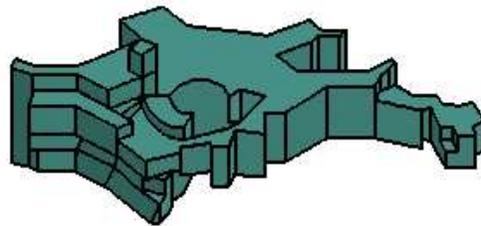


# CMB as a tool to probe the enrichment & reionization history of the universe

Kaustuv Basu

*in collaboration with*

C. Hernández-Monteagudo & R. Sunyaev



# Motivation

Use of scattering of Cosmic Microwave Background photons by atomic or ionic (fine-structure transitions), or molecular (rotational transitions) lines to detect the abundance of the scattering species

**Good thing:** The effect is stronger than expected at first (proportional to  $\tau$ , not  $\tau^2$ , where  $\tau \ll 1$ ) due to correlation with the primordial CMB anisotropies

**Bad thing:** Still signal is very weak, hidden under various foregrounds

**Aim:** To constrain enrichment and ionization history of the universe by this new technique



# Motivation

## Previous works...

- Dubrovich (1977,1993), de Bernardis et al. (1993) *primordial molecules (particularly LiH)*
- Maoli, Melchiorri, Tosti et al. (1996) *primordial molecules*
- Loeb (2001), Zaldarriaga & Loeb (2002) *neutral Li*

## CMB & FS lines...

- Varshalovich, Khersonskii & Sunyaev (1981) *scattering in FS lines to equalize  $T_m$  and  $T_{rad}$  at  $z < 150$*

## FS lines in emission...

- Suginozono & Spergel (1999)



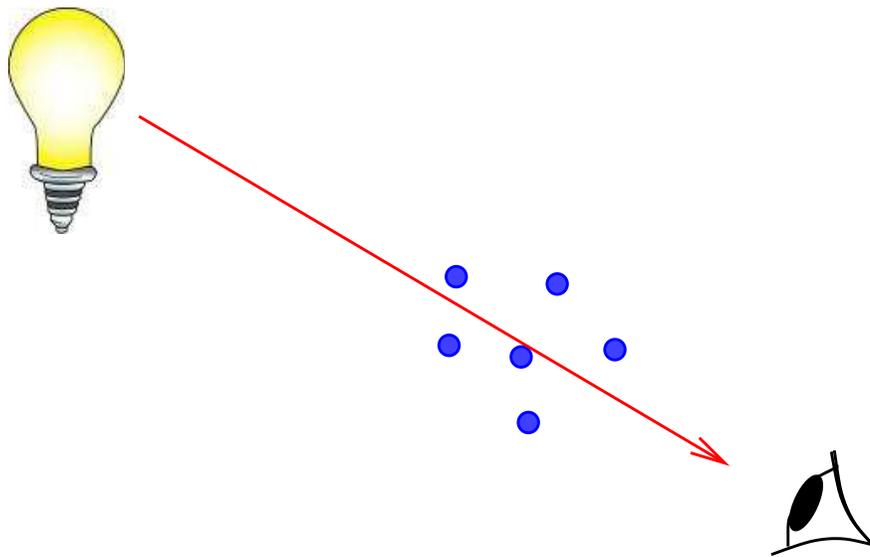
# Overview of talk

- Basic idea: resonant scattering & CMB
- Method of analysis
- Properties of the signal
- Ionization and enrichment histories
- Effect of overdensity
- Effect of foreground emissions
- Conclusions



# Basic Idea

Metallicity evolution of the universe must leave its imprint on the Cosmic Microwave Background Radiation  $\Rightarrow$  through resonance scattering of the background photons by atoms, ions and molecules

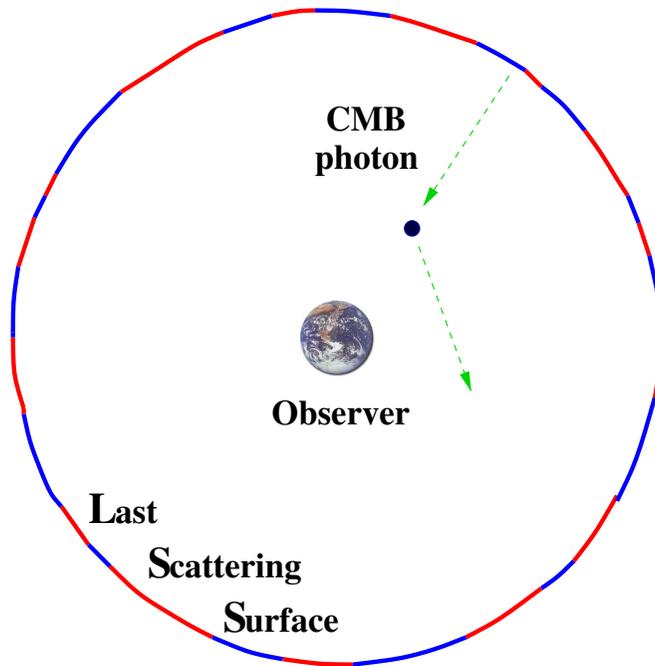


We wish to know about the state of intervening medium using the very well-understood background light: CMB!

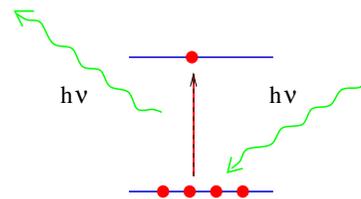


# Suppression & generation

Resonant scattering partially erases the original temperature anisotropies of the CMB, but also generates new fluctuations at the epoch of scattering



$$\frac{\Delta T}{T_0}(\theta) = e^{-\tau_\nu} \left. \frac{\Delta T}{T_0}(\theta) \right|_{orig.} + \left. \frac{\Delta T}{T_0}(\theta) \right|_{new}$$

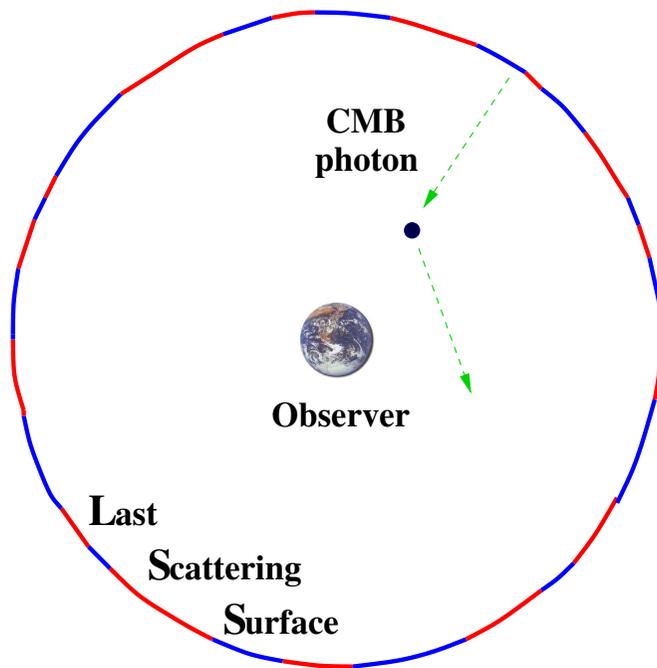


Scattering is *coherent*  
in scatterer's frame



# Suppression & generation

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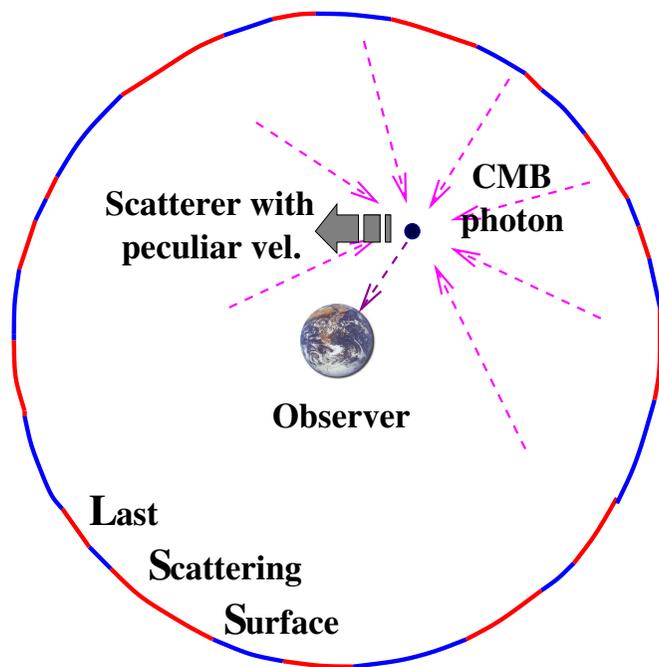
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“suppression (blurring)” & “generation”



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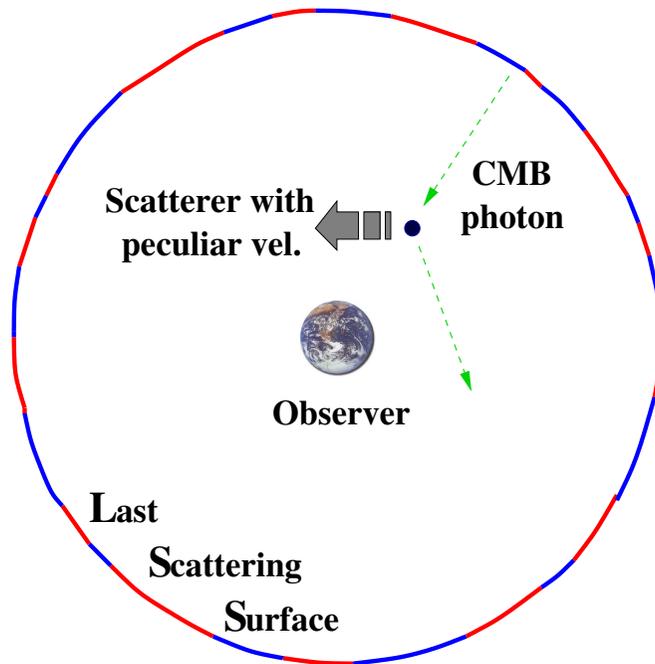
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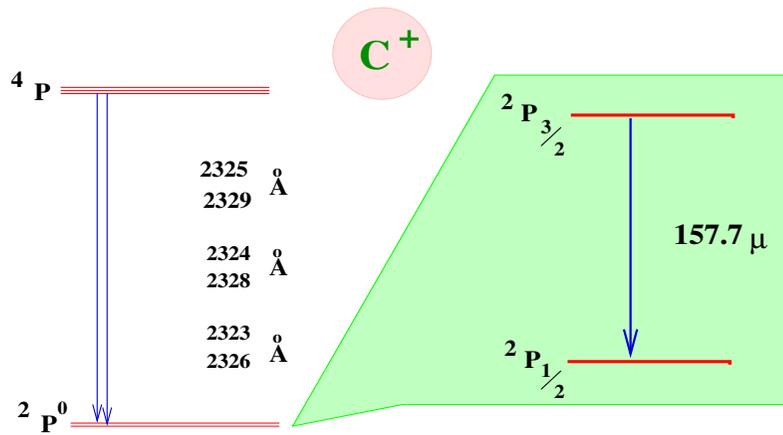
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$$\delta C_l = \tau_\nu \cdot \mathcal{C}_1 + \tau_\nu^2 \cdot \mathcal{C}_2 + \mathcal{O}(\tau_\nu^3)$$

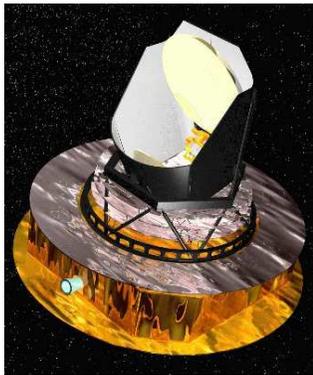


# Fine-structure lines



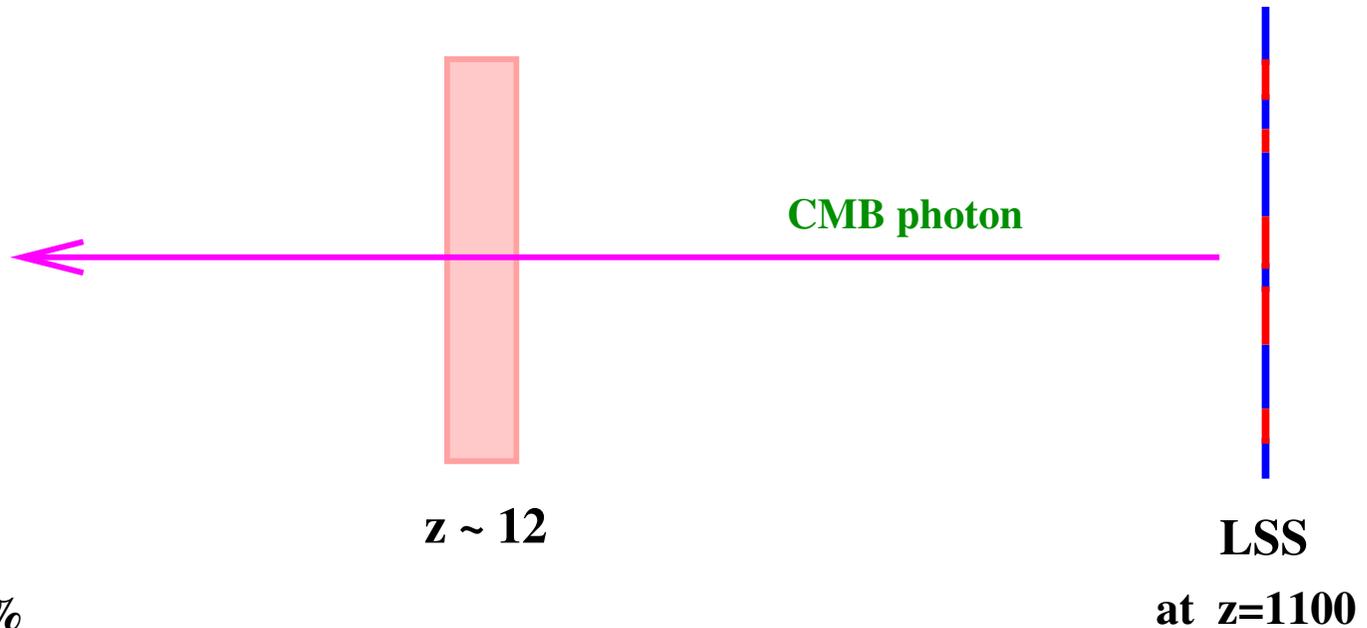
A-coefficient  $\sim 10^{-6} \text{ s}^{-1}$   
 $\Rightarrow$  optical depth  $\sim 10^{-5} - 10^{-7}$

