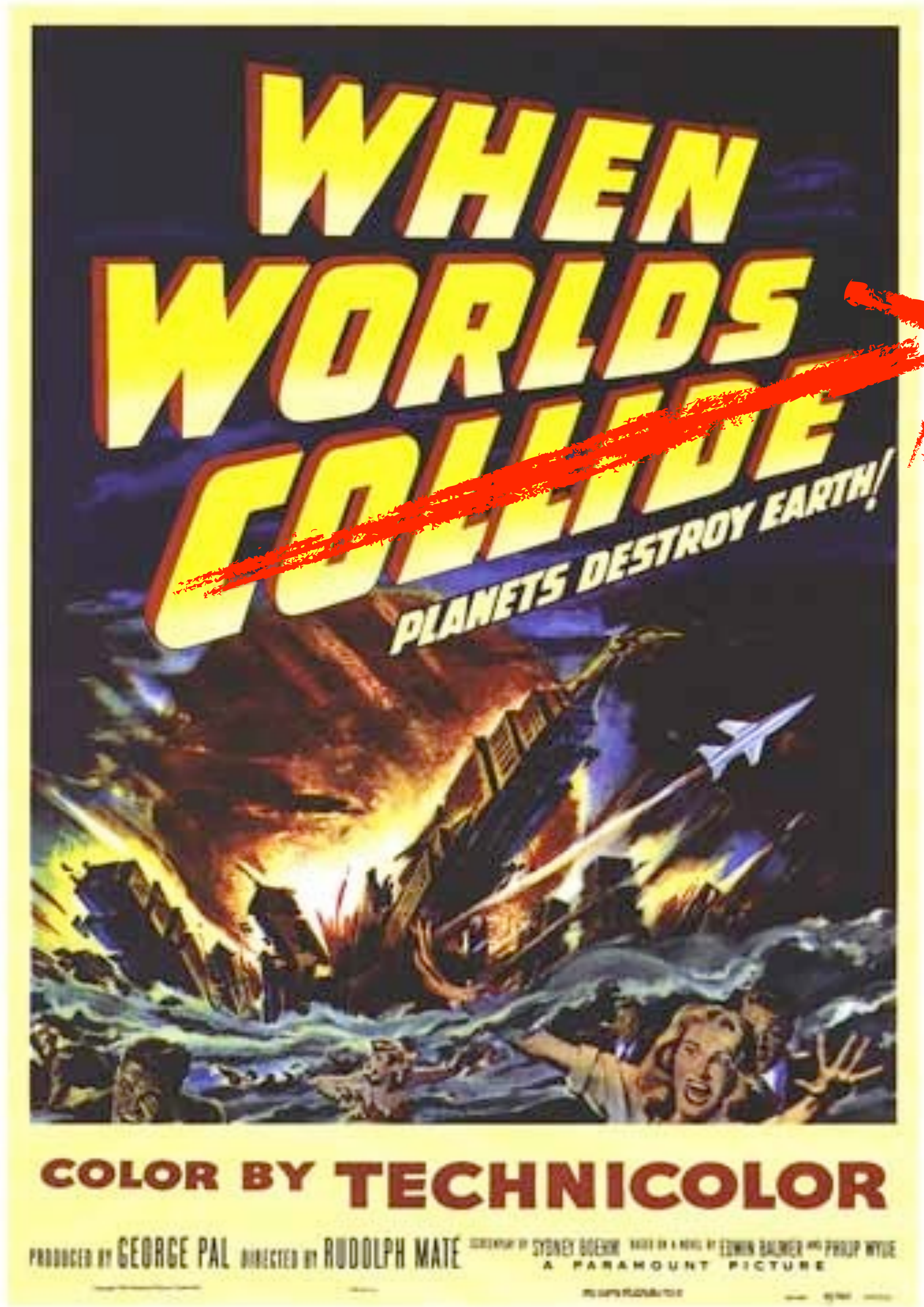


Polarize!

Thomas Levi
UBC

- JCAP 0804:034,2008 (arXiv: 0712.2261)
- JCAP 0904:025,2009 (arXiv: 0810.5128) with Spencer Chang and Matthew Kleban
- JCAP 1008:034,2009 (arXiv: 0910.4159) with Klaus Larjo
- JCAP 1012: 0832 (arXiv:1006.0832) with Bartek Czech, Matt Kleban, Klaus Larjo and Kris Sigurdson
- In progress with Matt Kleban and Kris Sigurdson

Motivation

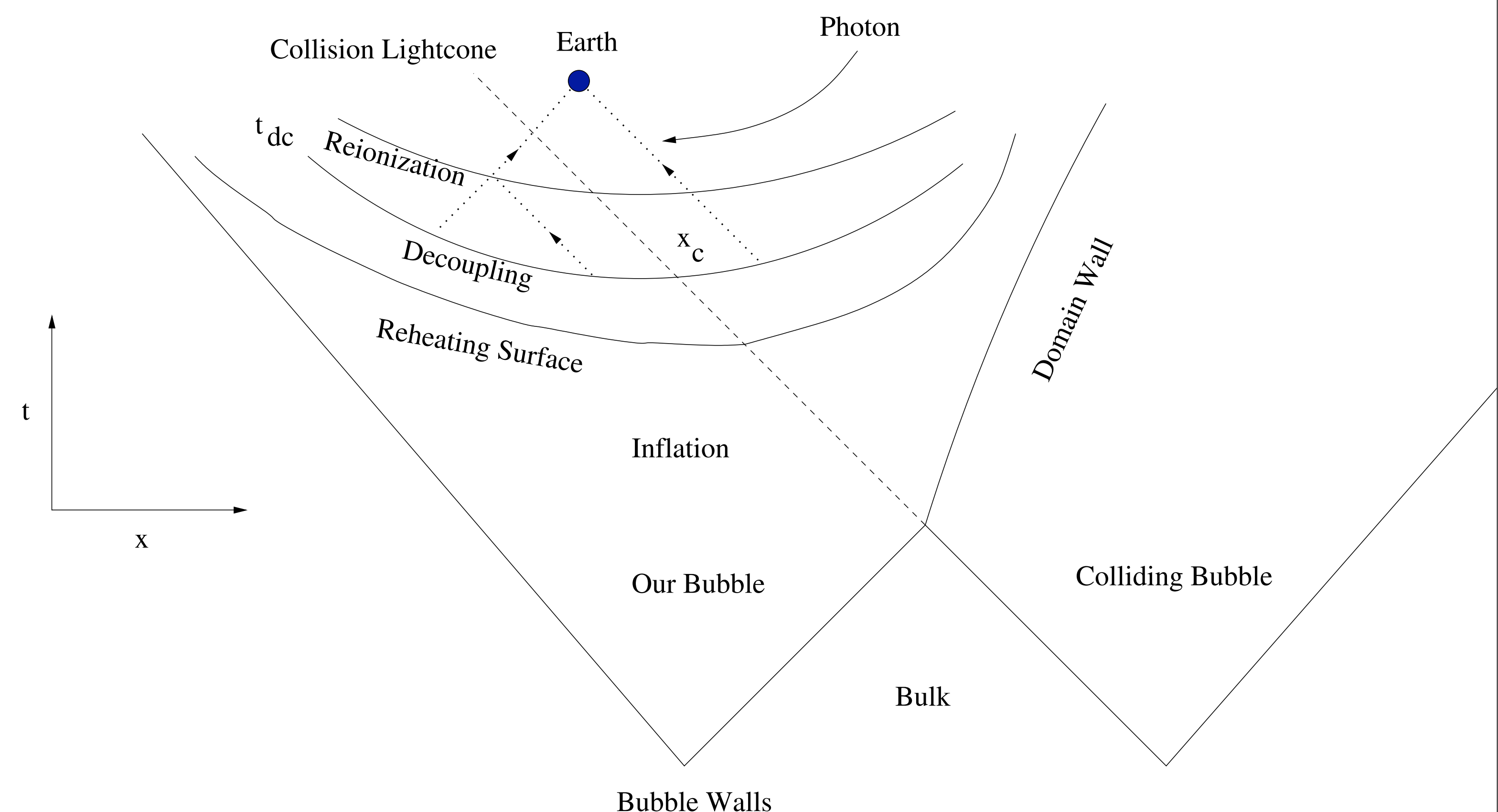
- Up to now, most of our analysis of effects of bubble collisions has been analytic and semi-analytic, ignoring details of the fluid components, evolution of perturbations etc.
- These approximations are valid above a degree scale (though we'd like to check that)
- Below a degree scale we need the full evolution
- We'll use full perturbation theory and a combination of analytic and numerical analysis to carry this out

Outline

- Brief review of setup
- The pieces
  - Initial conditions
  - Transfer functions
- Signals
  - Temperature
  - Polarization

The setup

- We assume that a bubble collision happens to create a DW moving away from us
- As Matt told you yesterday, we'll calculate the perturbation during inflation
- We'll then evolve it in a full cosmology with WMAP concordance parameters using perturbation theory
- We can then calculate temperature, polarization and track the evolution of overdensities



Setting up the calculation

- For each quantity we compute, we need two pieces:
  - An initial condition found during inflation for the Newtonian potential or curvature perturbation that encodes a bubble collision $\longrightarrow$ Independent of subsequent evolution and calculated analytically to first order in slow-roll
  - A transfer function that can take the initial condition and allow us to compute the physical quanties we are interested in $\longrightarrow$ Independent of bubble collision and calculated numerically in CAMB

