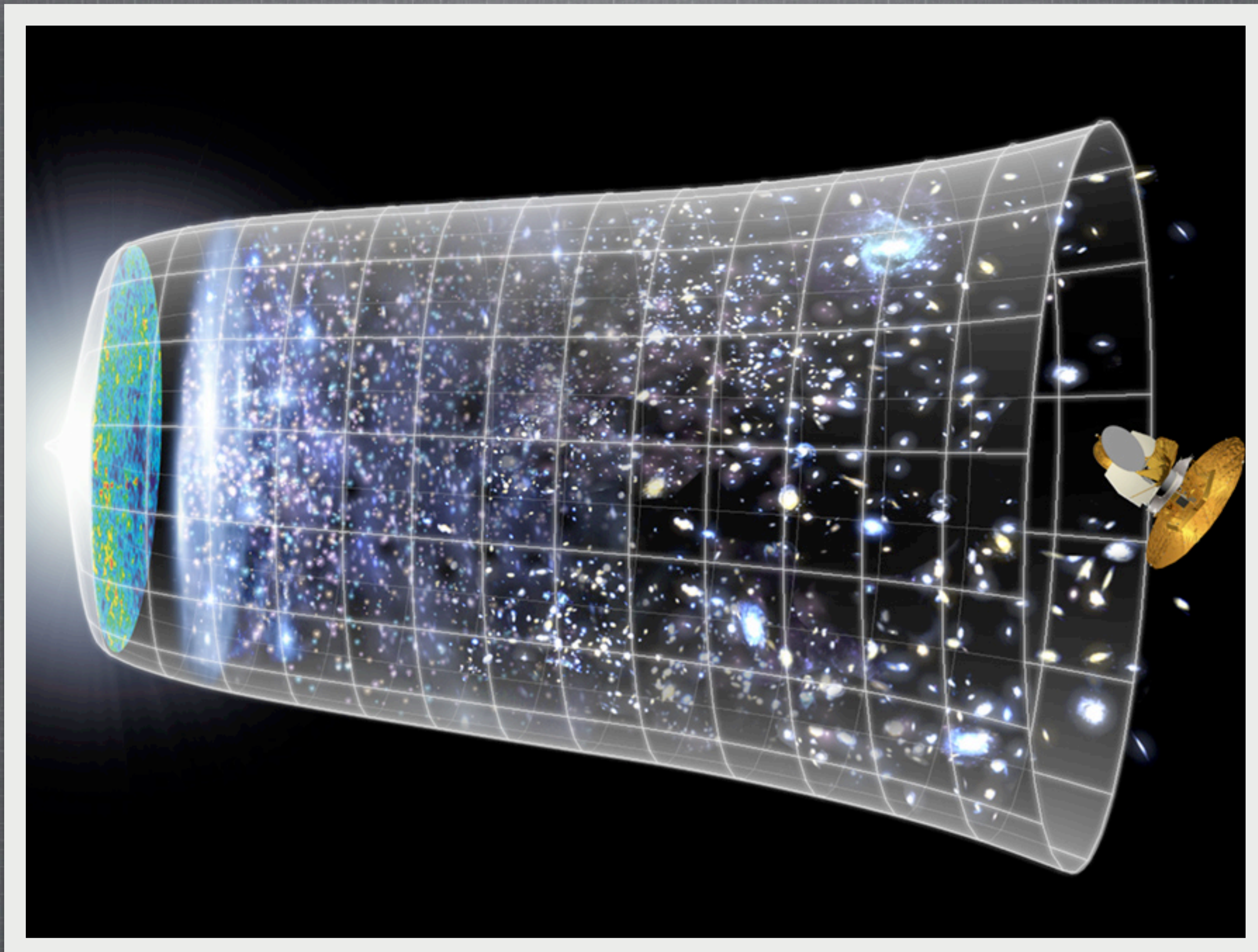


Image: NASA

COSMOLOGY: OVERVIEW

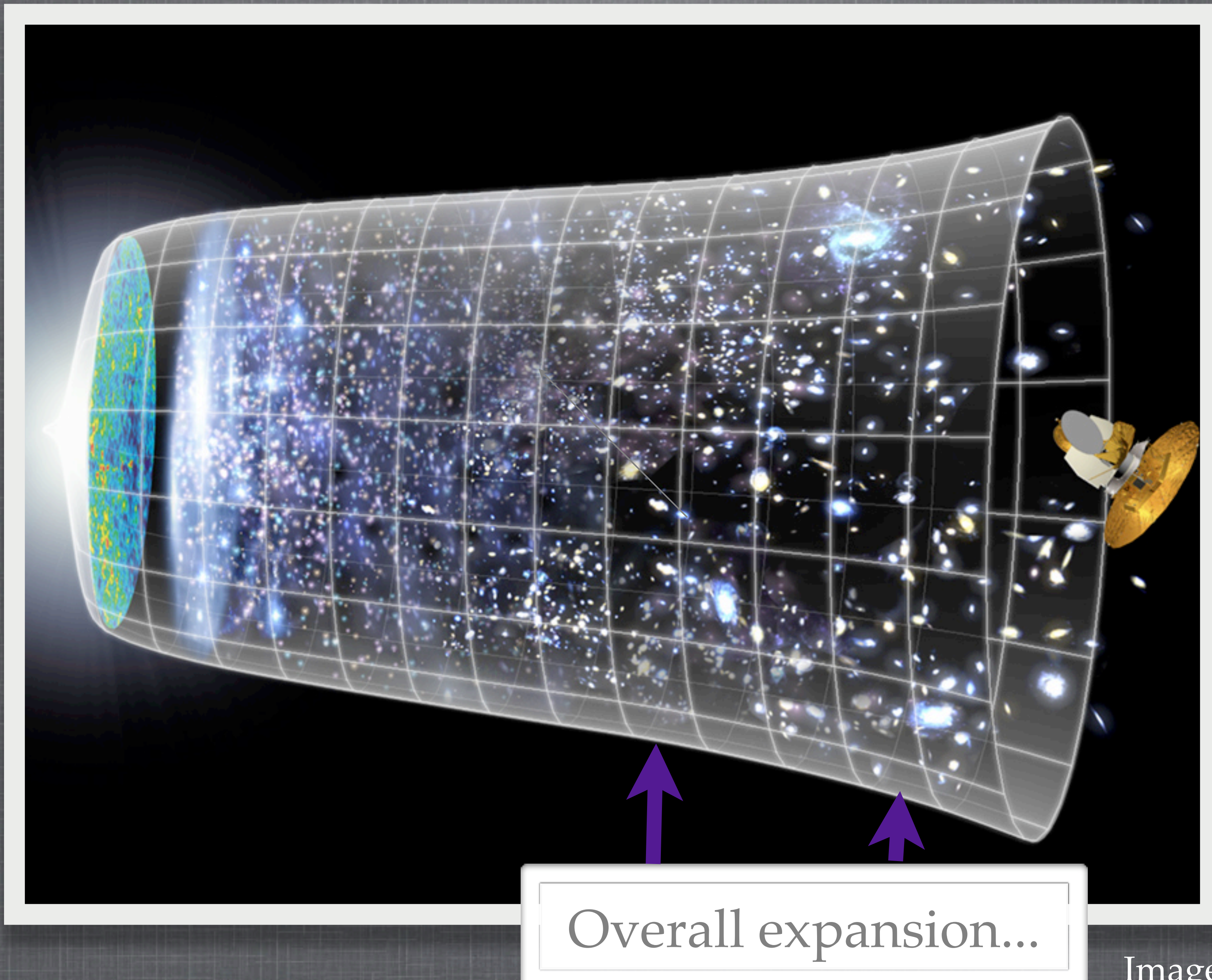
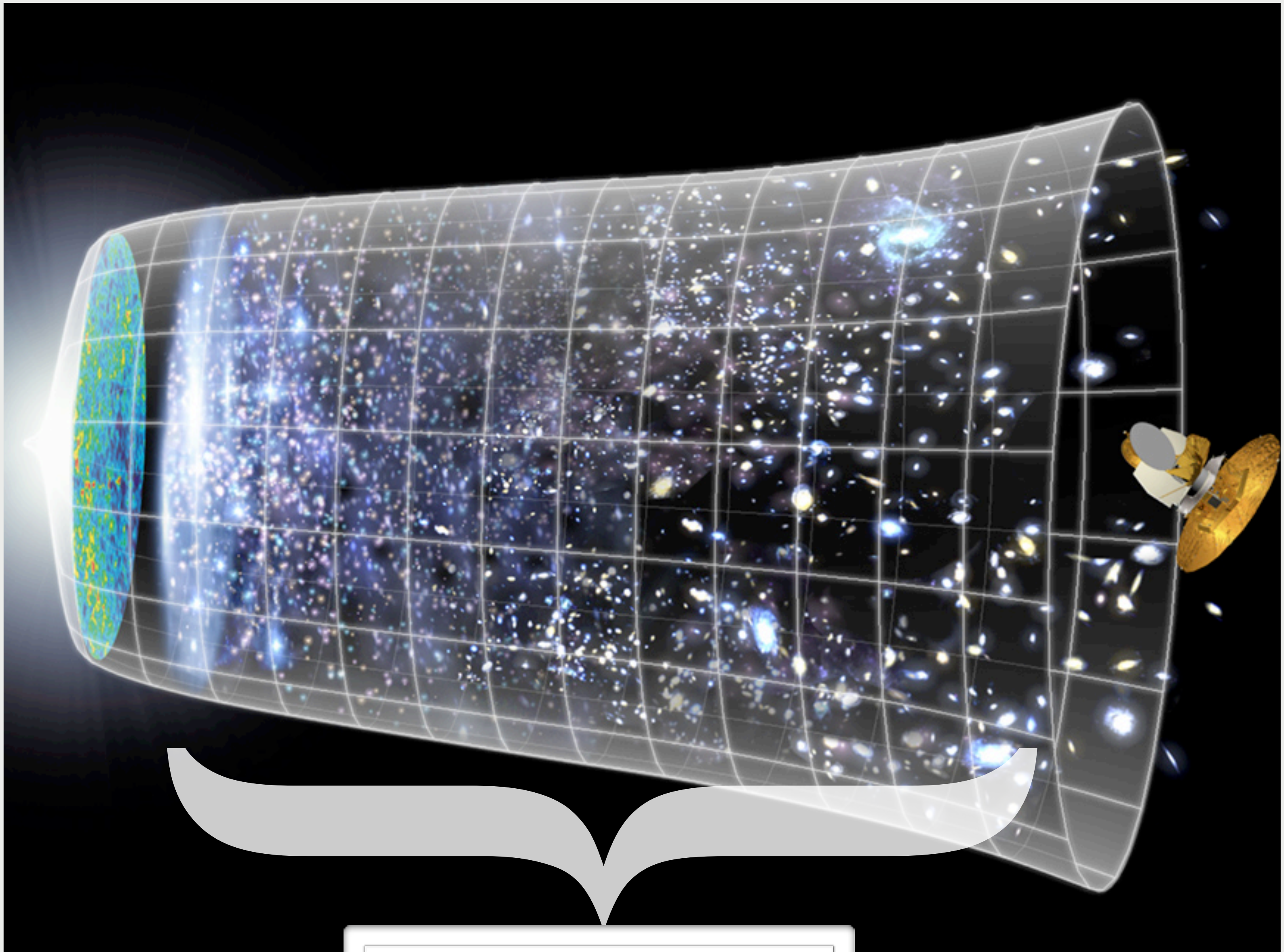


