The Cosmic Microwave Background: How It Works

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Academic Lecture Series

Fermilab

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General Relativity

- Metric geometry

$$ds^2 = g_{\mu\nu}\, dx_\mu\, dx_\nu \qquad g_{\mu\nu} = \begin{pmatrix} g_{\eta\eta} & g_{\eta x} & g_{\eta z} & g_{\eta z} \\ g_{\eta x} & g_{xx} & g_{xy} & g_{xz} \\ g_{\eta z} & g_{xy} & g_{yy} & g_{yz} \\ g_{\eta z} & g_{xz} & g_{yz} & g_{zz} \end{pmatrix}$$

- 10 free functions reduced by 4 to 6 by coordinate freedom
- Can decompose according to helicity (2scalar+2vector+2tensor)

$$g_{\mu\nu} = a[\eta]^2 \left(\bar{g}_{\mu\nu} + h^{S}_{\mu\nu} + h^{V}_{\mu\nu} + h^{T}_{\mu\nu}\right) \qquad dt = a[\eta]\, d\eta$$

$$\bar{g}_{\mu\nu} = \begin{pmatrix} -1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix} \quad h^{S}_{\mu\nu} = -2\begin{pmatrix} \Phi & 0 \\ 0 & \Psi \boldsymbol{I} \end{pmatrix} \quad h^{V}_{\mu\nu} = \begin{pmatrix} 0 & \boldsymbol{h}^{\perp} \\ \boldsymbol{h}^{\perp} & \boldsymbol{0} \end{pmatrix} \quad h^{T}_{\mu\nu} = \begin{pmatrix} 0 & 0 \\ 0 & \boldsymbol{H}^{\perp tr} \end{pmatrix}$$

$$\boldsymbol{\nabla} \cdot \boldsymbol{h}^{\perp} = 0 \qquad \boldsymbol{\nabla} \cdot \boldsymbol{H}^{\perp tr} = \mathrm{Tr}\left[\boldsymbol{H}^{\perp tr}\right] = 0$$

- Dynamics: Einstein's Eq's: $G_{\mu\nu}=8\pi G\, T_{\mu\nu}$

scalar	$\nabla^2 \Psi$	$=$	$4\pi a^2 G \left(\delta\rho - 3\frac{a'}{a}\nabla^{-2}(\boldsymbol{\nabla}\cdot\boldsymbol{S})\right)$	elliptical
scalar	$\nabla^2(\Phi - \Psi)$	$=$	$-12\pi a^2 G \frac{a'}{a}\nabla^{-2}\boldsymbol{\nabla}\cdot(\boldsymbol{\nabla}\cdot\Pi^{tr})$	elliptical
vector	$\nabla^2 \boldsymbol{h}^{\perp} - 6\left(\frac{a'}{a}\right)^2 \boldsymbol{h}^{\perp}$	$=$	$16\pi a^2 G\, \boldsymbol{S}^{\perp}$	elliptical
tensor	$\ddot{\boldsymbol{H}}^{\perp tr} + 2\frac{a'}{a}\dot{\boldsymbol{H}}^{\perp tr} - \nabla^2 \boldsymbol{H}^{\perp tr}$	$=$	$8\pi a^2 G\, \Pi^{\perp tr}$	hyperbolic

$$T^{\mu\nu} = \begin{pmatrix} \rho & \boldsymbol{S} \\ \boldsymbol{S} & \Pi \end{pmatrix}$$

Cosmic Relics:

- Photons: The 2.725K CMBR
- Neutrinos: (difficult to see directly) expect T_ν=1.955K
- Baryons: (origin of baryon anti-baryon asymmetry unknown)
- Dark Matter: (origin unknown)
- Scalar Perturbation: inhomogeneities
- ?Tensor Perturbations: gravitational radiation
- Dark Energy (origin unknown - only important recently?)

ΛCDM Model

Thermal:

$$\rho_{\rm tot} \cong \tfrac{1}{c^2}\Lambda + \frac{3\,H_0{}^2}{8\,\pi\,G}\;\frac{\Omega_{\rm m0}}{a^3} + \frac{\pi^2}{30}\;\frac{(k_{\rm B}\,T_{\gamma 0})^4}{(\hbar\,c)^3\,c^2}\;\frac{2+\frac{7}{8}\left(\frac{4}{11}\right)^{\frac{4}{3}}\left(2\,N_\nu^{\rm eff}\right)}{a^4}$$

$$p_{\rm tot} \cong -\Lambda + \frac{\pi^2}{90}\;\frac{(k_{\rm B}\,T_{\gamma 0})^4}{(\hbar\,c)^3}\;\frac{2+\frac{7}{8}\left(\frac{4}{11}\right)^{\frac{4}{3}}\left(2\,N_\nu^{\rm eff}\right)}{a^4}$$

$$\rho_{\rm b} \cong \frac{3\,H_0{}^2}{8\,\pi\,G}\;\frac{\Omega_{\rm b0}}{a^3} \qquad \Omega_{\rm b0}^{\rm BBN}\,h^2 = 0.0215 \pm 0.0025\ \text{(PDB)} \qquad h \equiv \frac{H_0}{100\ \text{km/sec/Mpc}}$$

$$T_{\gamma{\rm b}} \cong \frac{T_{\gamma 0}}{a\,\sqrt[3]{\frac{1}{2}\,g_*[a]}} \qquad T_{\gamma 0} = 2.72548 \pm 0.00057\ \text{K}$$

Inhomogeneities:

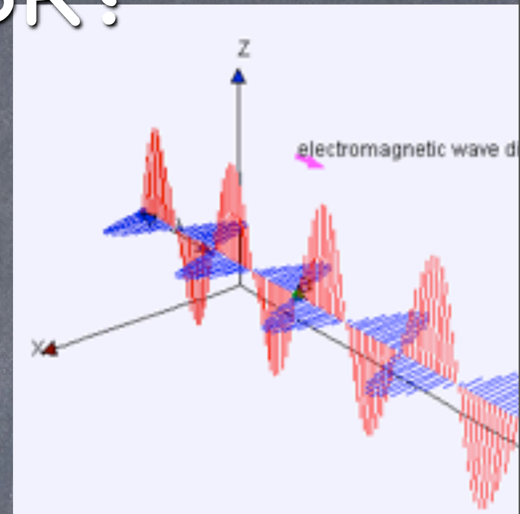
$$\Phi[\boldsymbol{x},\,t] = \int d^3\boldsymbol{k}\,e^{i\boldsymbol{k}\cdot\boldsymbol{x}}\,\tilde{\Phi}[\boldsymbol{k},\,t] \qquad \lim_{t\to 0}\left\langle \tilde{\Phi}[\boldsymbol{k},\,t]\,\tilde{\Phi}[\boldsymbol{k}',\,t]\right\rangle = A_{\rm S}\,k^{n_{\rm S}-4}\,\delta^{(3)}[\boldsymbol{k}-\boldsymbol{k}']$$

$$\boldsymbol{H}^{\perp\rm tr}[\boldsymbol{x},\,t] = \int d^3\boldsymbol{k}\,e^{i\boldsymbol{k}\cdot\boldsymbol{x}}\,\tilde{\boldsymbol{H}}^{\perp\rm tr}[\boldsymbol{k},\,t] \qquad \lim_{t\to 0}\left\langle \tilde{\boldsymbol{H}}^{\perp\rm tr}[\boldsymbol{k},\,t]\cdot\tilde{\boldsymbol{H}}^{\perp\rm tr}[\boldsymbol{k}',\,t]^{\dagger}\right\rangle = A_{\rm T}\,k^{n_{\rm T}}\left(\boldsymbol{I}-\hat{\boldsymbol{k}}\otimes\hat{\boldsymbol{k}}\right)\delta^{(3)}[\boldsymbol{k}-\boldsymbol{k}']$$

Parameters: $T_{\gamma 0}$, H_0, Λ, Ω_{m0}, Ω_{b0}, Ω_0, N_{eff}, A_S, A_T, n_S, n_T, τ

How to Describe the CMBR?

Microscopic Description



$$E_a[\boldsymbol{x},t] \propto \int d\nu\, e^{i2\pi\nu t} \int d^2\hat{\boldsymbol{c}}\, e^{i2\pi\,\nu\,\hat{\boldsymbol{c}}\cdot\boldsymbol{x}}\, \tilde{E}_a[\hat{\boldsymbol{c}},\nu]$$

in a small frequency bin:

$$\left\langle \begin{matrix} \tilde{E}_x \tilde{E}_x^* & \tilde{E}_x \tilde{E}_z^* \\ \tilde{E}_z \tilde{E}_x^* & \tilde{E}_z \tilde{E}_z^* \end{matrix} \right\rangle \propto \begin{pmatrix} I+Q & U+i\,V \\ U\text{-}iV & I\text{-}Q \end{pmatrix}$$

- I intensity
- Q,U linear polarization
- V circular polarization

By definition: I,Q,U,V real
Schwartz Inequality: $I^2 \geq Q^2+U^2+V^2$
Elliptically Polarized: $I^2=Q^2+U^2+V^2$
Linearly Polarized: $I^2=Q^2+U^2$ $V=0$
Circularly Polarized: $I=|V|$ $Q=U=0$
Unpolarized: $Q=U=V=0$

Light are a collection of electromagnetic waves.

- There could in principle be a lot of information in all the detailed correlations of the EM field.
- The interesting information is usually only in the time averaged 2nd moments of the E fields.

Expectation:
CMBR slightly linearly polarized
$I^2 \gg Q^2+U^2 \gg V^2$ Rees (1968)

How to Describe the CMBR?

Macroscopic Description

On cosmological length and times-scales (millions to billions of light-years):

$$I[\hat{\boldsymbol{c}}, \nu, \boldsymbol{x}, t],\ Q[\hat{\boldsymbol{c}}, \nu, \boldsymbol{x}, t],\ U[\hat{\boldsymbol{c}}, \nu, \boldsymbol{x}, t],\ V[\hat{\boldsymbol{c}}, \nu, \boldsymbol{x}, t]$$

- as we shall see V=0 is a good approximation.

- Spatial Fourier transform, e.g.

$$I[\hat{\boldsymbol{c}}, \nu, \boldsymbol{x}, t] = \sum_{\boldsymbol{k}} e^{i\,\boldsymbol{k}\cdot\boldsymbol{x}}\, \tilde{I}[\hat{\boldsymbol{c}}, \nu, \boldsymbol{k}, t]$$

- Angular decomposition: spherical harmonics

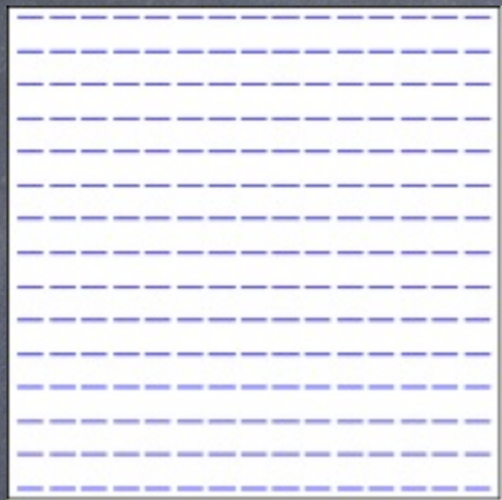
$$\tilde{I}[\hat{\boldsymbol{c}}, \nu, \boldsymbol{k}, t] = \sum_{\ell} \sum_{\mathrm{m}} Y_{(\ell, h)}[\hat{\boldsymbol{c}}]\, \tilde{I}_{(\ell, h)}[\nu, \boldsymbol{k}, t]$$

  - For each **k**, align "North Pole" of $Y_{(l, h)}$ to **k** direction then h gives helicity
    - as we shall see $I_{(l, h)}=0$ for $|h|>2$ is a good approximation.
- A simple $Y_{(l,h)}$ decomposition of Q,U is not the best!

