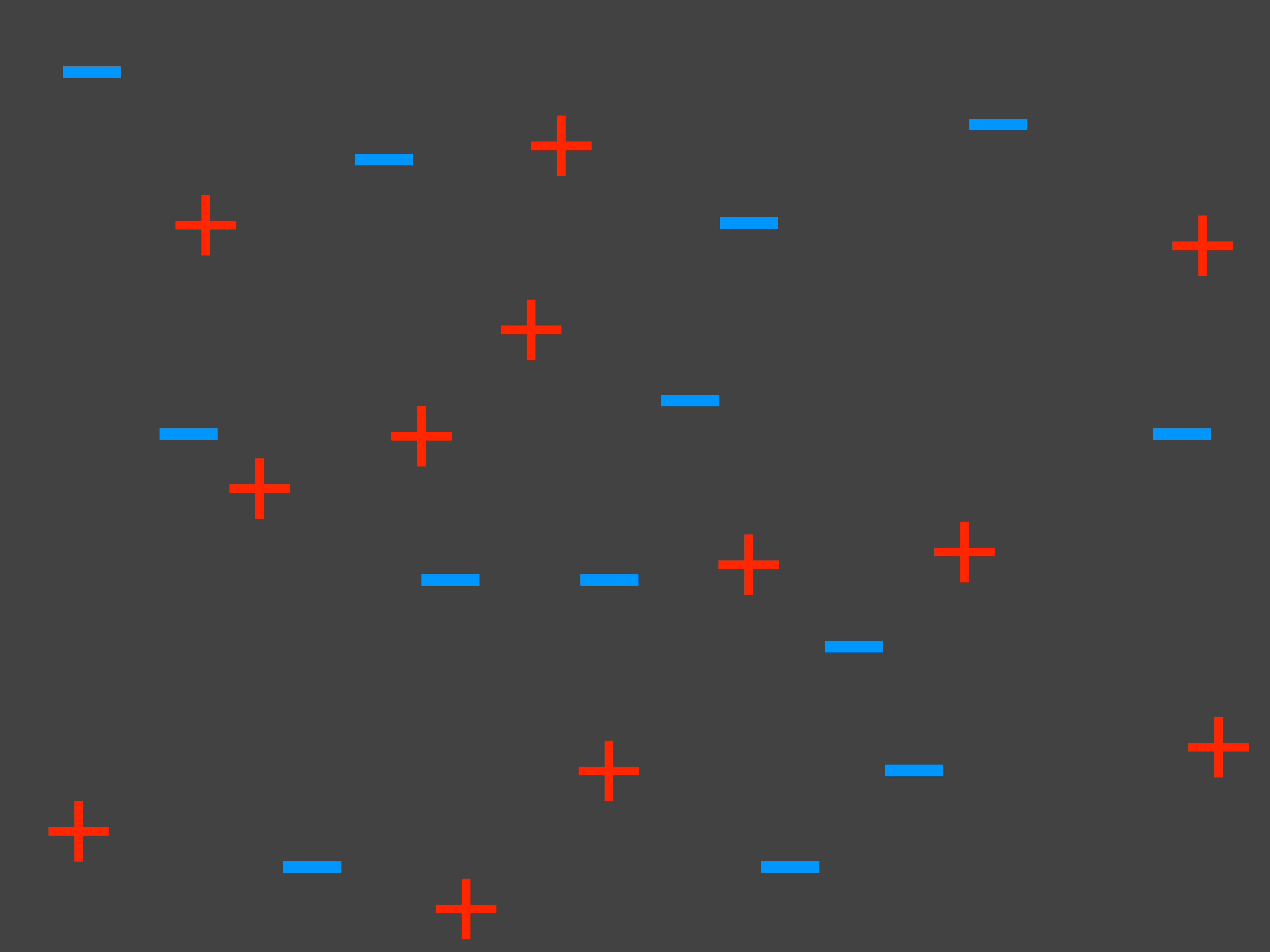
The lecture will begin shortly. Please mute your microphone until you are ready to speak.



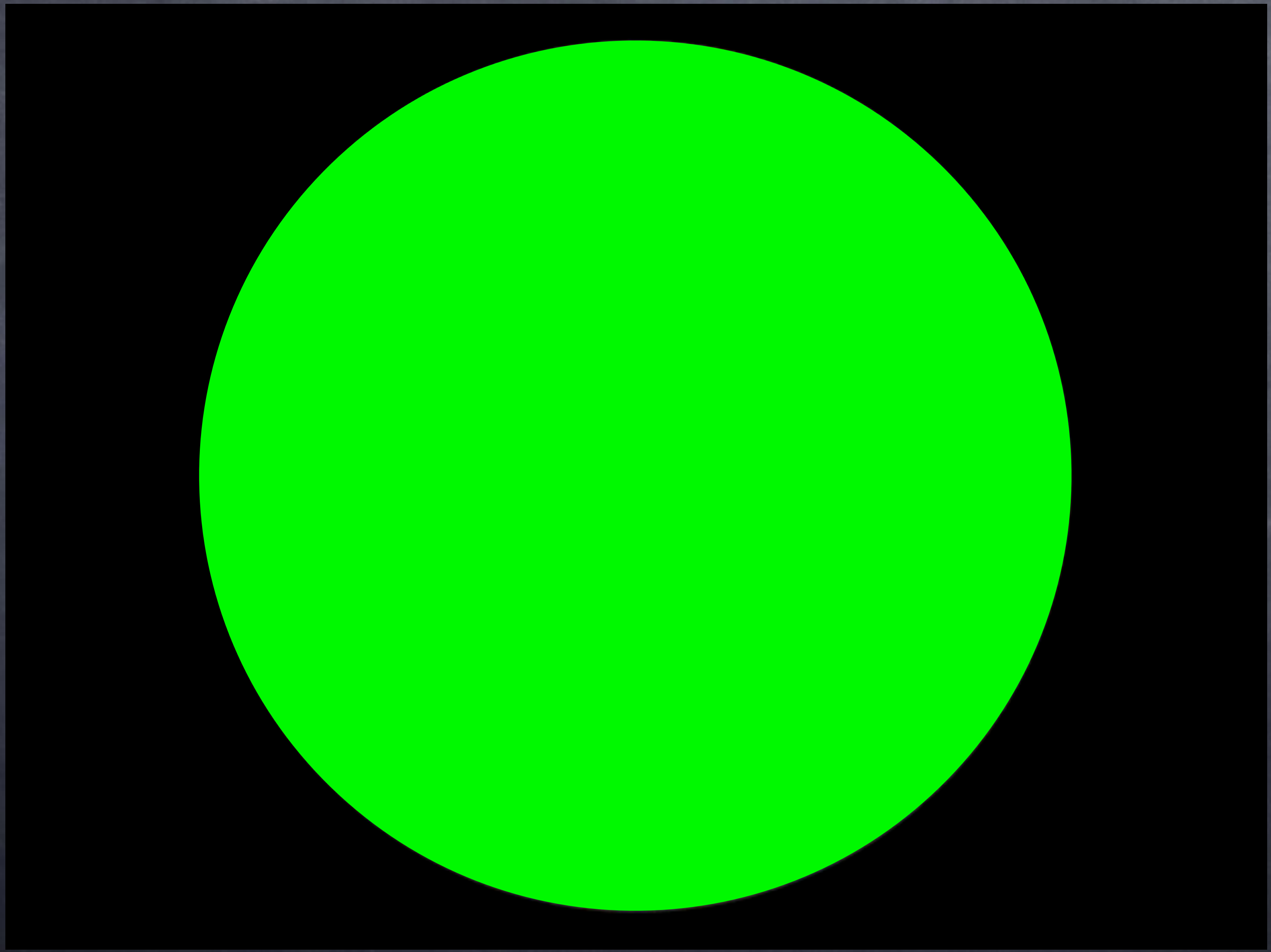
Cosmological Recombination

Douglas Scott

Summary

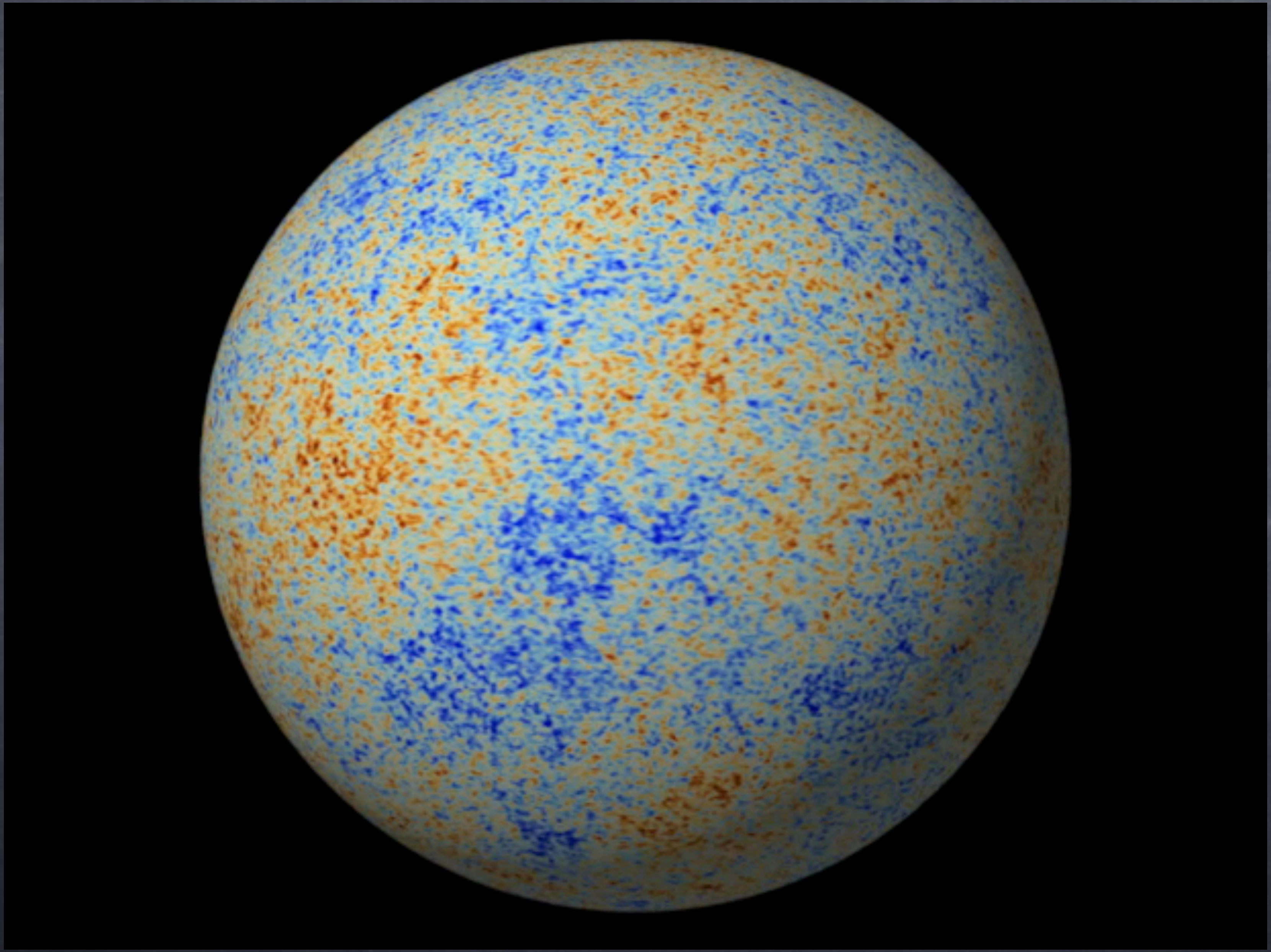
- Universe underwent a phase transition at about 400,000 years
- Precise evolution defines the "visibility function"
- Shape of V(z) affects CMB anisotropies, which help answer Big Questions
- Need to get the eV physics right to infer the correct 10^{15} GeV physics!
- Reaching ~0.1% accuracy is hard!
- But gory details can be worked out → fix simple ODE code → recfast (with fudges!)

CMB Sky



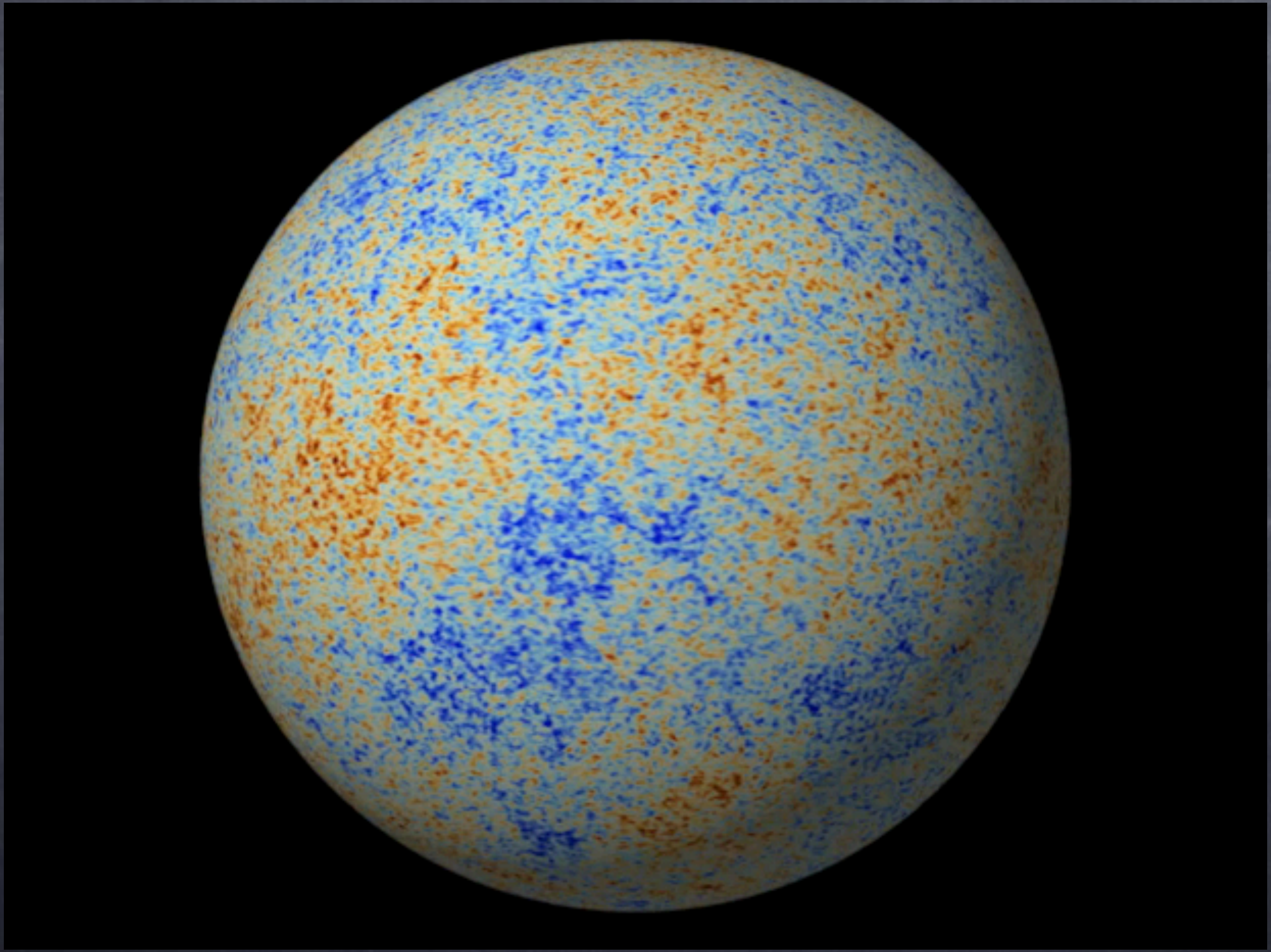
Temperature anisotropies at 400,000 years

CMB Sky



Temperature anisotropies at 400,000 years

CMB Sky

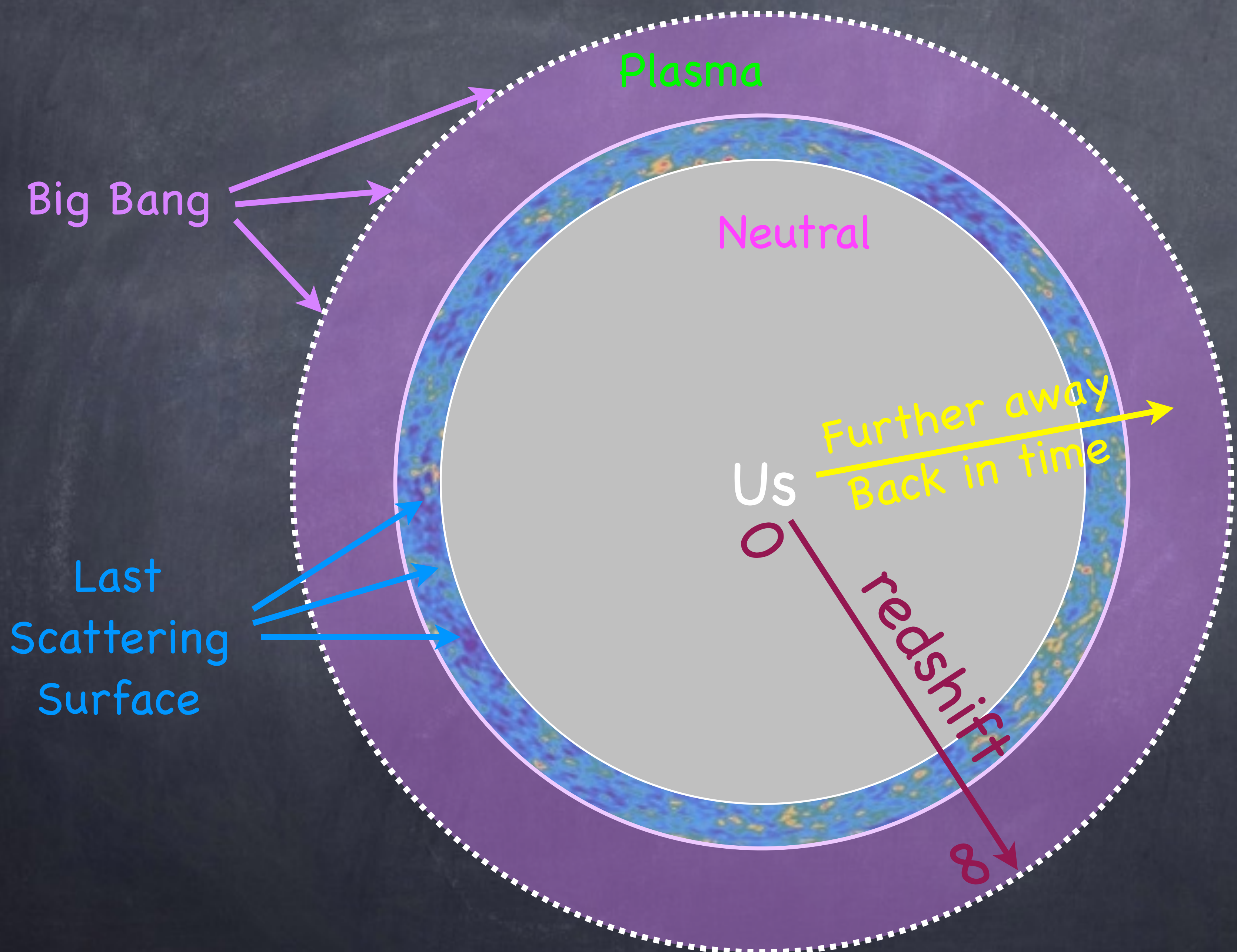


Temperature anisotropies at 400,000 years

CMB Sky

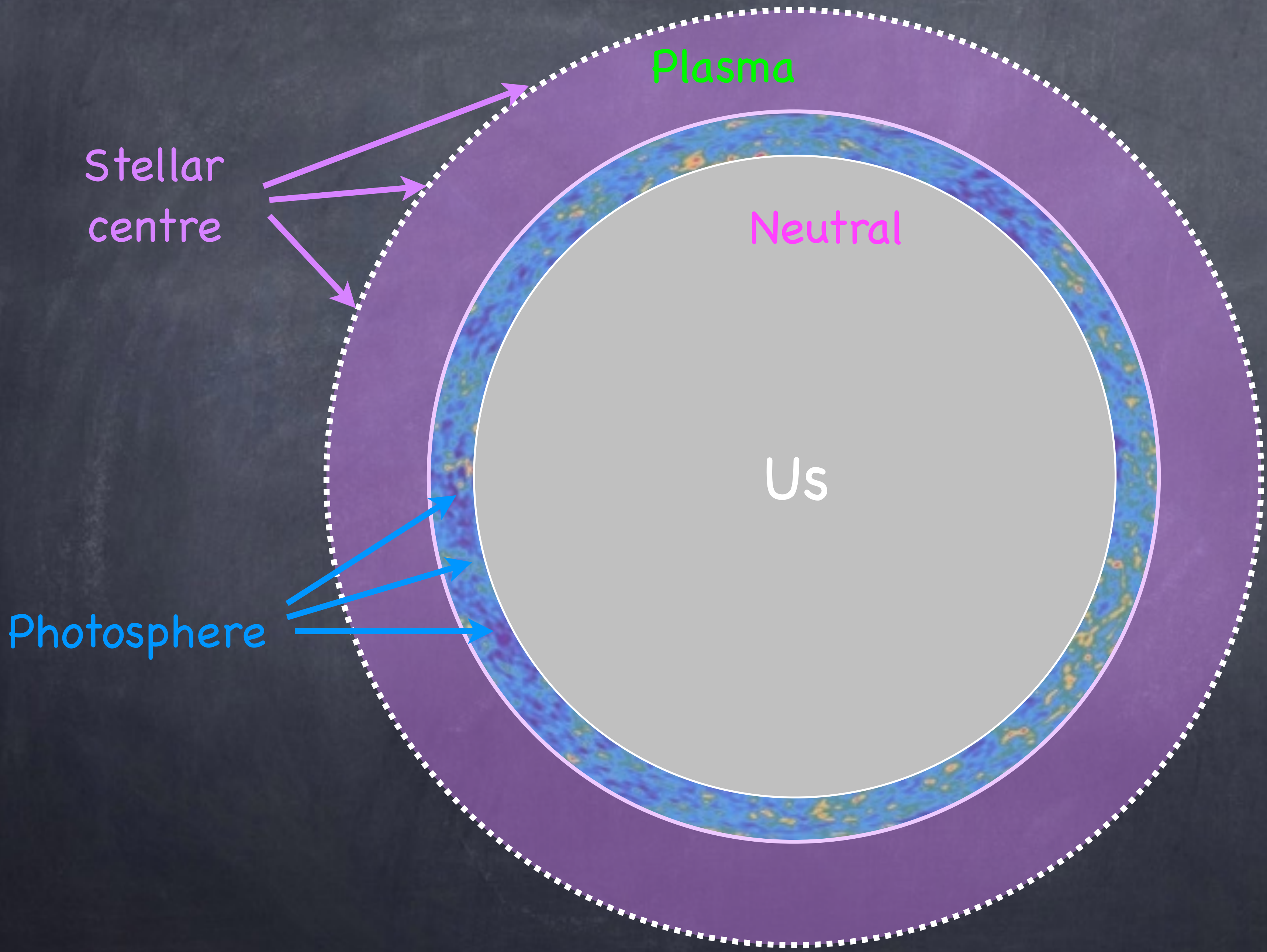
Temperature anisotropies at 400,000 years

The Universe is an inside-out star!

