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

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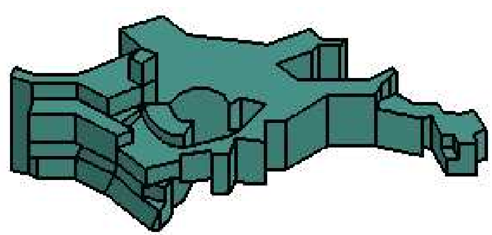
in collaboration with

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 τ, not τ^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...

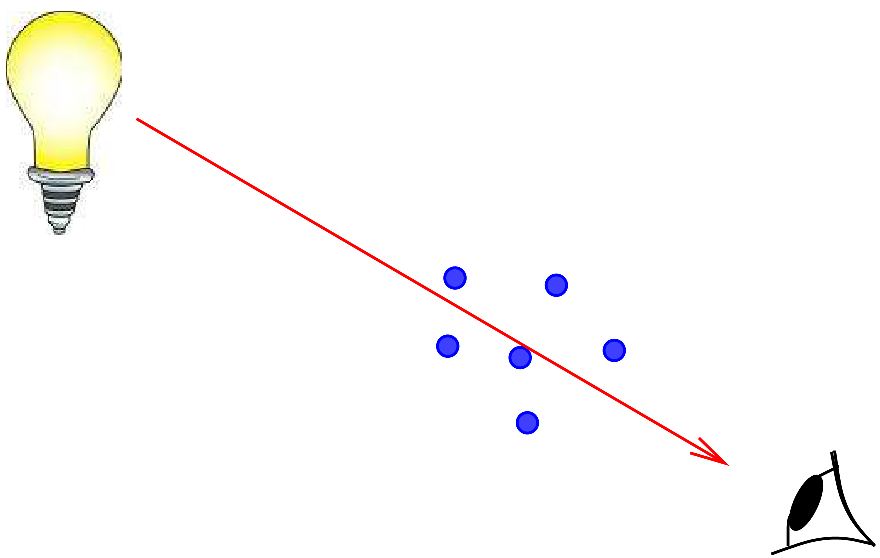
- Suginohara & Spergel (1999)

Overview of talk

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

Basic Idea

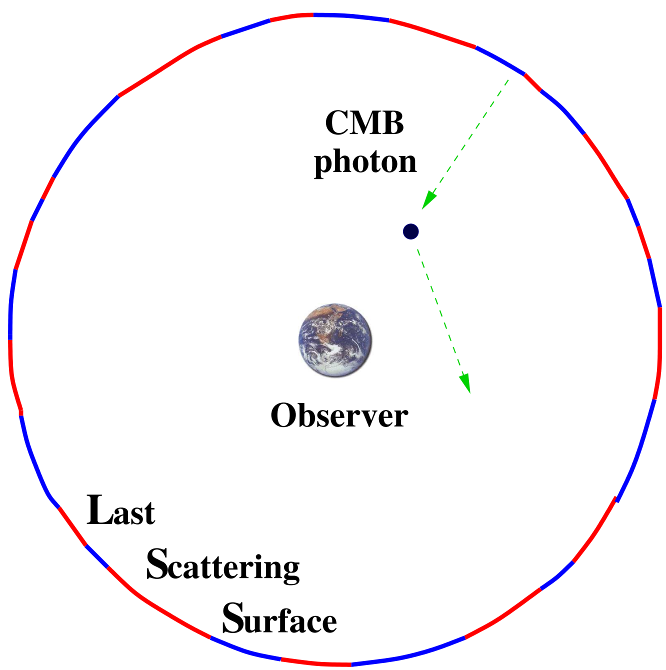
Metallicity evolution of the universe must leave its imprint on the Cosmic Microwave Background Radiation $\Rightarrow$ through resonance scattering of the background photons by atoms, ions and molecules



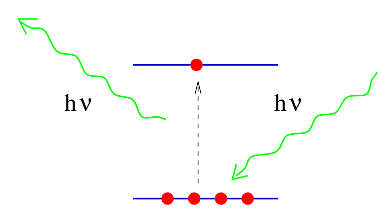
We wish to know about the state of intervening medium using the very well-understood background light: CMB!

Suppression & generation

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



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



Scattering is *coherent* in scatterer's frame

Suppression & generation

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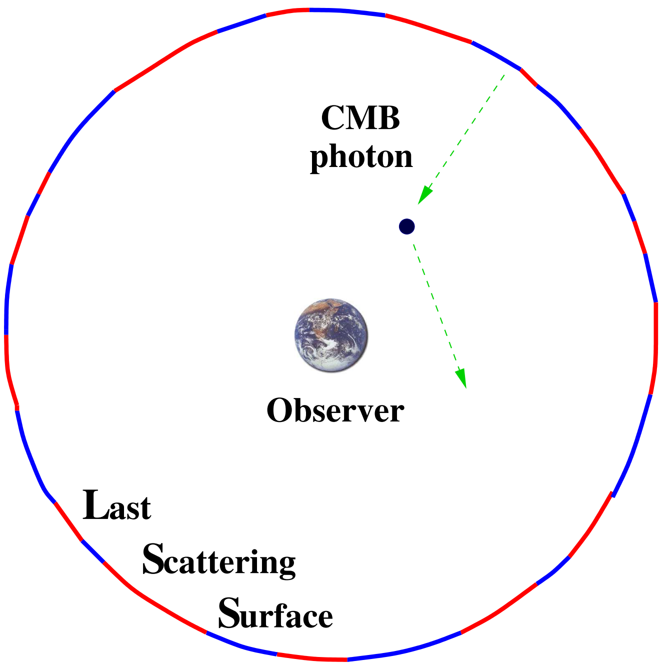

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"suppression (blurring)" & "generation"

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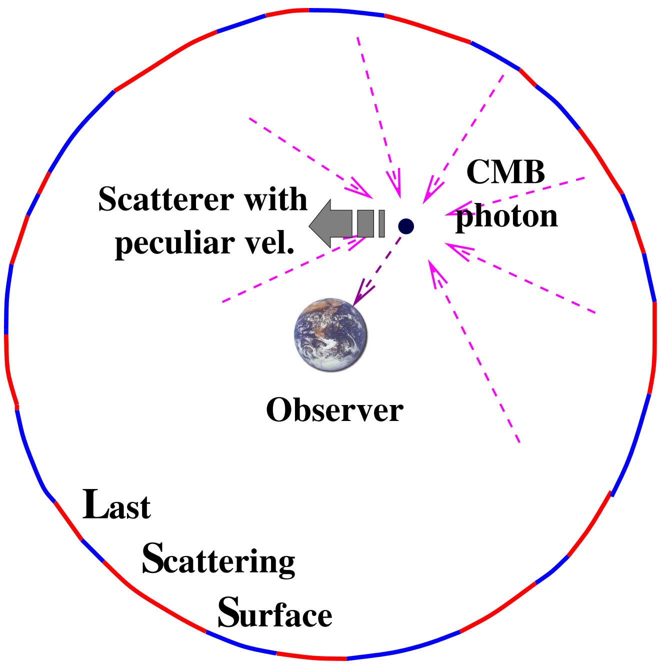

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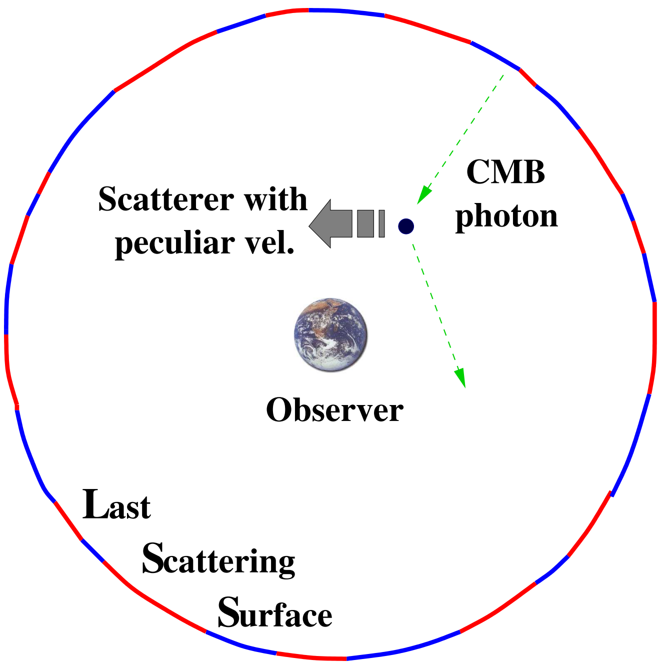

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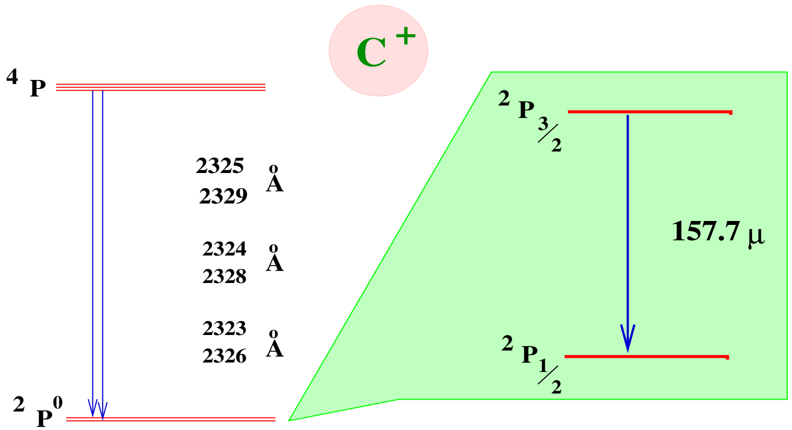
$$\delta C_l = \tau_\nu \cdot \mathcal{C}_1 + \tau_\nu^2 \cdot \mathcal{C}_2 + \mathcal{O}(\tau_\nu^3)$$

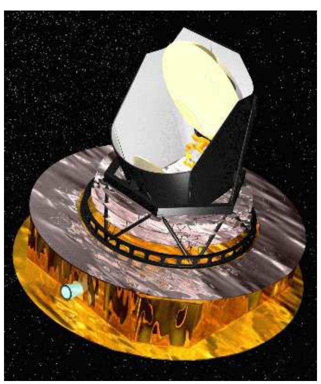
Fine-structure lines



A-coefficient $\sim 10^{-6}\ \mathrm{s}^{-1}$

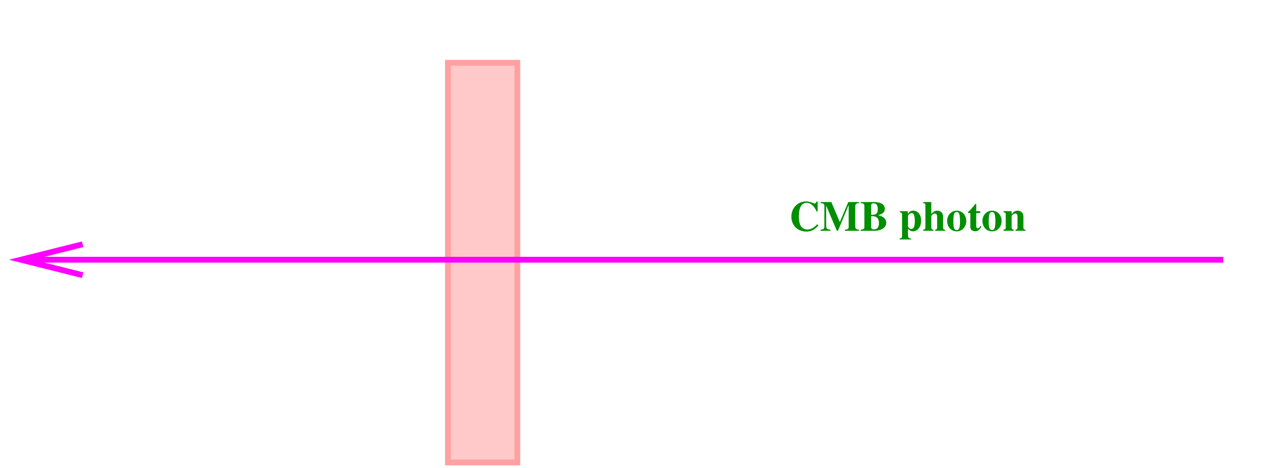
$\Rightarrow$ optical depth $\sim 10^{-5} - 10^{-7}$

