EXCITEMENT IN eV-SCALE PHYSICS: TWO COSMOLOGICAL CONSEQUENCES

I. Thermal axions

II. High-n hydrogen states and cosmological recombination

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TEP Seminar

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THERMAL AXIONS:

Telescope searches and cosmological constraints in non-standard thermal histories

Work done in collaboration with
Marc Kamionkiowski, Giovanni Covone, Tristan Smith, Eric Jullo, Jean-Paul Kneib, and Andrew Blain

Outline

- A new telescope search for decaying thermal relic axions:
  Phys. Rev. D75, 105018 (2007), astro-ph/0611502
  ESO VLT Programme 080.A-06
- Cosmological thermal axion constraints in non-standard thermal histories:
  Phys. Rev. D77 08502 0 (2008), arXiv:0711.1352

Outline, Axions:

- Whence axions?
- Parameter space
- A new telescope search
- Non-standard thermal histories
- Thermal axions in non-standard thermal histories

Axions solve the strong CP problem

- Strong interaction violates CP through θ -vacuum term

$$\mathcal{L}_{\mathrm{CPV}} = \frac{\theta g^2}{32\pi^2} G\tilde{G}$$

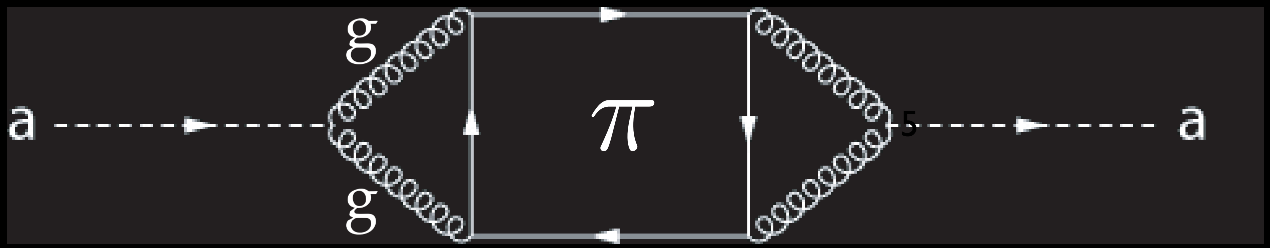
- Limits on the neutron electric dipole moment are strong. Fine tuning?

$$d_n \simeq 10^{-16}\ \theta \text{ e cm}$$
$$\theta \lesssim 10^{-10}$$

- New field (axion) and U(1) symmetry dynamically drive net CP-violating term to 0

$$\mathcal{L}_{\mathrm{CPV}} = \frac{\theta g^2}{32\pi^2} G\tilde{G} - \frac{a}{f_{\mathrm{a}}} g^2 G\tilde{G}$$

- Through coupling to pions, axions pick up a mass



$$m_{\mathrm{a}} \simeq \frac{m_\pi f_\pi}{f_{\mathrm{a}}} \frac{\sqrt{z}}{1+z}$$

$$z \equiv m_{\mathrm{u}}/m_{\mathrm{d}}$$

What are axions?

- Axions interact weakly with SM particles $\Gamma, \sigma \propto \alpha^2$
- Axions have a two-photon coupling

$$g_{a\gamma\gamma} = -\frac{3\alpha}{8\pi f_{\rm a}}\xi \qquad \xi \equiv \frac{4}{3}\left\{E/N - \frac{2\,(4+r)}{3\,(1+r)}\right\}$$

- Two populations of axions:

Cold (nonthermal) axions

$$m_{\rm a} \lesssim 10^{-2}\ {\rm eV}$$

$$\Omega_{\rm a}h^2 \simeq 0.13\left(\frac{m_{\rm a}}{10^{-5}\ {\rm eV}}\right)^{-1.18}$$

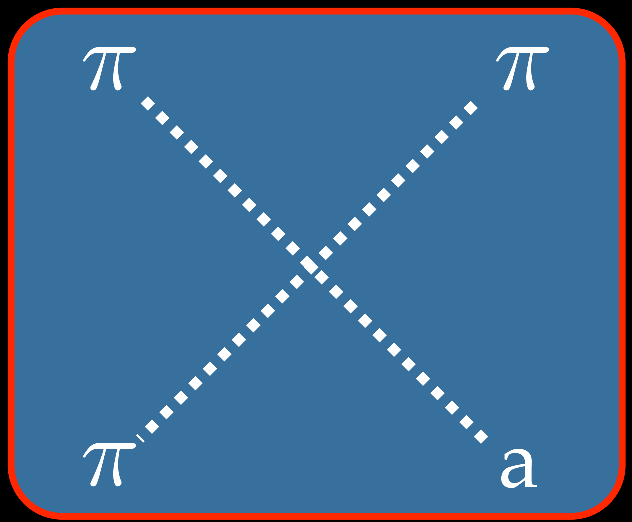
Hot (thermal) axions

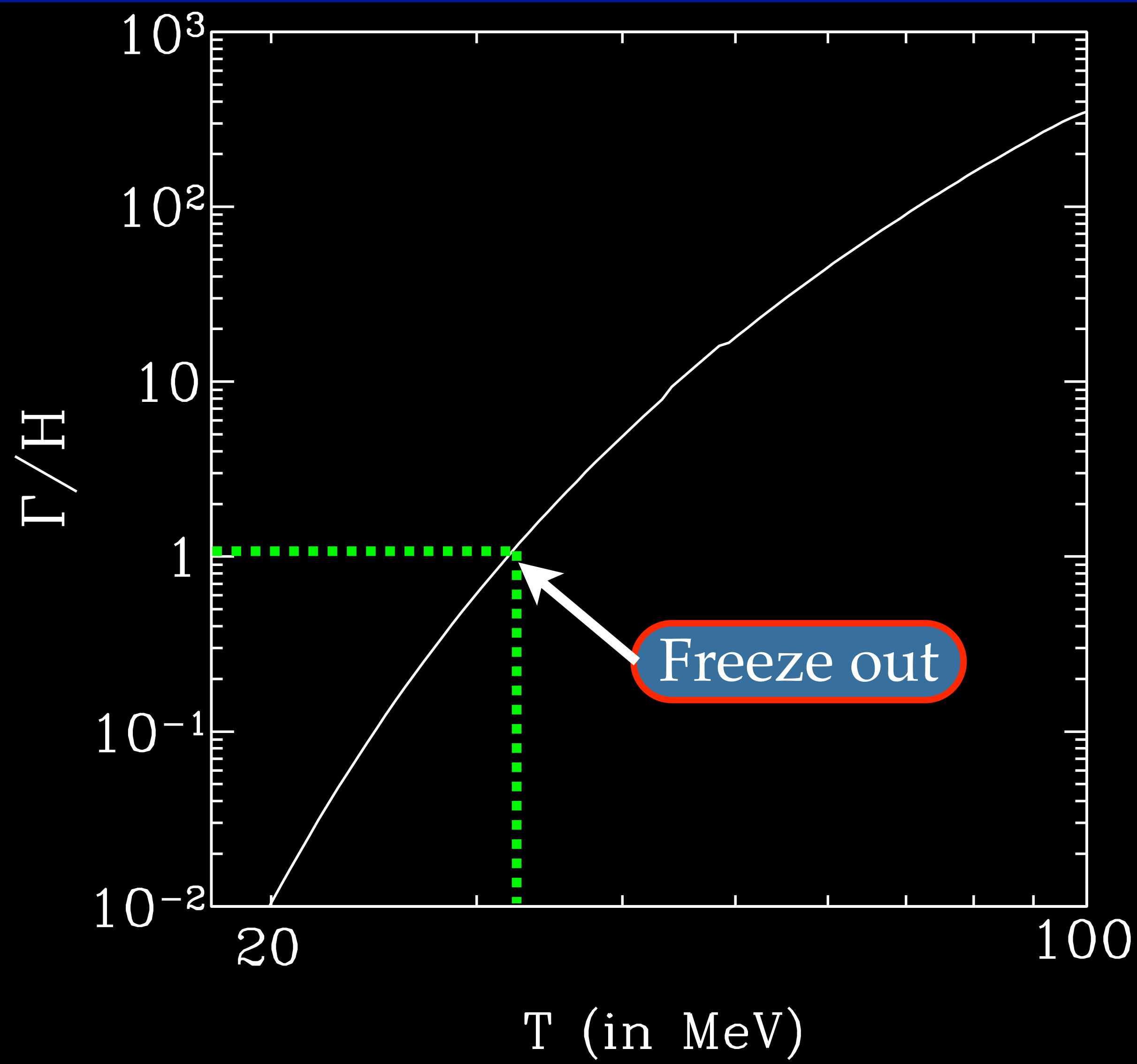
$$m_{\rm a} \gtrsim 10^{-2}\ {\rm eV}$$

$$\Omega_{\rm a}h^2 \simeq \frac{m_{\rm a}}{130\ {\rm eV}}\left(\frac{10}{g_{*{\rm S},{\rm F}}}\right)$$

Hot axion production at early times

Axion Production:

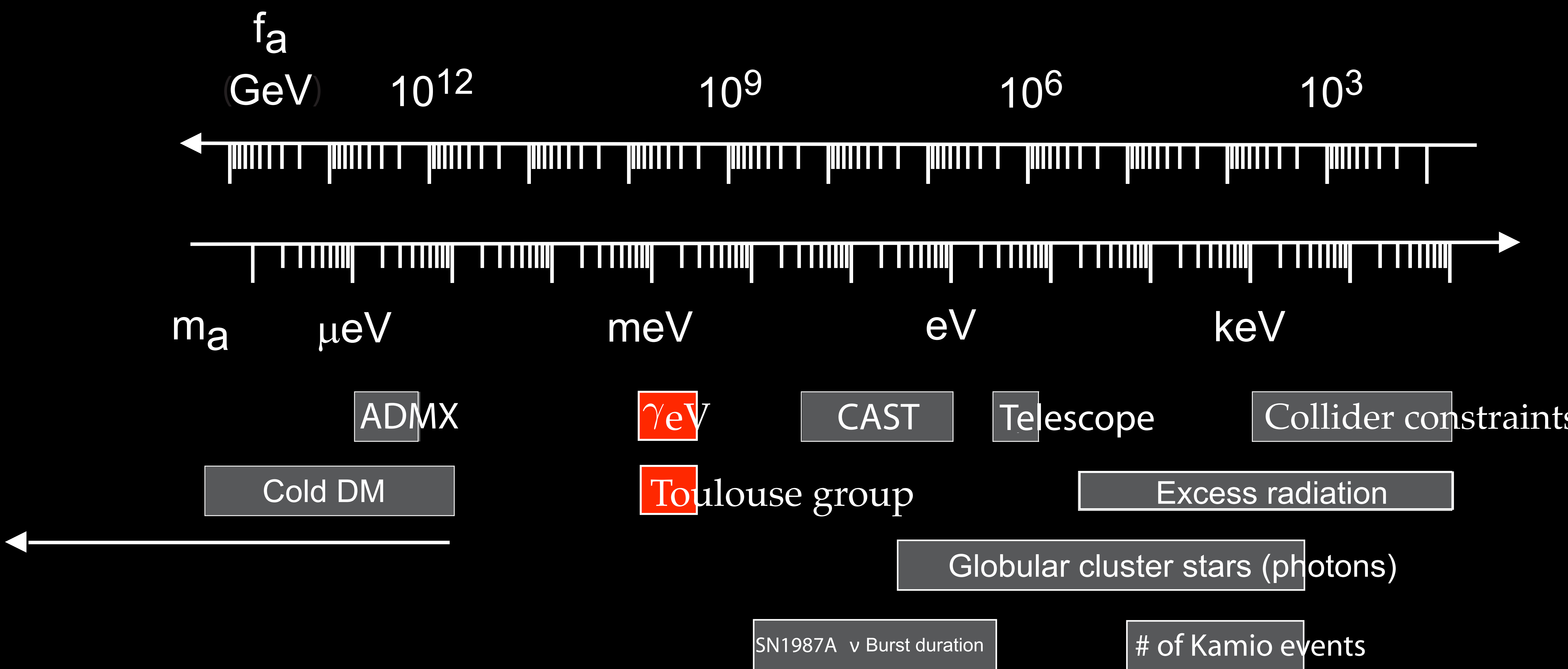




- ✳ Axions produced through interactions between non-relativistic pions in chemical equilibrium with rate

$$\Gamma \sim n_\pi \langle \sigma v \rangle = \frac{T^2 m_{\rm a}^2 (1-r)^2}{9 z f_\pi^4 m_\pi^2} \left(\frac{m_\pi T}{2\pi} \right)^{3/2} e^{-m_\pi / T}$$

Context: Axion constraints



Axion decay

- Axion decays monochromatically via $a \longrightarrow \gamma\gamma$ with in source frame $\lambda_a = \frac{24,800\text{Å}}{m_{\rm a,eV}}$
- For galaxies/clusters, line comparable to sky background

$$I_{\lambda_{\rm o}} \propto m_{\rm a}^7 \xi^2 \Sigma / \left(1 + z_{\rm cl}\right)^4$$

- First attempt made at KPNO 2.1m using Gold spectrograph on Abell clusters A1413, A2218, and A2256:

$$3 \text{ eV} \leq m_{\rm a} \leq 8 \text{ eV}$$

$$\xi \leq 0.08$$

Seeking axions with the VIMOS IFU

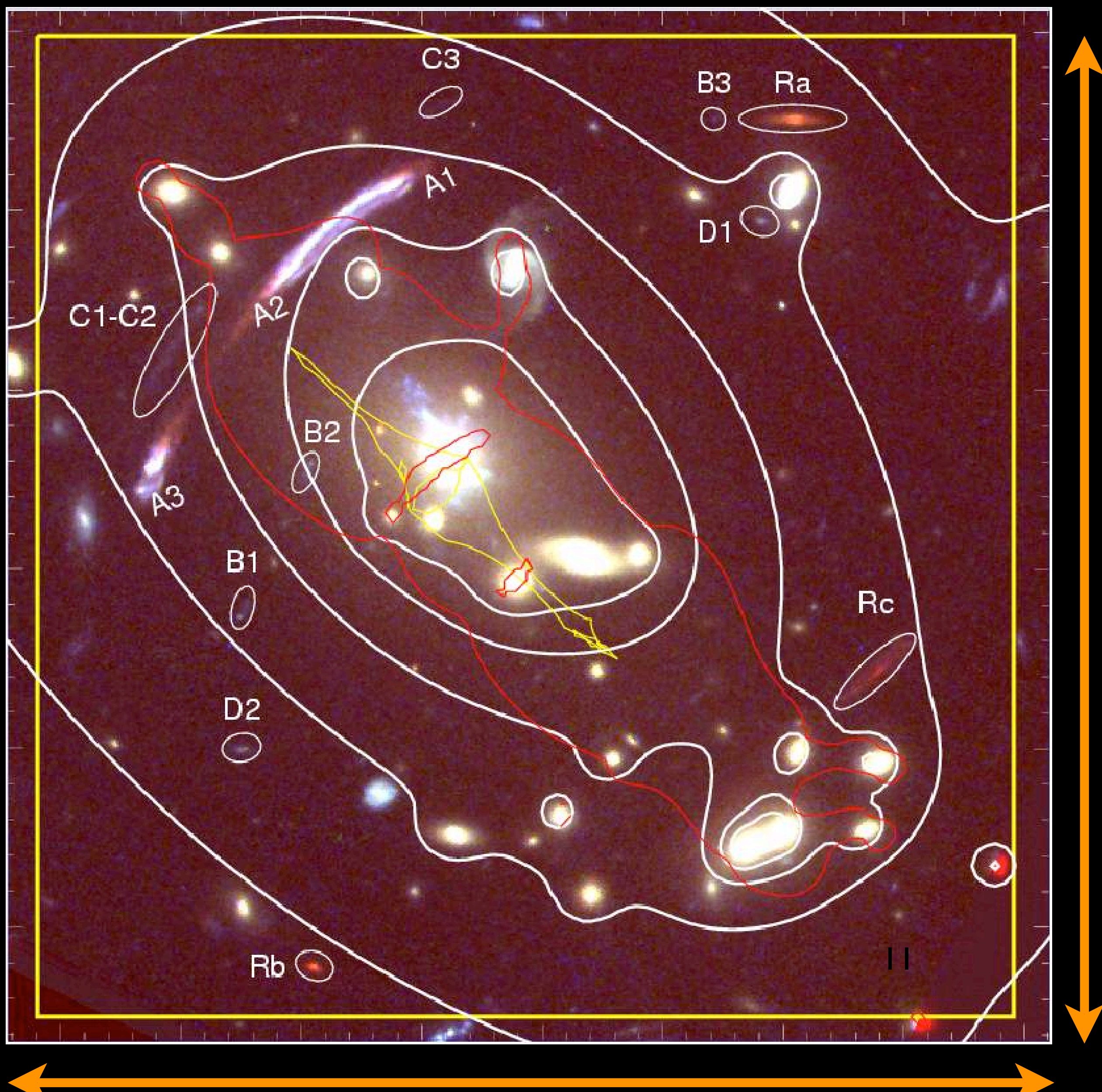
- VIMOS IFU (VLT, 6400 fibers) has largest f.o.v. of any instrument in its class: 54″x54″ mode used
- LR-Blue grism used: $4000\text{Å} \leq \lambda \leq 6800\text{Å}$ $(4.5\ \text{eV} \leq m_\text{a} \leq 7.7\ \text{eV})$. Dispersion of 5.4Å adequate to resolve axion line:

$$\delta\lambda = 195\ \sigma_{1000}\ m_{\text{a,eV}}^{-1}\ \text{Å}$$

- 10.8 ksec exposures of A2667 (z=0.233, 1 pointing) and A2390 (z=0.228, 3 pointings) taken as part of VIMOS study of these clusters