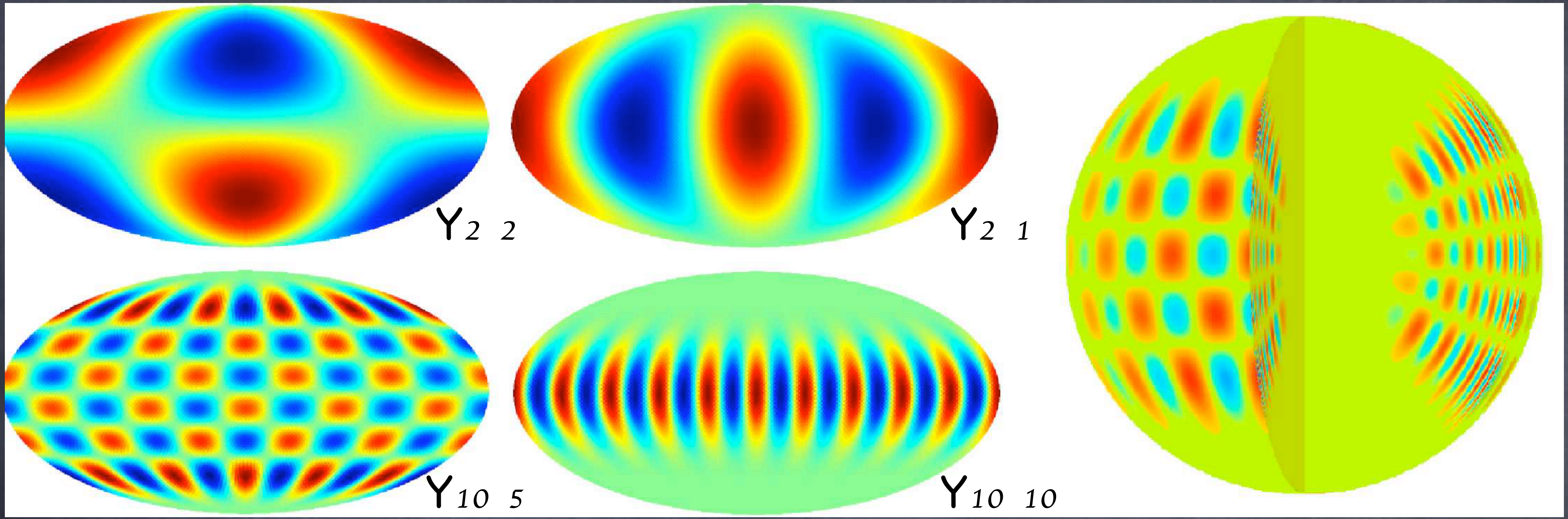


Crowe, Moss & Scott (2008)

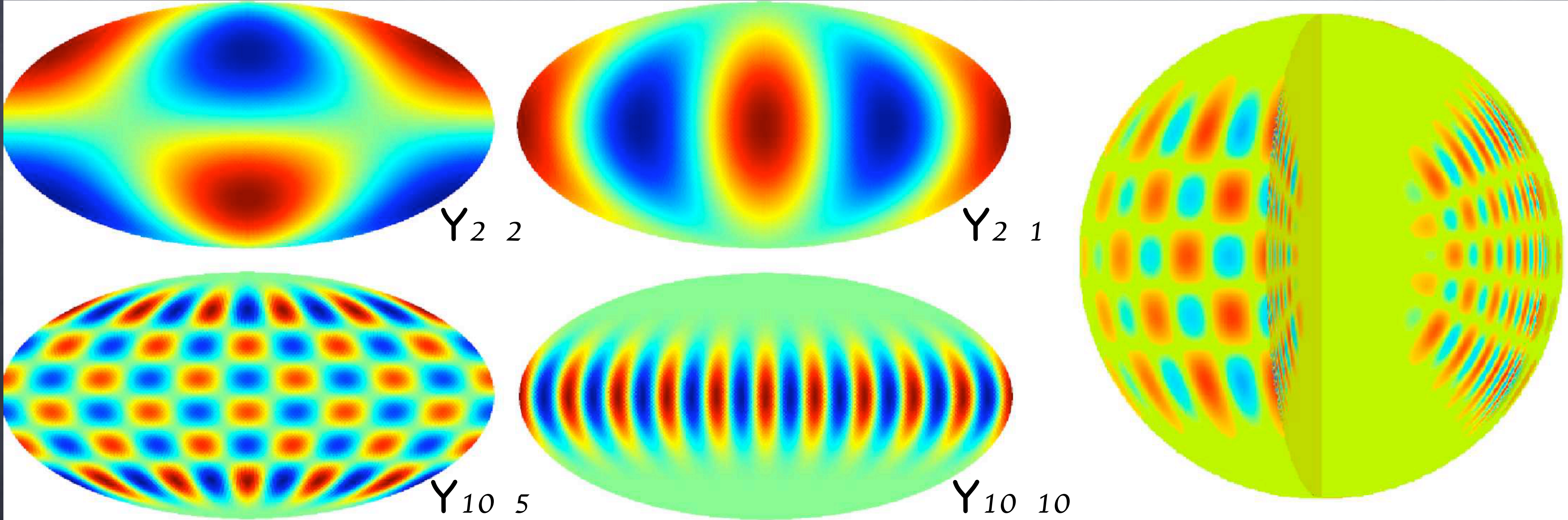
The Universe is an inside-out star!

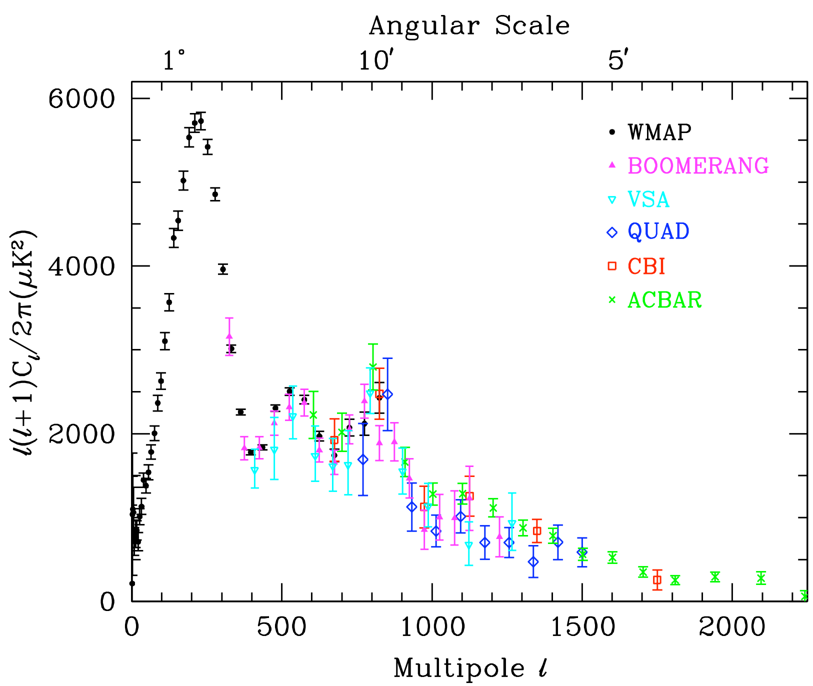


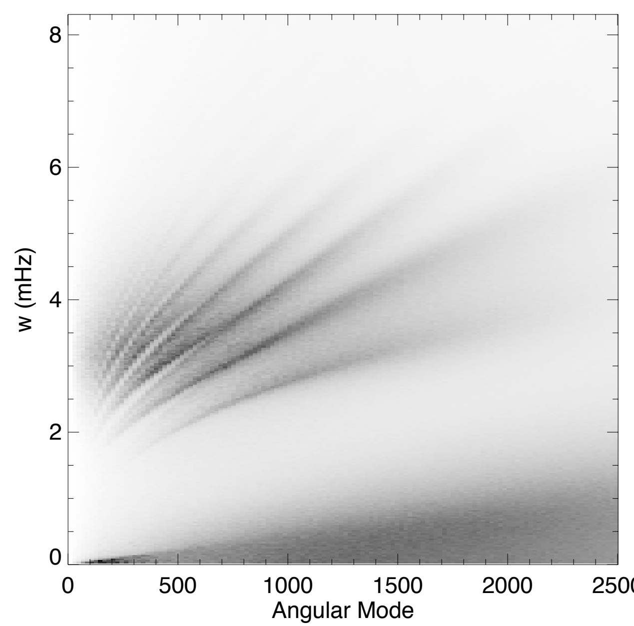
Crowe, Moss & Scott (2008)

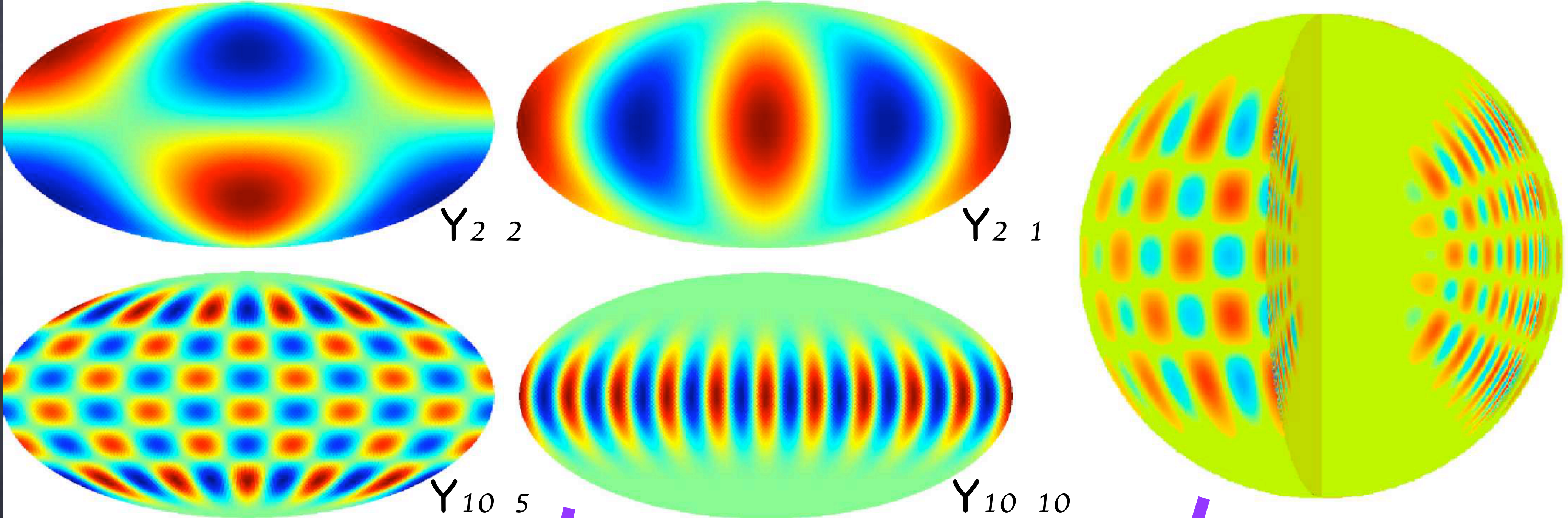


$Y_{2\ 2}$
$Y_{2\ 1}$
$Y_{10\ 5}$
$Y_{10\ 10}$

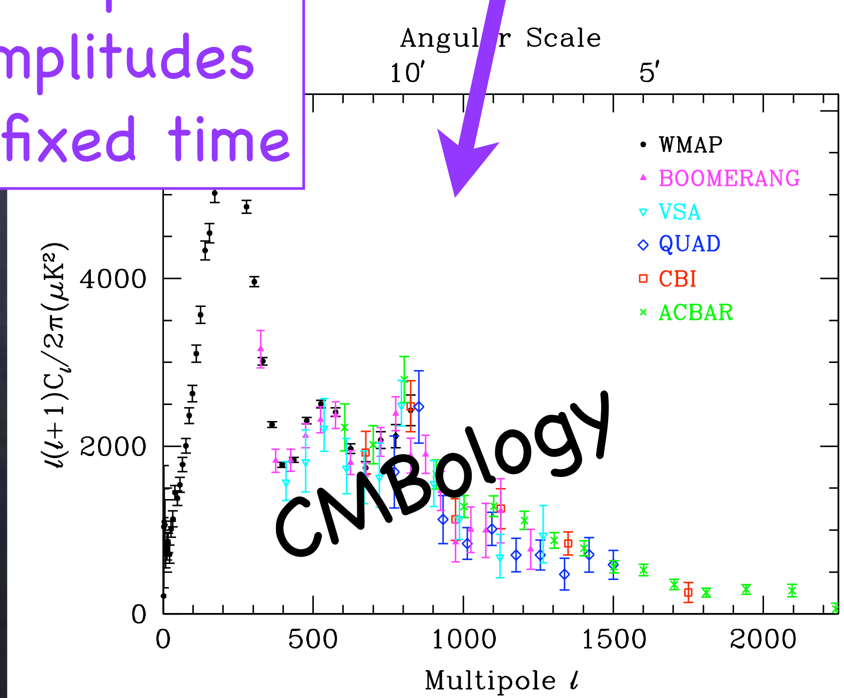

Y2 2
Y2 1
Y10 5
Y10 10


Angular Scale
1°
10′
5′
6000
4000
2000
0
0
500
1000
1500
2000
$\ell(\ell+1)C_\ell/2\pi(\mu K^2)$
Multipole ℓ
WMAP
BOOMERANG
VSA
QUAD
CBI
ACBAR

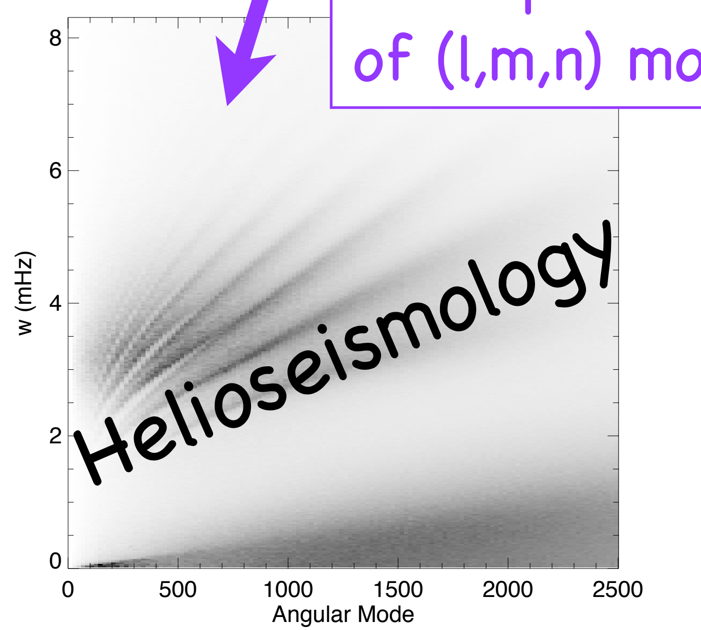

8
6
4
2
0
w (mHz)
0
500
1000
1500
2000
2500
Angular Mode

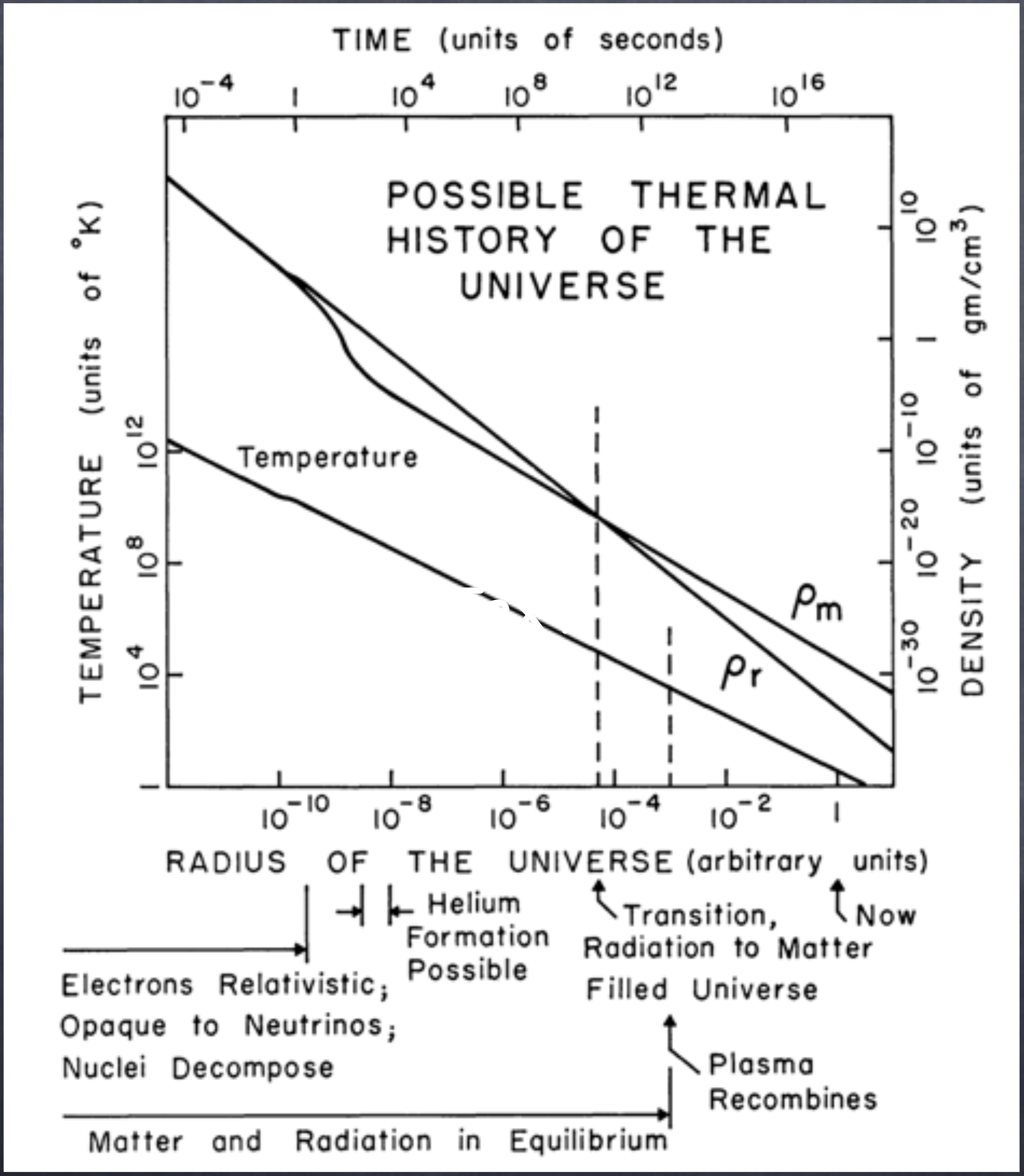


Use squared amplitudes at fixed time

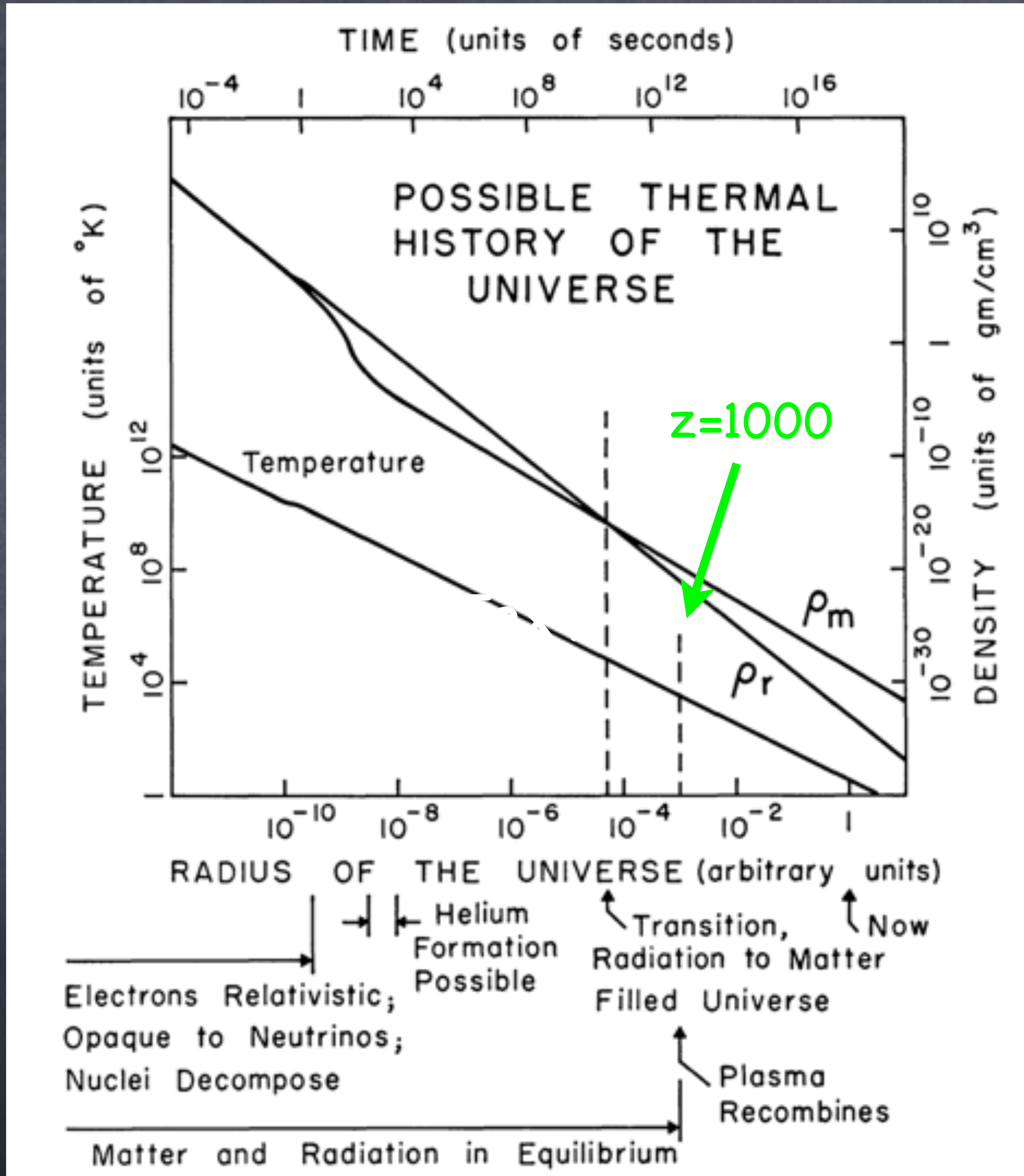


Use temporal frequencies of (l,m,n) modes





Dicke, Peebles, Roll & Wilkinson (1965)



Dicke, Peebles, Roll & Wilkinson (1965)

SOVIET PHYSICS JETP VOLUME 28, NUMBER 1 JANUARY, 1969

RECOMBINATION OF HYDROGEN IN THE HOT MODEL OF THE UNIVERSE

Ya. B. ZEL'DOVICH, V. G. KURT and R. A. SYUNYAEV

Applied Mathematics Institute, U.S.S.R. Academy of Sciences

Submitted December 27, 1967

Zh. Eksp. Teor. Fiz. 55, 278–286 (July, 1968)

The considerable emission of energetic quanta during recombination of hydrogen in an expanding universe leads to a slowing down of the recombination and to a distortion of the relict radiation spectrum in the Wien region. The energy exchange between electrons and radiation in the Compton effect maintains the temperature of matter equal to that of the radiation up to a time corresponding to a red shift of $z \sim 150$, and this leads, in particular, to a change in the time dependence of the Jeans wavelength of the gravitational instability of a homogeneous medium in an expanding universe.

