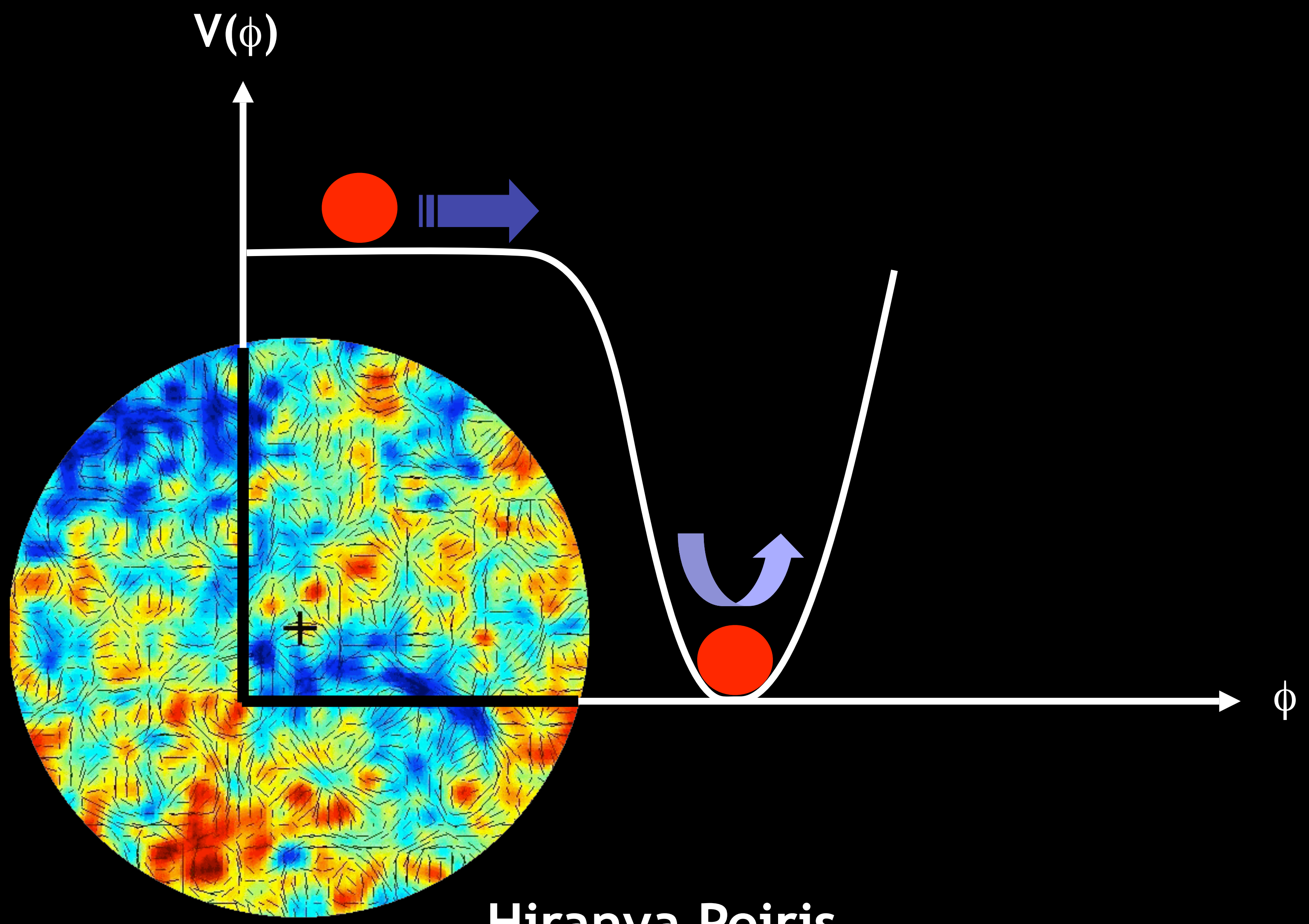
The physics of the cosmic microwave background



Hiranya Peiris

STFC Advanced Fellow

University of Cambridge

UNIVERSITY OF CAMBRIDGE

Before we start...

Acknowledgment: Anthony Challinor (University of Cambridge) for invaluable help in preparing these lectures.

Disclaimers:

- Time constraints necessitate brevity.
- Lectures intended to give only a flavour of the physics.
- Absolutely necessary to work through details (with the aid of a good textbook & the primary literature).

Recommended: Scott Dodelson, “Modern Cosmology” (2003)

Roadmap

Lecture 1: The physics of the cosmic microwave background.

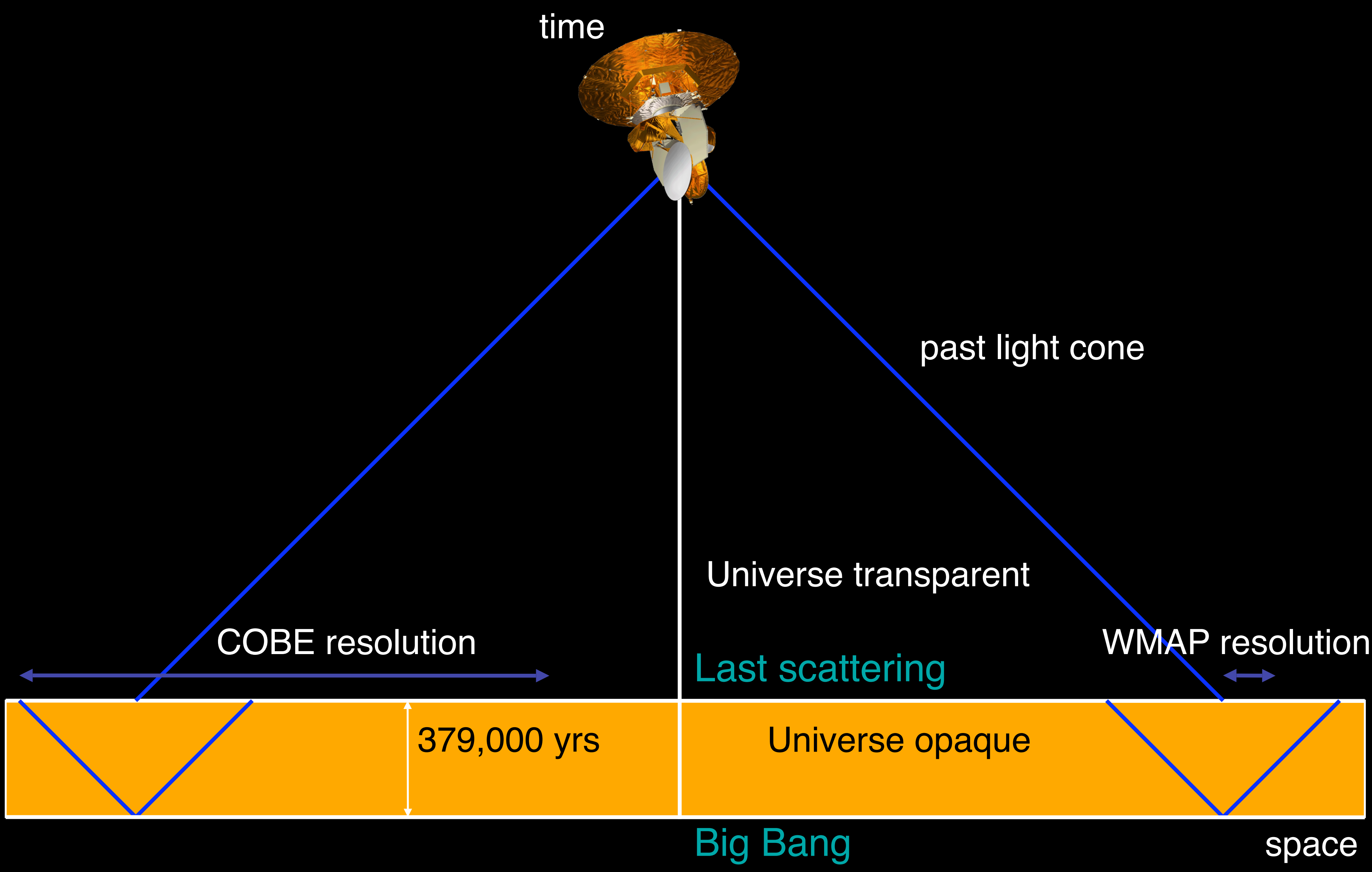
Lecture 2: What have we learnt about the early universe?

The Cosmic Microwave Background (CMB)

Credit: NASA/WMAP Science Team

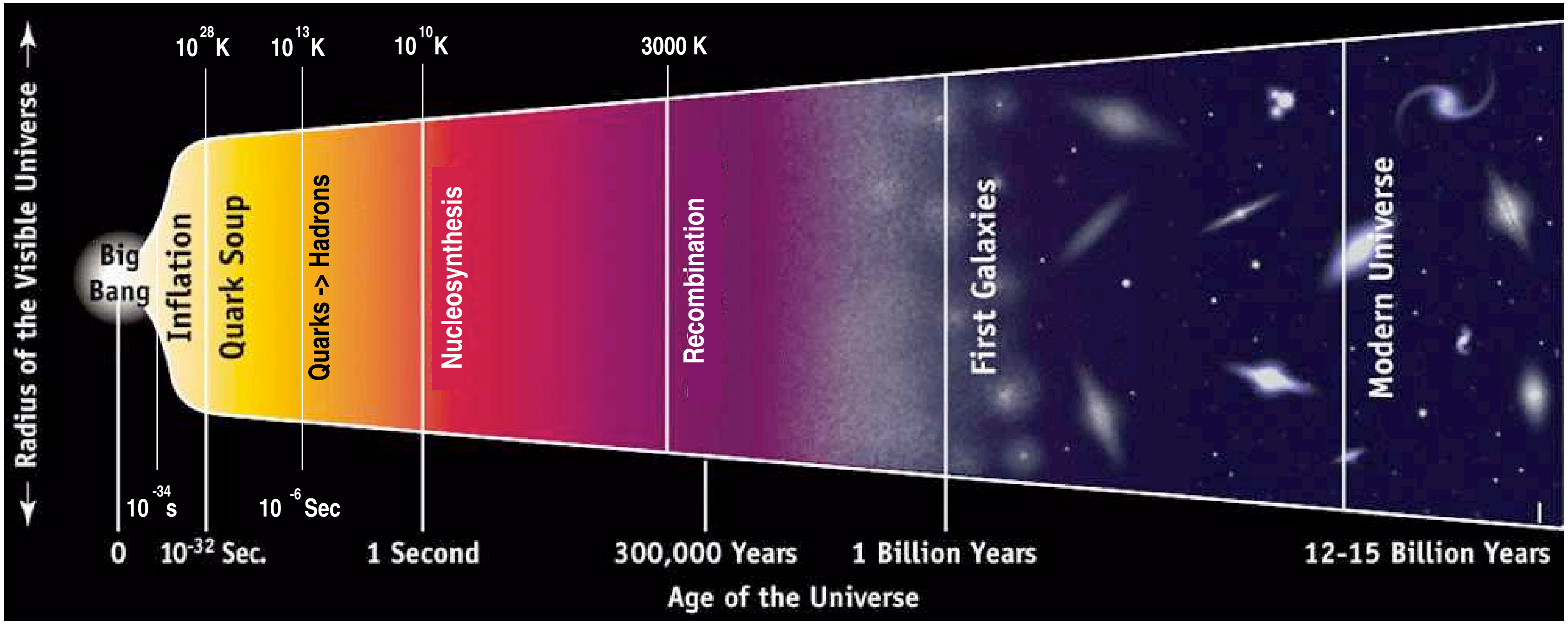
Space-time and CMB Physics

(NOT to scale)



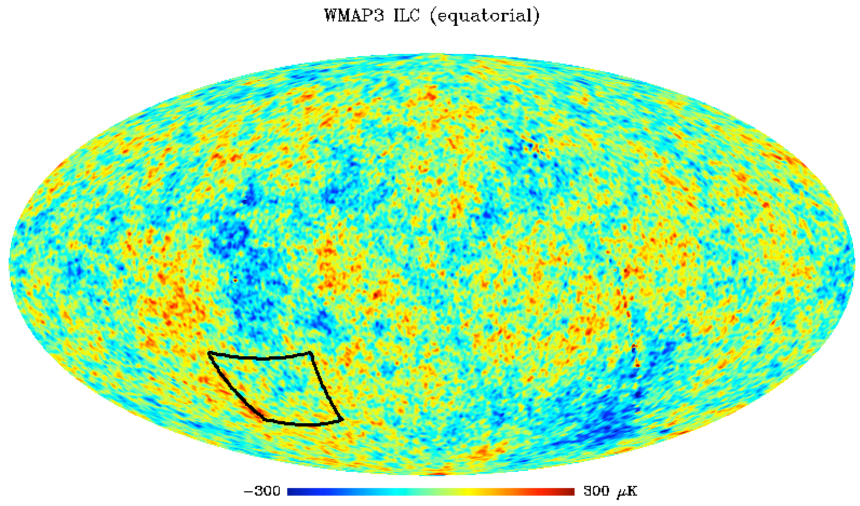
Thermal History

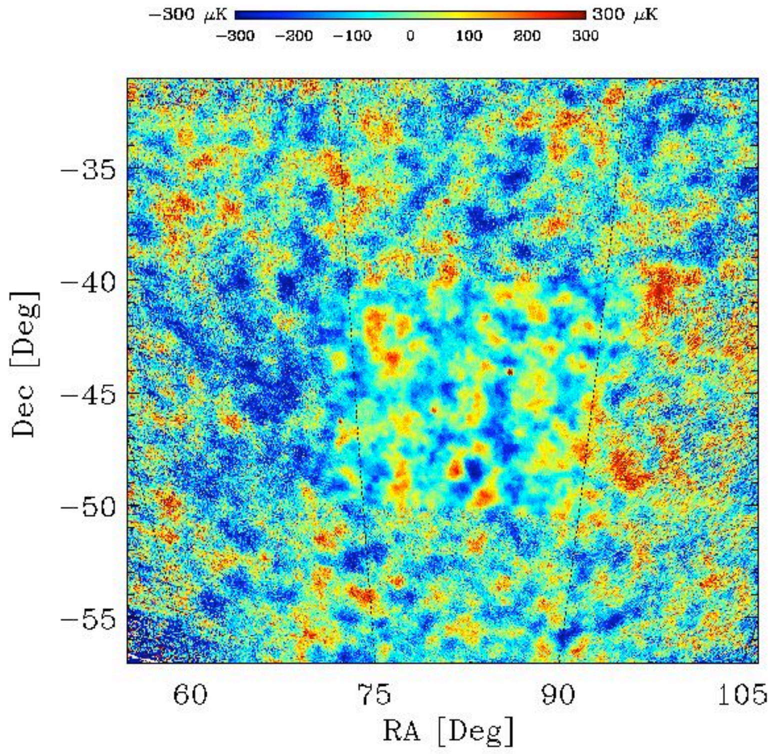
- CMB and matter plausibly produced during reheating at end of inflation
- CMB decouples around recombination, 300 kyr later
- Universe starts to reionize once first stars (?) form (somewhere in range $z = 10\text{–}20$) and 10% of CMB re-scatters



Mapping the CMB

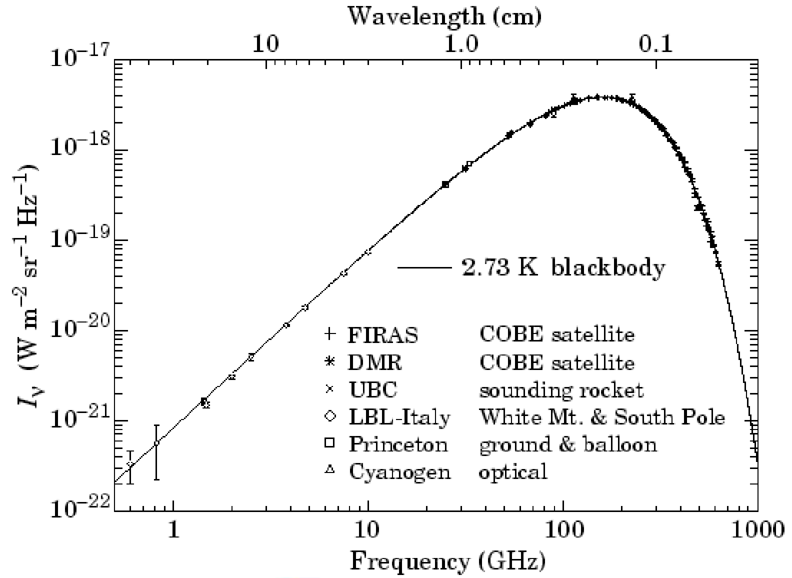
- WMAP3 internal-linear combination map (left) and BOOMERanG03 (right)
- Aim to answer in these lectures:
  - What is the physics behind these images?
  - What have we learned about cosmology from them?

