Modeling Radio Recombination Line Contamination in 21cm Intensity Mapping

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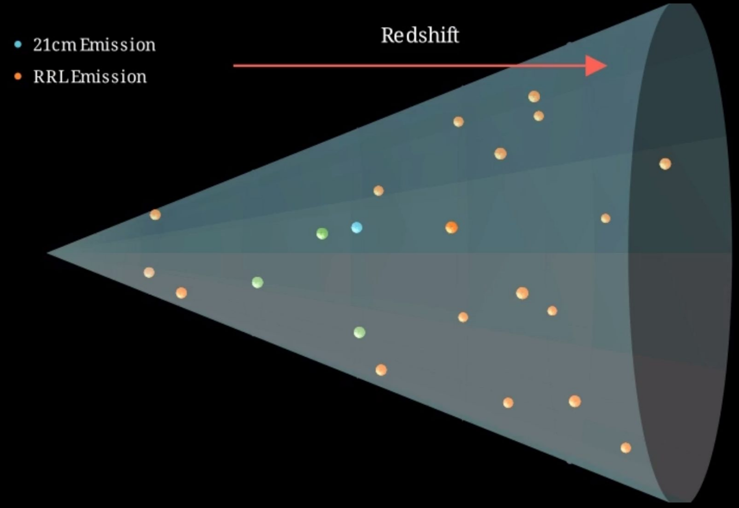


Matthew McQuinn

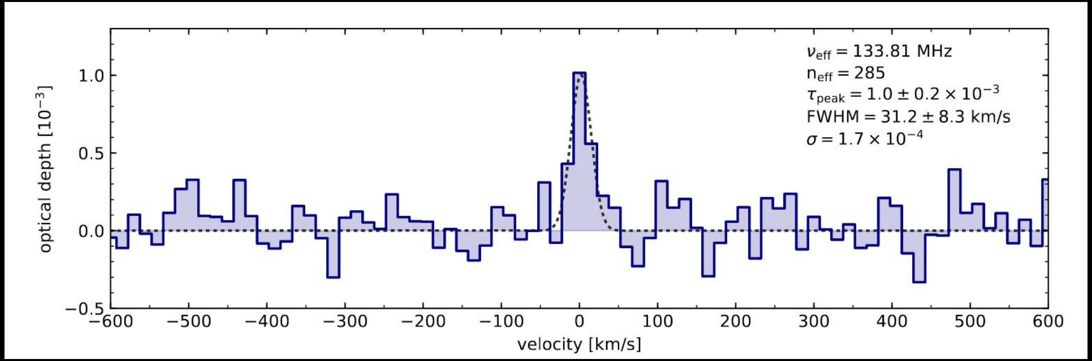
Yakov Faerman

Some Historical Context....

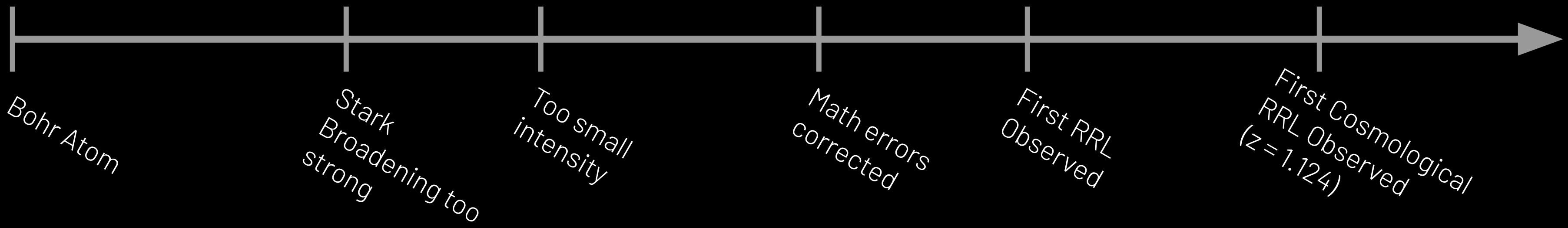
Radio Recombination Lines on Wikipedia now! (by me!)

(n > 50)

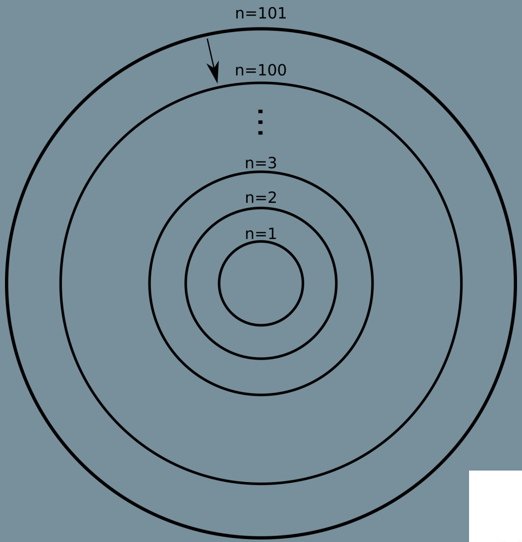
$$\nu = \frac{R}{c}\left(\frac{1}{n^2} - \frac{1}{(n+1)^2}\right)$$



Emig+ 2019



What are Radio Recombination Lines (RRL) and how are they produced?



Hydrogen Lines with *very* high quantum number ($n > 50$) and usually $\Delta n = 1$

$$\nu = \frac{R}{c}\left(\frac{1}{n^2} - \frac{1}{(n+1)^2}\right)$$

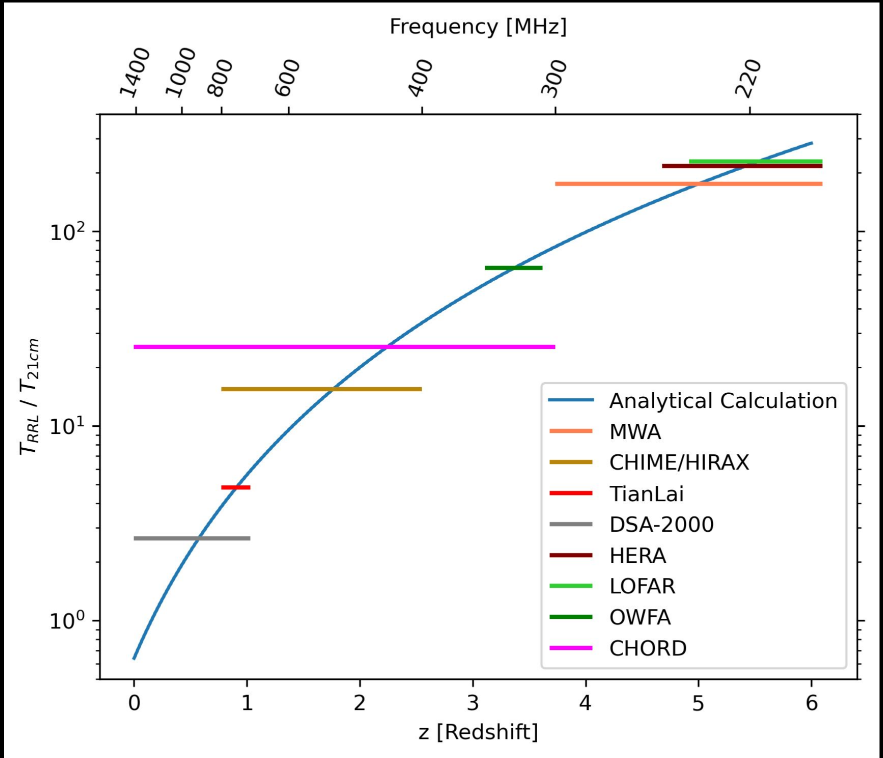
Produced through the **recombination** of electrons with Hydrogen in HII regions