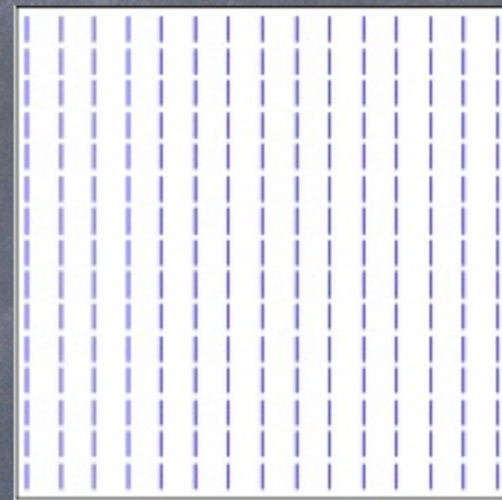
Graphical Representation of Linear Polarization

2d Symmetric Traceless Tensors

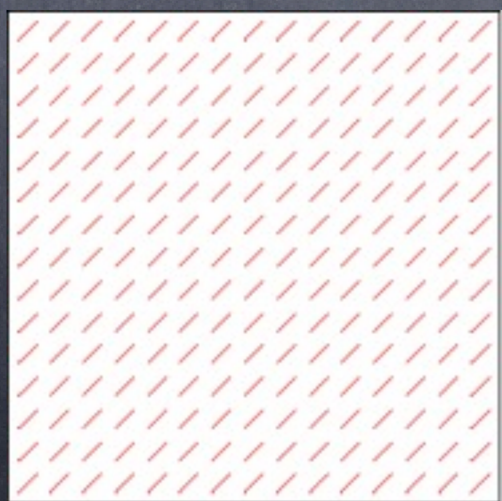
$Q > 0$



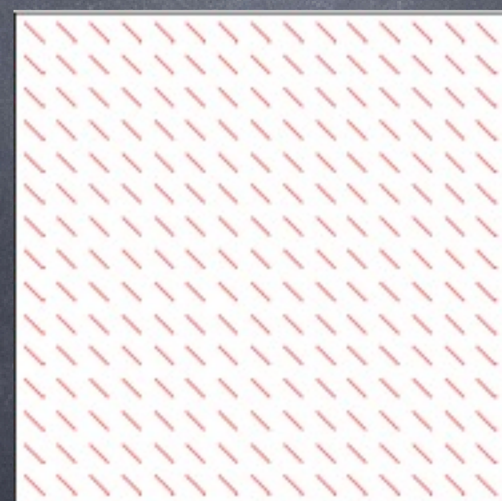
$Q < 0$



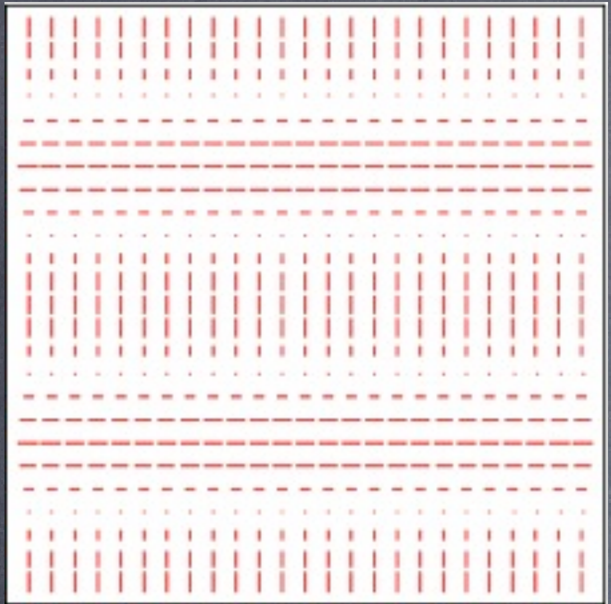
$U > 0$

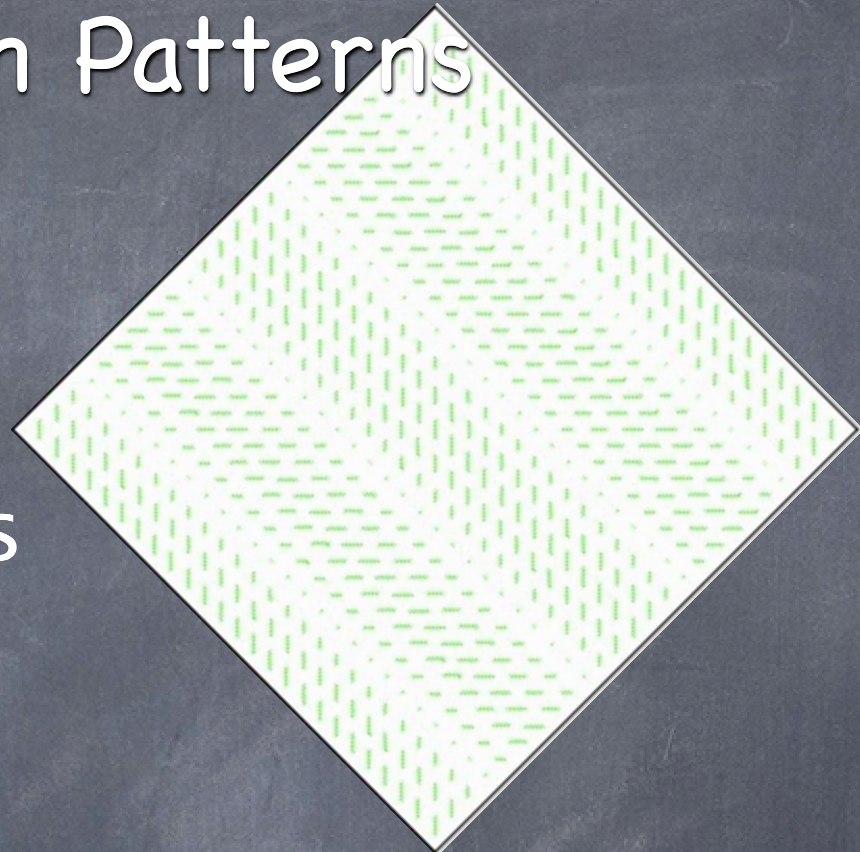


$U < 0$

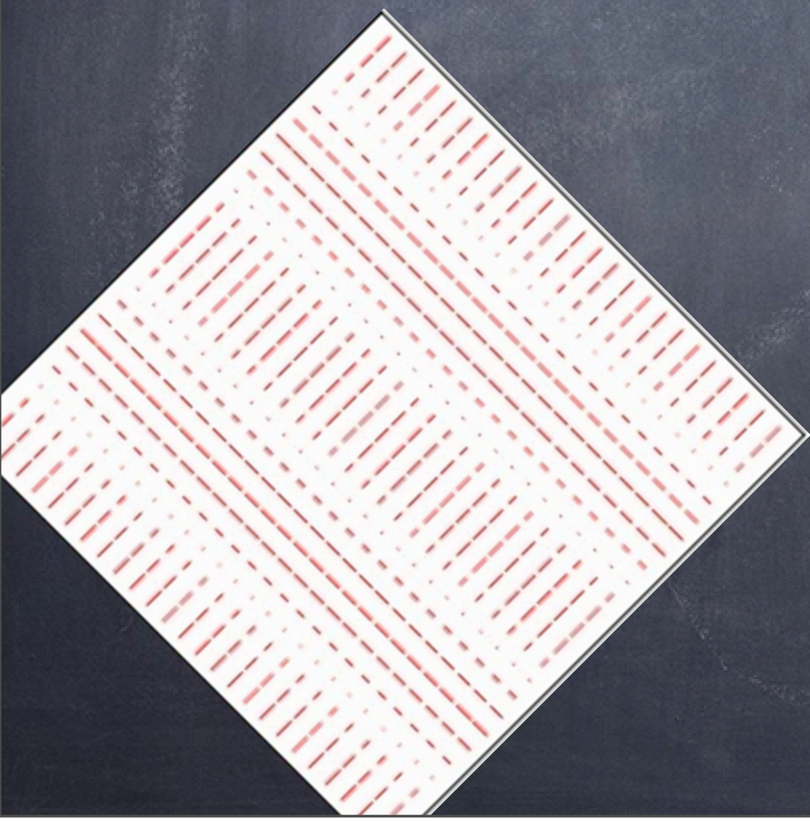


Linear Polarization Patterns

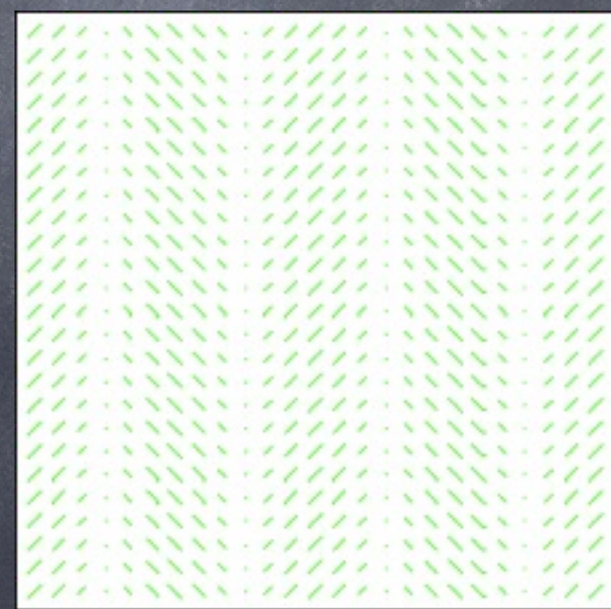




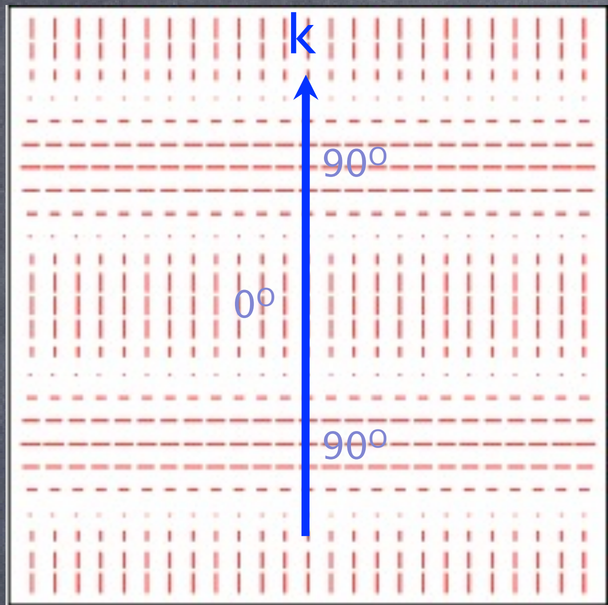
Q patterns



U patterns



Linear Polarization Patterns



0°–90° pattern

scalar pattern
gradient pattern
E-mode

Stebbins 1996

Kaminokowski, Kosowsky, Stebbins 1997

Seljak, Zaldarriaga 1997

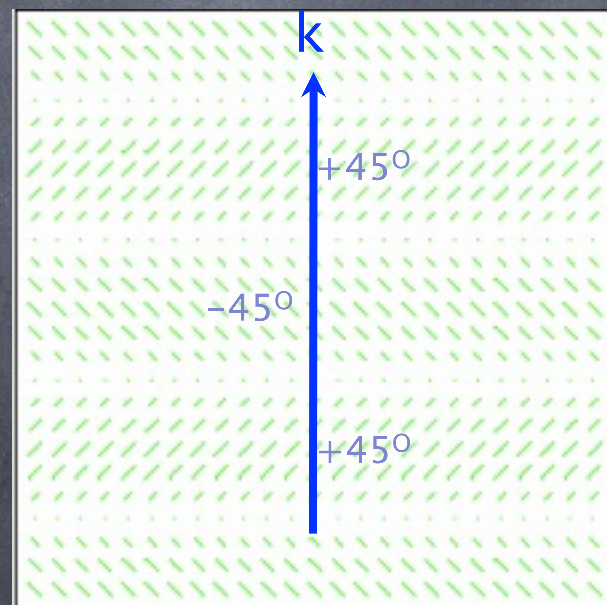
Stebbins 1996

Kaminokowski, Kosowsky, Stebbins 1997

Seljak, Zaldarriaga 1997

pseudo-scalar pattern
curl pattern
B-mode

±45° pattern



General E- B- Mode Decomposition

- in any 2-D Riemannian manifold one has 2 covariant tensors:
  - metric g_{ab} and Levi-Civita symbol $\varepsilon_{ab} = \sqrt{\mathrm{Det}[g_{ab}]}$ {{0,1},{-1,0}}
    - contracting a vector with ε_{ab} rotates by 90°
    - contracting a tensor with ε_{ab} rotates eigenvectors 45°
- starting with any (scalar) function f
  - construct corresponding E- and B- mode vectors
    - E-mode: covariant derivative: $f_{;a}$ B-mode: rotate by 90°: $f_{;b}\ \varepsilon^{b}{}_{a}$
  - construct corresponding E- and B- mode traceless symmetric tensors
    - E-mode: 2nd derivative - trace: $f_{;ab}-½(\nabla^2 f)\ \delta_{ab}$
    - B-mode: symmetrically rotate by 45°: $½(f_{;ac}\varepsilon^{c}{}_{b}+f_{;bc}\varepsilon^{c}{}_{a})$
- One can construct E-mode and B-mode tensors of any rank this way!