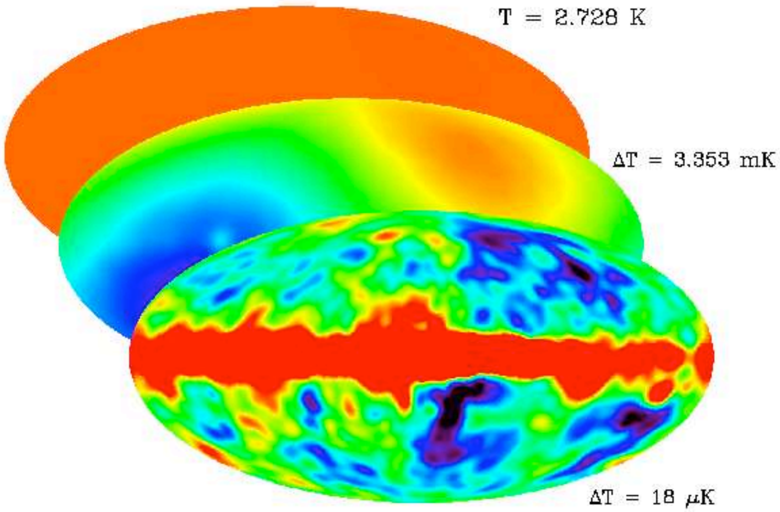




CMB spectrum and dipole anisotropy

- Microwave background almost perfect blackbody radiation
  - Temp. (COBE-FIRAS) 2.725 K
- Dipole anisotropy $\Delta T/T = \beta \cos\theta$ implies solar-system barycenter has velocity $v/c \equiv \beta = 0.00123$ relative to 'rest-frame' of CMB
- Variance of intrinsic fluctuations first detected by COBE-DMR: $(\Delta T/T)_{\rm rms} = 16\mu$K smoothed on 7° scale





Details of the thermal history

- Dominant element hydrogen recombines rapidly around $z \approx 1000$
  - Prior to recombination, Thomson scattering efficient and mean free path $1/(n_e \sigma_T)$ short cf. expansion time $1/H$
  - Little chance of scattering after recombination $\rightarrow$ photons free stream keeping imprint of conditions on last scattering surface

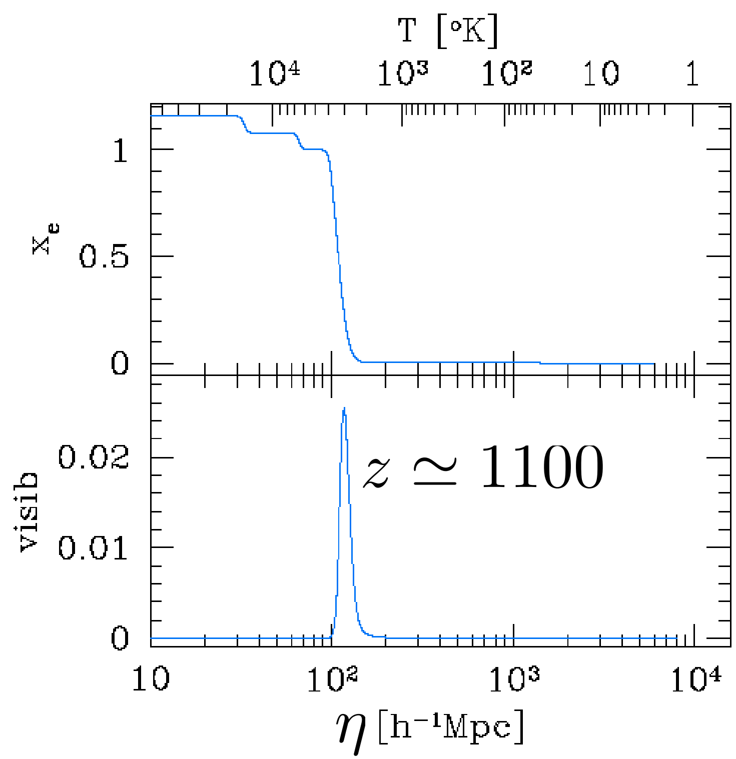
- Optical depth back to (conformal) time η for Thomson scattering:

$$\tau(\eta) = \int_{\eta}^{\eta_R} a n_e \sigma_T \, d\eta'$$

- $e^{-\tau}$ is prob. of no scattering back to η

- Visibility is probability of last scattering at η per $d\eta$:

$$\text{visibility}(\eta) = -\dot{\tau} e^{-\tau}$$



Anisotropies and the power spectrum

- Decompose temperature anisotropies in spherical harmonics

$$\Theta \equiv \Delta T(\hat{\boldsymbol{n}})/T = \sum_{lm} a_{lm} Y_{lm}(\hat{\boldsymbol{n}})$$

  - Under a rotation (R) of sky $a_{lm} \to D^l_{mm'}(R) a_{lm'}$
  - Demanding *statistical isotropy* requires, for 2-point function

$$\langle a_{lm} a^*_{l'm'} \rangle = D^l_{mM} D^{l'*}_{m'M'} \langle a_{lM} a^*_{l'M'} \rangle \quad \forall R$$

  - Only possible (from unitarity $D^{l*}_{Mm} D^l_{Mm'} = \delta_{mm'}$) if

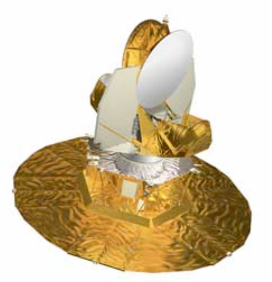
$$\langle a_{lm} a^*_{l'm'} \rangle = C_l \delta_{ll'} \delta_{mm'}$$

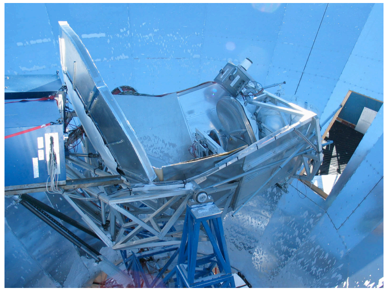
  - Symmetry restricts higher-order correlations also, but for *Gaussian* fluctuations all information in *power spectrum* C_l

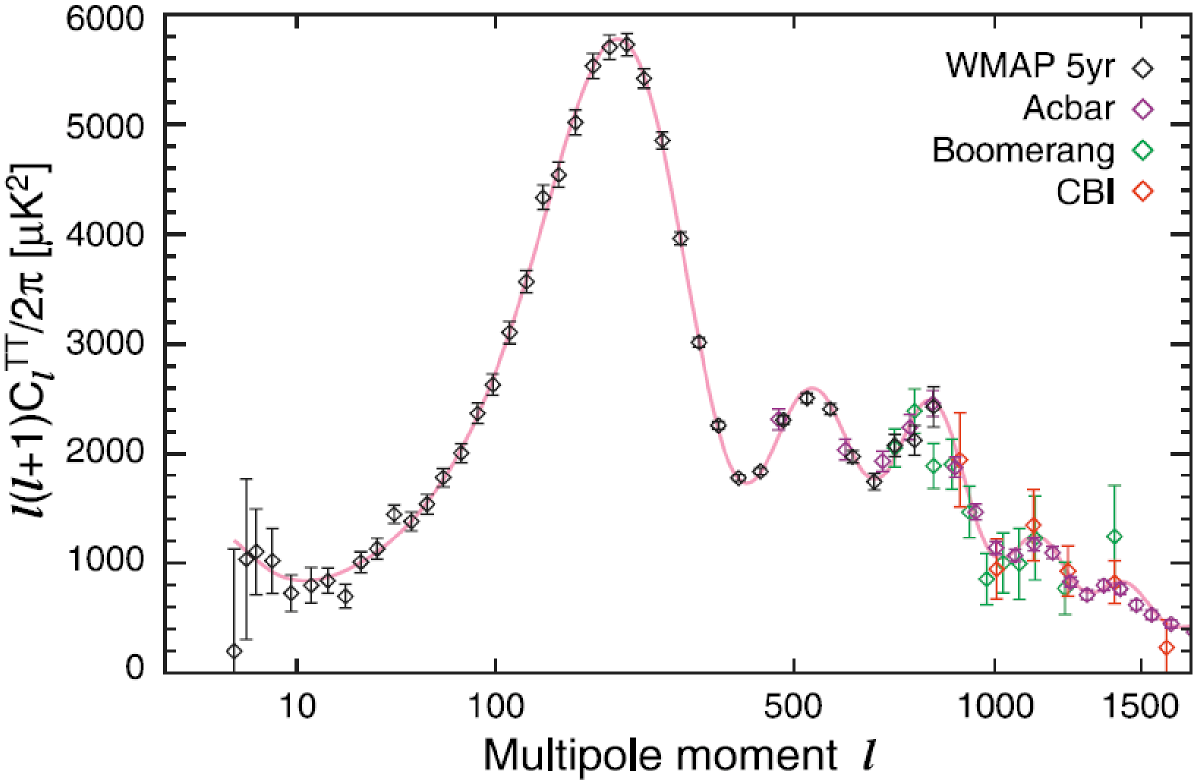
- Estimator for power spectrum $\hat{C}_l = \sum_m |a_{lm}|^2/(2l+1)$ has mean C_l and *cosmic variance*

$$\mathrm{var}(\hat{C}_l) = \frac{2}{2l+1} C_l^2$$

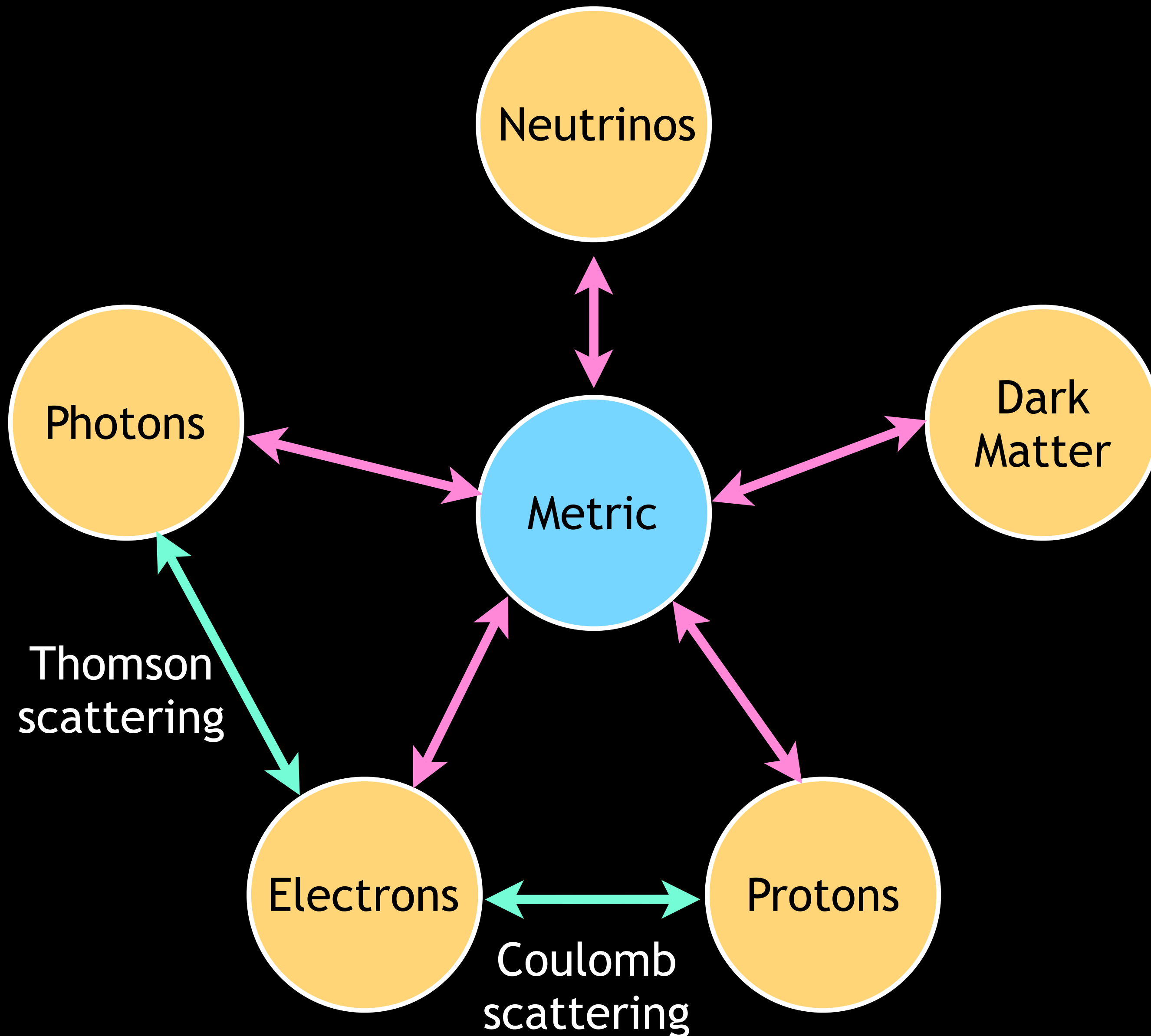
Measured power spectrum







Coupled Einstein-Boltzmann Equations



Einstein Equation

Relates the geometry to the energy:

$$G_{\mu\nu} \equiv R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R = 8\pi G T_{\mu\nu}$$

$g_{\mu\nu}$ metric tensor: “machine” to transform coordinates into physical invariants.

$R_{\mu\nu}$ Ricci tensor: depends on metric and its derivatives via Christoffel symbols.

R Ricci scalar: contraction of Ricci tensor, $R \equiv g^{\mu\nu} R_{\mu\nu}$

$G_{\mu\nu}$ Einstein tensor: describes geometry.

$T_{\mu\nu}$ Energy-momentum tensor: describes energy content.

Given a metric, LHS: (i) compute Christoffel symbols (ii) form Ricci tensor (iii) contact to form Ricci scalar (iv) form Einstein tensor. Finally equate to RHS.

Perturbed FRW metric in CNG

The Conformal Newtonian Gauge describes the perturbed FRW metric.

$$ds^2 = a^2(\eta)[(1+2\Psi)d\eta^2 - \delta_{ij}(1-2\Phi)dx^i dx^j]$$

where η = conformal time. Metric perturbations described by scalar potentials Ψ (Newtonian potential) and Φ (perturbation to spatial curvature).

Only describes scalar perturbations.

By the Decomposition Theorem, scalars, vectors and tensors evolve independently. Only scalars couple to matter.

Boltzmann Equation

Want to describe distributions of photons and matter inhomogeneities. Photons and neutrinos are only fully described by distribution functions (DFs) in phase space. Energy-momentum tensor is expressed through integrals over momenta of the DFs.

$$\frac{df}{dt} = C[f]$$

RHS: all possible collision terms

The DF gives number of particles in (invariant) phase space volume $d^3\vec{x}d^3\vec{p}$:

$$dN = f(\vec{x}, \vec{p}, t) d^3\vec{x} d^3\vec{p}$$

Zeroth order: Bose-Einstein (bosons) and Fermi-Dirac (fermions) DFs.

Collision terms due to Thomson or Coulomb scattering need to be computed for all species except cold dark matter.

Temperature anisotropies

- On degree scales, scattering time short c.f. wavelength of fluctuations and (local!) temperature is uniform plus dipole: $\Theta_0 + \boldsymbol{e} \cdot \boldsymbol{v}_b$
- Observed temperature anisotropy is snapshot of this at last scattering but modified by gravity:

$$[\Theta(\hat{\boldsymbol{n}}) + \psi]_R = \underbrace{\Theta_0|_*}_{\text{temp.}} + \underbrace{\psi|_*}_{\text{gravity}} + \underbrace{\boldsymbol{e} \cdot \boldsymbol{v}_b|_*}_{\text{Doppler}} + \underbrace{\int_*^R (\dot{\psi} + \dot{\phi})\, d\eta}_{\text{ISW}}$$

  with line of sight $\hat{\boldsymbol{n}} = -\boldsymbol{e}$, and Θ_0 isotropic part of Θ

  - Ignores anisotropic scattering, finite width of visibility function (i.e. last-scattering surface) and reionization
    - Will fix these omissions shortly

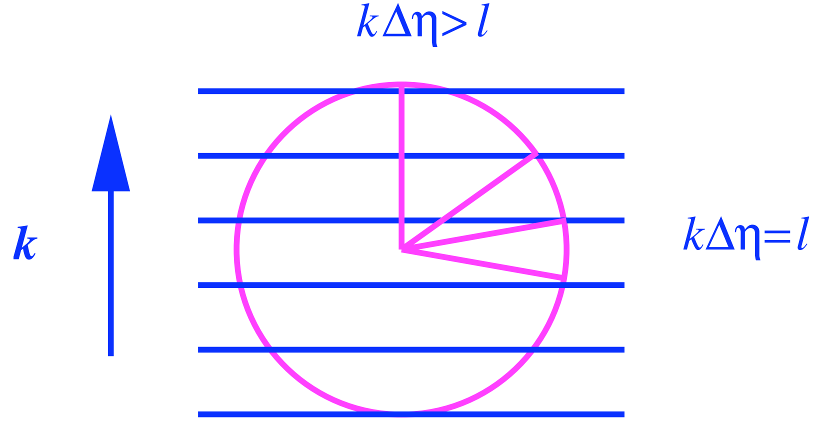
Spatial to angular projection

- Consider angular projection at origin of potential $\psi(\boldsymbol{x}, \eta_*)$ over last-scattering surface; for a single Fourier component

$$\begin{aligned}\psi(\hat{\boldsymbol{n}}) &= \psi(\hat{\boldsymbol{n}}\Delta\eta, \eta_*) \qquad \Delta\eta \equiv \eta_R - \eta_* \\ &= \psi(\boldsymbol{k}, \eta_*) \sum_{lm} 4\pi i^l j_l(k\Delta\eta) Y_{lm}(\hat{\boldsymbol{n}}) Y_{lm}^*(\hat{\boldsymbol{k}})\end{aligned}$$

$$\psi_{lm} \sim 4\pi\psi(\boldsymbol{k}, \eta_*) i^l j_l(k\Delta\eta) Y_{lm}^*(\hat{\boldsymbol{k}})$$

