Title: Understanding the Cosmic Recombination Epoch

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Abstract: TBA

Understanding the Cosmic Recombination Epoch

Christopher Hirata

May 4, 2010

Perimeter

Thanks to: Eric Switzer, Dan Grin, John Forbes, Yacine Ali-Haïmoud, Esfandiar Alizadeh

Outline

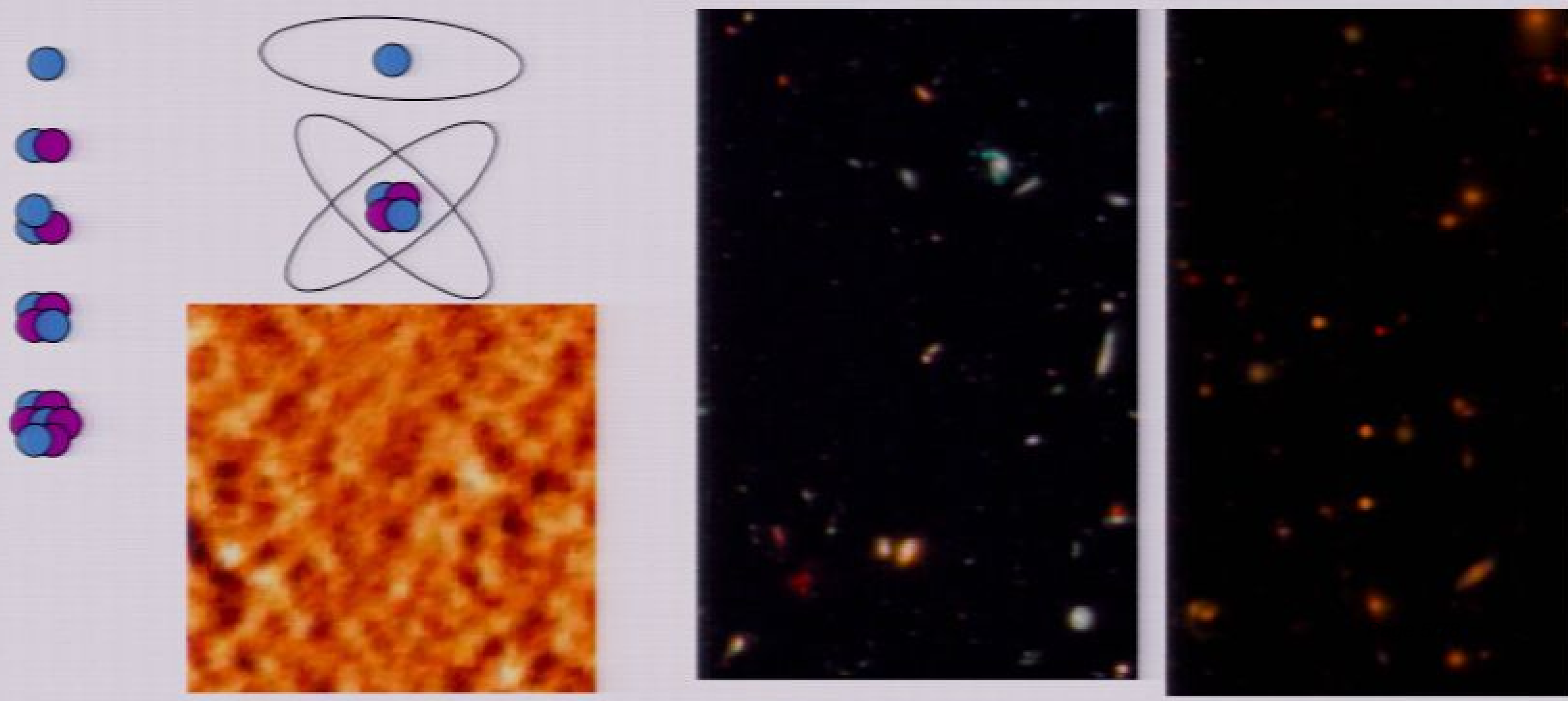
1. Recombination in the Cosmological Context
2. The Standard Picture
3. Precise Calculations
4. Testing the Theory

Recombination in the Cosmological Context

History of the Universe

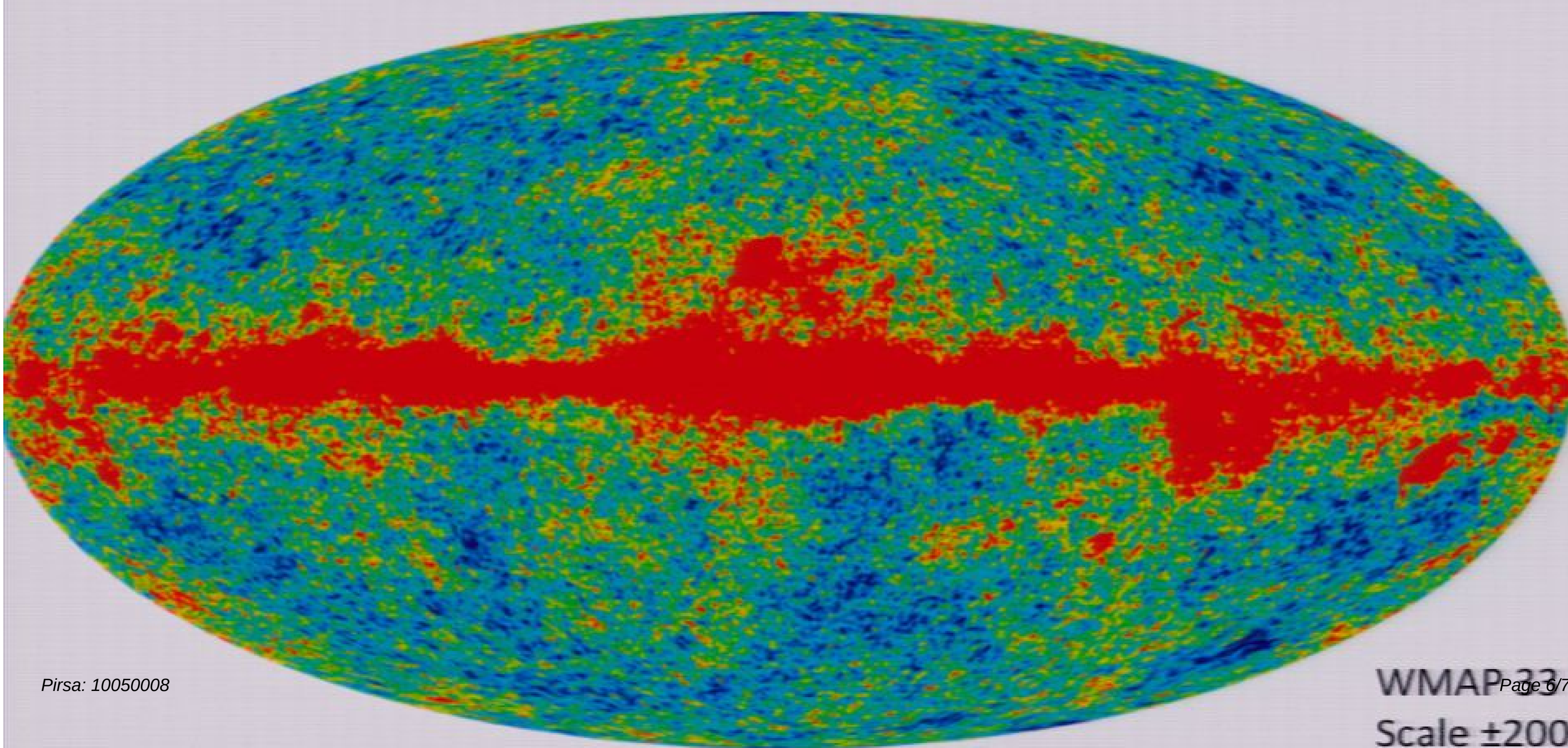
10^{-35} s? Inflation?	2×10^{2} s First nuclei	10^{13} s Recombination: First atoms **Universe becomes transparent**	~10^{16} s First stars and galaxies	2×10^{17} s Universe starts Accelerating	4×10^{17} s Today
	$T \sim 1$ GK, $z \sim 3\times10^{8}$	$T \sim 3000$ K, $z \sim 1100$	$T_{CMB} \sim 40$K, $z \sim 15$	$T_{CMB} = 5$K, $z = 0.7$	$T_{CMB} = 3$K, $z = 0$

?

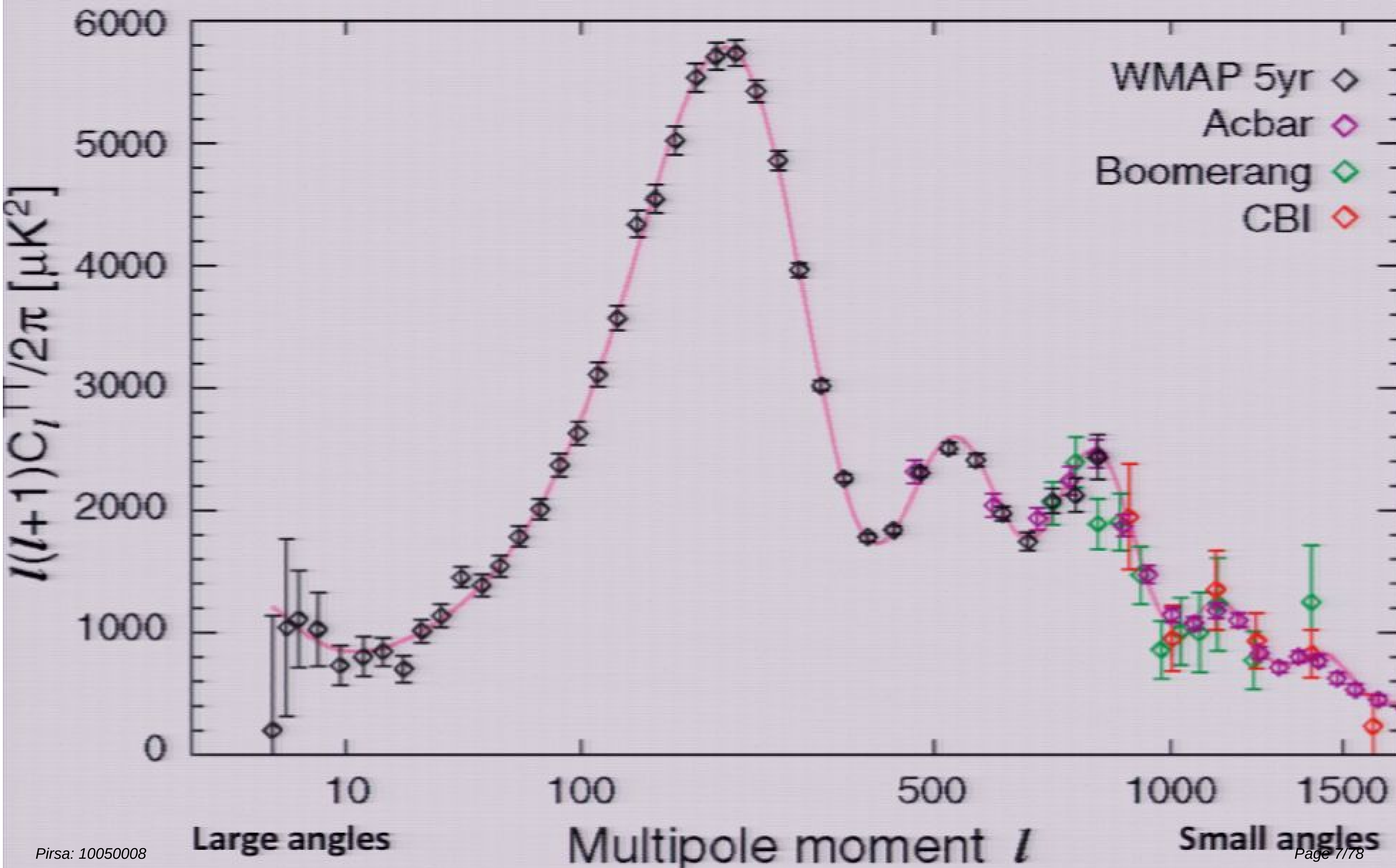


Cosmic Microwave Background Anisotropies

- Mean T = 2.7255±0.0006 K [Fixsen 2009].
- Small perturbations ~ 100 µK.



The Power Spectrum



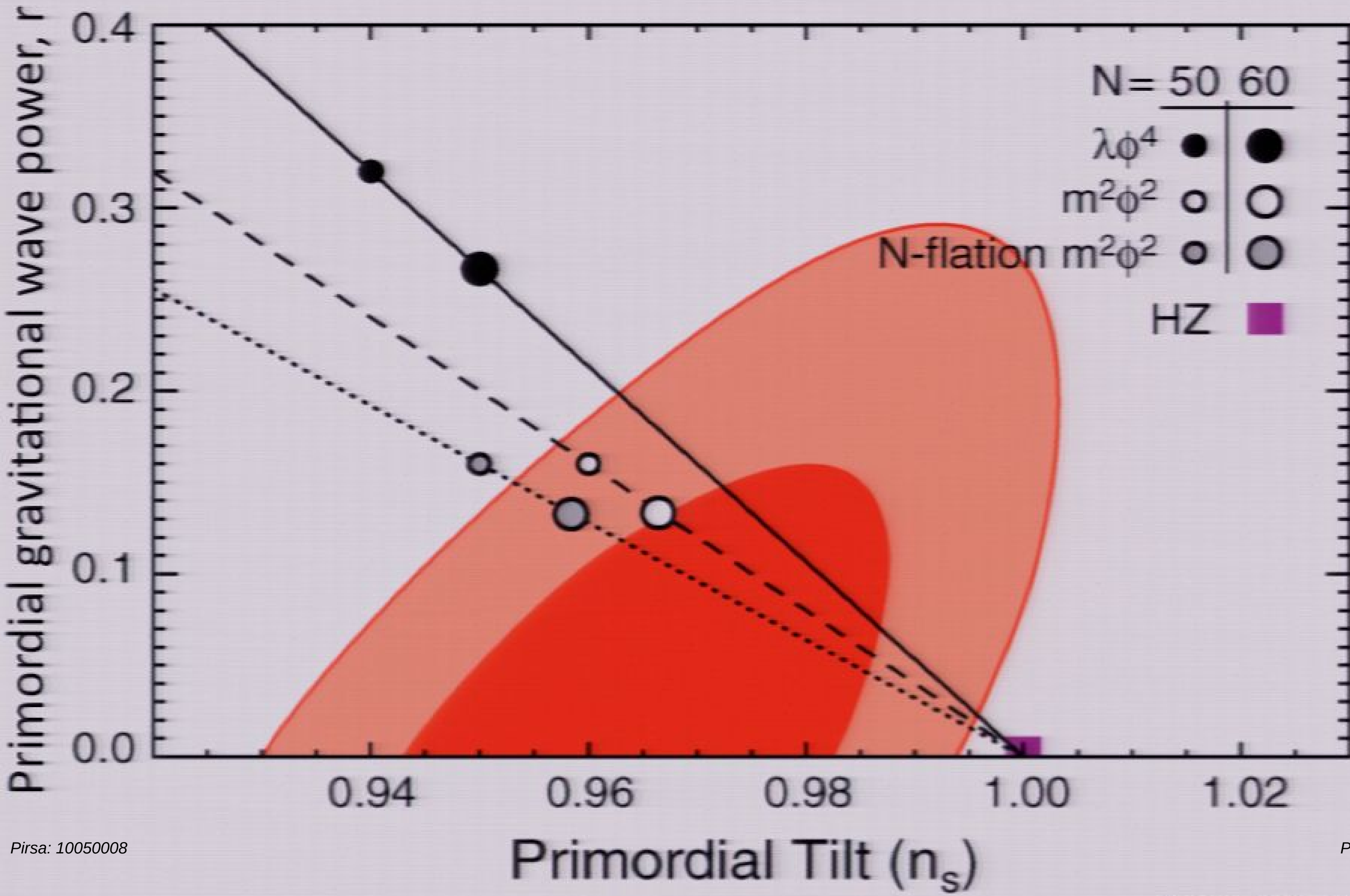
Primordial Inhomogeneities

- Density perturbations ("scalars"): the contribution from each logarithmic range in *k* is:

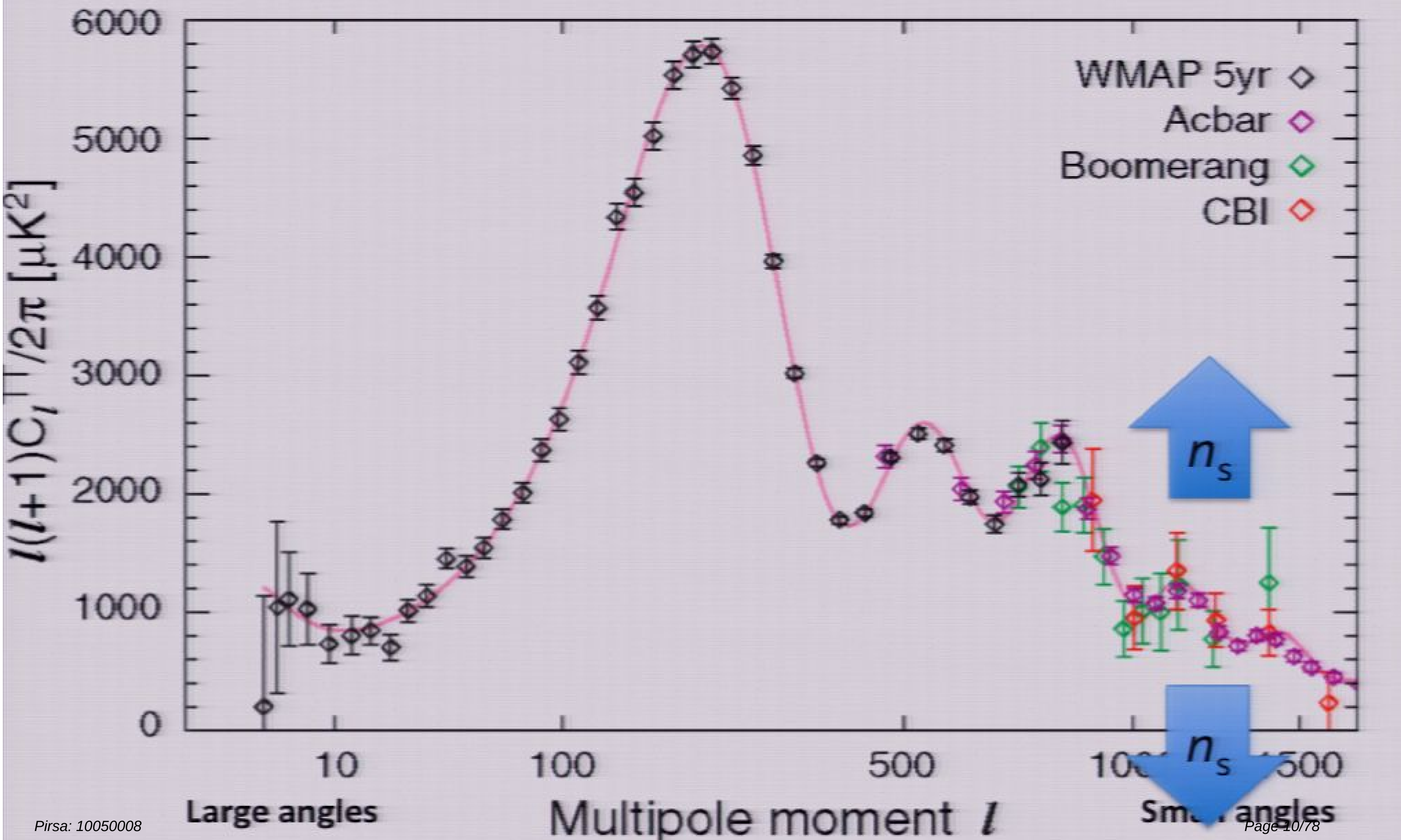
$$\mathrm{Var}\frac{\delta\rho}{\rho} \propto k^{n_s-1}.$$

- Most studied candidate to generate perturbations is inflation:
  - Period of nearly exponential expansion in very early Universe, powered by some new field (the "inflaton" ϕ).
  - $n_s \approx 1$ since each e-fold of expansion similar to the previous one ... but not quite since inflation must end.
  - Different models & alternatives populate (n_s,r) plane