E- B- Mode Spherical Harmonics

- E- B- mode decomposition applied to complete scalar basis gives complete tensor basis!
  - on (direction) 2-sphere use spherical harmonic basis: $Y_{(l,m)}$
  - gives E- B- mode basis for symmetric traceless tensors on sphere
    - $Y^E_{((l,m)ab} \propto Y_{((l,m);ab} - ½(\nabla^2 Y_{((l,m)})\ \delta_{ab}$ $\qquad Y^B_{(l,m)ab} \propto ½(Y_{((l,m);ac}\varepsilon^c{}_b + Y_{(l,m);bc}\varepsilon^c{}_a)$
    - $Y^E_{(0,m)ab} = Y^B_{(0,m)ab} = Y^E_{(1,m)ab} = Y^B_{(1,m)ab} = 0$
  - these can be used to describe linear polarization:

$$P_{ab} = \begin{pmatrix} I+Q & U+i\,V \\ U\text{-}iV & I\text{-}Q \end{pmatrix}$$

$$= \sum_k e^{i\,\mathbf{k}\cdot\mathbf{x}} \sum_\ell \sum_h \left(\begin{pmatrix} I_{(\ell,h)} & +i\,V_{(\ell,h)} \\ -i\,V_{(\ell,h)} & I_{(\ell,h)} \end{pmatrix} Y_{(\ell,h)} + E_{(\ell,h)}\, Y^E_{(\ell,h)} + B_{(\ell,h)}\, Y^B_{(\ell,h)} \right)$$

- Equivalent formulation uses spin-weighted spherical harmonic functions $Y_{(s,l,m)}$
  - $Q + i\,U = \Sigma_k\ e^{i\,k\cdot x}\ \ \Sigma_\ell \Sigma_h\, Y_{(2,\ell,h)}$

How to Describe the CMBR?
Intensity and Units

In astronomy $I[\hat{c}, \nu, x, t]$ usually has units: ergs/cm^2/sec/steradian/Hz

- recall Poynting energy flux $S = E \times B/(8\pi) = |E|^2/(8\pi)$ (Gaussian CGS units)
- radio astronomy: often convenient to define a Rayleigh Jeans Brightness temperature

$$kT_{RJ} = \tfrac{1}{2}(c/\nu)^2 I$$

- this gives the thermodynamic temperature if $h\nu \ll kT$,
- theoretically it is most convenient to use the quantum mechanical occupation number

$$n^T[\nu] = \tfrac{1}{2}(c/\nu)^2 I/(h\nu) = kT_{RJ}/(h\nu)$$

- for a blackbody $n = n_{BB}[\nu, T] = 1/(e^{(h\nu)/(kT)}-1)$ N.B.
- one can multiply E,B,V by $\tfrac{1}{2}(c/\nu)^2/(h\nu)$ to put them in dimensionless occupation number units: n^T, n^E, n^B, n^V

Spectral Decomposition

One may also decompose the spectrum of each component X=I,E,B,V:

- $n^X_{(\ell,h)}[\nu,\mathbf{k},t] = \Sigma_p\ (-1)^p/p!\ n^X_{(\ell,h,p)}[k,t]\ \ \partial^p n_{BB}[\nu,T]/\partial(\ln\nu)^p$
- this is a (generalized) Fokker Planck expansion about a blackbody.
- p=0 corresponds to a pure blackbody - only $n^T_{(0,0,0)} = 1 \neq 0$
- p=1 is spectral deviation from temperature shift
  - Doppler, gravitational redshifts, etc.
  - all 1st order anisotropies and polarizations will have this form
- p=2 arises from a mixture temperatures shifts
  - it only arises to 2nd order in perturbations theory (small)
  - Thermal Sunyaev-Zel'dovich (SZ) effect:
    - hot plasma ($v_{e,rms} = (m_p/m_e)^{1/2}\ v_{p,rms} = 0.1\ c$) thermal

How to Describe the CMBR?
Summary

- Mode decomposed each Stokes parameter w/ "quantum numbers"
  - **k** spatial dependence
  - h helicity: =0 scalar, =1 vector, =2 tensor
  - ℓ angular wavenumber
  - p spectral mode

Statistical Description of CMBR

- Assume CMBR can be described as a realization of statistical distribution
- Assume statistical homogeneity and isotropy
- These assumptions severely restricts form of 2-point statistics
  - translation symmetry requires different **k** modes uncorrelated
  - rotational symmetry requires different h modes uncorrelated

$$\langle n^X{}_{(\ell,h,p)}[k,t]\; n^Y{}_{(\ell',h',p')}[k',t']^* \rangle = C^{XY}{}_{(\ell,\ell';h;p,p')}[|k|;t,t']\; \delta_{k,k'}\; \delta_{h,h'}$$

Statistical Description of Observed CMBR

- We only get to measure CMBR from one vantage point at one time

$$\begin{pmatrix} I+Q & U+i\,V \\ U\text{-}iV & I\text{-}Q \end{pmatrix} = ½(c/\nu)^2/(h\nu)\ \Sigma_p\ (-1)^p/p!\ \partial^p n_{BB}[\nu,T]/\partial(\ln\nu)^p \sum_\ell \sum_m$$

$$\left(\begin{pmatrix} n^T{}_{(\ell,m,p)} & +i\ n^V{}_{(\ell,m,p)} \\ -i\ n^V{}_{(\ell,m,p)} & n^T{}_{(\ell,m,p)} \end{pmatrix} Y_{(\ell,m)} + n^E{}_{(\ell,m,p)}\, Y^E{}_{(\ell,m)} + n^B{}_{(\ell,m,p)}\, Y^B{}_{(\ell,m)} \right)$$

- where $n^X{}_{(\ell,m,p)} = \Sigma_k\ \Sigma_h\ D^\ell{}_{mh}[\mathbf{k}]\ \ n^X{}_{(\ell,h,p)}[k,t]$
- since the k's are isotropically distributed our sky is isotropic:
  - $\int d^2\hat{c}\ D^\ell{}_{mh}[\hat{c}]\ D^{\ell'}{}_{m'h}[\hat{c}] = 4\pi\ \delta_{\ell,\ell'}\ \delta_{m,m'}$
    - $\langle n^X{}_{(\ell,m,p)}\ \ n^Y{}_{(\ell',m',p')}{}^* \rangle = C^{XY}{}_{(\ell;p,p')}\ \delta_{\ell,\ell'}\ \delta_{m,m'}$
  - where $C^{XY}{}_{(\ell;p,p')} = \Sigma_k\ \Sigma_h\ \ C^{XY}{}_{(\ell,\ell';h;p,p')}[|k|;t_0,t_0]$

Statistical Description of Observed CMBR

- To first order we only observe p=1: $C^{XY}{}_{\ell} = C^{XY}{}_{(\ell;1,1)}$
- Circular polarization damped
- possible modes:
  - parity even: $C^{TT}{}_{\ell}$, $C^{EE}{}_{\ell}$, $C^{BB}{}_{\ell}$, $C^{TE}{}_{\ell}$
  - parity odd: $C^{TB}{}_{\ell}$, $C^{EB}{}_{\ell}$

Boltzmann Equation

- Dynamics determined by free-streaming and scattering
  - $D_t n^X = C^X$
  - $\partial_t n^X[\hat{\mathbf{c}},\nu,\mathbf{x},t] + c\hat{\mathbf{c}}\cdot\nabla n^X[\hat{\mathbf{c}},\nu,\mathbf{x},t] + (\partial_t\hat{\mathbf{c}})\cdot\nabla_{\hat{c}} n^X[\hat{\mathbf{c}},\nu,\mathbf{x},t] + (\partial_t \ln\nu)\partial_{\ln\nu} n^X[\hat{\mathbf{c}},\nu,\mathbf{x},t] = C^X[\hat{\mathbf{c}},\nu,\mathbf{x},t]$
  - only Thompson (non-relativistic Compton) scattering is important!
  - absorption and emission unimportant
    - $d\sigma[\hat{\mathbf{c}},\hat{\mathbf{c}}';\nu,\nu']/(d^2\hat{\mathbf{c}}' d\nu') = 3/16\pi\ \sigma_T\ (1+\hat{\mathbf{c}}\cdot\hat{\mathbf{c}}')\ \delta[\nu-\nu']$
    - $S^X[\hat{\mathbf{c}},\nu,\mathbf{x},t] = 3/16\pi\ c\sigma_T n_e[\mathbf{x},t]\ \Sigma_Y \int d^2\hat{\mathbf{c}}'(1+\hat{\mathbf{c}}\cdot\hat{\mathbf{c}}')\ n^Y[\hat{\mathbf{c}}',\nu,\mathbf{x},t]$
    - lensing term $(\partial_t\hat{\mathbf{c}})\cdot\nabla_{\hat{c}} n^X[\hat{\mathbf{c}},\nu,\mathbf{x},t]$ is 2nd order
  - $\partial_t \ln\nu = -\hat{\mathbf{c}}\cdot\nabla\Phi + \partial_t\Phi + \hat{\mathbf{c}}\cdot\partial_t\mathbf{H}^{\perp tr}\cdot\hat{\mathbf{c}}$ independent of ν

