Cosmological Hydrogen Recombination: The effect of high-n states

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Irvine TASC meeting, 10/24/08

Outline

- Cosmological Recombination in a nutshell
- Breaking the naive model
- Why should you care? Effects on CMB, inferences about primordial physics
- Our tools
- Preliminary results!

Cosmological Recombination in a Nutshell

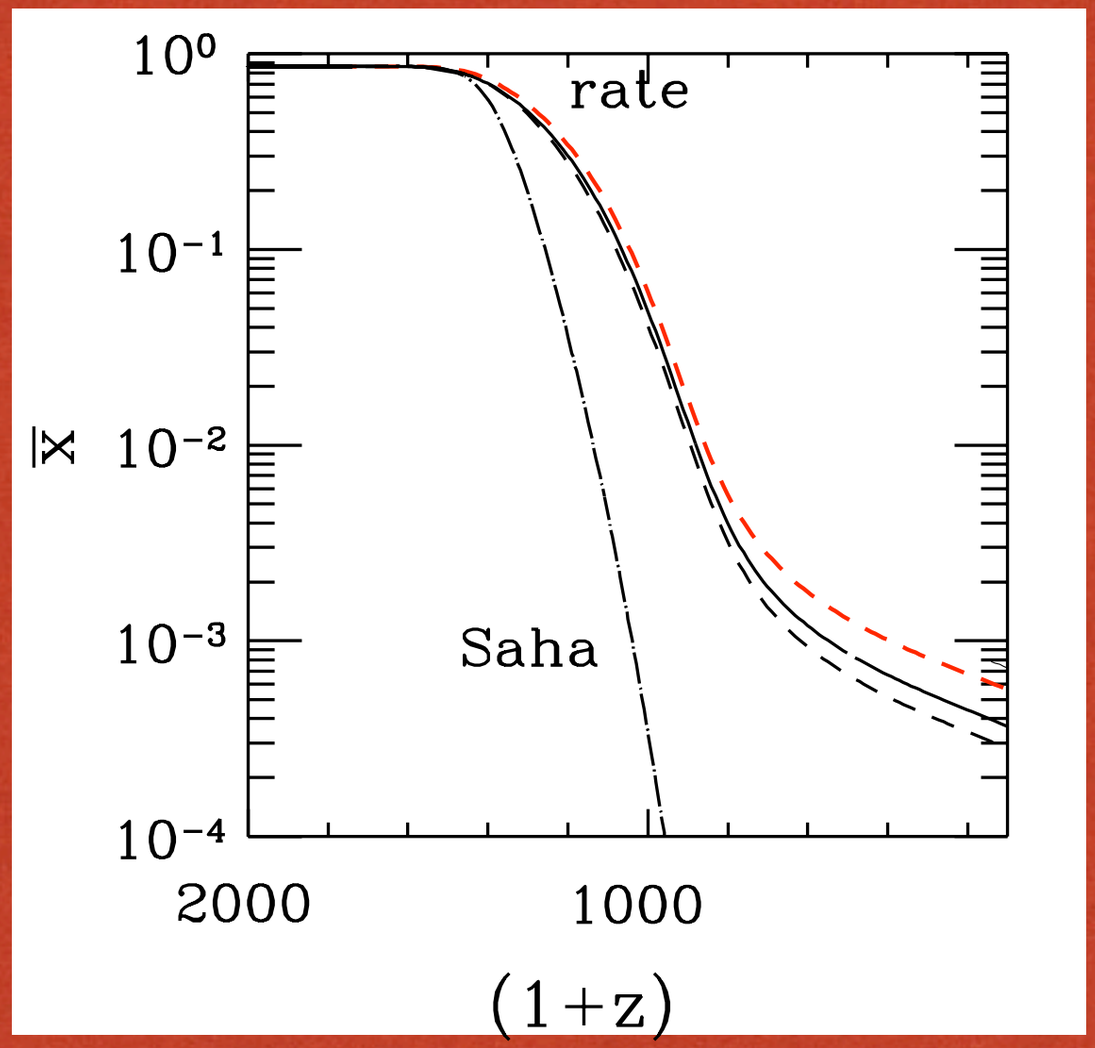
- $p + e^- \leftrightarrow H^{(n)} + \gamma^{(nc)}$ outrun by Hubble expansion, Saha Eq. fails: **Relic free electrons!**
- For continuum $\rightarrow$ 1s, 2p $\rightarrow 1s$, $t_{\rm mf} < H^{-1}(T)$
- Two ways out of $n = 2$ bottleneck
  - Two-photon decays: $H^{2s} \rightarrow H^{1s} + \gamma + \gamma$ $\boldsymbol{\Lambda}_{2\mathrm{s}\rightarrow 1\mathrm{s}} = \mathbf{8.22}\ \mathrm{s}^{-1}$
  - Redshifting out of resonance: $R \sim \lambda_\alpha^{-3}(\dot{a}/a)n_{1s}^{-1}$
- Peebles (1967) assumes radiative eq. between n=2 and excited states, and between eq. between *angular momentum (l)* substates