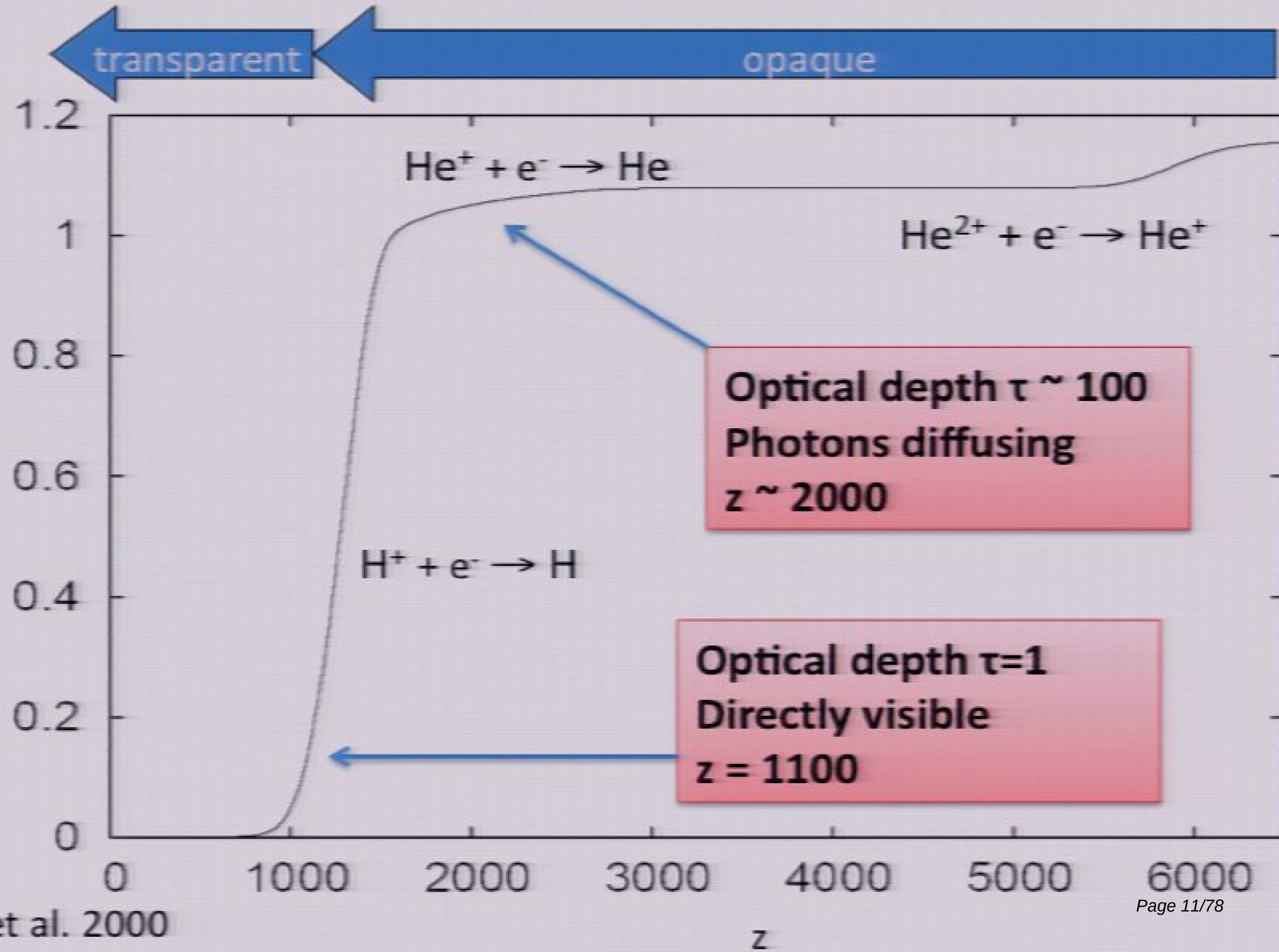
Tests of Inflation



Effects on the Power Spectrum



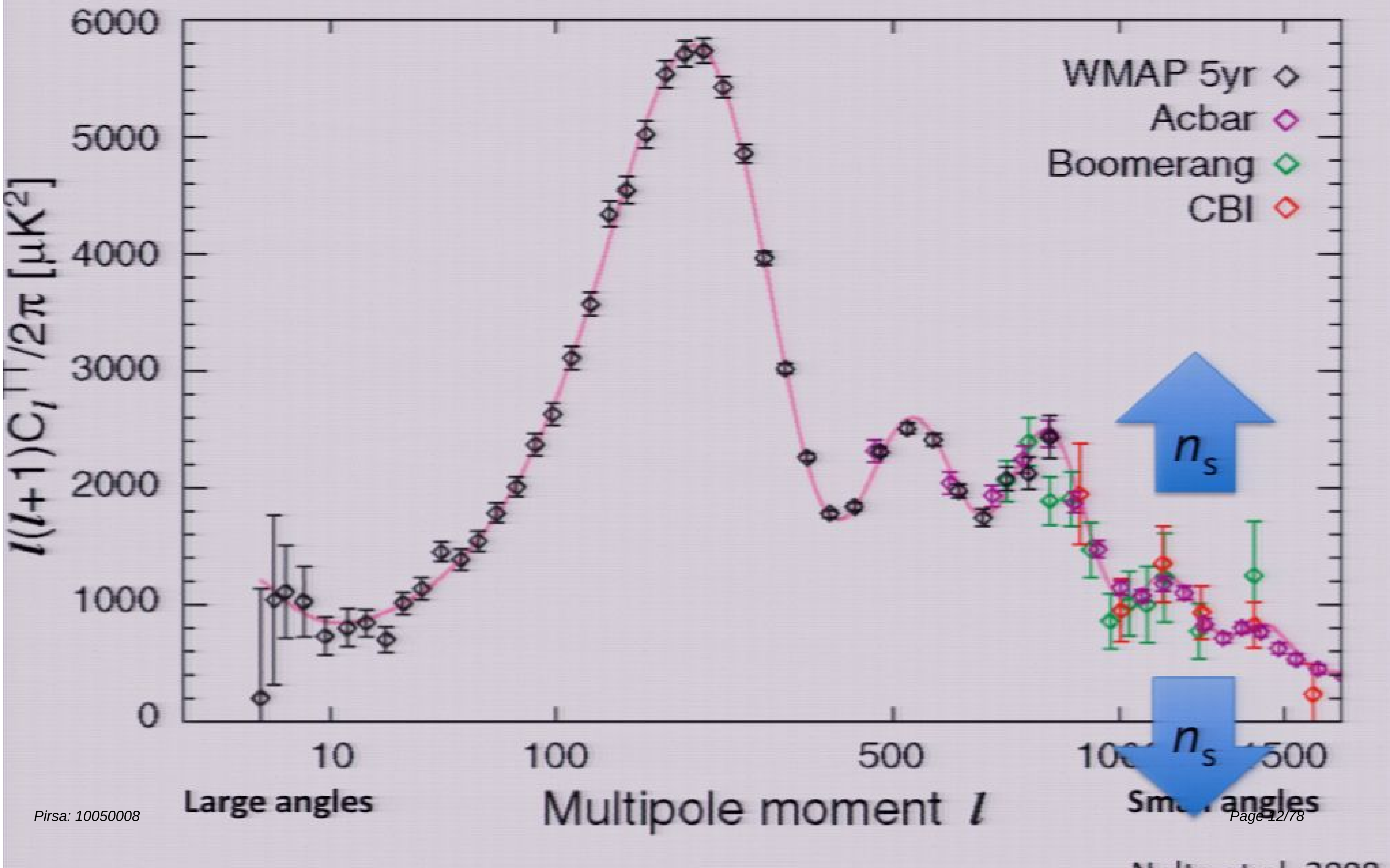
Standard Recombination History



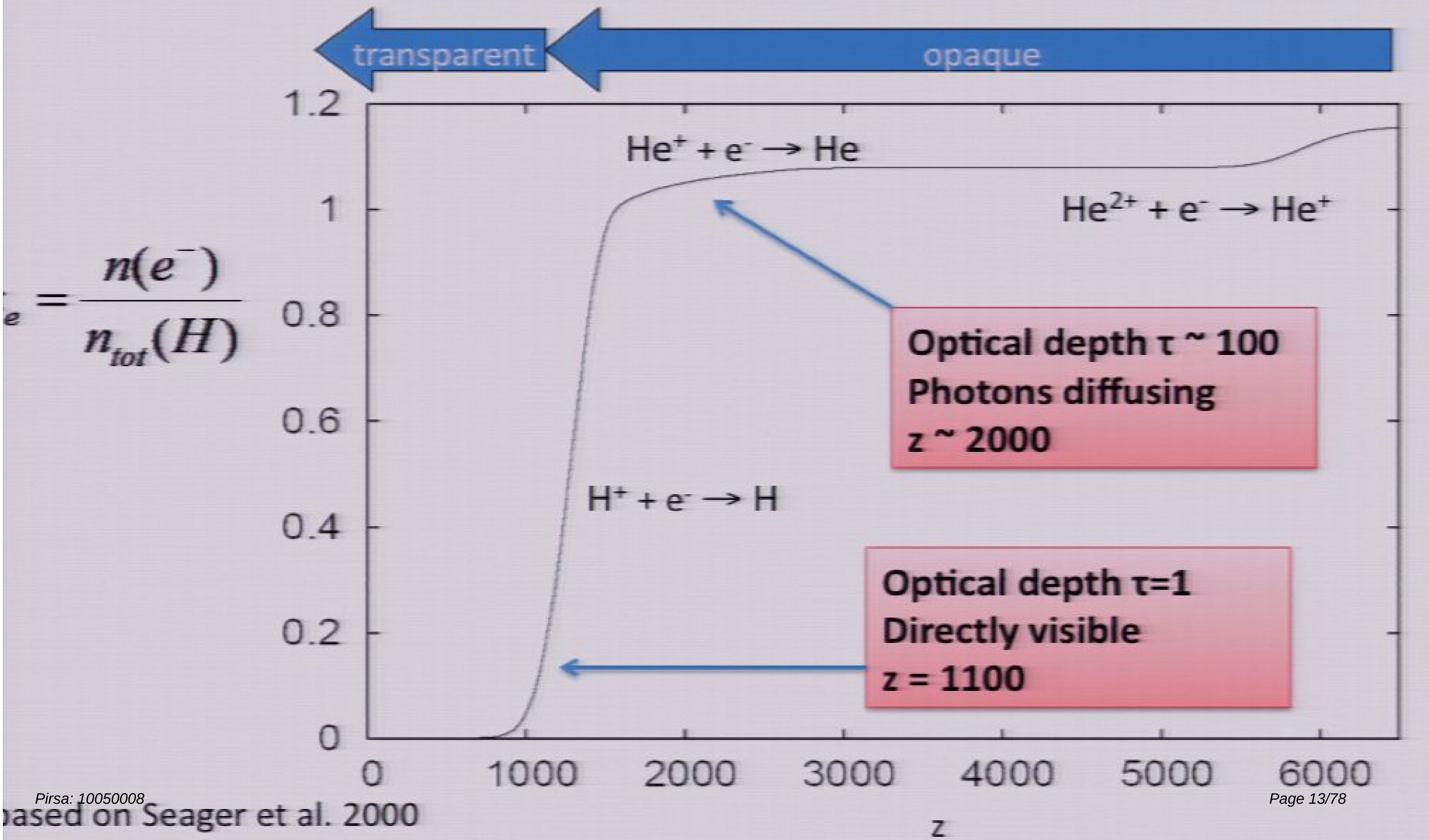
$$x_e = \frac{n(e^-)}{n_{tot}(H)}$$

based on Seager et al. 2000

Effects on the Power Spectrum



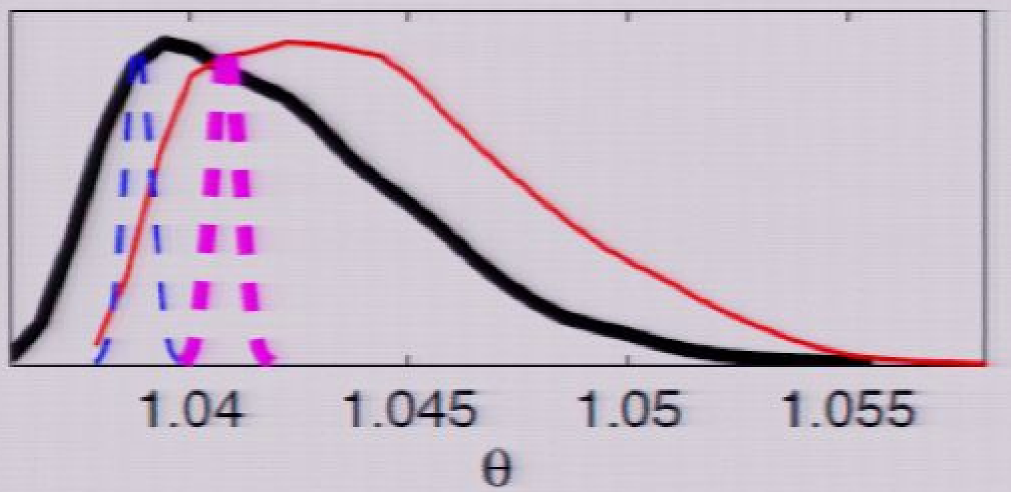
Standard Recombination History



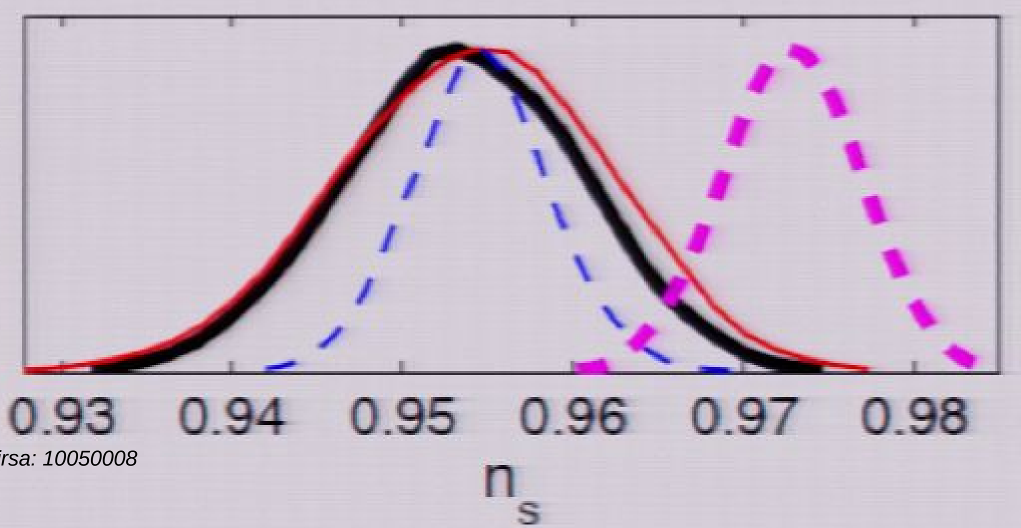
based on Seager et al. 2000

Effect on Parameter Estimation

[Lewis, Weller, Battye 2006]



Angular diameter distance measurement (CMB's contribution to dark energy constraints!)



Analysis of mock Planck data with two versions of the recombination Calculation

Blue → magenta contours

Basic Objective

- Provide theoretical computations of the recombination history of the Universe with sufficient accuracy for the next generation of CMB experiments (particularly Planck).

The Standard Picture of Cosmic Recombination

he Simplest (and First) H II Region in the Universe

- Cosmic recombination is a simple problem!
  - Homogeneous & isotropic (with 10^{-4} perturbations)
  - Expansion history from Friedmann equation
  - Composition: H + He, with small amounts of D, ^{3}He, Li (no dust)
  - Initially blackbody radiation field

Thermal Equilibrium

- Our first thought is to use the Saha equation:

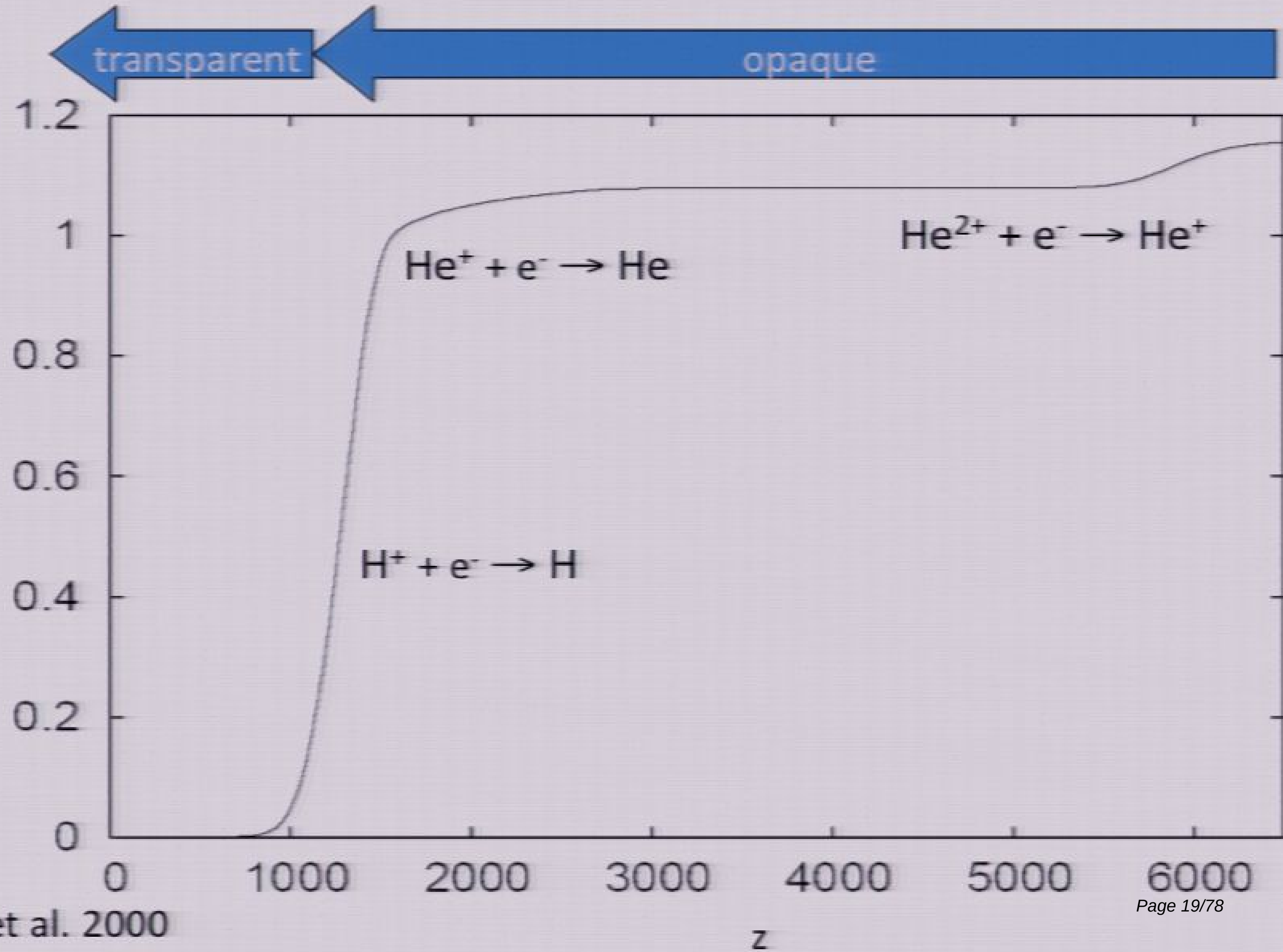
$$\frac{n(\mathrm{H},1s)}{n_e n_p} = \frac{x_{1s}}{n_\mathrm{H} x_e x_p} = \left(\frac{2\pi m_e kT}{h^2}\right)^{-3/2} e^{hR/kT}$$

- Prediction: 50% of H recombined by z=1370, 90% by z=1250, 99% by z=1140.

