Imprints on the CMB from the dark ages

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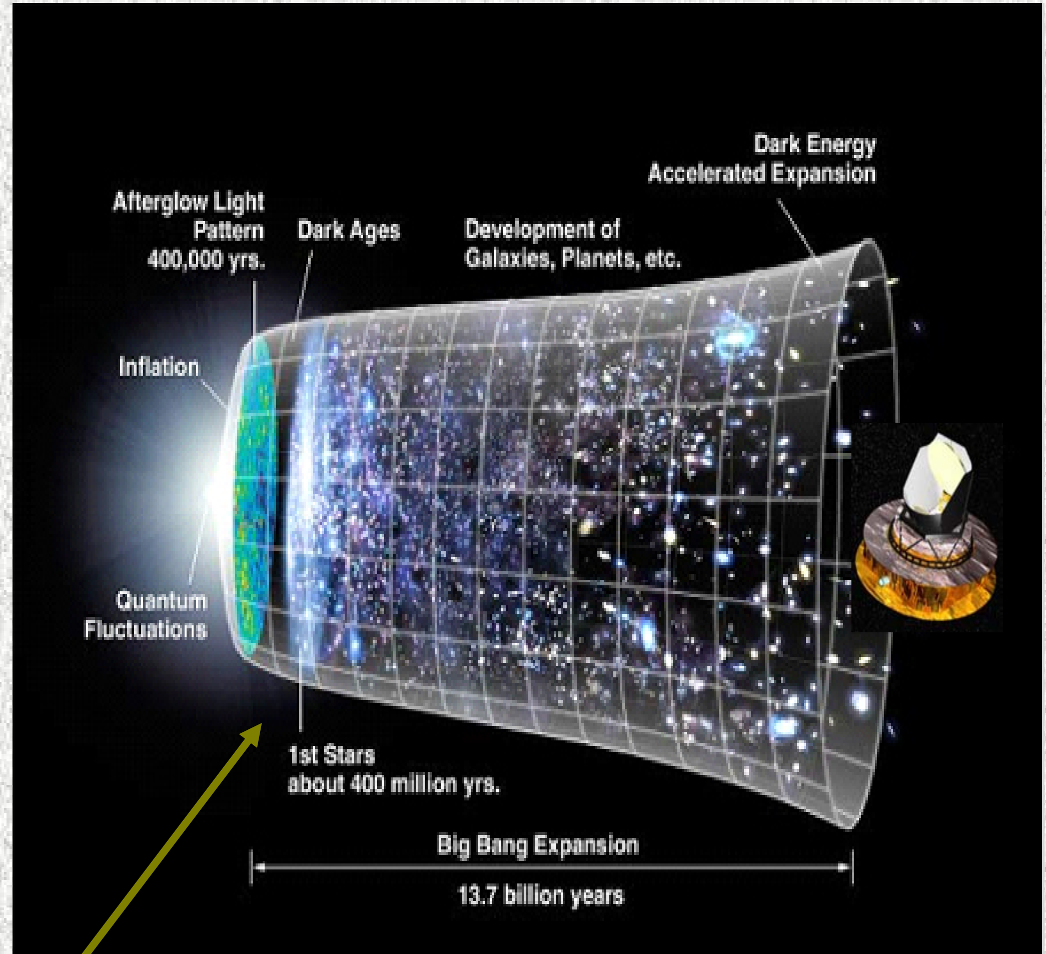
Outline

• *Standard* CMB secondary anisotropies generated during the end of the dark ages and beginning of reionization

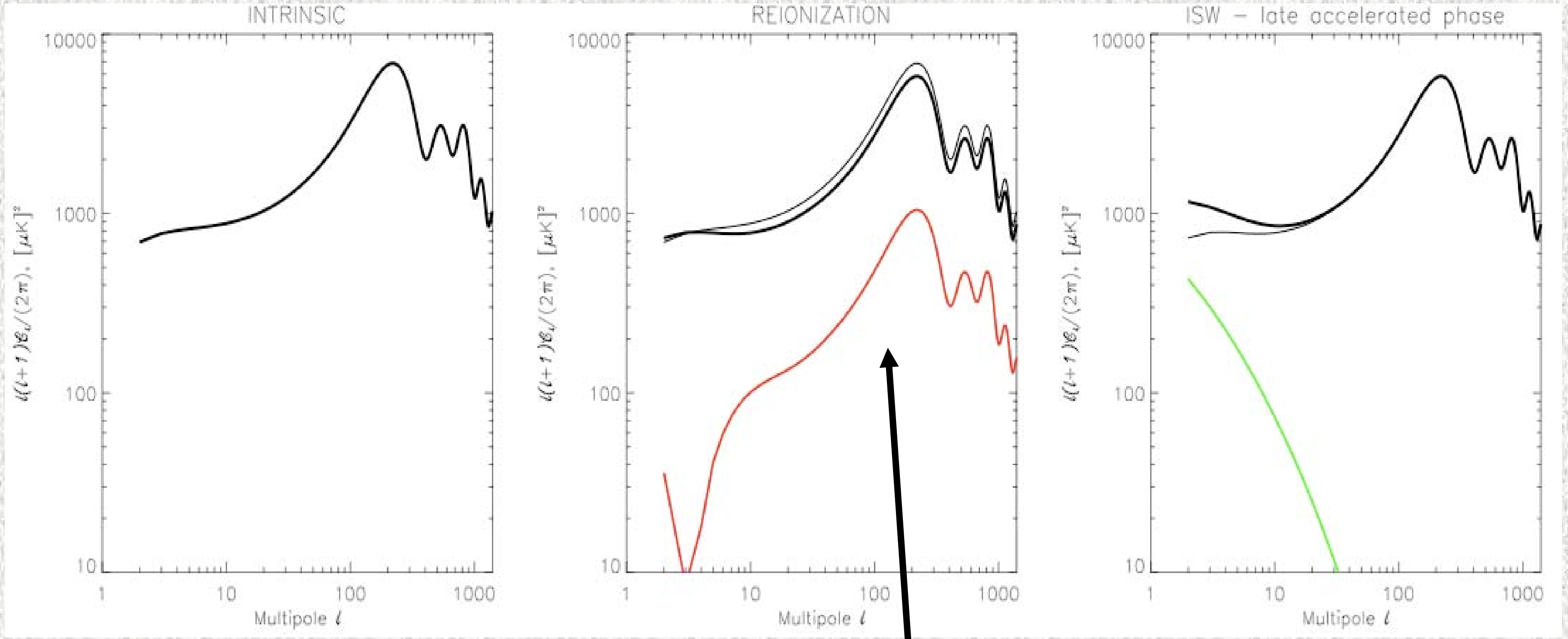
• Physics of the resonant scattering of CMB photons off metallic resonant transitions

• Collisional emission in rotational levels of CO molecules at moderate to high redshift

• The Wouthuysen-Feld effect in OI: UV induced CMB distortion in the 63μ OI transition



Let us focus on ***Reionization***...



$\delta C_l \approx - 2\, \tau_T\, C_l$

Biggest effect is ***frequency independent...***

FREQUENCY DEPENDENT SECONDARY EFFECTS DURING REIONIZATION:

Effects preserving the CMB black body spectrum:

* Resonant scattering on fine structure ***lines*** of ions, metals and molecules

*Effects **distorting** the CMB black body spectrum:*

* Collisional emission on fine structure ***lines*** of ions, metals and molecules
* Wouthuysen-Field effect (UV pumping) in OI 63.2 micron ***transition***
* Reprocessed UV emission in the microwave range by dust particles

The presence of LINES in the CMB:

- If a given species X has a resonant transition with a given resonant frequency, the observed CMB will interact with that species at a redshift

$$\nu_{X_i}/\nu_{obs} = 1 + z_{X_i}$$

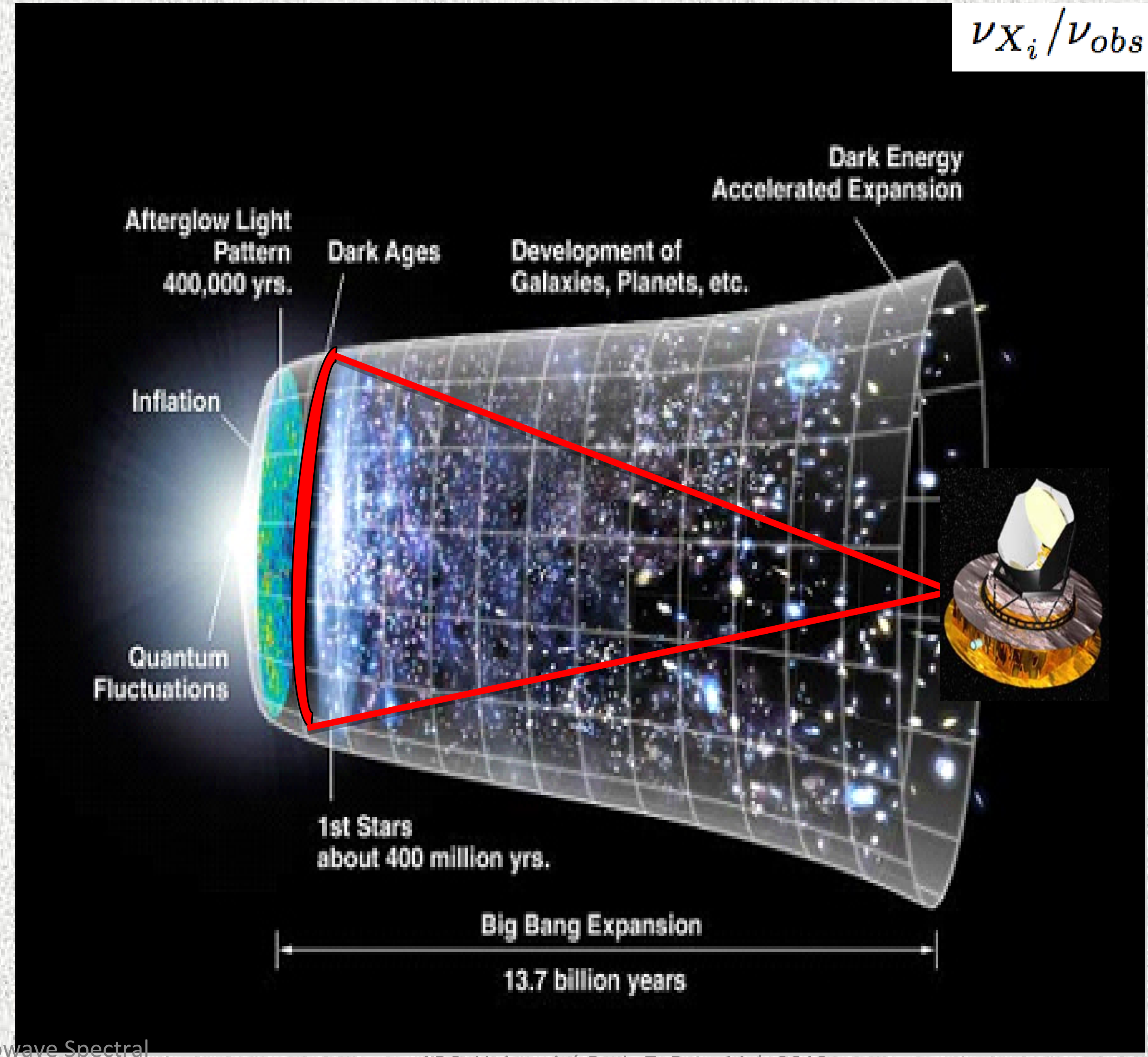
- In *multifrequency* experiments like Planck, a low frequency channel can be used as ***reference***, since it will probe ***highest redshifts*** (for which the species ***abundance*** should be ***lowest***)

$$\tau_{X_i}(z) = f_i \; \frac{\pi e^2}{m_e c} \frac{\lambda_i n_{X_i}(z)}{H(z)}$$

- By changing the observing frequency, one can perform ***tomography*** of the species during reionization

Basu, CHM & Sunyaev (A&A, 2004), CHM & Sunyaev (MNRAS, 2005), CHM, Rubiño-Martín & Sunyaev (A&A 2005), CHM, Verde & Jimenez (ApJ, 2006)