**143 GHz**

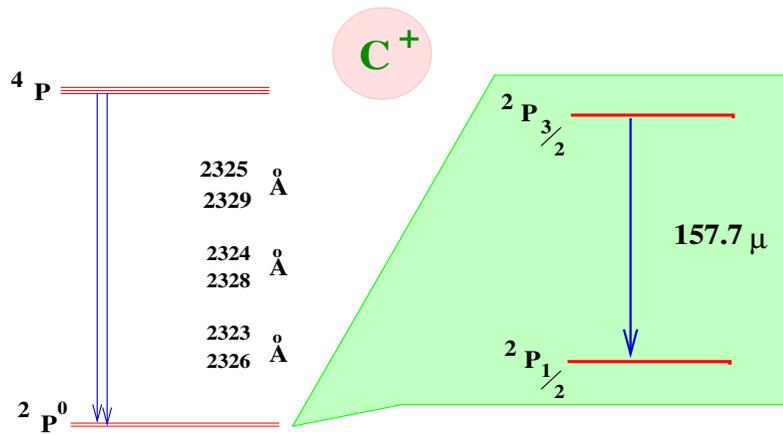


**Planck HFI**

**Bandwidth  $\sim 25\%$**

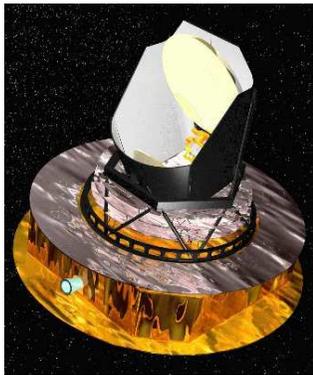


# Fine-structure lines



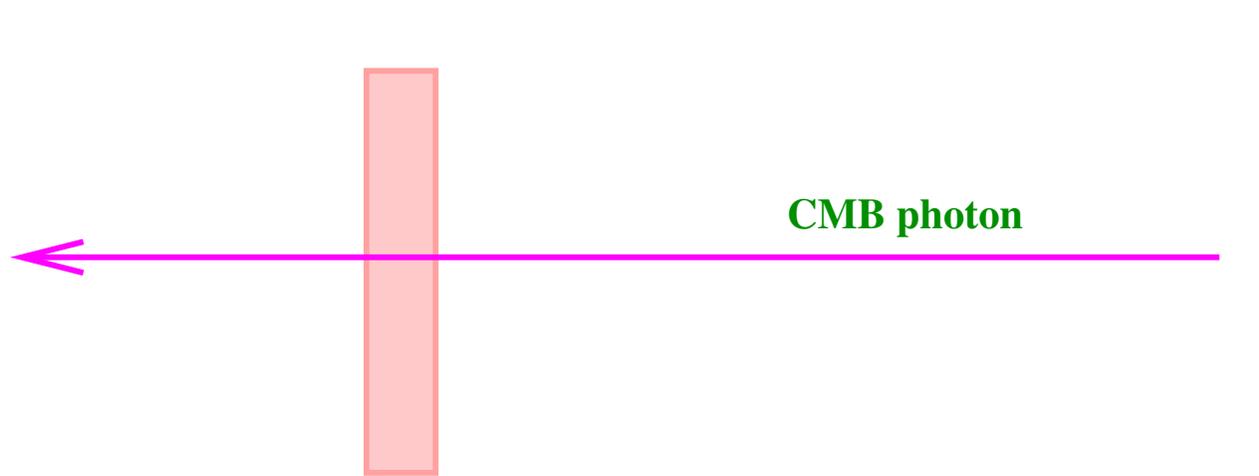
A-coefficient  $\sim 10^{-6} \text{ s}^{-1}$   
 $\Rightarrow$  optical depth  $\sim 10^{-5} - 10^{-7}$

**217 GHz**



**Planck HFI**

**Bandwidth  $\sim 25\%$**



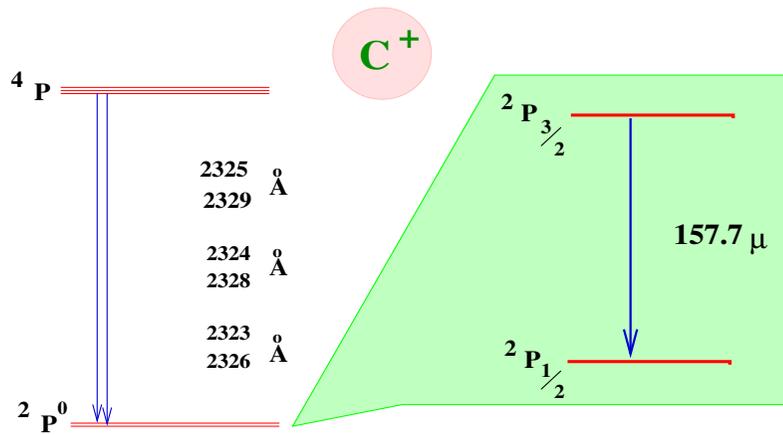
**$z \sim 8$**

**LSS**

**at  $z=1100$**

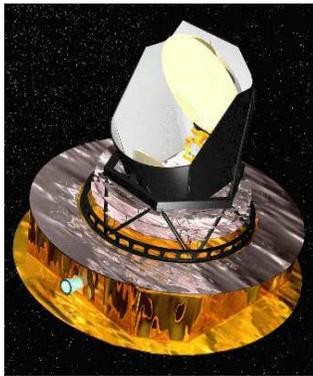


# Fine-structure lines



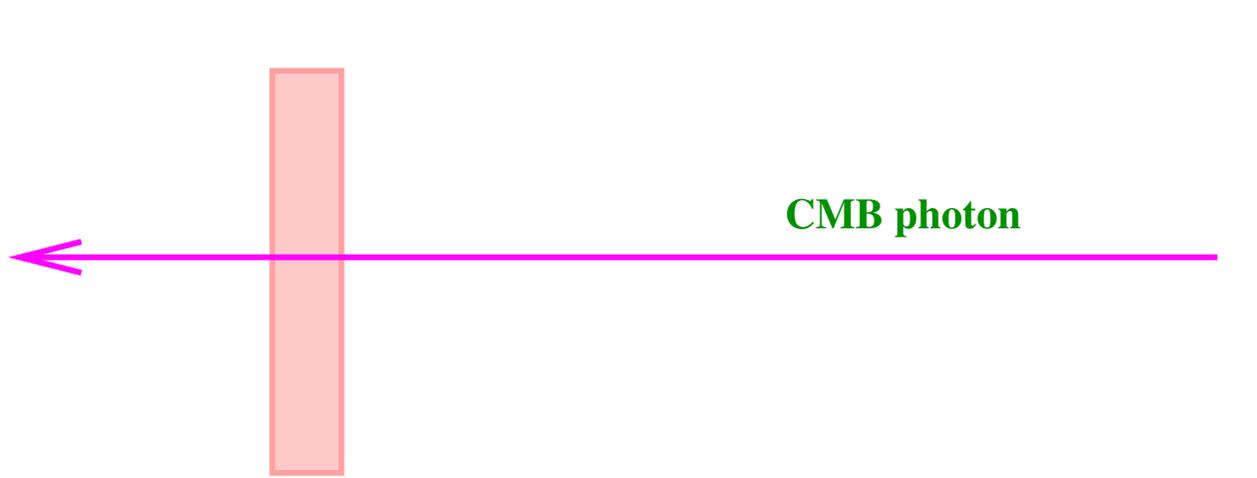
A-coefficient  $\sim 10^{-6} \text{ s}^{-1}$   
 $\Rightarrow$  optical depth  $\sim 10^{-5} - 10^{-7}$

**353 GHz**



**Planck HFI**

**Bandwidth  $\sim 25\%$**



**$z \sim 4$**

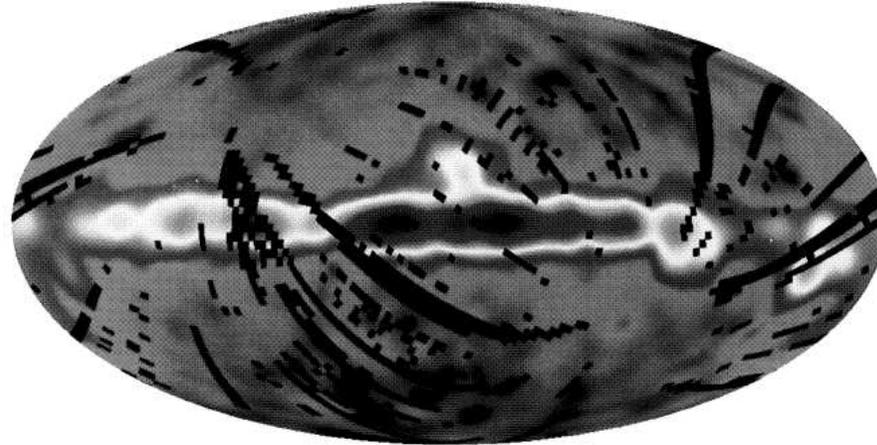
**LSS**

**at  $z=1100$**

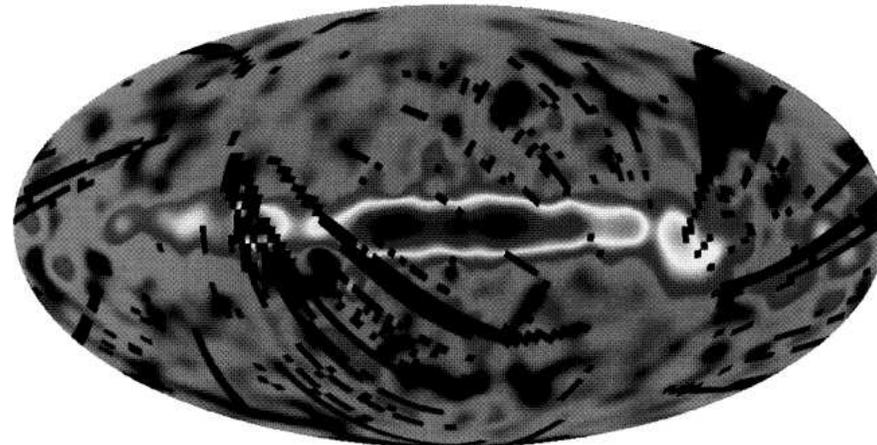


# Fine-structure lines

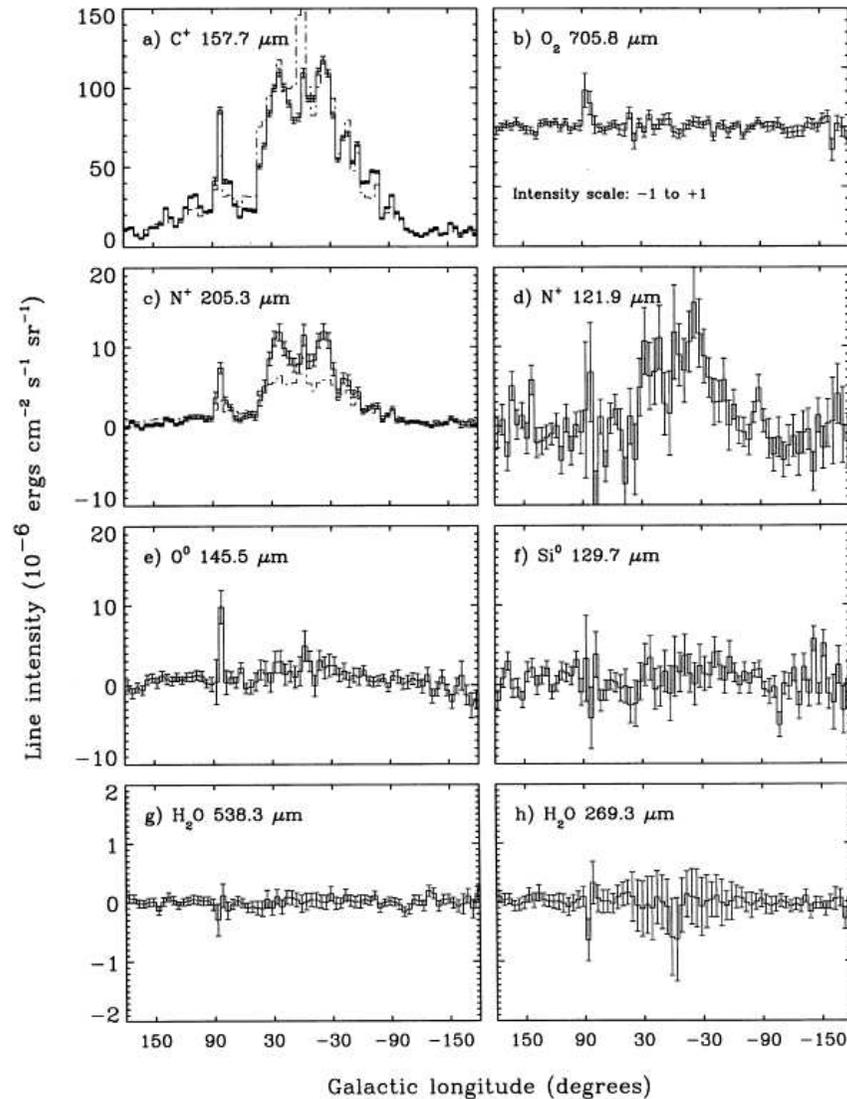
*COBE* FIRAS 158  $\mu\text{m}$  C<sup>+</sup> Line Intensity



*COBE* FIRAS 205  $\mu\text{m}$  N<sup>+</sup> Line Intensity



# Fine-structure lines



COBE showed that  $\text{C}^+$  FS line is the brightest cooling line in our Galaxy!



# Proposition

- Method to determine the abundance of atoms, ions and molecules in **low density optically thin** regions of the universe by using the signature of resonant scattering of CMB photons



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- Focusing on Planck HFI, also ACT, SPT, APEX...



