EXCITEMENT IN eV-SCALE PHYSICS: TWO COSMOLOGICAL CONSEQUENCES

I. Thermal axions

II. High-n hydrogen states and cosmological recombination

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Astronomy Colloquium

University of British Columbia

23/10/09

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

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

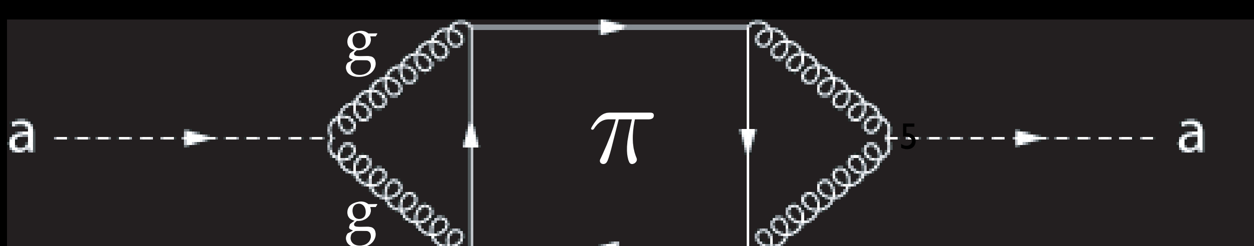
- Limits on the neutron electric dipole moment are strong. Fine tuning?

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

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

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

- Through coupling to pions, axions pick up a mass



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

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

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

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

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

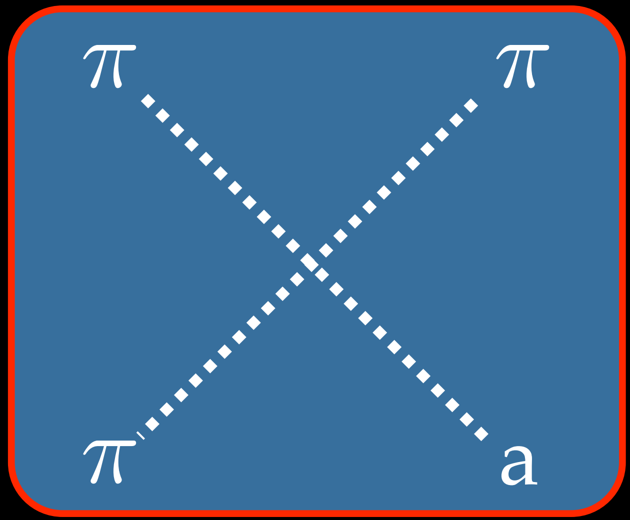
Hot (thermal) axions

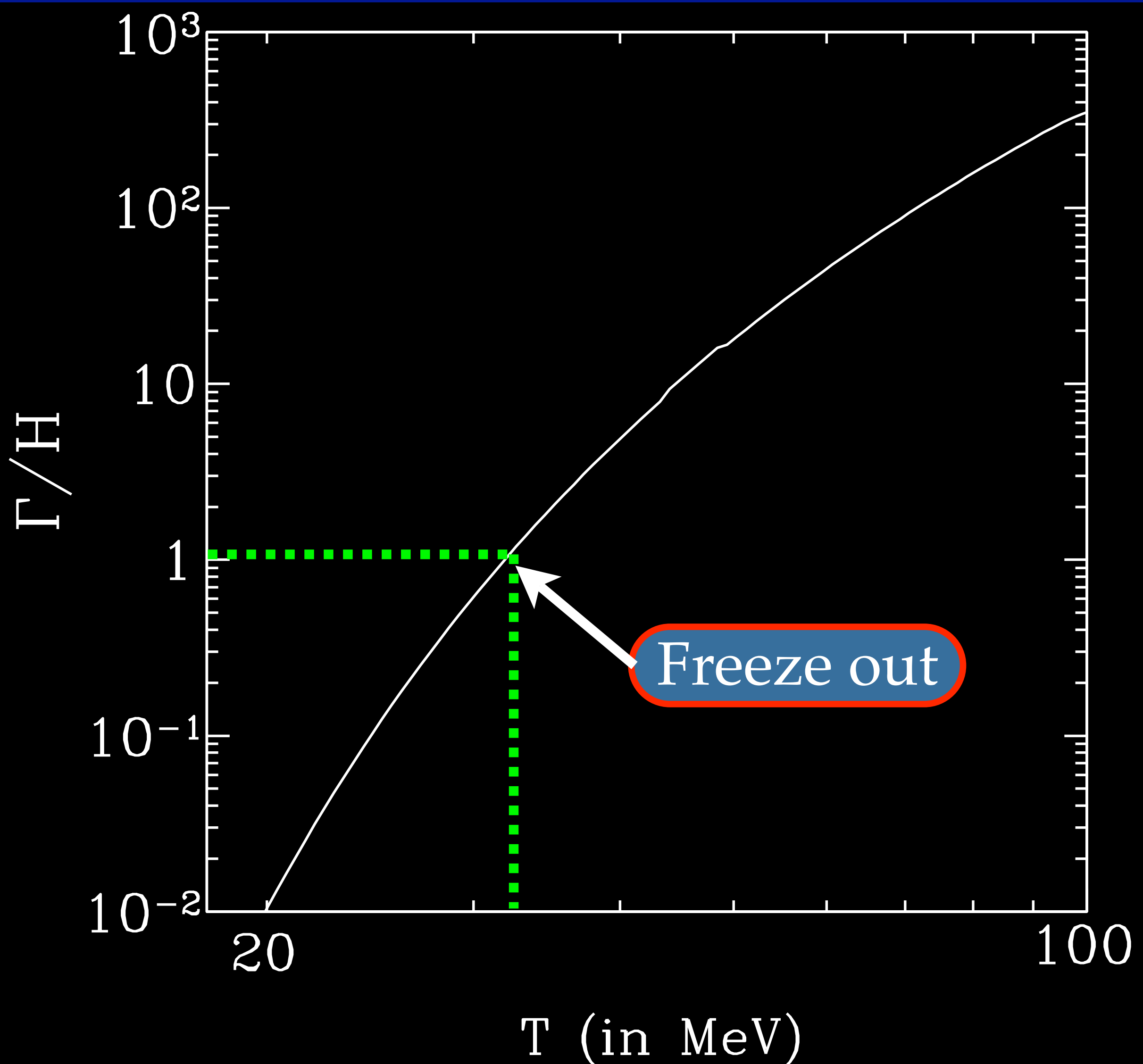
$$m_{\rm a} \gtrsim 10^{-2}\ {\rm eV}$$

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

Hot axion production at early times

Axion Production:

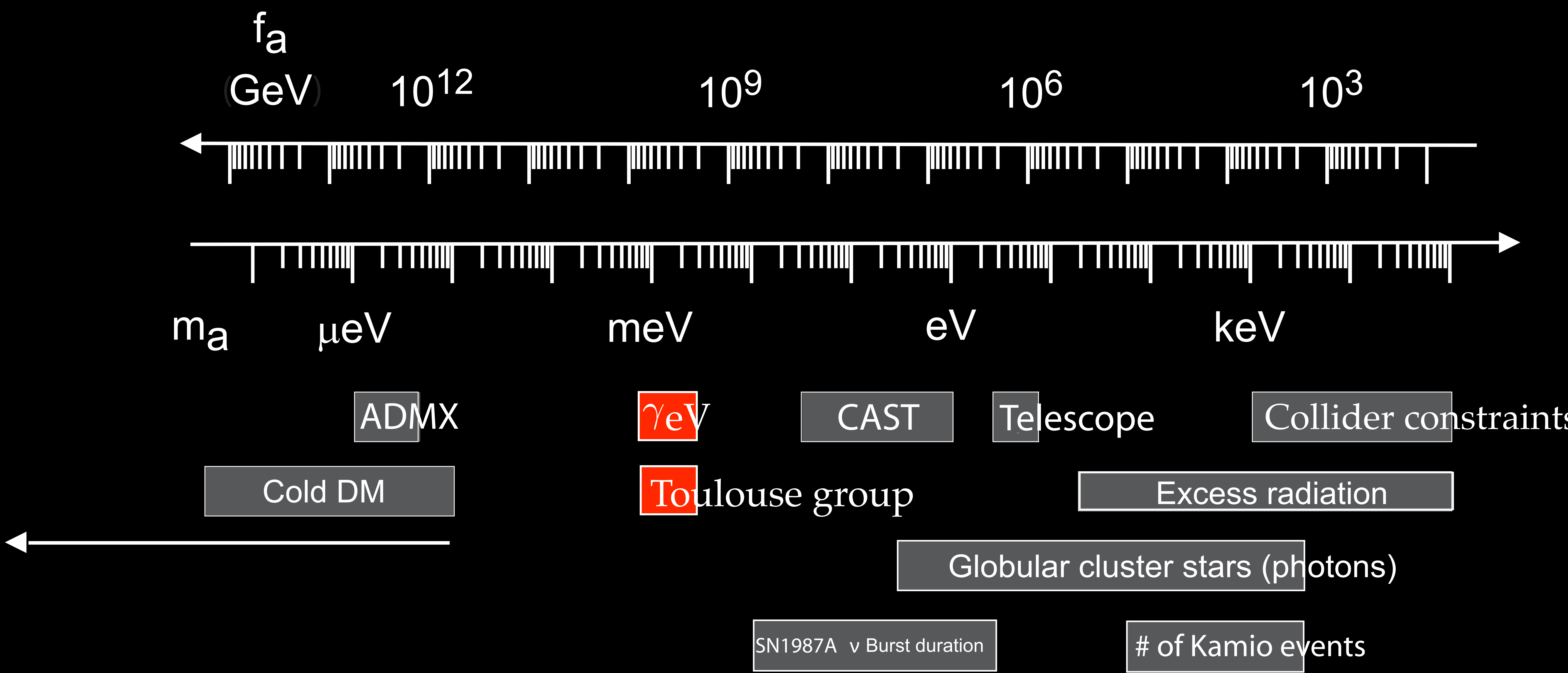




✳ Axions produced through interactions between non-relativistic pions in chemical equilibrium with rate

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

Context: Axion constraints



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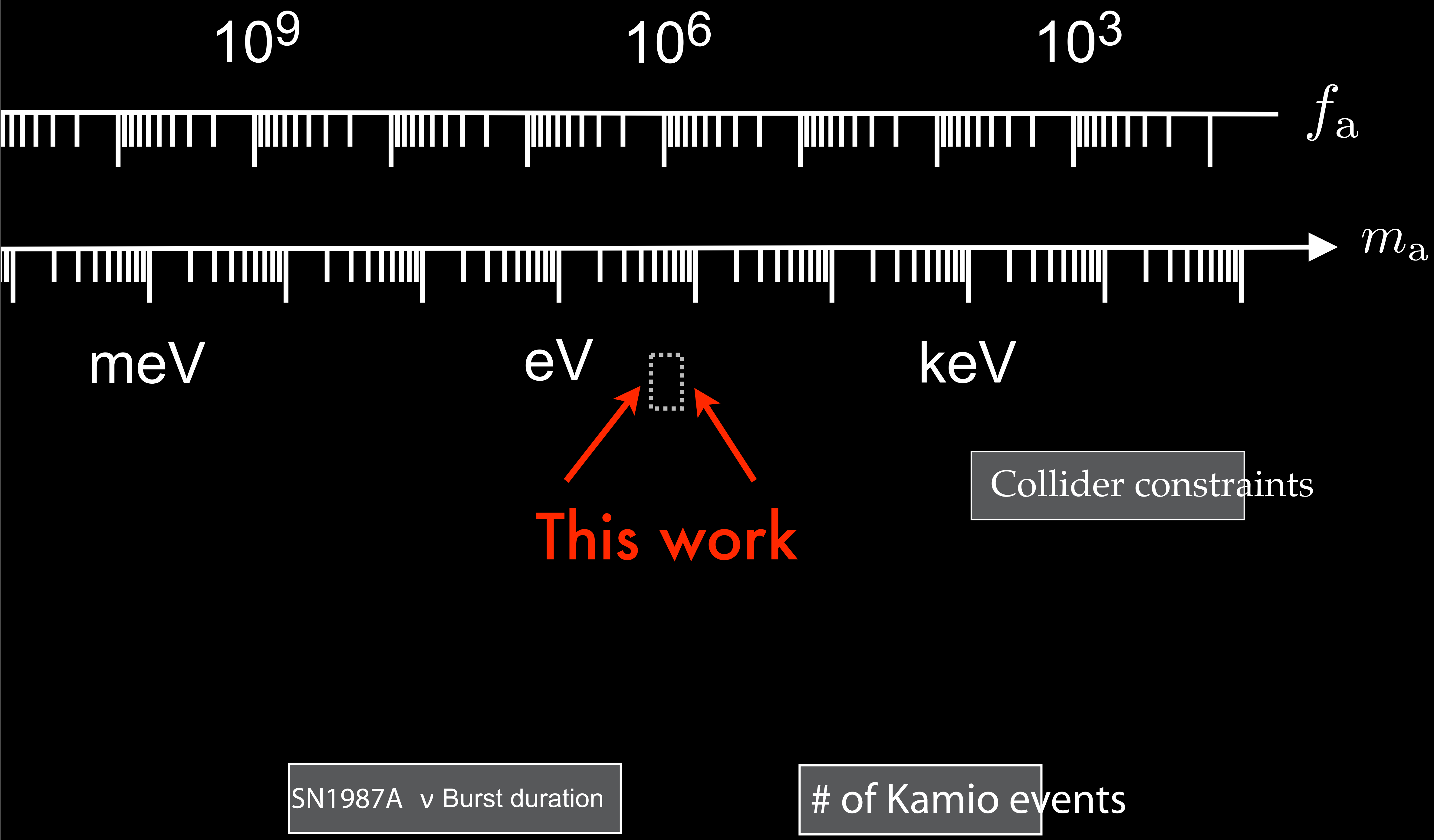
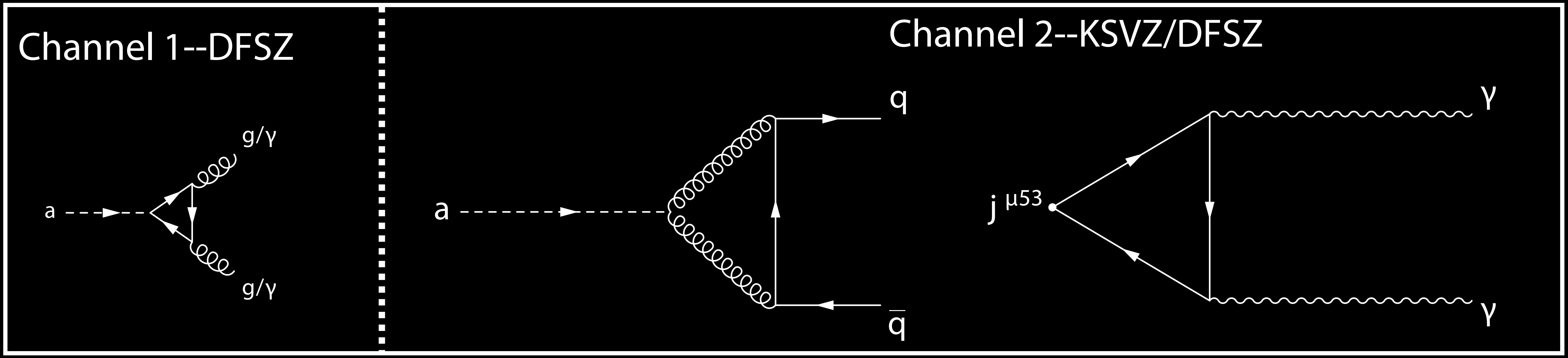


Axion models and EM couplings



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$$\xi \equiv \frac{4}{3}\left\{E/N - \frac{2(4+z)}{3(1+z)}\right\}$$

- ξ is model-dependent and may vanish

$$\xi = \frac{4}{3}\left\{E/N - 1.92 \pm 0.08\right\}$$

Axion decay

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

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

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

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

$$\boxed{\xi \leq 0.08}$$

Seeking axions with the VIMOS IFU

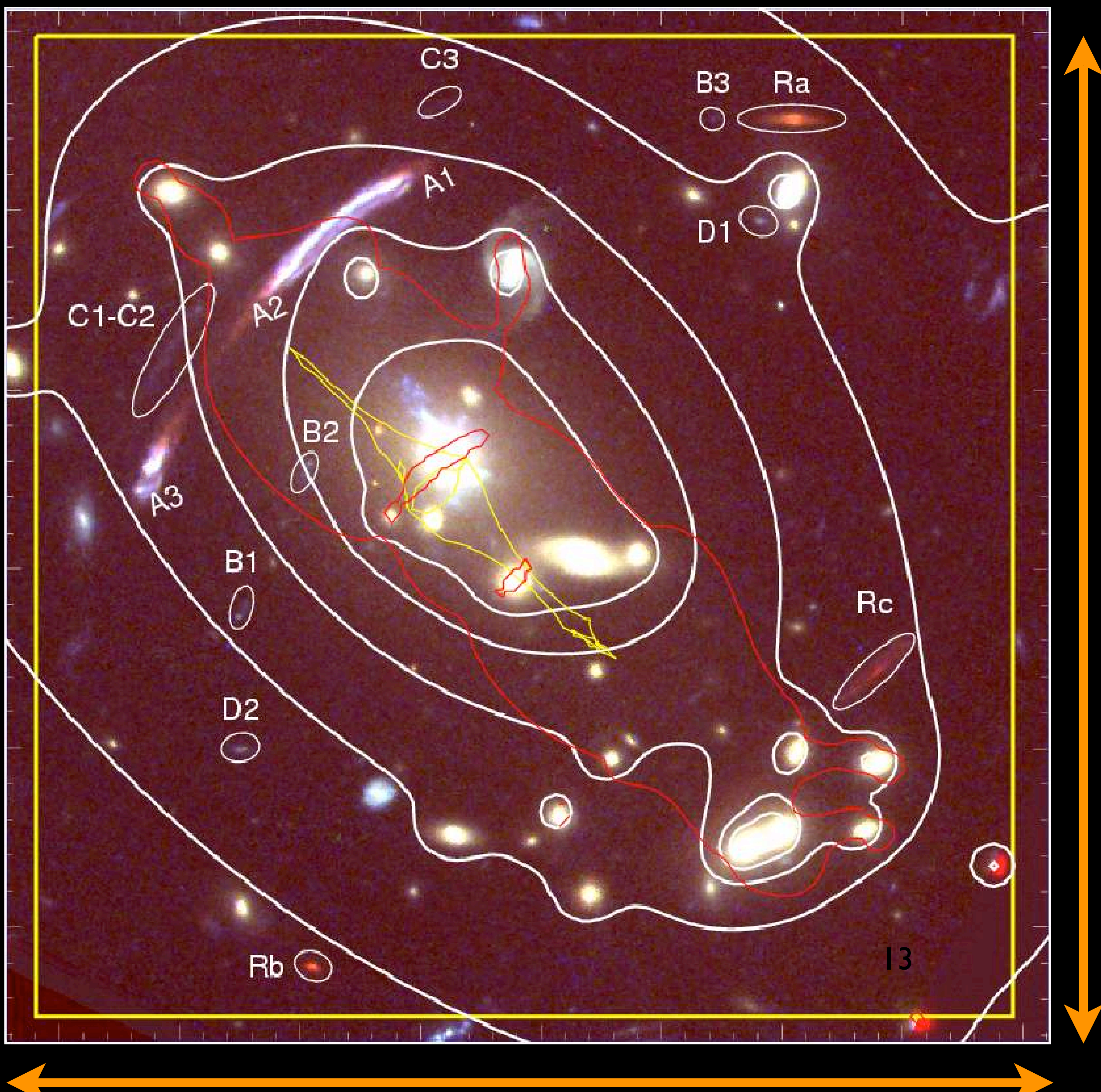
- VIMOS IFU (VLT, 6400 fibers) has largest f.o.v. of any instrument in its class: 54″x54″ mode used
- LR-Blue grism used: $4000\text{Å} \leq \lambda \leq 6800\text{Å}$ $(4.5\ \text{eV} \leq m_\text{a} \leq 7.7\ \text{eV})$. Dispersion of 5.4Å adequate to resolve axion line:

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

- 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

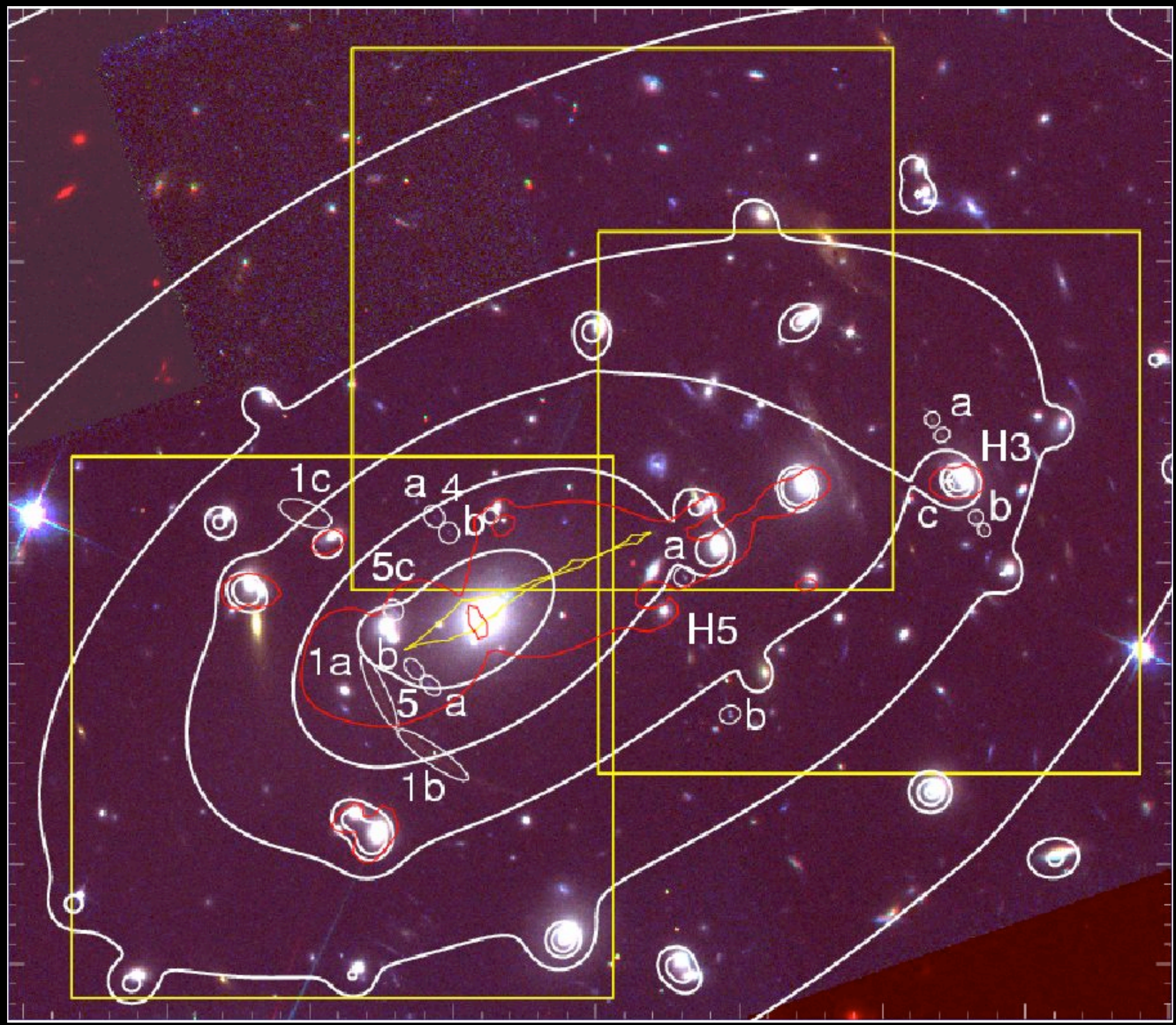
Applying the imaging

A2667



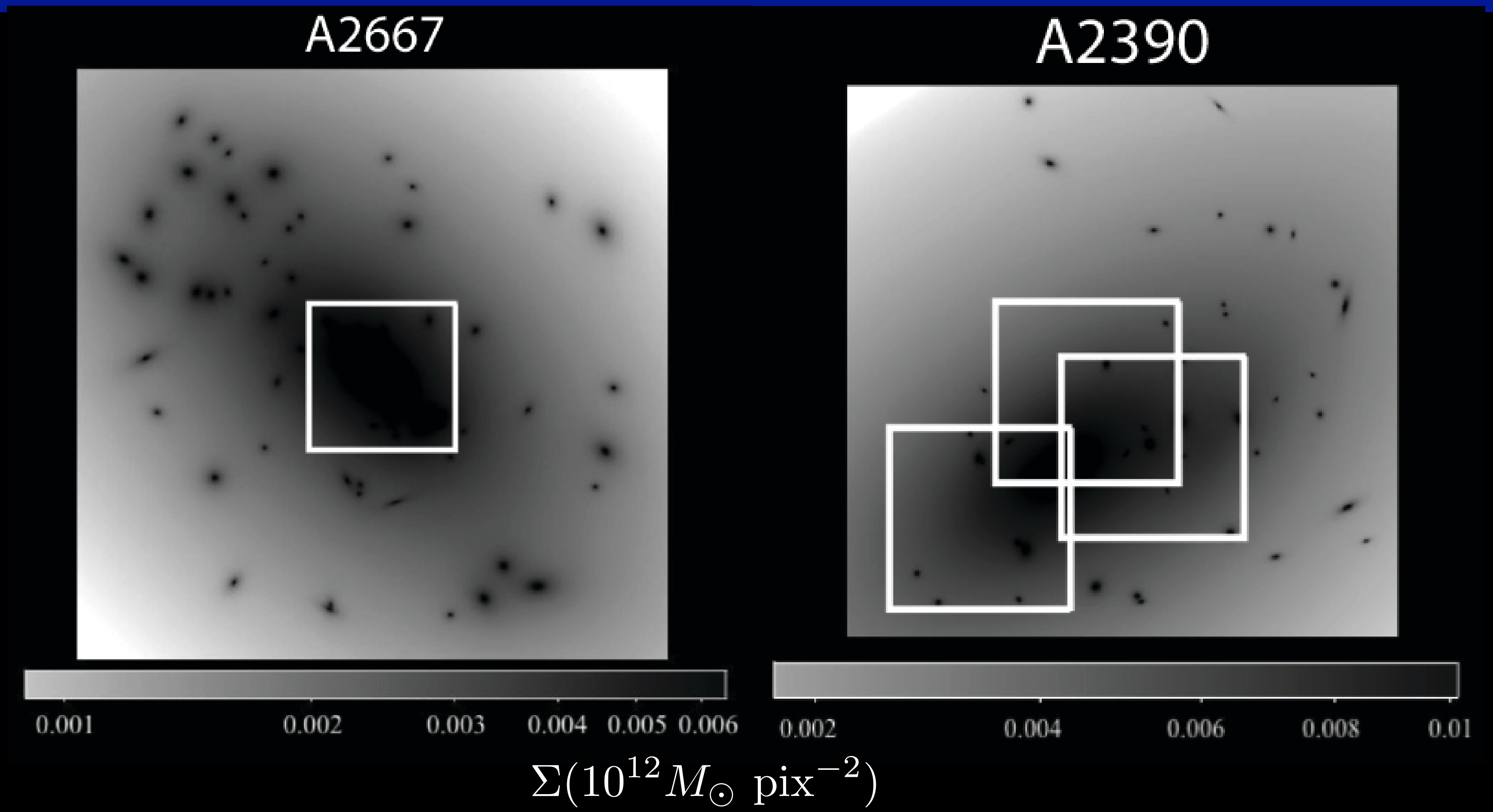
200 kpc

A2390



✳Bright sources masked

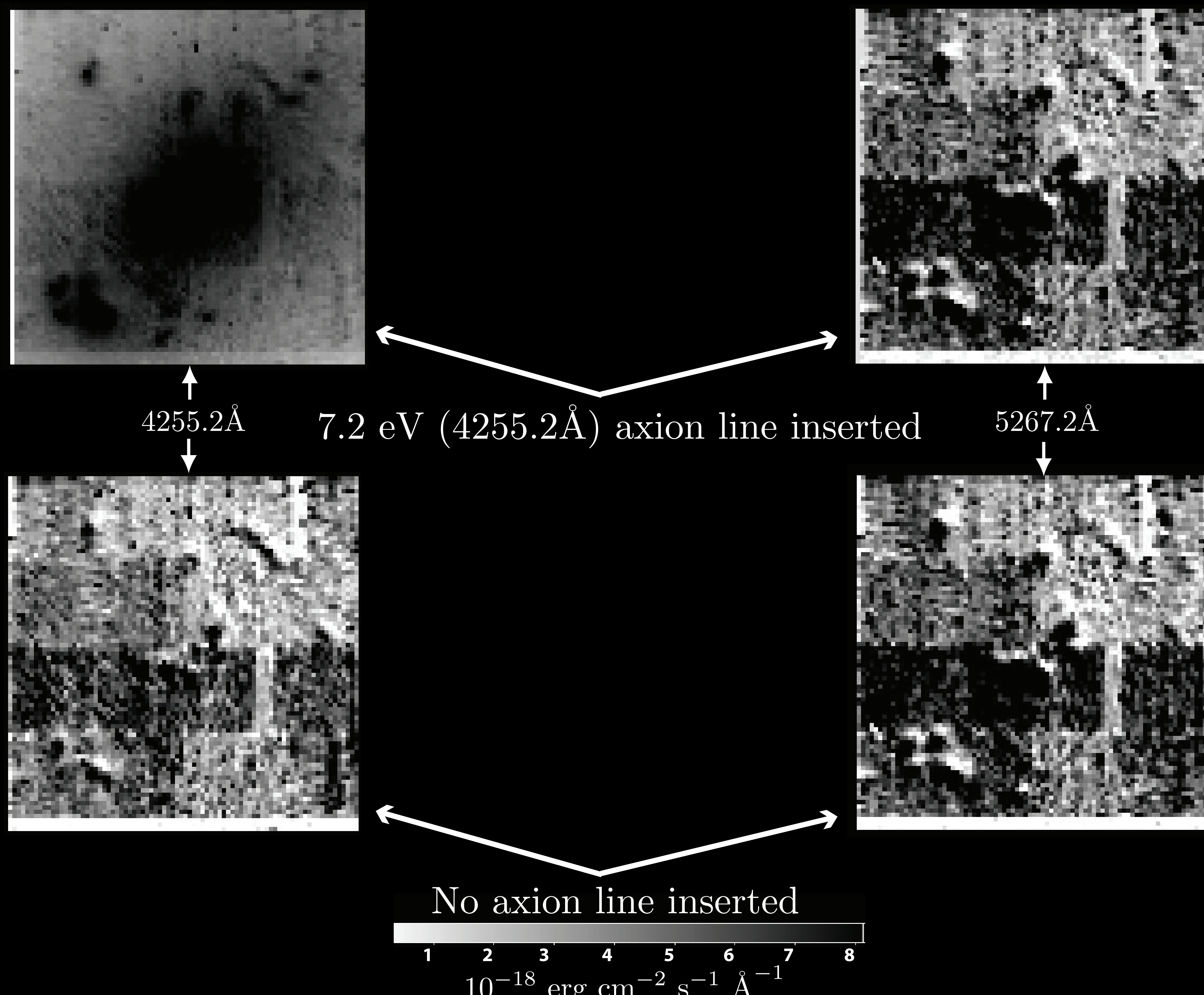
Lensing maps



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

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

Are we kidding ourselves? No!



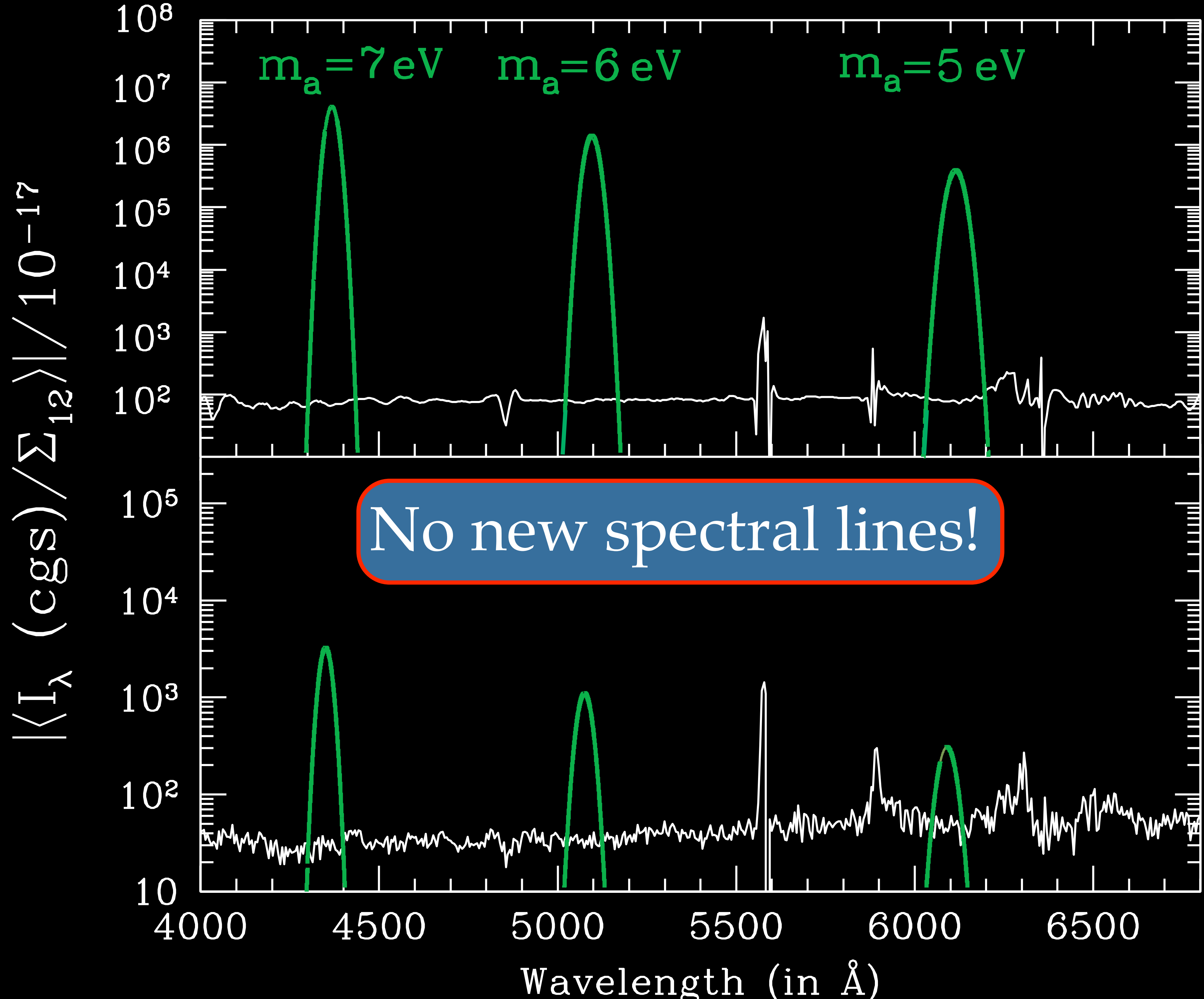
Data analysis

- 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



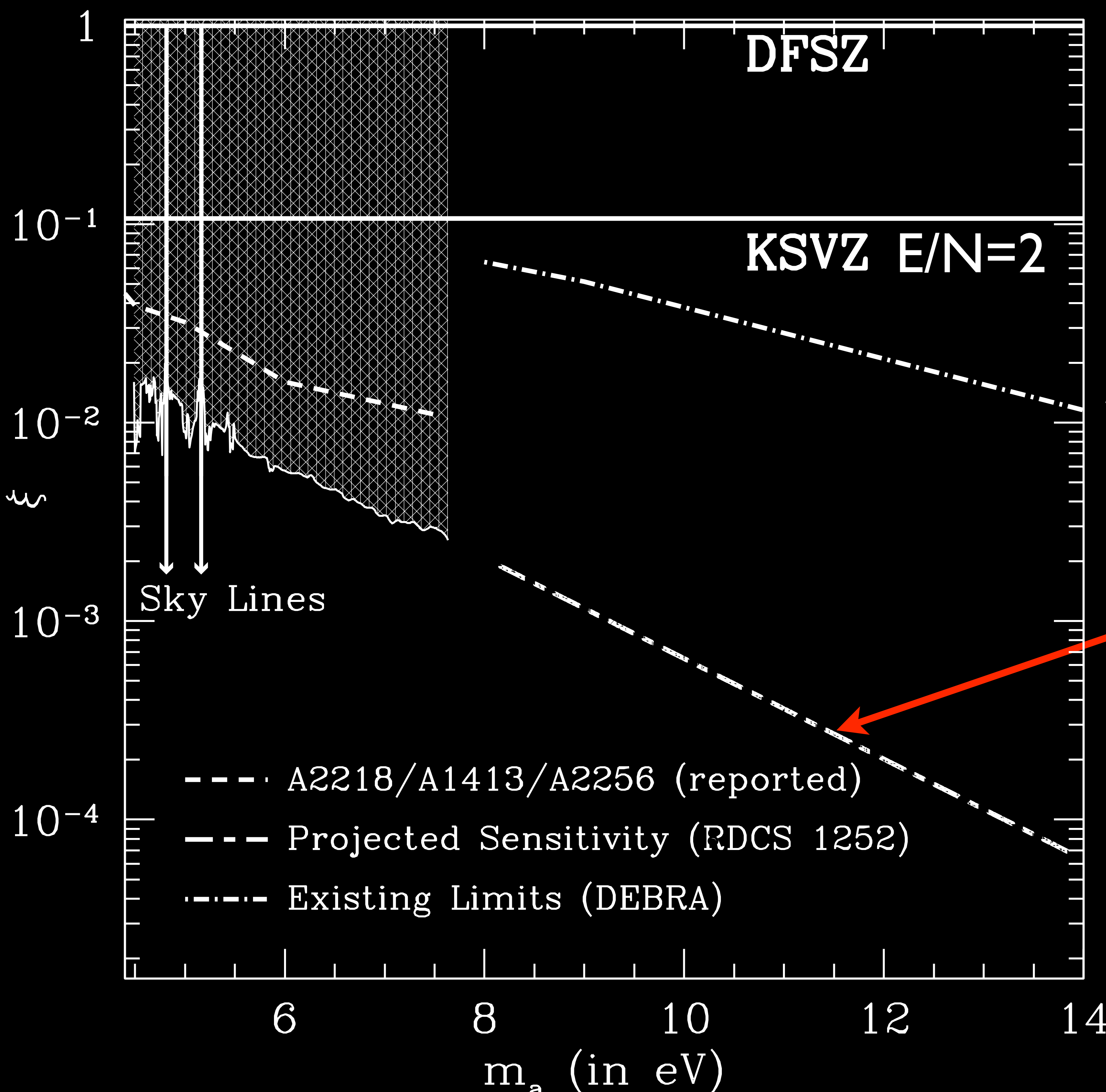
A2667

$\xi = 1$

A2390

$\xi = 0.1$

Extending the optical axion window



- Sensitivity improves at higher redshift!

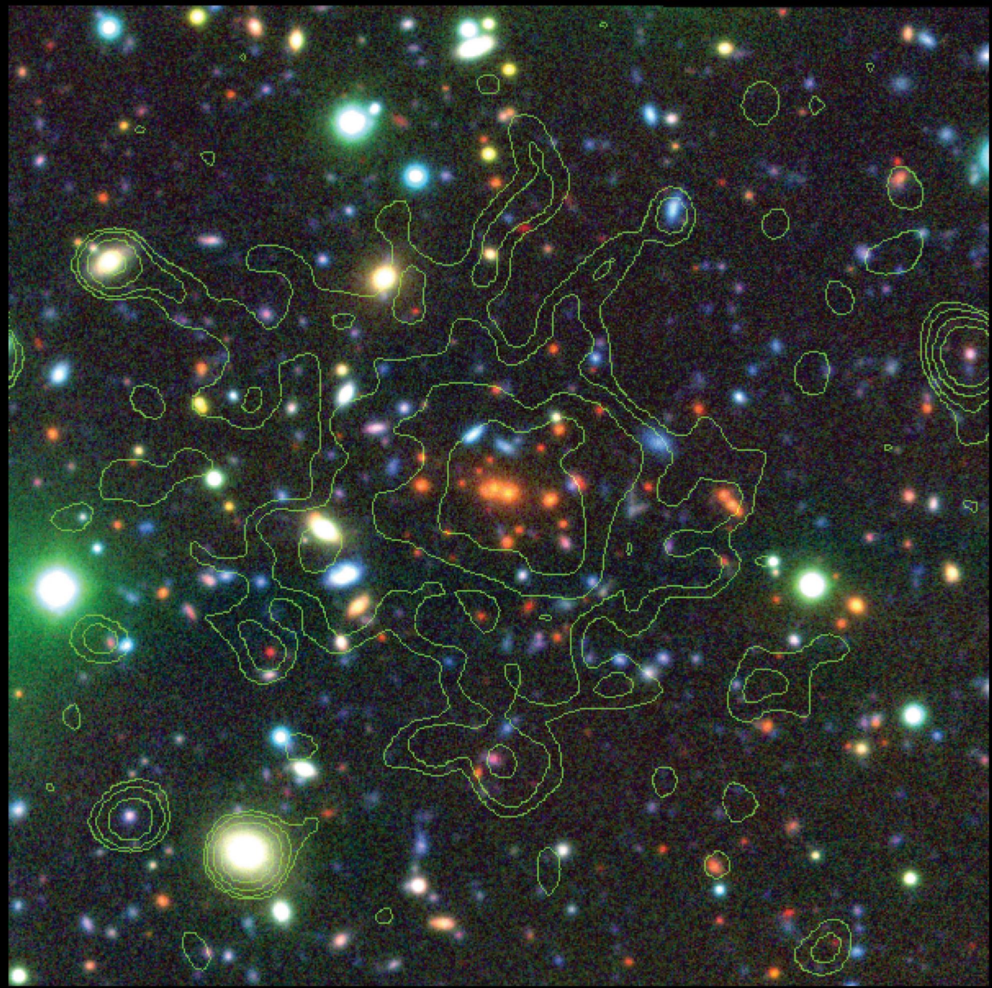
$$I_{\lambda_o} \propto m_a^7 (1+z_{cl})^{-4}$$