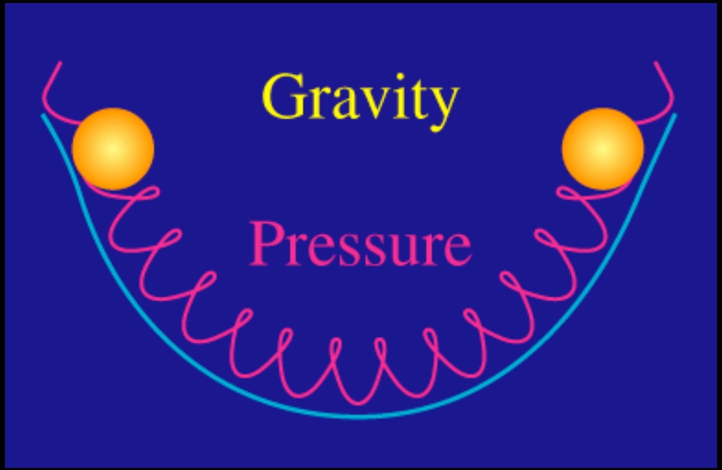
- $j_l(k\Delta\eta)$ peaks when $k\Delta\eta \approx l$ but for given l considerable power from $k > l/\Delta\eta$ also (wavefronts perpendicular to line of sight)



– CMB anisotropies at multipole l mostly sourced from fluctuations with linear wavenumber $k \sim l/\Delta\eta$ where conformal distance to last scattering $\approx$ 14 Gpc

CMB as a sound wave

(graphic by W. Hu)



Forced damped harmonic oscillator

Last scattering surface : snapshot of the photon-baryon fluid

On large scales : primordial ripples, purely GR Effects

On smaller scales: { Photons radiation pressure / Gravity compression } Sound waves

Stop oscillating at recombination

Smaller than photon mean free path: Exponentially damped by photon diffusion

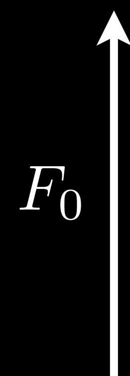
Horizon size at last scattering surface is fundamental mode

Peebles & Yu (1970), Sunyaev & Zel'dovich (1970), Sachs and Wolfe (1968), Silk (1968)

SHO analogy I

Consider simple harmonic oscillator with mass *m*, force constant *k* driven by external force F_0.

$$\ddot{x} + \frac{k}{m}x = \frac{F_0}{m}$$



Assuming oscillator is initially at rest,

$$x = A\cos(\omega t) + \frac{F_0}{m\omega^2}$$

Peaks at $t = \dfrac{n\pi}{\omega}$.

unforced: peak heights equal
forced: odd (even) peaks higher (lower)
forcing disparity greater for lower
Even peaks correspond to negative *x*

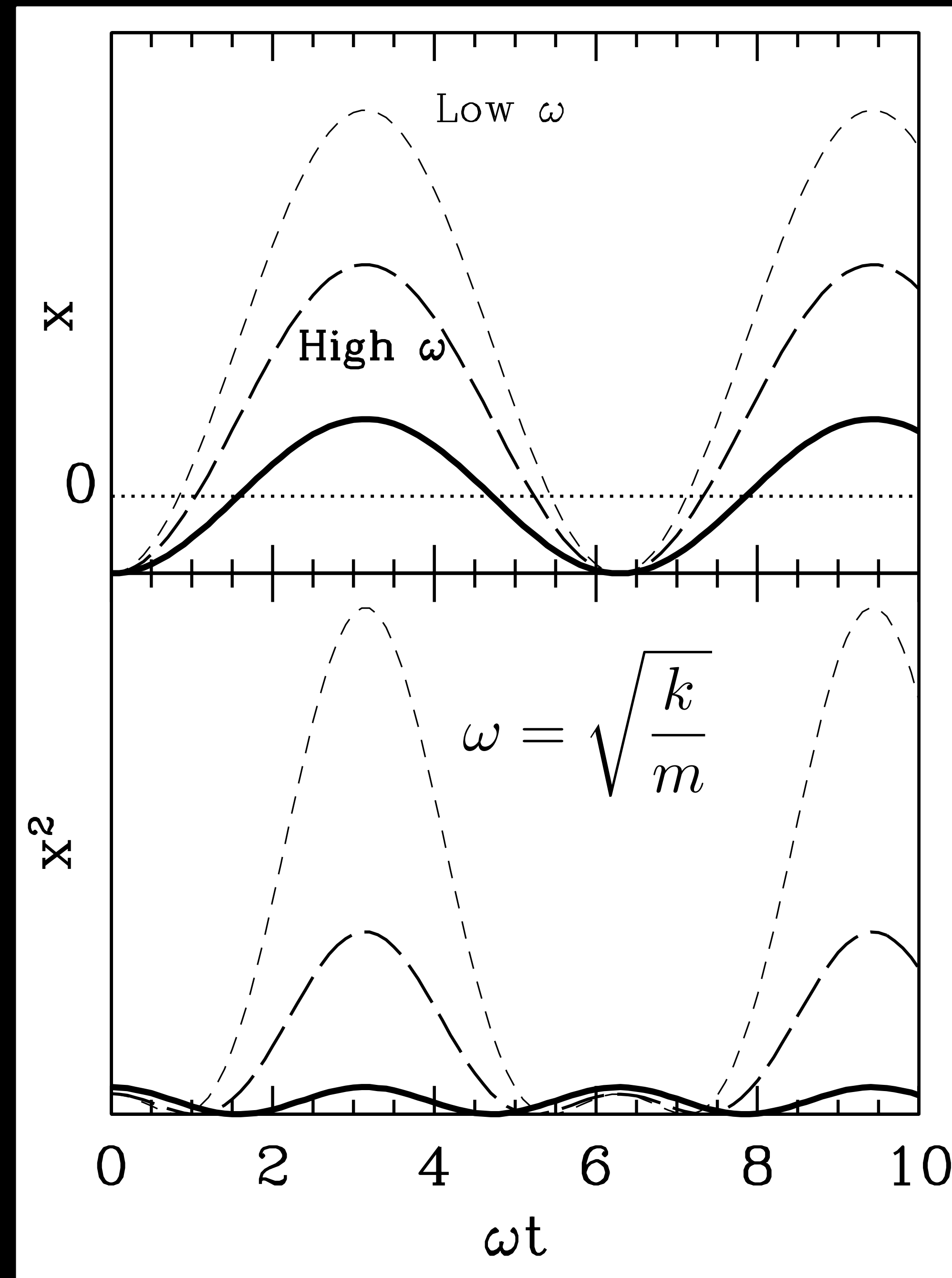


Figure from Dodelson, “Modern Cosmology”

SHO analogy II

Cartoon gravitational instability:

$$\ddot{\delta} + [\text{Pressure} \;-\; \text{Gravity}]\delta = 0$$

Oscillator analogy:

$$\ddot{\Theta}_0 + k^2 c_s^2 \Theta_0 = F$$

F_0

F is force due to gravity, c_s^2 is sound speed of entire photon-baryon fluid.

Add more baryons; sound speed (frequency) goes down.

Modes enter horizon and start to oscillate. See their phases frozen at recombination. Peaks are maximum amplitudes.

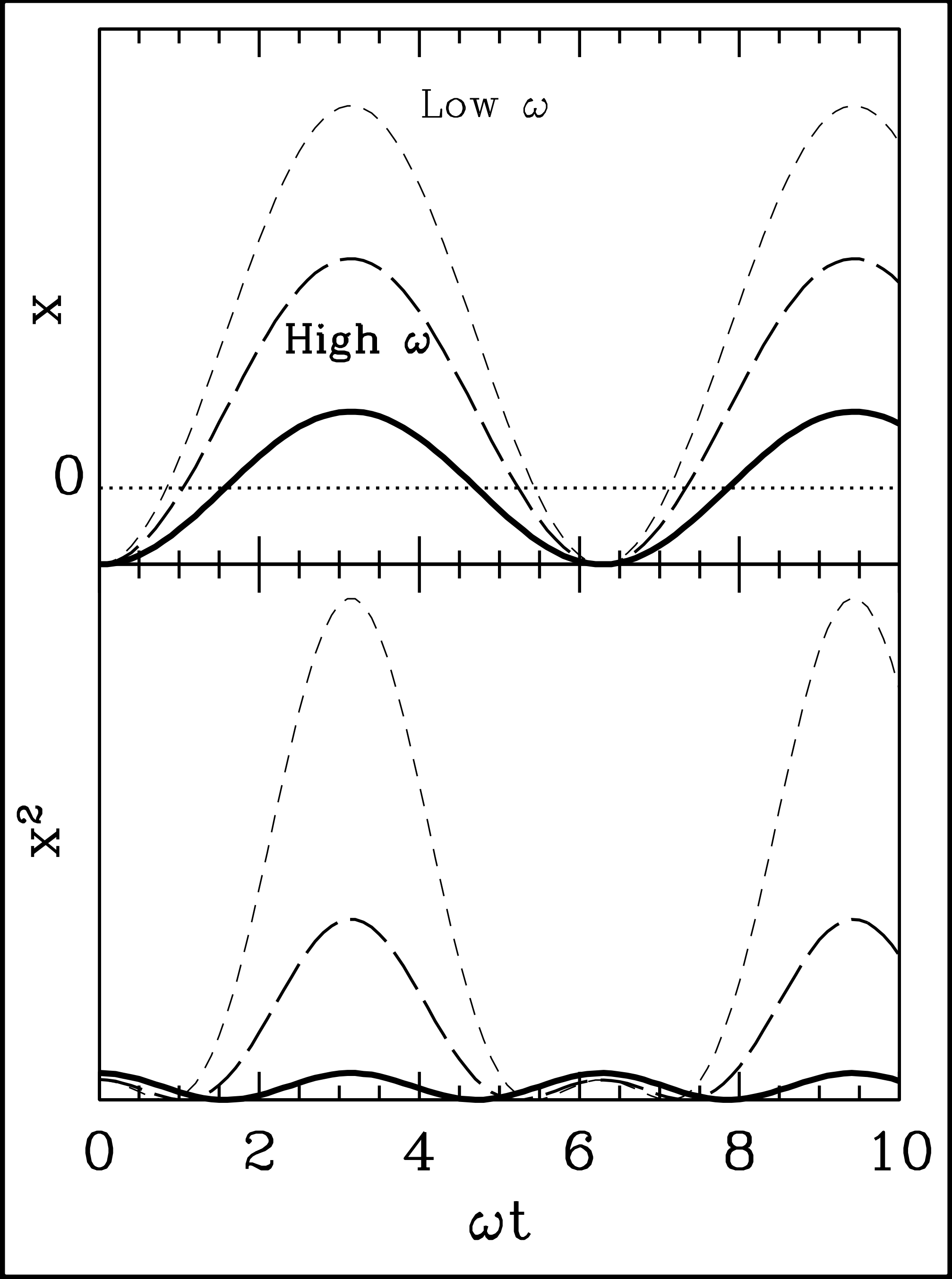


Figure from Dodelson, “Modern Cosmology”

Acoustic physics

- Photon isotropic temperature Θ_0 and electron velocity v_b at last scattering depend on acoustic physics of pre-recombination plasma
- Large-scale approximation: ignore diffusion and slip between CMB and baryon bulk velocities (requires scattering rate $\gg k$)
  - Photon-baryon plasma behaves like perfect fluid responding to gravity (drives infall to wells), Hubble drag of baryons, gravitational redshifting and baryon pressure (resists infall):

$$\ddot{\Theta}_0 + \underbrace{\frac{\mathcal{H}R}{1+R}\dot{\Theta}_0}_{\text{Hubble drag}} + \underbrace{\frac{1}{3(1+R)}k^2\Theta_0}_{\text{pressure}} = \underbrace{\ddot{\phi}}_{\text{redshift}} + \frac{\mathcal{H}R}{1+R}\dot{\phi} - \underbrace{\frac{1}{3}k^2\psi}_{\text{infall}}$$

    where $R \equiv 3\rho_b/(4\rho_\gamma) \propto a$

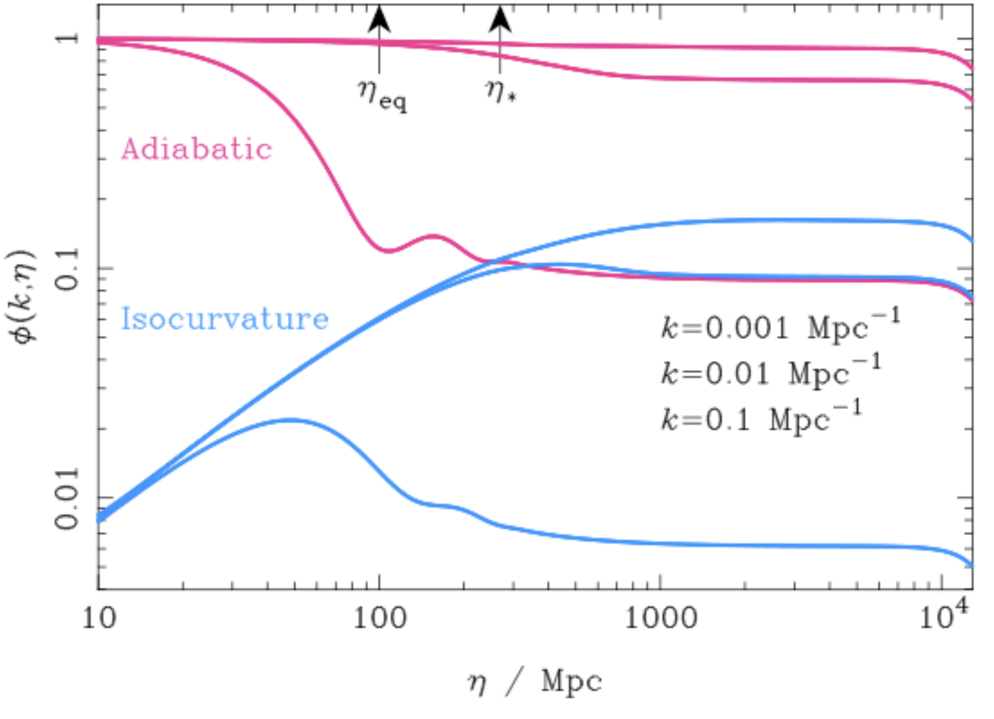
  - WKB solutions of homogeneous equation:

$$(1+R)^{-1/4}\cos kr_s \quad , \quad (1+R)^{-1/4}\sin kr_s$$

    with *sound horizon* $r_s \equiv \int_0^\eta \frac{d\eta'}{\sqrt{3(1+R)}}$ *sound speed* $c_s = \frac{1}{\sqrt{3(1+R)}}$

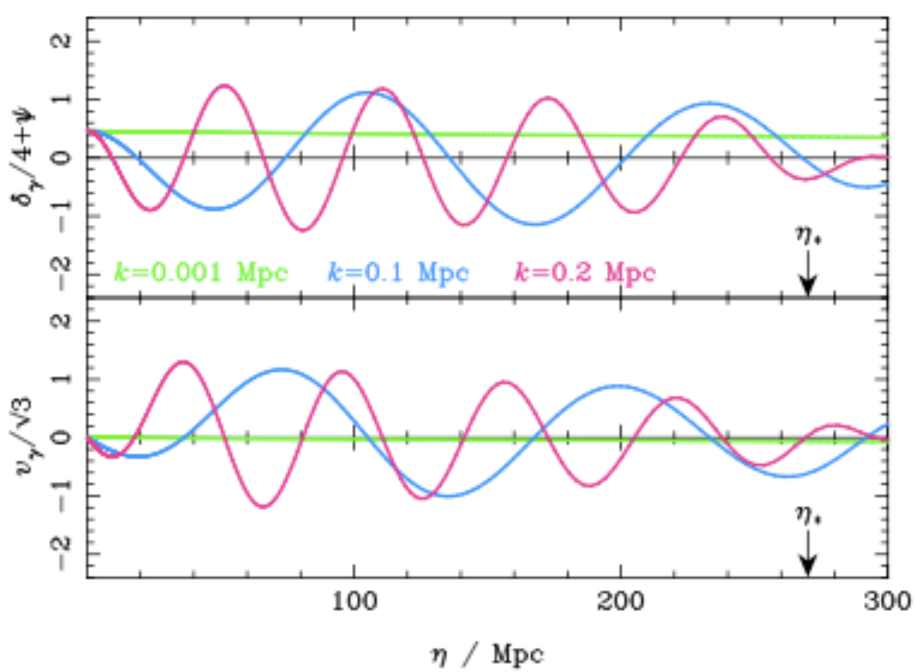
Gravitational potential and acoustic driving

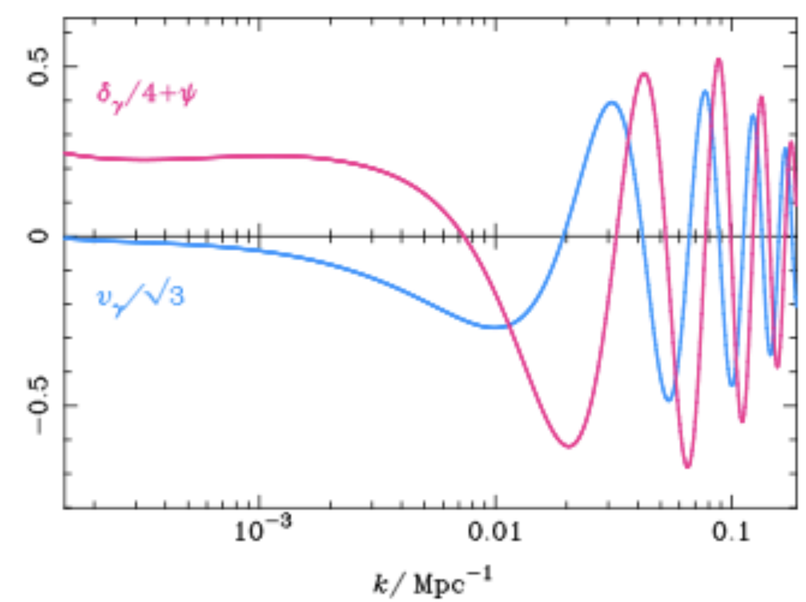
- For adiabatic initial conditions (e.g. simple inflation models), no *relative* perturbations between number densities of species
  - Density perturbations of all species vanish on same hypersurface — its curvature equals comoving curvature $\mathcal{R}$ on super-Hubble scales
- Adiabatic driving term mimics $\cos k\eta$
  - Oscillator is resonantly driven inside sound horizon whilst CDM sub-dominant
  - Potentials constant in matter domination then decay as DE dominates