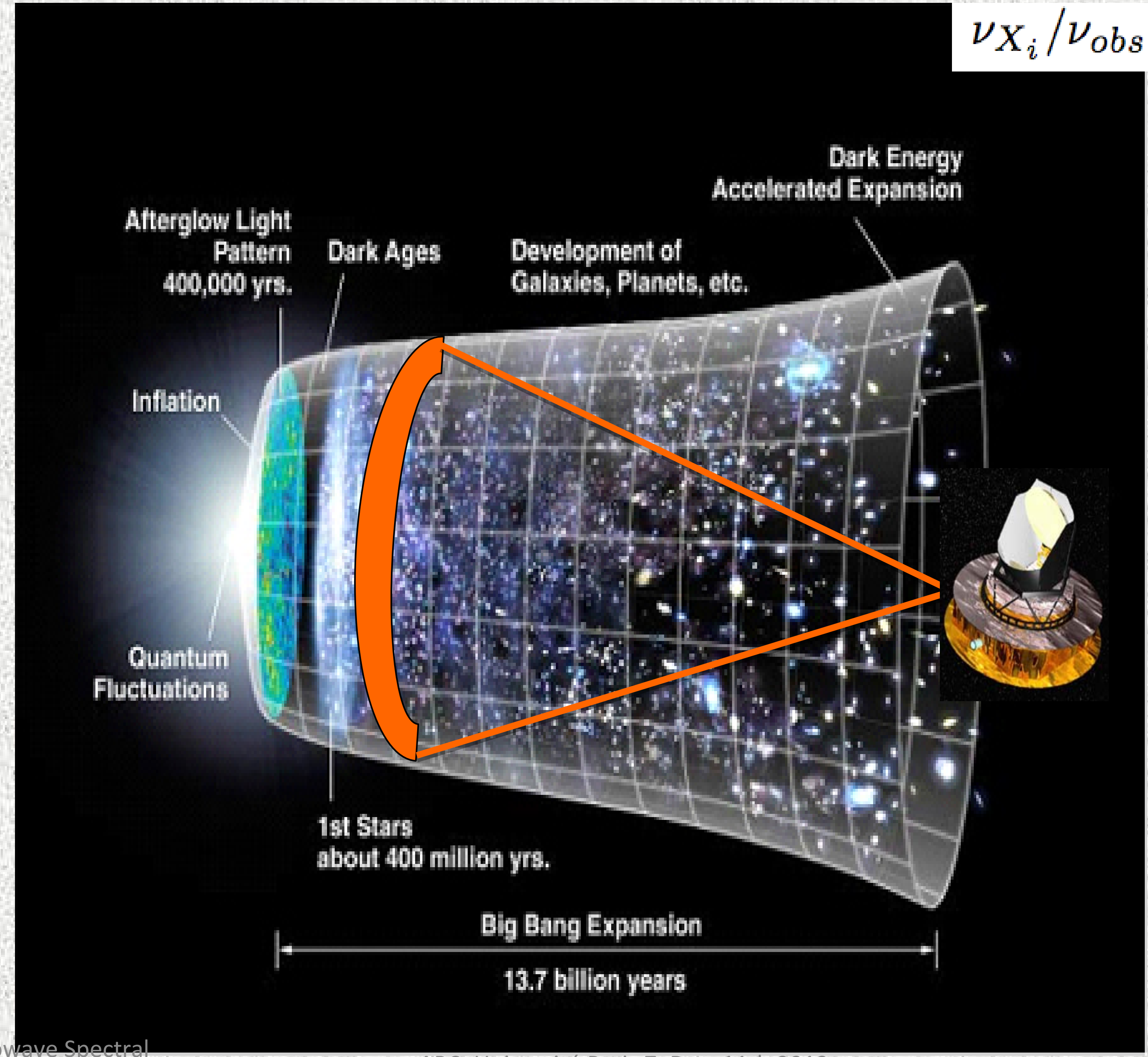
$$\nu_{X_i}/\nu_{obs} = 1 + z_{X_i}$$



@ 100 GHz

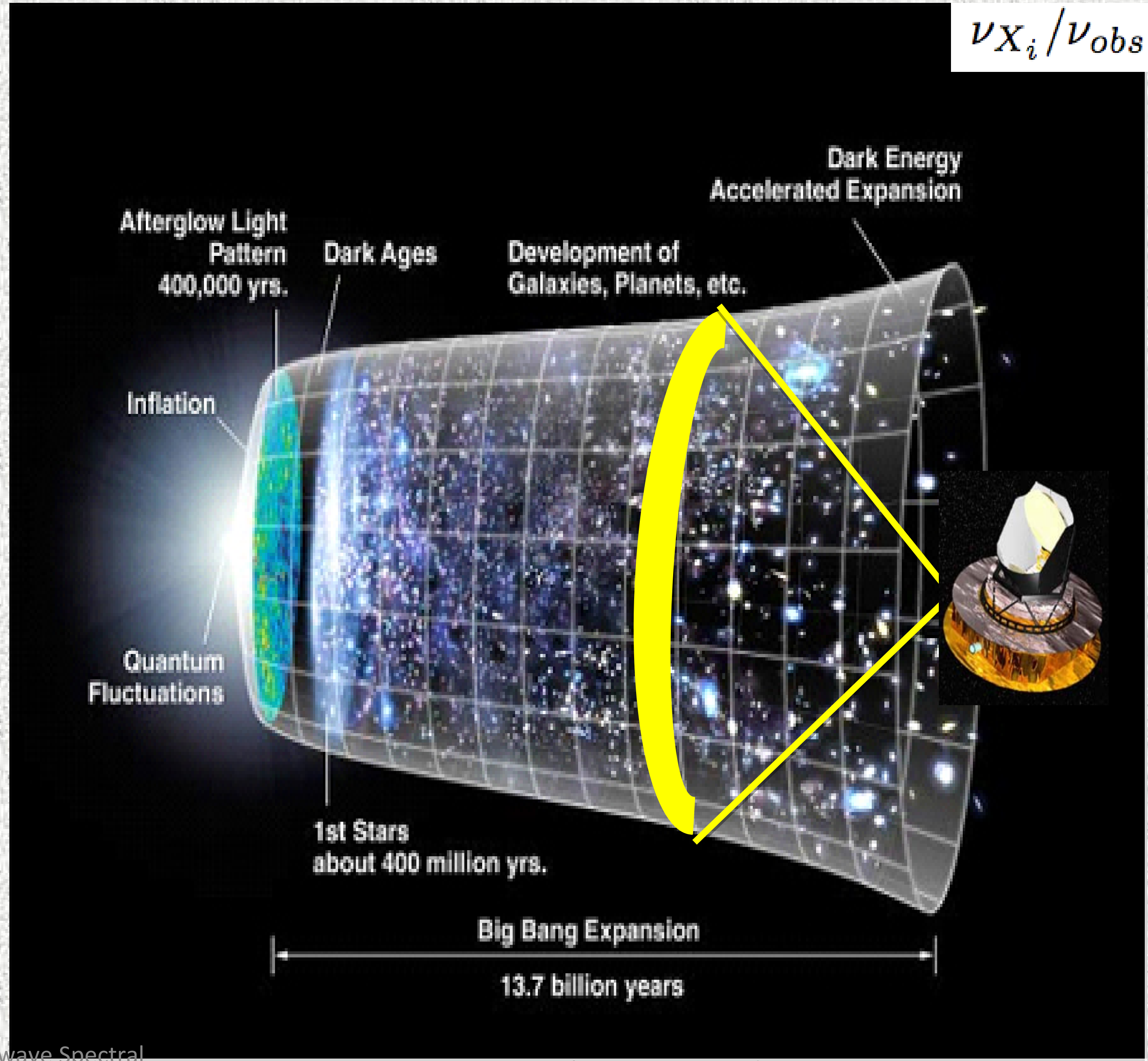
$$\nu_{X_i}/\nu_{obs} = 1 + z_{X_i}$$

@ 143 GHz



$$\nu_{X_i}/\nu_{obs} = 1 + z_{X_i}$$

@ 217 GHz



End of the Dark Ages and beginning of Reionization

Imprint of metals and molecules synthesized during reionization on the CMB via ***frequency dependent signals***:

- **Resonant scattering** on fine structure lines of metal and ionic species
- **Collisional emission** on those same lines and species + on molecules like CO
- **UV pumping** on the Balmer-alpha line of OI at 63.2 micron

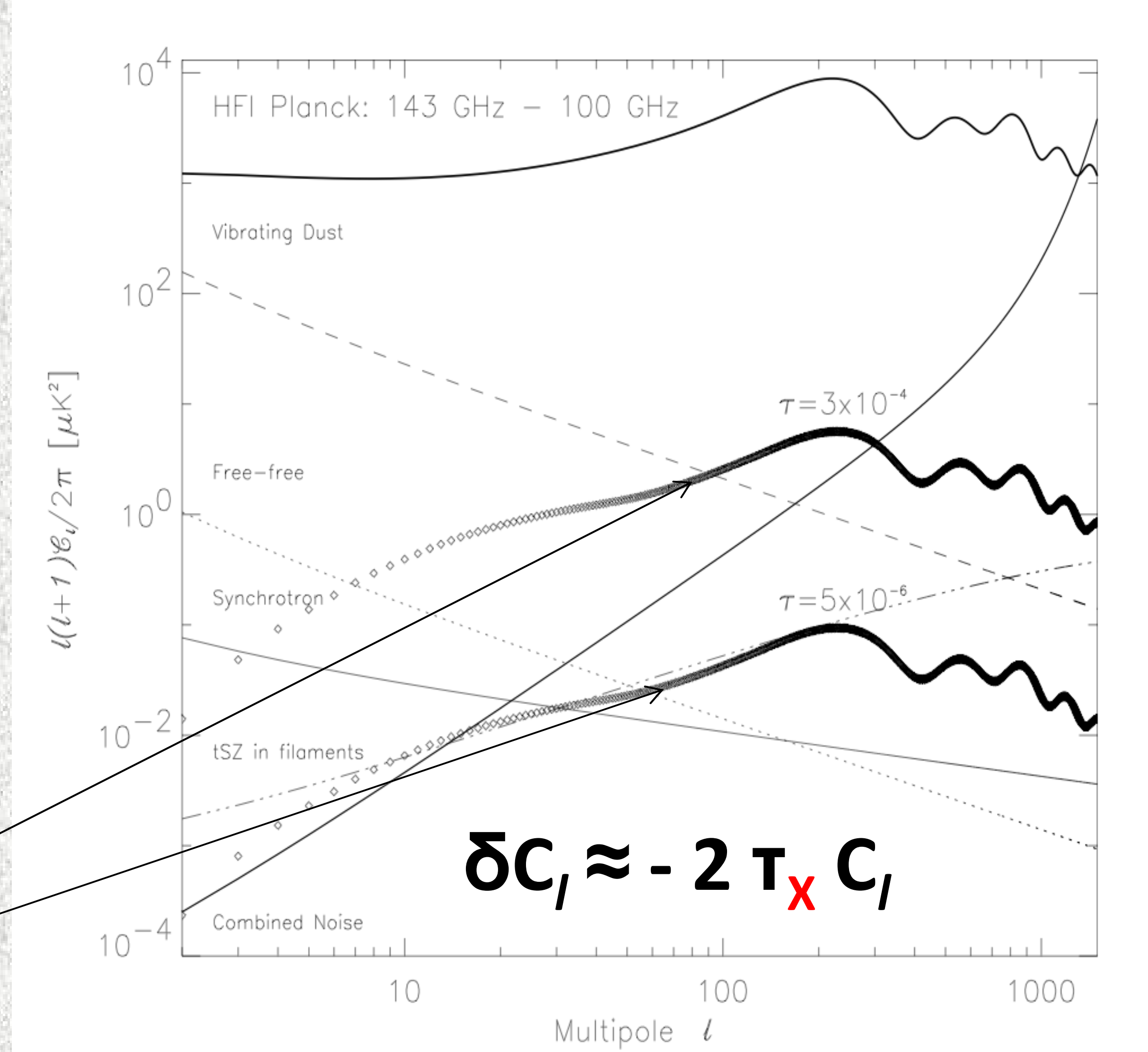
Resonant scattering

IMPACT OF RESONANT SCATTERING ON CMB POWER SPECTRUM

The biggest effect is a mere ***frequency dependeng blurring*** of the intrinsic CMB intensity anisotropies !! (almost like in CMB reionization …)

$$\tau_{X_i}(z) = f_i \, \frac{\pi e^2}{m_e c} \, \frac{\lambda_i n_{X_i}(z)}{H(z)}$$

Basu, CHM & Sunyaev (04)