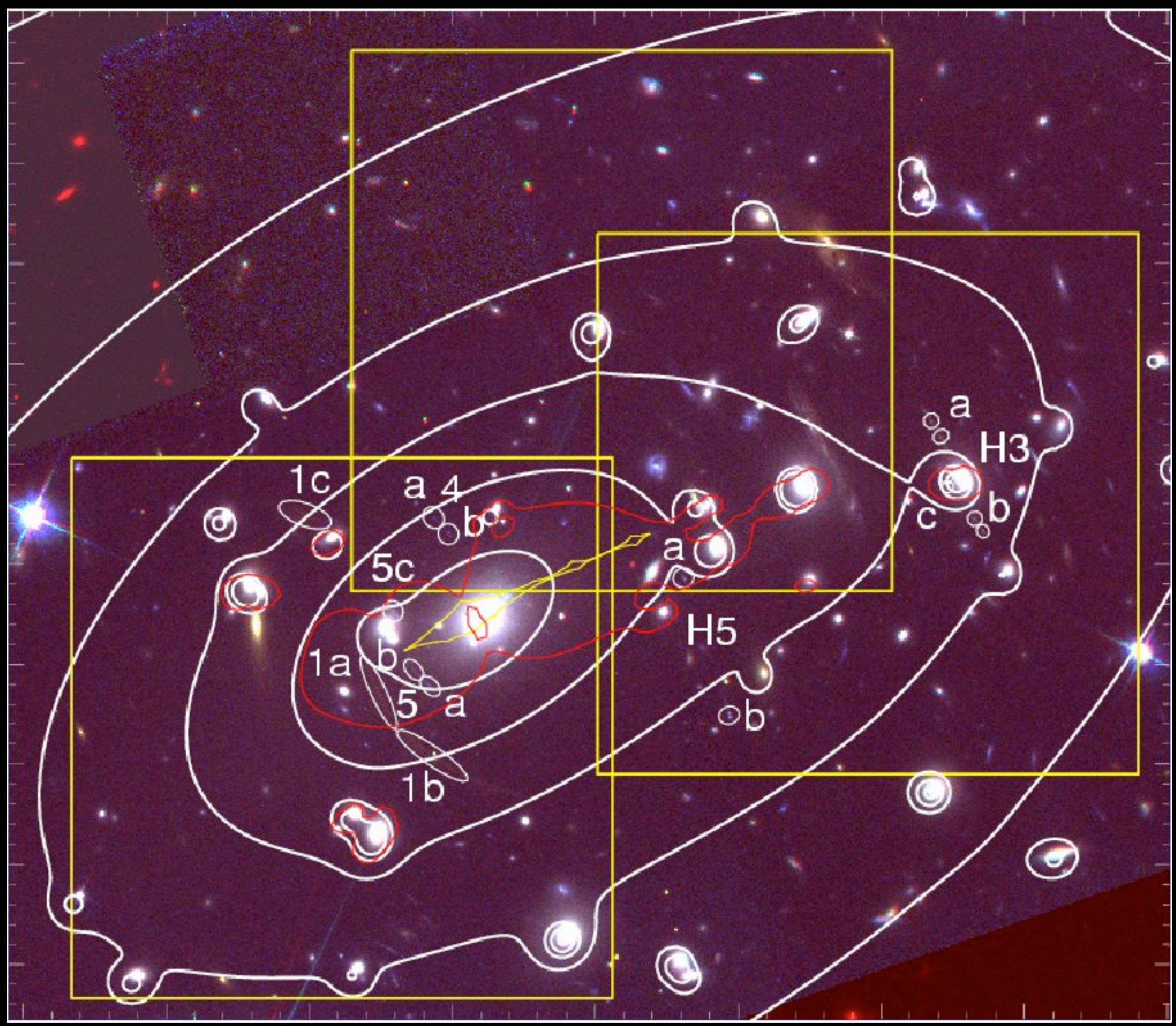
Applying the imaging

A2667



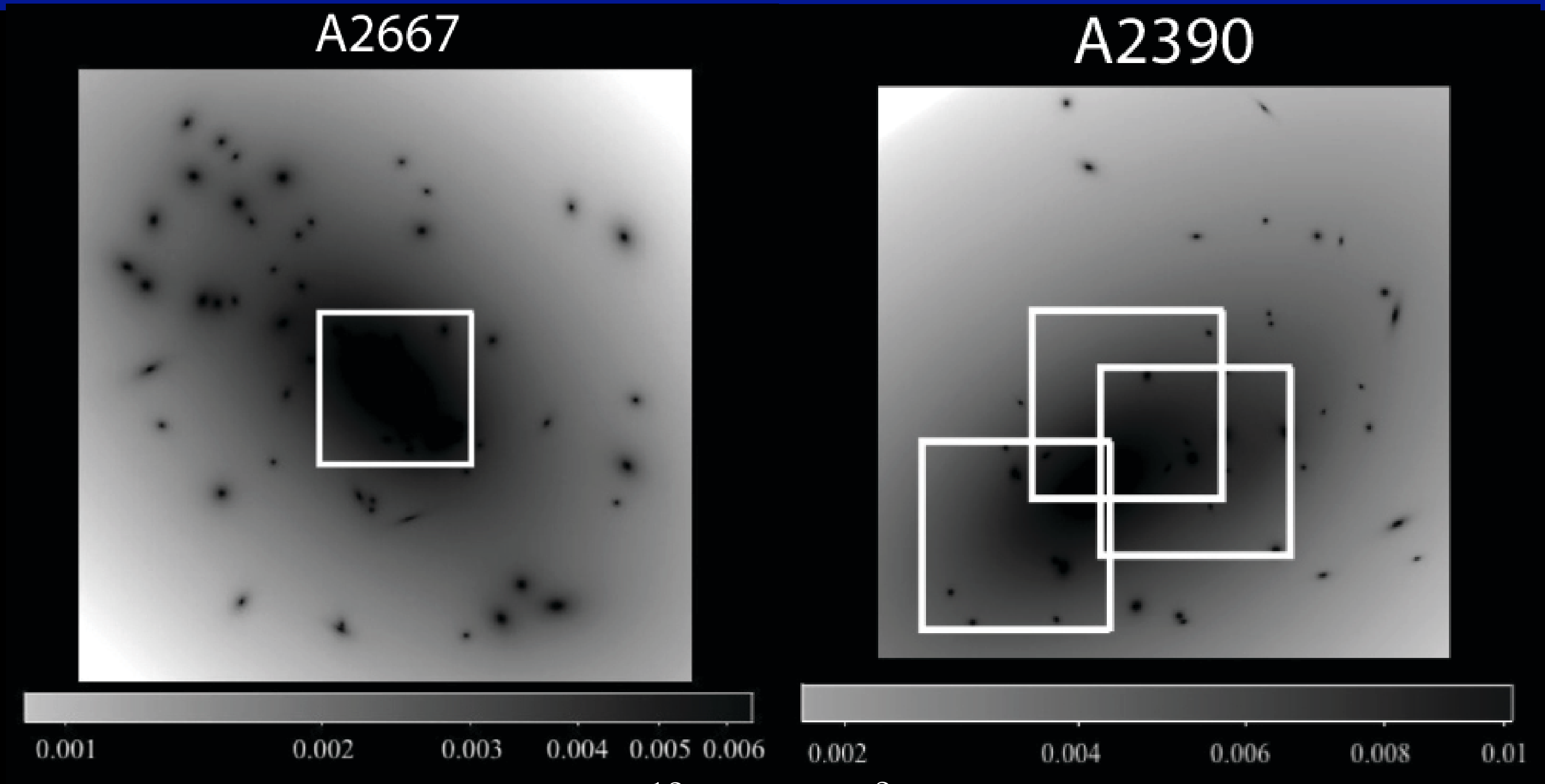
200 kpc

A2390



✳Bright sources masked

Lensing maps

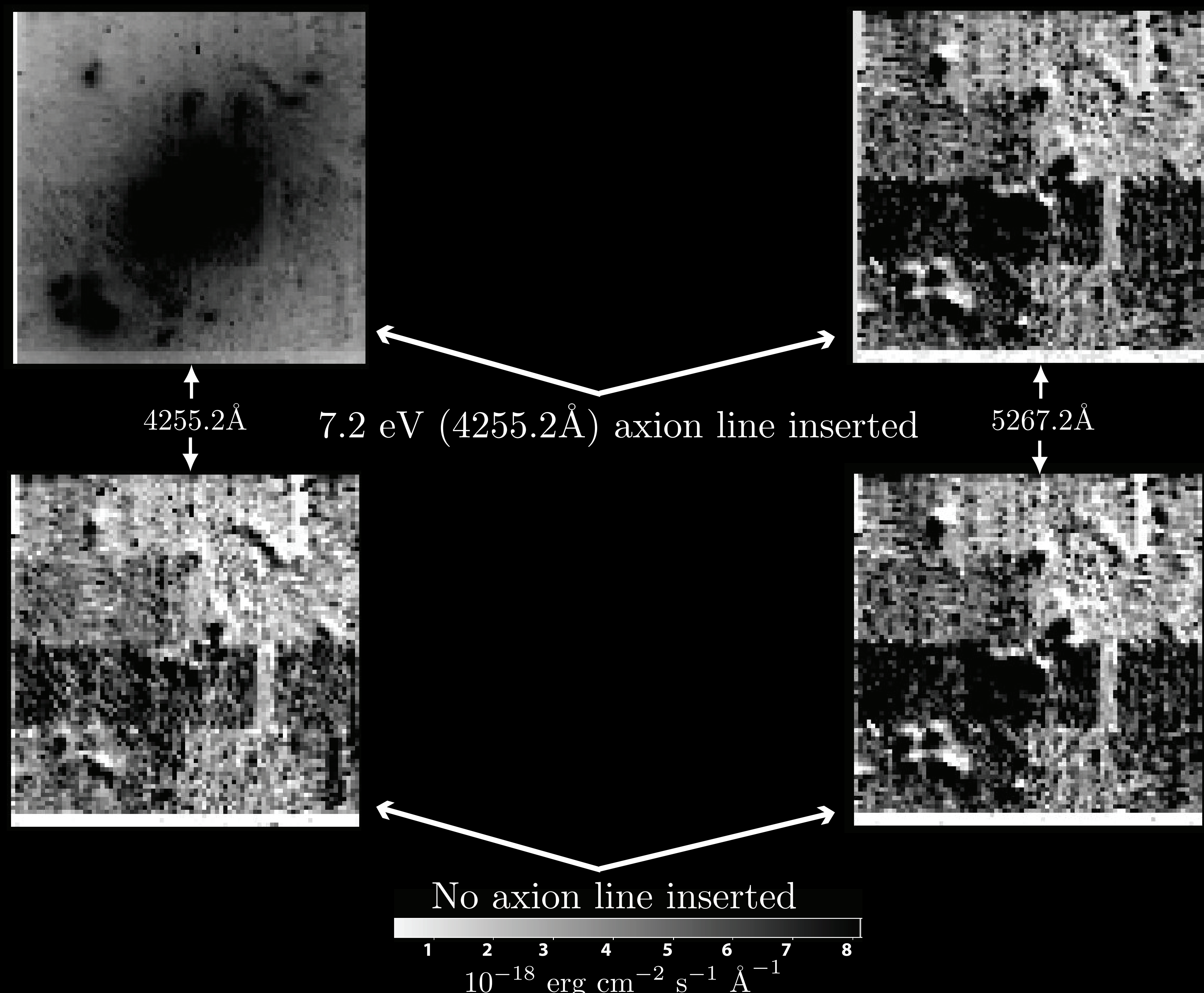


$\Sigma(10^{12} M_{\odot}\ \mathrm{pix}^{-2})$

- Cluster galaxies selected by redshift
- BCG, galaxies near arcs, cluster-scale mass component modeled individually

$$\Sigma(R) = \frac{\Sigma_0 r_0}{1 - r_0/r_\mathrm{t}} \left(\frac{1}{\sqrt{r_0^2 + R^2}} - \frac{1}{\sqrt{r_\mathrm{t}^2 + R^2}} \right)$$

Are we kidding ourselves? No!



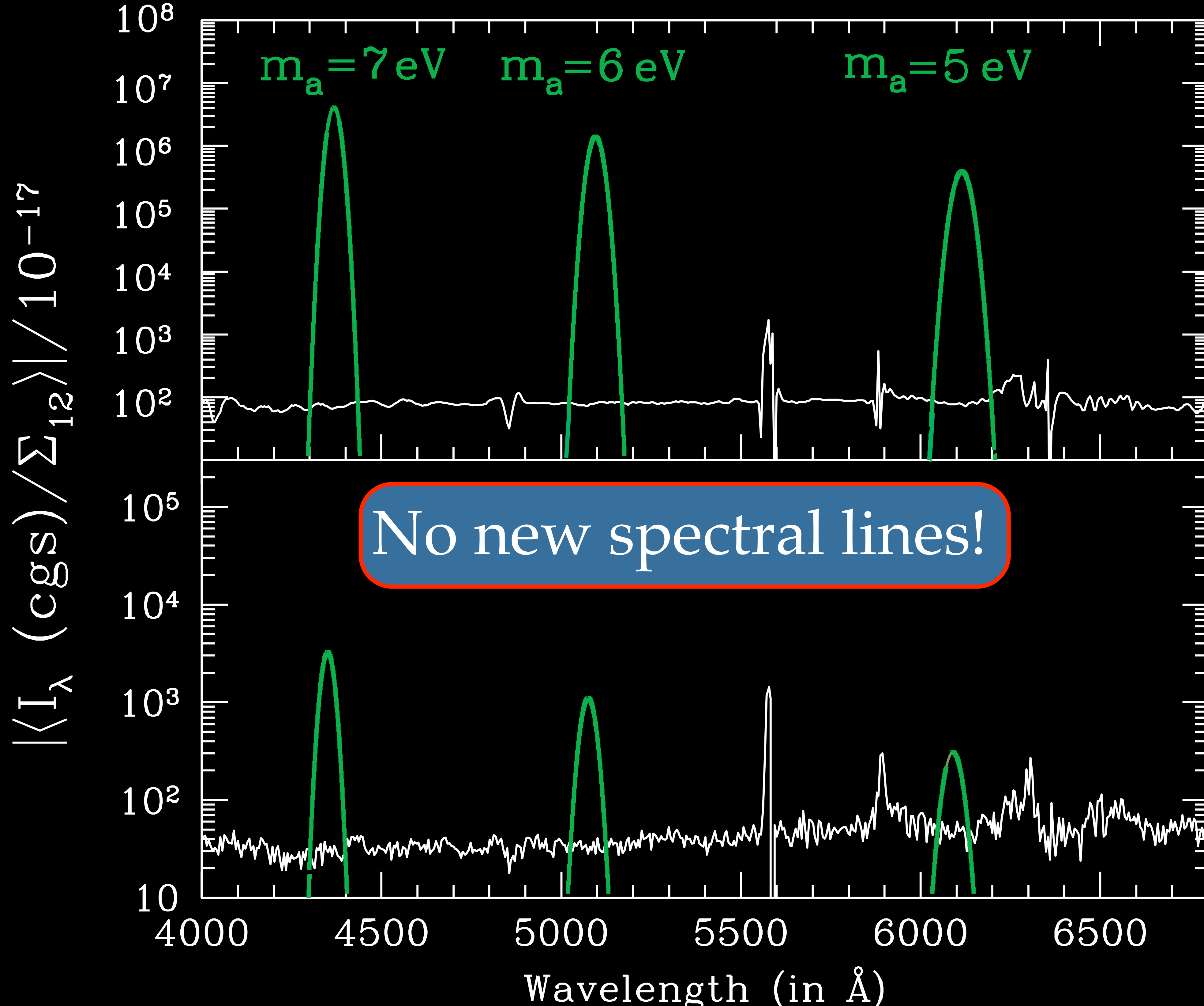
Data analysis

- Signal modeled as sum of density-dependent signal and uniform sky background with noise (Poisson, CCD bias, read-out, flat-fielding, fiber crosstalk , mass map errors)

$$I_{\lambda,\mathrm{i}}^{\mathrm{mod}} = \langle I_\lambda / \Sigma_{12} \rangle \, \Sigma_{12,\mathrm{i}} + b_\lambda$$

- End result is a 1D spectrum of the cluster. Fibers weighted to extract density-dependent part of signal: $\langle I_\lambda / \Sigma_{12} \rangle$

Data analysis



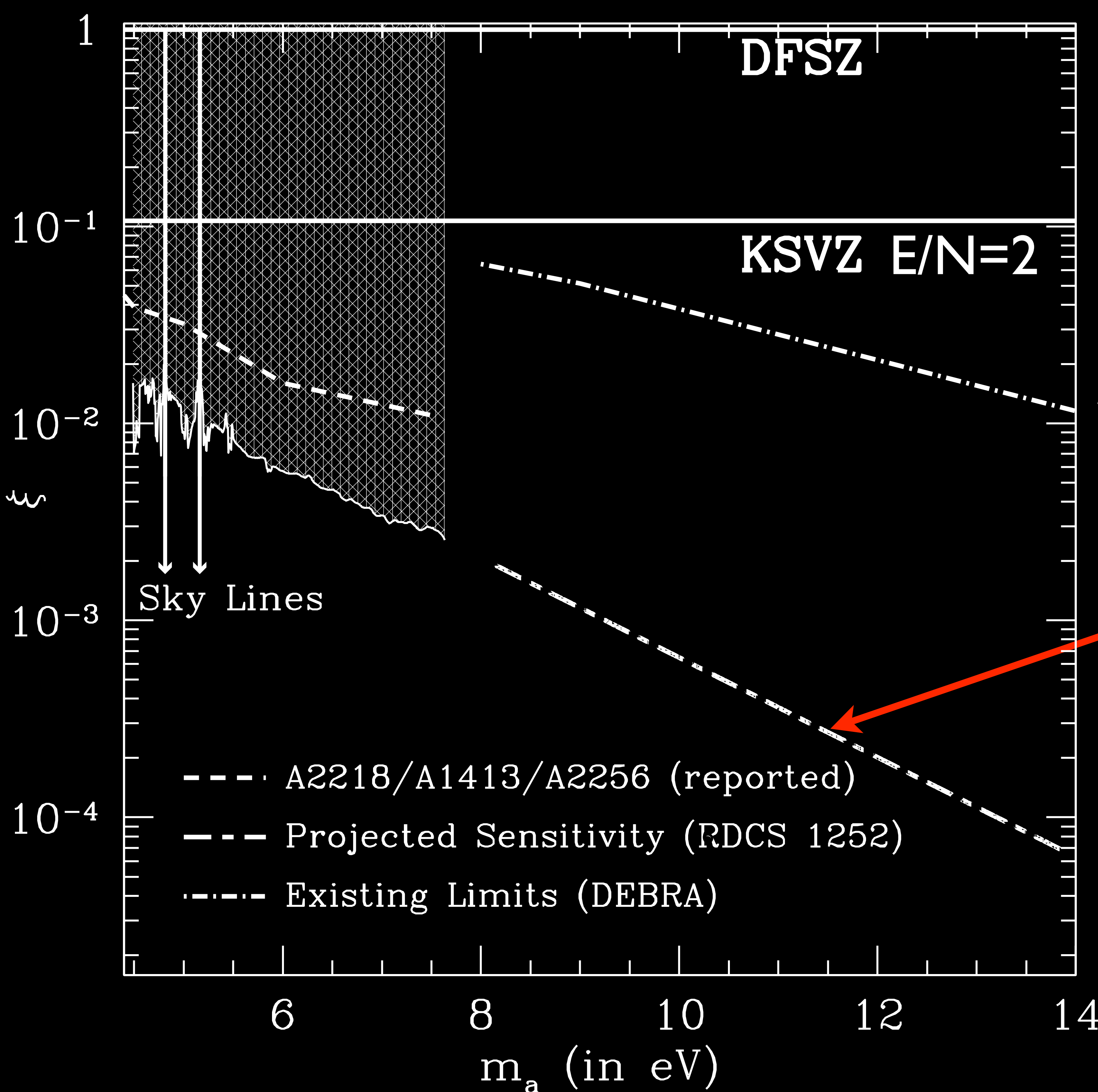
A2667

$\xi = 1$

A2390

$\xi = 0.1$

Extending the optical axion window



- Sensitivity improves at higher redshift!

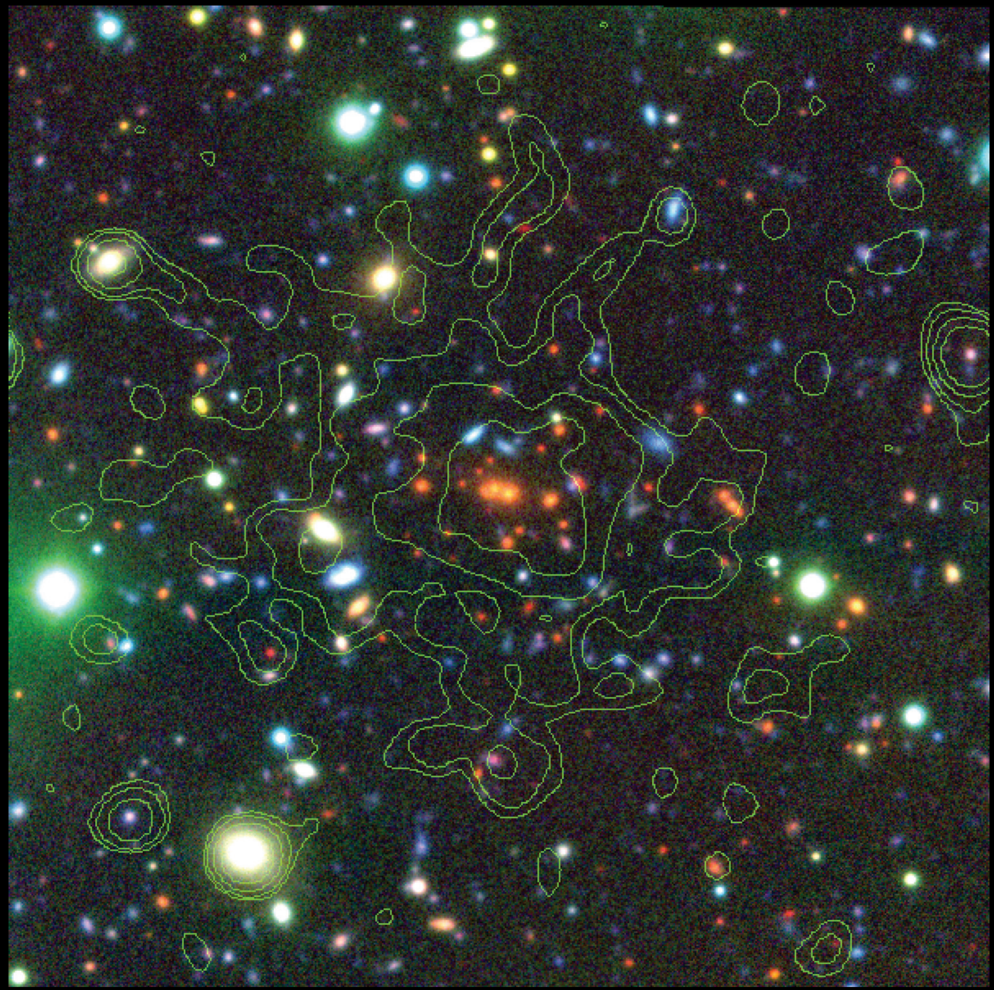
$$I_{\lambda_o} \propto m_a^7 (1+z_{cl})^{-4}$$

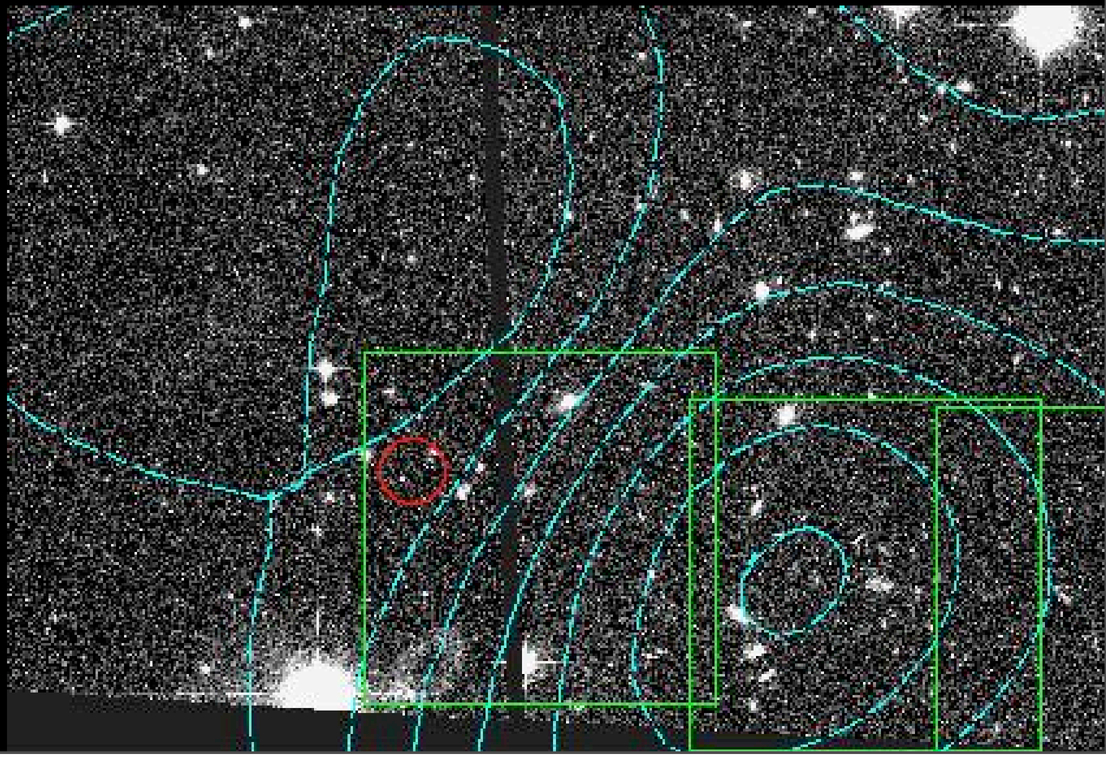
$$m_a = 24,800 \text{ Å} (1+z_{cl}) / \lambda_a$$

$$\xi \propto I_{\lambda_o}^{1/2} (1+z_{cl})^{-3/2}$$

RDCS 1252

- RDCS 1252 is a $8 \times 10^{14} M_{\odot}$ cluster at $z = 1.237$
- Allotted 25 hrs of time for VIMOS IFU spectra using LR-Blue grism
- Publicly available weak-lensing mass maps (Lombardi et al. 2005), 2 arcs?