Example: Temperature

- We can express the temperature anisotropy as

$$\Delta_T(\mathbf{x},\hat{n},\eta) = \int d^3k e^{i\mathbf{k}\cdot\mathbf{x}} \Delta_T(\mathbf{k},\hat{n},\eta)$$

$$= \int d^3k e^{i\mathbf{k}\cdot\mathbf{x}} \sum_{l=0}^{\infty} (-i)^\ell (2\ell+1) \Delta_{T,\ell}(\mathbf{k},\eta) P_\ell(\mathbf{k}\cdot\hat{n})$$

at the origin (our sky)

$$\Delta_T(\hat{n}) = \sum_{l=0}^{\infty} \sum_{m=-\ell}^{m=\ell} a_{lm} Y_{lm}(\hat{n}) \qquad a_{lm} = (-i)^\ell 4\pi \int d^3k Y^*_{lm}(\hat{k}) \Delta_{T,\ell}(\mathbf{k},\eta)$$

where

$$\Delta_{T,\ell}(\mathbf{k},\eta) = \zeta_i(\mathbf{k}) \Delta_{T,\ell}(k,\eta) = \frac{4R_\nu + 15}{10} \Phi_i(\mathbf{k}) \Delta_{T,\ell}(k,\eta) \approx 1.66 \Phi_i(\mathbf{k}) \Delta_{T,\ell}(k,\eta)$$

Initial condition (Newtonian potential)

Transfer function: found numerically in (modified) CAMB

- Similar formulas for polarization and overdensities can be found

The initial condition

As Matt told you, we use Newtonian gauge, and expand the scalar to first order in slow-roll

$$ds^2 = a^2(\tau)\left(-(1+2\Phi)d\tau^2 + (1+2\Psi)d\mathbf{x}^2\right) \quad , \quad \Psi = \Phi \quad \text{during inflation (no anisotropic stress)}$$

$$\varphi = \varphi_0 + \delta\varphi$$

We need to solve the linearized Einstein and Klein-Gordon equations

$$\nabla^2\Phi - 3\mathcal{H}\Phi' - (\mathcal{H} + 2\mathcal{H}^2)\Phi = \frac{3}{2}l_p^2\left(\varphi_0'\delta\varphi' + V_{,\varphi}a^2\delta\varphi\right)$$

$$\Phi' + \mathcal{H}\Phi = \frac{3}{2}l_p^2\varphi_0'\delta\varphi$$

$$\Phi'' + 3\mathcal{H}\Phi' + (\mathcal{H} + 2\mathcal{H}^2)\Phi = \frac{3}{2}l_p^2\left(\varphi_0'\delta\varphi' - V_{,\varphi}a^2\delta\varphi\right)$$

$$\varphi_0'' + 2\mathcal{H}\varphi_0' + V_{,\varphi}a^2 = 0$$

$$\delta\varphi'' + 2\mathcal{H}\delta\varphi' - \nabla^2\delta\varphi + V_{,\varphi\varphi}a^2\delta\varphi - 4\varphi_0'\Phi' + 2V_{,\varphi}a^2\Phi = 0$$

$$\frac{3}{2}l_p^2\varphi_0'^2 = \mathcal{H}^2 - \mathcal{H}'$$

During slow-roll we can approximate the potential as

$$V = V_0 + \mu\varphi + \ldots \qquad \epsilon = \frac{1}{2l_p^2}\left(\frac{V_{,\varphi}}{V}\right)^2 \sim \frac{\mu^2}{V_0^2} \qquad |\eta| = \frac{1}{l_p^2}\left|\frac{V_{,\varphi\varphi}}{V}\right| < \epsilon$$

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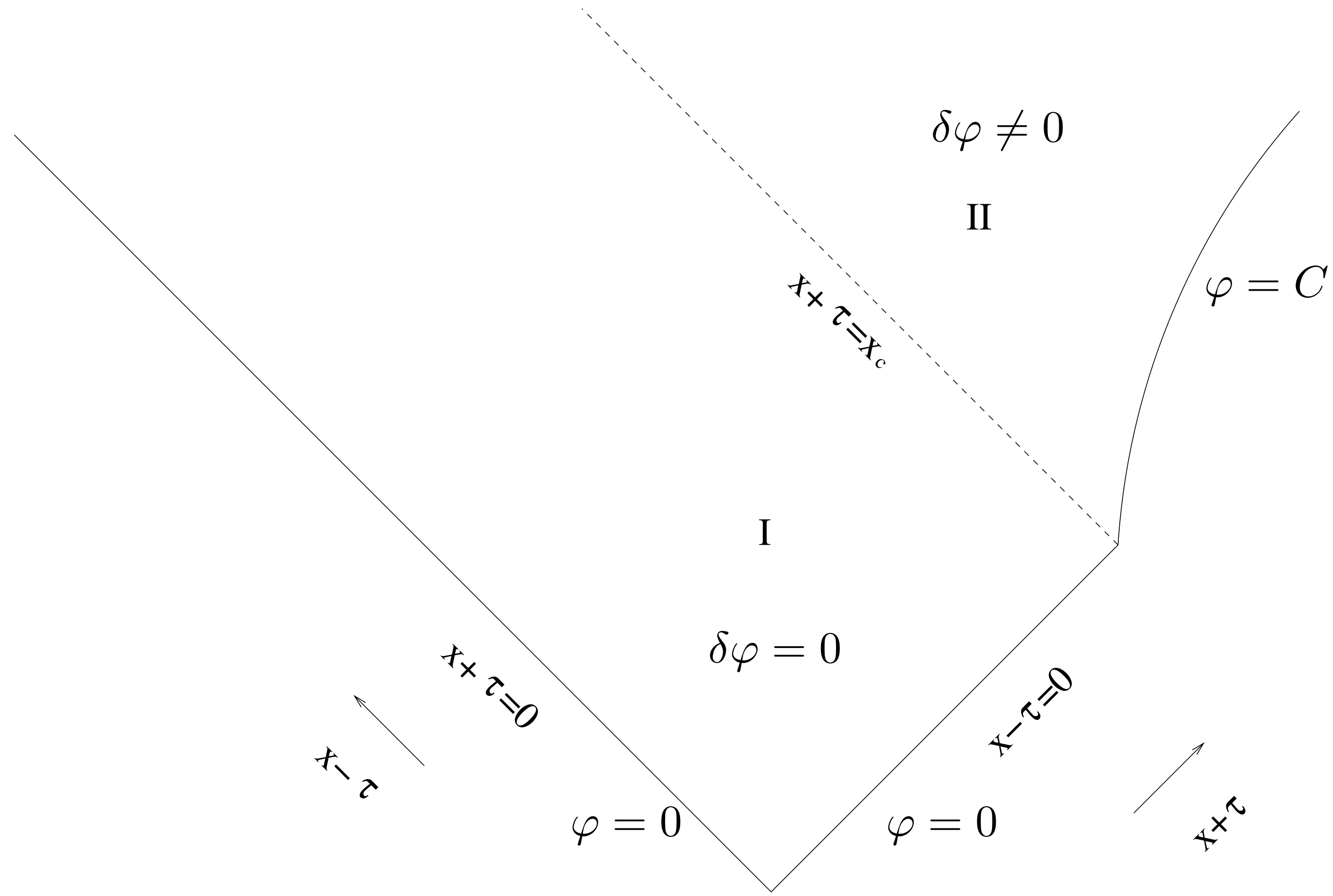
Higher order in slow-roll, as Matt (w
supposed) showed yesterday

$$\frac{3}{2}l_p^2\varphi_0'^2 = \mathcal{H}^2 - \mathcal{H}'$$

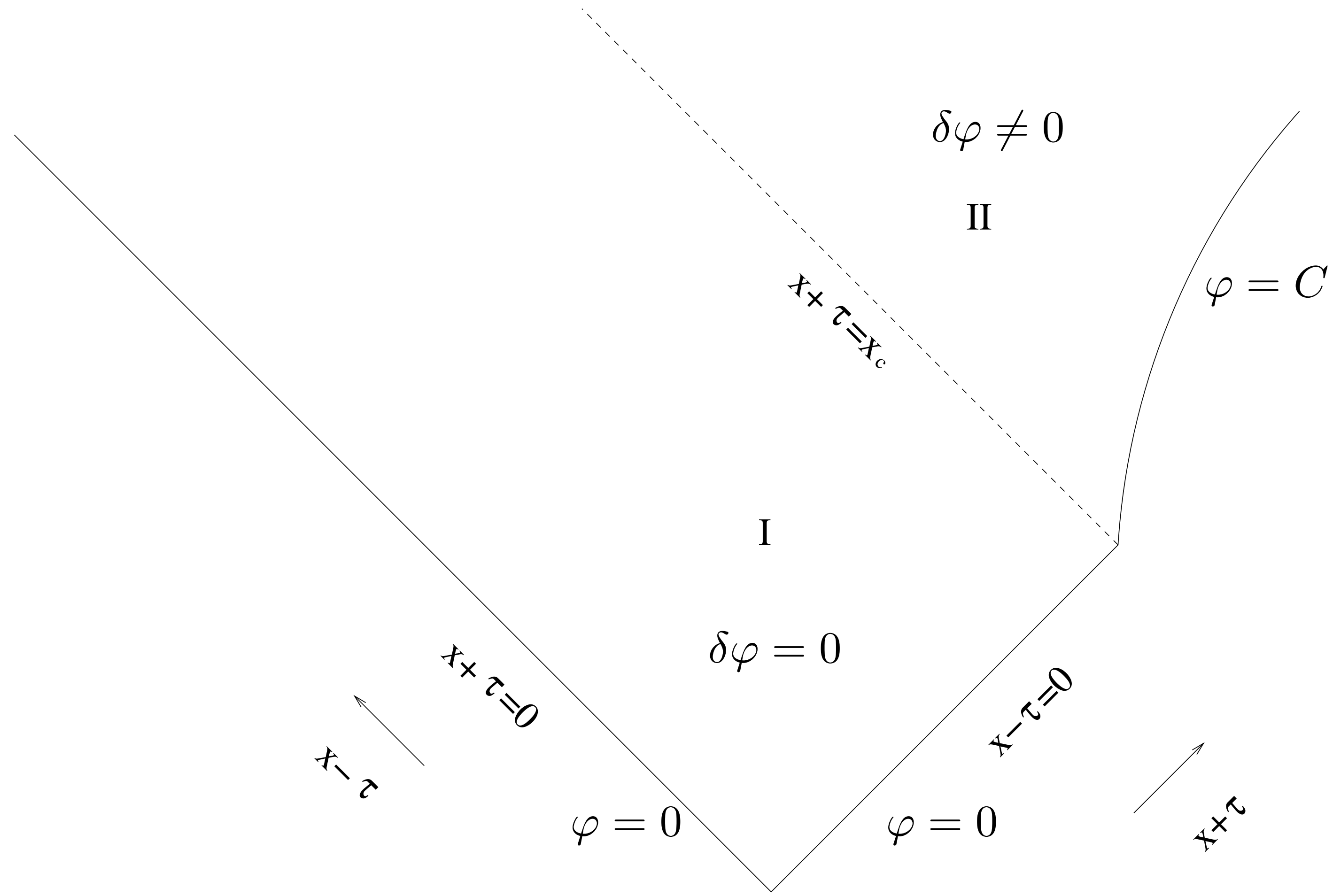
During slow-roll we can approximate the potential as

$$V = V_0 + \mu\varphi + \dots \qquad \epsilon = \frac{1}{2l_p^2}\left(\frac{V_{,\varphi}}{V}\right)^2 \sim \frac{\mu^2}{V_0^2} \qquad |\eta| = \frac{1}{l_p^2}\left|\frac{V_{,\varphi\varphi}}{V}\right| < \epsilon$$