Boltzmann Equation

$$\dot{\tilde{a}}^{\mathrm{T}}_{(l,m)} + ik\left(f^{\mathrm{T}}_{(l+1,m)}\,\tilde{a}^{\mathrm{T}}_{(l+1,m)} + f^{\mathrm{T}}_{(l,m)}\,\tilde{a}^{\mathrm{T}}_{(l-1,m)}\right) = -\dot{\tau}\left((1-\delta_{l0}-\frac{1}{10}\delta_{l2})\tilde{a}^{\mathrm{T}}_{(l,m)} + \frac{\sqrt{3}}{20}\delta_{l2}\tilde{a}^{\oplus}_{(2,m)}\right)$$

$$\dot{\tilde{a}}^{\mathrm{V}}_{(l,m)} + ik\left(f^{\mathrm{T}}_{(l+1,m)}\,\tilde{a}^{\mathrm{V}}_{(l+1,m)} + f^{\mathrm{T}}_{(l,m)}\,\tilde{a}^{\mathrm{V}}_{(l-1,m)}\right) = -\dot{\tau}\left((1-\frac{1}{2}\delta_{l2})\tilde{a}^{\mathrm{V}}_{(l,m)}\right)$$

$$\dot{\tilde{a}}^{\oplus}_{(l,m)} + ik\left(f^{\mathrm{P}}_{(l+1,m)}\,\tilde{a}^{\oplus}_{(l+1,m)} + f^{\mathrm{P}}_{(l,m)}\,\tilde{a}^{\oplus}_{(l-1,m)} + i\,f^{\oplus\otimes}_{(l,m)}\,\tilde{a}^{\otimes}_{(l,m)}\right) = -\dot{\tau}\left((1-\frac{3}{5}\delta_{l2})\tilde{a}^{\oplus}_{(l,m)} + \frac{2\sqrt{3}}{5}\delta_{l2}\tilde{a}^{\mathrm{T}}_{(2,m)}\right)$$

$$\dot{\tilde{a}}^{\otimes}_{(l,m)} + ik\left(f^{\mathrm{P}}_{(l+1,m)}\,\tilde{a}^{\otimes}_{(l+1,m)} + f^{\mathrm{P}}_{(l,m)}\,\tilde{a}^{\otimes}_{(l-1,m)} - i\,f^{\oplus\otimes}_{(l,m)}\,\tilde{a}^{\oplus}_{(l,m)}\right) = -\dot{\tau}\,\tilde{a}^{\otimes}_{(l,m)}$$

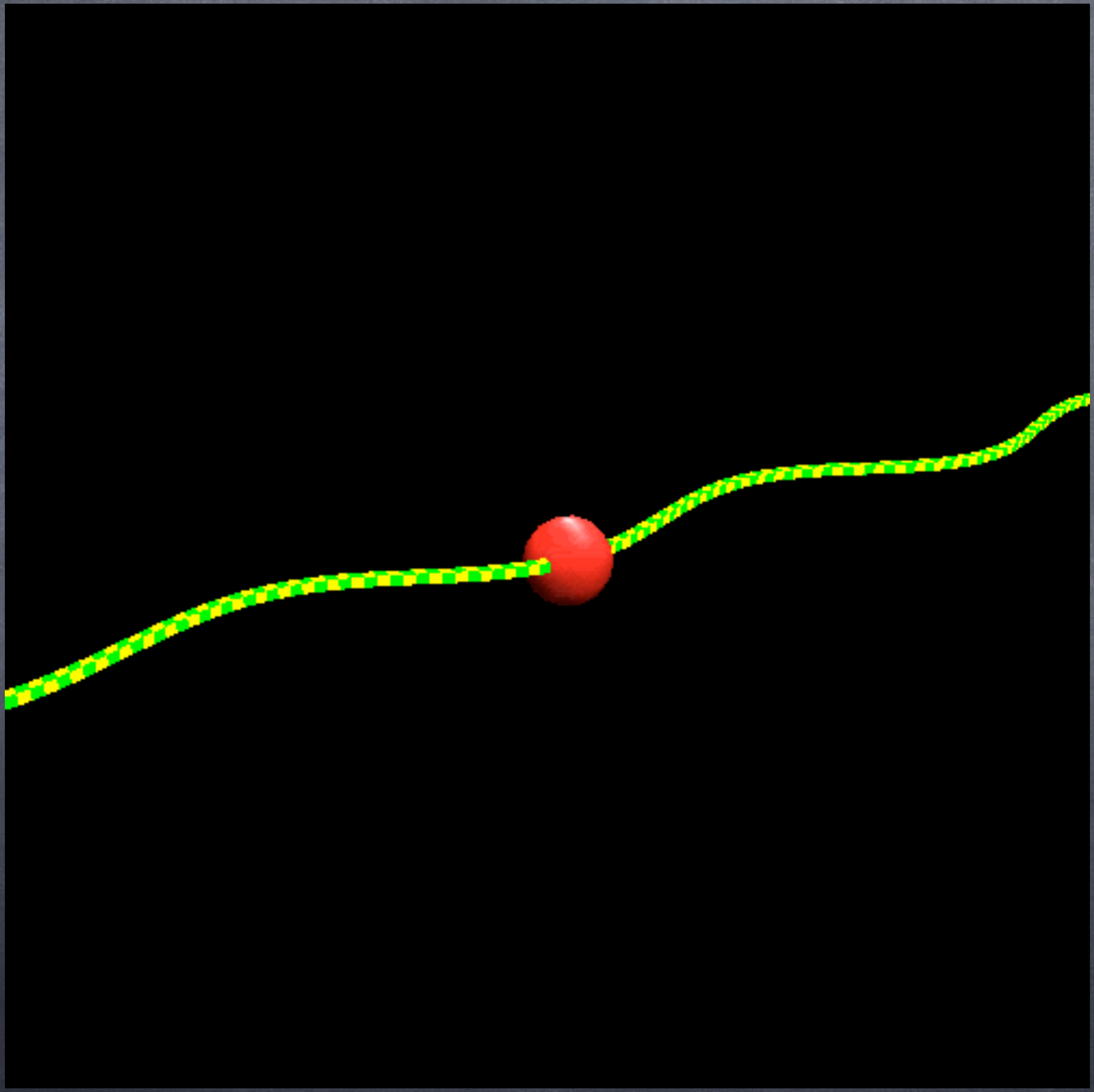
$$f^{\mathrm{T}}_{(l,m)} = \sqrt{\frac{l^2-m^2}{4l^2-1}}$$

$$f^{\mathrm{P}}_{(l,m)} = \sqrt{\frac{(l^2-m^2)(l^2-4)}{l^2(4l^2-1)}}$$

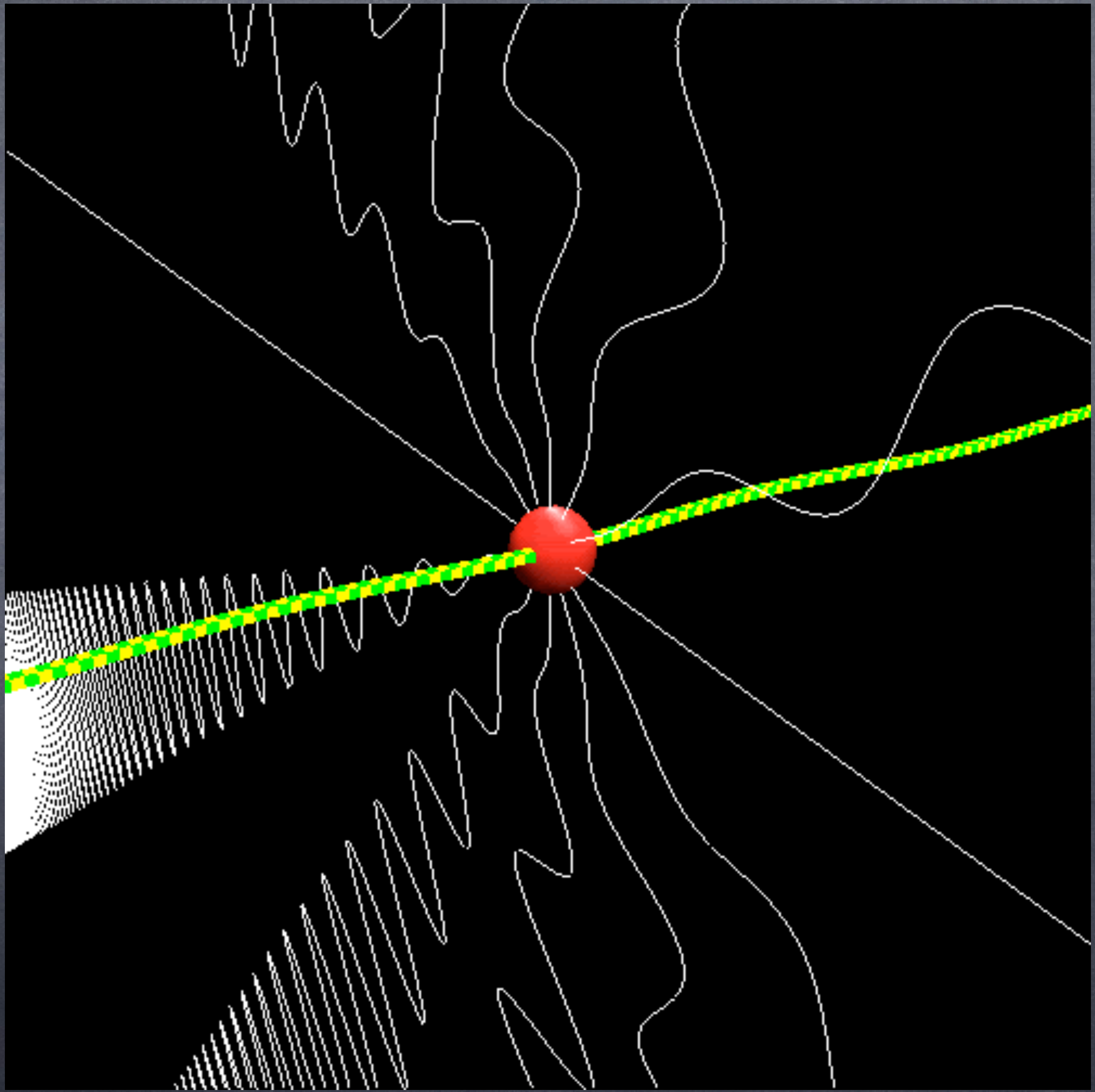
$$i\,f^{\oplus\otimes}_{(l,m)} = \frac{2im}{l(l+1)}$$