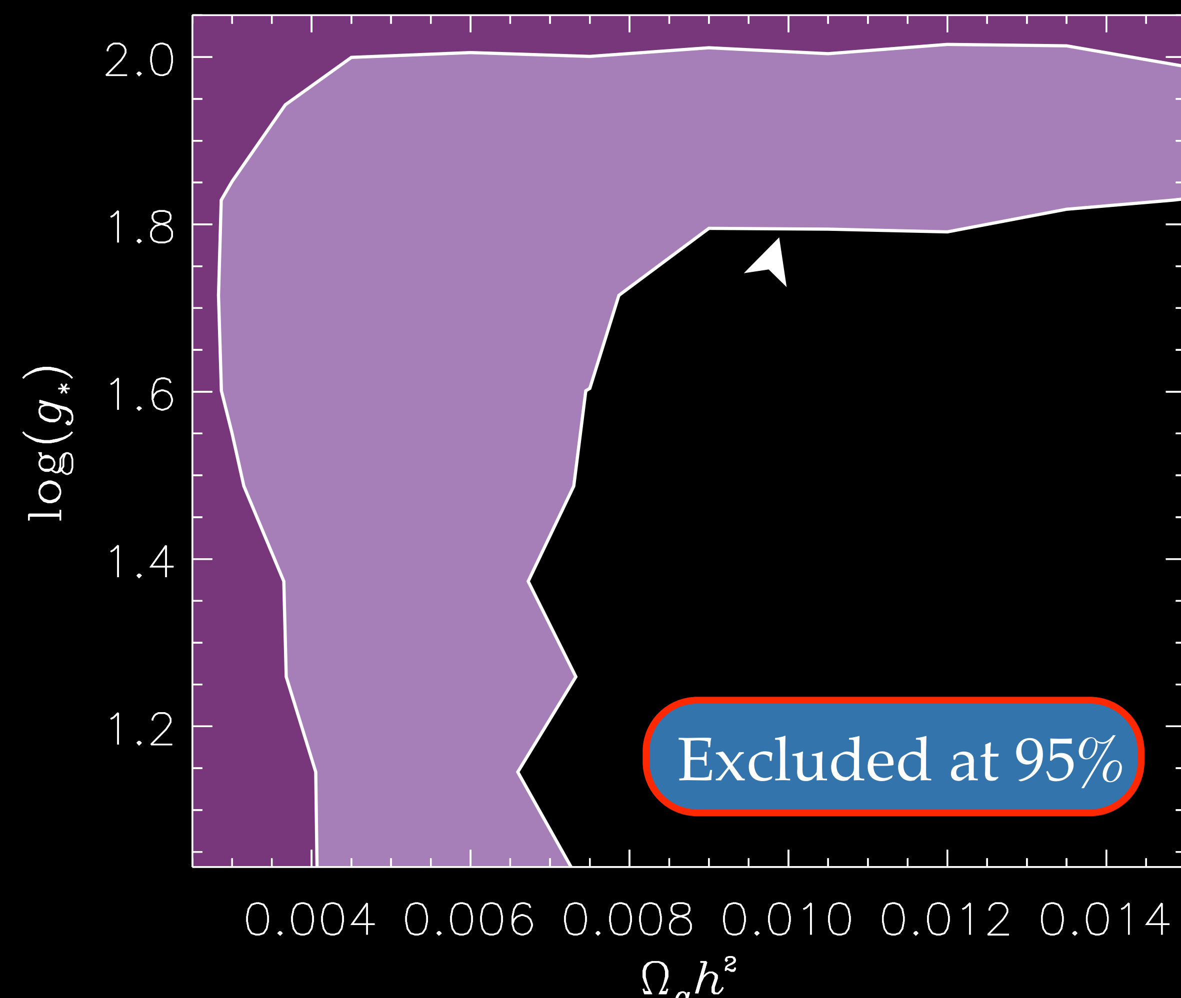




3 pointings cover range of WL mass contours

The physics of cosmological axion constraints

- Axions are relativistic at early times, free stream and suppress power by $\Delta P/P \simeq -8\Omega_{\rm a}/\Omega_{\rm m}$ when $\lambda \lesssim \lambda_{\rm fs}$
- SDSS galaxy P(k) and WMAP1 yield exclusion region (Hannestad et al. 2004)
- Need $g_{*{\rm S},{\rm F}} \gtrsim 87$ to agree with data
- 2D constraints can be applied to our two-parameter $(m_{\rm a}, T_{\rm rh})$ model



$$\lambda_{\rm fs} \to \lambda_{\rm nl} \simeq 30\ h^{-1}\ {\rm Mpc}$$

$$\frac{T_{\rm a}}{T_\nu} \simeq \left(\frac{10.75}{g_{*{\rm S},{\rm F}}}\right)^{1/3}$$

Motivation for low-temperature reheating

- No strong evidence for nature of expansion history before 4 MeV
- Thermal gravitino bounds (closure, BBN) require $T_{\rm rh} \lesssim 10^8\ \mathrm{GeV}$ or $T_{\rm rh} \lesssim 1\ \mathrm{GeV}$
- If gravitational decay of string theory modulus reheats the universe:

$$T_{\rm rh} \sim 10\ \mathrm{MeV} \left(\frac{m_\phi}{\mathrm{TeV}}\right)^{3/2}$$

Low-temperature reheating (LTR)

- Simple model in which $\phi \rightarrow$ radiation is responsible for extended reheating phase

$$\frac{d\rho_{\rm R}}{dt} + 4H\rho_{\rm R} = \Gamma_{\phi}\rho_{\phi} \qquad \frac{d\rho_{\phi}}{dt} + 3H\rho_{\phi} = -\Gamma_{\phi}\rho_{\phi}$$

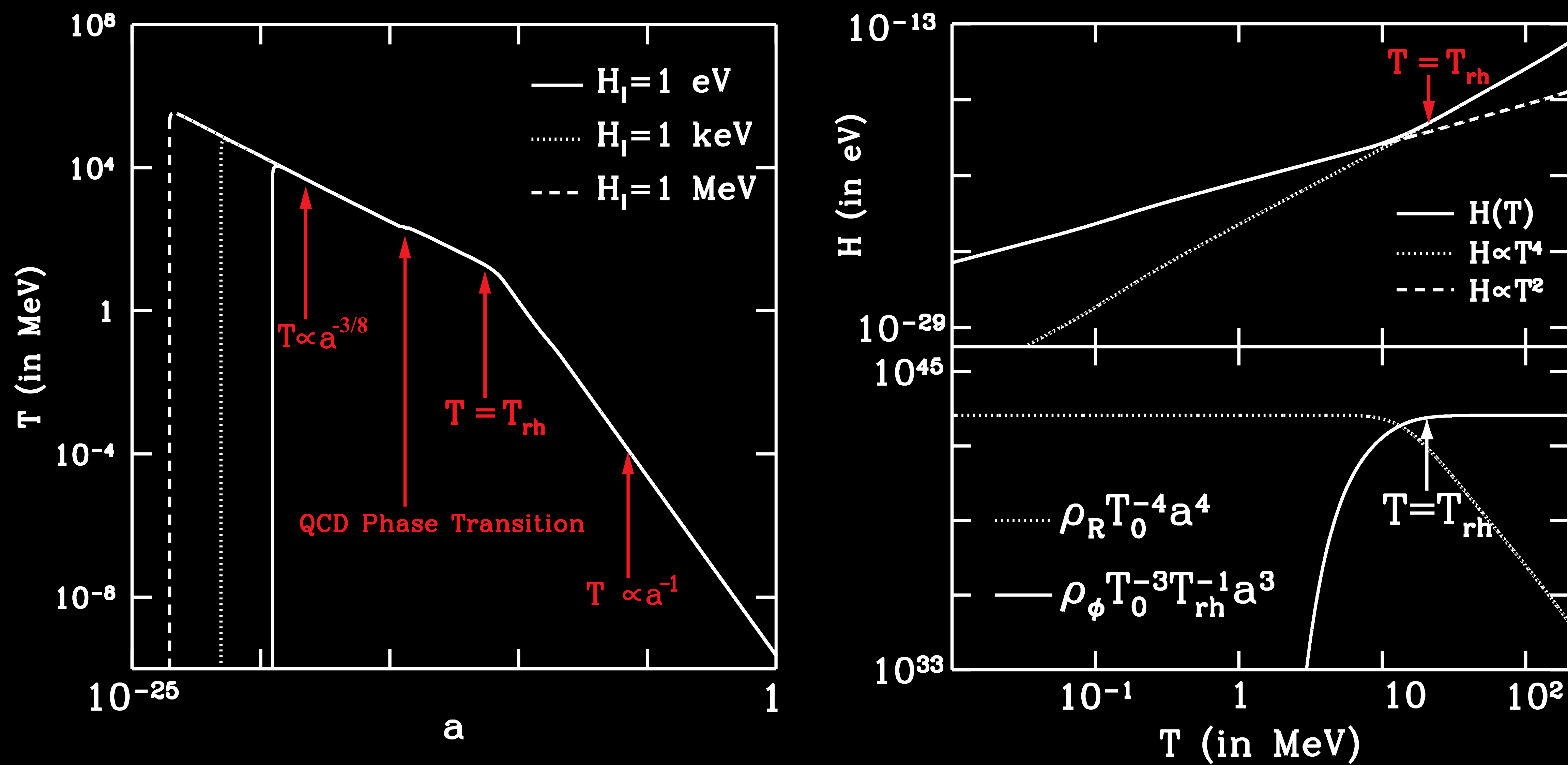
- $T_{\rm rh} \gtrsim 4~{\rm MeV}$ to avoid changing successful predictions of BBN

- Decay products thermalize and entropy generated

$$T = \left[\frac{30}{\pi^2 g_*(T)}\right]^{1/4} \rho_{\rm R}^{1/4}$$

- Past work considered effects on WIMP, SM neutrino, sterile neutrino, and cold axion abundances and constraints. New work: LSS/CMB/total density constraints to hot axions in LTR

Low-temperature reheating (LTR)



- Entropy generation slows down temperature decrease

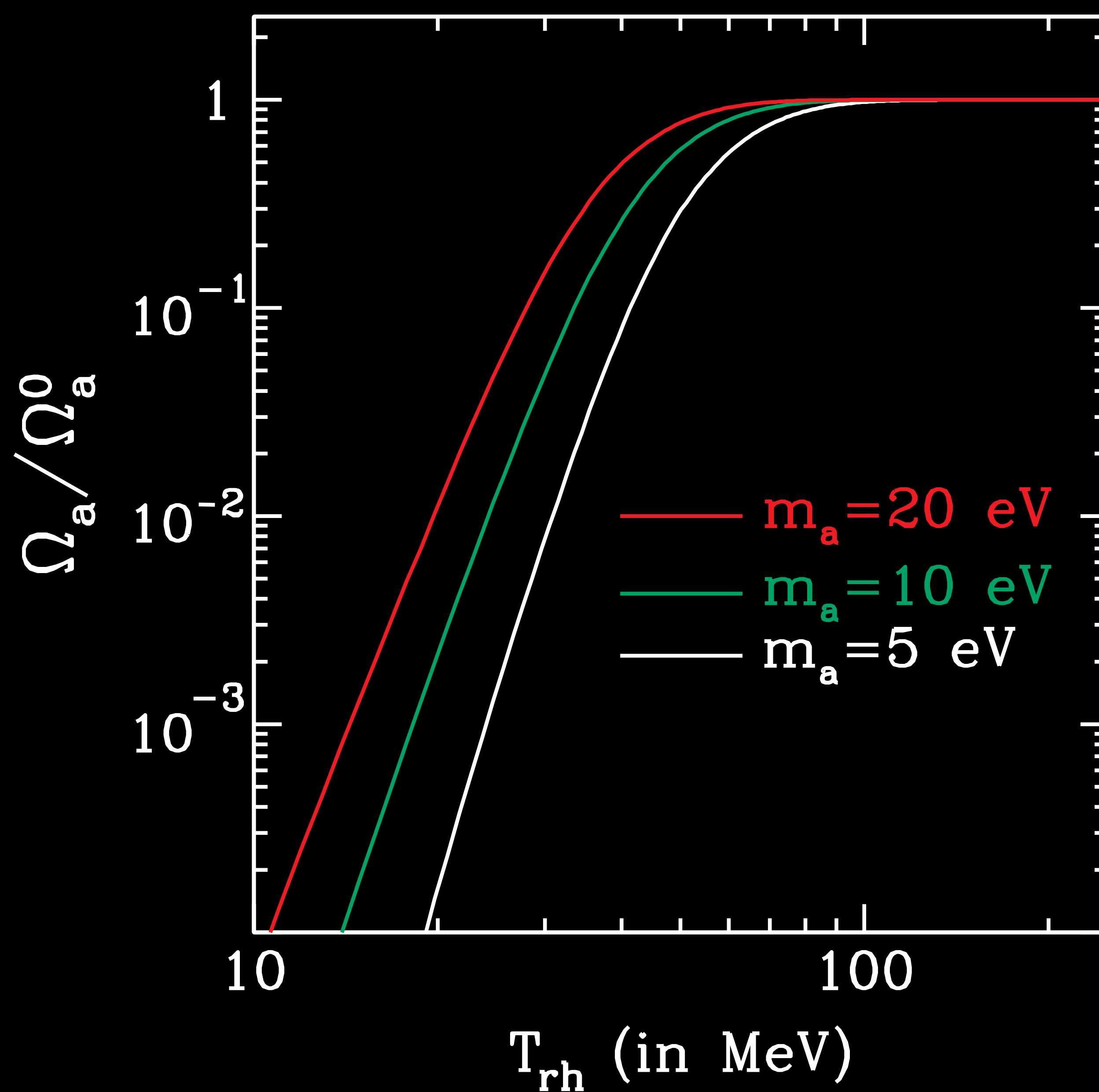
$$T \propto a^{-3/8} \text{ until } T \lesssim T_{\rm rh}, \text{ then } T \propto a^{-1}$$

- Hubble expansion is faster

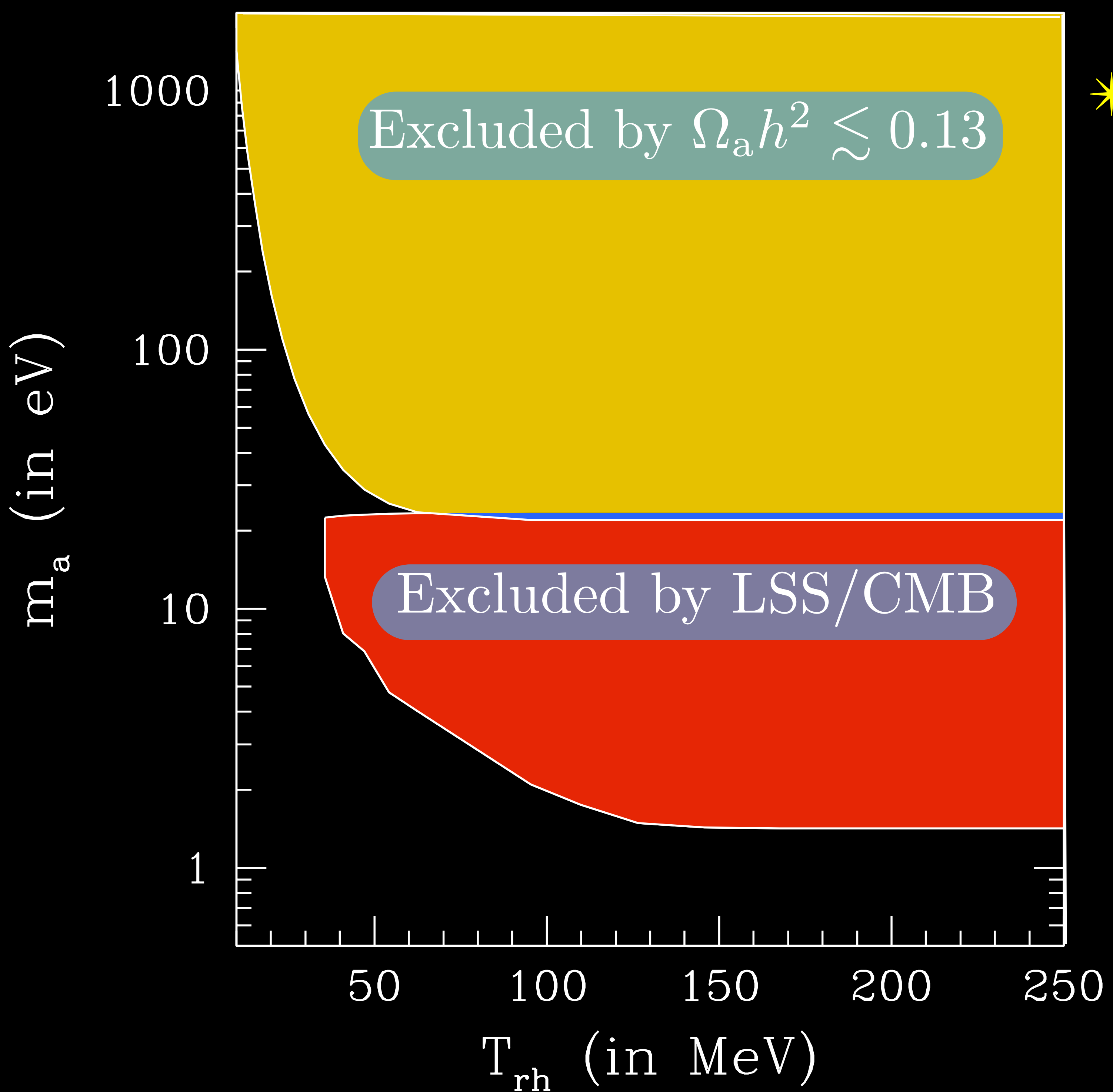
$$H \propto T^4 \text{ until } T \lesssim T_{\rm rh}, \text{ then } H \propto T^2$$

Axion abundance in LTR

- Higher T_{F} means higher initial equilibrium abundance
- Entropy generation dramatically suppresses abundances



New constraints



- $\lambda_{fs}\,(T_{rh}, m_a)$ & $\Omega_a h^2\,(T_{rh}, m_a)$ calculated to trace out allowed region

If $m_a \gtrsim 23$ eV , no LSS constraint to `hot axions'

Standard constraints recovered if $T_{rh} \gtrsim 170$ MeV

If $T_{rh} \lesssim 35$ MeV , $\lambda_{fs} \lesssim \lambda_{nl}$, LSS constraints completely relaxed

Cosmological Hydrogen Recombination: The effect of extremely high-n states

Daniel Grin

in collaboration with Christopher M. Hirata

arXiv:0911.1359, submitted to Phys. Rev. D.

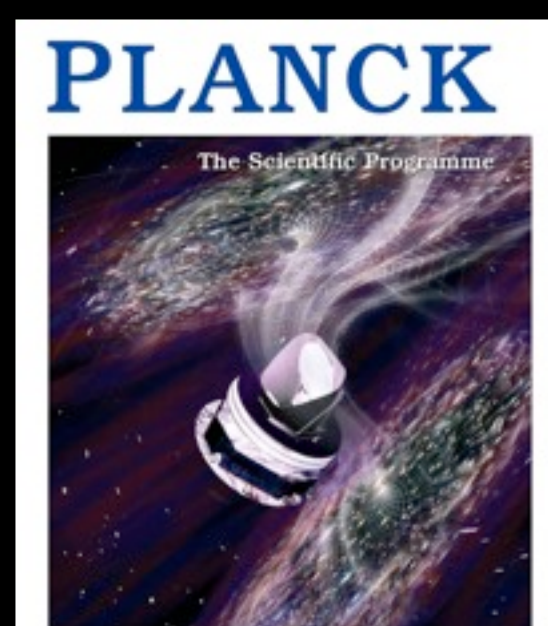
OUTLINE

- Motivation: CMB anisotropies and recombination spectra
- Breaking the Peebles/RecFAST mold
- RecSparse: a new tool for high-n states
- Results
- Ongoing/future work

CLONE WARS

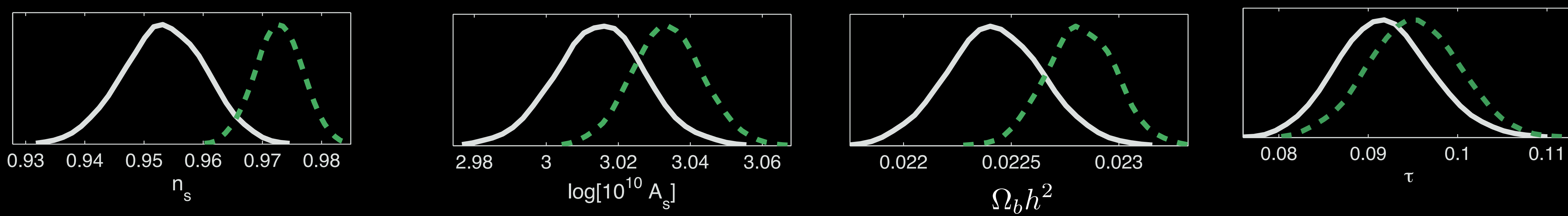
- Planck (launched May 2009) will make cosmic-variance limited CMB anisotropy measurements up to l~2500 (T), and l~1500 (E)

- Wong 2007 and Lewis 2006 show that $x_e(z)$ needs to be predicted to 0.1% accuracy for Planck data analysis



RECOMBINATION, INFLATION, AND REIONIZATION

- Planck uncertainty forecasts using MCMC



$$\mathrm{P(k)}=\mathrm{A}_s\,(k\eta_0)^{n_s-1}$$

- Cosmological parameter inferences will be off if recombination is improperly modeled (Wong/Moss/Scott 2007)
- Leverage on new physics comes from high l. Here the details of recombination matter!
- Inferences about inflation will be wrong if recombination is improperly modeled

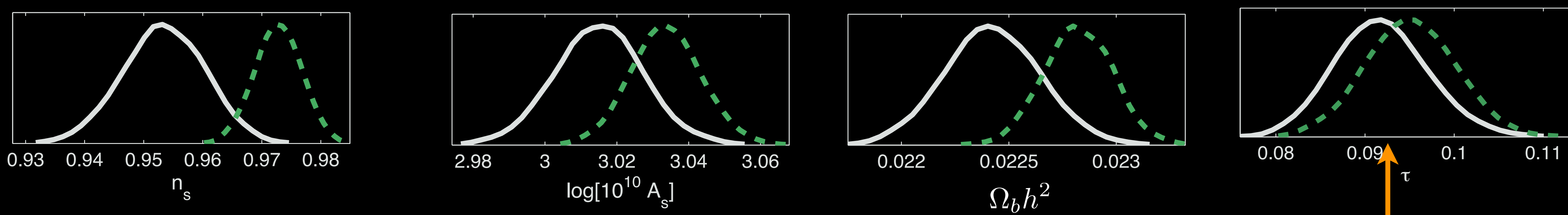
$$\mathrm{n}_s = 1 - 4\epsilon + 2\eta \qquad \epsilon = \frac{m_{\mathrm{pl}}^2}{16\pi}\left[\frac{V'(\phi)}{V(\phi)}\right]^2 \qquad \mathrm{A}_s^2 = \frac{32}{75}\frac{V}{m_{\mathrm{pl}}^4\epsilon}\bigg|_{k_{\mathrm{pivot}}=aH}$$

CAVEAT EMPTOR:

Need to do eV physics right to infer anything about 10^{15} GeV physics!

RECOMBINATION, INFLATION, AND REIONIZATION

- Planck uncertainty forecasts using MCMC



$$P(k) = A_s \, (k\eta_0)^{n_s - 1}$$

Bad recombination history yields biased inferences about reionization

Who Cares?