Boundary conditions



Boundary conditions



To first order in slow-roll the solution is

$$\varphi_0 = \frac{\mu}{3}\ln(-\tau) \qquad \mathcal{H} \approx -\frac{1}{\tau} - \frac{\mu^2 l_p^2}{6\tau} \qquad a(\tau) \approx \frac{1}{\tau} - \frac{\mu^2 l_p^2}{6}\frac{\ln\tau}{\tau}$$

$$\delta\varphi = \lambda(x - x_c)\Theta(x + \tau - x_c)$$

$$\Phi = -\frac{1}{2}\mu l_p^2 \lambda(x + \tau - x_c)\Theta(x + \tau - x_c)$$
$$\approx -\frac{1}{2}\mu l_p^2 \lambda(x - x_c)\Theta(x - x_c)$$

Initial condition

The transfer functions

- All of the transfer functions are independent of the initial conditions and hence the collision
- They take any initial curvature perturbation and evolve it to the appropriate time and quantity
- Their evolution is governed by solving the relevant Boltzmann, gravitational and fluid equations
- We use a modified version of CAMB to compute each transfer function, using WMAP-7 best fit values and a single reionization model
- We then reconstruct the temperature, polarization and overdensities in position space by performing a numerical Fourier series transform in Mathematica with periodic BCs, ensuring the size of the box is much larger than our Hubble patch
- Our results are accurate up to a multipole of $\ell = 2000$

The temperature (analytic result)

- On large scales we expect the temperature anisotropy to be dominated by the SW effect

$$\frac{\delta T}{T} = -\frac{1}{3}\Phi_{ls} \sim (x - x_c)\Theta(x - x_c)$$

- This in fact was our analytic result from before, and gives a dipole inside the spot with no edge
- The full result (notably on smaller scales) requires solving the full evolution equations, which we have numerically

Review: Temperature

- We can express the temperature anisotropy as

$$\Delta_T(\mathbf{x},\hat{n},\eta) = \int d^3k e^{i\mathbf{k}\cdot\mathbf{x}} \Delta_T(\mathbf{k},\hat{n},\eta)$$

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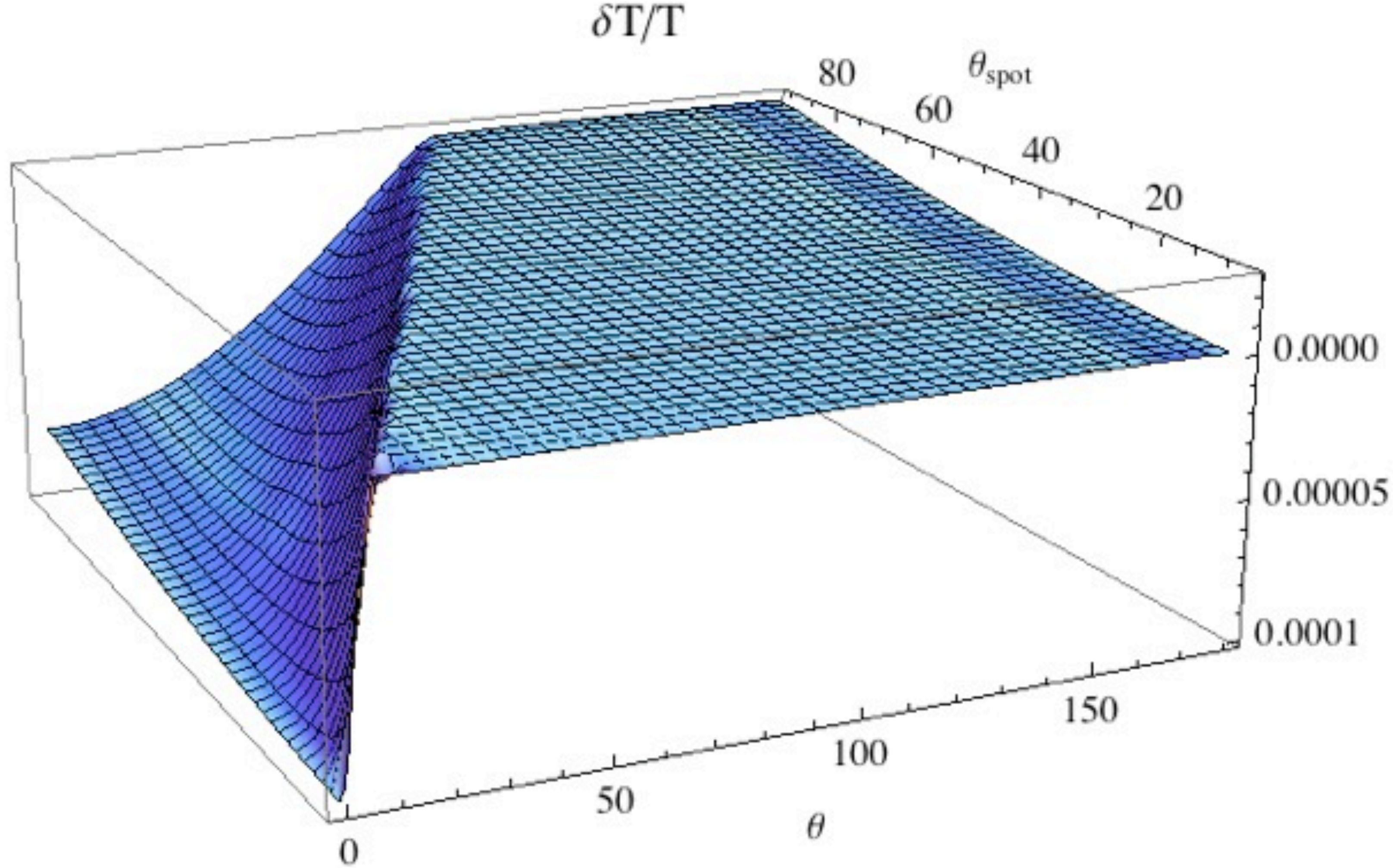
Initial condition (Newtonian potential)

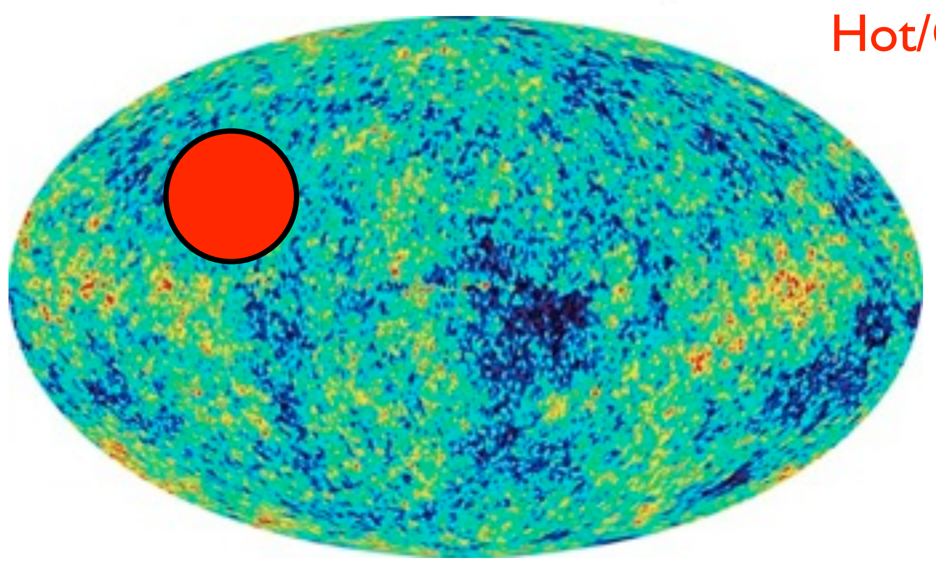
Transfer function: found numerically in (modified) CAMB