- But the real Universe recombines out of equilibrium (even though αn>>H). v1.0 due to Peebles 1968; Zel'dovich, Kurt, Sunyaev 1968

Standard Recombination History

$$ {}_{e} = \frac{n(e^{-})}{n_{tot}(H)} $$



ased on Seager et al. 2000

The Process

- H cannot recombine directly because the Universe becomes opaque to ionizing photons:

$$H^+ + e^- \rightarrow H(1s) + \gamma \qquad h\nu > 13.6\ \text{eV}$$
$$H(1s) + \gamma \rightarrow H^+ + e^-$$

- Therefore recombination occurs in smaller steps involving excited states, e.g.:

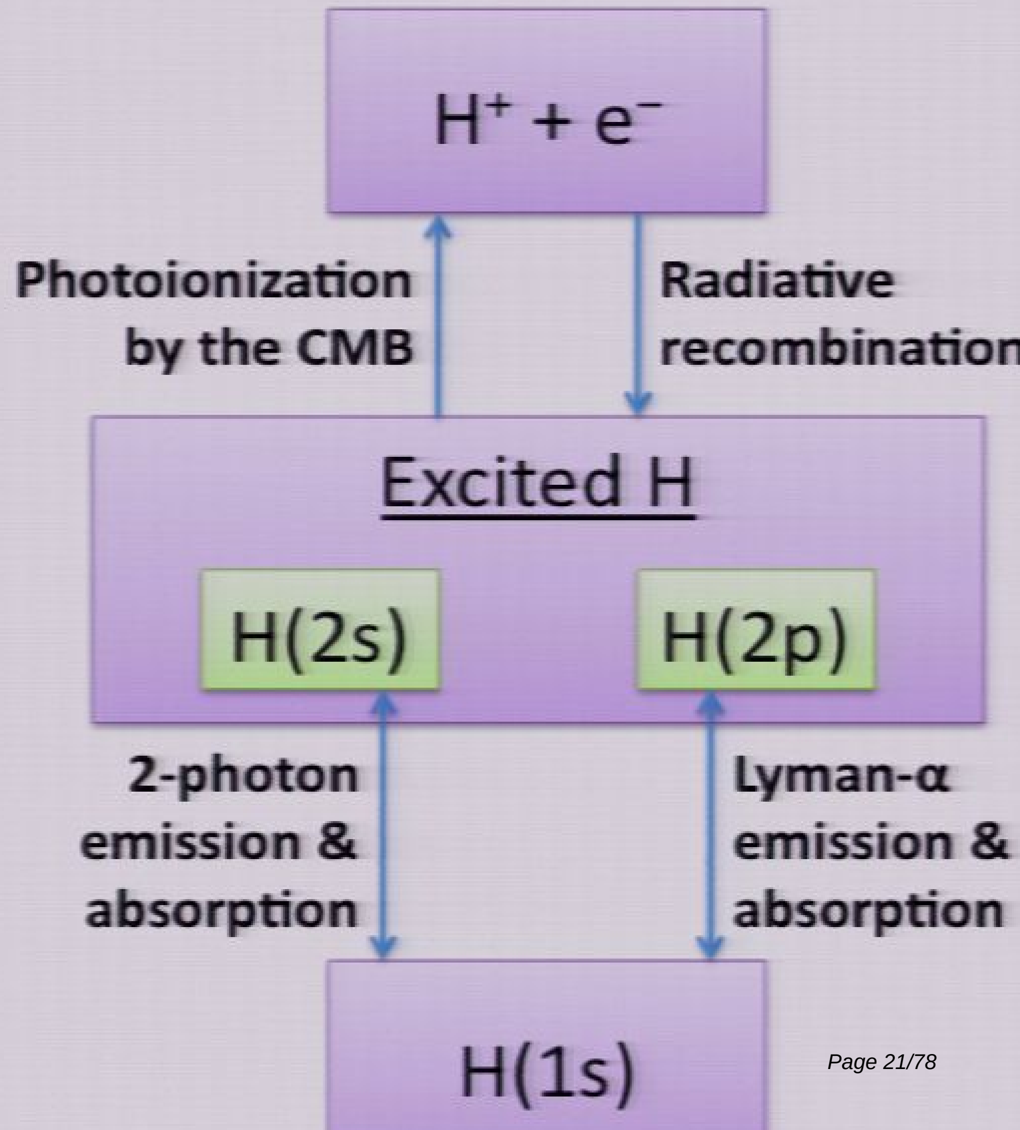
$$H^+ + e^- \rightarrow H(2p) + \gamma$$
$$H(2p) \rightarrow H(1s) + \gamma$$

- Similar to Case B recombination in the ISM – except for the presence of CMB.

The Process

- Original analysis assumed excited levels of H rapidly redistributed into Boltzmann equilibrium. (Removed in modern codes.)
- Ultimate routes to ground state:

$$H(2p) \leftrightarrow H(1s) + \gamma(\mathrm{Ly}\alpha)$$
$$H(2s) \leftrightarrow H(1s) + \gamma + \gamma.$$



Stage I: Forming Excited H

- The production rate of excited H atoms (per H nucleus per unit time) is:

$$\dot{x}(\mathrm{H}^*)\big|_{\mathrm{rec}} = \alpha_{\mathrm{B}} n_{\mathrm{H}} x_e x_p$$

- We can compute photoionization by the CMB using the principle of detailed balance:

$$\dot{x}(\mathrm{H}^*)\big|_{\mathrm{rec+pi}} = \alpha_{\mathrm{B}}\left[n_{\mathrm{H}} x_e x_p - \frac{2}{Z(\mathrm{H}^*)}\left(\frac{2\pi m_e kT}{h^2}\right)^{3/2} e^{-hR/4kT} x(\mathrm{H}^*)\right]$$

  - Photoionization term gives no net production in Saha equilibrium
  - $Z(\mathrm{H}^*)$ = partition function, R = Rydberg

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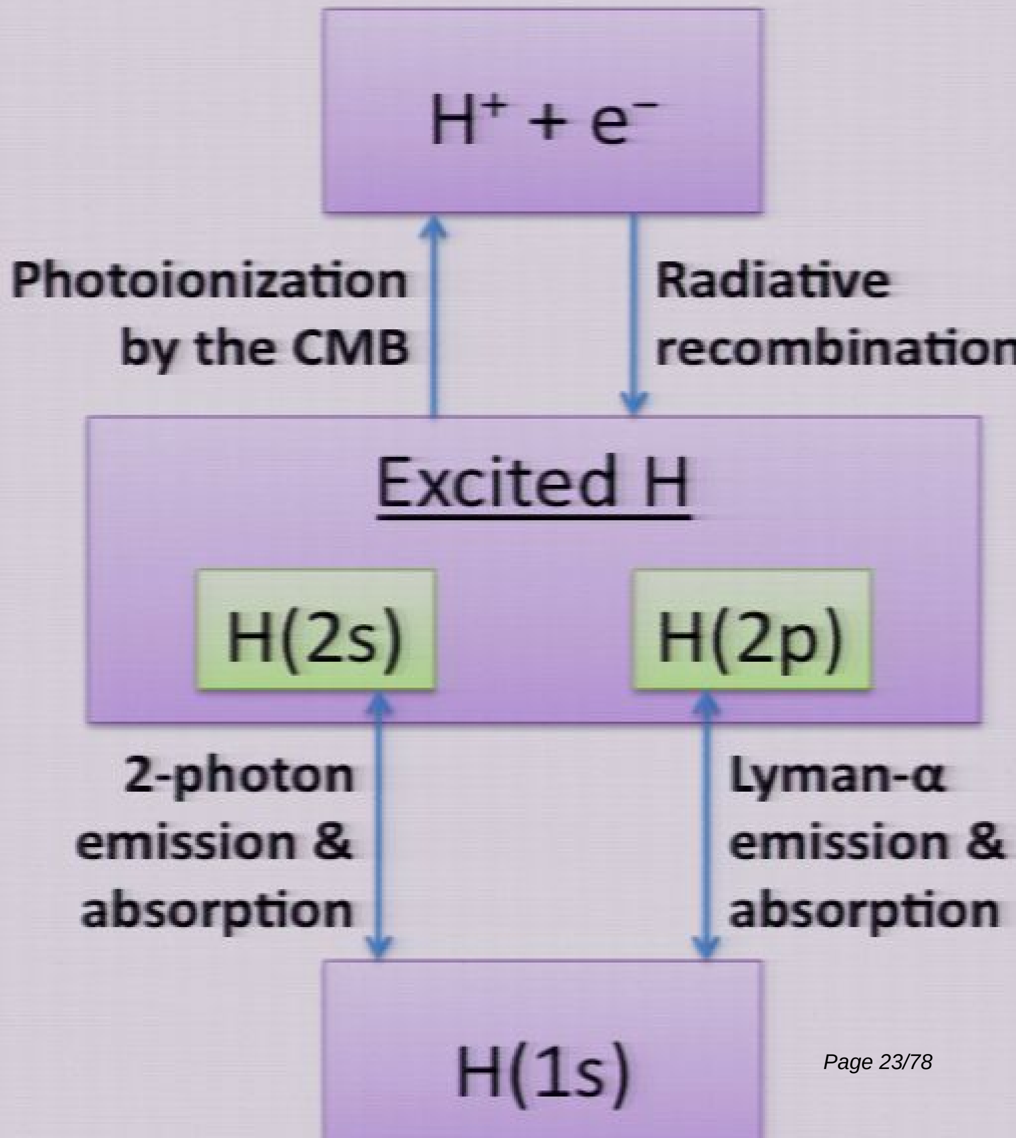

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  – Photoionization term gives no net production in Saha equilibrium
  – $Z(\mathrm{H}^*)$ = partition function, R = Rydberg

Stage II: Reaching the Ground State

- Two pathways:
  - 2γ
  - Lyman-α
- The raw 2s two-photon decay rate is:

$$\dot{x}_{1s}\big|_{2\gamma\downarrow} = \Lambda_{2s} x_{2s}, \qquad \Lambda_{2s} = 8.2\mathrm{s}^{-1}.$$

- Using the principle of detailed balance, we can compute the correction associated with 2γ absorption, H(1s)+γ+γ→H(2s).

$$\dot{x}_{1s}\big|_{2\gamma} = \Lambda_{2s}(x_{2s} - e^{-3hR/4kT} x_{1s}) = \Lambda_{2s}\left[\frac{2}{Z(\mathrm{H}^*)} x(\mathrm{H}^*) - e^{-3hR/4kT} x_{1s}\right]$$

Stage II: Reaching the Ground State

- Lyman-α is trickier because the line is optically thick: emitted photons are almost immediately re-absorbed.
- Within the line, an equilibrium is reached between absorption and emission:

$$\mathrm{H(2p)} \leftrightarrow \mathrm{H(1s)} + \gamma(\mathrm{Ly}\alpha)$$

$$Ax_{2p} = 3Ax_{1s}f(\mathrm{Ly}\alpha)$$

$$f(\mathrm{Ly}\alpha) = \frac{x_{2p}}{3x_{1s}} = \frac{2x(\mathrm{H}^*)}{Z(\mathrm{H}^*)x_{1s}}$$

- A net reaction requires removal of Lyα photons. Remember: no dust, no metals, no outer boundary, ...
- But the Universe is expanding: photons can redshift out of Lyman-α.

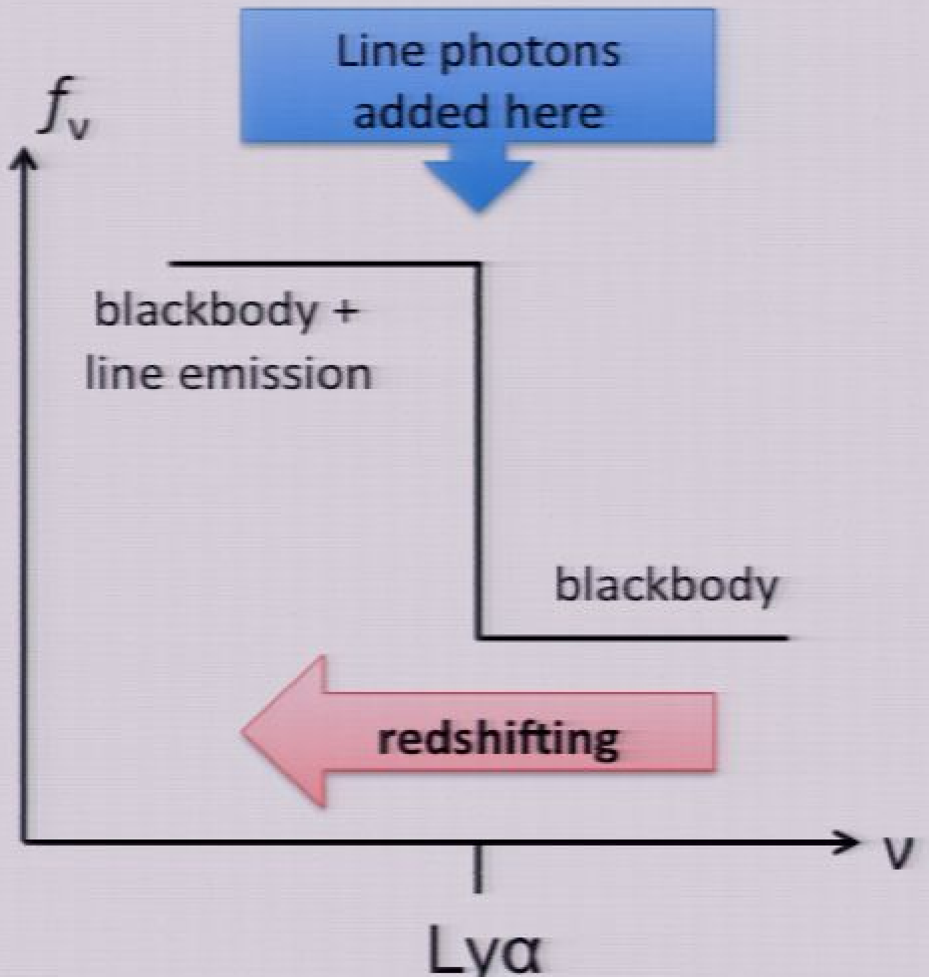
Stage II: Reaching the Ground State

There is a jump in the photon phase space density associated with the Lyman-α line:

$$\mathrm{Ly}\alpha-) - f(\mathrm{Ly}\alpha+) = \frac{2x(\mathrm{H}^*)}{Z(\mathrm{H}^*)x_{1s}} - e^{-3hR/4kT}$$

The rate at which photon modes redshift through Lyα is:

$$\frac{d\#\,\mathrm{modes}}{dt\ [\text{per H nucleus}]} = \frac{8\pi H}{\lambda^3_{\mathrm{Ly}\alpha} n_{\mathrm{H}}}$$



Net decay rate: $$\dot{x}_{1s}\big|_{\mathrm{Ly}\alpha} = \frac{8\pi H}{\lambda^3_{\mathrm{Ly}\alpha} n_{\mathrm{H}}}\left[\frac{2x(\mathrm{H}^*)}{Z(\mathrm{H}^*)x_{1s}} - e^{-3hR/4kT}\right]$$

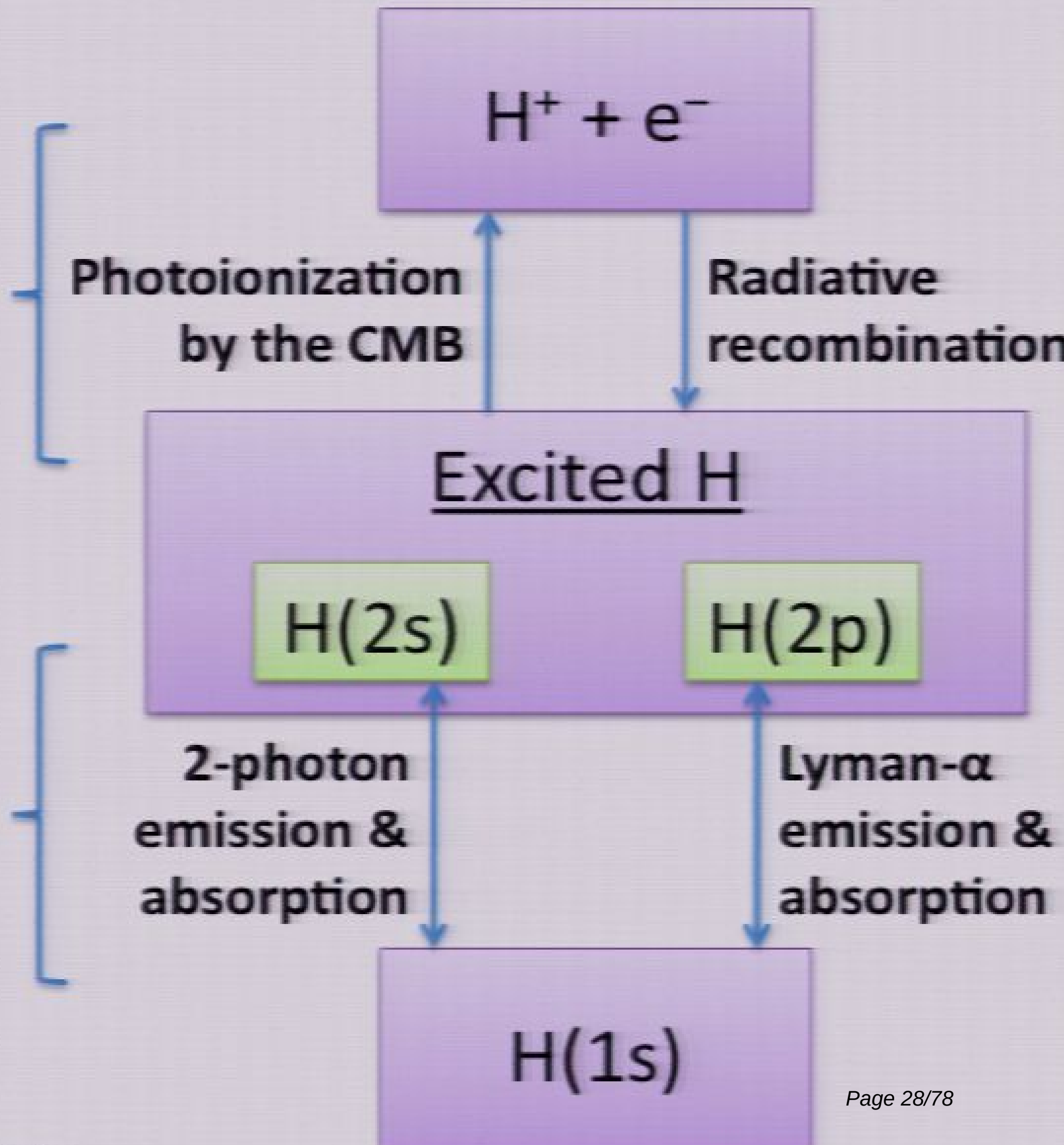
Putting It All Together

Stage I
Net rate:

$$n_{\mathrm{H}} x_e x_p - \frac{2x(\mathrm{H}^*)}{Z(\mathrm{H}^*)}\left(\frac{2\pi m_e kT}{h^2}\right)^{3/2} e^{-hR/4kT} \Big]$$

Stage II
Net rate:

$$_{2s} + \frac{8\pi H}{\lambda^3_{\mathrm{Ly}\alpha} n_{\mathrm{H}}}\left[\left[\frac{2x(\mathrm{H}^*)}{Z(\mathrm{H}^*)} - e^{-3hR/4kT} x_{1s}\right]\right]$$



dy state approximation: Equate net rates

Putting It All Together

- Net recombination rate:

$$-\frac{dx_e}{dt}=\alpha_{\rm B}\left[n_{\rm H}x_e x_p-\frac{2x({\rm H^*})}{{\rm Z(H^*)}}\left(\frac{2\pi m_e kT}{h^2}\right)^{3/2}e^{-hR/4kT}\right]=\left[\Lambda_{2s}+\frac{8\pi H}{\lambda_{{\rm Ly}\alpha}^3 n_{\rm H}}\right]\left[\frac{2x({\rm H^*})}{{\rm Z(H^*)}}-e^{-3hR/4kT}x_{1s}\right]$$

- Eliminate $x(\mathrm{H}^*)$ to obtain the Peebles ODE:

$$-\frac{dx_e}{dt}=\alpha_{\rm B}\frac{\Lambda_{2s}+\dfrac{8\pi H}{\lambda_{{\rm Ly}\alpha}^3 n_{\rm H}}}{\Lambda_{2s}+\dfrac{8\pi H}{\lambda_{{\rm Ly}\alpha}^3 n_{\rm H}}+\alpha_{\rm B}\left(\dfrac{2\pi m_e kT}{h^2}\right)^{3/2}e^{-hR/4kT}}\left[n_{\rm H}x_e x_p-\left(\frac{2\pi m_e kT}{h^2}\right)^{3/2}e^{-hR/kT}x_{1s}\right]$$

Recombination coefficient

Branching coefficient to ground state

Recombinations minus ionizations

Extensions to the Simplest Model

The "standard" calculation in most CMB codes until a few years ago (Seager et al 2000)