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- Possible to **avoid** the limit imposed by cosmic variance by comparing results from different channels

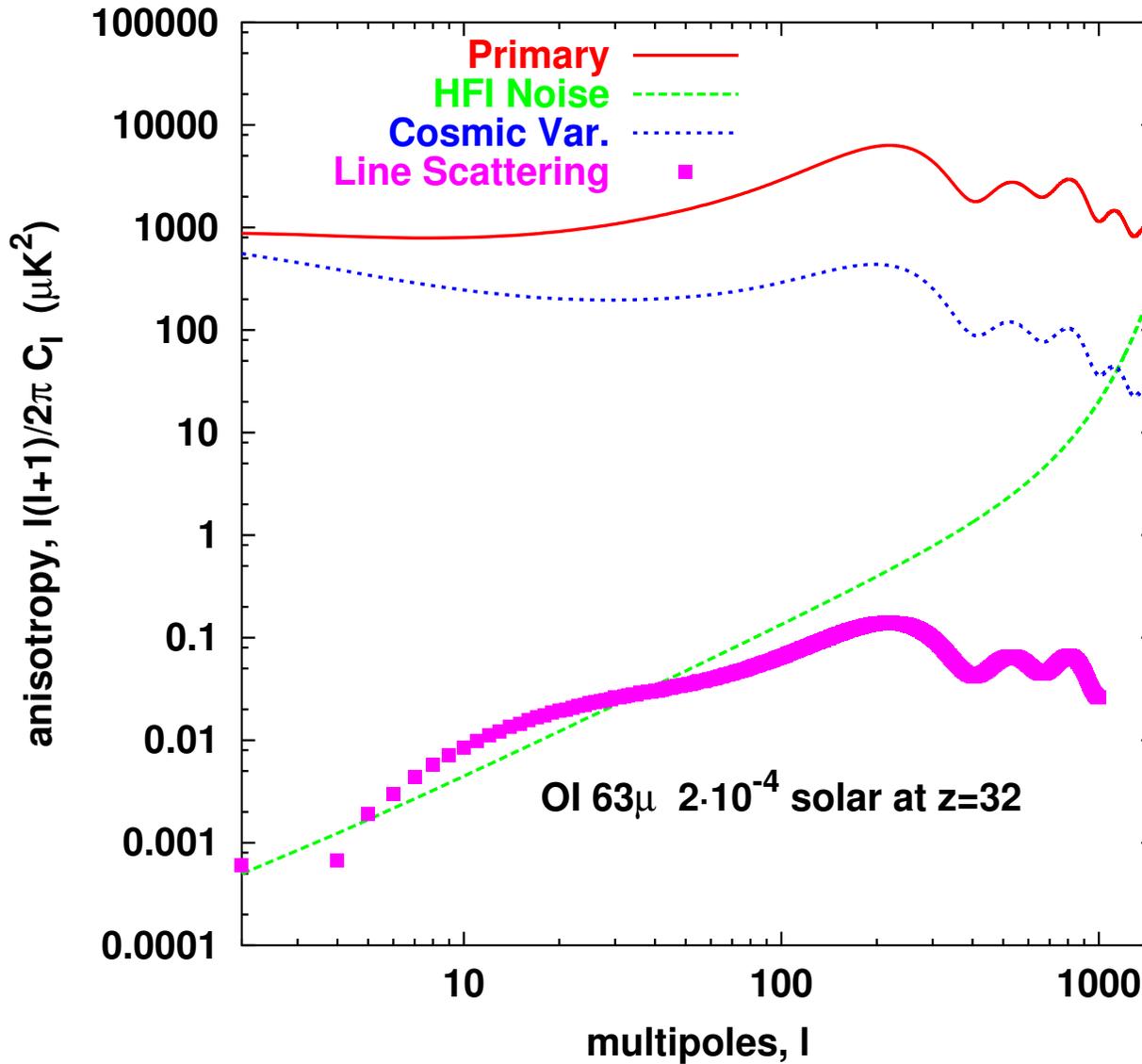


# Proposition

- Method to determine the abundance of atoms, ions and molecules in *low density optically thin* regions of the universe by using the signature of resonant scattering of CMB photons
- Focusing on Planck HFI, also ACT, SPT, APEX...
- *Frequency dependent* optical depth ( $\tau_\nu$ ) – different signal in different channels
- Possible to *avoid* the limit imposed by cosmic variance by comparing results from different channels
- Strong constraints on the abundance of scattering species ( $10^{-2} - 10^{-4}$  solar fraction), e.g. C, N, O, Si, S and Fe, in the redshift range  $1 < z < 50$



# Proposition



# Formalism

The change in observed temperature anisotropies...

$$\Delta T_{obs}(\nu) = (1 - \tau_\nu)\Delta T_{orig} + \tau_\nu\Delta T_{new}^{lin} + \mathcal{O}(\tau_\nu^2)$$

can be expressed as a change in angular power spectrum multipoles

$$\delta C_l(\nu) = \tau_\nu \cdot \mathcal{C}_1(\nu) + \tau_\nu^2 \cdot \mathcal{C}_2(\nu) + \mathcal{O}(\tau_\nu^3)$$



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giving a *linear relation* between abundance and power spectrum distortion

$$[\text{abundance}] \propto \tau_\nu \approx \frac{\delta C_l}{C_1}$$



# Formalism

Expected uncertainty in the obtained  $C_l$ -s

$$\sigma_{C_l}^2 = \frac{2}{(2l+1)f_{sky}} (C_l + w^{-1} B_l^{-2})^2$$

with **Cosmic Variance** and **Pixel Noise**  $\left( w^{-1} = \frac{4\pi}{N} \sigma^2(\nu) \right)$



# Formalism

Expected uncertainty in the obtained  $C_l$ -s

$$\sigma_{C_l}^2 = \frac{2}{(2l+1)f_{sky}} (C_l + w^{-1}B_l^{-2})^2$$

*reference channel*  $\nu_1$   
*probe channel*  $\nu_2$

Subtracting the signal from two channels...

$$\sigma_{\delta C_l}^2 = \frac{2}{(2l+1)f_{sky}} \left[ \left( \delta C_l^{probe} + w_{probe}^{-1} B_{l,probe}^{-2} \right)^2 + \left( w_{ref}^{-1} B_{l,ref}^{-2} \right)^2 \right]$$

gives minimum detectable abundance

$$[X_i]_{min} \sim (\tau_{X_i})_{min} \simeq \frac{\sigma_{\delta C_l}}{C_1}$$



# Minimum abundances

Minimum detectable abundance for selected atoms and ions

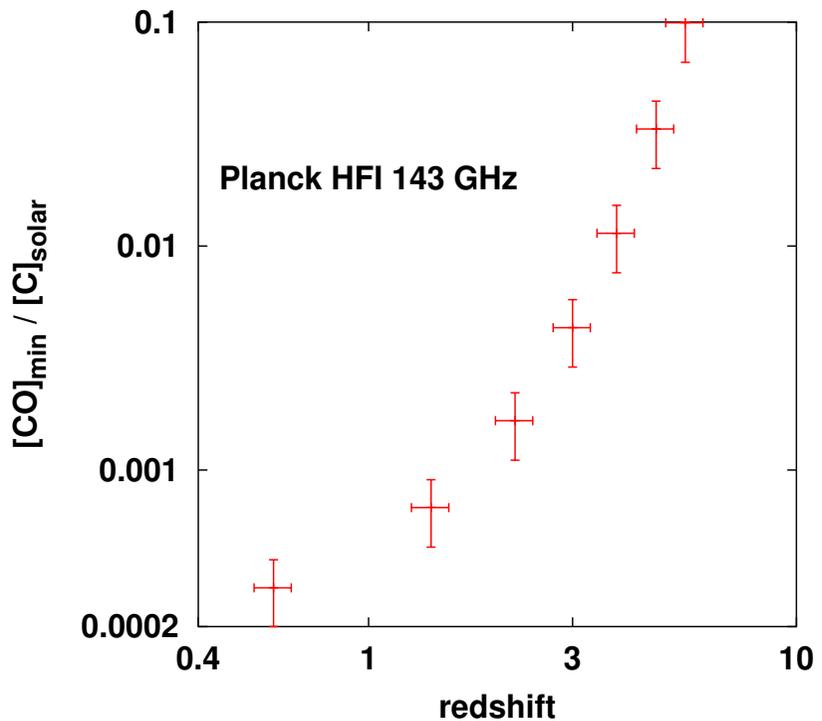
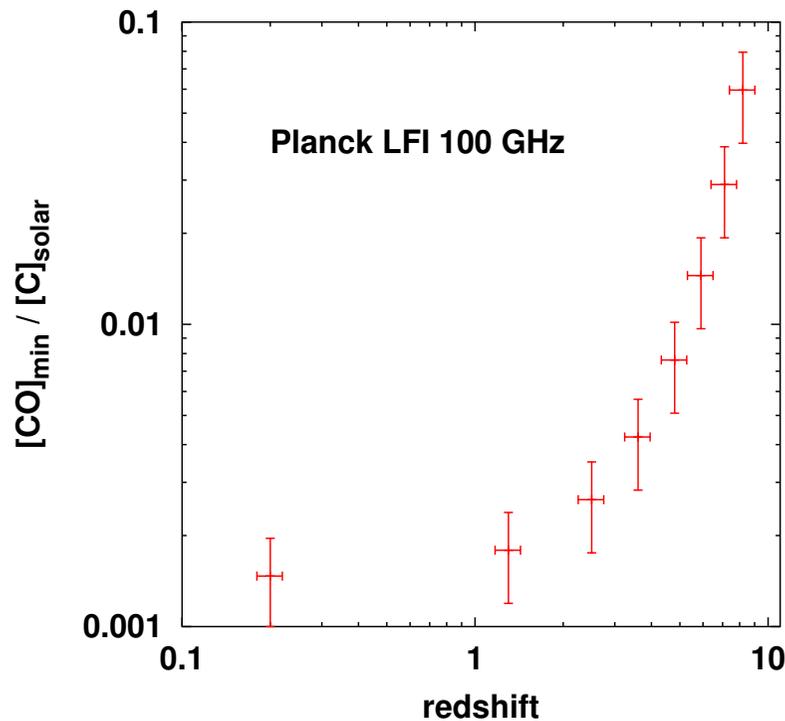
Atom / Ion	Fine-Str. line	HFI freq. (GHz)	Scattering redshift	Opt. depth for $10^{-2}$ Sol. abun.	Min. Abundance detectable (solar)
<b>C II</b>	157.74 $\mu$	143	12.3	$1.6 \times 10^{-5}$	$6.2 \times 10^{-3}$
		217	7.9	$1.1 \times 10^{-5}$	$3.0 \times 10^{-3}$
		353	4.4	$5.6 \times 10^{-6}$	$3.6 \times 10^{-2}$
<b>N II</b>	205.30 $\mu$	143	9.2	$8.9 \times 10^{-6}$	$2.6 \times 10^{-3}$
		217	5.8	$6.5 \times 10^{-6}$	$3.8 \times 10^{-3}$
		353	3.1	$3.5 \times 10^{-6}$	$6.8 \times 10^{-2}$
<b>O I</b>	63.18 $\mu$	143	32.2	$1.1 \times 10^{-4}$	$1.7 \times 10^{-4}$
		217	21.2	$6.3 \times 10^{-5}$	$6.4 \times 10^{-4}$
		353	12.5	$3.1 \times 10^{-5}$	$4.9 \times 10^{-2}$
<b>O III</b>	88.36 $\mu$	143	22.8	$1.8 \times 10^{-4}$	$1.2 \times 10^{-4}$
		217	14.8	$1.4 \times 10^{-4}$	$1.8 \times 10^{-3}$
		353	8.6	$7.4 \times 10^{-5}$	$4.4 \times 10^{-3}$



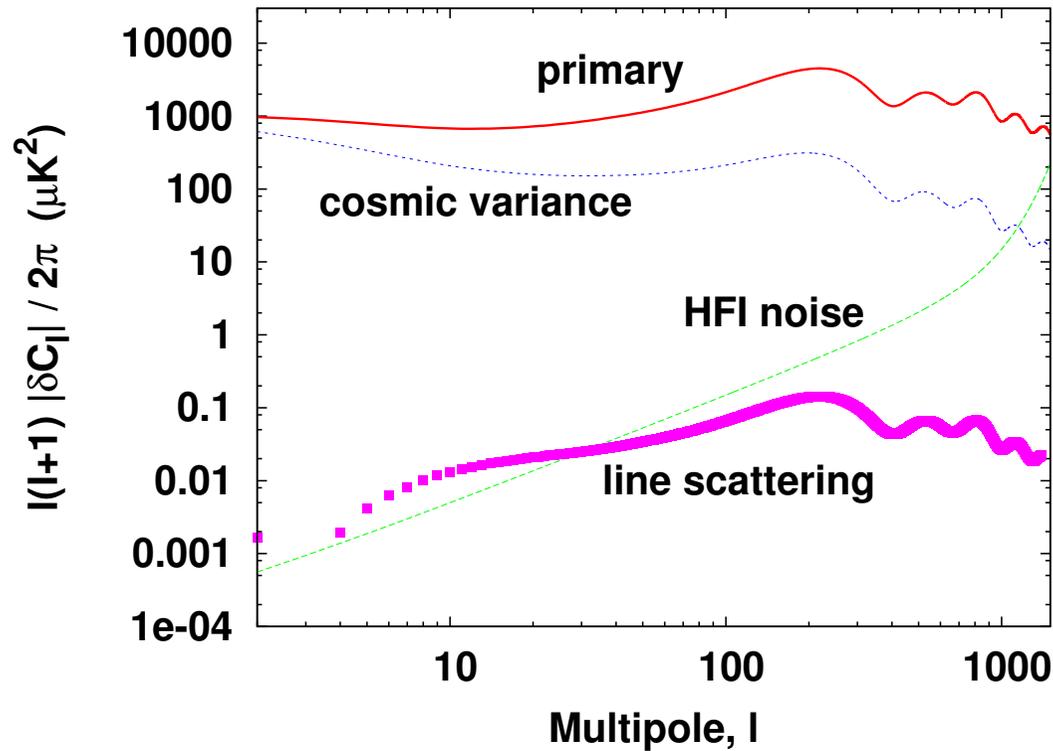
# Minimum abundances

Minimum detectable abundance for **CO molecules** with LFI 100 GHz

$J' \rightarrow J''$	Wavelength ( $\mu$ )	$z$ Scatter.	$\tau$ for $10^{-2}[\text{C}]_{\odot}$	Min. Abundance
$0 \rightarrow 1$	2600.78	0.2	$4.6 \times 10^{-5}$	$2.3 \times 10^{-3}$
$1 \rightarrow 2$	1300.41	1.3	$9.0 \times 10^{-5}$	$2.0 \times 10^{-3}$



