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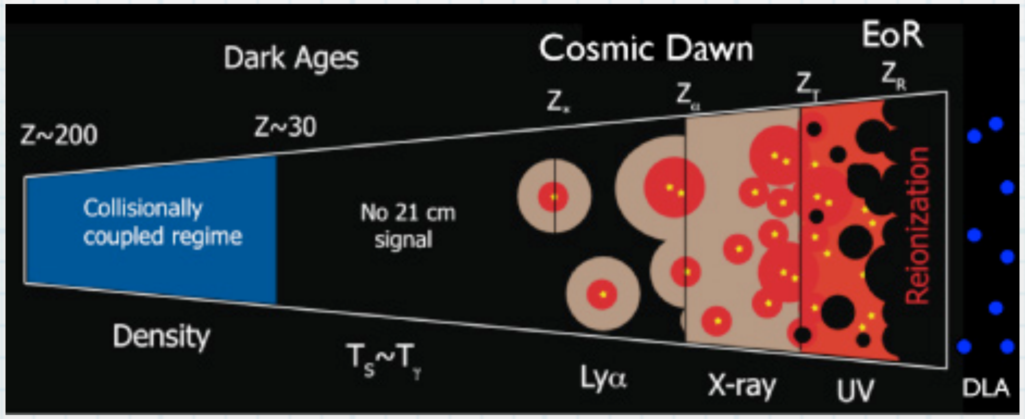
Signatures of Modified Gravity

on the 21cm power spectrum at reionisation



Dark Energy Interactions workshop
1-3 October 2014

What is the 21cm Cosmic Background ?

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* 21 cm ? **Transition between 1S hyperfine levels of neutral hydrogen atoms**
* Neutral H atoms ? **From recombination... until reionisation**
* Hyperfine Transitions ? **Several physical processes**

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21cm photons in the tail of the CMB black-body spectrum Absorption or stimulated Emission

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Spontaneous Emission	21cm photons in the tail of the CMB black-body spectrum Absorption or stimulated Emission	Spin-changing collisions with H atoms and electrons	Wouthuysen-Field effect : Resonant scattering of Ly-alpha photons causing a spin-flip via an intermediate excited state

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Spontaneous Emission

Negligible

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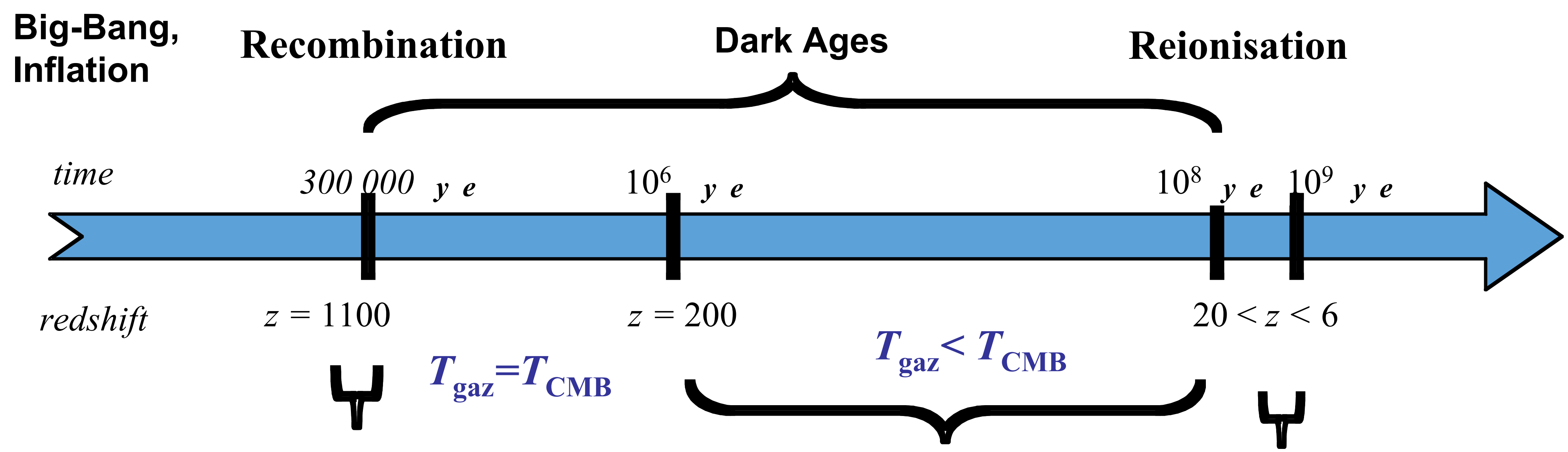