THE ASTROPHYSICAL JOURNAL, Vol. **153**, July 1968

RECOMBINATION OF THE PRIMEVAL PLASMA*

P. J. E. PEEBLES

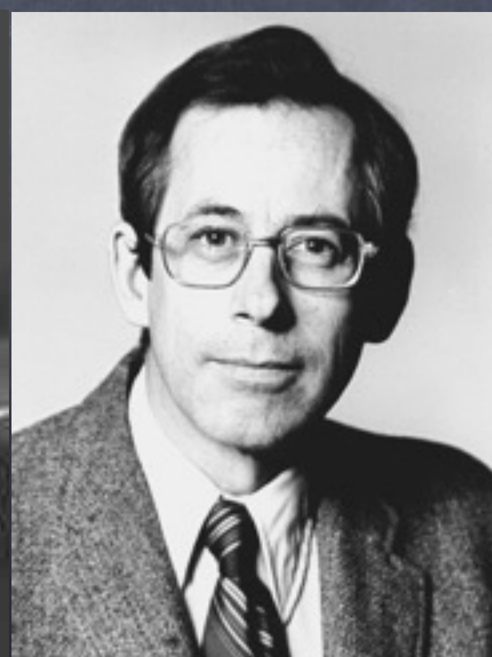
Palmer Physical Laboratory, Princeton University, Princeton, New Jersey

Received December 11, 1967

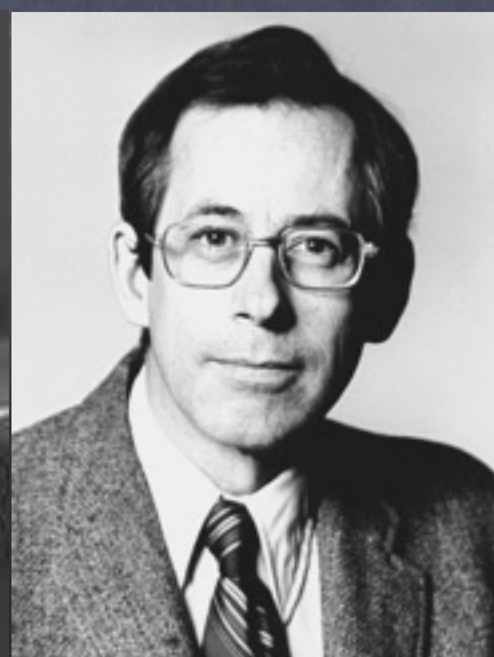
ABSTRACT

A theory is presented for the plasma recombination that would have taken place when the Universe had expanded and cooled to a Primeval Fireball temperature of about 4000° K. The computed residual ionization of the hydrogen following this recombination is in the range of 2×10^{-5} to 2×10^{-4}, depending on the assumed cosmological model. In the closed cosmological model the matter temperature would have effectively decoupled from the radiation at a temperature of 1200° K, while in the lowest density model the matter temperature would not have fallen much below the radiation temperature before the galaxies formed. Also computed is the effect of the recombination radiation on the spectrum of the Primeval Fireball.

Basic calculations completed by 1968 in 2 seminal papers



Basic calculations completed by 1968 in 2 seminal papers



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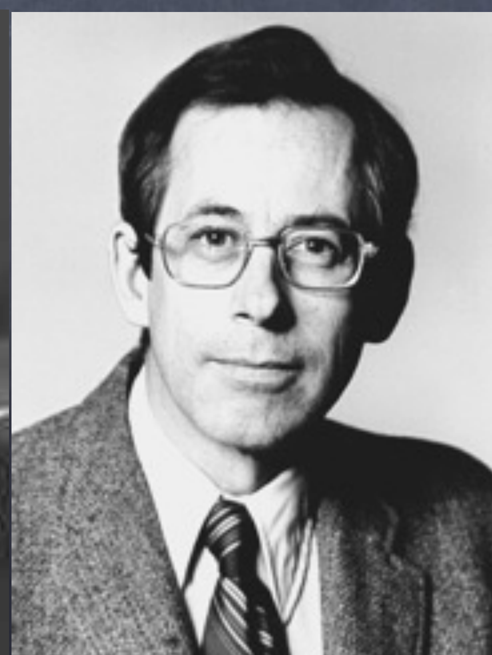
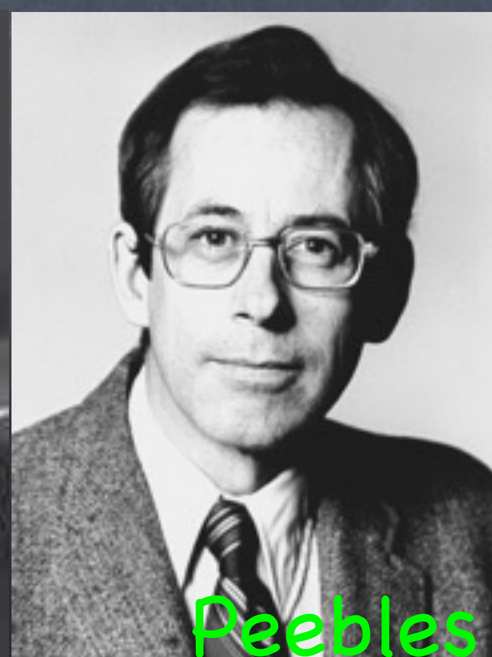
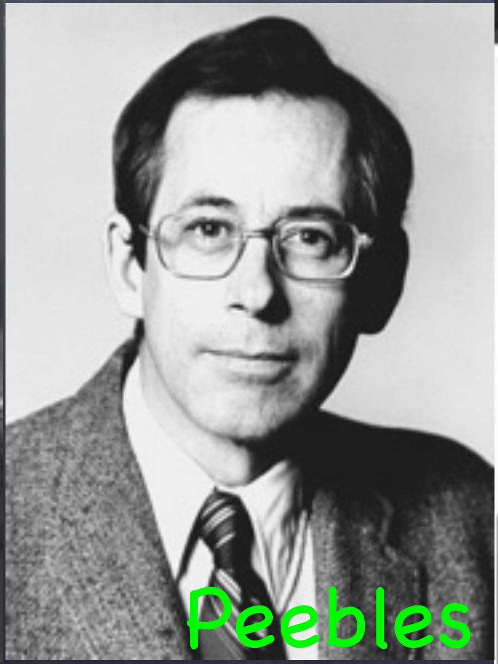


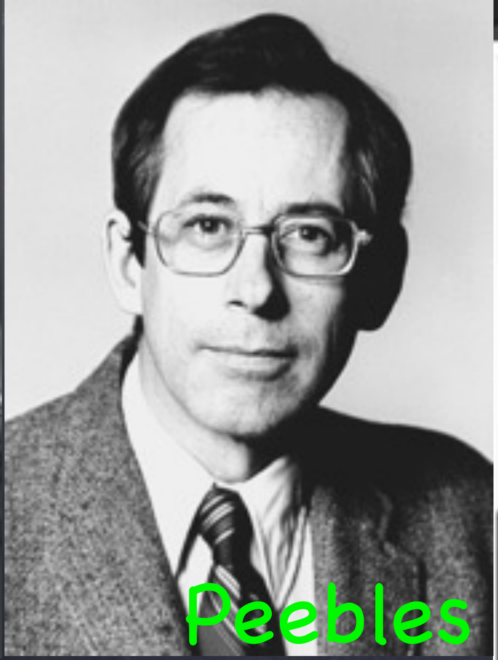
Basic calculations completed by 1968 in 2 seminal papers



Basic calculations completed by 1968 in 2 seminal papers



Basic calculations completed by 1968 in 2 seminal papers



When did the Universe recombine?

- Temperature cools with expansion: $T(z)=T_0(1+z)$
- $3kT=13.6eV \Rightarrow z\approx 23{,}000$

  But $\sim 10^9$ photons per baryon
- Saha in a cooling bath $\Rightarrow z\approx 1500$ (for $x=0.5$)

  But Lyα optically thick, 2-photon slow, and "freeze-out" of free electron fraction
- $V(z)\equiv \exp(-\tau)d\tau$ peaks at $z\approx 1100$

  But what about low and high z tails?
- Historically, $\Delta z/z\approx 0.1$ led to ~ 10 reduction in $\Delta T/T$ estimates

Saha (equilibrium) equation

$$\left(\frac{n_i}{n_\mathrm{e} n_\mathrm{c}}\right) = \frac{g_i}{2g_\mathrm{c}} \left(\frac{h_\mathrm{P}^2}{2\pi m_\mathrm{e} k_\mathrm{B} T_\mathrm{M}}\right)^{3/2} \mathrm{e}^{E_i/k_\mathrm{B} T_\mathrm{M}}$$

continuum

electrons

bound state

statistical weights

kinetic temperature of matter

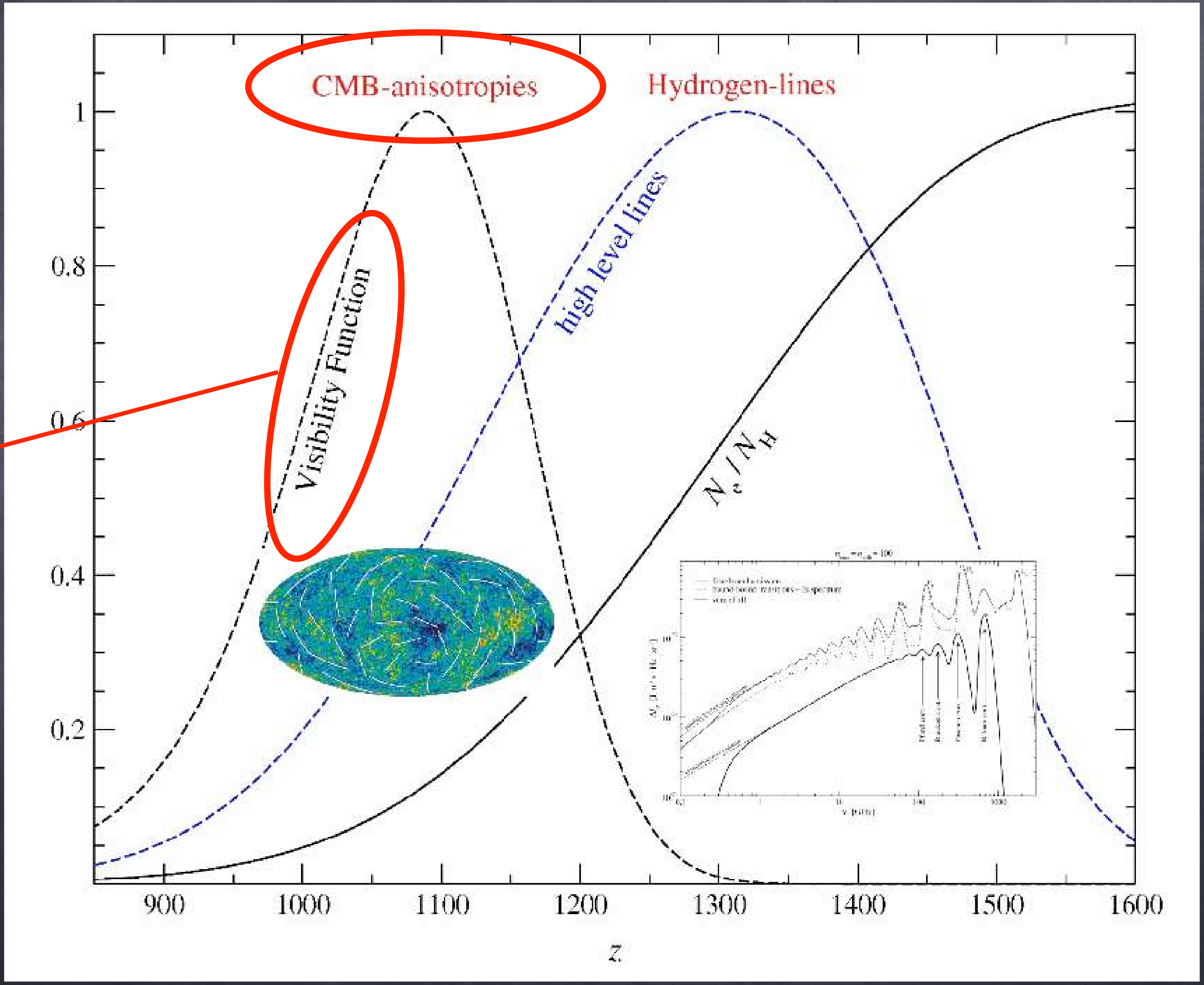
bound energy level

Easy to solve for $x_\mathrm{e} \equiv \left(\frac{n_\mathrm{e}}{n_\mathrm{H}}\right)$

with $T_\mathrm{M} \propto (1+z), n \propto (1+z)^3$

Profile of the Cosmic Photosphere

$$V(z) \equiv e^{-\tau} d\tau / dz$$

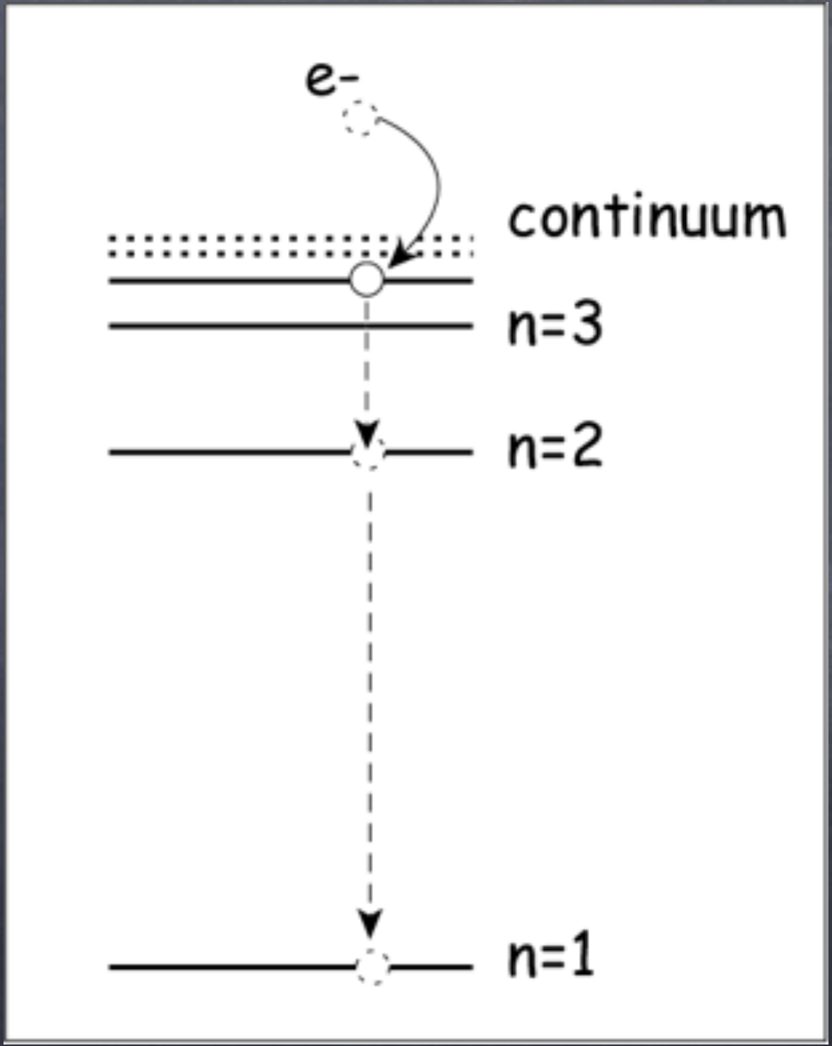


Sunyaev & Chluba (2007)

How did the Universe recombine?

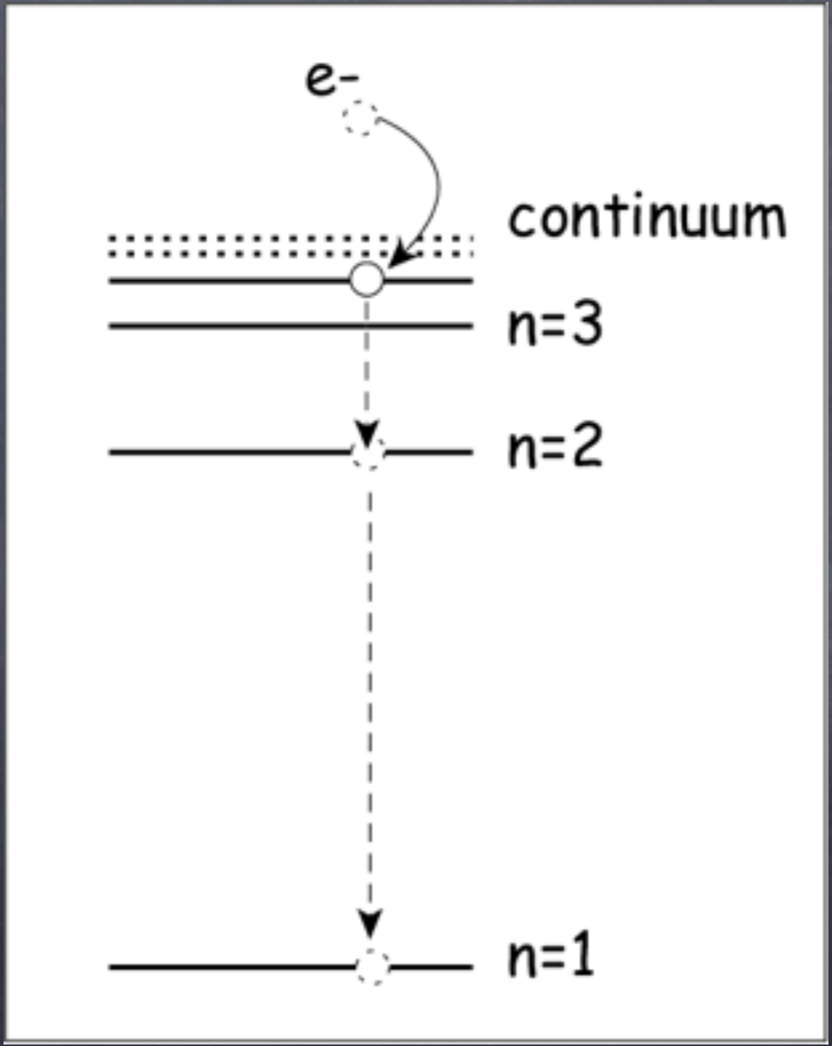
- Unlike in the Lab and most other astro systems!
- Radiation determines everything (can ignore collisional rates)
- Wien tail means that there are zillions of $n \rightarrow 2$ photons compared with $2 \rightarrow 1$ photons
- So once an electron gets to ground state it's safe
- Primary effects are those involving $2 \rightarrow 1$
- More than ½ H atoms used the 2-photon channel (not so forbidden!)

Effective 3-level atom



Effective 3-level atom

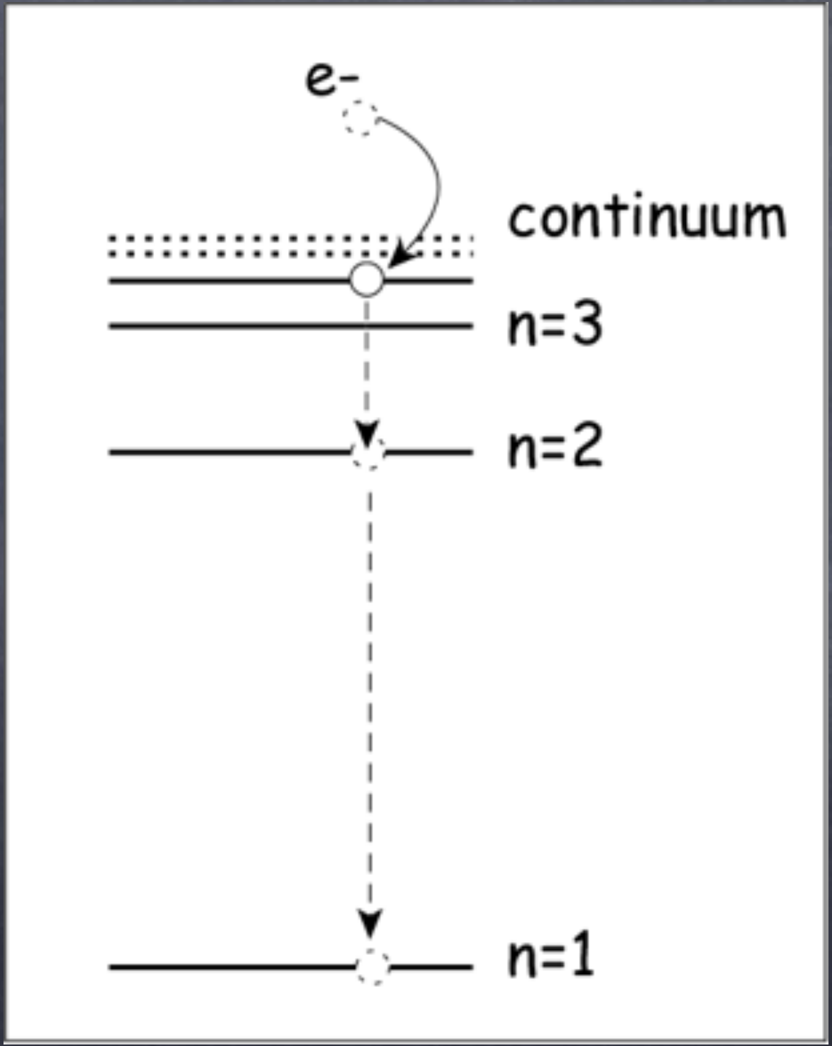
Ground state



Effective 3-level atom

1st excited state

Ground state

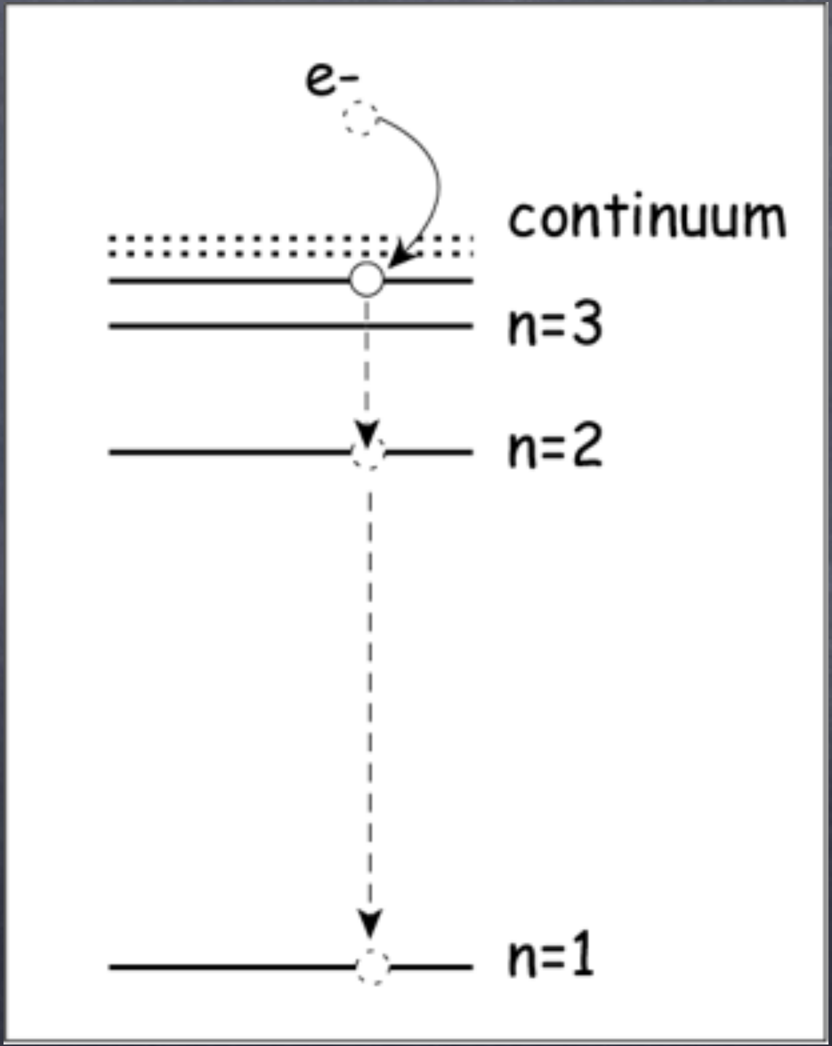


Effective 3-level atom

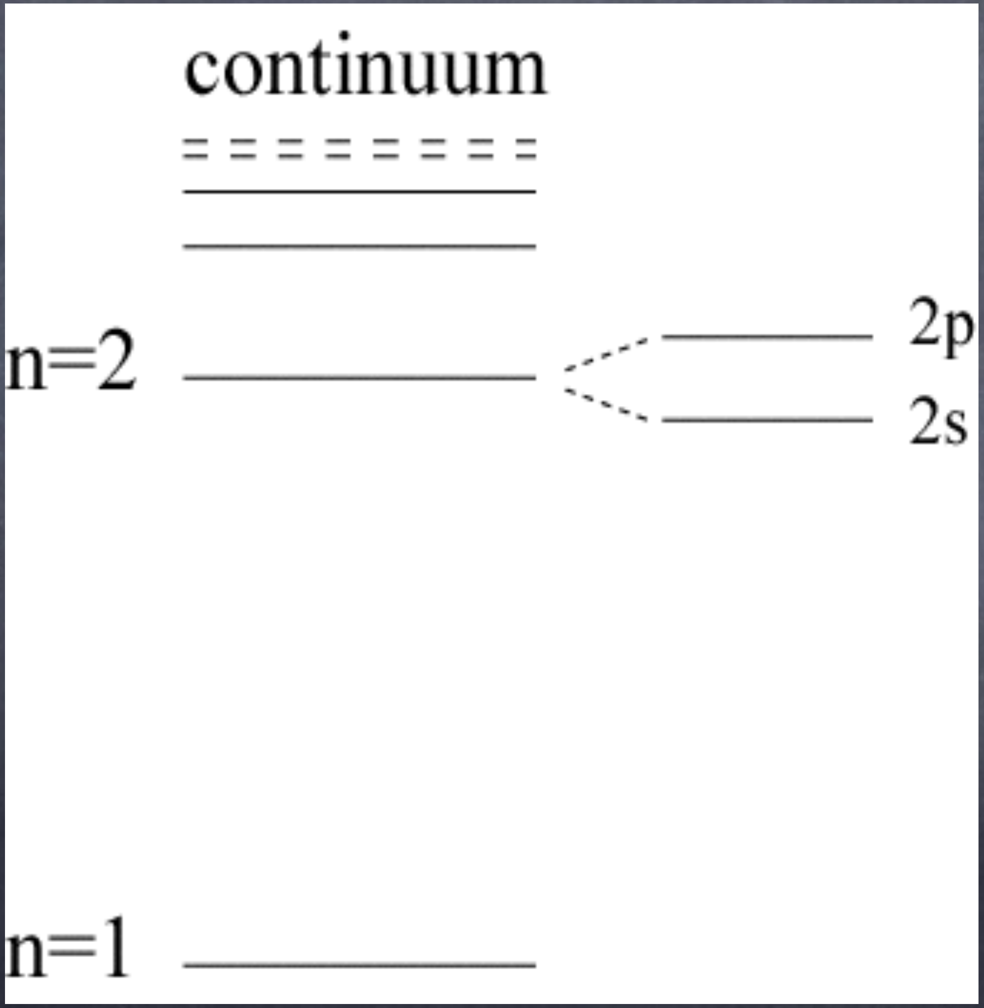
All higher states
in equilibrium
with continuum