Acoustic oscillations: adiabatic models

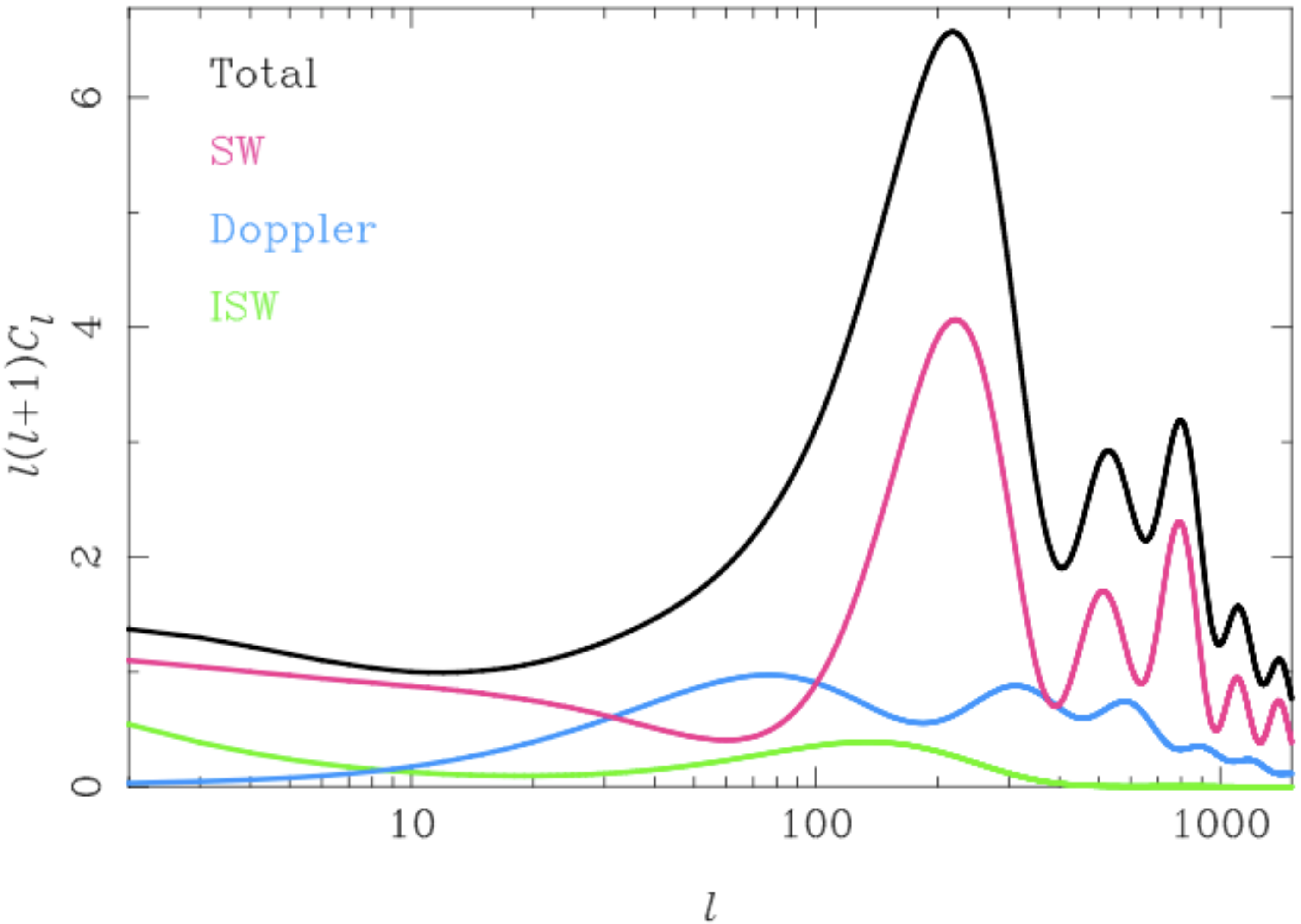
- $\delta_\gamma/4 \equiv \Theta_0$ starts out constant at $-\psi(0)/2 \Rightarrow$ cosine oscillation $\cos kr_s$ about equilibrium point $-(1+R)\psi$
  - Modes with $k\int_0^{\eta_*} c_s\, d\eta = n\pi$ are at extrema at last scattering $\Rightarrow$ acoustic peaks in power spectrum
  - $v_b \approx v_\gamma$ follows from continuity equation ($\pi/2$ out of phase with Θ_0 so Doppler effect 'fills in' zeroes of $\Theta_0 + \psi$)





Adiabatic anisotropy power spectrum

- Temperature power spectrum for scale-invariant curvature fluctuations



Tightly coupled solution

Elegant solution first due to Sugiyama & Hu (1995):

$$\begin{aligned}\Theta_0(\eta) + \Phi(\eta) &= [\Theta_0(0) + \Phi(0)] \cos(kr_s) \\ &+ \frac{1}{\sqrt{3}} \int_0^{\eta} d\eta' [\Theta_0(\eta') + \Phi(\eta')] \sin[k(r_s(\eta) - r_s(\eta'))].\end{aligned}$$

- Gets peak locations right and obtains odd/even height disparities fairly well.
- Neatly divides problem into
  (i) calculation of external gravitational potentials generated by CDM.
  (ii) effect of these potentials on the anisotropies.
- Clearly illustrates that cosine mode is the one excited by inflationary models.

Complications: photon diffusion

- Photons diffuse out of dense regions damping inhomogeneities in Θ_0 (and creating higher moments of Θ)
  - In time $d\eta$, when mean-free path $\ell = (an_e\sigma_T)^{-1} = 1/|\dot\tau|$, photon random walks mean square distance $\ell d\eta$
  - Defines a diffusion length by last scattering:

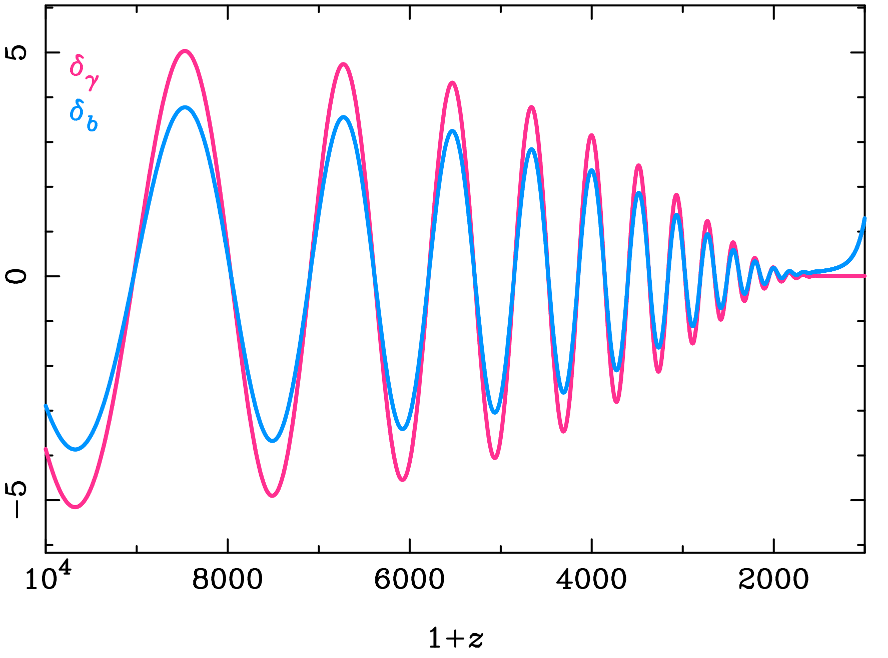
$$k_D^{-2} \sim \int_0^{\eta_*} |\dot\tau|^{-1} d\eta \approx 0.2(\Omega_m h^2)^{-1/2}(\Omega_b h^2)^{-1}(a/a_*)^{5/2}\,\mathrm{Mpc}^2$$

- Get exponential suppression of photons (and baryons)

$$\Theta_0 \propto e^{-k^2/k_D^2} \cos kr_s$$

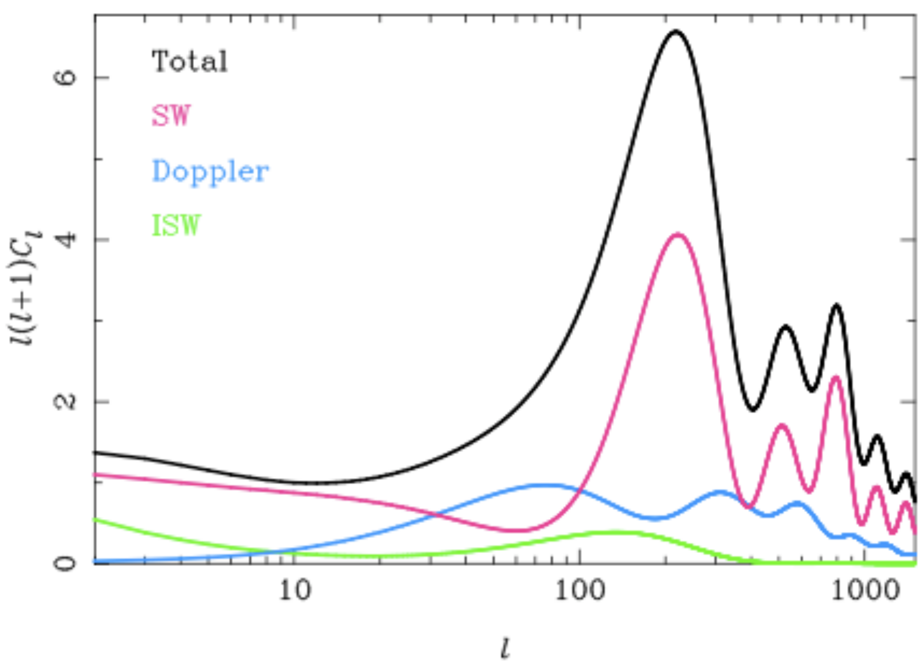
on scales below $\sim$ 30 Mpc at last scattering

  - Implies e^{-2l^2/l_D^2} *damping tail* in power spectrum



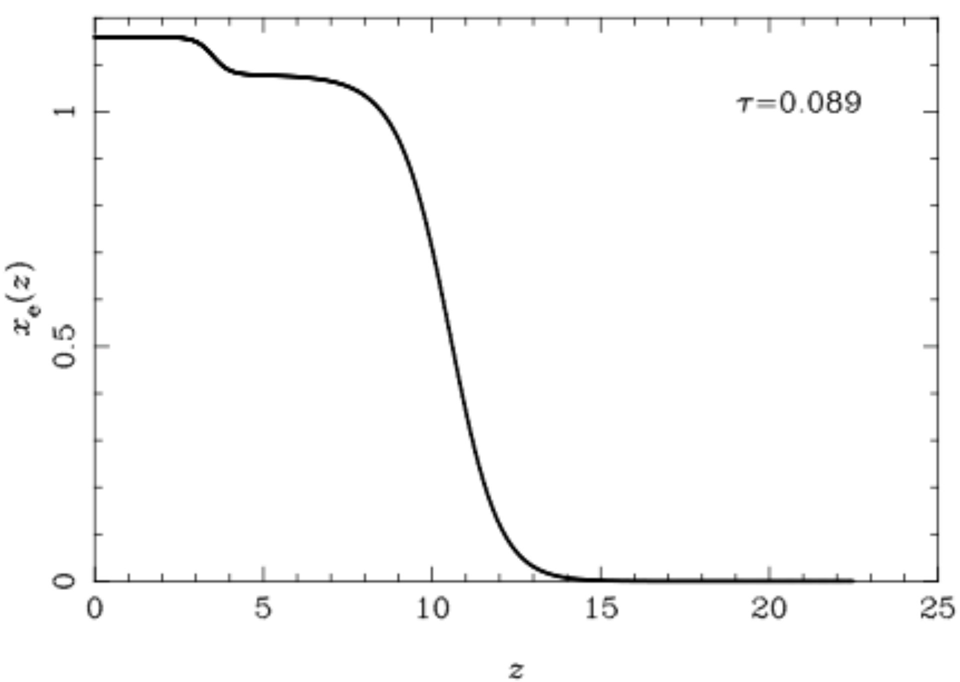
Integrated Sachs-Wolfe Effect

- Linear $\Theta_{\rm ISW} \equiv \int (\dot\phi + \dot\psi)\, d\eta$ from late-time dark-energy domination and residual radiation at η_*; non-linear small-scale effect from collapsing structures
  - In adiabatic models early ISW adds coherently with SW at first peak since $\Theta_0 + \psi \sim -\psi/2$ same sign as $\dot\psi$
  - Late-time effect is large scale (integrated effect $\Rightarrow$ peak–trough cancellation suppresses small scales)
  - Late-time effect in dark-energy models produces positive correlation between large-scale CMB and LSS tracers for $z < 2$



Reionization: effect of rescattering

- Lyman-α optical depth, as measured by quasar absorption spectra, rises rapidly around $z \sim 6$ – probing the end of the epoch of reionization
- CMB Thomson scatters off all (re-)ionized gas back to z_* with optical depth $\tau = \int_{\eta_*}^{\eta_R} a n_e \sigma_T \, d\eta$
  - Produces a further low redshift peak in the visibility function (important for polarization – see later)



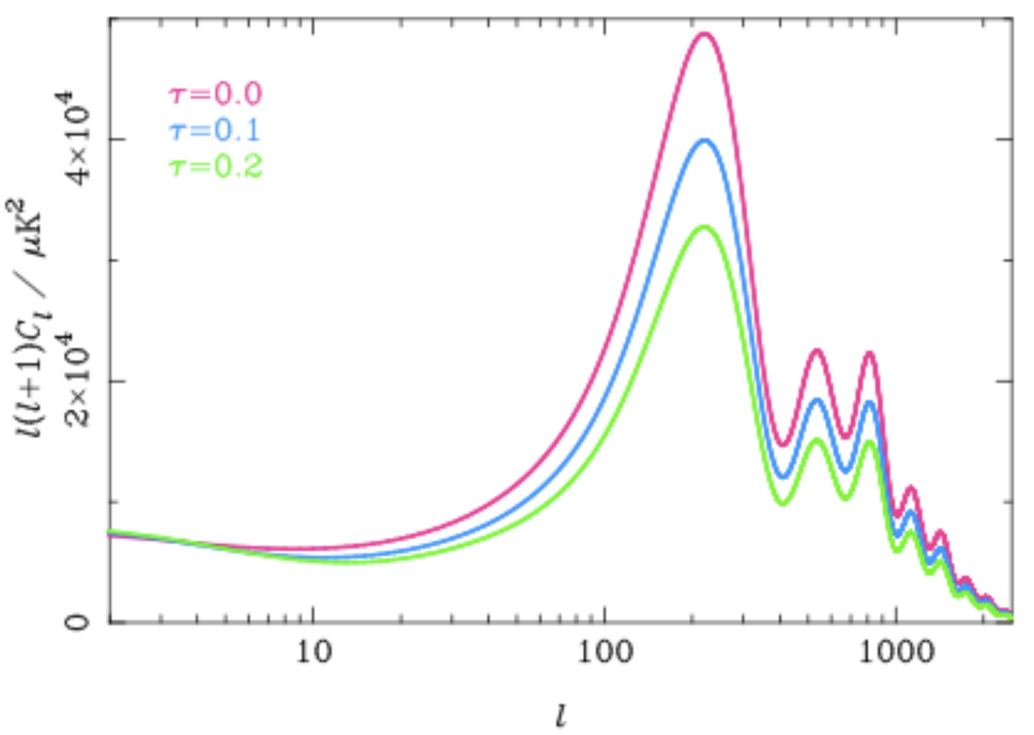
Reionization: effect of rescattering

- CMB re-scatters off re-ionized gas; ignoring anisotropic (Doppler and quadrupole) scattering terms, locally at reionization have

$$\Theta(\boldsymbol{e}) + \psi \to e^{-\tau}[\Theta(\boldsymbol{e}) + \psi] + (1 - e^{-\tau})(\Theta_0 + \psi)$$

  - Outside horizon at reionization, $\Theta(\boldsymbol{e}) \approx \Theta_0$ and scattering has no effect
  - Well inside horizon, $\Theta_0 + \psi \approx 0$ and observed anisotropies

$$\Theta(\hat{\boldsymbol{n}}) \to e^{-\tau}\Theta(\hat{\boldsymbol{n}}) \quad \Rightarrow \quad C_l \to e^{-2\tau} C_l$$