Image: NASA

Cosmology: Overview



Stars, galaxies...

Image: NASA

COSMOLOGY: OVERVIEW

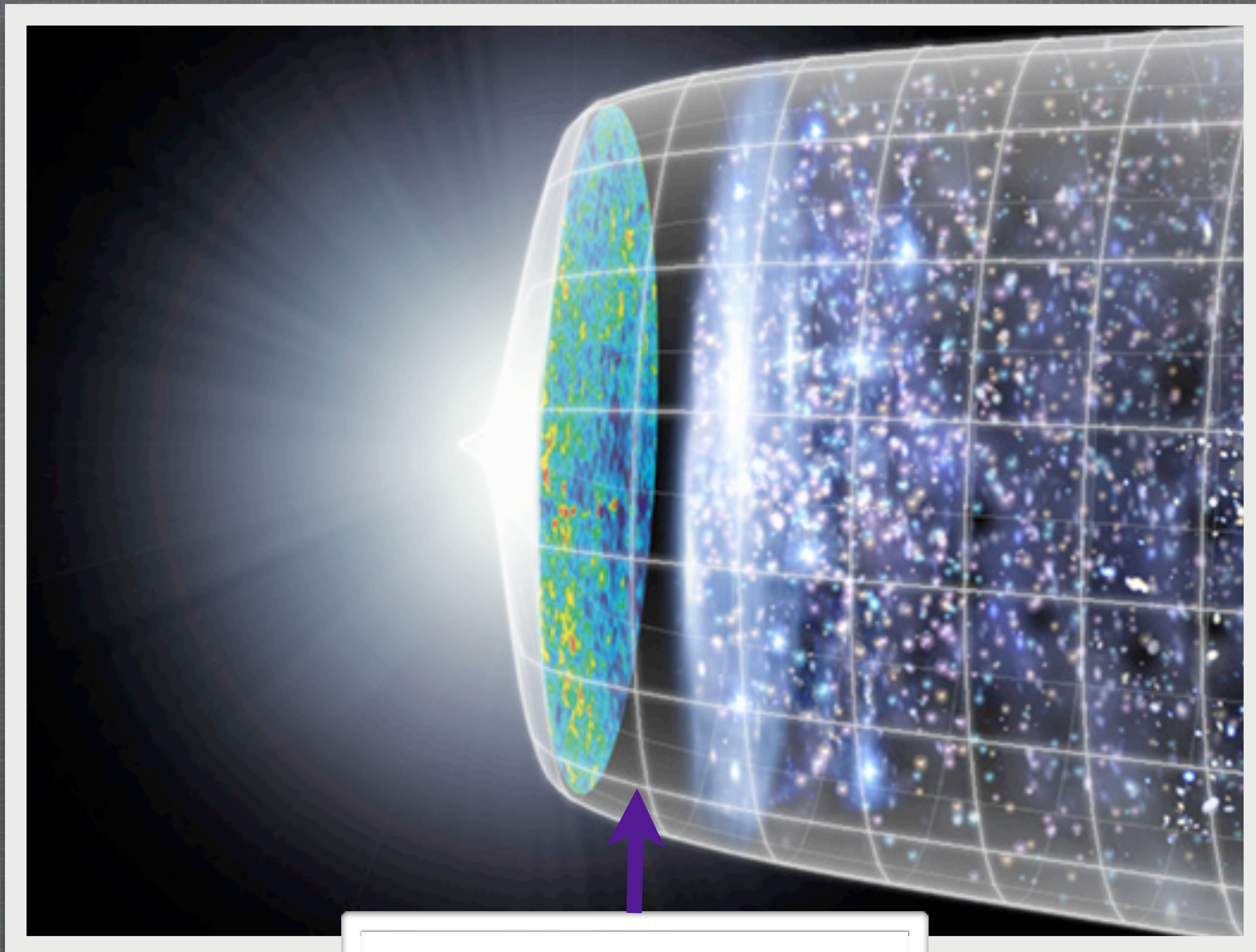


Image: NASA

Cosmology: Overview