1st excited state

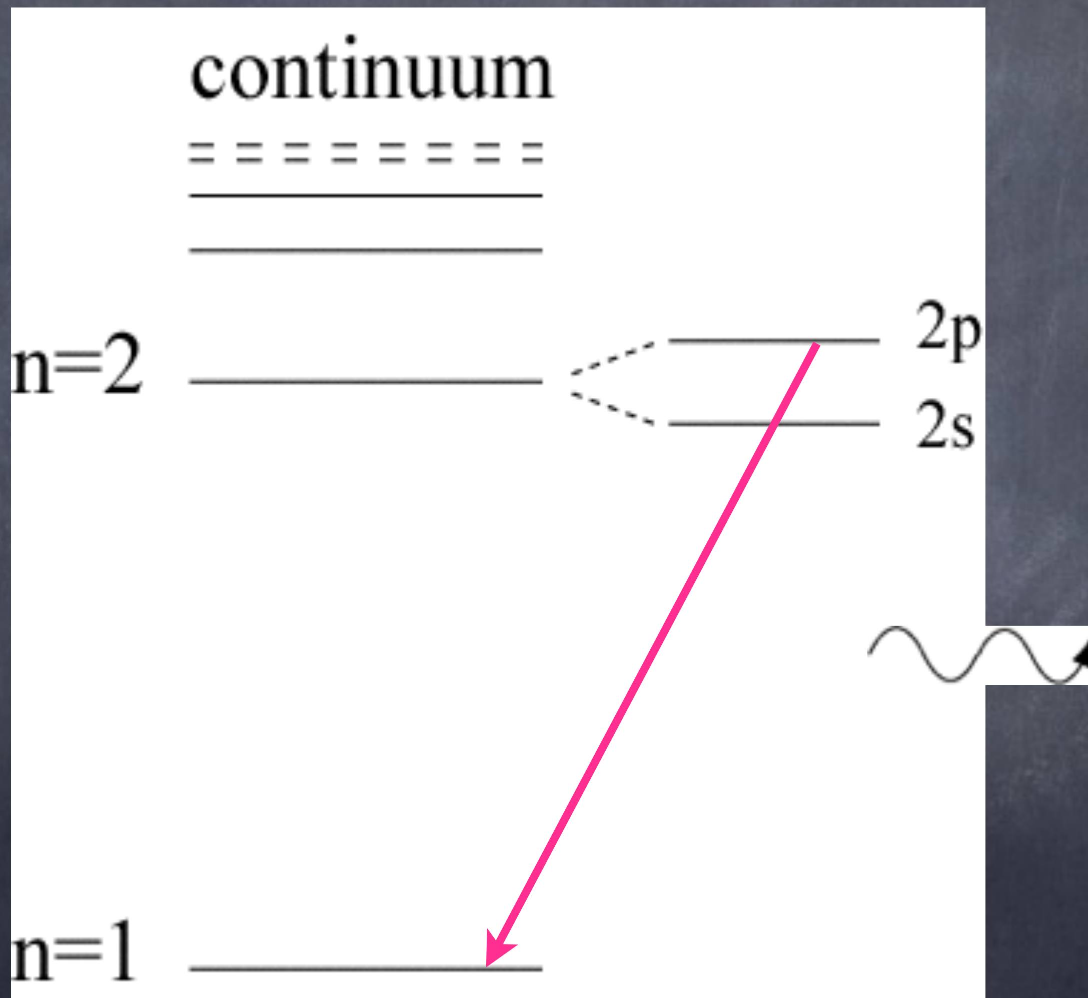
Ground state



How to get to the ground state in H

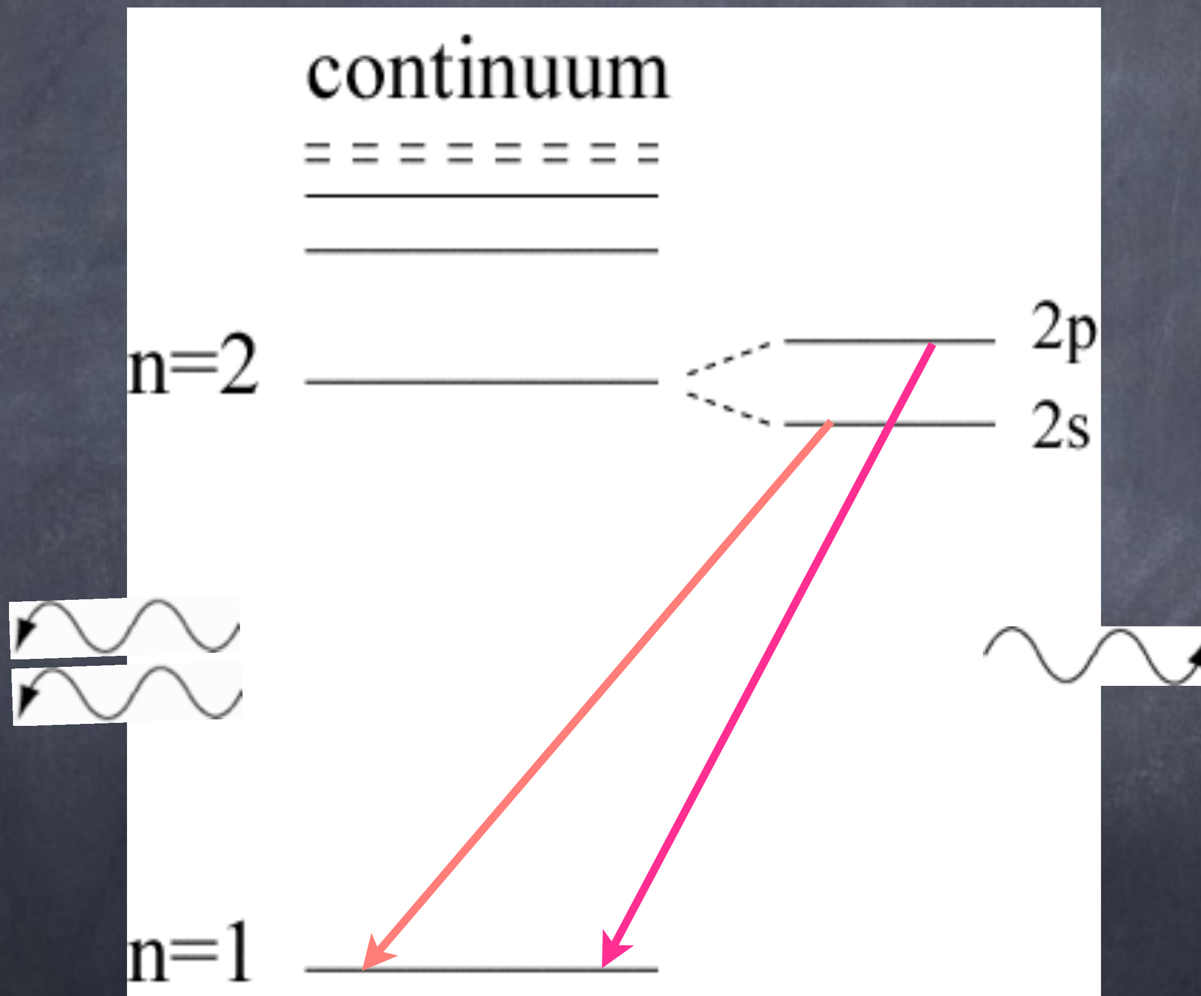


How to get to the ground state in H



How to get to the ground state in H

$h\nu_1 + h\nu_2$
$= 10.2eV$



$h\nu = 10.2eV$
Ly α

recast

recast

Solve ODE for level population

recast

Solve ODE for level population

using public code "dverk"

recast

Solve ODE for level population

using public code "dverk"

written in fortran

recast

Solve ODE for level population

using public code "dverk"

written in fortran

with clunky initial condition generator

recast

Solve ODE for level population

using public code “dverk”

written in fortran

with clunky initial condition generator

add helium deionization

recast

Solve ODE for level population

using public code “dverk”