143 GHz



Planck HFI

Bandwidth ~ 25%

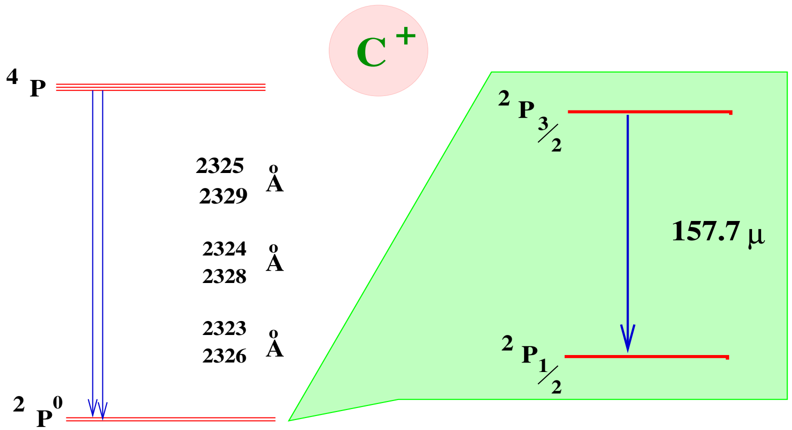


z ~ 12

LSS

at z=1100

Fine-structure lines



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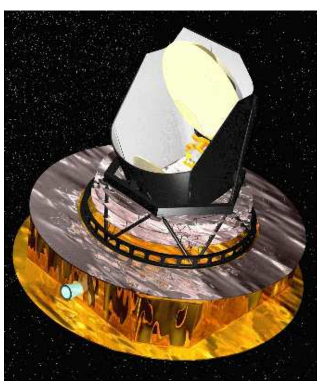
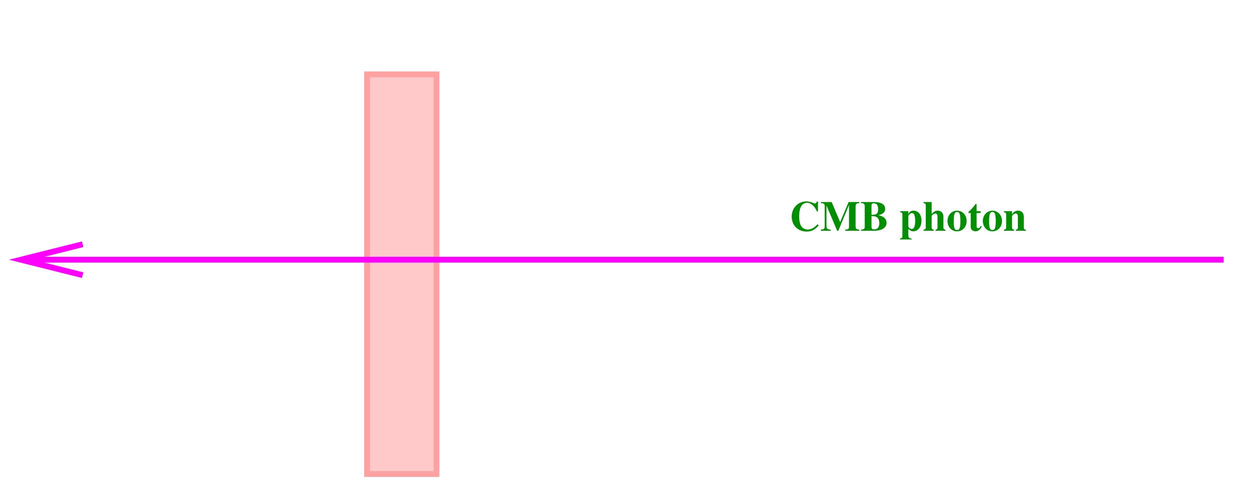
217 GHz





Planck HFI

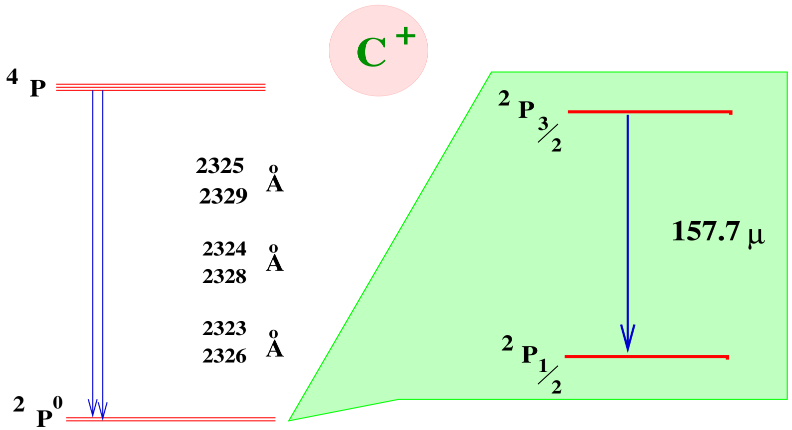
Bandwidth ~ 25%

z ~ 8

LSS

at z=1100

Fine-structure lines



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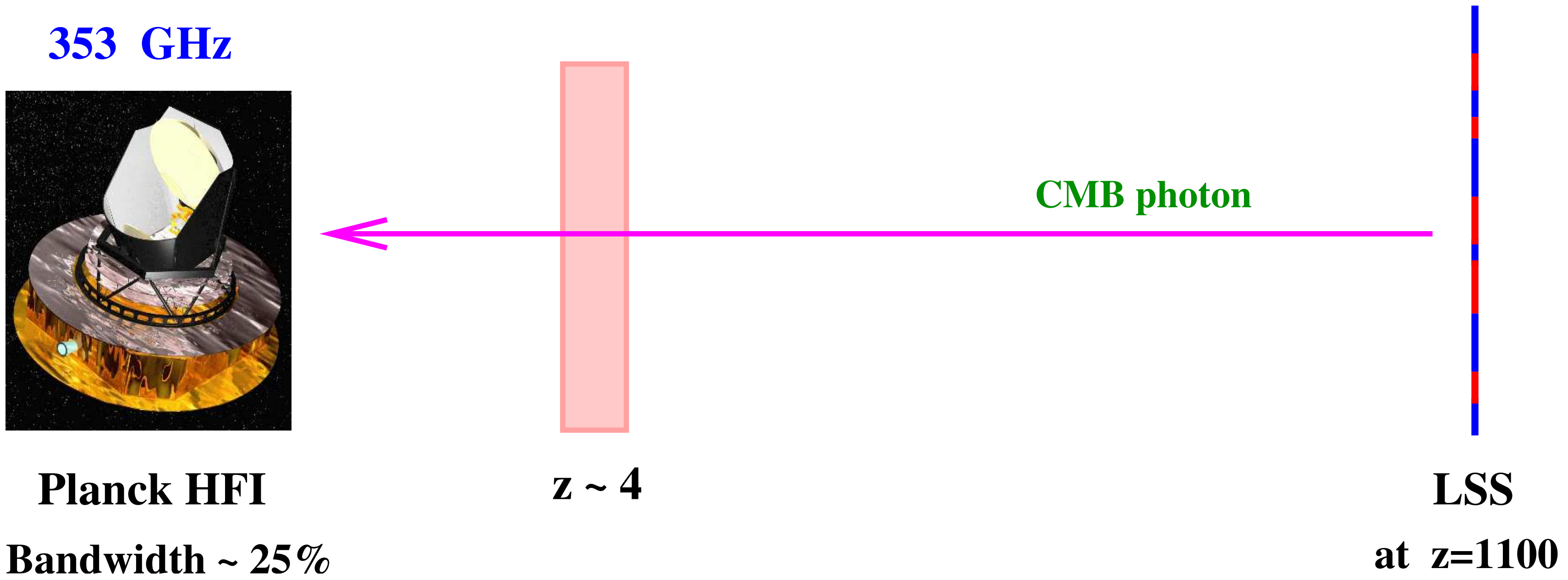
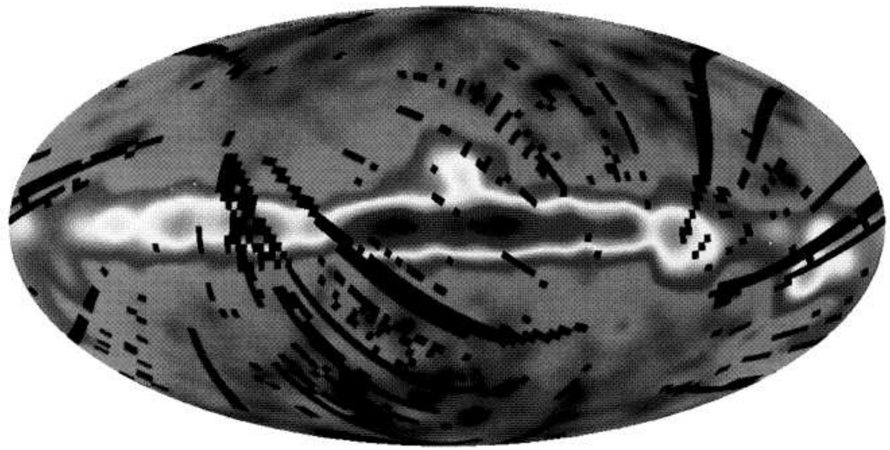
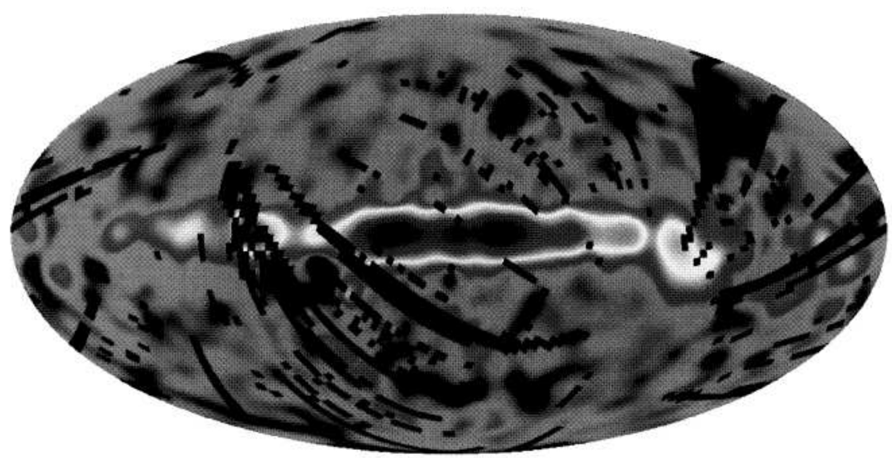


Fine-structure lines

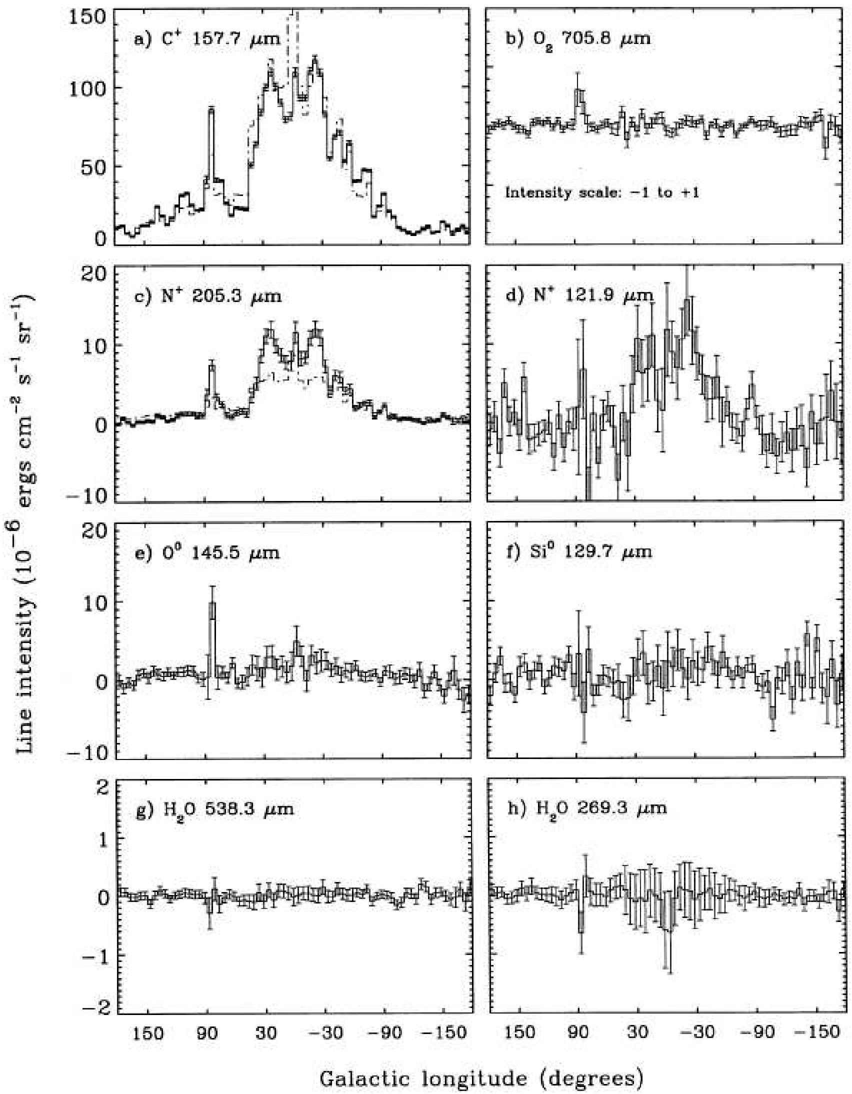
COBE FIRAS 158 μm C^+ Line Intensity



COBE FIRAS 205 μm N^+ Line Intensity



Fine-structure lines



COBE showed that C^+ FS line is the brightest cooling line in our Galaxy!