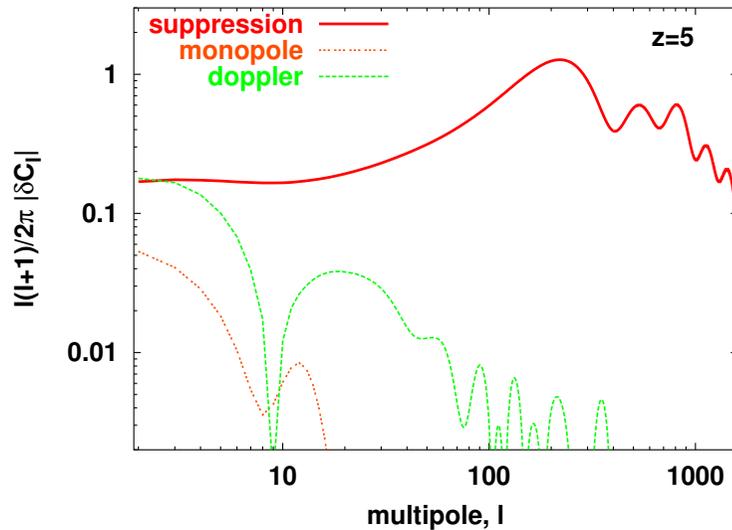
# Nature of distortions



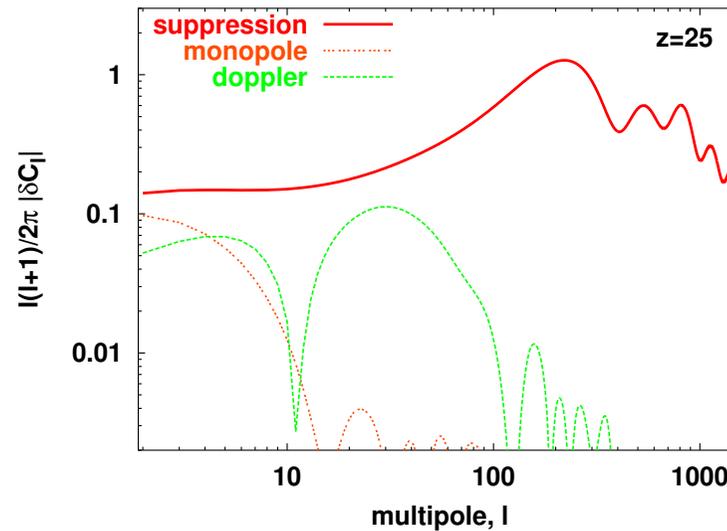
The resultant temperature anisotropy is a combination of **suppression** and **generation** terms...



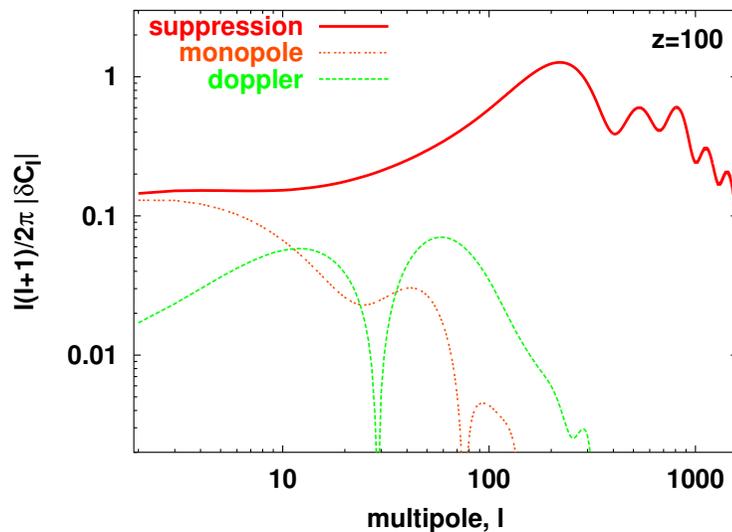
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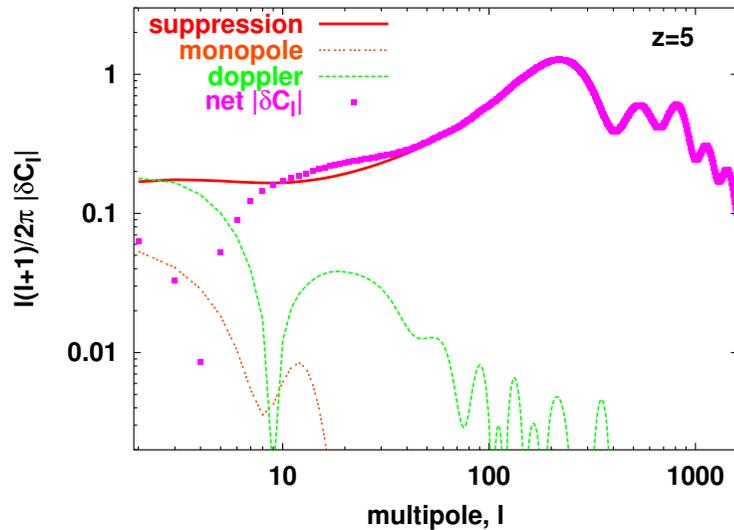
Velocity term grows with time, monopole term dies



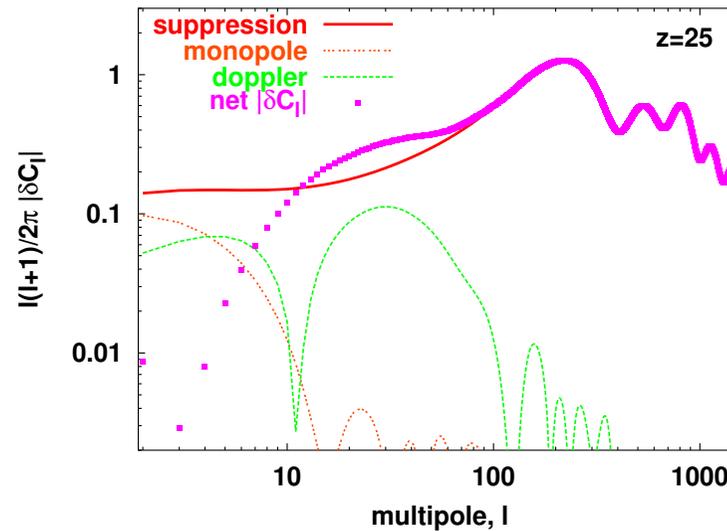
The suppression term remains the same



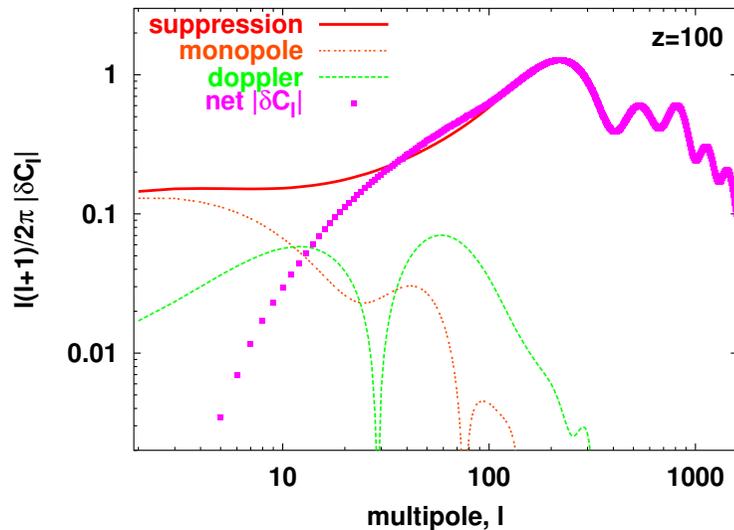
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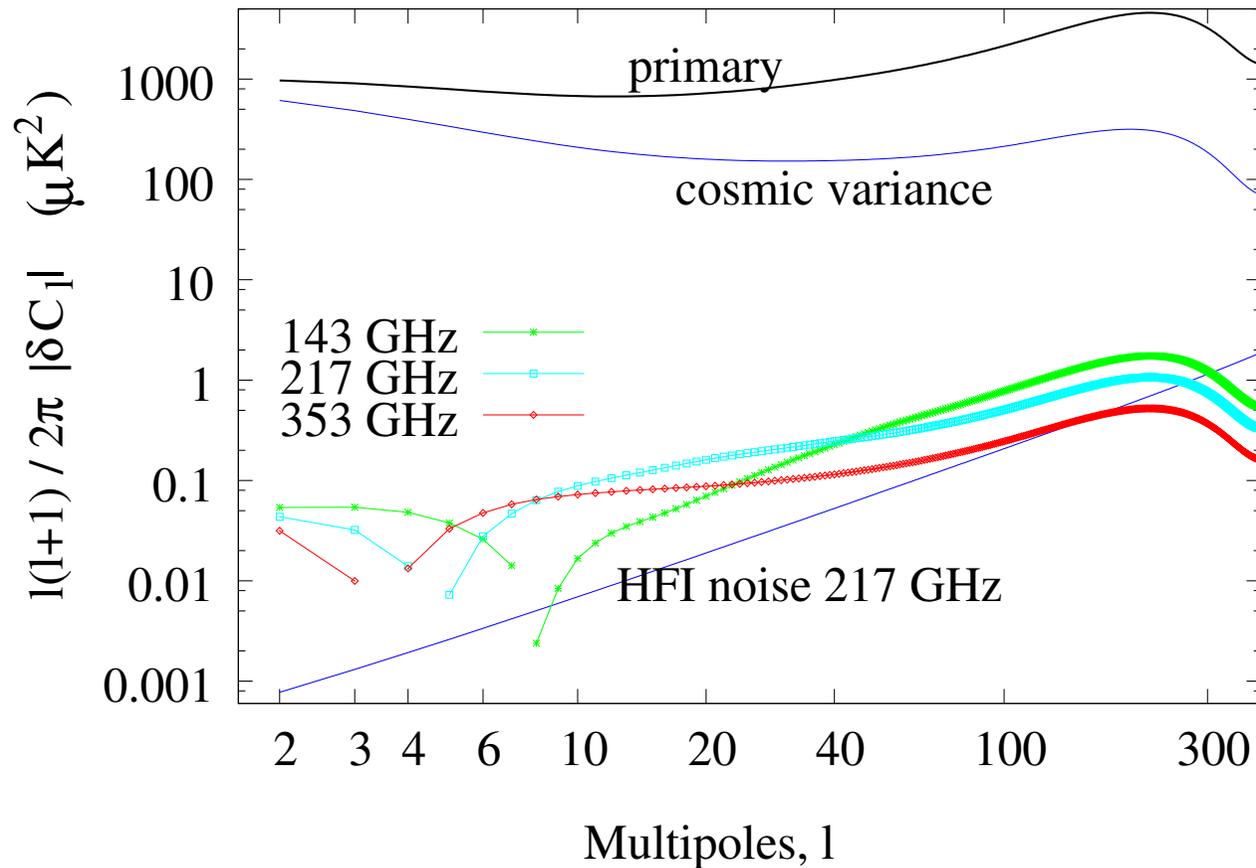


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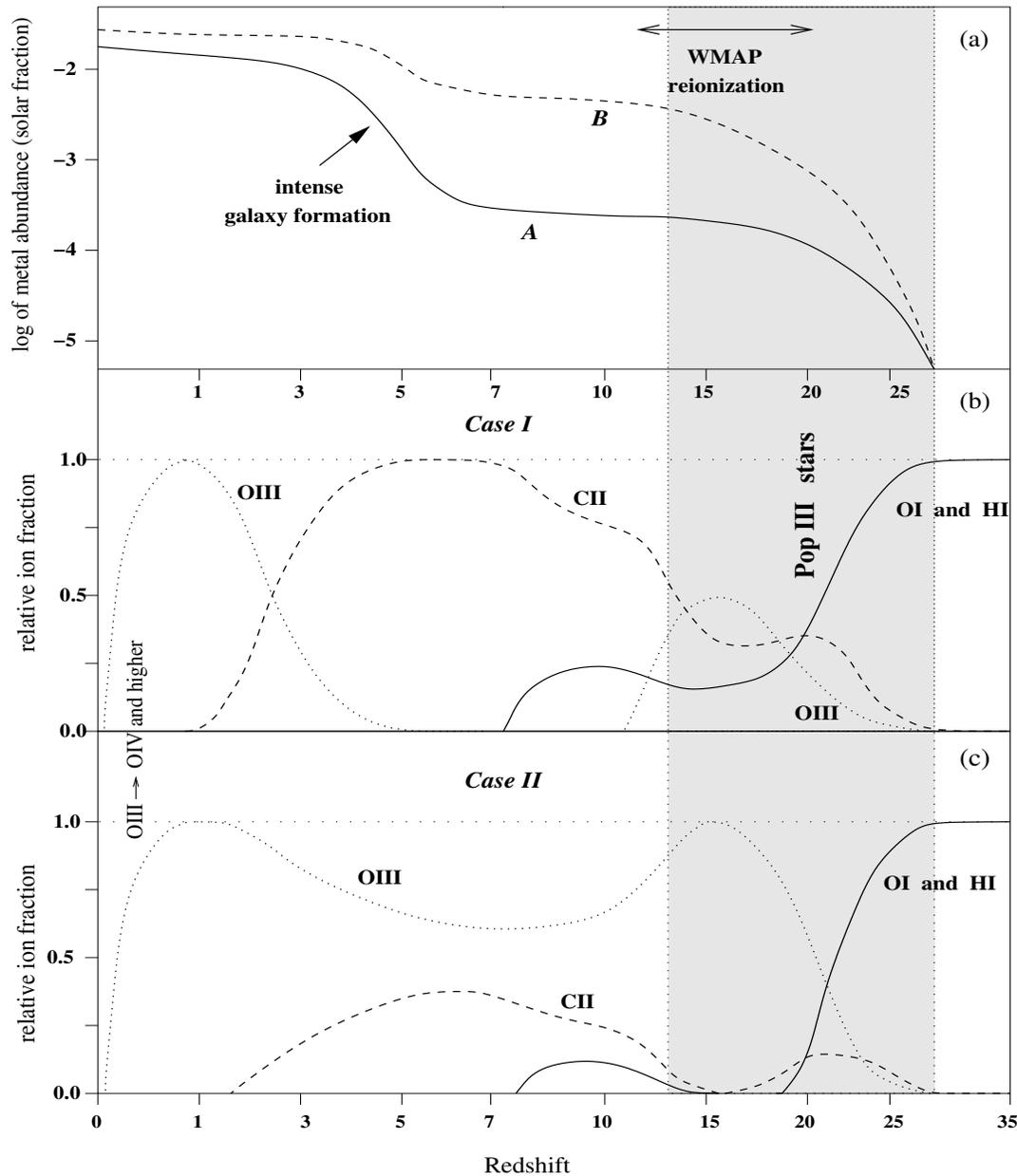


# Nature of distortions

At small angular scales ( $l \gtrsim 200$ ), we have simply  $\delta C_l \simeq -2 \tau_{X_i} C_l^{prim.}$   
making prediction of effect very easy for ground-based experiments!