written in fortran

with clunky initial condition generator

add helium deionization

and later “fudge factors”

```
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
C Integrator for Cosmic Recombination of Hydrogen and Helium,
C developed by Douglas Scott (dscott@astro.ubc.ca)
C based on calculations in the papers Seager, Sasselov & Scott
C (ApJ, 523, L1, 1999; ApJS, 128, 407, 2000)
C and "fudge" updates in Wong, Moss & Scott (2008).
C
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recfast

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CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
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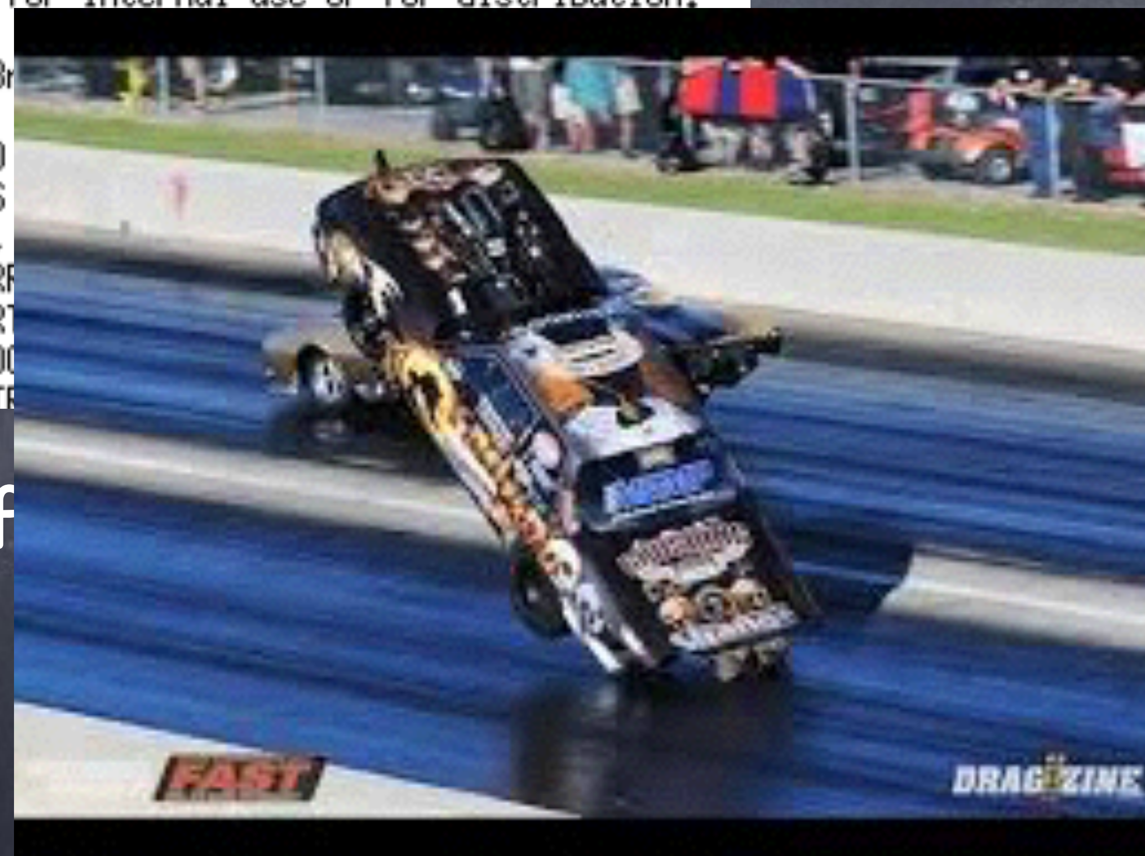


recf

a fast wreck

recfast: basic equations

$$H(z)(1+z)\frac{dx_{\rm p}}{dz} = \left(x_{\rm e}x_{\rm p}n_{\rm H}\alpha_{\rm H}F_{\rm H} - \beta_{\rm H}(1-x_{\rm p})\mathrm{e}^{-h\nu_{\rm H2s}/kT_{\rm M}}\right)C_{\rm H}$$

$$H(z)(1+z)\frac{dx_{\rm HeII}}{dz} = \left(x_{\rm HeII}x_{\rm e}n_{\rm H}\alpha_{\rm HeI} - \beta_{\rm HeI}(f_{\rm He}-x_{\rm HeII})\mathrm{e}^{-h\nu_{{\rm HeI},2^1{\rm s}}/kT_{\rm M}}\right)C_{\rm HeI}$$
$$+\left(x_{\rm HeII}x_{\rm e}n_{\rm H}\alpha^{\rm t}_{\rm HeI} - \frac{g_{{\rm HeI},2^3{\rm s}}}{g_{{\rm HeI},1^1{\rm s}}}\beta^{\rm t}_{\rm HeI}(f_{\rm He}-x_{\rm HeII})\mathrm{e}^{-h\nu_{{\rm HeI},2^3{\rm s}}/kT_{\rm M}}\right)C^{\rm t}_{\rm HeI}$$

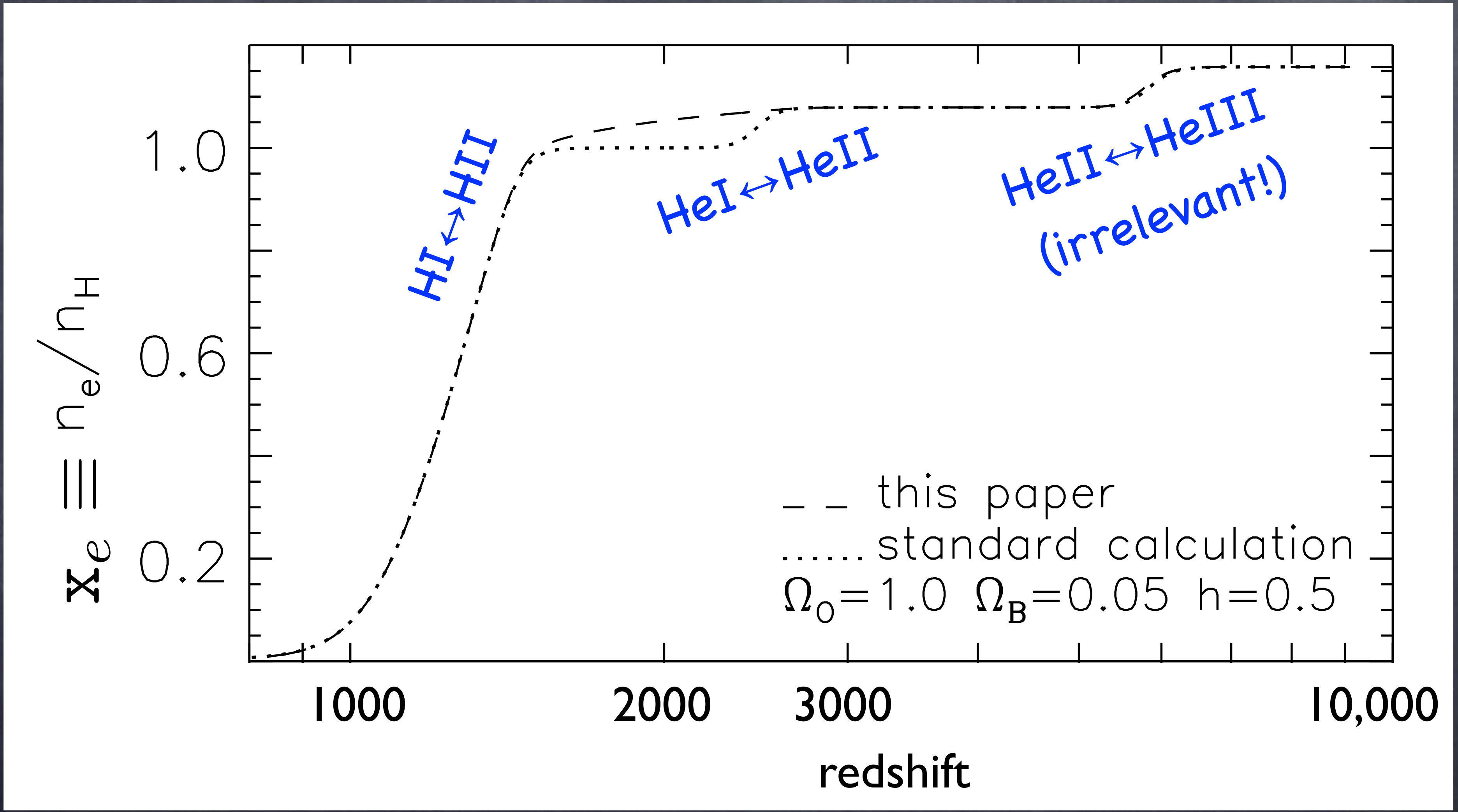
with $$C_{\rm H} = \frac{1+K_{\rm H}\Lambda_{\rm H}n_{\rm H}(1-x_{\rm p})}{1+K_{\rm H}(\Lambda_{\rm H}+\beta_{\rm H})n_{\rm H}(1-x_{\rm p})}$$

$$C_{\rm HeI} = \frac{1+K_{\rm HeI}\Lambda_{\rm He}n_{\rm H}(f_{\rm He}-x_{\rm HeII})\mathrm{e}^{h\nu_{\rm ps}/kT_{\rm M}}}{1+K_{\rm HeI}(\Lambda_{\rm He}+\beta_{\rm HeI})n_{\rm H}(f_{\rm He}-x_{\rm HeII})\mathrm{e}^{h\nu_{\rm ps}/kT_{\rm M}}}$$

$$C^{\rm t}_{\rm HeI} = \frac{1}{1+K^{\rm t}_{\rm HeI}\beta^{\rm t}_{\rm HeI}n_{\rm H}(f_{\rm He}-x_{\rm HeII})\mathrm{e}^{h\nu^{\rm t}_{\rm ps}/kT_{\rm M}}}$$

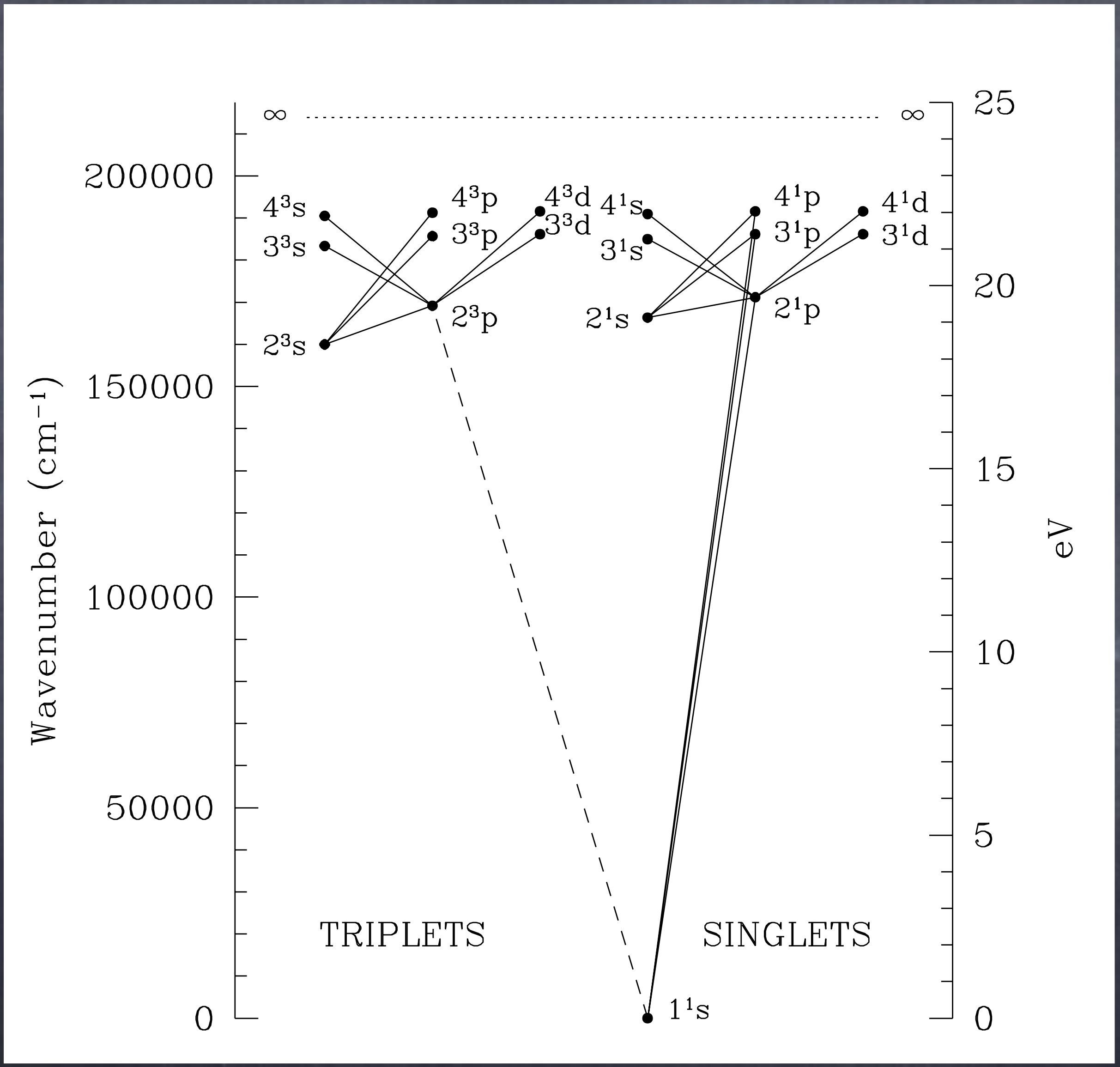
$$F_{\rm H} = 1.14 \quad F_{\rm He} = 0.86$$

3 main recombination transitions



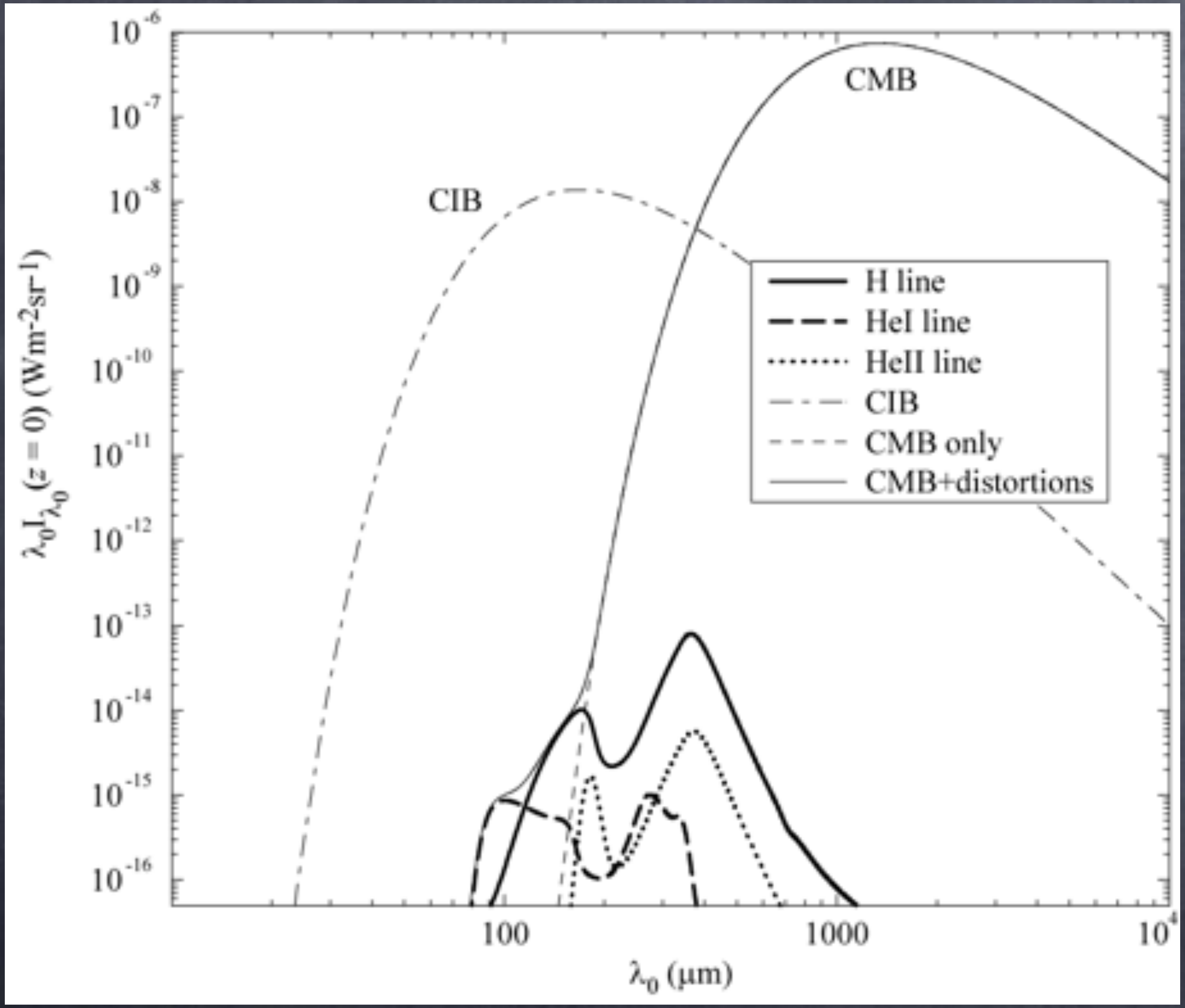
Seager, Sasselov & Scott (2000)
[but not correct!]

Grotrian diagram for Helium



Complicated!

What happens to the recombination photons?



For Ly α and 2-photon here

Other lines can also be calculated

Definite prediction but measurable??

recfast

http://www.astro.ubc.ca/people/scott/recfast.html

latest version 1.5.2

good enough for Planck

essentially solves a "3-level atom"
simultaneously for H and for He
(it's ZKS (1968) with attention to accuracy)

includes "fudge factors" to approximate the
results of more accurate calculations

the corrections are cosmology-independent
because standard cosmology is so well constrained
(but not true for far-out theories)

The devil is in the details

- How big an effect on the anisotropy power spectra is implied by uncertainty in V(z)?
- Hu, Scott, Sugiyama & White (1995):
  1% effects are not fully under control
- Seager, Sasselov & Scott (1999,2000): recfast
- Seljak, Sugiyama, White & Zaldarriaga (2003):
  0.1% accuracy <u>if</u> you use same recombination
- Lots of new detailed effects in last ~10 years
- Moss, Scott & Wong (2008):
  Most effects can be "fudged" in 3-level code
- 0.1% is very challenging, but now done

Why should I care?!

Why should I care?!

Shape of $V(z)$ affects CMB anisotropies

Why should I care?!

Shape of V(z) affects CMB anisotropies

CMB used to estimate cosmological parameters

Why should I care?!

Shape of V(z) affects CMB anisotropies

CMB used to estimate cosmological parameters

So wrong V(z) can bias cosmological parameters

Why should I care?!

Shape of V(z) affects CMB anisotropies

CMB used to estimate cosmological parameters

So wrong V(z) can bias cosmological parameters

Subtly wrong V(z) can bias the parameters

Why should I care?!

Shape of V(z) affects CMB anisotropies

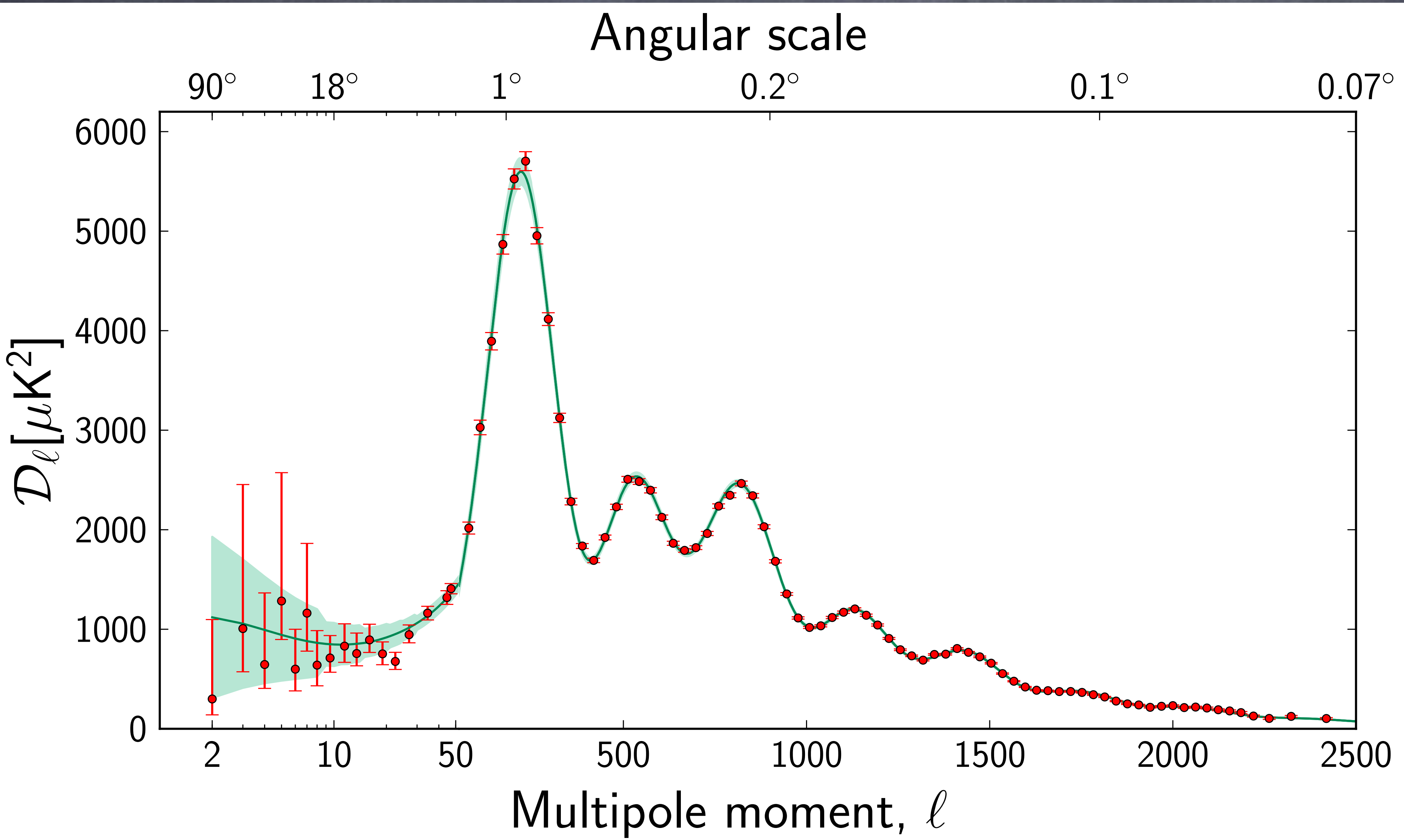
CMB used to estimate cosmological parameters

So wrong V(z) can bias cosmological parameters

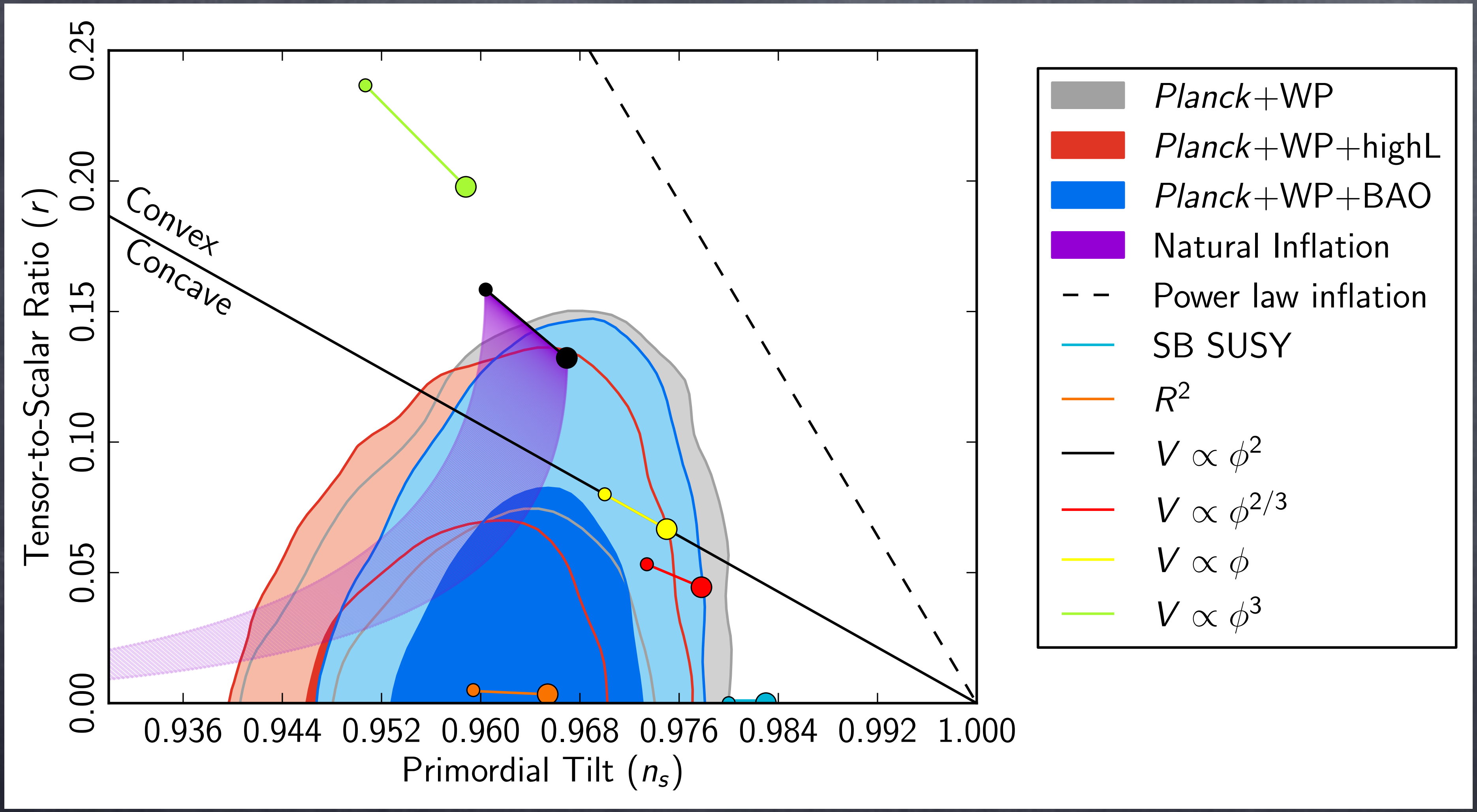
Subtly wrong V(z) can bias the parameters

Need to get the ~eV physics insanely precise
in order not to screw up the ~10^{15} GeV physics!

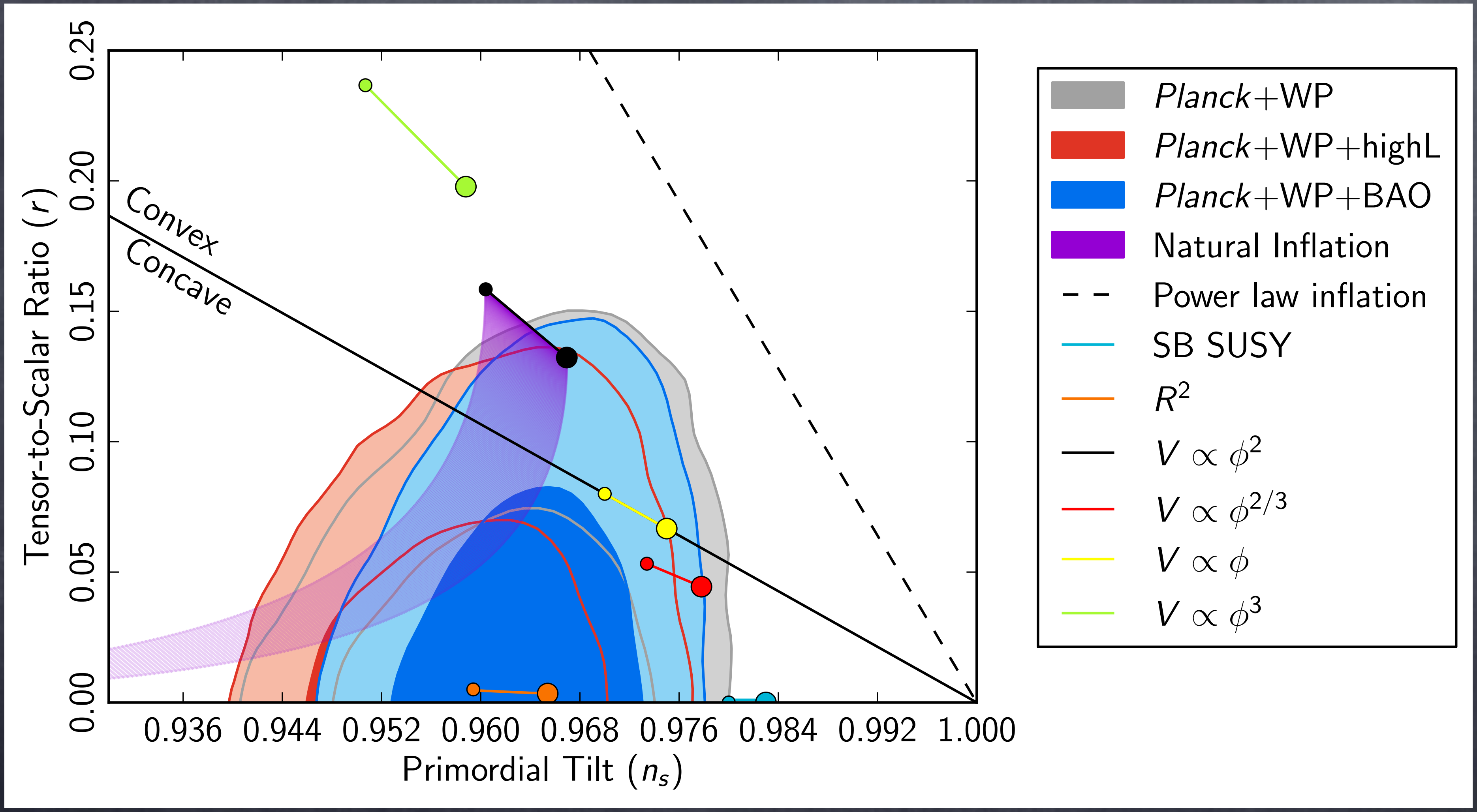
Planck's exquisite power spectrum!



Planck (+others) constraining inflation

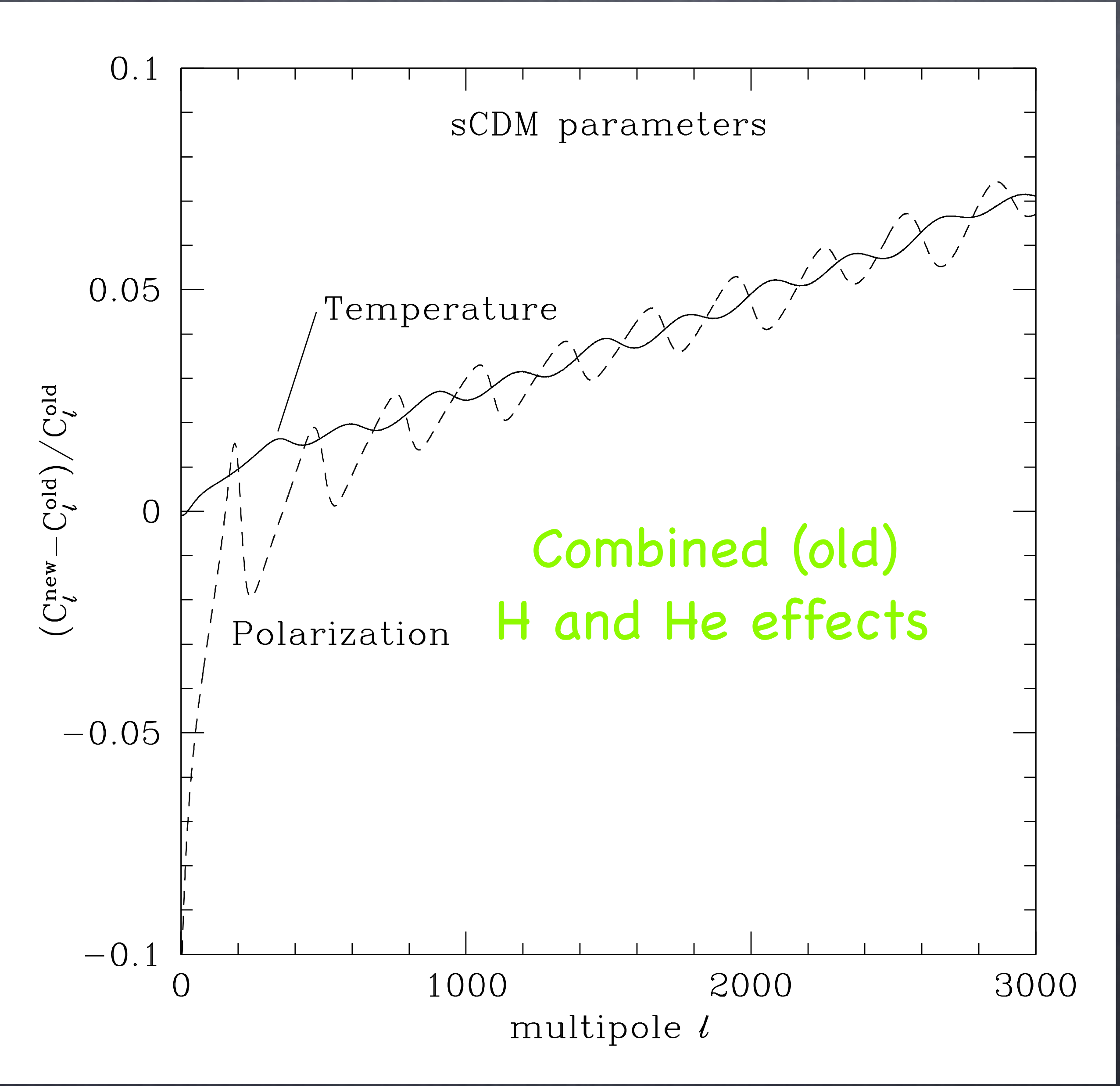


Planck (+others) constraining inflation



But this can be biased if we don't get high-z V(z) right

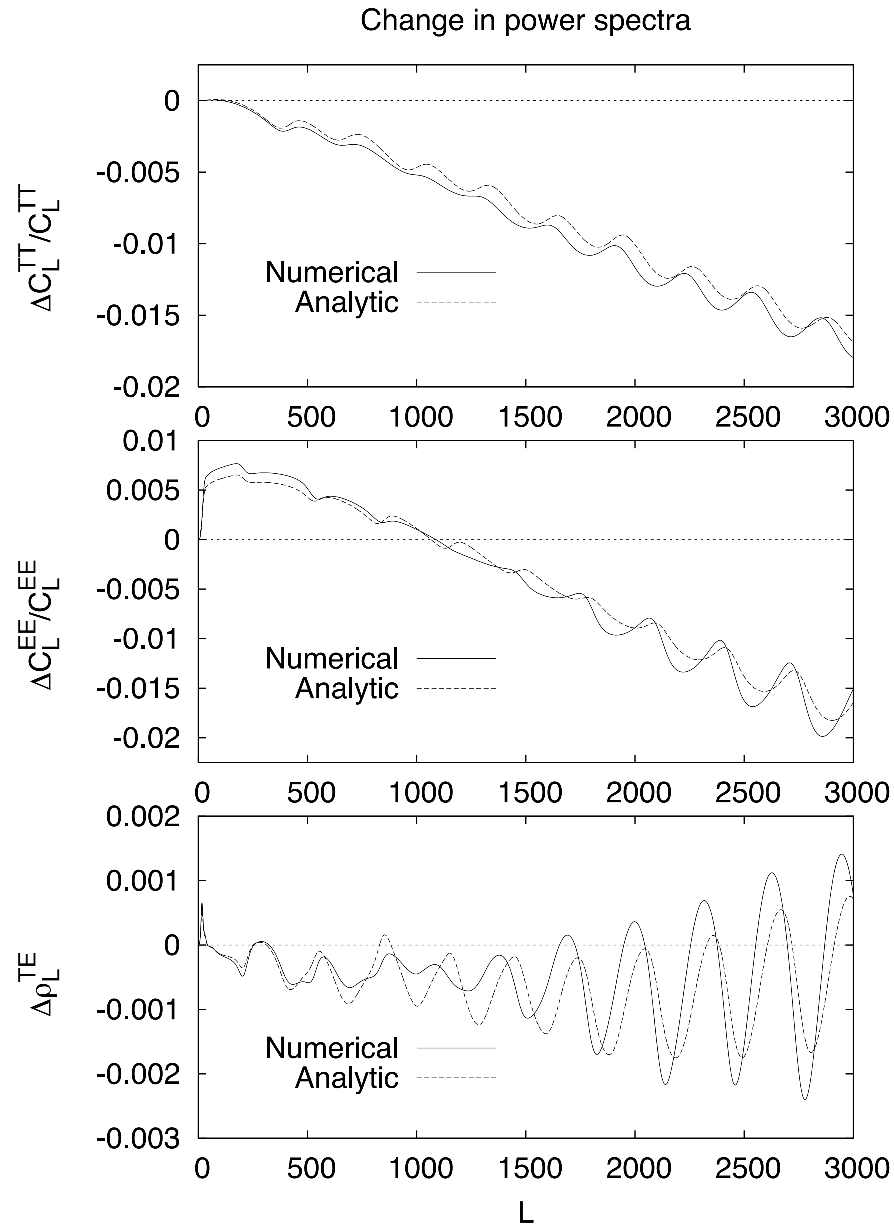
With a given recombination history, can calculate V(z) and hence effect on anisotropies



Seager, Sasselov & Scott (2000)

New H effects

Better treatment of 2-photon transitions (including intermediate resonant states) plus Raman scattering



Hirata (2008)

Burst of activity, motivated by CMB anisotropies

Burst of activity, motivated by CMB anisotropies

About a paper a year for 30 years!
Then lots of activity (now slowing?)

Burst of activity, motivated by CMB anisotropies

About a paper a year for 30 years!
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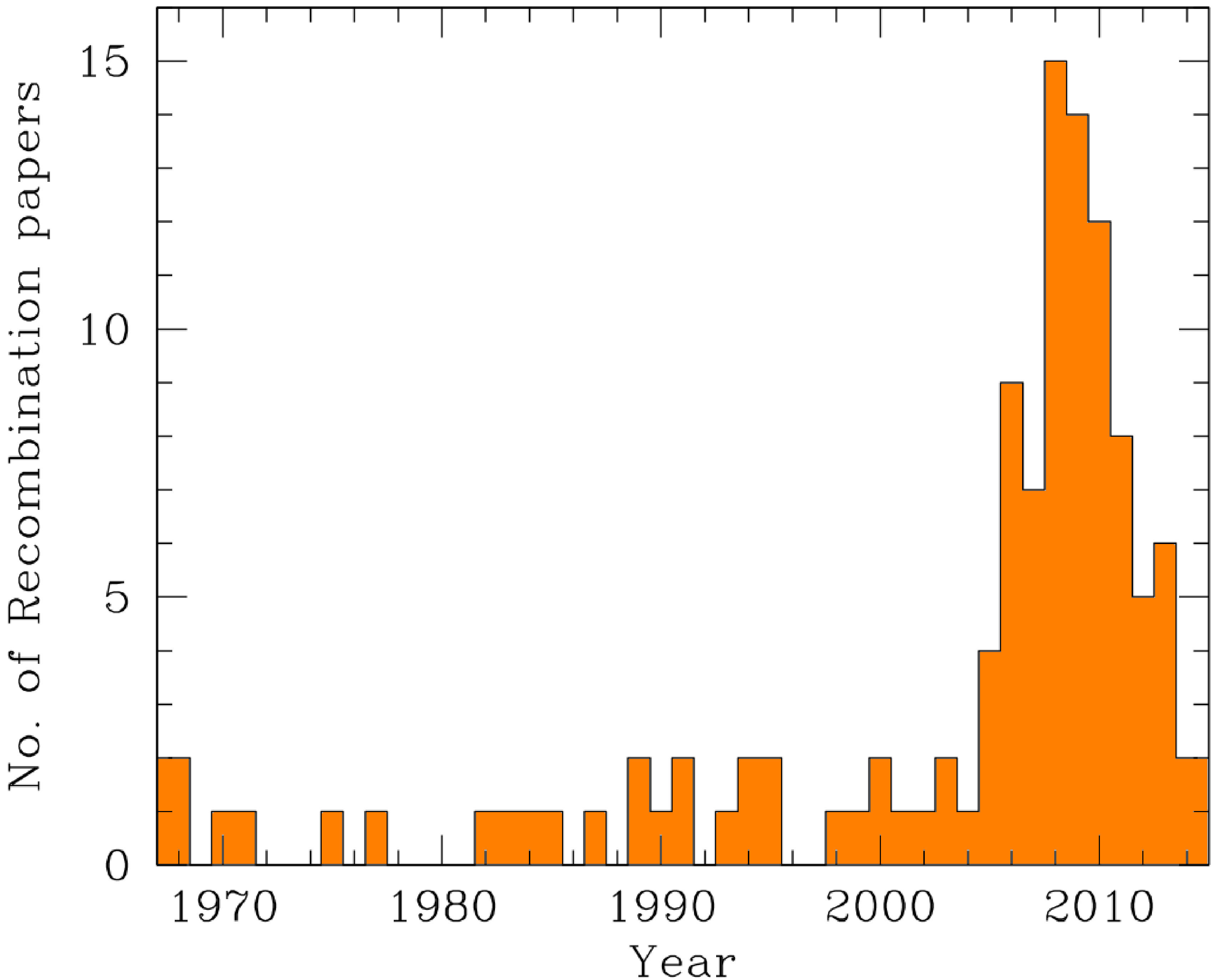
The 0.1% goal is extremely hard for <u>any</u> calculation of anything

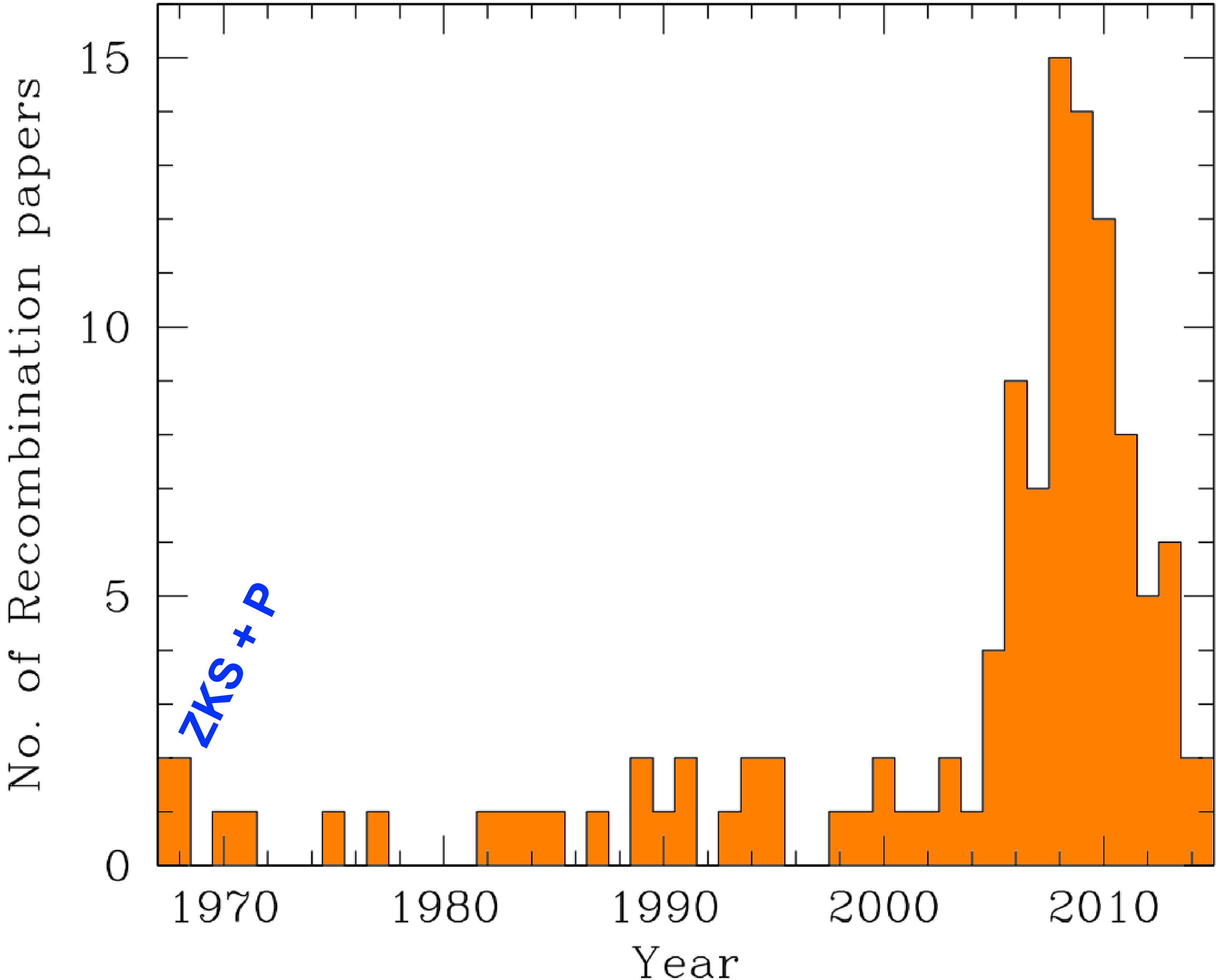
Burst of activity, motivated by CMB anisotropies

About a paper a year for 30 years!
Then lots of activity (now slowing?)

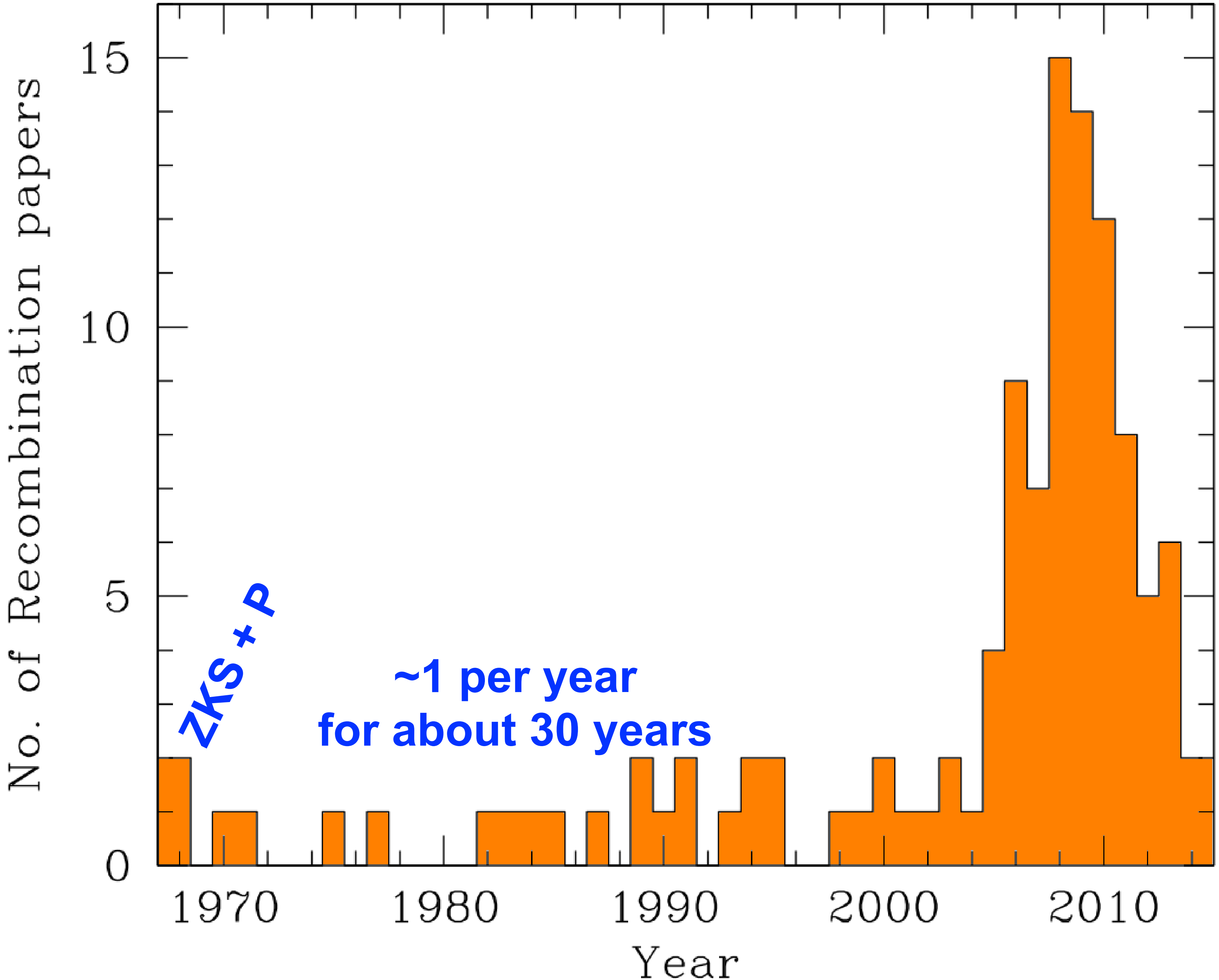
The 0.1% goal is extremely hard for <u>any</u> calculation of anything

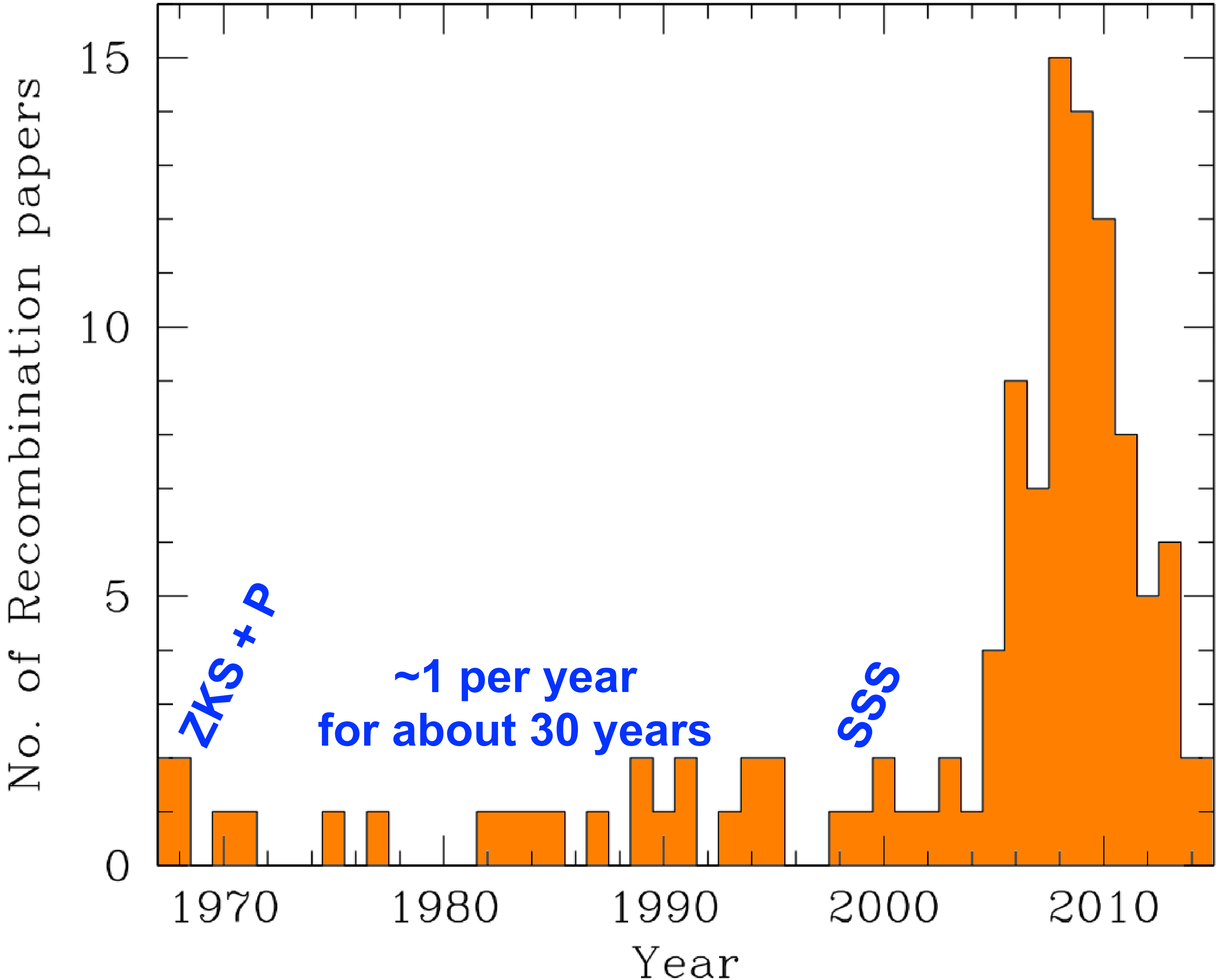
It won't get any easier
Future recombination calculations are not for the faint of heart!
But they will eventually be necessary!


No. of Recombination papers
15
10
5
0
1970
1980
1990
2000
2010
Year

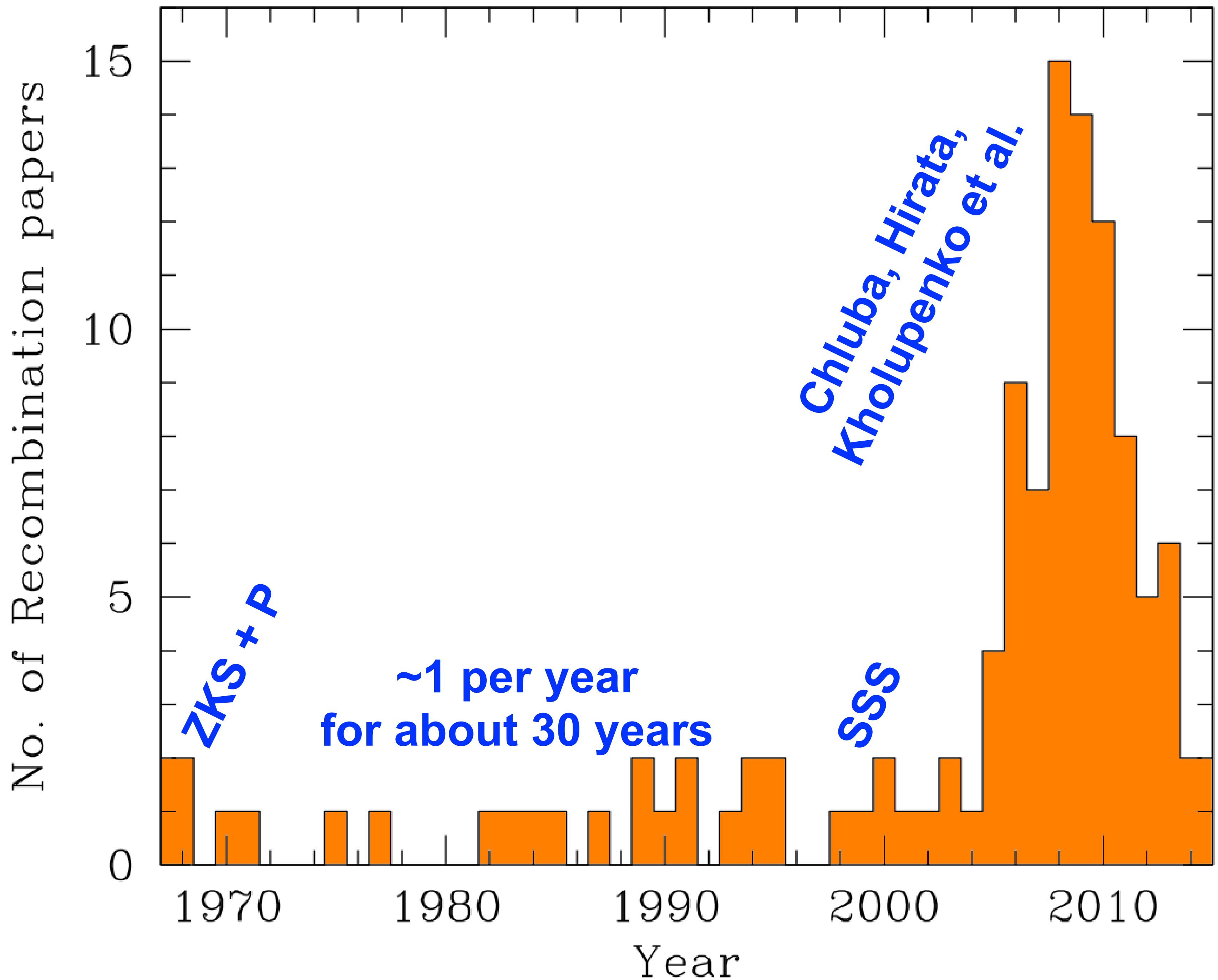


ZKS + P
15
10
5
0
1970
1980
1990
2000
2010
Year
No. of Recombination papers

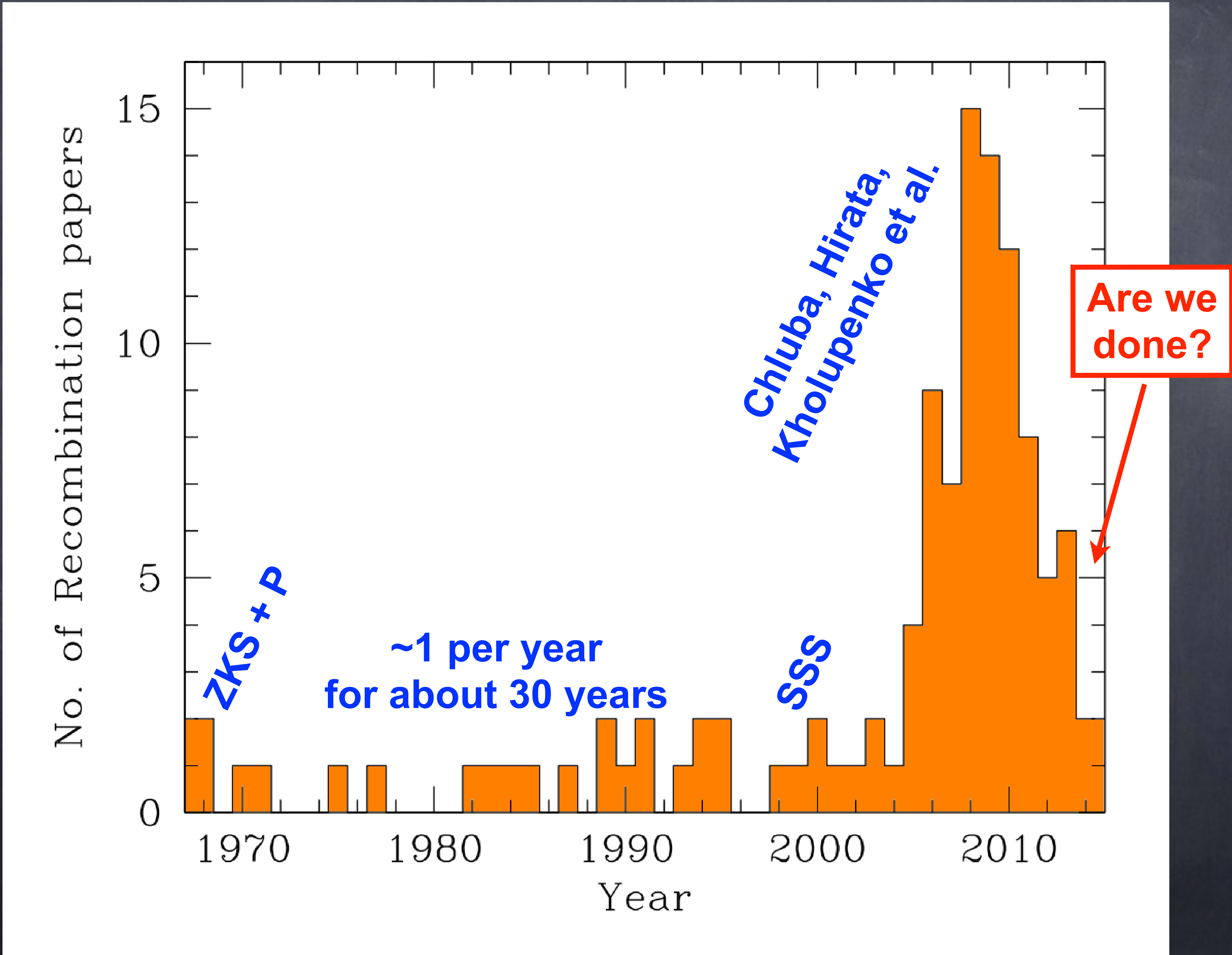

No. of Recombination papers
15
10
5
0
1970
1980
1990
2000
2010
Year
ZKS + P
~1 per year
for about 30 years



No. of Recombination papers
Year
0
5
10
15
1970
1980
1990
2000
2010
ZKS + P
~1 per year
for about 30 years
SSS



No. of Recombination papers
Year
0
5
10
15
1970
1980
1990
2000
2010
ZKS + P
~1 per year
for about 30 years
SSS
Chluba, Hirata,
Kholupenko et al.



No. of Recombination papers
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Year
