The High-Redshift 21-cm Signal

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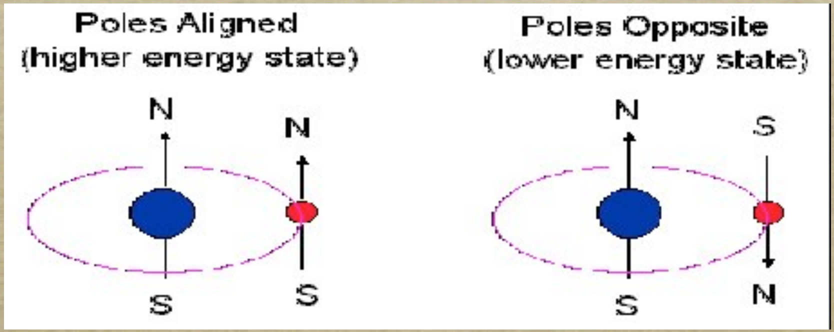
Outline

- *Physics of the 21 cm Transition* *(the very, very short version; see Furlanetto, Oh, & Briggs 2006 for more detail)*
  - *The Pre-reionization Signal*
- *The First Stars and the UV Background*
- *Conclusions*

The Spin-Flip Transition

- *Protons and electrons both have spin and hence magnetic moments*
- *Produces 21 cm photons (ν~1.4 GHz)*



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The 21 cm Signal

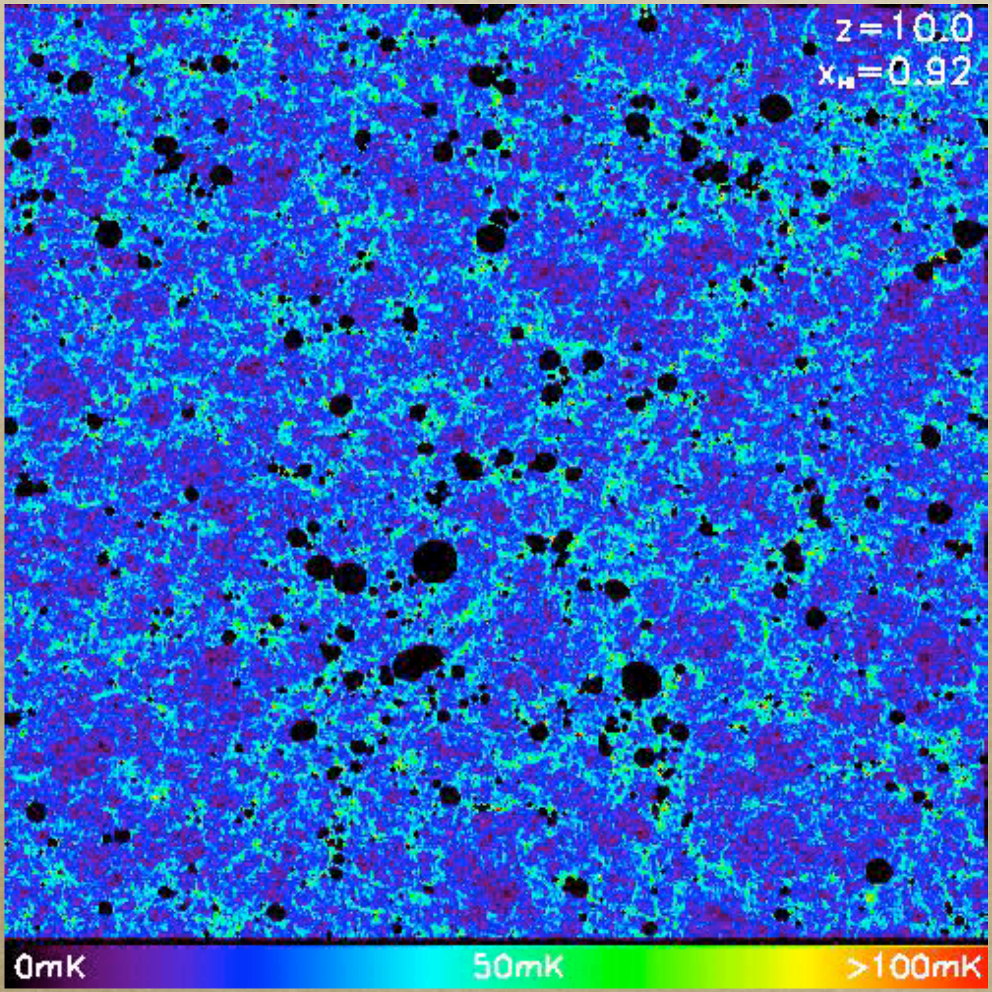
$$\delta T_b \approx 23 x_{HI} (1+\delta) \left(\frac{1+z}{10}\right)^{1/2} \left(\frac{T_S - T_{bkgd}}{T_S}\right) \left(\frac{H(z)/(1+z)}{\partial \mathrm{v}_{\mathrm{r}} / \partial r}\right) \mathrm{mK}$$