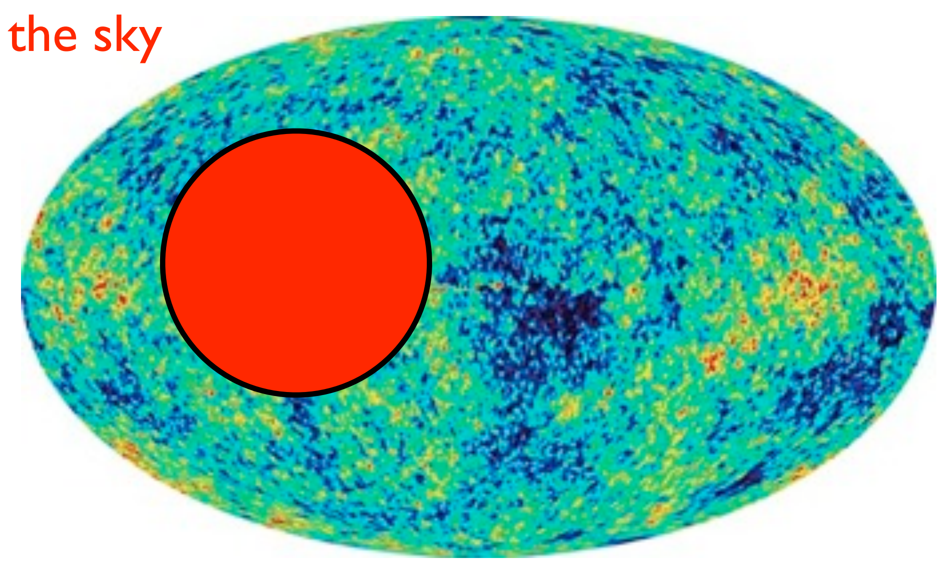
Temperature: The full result

- It turns out for temperature, the analytic approximation is quite accurate



Hot/Cold spot on the sky





Temperature: Features

- For any collision, we obtain a hot or cold spot
- The size of the spot depends on where we are compared to the collision lightcone
- The magnitude of the temperature depends on details of the collision and the number of efolds of inflation. Roughly it goes like $\frac{\delta T}{T} \sim e^{N_* - N}$ where $e^{N_*} = T_{reh}/T_0$
- There is no edge to a spot from a collision at any size

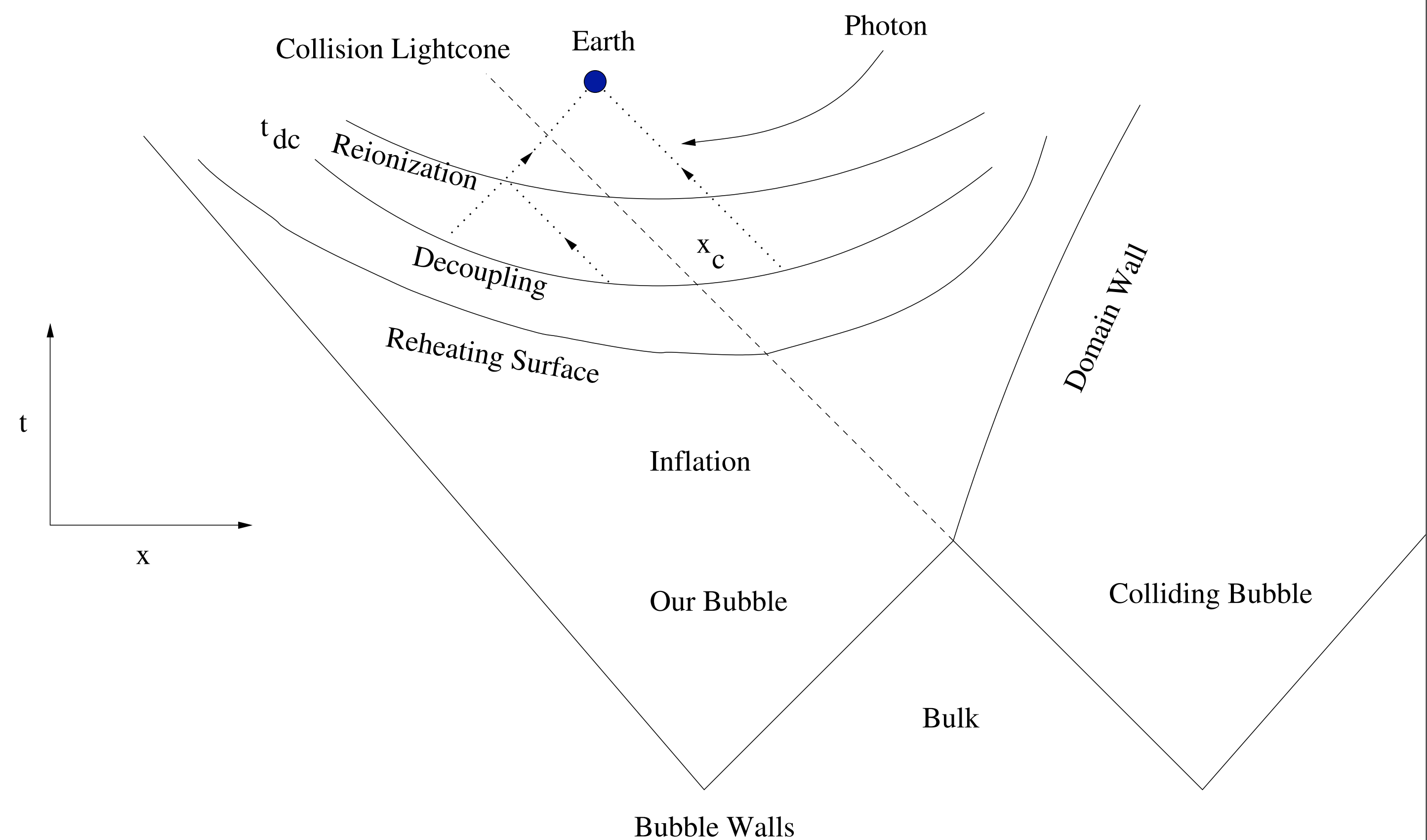
Polarization

- We've seen that each bubble collision naturally leads to a cold/hot spot on the sky with a temperature dipole inside the spot

- Other models can be used to explain the cold spot (textures, voids, even Gaussian fluctuations if they are really large)

- We can use polarization (and possibly other effects) to correlate with the temperature pattern and predict a unique signal from a bubble collision

- The magnitude of polarization is within reach of current and next generation experiments (e.g. Planck, SPIDER,...)



What causes CMB polarization?

- Thomson Scattering of photons by free (ionised) electrons causes polarization if the *electron* sees a distribution of incident radiation with a non-zero quadropole

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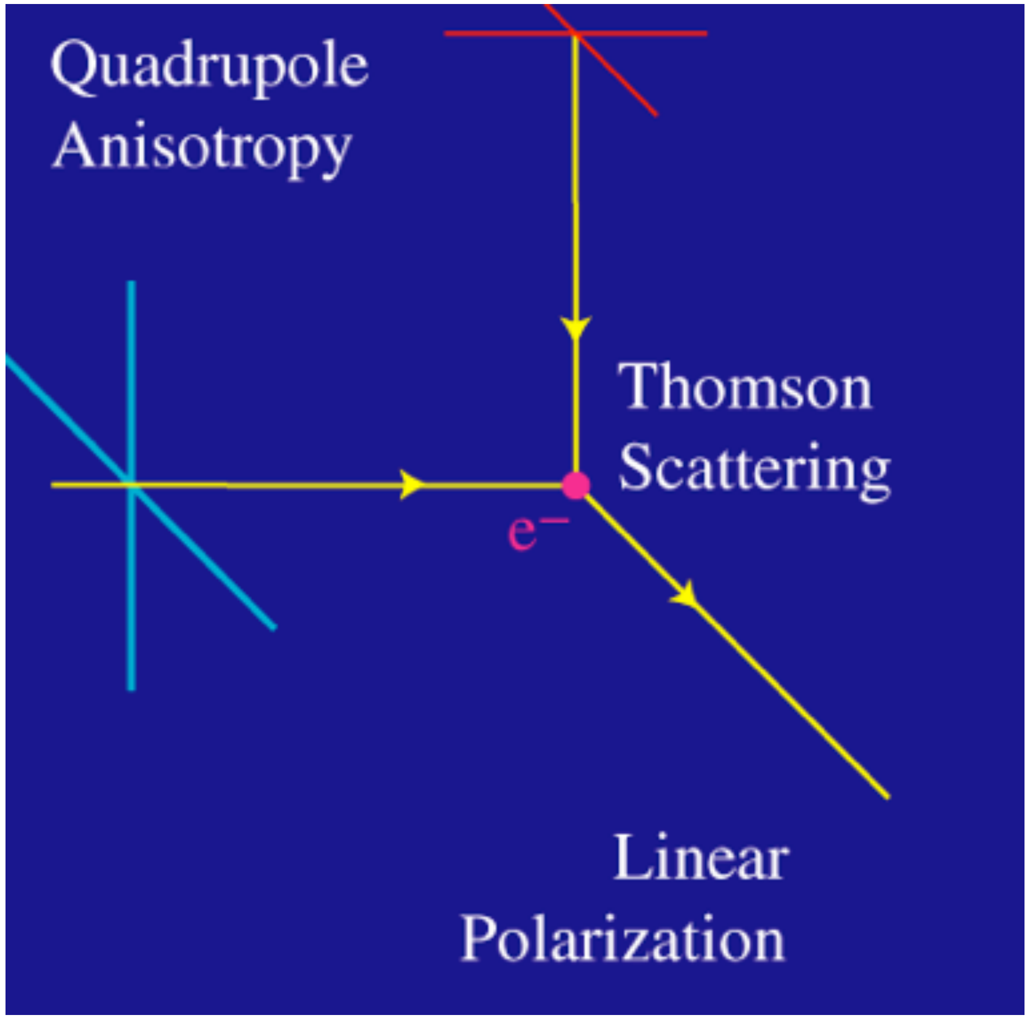
- Thomson Scattering of photons by free (ionised) electrons causes polarization if the *electron* sees a distribution of incident radiation with a non-zero quadropole