$$\mathcal{N}_n = \mathcal{N}_2 e^{-(E_n - E_2)/T}$$

$$\mathcal{N}_{nl} = \mathcal{N}_n \frac{(2l+1)}{n^2}$$

PEEBLES MODEL ASSUMPTIONS/RESULTS

- Blackbody spectrum of radiation assumed



$\Omega_m h^2 \uparrow$

$\Omega_b h^2 \uparrow$

- State of the Art for 30 years!

Breaking the naive model

- ~~Equilibrium~~ between *l states* (z<900)
- Cool radiation field: ~~Boltzmann eq. of higher n~~ (z<900)
- Radiation field is non-thermal
- Compton scattering inefficient $T_{\mathrm{m}} \neq T_{\gamma}$ (z<500)
- Higher level 2γ transitions (Hirata 2008) (z<800)
- Lyman-α diffusion

Breaking the naive model

- Radiation field is cool: ~~Boltzmann eq. of higher n~~
- Treated by Seager et al. (2000) $n_{\max} = 300$ RecFAST!!!
- ~~Equilibrium~~ between *l states*
- Treated by Chluba et al. (2005) for $n_{\max} = 100$
- Beyond this, testing convergence with $n_{\max}$ is hard!

$$t_{\text{compute}} \sim \mathcal{O}\,(\text{weeks})$$

How to proceed if we want 0.1% accuracy in $x_e(z)$?

BREAKING THE NAIVE MODEL

- Radiation field is cool: ~~Boltzmann eq. of higher n~~
- Treated by Seager et al. (2000) $n_{\max} = 300$ RecFAST!!!
- ~~Eq.~~ between *l states*: dipole selection bottleneck: $\Delta l = \pm 1$
- Treated by Chluba et al. (2005) for $n_{\max} = 100$
- Beyond this, testing convergence with $n_{\max}$ is hard!

$$t_{\rm compute} \sim \mathcal{O}\,(\text{weeks})$$

WHY PROCEED?