- *Four factors:*
    - *Neutral fraction*
    - *Density*
    - *Excitation temperature*
    - *Velocity (redshift-space distortions)*

Reionization

$$\delta T_b \approx 23 x_{HI} (1+\delta) \left(\frac{1+z}{10}\right)^{1/2} \left(\frac{T_S - T_{bkgd}}{T_S}\right) \left(\frac{H(z)/(1+z)}{\partial \mathrm{v}_r / \partial r}\right) \mathrm{mK}$$

- *First stars and galaxies produce ionizing photons*
- *Ionized bubbles grow and merge*



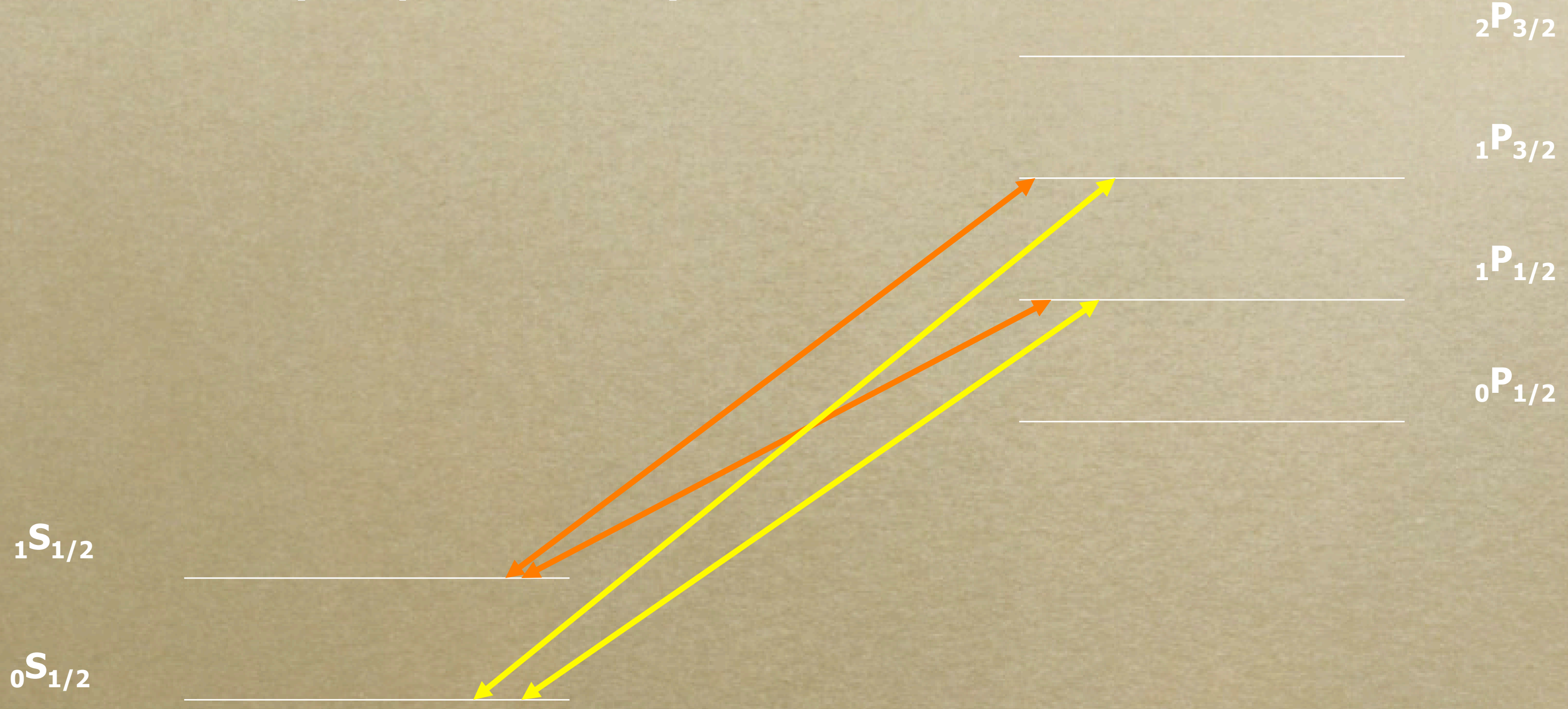
Mesinger & Furlanetto (2007)