- Incorporation of helium (similar physics)
- Resolve excited levels of the H atom
- Collisions
- Stimulated recombinations, $H^+ + e^- + \gamma \rightarrow H(nl) + 2\gamma$
- Gas temperature evolution
- Escape allowed from all Lyman series lines

Precise Calculations

Extensions to the Simplest Model

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Putting It All Together

- Net recombination rate:

$$-\frac{dx_e}{dt}=\alpha_B\left[n_H x_e x_p-\frac{2x(H^*)}{Z(H^*)}\left(\frac{2\pi m_e kT}{h^2}\right)^{3/2}e^{-hR/4kT}\right]=\left[\Lambda_{2s}+\frac{8\pi H}{\lambda_{Ly\alpha}^3 n_H}\right]\left[\frac{2x(H^*)}{Z(H^*)}-e^{-3hR/4kT}x_{1s}\right]$$

- Eliminate *x*(H*) to obtain the Peebles ODE:

$$-\frac{dx_e}{dt}=\alpha_B\frac{\Lambda_{2s}+\dfrac{8\pi H}{\lambda_{Ly\alpha}^3 n_H}}{\Lambda_{2s}+\dfrac{8\pi H}{\lambda_{Ly\alpha}^3 n_H}+\alpha_B\left(\dfrac{2\pi m_e kT}{h^2}\right)^{3/2}e^{-hR/4kT}}\left[n_H x_e x_p-\left(\frac{2\pi m_e kT}{h^2}\right)^{3/2}e^{-hR/kT}x_{1s}\right]$$

Recombination coefficient

Branching coefficient to ground state

Recombinations minus ionizations

Stage II: Reaching the Ground State

There is a jump in the photon phase space density associated with the Lyman-α line:

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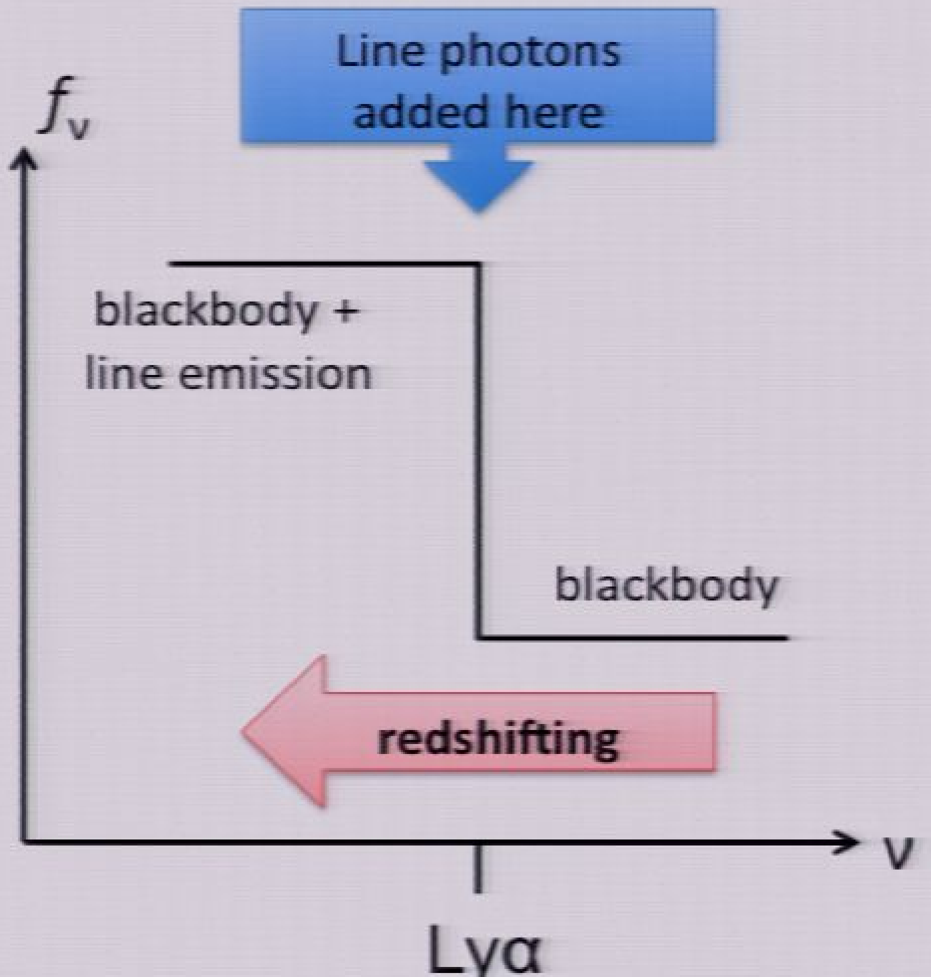

Net decay rate: $$\dot{x}_{1s}\big|_{\mathrm{Ly}\alpha} = \frac{8\pi H}{\lambda^3_{\mathrm{Ly}\alpha} n_\mathrm{H}}\left[\frac{2x(\mathrm{H}^*)}{Z(\mathrm{H}^*)x_{1s}} - e^{-3hR/4kT}\right]$$

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- Gas temperature evolution
- Escape allowed from all Lyman series lines

Precise Calculations

The Need for Improvement

- When CH was in graduate school, we were told that primary CMB power spectrum prediction was solved.

> *"Fortunately, to work in these research areas, it is not necessary to understand fully their complexity because there exist fitting functions and publicly available computer programs that can carry out these tasks. These can be treated as a black box – you feed in the input and out comes the desired answer."*
>
> *– Liddle & Lyth, 2000 (Introduction)*

- In 2005, Dubrovich & Grachev shattered our quiet, self-confident existence by telling us that these tools had errors of up to several percent.

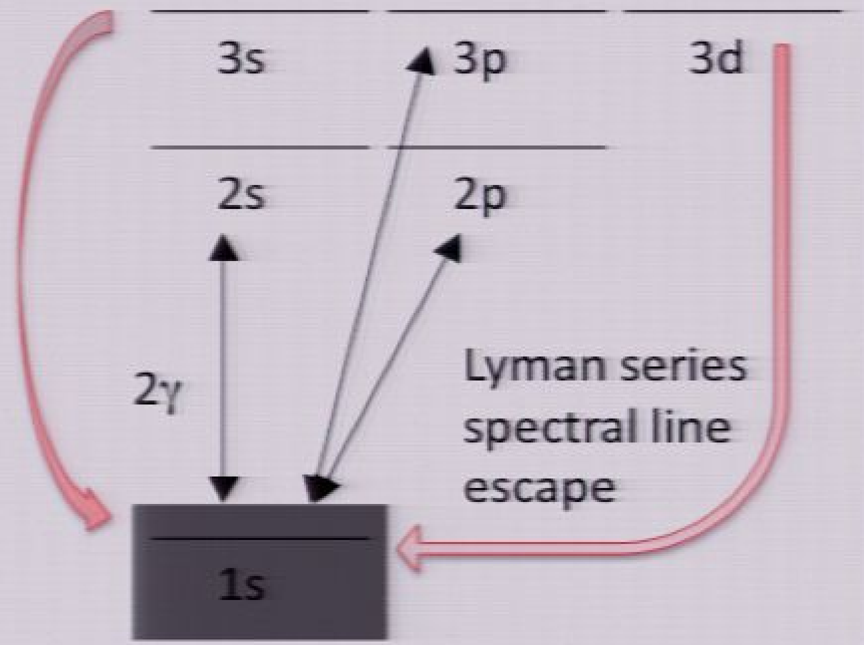
Paths to the H Ground State

Dueto thermal CMB field, there should be excited H atoms in 3d:

$$\frac{n_{3d}}{n_{2s}} \approx 5\exp\frac{-\Delta E}{kT} \sim 0.01 @ z = 1300$$

What about 3d→1s decays?

H(3d) → H(1s) + γ + γ



Two-Photon Decays

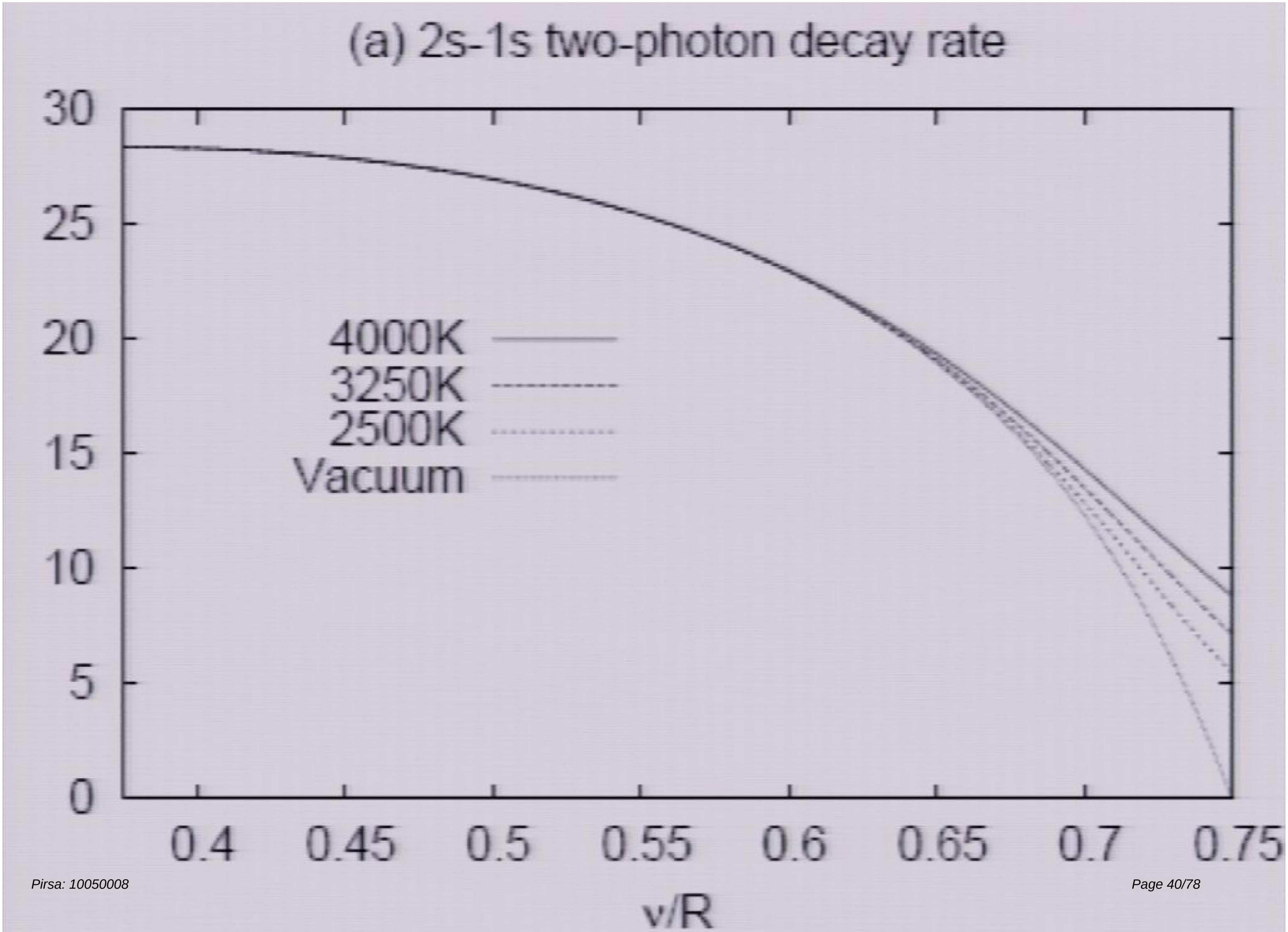
- In principle, this is a simple calculation: one replaces the decay rate:

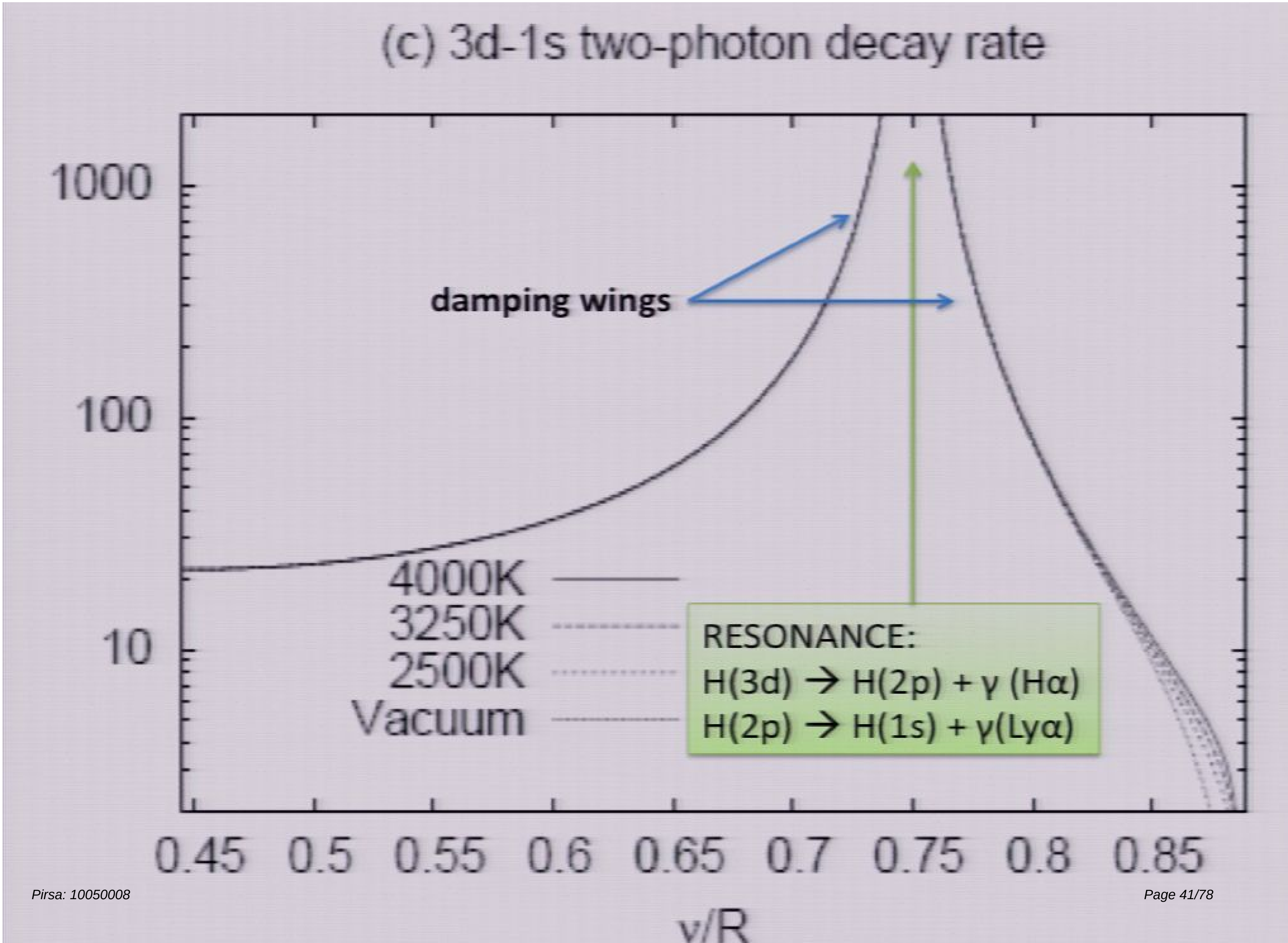
$$\Lambda_{2s} \rightarrow \Lambda_{2s} + (\Lambda_{3s} + 5\Lambda_{3d})e^{-(E_3-E_2)/kT} + \ldots$$

- The decay rate for simultaneous emission of 2 photons is provided by Göppert-Mayer (1931) & subsequent work:

$$\Lambda_{u\rightarrow l} = \frac{\alpha_{fs}^6 h^2}{27e^4 a_0^4 R^4} \int_{\nu_{max}/2}^{\nu_{max}} \nu^3 \nu'^3 \left| \sum_q \left[\frac{\langle l|d_i|q\rangle\langle q|d_j|u\rangle}{E_q - E_l + h\nu} + \frac{\langle l|d_j|q\rangle\langle q|d_i|u\rangle}{E_q - E_l + h\nu'} \right] \right|^2 d\nu$$

- Note: $h\nu + h\nu' = E_u - E_l$.

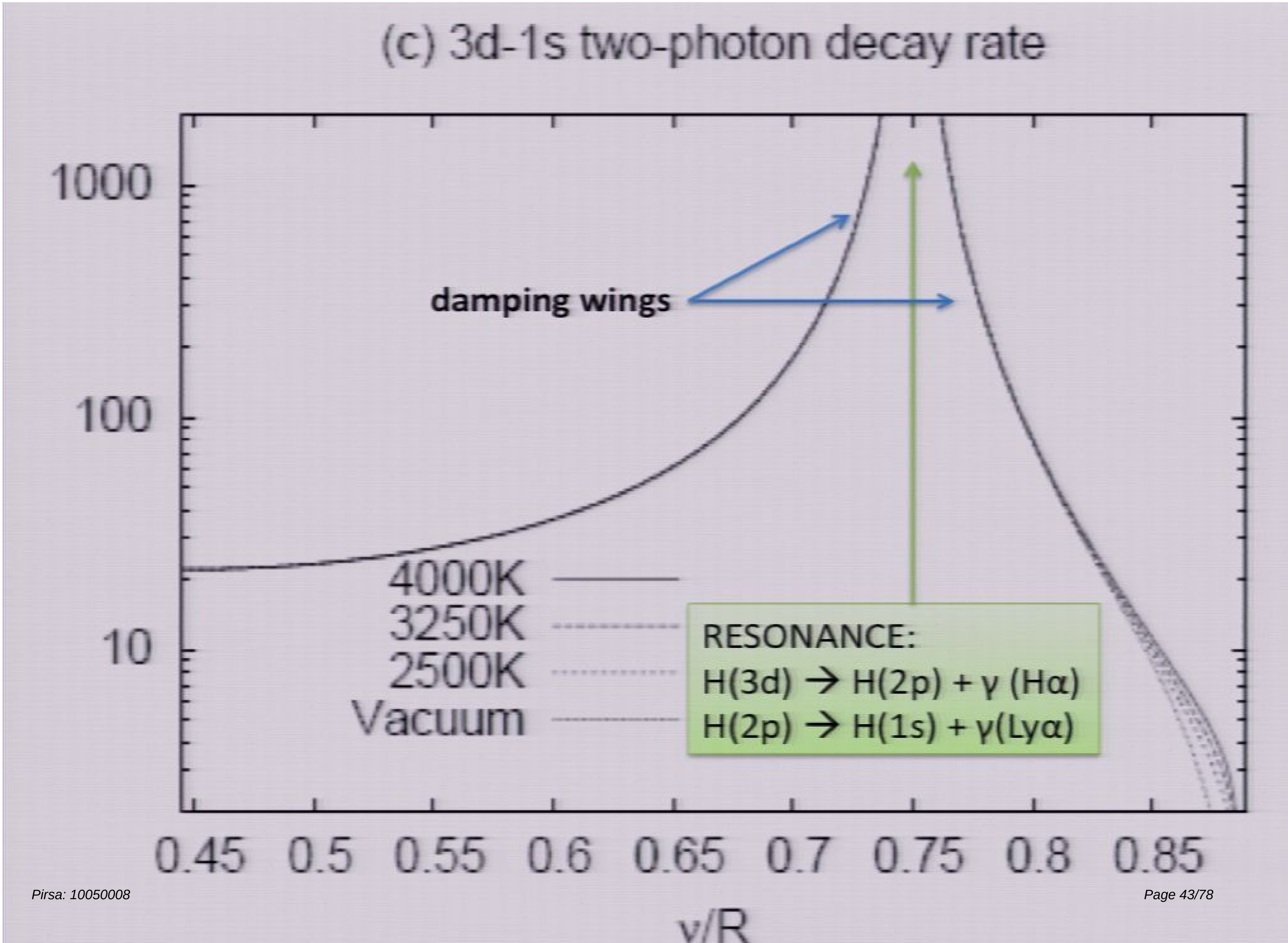

(a) 2s-1s two-photon decay rate
30
25
20
15
10
5
0
4000K
3250K
2500K
Vacuum
0.4
0.45
0.5
0.55
0.6
0.65
0.7
0.75
ν/R


(c) 3d-1s two-photon decay rate
1000
100
10
damping wings
4000K
3250K
2500K
Vacuum
RESONANCE:
H(3d) → H(2p) + γ (Hα)
H(2p) → H(1s) + γ(Lyα)
0.45
0.5
0.55
0.6
0.65
0.7
0.75
0.8
0.85
ν/R

Treatment in Recombination

- Post-2005, there was a debate over the correct handling of 2γ decays in recombination [Dubrovich & Grachev 2005; Wong & Scott 2007; Chluba & Sunyaev 2007].