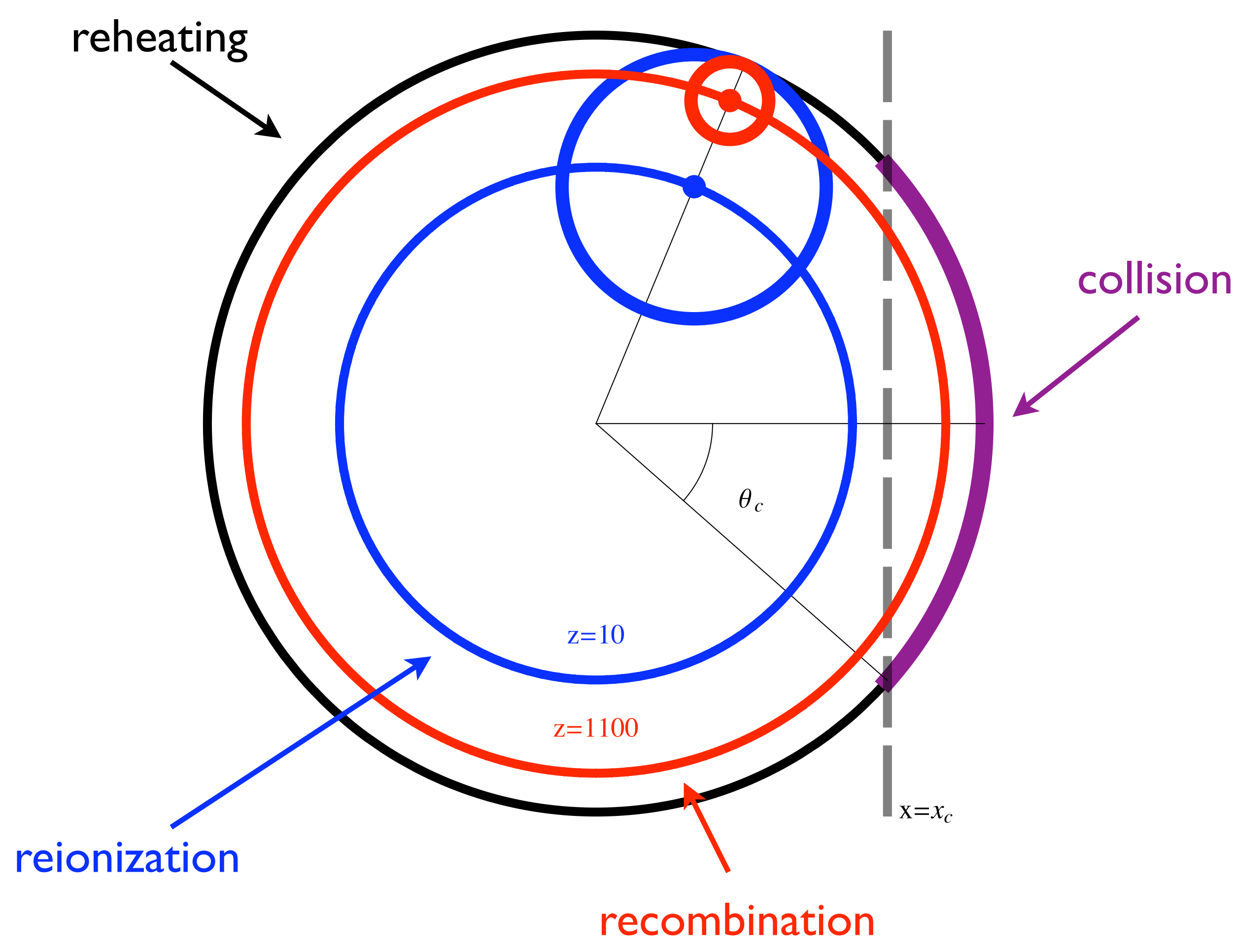


What causes CMB polarization?

- Thomson Scattering of photons by free (ionised) electrons causes polarization if the *electron* sees a distribution of incident radiation with a non-zero quadropole moment

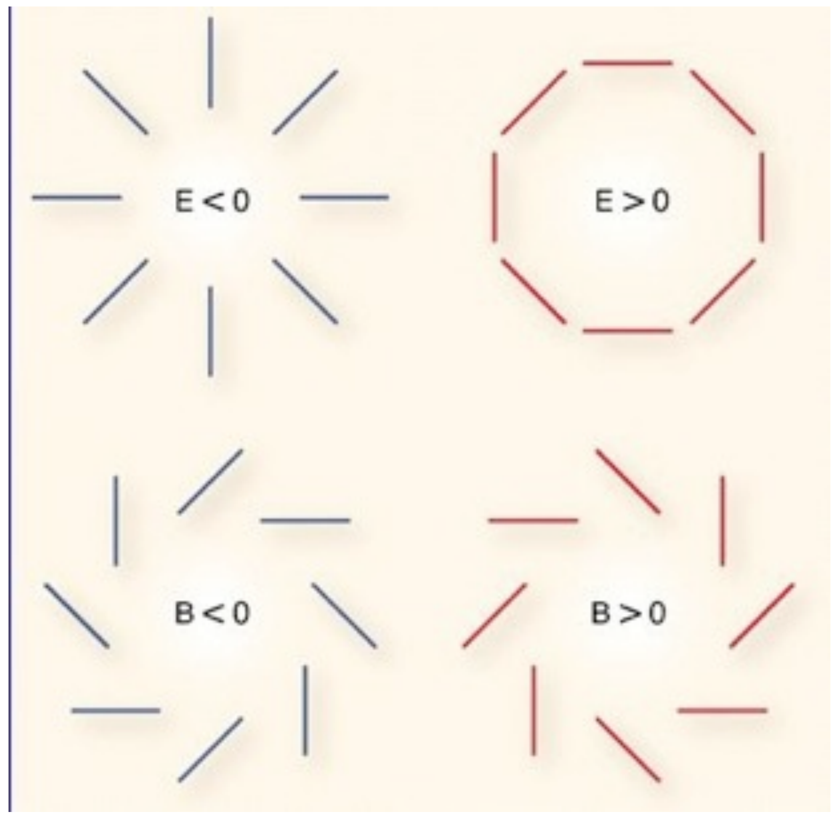
- Scattering occurs primarily at recombination (z~1100) and reionization (z~10)

- Since we have a spot on the sky, some of these electrons will see a quadrupole and so we would expect a disk or ring of polarization centered on the cold/hot spot



What polarization do we expect?

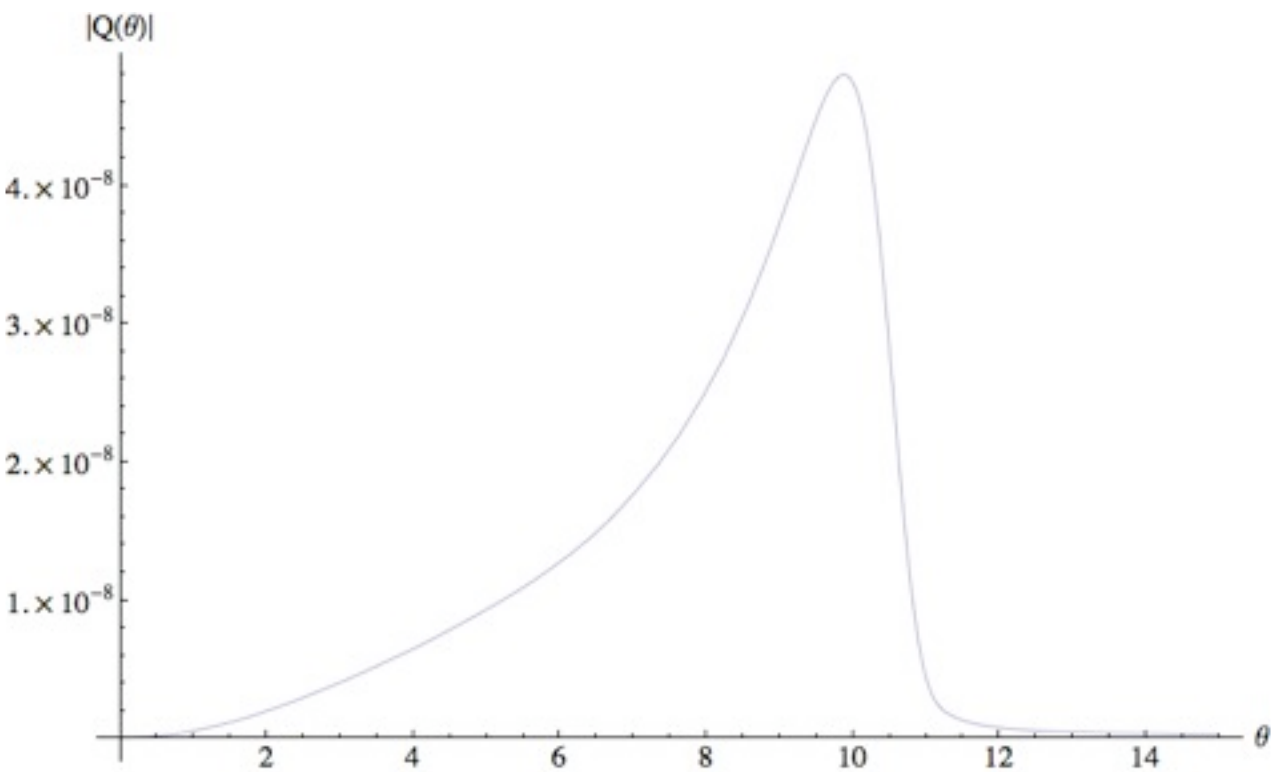
- By symmetry the polarization should only depend on the angular distance from the center of the spot and its temperature (hot vs. cold)
- This is called E-mode polarization (as opposed to B-mode), which is what we expect for a scalar perturbation
- If we choose our coordinates so the pole is at the center of the spot this is purely the Stokes parameter Q-mode (as opposed to U), in this case the difference between E and Q is just a prefactor related to spherical harmonics vs. spin weighted ones