→ Electron cascades down through energy levels, emitting photons

Earlier estimates assume a 'fixed' optical depth (τ_L=0.1)*

$$T_b = 3.5 \times 10^{-4}\ \mathrm{K} \left(\frac{\rho_{\mathrm{SFR}}}{0.1\ \mathrm{M_\odot\ yr^{-1}Mpc^{-3}}}\right)\left(\frac{\tau_L}{0.1}\right)\left(\frac{\nu_{obs}}{150\ \mathrm{MHz}}\right)^{-2.8}(1+z_{RRL})^{-2.3}$$

$$T_{21} = 9\,(1+z)^{1/2}\,x_{\mathrm{HI}}\ \mathrm{mK}$$

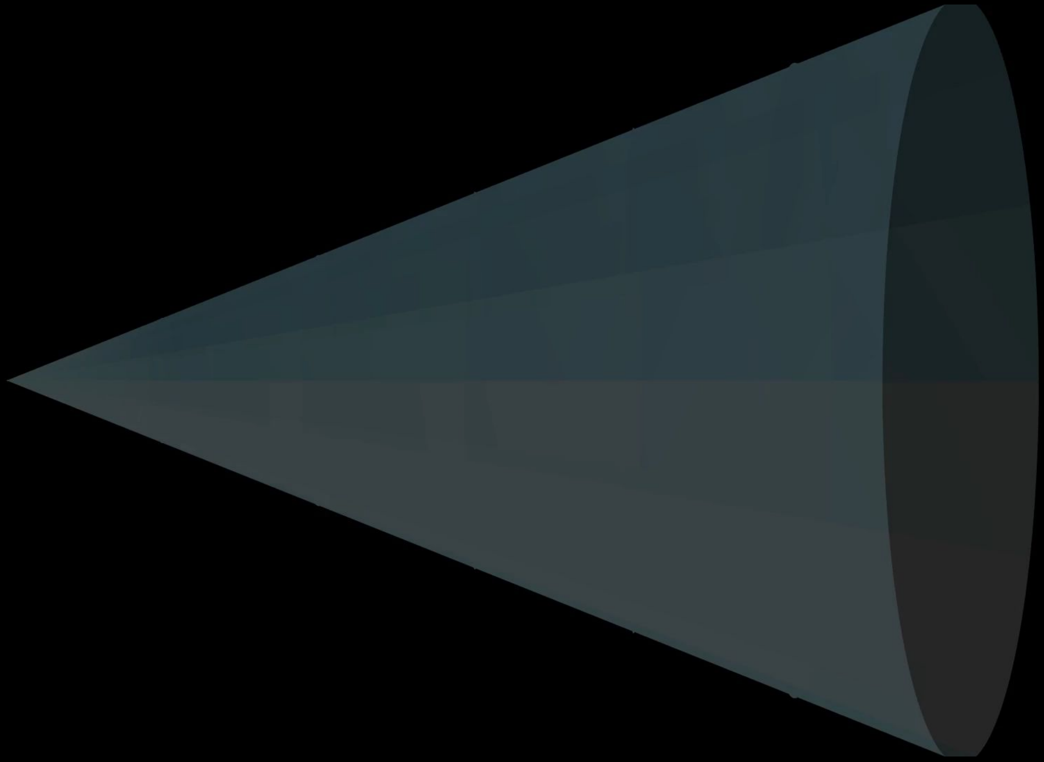


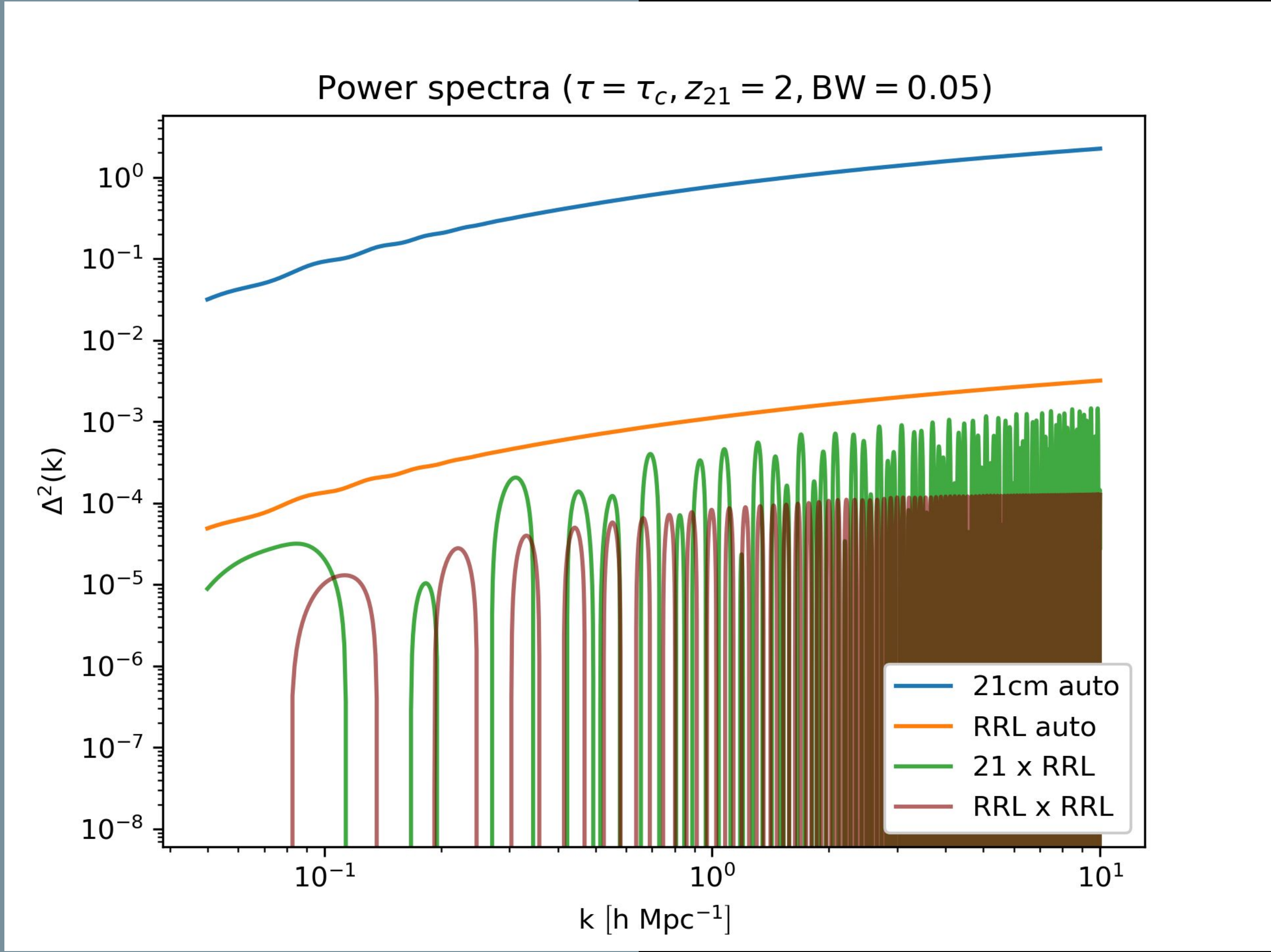
Can use this as motivation to explore optimistic (pessimistic) experimental contamination

*This optical depth is a *significant overestimate*

Petrovic & Oh 2011

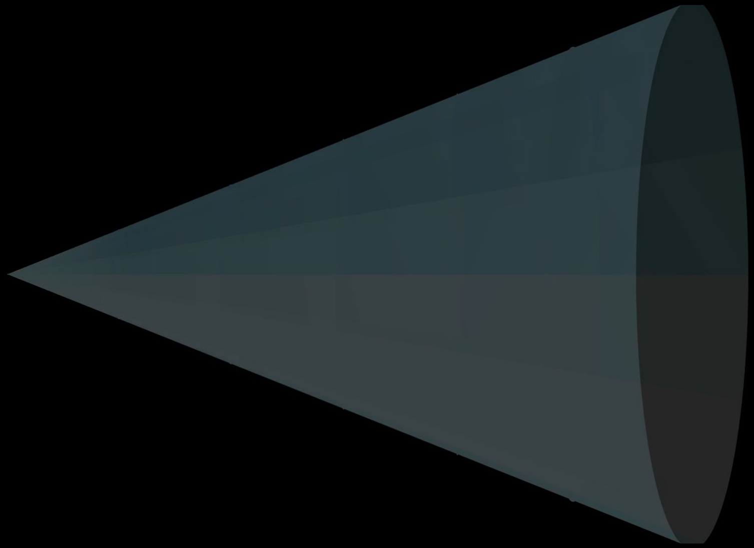
RRLs are individually weak, but in Intensity Mapping, this signal can get **stacked**