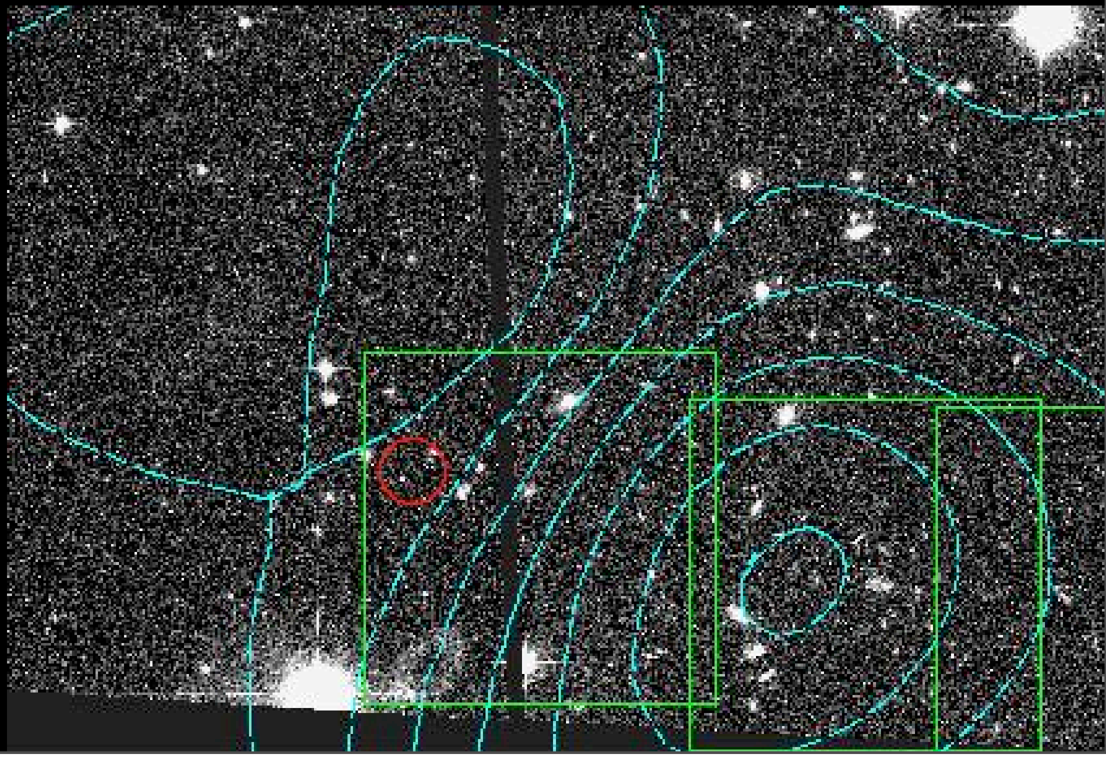
$$m_a = 24,800 \text{ Å} (1+z_{cl}) / \lambda_a$$

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

RDCS 1252

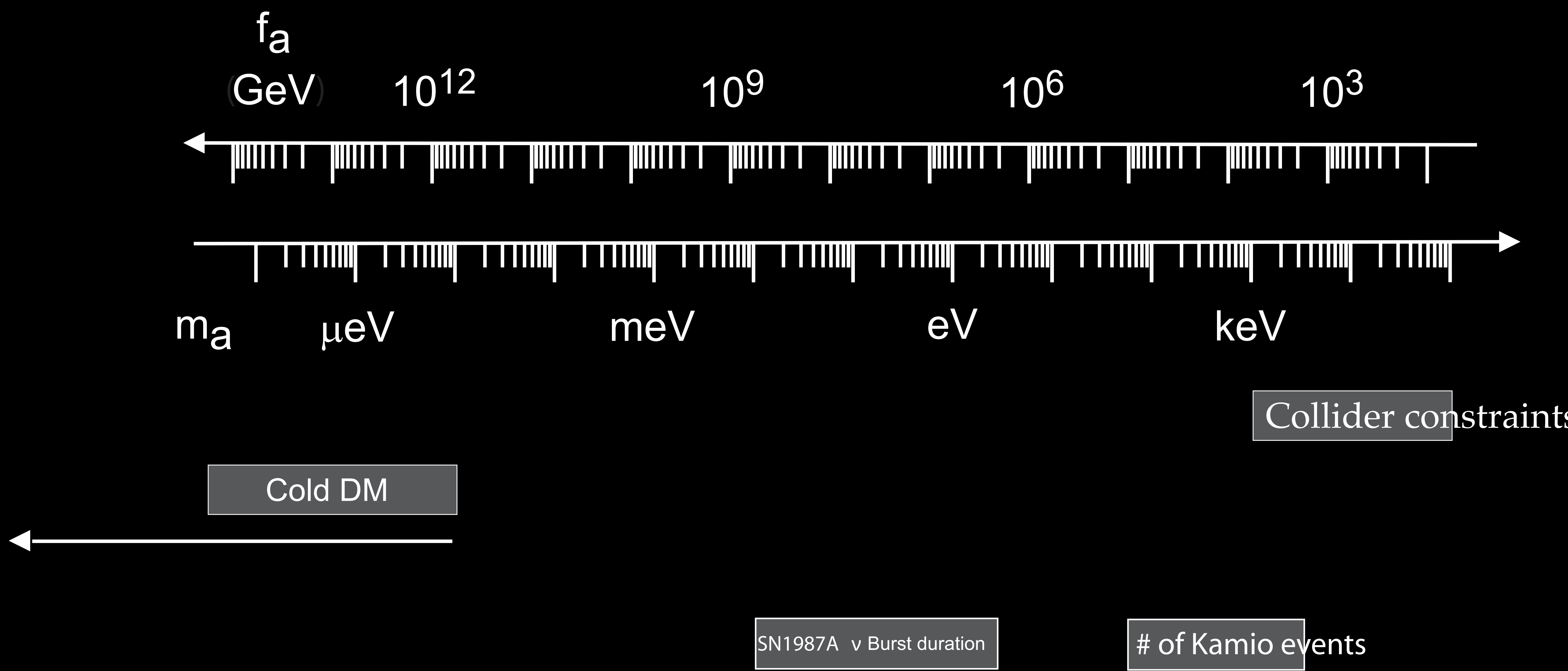
- RDCS 1252 is a $8 \times 10^{14} M_{\odot}$ cluster at $z = 1.237$
- Allotted 25 hrs of time for VIMOS IFU spectra using LR-Blue grism
- Publicly available weak-lensing mass maps (Lombardi et al. 2005), 2 arcs?





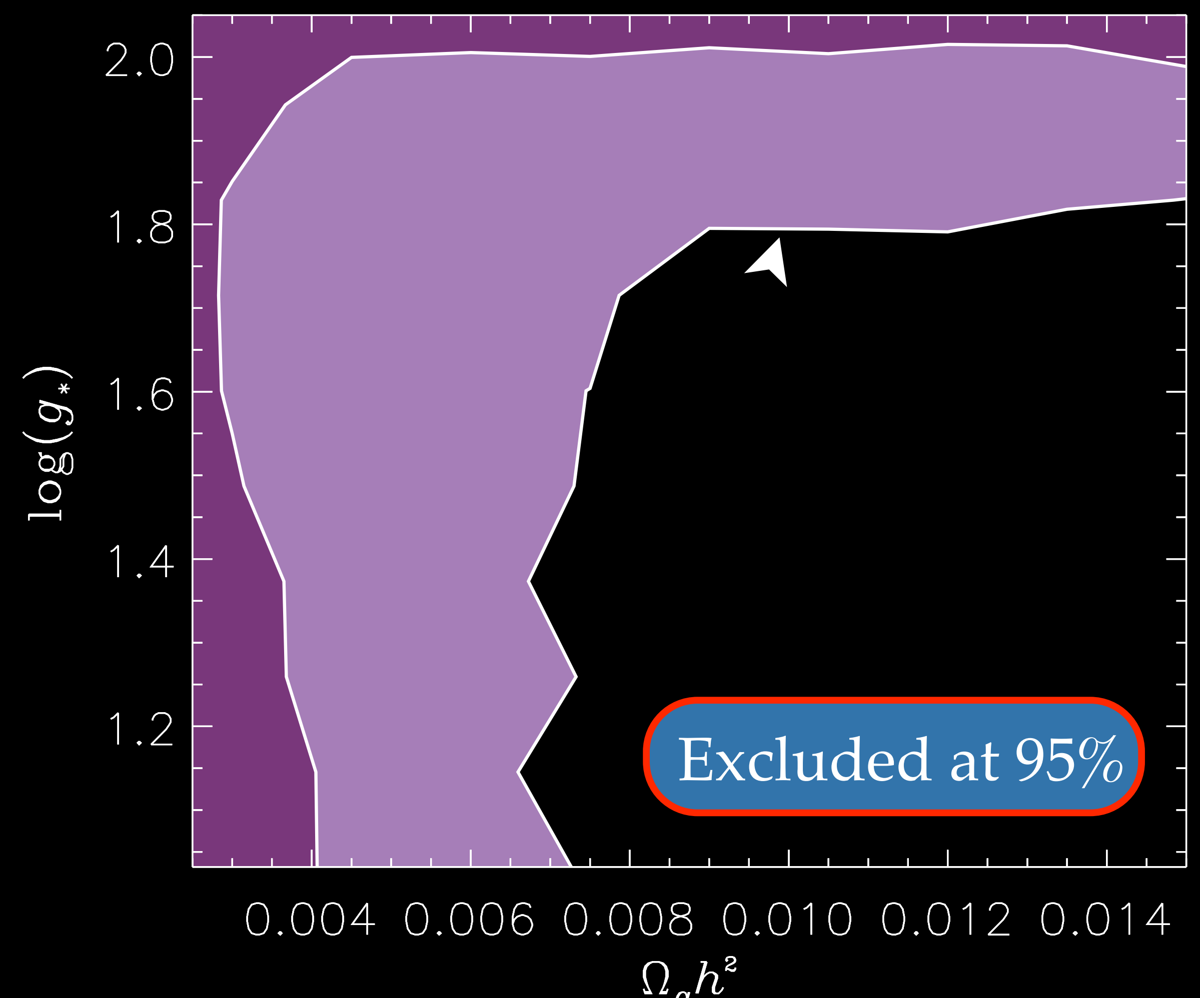
3 pointings cover range of WL mass contours

Context: Axion constraints



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 $T_{\rm rh} \lesssim 1\ \mathrm{GeV}$
- Light SM neutrinos become a viable WDM candidate if $T_{\rm rh} \sim 1 - 10\ \mathrm{MeV}$
- 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

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

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

- Decay products thermalize and entropy generated

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

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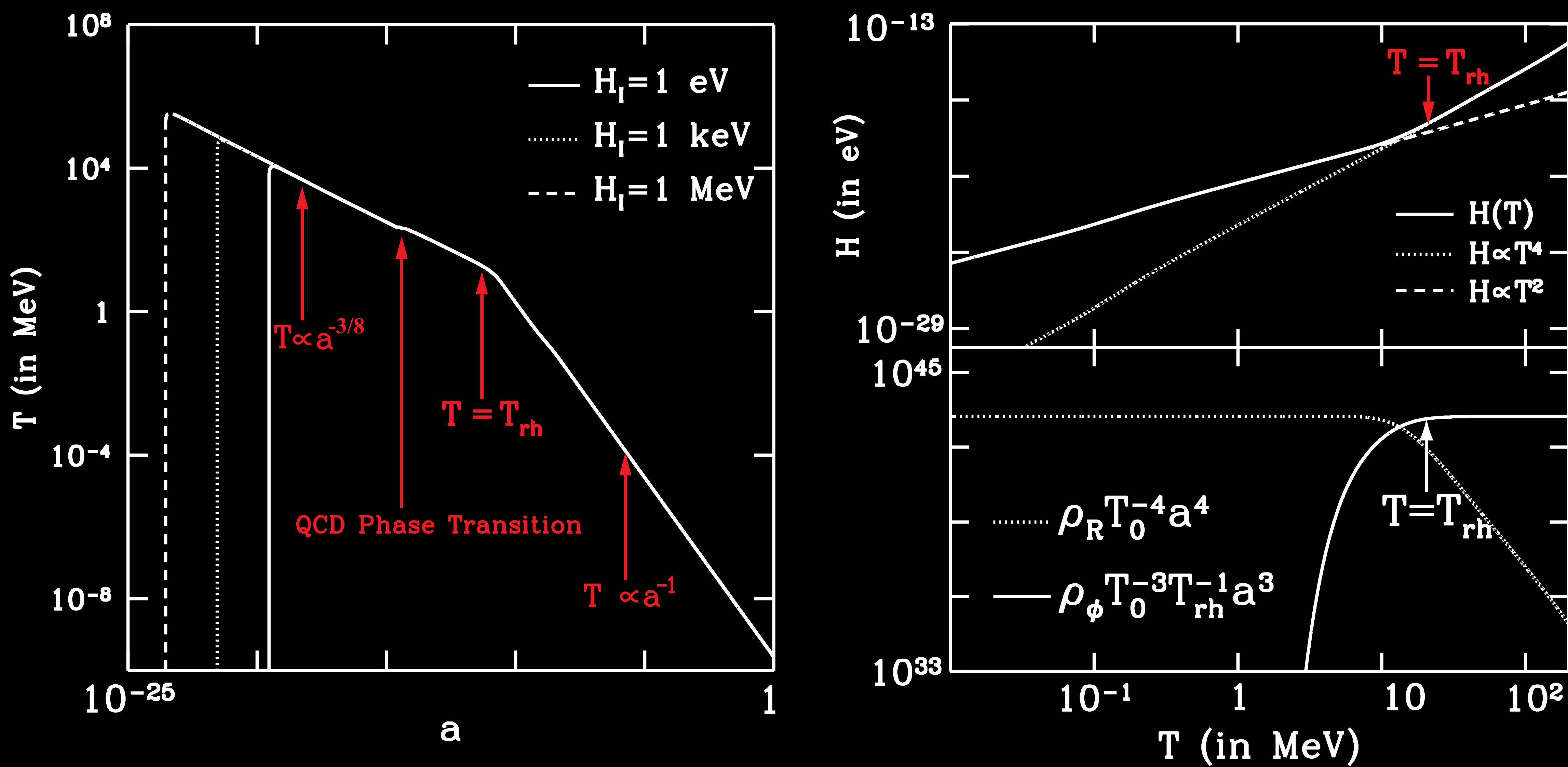
- Past work considered effects on WIMP, SM neutrino, sterile neutrino, and cold axion abundances and constraints. New work: LSS/CMB/total density constraints to hot axions in LTR

Low-temperature reheating (LTR)



- Entropy generation slows down temperature decrease

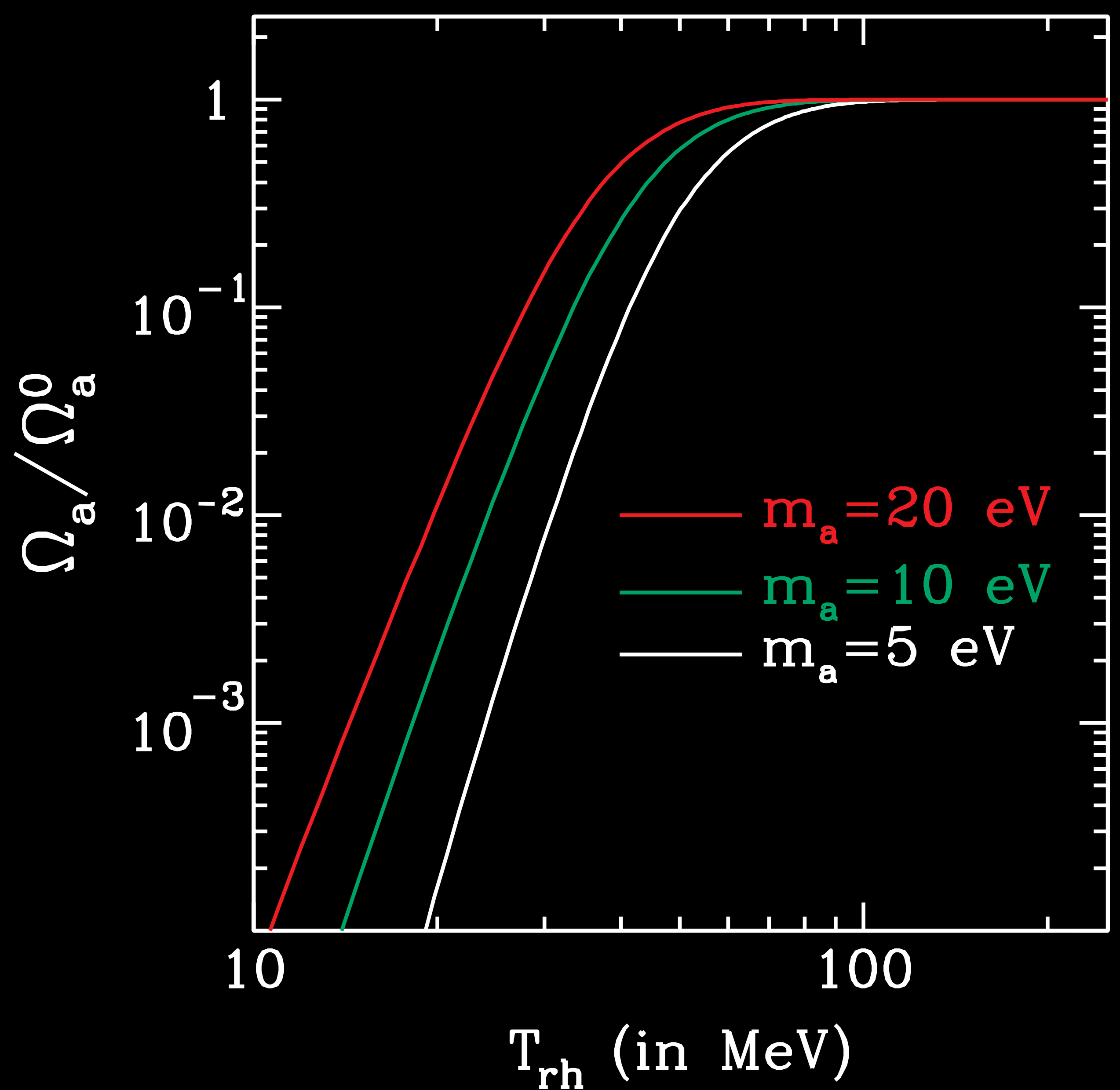
$$T \propto a^{-3/8} \text{ until } T \lesssim T_{\rm rh}, \text{ then } T \propto a^{-1}$$

- Hubble expansion is faster

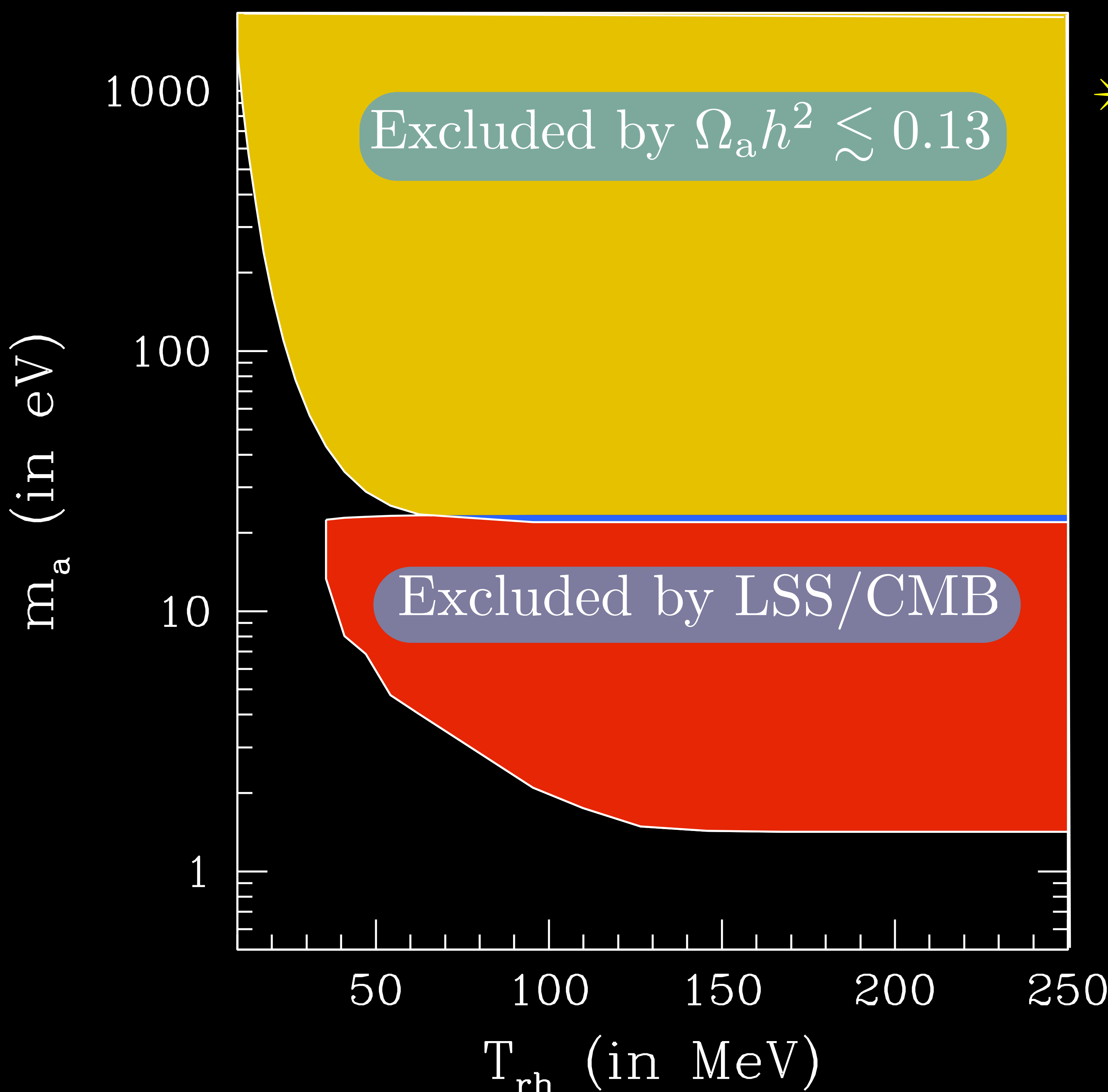
$$H \propto T^4 \text{ until } T \lesssim T_{\rm rh}, \text{ then } H \propto T^2$$