$\partial_t \tau = c\ \sigma_T\, n_e$

Thomson Scattering



Thomson Scattering



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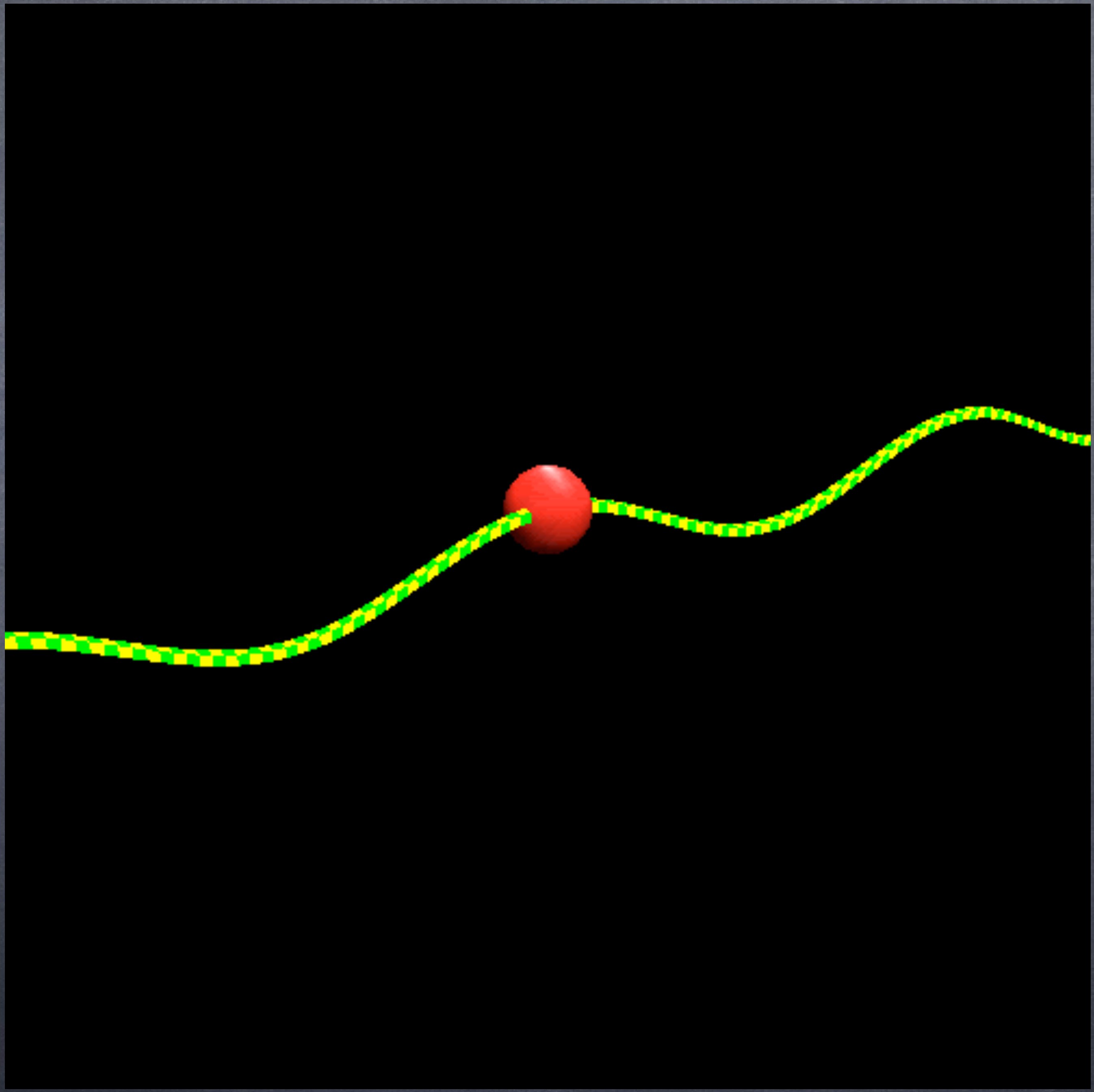
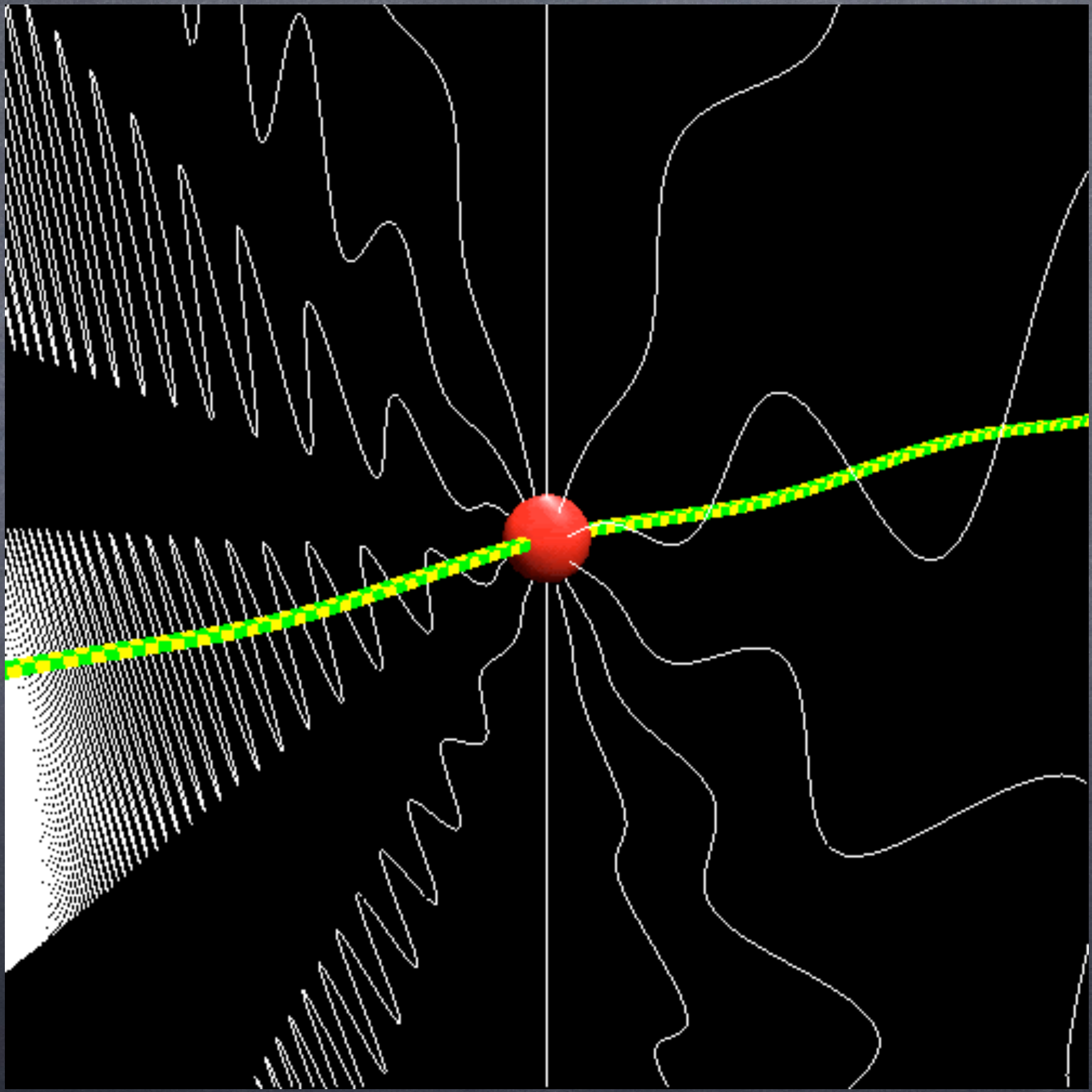
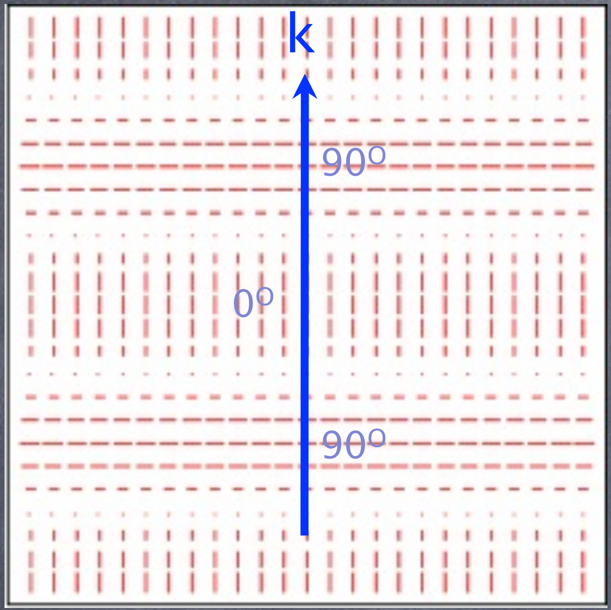