- The key is that radiation emitted near Lyα is rapidly re-absorbed. We thus need a full treatment of radiative transfer including the 2γ opacity.


(c) 3d-1s two-photon decay rate
1000
100
10
damping wings
4000K
3250K
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Vacuum
RESONANCE:
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ν/R

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roduction & Destruction of FUV Photons

- Energies below Lyα:

two-photon/2s $\mathrm{H}(2s) \leftrightarrow \mathrm{H}(1s) + \gamma_{<\mathrm{Ly}\alpha} + \gamma_{<<\mathrm{Ly}\alpha}$

two-photon/*n*≥3 $\mathrm{H}(3d) \leftrightarrow \mathrm{H}(1s) + \gamma_{<\mathrm{Ly}\alpha} + \gamma_{>\mathrm{H}\alpha}$

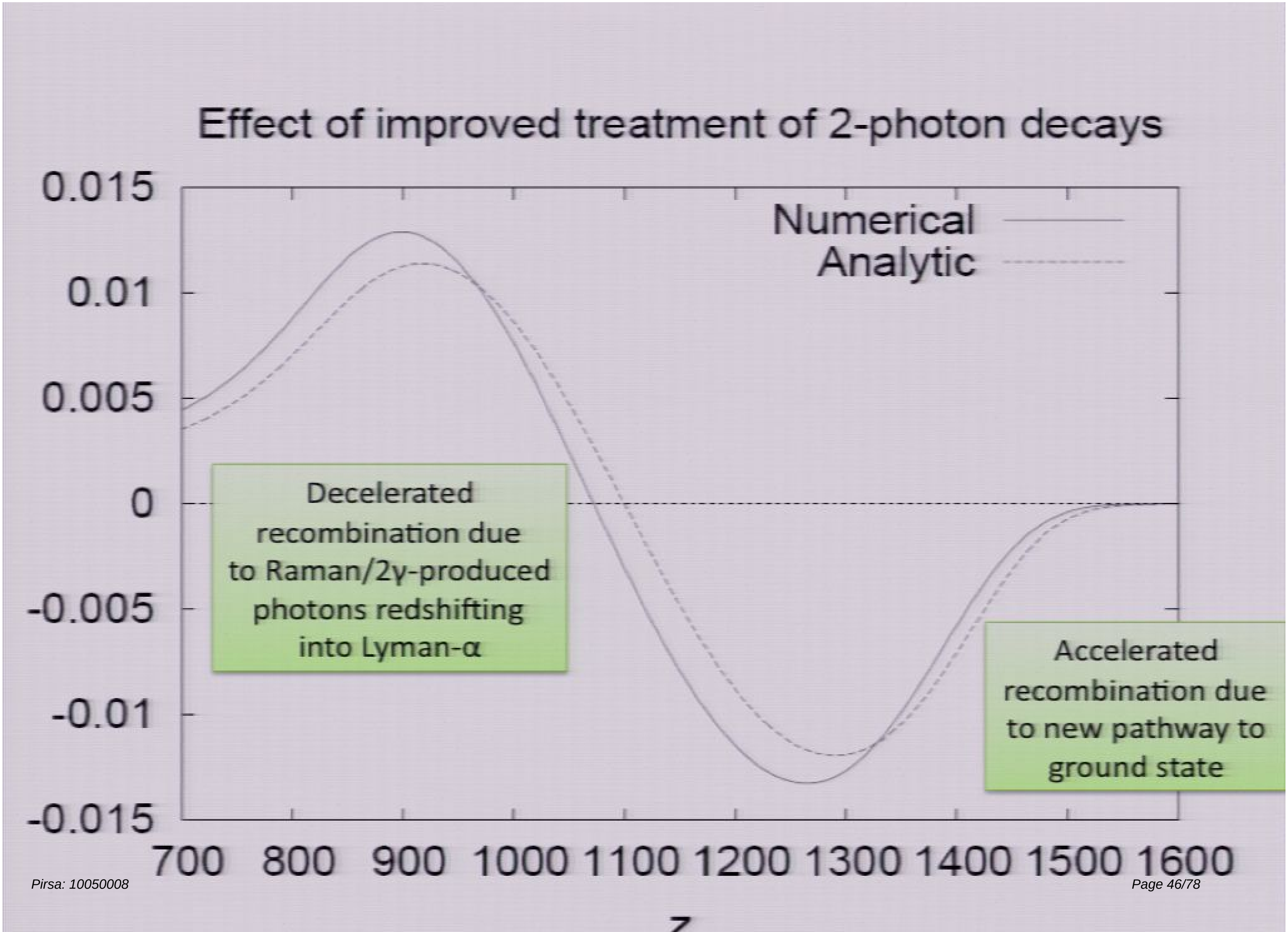
[absorbs photons that escaped out of Lyα]

- Between Lyα and Lyβ:

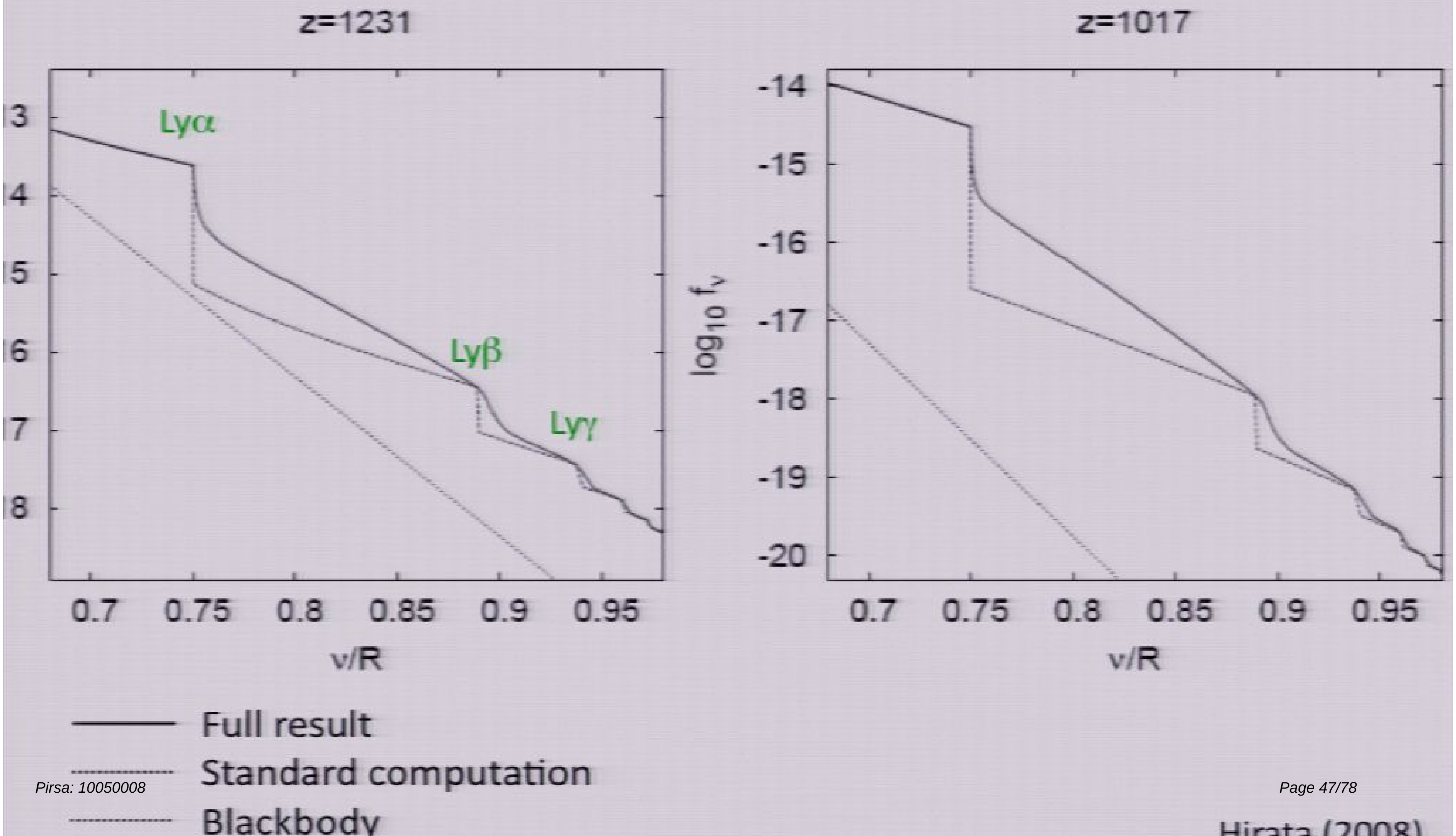
two-photon/*n*≥3 $\mathrm{H}(3d) \leftrightarrow \mathrm{H}(1s) + \gamma_{>\mathrm{Ly}\alpha} + \gamma_{<\mathrm{H}\alpha}$

Raman/2s $\mathrm{H}(2s) + \gamma_{<\mathrm{H}\alpha} \leftrightarrow \mathrm{H}(1s) + \gamma_{>\mathrm{Ly}\alpha}$

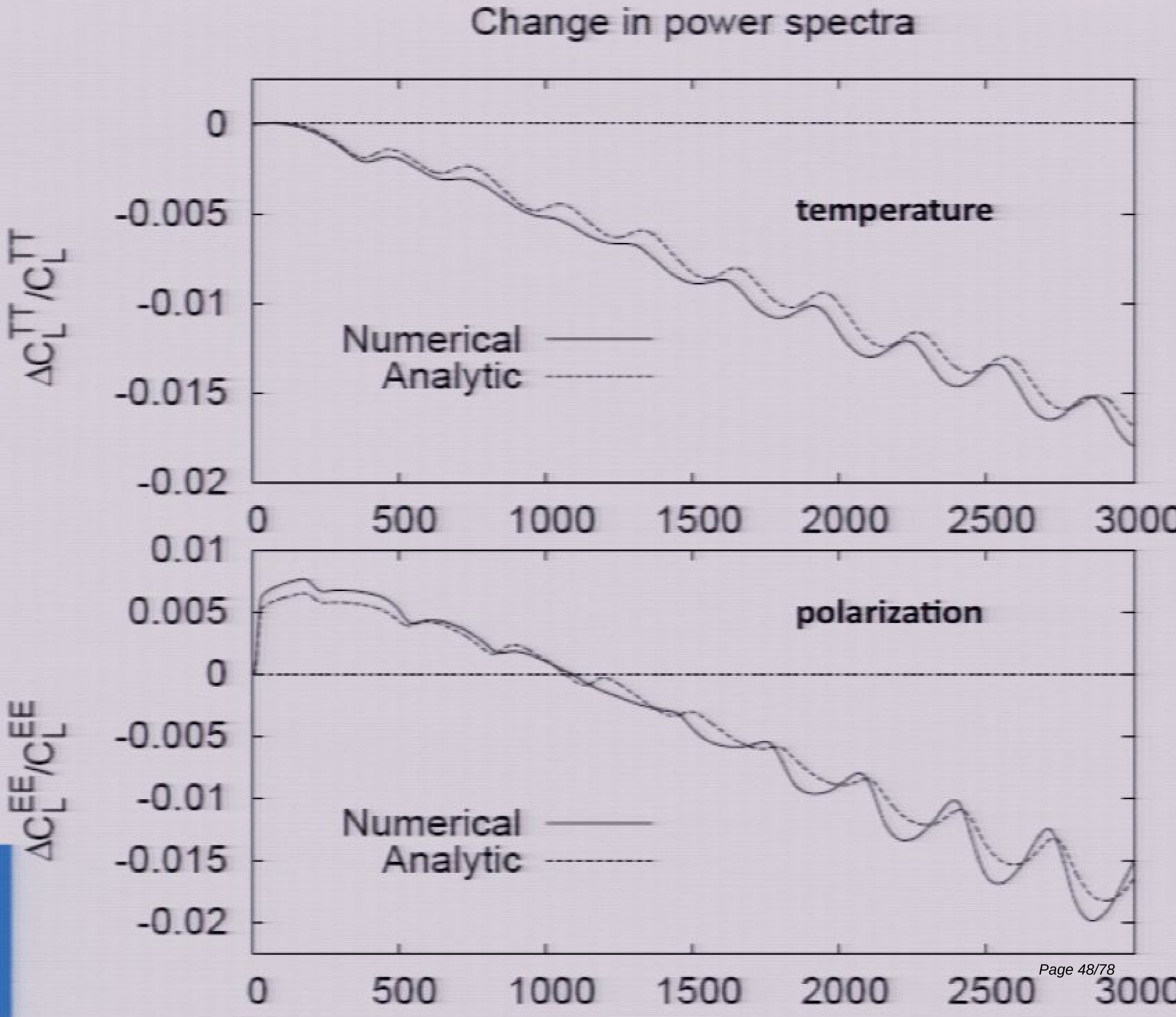
[these photons will redshift into Lyα and get absorbed]


Effect of improved treatment of 2-photon decays
0.015
0.01
0.005
0
-0.005
-0.01
-0.015
700 800 900 1000 1100 1200 1300 1400 1500 1600
z
Numerical
Analytic
Decelerated recombination due to Raman/2γ-produced photons redshifting into Lyman-α
Accelerated recombination due to new pathway to ground state

Phase space density

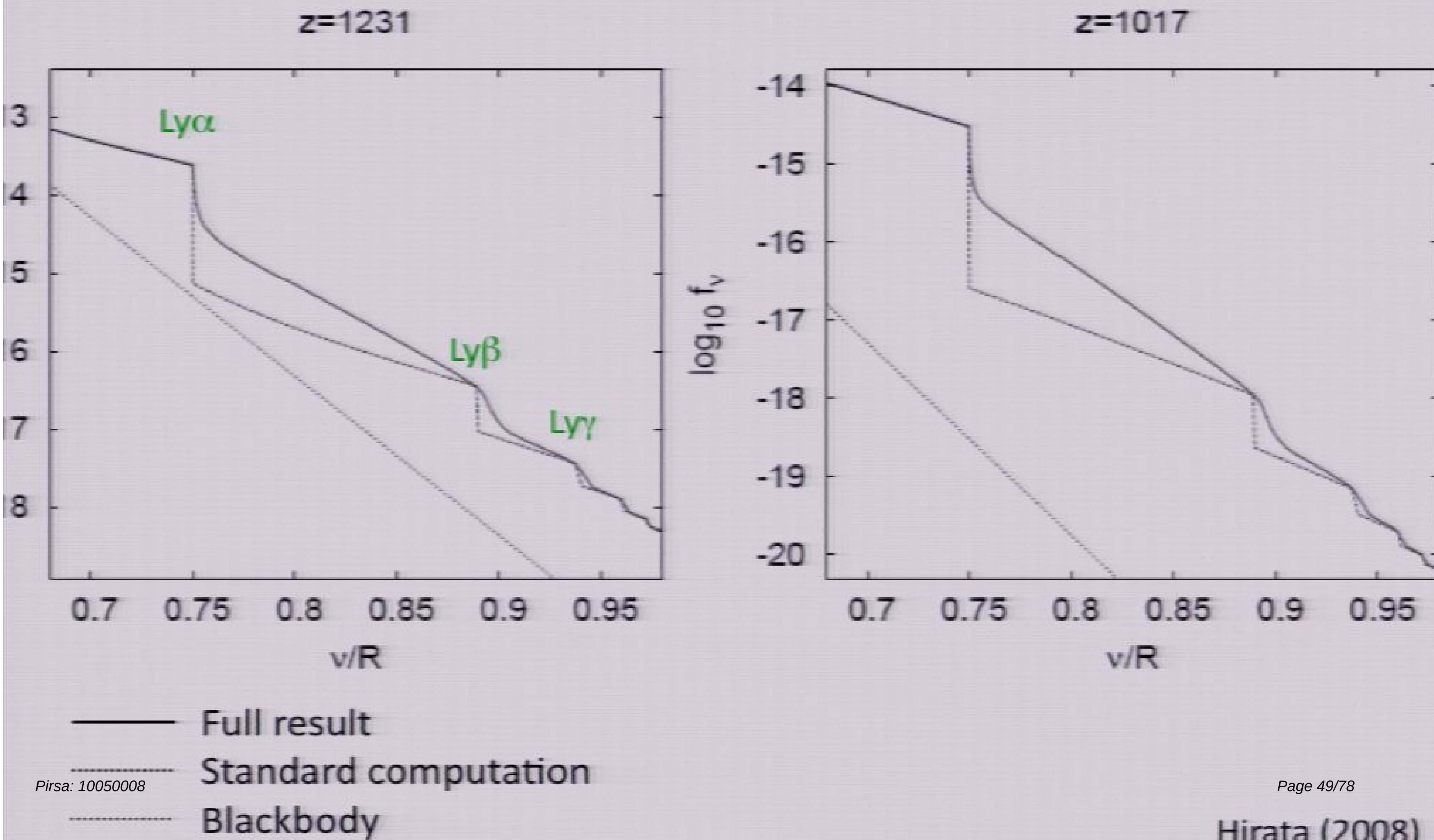


Hirata (2008)



rection:
9σ ACBAR
7σ WMAP5
Planck

Phase space density



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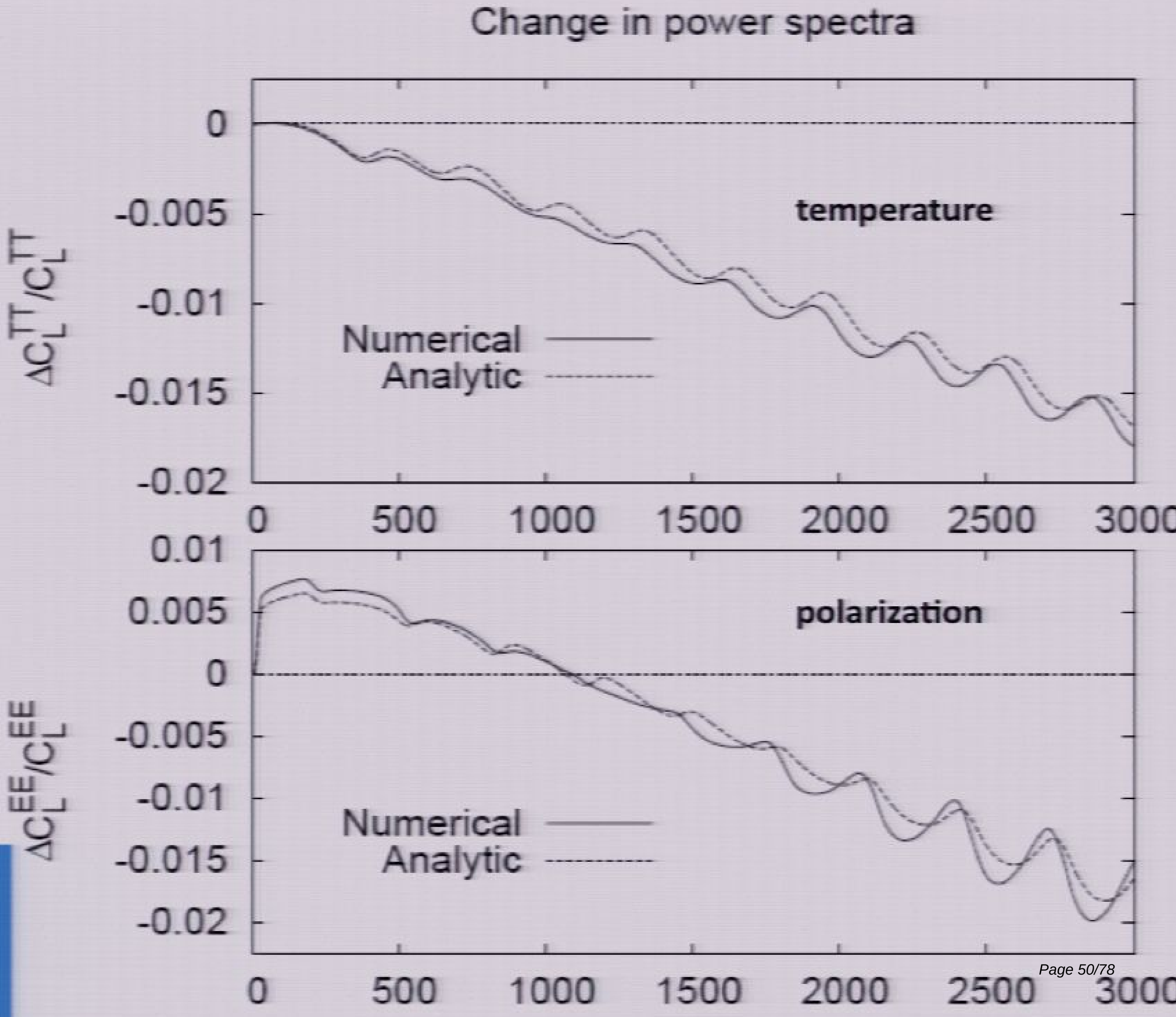