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

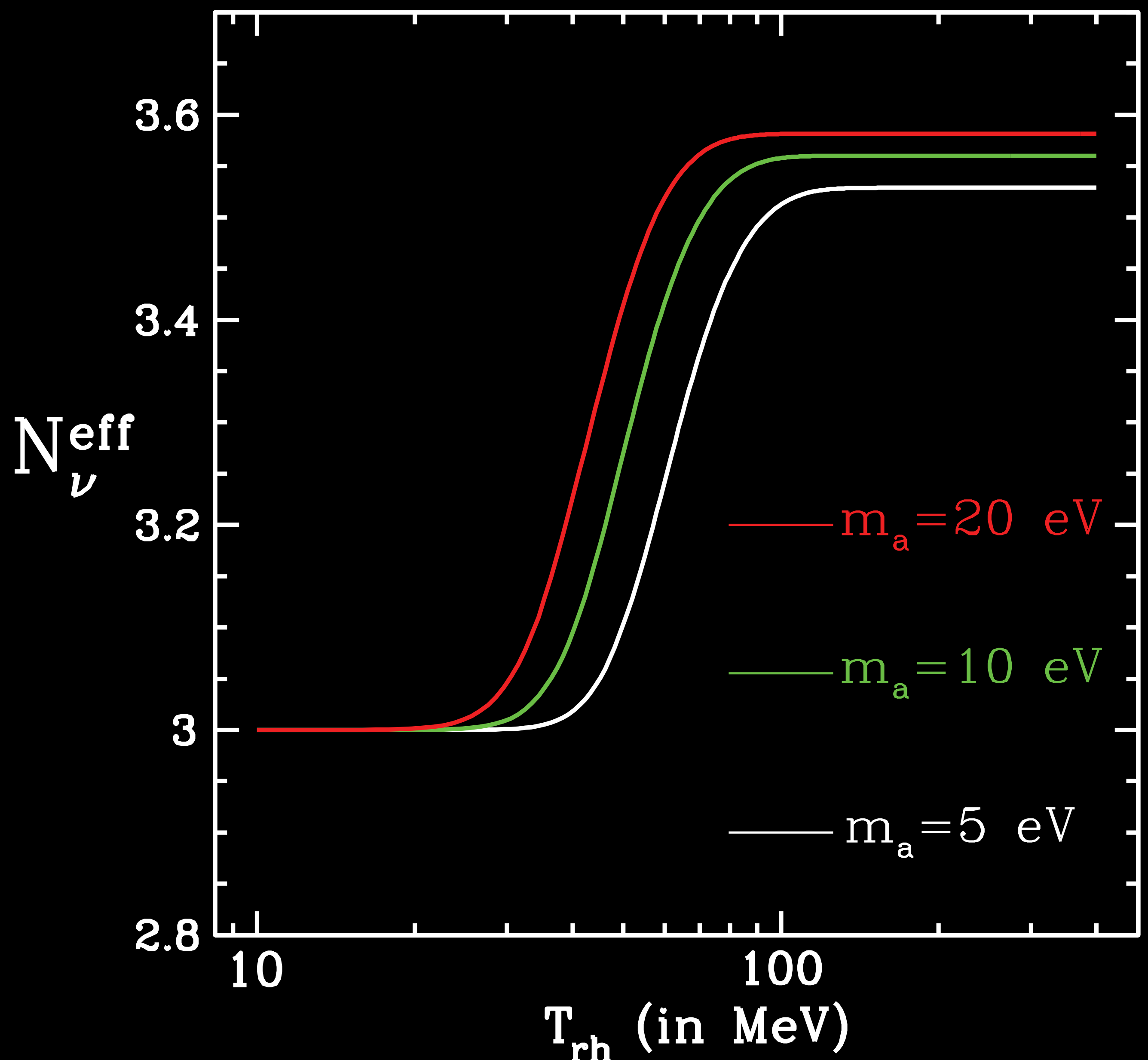
If $m_a \gtrsim 23$ eV , no LSS constraint to `hot axions'

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

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

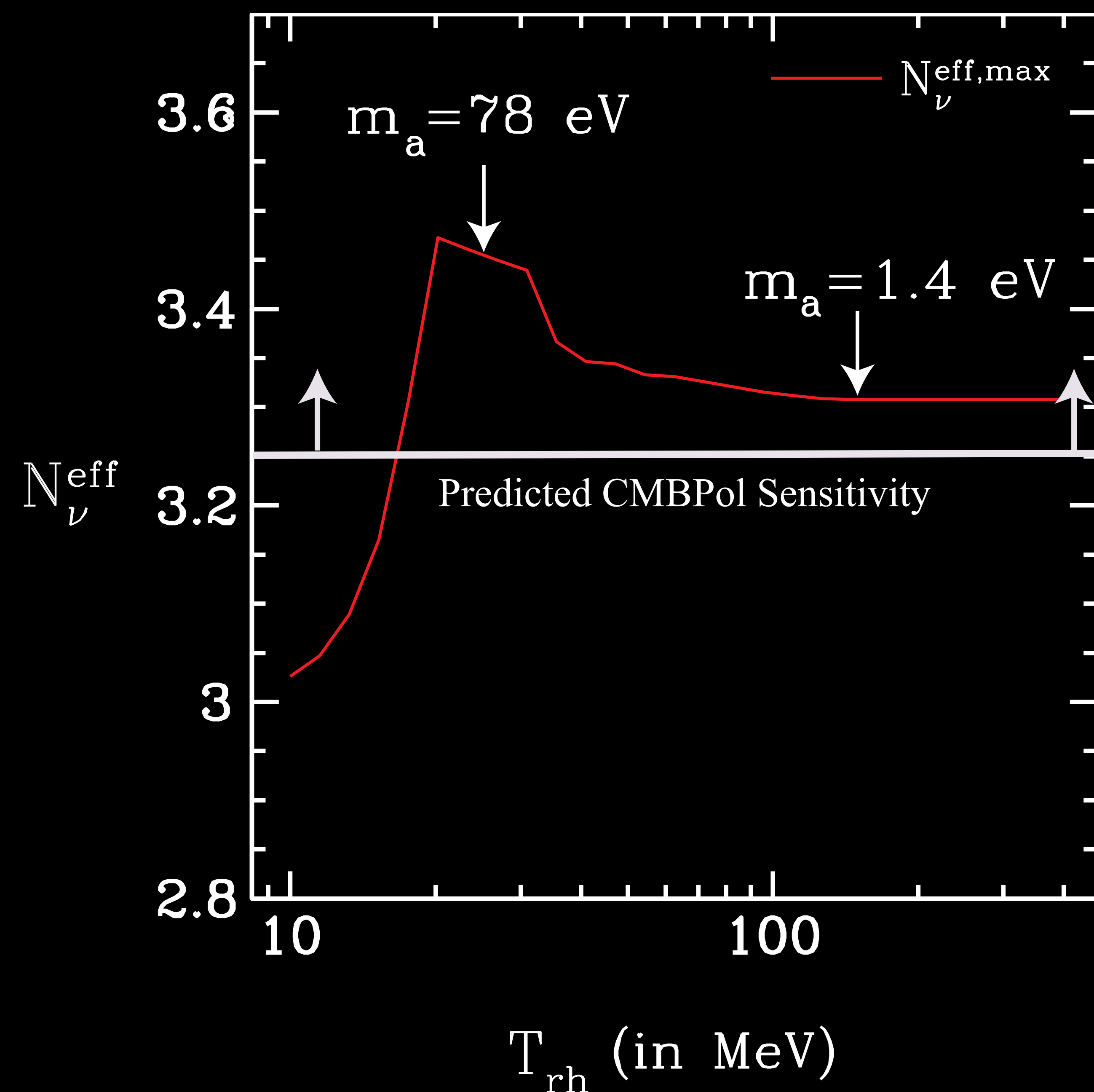
Axionic contribution to pre-BBN radiation energy density in LTR

- Axions are relativistic at T~ 1 MeV and contribute to N_ν^{eff}
- Entropy generation suppresses the axionic contribution to N_ν^{eff}



Future limits from abundance of ^{4}He

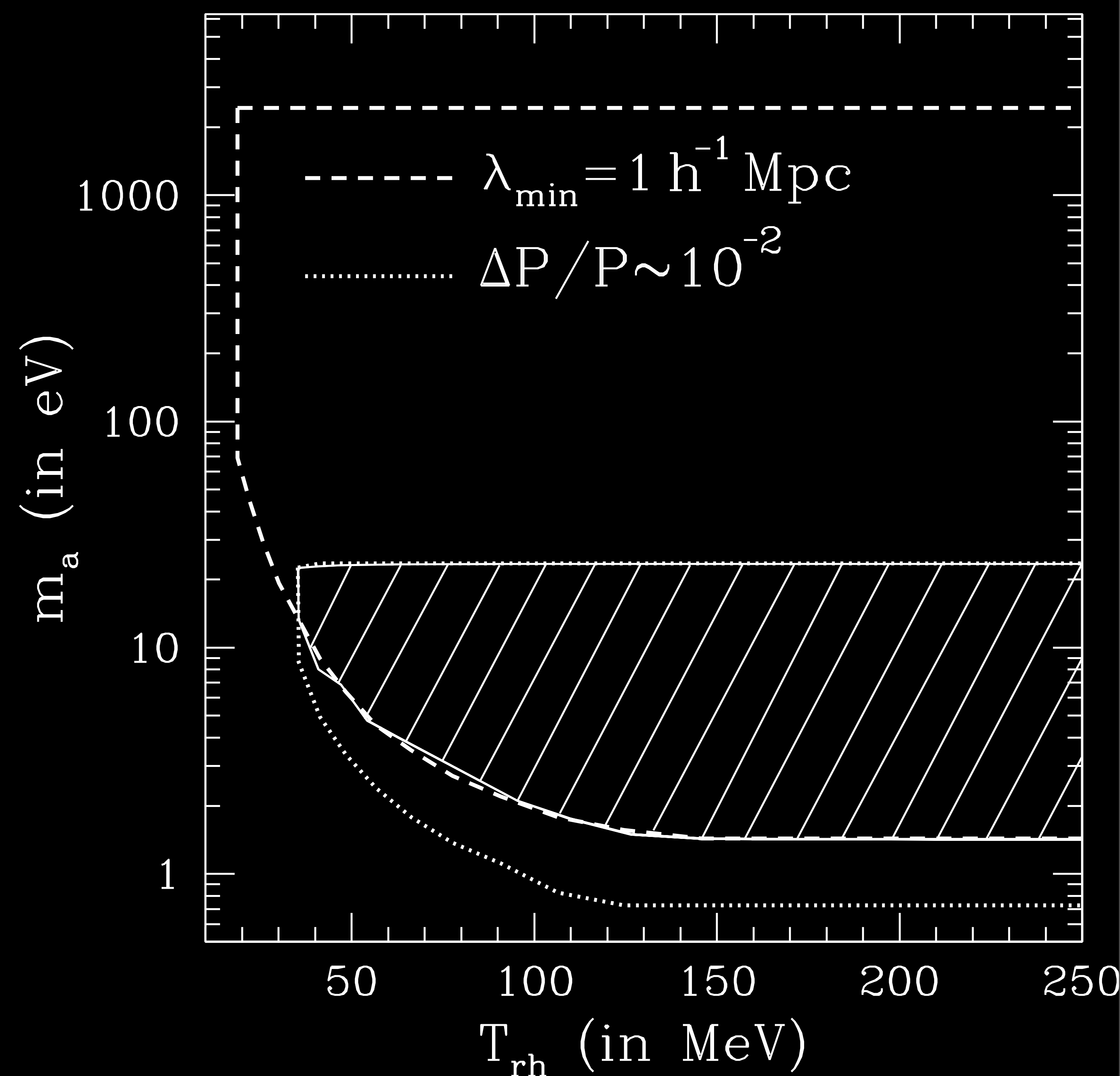
- $N_\nu^{\rm eff}$ contributes to $H(T)$ during radiation domination, setting the abundance of ^{4}He
- Current measurements yield constraint $N_\nu^{\rm eff} \leq 3.8$
- ^{4}He affects CMB TT, TE, and EE spectra: CMBPOL constraints!



Future surveys

- LSST predicted to reach $\Delta P/P \sim 10^{-2}$ for a sample population similar to SDSS main

- Assuming 21-cm or Lyα observations on very small comoving scales, limits at low reheating temperatures may be improved



Cosmological Hydrogen Recombination: The effect of high-n states

Daniel Grin
in collaboration with Christopher M. Hirata

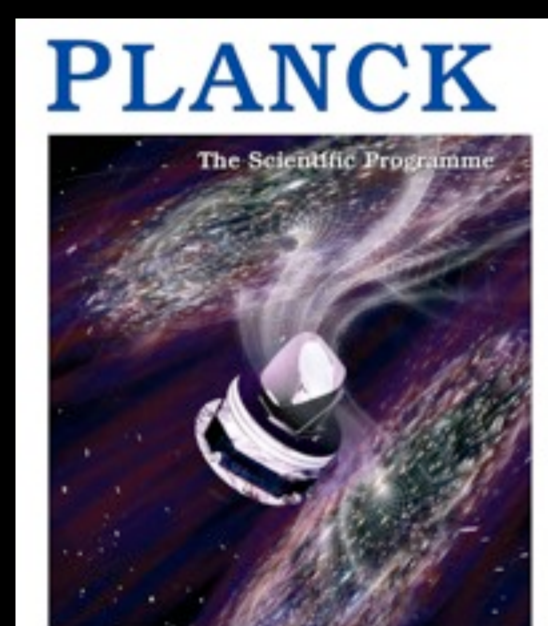
OUTLINE

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

CLONE WARS

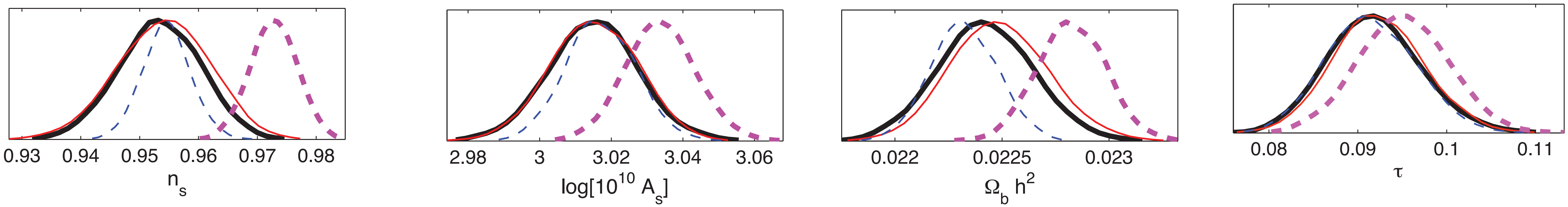
- Planck (launched May 2009) will make cosmic-variance limited CMB anisotropy measurements up to l~2500 (T), and l~1500 (E)

- Wong 2007 and Lewis 2006 show that $x_e(z)$ needs to be predicted to several parts in 10^4 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

$$\mathrm{n}_s = 1 - 4\epsilon + 2\eta \qquad \epsilon = \frac{m_{\mathrm{pl}}^2}{16\pi}\left[\frac{V'(\phi)}{V(\phi)}\right]^2$$

CAVEAT EMPTOR:

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

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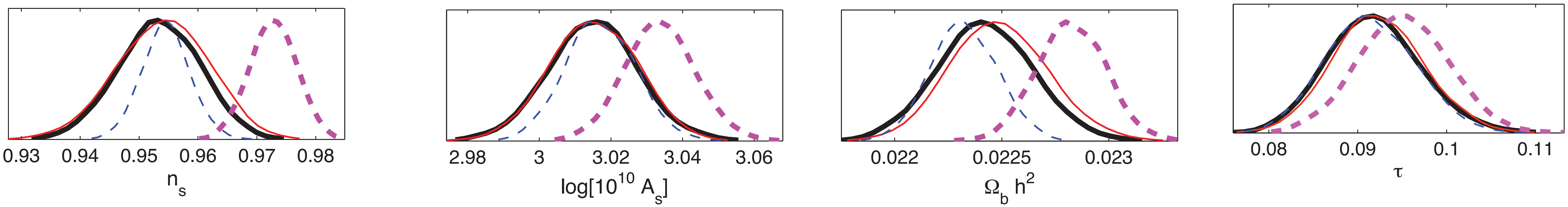

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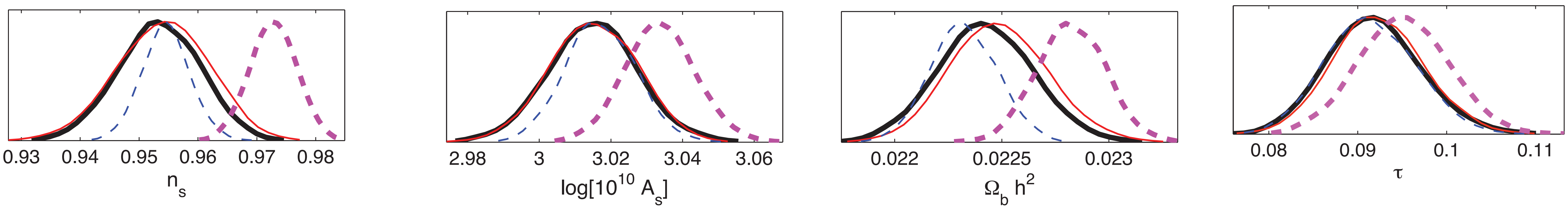

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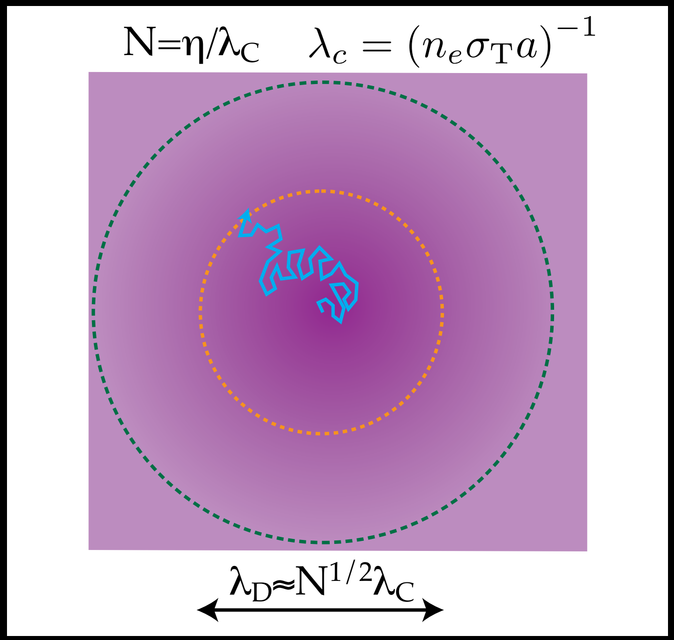
ORIGIN OF EFFECTS ON CMB TEMPERATURE

- Thompson scattering decouples during recombination: Visibility function!

$$g(\tau) = \dot{\tau} e^{-\tau}$$

$$\tau = \int_0^{\eta_{\rm dec}} n_e \sigma_T a(\eta) d\eta$$

- Diffusion (Silk) damping scale set by



$$l_{\rm damp} \sim 1000$$

- Relic $x_e(z)$ sets probability of re-scattering CMB photon through τ

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

- Duration of decoupling determines amt. of time available to develop a quadrupole and then re-scatter that quadrupole to polarize CMB

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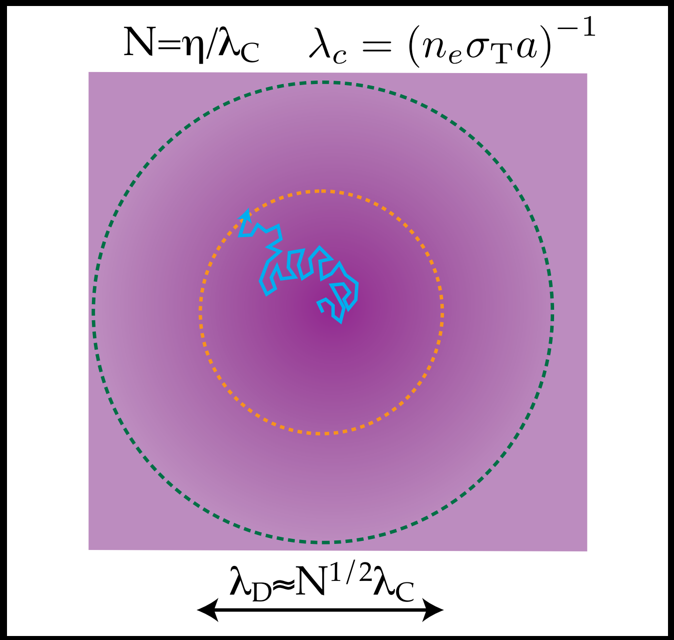