# Ionization & enrichment histories



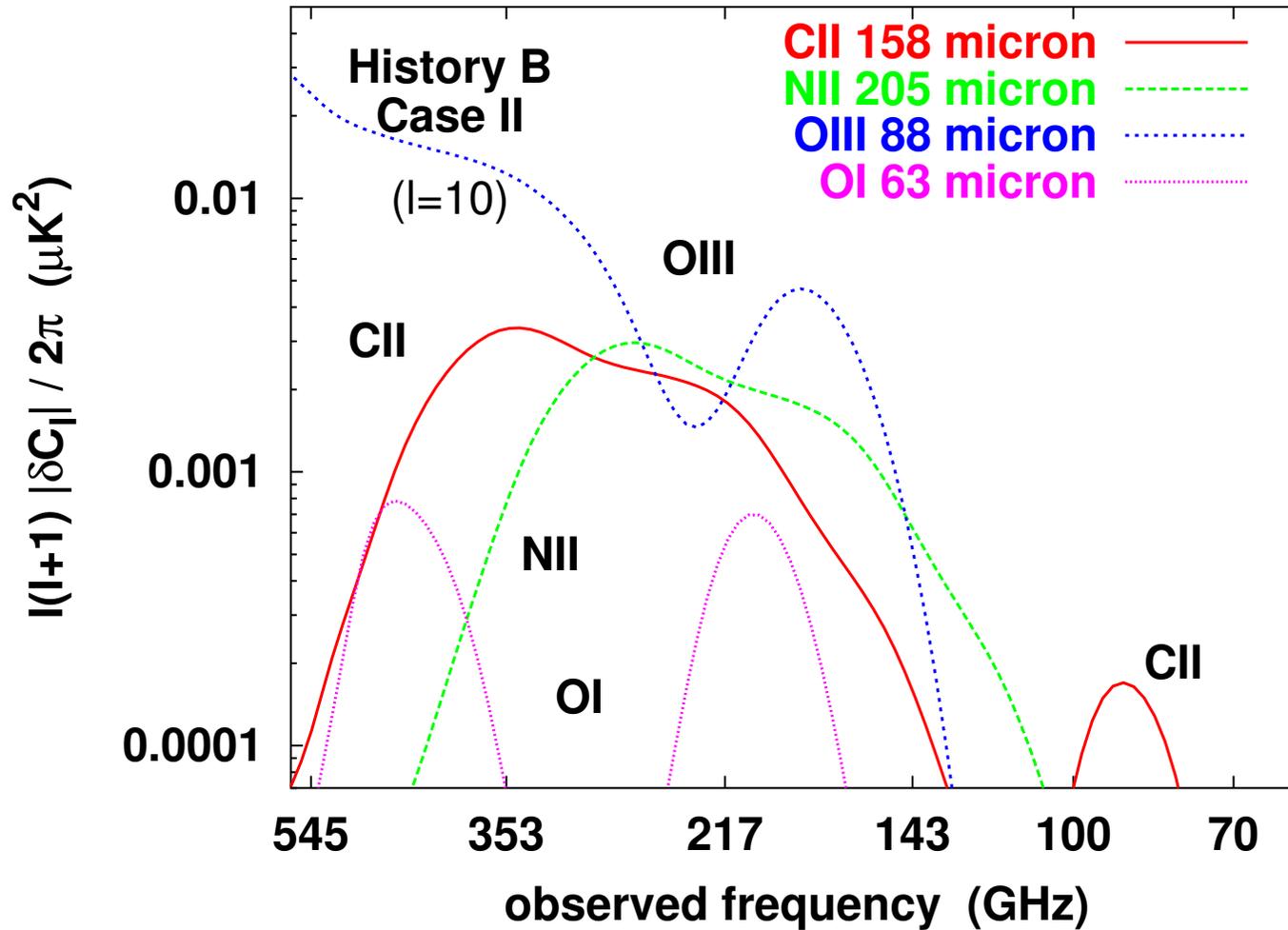
Two levels of mean metallicity: **A** (conservative) and **B** (optimistic)

Reionization by relatively cold stars  $\Rightarrow$  more CII

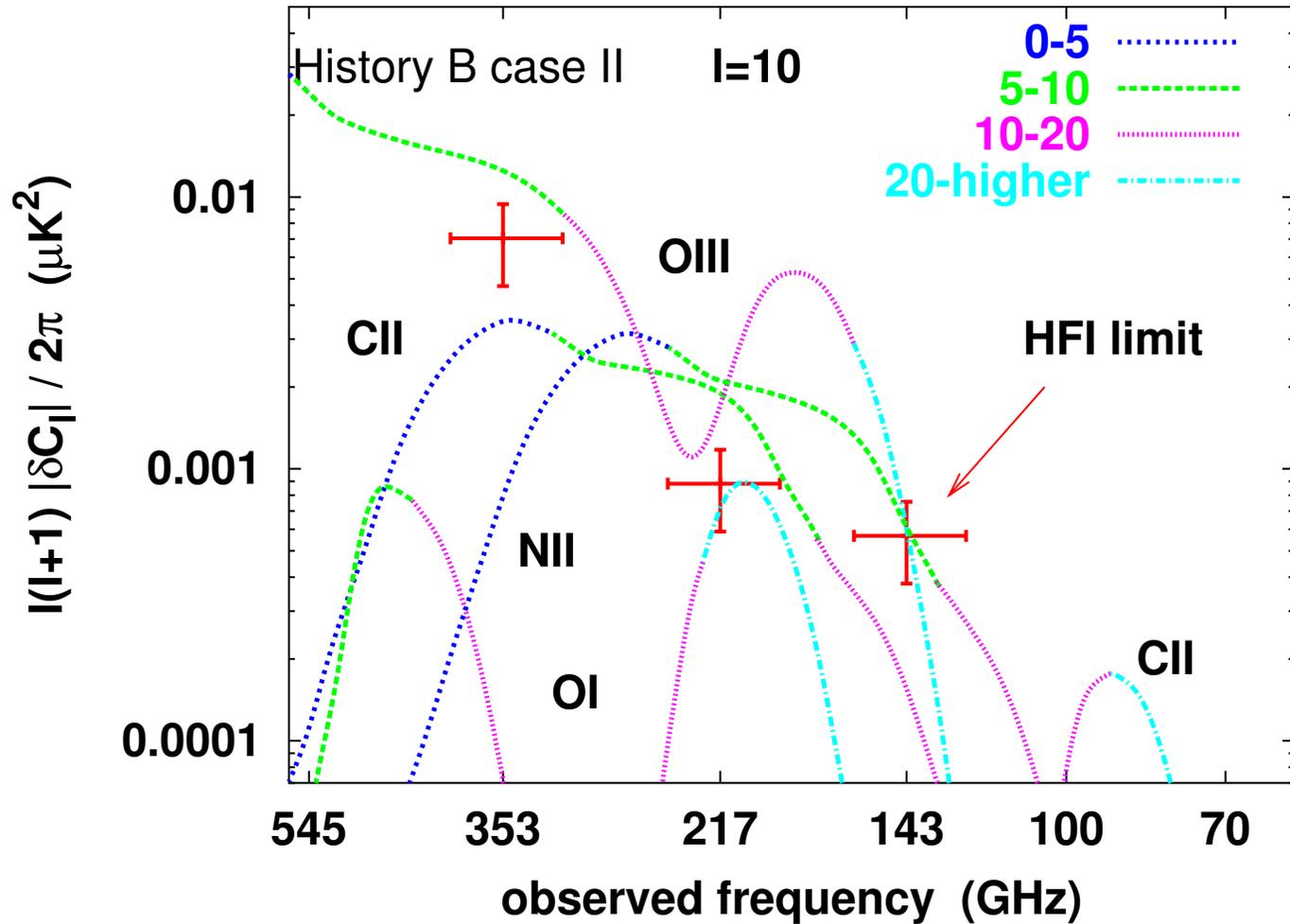
...and by hot stars and quasars  $\Rightarrow$  more OIII