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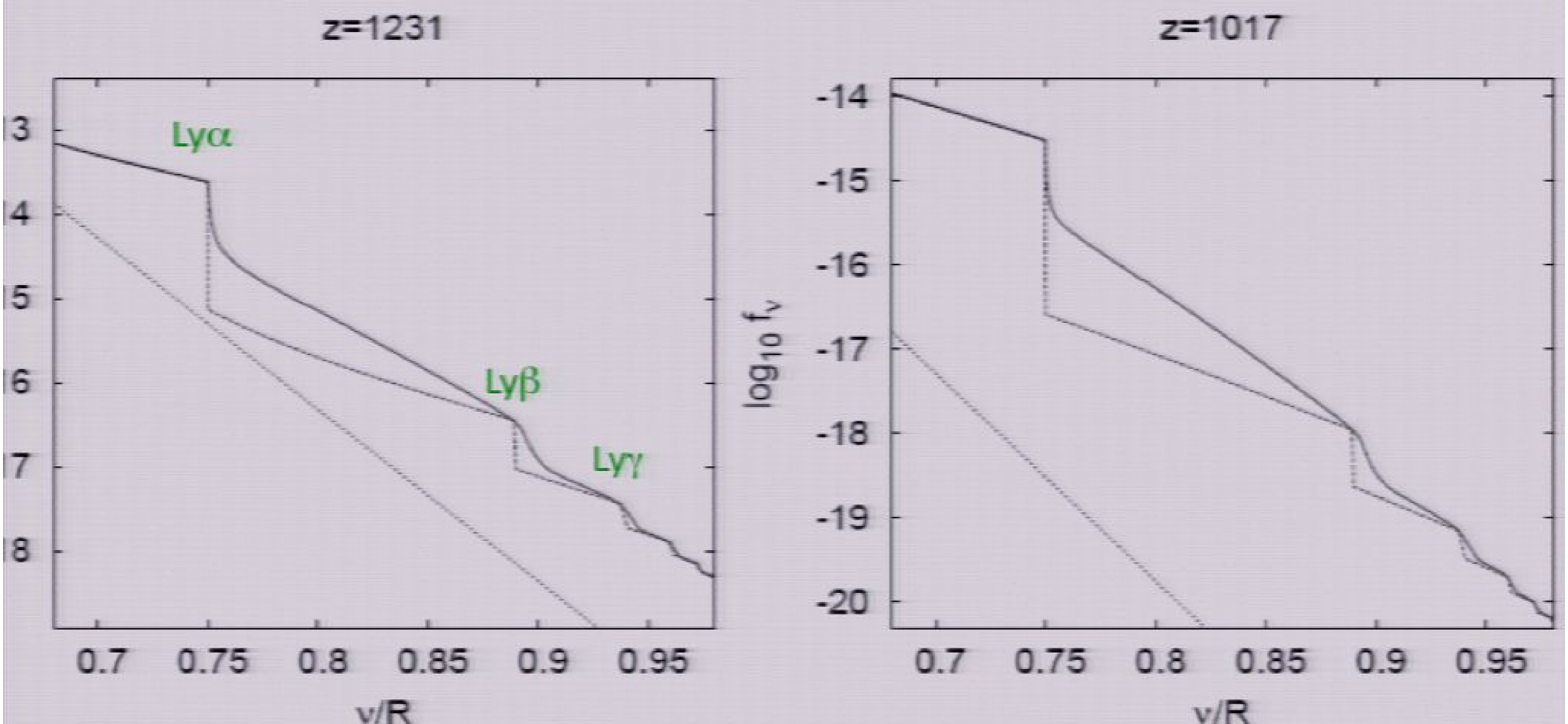
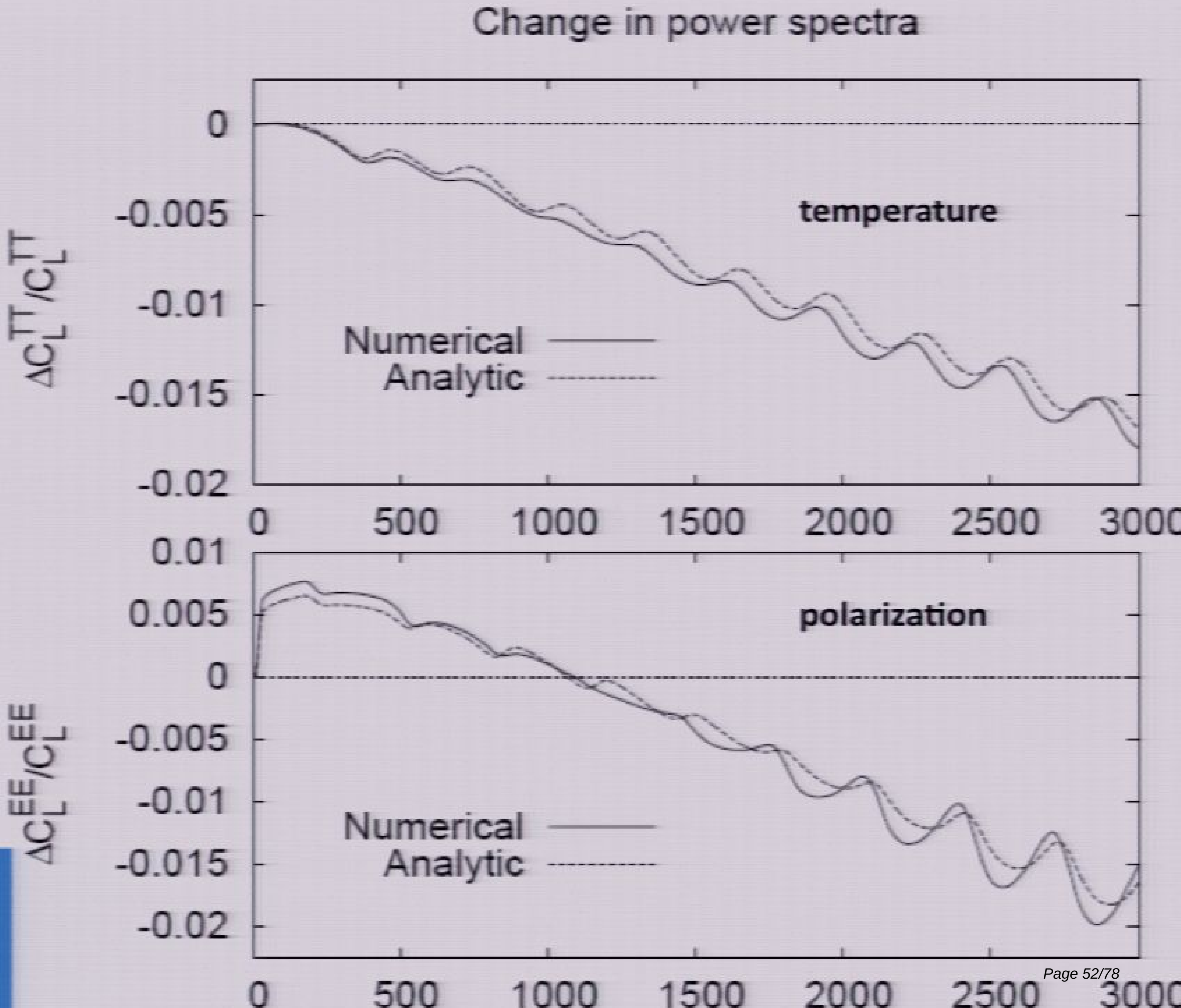
7σ WMAP5
Planck

Phase space density



Full result
Standard computation
Blackbody

Hirata (2008)



rection:
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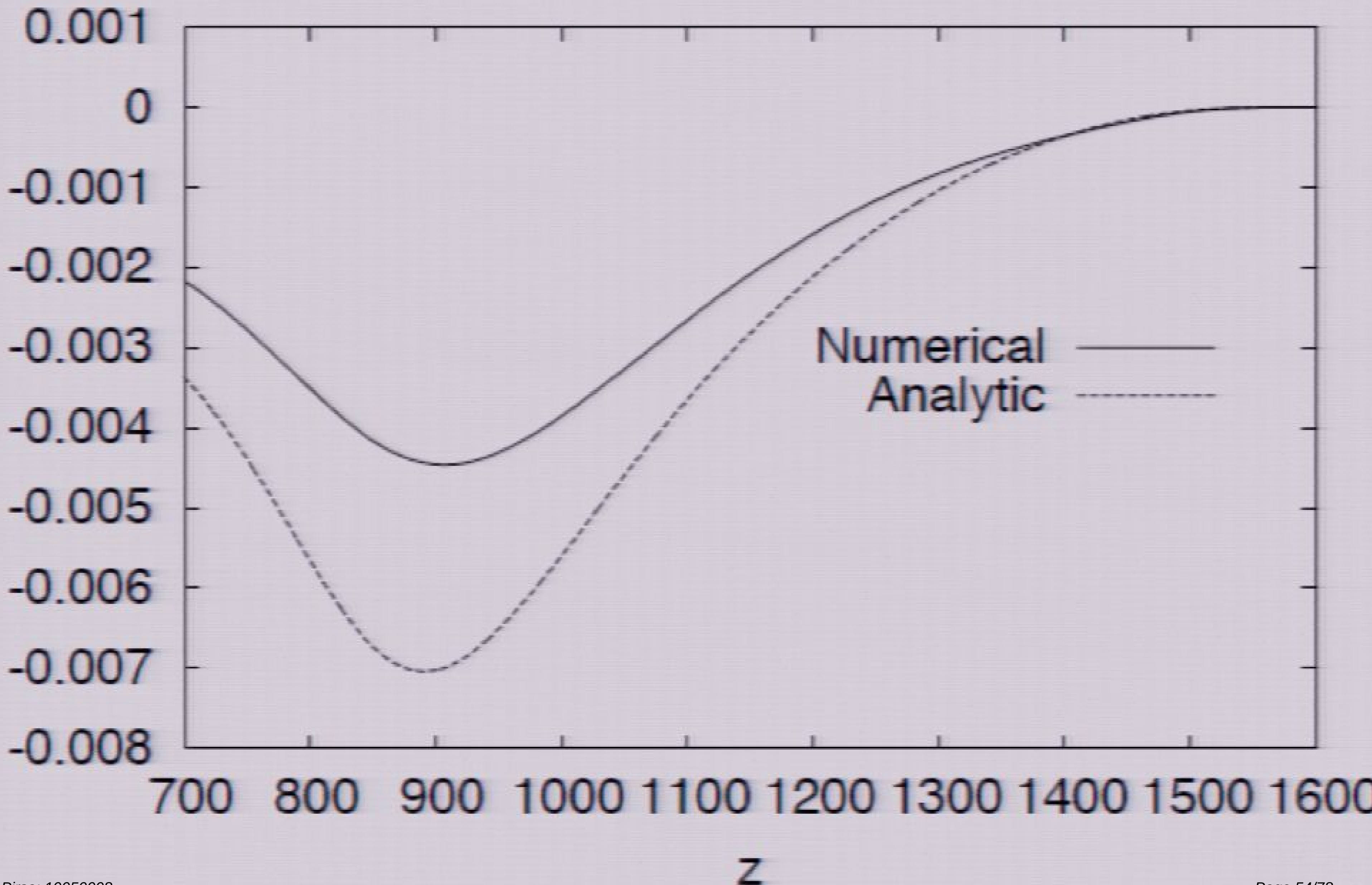
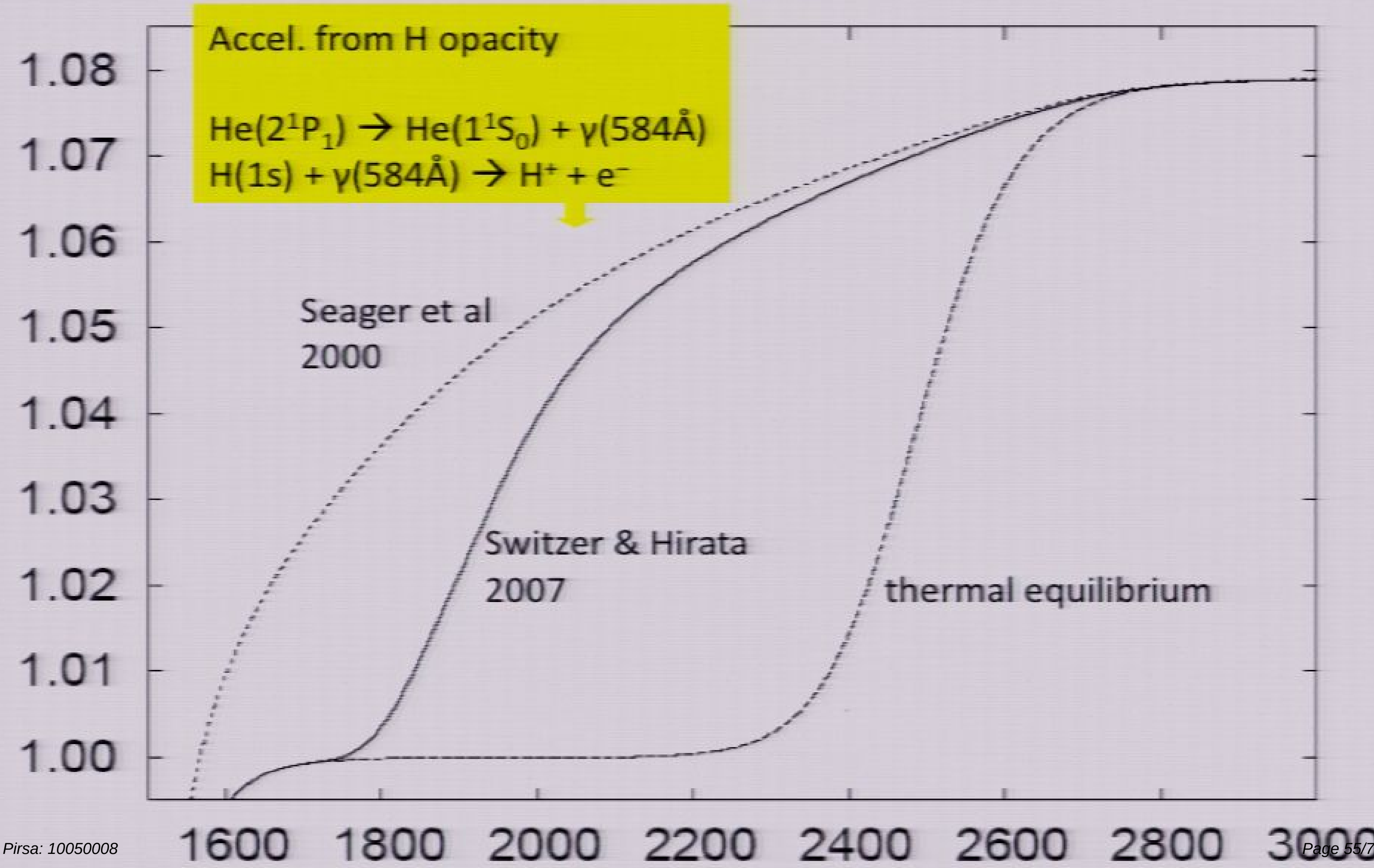
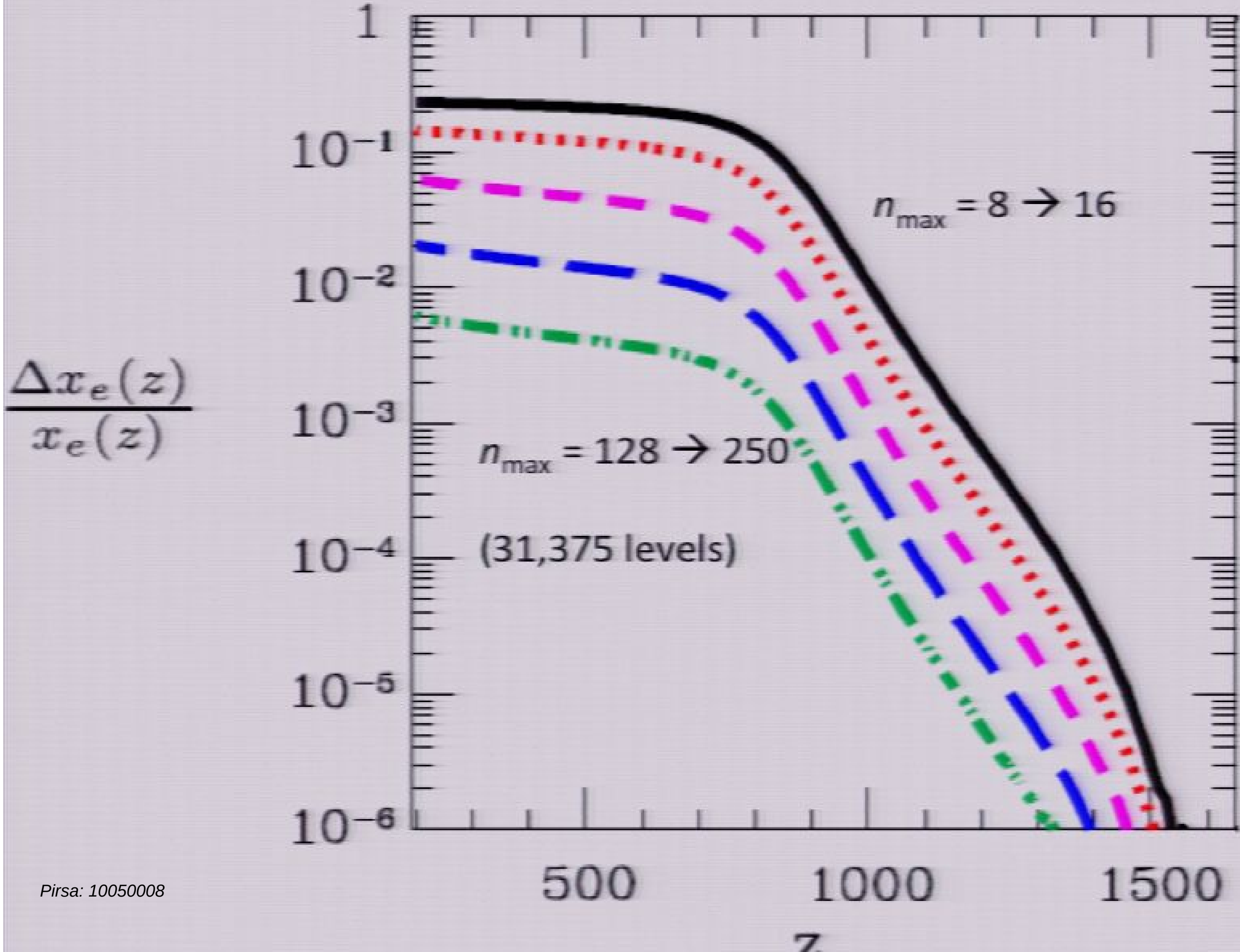


Hirata & Forbes 2009

Helium recombination



Convergence with Number of Levels



Grin & Hirata 2009

Ongoing Work

[Grin, Ali-Haïmoud, Alizadeh]

- Overlap of high-lying Lyman lines
- Thomson scattering
- Deviations from Fokker-Planck equation
- H_2 formation & destruction

- Plan is to complete project by end of 2010.
- Will need a new fast public code to implement in CMB analyses (promised NSF by 9/2011). [Yacine has an idea …]

Testing the Theory

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Testing the Theory

Testing

- We are going to draw inferences on the earliest moments of the Universe on the basis of recombination computations, so we need to make sure it is not in error due to:
  - Bugs
  - Missing obscure atomic physics processes
  - Exotica (e.g. new decaying particles)

- Hence we need:
  - Code comparisons [Grin vs. Chluba; ongoing]
  - Empirical validation of the theory

Can We See the Relic Photons?