The Wouthuysen-Field Mechanism

$$\delta T_b \approx 23 x_{HI} (1+\delta) \left(\frac{1+z}{10}\right)^{1/2} \left(\frac{T_S - T_{bkgd}}{T_S}\right) \left(\frac{H(z)/(1+z)}{\partial v_r / \partial r}\right) \text{mK}$$

Selection Rules:

$\Delta F=0,1$ (except $F=0 \rightarrow F=0$)

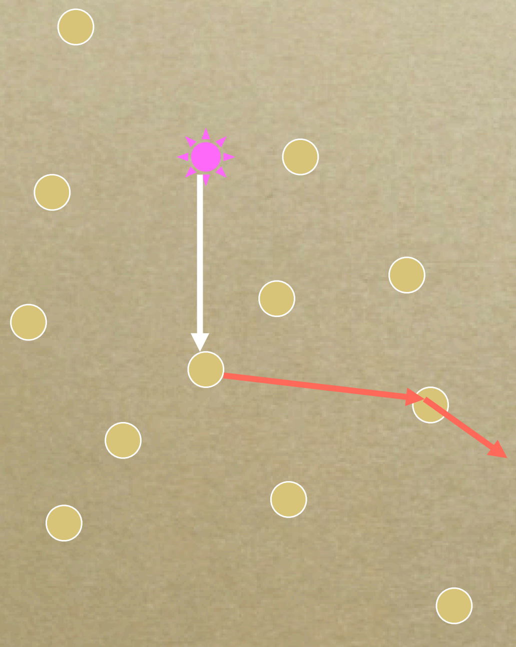


Wouthuysen 1952, Field 1958, Hirata 2006

Becomes effective when ~0.1 Lyman-α photons per hydrogen atom in the Universe

IGM Heating: X-rays

$$\delta T_b \approx 23 x_{HI} (1+\delta) \left(\frac{1+z}{10}\right)^{1/2} \left(\frac{T_S - T_{bkgd}}{T_S}\right) \left(\frac{H(z)/(1+z)}{\partial \mathrm{v}_r / \partial r}\right) \mathrm{mK}$$

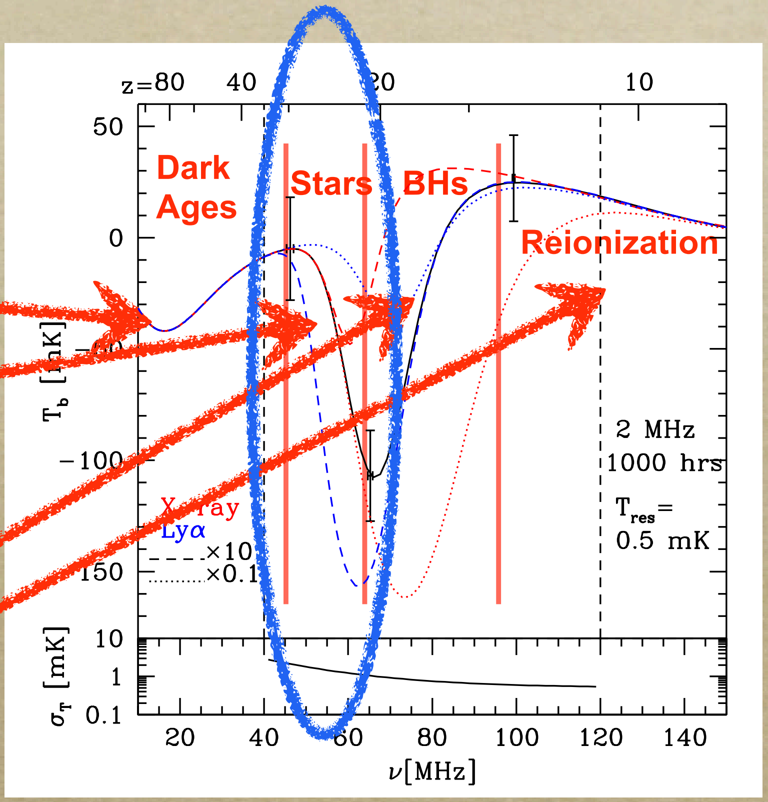


- *X-rays scatter through the IGM and deposit energy as…*
  - *Ionization*
  - *Collisional excitation*
  - *Heating*