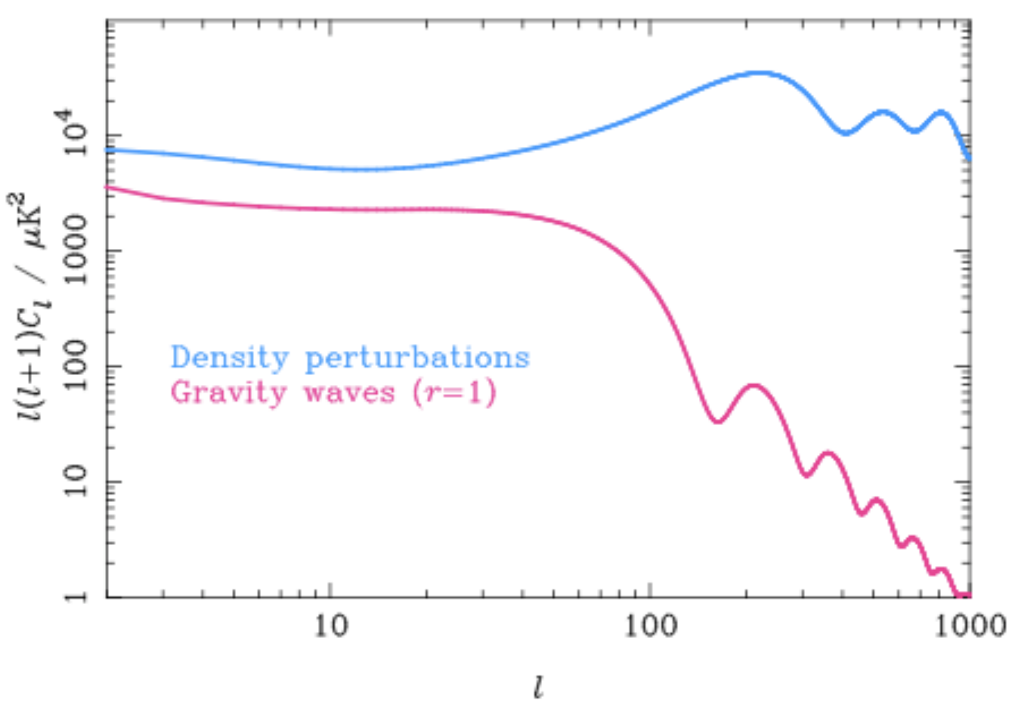


Gravitational waves

- Tensor metric perturbations $ds^2 = a^2[d\eta^2 - (\delta_{ij} + h_{ij})dx^i dx^j]$ with $\delta^{ij}h_{ij} = 0$
  - Shear $\propto \dot{h}_{ij}$ gives anisotropic redshifting $\Rightarrow$

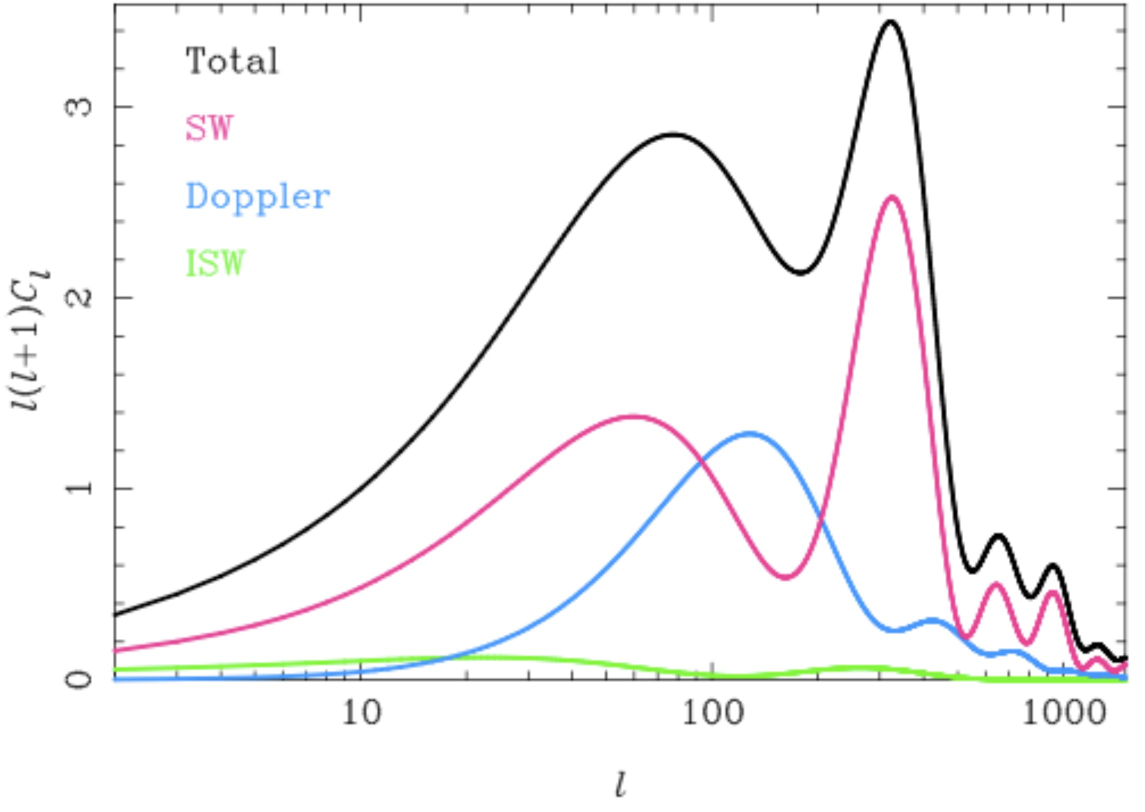
$$\Theta(\hat{\boldsymbol{n}}) \approx -\frac{1}{2}\int d\eta\, \dot{h}_{ij}\hat{n}^i\hat{n}^j$$

  - Only contributes on large scales since h_{ij} decays like a^{-1} after entering horizon



Isocurvature modes

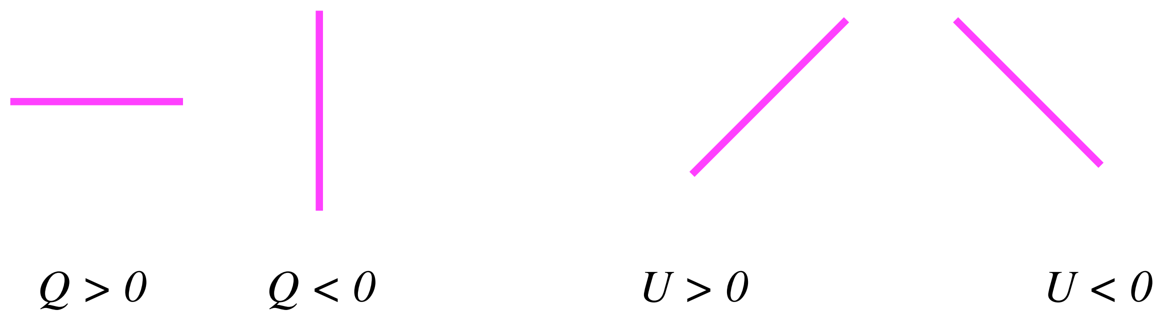
- CDM isocurvature most physically motivated (perturb CDM relative to everything else)
- Starts off with $\delta_\gamma(0) = \phi(0) = 0$ so matches onto $\sin kr_s$ modes
- Temperature power spectrum for $n_{\rm iso} = 2$ entropy fluctuations (CDM isocurvature mode)



CMB polarization: Stokes parameters

- For plane wave along z, symmetric trace-free correlation tensor of electric field $\boldsymbol{E}$ defines (transverse) linear polarization tensor:

$$\mathcal{P}_{ab} \equiv \begin{pmatrix} \frac{1}{2}\langle E_x^2 - E_y^2 \rangle & \langle E_x E_y \rangle \\ \langle E_x E_y \rangle & -\frac{1}{2}\langle E_x^2 - E_y^2 \rangle \end{pmatrix} \equiv \frac{1}{2}\begin{pmatrix} Q & U \\ U & -Q \end{pmatrix}$$



- Under right-handed rotation of x and y through ψ about propagation direction (z)

$$Q \pm iU \rightarrow (Q \pm iU)e^{\mp 2i\psi} \quad \Rightarrow \quad Q + iU \text{ is spin -2}$$

E and B modes

- Decomposition into E and B modes (use θ, $-\phi$ basis to define Q and U)

$$\mathcal{P}_{ab}(\hat{\boldsymbol{n}}) = \nabla_{\langle a}\nabla_{b\rangle}P_E + \epsilon^c{}_{(a}\nabla_{b)}\nabla_c P_B$$
$$\Rightarrow \quad Q + iU = \bar{\eth}\bar{\eth}(P_E - iP_B)$$

  – Spin-lowering operator: $\bar{\eth}\,{}_s\eta = -\sin^{-s}\theta(\partial_\theta - i\mathrm{cosec}\,\partial_\phi)(\sin^s\theta\,{}_s\eta)$

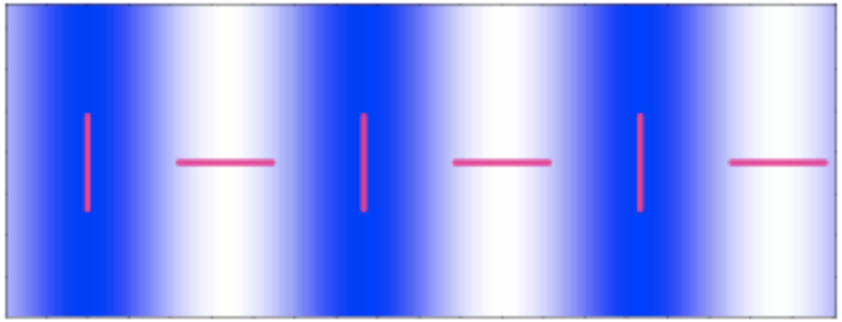
- Expand P_E and P_B in spherical harmonics, e.g.

$$P_E(\hat{\boldsymbol{n}}) = \sum_{lm}\sqrt{\frac{(l-2)!}{(l+2)!}}E_{lm}Y_{lm}(\hat{\boldsymbol{n}}) \quad \Rightarrow \quad (Q \pm iU)(\hat{\boldsymbol{n}}) = \sum_{lm}(E_{lm} \mp iB_{lm})_{\mp 2}Y_{lm}(\hat{\boldsymbol{n}})$$

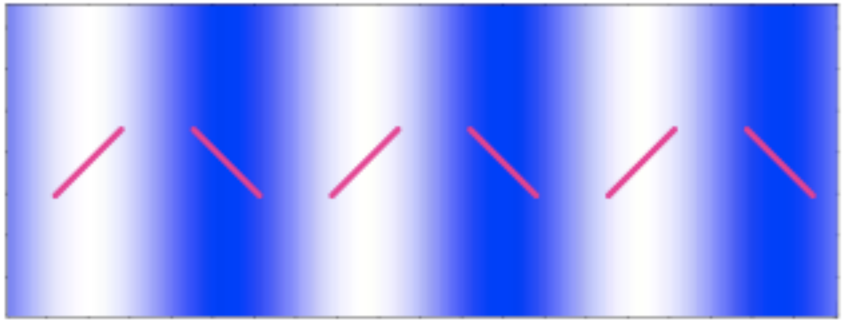
  – Spin-weight harmonics ${}_sY_{lm}$ provide orthonormal basis for spin-s functions

- Only three power spectra if parity respected in mean: C_l^E, C_l^B and C_l^{TE}

Pure E mode

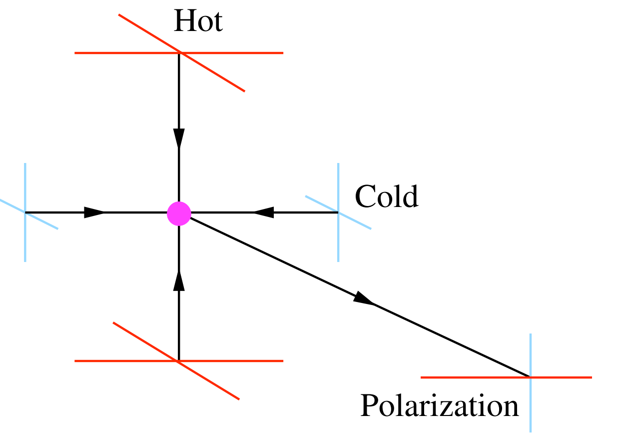


Pure B mode



CMB polarization: Thomson scattering

- Photon diffusion around recombination → local temperature quadrupole
  - Subsequent Thomson scattering generates (partial) linear polarization with r.m.s. $\sim 5\,\mu$K from density perturbations



- Thomson scattering of radiation quadrupole produces linear polarization (dimensionless temperature units!)

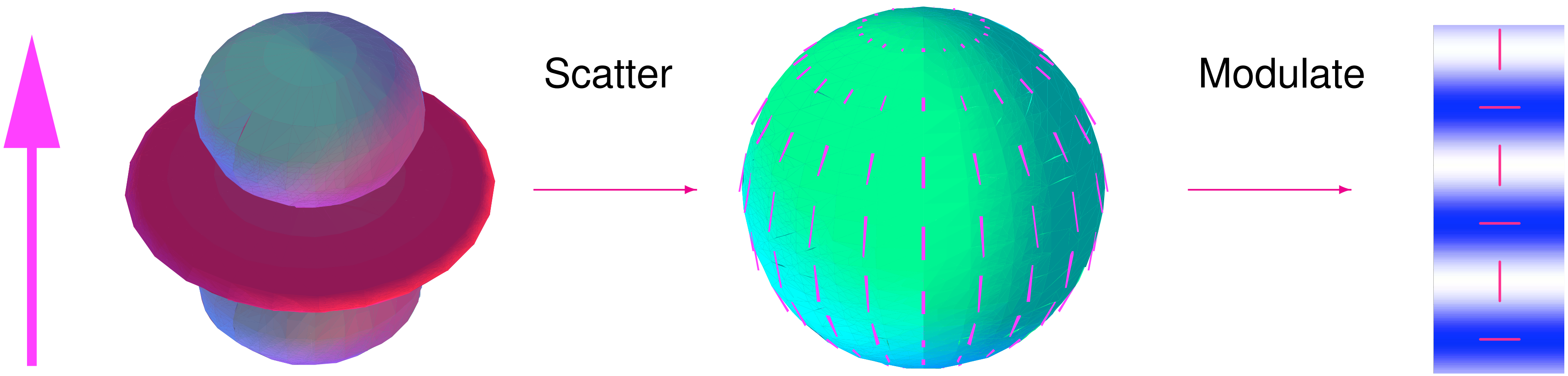
$$d(Q \pm iU)(\boldsymbol{e}) = \frac{3}{5} a n_e \sigma_T d\eta \sum_m {}_{\pm 2}Y_{2m}(\boldsymbol{e}) \left(E_{2m} - \sqrt{\frac{1}{6}} \Theta_{2m} \right)$$

  - Purely electric quadrupole ($l = 2$)

- In linear theory, generated $Q + iU$ then conserved for free-streaming radiation
  - Suppressed by $e^{-\tau}$ if further scattering at reionization

CMB polarization: scalar perturbations

- Single plane wave of scalar perturbation has $\Theta_{2m} \propto Y^*_{2m}(\hat{\boldsymbol{k}}) \Rightarrow$ with $\hat{\boldsymbol{k}}$ along z, $dQ \propto \sin^2\theta$ and $dU = 0$

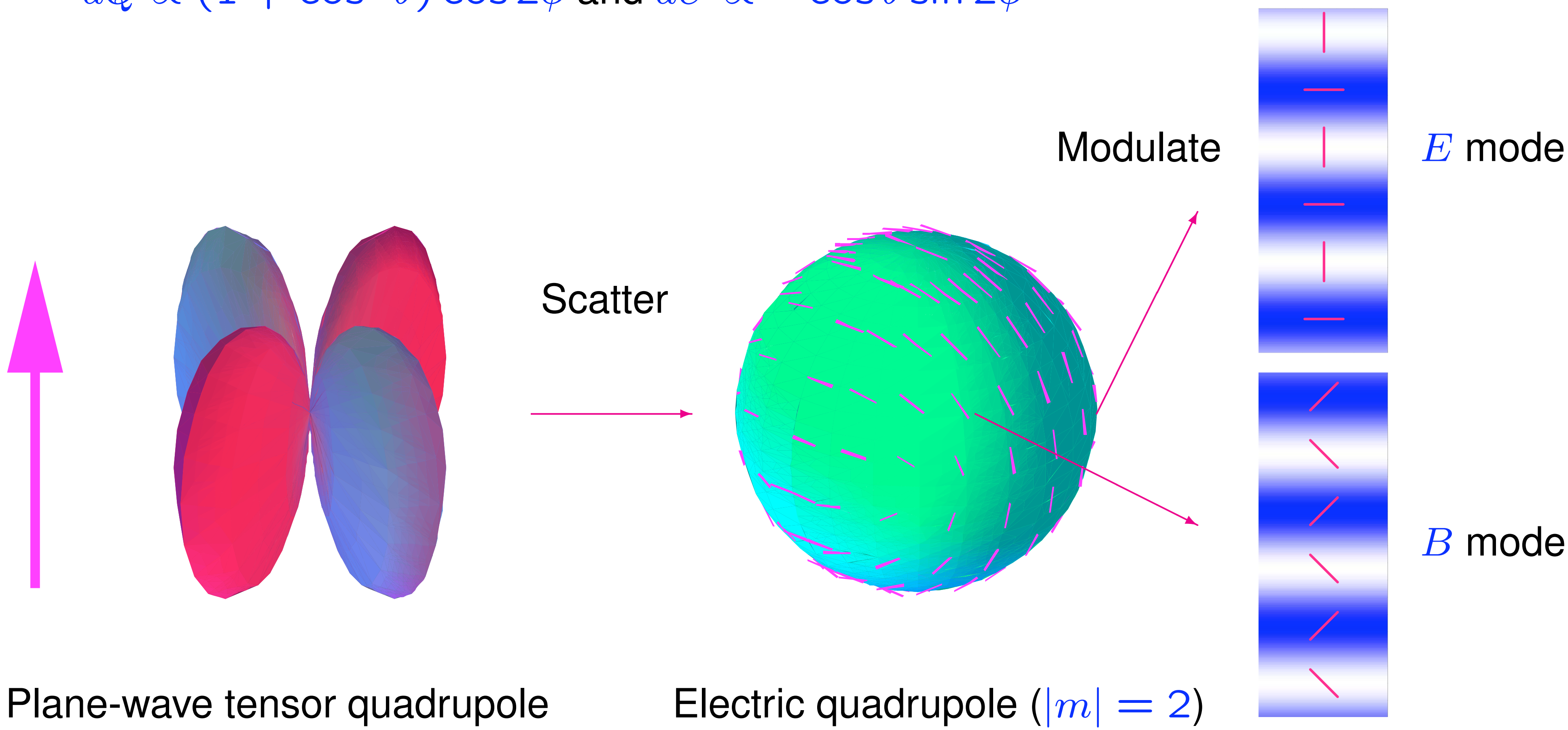


Plane-wave scalar quadrupole · Electric quadrupole ($m = 0$) · Pure E mode

- Linear scalar perturbations produce only E-mode polarization
- Mainly traces baryon velocity at recombination $\Rightarrow$ peaks at troughs of ΔT