- Unfortunately, probably not …
- Lyman-α @ z=1300 → λ = 160 μm today
- There are "a few" cosmic recombination photons per baryon.
- Compare to far infrared background:

$$\frac{\#\text{FIR photons}}{\text{baryon}} = \frac{\varepsilon}{E_{\text{FIR}}} f_* f_{\text{H}\to\text{He}} f_{\text{dust}}.$$

f_* = fraction of baryons that form stars

$f_{\text{H}\to\text{He}}$ = fraction of H in stars that gets converted to He in lifetime of Universe

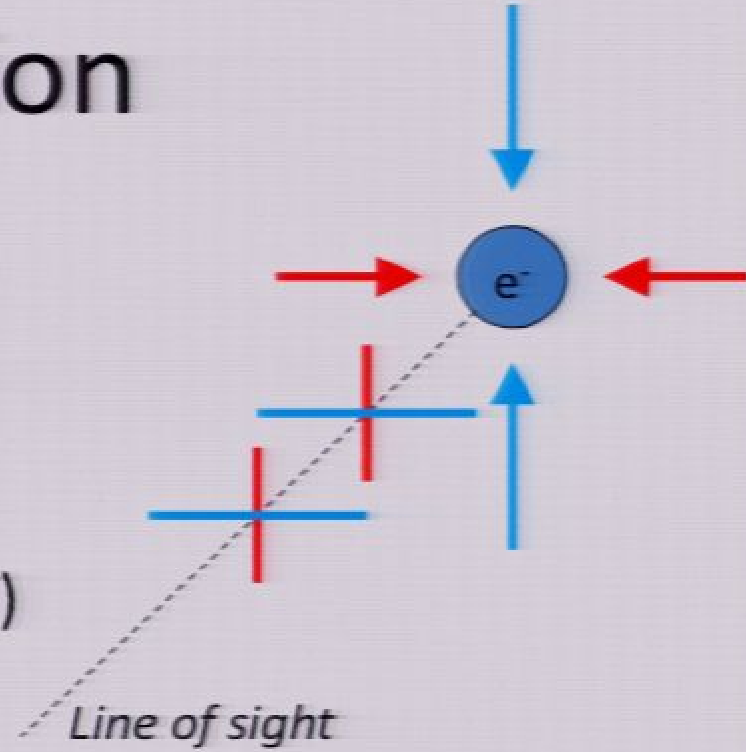
ε = energy yield of H fusion per baryon (~ 6 MeV)

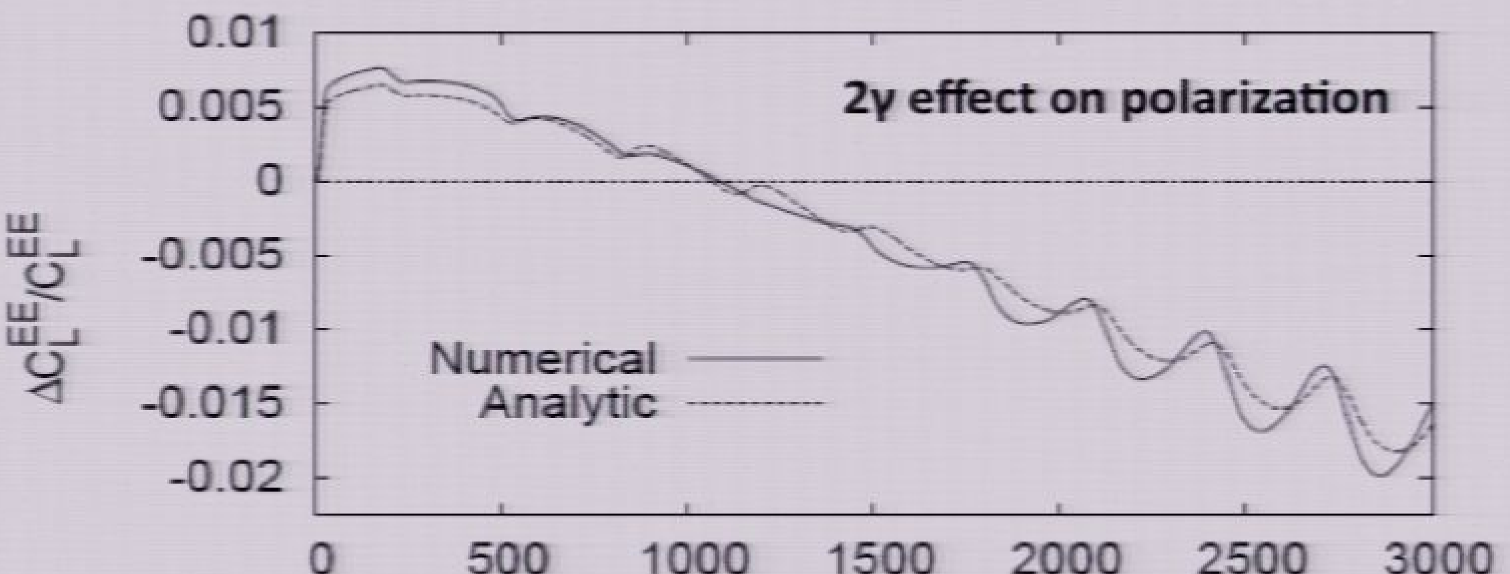
E_{FIR} = energy of a FIR photon (~0.01 eV)

f_{dust} = fraction of starlight re-processed into the FIR by dust

CMB Polarization

- Produced during recombination by scattering of anisotropy off of electrons.
- More extended recombination → increased polarization/anisotropy (EE/TT) ratio at 15′-1° scales.





Conclusions

- The recombination era is a critical period for interpreting CMB observables, and for learning about even earlier periods in cosmic history.
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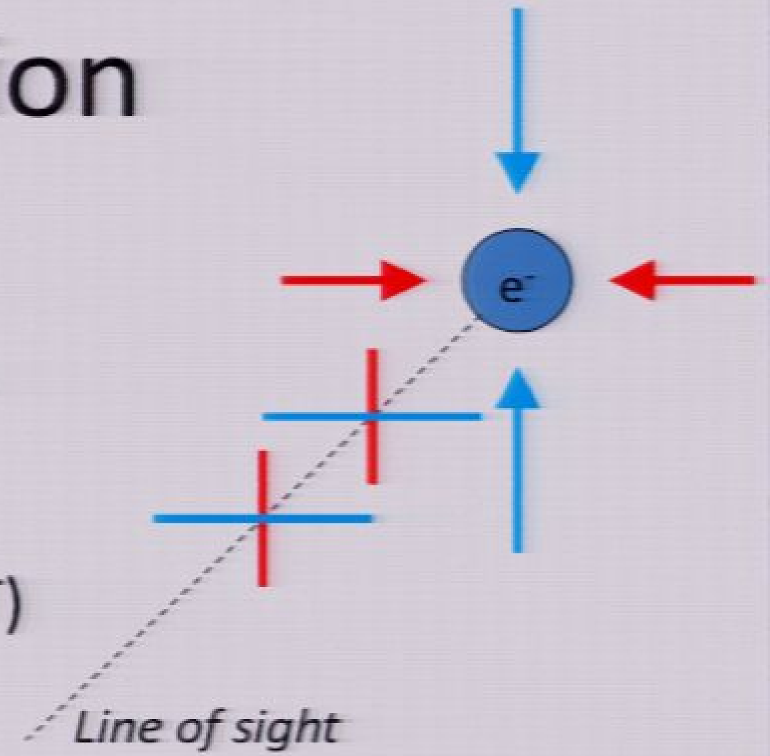

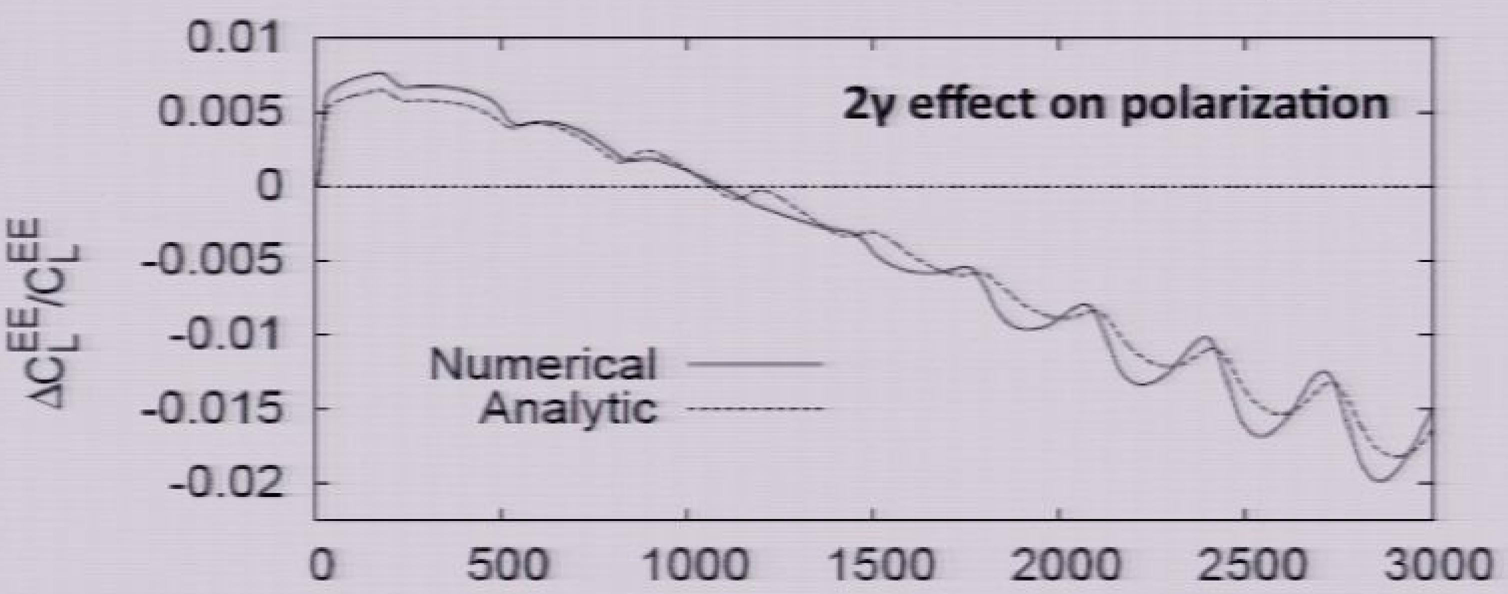

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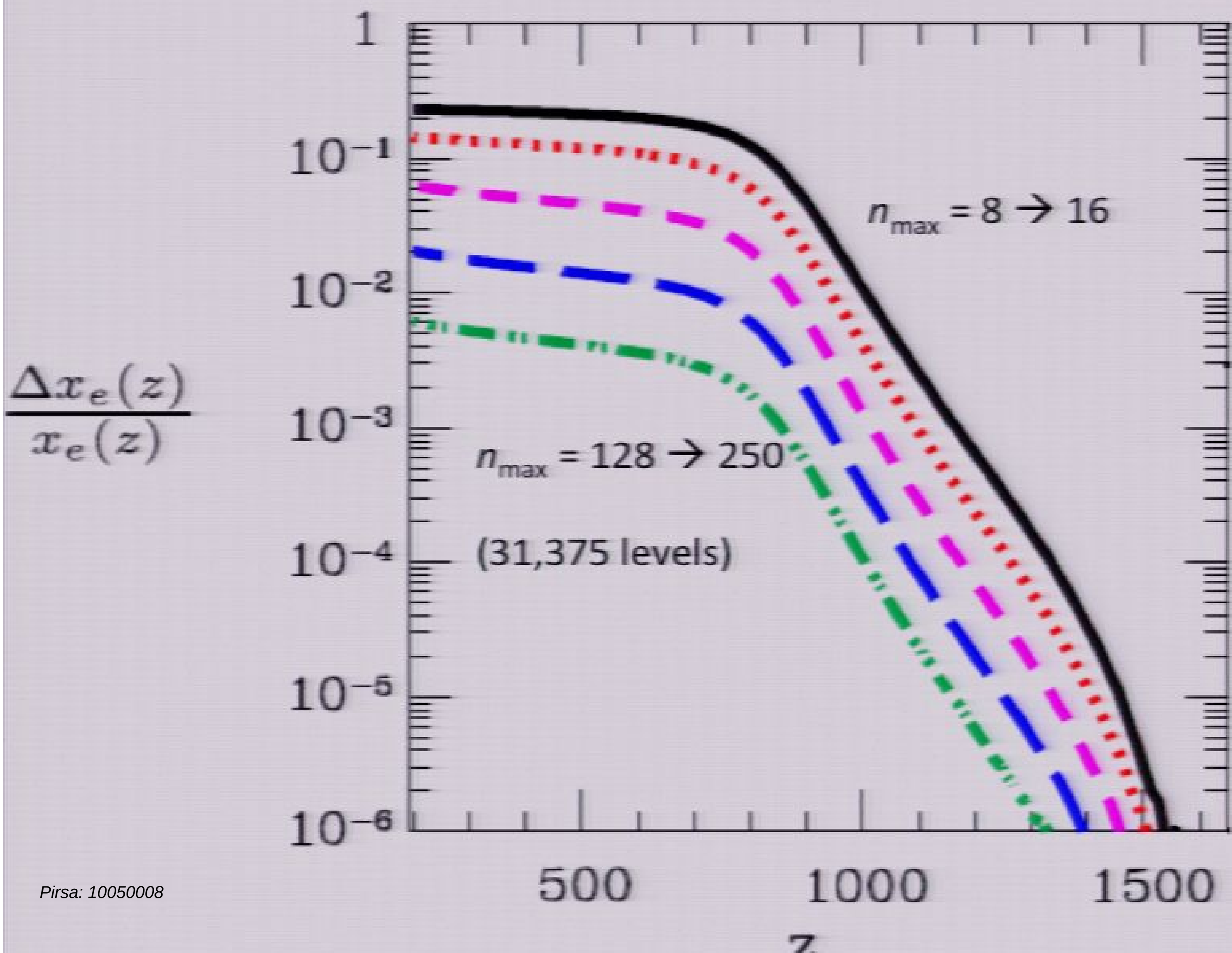
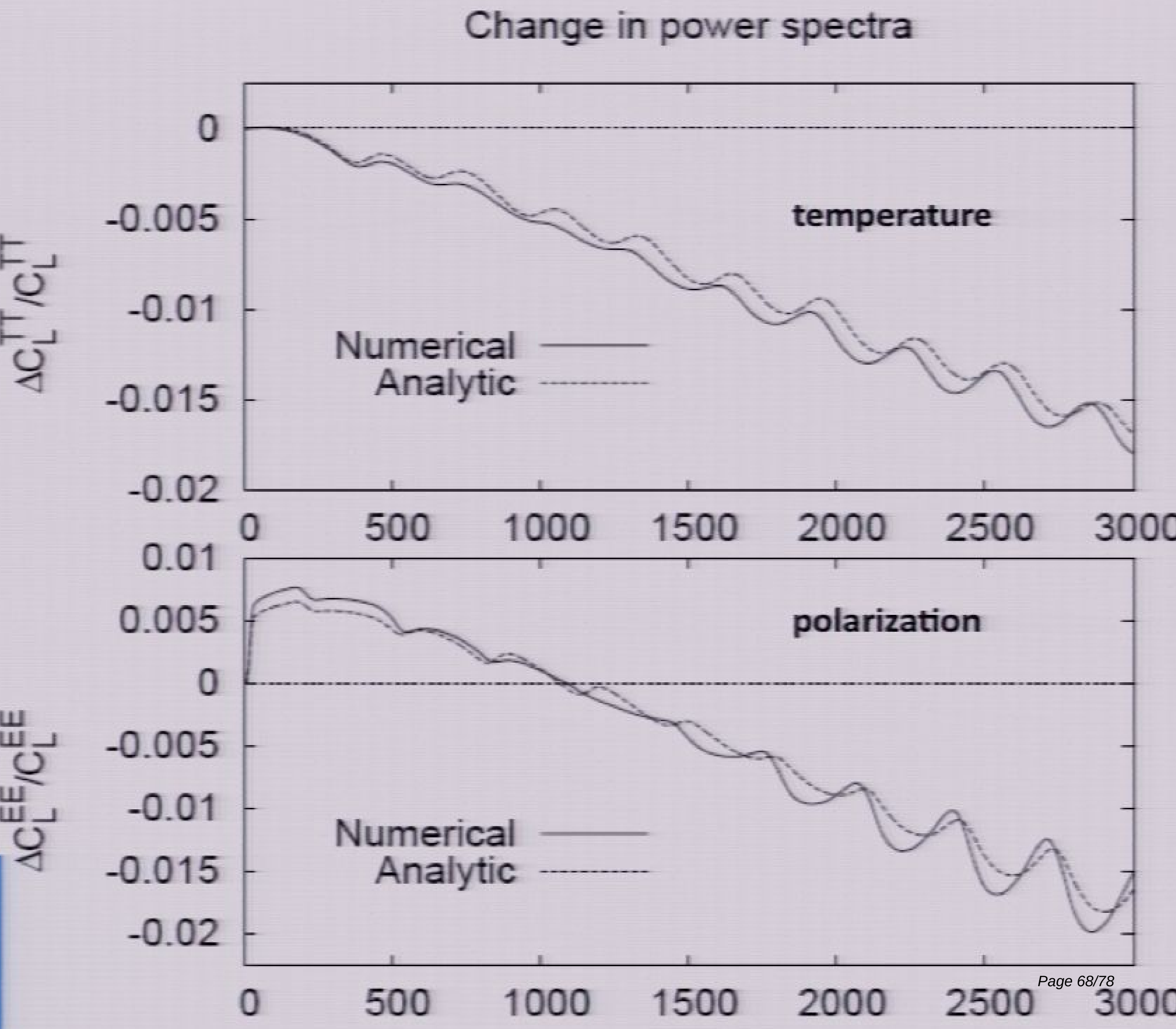


Grin & Hirata 2009



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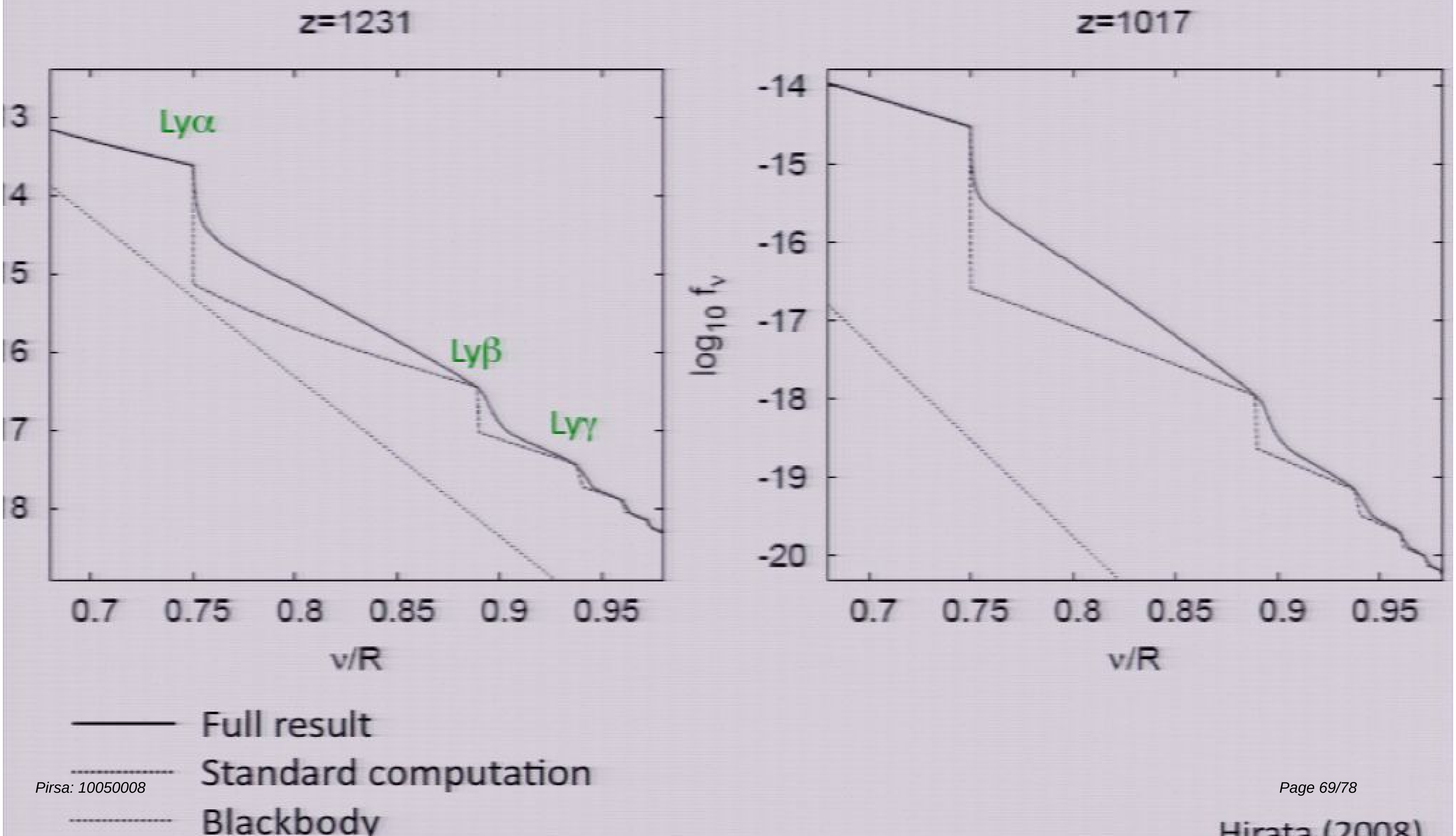
Phase space density