Smearing and moving the surface of last scattering (SLS)

- Photons kin. decouple when Thompson scattering freezes out

$$\gamma + e^- \Leftrightarrow \gamma + e^-$$

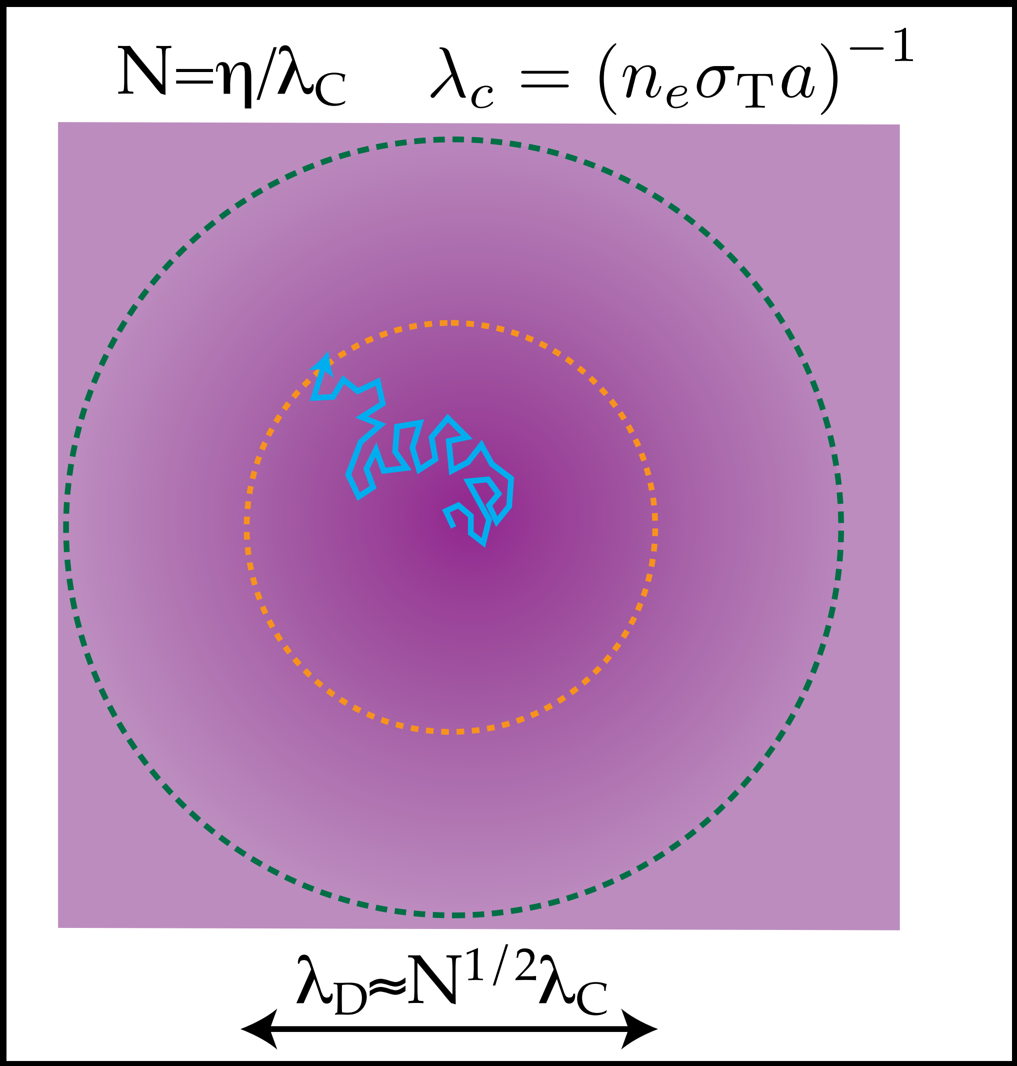
- Acoustic mode evolution influenced by visibility function

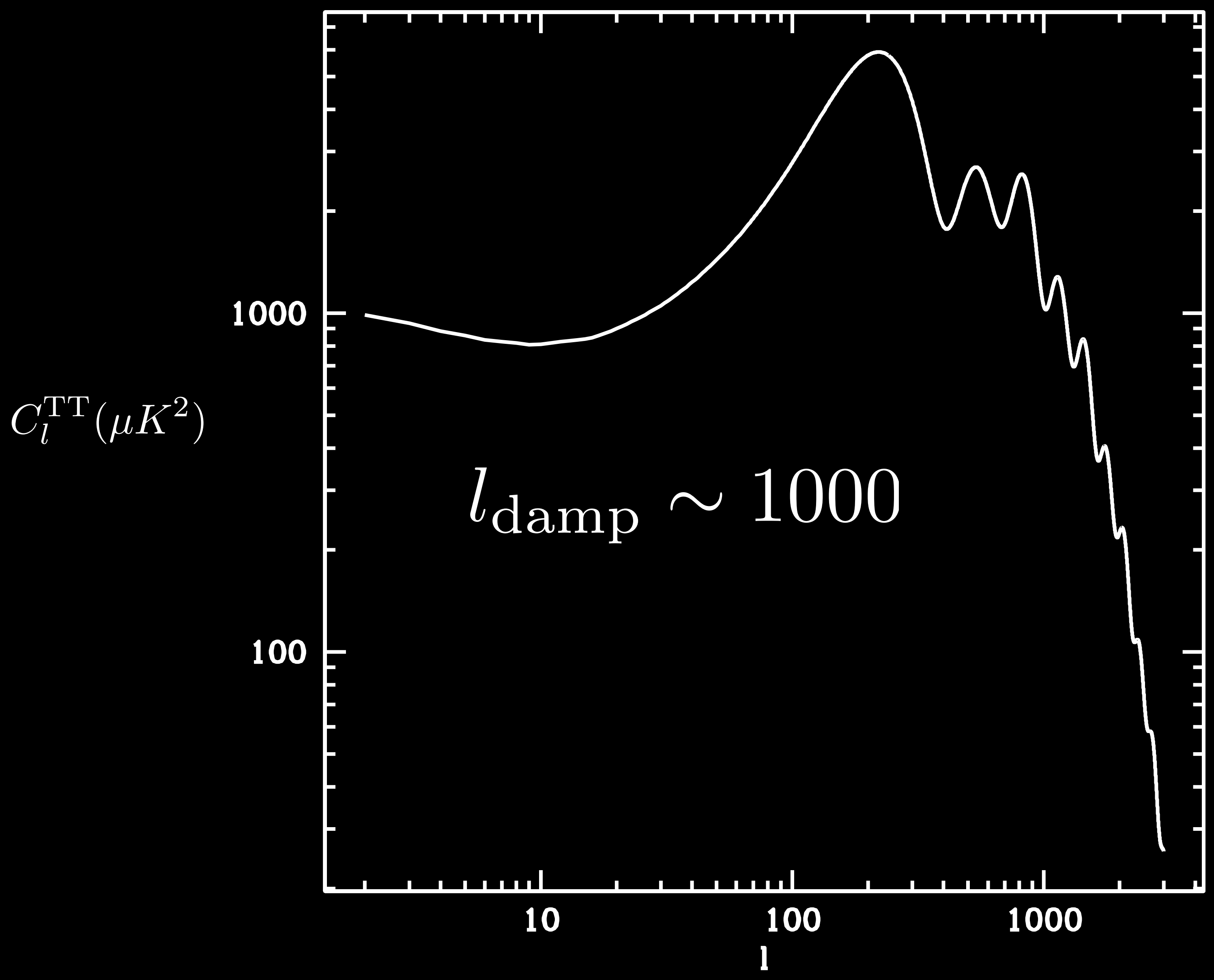
$$g = \dot{\tau} e^{-\tau} \qquad \tau(z) = \int_0^{\eta(z)} n_e \sigma_T a(\eta') d\eta'$$

- $z_{\rm dec} \simeq 1100$: Decoupling occurs during recombination

$$C_l \to C_l e^{-2\tau(z)} \text{ if } l > \eta_{\rm dec}/\eta(z)$$

WHO CARES? THE SILK DAMPING TAIL





- Inhomogeneities are damped for $\lambda < \lambda_D$

WHO CARES? CMB POLARIZATION

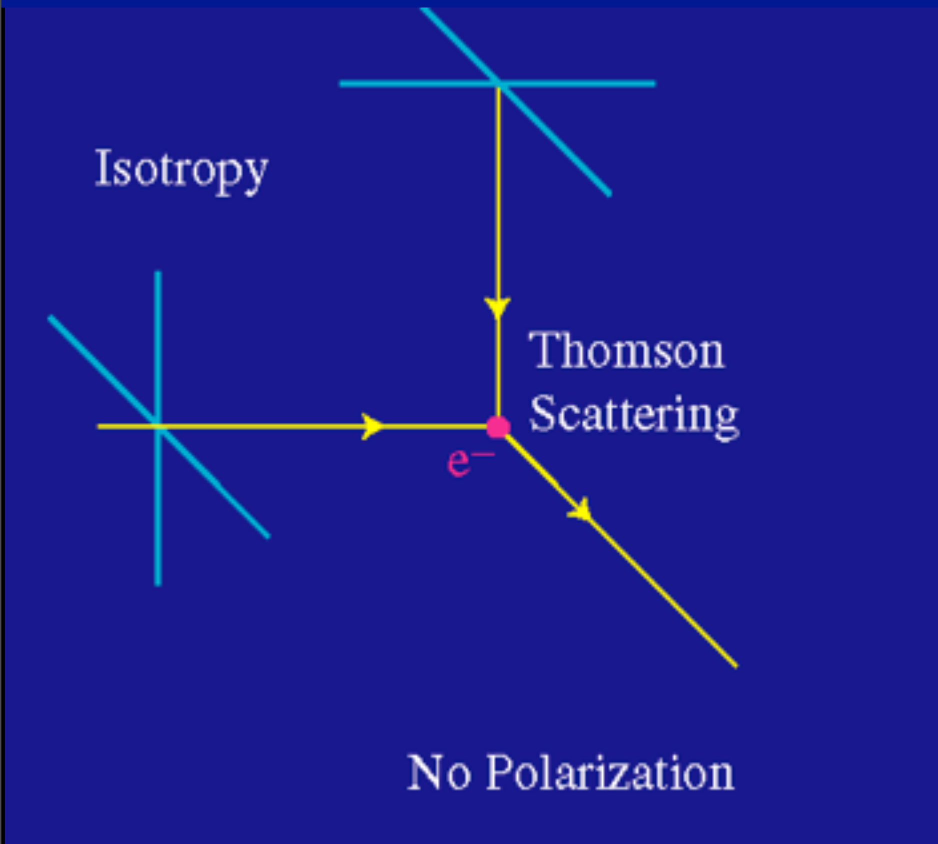
From Wayne Hu's website

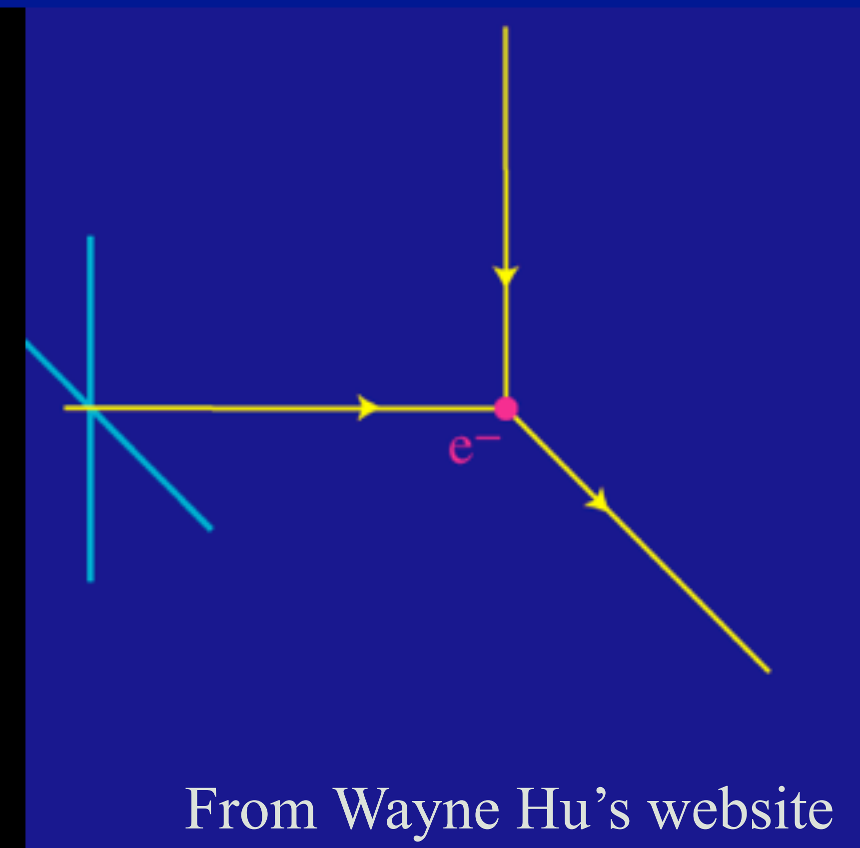
- Need time to develop a quadrapole

$$\Theta_l\left(k\eta\right) \sim \frac{k\eta}{2\tau}\Theta_l\left(k\eta\right) \ll \Theta_l\left(\eta\right) \text{ if } l \geq 2, \text{ in tight coupling regime}$$

- Need to scatter quadrapole to polarize CMB

WHO CARES? CMB POLARIZATION





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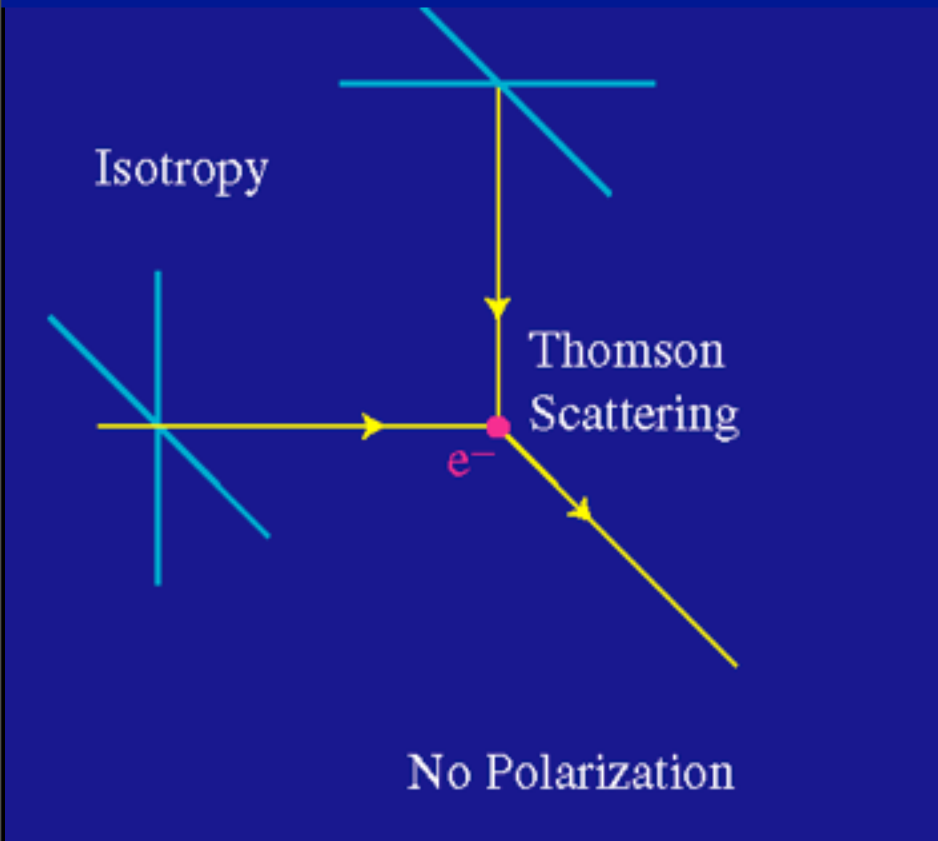
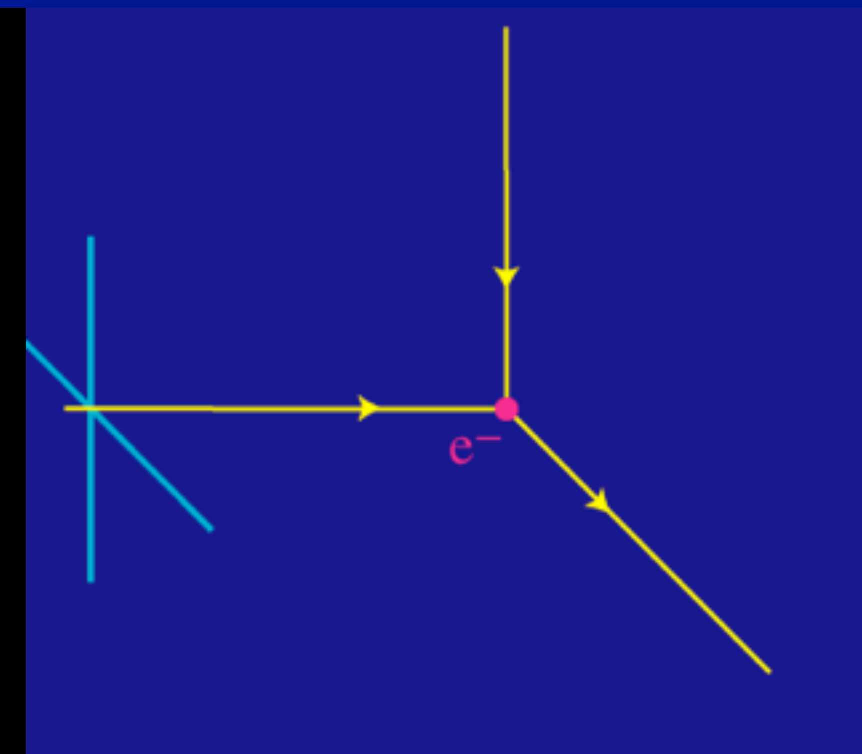
WHO CARES?
CMB POLARIZATION





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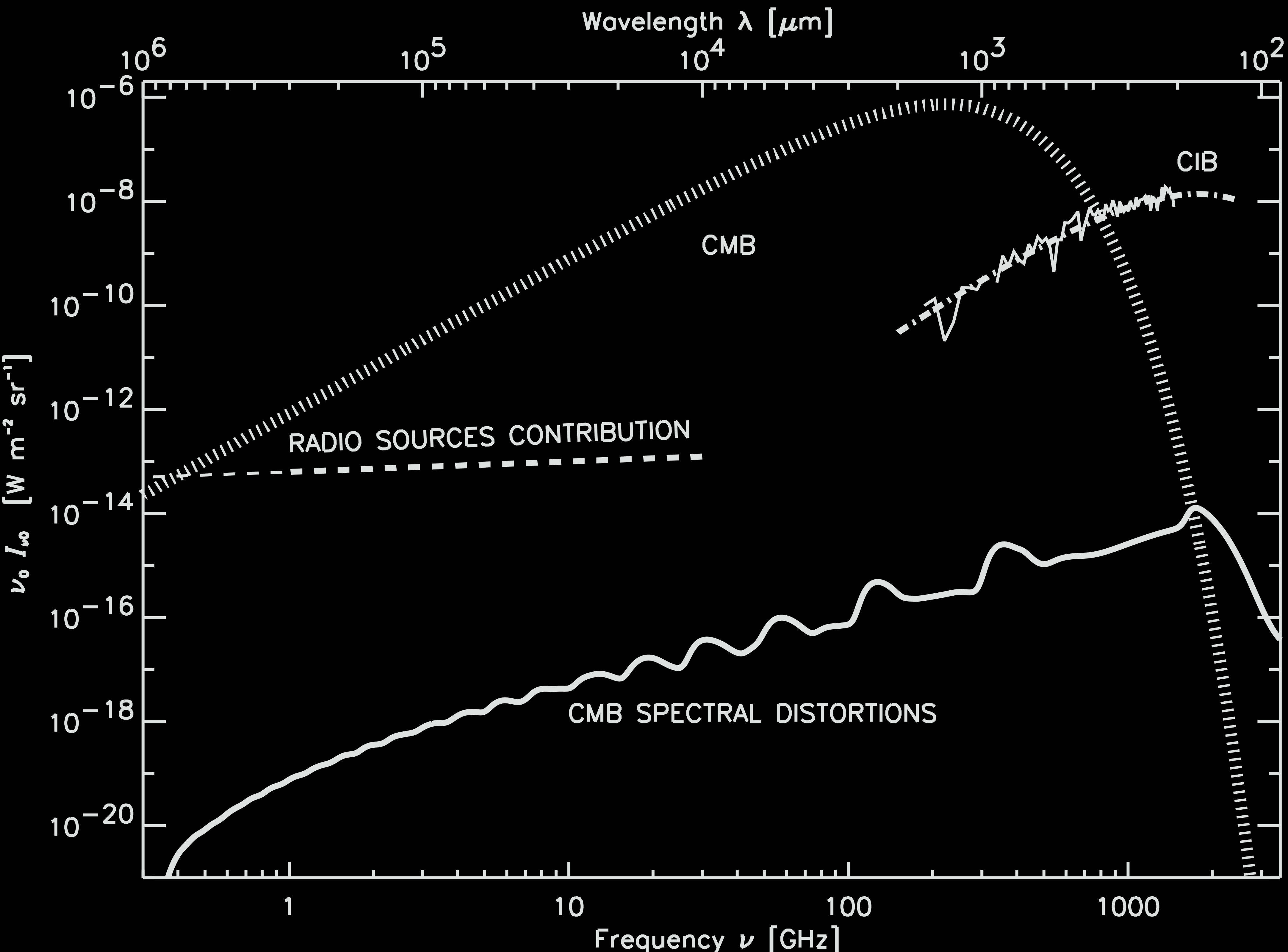
WHO CARES?
SPECTRAL DISTORTIONS FROM RECOMBINATION



EQUILIBRIUM ASSUMPTIONS

✴Radiative/collisional eq. between different l

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

✴ Radiative eq. between different n-states

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

✴Matter in eq. with radiation due to Thompson scattering

$$T_m = T_\gamma \text{ since } \frac{\sigma_{\rm T} a T_\gamma^4 c}{m_e c^2} < H(T)$$

EQUILIBRIUM ASSUMPTIONS

✴Radiative/collisional eq. between different l

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

Seager/Scott/Sasselov 2000/RECFAST!

✴ Radiative eq. between different n-states

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

Non-eq rate equations

✴Matter in eq. with radiation due to Thompson scattering

$$T_m = T_\gamma \text{ since } \frac{\sigma_{\rm T} a T_\gamma^4 c}{m_e c^2} < H(T)$$

THESE ARE REAL STATES

- Still inside plasma shielding length for n<100000
- $r \sim a_0 n^2$ is as large as 2μm for $n_{\max} = 200$
- $\frac{\Delta E|_{\text{thermal}}}{E} < \frac{2}{n^3}$
- Similarly high n are seen in emission line nebulae

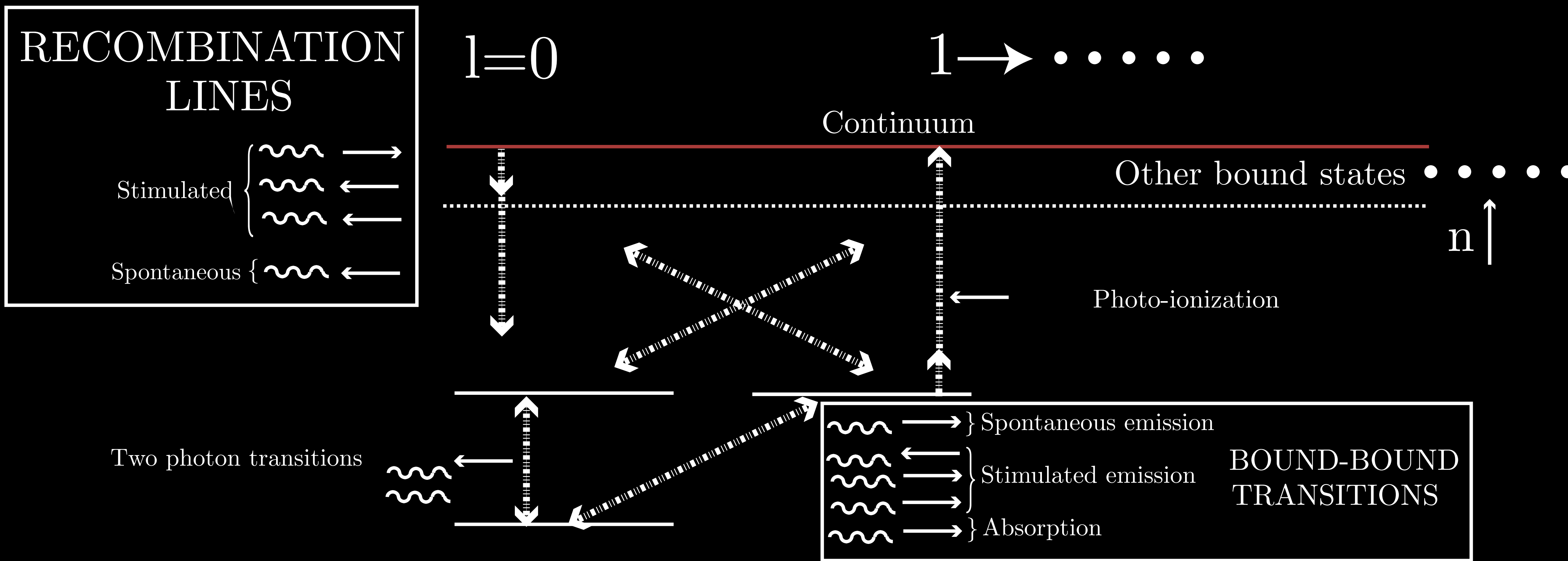
BREAKING EQUILIBRIUM

- Chluba et al. (2005,6) follow l, n separately, get to $n_{\rm max} = 100$
- 0.1 %-level corrections to CMB anisotropies at $n_{\rm max} = 100$
- ~~Equilibrium~~ between *l states:* $\Delta l = \pm 1$ bottleneck
- Beyond this, testing convergence with $n_{\rm max}$ is hard!

$$t_{\rm compute} \sim \mathcal{O}\,(\text{years}) \ \text{ for } \mathrm{n}_{\rm max} = 300$$

How to proceed if we want 0.01% accuracy in $x_e(z)$?