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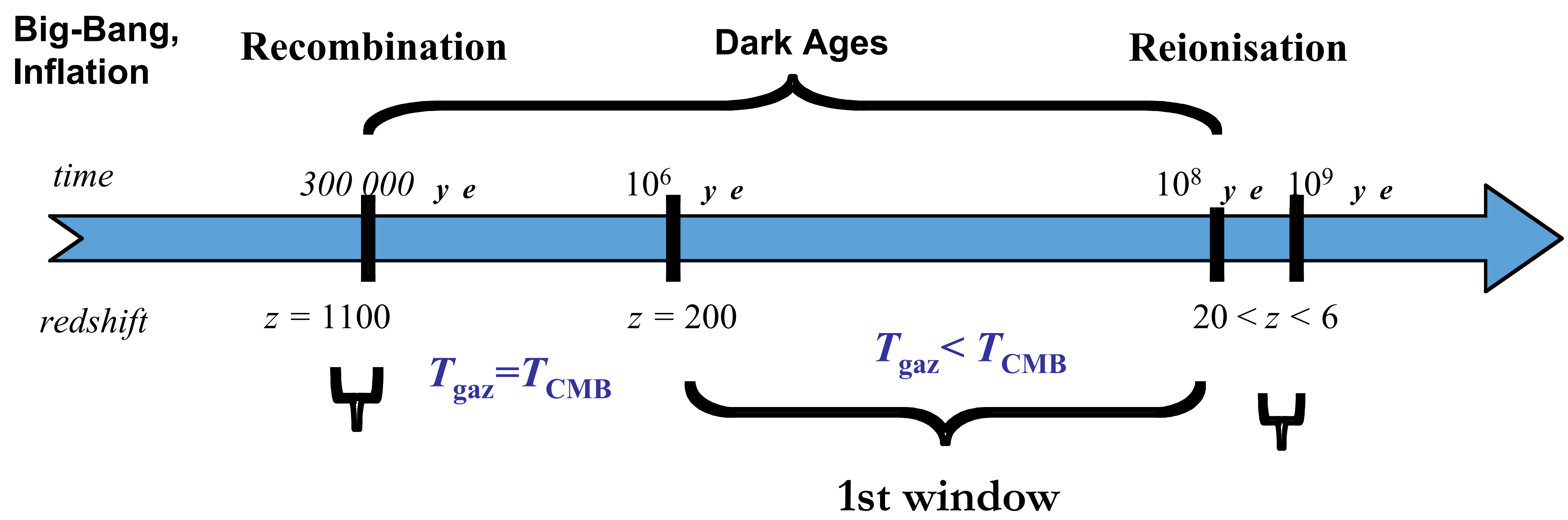
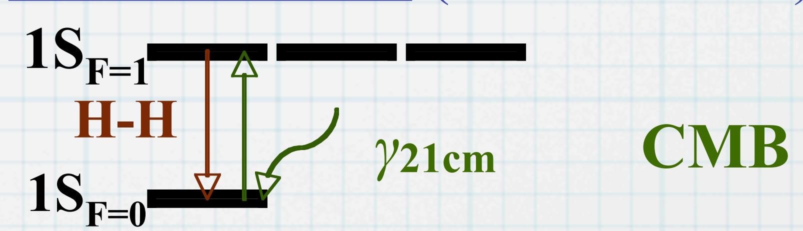


1st window: Dark ages

Signal driven by CMB and Collisions

Collisions H-H ($200 > z > 30$)