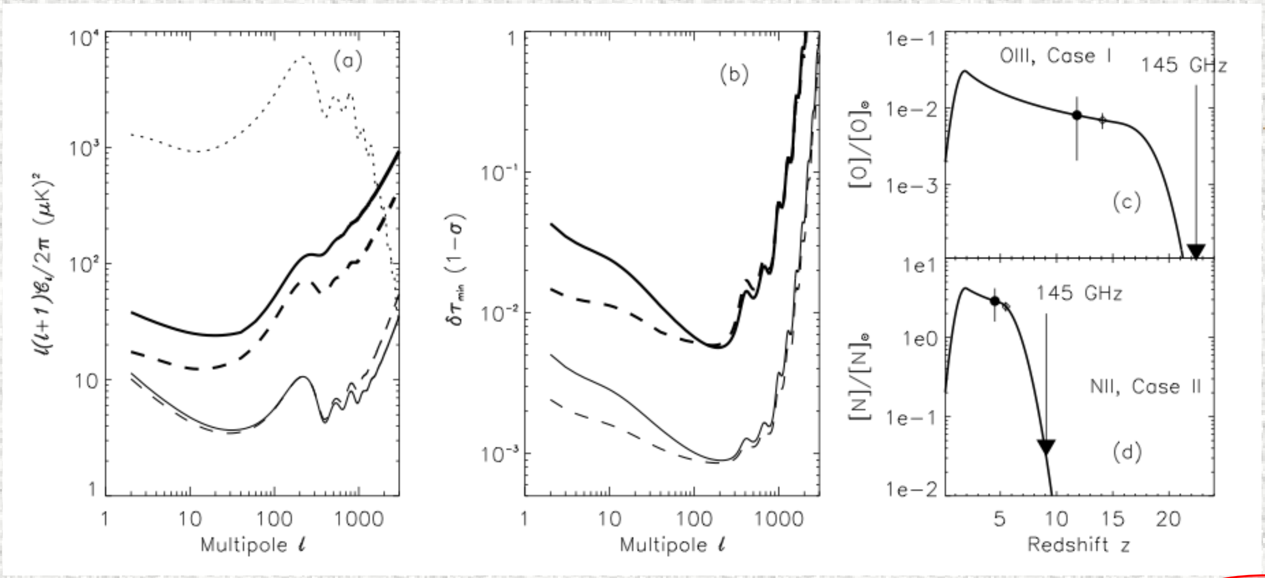


$$\delta C_l \approx -2\,\tau_X\, C_l$$

Change in angular power spectrum (C_l) ~ *Optical depth in the line*
~ Abundance of metals **at resonant redshift ~ PLANCK *will set constraints*** *on metal/ion* ***abundances*** *at very high redshift* (z~8-50) *with* ***CMB observations !***

IMPACT OF RESONANT SCATTERING ON CMB POWER SPECTRUM

Technical requirements



$$\tau_{X_i}(z) = f_i \frac{\pi e^2}{m_e c} \frac{\lambda_i n_{X_i}(z)}{H(z)}$$

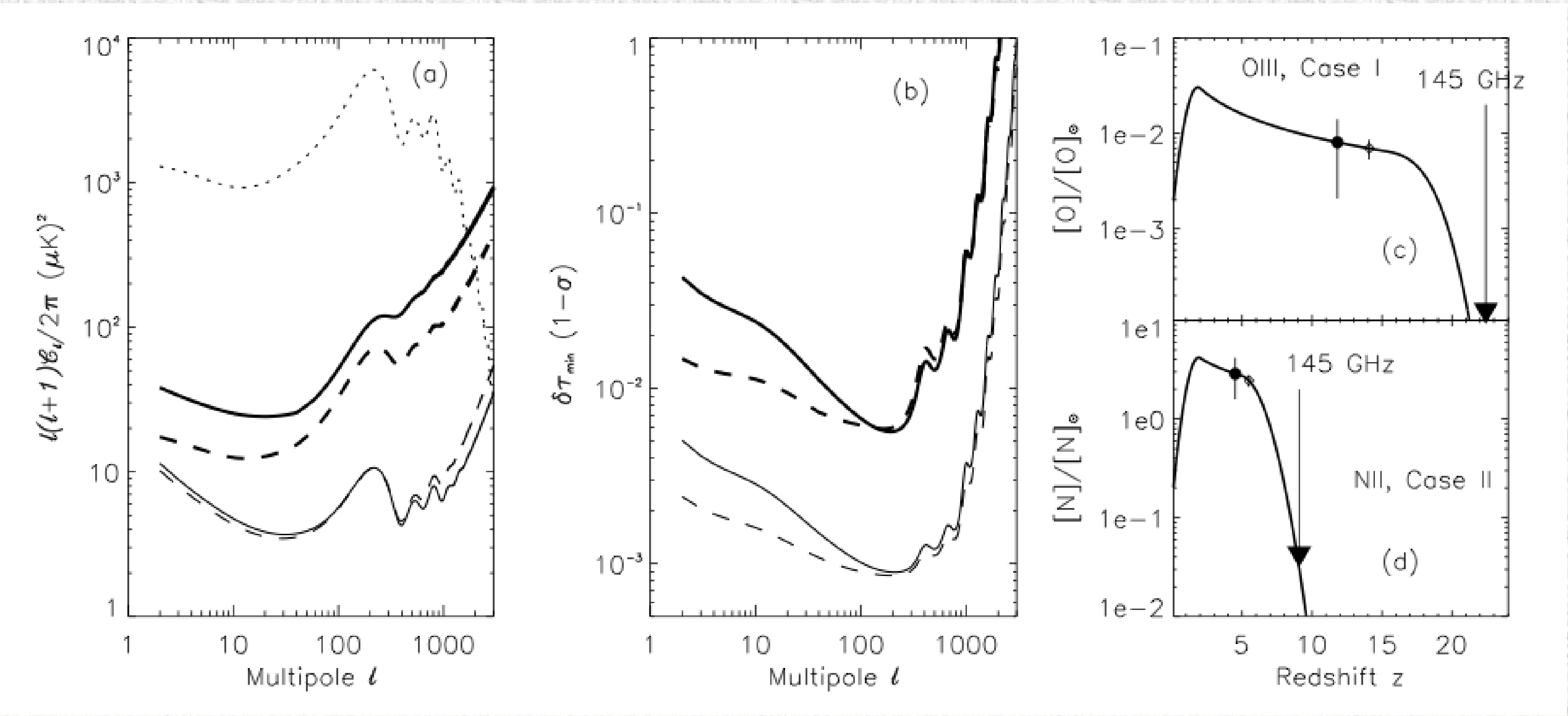
$$a^j_{lm} \equiv \frac{\tilde{a}^j_{lm}}{(W^j_{lm})^{\rm model}} = f_j \left[B^j_{lm} \left(a^{\rm CMB}_{lm} + g_{{\rm tSZ},j} a^{\rm tSZ}_{lm} + \sum_M g_{M,j} a^M_{lm} + \sum_F g_{F,j} a^F_{lm} \right) + N^j_{lm} \right].$$

$$|a^j_{lm}|^2 - |a^i_{lm}|^2 \simeq 2|a^{\rm CMB}_{lm}|^2 [{\rm Re}(\delta f_{ji} + \delta\epsilon^{ji}_{lm}) - \delta\tau^{ji}_{\rm eff}] + |a^{\rm tSZ}_{lm}|^2 \Delta[(g^{ji}_{\rm tSZ})^2] + \sum_F |a^F_{lm}|^2 \Delta[(g^{ji}_F)^2] + 2\sum_{F_u > F_v} {\rm Re}\,[a^{F_u}_{lm}(a^{F_v}_{lm})^*] \Delta(g^{ji}_{F_u} g^{ji}_{F_v}) + |N_j|^2 - |N_i|^2 + 2\,{\rm Re}\,[a^{\rm CMB}_{lm}(a^{\rm tSZ}_{lm})^*] \Delta g^{ji}_{\rm tSZ} + 2\sum_F {\rm Re}\,[a^{\rm CMB}_{lm}(a^F_{lm})^*] \Delta g^{ji}_F$$

CHM, Verde & Jiménez (06)

Constraints on τ are mostly limited by uncertainties in ***the inter-channel calibration and PSF characterisation***

$$\tau_{X_i}(z) = f_i \frac{\pi e^2}{m_e c} \frac{\lambda_i n_{X_i}(z)}{H(z)}$$



There are signatures on **polarization** as well, see talk by José Alberto Rubiño-Martín tomorrow …