ZKS + P
~1 per year
for about 30 years
SSS
Chluba, Hirata,
Kholupenko et al.
Are we
done?

List of some issues to address in order to achieve precision + there are many more effects!

List of some issues to address in order to achieve precision + there are many more effects!

Effect	Max. Δx_e	z	References
Energy level			
Seperate L-state in H I atom	-0.7%	1090	[6, 50]
	+1%	≤ 900	
Bound-bound transition			
Inclusion of He I 2^3P_1–1^1S_0	-1.1%	1750	[19, 64]
	-0.3%*	1900	[62]
Inclusion of He I n^3P_1–1^1S_0 ($n \geq 3$)	-4×10^{-3}%*	2000	[62]
Inclusion of H I ns, nd–1s ($n \geq 3$):			
- effective rate only	-0.4%	1200	[9, 64]
- with feedback	-1.2%	1250	[26]
- with feedback and Raman scattering	+1.3%	900	[26]
Inclusion of He I n^1S, n^1D–1^1S_0 ($n \geq 3$):			
- effective rate only	-0.5%	1800	[19, 64]
- with feedback and Raman scattering	-0.05%	2000	[27]
Bound-free transition			
Direct recombination for H I	-6×10^{-4}%	1280	[8]
Direct recombination for He I	-0.02%	1900	[28, 61]
Radiative transfer			
Continuum opacity of H I in He I 2^1P_1–1^1S_0	-2.5%*	1800	[61, 62]
Feedback between He I 2^3P–1^1S_0 and 2^1P_1–1^1S_0	+1.5%*	1800-2600	[61, 62]
Stimulated and induced H I 2s–1s	+0.6%	900	[7, 26, 32]
Diffusion of Lyα line profile (with recoil of H atoms)	~-1%	900	[23, 24, 35, 36]
Continuum opacity of H I modified to feedback in He I lines	-0.5%*	1800	[61, 62]
Continuum opacity of H I in He I n^1P–1^1S_0, n^3P–1^1S_0 ($n \geq 3$), n^1D–1^1S_0	-0.05%*	1900	[61, 62]
Coherent scattering in n^1P–1^1S_0	-0.02%*	2000	[61]
Evolution of T_M	$\pm 10^{-3}$%	-	[28, 56, 61]
Secondary distortions from He I & H I in H I recombination	+0.1%	-	[56, 60]
Others			
He I 2^3P_1–1^1S_0 spontaneous rate	±0.1%	1900	[62]
CMB monopole temp. T_{CMB} ±1 mK	±0.5%	900	[10]
Formation of hydrogen molecule	-1%	< 150	[56]

Table 2.1: Summary of the improvements and uncertainties in numerical recombination calculation. Here Δx_e is the difference from the value given by RECFAST [55]. *Note: This is the relative change compared with the full radiative model in Switzer & Hirata (2007) [62].

Wan Yan Wong's thesis (2008)

Progress

- New codes produced - more physics, but more computating time:
  - Hyrec - Ali-Haïmoud & Hirata (2011)
  - Cosmorec - Chluba & Thomas (2011)
- Useful code comparisons carried out
- General agreement that calculations accurate enough for primary CMB anisotropies
- But there's always more to do!

Are we done?

- Have we included all the levels needed for H?
- Are all rates and cross-sections for He known?
- Included all interactions between H and He?
- Radiative transfer good enough? Line redistribution?
- Will we eventually need ray tracing?
- Is the line spectrum accurate (for measurement?)
- Are any other scattering effects important?
- Do we ever need to think about perturbations?
- Other things we haven't thought of yet?
- Can we constrain unknown effects by constraining phenomenological parameters in MCMC fits to data?

recfast

recfast

Started in 1989!

recfast

Started in 1989!

Adapted recombination history to include decaying particles

recfast

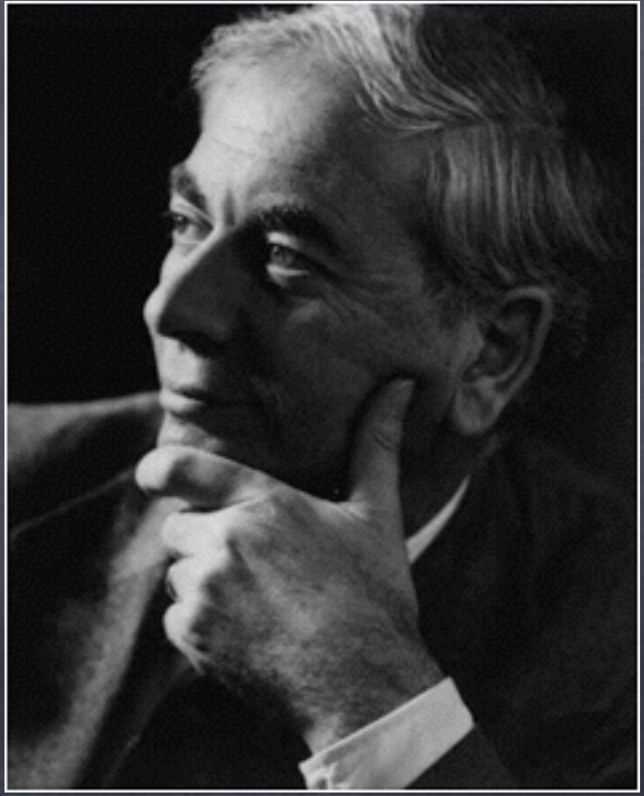
Started in 1989!

Adapted recombination history to include decaying particles

recfast

Started in 1989!

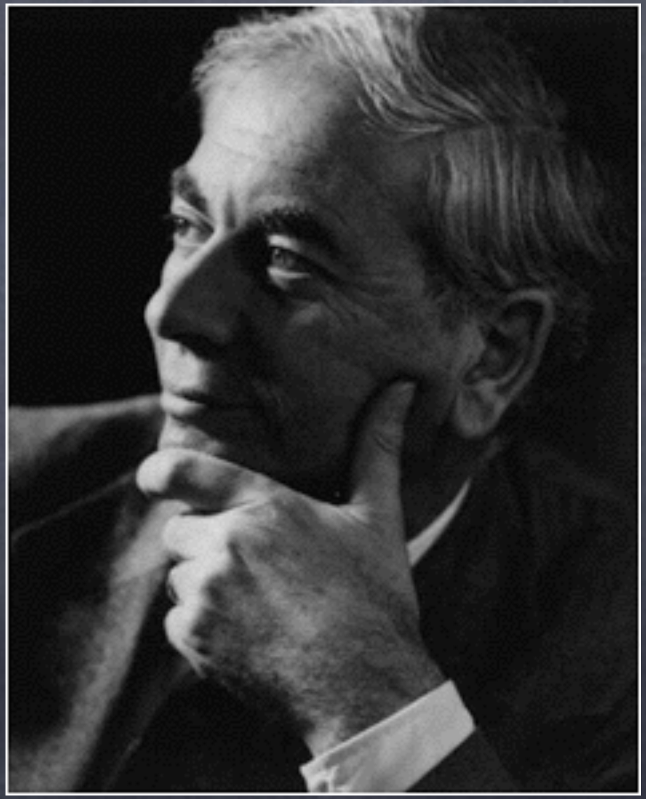
Adapted recombination history to include decaying particles



recfast

Started in 1989!

Adapted recombination history to include decaying particles



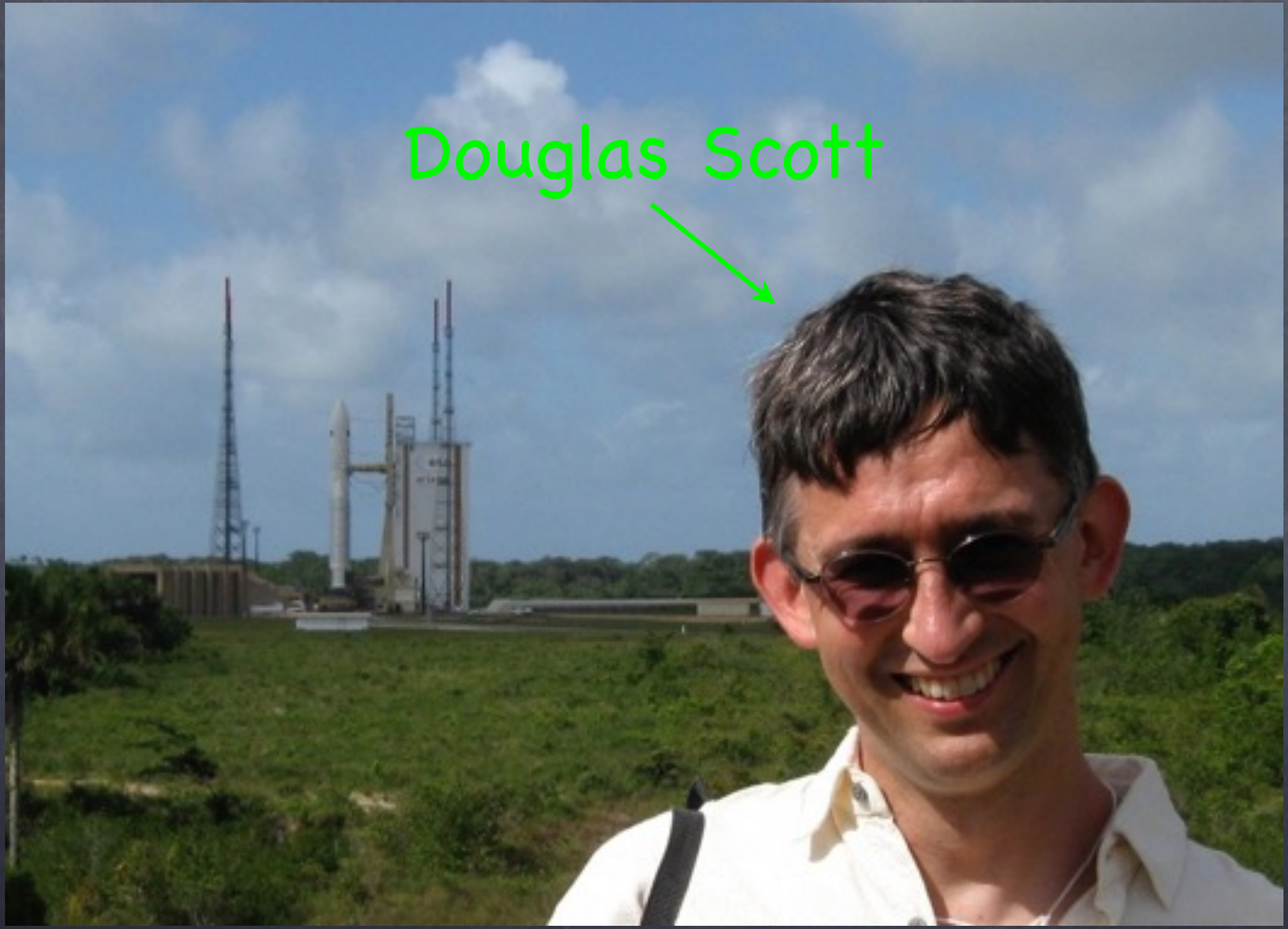
Scott, Rees & Sciama 1991

(see Appendix A of Ph.D. thesis)

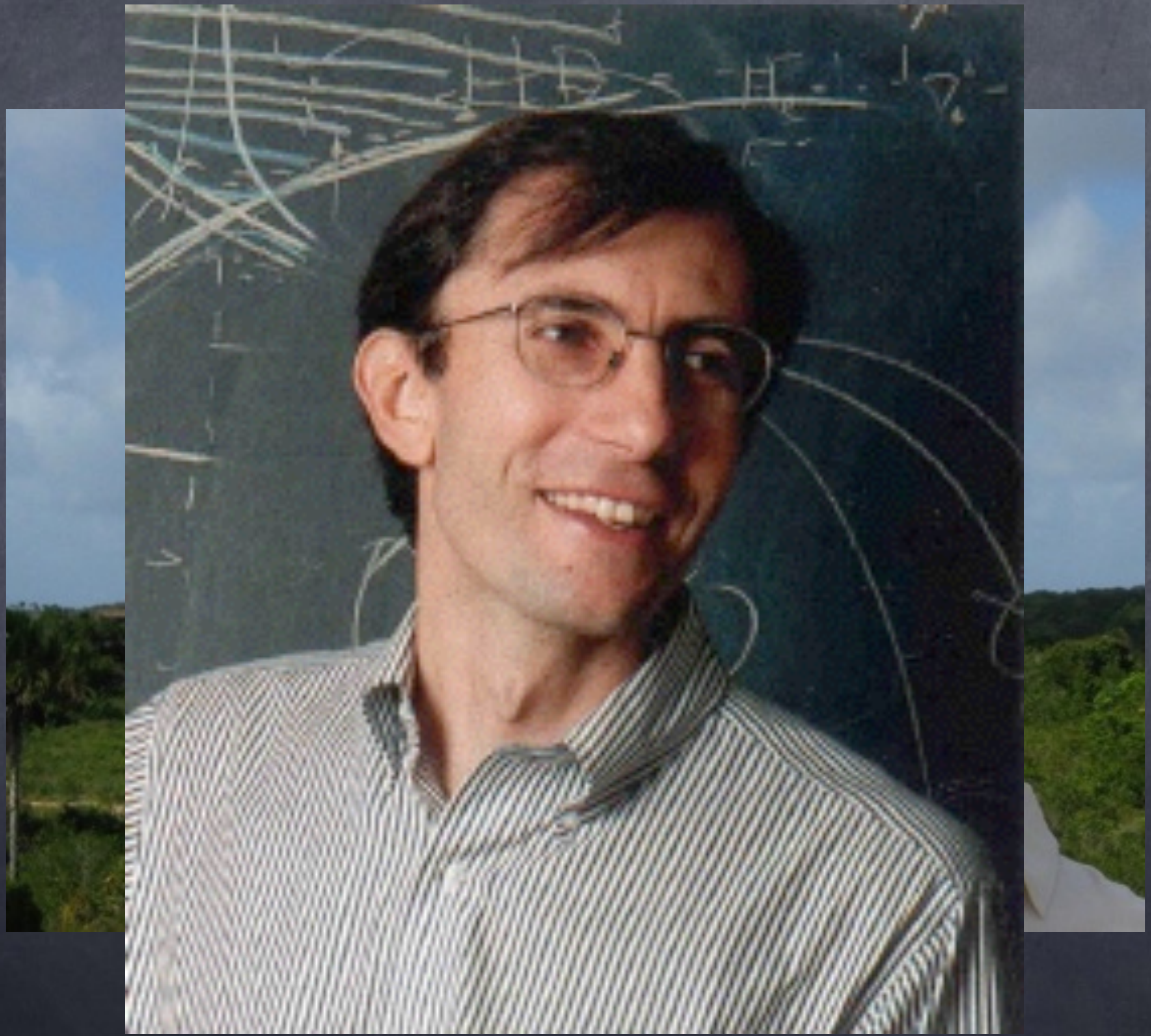
recfast

recfast

recfast



recfast



recfast

recfast


Origins Institute
PUBLIC LECTURE
Sara SEAGER
MASSACHUSETTS INSTITUTE OF TECHNOLOGY
INTERNATIONAL YEAR OF ASTRONOMY
2009
PUBLIC LECTURE

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SaraSEA
MASSACHUSETTS INSTITUTE
INTERNATIONAL YEAR
OF ASTRONOMY 200
Wan Yan Wong

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Origins
INSTITUTE
INTERNATIONAL YEAR
OF ASTRONOMY
Adam Moss

RECFAST

A code to calculate the recombination history of the Universe

This code is meant to reproduce the calculations described in the paper "A new calculation of the recombination epoch", Seager, S., Sasselov, D. & Scott, D., 1999, ApJ, 523, L1 (astro-ph/9909275), which is a fast approximation to the detailed calculations described in "How exactly did the Universe become neutral?" Seager, S., Sasselov, D. & Scott, D., 2000, ApJS, 128, 407 (astro-ph/9912182). And with some updates (to He etc.) which are described in Wong, W.Y., Moss, A. & Scott, D., 2008, MNRAS, 386, 1023 (arXiv:0711.1357), together with the Compton coupling treatment in Scott, D. & Moss A., 2009, MNRAS, 397, 445 (arXiv:0902.3438).

It solves a modified 3-level atom for each of hydrogen and helium, along with some corrections motivated by more detailed calculations. It is thus *fast*, while being accurate enough for current CMB experiments.

Here are things that the code treats:

- Solves H and He simultaneously
- Kinetic temperature of matter evolved separately, including Compton and adiabatic cooling
- Careful consideration of dependency of quantities on $T_{\rm M}$ and $T_{\rm R}$
- Accurate values of all relevant physical constants
- Full treatment of background cosmology, including radiation, Lambda and curvature (but no explicit "w")
- Saha assumed for ionized helium
- Accurate look-up table for recombination coefficients
- Approximation for H recombination at low redshift, to account for out of equilibrium
- Singlet and triplet states considered for neutral He
- Additional "fudge factor" for He recombination
- Solves for temperature difference between matter and radiation, giving smoother transition in $T_{\rm M}$ evolution
- Includes an extra "fudge" function to correct $K(z)$ to approximate the H physics corrections from detailed codes (see Rubino-Martin et al. 2010)
- Extra "fudge factor" Gaussians, designed to make correction for additional He physics for cosmologies near the standard one

This results in $x_e(z)$ producing (it is believed) better than 0.1 percent accuracy for CMB anisotropy C_l.

There are 2 separate versions of the code, one in `fortran` (developed by DS), and one in c (developed by SS).

Grab code recfast.for from web page

To compile with a modern compiler (because of old fortran dialect that uses tabs for line continuation):