Proposition

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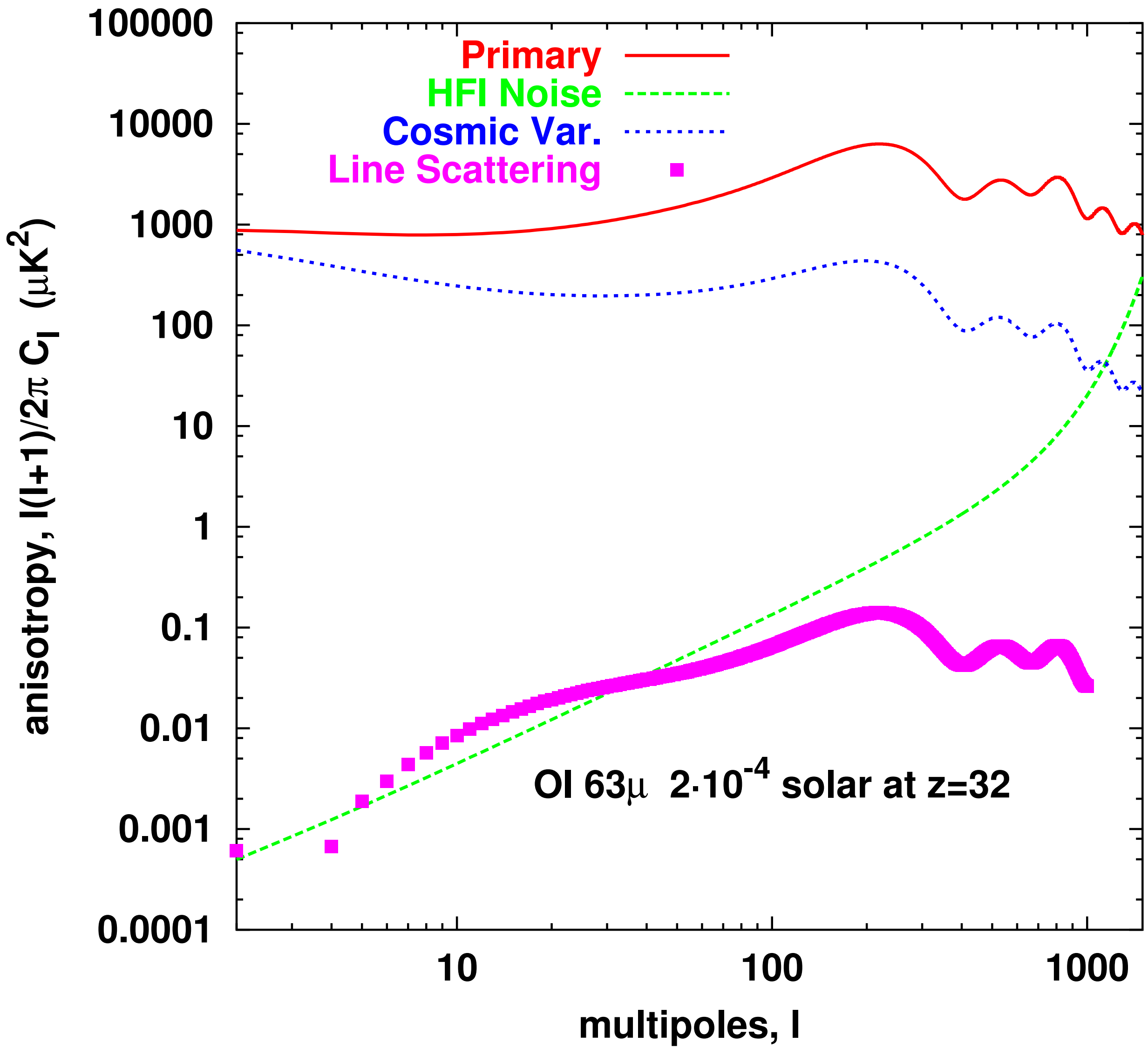
- Focusing on Planck HFI, also ACT, SPT, APEX...
- *Frequency dependent* optical depth (τ_ν) – different signal in different channels
- Possible to *avoid* the limit imposed by cosmic variance by comparing results from different channels
- Strong constraints on the abundance of scattering species ($10^{-2} - 10^{-4}$ 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

$$\text{[abundance]} \; \propto \; \tau_\nu \; \approx \; \frac{\delta C_l}{\mathcal{C}_1}$$

Formalism

Expected uncertainty in the obtained C_l-s

$$\sigma^2_{C_l} = \frac{2}{(2l+1)f_{sky}} \left(C_l + w^{-1} B_l^{-2}\right)^2$$

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

$$\sigma^2_{C_l} = \frac{2}{(2l+1)f_{sky}} \left(C_l + w^{-1}B_l^{-2}\right)^2$$

Subtracting the signal from two channels...

$$\sigma^2_{\delta C_l} = \frac{2}{(2l+1)f_{sky}} \left[\left(\delta C_l^{probe} + w^{-1}_{probe}B^{-2}_{l,probe}\right)^2 + \left(w^{-1}_{ref}B^{-2}_{l,ref}\right)^2\right]$$

gives minimum detectable abundance

$$[X_i]_{min} \sim \left(\tau_{X_i}\right)_{min} \simeq \frac{\sigma_{\delta C_l}}{\mathcal{C}_1}$$

Minimum abundances

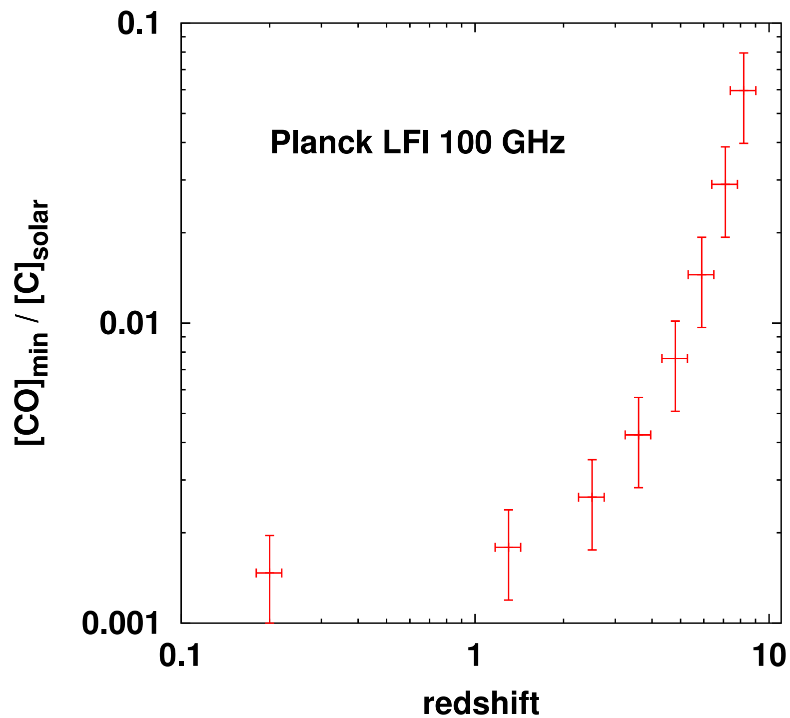
Minimum detectable abundance for selected atoms and ions

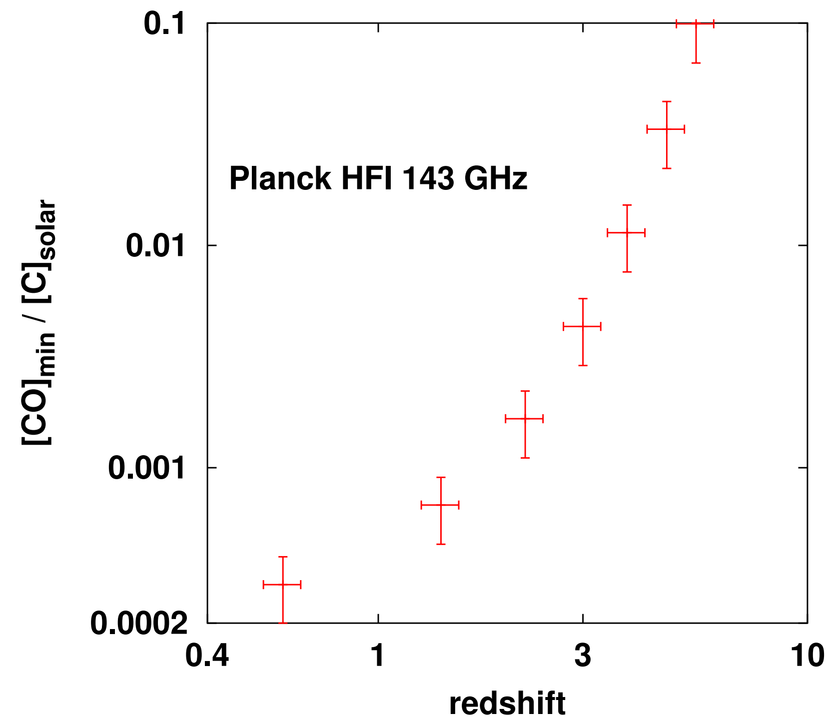
Atom / Ion	Fine-Str. line	HFI freq. (GHz)	Scattering redshift	Opt. depth for 10^{-2} Sol. abun.	Min. Abundance detectable (solar)
C II	157.74μ	143	12.3	1.6×10^{-5}	6.2×10^{-3}
		217	7.9	1.1×10^{-5}	3.0×10^{-3}
		353	4.4	5.6×10^{-6}	3.6×10^{-2}
N II	205.30μ	143	9.2	8.9×10^{-6}	2.6×10^{-3}
		217	5.8	6.5×10^{-6}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

Minimum abundances

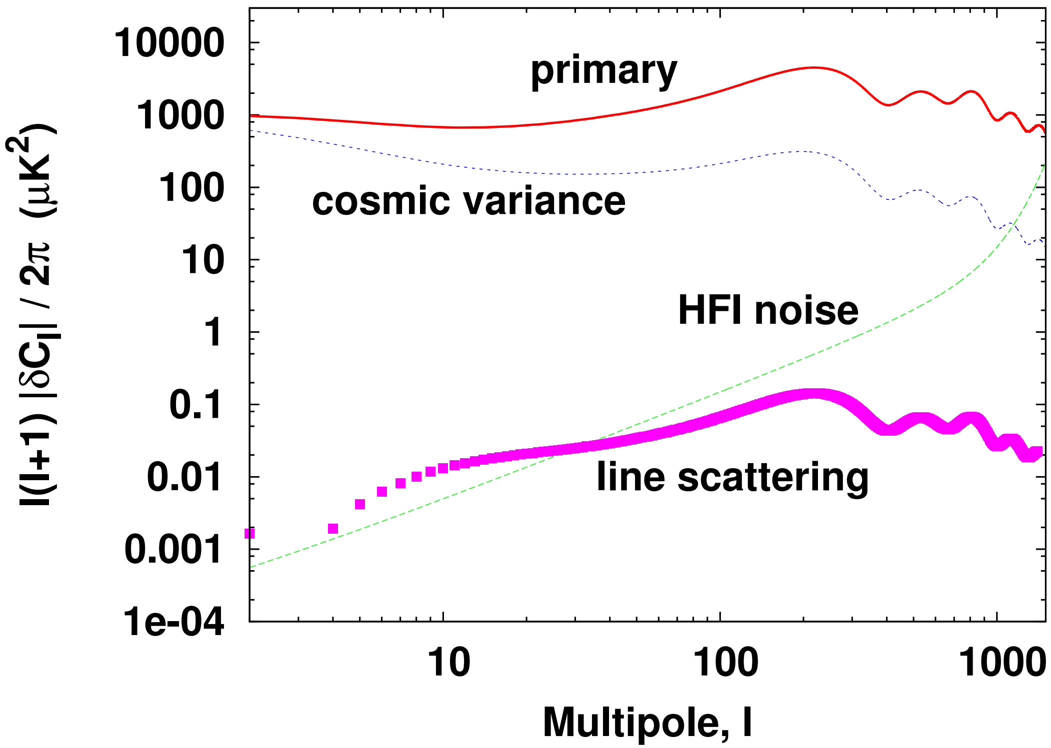
Minimum detectable abundance for CO molecules with LFI 100 GHz

J′→J″	Wavelength (μ)	z Scatter.	τ for $10^{-2}[C]_\odot$	Min. Abundance
$0 \to 1$	2600.78	0.2	4.6×10^{-5}	2.3×10^{-3}
$1 \to 2$	1300.41	1.3	9.0×10^{-5}	2.0×10^{-3}