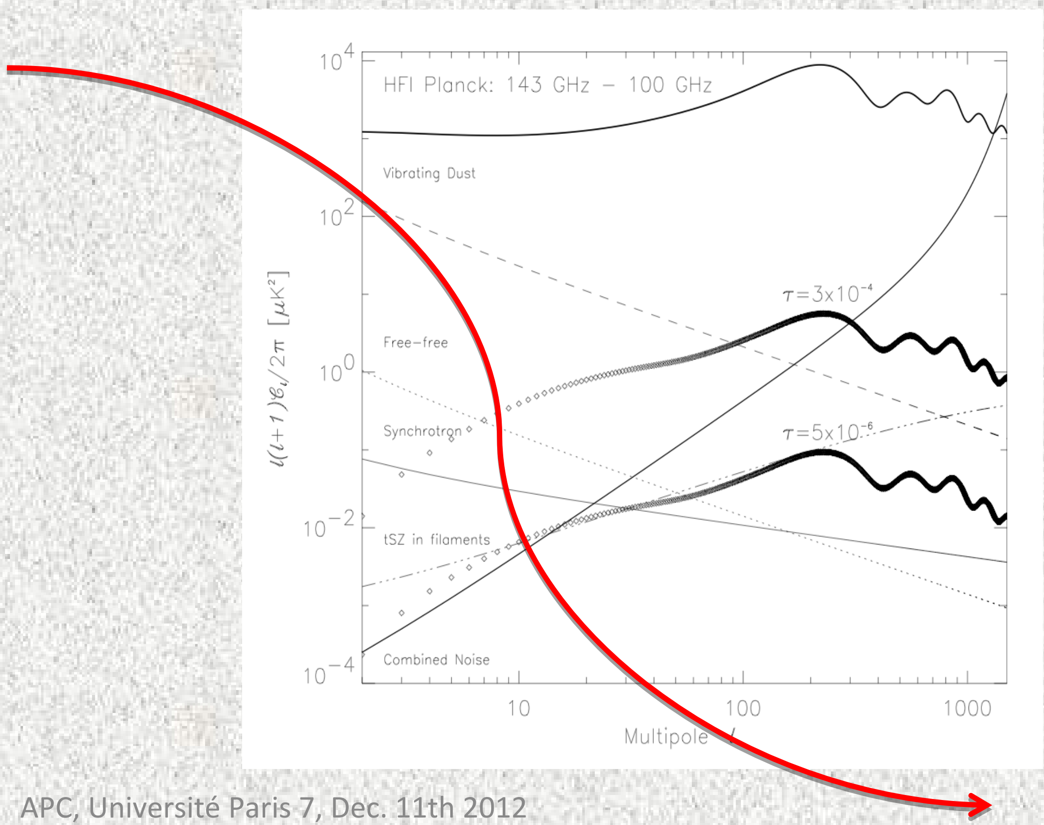
CHM, Verde & Jiménez (06)

IMPACT OF RESONANT SCATTERING ON CMB POWER SPECTRUM

Second order effects

- The ***clustering*** of bubbles containing metals and the ***peculiar motions*** of the scatterers introduce ***second order*** anisotropies

- However, these are **not linear** in the **optical depth (τ), but quadratic (τ^2)** , thus yielding much smaller amplitudes (just like for *patchy reionization signatures in the high-l regime….*)



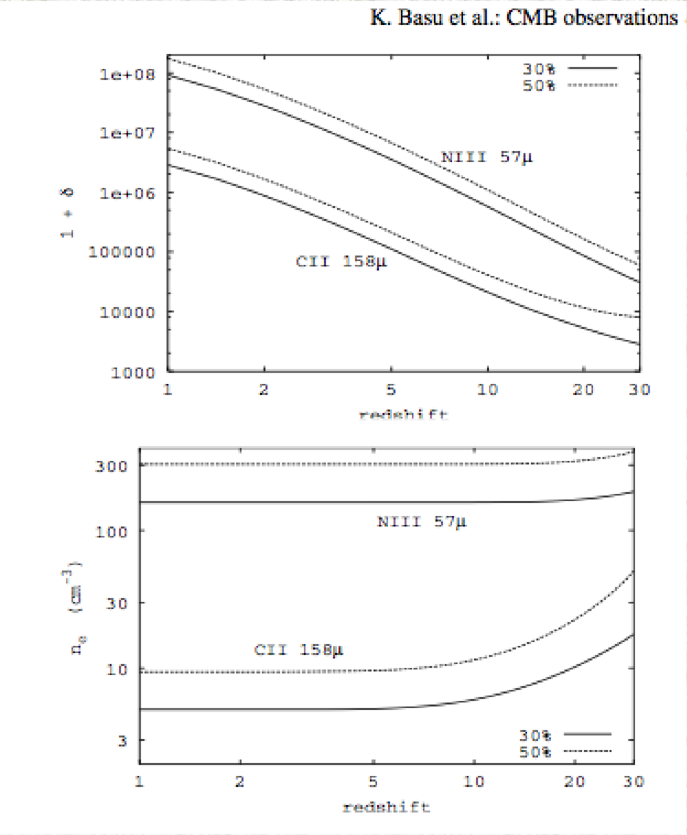
Collisional emission

Collisionally induced emission in dense regions: the clustering of star forming regions

- One needs to go to **highly overdense** regions in order to change significantly the lower level population in the fine structure transitions of interest and hence modify the optical depth (δ **~1e4 -- 1e7**)

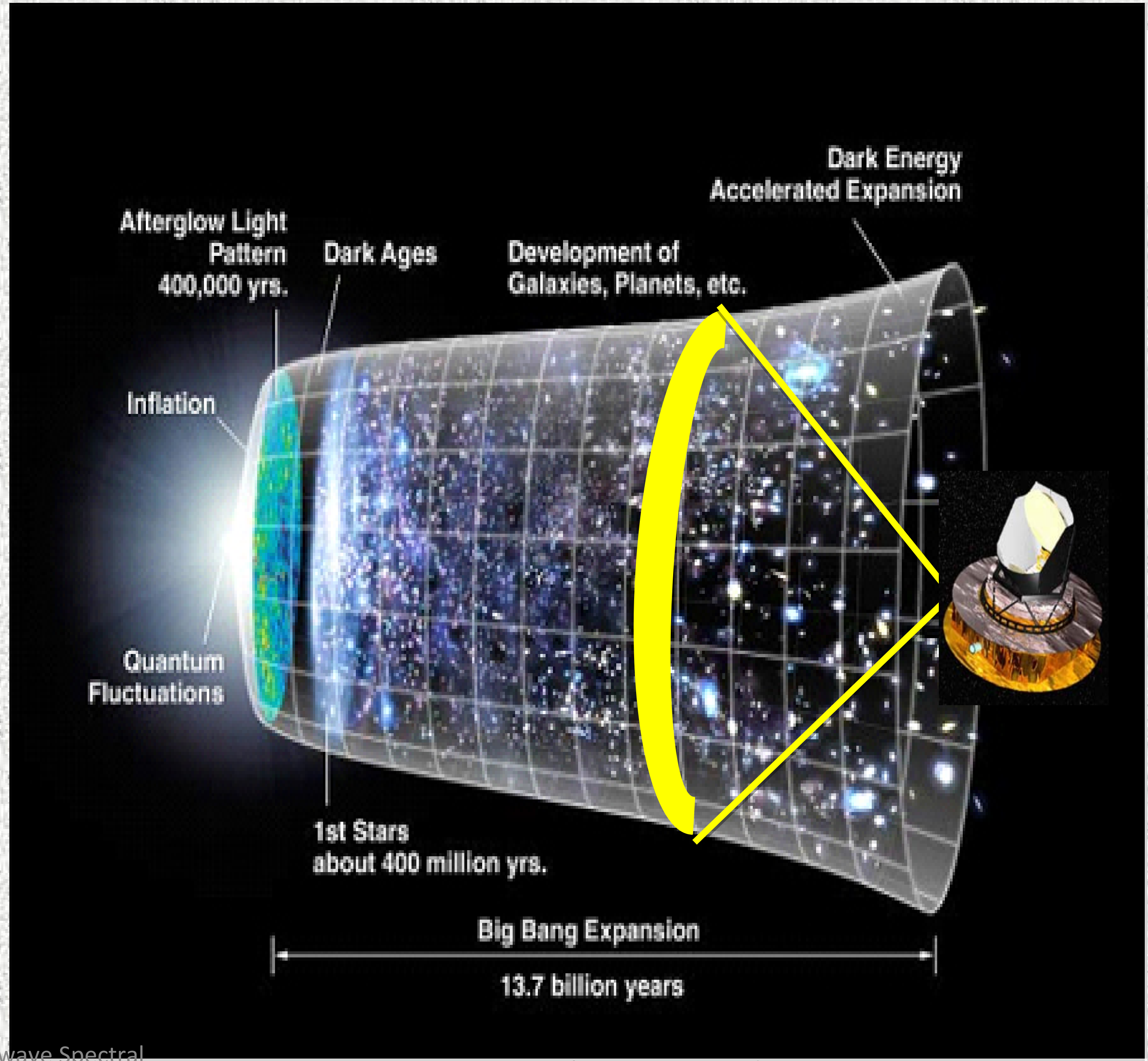
- In all other regions the **resonant scattering is the dominant process**