RecSparse and the multi-level atom



- ✳ We implement a multi-level atom computation in a new code, RecSparse!
- ✳ Bound-bound rates evaluated using Gordon (1929) formula and verified using WKB
- ✳ Bound-free rates tabulated and integrated at each T_m
- ✳ Boltzmann eq. solved for T_m (T_γ)

STEADY-STATE FOR EXCITED LEVELS

- ✳ Evolution equations may be re-written in matrix form

$$\frac{d\vec{x}}{dt} = \mathbf{R}\vec{x} + \vec{s}$$

STEADY-STATE FOR EXCITED LEVELS

- Evolution equations may be re-written in matrix form

$$\frac{d\vec{x}}{dt} = \mathbf{R}\vec{x} + \vec{s}$$

$$\vec{x} = \begin{pmatrix} \vec{x}_0 \\ \vec{x}_1 \\ \cdots \\ \vec{x}_{n_{\max}-1} \end{pmatrix}$$

STEADY-STATE FOR EXCITED LEVELS

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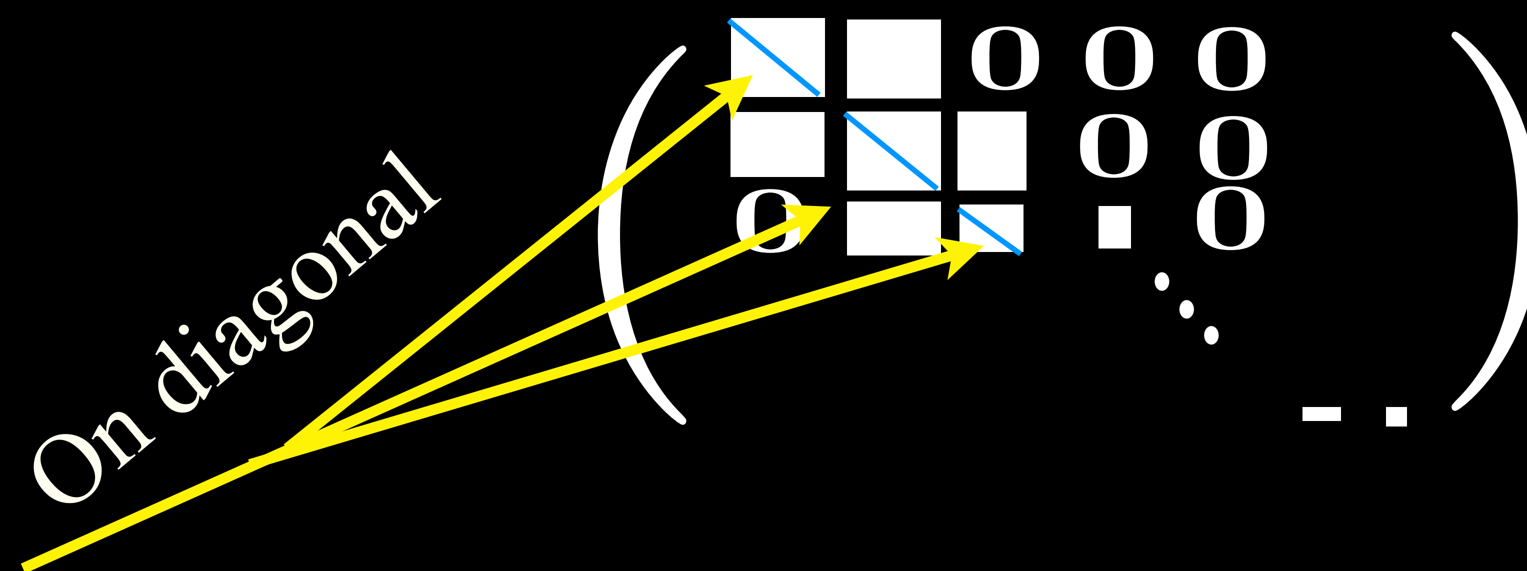

For state l, includes BB transitions out of l to all other l”, photo-ionization, 2γ transitions to ground state

STEADY-STATE FOR EXCITED LEVELS

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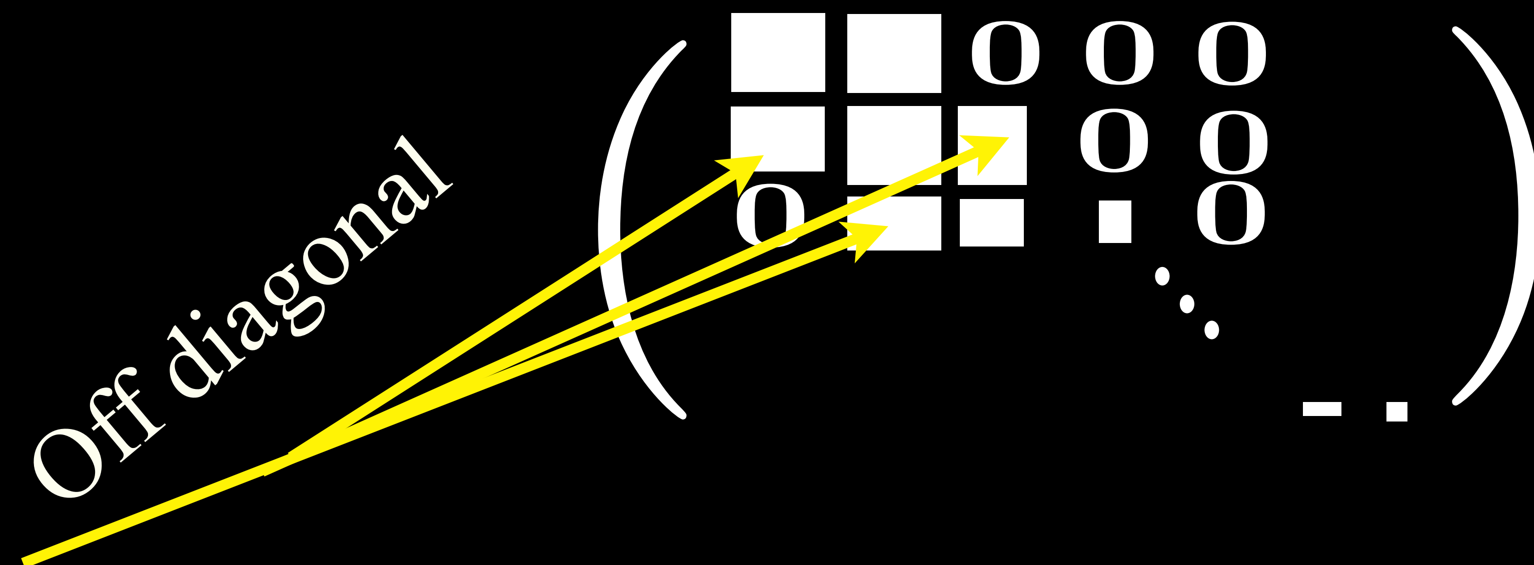


For state l, includes BB transitions into l from all other l’

STEADY-STATE FOR EXCITED LEVELS

✳ Evolution equations may be re-written in matrix form

$$\frac{d\vec{x}}{dt} = \mathbf{R}\vec{x} + \vec{s}$$

- Includes recombination to l,
  1 and 2γ transitions from ground state

STEADY-STATE FOR EXCITED LEVELS

For n>1, $t_{\rm rec}^{-1} \sim 10^{-12} s^{-1} \ll \mathbf{R}$, $\vec{s} \rightarrow \vec{x} \simeq \mathbf{R}^{-1}\vec{s}$

$\mathbf{R} \lesssim 1\ \mathrm{s}^{-1}$ (e.g. Lyman-α)

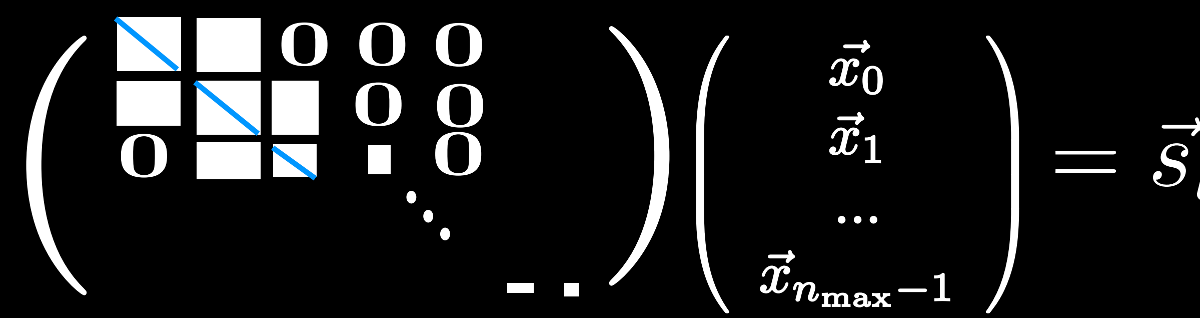
- Evolution equations may be re-written in matrix form

$$\frac{d\vec{x}}{dt} = \mathbf{R}\vec{x} + \vec{s}$$

Rapid matrix inversion: Sparsity to the rescue

- Matrix is $\sim n_{max}^2 \times n_{max}^2$
- Dipole selection rules: $\Delta l = \pm 1$

$$\mathrm{M}_{l,l-1}\vec{x}_{l-1} + \mathbf{M}_{l,l}\vec{x}_l + \mathbf{M}_{l,l+1}\vec{x}_{l+1} = \vec{s}_l$$



- RecSparse generates rec. history with 10^{-8} precision, with computation time $\sim n_{max}^{2.5}$: Huge improvement!
- Case of $n_{\mathrm{max}} = 100$ runs in less than a day, $n_{\mathrm{max}} = 200$ takes ~ 4 days.

FORBIDDEN TRANSITIONS AND RECOMBINATION

- Higher-n 2γ transitions in H important at 7-σ for Planck (TT/EE) data analysis (Hirata 2008, Kholupenko 2006)
- Some forbidden transitions are important in Helium recombination (Dubrovich 2005, Lewis 2006) and would bias cosmological parameter estimation.
- *Are other forbidden transitions in hydrogen important, particularly for Planck data analysis? Maybe quadrupole transitions, since they are optically thick?*

QUADRUPOLE TRANSITIONS AND RECOMBINATION

- Ground-state electric quadrupole (E2) lines are optically thick!

$$R \propto AP \propto A/\tau \text{ if } \tau \gg 1$$
$$\tau \propto A \rightarrow R \rightarrow A/A \rightarrow \text{const}$$

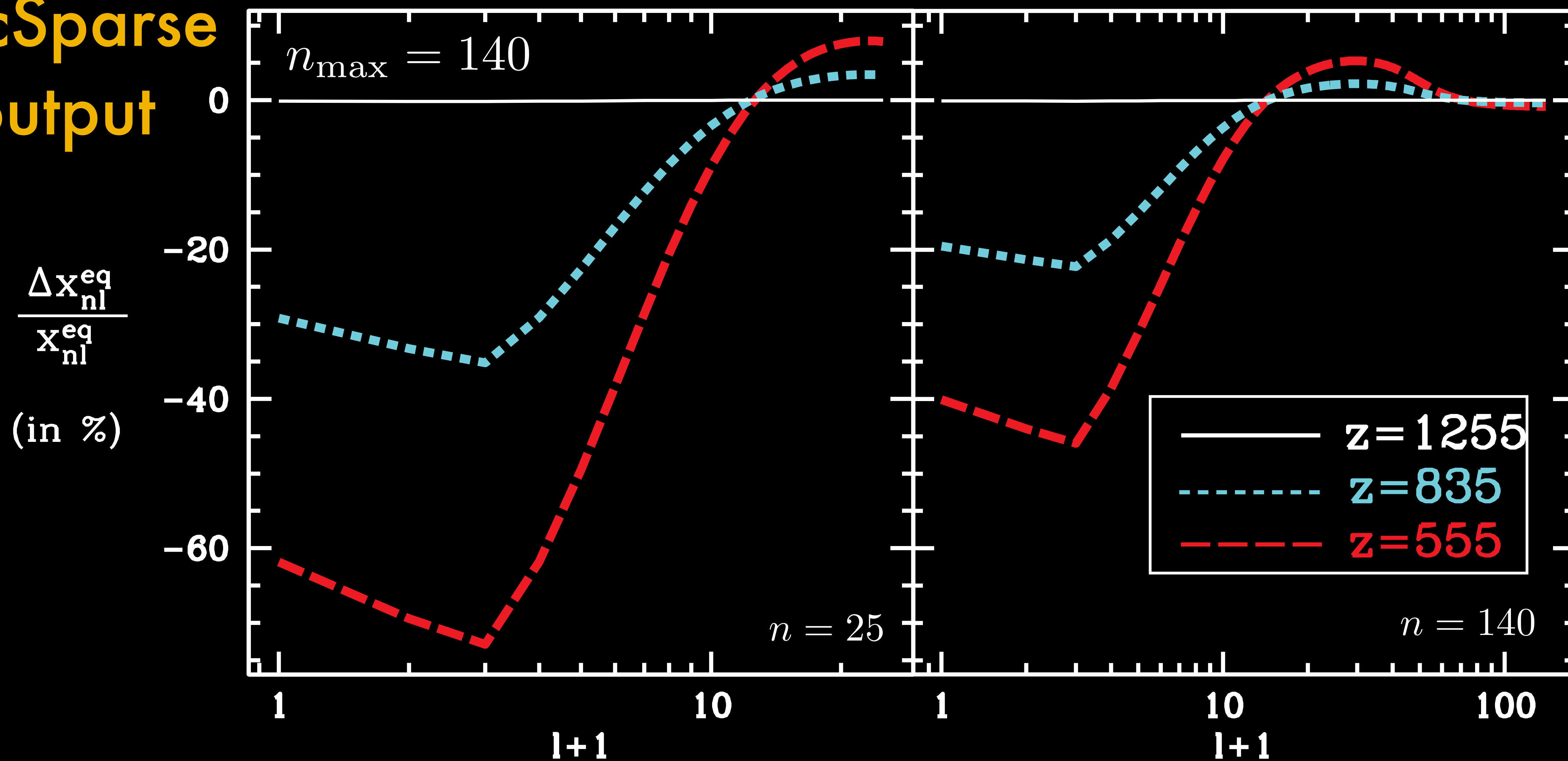
- Coupling to ground state will dominate: $A \propto \omega^5$

- Detailed balance yields net rate $R_{nd\rightarrow np}^{\text{quad}} = A_{nd\rightarrow 1s}\left(x_{nd} - \frac{5}{3}x_{np}\right)$

RESULTS: STATE OF THE GAS

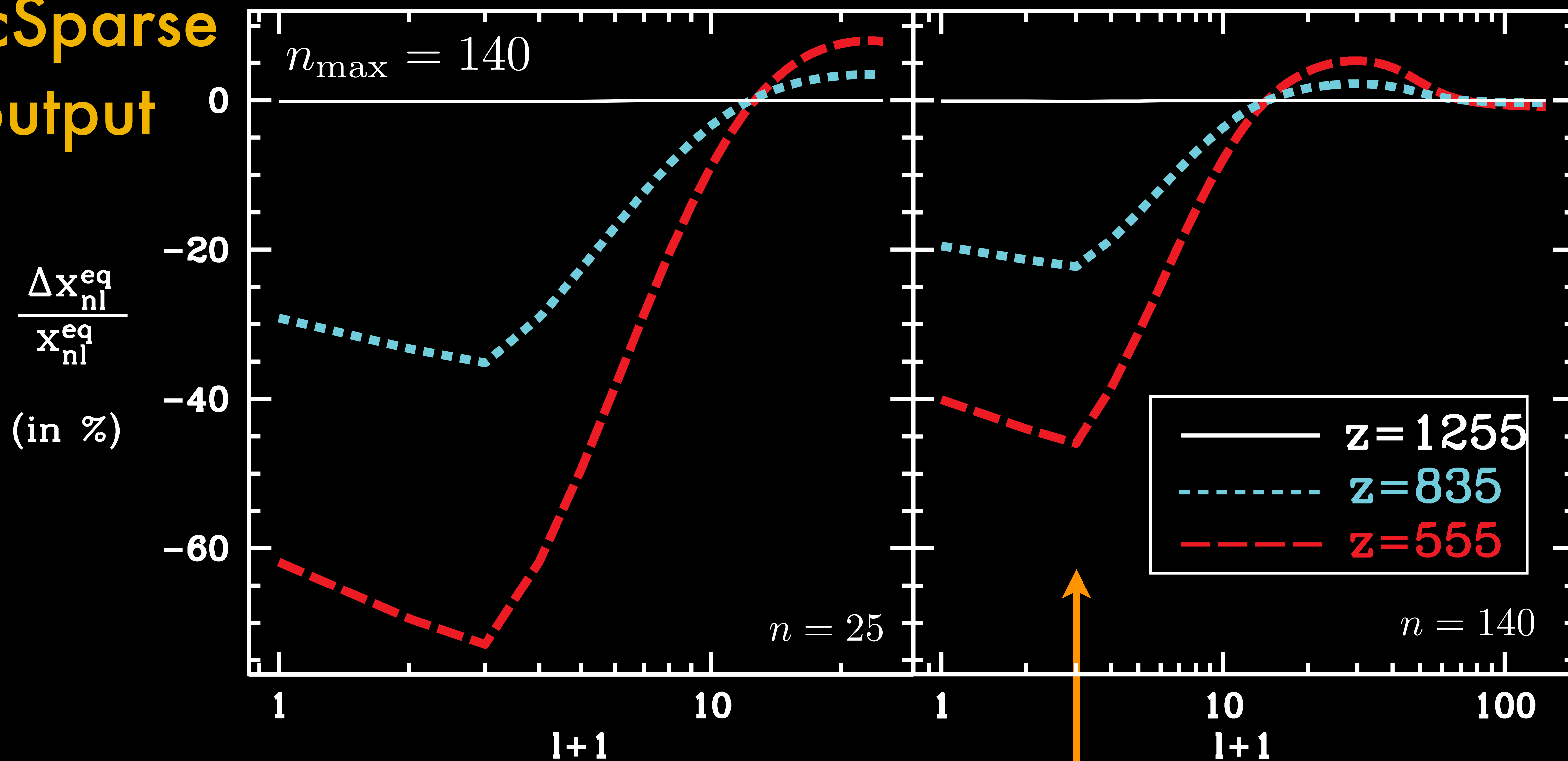
DEVIATIONS FROM BOLTZMANN EQ: L-SUBSTATES

RecSparse output



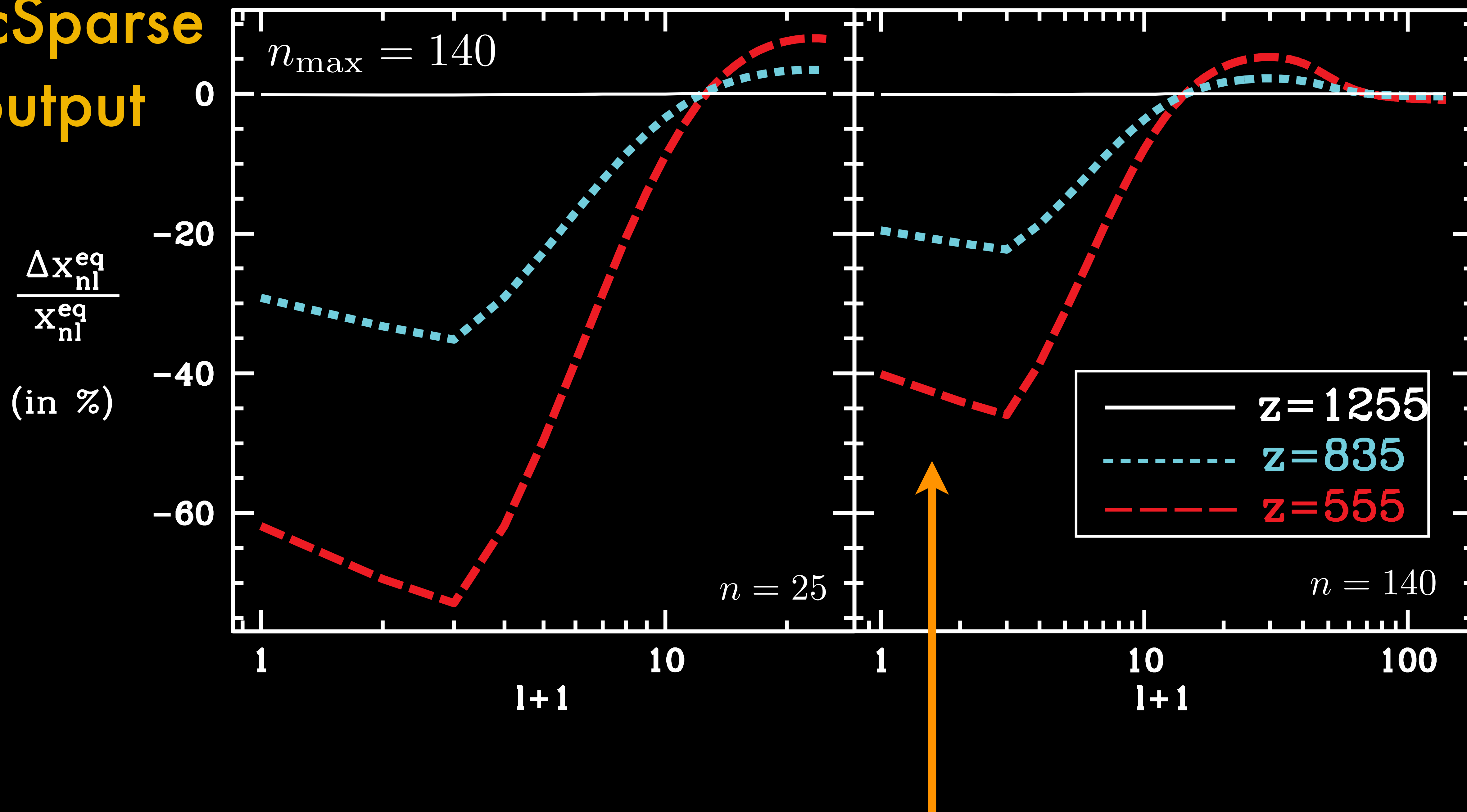
DEVIATIONS FROM BOLTZMANN EQ: L-SUBSTATES