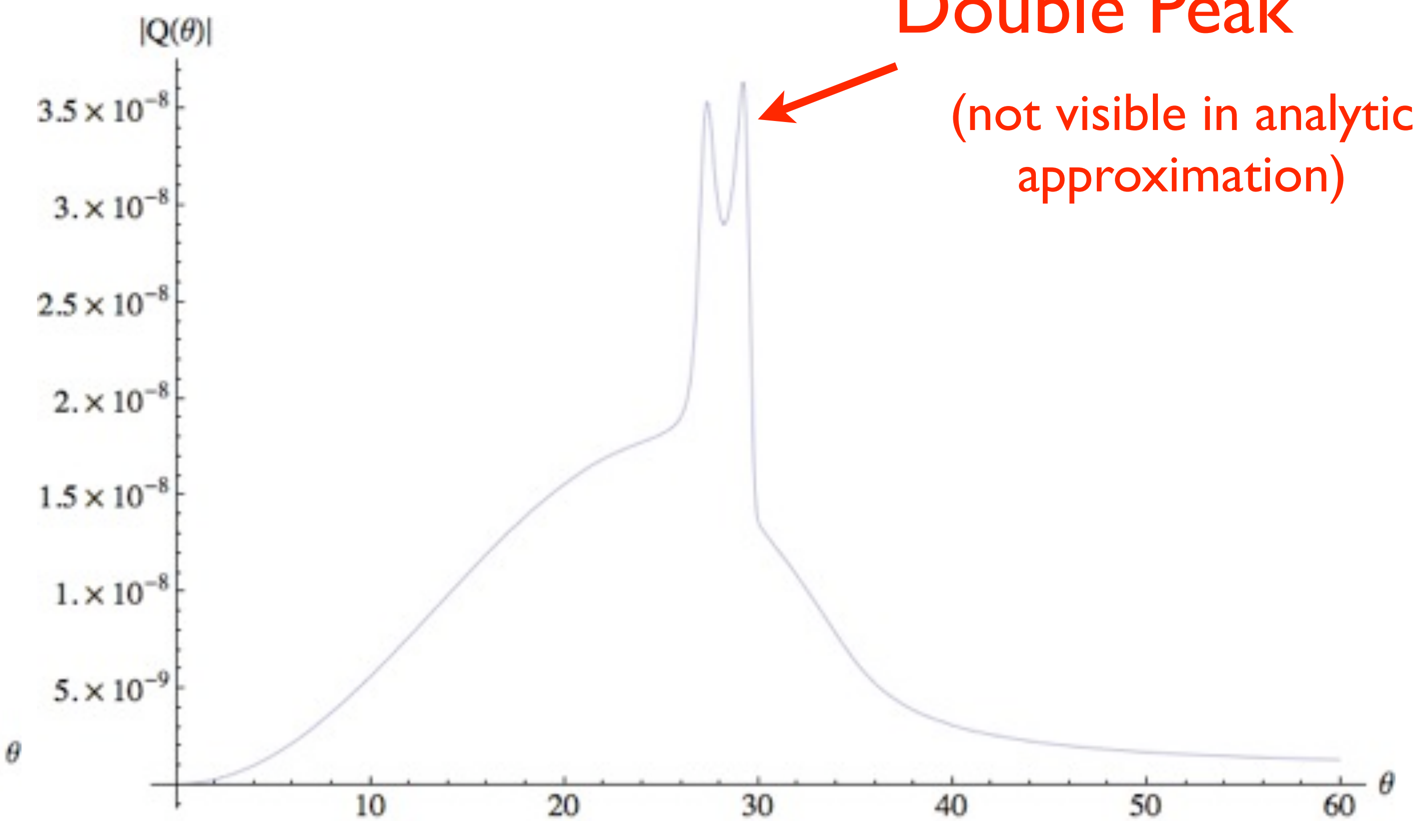


$\sim Q$

$\sim U$

Polarization: results (two examples)



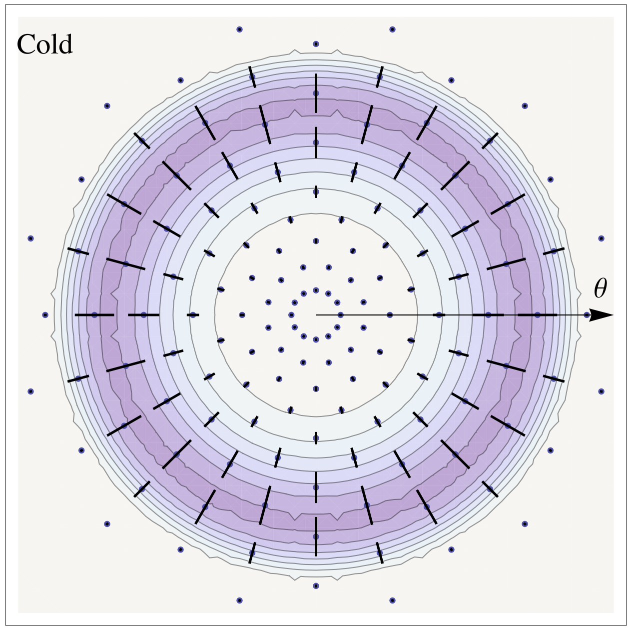


$\delta T/T = 2 \times 10^{-4}$ $\theta_{spot} \approx 11.7^\circ$

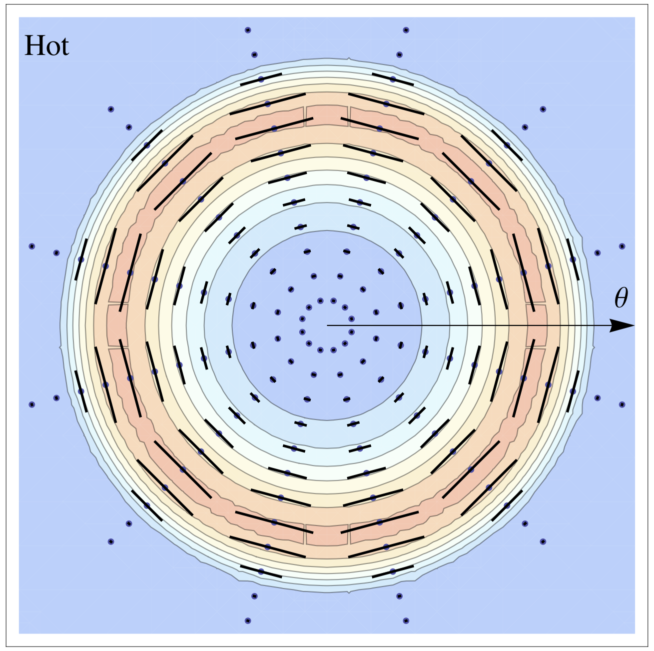
$\chi^2_{\rm Planck} \approx 1.4$ $\chi^2_{\rm SPIDER} \approx 10.0$

$\delta T/T = 5 \times 10^{-5}$ $\theta_{spot} \approx 30^\circ$

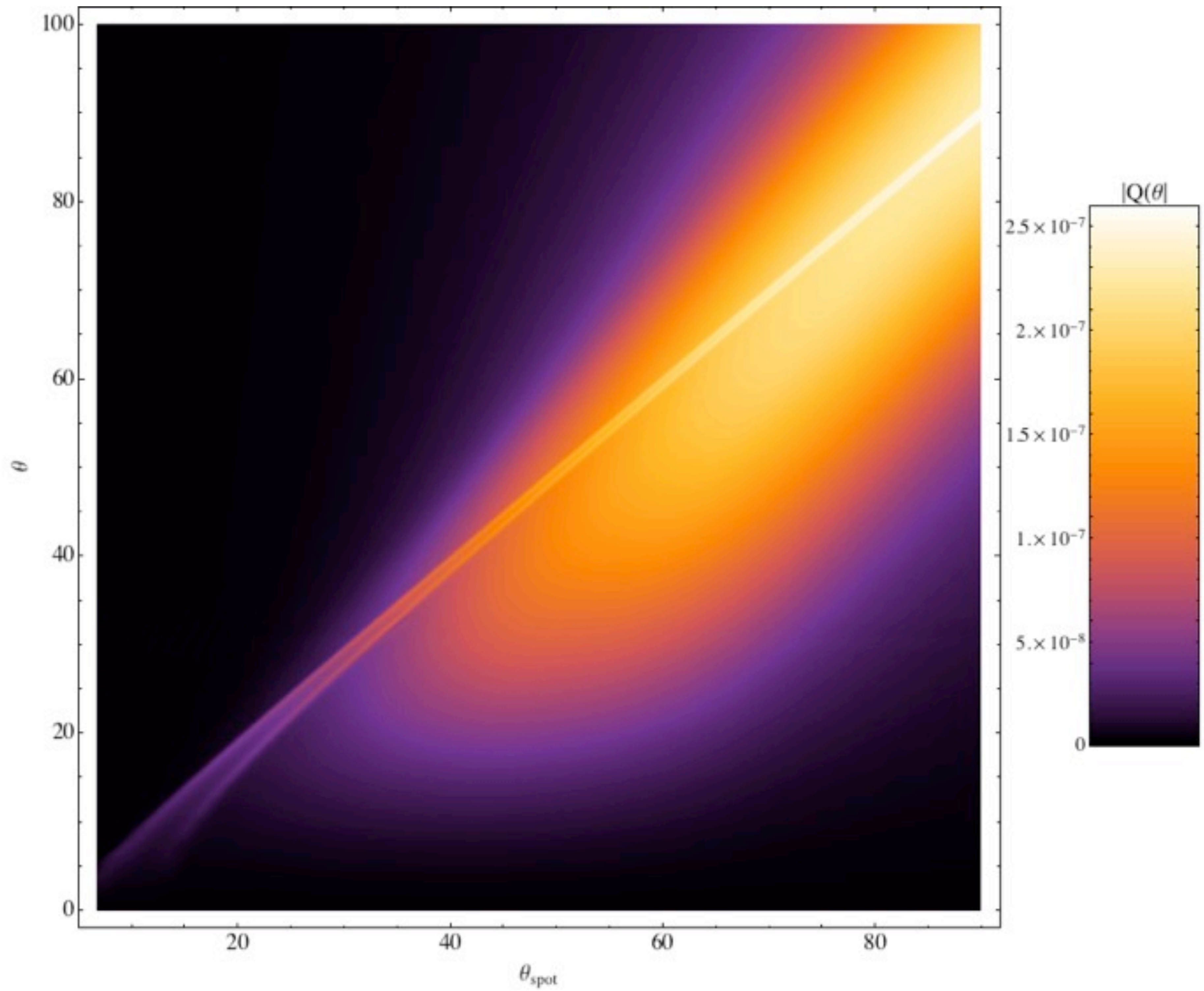
$\chi^2_{\rm Planck} \approx 6.3$ $\chi^2_{\rm SPIDER} \approx 44.8$