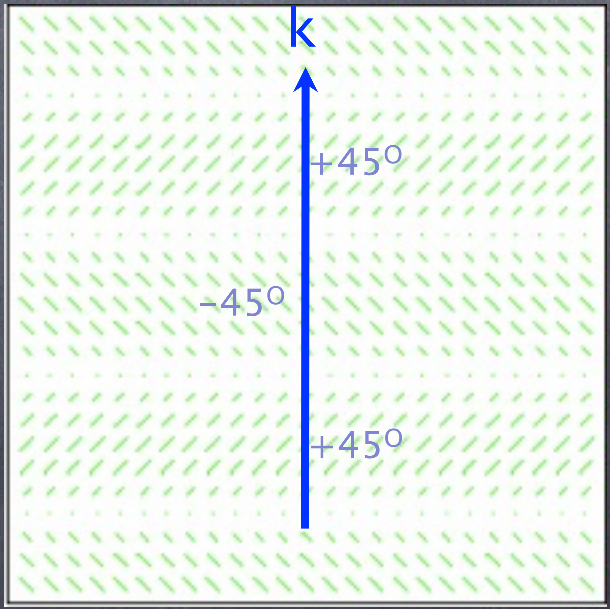
Thomson Scattering



Linear Polarization Patterns

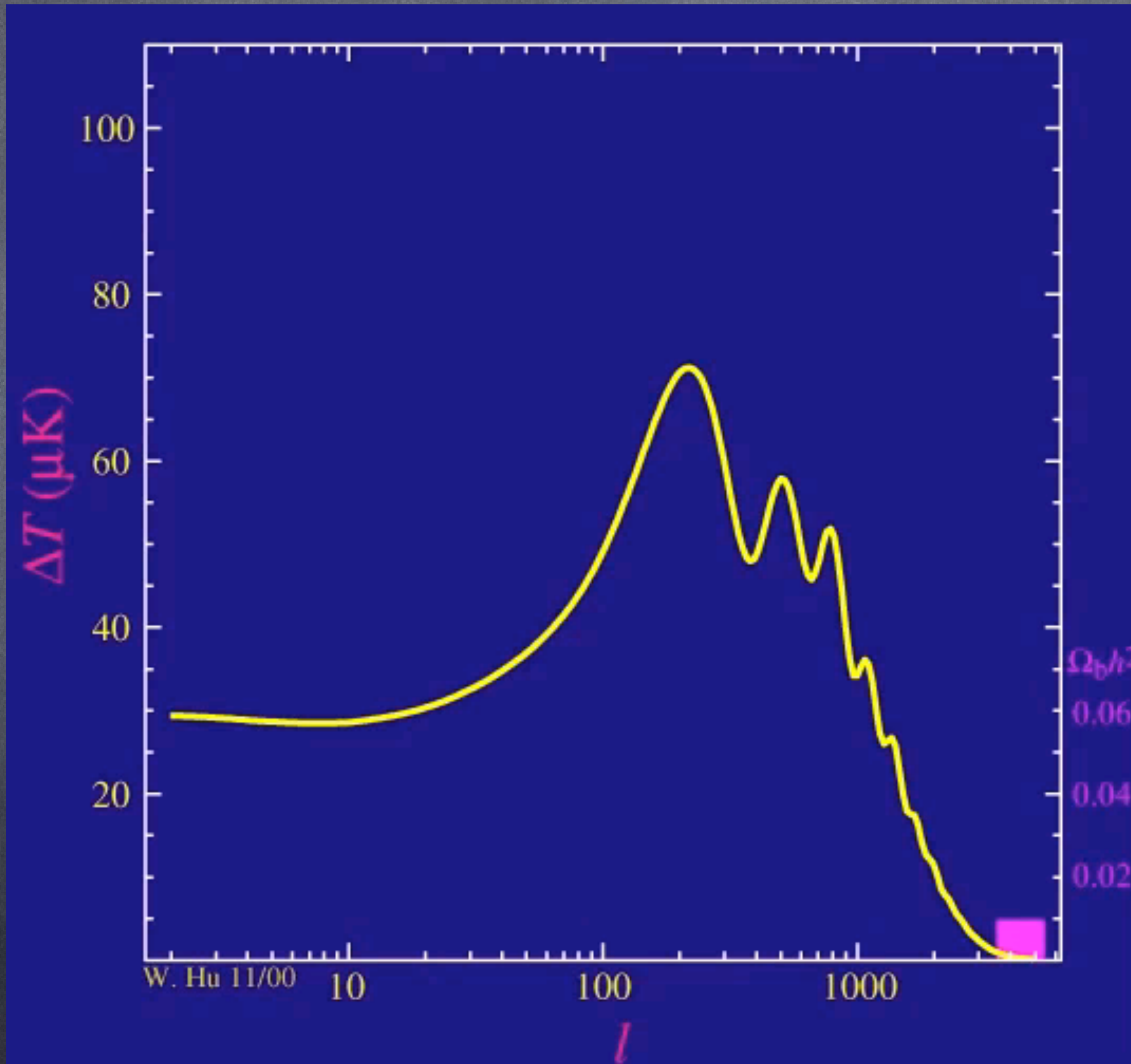


0°–90° pattern



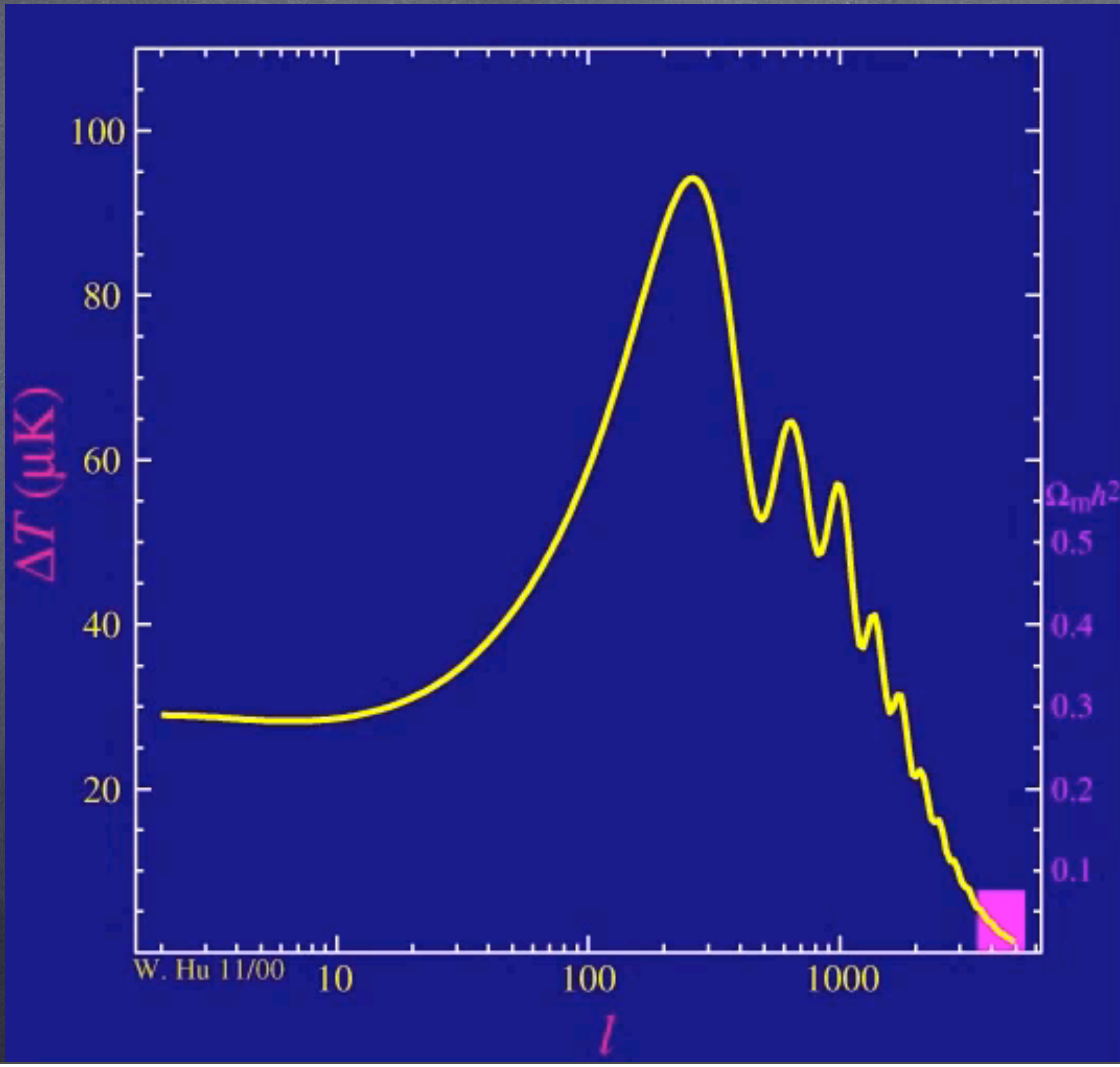
±45° pattern

Baryon Density



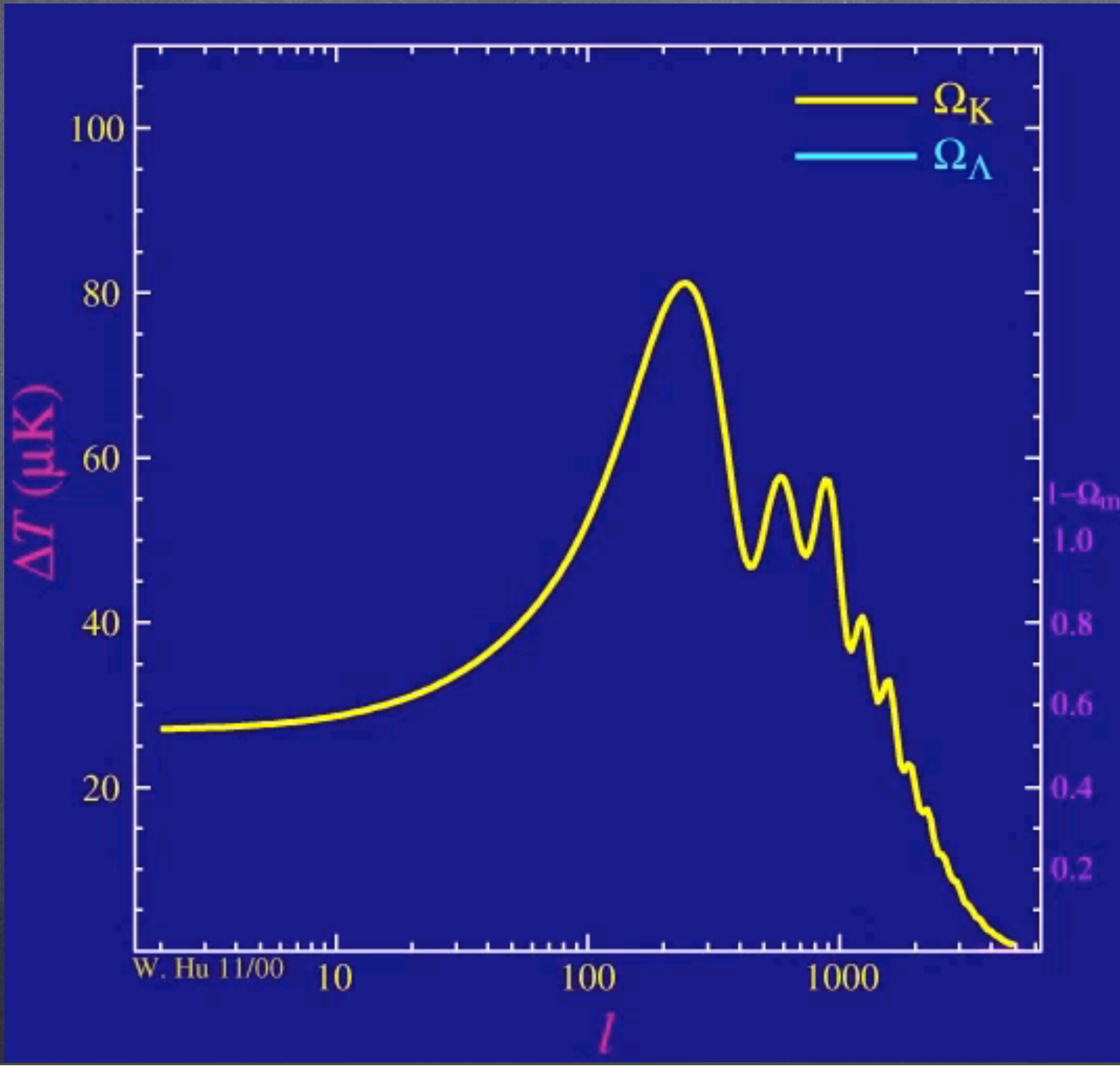
http://background.uchicago.edu/~whu/animbut/anim1.html

Dark Matter Density



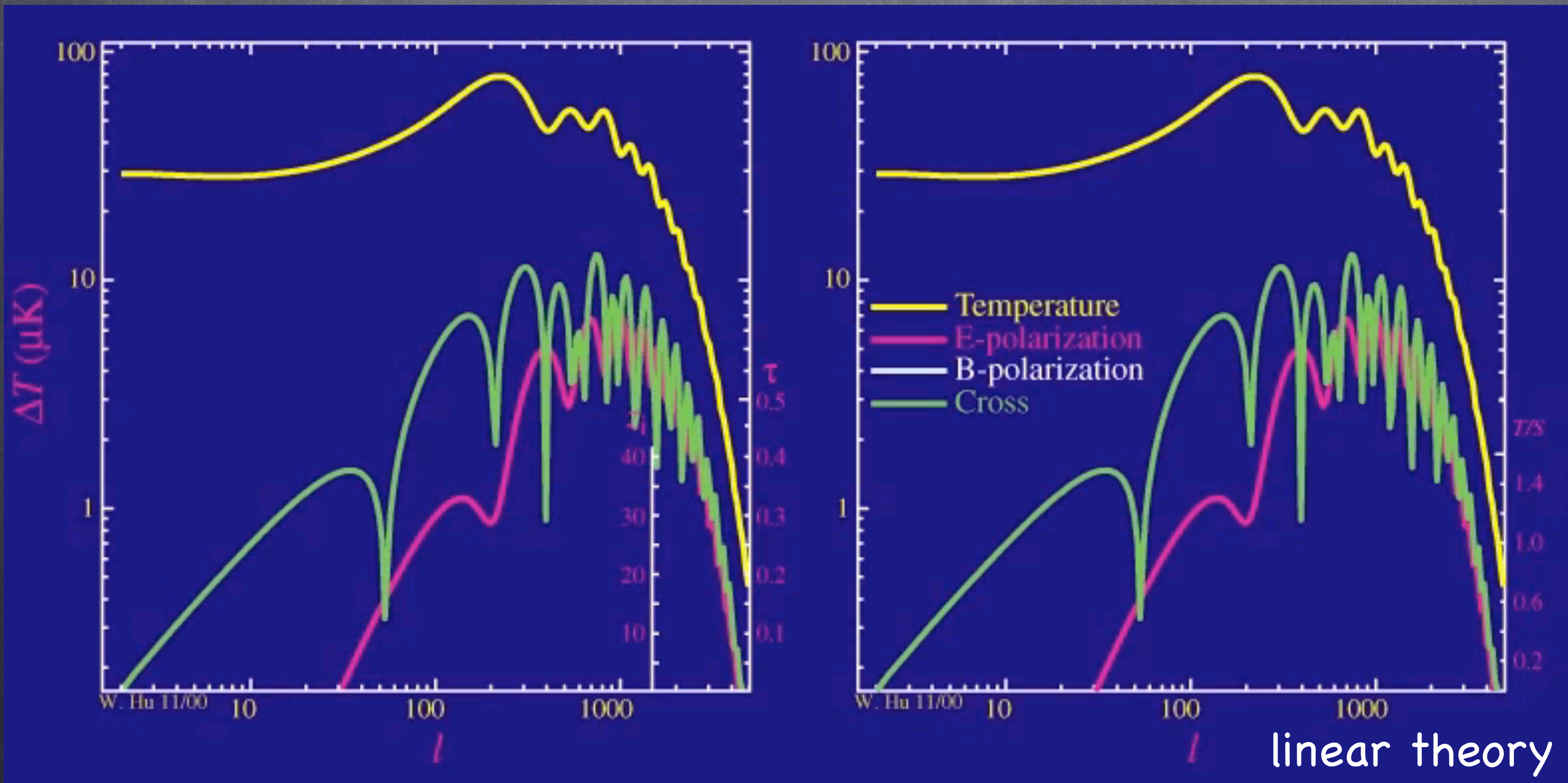
http://background.uchicago.edu/~whu/animbut/anim2.html