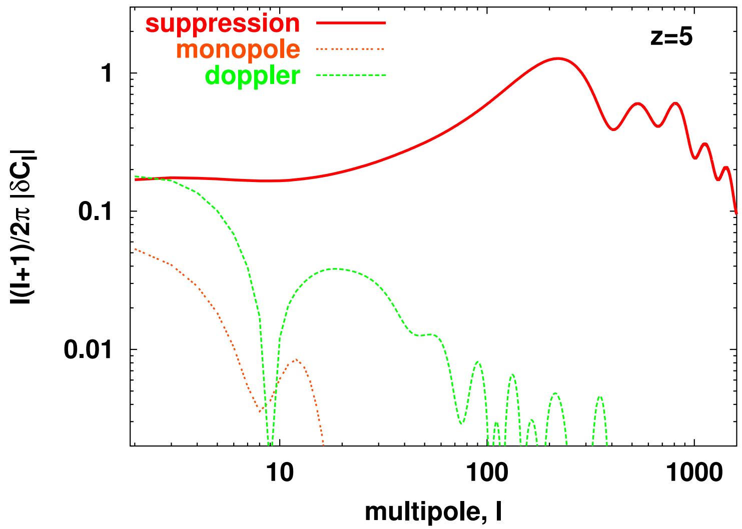


Nature of distortions

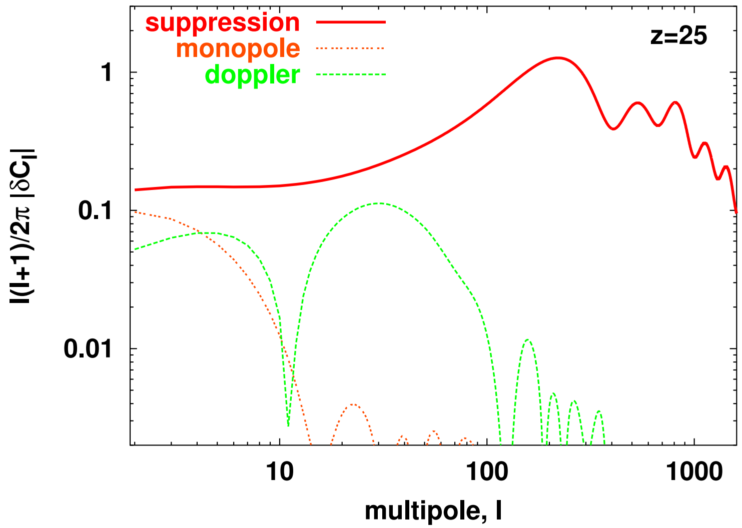


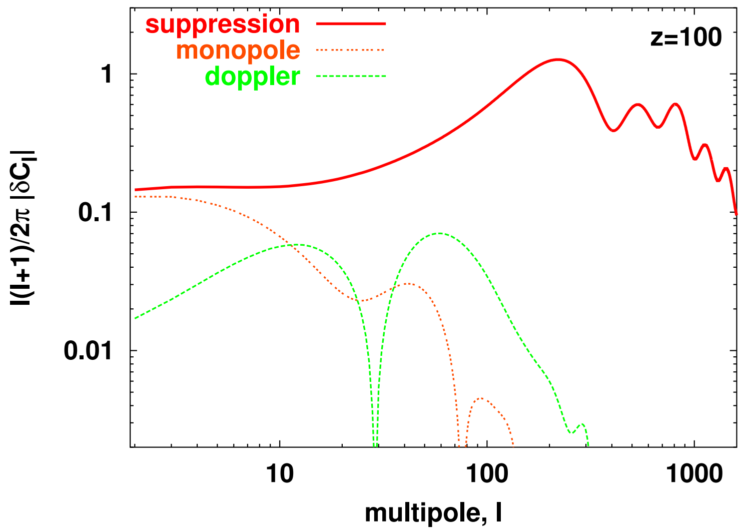
The resultant temperature anisotropy is a combination of suppression and generation terms...

Nature of distortions



Velocity term grows with time, monopole term dies





The suppression term remains the same

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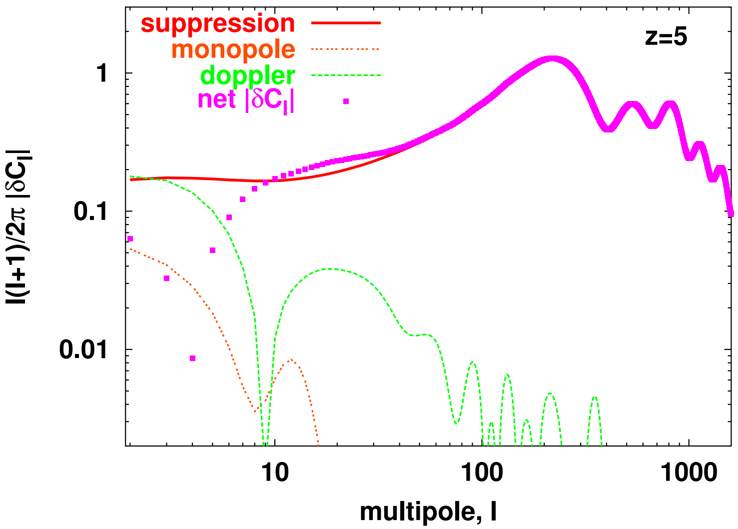

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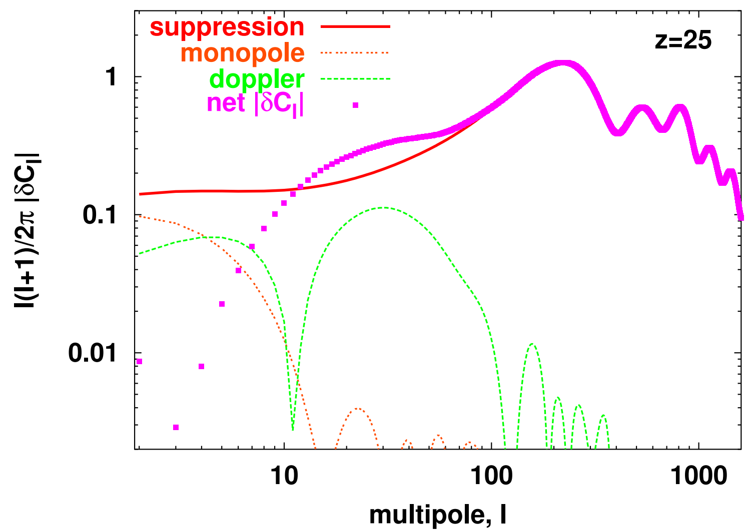
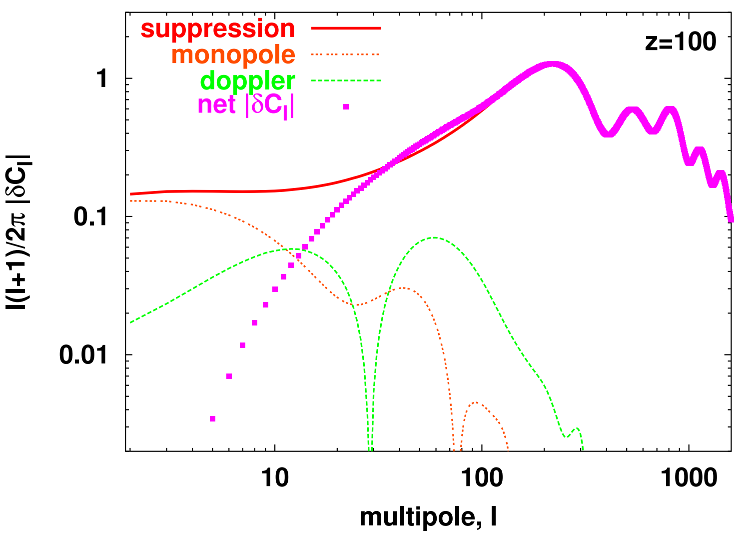
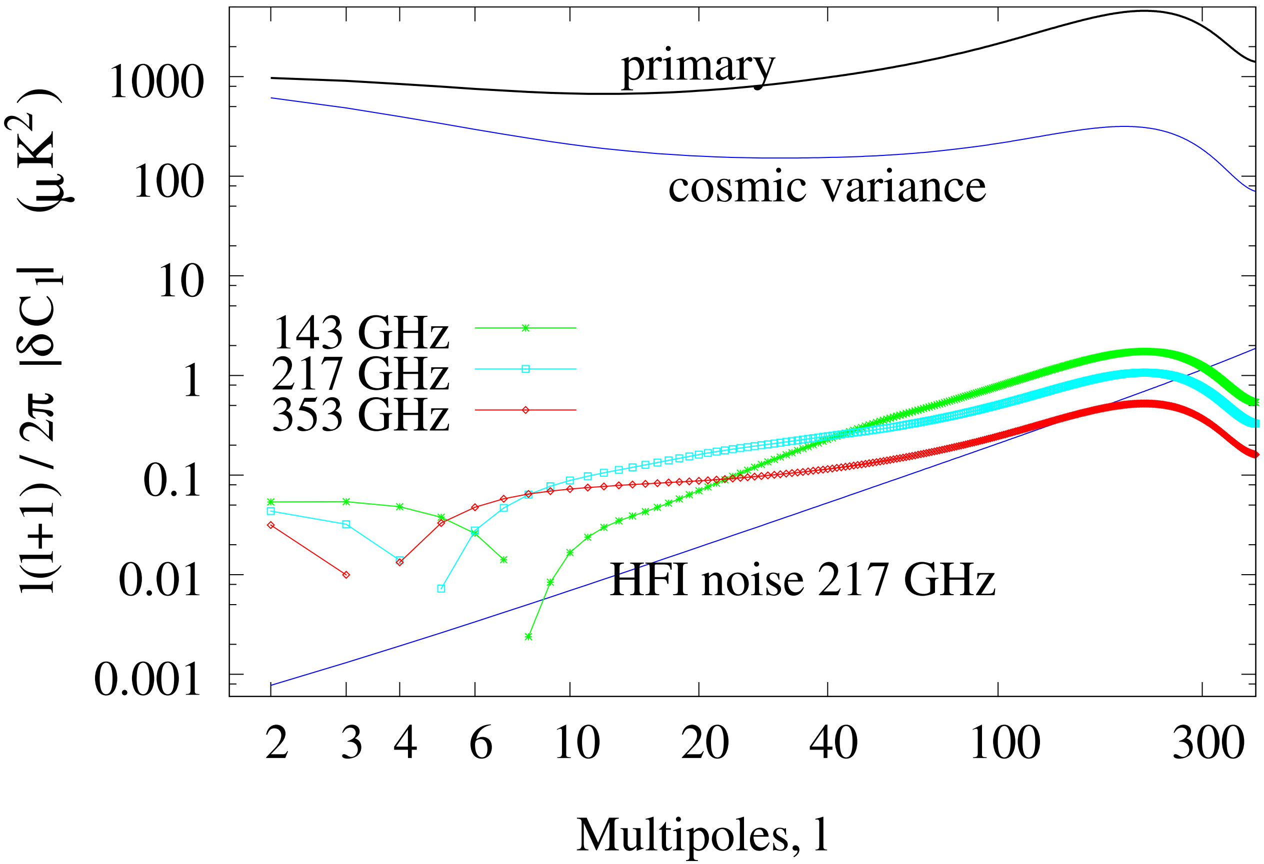