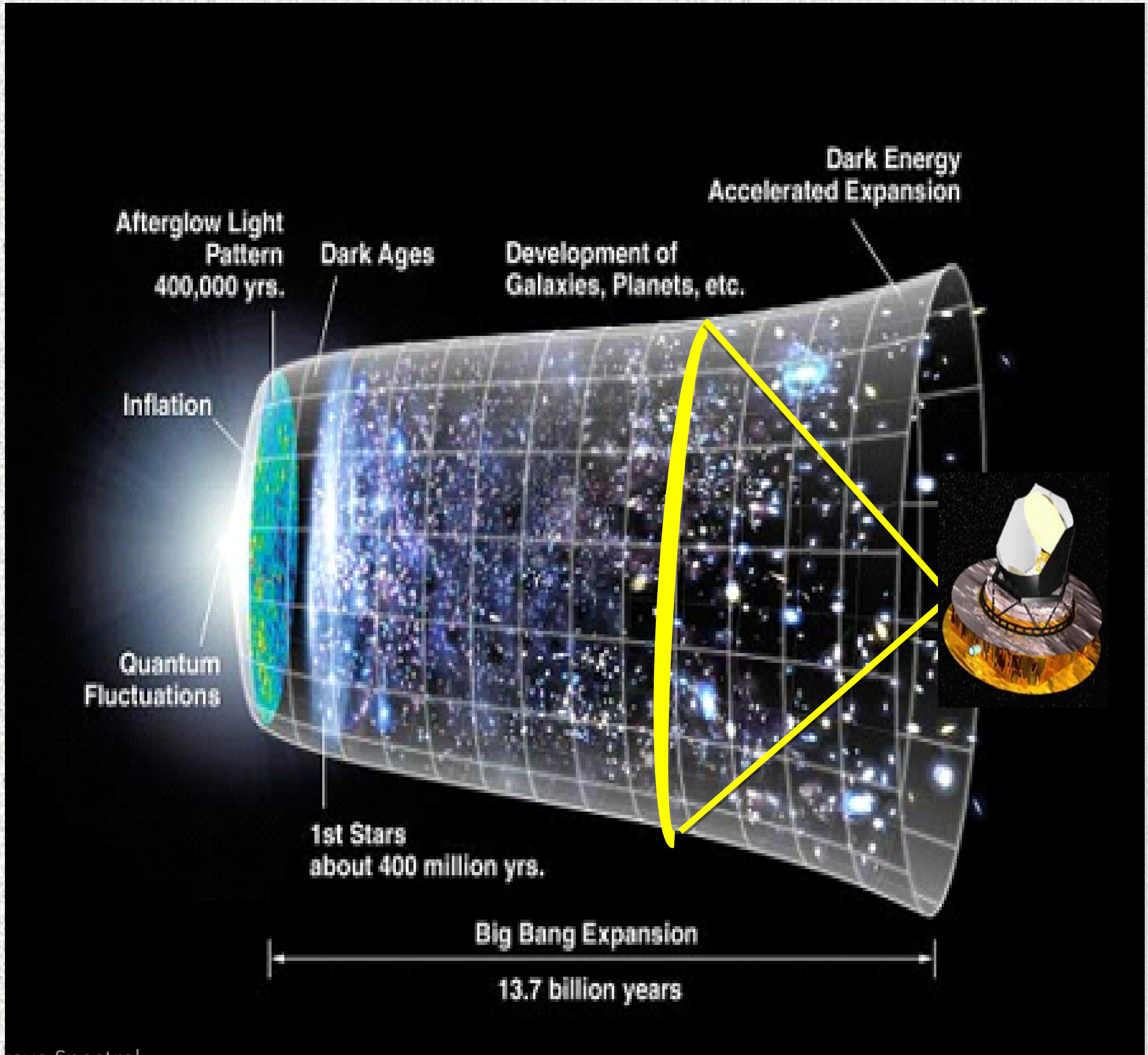
- However, the anisotropy pattern of line emission allows playing with the ***radial coordinate – frequency resolution***



Basu, CHM & Sunyaev, (A&A 2004)

$$\frac{\Delta\nu}{\nu_{obs}} = 0.2$$

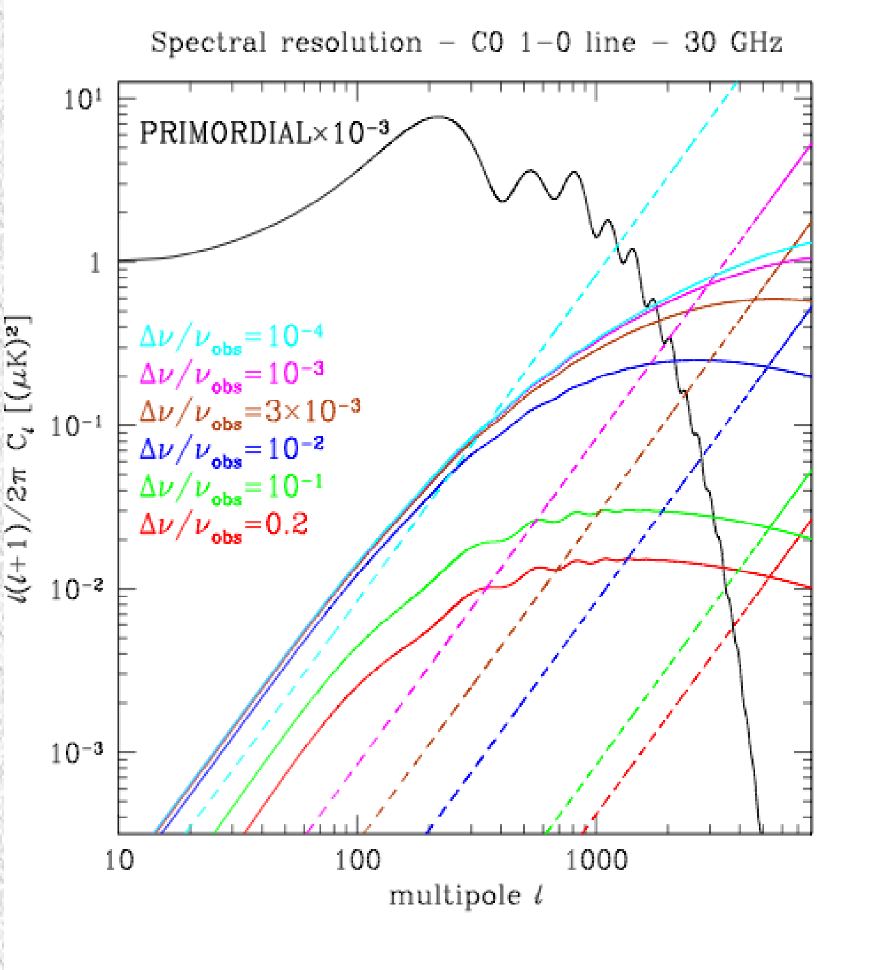




$$\frac{\Delta\nu}{\nu_{obs}} = 10^{-3}$$

Collisionally induced emission in dense regions: the clustering of star forming regions

- The ***spectral width*** of the observing experiment conditions the *width of the **redshift shell*** interacting with the CMB: ***this allows projecting out all "non-line" foregrounds (including** CMB!)*