CMB polarization: tensor perturbations

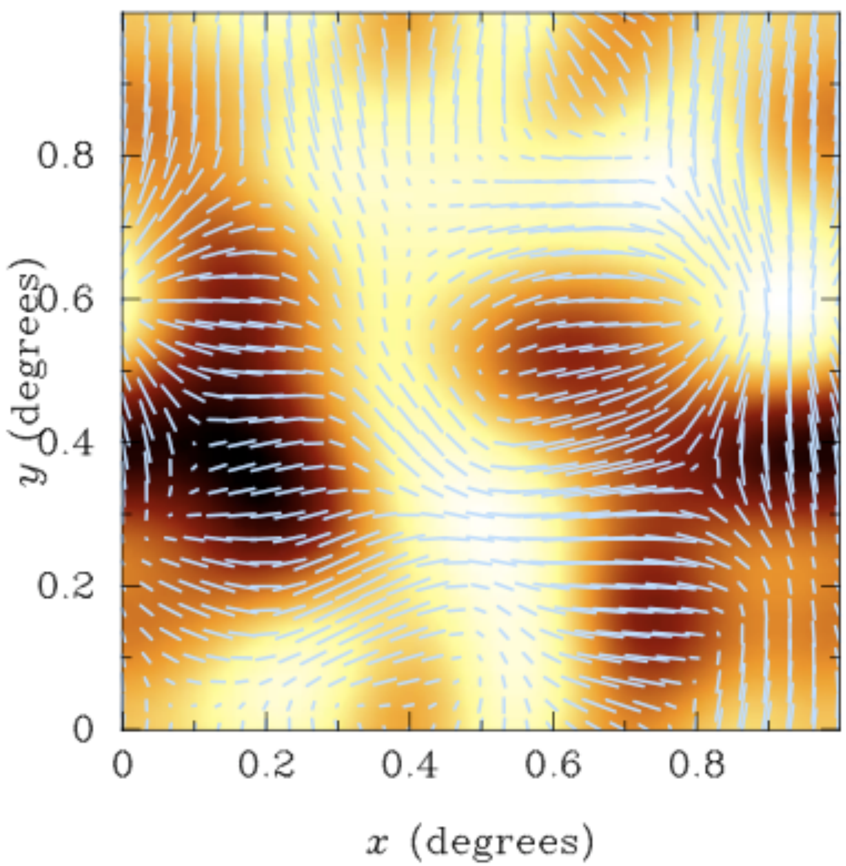
- For single $+$-polarized gravity wave with $\hat{\boldsymbol{k}}$ along z, $\Theta_{2m} \propto \delta_{m2} + \delta_{m\,-2}$ so $dQ \propto (1+\cos^2\theta)\cos 2\phi$ and $dU \propto -\cos\theta \sin 2\phi$



- Gravity waves produce both E- and B-mode polarization (with roughly equal power)

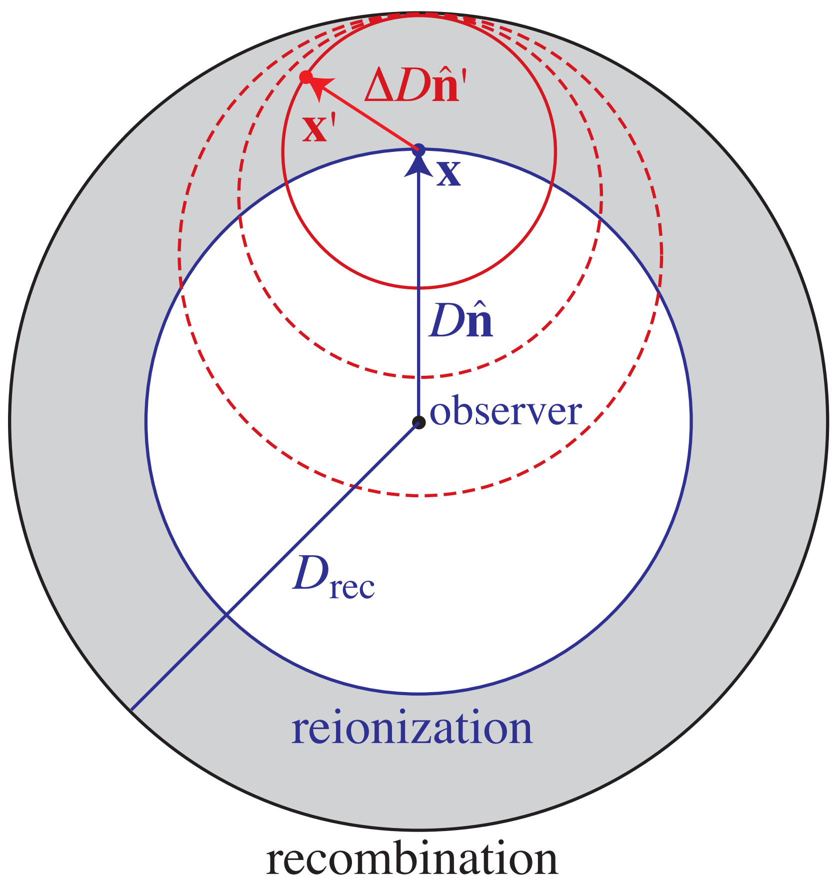
Correlated polarization in real space

- On largest scales, infall into potential wells at last scattering generates e.g. tangential polarization around large-scale hot spots
- Sign of correlation scale-dependent inside horizon



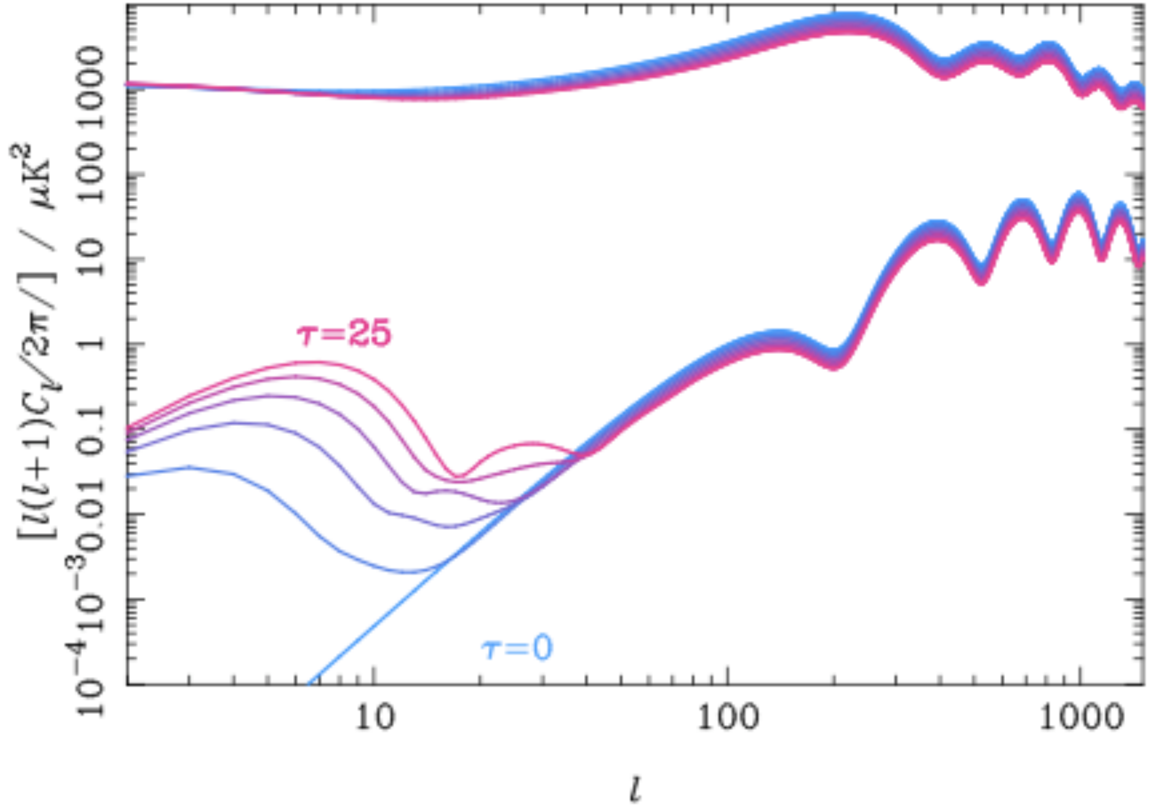
Polarization from reionization

$$(Q \pm iU)(\hat{\mathbf{n}}) = -\frac{\sqrt{6}}{10} \int dD \frac{d\tau}{dD} e^{-\tau(D)} \times \sum_{m=-2}^{2} T_{2m}(D\hat{\mathbf{n}})_{\pm 2} Y_{2m}(\hat{\mathbf{n}})$$



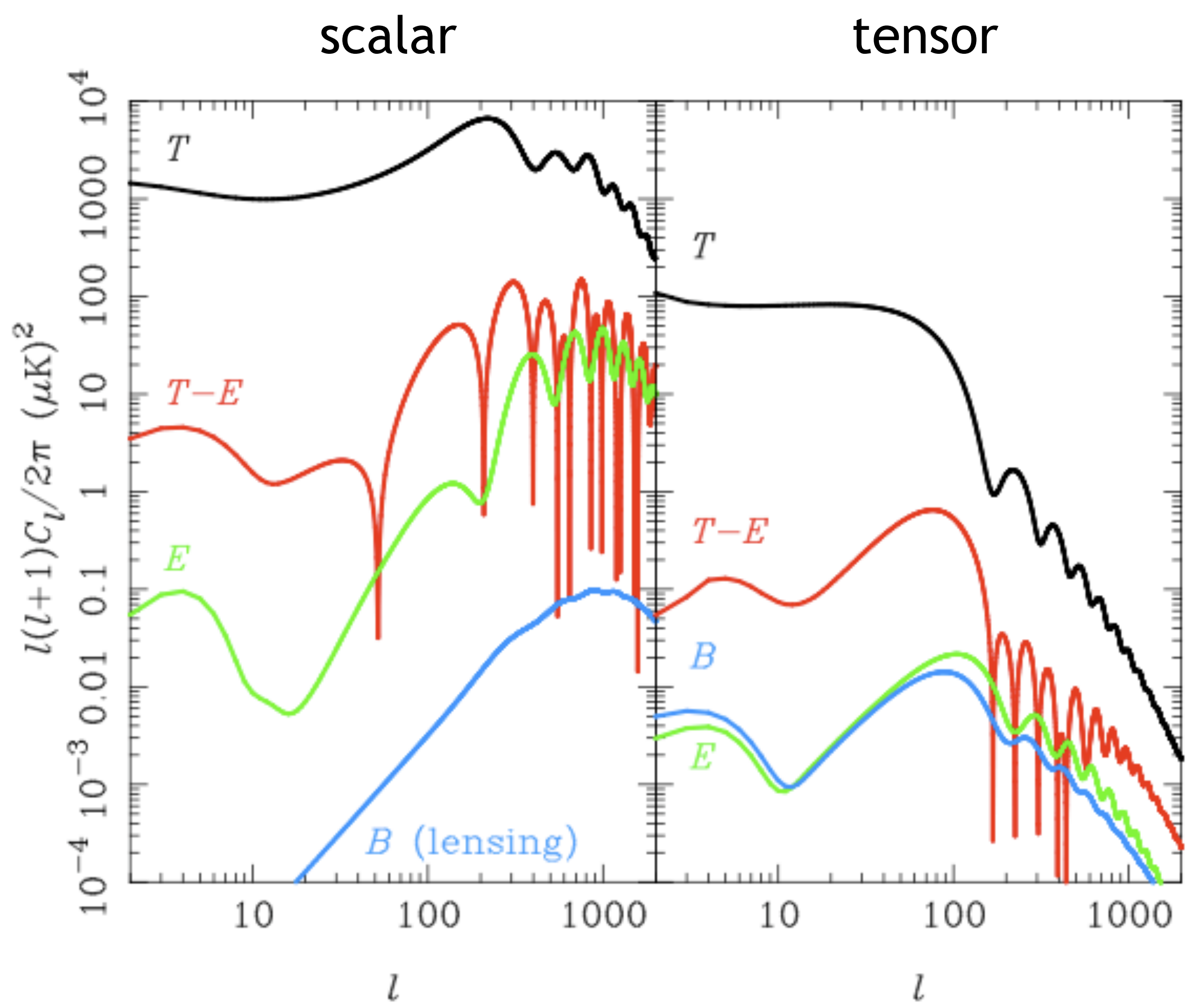
Large angle polarization from reionization

- Temperature quadrupole at reionization peaks around $k(\eta_{\rm re} - \eta_*) \sim 2$
  - Re-scattering generates polarization on this linear scale → projects to $l \sim 2(\eta_0 - \eta_{\rm re})/(\eta_{\rm re} - \eta_*)$
  - Amplitude of polarization $\propto$ optical depth through reionization → best way to measure τ with CMB



Scalar & tensor power spectra

- For scalar perturbations (left), δ_γ oscillates $\pi/2$ out of phase with $v_\gamma \Rightarrow C_l^E$ peaks at minima of C_l^T

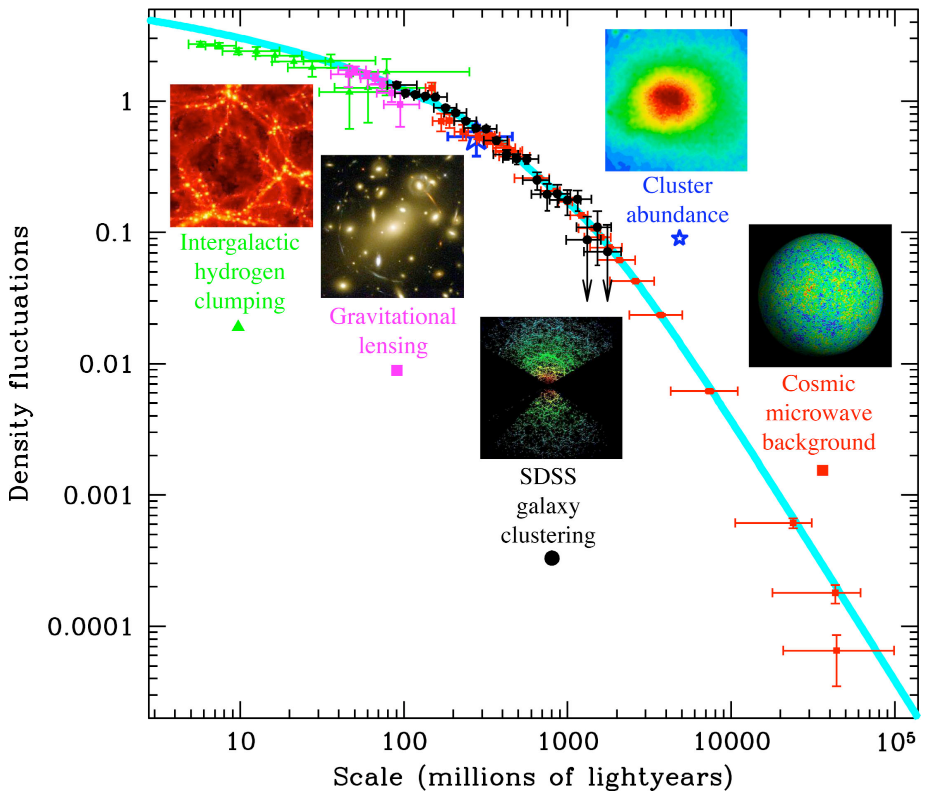


Parameters from CMB: matter & geometry

- Acoustic physics (dark energy and curvature negligible):
  - Peak locations depend on sound horizon r_s at last scattering
  - Damping scale $1/k_D$(roughly geometric mean of horizon and mean free path)
  - Both depend only on $\Omega_b H_0^2$ and $\Omega_m H_0^2$ for fixed T_{CMB}
  - Peak heights depend on baryon loading ($\Omega_b H_0^2$) and gravitational driving ($\Omega_m H_0^2$; see shortly) $\rightarrow$ r_s and k_D then calibrated standard rulers
- Main influence of geometry, dark energy and sub-eV massive neutrinos then through *angular diameter distance* to last scattering
  - d_A accurately determined from angular size of standard rulers r_s and k_D
  - Weak influence on large scales (where cosmic variance bad) through ISW