Curvature & Cosmological Constant



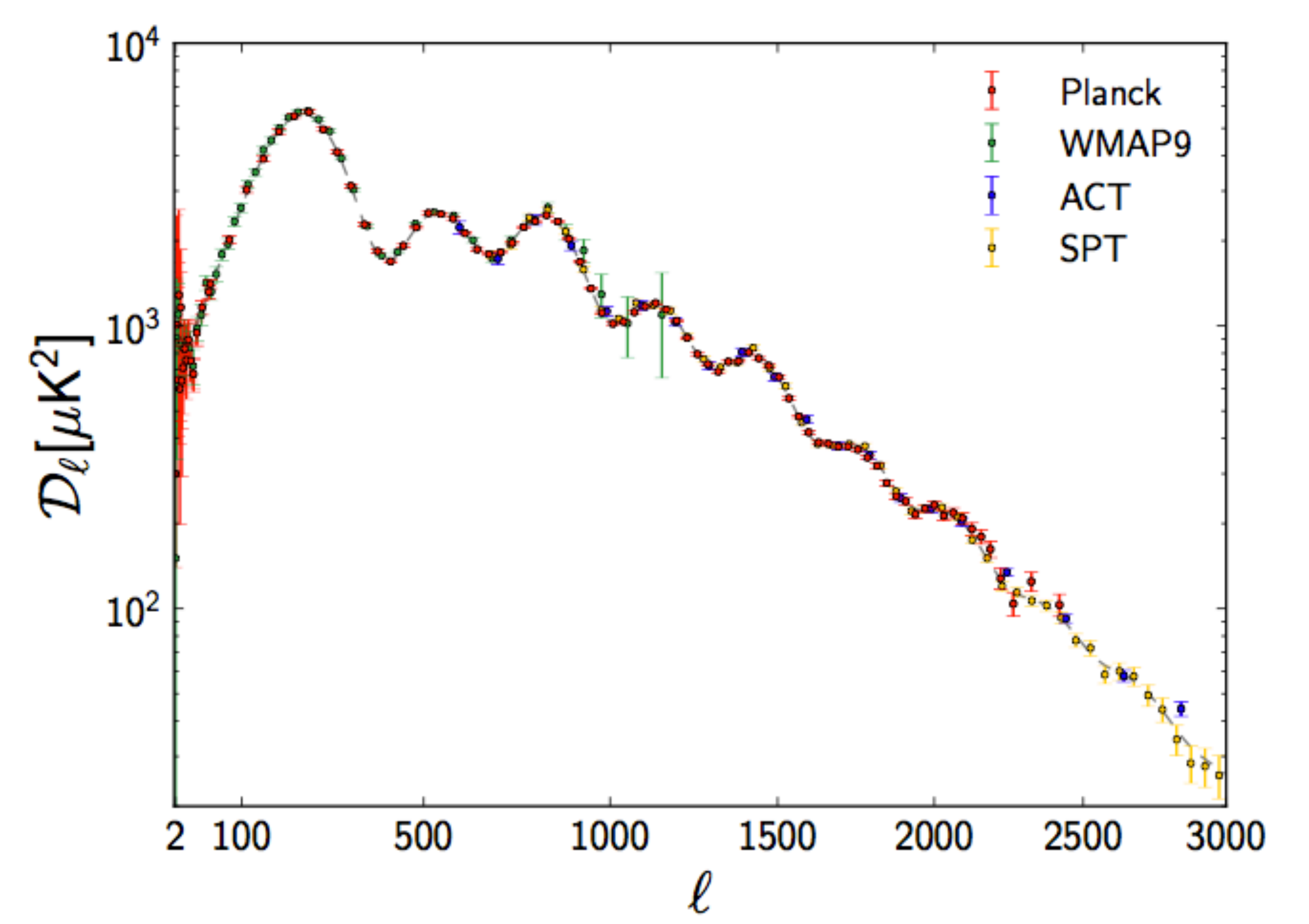
http://background.uchicago.edu/~whu/animbut/anim3.html