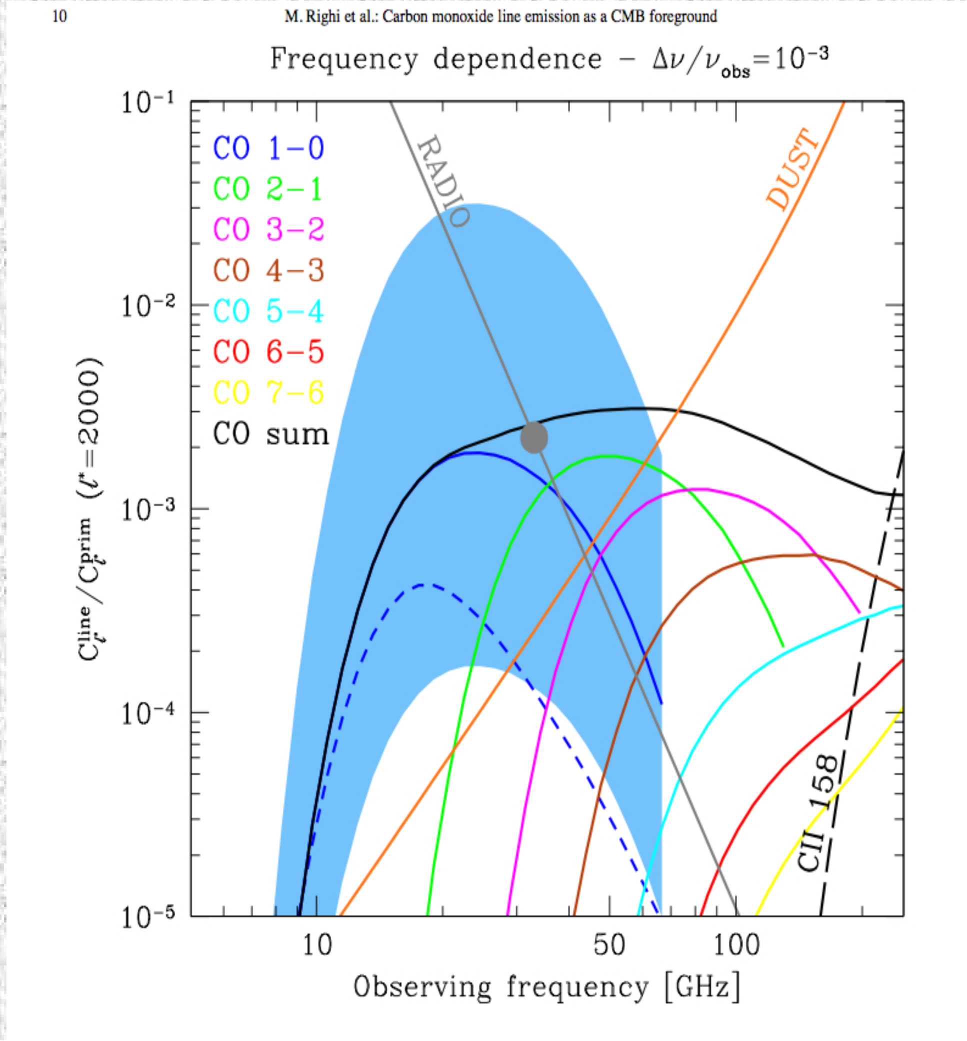


Collision induced CO 1->0 line emission at 30 GHz and resulting anisotropy, after implementing a Kennicut-law type relation between CO luminosity and Star Formation Rate in nearby galaxies and extrapolate it to higher-z using a Lacey & Cole approach

Righi, CHM & Sunyaev, (A&A 2008)

For relative spectral width of 1e-3, the CO J=1-0 115 GHz is the ***largest*** foreground at \ell~2,000 between 30 – 70 GHz

Future NIR and FIR surveys may be able to detect the presence of these collisions at moderate to high redshifts **on different transitions in OI, NII, OIII …**



Righi, CHM & Sunyaev, (A&A 2008)

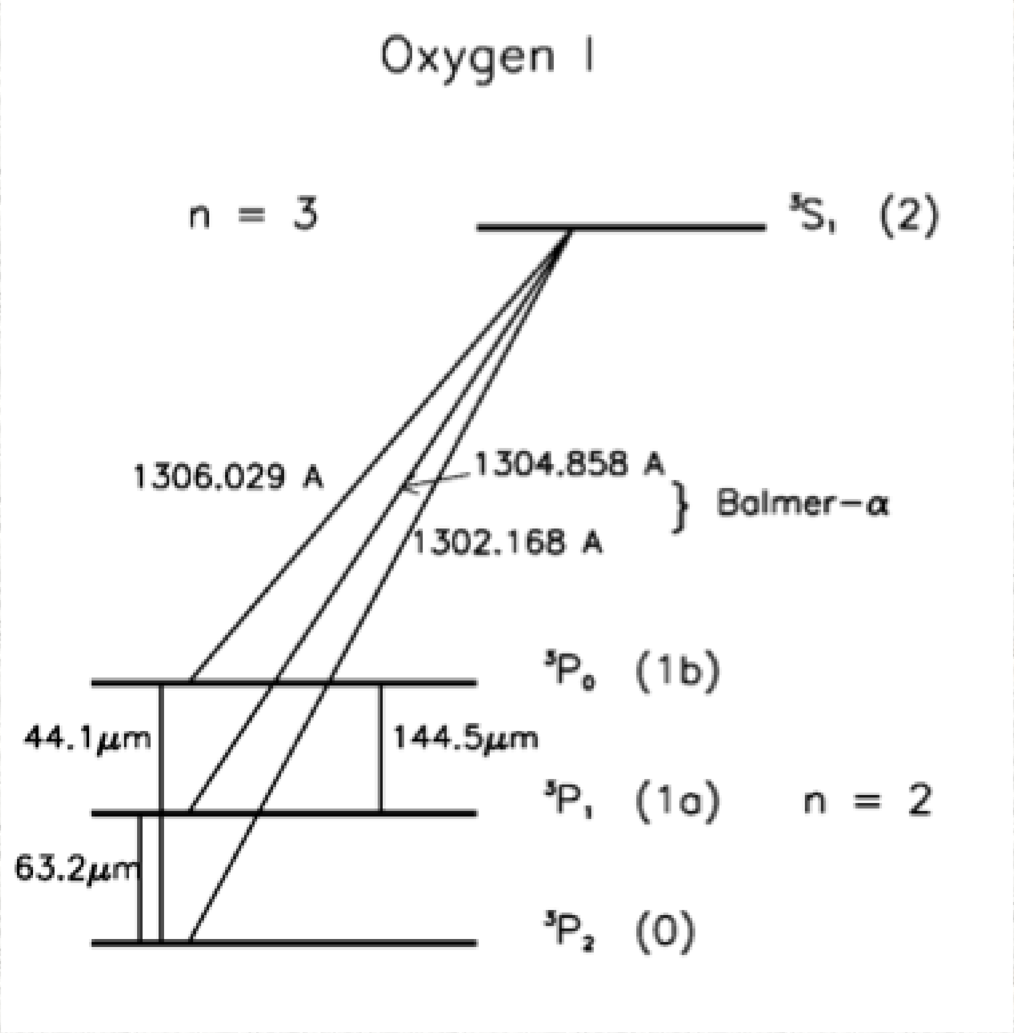
Wouthuysen-Feld effect on OI

The **Wouthuysen-Feld effect** or **UV pumping** in OI and the resulting induced distortion on the CMB

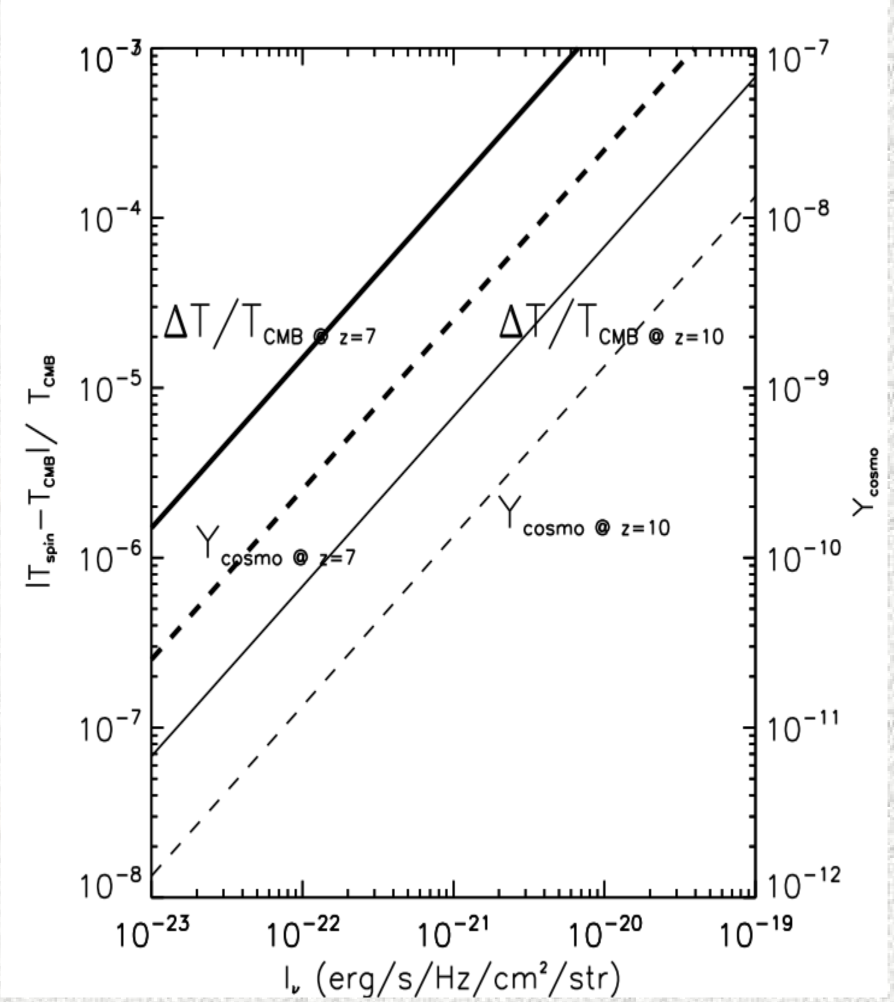
UV radiation pumps systems from (0-1a-1b) to (2), ***distorting the CMB-induced equilibrium*** between the (0-1a-1b) levels

$$\frac{n_j}{n_i} = \frac{P_{ij}^{UV} + B_{ij} I_\nu}{P_{ji}^{UV} + B_{ji} I_\nu + A_{ji}} \equiv \frac{g_j}{g_i} \exp\left(\frac{-T_{*,ji}}{T_{S,ji}}\right).$$