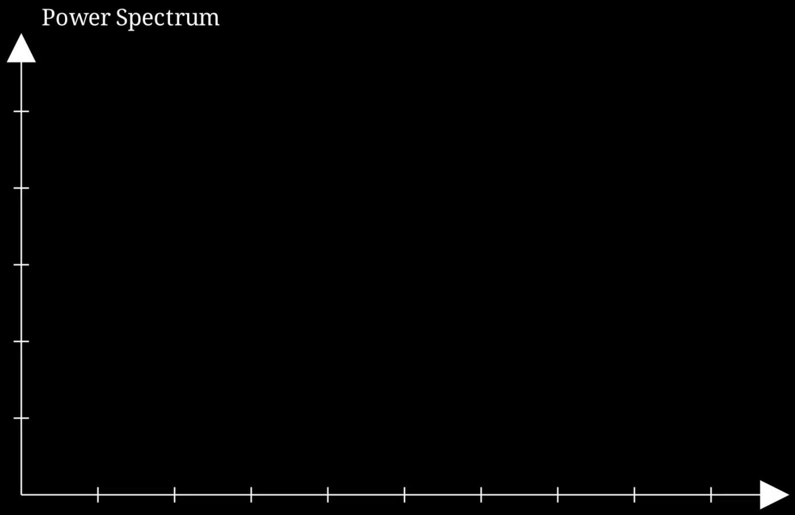


"Stacking" RRLs result in 3 different power spectra

- RRL Auto-Power Spectra
- 21cm x RRL Cross-Power Spectra
- RRL_1 x RRL_2 Cross-Power Spectra

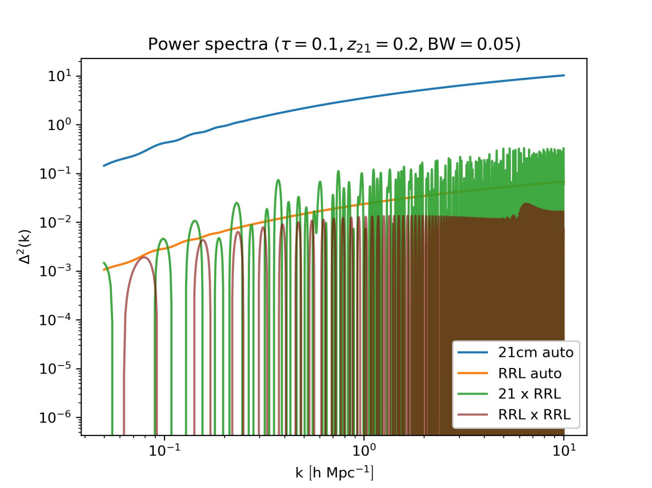


And going back to the animation...
we can see how each power spectrum changes with more contamination