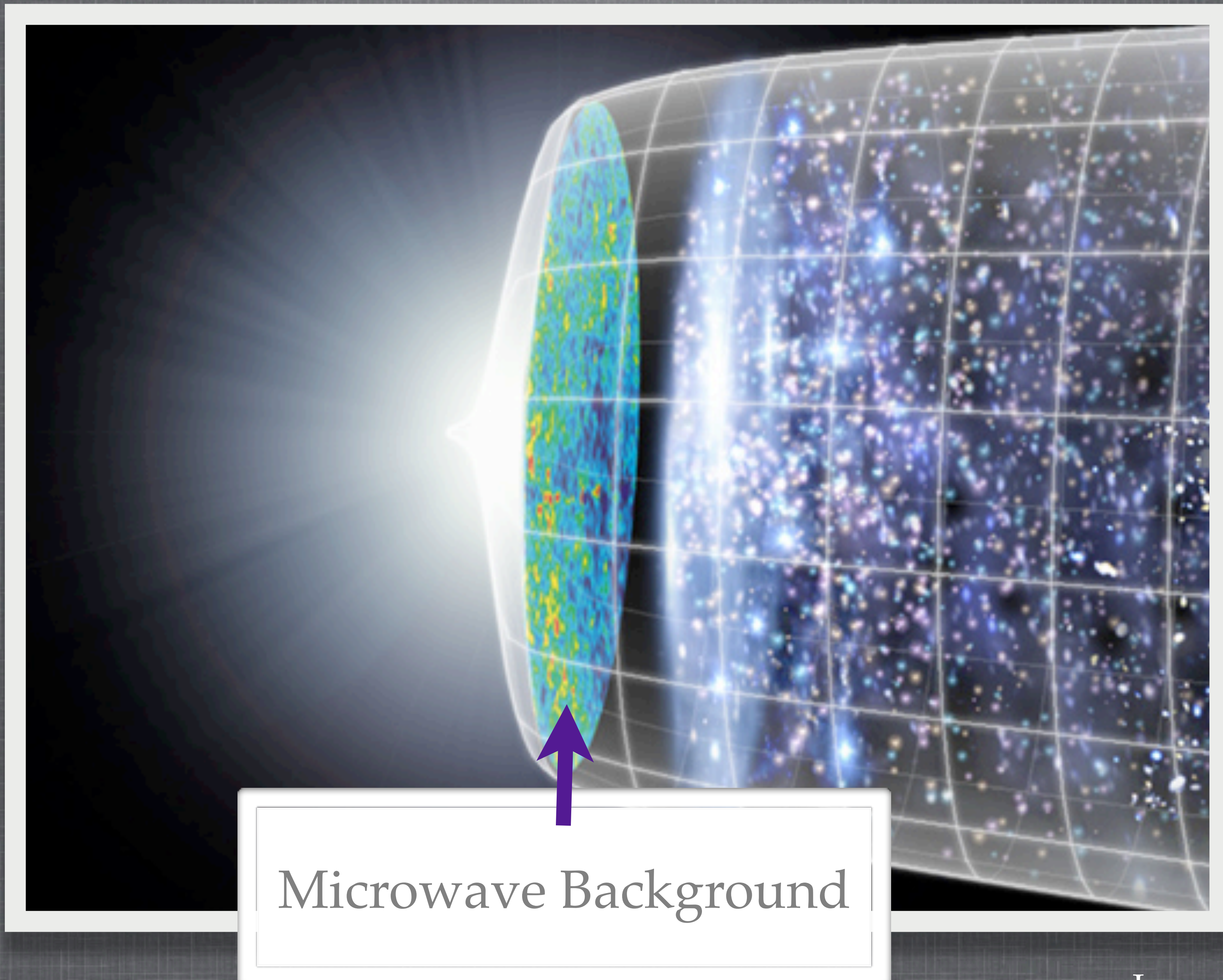


Image: NASA

Cosmology: Overview

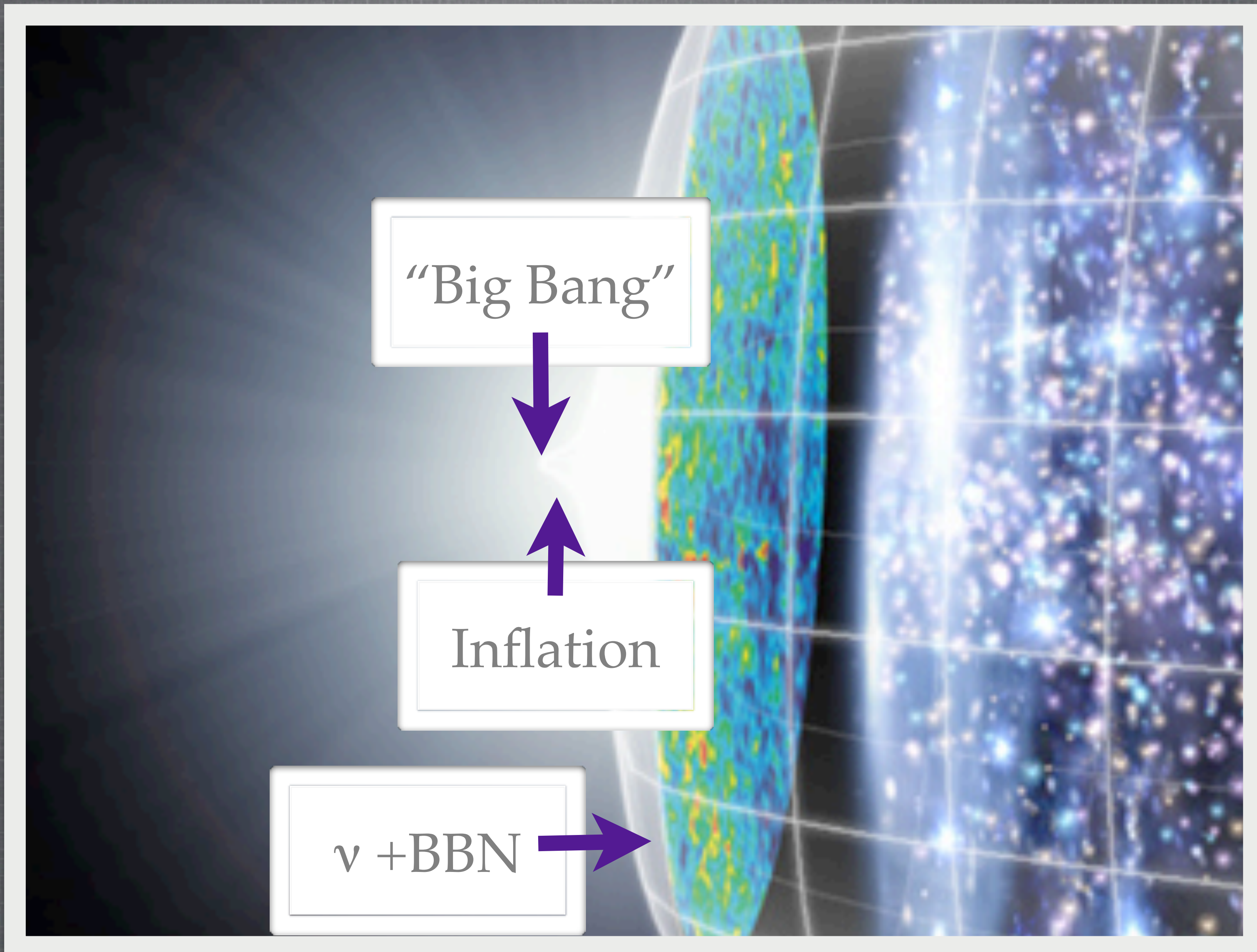
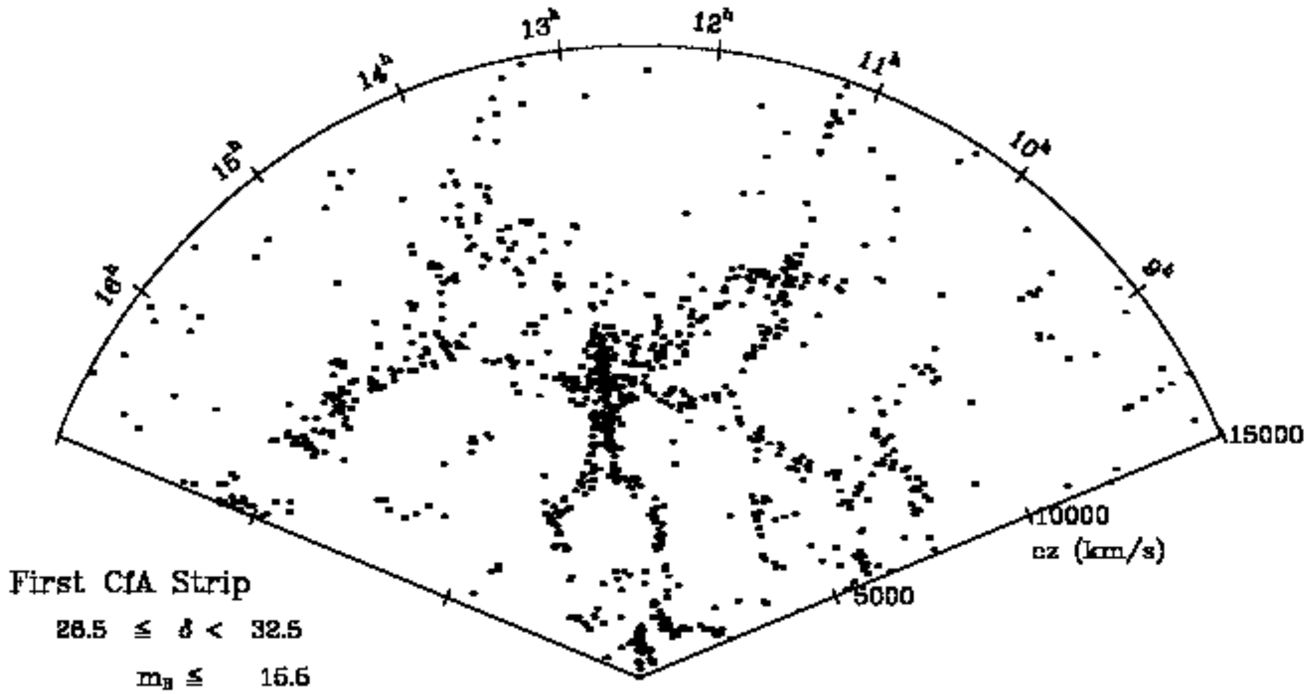
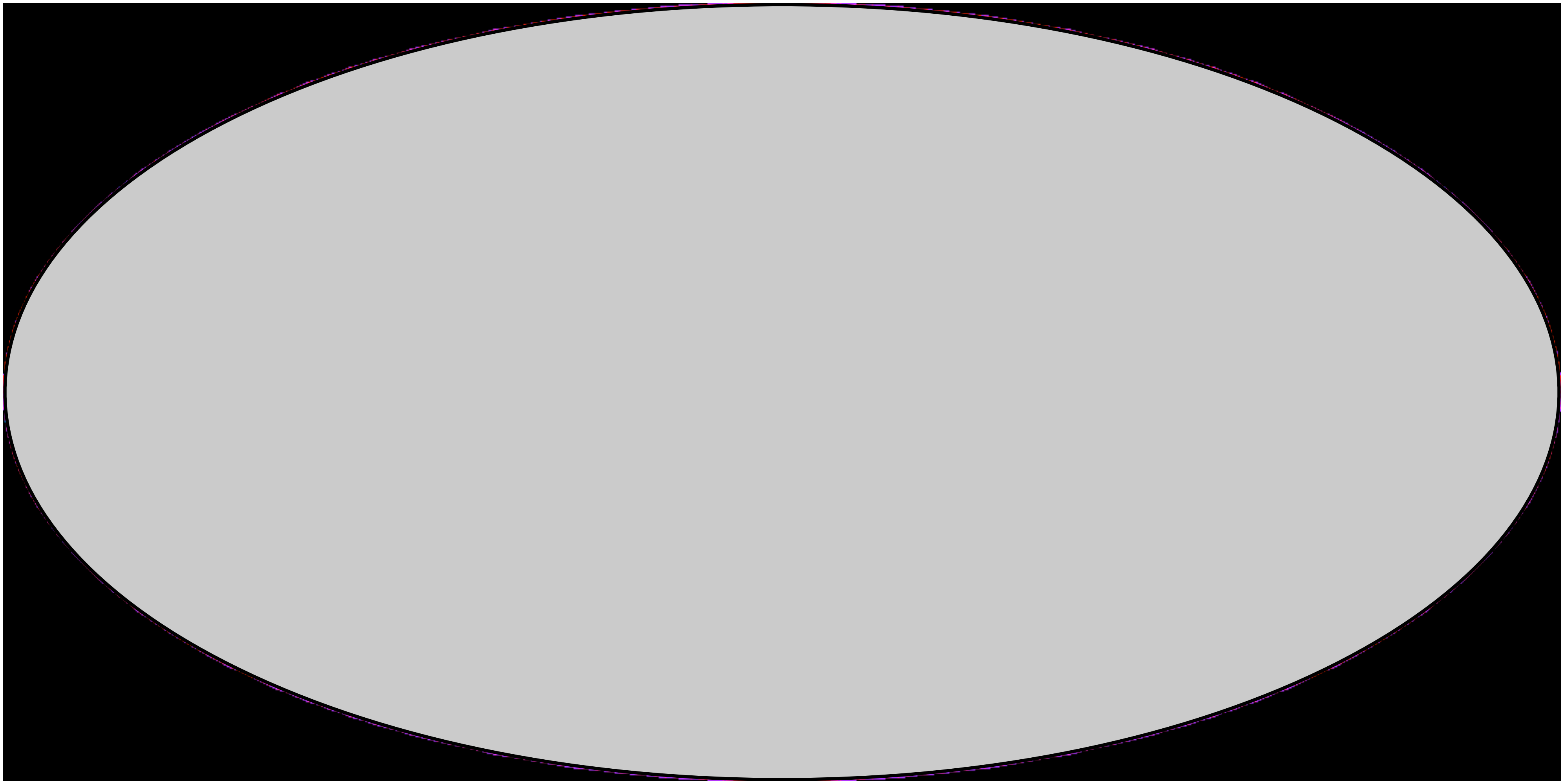