CHM, Haiman, Verde & Jimenez, ApJLetters 2007

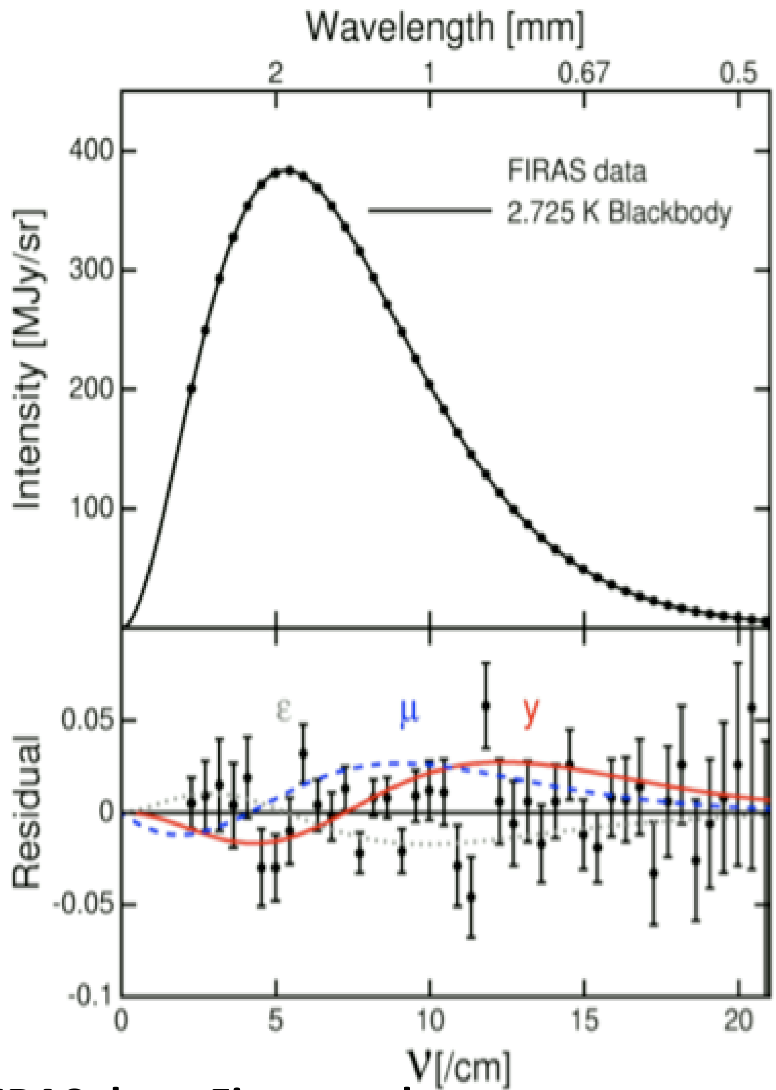


UV pumping induced distortion of the CMB



CHM, Haiman, Verde & Jimenez, ApJLetters 2007

UV background generated by first stars changes $\mathbf{T_{spin}}$ in fine structure transitions of **neutral oxygen** OI (64micron, 148micron) **~ distortion** in CMB spectrum and **temperature anisotropies ~ constraints** on **neutral oxygen during reionization.**



FIRAS data, Fixen et al.

- FIRAS data can already constrain OI abundance to be less than 5 – 40 $Z_\odot$ at $z > 10$ $\Rightarrow$ **first constraints on OI at reionization!**
- Future experiments (improved versions of FIRAS) should be able to set tight constraints on OI during the reionization epoch.

CHM, Haiman, Verde & Jimenez, ApJLetters 2007

What are the effects of OI clustering ??

$$y_{\rm eff}(\nu_{\rm obs}, \hat{\boldsymbol{n}}) \approx \int dM \left[\mathcal{B} * \left(\frac{dn}{dM} * W_b\right)\right] \hat{y}.$$

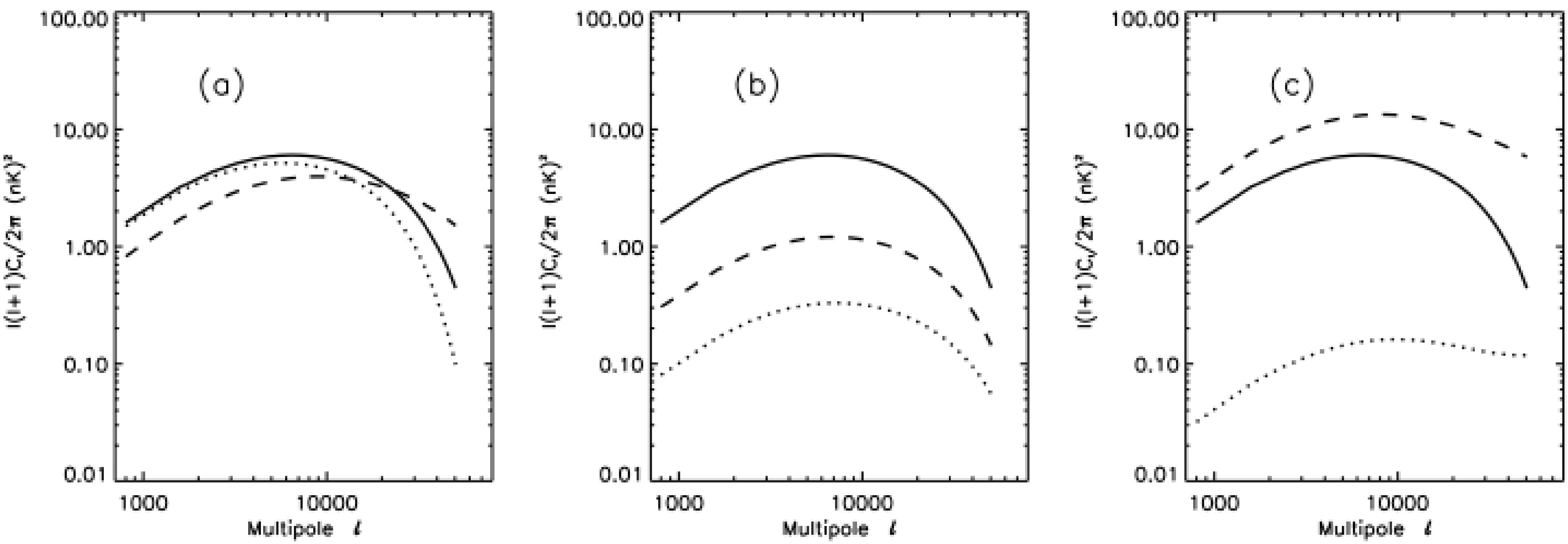
As OI gets expelled in **bubbles** from SN winds, these grow in size … the total contribution along a given line of sight must account for the **halo mass function** (giving rise to the bubbles) and the **instrumental frequency** and **angular responses** ….

Since halos are **correlated**, so these bubbles will, and this can be computed …

What are the effects of OI clustering ??

$$y_{\rm eff}(\nu_{\rm obs}, \hat{\boldsymbol{n}}) \approx \int dM \left[\mathcal{B} * \left(\frac{dn}{dM} * W_b\right)\right] \hat{y}.$$

$$\langle y_{\rm eff}(\hat{\boldsymbol{n}}_1) y_{\rm eff}(\hat{\boldsymbol{n}}_2)\rangle = \int dM_1\, dM_2\, \langle \tilde{n}_1 \tilde{n}_2\rangle \hat{y}_1 \hat{y}_2$$
$$= \int dM_1\, dM_2\, \bar{\tilde{n}}_1 \bar{\tilde{n}}_2 \hat{y}_1 \hat{y}_2 [1 + \tilde{\xi}_{hh}(\boldsymbol{r}_1, M_1, \boldsymbol{r}_2, M_2)]$$



CHM, Haiman, Verde & Jiménez (08)

At the nK level … ALMA??

Summary

•Metals at the end of the Dark Ages can interact with CMB photons via *resonant scattering, collisional emission* and the *Wouthuysen-Feld effect*

• The **most frequent** mechanism is the **resonant scattering**, which affect all species outside the most overdense regions. ***Constraints on metal production during the dark ages may be obtained after accurate inter channel calibration and PSF characterisation***

• At the same time, **collisional emission** can be separated from other dominant signals due to **its dependence with the observing spectral resolution**

• Distortion of the CMB due to the **Wouthuysen-Feld effect on OI** lies at the **nK level** and may provide an **independent way** to set constraints on OI at the end of reionization by upcoming measurements of CMB distortions.