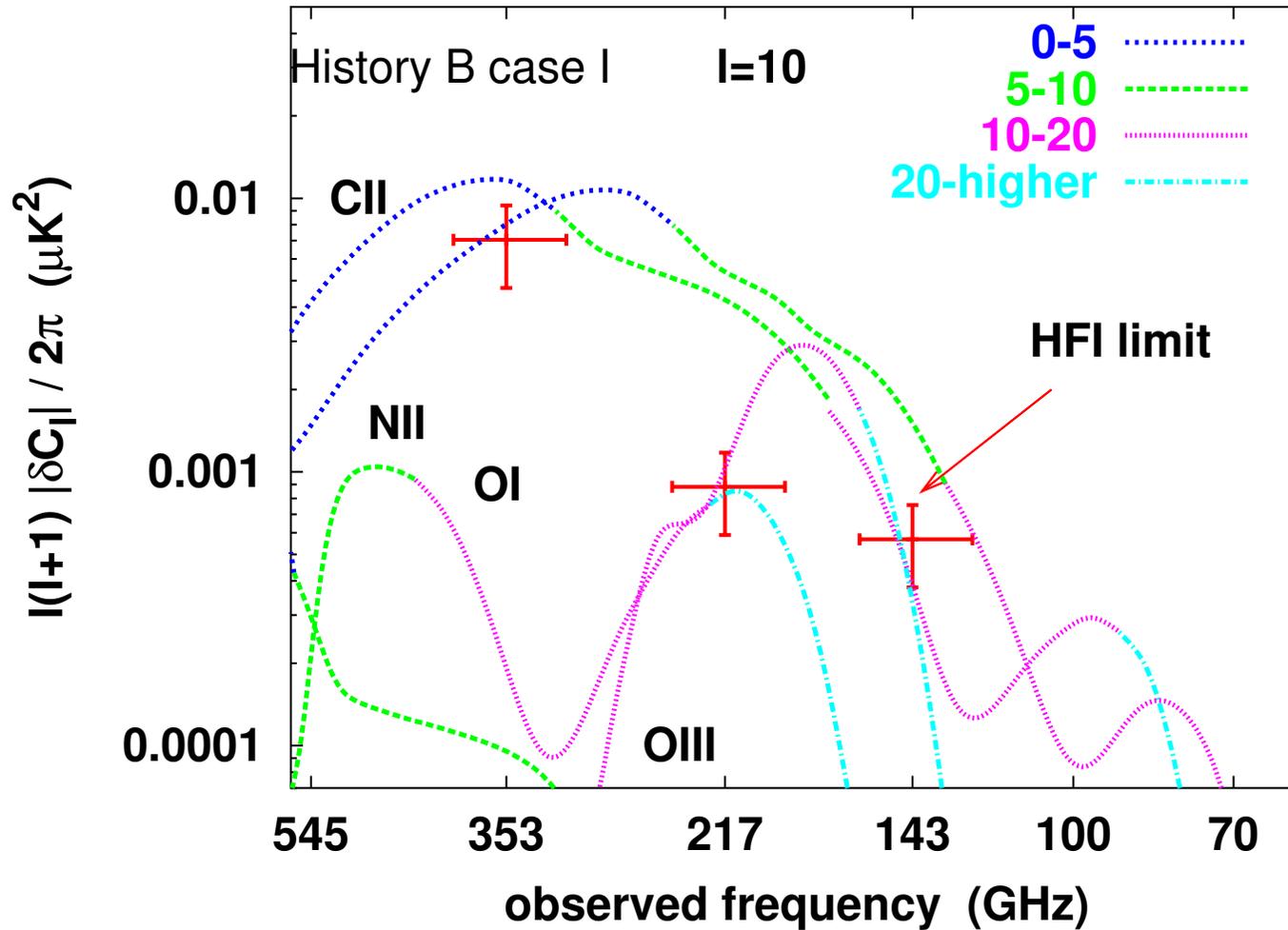
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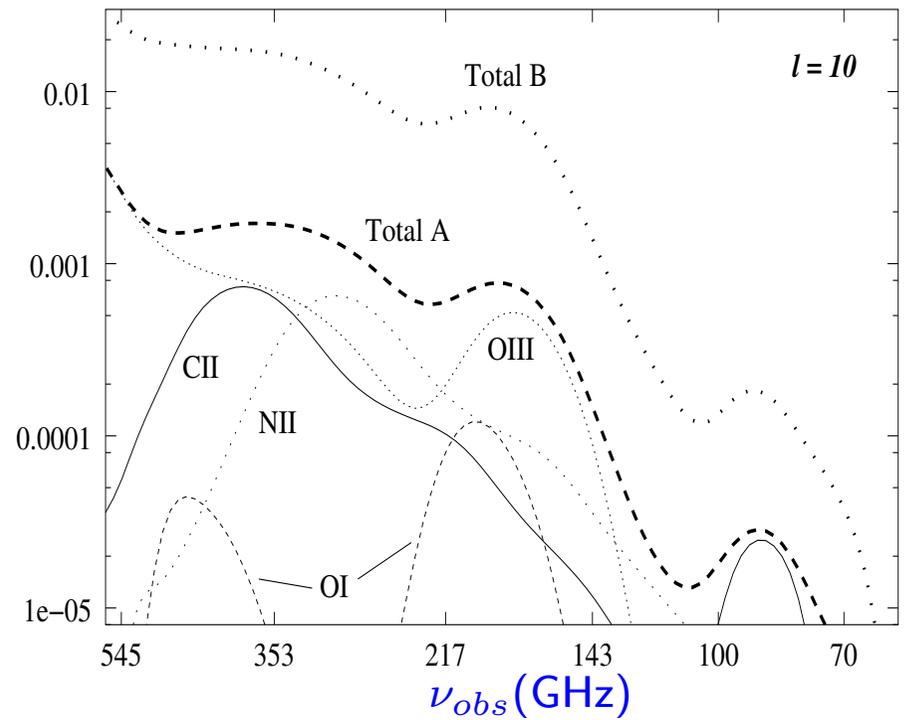
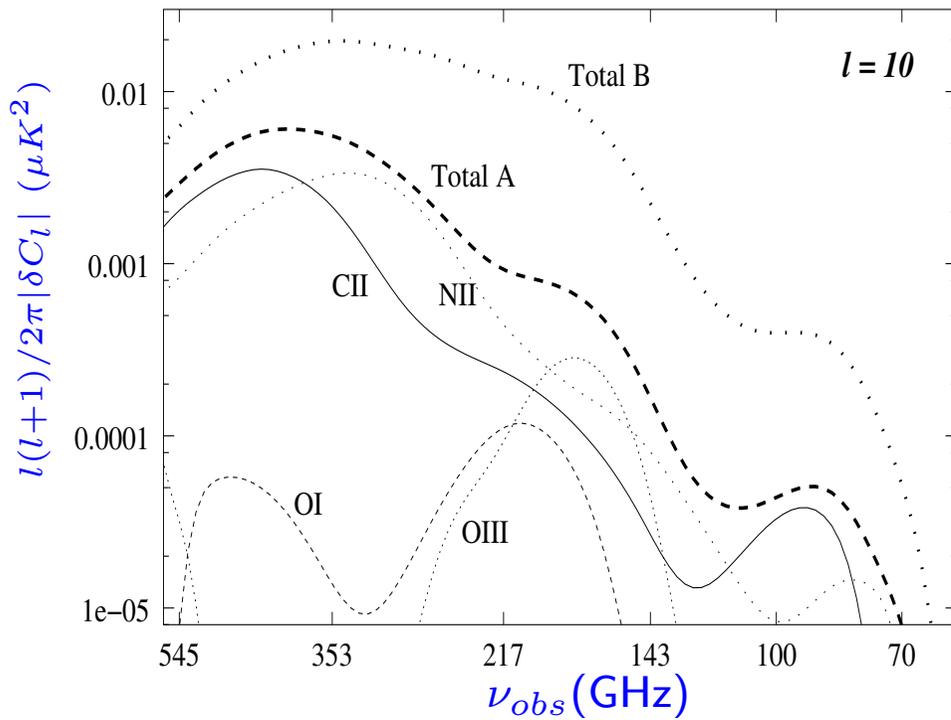
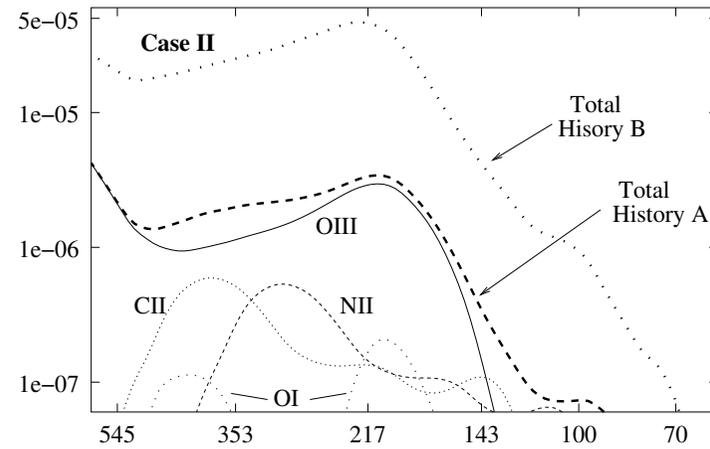
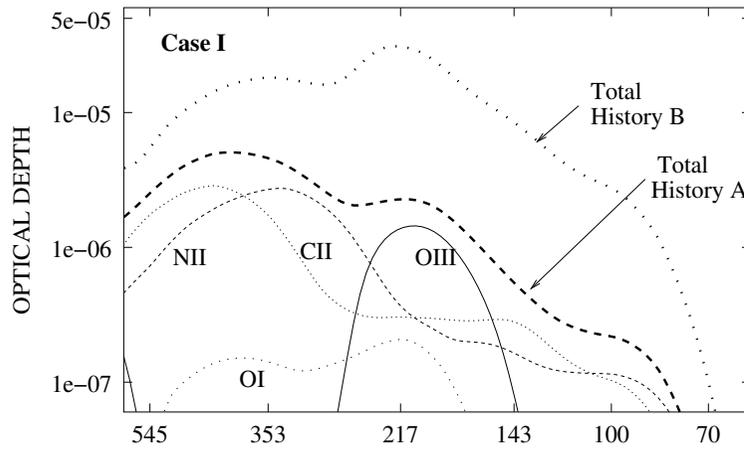
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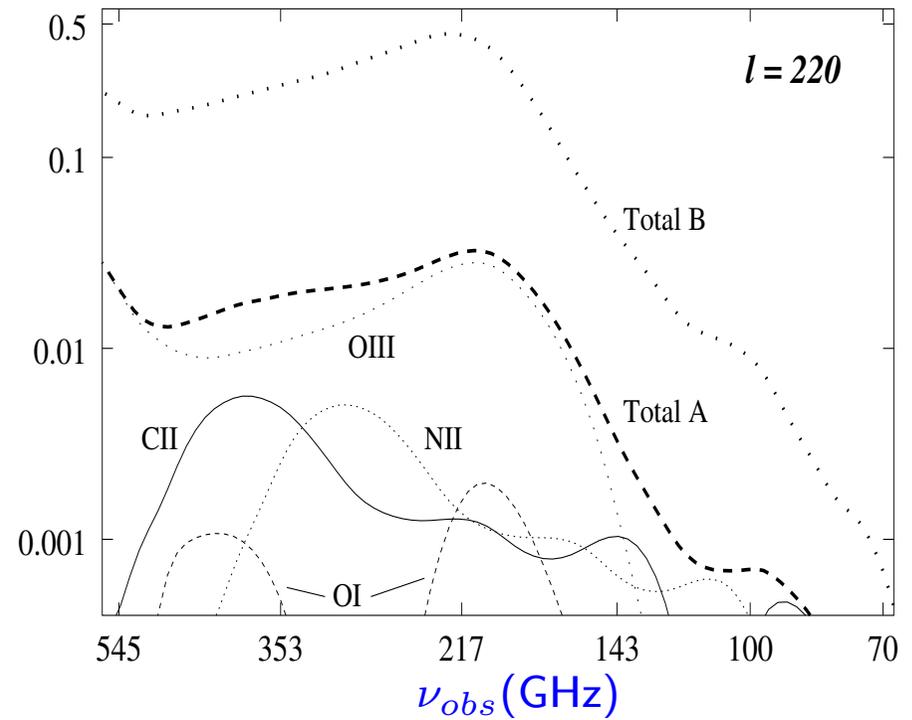
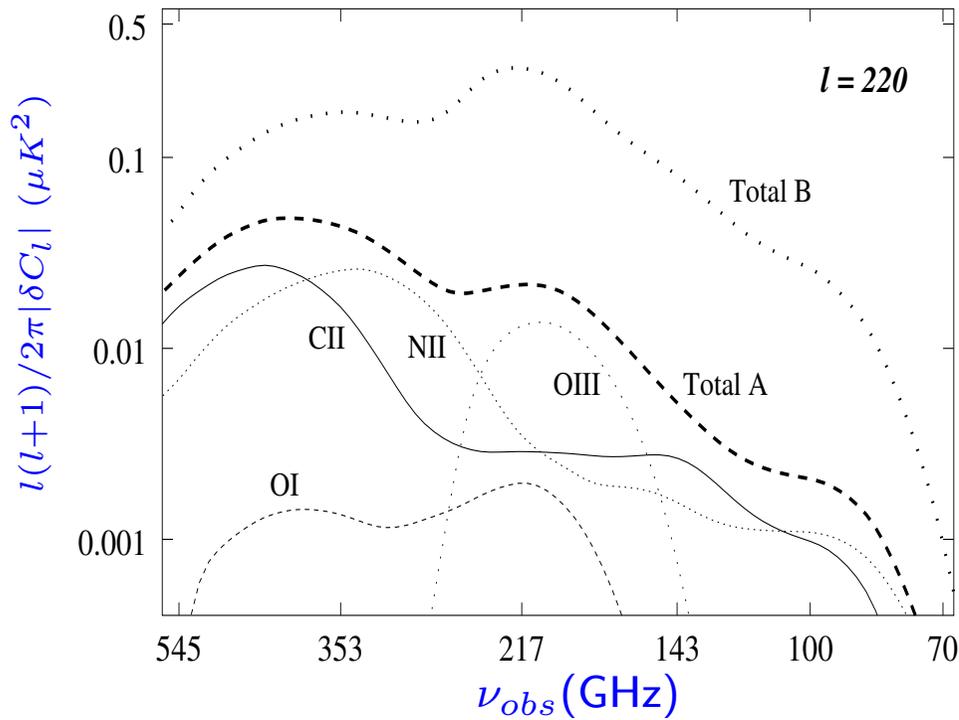
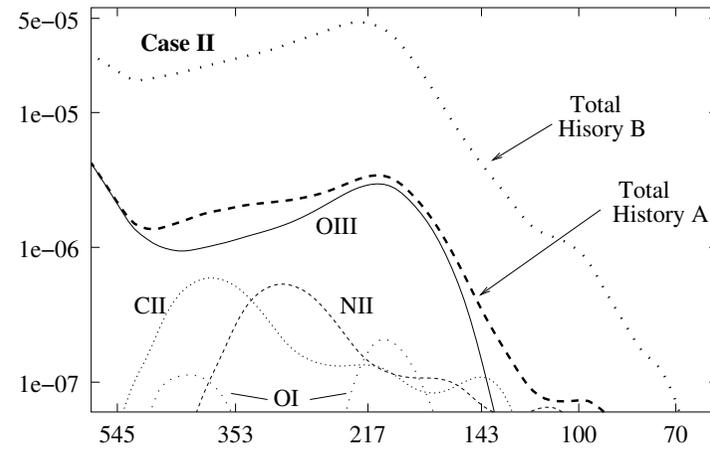
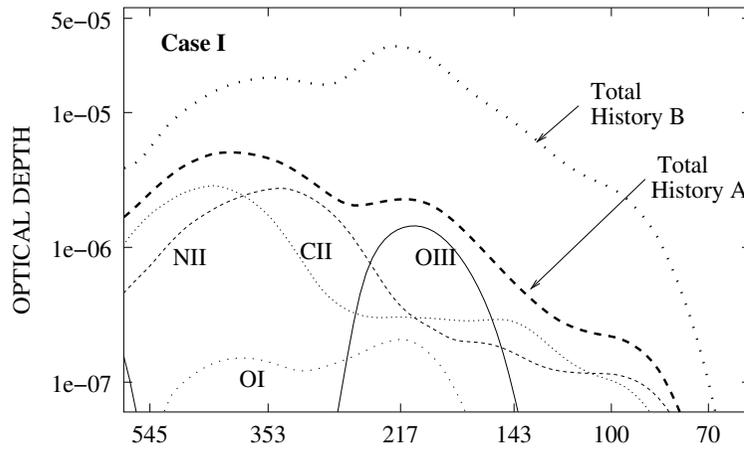
# Ionization & enrichment histories