Recombination and the CMB

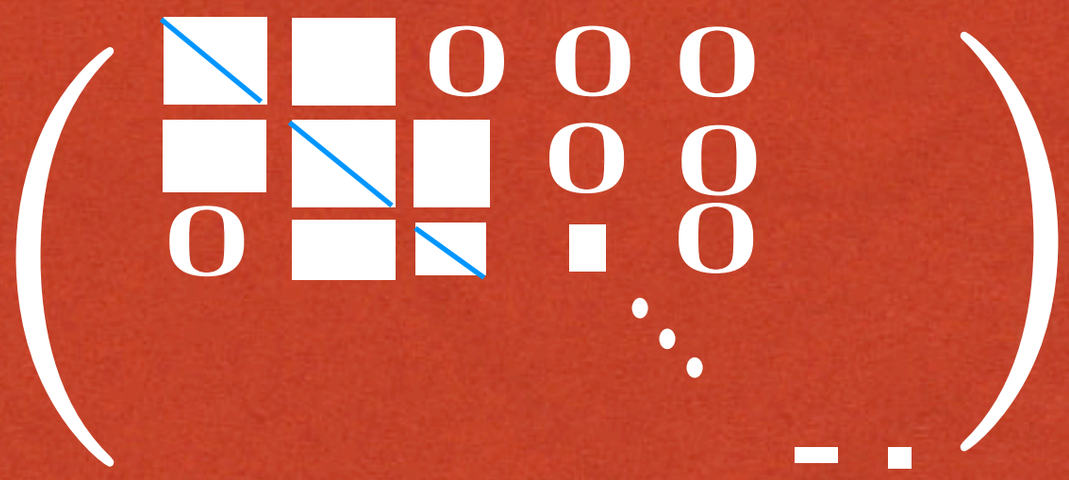
- $\gamma - e^-$ decouple at $z_{\rm dec} \simeq 1090$, during recombination
- If $\Delta z_{\rm rec} \uparrow$, γ have more time to diffusively (Silk) damp C_l
- If $\Delta z_{\rm rec} \uparrow$, low-$\lambda$ modes cancel more along l.o.s.
- Polarization $\Pi \propto \Theta_2(\eta)$, $\Theta_2(\eta)$ until $g \sim 1$, so $\Delta z_{\rm rec} \uparrow \longrightarrow \Pi \uparrow$
- Modes with $\lambda < H^{-1}(\eta)$ suppressed : $C_l \to C_l e^{-2\tau}$
- Planck will be CV limited out to $l \sim 2500$:
  Possible degeneracies between
  cosmo parameters (e.g. n_s) and atomic physics!

THE MULTI-LEVEL ATOM

- Bound-free rates (Hummer and Storey 1965)
- Bound-bound rates (Hummer and Storey 1965)
- Solve for escape fraction of lines with Sobolev approx
- Add line photons and follow evolution of $f(E_\gamma, T)$