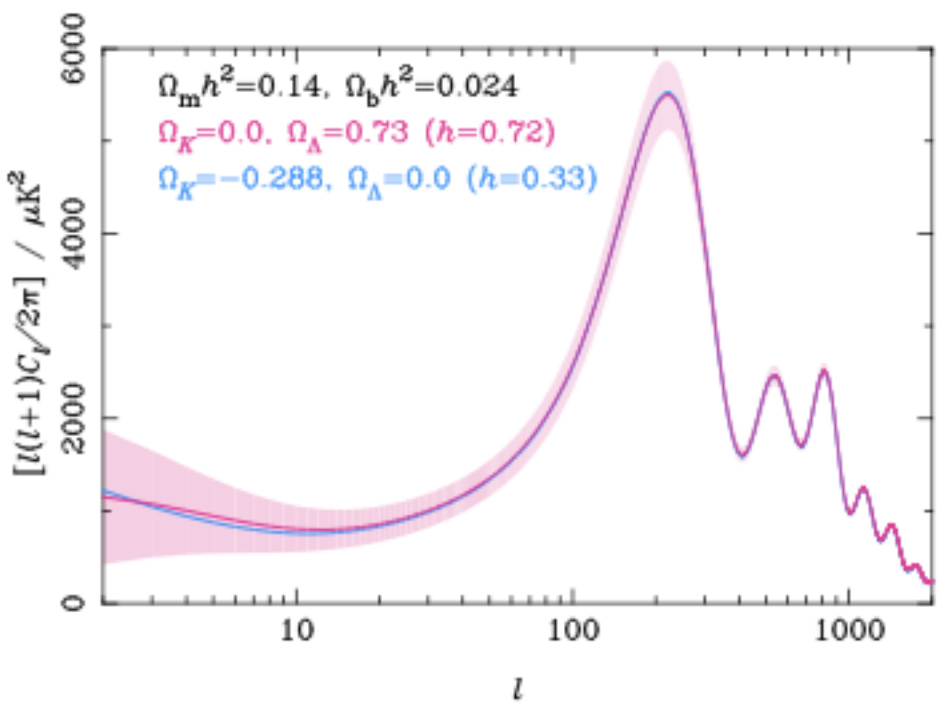
Parameters from CMB: primordial power spectrum

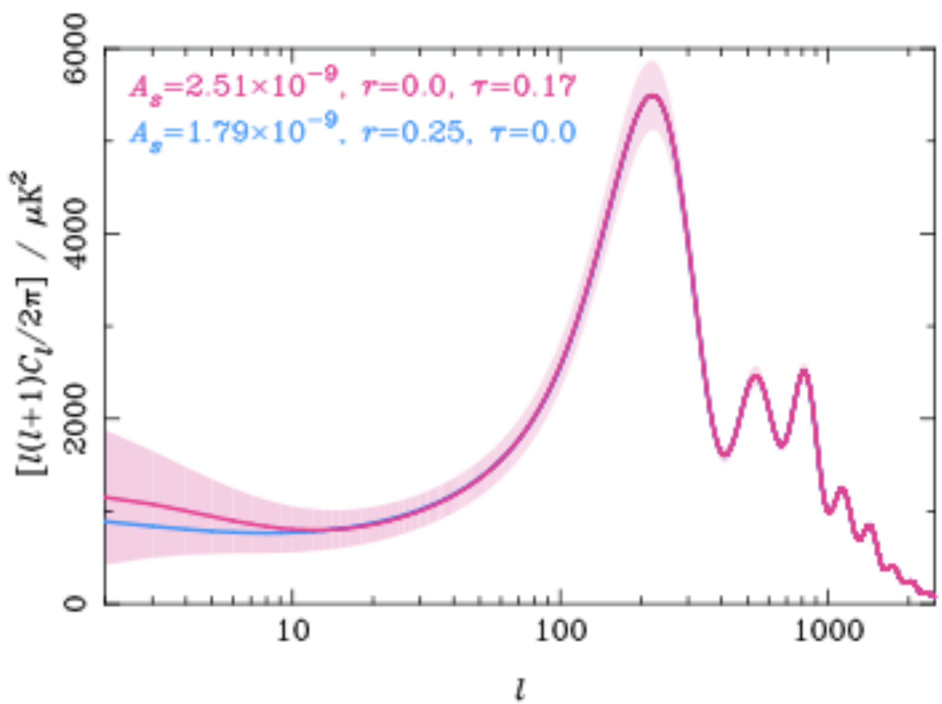
- Scalar power spectrum C_l essentially $e^{-2\tau}\mathcal{P}_{\mathcal{R}}(k)$ at $k \approx l/d_A$ processed by acoustic physics
  - CMB probes scales $5\,\mathrm{Mpc} < k^{-1} < 5000\,\mathrm{Mpc}$
- Tensor power spectra sensitive to $e^{-2\tau}\mathcal{P}_h(k)$



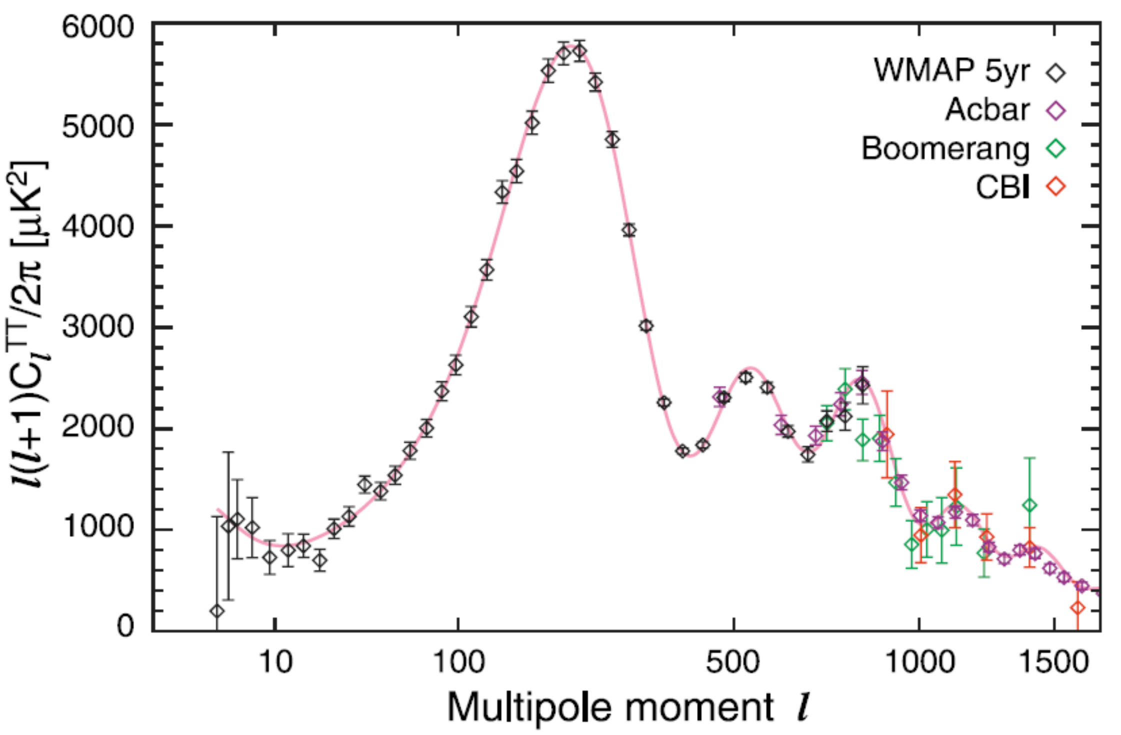
Degeneracies

- Some parameters not determined by linear T anisotropies alone:
  - Angular diameter test gives only $d_A = d_A(\Omega_K, \Omega_{\rm de}, w, \ldots)$ once matter densities determined from peak morphology
    - $*$ Disentangling dark energy and K relies on large-scale anisotropies, where cosmic variance large, or other datasets (e.g. Hubble, supernovae, shape of matter power spectrum or baryon oscillations)
  - Addition of gravity waves and renormalisation mimics reionization but can break with *polarization*



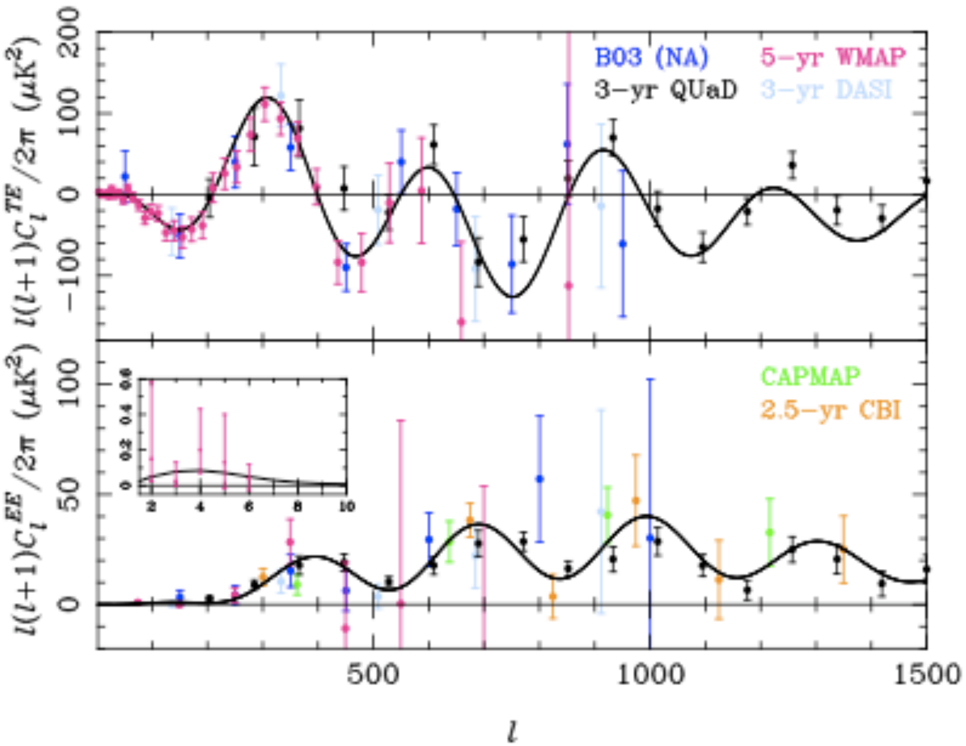


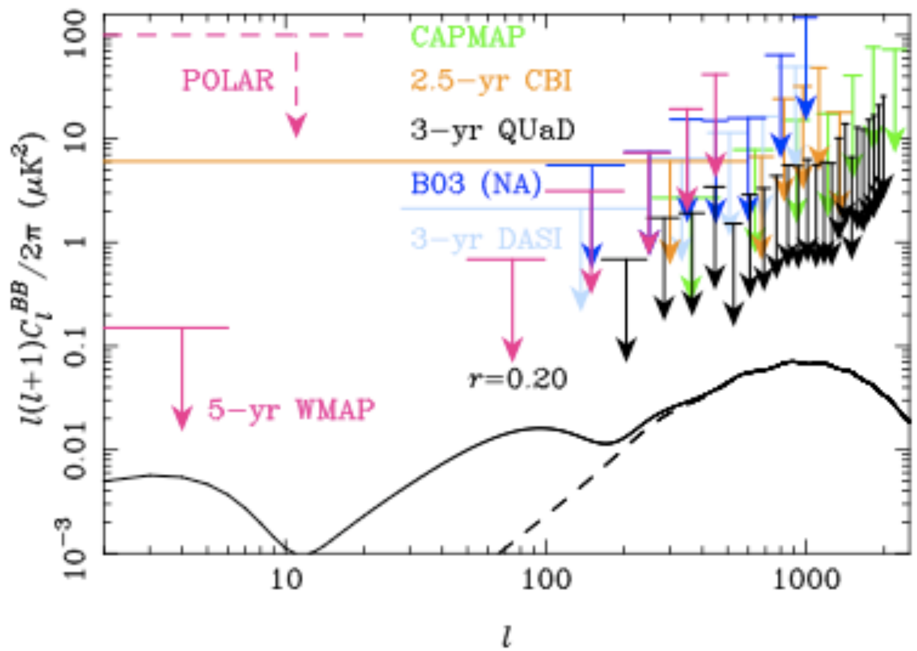
Current temperature data



- Sachs-Wolfe Plateau and late-time ISW effect
- Acoustic peaks at ‘adiabatic’ locations
- Damping tail/photon diffusion
- Weak gravitational lensing (see later)

Current polarization data

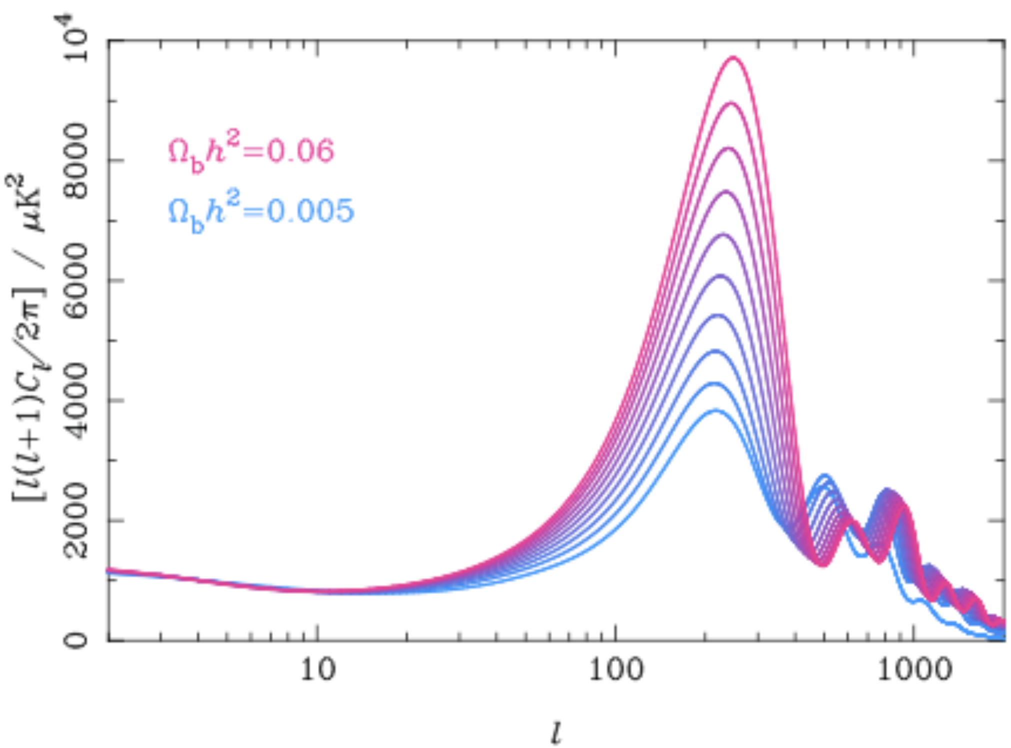




- Acoustic peaks at 'adiabatic' locations
- E-mode polarization and cross-correlation with ΔT
- Large-angle polarization from reionization

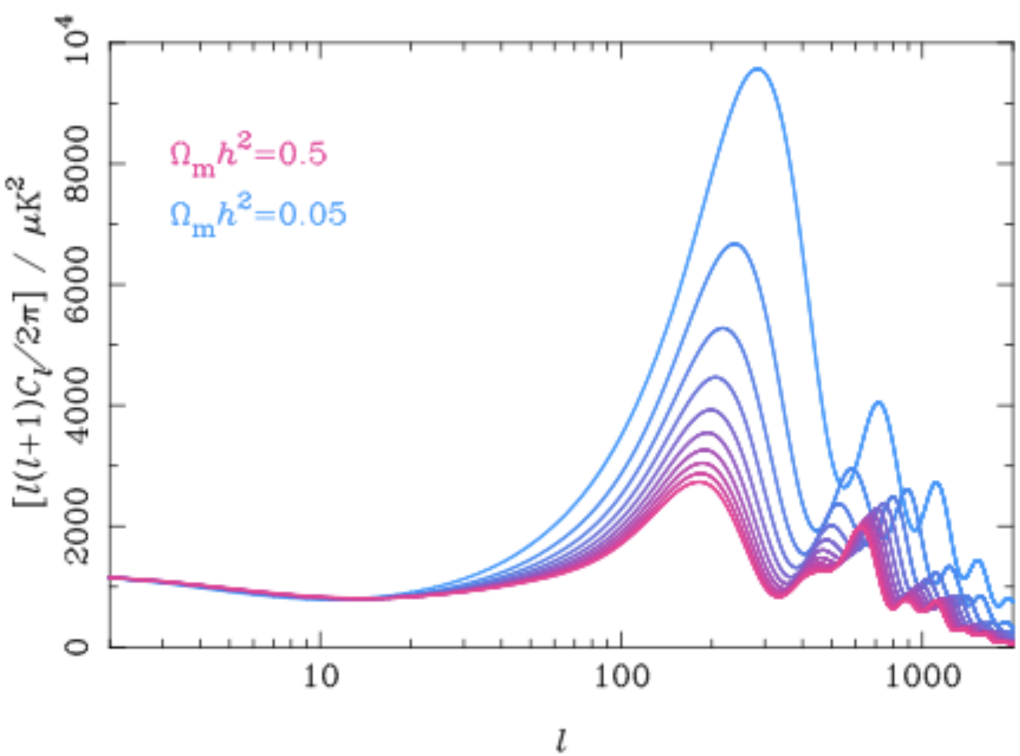
Acoustic peak heights: baryon density

- Peak spacing fixed by $r_s(\Omega_m h^2, \Omega_b h^2)$ and angular diameter distance d_A
  - Θ_0 oscillates with midpoint $\approx -(1+R)\psi$ so $\Theta_0 + \psi$ (S-W source) oscillates around $-R\psi$
  - Increasing $\Omega_b h^2$ (hence R) boosts compressional peaks (1, 3 etc. for adiabatic) and reduces r_s
- Current constraints from CMB alone (weak priors): $\Omega_b h^2 = 0.02273 \pm 0.00062$ (i.e. to 3%; Dunkley et al. 2008)
  - Should improve to sub-percent level with Planck data