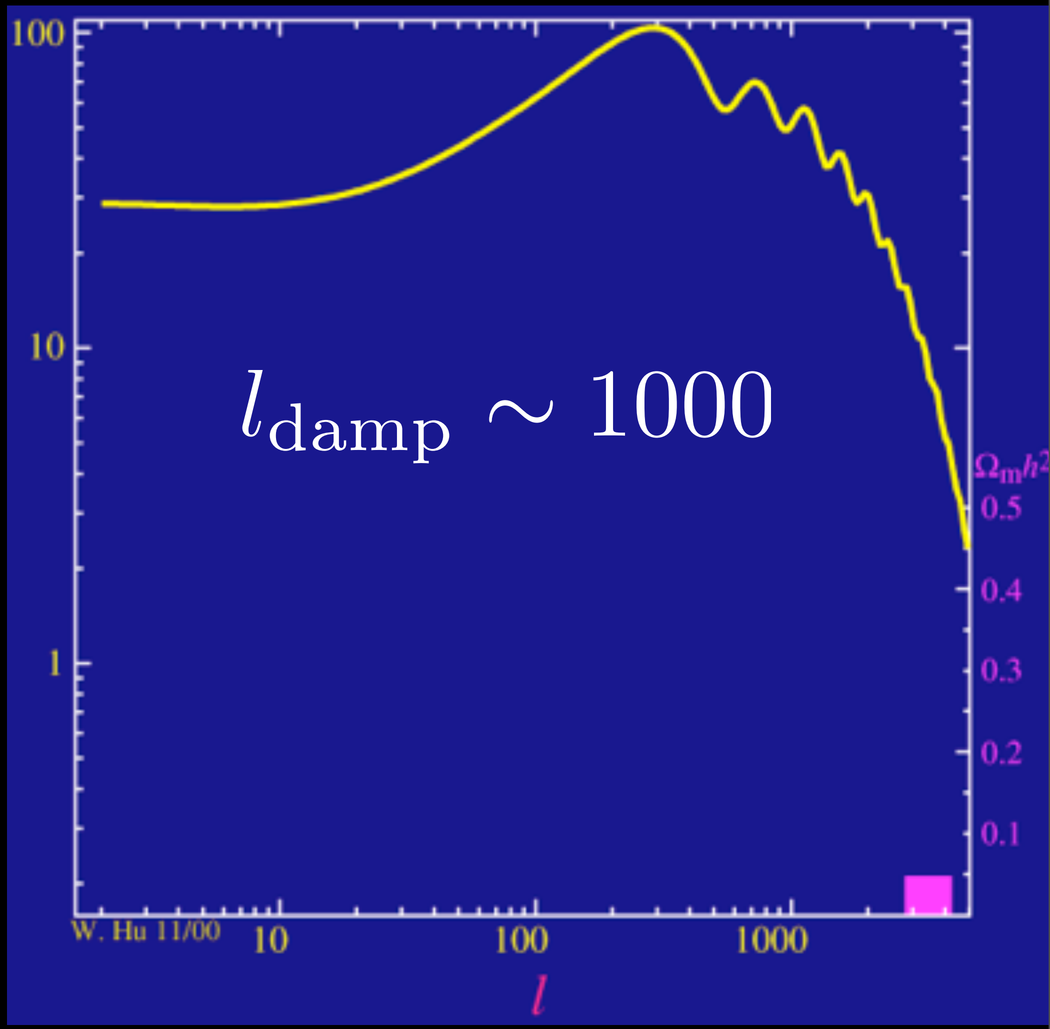

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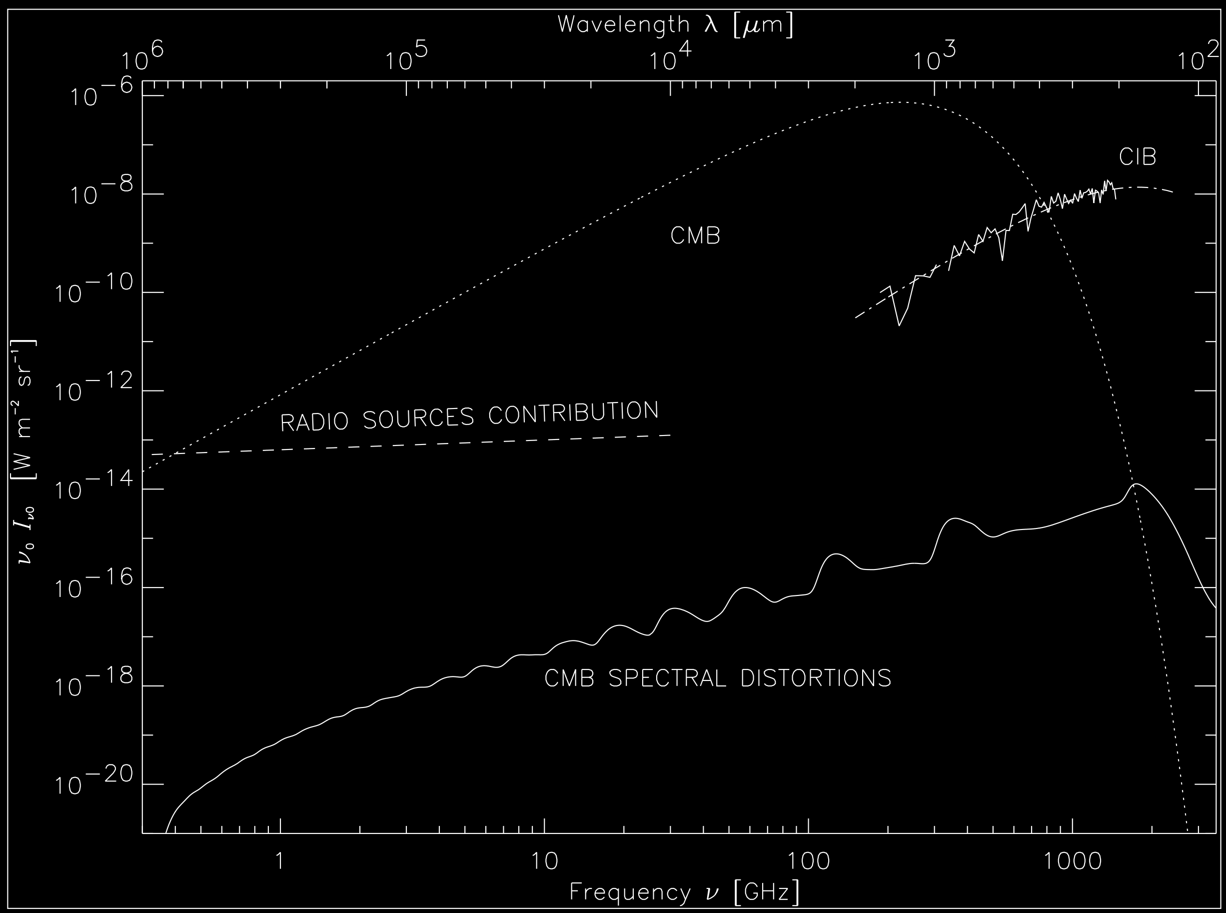
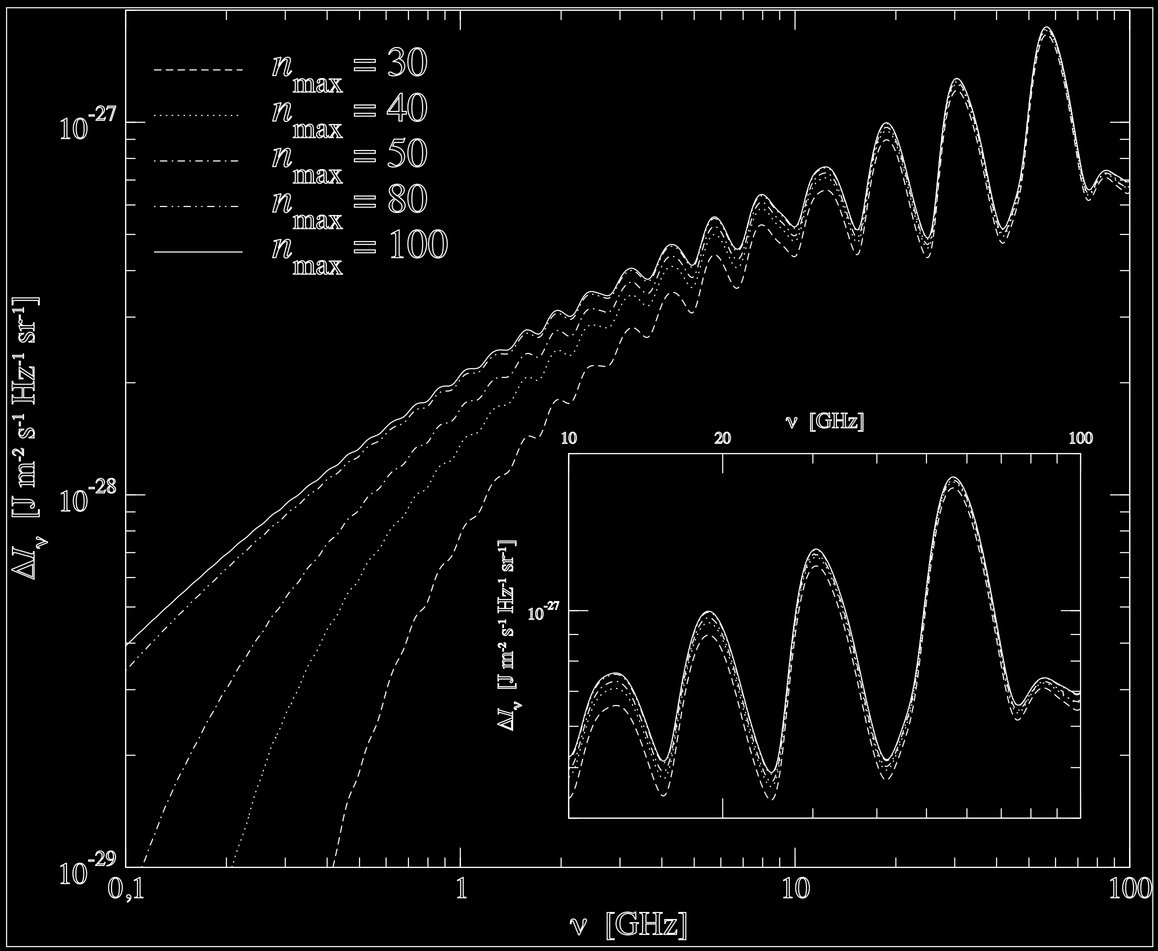
SPECTRAL DISTORTIONS





- ✴ Deviations from perfect CMB blackbody due to recomb. lines could be detected someday

SAHA EQUILIBRIUM IS INADEQUATE

$$p + e^- \leftrightarrow H^{(n)} + \gamma^{(nc)}$$

- Chemical equilibrium does reasonably well predicting "moment of recombination"

$$\frac{x_e^2}{1 - x_e} = \left(\frac{13.6}{T_{\rm eV}}\right)^{3/2} e^{35.9 - 13.6/T_{\rm eV}}$$

$x_e = 0.5$ when $T = T_{\rm rec} \simeq 0.3$ eV $\quad z_{\rm rec} \simeq 1300$

- Further evolution falls prey to reaction freeze-out

$$\Gamma = 6 \times 10^{-22}\ {\rm eV}\ x_e(T) \left(13.6/T_{\rm eV}\right)^{-5/2} \ln\left(13.6/T_{\rm eV}\right)$$

$$H = 1.1 \times 10^{-26}\ {\rm eV}\ T_{\rm eV}^{3/2}$$

$\Gamma < H$ when $T < T_{\rm F} \simeq 0.25$ eV

BOTTLENECKS/ESCAPE ROUTES

- BOTTLENECKS
  - Ground state recombinations are ineffective

$$\tau_{c\rightarrow 1s}^{-1} = 10^{-1}\ \mathrm{s}^{-1} \gg H \simeq 10^{-12}\ \mathrm{s}^{-1}$$

- Resonance photons are re-captured, e.g. Lyman α

$$\tau_{2p\rightarrow 1s}^{-1} = 10^{-2}\ \mathrm{s}^{-1} \gg H \simeq 10^{-12}\ \mathrm{s}^{-1}$$

- ESCAPE ROUTES (e.g. n=2)
  - Two-photon processes

$$H^{2s} \rightarrow H^{1s} + \gamma + \gamma \qquad \mathbf{\Lambda}_{\mathrm{2s}\rightarrow\mathrm{1s}} = \mathbf{8.22}\ \mathrm{s}^{-1}$$

  - Redshifting off resonance $R \sim \left(n_{\mathrm{H}}\lambda_{\alpha}^{3}\right)^{-1}\left(\frac{\dot{a}}{a}\right)$

EQUILIBRIUM ASSUMPTIONS

- Radiative eq. between different n-states

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

- Radiative/collisional eq. between different l

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

- Matter in eq. with radiation due to Thompson scattering

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

BREAKING THE MOLD

- Radiation field is cool: ~~Boltzmann eq. of higher n~~
- Seager/Sasselov/Scott (2000) $n_{\max} = 300$
- ~~Equilibrium~~ between *l states*
- Treated by Chluba et al. (2005) for $n_{\max} = 100$
- Radiation and matter field fall out of eq.

$$\dot{T_M} + 2HT_m = \frac{8x_e\sigma_{\rm T}aT_\gamma^4}{3m_ec\,(1+f_{\rm He}+x_e)}\,(T_M - T_\gamma)$$

BREAKING THE MOLD

- Radiation field is cool: ~~Boltzmann eq. of higher n~~
- Seager/Sasselov/Scott (2000) $n_{\rm max} = 300$ RecFAST!!!
- ~~Equilibrium~~ between *l states*
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BREAKING THE SIMPLEST MODEL

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

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

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

THE MULTI-LEVEL ATOM (MLA)

- Bound-free rate equation (Rates from recursion, checked with WKB)
- Bound-bound rates (Rates from Gordon+recursion, checked with WKB)

$$\dot{x}^{bb}_{nl} = \sum_{n',l'=l\pm 1} \left(A^{ll'}_{nn'} (1 + f_{nn'}) x_{n',l'} - \frac{g_{n'l'}}{g_{nl}} f_{nn'} x_{nl} \right) P^{ll'}_{nn'}$$

THE MULTI-LEVEL ATOM (MLA)

Spontaneous

- Bound-free rate equation (Rates from recursion, checked with WKB)
- Bound-bound rates (Rates from Gordon+recursion, checked with WKB)

$$\dot{x}_{nl}^{bb} = \sum_{n',l'=l\pm1} (A_{nn'}^{ll'}(1 + f_{nn'})x_{n',l'} - \frac{g_{n'l'}}{g_{nl}} f_{nn'} x_{nl})\ P_{nn'}^{ll'}$$

THE MULTI-LEVEL ATOM (MLA)

Stimulated

- Bound-free rate equation (Rates from recursion, checked with WKB)
- Bound-bound rates (Rates from Gordon+recursion, checked with WKB)

$$\dot{x}_{nl}^{bb} = \sum_{n',l'=l\pm1} \left(A_{nn'}^{ll'}(1+f_{nn'})x_{n',l'} - \frac{g_{n'l'}}{g_{nl}} f_{nn'} x_{nl}\right) P_{nn'}^{ll'},$$

THE MULTI-LEVEL ATOM (MLA)

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- Phase-space density blueward of line
- Escape probability of resonance photon

THE MULTI-LEVEL ATOM (MLA)

- Two photon transitions between n=1 and n=2 are included:

$$\dot{x}_{2s\to 1s,2\gamma} = -\dot{x}_{1s\to 2s,2\gamma} = \Lambda_{2s}(-x_{2s} + x_{1s}e^{-E_{2s\to 1s}/T_\gamma})$$

- Net recombination rate:

$$x_e \simeq 1 - x_{1s} \to \dot{x}_e \simeq -\dot{x}_{1s} = -\dot{x}_{1s\to 2s}$$
$$+\sum_{n,l>1s} A_{n1}^{l0} P_{n1}^{l0} \left\{ \frac{g_{nl}}{2} f_{n1}^{+} x_{1s} - (1 + f_{n1}^{+}) x_{nl} \right\}$$

RADIATION FIELD: BLACK BODY +

- Escape probability treated in Sobolev approx.

$$P^{l,l'}_{n,n'} = \frac{1-e^{-\tau_s}}{\tau_s} \qquad \tau_s = \frac{c^3 n_{\rm H}}{8\pi H \nu^3_{nn'}} A^{ll'}_{nn'} \left[\frac{g^{l'}_{n'}}{g^l_n} x^l_n - x^{l'}_{n'} \right]$$

$$\mathcal{R}(\nu,\nu') = \phi(\nu)\phi(\nu') \qquad \frac{v_{\rm th}}{H(z)} \ll \lambda$$

- Excess line photons injected into radiation field

$$\left(\frac{8\pi\nu^3_{nn'}}{c^3 n_H}\right)\left(f^+_{nn'} - f^-_{nn'}\right) = A^{ll'}_{nn'} P^{ll'}_{nn'} \left[x^l_n \left(1 + f^+_{nn'}\right) - \frac{g^l_n}{g^{l'}_{n'}} x^{l'}_{n'} f^+_{nn'} \right]$$

- Photons are conserved outside of line regions

$$f^{+10}_{n1} = f^{-10}_{n+1,1} \left[\frac{1-(n+1)^{-2}}{1-n^{-2}} (1+z) - 1 \right]$$

RADIATION FIELD: BLACK BODY+

* Escape probability treated in Sobolev approx.

$$P^{l,l'}_{n,n'} = \frac{1 - e^{-\tau_s}}{\tau_s}$$

$$\boxed{\tau_s = \frac{c^3 n_{\mathrm{H}}}{8\pi H \nu^3_{nn'}} A^{ll'}_{nn'} \left[\frac{g^{l'}_{n'}}{g^l_n} x^l_n - x^{l'}_{n'} \right]}$$

$$\mathcal{R}(\nu, \nu') = \phi(\nu)\phi(\nu')$$

- Ongoing work by collabs and others uses FP eqn. to obtain evolution of $f(\nu)$ more generally, including atomic recoil/diffusion, and full time-dependence of problem, coherent and incoherent scattering, overlap of higher-order Lyman lines, 2γ decay

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

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

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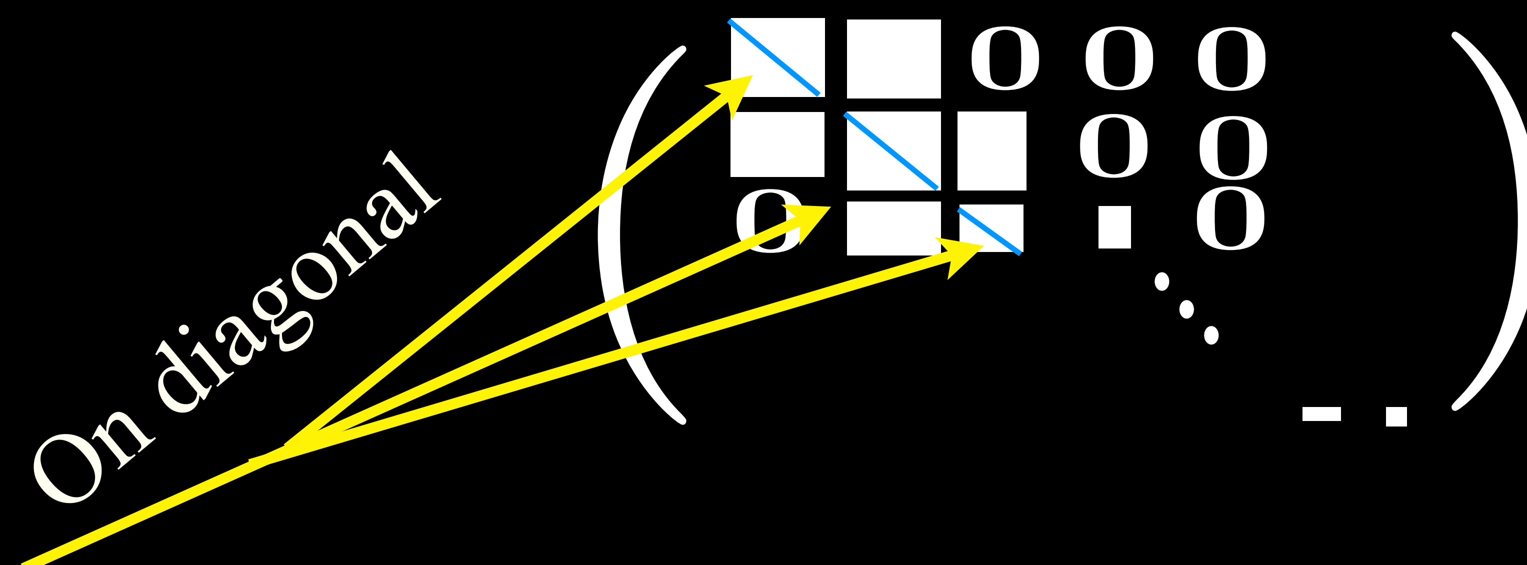

For state l, includes BB transitions out of l to all other l”, photo-ionization, 2γ transitions to ground state