```
gfortran -ffixed-line-length-0 -std=legacy recfast.for -o recfast
```

(There are probably other solutions, and other compilers that could be used)

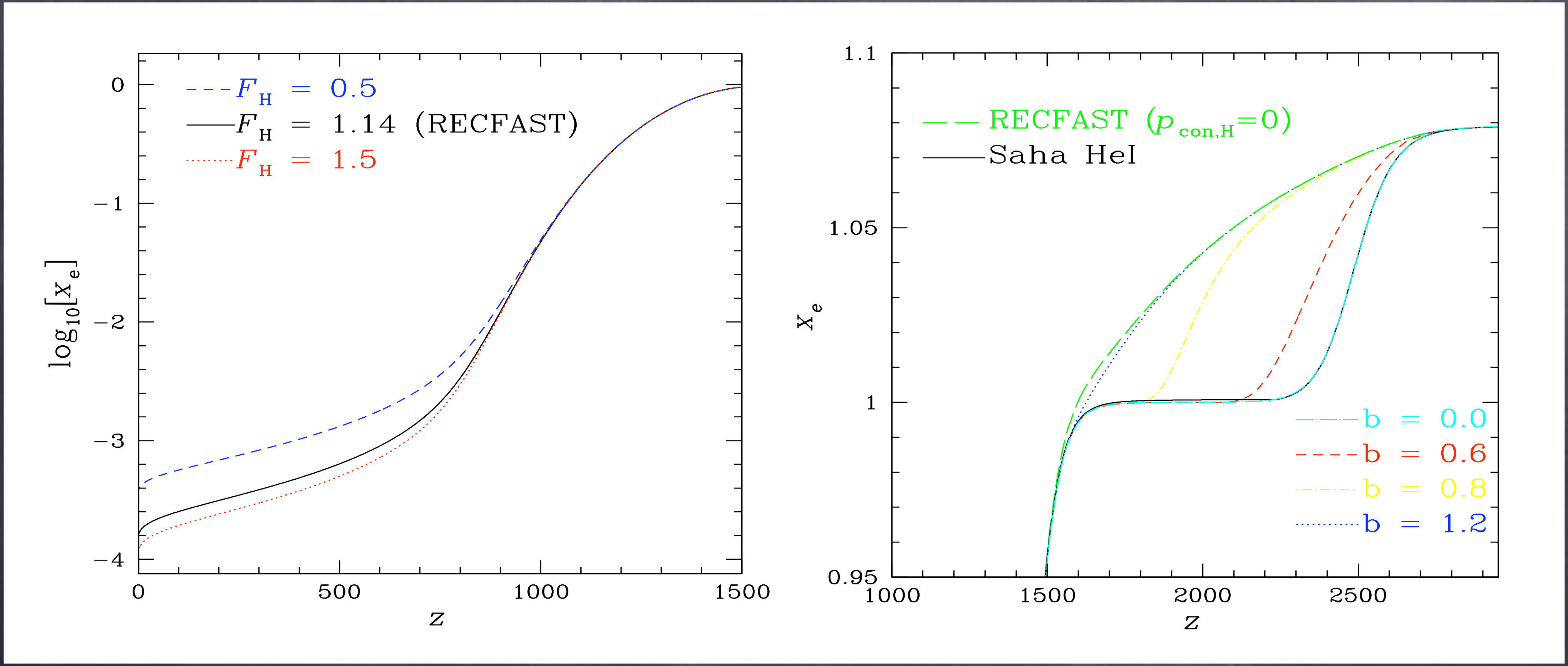
Then run with ./recfast

Answer questions about parameters etc., e.g.