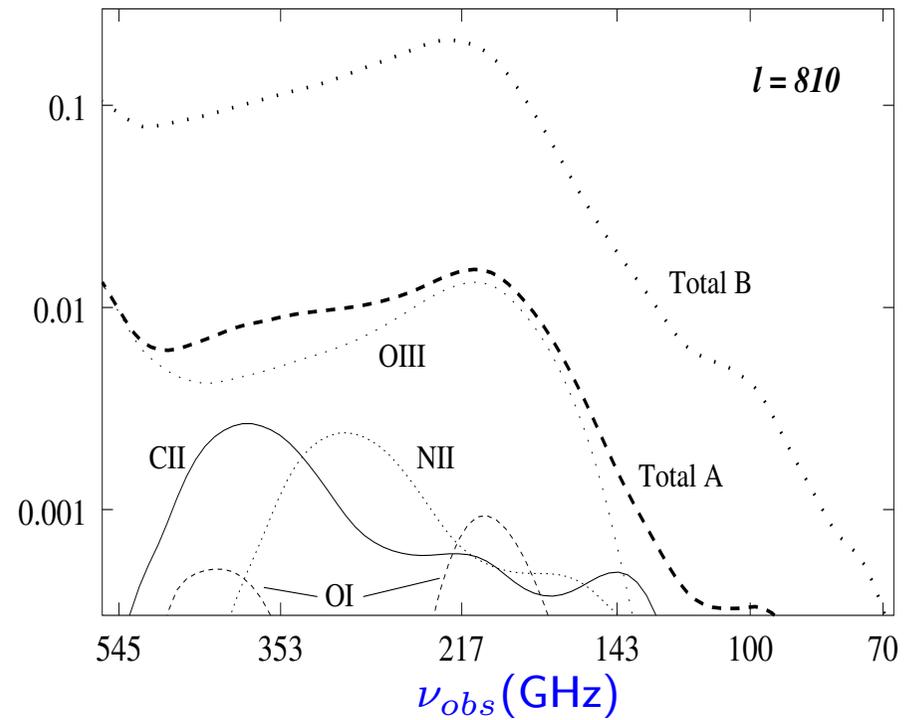
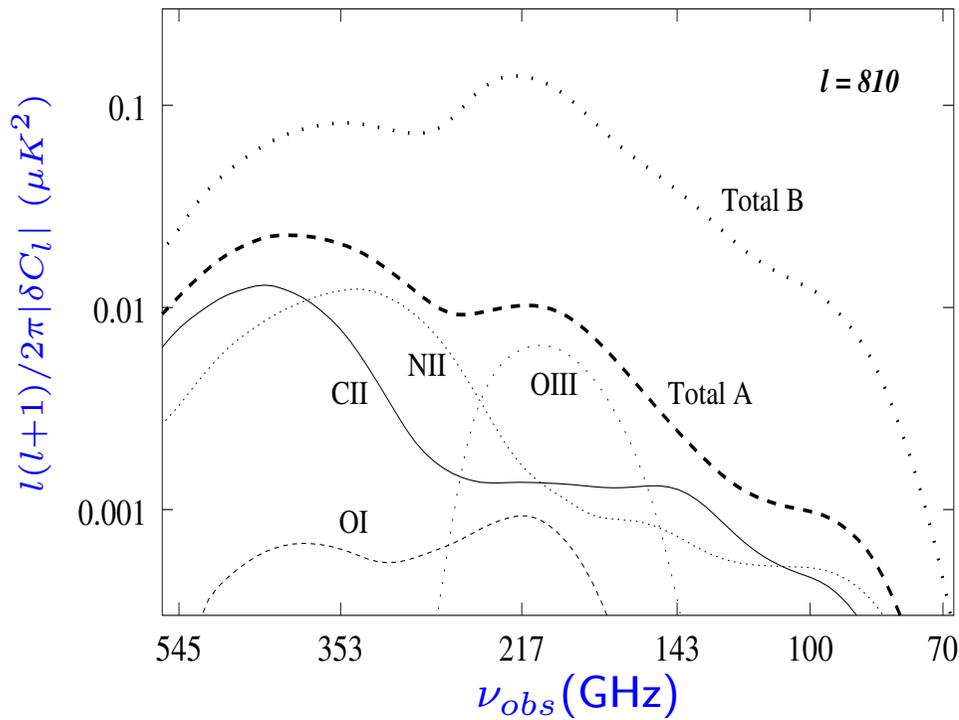
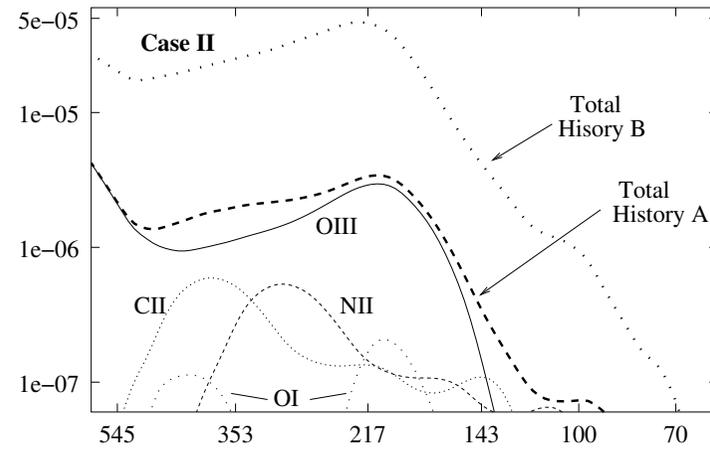
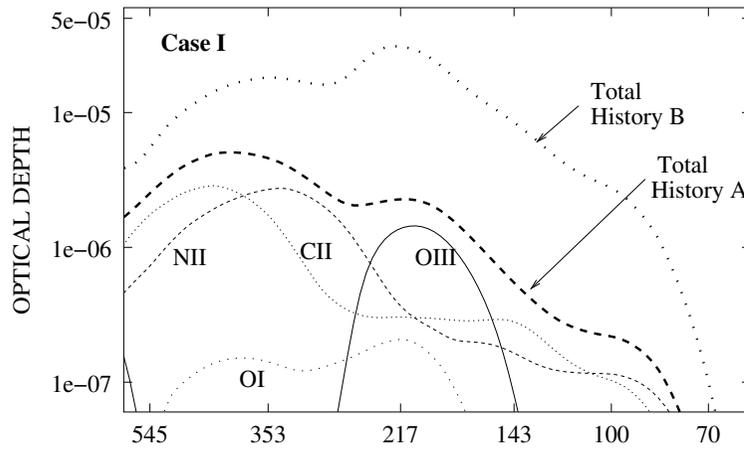
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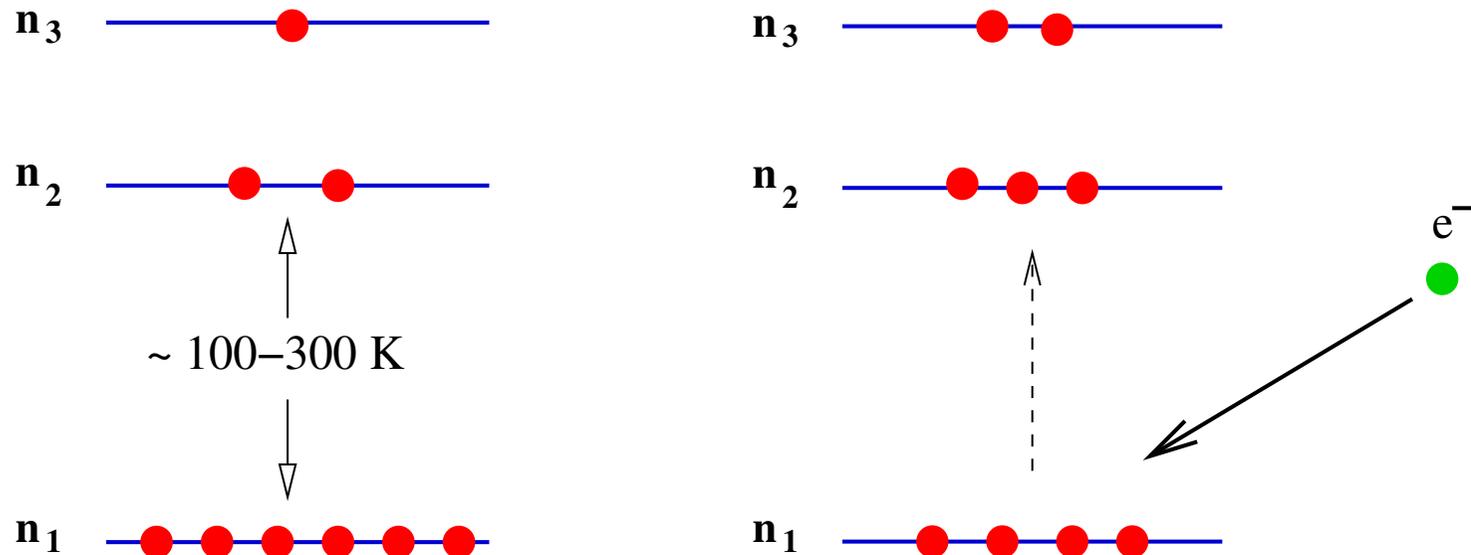
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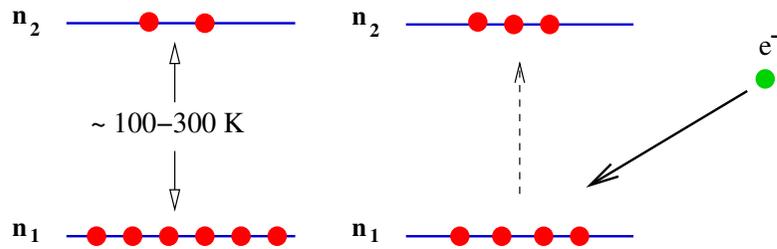
# Effect of overdensity



If density is high, collision with electrons (also H, He,..) will *reduce* the number of atoms/ions in the ground level, thereby **decreasing the optical depth in scattering**

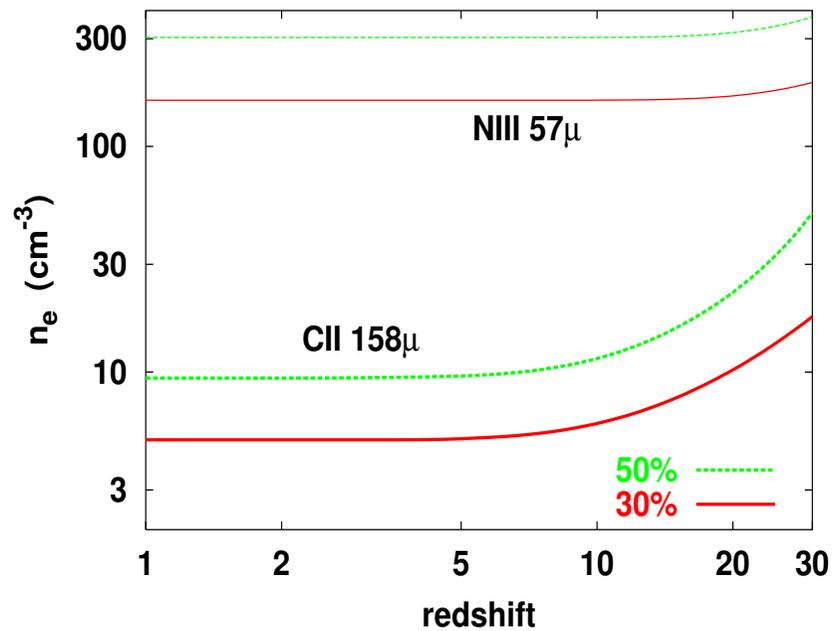
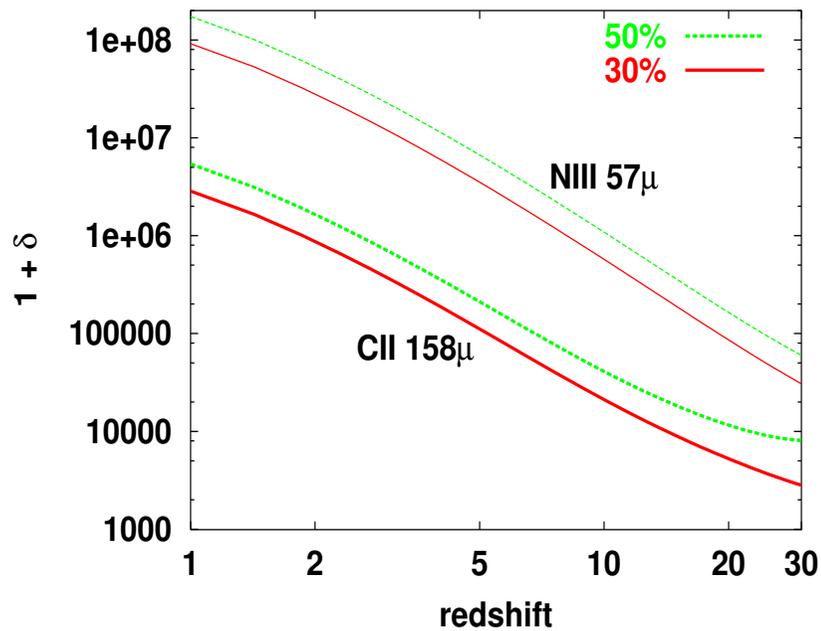


# Effect of overdensity



For a two-level system:

$$n_u (A_{ul} + B_{ul} J_{\nu_{ul}} + n_e \gamma_{ul}) = n_l (B_{lu} J_{\nu_{ul}} + n_e \gamma_{lu})$$



# Effect of overdensity

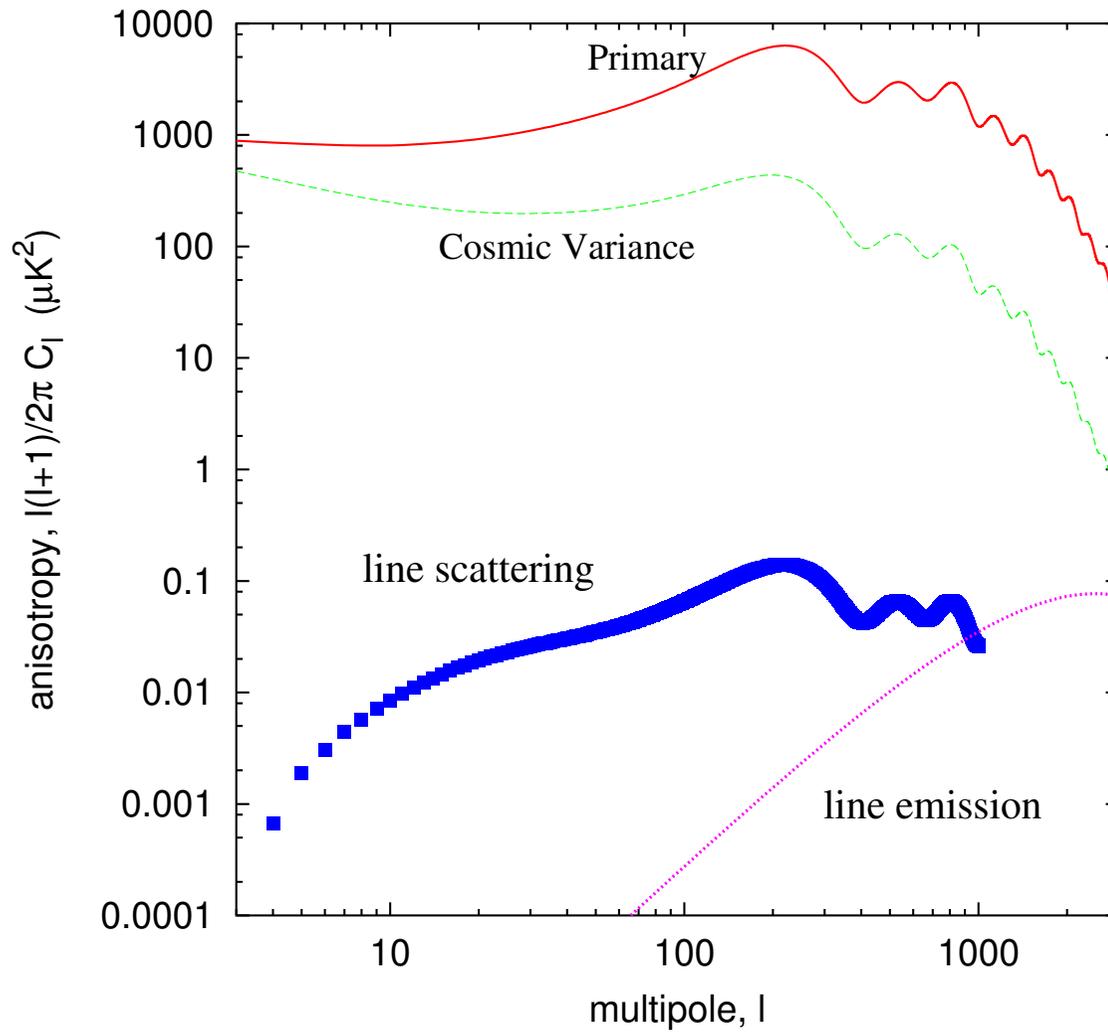
Proposed method detects effect of scattering in the low-density optically thin gas, with overdensity  $\delta < 10^3$ - $10^4$

There is simultaneous effect of free-free, line and dust emission from non-uniformly distributed regions with huge over-density, where active star formation is taking place