RecSparse output



Lower l states can easily cascade down, and are relatively under-populated

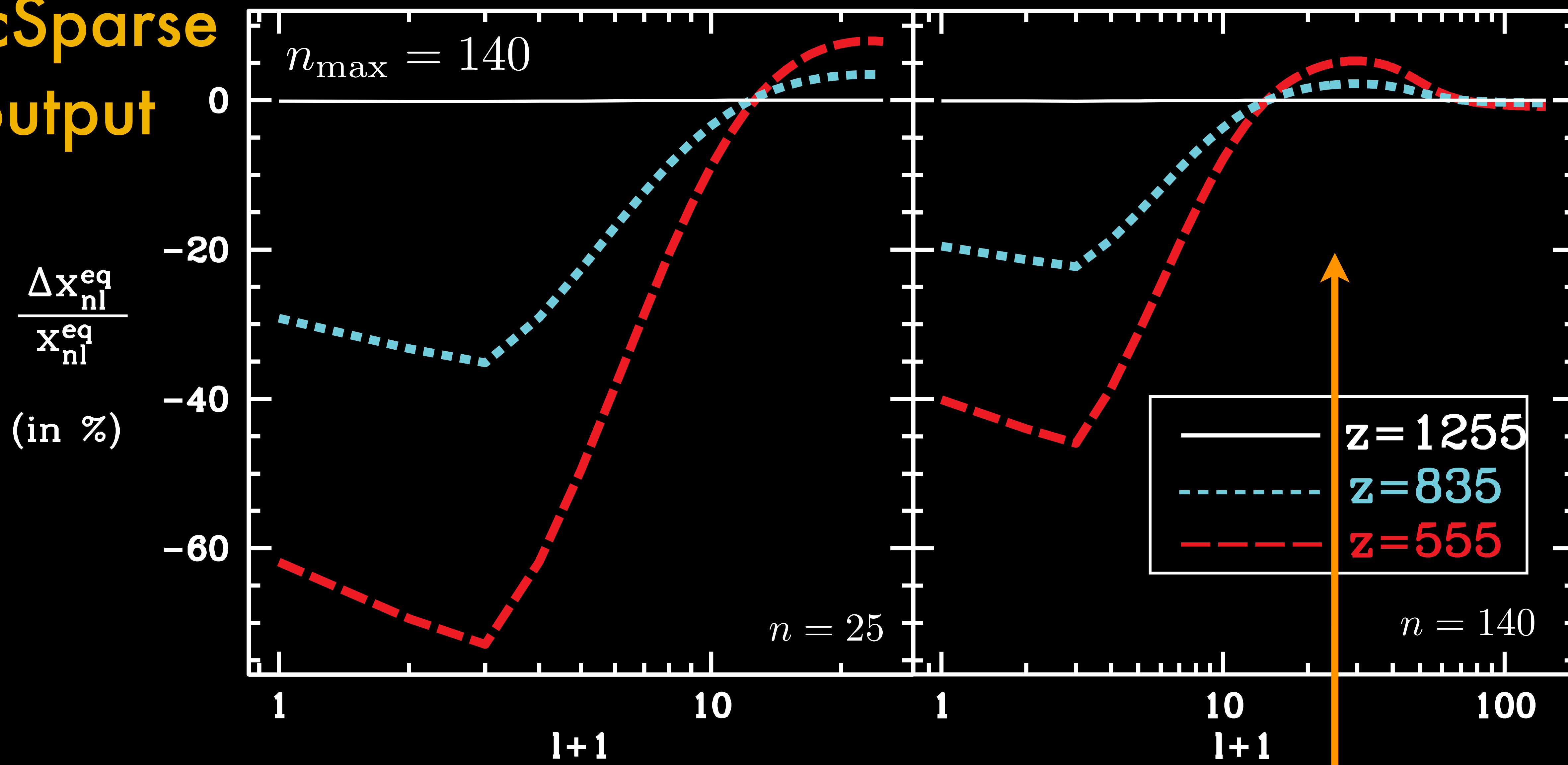
RecSparse output



l=0 can't cascade down, so s states are not as under-populated

DEVIATIONS FROM BOLTZMANN EQ: L-SUBSTATES

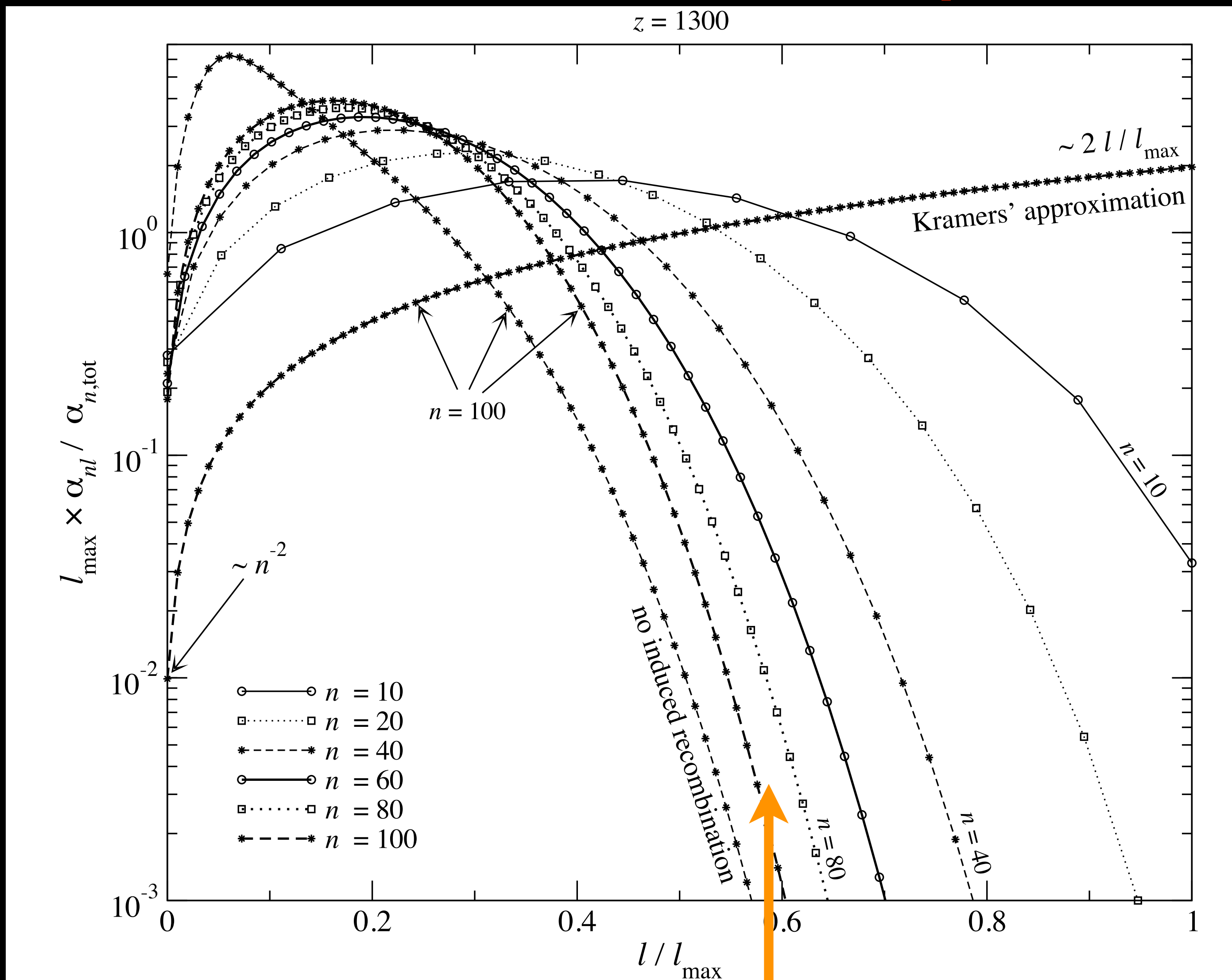
RecSparse output

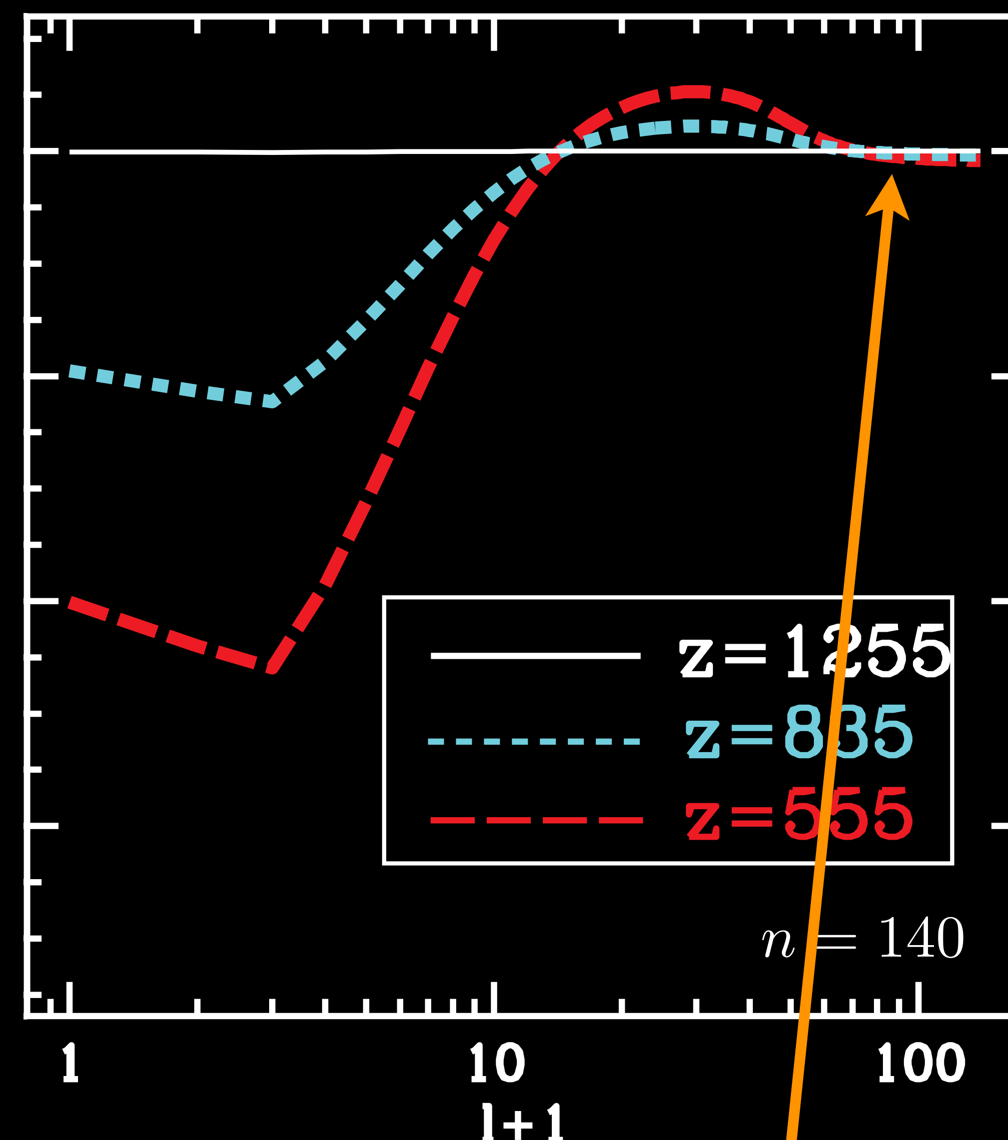


Higher l are bottlenecked by $\Delta l = \pm 1$ (over-pop)

DEVIATIONS FROM BOLTZMANN EQ: L-SUBSTATES

Chluba/Rubino-Martin/Sunyaev 2006

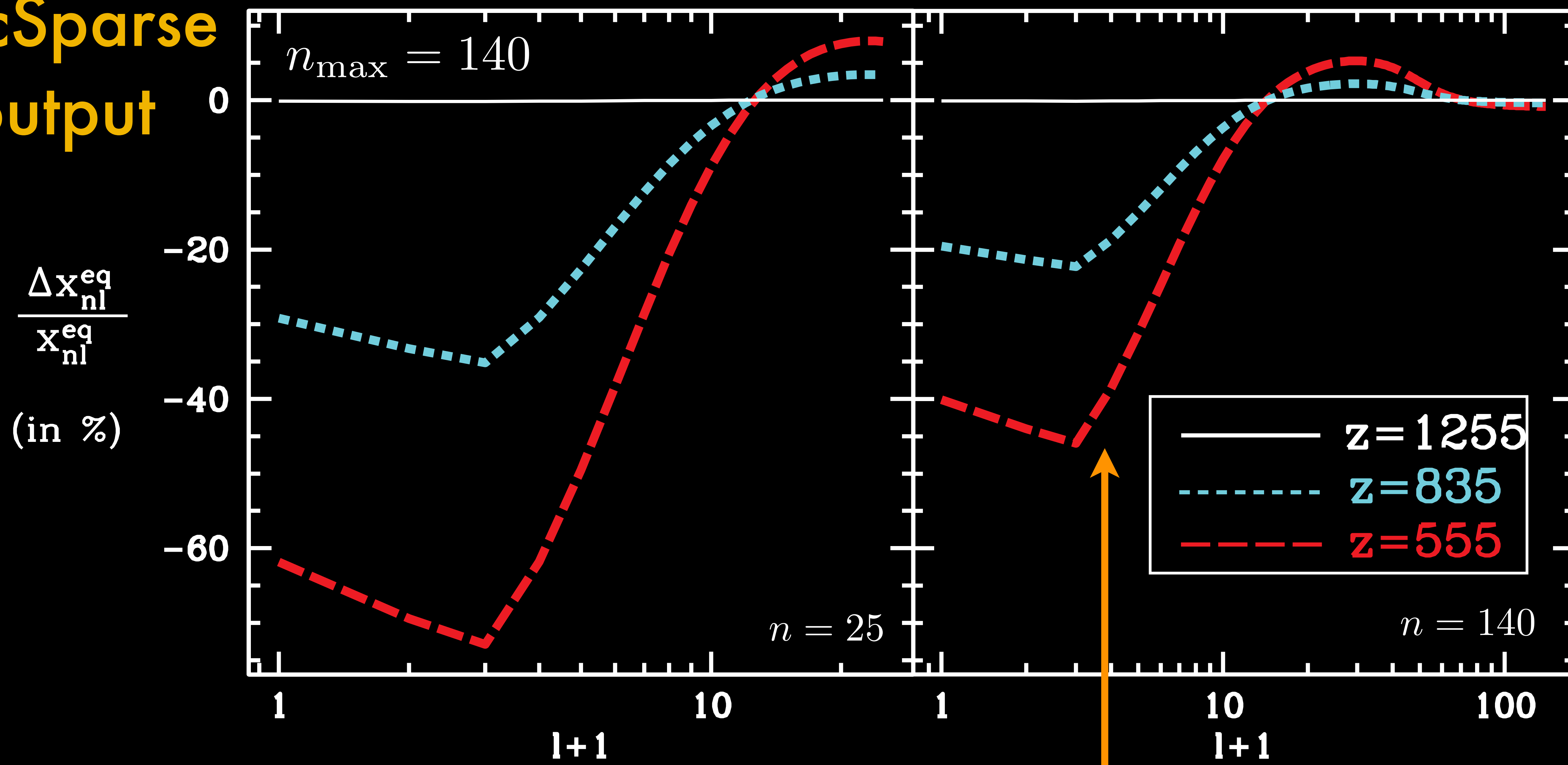




Highest l states recombine inefficiently, and are under-populated

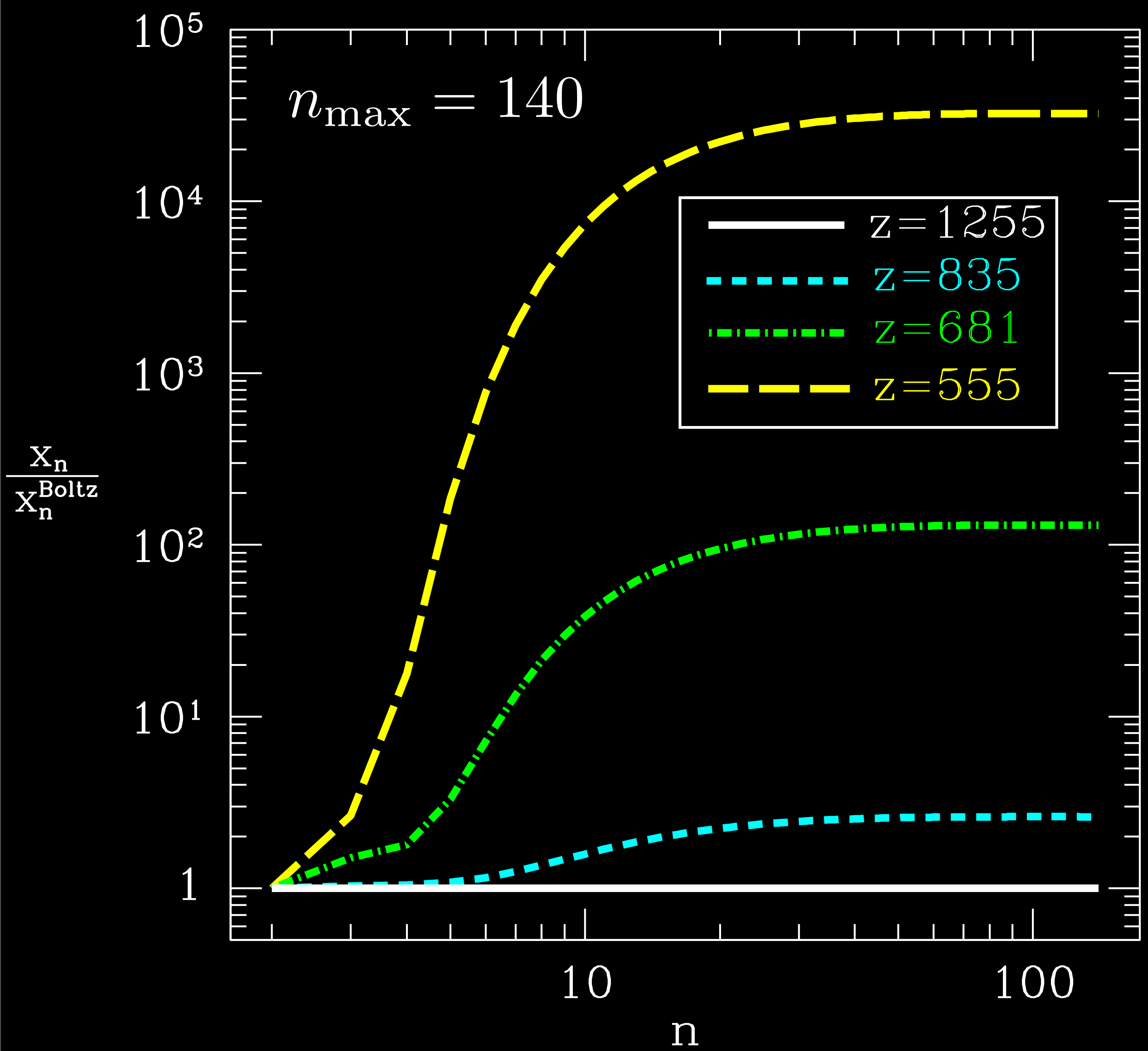
DEVIATIONS FROM BOLTZMANN EQ: L-SUBSTATES

RecSparse output



l-substates are highly out of Boltzmann eqb'm at late times

DEVIATIONS FROM BOLTZMANN EQUILIBRIUM: DIFFERENT N-SHELLS

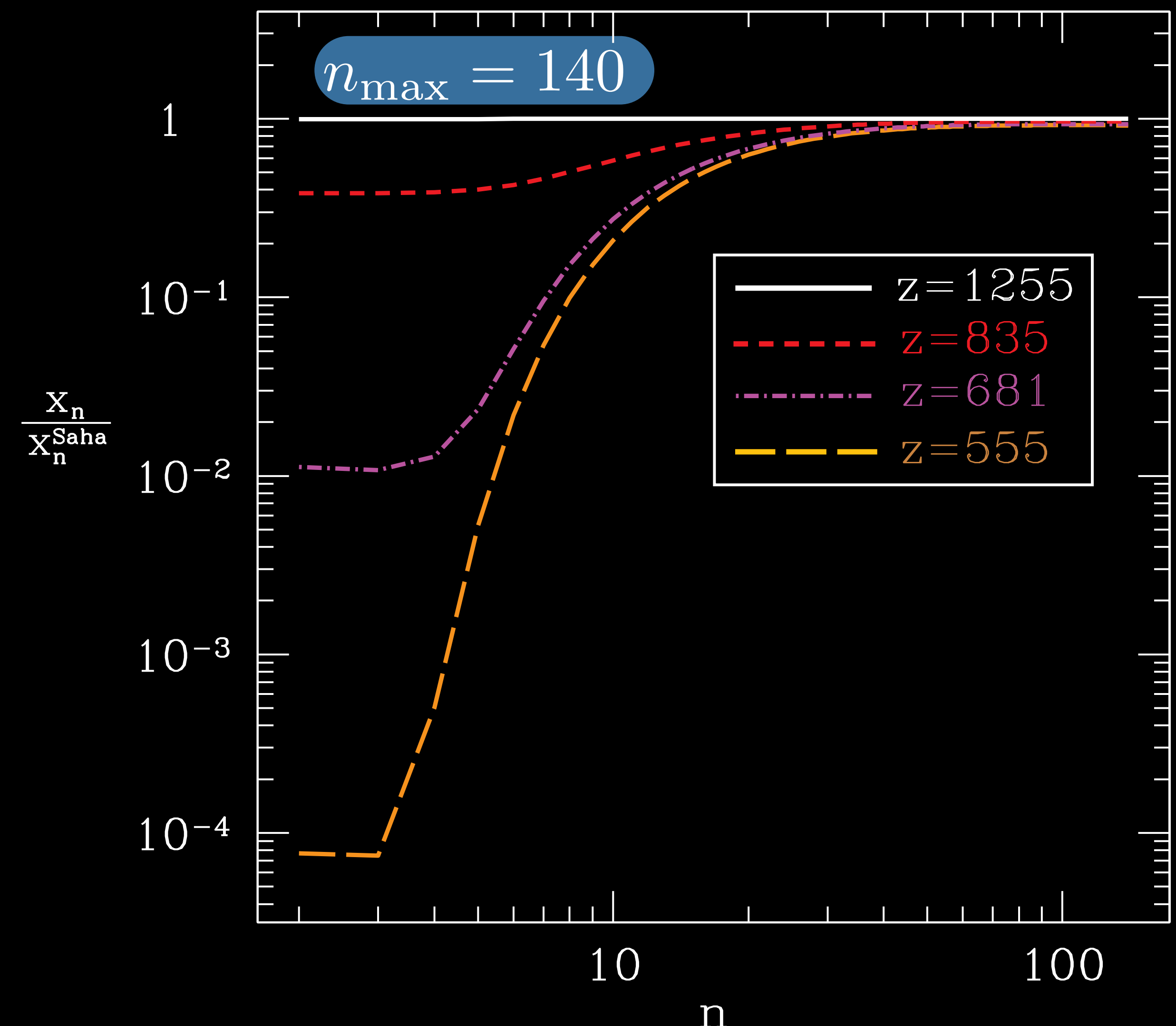


$$\alpha_n n_e > \sum_{n'l}^{n'<n} A_{nn'}^{ll\pm1}$$

- No inversion relative to n=2 (just-over population)
- Population inversion seen between some excited states: Does radiation stay coherent? Does recombination mase? Stay *tuned*
- Dense regions may mase more efficiently: maser spots as probe of l.s.s at early times? (Spaans and Norman 1997)

DEVIATIONS FROM SAHA EQUILIBRIUM

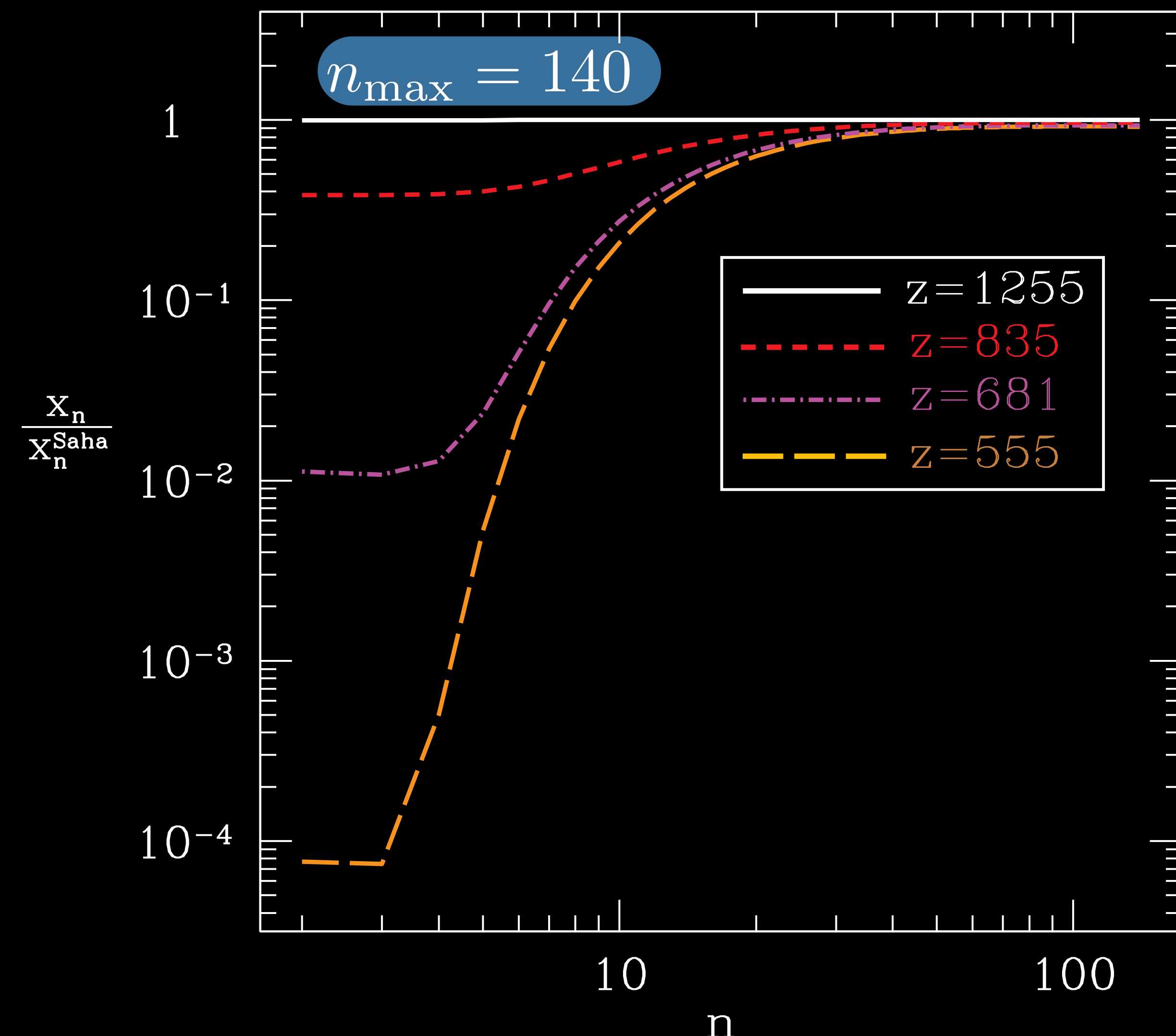
HUGE DEVIATIONS FROM SAHA EQ!