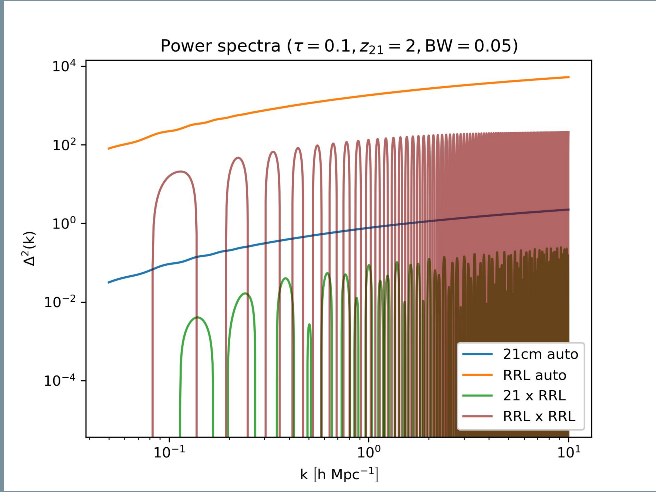


Fixed τ Model

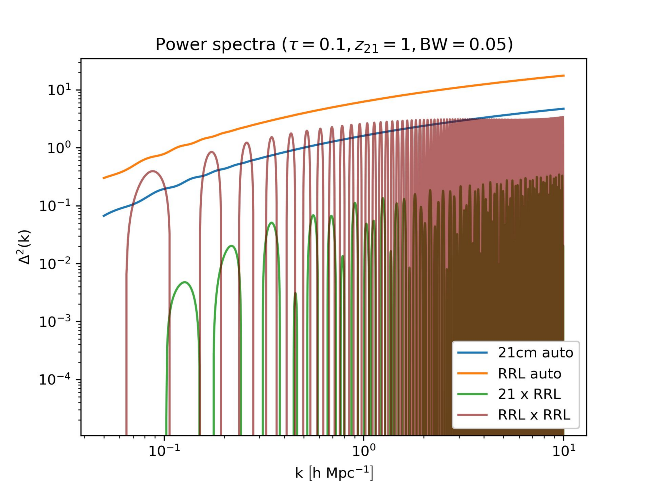
z = 0.2



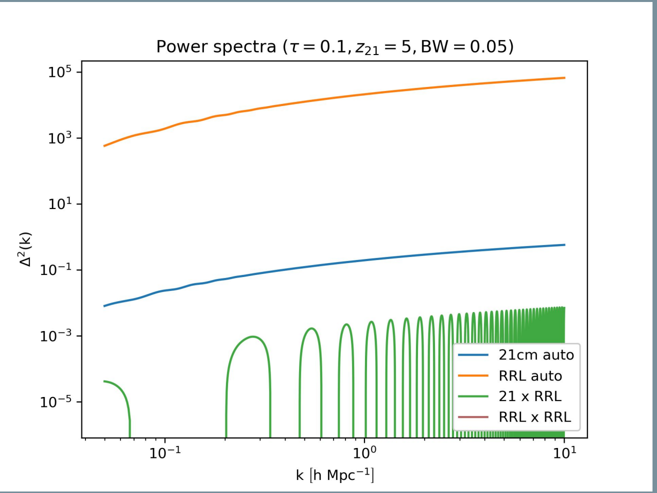
z = 2



z = 1

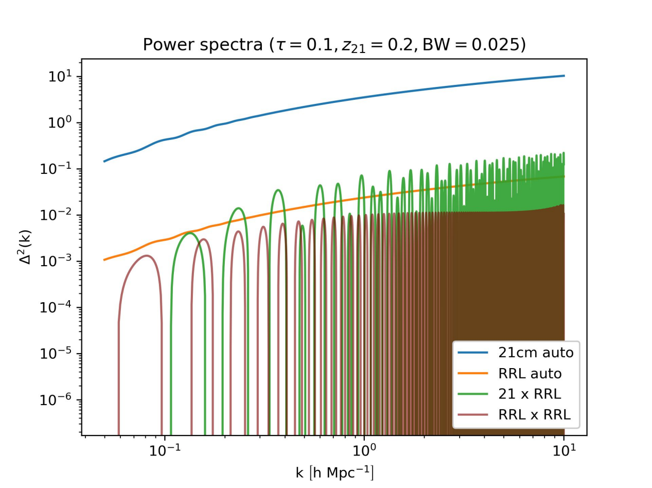


z = 5

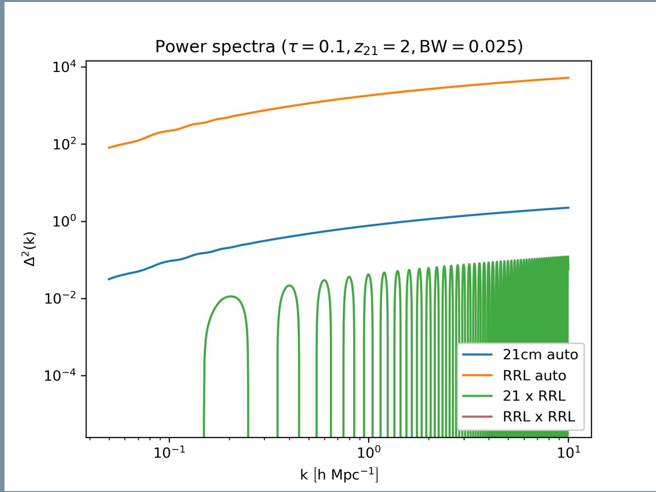


BW = 0.025

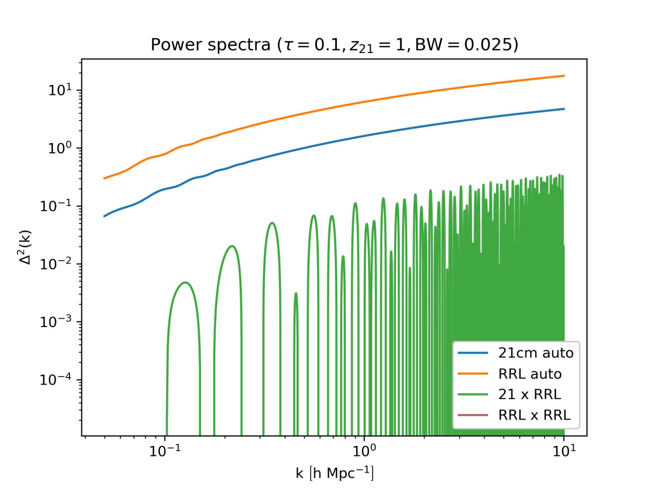
z = 0.2



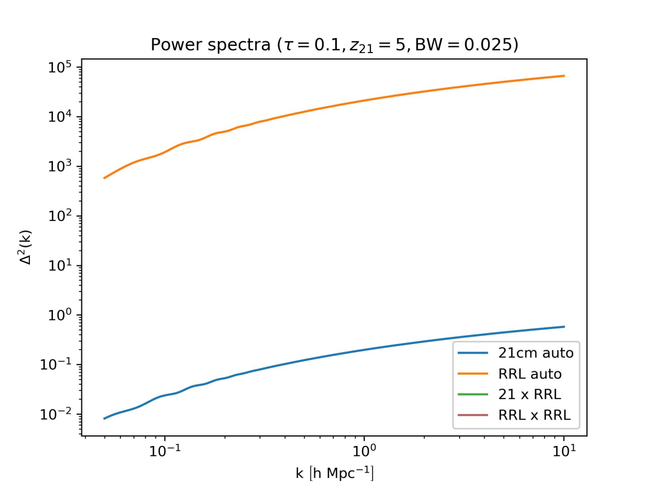
z = 2



z = 1

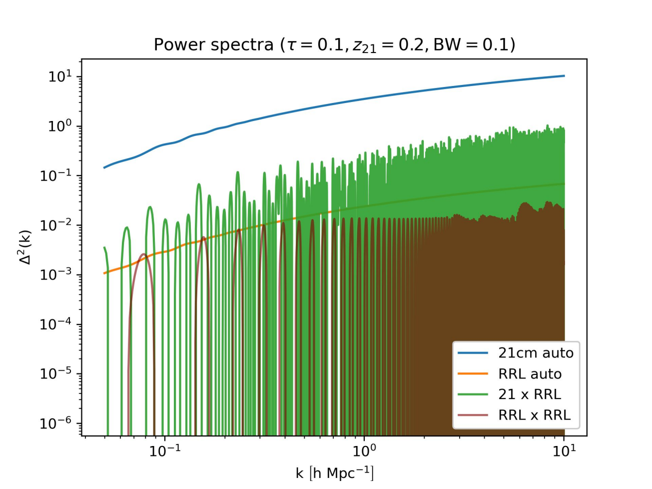


z = 5

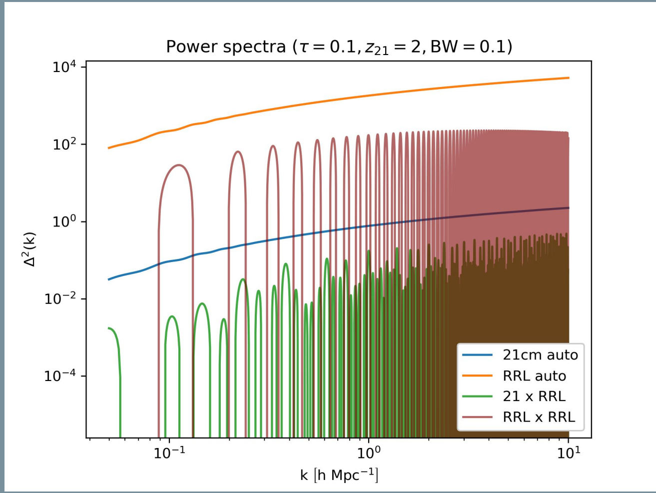


BW = 0.1