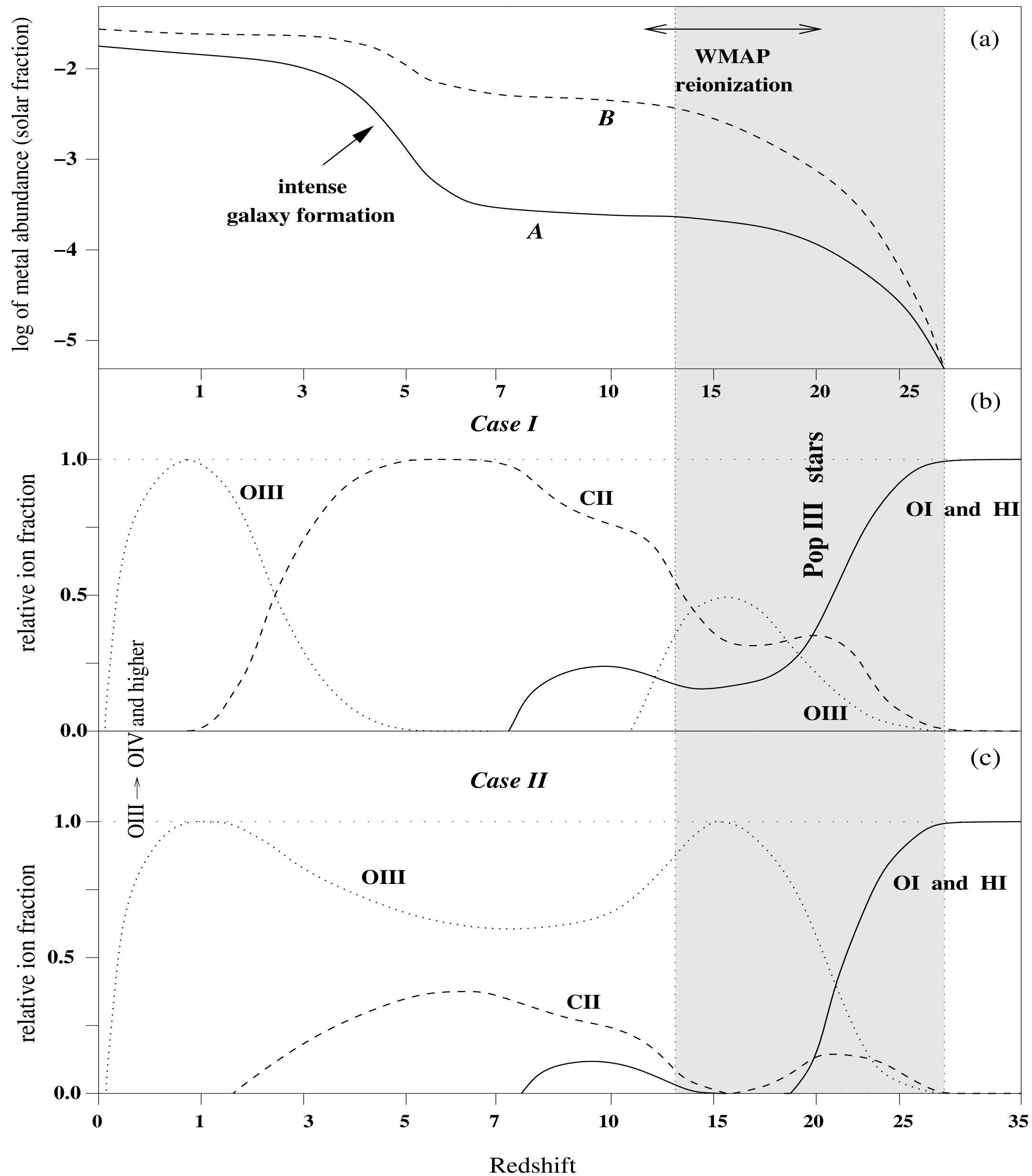
The suppression term remains the same

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

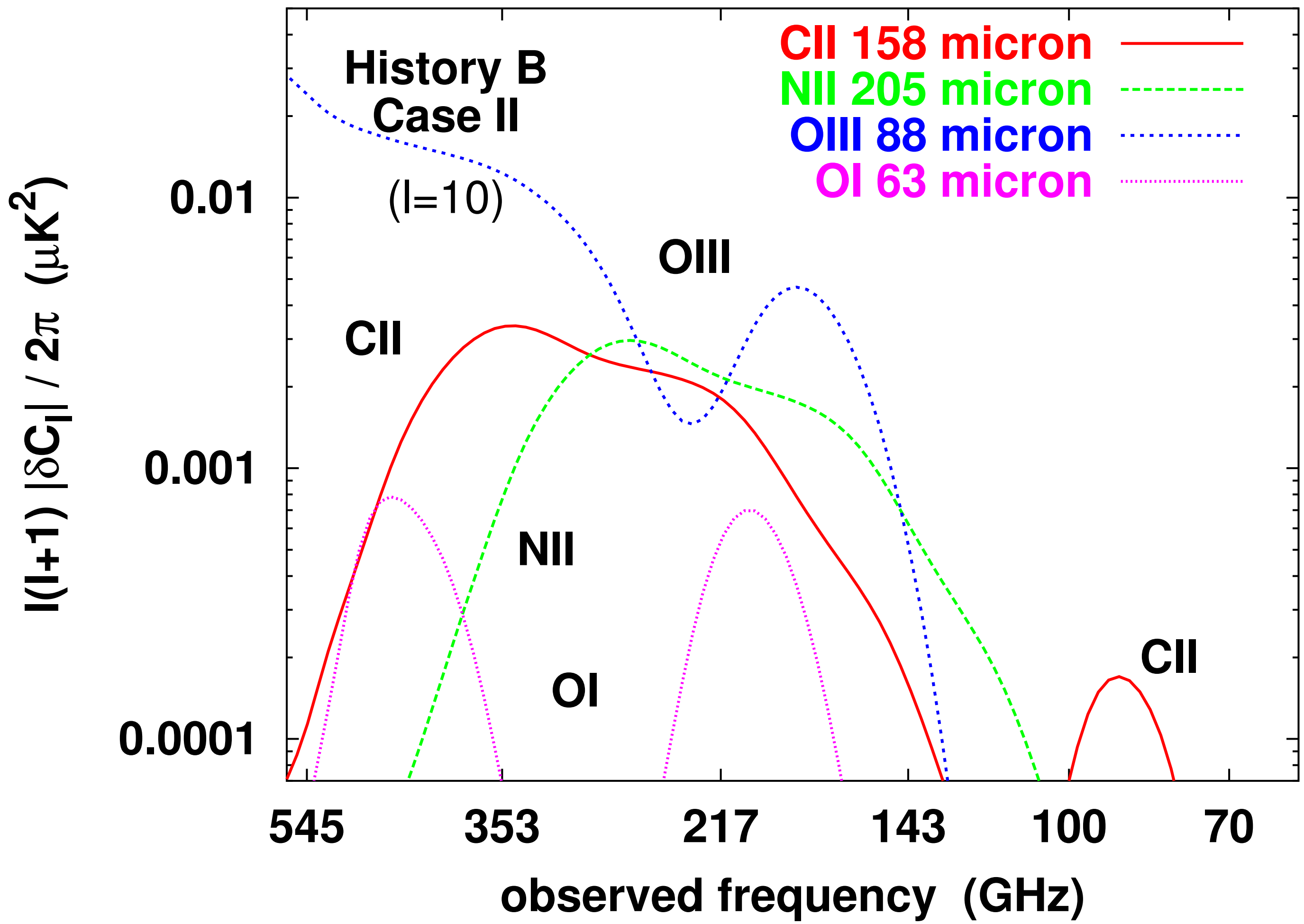


Two levels of mean metallicity: A (conservative) and B (optimistic)

Reionization by relatively cold stars ⇒ more CII

...and by hot stars and quasars ⇒ more OIII

Ionization & enrichment histories



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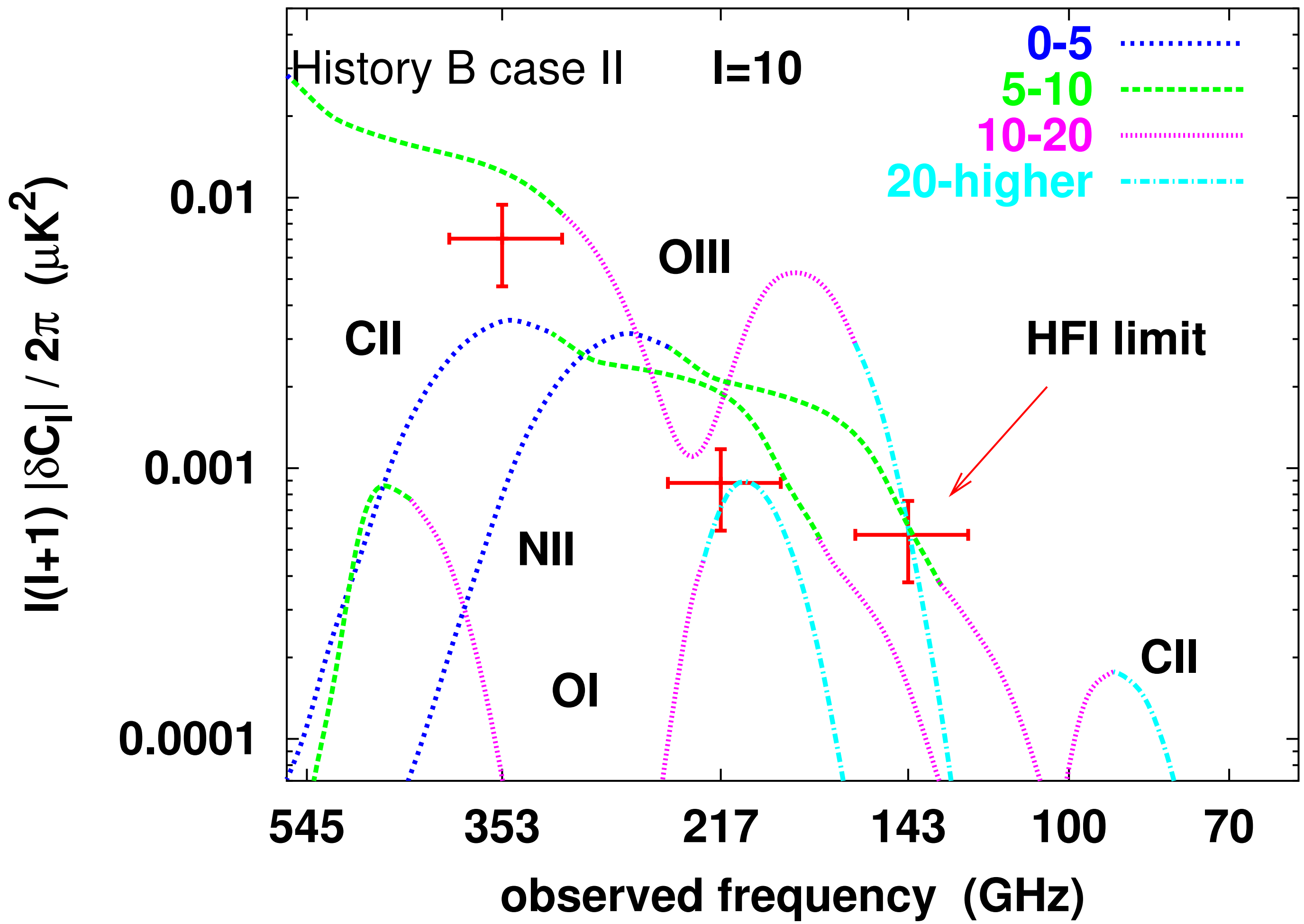

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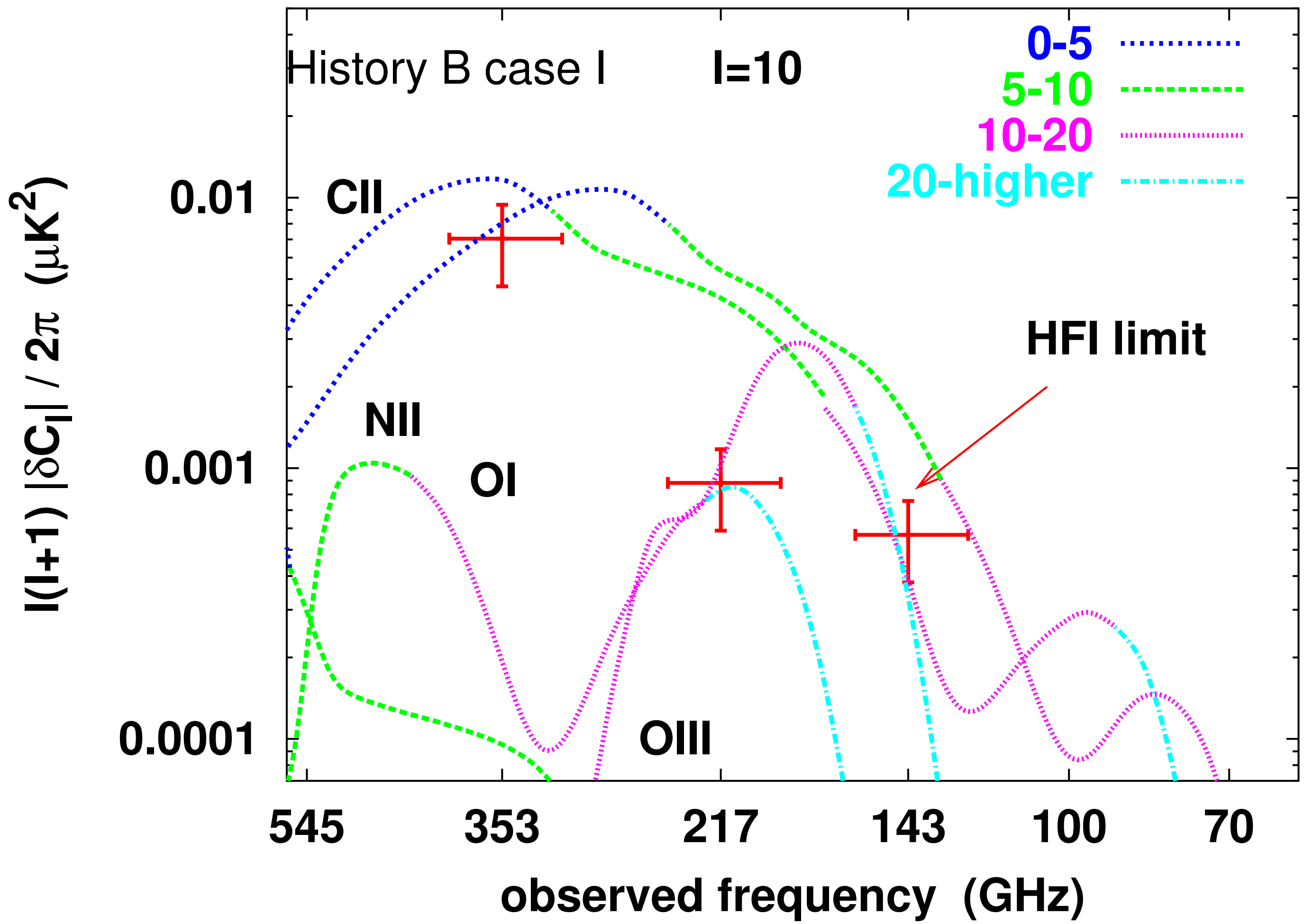