- ✳ n=1 suppressed due to freeze-out of x_e
- ✳ Remaining levels 'try' to remain in Boltzmann eq. with n=2
- ✳ Super-Boltz effects and two-γ transitions (n=1$\longrightarrow$ n=2) yield less suppression for n>1
- ✳ Effect larger at late times (low z) as rates fall

DEVIATIONS FROM SAHA EQUILIBRIUM

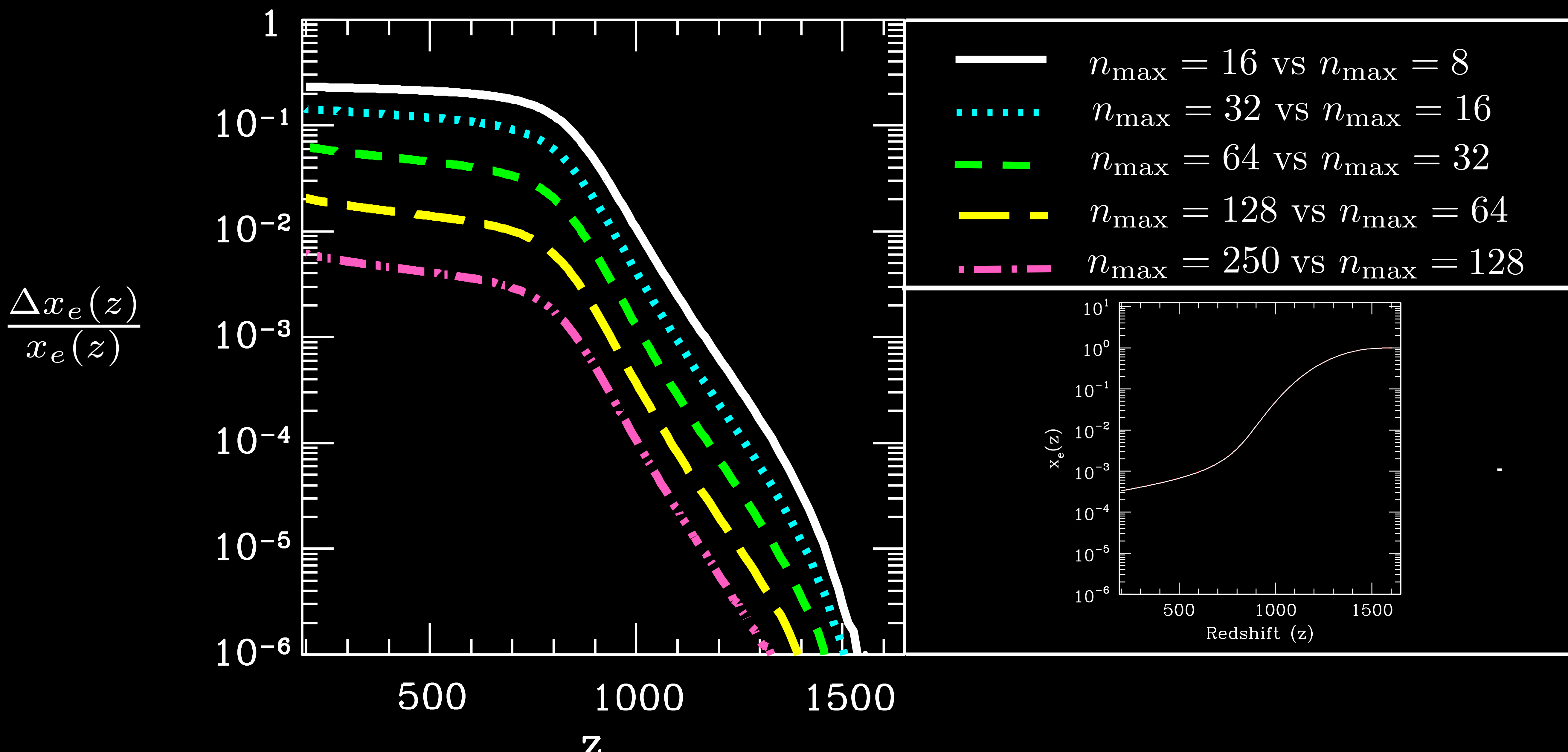
HUGE DEVIATIONS FROM SAHA EQ!



- Effect of states with n> could be approximated using asymptotic Einstein coeffs. and Saha eq. populations: but Saha is more elusive at high n/late times.
- At z=200, we estimate n_{max}~1000 needed, unless collisions included

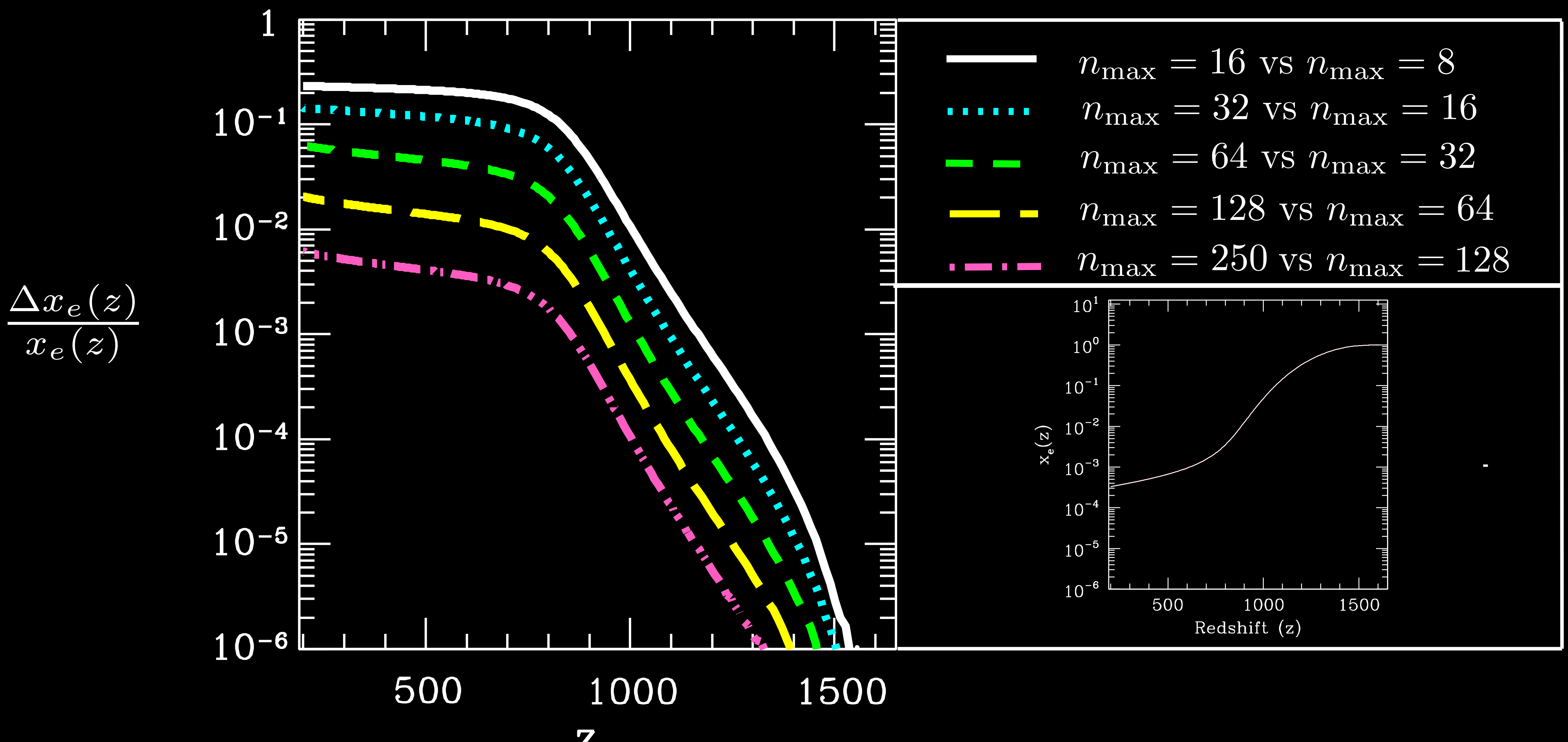
RESULTS: RECOMBINATION HISTORIES

RESULTS: RECOMBINATION HISTORIES INCLUDING HIGH-N



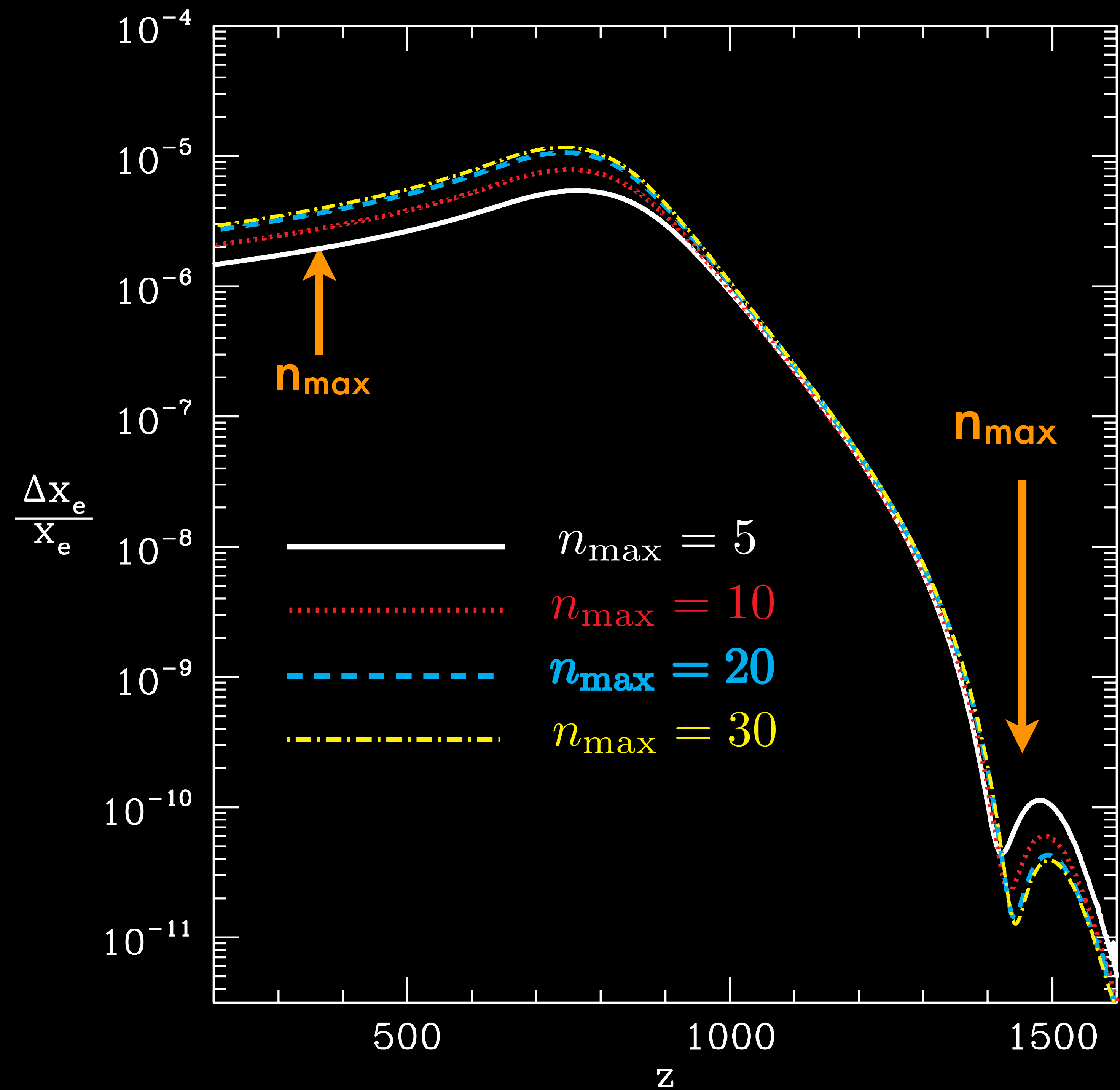
- $x_e(z)$ falls with increasing $n_{\rm max} = 10 \rightarrow 200$, as expected.
- Rec Rate>downward BB Rate> Ionization, upward BB rate
- For $n_{max} = 100$, code computes in only 2 hours

RESULTS: RECOMBINATION HISTORIES INCLUDING HIGH-N



- Relative convergence is not the same thing as absolute convergence: Want to see Saha asymptote and impose well-motivated cutoff!
- Collisions could help
- These are lower limits to the actual error
- n_{max}=250 and n_{max}=300 under way to further test convergence (more time consuming)

RESULTS: RECOMBINATION WITH HYDROGEN

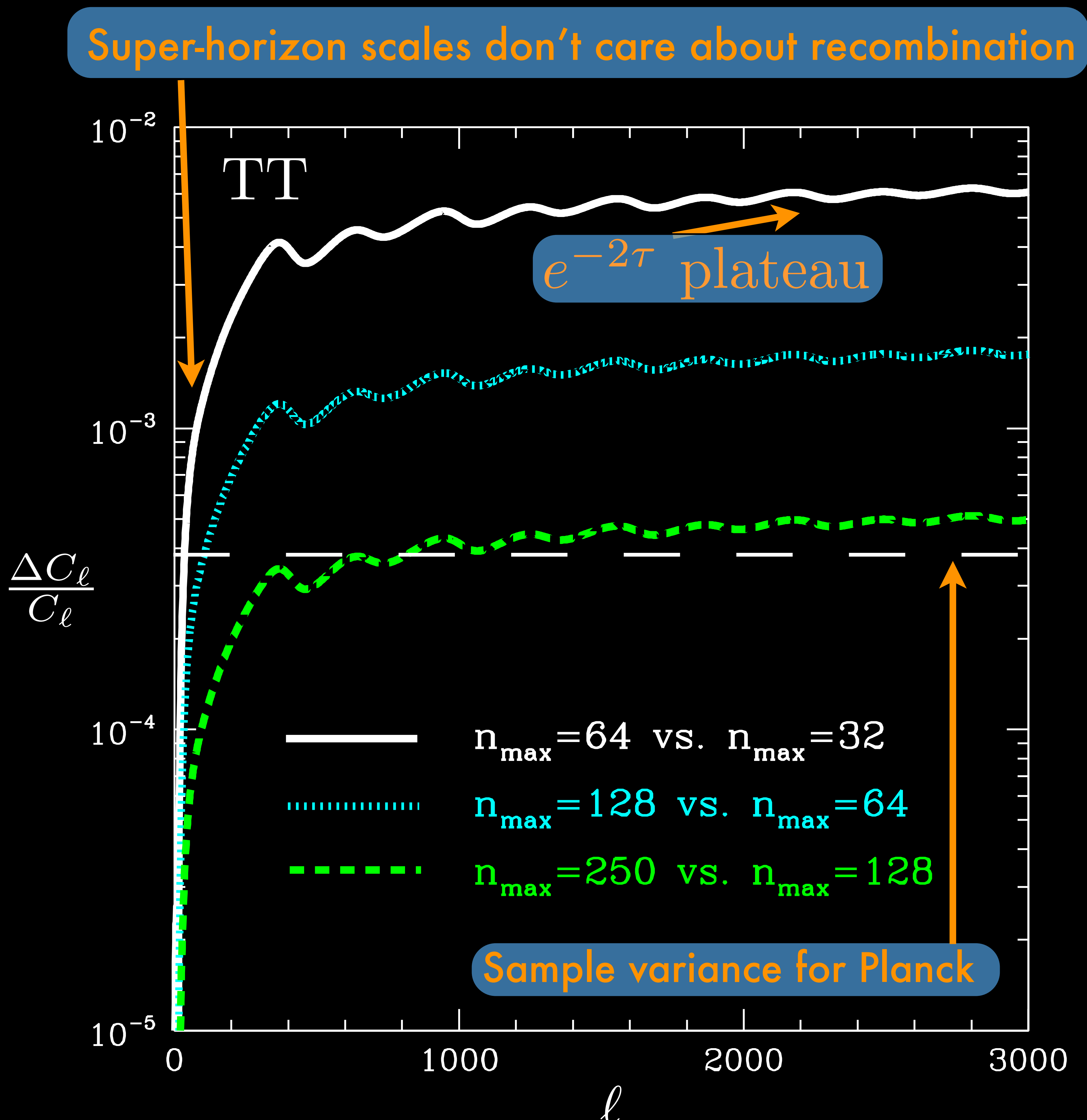


$$\Delta x_e \equiv x_e\big|_{\text{no } E2 \text{ transitions}} - x_e\big|_{\text{with } E2 \text{ transitions}}$$

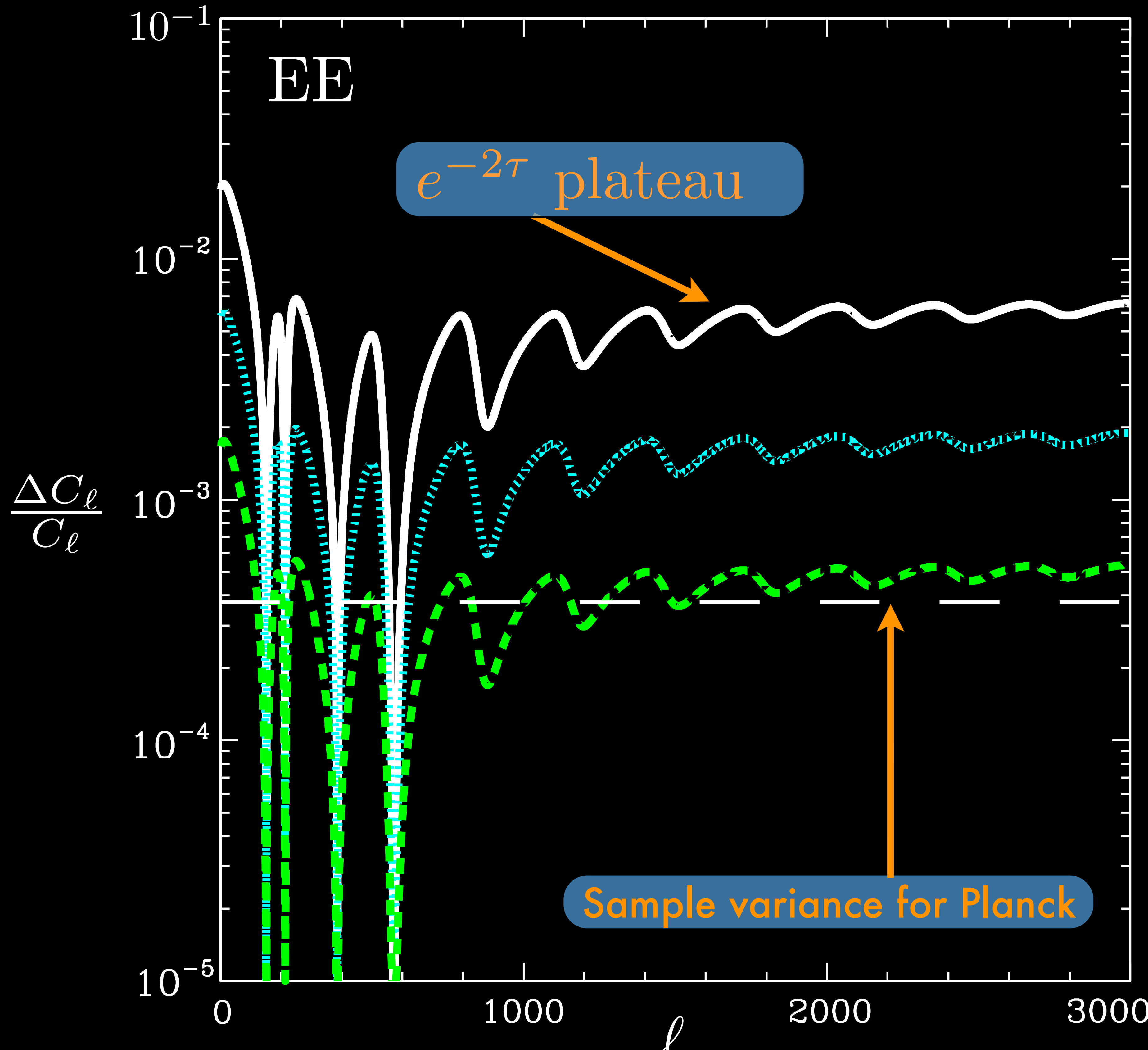
Negligible for Planck!

