

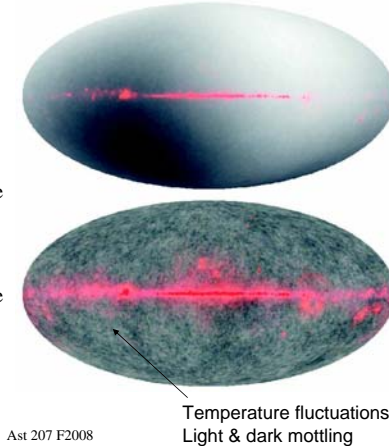
## First stars, quasars, & galaxies—12 Nov

- Important events in the history of the universe
  - Formation of helium (Done)
  - Universe becomes un-ionized. Radiation and matter decoupled (Mon)
  - Galaxies and stars form (Today)
- Decoupling is when universe changed from ionized to neutral and opaque to transparent
- CBR is snapshot of universe at 300,000yr.
- WMAP satellite measured fluctuations in CBR.
- WMAP saw evidence of the first stars when universe was 200 Myr old.

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## Remove motion

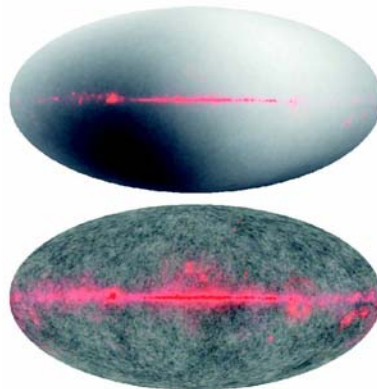
- Remove motion and show with increased contrast
- Largest fluctuations are at an angular scale of  $1^\circ$ .
  - If I look at two points in the sky separated by  $0.1^\circ$ , their temperatures are likely to be the same.
  - If I look at two points in the sky separated by  $1^\circ$ , their temperatures are likely to be different.
  - If I look at two points in the sky separated by  $10^\circ$ , their temperatures are not correlated.



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## What causes the fluctuations with $1^\circ$ angular scale?

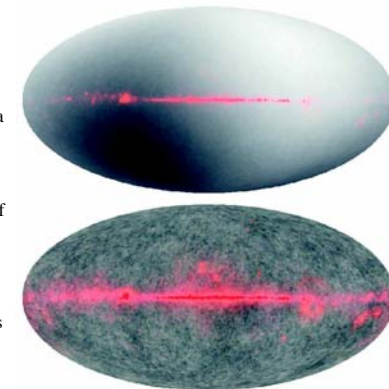
- Largest fluctuations are at an angular scale of  $1^\circ$ .
  - Principles
    - Matter & light interact. The pressure of light dominates gas pressure.
    - The universe is 300000yr old.
  - Matter tries to clump together on a scale of 1000 light years. The pressure of light pushes against gravity. Light smooths out the clump.
1. A clump tries to form on a scale of 1M light years. Can it form?
    - A. Y
    - B. N



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## What causes the fluctuations with $1^\circ$ angular scale?

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  - Principles
    - Matter & light interact. The pressure of light dominates gas pressure.
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  - Matter tries to clump together on a scale of 1000 light years. The pressure of light pushes against gravity. Light smooths out the clump.
1. A clump tries to form on a scale of 1M light years. Can it form? N. Light (and force of gravity) has only been able to travel 300000 light years.
  - If I look at two points in the sky separated by  $1^\circ$ , their temperatures are likely to be different. This is the scale of 300000 light years.



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## First Stars

- WMAP finding
  - Cosmic radiation is weakly polarized for points in the sky separated by 40deg.
- Scattering creates polarization.
- Universe became un-ionized at decoupling.
- First stars and quasars emit ultraviolet radiation and re-ionized matter.
- Re-ionized matter scatters light strongly.
- Largest effect for points separated by
  - Speed of Light \* age at re-ionization
- First stars & quasars turned on at 200Myr.



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## Simulations with dark matter

- Dark matter does not interact with light.
  - Dark matter interacts with ordinary matter only through gravity.
1. I have some dark matter at rest in my cupped hand. What happens to it?
    - A. It stays in my hand.
    - B. It floats away.
    - C. It falls through my hand.

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