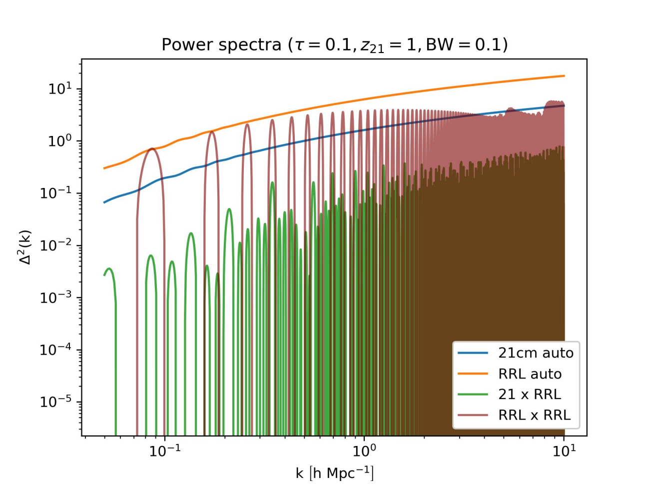
z = 0.2



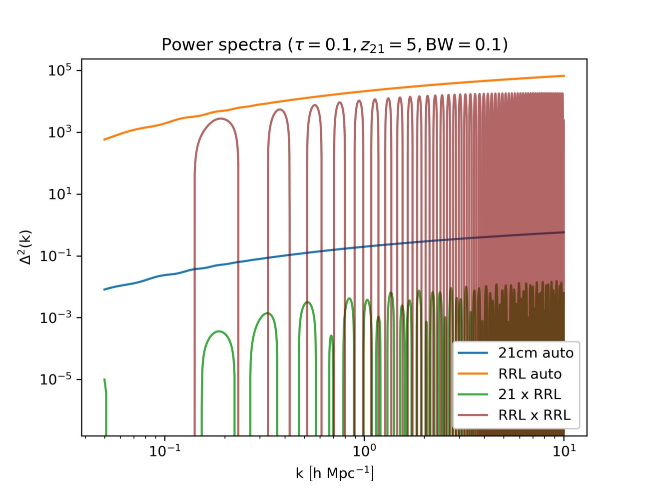
z = 2

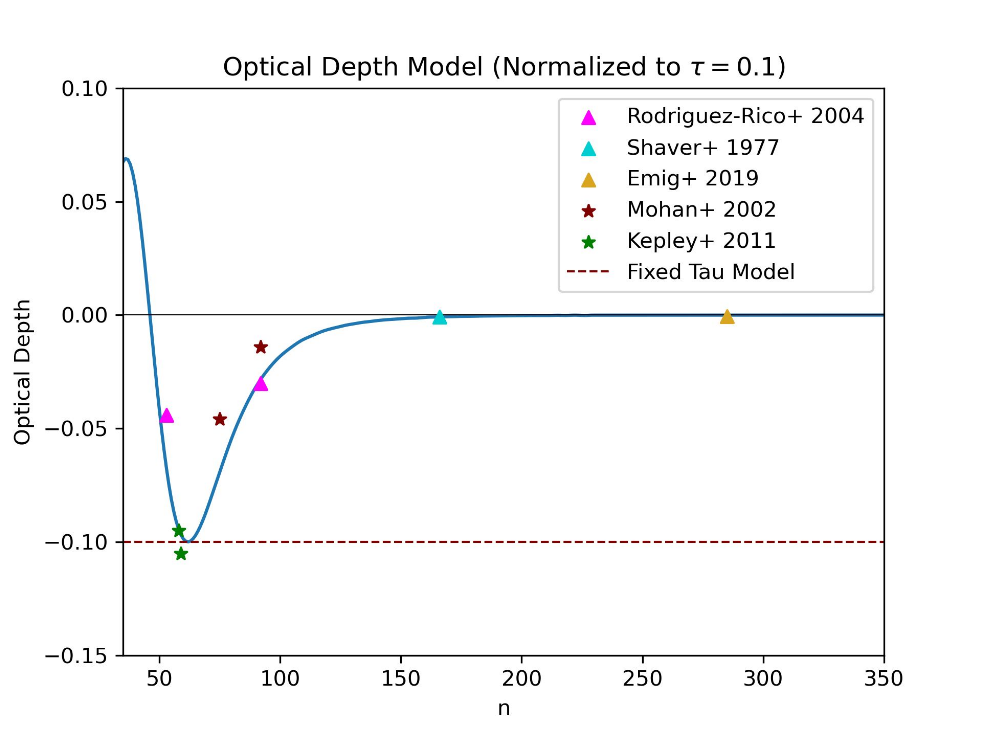


z = 1

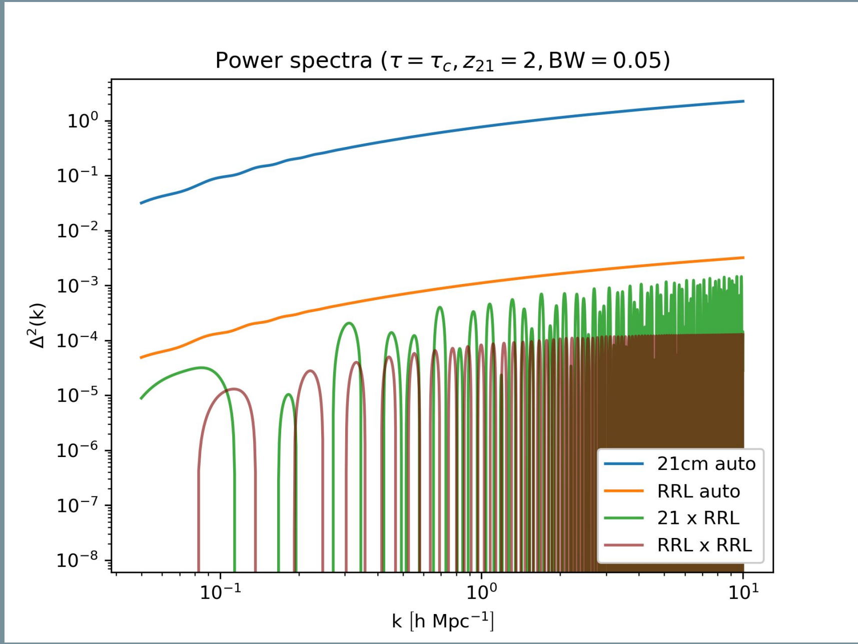


z = 5





We can instead use a more physical optical depth (τ) model

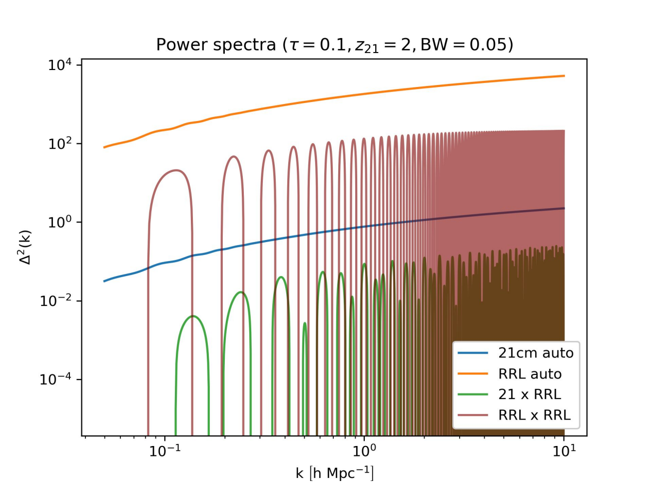


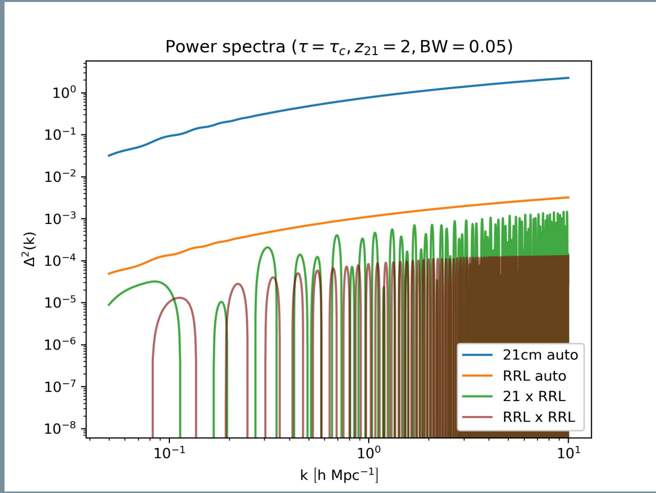
And normalize to RRL observations

Fixed T

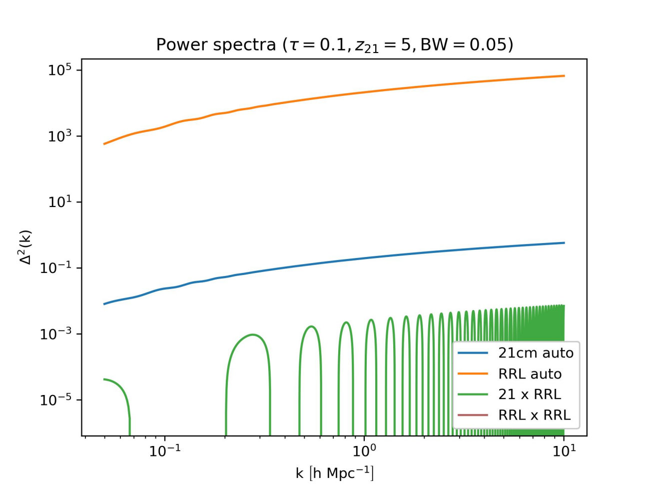
'Physical' T

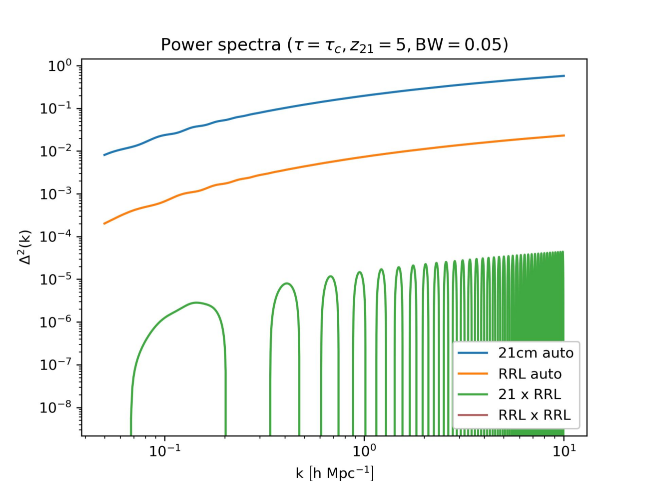
z = 2





z = 5