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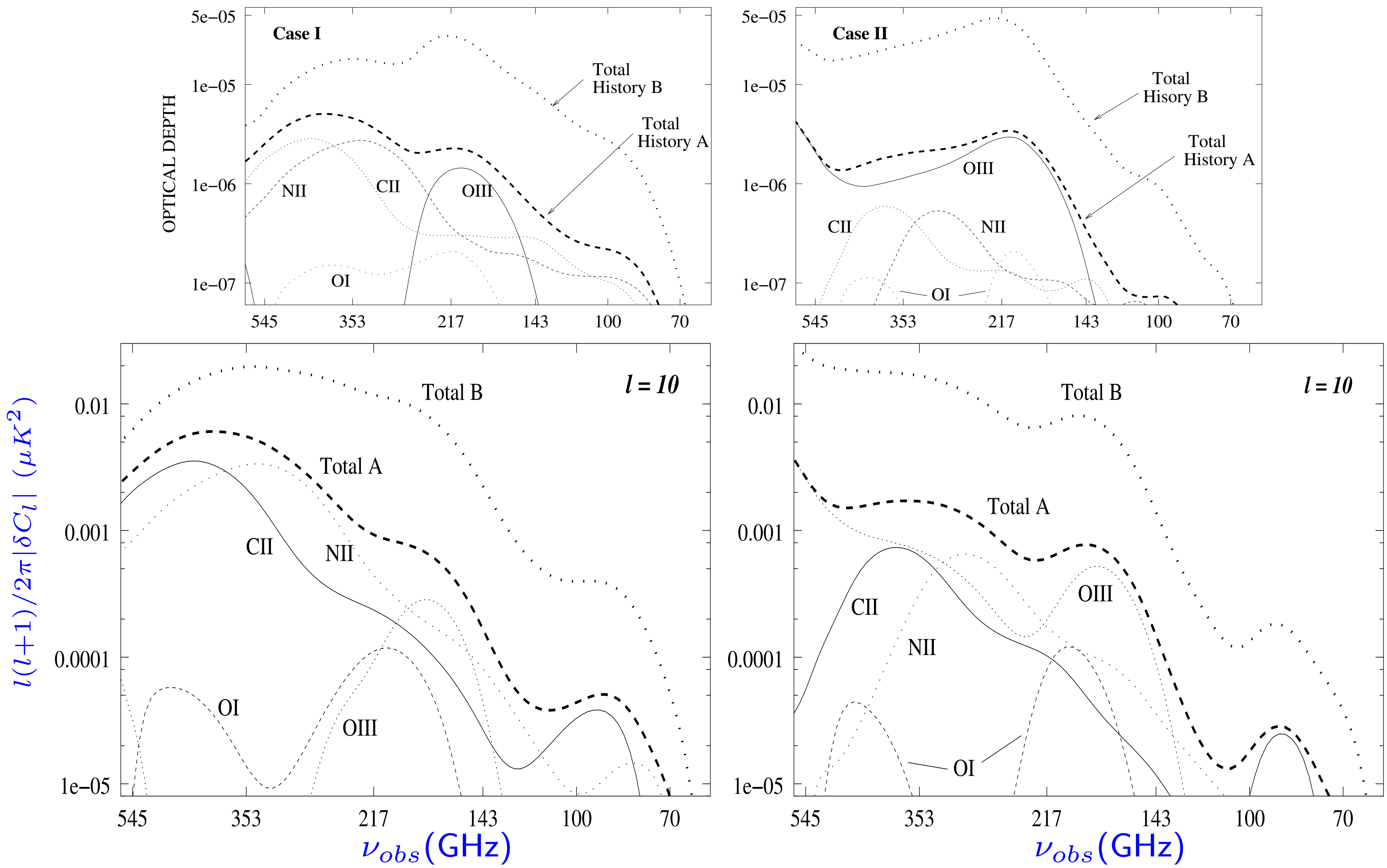

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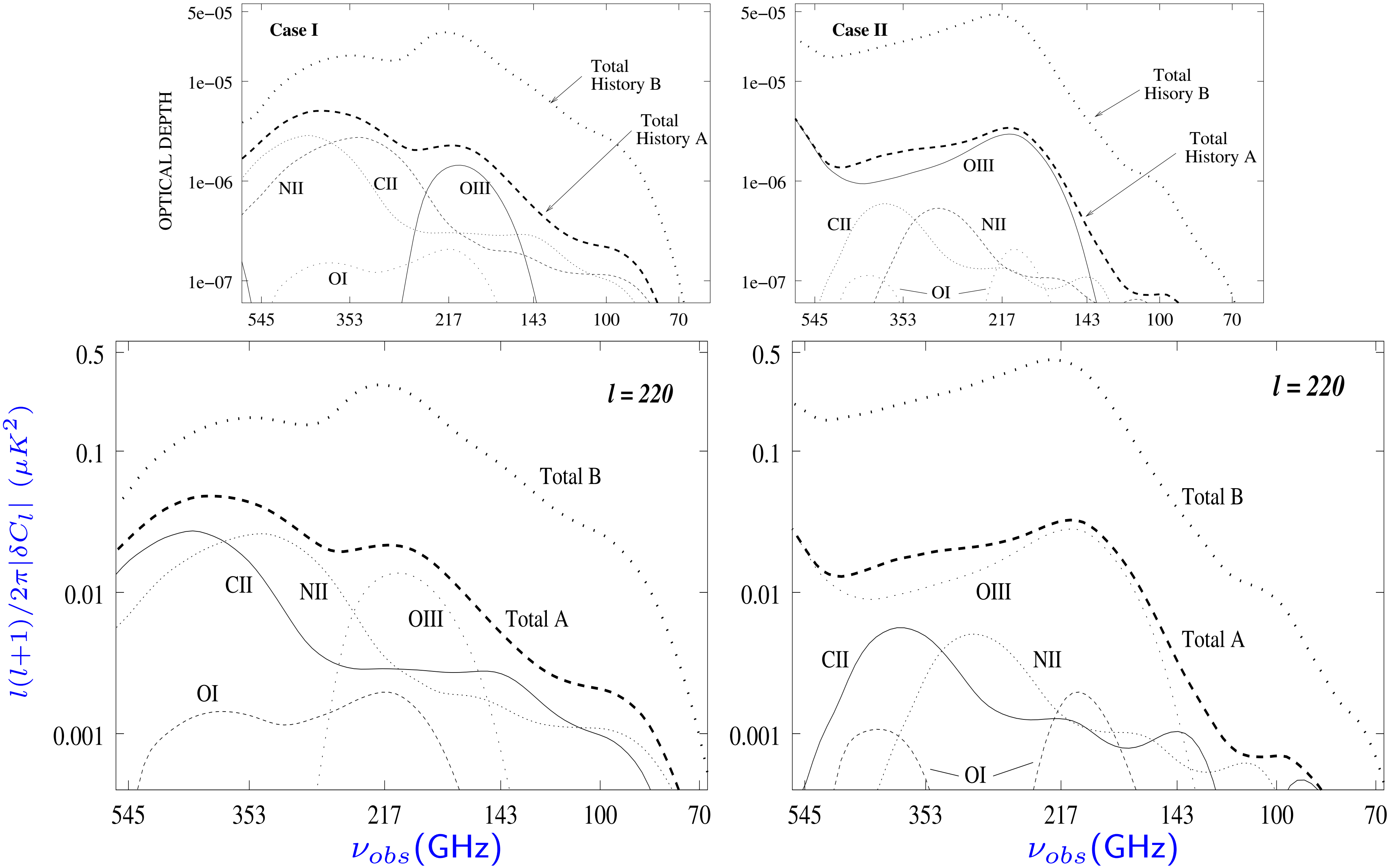

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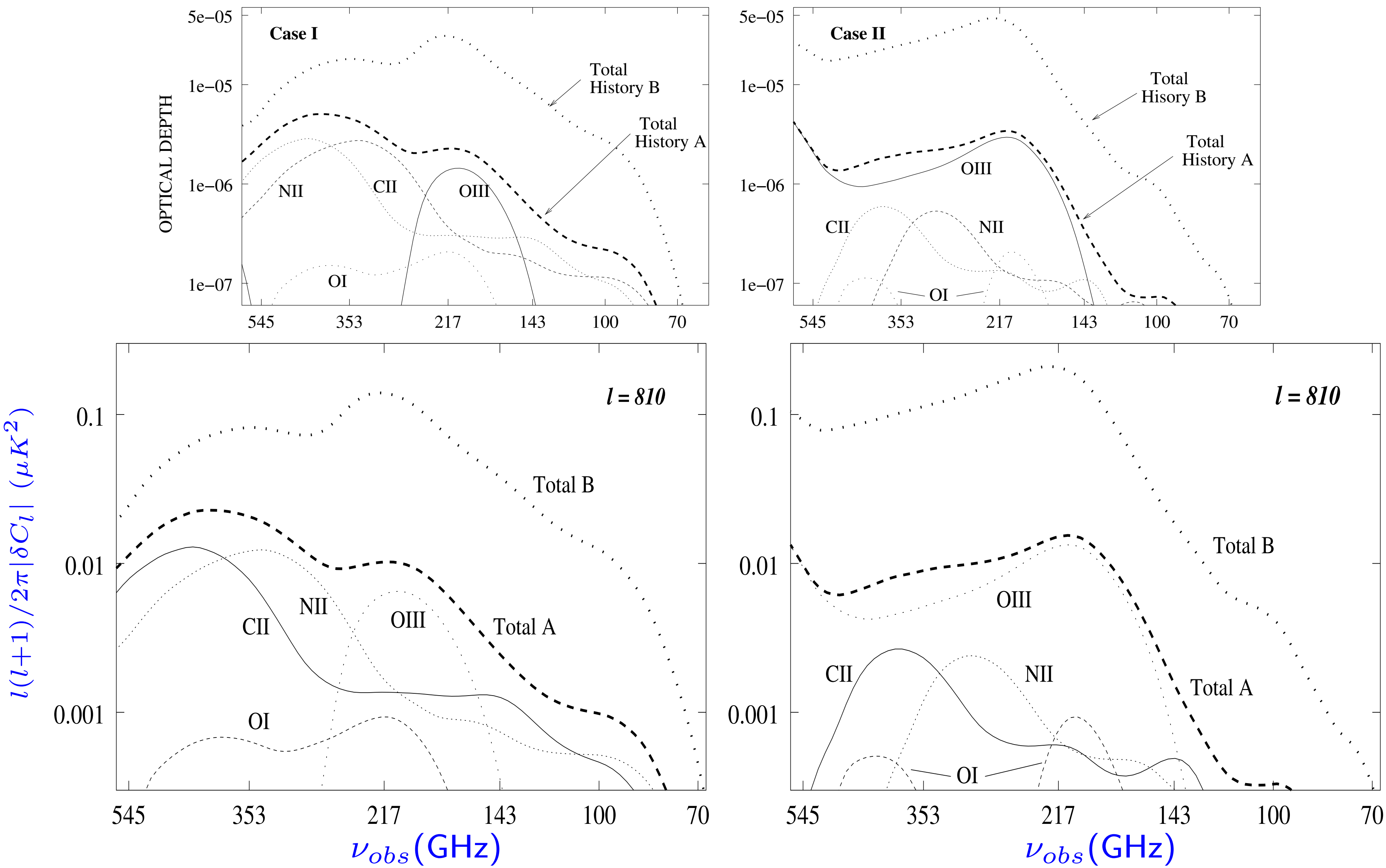
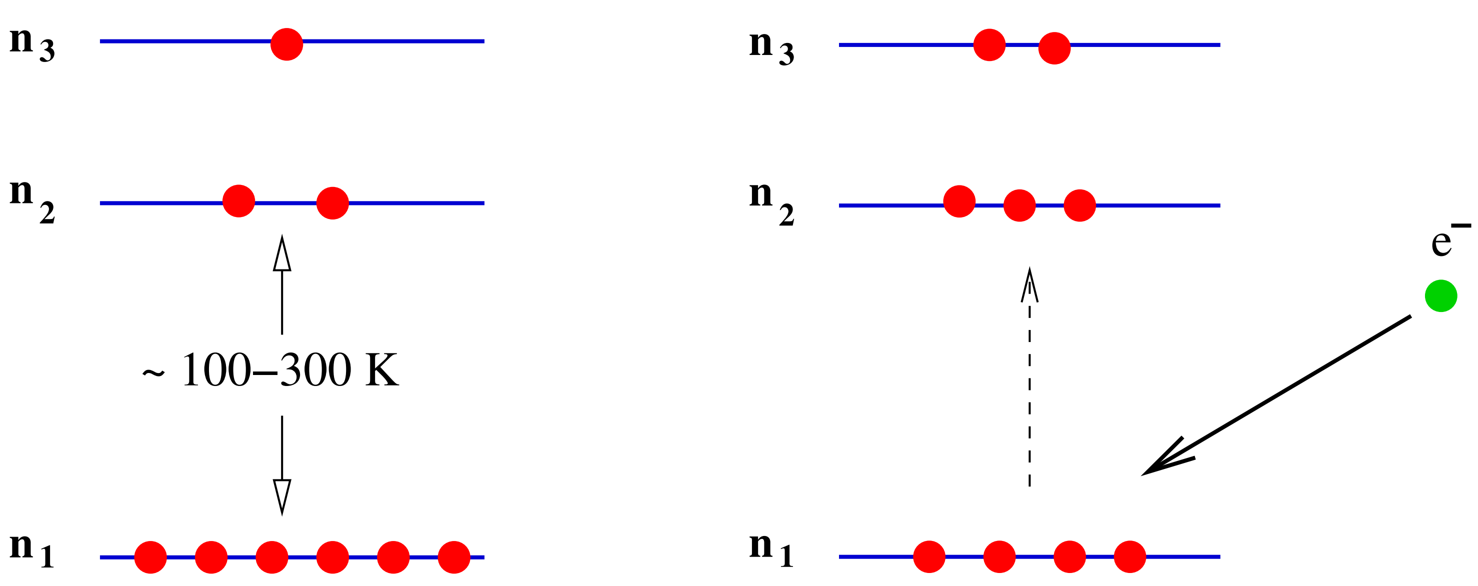
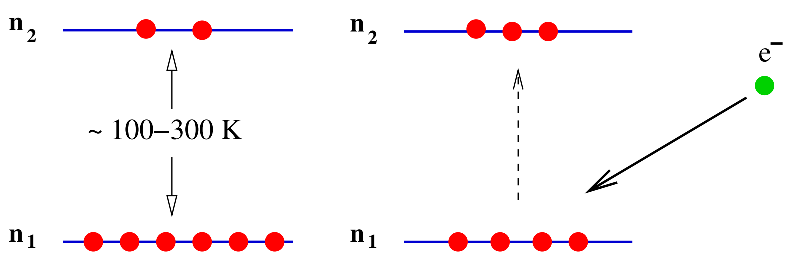