STEADY-STATE FOR EXCITED LEVELS

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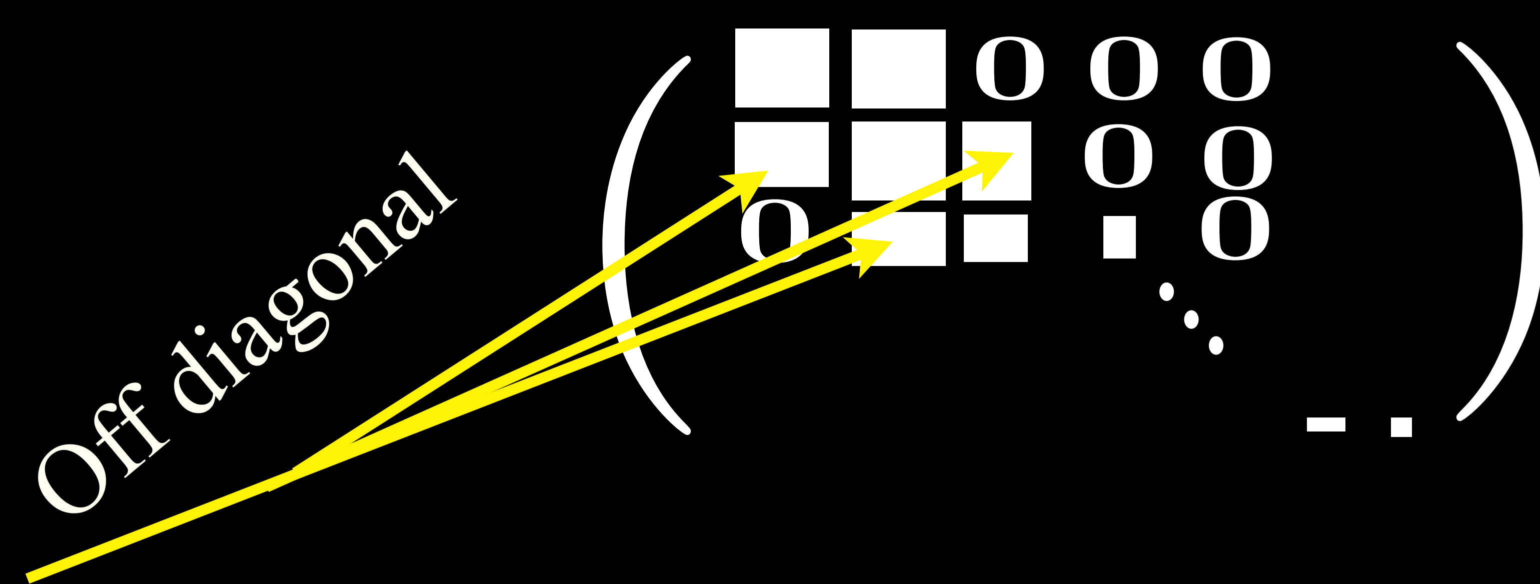


For state l, includes BB transitions into l from all other l’

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

✳ Evolution equations may be re-written in matrix form

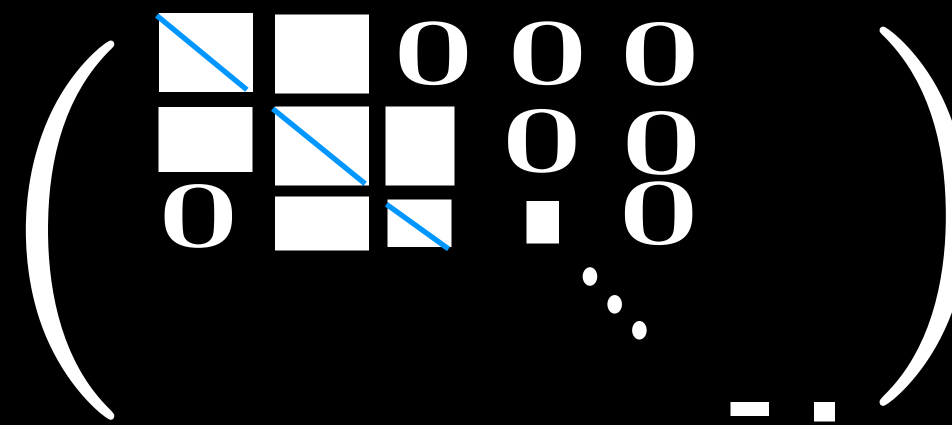
$$\frac{d\vec{x}}{dt} = \mathbf{R}\vec{x} + \vec{s}$$

- 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)

Rapid matrix inversion: Sparsity to the rescue

- Matrix is $\sim n_{max}^2 \times n_{max}^2$
- Brute force would require $A n_{max}^6 \sim 1000$ s for $n_{max} = 200$ for a single time step
- Sparsity to the rescue: $\Delta l = \pm 1$



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

$$\vec{v}_l = \chi_\mathbf{l}\left[\vec{s}_l - \mathbf{M_{l,l+1}}\vec{v}_l + \Sigma^0_{l'=l-1}\sigma_{l,l'}\vec{s}_{l'}\,(-1)^{l'-l}\right]$$

$$\chi_l = \begin{cases} \mathbf{M}_{00}^{-1} & \text{if } l = 0 \\ \left(\mathbf{M}_{l+1,l+1} - \mathbf{M}_{l+1,l}\chi_l\mathbf{M}_{l,l+1}\right)^{-1} & \text{if } l > 0 \end{cases}$$

$$\sigma_{l,l-1} = \mathbf{M}_{l,l-1}\chi_{l-1}$$

$$\sigma_{l,i} = \sigma_{l,i+1}\mathbf{M}_{i+1,i}\chi_i$$

- RecSparse generates rec. history with 10^{-8} precision, with computation time $\sim n_{max}^{2.5}$: Huge improvement!
- Case of $n_{\max} = 100$ runs in a day, $n_{\max} = 200$ takes ~ 1 week.

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.
- ***Unfinished business***: *Are other forbidden transitions in hydrogen important, particularly for Planck data analysis?*

QUADRUPOLE TRANSITIONS AND RECOMBINATION

- Electric quadrupole (E2) transitions are suppressed but conceivably not irrelevant at the desired level of accuracy:

$$\frac{A^{\rm quad}_{m,l\pm 2\to n,l}}{A^{\rm dipole}_{m,l\pm 1\to n,l}} \sim \alpha^2 \approx 5\times 10^{-5}$$

- Coupling to ground state will overwhelmingly dominate:

$$\frac{A^{\rm quad}_{n,2\to 1,0}}{A^{\rm quad}_{n,2\to m,0}} \propto \frac{\omega^5_{n1}}{\omega^5_{nm}} = \left(\frac{1-\frac{1}{n^2}}{\frac{1}{m^2}-\frac{1}{n^2}}\right)^5 \geq 1024 \text{ if } m\geq 2$$

- GS E2 lines are optically thick!

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

- Magnetic dipole rates suppressed by several more orders of magnitude
- Hirata, Switzer, Kholupenko, others have considered other `forbidden' processes, two-photon processes in H, E2 transitions in He

QUADRUPOLE TRANSITIONS AND RECOMBINATION

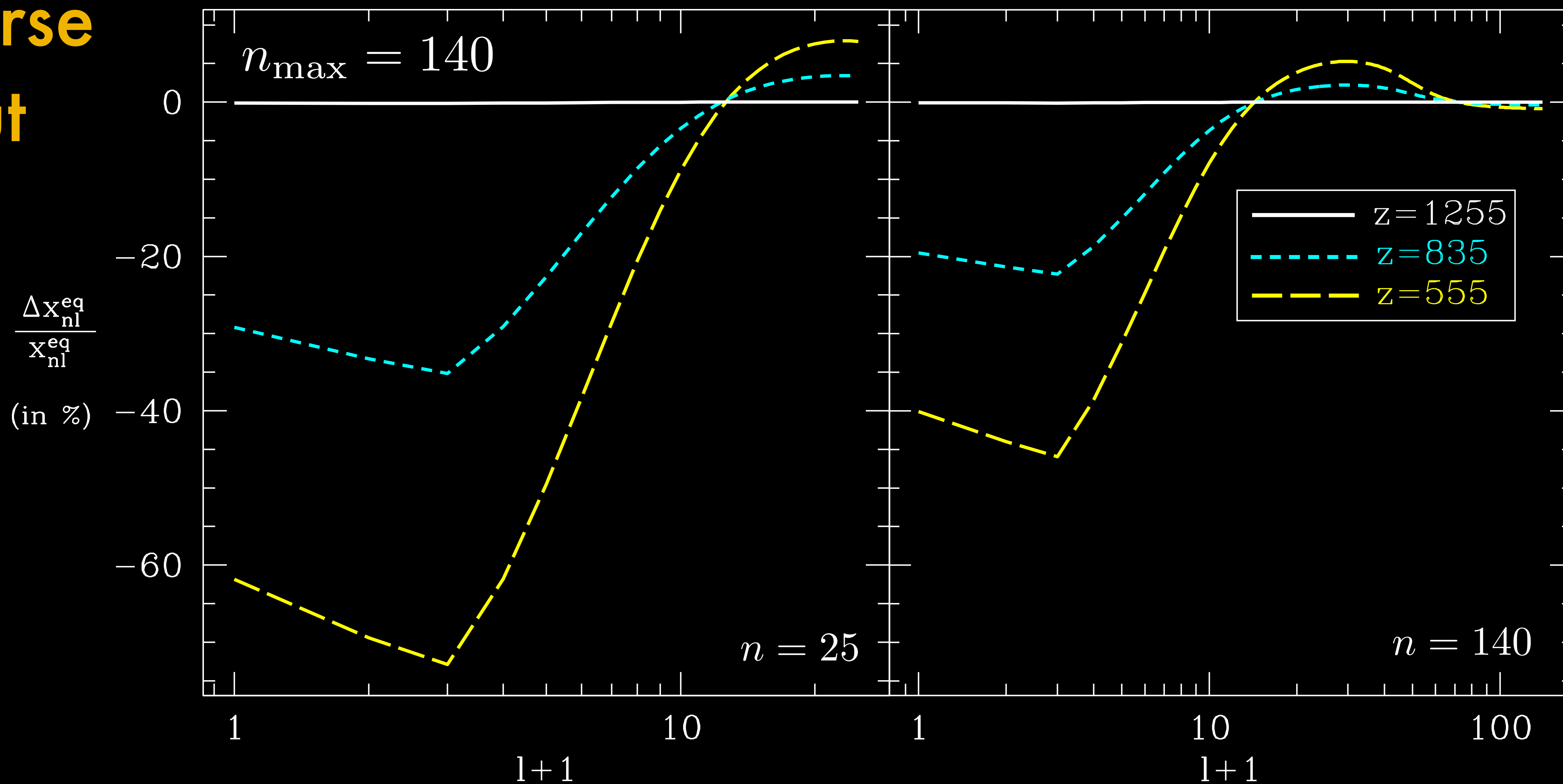
- Lyman lines are optically thick, so $nd \rightarrow 1s$ immediately followed by $1s \rightarrow np$, so this can be treated as an effective $d \rightarrow p$ process with rate $A_{nd\rightarrow 1s}x_{nd}$.

- Same sparsity pattern of rate matrix, similar to l-changing collisions

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

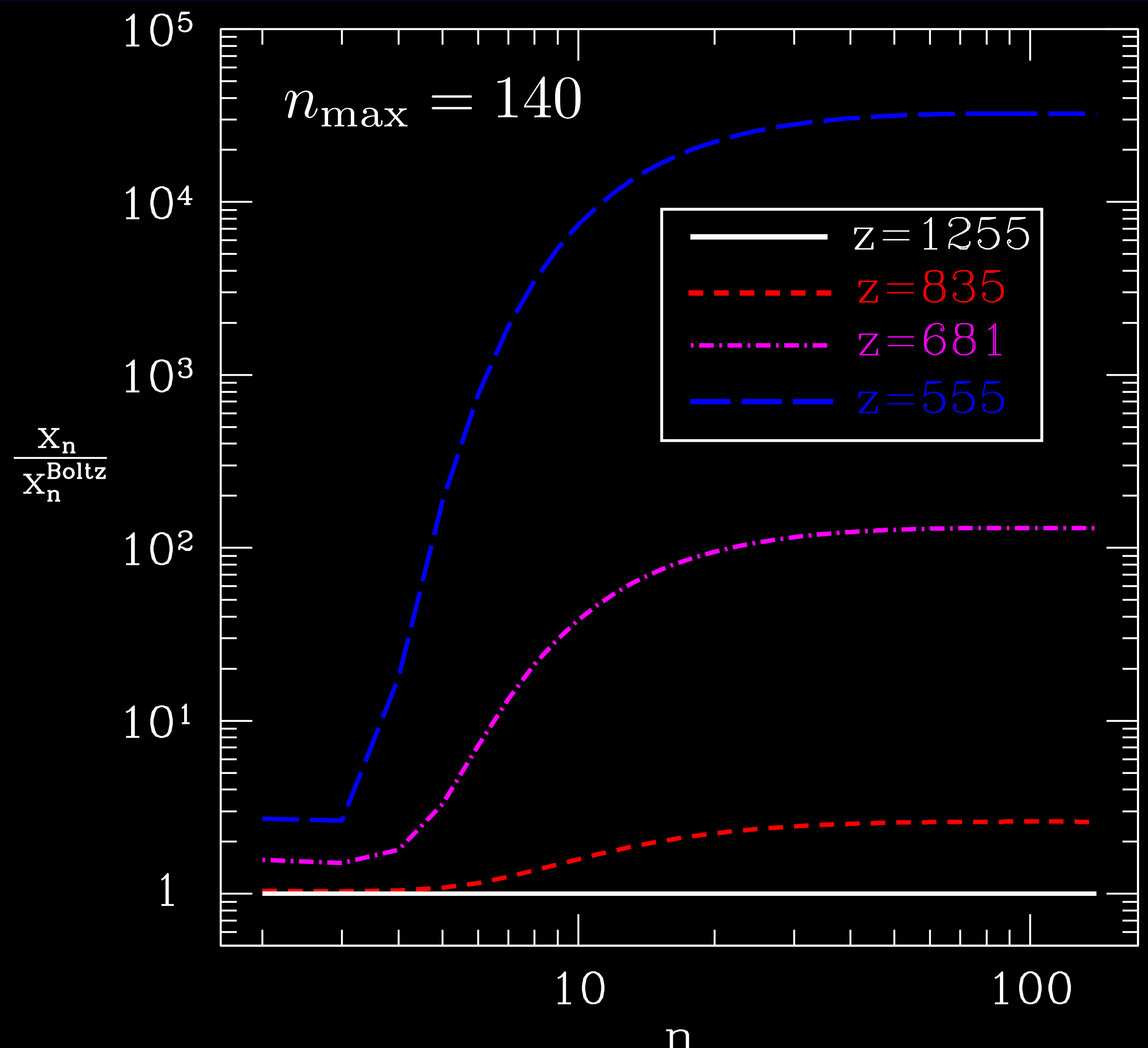
DEVIATIONS FROM BOLTZMANN EQ: L-SUBSTATES

RecSparse output



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

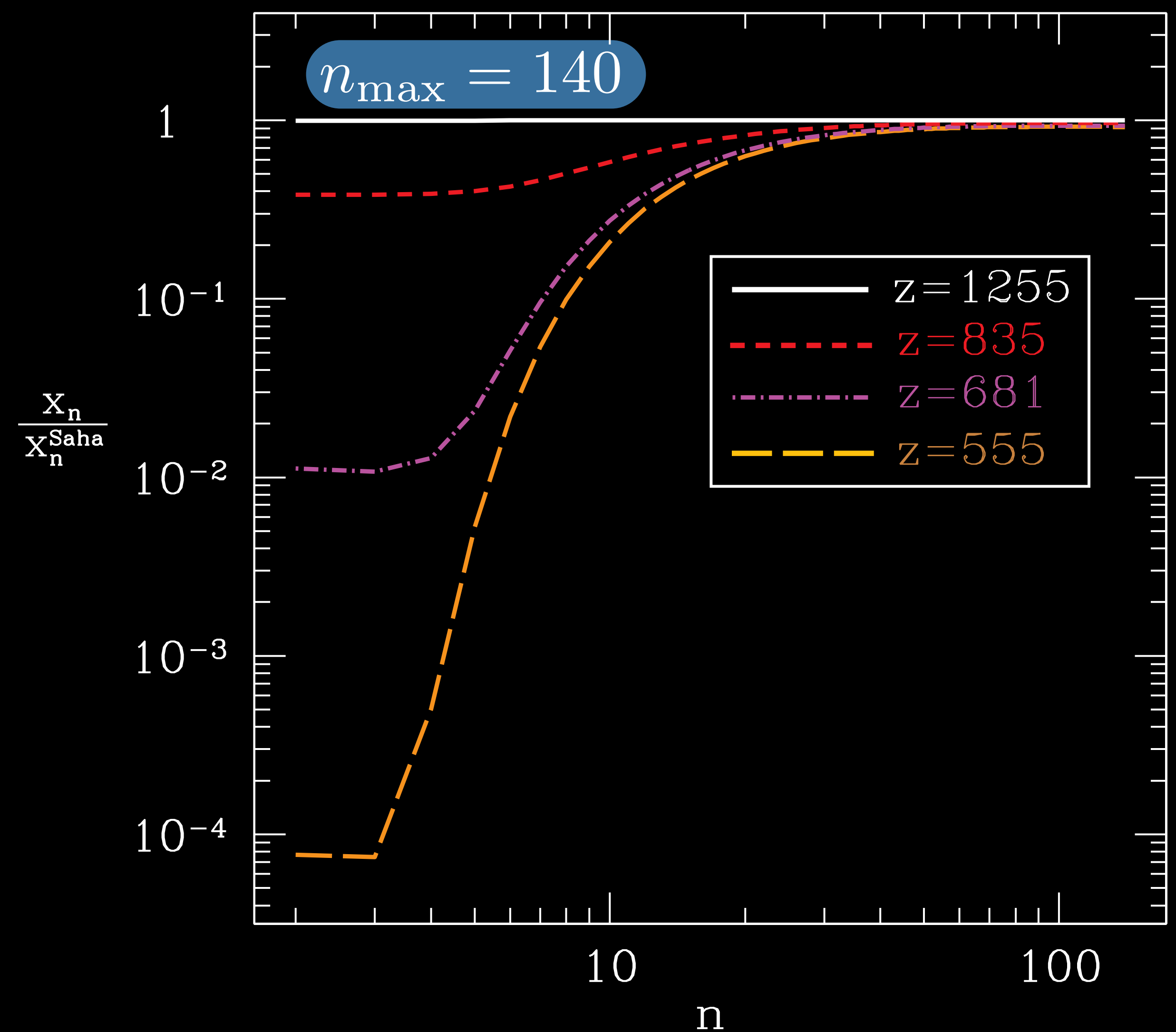
DEVIATIONS FROM BOLTZMANN EQUILIBRIUM: DIFFERENT N-SHELLS



Monday, September 27, 2010

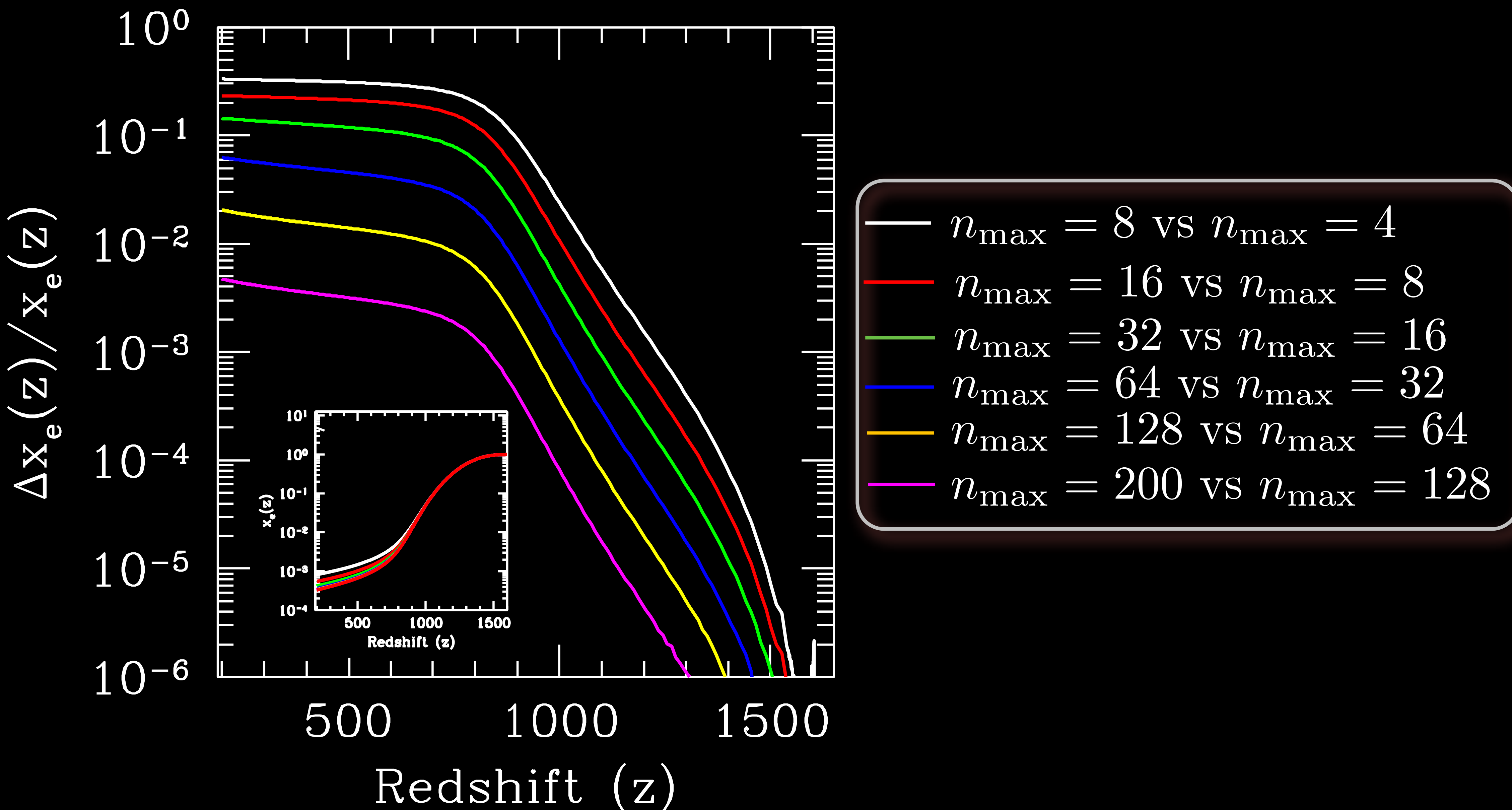
DEVIATIONS FROM SAHA EQUILIBRIUM

HUGE DEVIATIONS FROM SAHA EQ!