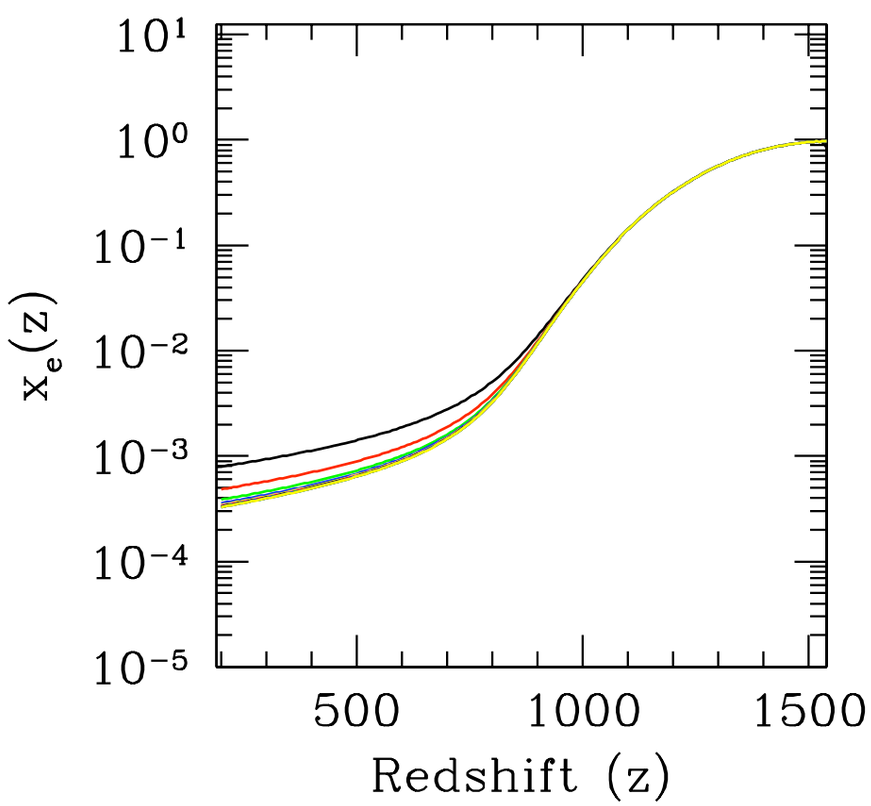
Speeding it up

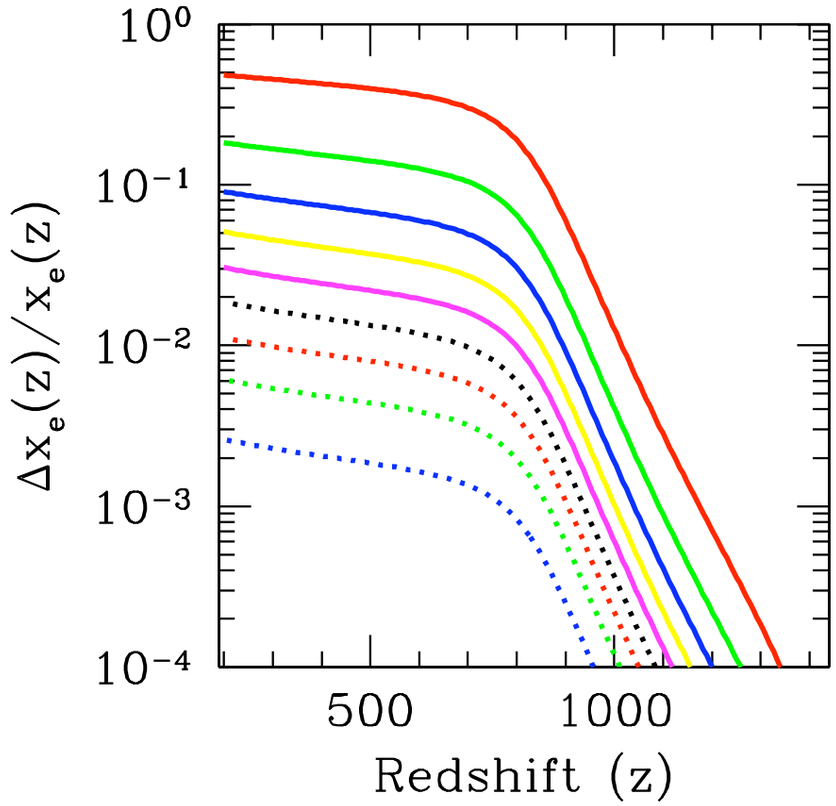
- Excited state populations obey $\frac{d\vec{x}}{dt} = \mathbf{R}\vec{x} + \vec{s}$
- Rate on LHS is $t_{\rm rec}^{-1} \sim 10^{-12} s^{-1} \ll \mathbf{R}\ , \vec{s} \rightarrow \vec{x} \simeq \mathbf{R}^{-1}\vec{s}$
  - Steady state approximation good for n>1.



- Matrix is $\sim n_{max}^2 \times n_{max}^2$
- Brute force would require for $n_{max}^6 \sim 1000$ s for $n_{max} = 200$ for a single time step
- Sparsity to the rescue $\mathbf{M}_{l,l-1}\vec{x}_{l-1} + \mathbf{M}_{l,l}\vec{x}_l + \mathbf{M}_{l,l+1}\vec{x}_{l+1} = \vec{s}_l$

Preliminary Results





- $x_e(z)$ falls with increasing $n_{max} = 10 \rightarrow 100$, as expected:
- Rec Rate>downward BB Rate> Ionization, upward BB rate
- Even for $n_{max} = 100$, code computes in only 2 hours
- To add: Spectral distortions, collisional rates, increase n_{max}