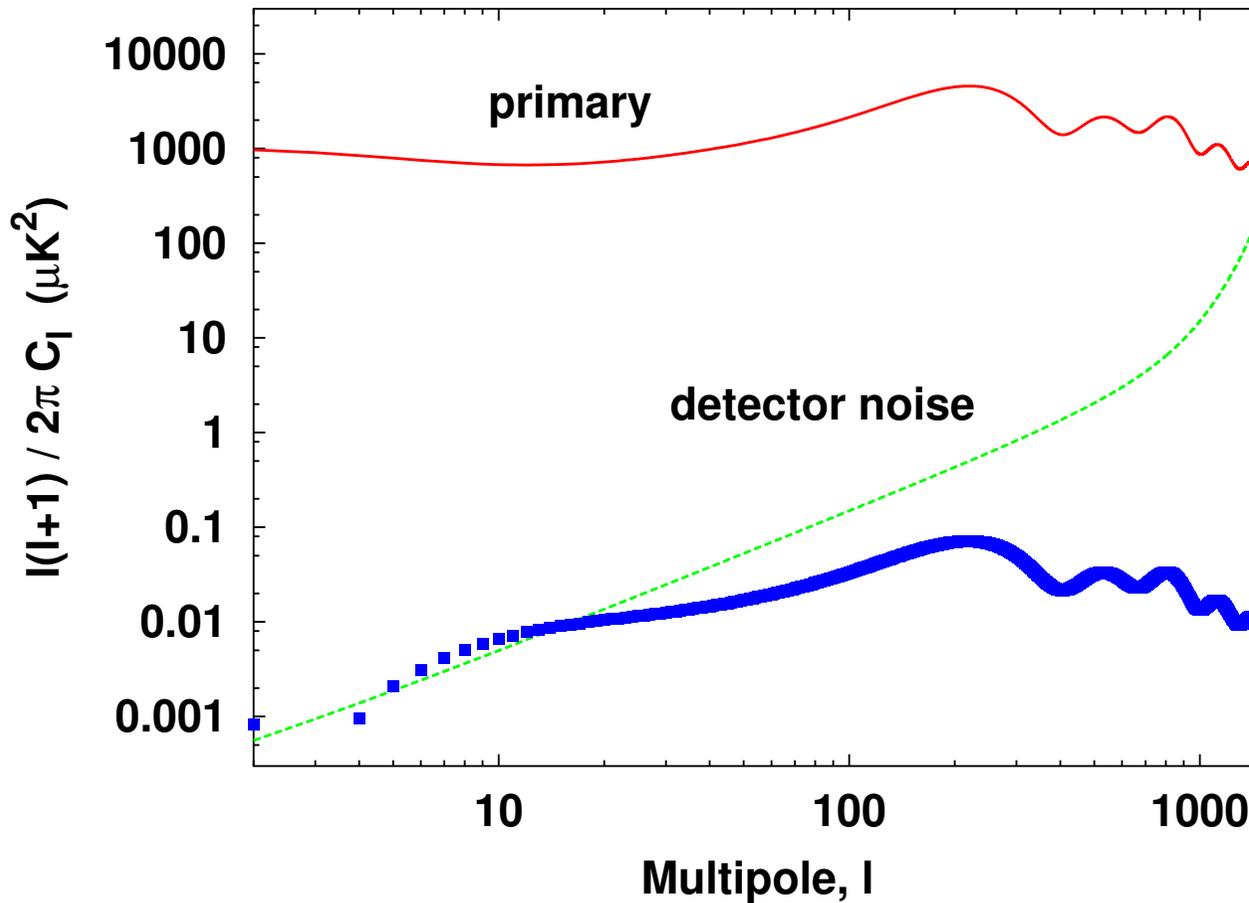
These two effects are **independent and complimentary**, producing simultaneous distortions in the angular power spectrum of CMB in different angular scales



# Effect of overdensity



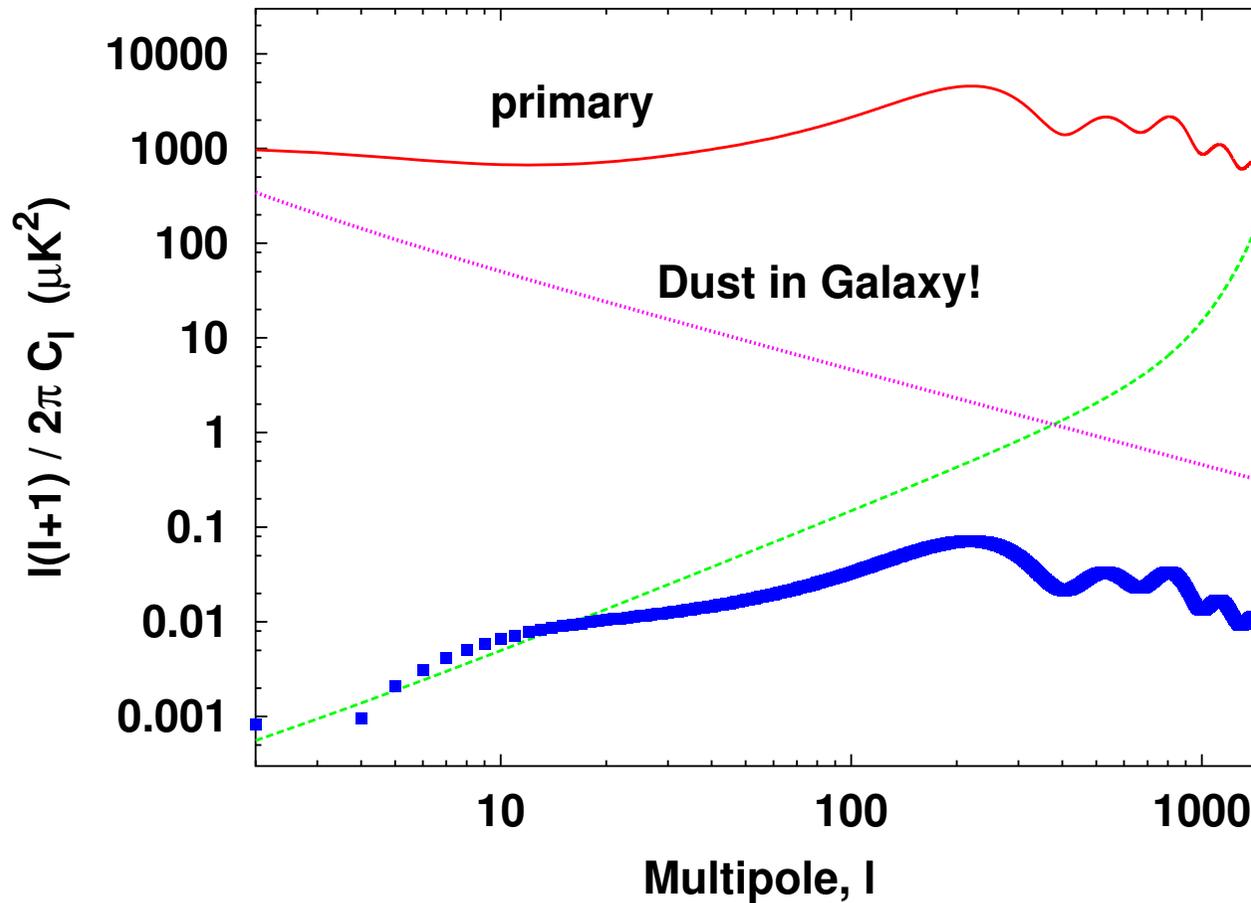
# Effect of foregrounds



The picture is not so simple because of foregrounds!



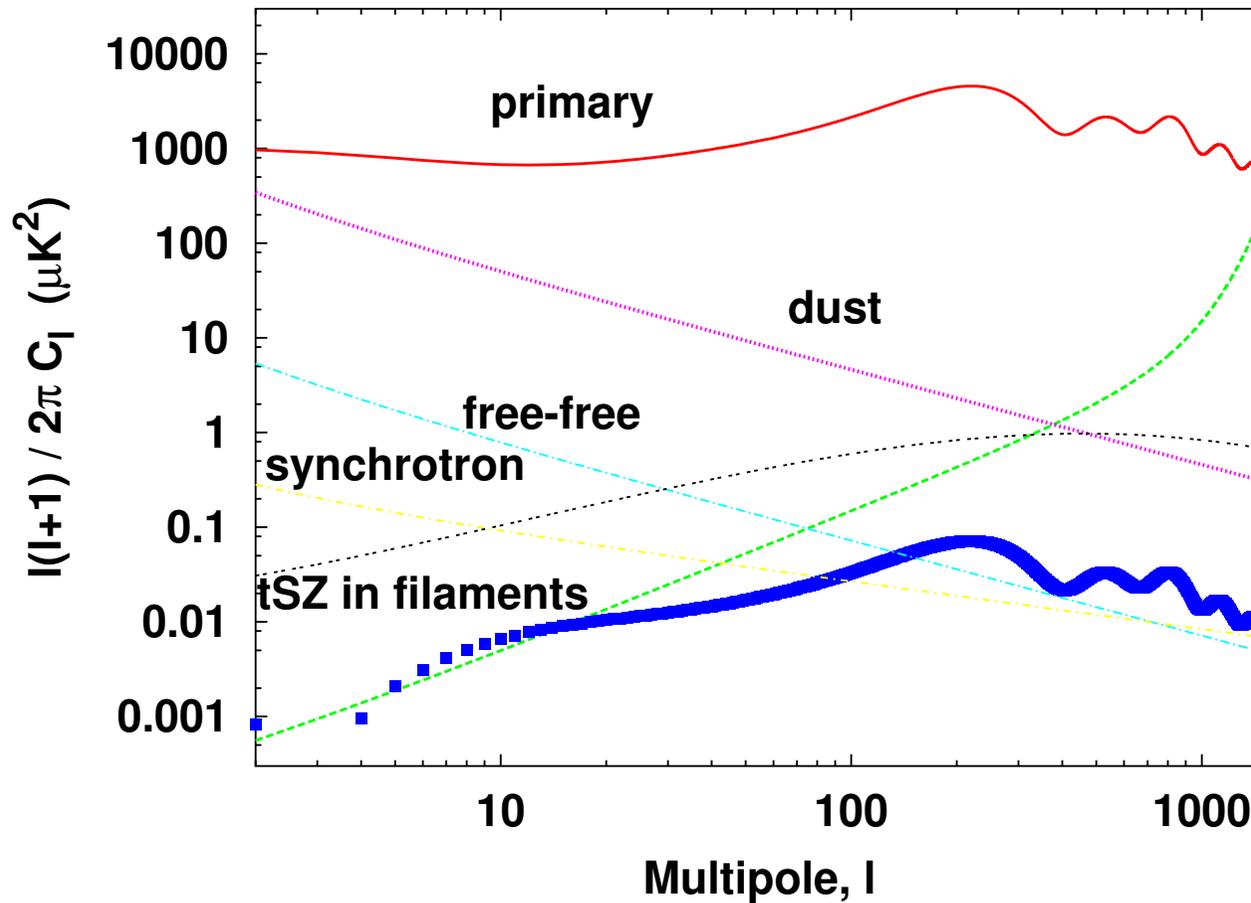
# Effect of foregrounds



At high frequencies thermal radiation from Galactic dust dominates



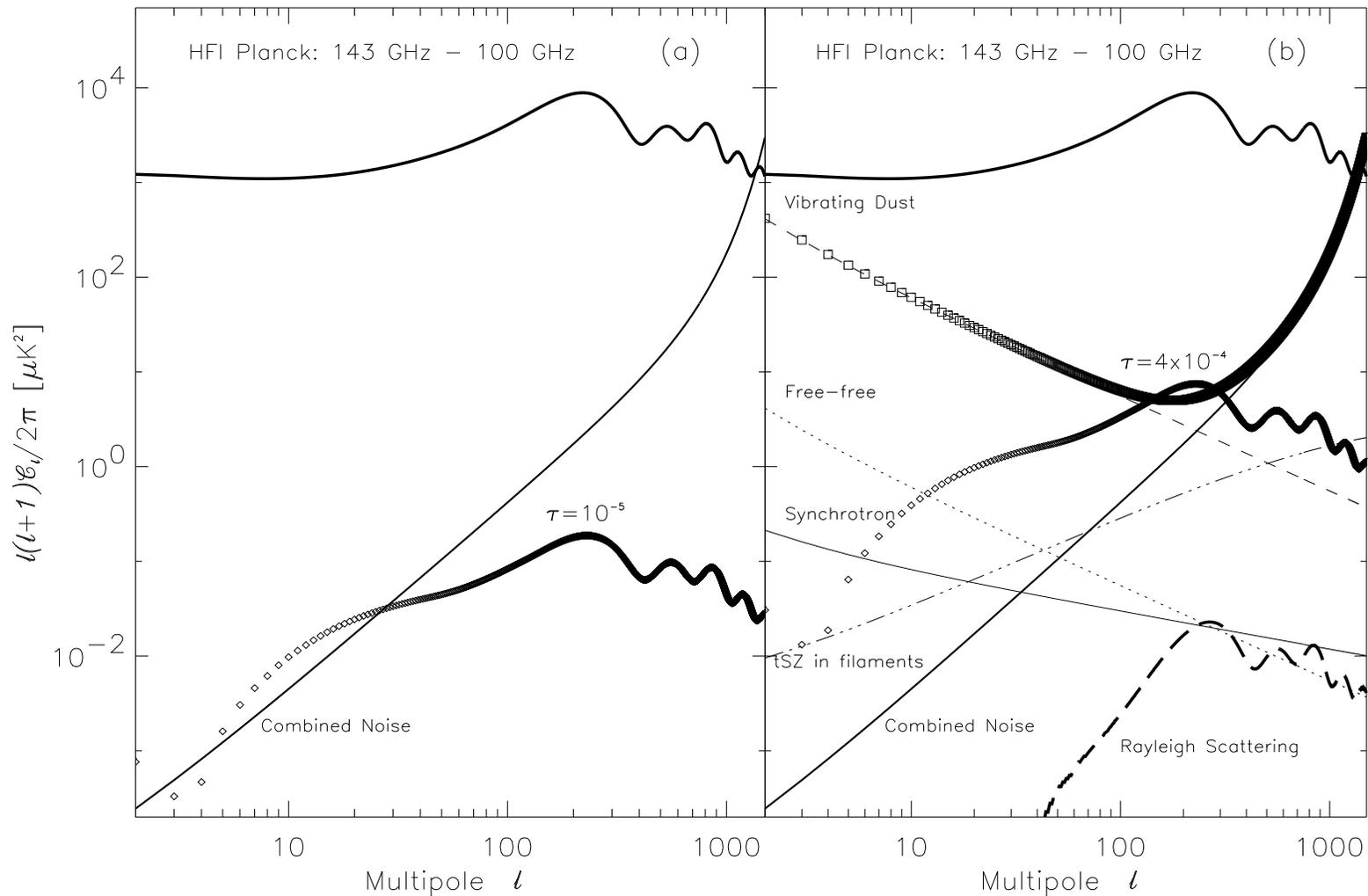
# Effect of foregrounds



Various other Galactic & extra-galactic foregrounds



# Effect of foregrounds



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**Basu, Hernández & Sunyaev, A&A 2004, 416, 447-466**