RESULTS: CMB ANISOTROPIES

RESULTS: TT $C_l s$ WITH HIGH-N STATES



RESULTS: EE $C_l s$ WITH HIGH-N STATES



THE UPSHOT FOR COSMOLOGY

- Can explore effect on overall Planck likelihood analysis

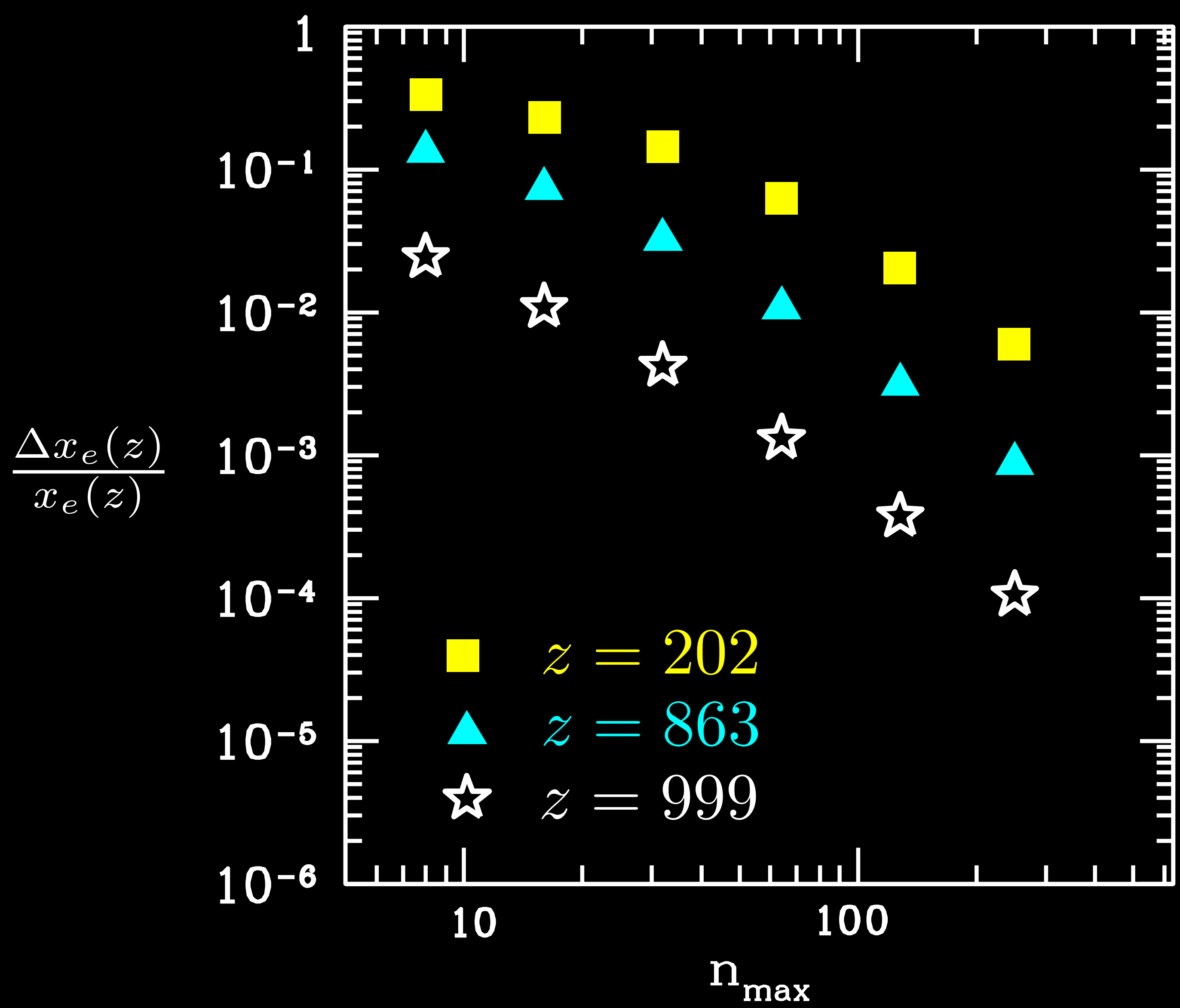
$$Z^2 = \sum_{ll',X,Y} F_{ll'} \Delta C_l^{\mathrm{X}} \Delta C_l^{\mathrm{Y}}$$

$$\begin{aligned} Z &= 1.8 \text{ if } n_{\max} = 64, \\ Z &= 0.50 \text{ if } n_{\max} = 128, \\ Z &= 0.14 \text{ if } n_{\max} = 250. \end{aligned}$$

WRAPPING UP

- RecSparse: a new tool for MLA recombination calculations
  - Highly excited levels (n~64 and higher) are relevant for CMB data analysis
  - E2 transitions in H are not relevant for CMB data analysis
- Future work:
  - Include line-overlap
  - Develop cutoff method for excluded levels
  - Generalize RecSparse to calc. rec. line. spectra
  - Collisional rates
  - Monte-Carlo analyses
  - Cosmological masers

CONVERGENCE



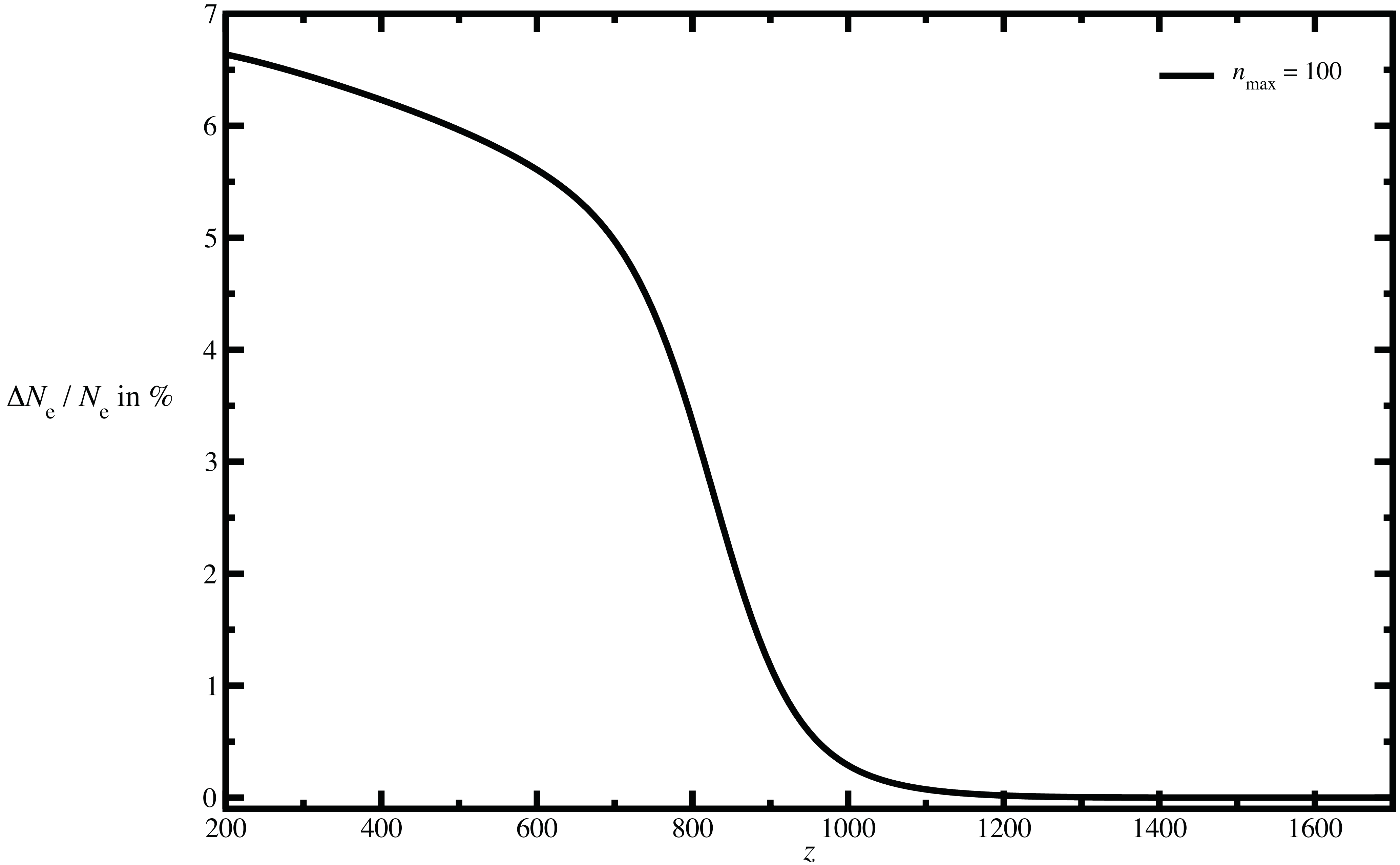
- Relative error well described by power law at high $n_{\rm max}$

$$\Delta x_e / x_e \propto n_{\rm max}^{-1.9}$$

- Can extrapolate to absolute error

THE EFFECT OF RESOLVING L- SUBSTATES

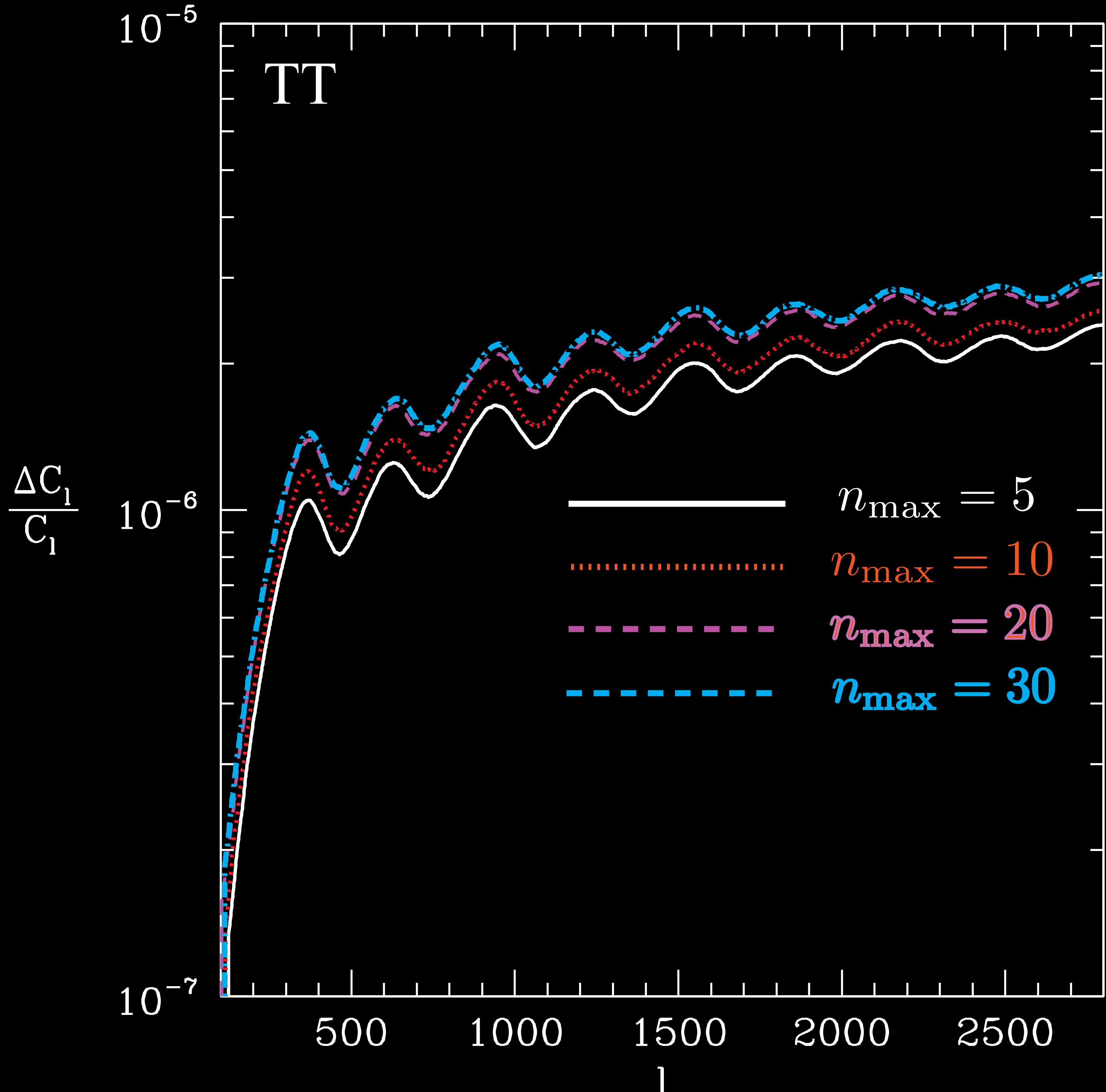
Resolved l vs unresolved l



- ‘Bottlenecked’ l-substates decay slowly to 1s: Recombination is slower; Chluba al. 2006

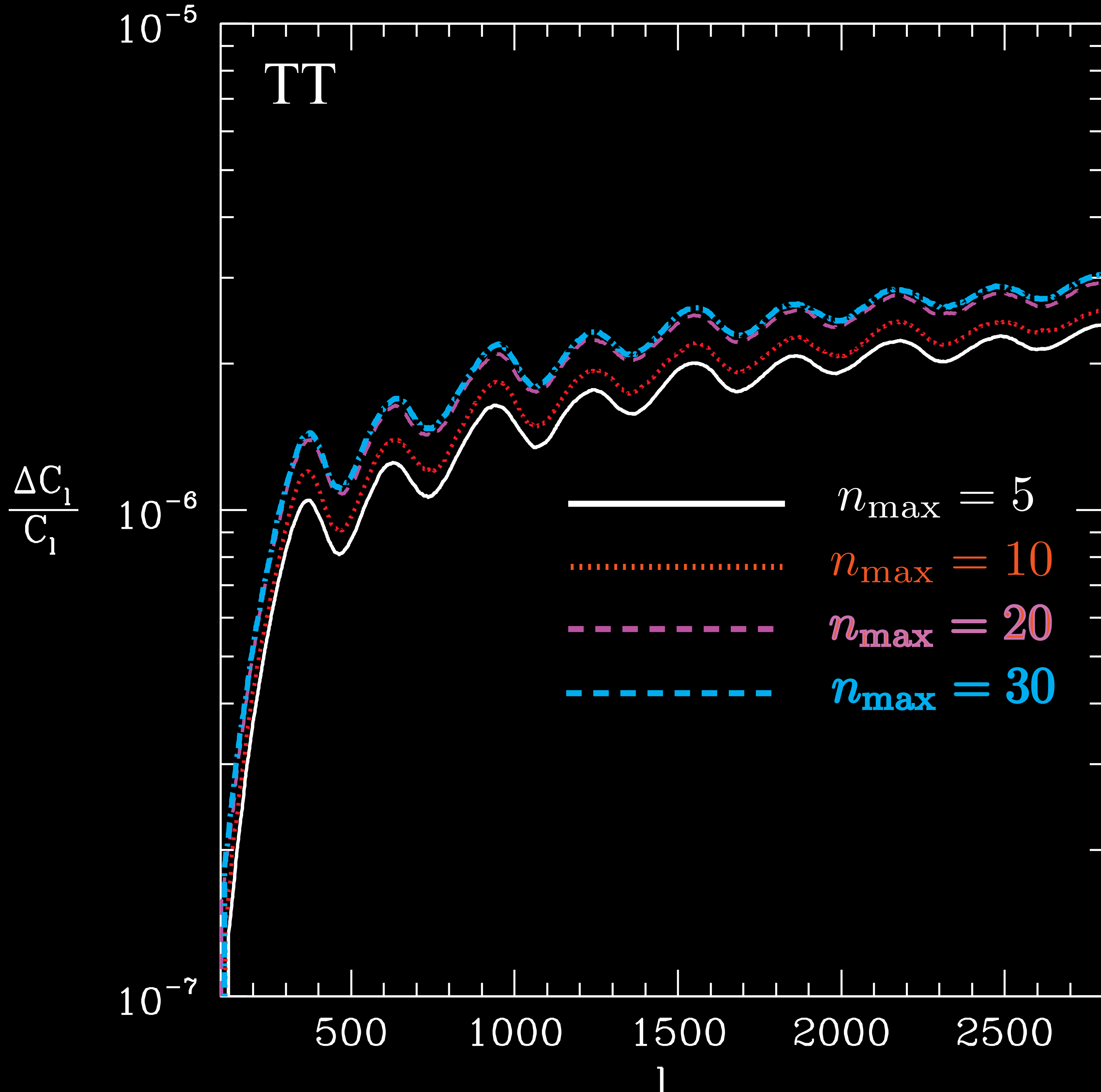
RESULTS: TEMPERATURE (TT) $C_l s$ WITH HYDROGEN QUADRUPOLES,

Bulk of integral from late times, higher $n_{max} \rightarrow$ lower $x_e \rightarrow$ lower $\tau \rightarrow$ higher $e^{-2\tau} \rightarrow$ higher C_l



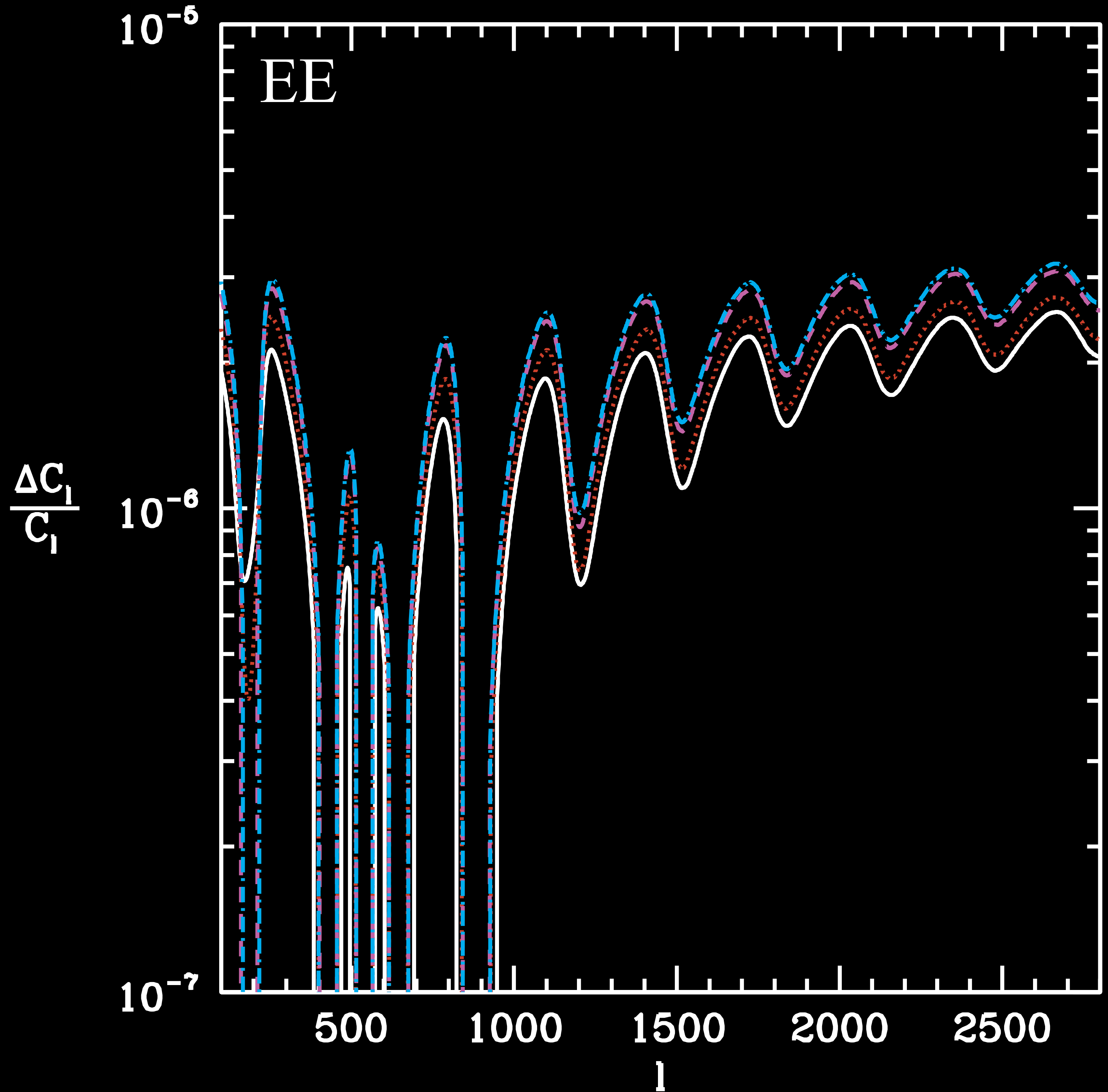
RESULTS: TEMPERATURE (TT) C_ls WITH HYDROGEN QUADRUPOLES,

Bulk of integral from late times, higher $n_{max} \rightarrow$ lower $x_e \rightarrow$ lower $\tau \rightarrow$ higher $e^{-2\tau} \rightarrow$ higher C_l



Overall effect is negligible for CMB experiments!

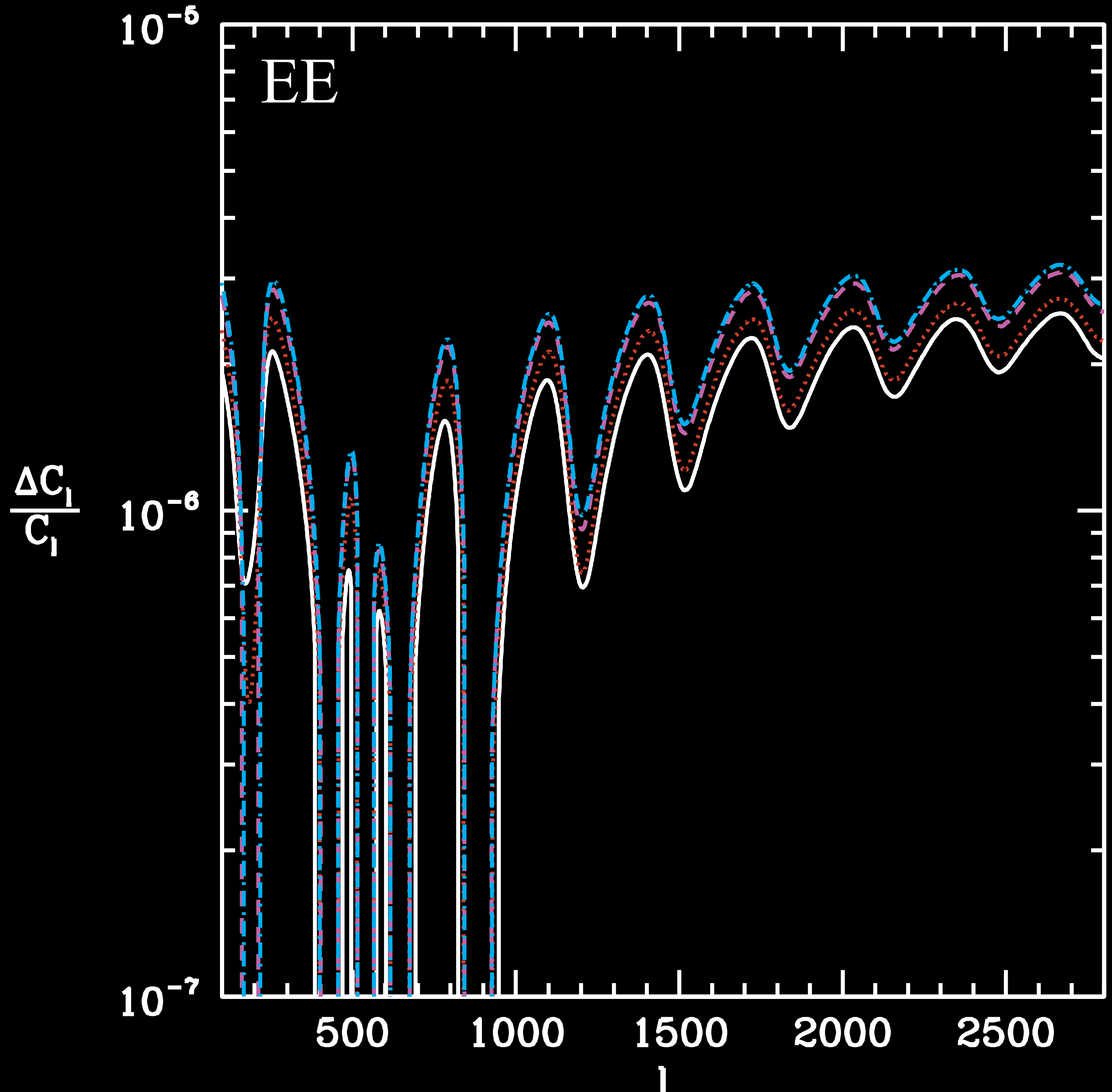
RESULTS: POLARIZATION (EE) C_ls WITH HYDROGEN QUADRUPOLES



$$\Delta C_l \equiv C_l|_{\text{with } E2 \text{ transitions}} - x_e|_{\text{no } E2 \text{ transitions}} .$$

Bulk of integral from late times, higher n_{max} $\rightarrow$ lower x_e $\rightarrow$ lower τ $\rightarrow$ higher $e^{-2\tau}$ $\rightarrow$ higher C_l

RESULTS: POLARIZATION (EE) C_ls WITH HYDROGEN QUADRUPOLES



$$\Delta C_l \equiv C_l|_{\text{with } E2 \text{ transitions}} - x_e|_{\text{no } E2 \text{ transitions}} .$$

Overall effect is negligible for upcoming CMB experiments!

Bulk of integral from late times, higher n_{max} $\rightarrow$ lower x_e $\rightarrow$ lower τ $\rightarrow$ higher $e^{-2\tau}$ $\rightarrow$ higher C_l