```
filename.out
0.04 0.20 0.76
70 2.725 0.25
1
6
```

Old fudges!

The devil is in the details



Fudge factor to approximate out-of-equilibrium H at lower redshifts

Fudge factor to approximate several Helium effects at higher redshifts

Wong, Moss & Scott (2008)

The devil is in the details

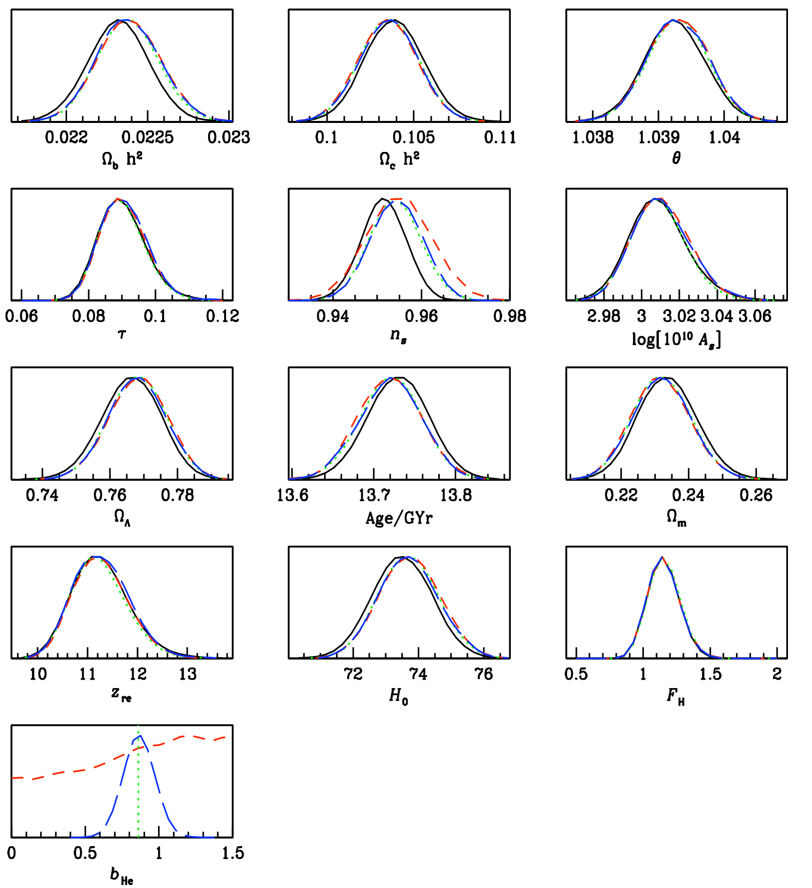


Figure 5. Marginalized posterior distributions for forecast *Planck* data with hydrogen and helium phonomenological parameters both allowed to vary. The solid (black) curve shows the constraints using the original RECFAST code and allowing $F_{\rm H}$ to be a free parameter. The other curves also allow for the variation of $F_{\rm H}$ and use the fitting function for He I recombination described in Section 2: the dotted (green) line sets $b_{\rm He}$ equal to 0.86; the dashed (red) one is with a flat prior for $b_{\rm He}$ from 0 to 1.5; and the long-dashed (blue) one is with a narrow prior for $b_{\rm He}$, consisting of a Gaussian centred at 0.86 and with $\sigma = 0.1$.

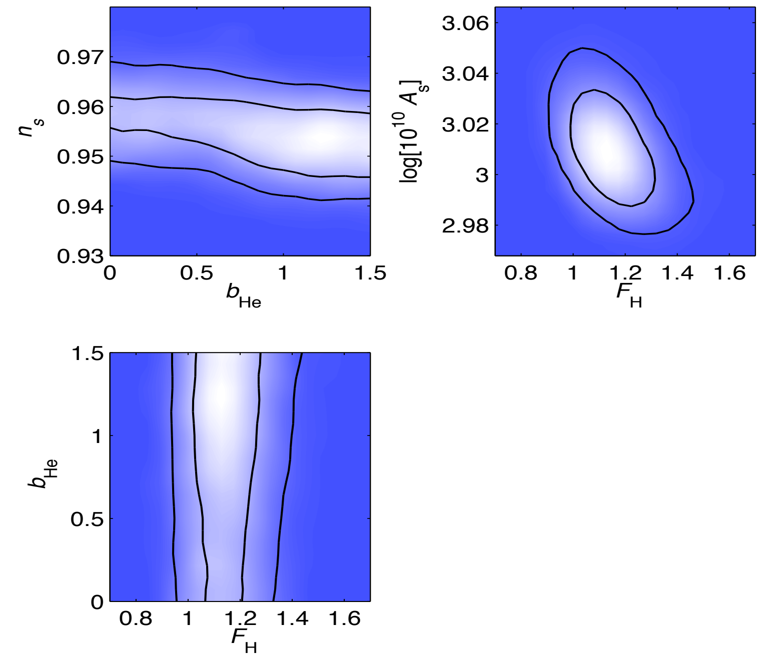


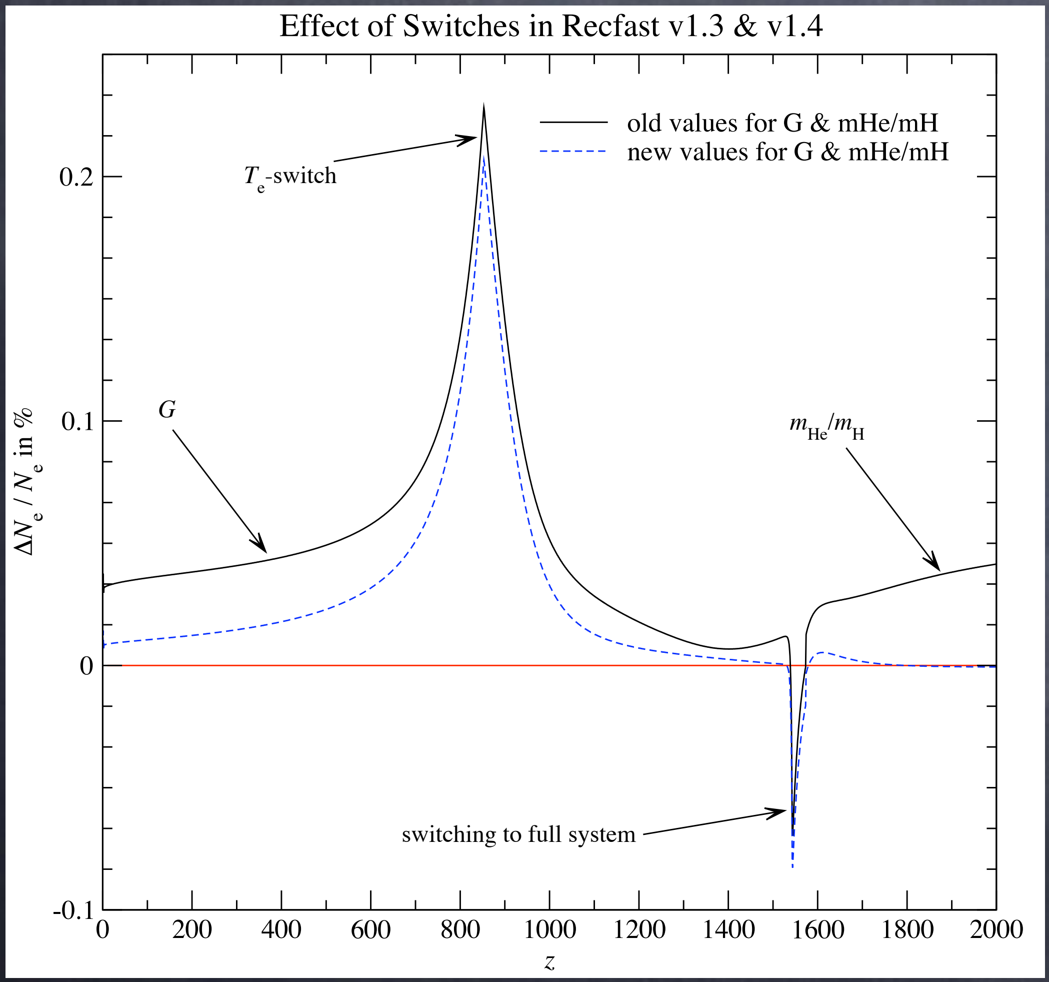
Figure 6. Projected 2D likelihood for the four parameters $n_{\rm s}$, $A_{\rm s}$, $F_{\rm H}$ and $b_{\rm He}$. Shading corresponds to the marginalized probabilities with contours at 68 per cent and 95 per cent confidence.

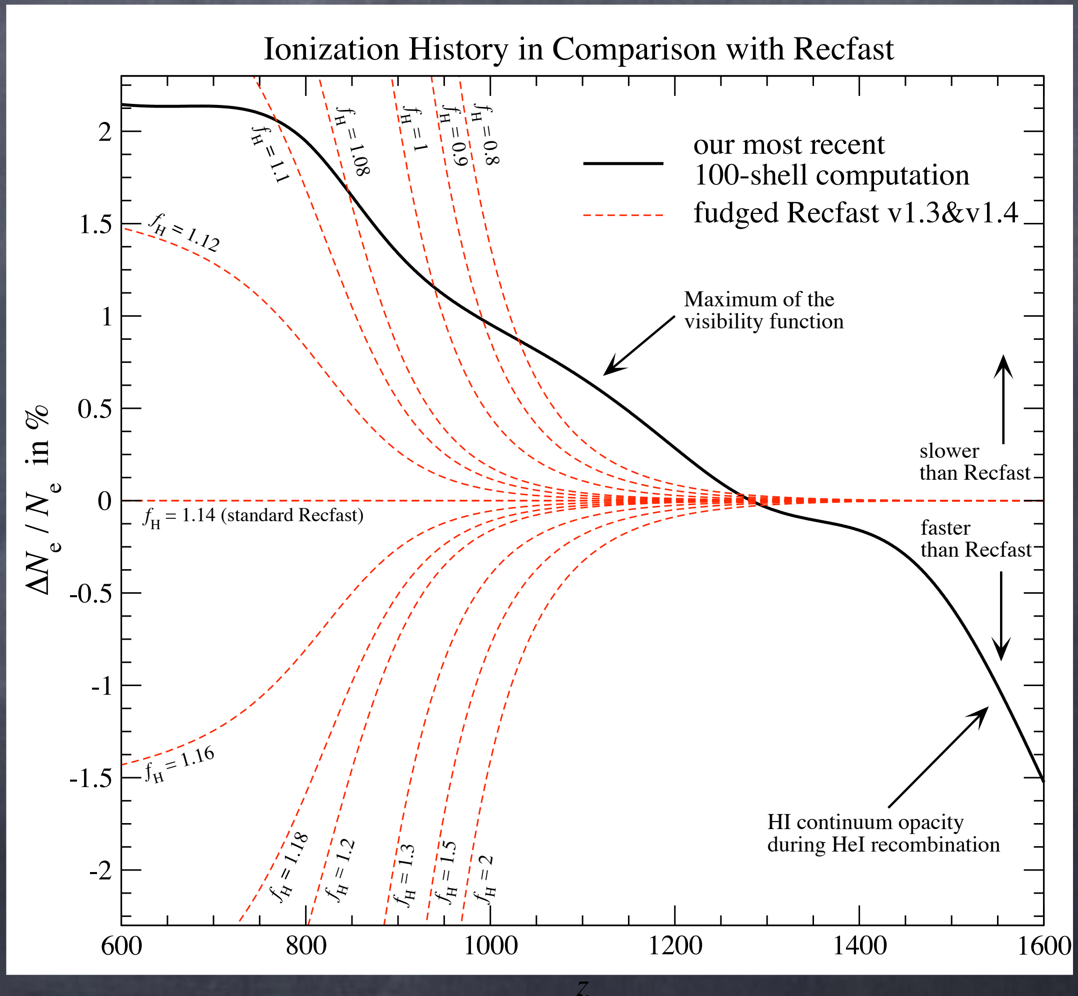
Look at expected constraints on cosmological parameters plus extra fudge parameters

- biggest effect on n
- also some correlations

Wong, Moss & Scott (2008)

Some problems with RECFAST





Switches in code

Low z fudge

Matter temperature

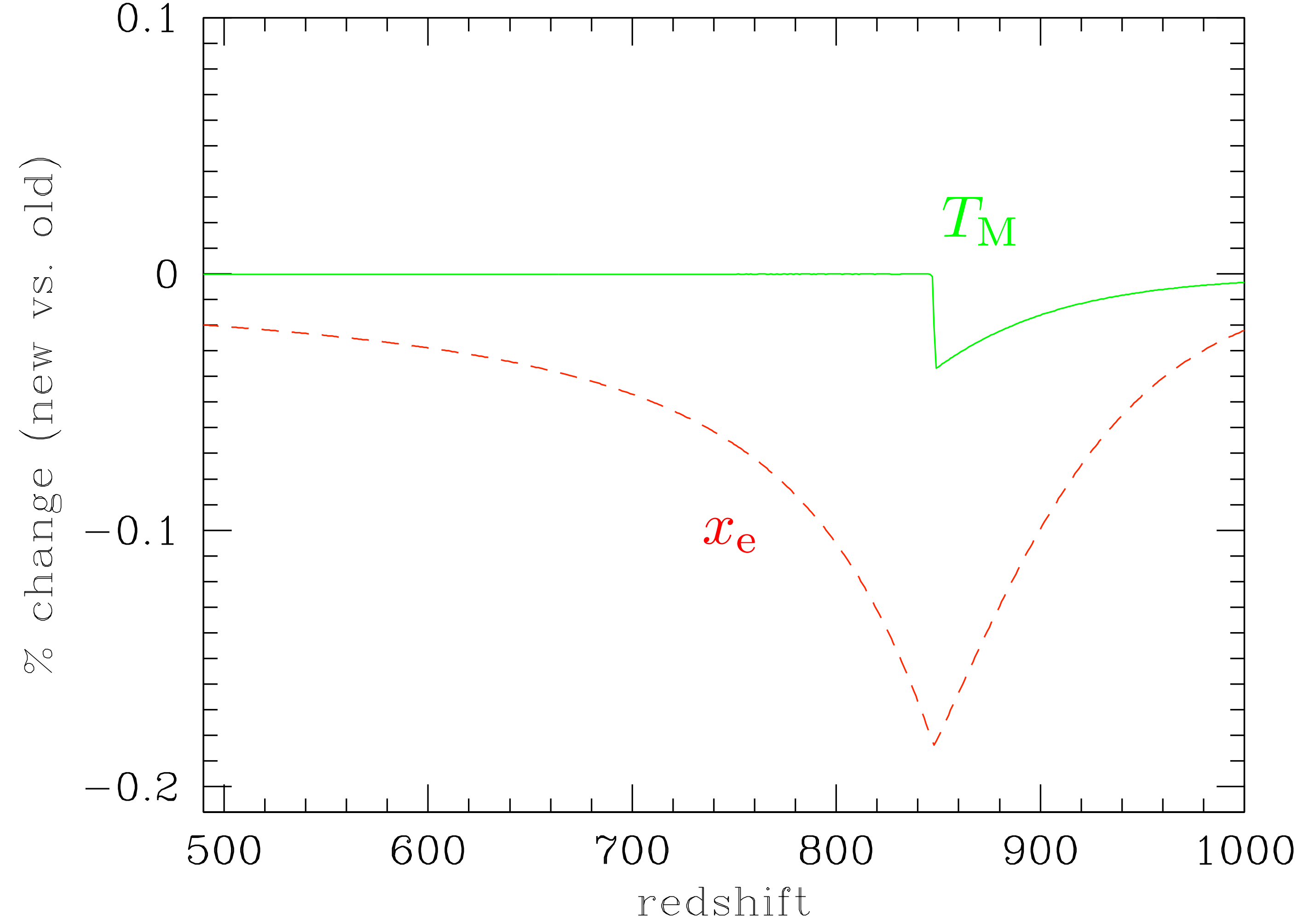
Basic equation: $$(1+z)\frac{dT_{\rm M}}{dz} = \frac{(T_{\rm M}-T_{\rm R})}{Ht_{\rm C}} + 2T_{\rm M}$$

with $$t_{\rm C} = \frac{3m_{\rm e}c}{8\sigma_{\rm T}a_{\rm R}T_{\rm R}^4}\,\frac{1+f_{\rm He}+x_{\rm e}}{x_{\rm e}}$$

Solve with $T_{\rm M} = T_{\rm R} - \epsilon$ and $T_{\rm R} \propto (1+z)$

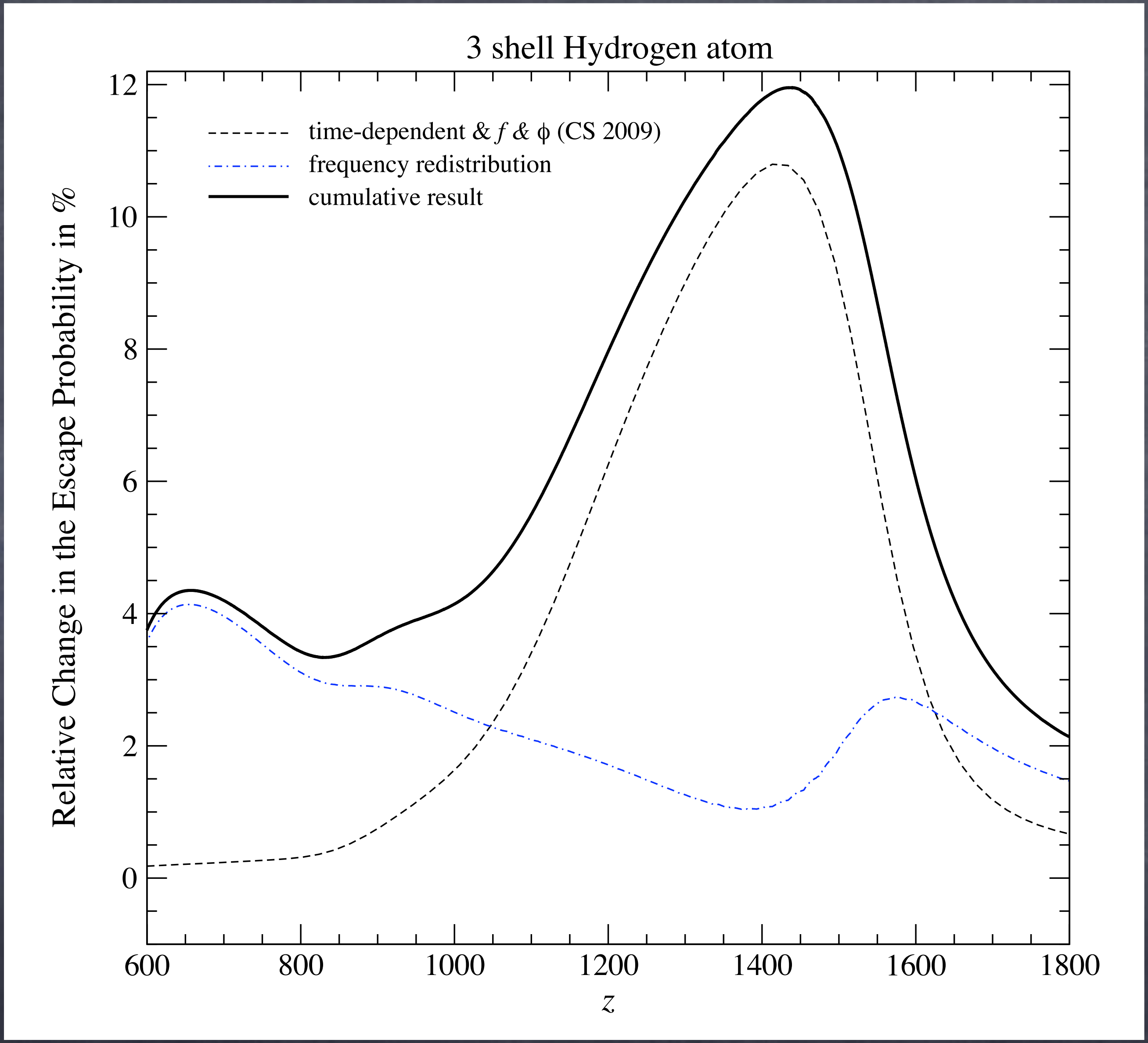
$$\rightarrow \quad \frac{dT_{\rm M}}{dz} = \frac{T_{\rm R}}{(1+z)} + \epsilon\left\{\frac{1+f_{\rm He}}{1+f_{\rm He}+x_{\rm e}}\,\frac{dx_{\rm e}/dz}{x_{\rm e}} + \left[\frac{3}{(1+z)} - \frac{dH/dz}{H}\right]\right\}$$

which can be used to follow matter until ε not small

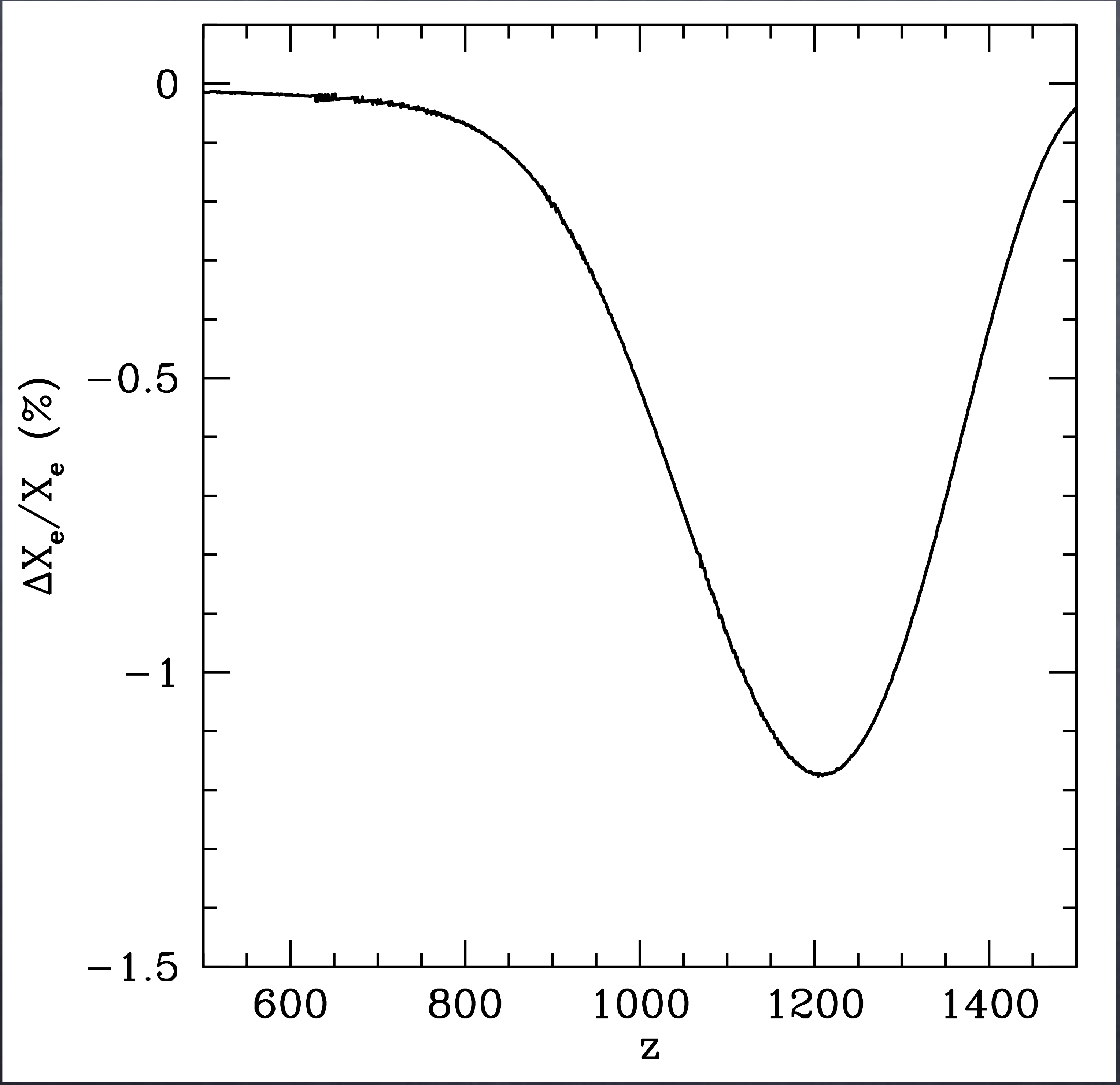


0.1
0
−0.1
−0.2
500
600
700
800
900
1000
redshift
% change (new vs. old)
$T_{\rm M}$
$x_{\rm e}$

New fudge example

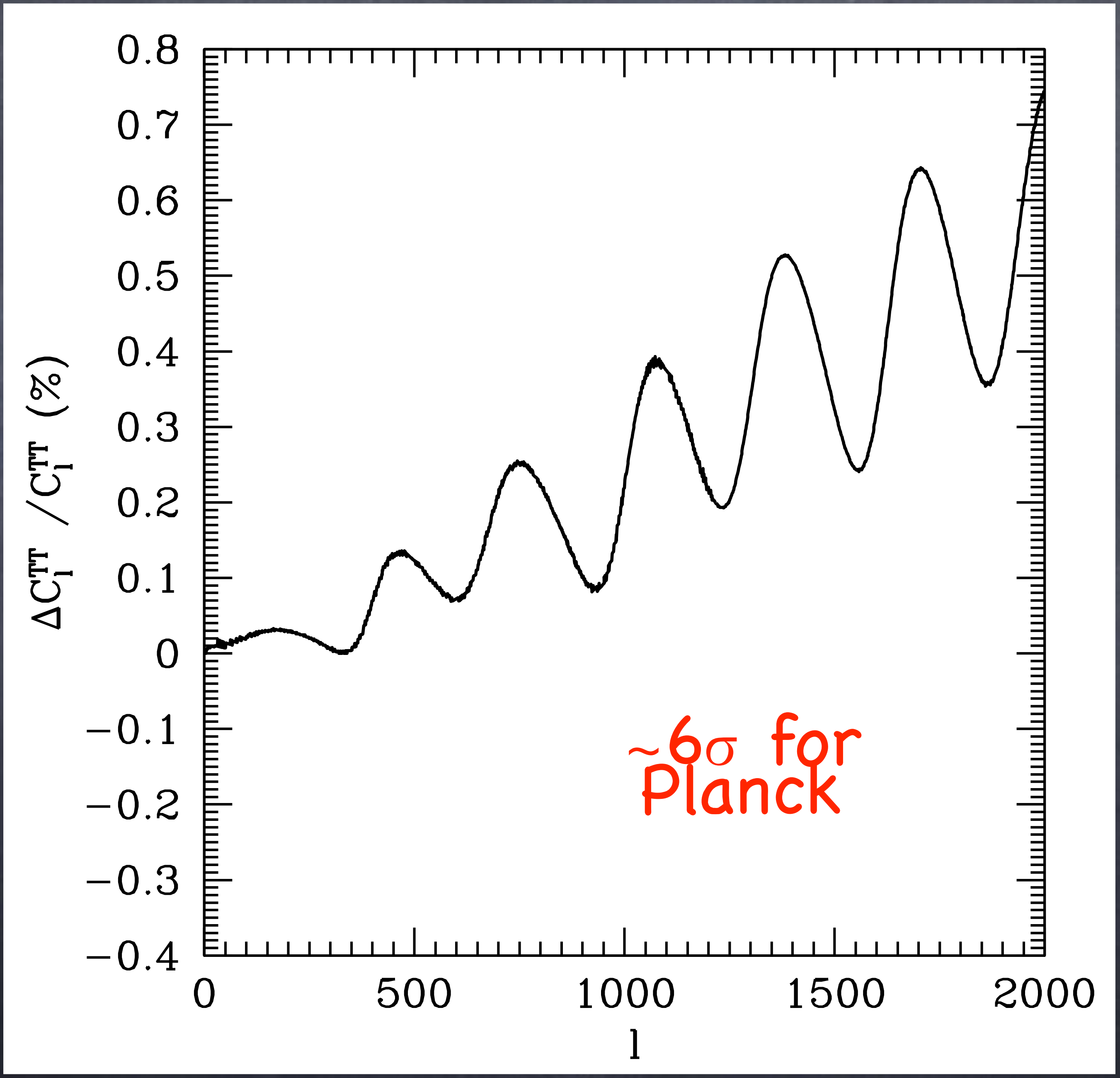


Gaussian: mean=1450; width=200; A=0.1



0
−0.5
−1
−1.5
600
800
1000
1200
1400
z
ΔX_e/X_e (%)

Variation in CMB power spectrum



recfast 2.0?

- Include corrections for all new effects
    - Changes to Sobolev escape probability
    - More elaborate H fudge (function) for low z
- Improve switches for He
- Check cosmology dependence
- Rewrite in C/python