Effect of overdensity



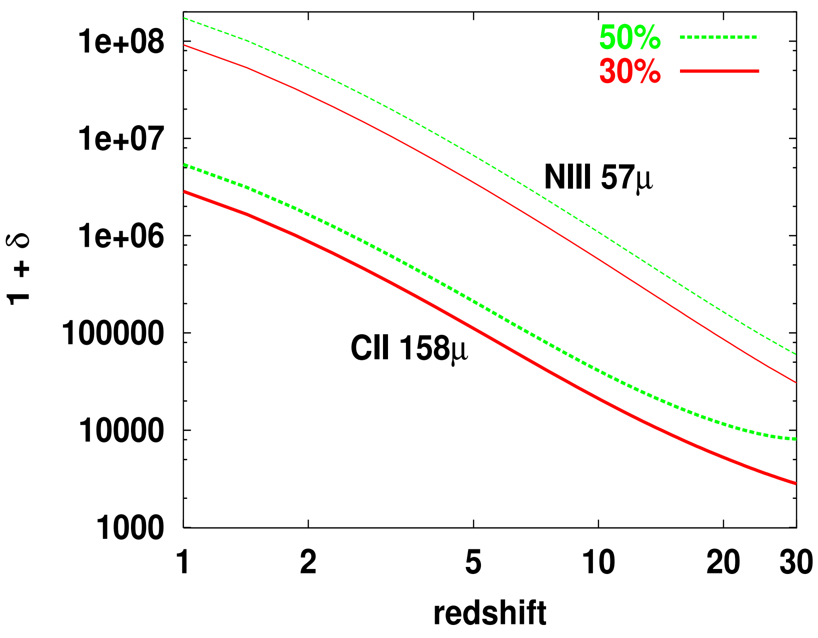
If density is high, collision with electrons (also H, He,..) will *reduce* the number of atoms/ions in the ground level, thereby decreasing the optical depth in scattering

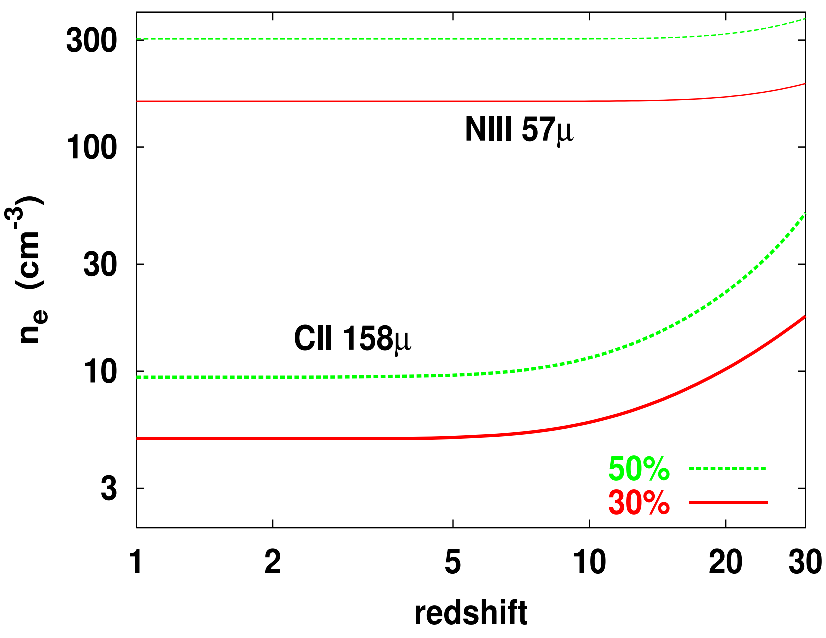
Effect of overdensity



For a two-level system:

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





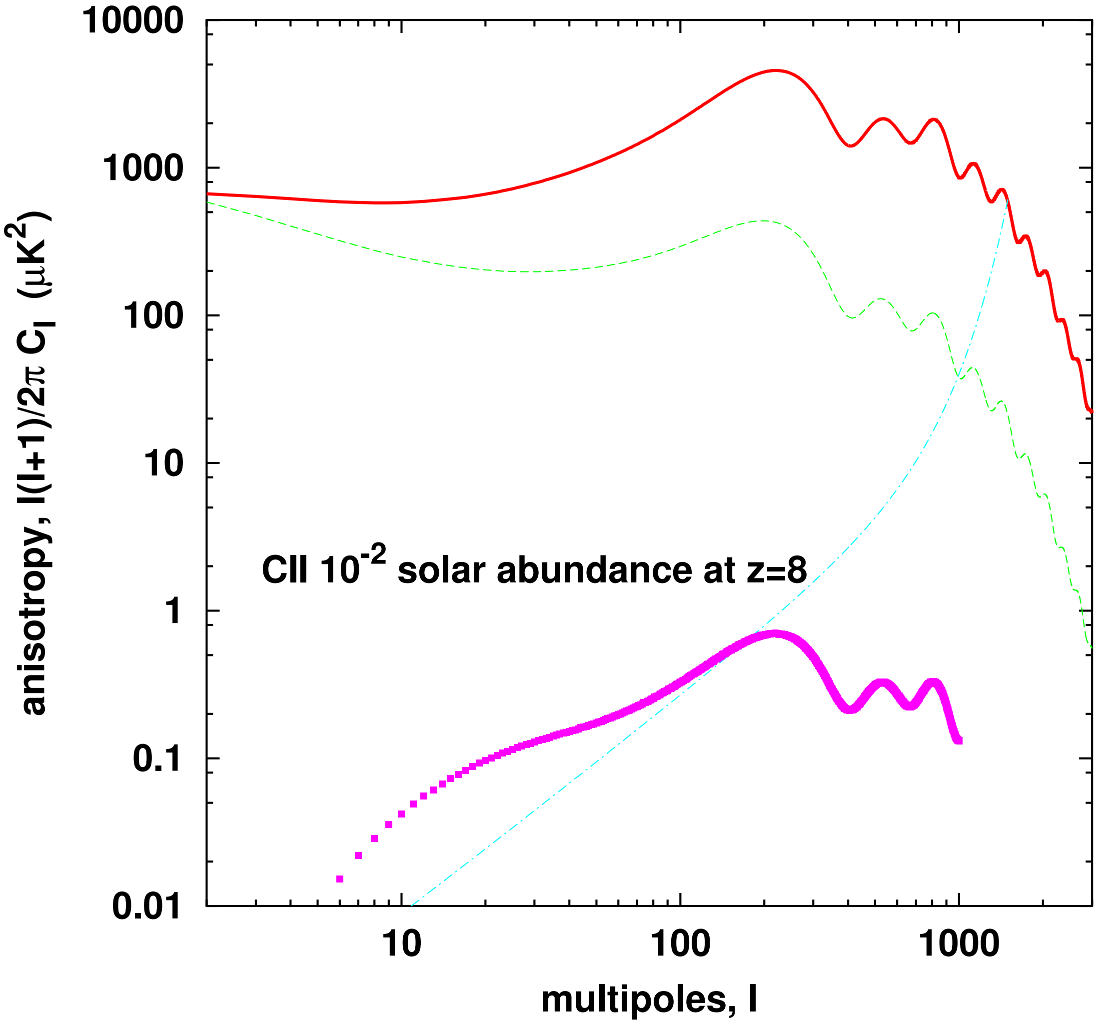
Effect of overdensity

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



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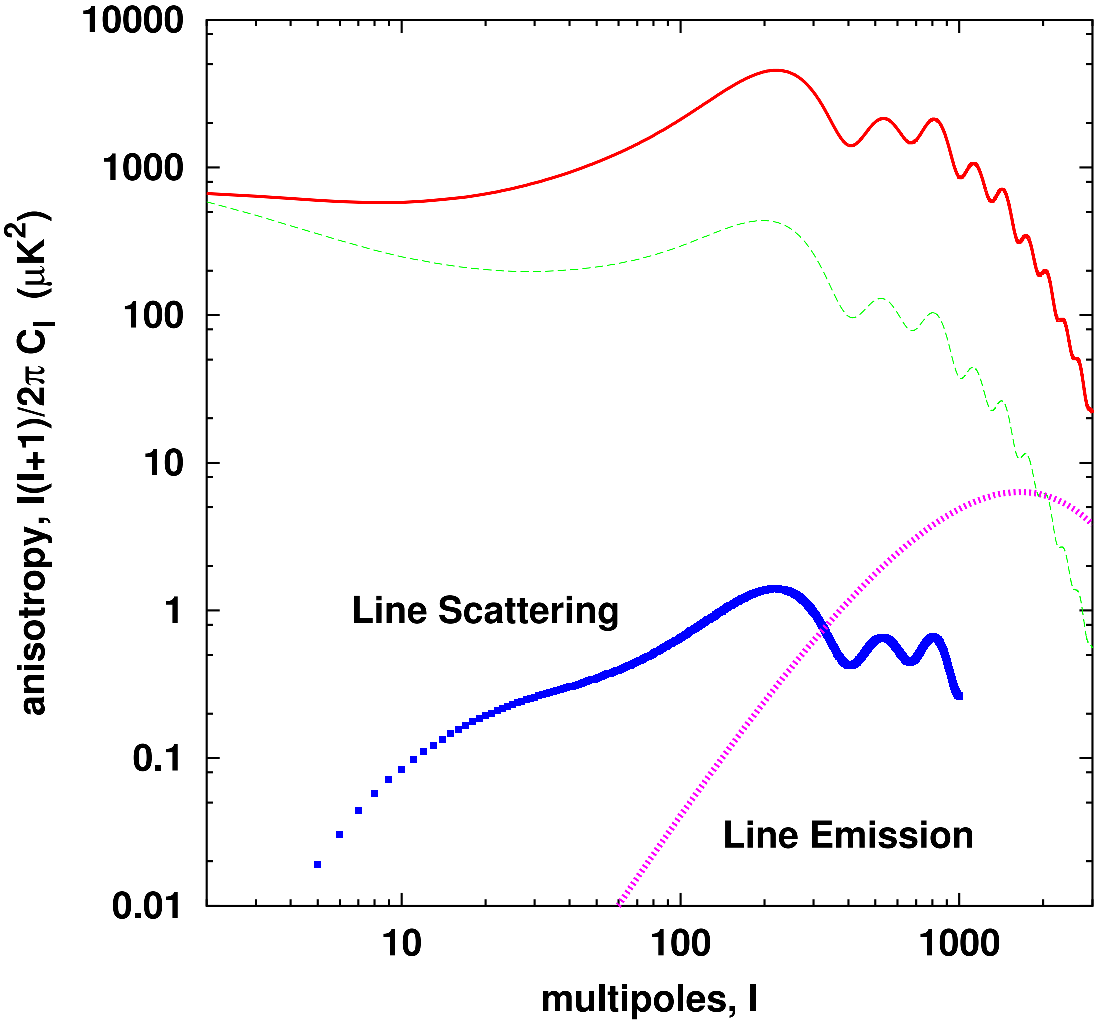
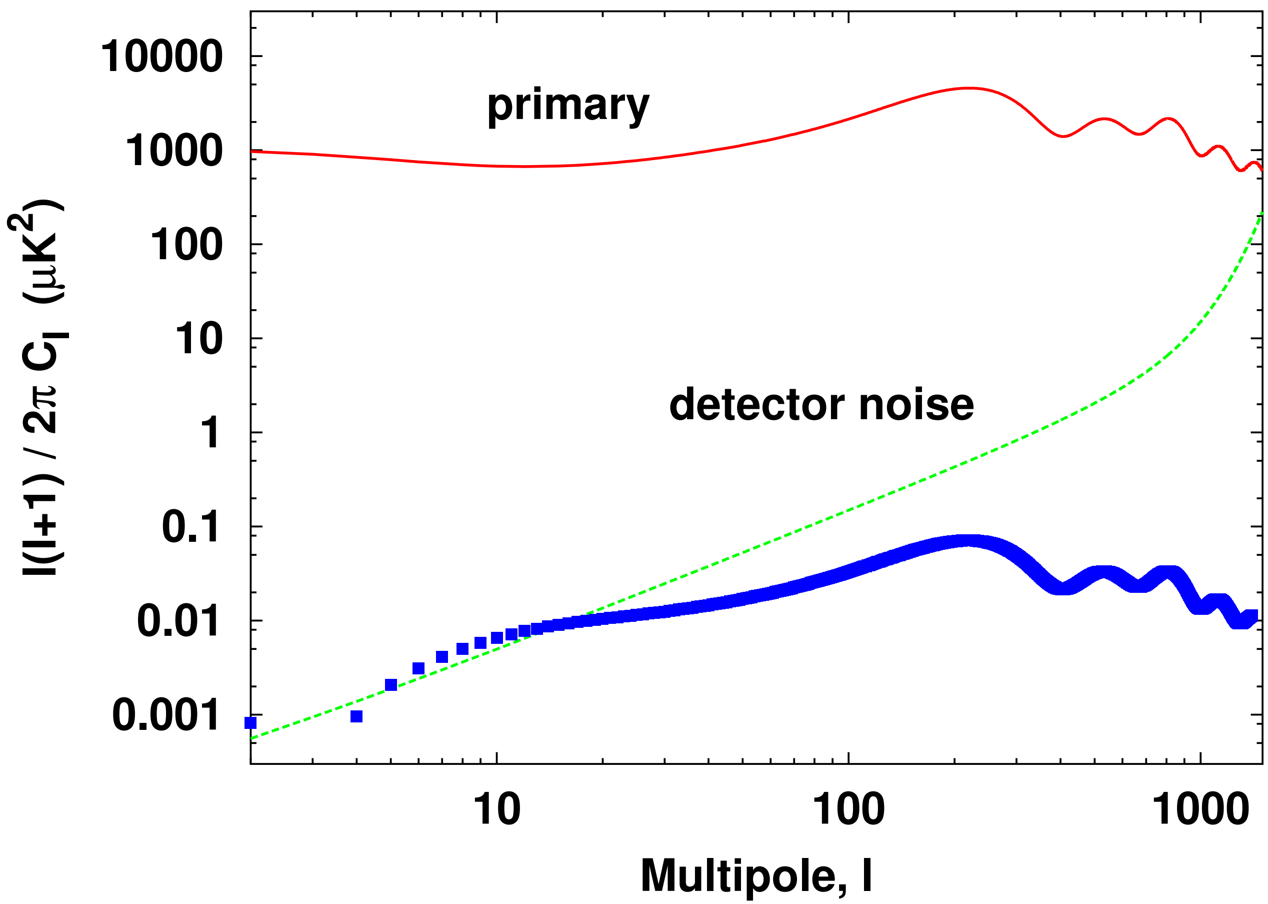
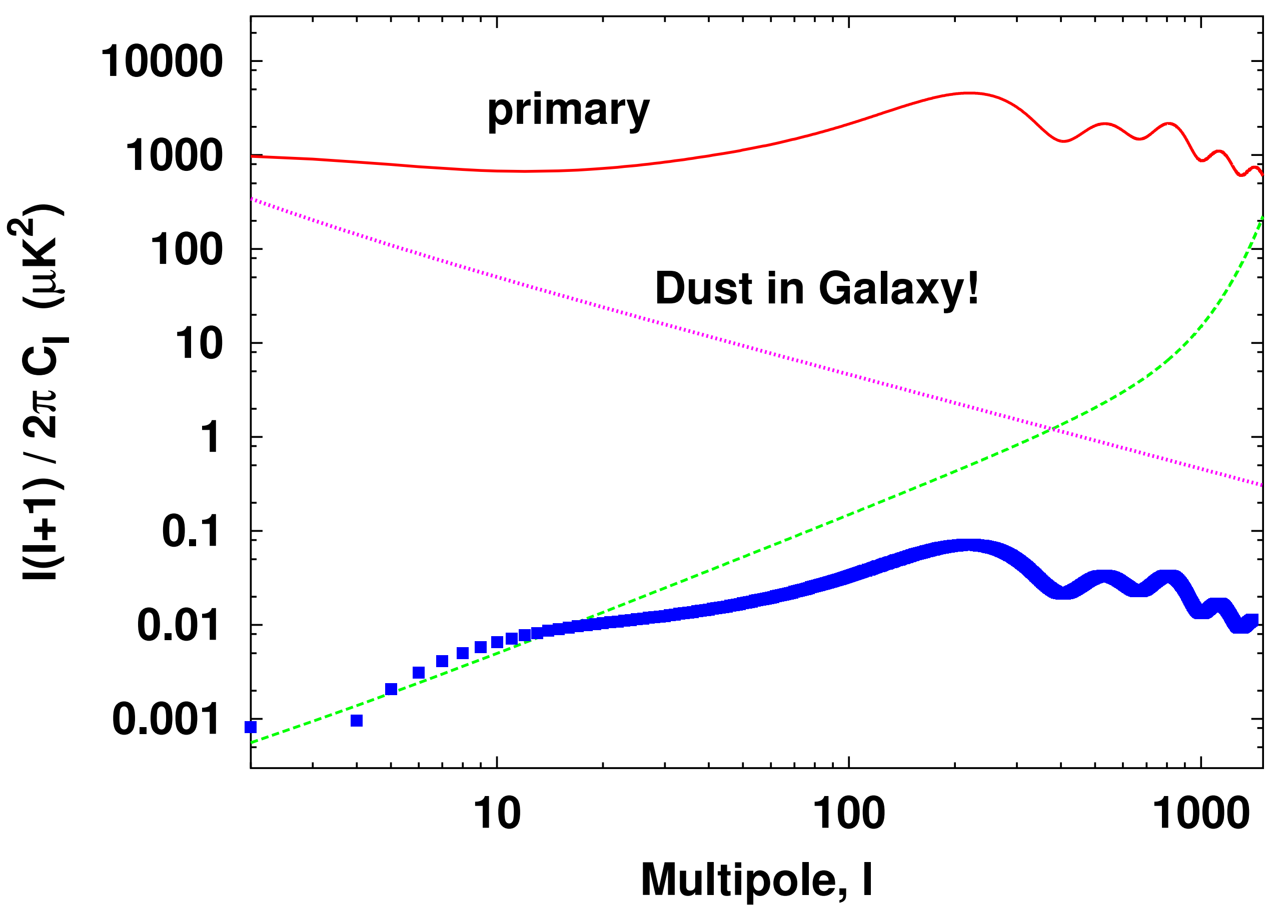