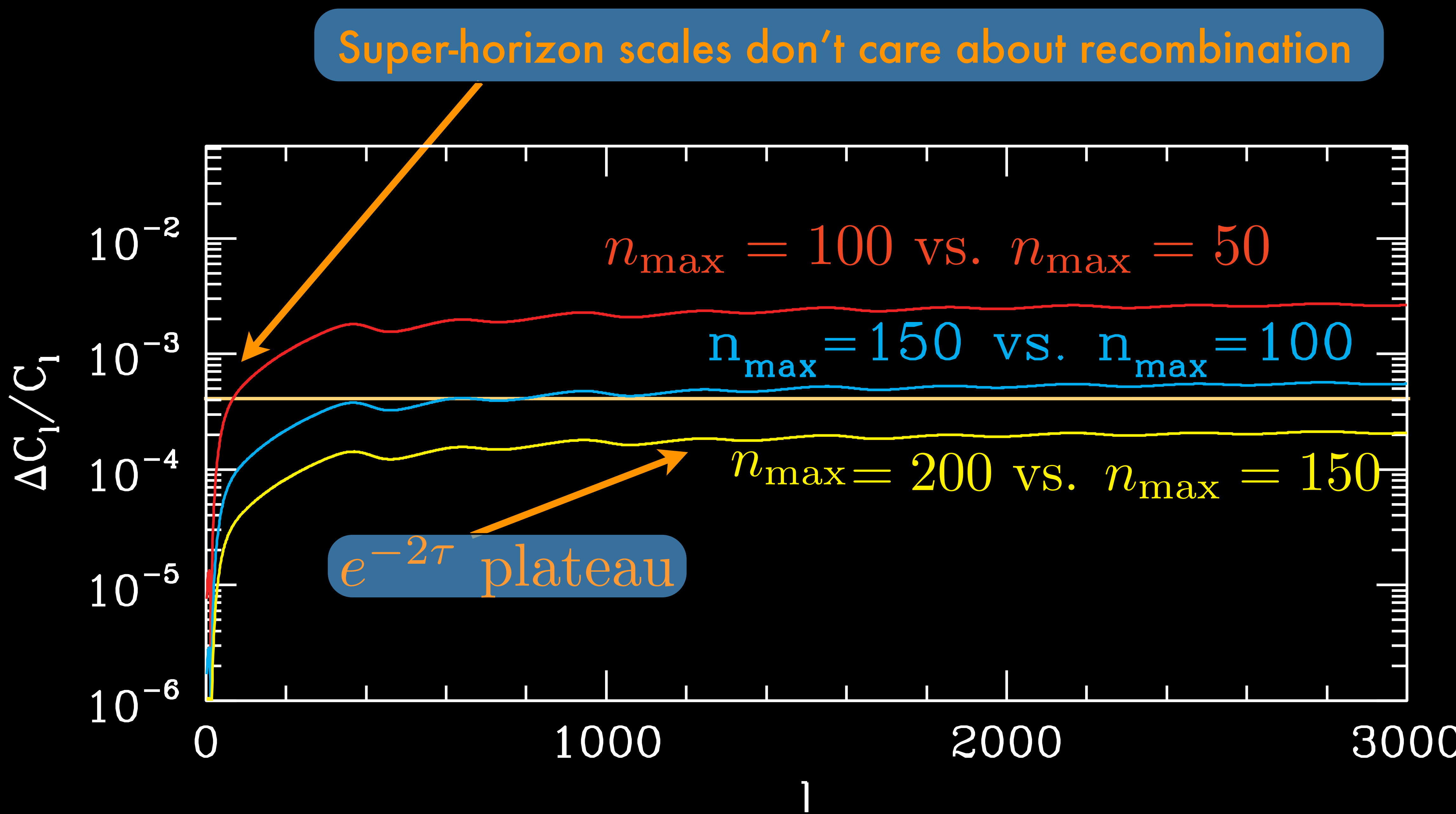
- n=1 suppressed due to freeze-out of x_e
- Remaining levels ‘try’ to remain in Boltzmann eq. with n=2
- Super-Boltz effects and two-γ transitions (n=1$\longrightarrow$ n=2) yield less suppression for n>1
- Effect larger at late times (low z) as rates fall

RESULTS: RECOMBINATION HISTORIES INCLUDING HIGH-N

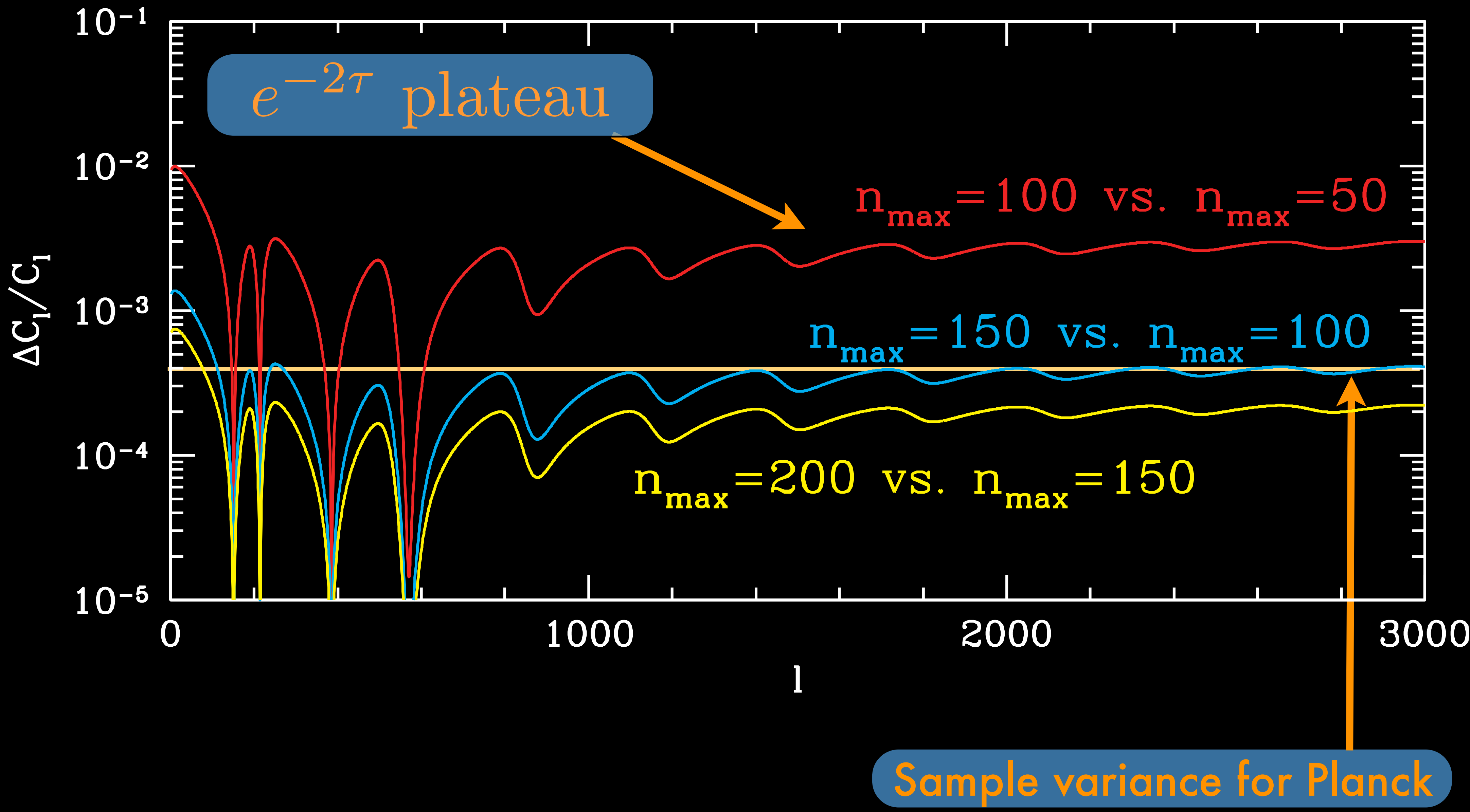


- $x_e(z)$ falls with increasing $n_{\max} = 10 \rightarrow 200$, as expected.
- Rec Rate>downward BB Rate> Ionization, upward BB rate
- For $n_{max} = 100$, code computes in only 2 hours

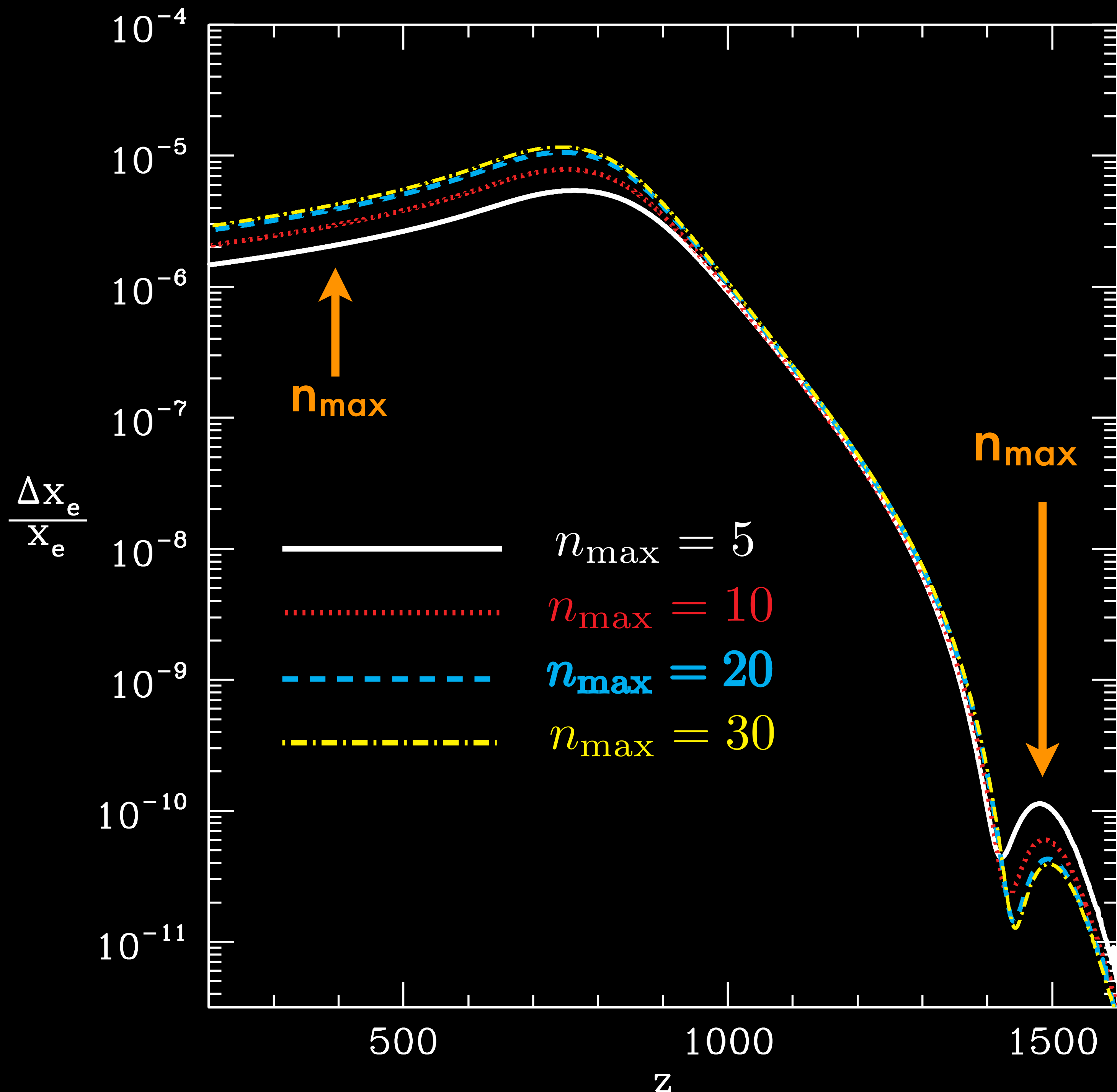
RESULTS: TT $C_l s$ WITH HIGH-N STATES



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



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!

WRAPPING UP

- RecSparse: a new tool for MLA recombination calculations (watch arXiv in coming weeks for a paper on these results)
  - Highly excited levels (n~150 and higher) are relevant for CMB data analysis
  - E2 transitions in H are not relevant for CMB data analysis
- To do: include collisions and line overlap in RecSparse
- Full incorporation into CosmoMC and analysis of errors/degeneracies with cosmo. parameters

Subtleties

- Non-equilibrium production
- $T_{\rm F} \gtrsim 200\ {\rm MeV}$ necessitates use of different cross sections
- At low values of $m_{\rm a}$, coherent oscillation may become important
- For very low $T_{\rm rh}$, ν may not have time to thermalize, and π may fall out of equilibrium
- All these effects negligible for $T_{\rm rh} \gtrsim 10\ {\rm MeV}$ and $m_{\rm a} \gtrsim 0.6\ {\rm eV}$

Kination

- Kination refers to an epoch (typically pre-BBN) during which the universe's energy budget is dominated by the *kinetic* energy of a scalar field

$$T/V = \dot{\phi}^2/2V(\phi) \gg 1 \rightarrow w = \frac{\dot{\phi}^2/2 - V(\phi)}{\dot{\phi}^2/2 + V(\phi)} \simeq 1$$
$$\rho \propto a^{-3(1+w)} \qquad H \propto T^3$$

- Kination may alleviate the challenges of EW baryogenesis and be relevant in quintessential inflation

- No entropy generation during kination, so kination complements LTR

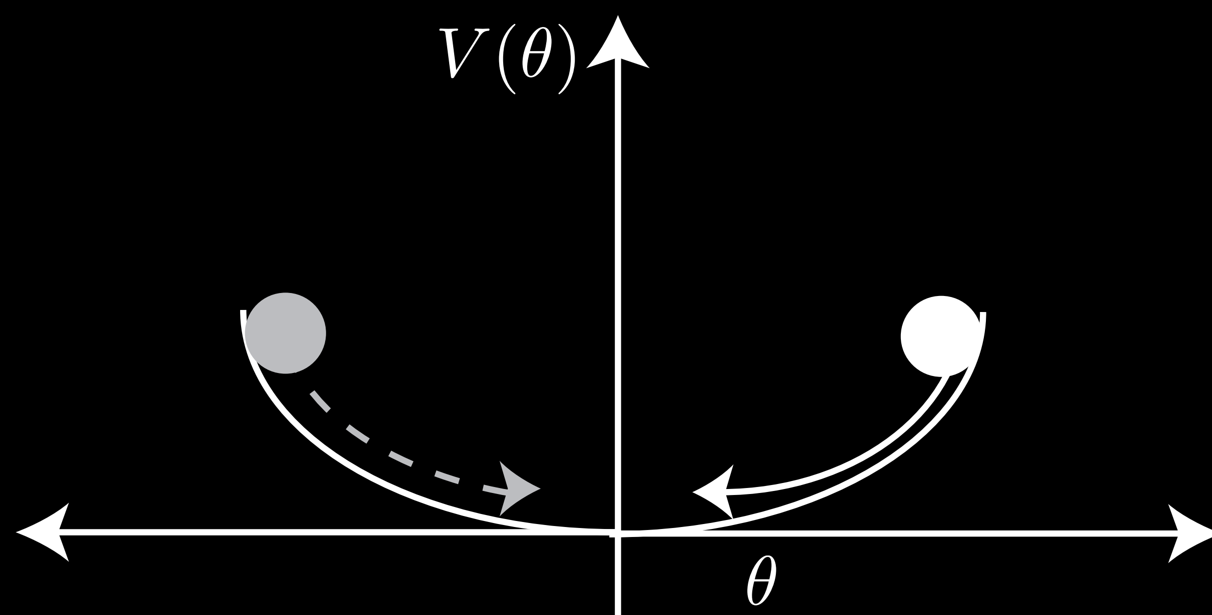
- Analysis does not rely on details of kination models, general for models with $H = H_{\rm rad}\left(T/T_{\rm kin}\right)$ until $T_{\rm kin}$, $H = H_{\rm rad}$ afterwards

- Past work considered neutralino abundance in kination models. *New work: LSS/CMB/total density constraints to hot axions in kination models*

New constraints

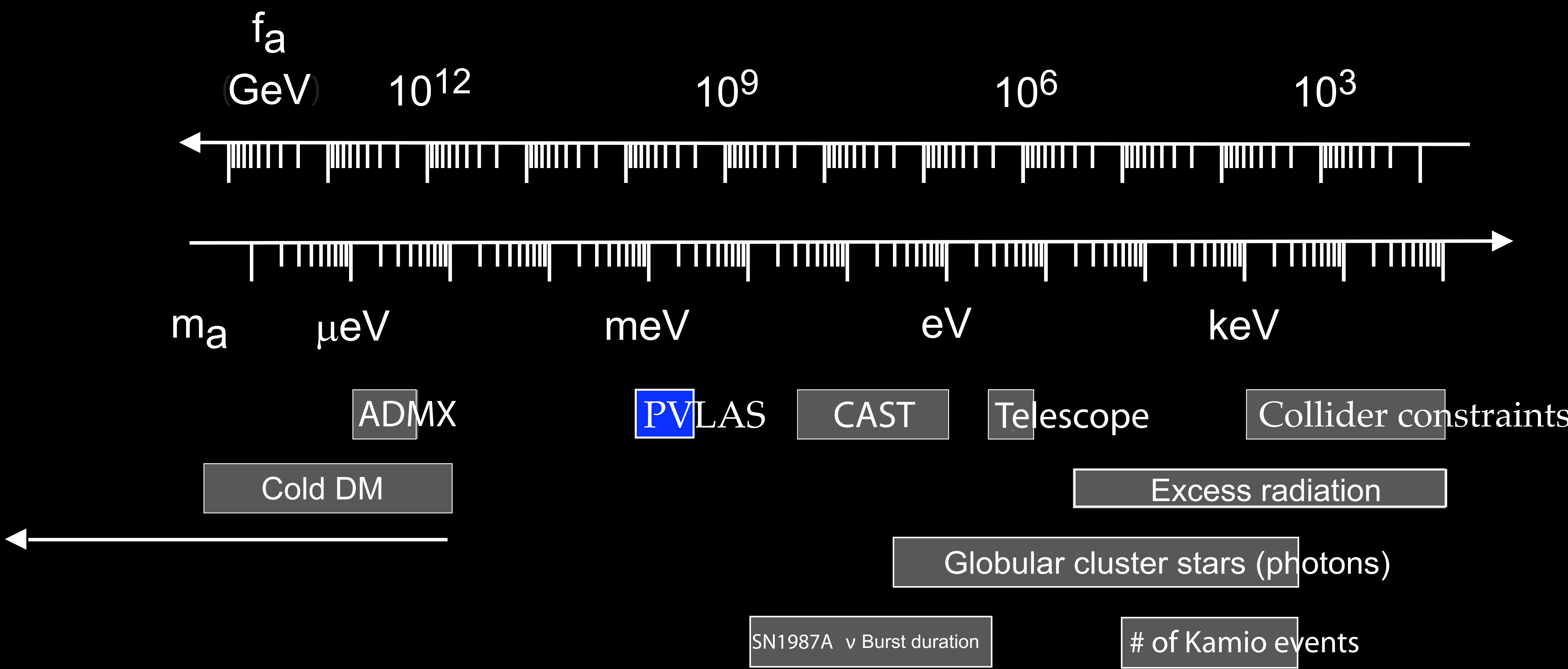
- In the case of kination, the new constraints are less dramatically different:
  If $T_{\rm kin} \simeq 10$ MeV, the allowed regions are $m_{\rm a} \lesssim 3.2$ eV and $17\ {\rm eV} \lesssim m_{\rm a} \lesssim 26\ {\rm eV}.$
  If $T_{\rm kin} \gtrsim 110$ MeV, standard results are recovered.