Image: NASA



Data: Large Scale Structure

1982-2004

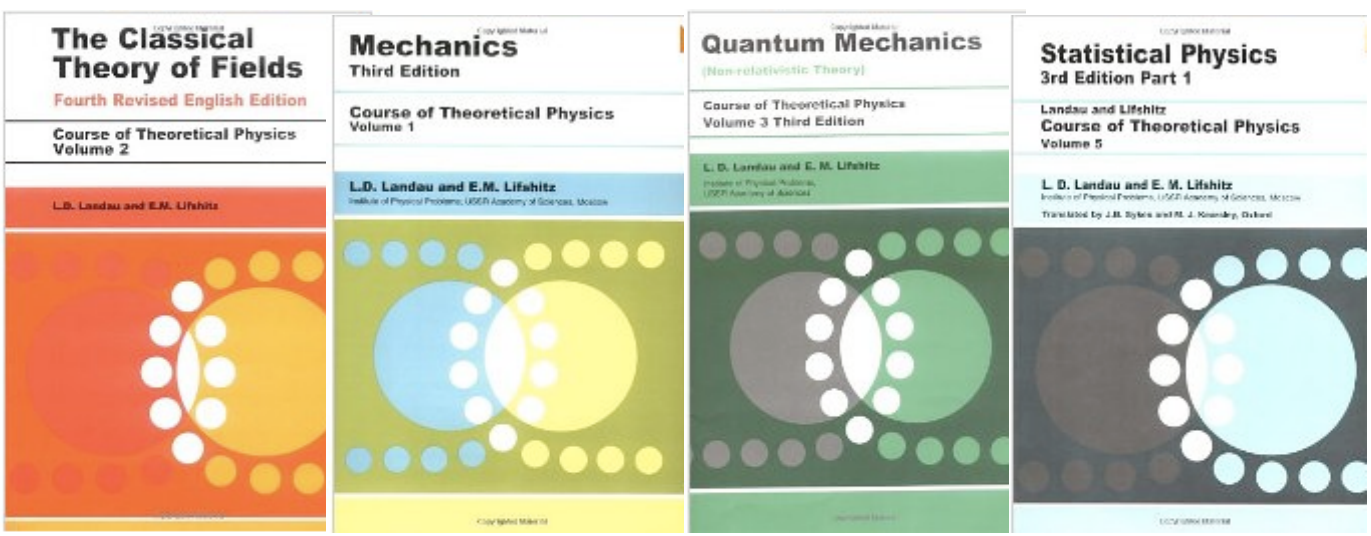


Data: CMB Sky [2.72 K]

<1990-2010

Concordance Cosmology

- Much of cosmology is "applied physics"
  - Universe is a (big) physical system
  - General relativity, perturbations, thermodynamics, quantum field theory...
  - Almost everything you need is here:



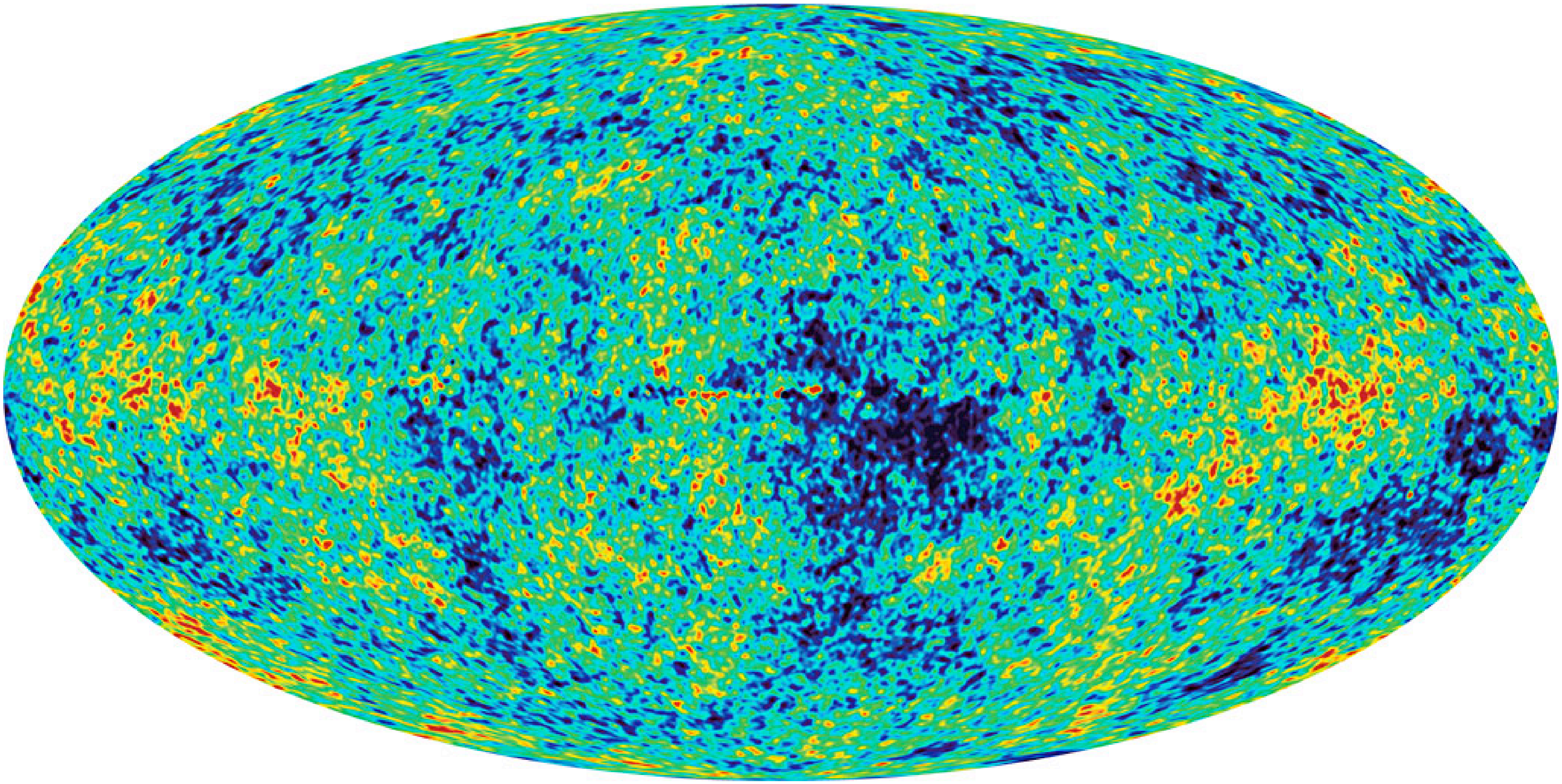
Concordance Cosmology

- Initial conditions + physics: work out how system evolves
  - When do we *set* initial conditions?
- Nature: sets initial conditions at the big bang (whatever that is!)
- Concordance model
  - Set initial conditions at earliest time we understand physics
  - Density decreasing (generically true for expanding universe)
- What free parameters do we need?