patterns on the sky



Polarization: Full results



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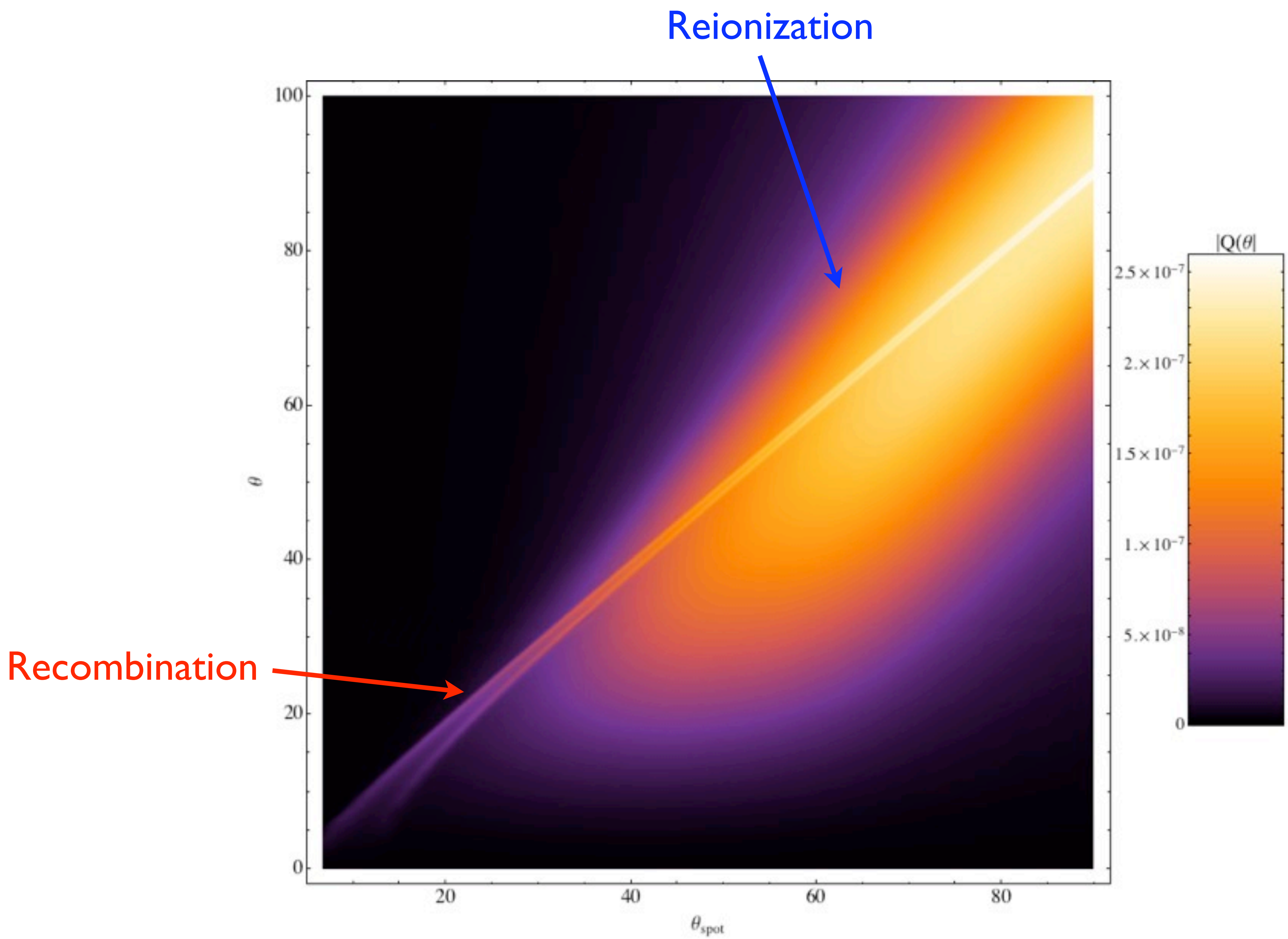
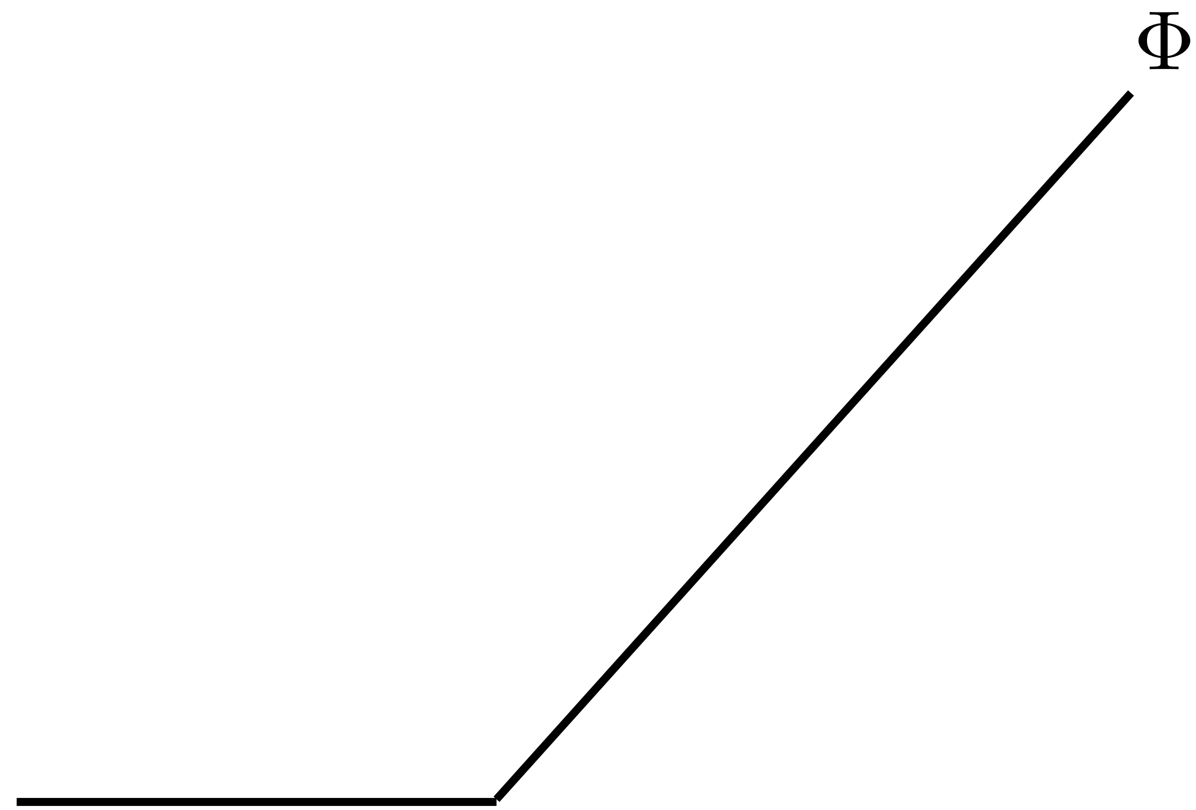


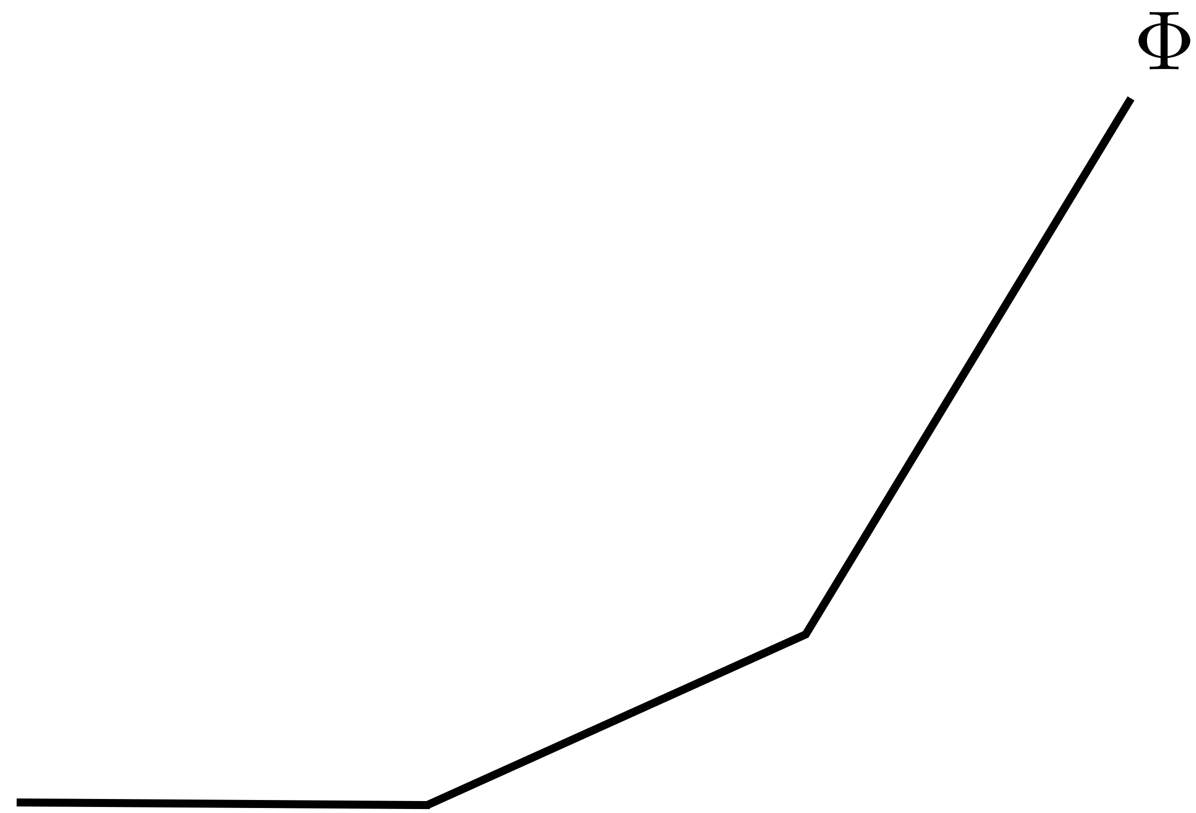
Why a double peak?