2 axion populations: Cold axions

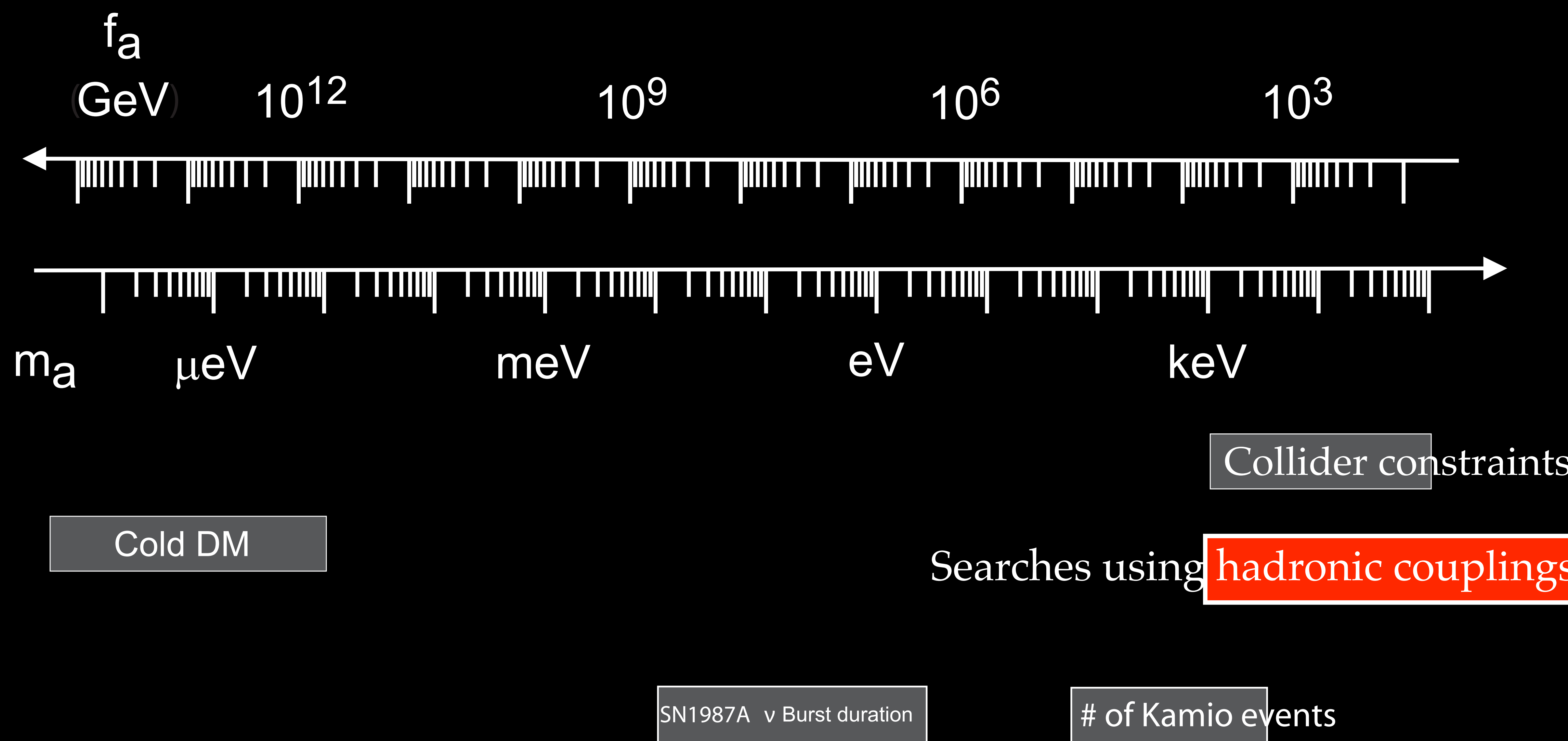


- Before PQ symmetry breaking, θ is generically displaced from vacuum value
- EOM: $\ddot{\overline{\theta}} + 3H\dot{\overline{\theta}} + m_{\mathrm{a}}^{2}(T)\,\overline{\theta} = 0$ $\quad m_{\mathrm{a}}(T) \simeq 0.1 m_{\mathrm{a}}(T=0)\,(\Lambda_{\mathrm{QCD}}/T)^{3.7}$
- After $m_{\mathrm{a}}(T) \gtrsim 3H(T)$, coherent oscillations begin, leading to $n_{\mathrm{a}} \propto a^{-3}$
- Relic abundance $\boxed{\Omega_{\mathrm{a}} h^{2} \simeq 0.13 \times g(\theta_0)\left(m_{\mathrm{a}}/10^{-5}\mathrm{eV}\right)^{-1.18}}$
- Particles are cold

Context: Axion constraints



Pitfalls of direct axion searches



✳ Searches using non-vanishing nuclear couplings (resonant detection of solar axions using Fe, Kr, and Li) yielding first results

✳ Other model independent constraints desirable

ORIGIN OF EFFECTS ON CMB POLARIZATION

- Need to scatter quadrapole to polarize CMB

$$\Theta_l^P\left(k\right) = \int d\eta \dot{\tau} e^{-\tau(\eta)} \Theta_{T,2}\left(k,\eta\right) \frac{l^2}{\left(k\eta\right)^2} j_l\left(k\eta\right)$$

- Need time to develop a quadrapole

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

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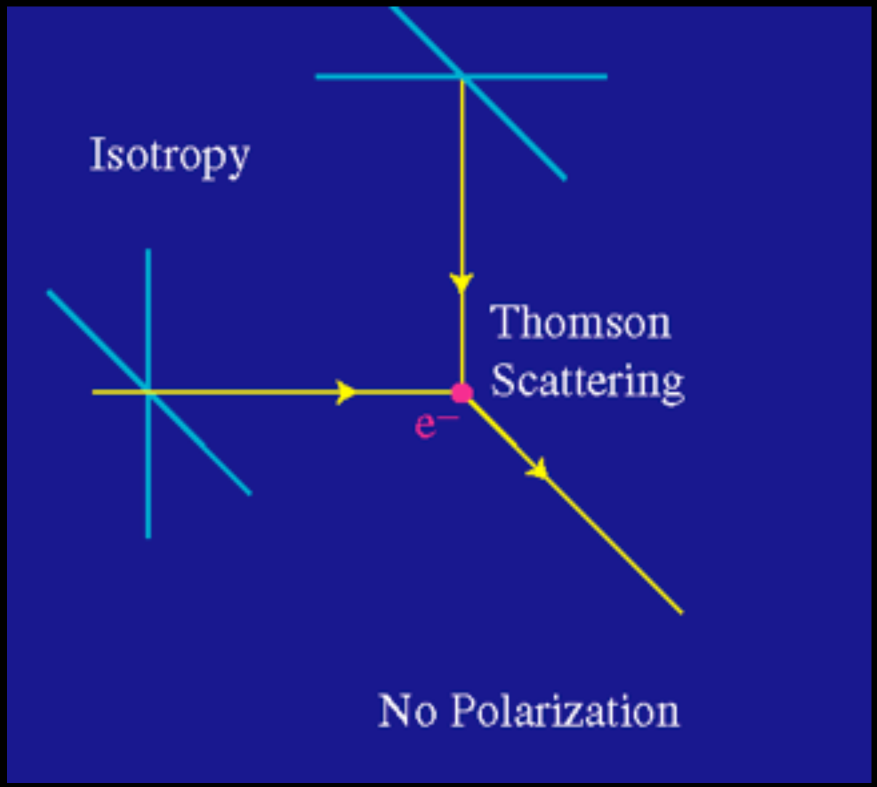

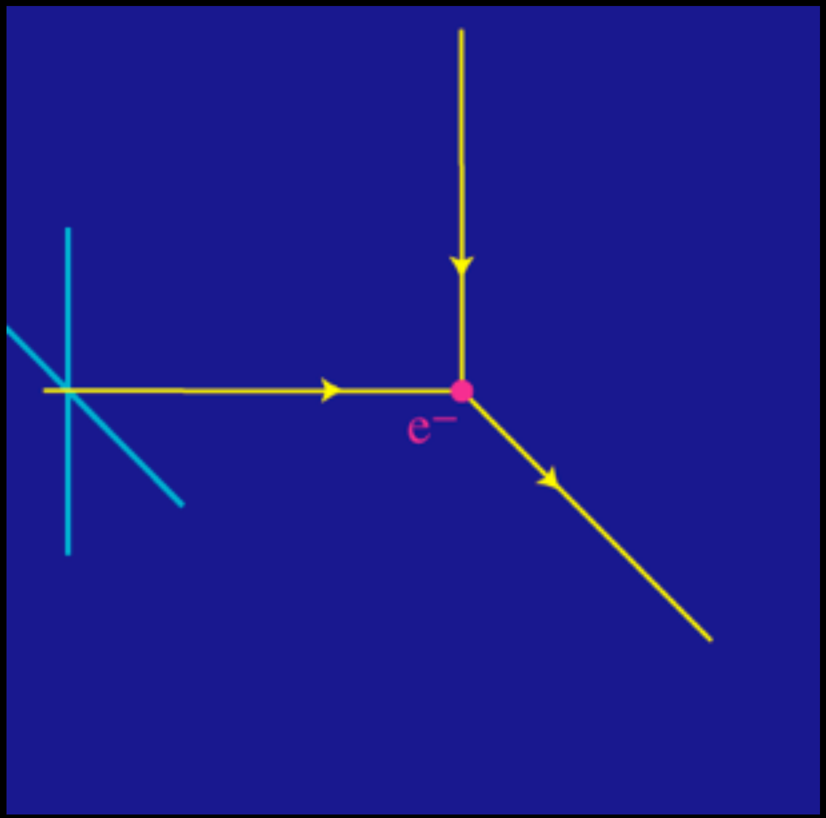

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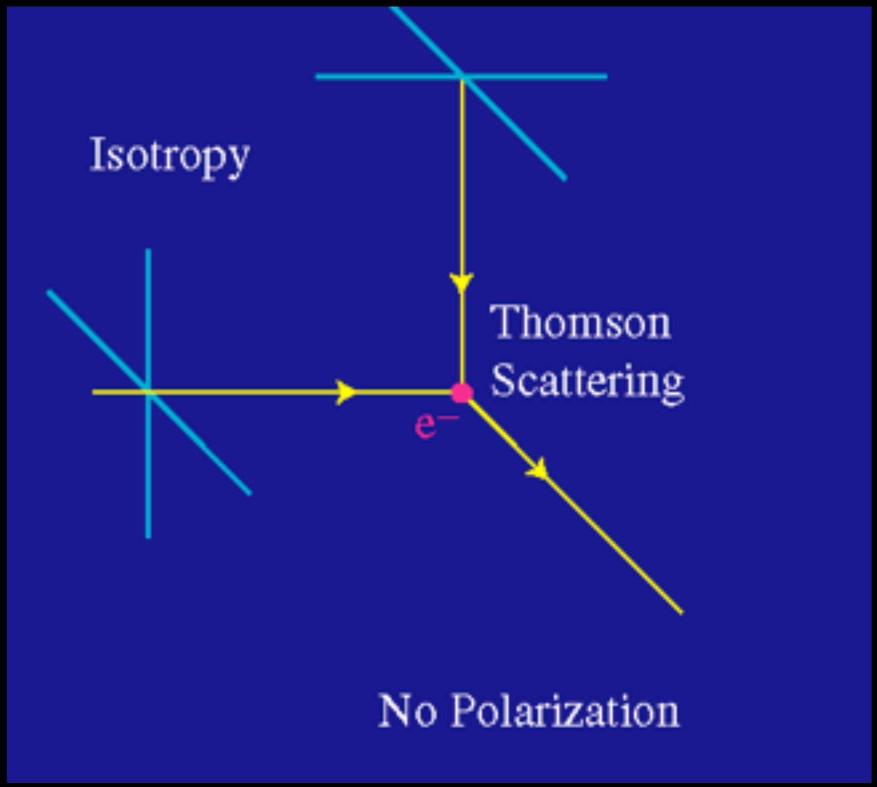

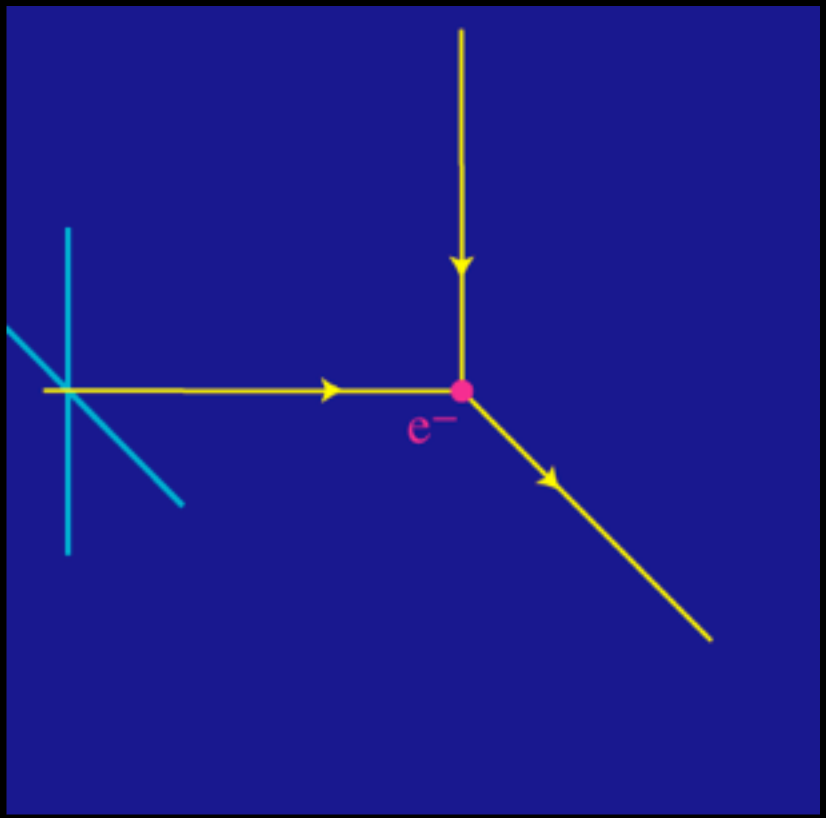

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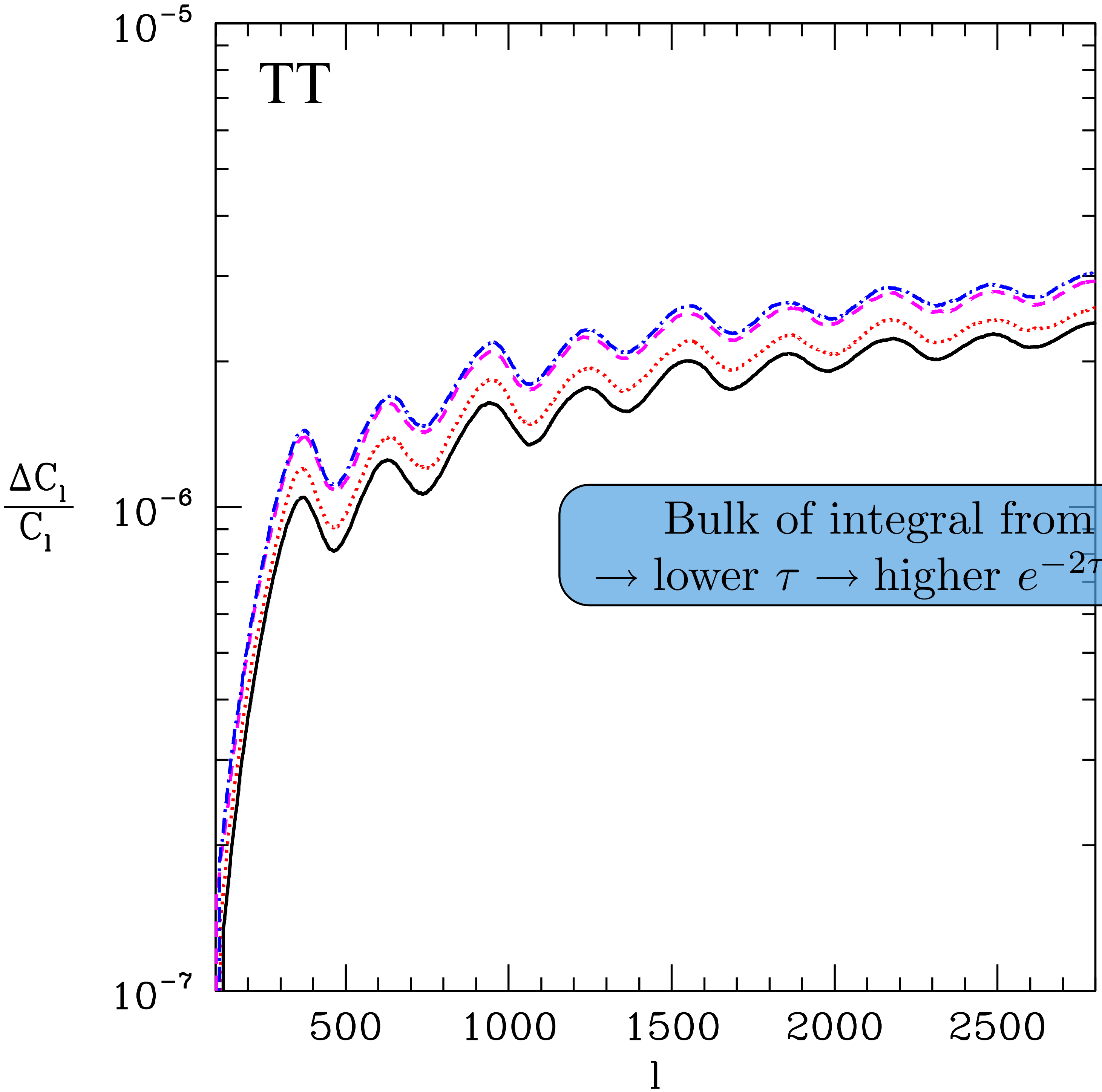
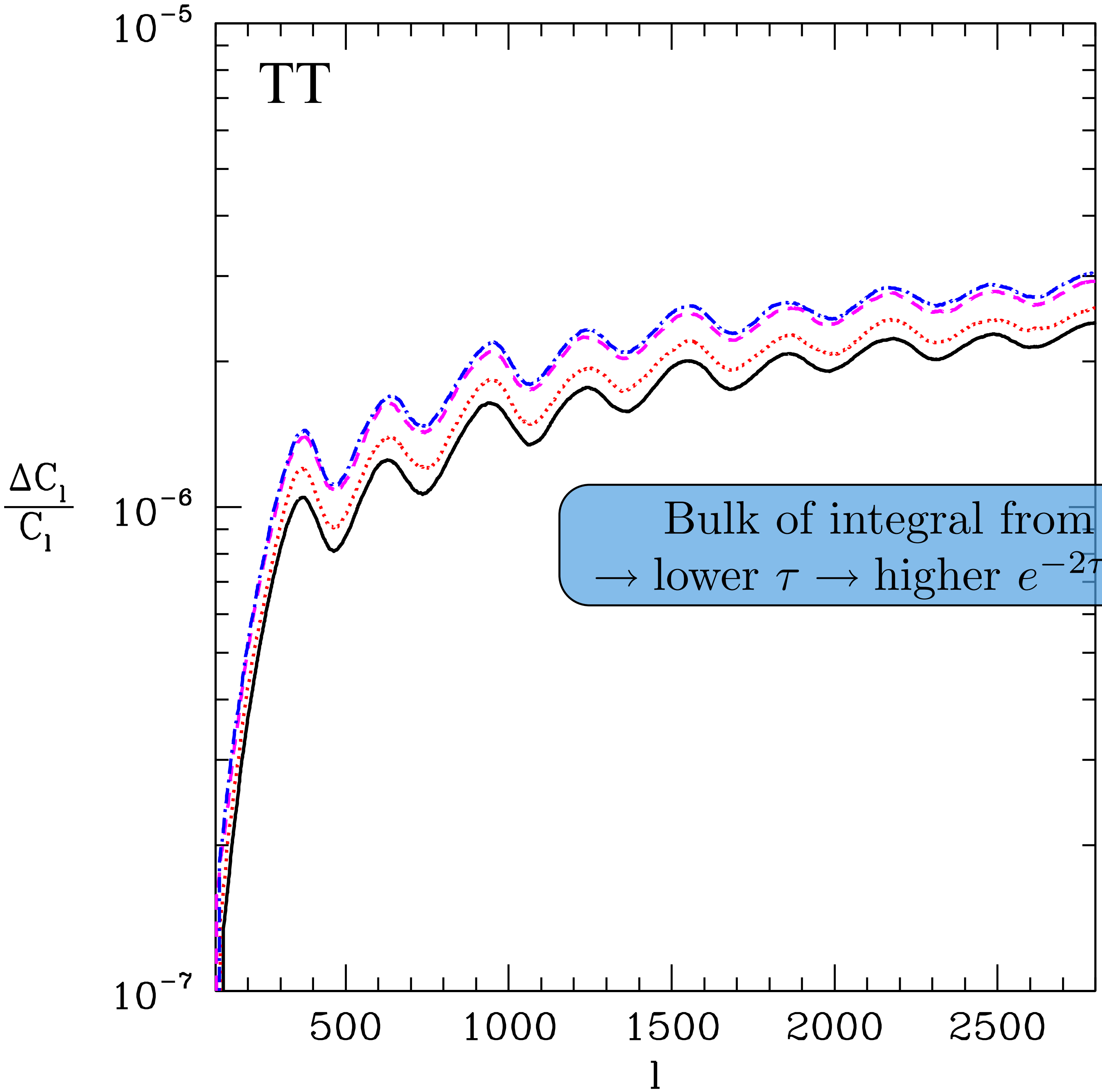
results: cmb anisotropies with hydrogen quadrupoles, temperature (tt) $C_l s$



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

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

results: cmb anisotropies with hydrogen quadrupoles, temperature (tt) $C_l s$



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Overall effect is negligible for upcoming CMB experiments!

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