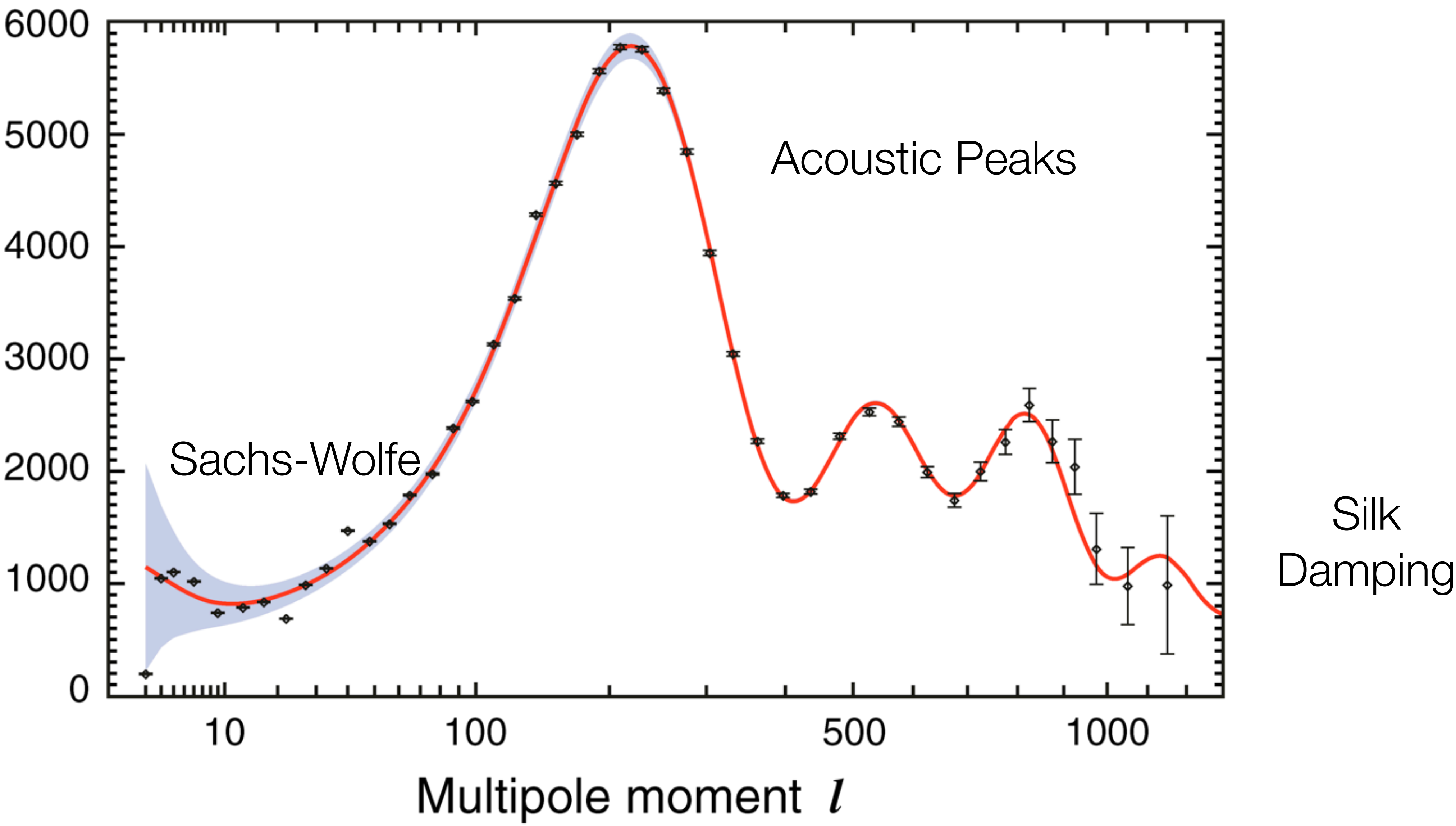
Concordance Parameters

h	Hubble's "constant"	When we are looking
τ	Reionization	First stars (gastrophysics, nuclear physics)
A_{SZ}	Sunyaev-Zeldovich Amplitude	Scattering of photons by hot gas in clusters
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 Magic?
A_s, n_s	Primordial Perturbations	Inflation GUT/string physics?

From Data to Parameter Values



What is the Physics Here?



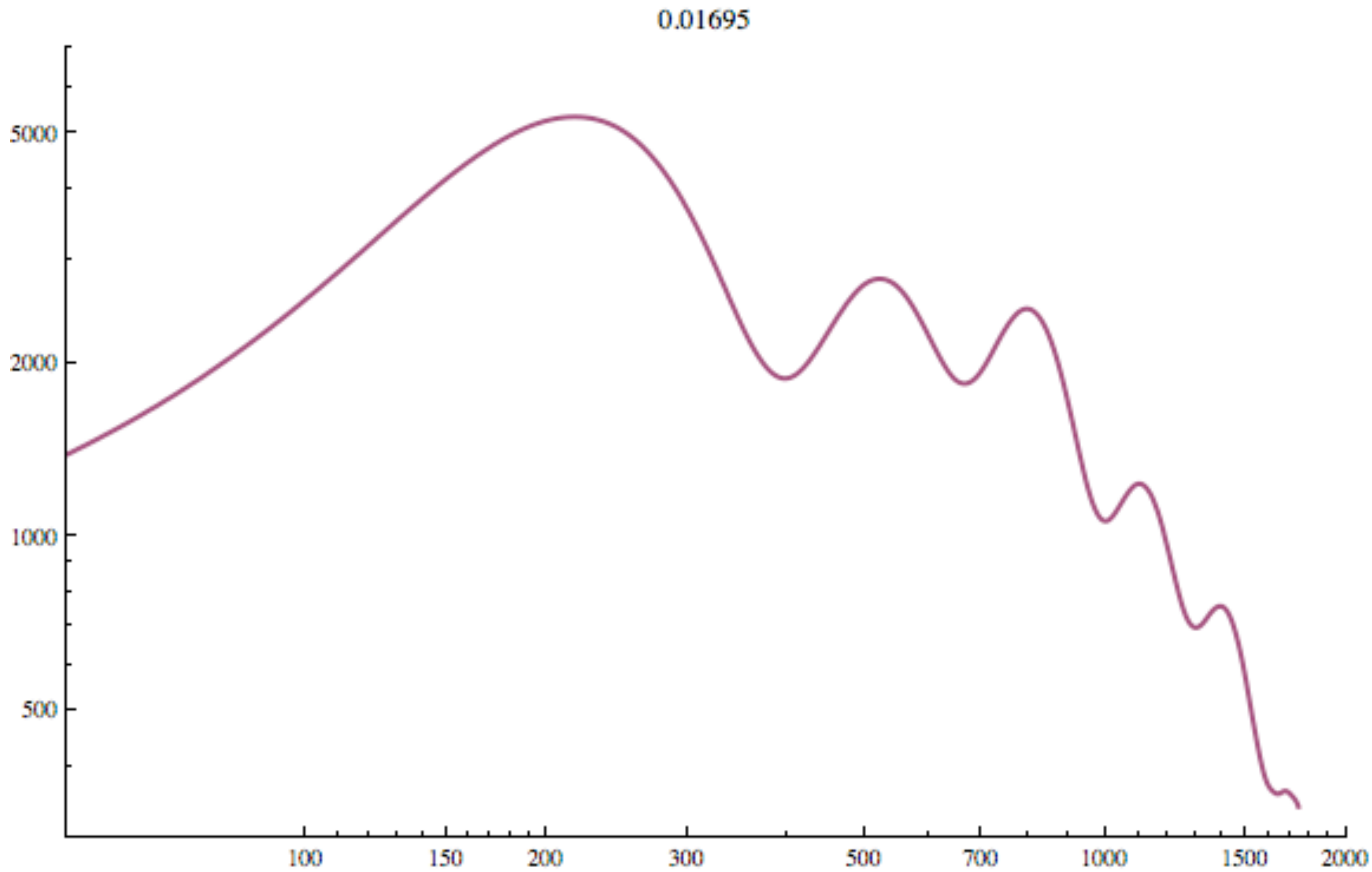
CMB Physics

- Sachs-Wolfe: photon in overdense region
  - Locally hotter (because denser)
  - But in a (dark matter) potential well: must climb out
  - Partial cancellation: cold spots are *overdense* regions
- Silk Damping: small wavelength perturbation
  - Washed out by diffusion
  - CMB power spectrum cut off at large multipole