Effect of foregrounds



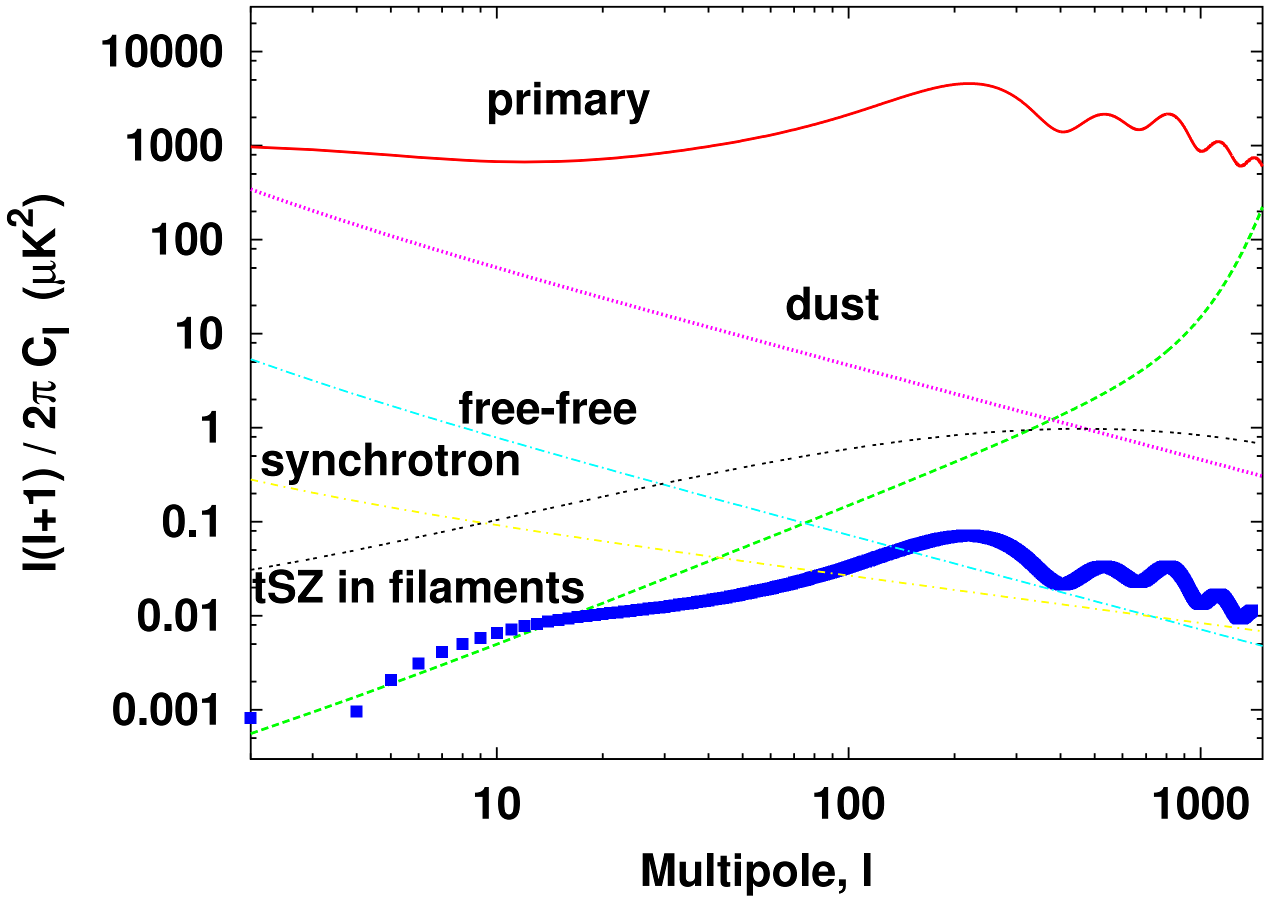
The picture is not so simple because of foregrounds!

Effect of foregrounds



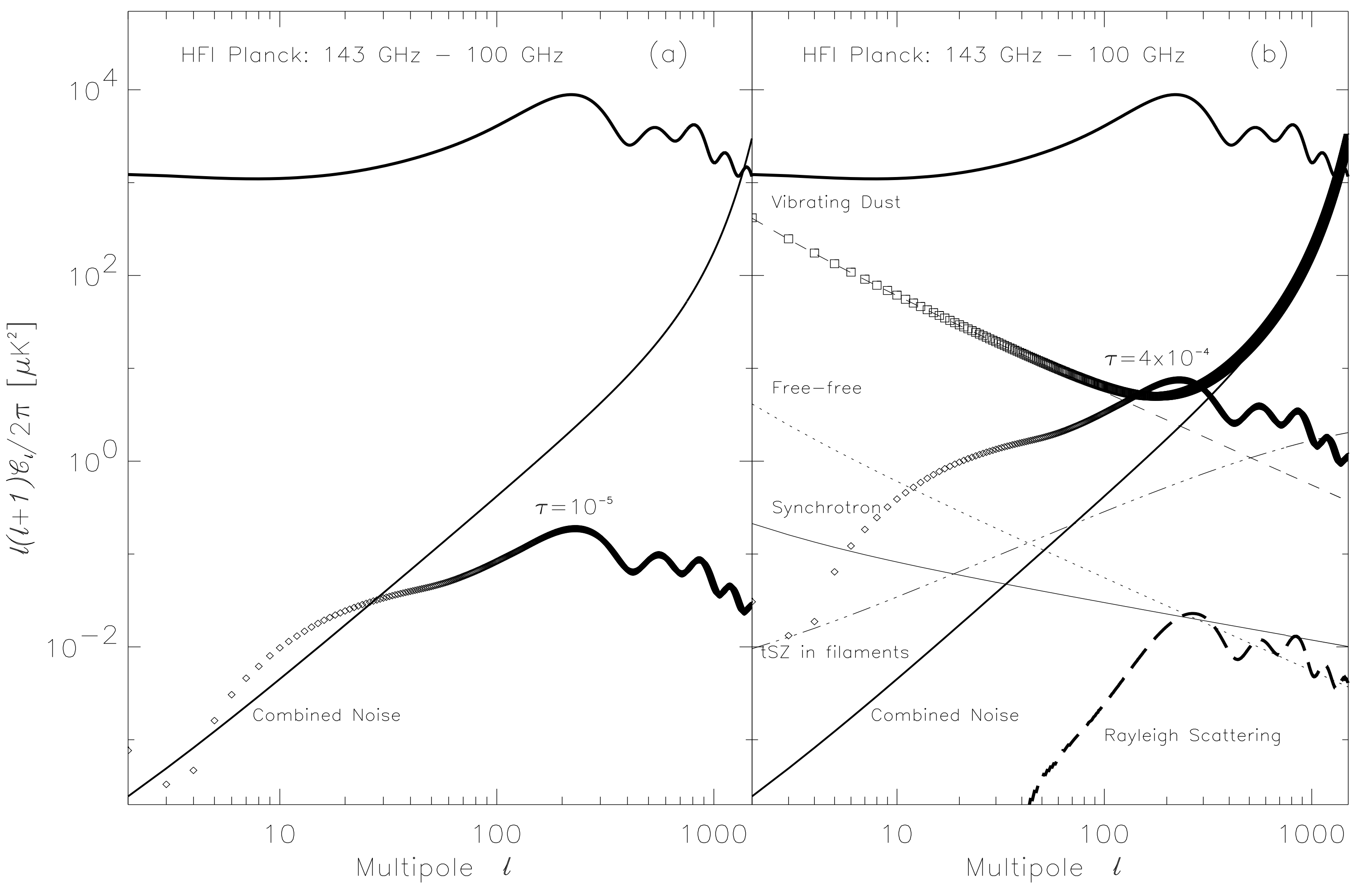
At high frequencies thermal radiation from Galactic dust dominates

Effect of foregrounds



Various other Galactic & extra-galactic foregrounds

Effect of foregrounds



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