Shull & van Steenberg 1985,
Furlanetto & Johnson Stoever 2009

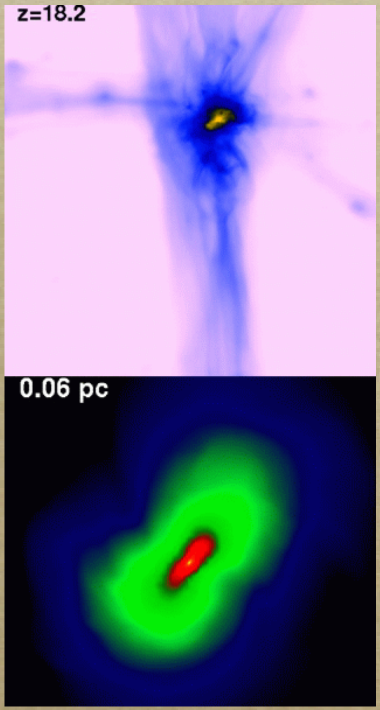
21 cm Astrophysics: The Monopole

- *Four Phases*
  - *Dark Ages*
  - *First Stars*
  - *First Black Holes*
  - *Reionization*



J. Pritchard

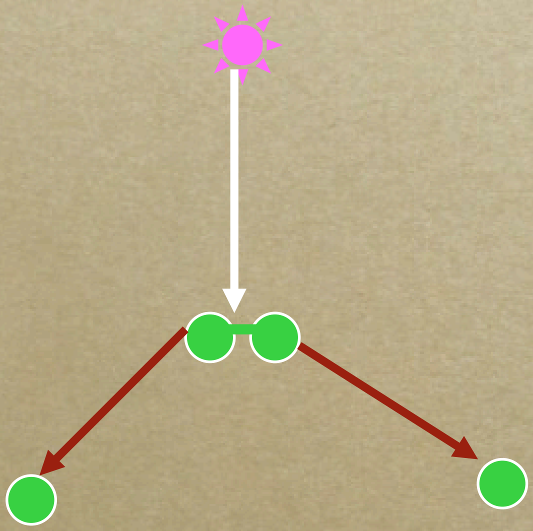
Early Star Formation Is Unique



T. Abel

- *Gas in dark matter halos must cool to form stars*
- *Usual coolant ("metals") absent!*
- *Cooling occurs via collisional excitation and radiative de-excitation of* H_2
  - *First halos too cold for atomic H*
- *Different thermodynamics: first stars are massive and hot*

The Lyman-Werner Background



- *UV photons between 11.5-13.6 eV dissociate* H_2

$$H_2+\gamma \rightarrow H_2^* \rightarrow 2H+\gamma$$

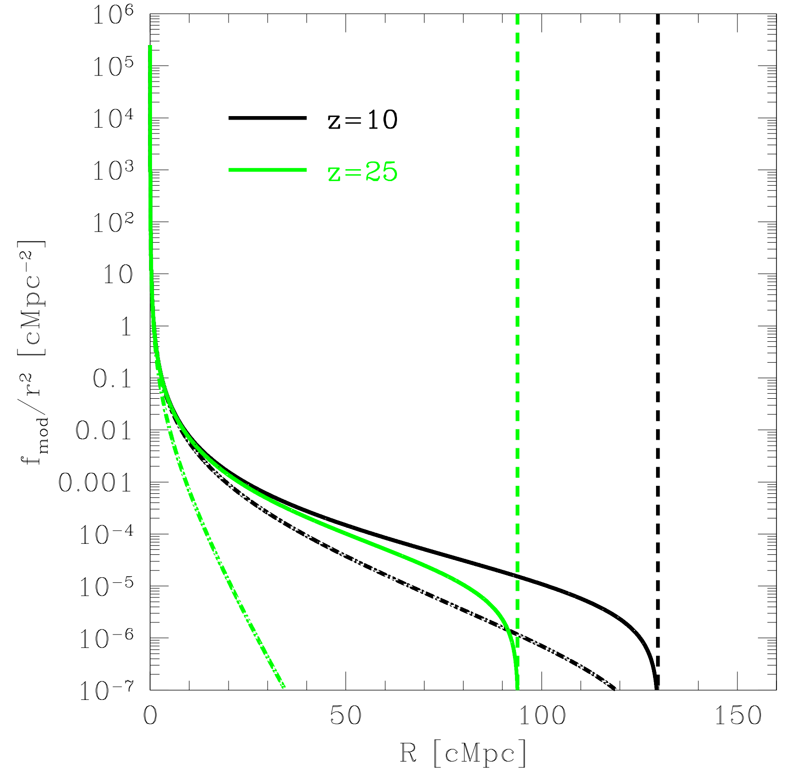
Same photons as for W-F coupling (almost)!