- The initial condition near the end of inflation is a kink in Φ



Why a double peak?

- The initial condition near the end of inflation is a kink in Φ
- This kink evolves into a smooth function within the soundcone from the end of inflation to recombination (sum of left and right moving waves)
- However, at the edge of the soundcone, the first derivative is still discontinuous
- So the second derivative is still large there, and hence the quadrupole seen by electrons are large
- Any electron whose LSS intersects one of the sub-kinks will see a quadrupole and give a peak for that sub-kink. If the LSS is larger than the twice the width of the soundcone, it instead makes a broader, single peak



Summary of Effects

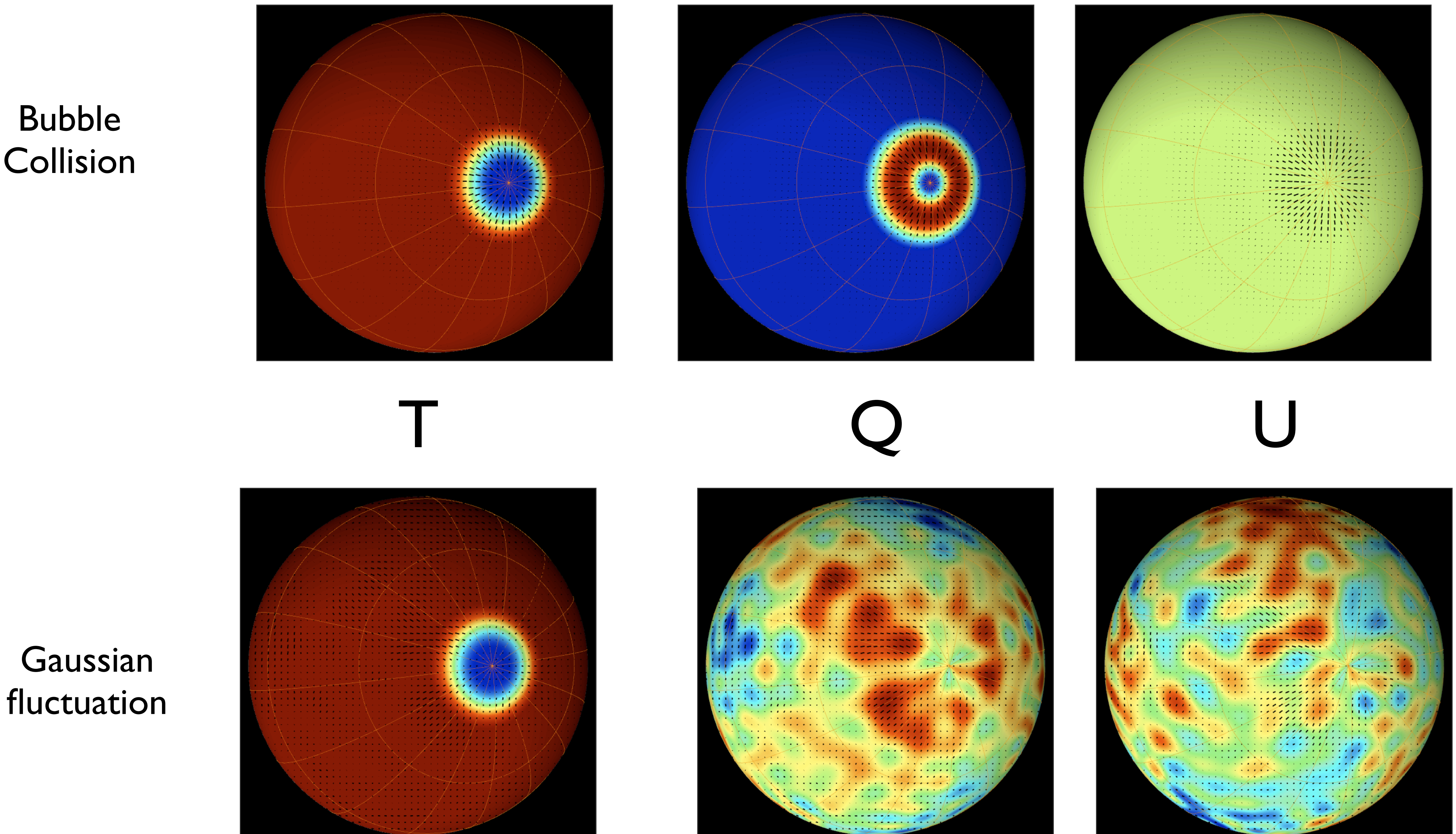
- *Temperature*
  - For any collision, we obtain a hot or cold spot
  - The size of the spot depends on where we are compared to the collision lightcone
  - The magnitude of the temperature depends on details of the collision and the number of efolds of inflation.
  - There is no edge to a spot from a collision at any size
- *Polarization*
  - Polarization is pure E (or Q)-mode
  - It is centered on the temperature spot
  - For spots larger than ~ 12 degrees (angular radius) we see a double peak around a degree scale or below (from scattering at recombination)
  - Can correlate with signal in temperature and should be detectable by current and next generation polarization experiments

Comparison to other causes (textures and voids)

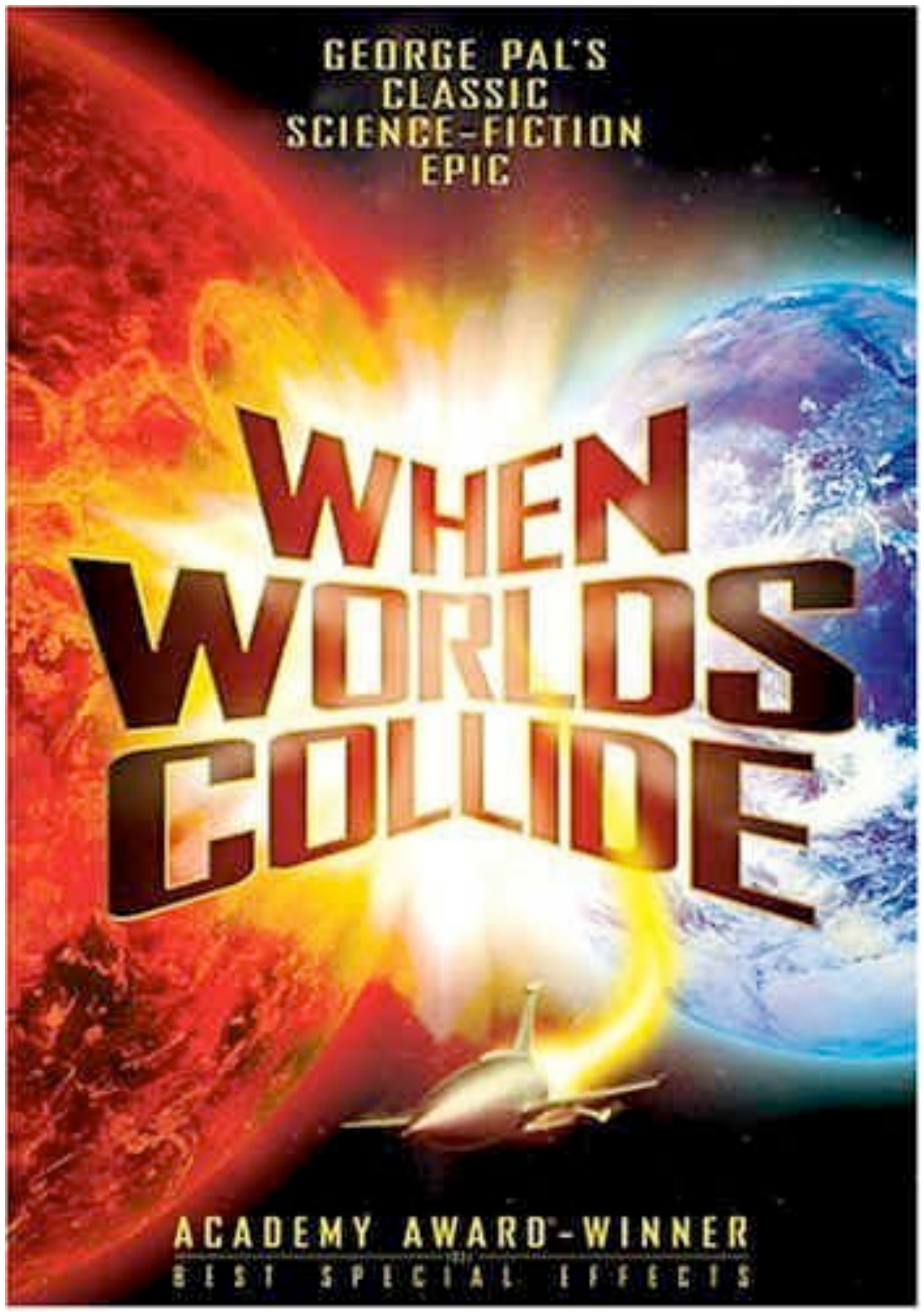
- How unique is this signal?
- Other explanations for the cold spot are textures, voids and random fluctuations
  - Textures and voids occur relatively late ($z<5$) and do not produce a measurable polarization signal, so completely different signal
- Planck, SPIDER and other experiments should be able to tell us

Comparison with random fluctuations

- To fully determine this, a statistical study on simulations needs to be run
- We can generate a few though and show it's not likely to be the same
- Collisions have a unique (planar) symmetry for all times, so the more effects we sample, the more "times" we're seeing this at



Conclusions and future directions



- We've analyzed the dynamics of bubble collisions analytically and numerically up to a multipole of 2000
- Effects can be detected in the CMB, and polarization. Have we already seen some of these (preliminary analysis carried out by Feeney et al. in temperature)? Need polarization data
- The predictions for correlation of temperature and polarization for the cold spot seem to be unique $\longrightarrow$ chance to test predictions of the string landscape!
- We encourage observations/analysis in real space (as opposed to momentum) to try and detect more, fainter spots
- Didn't have time here, but ask me later about overdensities and their evolution
- Lots of things to do, all of which could lead to observable effects!