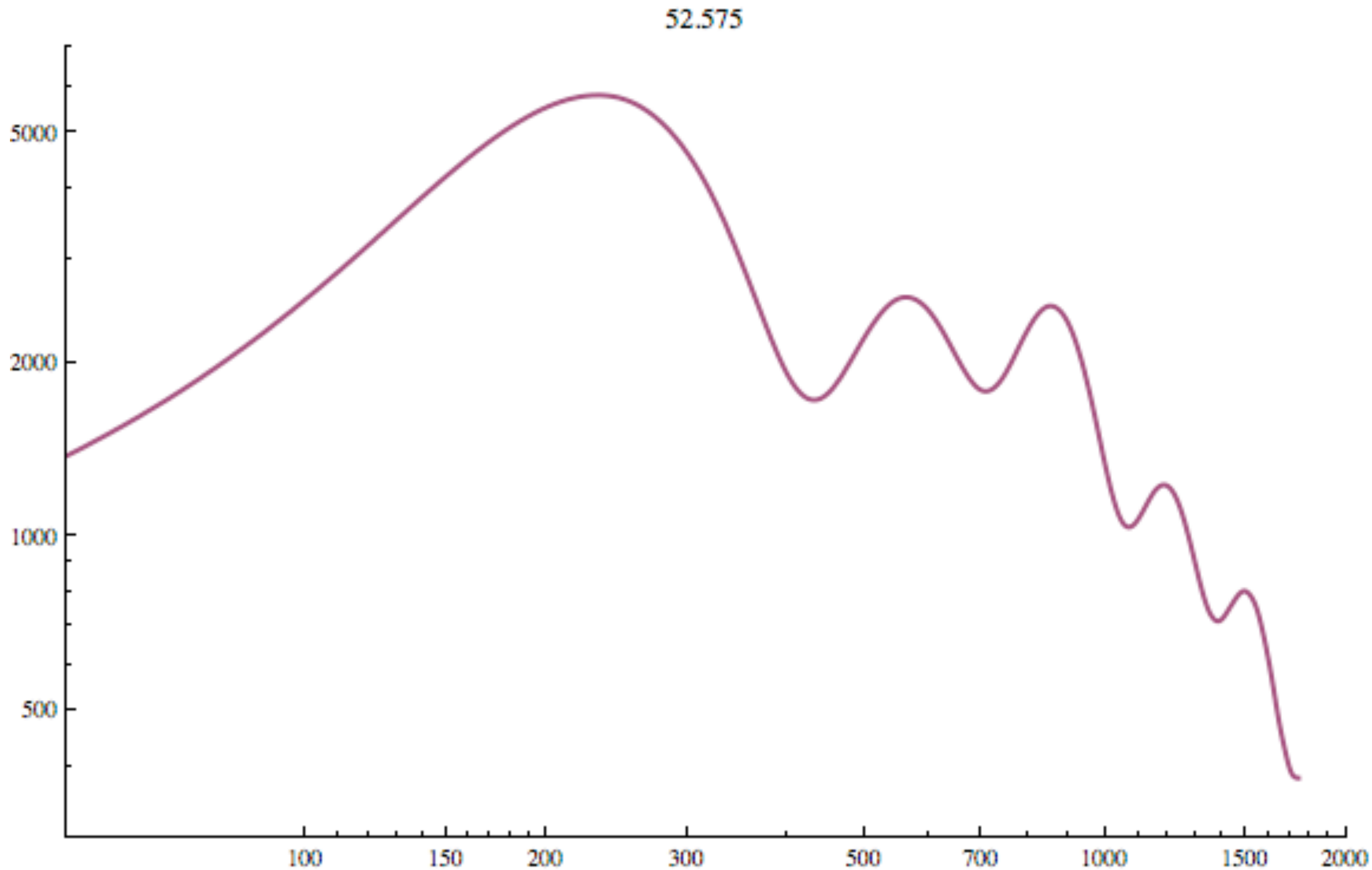
CMB Physics

- Acoustic Peaks
  - We are showing angular power spectrum
  - Photon-electron-photon plasma tightly coupled
  - Small modes undergo more oscillations
  - System decouples at “recombination”
- Full system of Boltzmann equations solved
  - Initial power spectrum $P(k) = A_s\, k^{n-1}$

For example: Baryon Fraction

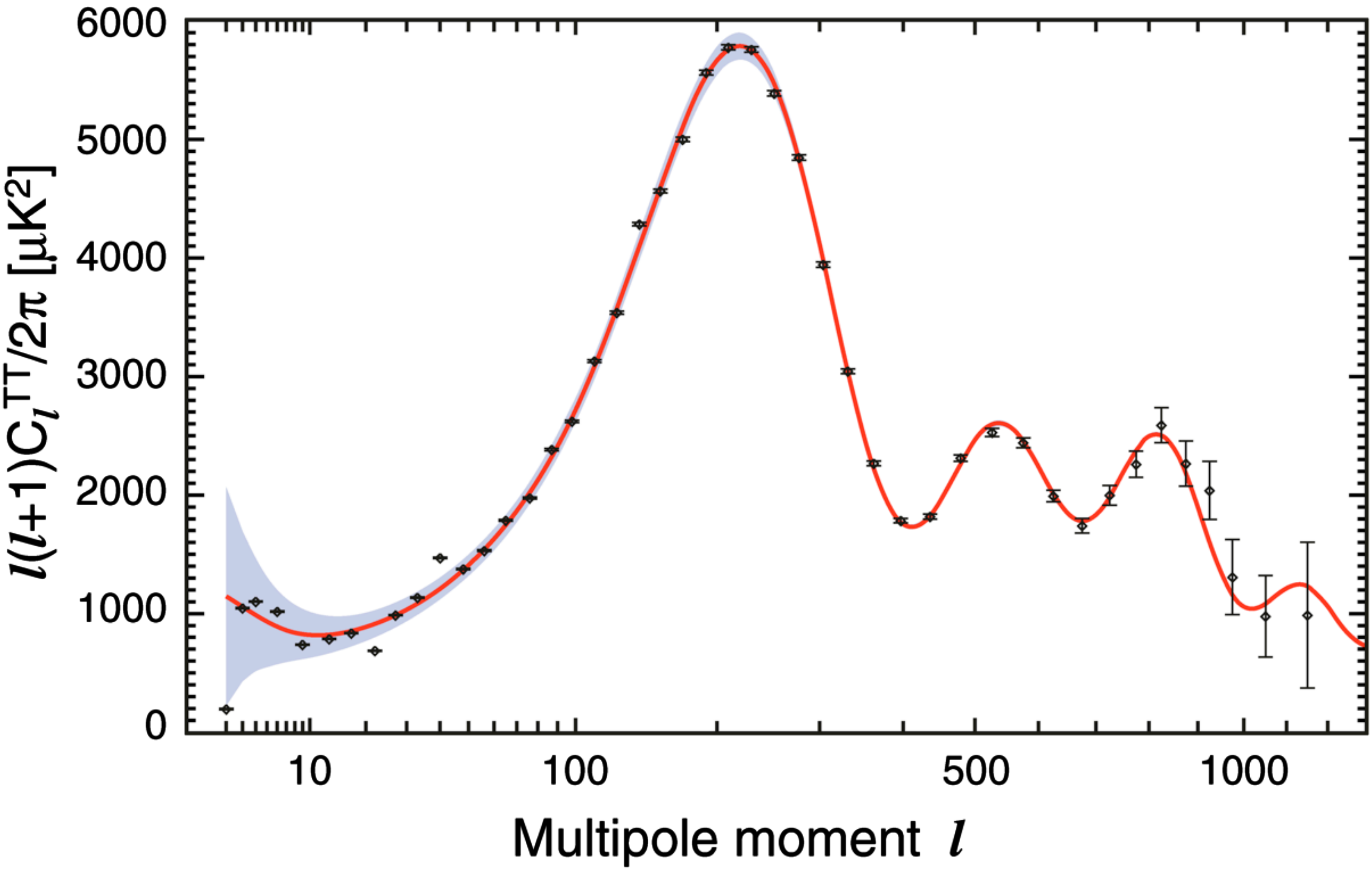


For example: Hubble Parameter



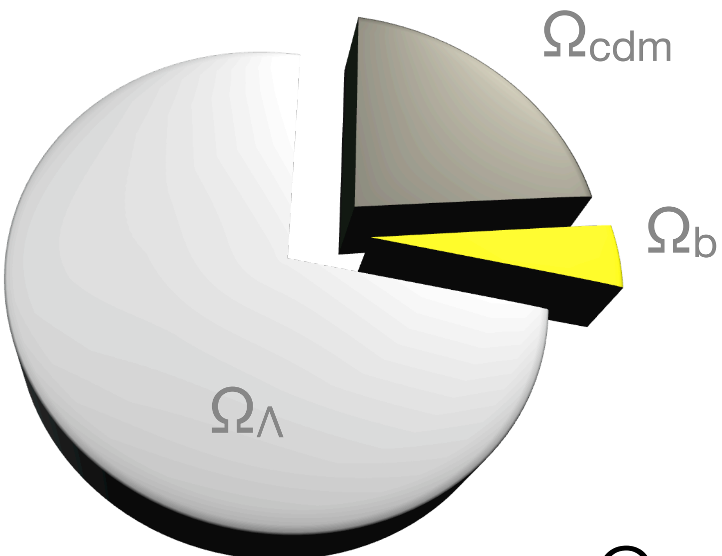
Hubble Parameter Dependence

- Einstein equations (flat universe):
  - $$H^2 = \left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi}{3M_p^2}\rho$$
- Expansion rate scales with density
  - Varying **H** equivalent to varying density today
  - Changes total growth between present and recombination
  - Does not change CMB physics itself
  - Scale changes, shape fixed.