The End of Very Massive Stars

- *Amplitude required to suppress H_2 cooling depends on size of halo*
    - *Pop III halos will gradually shift to higher masses over time*
    - *“Self-regulation” to maintain LW background at just the right threshold*
    - *$T_{vir}=10^4$ K allows atomic hydrogen cooling: normal stars!*
- *Roughly, threshold sits at ~0.1 photons/baryon*
- *WF threshold also ~0.1 photon/baryon!*

How Far Does Lyman-Werner Radiation Reach?

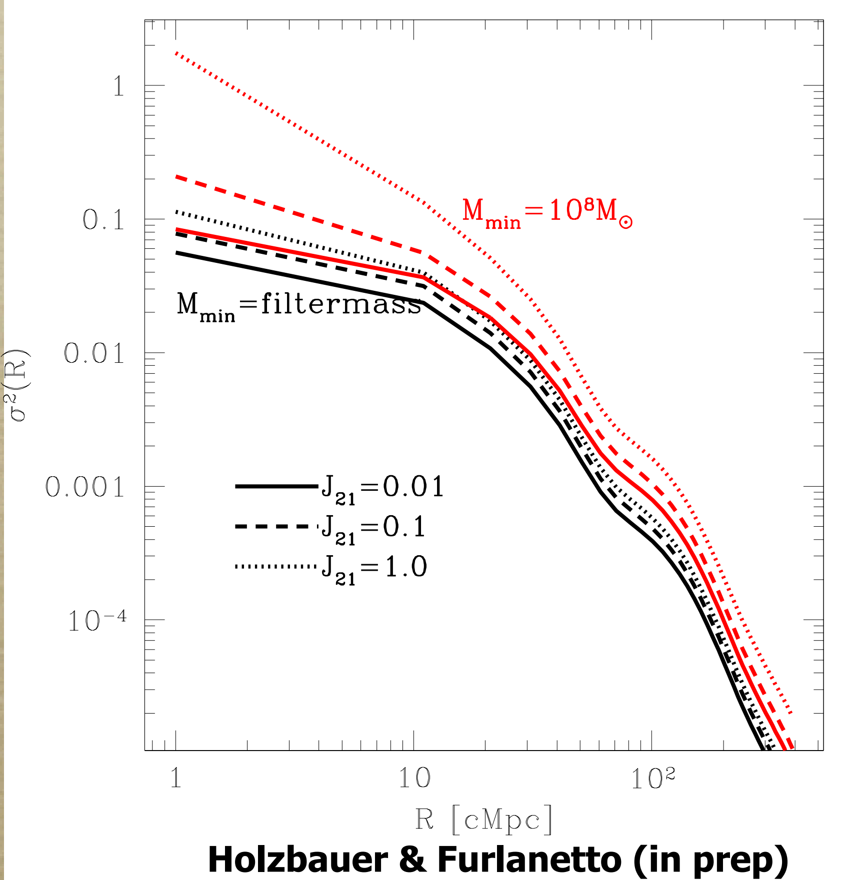
- *Neutral IGM means heavy absorption in Lyman-series*
- *Photons destroyed once they redshift into nearest Lyman line*
- *Maximum distance is to Lyman-α*



Holzbauer & Furlanetto (in prep)

Fluctuations in the Lyman-Werner Background

- *In real space: fluctuations on >10 Mpc scales are ~1-10%*
- *Highly uniform background: global measurement gives good estimate of transition from very massive stars to"normal" stars*



Holzbauer & Furlanetto (in prep)

Conclusions

- *HI 21 cm line promising probe of astrophysics of first sources*
  - *First stars: UV background*
  - *First black holes: X-ray background*
  - *High-z galaxies: reionization*
- *UV background also crucial for transition from very massive to “normal” stars*
  - *Background quite uniform*
  - *Global 21-cm background measurement, as from DARE, provides robust estimate of this transition*