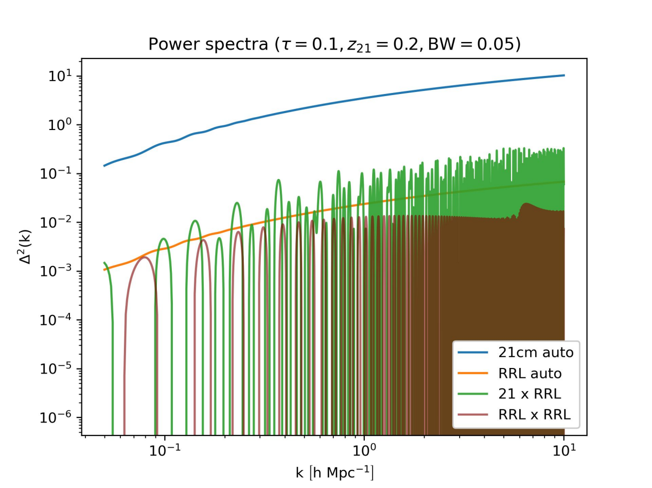


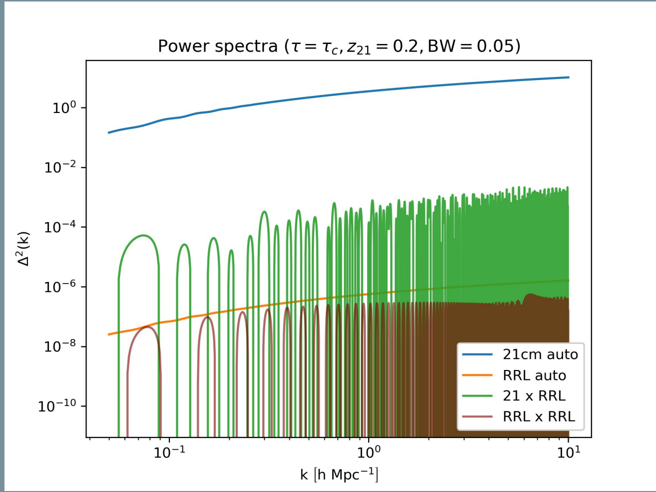


Fixed T

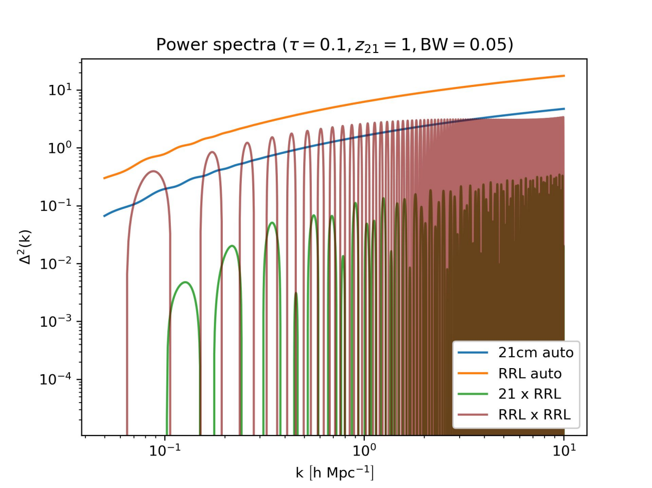
Model T

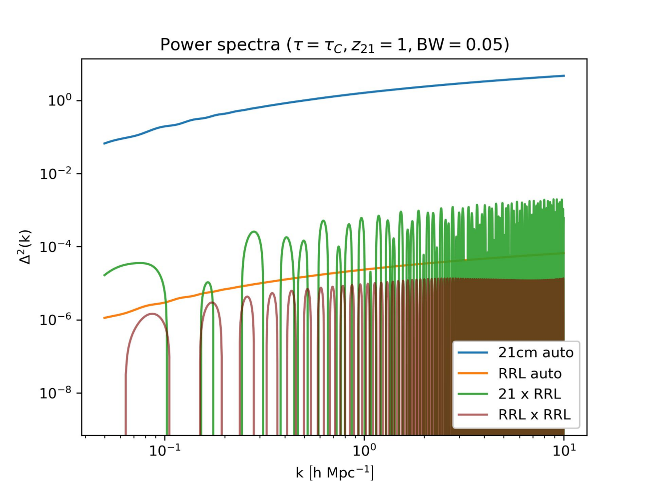
$z = 0.2$



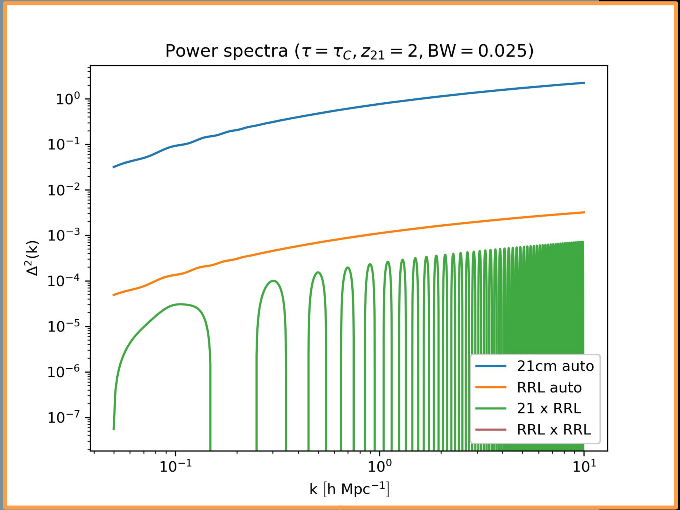


$z = 1$

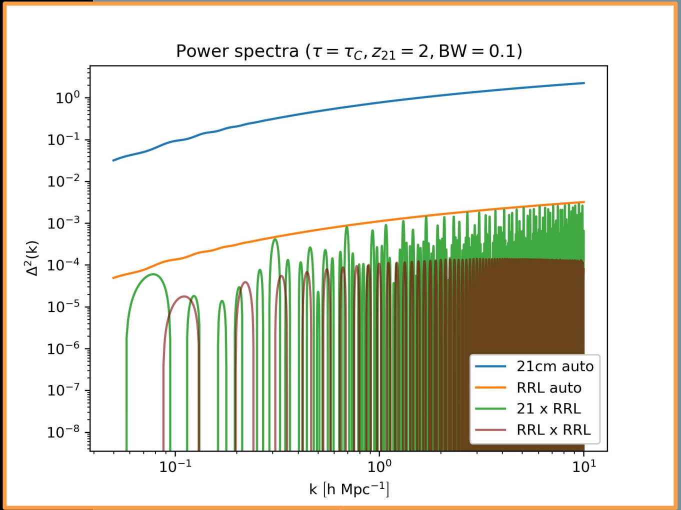




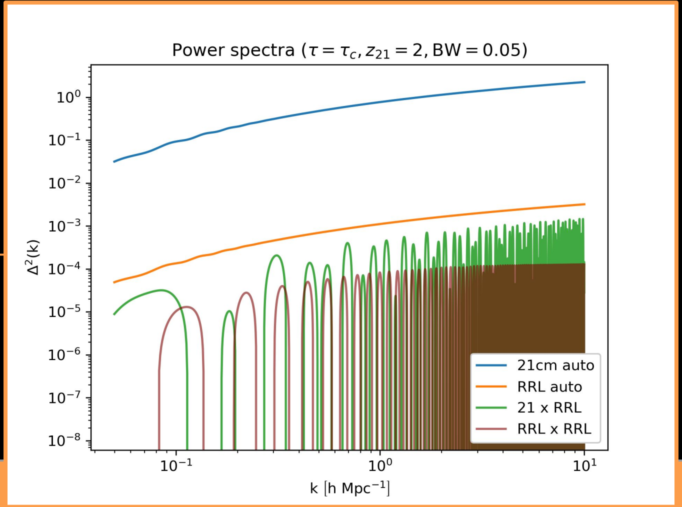
At $z = 2$, changing bandwidth (BW) influences how many RRLs contaminate the signal



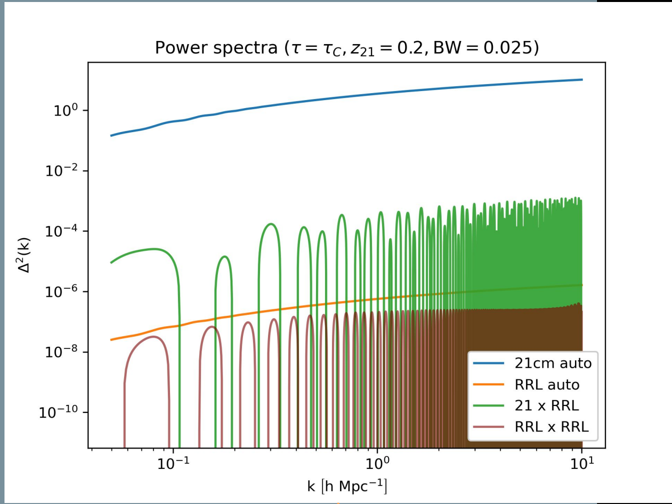
$\mathrm{BW} = z_{21\,\mathrm{obs}} \pm 0.025$