Fit & Residuals

Parameter	*WMAP* 7-year ML[a]	*WMAP*+BAO+H_0 ML	*WMAP* 7-year Mean[b]
$100\Omega_b h^2$	2.270	2.246	$2.258^{+0.057}_{-0.056}$
$\Omega_c h^2$	0.1107	0.1120	0.1109 ± 0.0056
Ω_Λ	0.738	0.728	0.734 ± 0.029
n_s	0.969	0.961	0.963 ± 0.014
τ	0.086	0.087	0.088 ± 0.015
$\Delta^2_{\mathcal{R}}(k_0)$[c]	2.38×10^{-9}	2.45×10^{-9}	$(2.43 \pm 0.11) \times 10^{-9}$
σ_8	0.803	0.807	0.801 ± 0.030
H_0	71.4 km/s/Mpc	70.2 km/s/Mpc	71.0 ± 2.5 km/s/Mpc



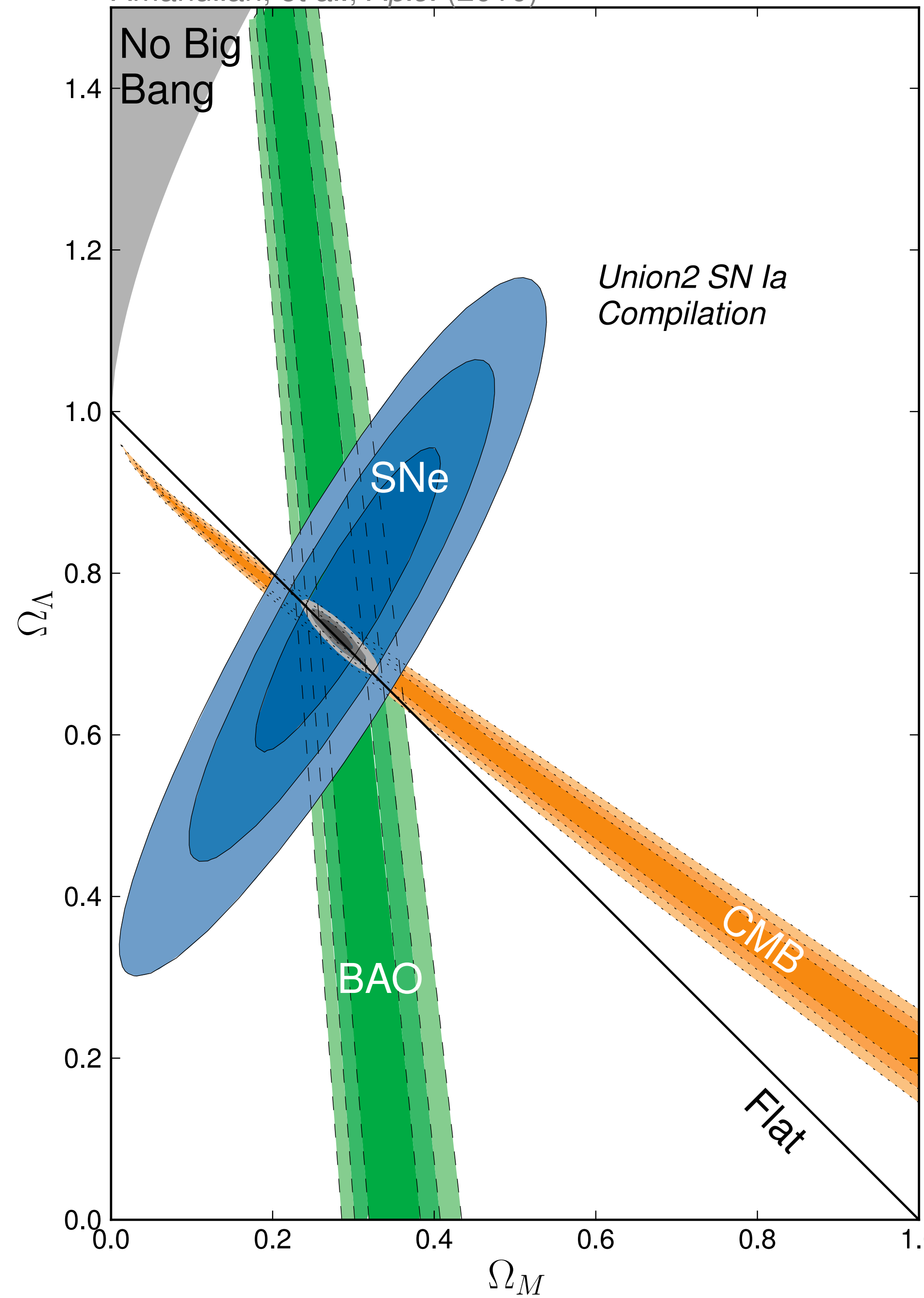
Cosmological Parameters

Komatsu et al. 2010

Complementarity

- I focussed on CMB, but:
- Have data from
  - Baryon Acoustic Oscillations
  - Supernovae
  - Weak lensing
- Leads to orthogonal constraints
  - No new parameters needed

Amanullah, et al., *Ap.J.* (2010)



Implications: #1a - 1e

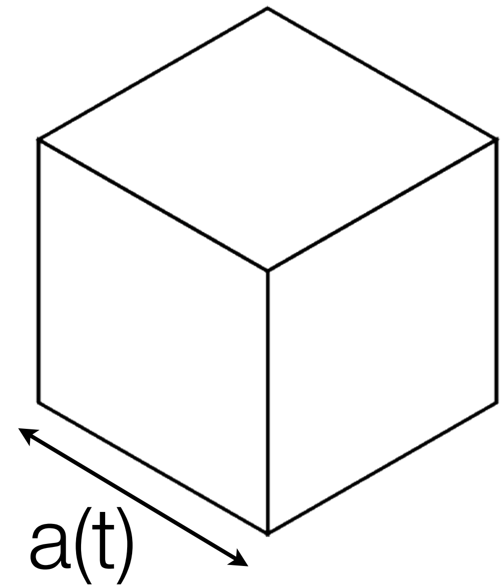
- Accelerator physics
  - No evidence for physics beyond standard model
- But Five Numbers from Cosmology
  - Ω_{CDM} $\Sigma n_i m_i$ [more than one species, n_i & m_i *unknown*]
  - Ω_b $n_b m_b$ both known; generation mechanism *unknown*
  - Ω_Λ Dark energy density / cosmological constant
  - A_s, n_s Set by inflation (?) - beyond standard model physics
- Not much actual help, though...

How Can the Parameter Set Change?

- Need better data (will not a problem!)
  - CMB Planck, ground and balloon based experiments
  - Large Scale Structure - BoSS, JDEM, Euclid, LSST...
  - 21cm: LoFAR, Miluera, SKA...
  - Gravitational waves (LISA, BBO, DECIGO)
- New parameters likely sub-leading, relative to current set.
- 1σ range: Improve by a factor of ~5 (or more) in next decade??

Lemma: Energy Density v. Time

- Relativistic gas: $\rho \sim T^4$ [temperature]
  - Number density $\sim 1/a^3$
  - Energy / particle (redshift) $\sim 1/a$
  - Number density x Energy = $\rho \sim a^{-4}$
  - Temperature $\sim 1/a(t)$
  - Assumes species do not interact
- Radiation dominated universe: $a(t) \sim t^{1/2}$ [General relativity]
- Matter: $\rho \sim a^{-3}$, $a(t) \sim t^{2/3}$ [General relativity]