Hirata (2008)

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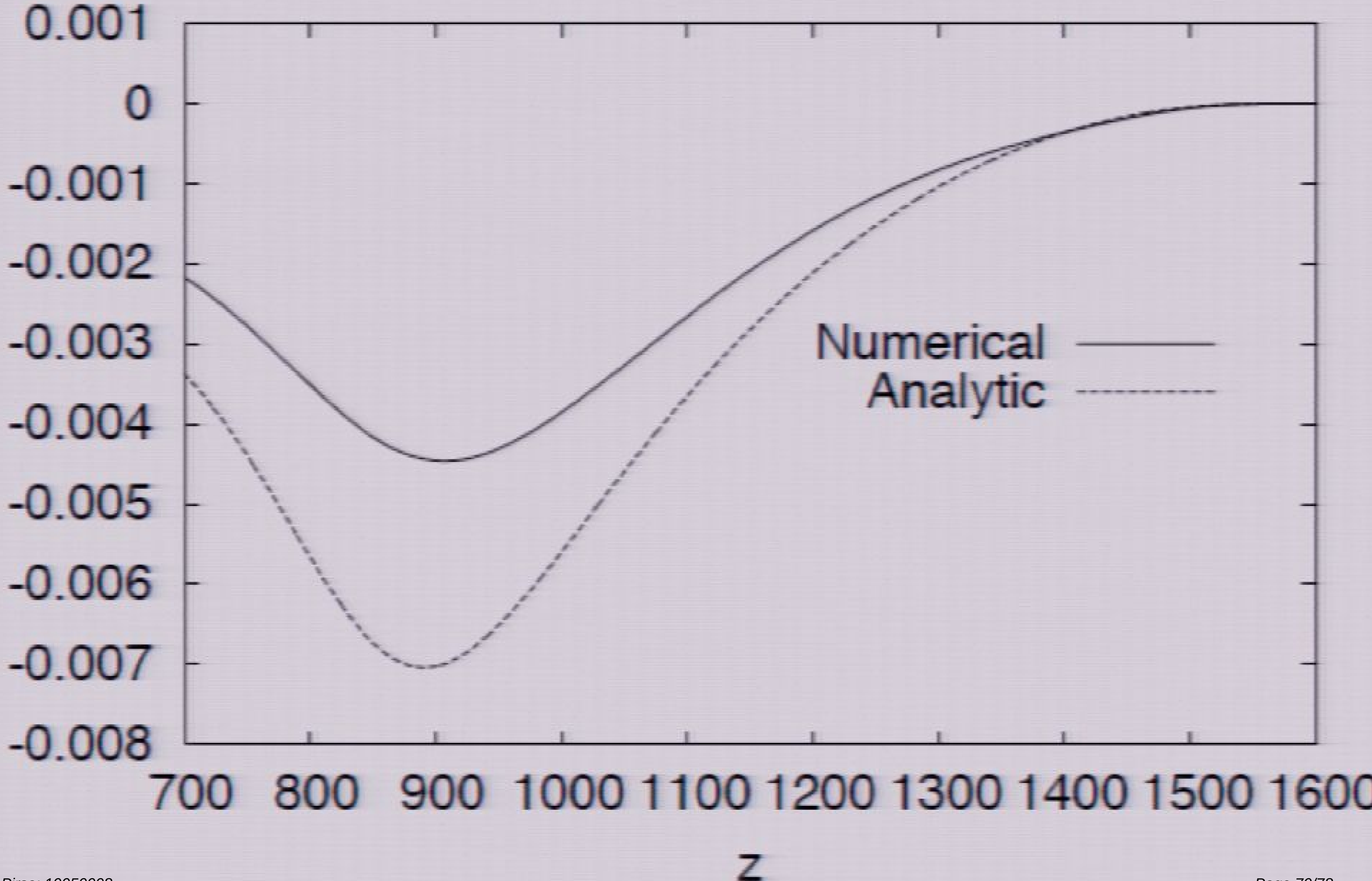

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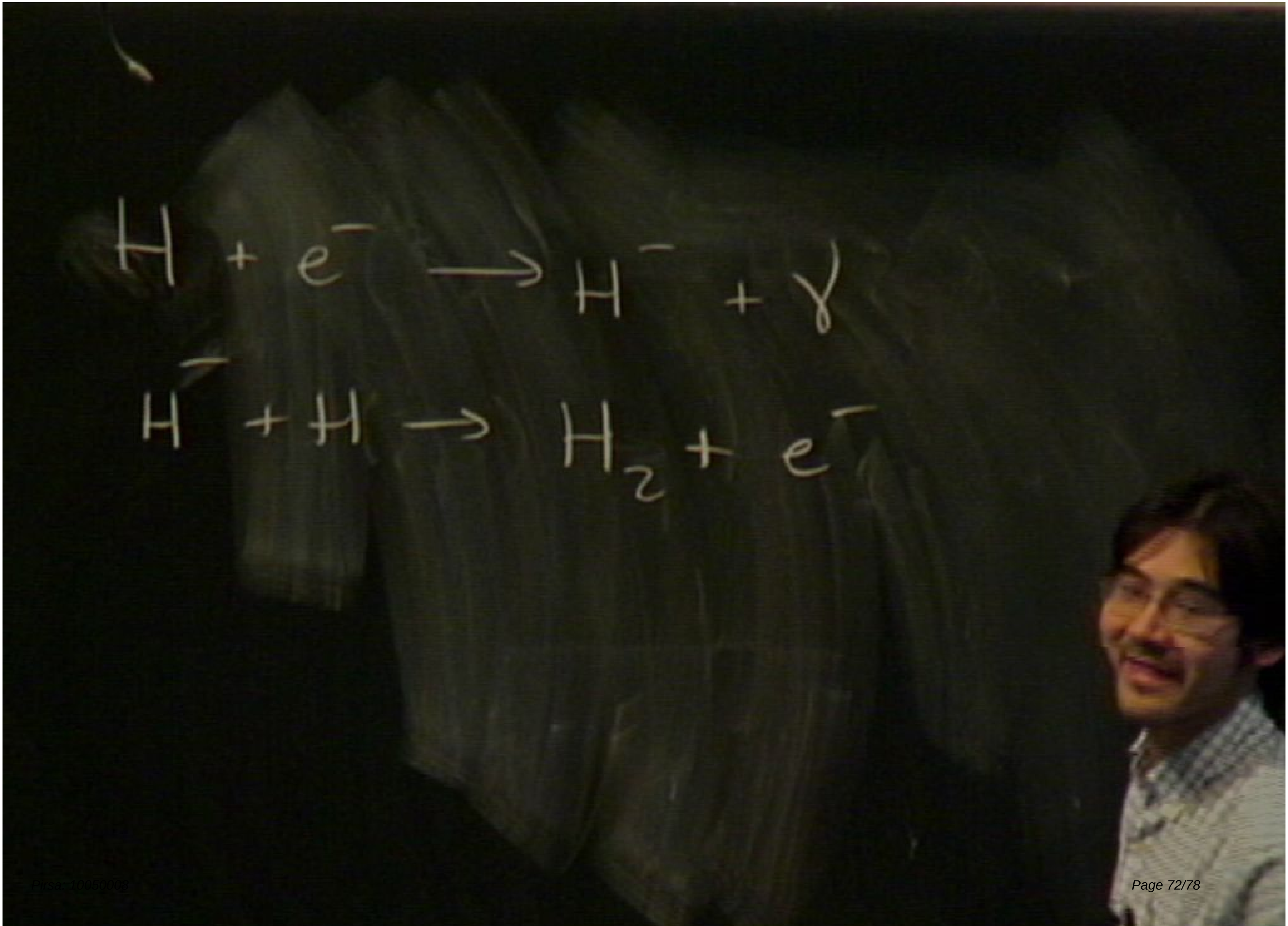
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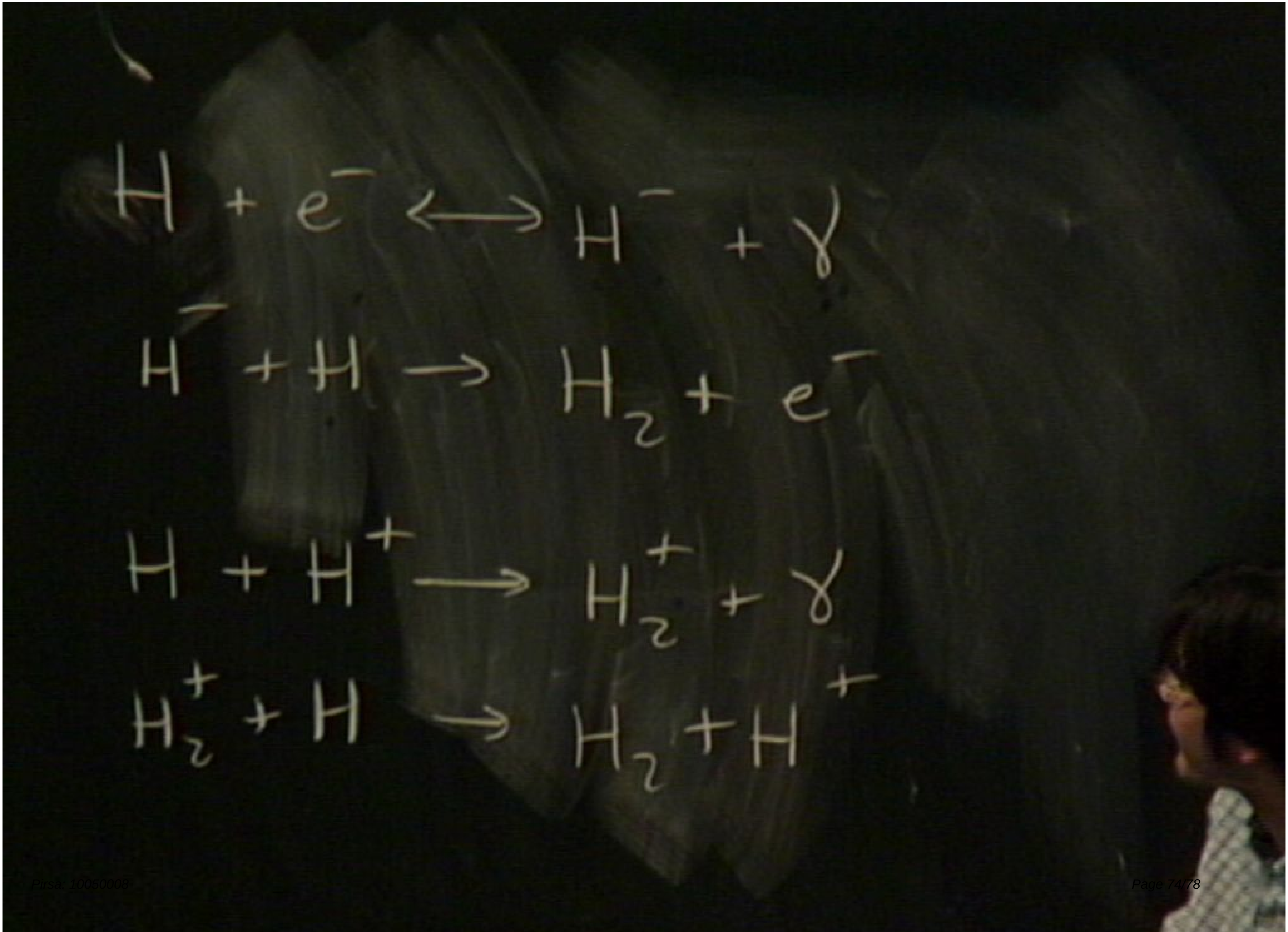
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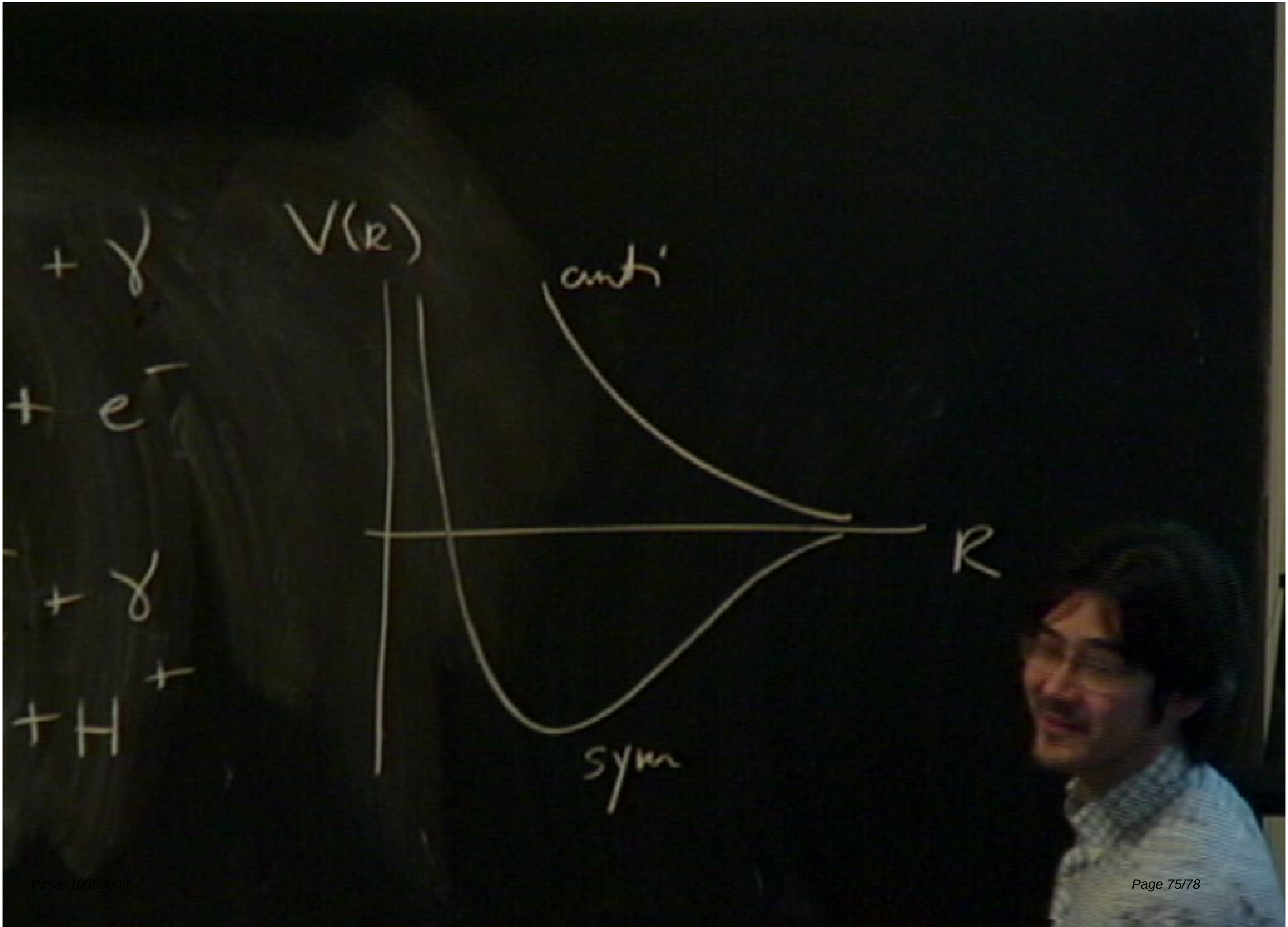
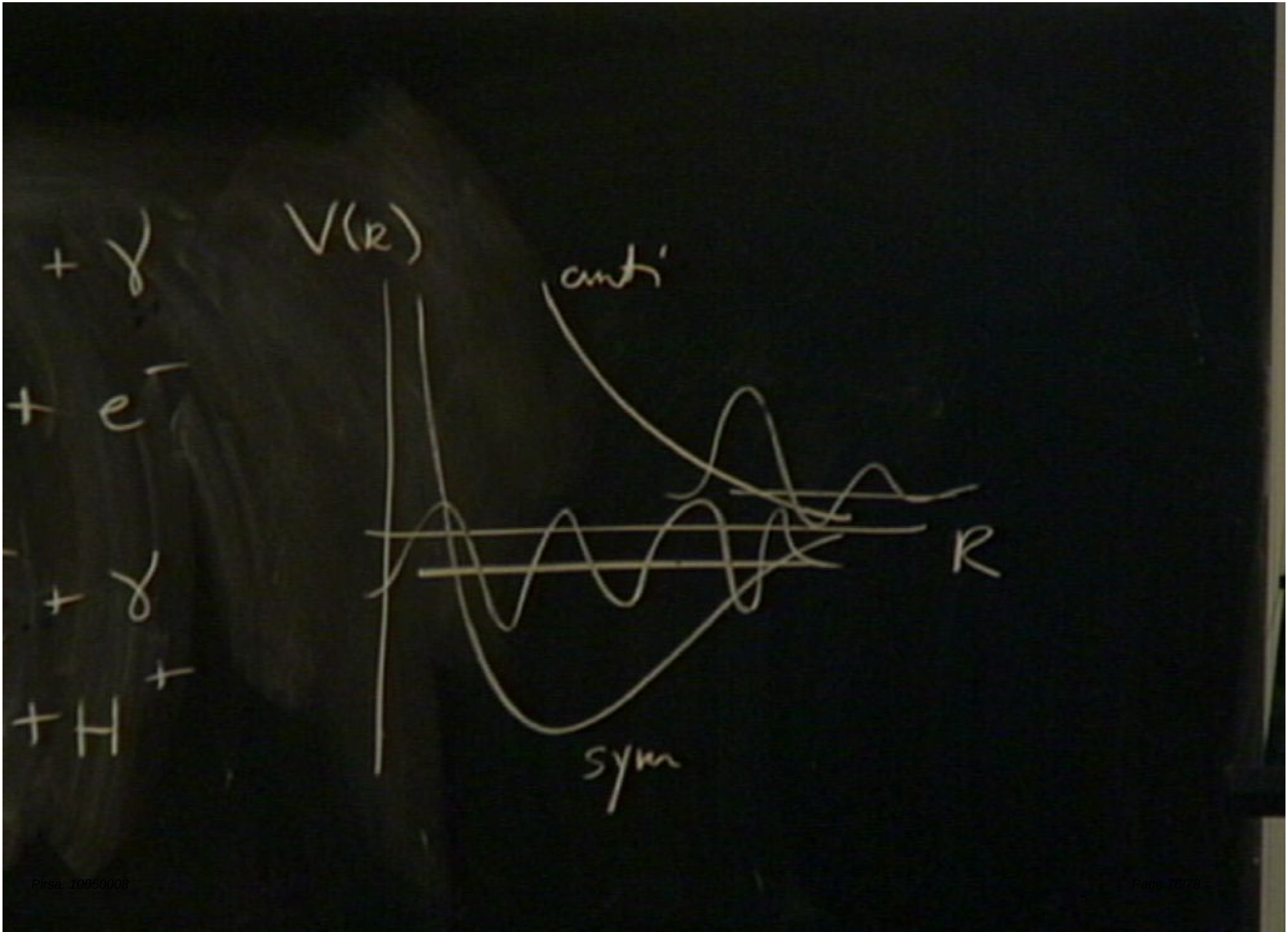

+ γ
+ e⁻
+ γ
+ H⁺
V(R)
anti
R
sym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$$H_2(X) + \gamma_{UV} \longrightarrow H_2(B, C)$$

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