Reionization Optical Depth
Tensor Modes

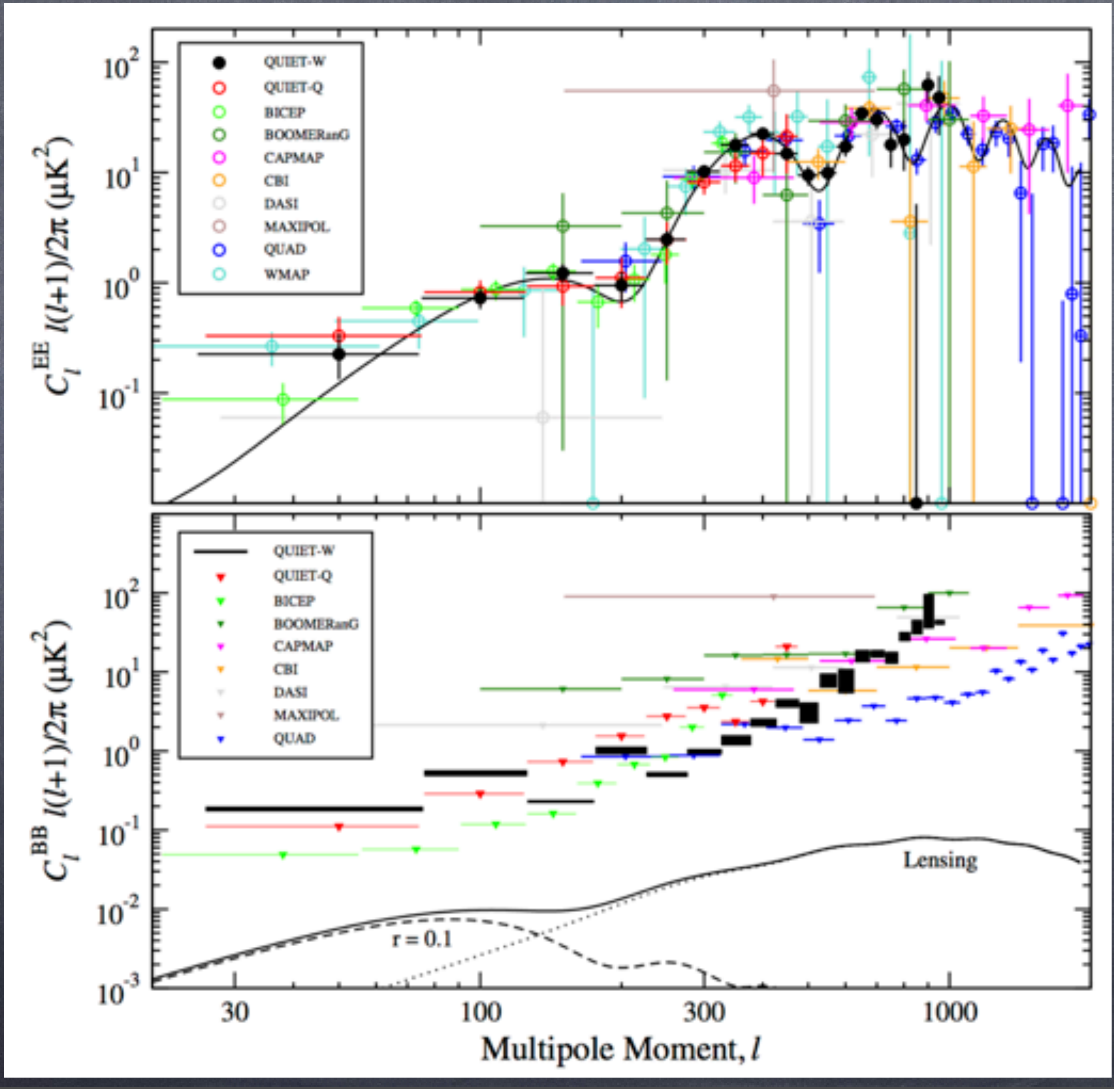


http://background.uchicago.edu/~whu/animbut/anim4.html

Results: Temperature

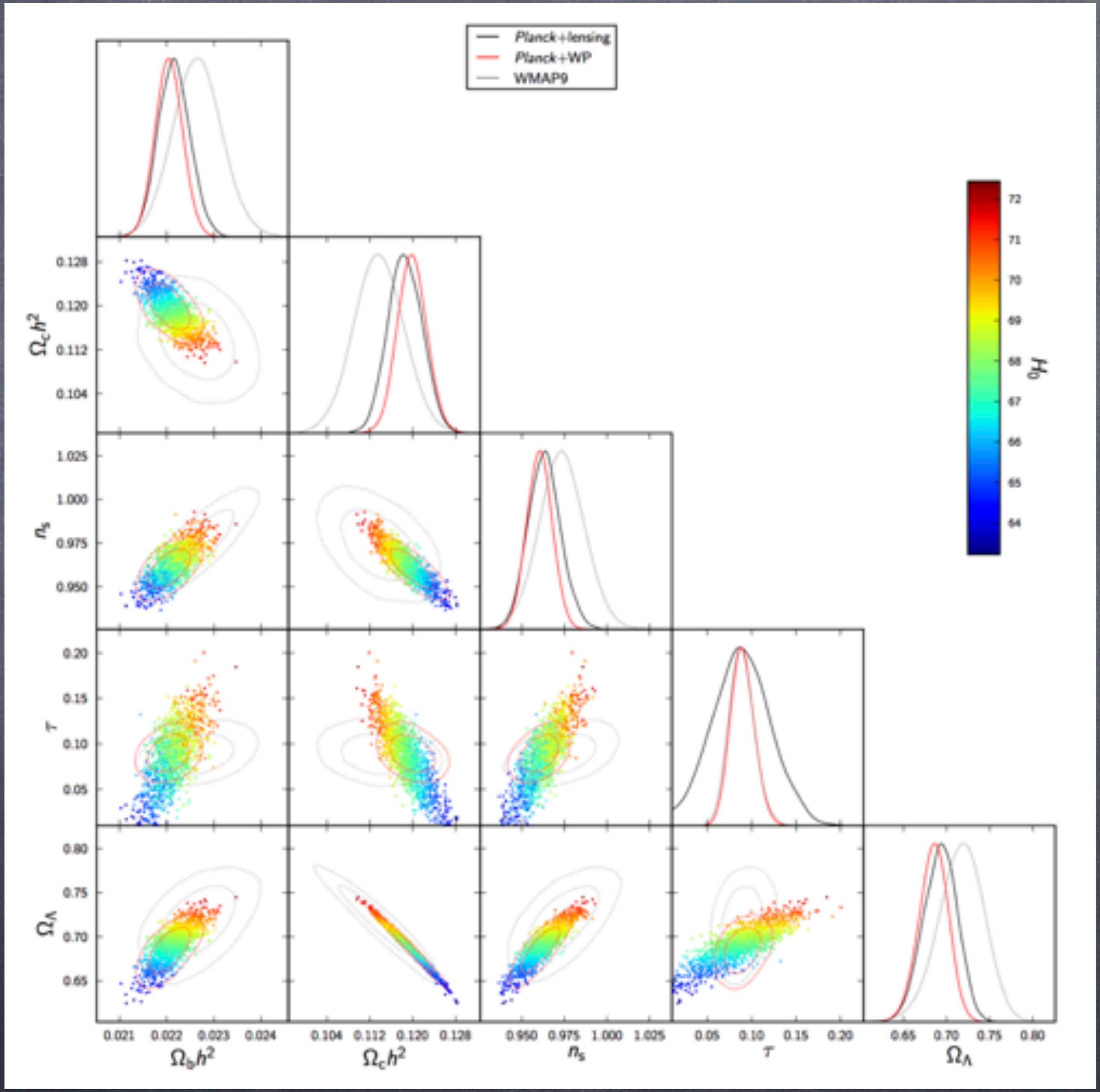


Results: Polarization



QUIET
2012

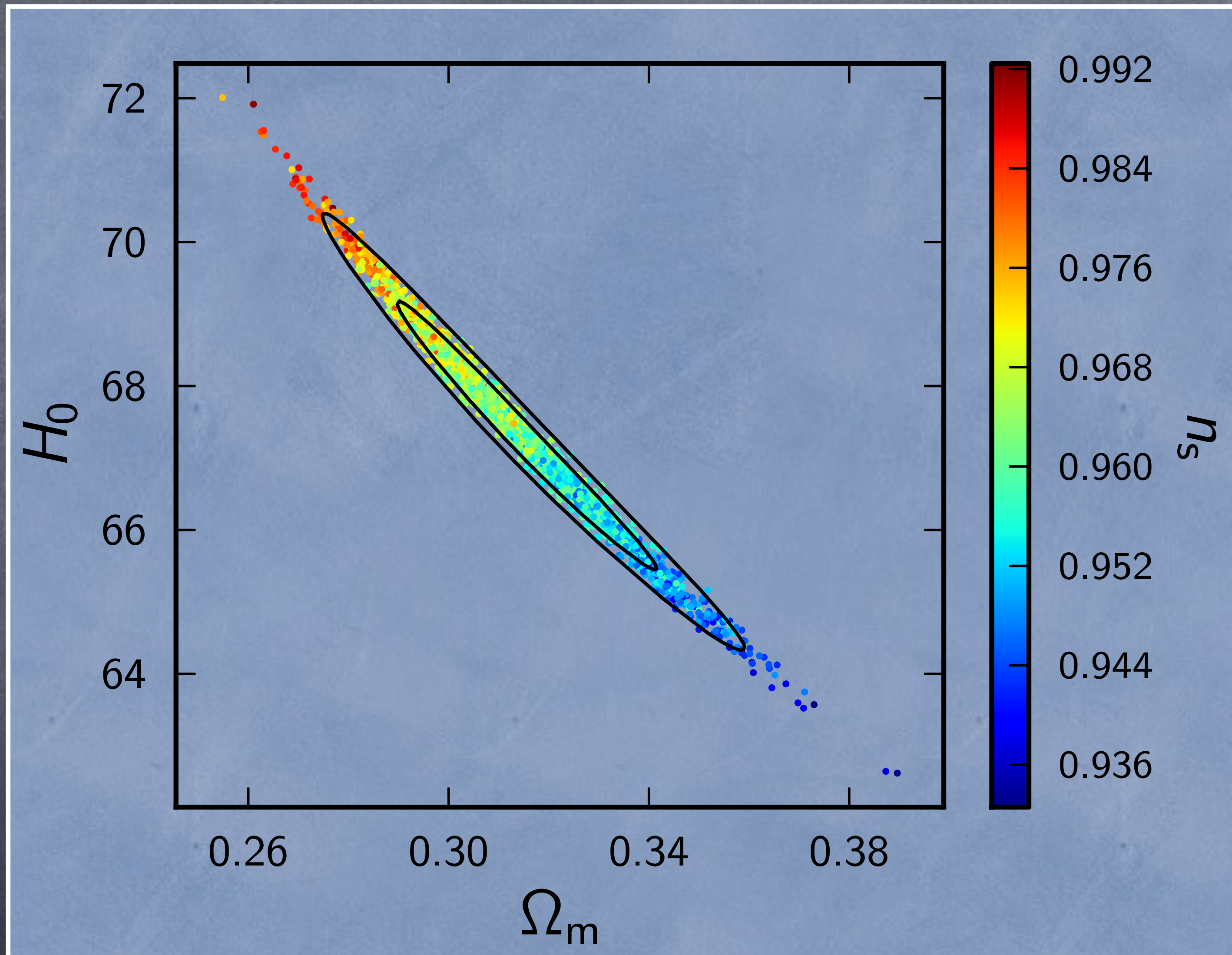
Results: Parameters



PLANCK 2013

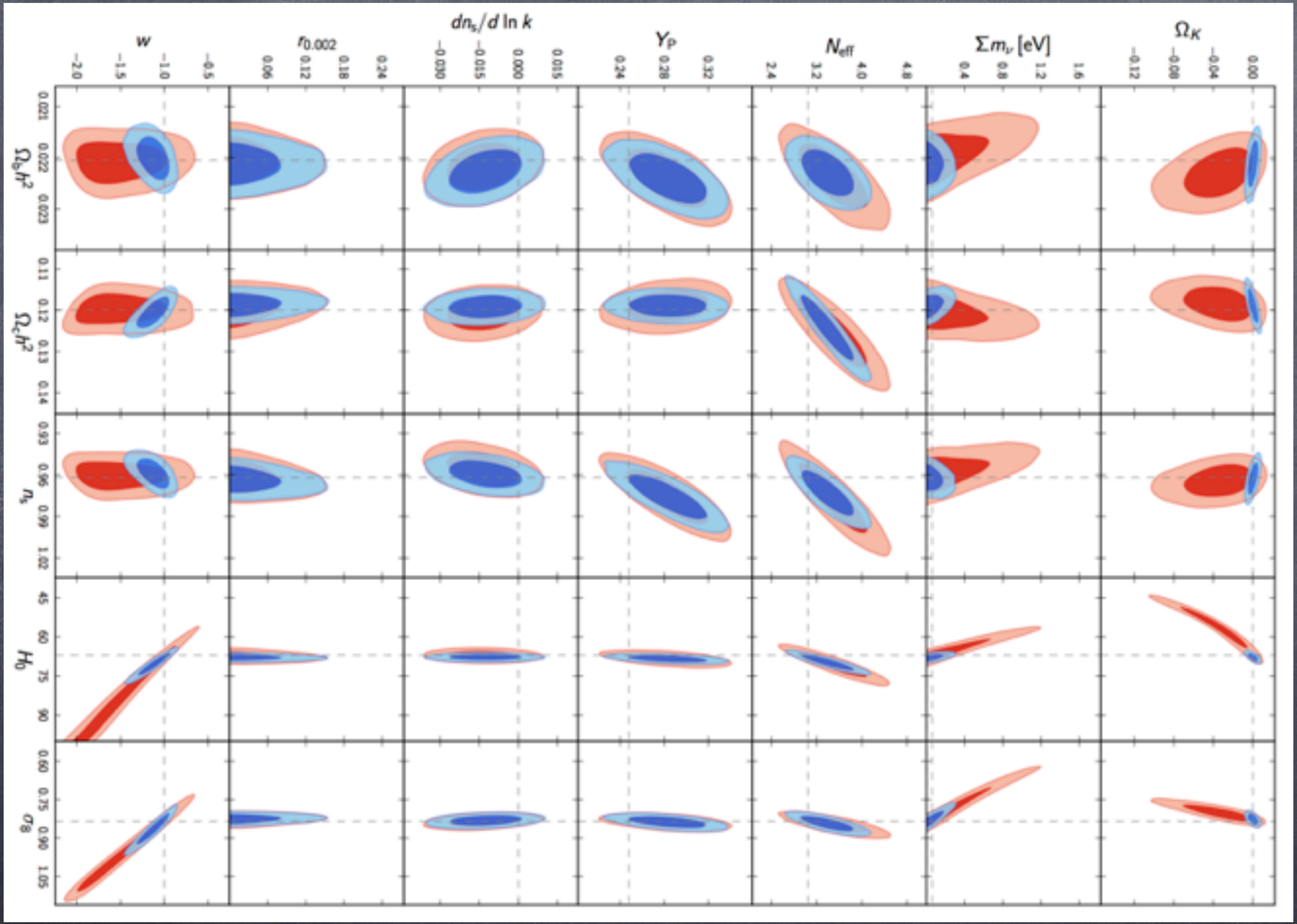
WP=WMAP Polarization

Parameter Degeneracy



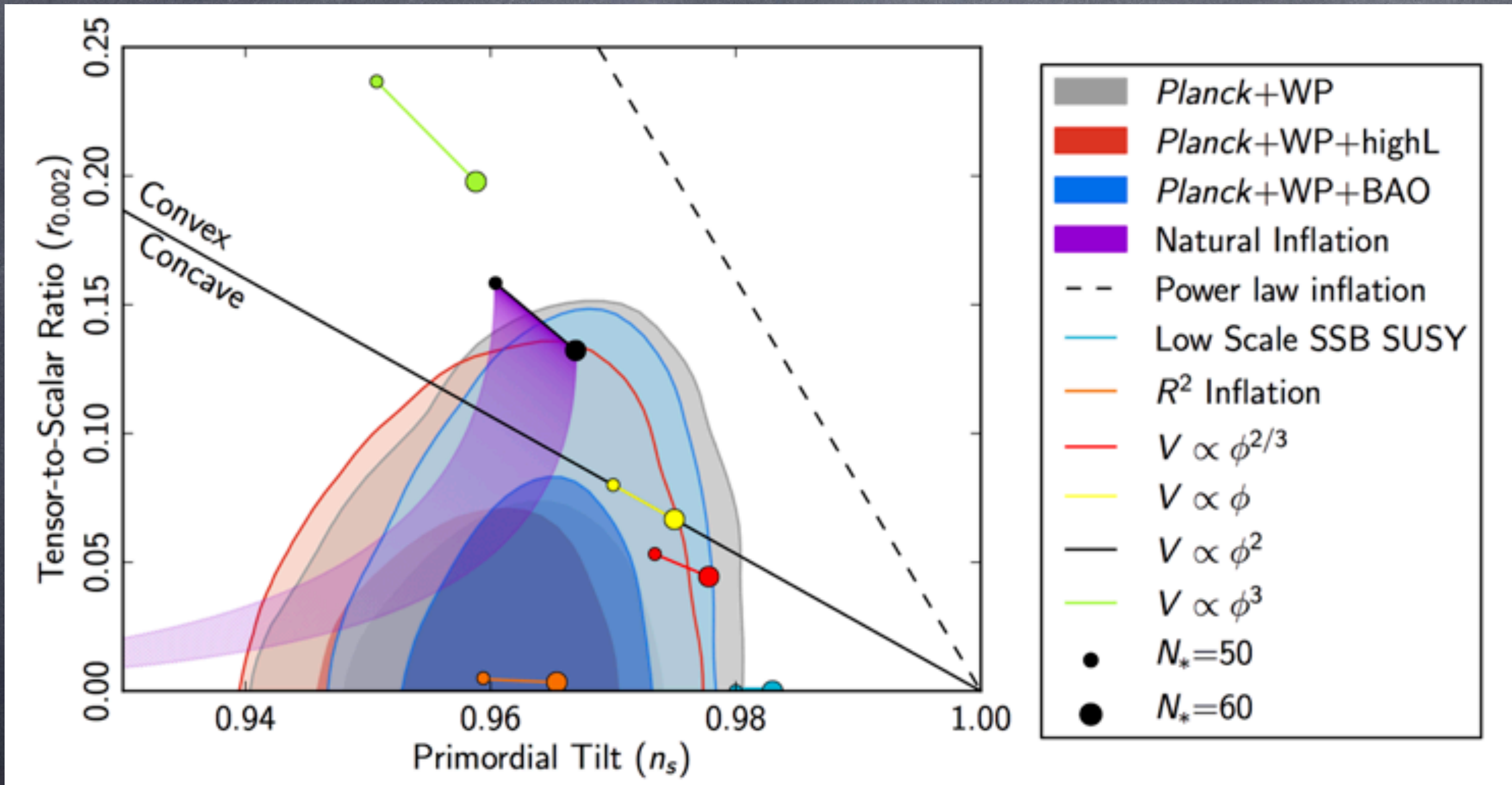
PLANCK
2013

Results: Other Parameters



PLANCK 2013 PLANCK+WP PLANCK+WP+BAO

Constraints on Inflation



PLANCK 2013

CONCLUSIONS

- THE CMBR IS A FAIRLY SIMPLE AND CLEAN AND EASY TO TO UNDERSTAND SYSTEM ALLOWING VERY PRECISE MEASUREMENTS OF ITS PROPERTIES
- BECAUSE OF THIS THE CMBR HAS AND WILL CONTINUE TO PROVIDE SOME OF THE BEST CONSTRAINTS ON COSMOLOGICAL PARAMETERS