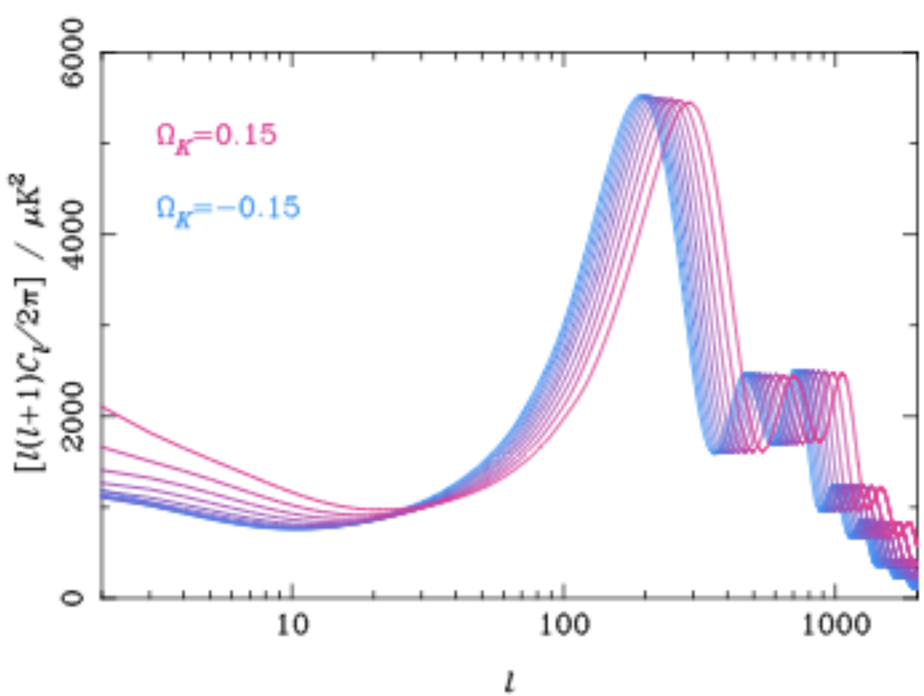
Acoustic peak heights: CDM density

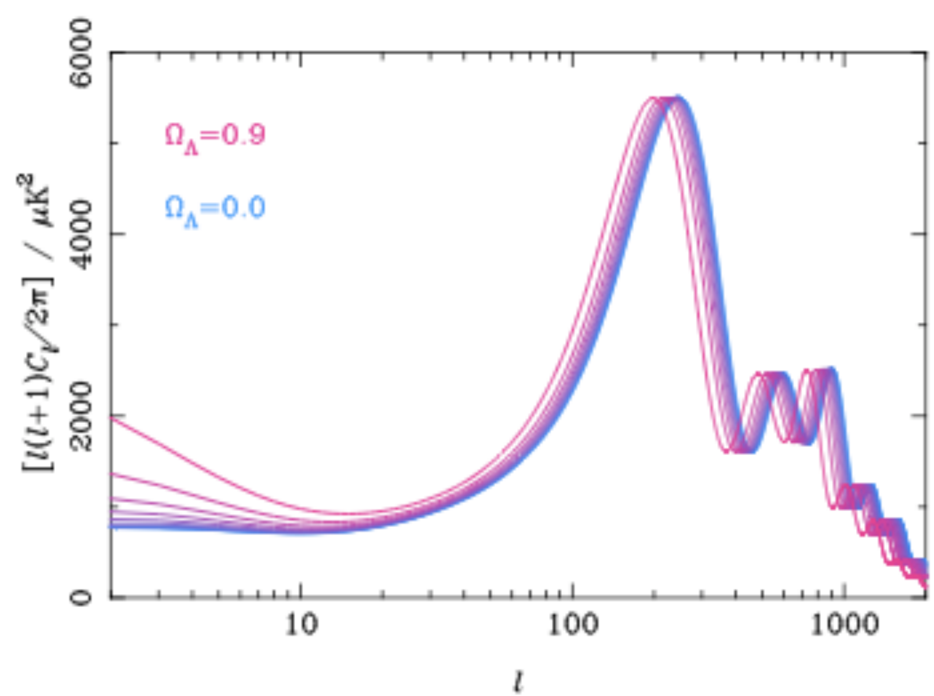
- Increasing $\Omega_c h^2$ reduces d_A and shifts matter-radiation equality to earlier times
  - Reduces resonant driving $\ddot{\phi}$ for low-order peaks and reduces early-ISW contribution to 1st peak
- Current constraints from CMB alone (weak priors): $\Omega_c h^2 = 0.1099 \pm 0.0062$ (i.e. to 6%; Dunkley et al. 2008)
  - Should improve to sub-percent level with Planck data



Peak locations: curvature & dark energy

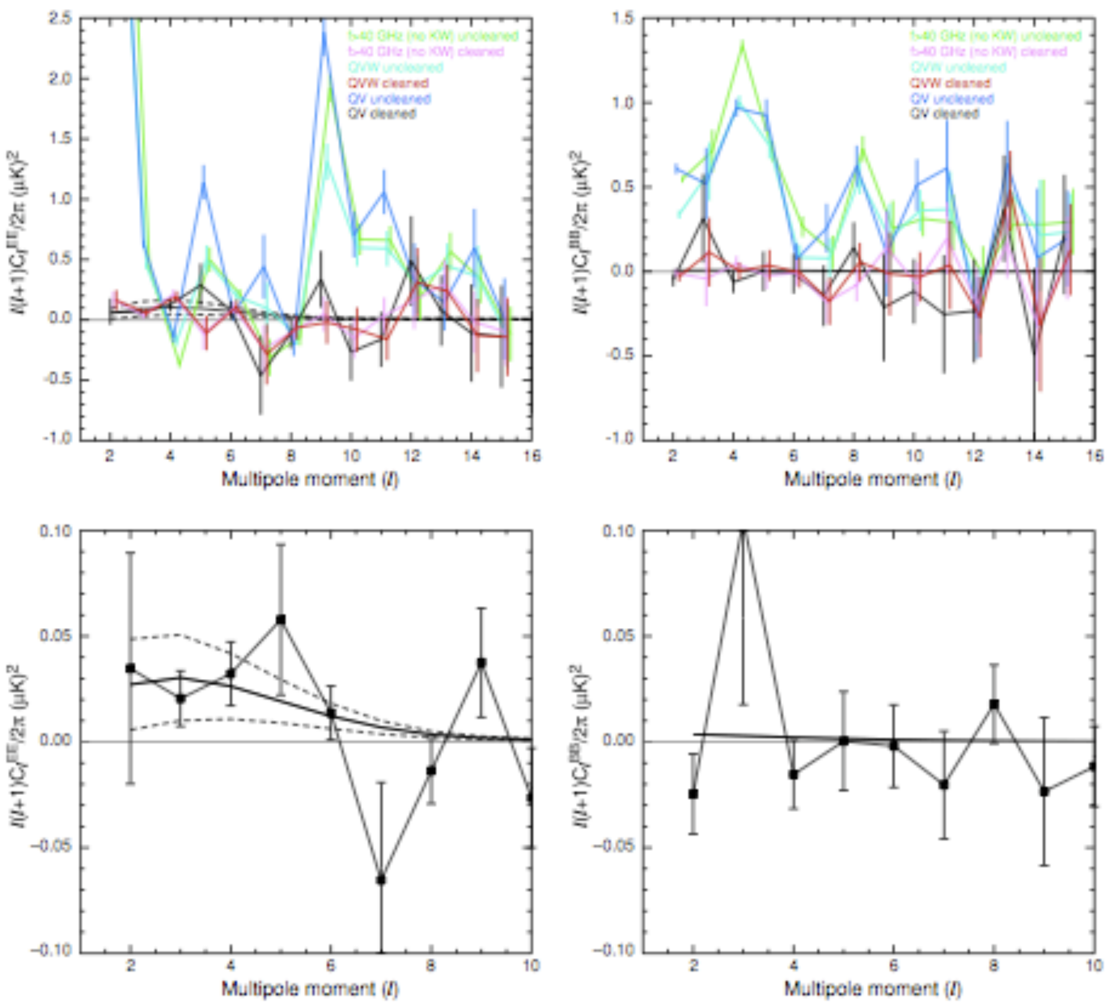
- Mainly affect CMB through d_A; small effects from ISW and mode quantisation for $K > 0$
  - CMB alone only well constrains $d_A = 14.1 \pm 0.2\,\mathrm{Gpc}$
  - $\Lambda = 0$, closed models fit CMB alone but have very low h, high $\Omega_m h$ cf. LSS, and don't fit ISW-LSS correlation (see later)
  - WMAP5 plus BAO gives $\Omega_K = -0.005 \pm 0.006$ ($w = -1$) and $\Omega_\Lambda = 0.734 \pm 0.017$





Reionization

- WMAP5 EE large-angle correlation $\Rightarrow \tau = 0.087 \pm 0.017$ (Dunkley et al. 2008)
  - Requires aggressive cleaning of polarized Galactic foregrounds (synchrotron and thermal dust emission)



CMB spectrum: parameter dependences

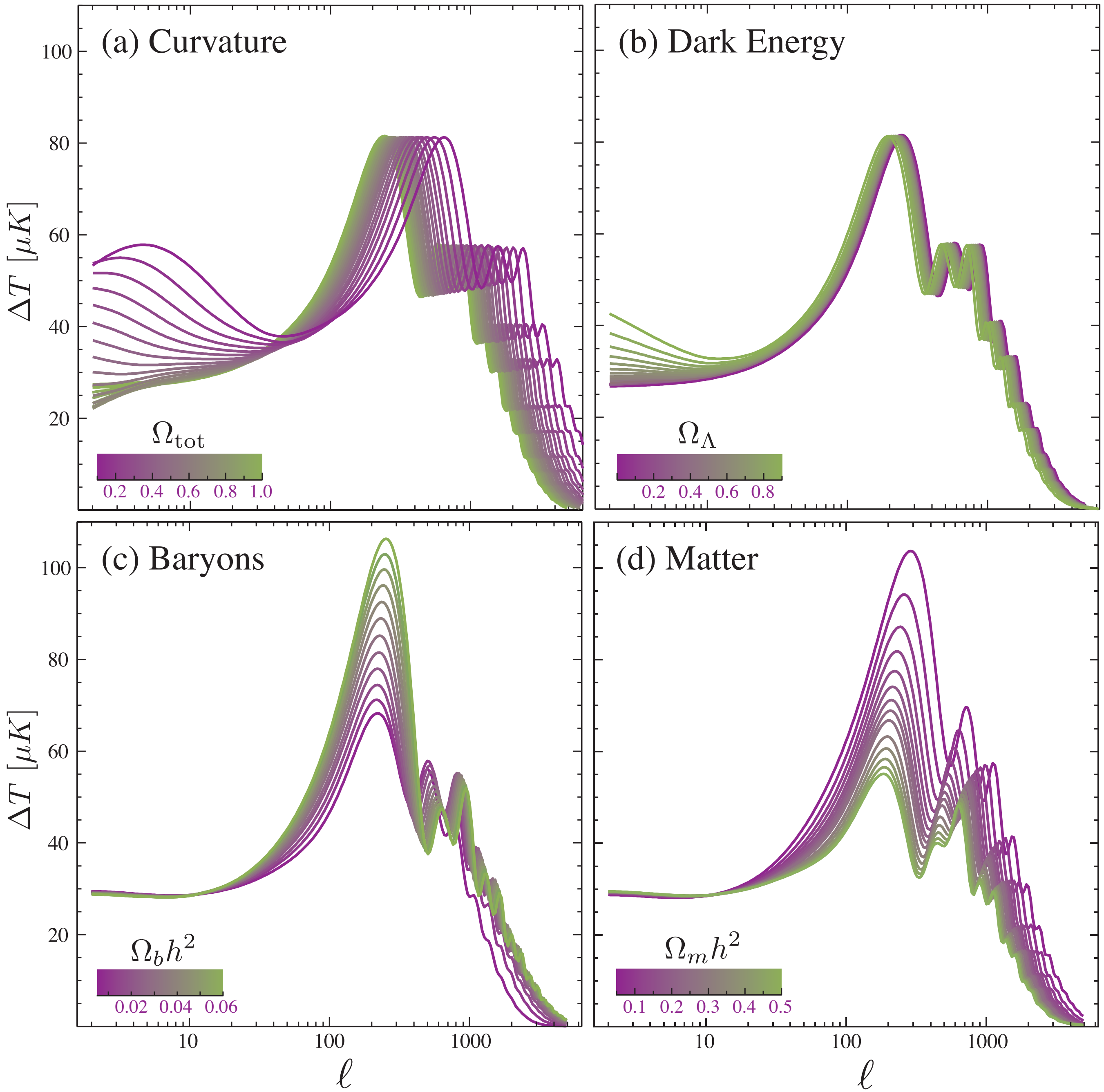


Image from W. Hu

Timeline

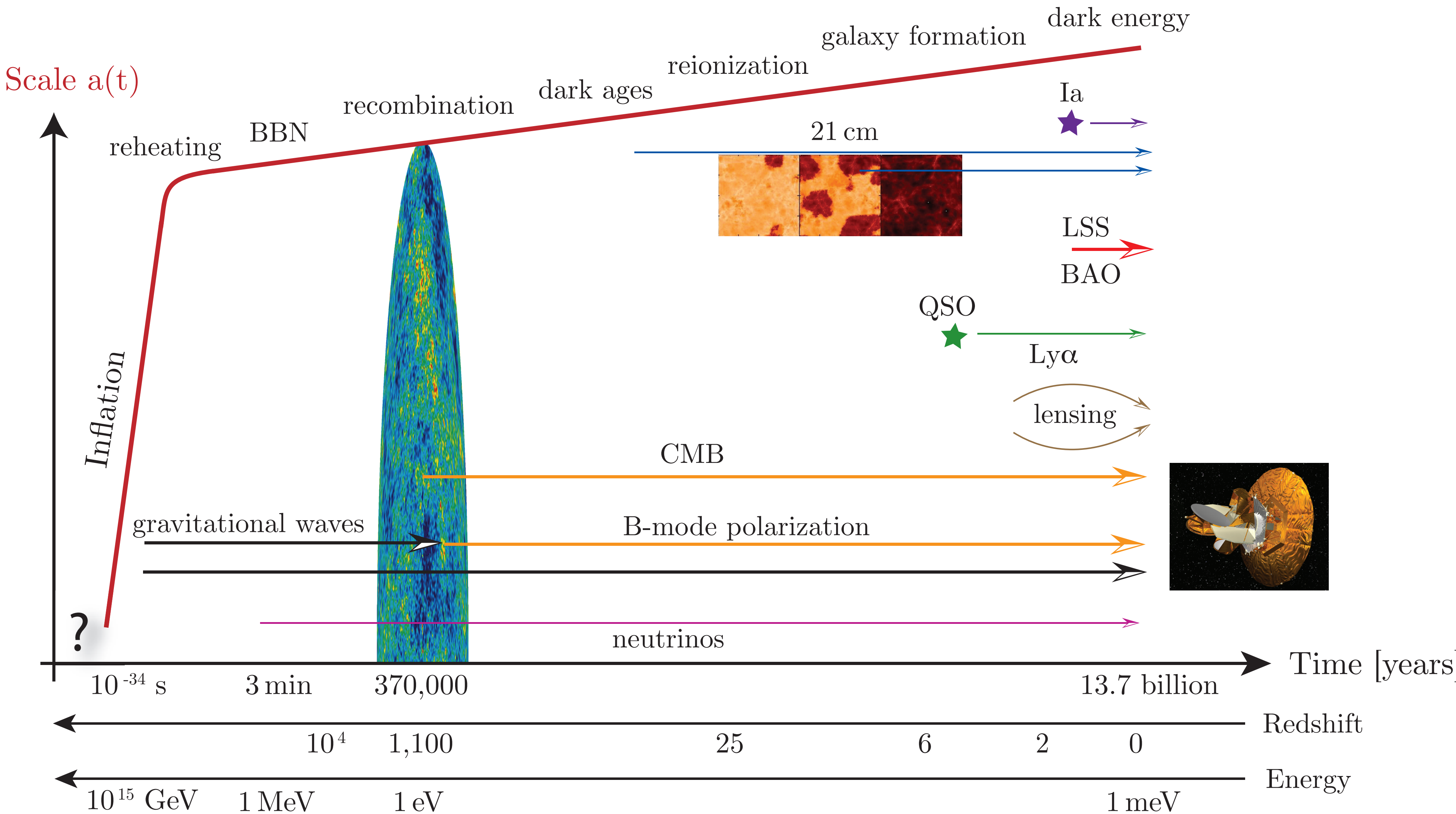


Image from D. Baumann