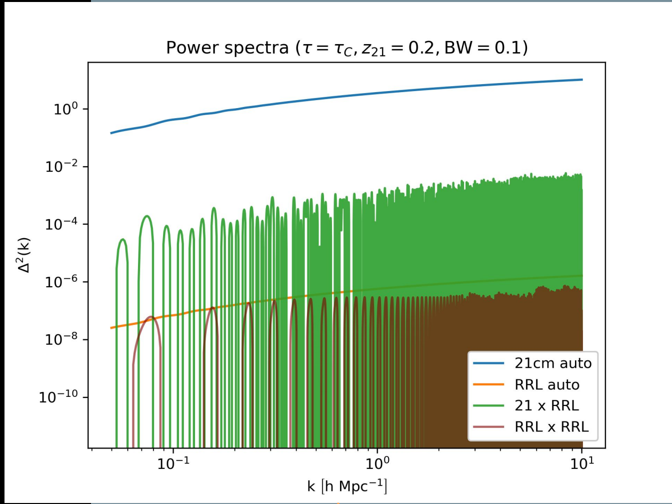
$\mathrm{BW} = z_{21\,\mathrm{obs}} \pm 0.1$



$\mathrm{BW} = z_{21\,\mathrm{obs}} \pm 0.05$

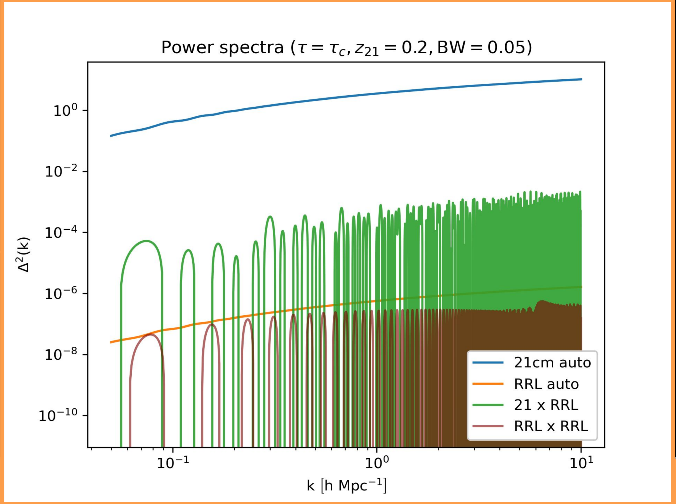


At z = 0.2, changing bandwidth (BW) influences how many RRLs contaminate the signal



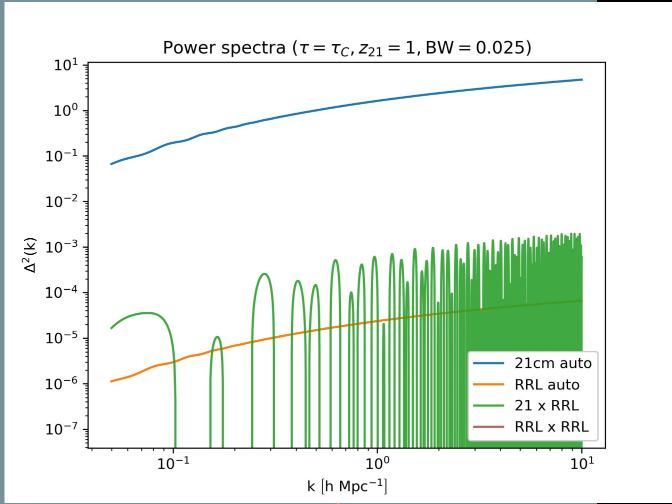
$BW = z_{obs} \pm 0.025$

$BW = z_{obs} \pm 0.1$

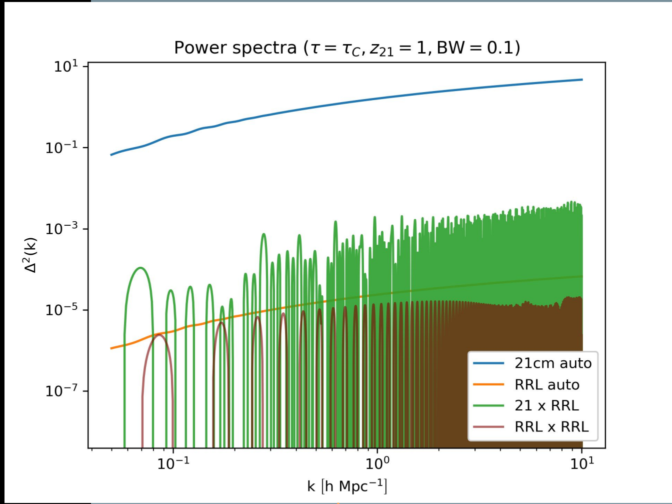


$BW = z_{obs} \pm 0.05$

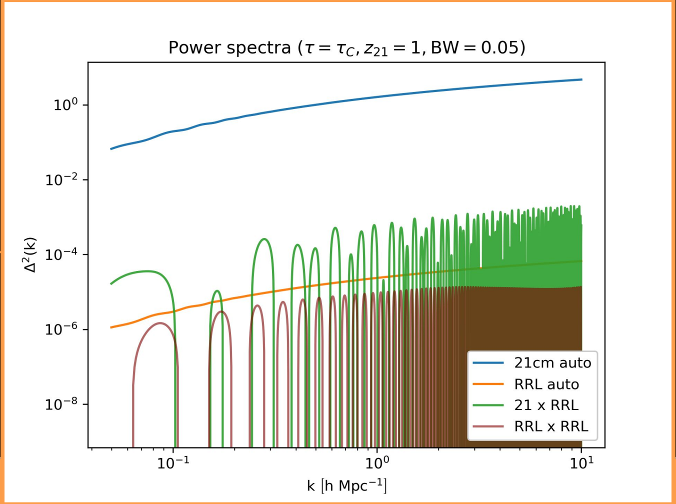
While this RRL strength may seem slightly worrying…



At $z = 1$, changing bandwidth (BW) influences how many RRLs contaminate the signal