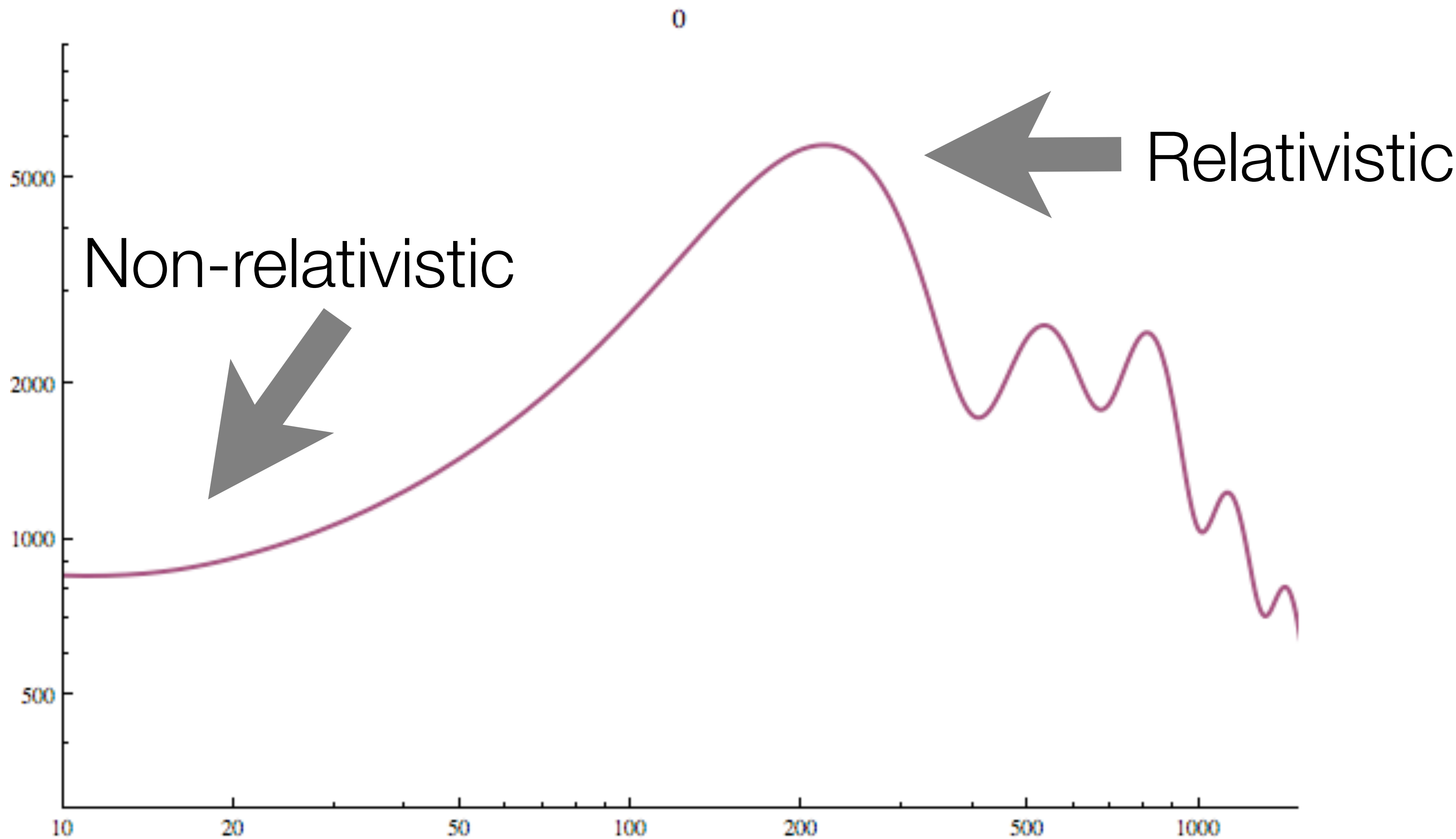
Implication #2: Neutrino Sector

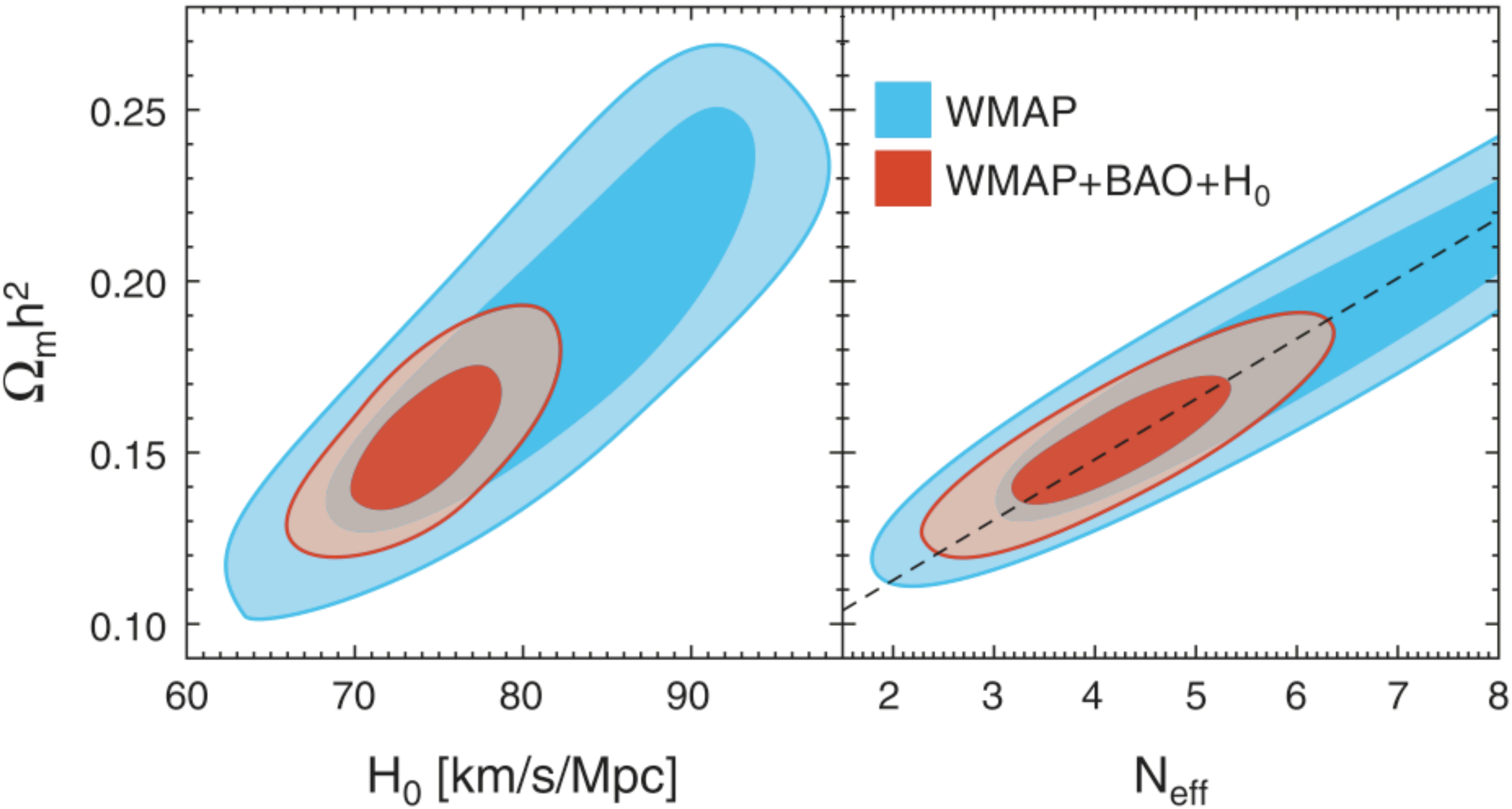
- Hot big bang predicts cosmological neutrino background
  - Early universe: very hot, neutrinos in thermal equilibrium
  - Neutrinos decouple *before* electron-position annihilation
  - $e^+ + e^-$ decay "heats" photons, relative to neutrinos
  - Temperature *ratio* predicted, CMB temperature *measured*
- When CMB decouples, universe ~10% neutrinos
  - Take neutrinos out, get (small) changes
  - Measure neutrino physics from CMB + large scale structure

Numbers...

- CMB Photons: $T_\gamma = 2.726$ K $= 2.35\times10^{-4}$ eV (measured)
  - Massless ν: $T_\nu \sim 1.9$K $= 1.7\times10^{-4}$ eV (predicted, thermal eq.)
- Photons at z = 1,090: $T_\gamma = 2.97\ 10^3$ K $= 0.255$ eV
  - Note this is much less than ionization energy of hydrogen
  - Massless ν: $T_\nu \sim 2.07\ 10^3$ K $= .17$ eV
- Minimum $\Sigma m_\nu \sim 0.05$ eV (normal hierarchy, observed splittings)
  - $m_\nu > 0.25$ eV non-relativistic at decoupling
  - $2.4\times10^{-4} < m_\nu < 0.25$: non-relativistic *after* decoupling

Total Neutrino Mass (Three Species)





WMAP: 7 Year Analysis
[Komatsu et al.]

Neutrino Number

- Looking at N massless degrees of freedom
  - These need not be “neutrinos”
  - Any massless, noninteracting particle contributes same way
  - Assuming thermal equilibrium in early universe $N_{eff} > 3$
- Can add (e.g.) graviton background (non thermal)
  - N_{eff} is a continuous parameter
  - Now bounded ABOVE and BELOW

Neutrino Mass

- Assume three neutrinos, compute mass
  - Masses degenerate (know splittings, and current bound)
  - But will not stay that way
- Neutrinos relativistic at z=1000, non-relativistic today
  - Lower mass neutrinos become non-relativistic later
  - Impact on structure formation (few % level)
  - WMAP7: $\Sigma m_\nu < 0.58$ eV (95%)
  - Large scale structure: $\Sigma m_\nu < 0.28$ eV (95%): Thomas (2010)

Caveats and Future Prospects...

- Systematics
  - Errors here statistical
  - Systematics (choice of dataset, etc) “not small”
- Priors
  - Constraints *assume* a background cosmology
- Expect upper bound 0.1 eV in five years (Planck, Sloan-3 etc)
  - Maybe a decade to reach 0.05 eV