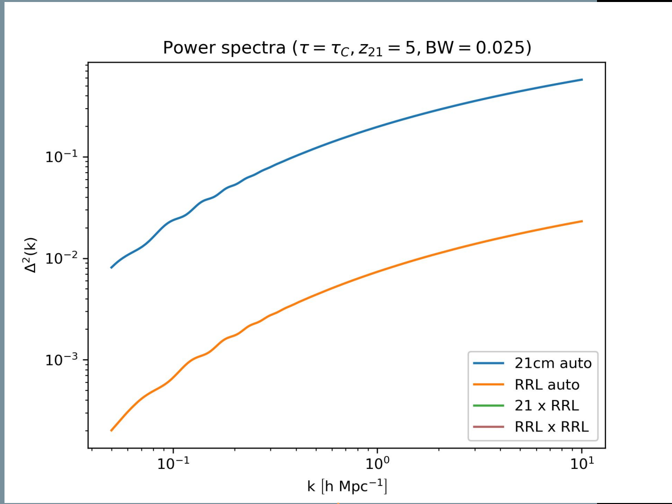
$\mathrm{BW} = z_{obs} \pm 0.025$



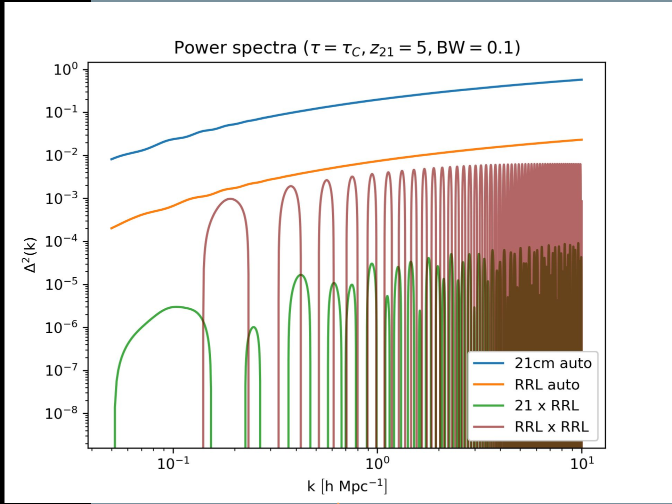
$\mathrm{BW} = z_{obs} \pm 0.1$

$\mathrm{BW} = z_{obs} \pm 0.05$

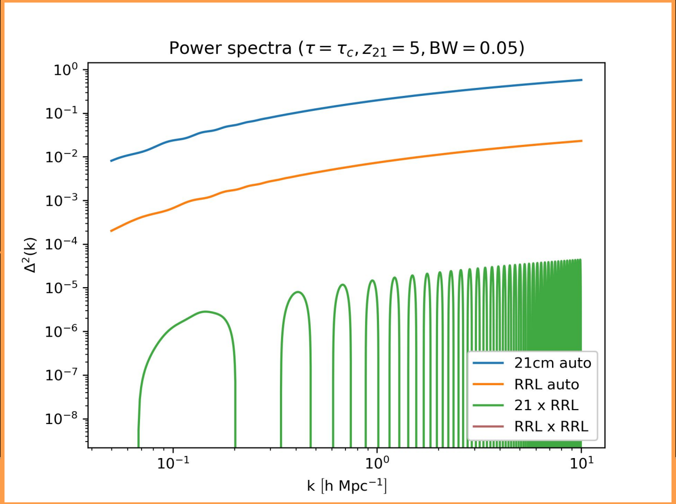
While this RRL strength may seem slightly worrying...



At z = 5, changing bandwidth (BW) influences how many RRLs contaminate the signal



BW = $z_{obs} \pm 0.025$



BW = $z_{obs} \pm 0.1$

BW = $z_{obs} \pm 0.05$

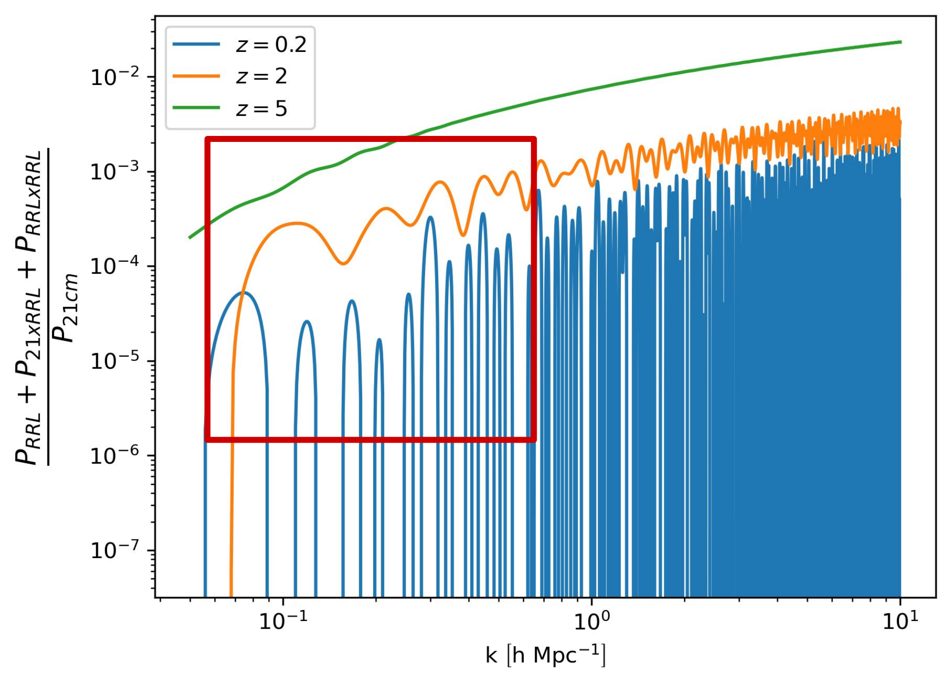
While this RRL strength may seem slightly worrying...

RRL power spectra residuals

Want to measure 10% BAO to 1% accuracy

Oscillations at 0.1 level can shift BAO peak and so incorrect angular distances

BW = 0.05



Conclusions and Takeaways for LIM

Thank you!

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- RRLs are an important contaminant for **precision cosmology** in Intensity Mapping

- Cross-power spectra from RRLs introduce **ringing effects** that may impact estimates from BAO

- Current optical depth models for RRLs predict **significant contamination** in the 21cm Power Spectrum

- **Next steps**: Improve physical optical depth model across redshift

$$P_{RRL\times RRL} = \frac{J_{RRL}}{J_{21}} G^2(z_{RRL}) b_{RRL}^2 \frac{T_{RRL}^2}{T_{21}^2} \mathscr{P}_{RRL\times RRL}$$

$$\mathscr{P}_{RRL\times RRL} = P_{\text{matter}}(k_{\text{shift}})$$

$$k_{\text{shift}} = k \times \frac{(1+z_{\text{RRL}})}{(1+z_{21})} \cdot \frac{H(z_{21})}{H(z_{\text{RRL}})}$$

$$P_{21\times RRL} = \frac{J_{RRL}}{J_{21}} G(z_{21}) G(z_{RRL}) b_{21} b_{RRL} \frac{T_{RRL}}{T_{21}} \mathscr{P}_{21\times RRL}$$

$$\mathscr{P}_{21\times RRL} = 2P_{\text{matter}}(k)\ e^{ik\Delta x_{21-RRL}}$$

$$P_{RRL_1\times RRL_2} = \frac{J_{RRL}}{J_{21}} G(z_{RRL_1}) G(z_{RRL_2}) b_{RRL_1} b_{RRL_2} \frac{T_{RRL_1} T_{RRL_2}}{T_{21}^2} \mathscr{P}_{RRL_1\times RRL_2}$$

$$\mathscr{P}_{RRL_1\times RRL_2} = 2P_{\text{matter}}(k_{\text{shift}})\ e^{ik_{\text{shift}}\Delta x_{RRL_1-RRL_2}}$$

$$\left\langle \widetilde{\delta \overline{T}}_{tot} \widetilde{\delta \overline{T}}^*_{tot} \right\rangle = \left| \overline{T}_{21}(z_{21}) G(z_{21}) b_{21} \right|^2 \tag{25}$$
$$+ \sum_{\ell} J^{-1} \overline{JT}^2_{RRL_\ell} \int_{-\infty}^{\infty} \frac{dk'}{2\pi} P_{RRL_\ell - RRL_\ell}(\mathbf{k}_\perp, k_\parallel - k') e^{-i(k_\parallel - k')\Delta x} \; L \text{ sinc} \left(\frac{k'L}{2} \right)$$
$$+ \sum_{m} J^{-1} \overline{JT}_{21} \overline{JT}_{RRL_m} \int_{-\infty}^{\infty} \frac{dk'}{2\pi} P_{21 - RRL_m}(\mathbf{k}_\perp, k_\parallel - k') e^{-i(k_\parallel - k')\Delta x} \; L \text{ sinc} \left(\frac{k'L}{2} \right)$$
$$+ \sum_{p,q} J^{-1} \overline{JT}_{RRL_p} \overline{JT}_{RRL_q} \int_{-\infty}^{\infty} \frac{dk'}{2\pi} P_{RRL_p - RRL_q}(\mathbf{k}_\perp, k_\parallel - k') e^{-i(k_\parallel - k')\Delta x} \; L \text{ sinc} \left(\frac{k'L}{2} \right)$$

In the simplest form, we can generalize the full expression as

$$P_{\text{obs}}(\vec{k}) = P_{21}(z_{21}) + \sum_{\ell} P^{\ell}_{RRL}(z^{\ell}_{RRL}) + \sum_{m} P^{m}_{RRL-21}(z_{21}, z^{m}_{RRL}) + \sum_{p,q} P^{p,q}_{RRL_p - RRL_q}(z^{p}_{RRL}, z^{q}_{RRL}) \tag{26}$$