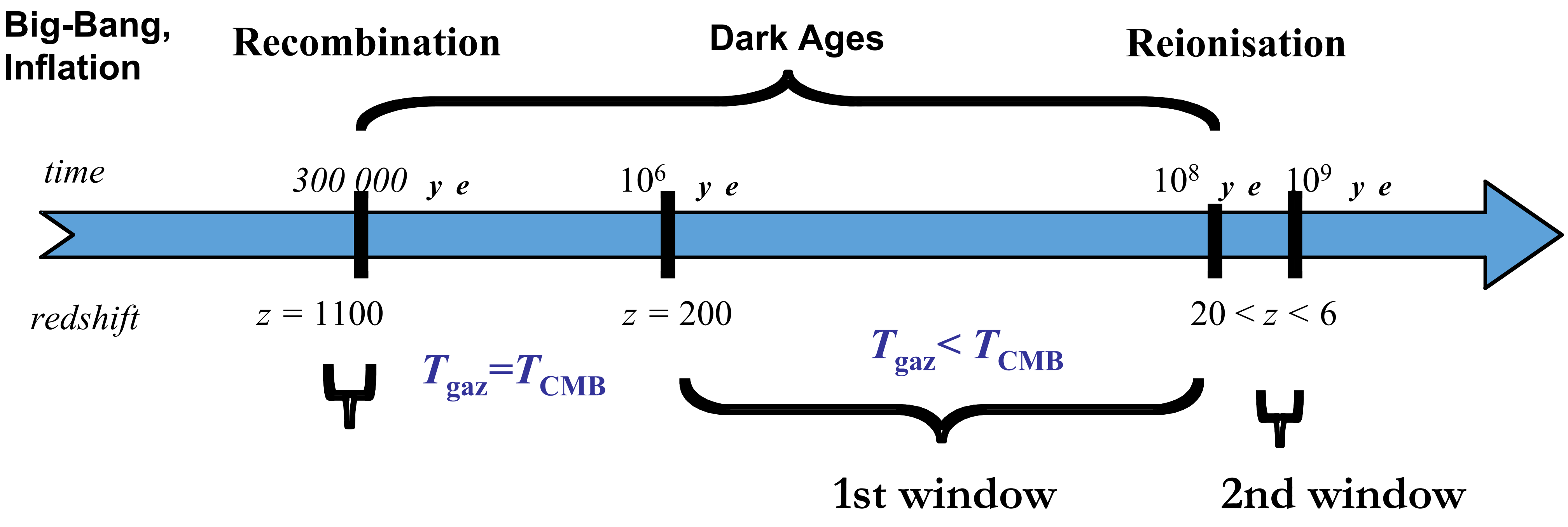
Observation:

Absorption of redshifted γ_{21cm} CMB photons,

Depends on the density of neutral H atoms

Direct probe of the matter power spectrum

What is the 21cm Cosmic Background ?



1st window: Dark ages

Signal driven by CMB and Collisions

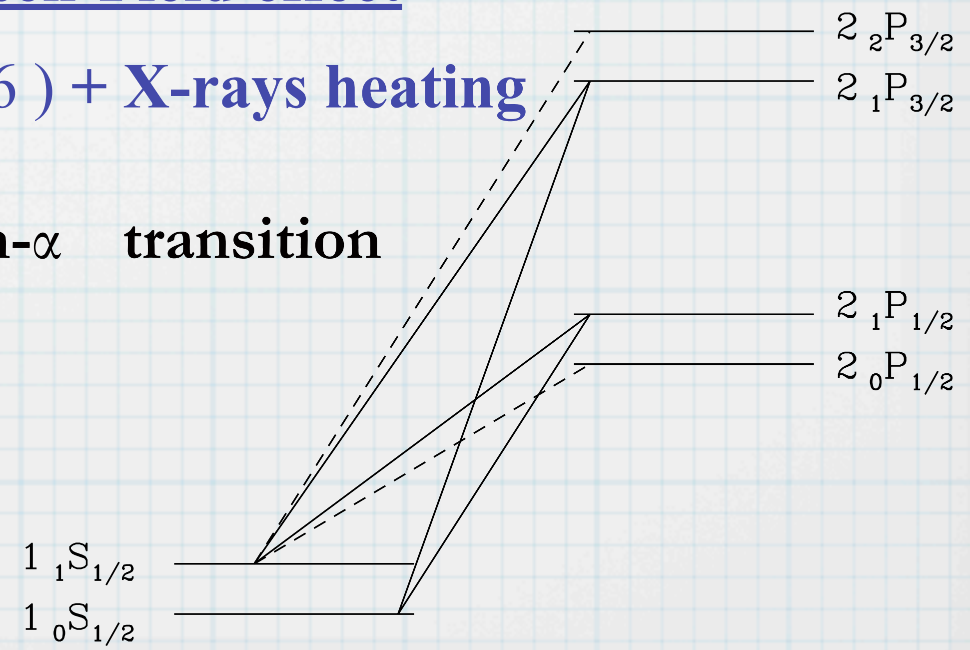
2nd window: Reionisation

Signal driven by CMB and Wouthuysen-Field effect (Ly-alpha radiation from the first stars)

Wouthuysen-Field effect

$(20 < z < 6)$ + **X-rays heating**

Lyman-α transition



Advantages-Disadvantages

* Disadvantages :
  * Low Signal to noise ratio
  * Details of the reionisation era not known
  * Ionospheric foregrounds: opacity for frequencies < 30 Mhz ($z > 50$)
* Advantages :
  * 3D Tomography of the Universe over the redshift range $200 < z < 2$
  * Dark ages: simple physics => direct probe of density perturbations
  * Probe much smaller scales than with CMB anisotropies (no Silk damping)
  * At high redshift, smaller scales are in the linear regime

The 21cm power spectrum at reionisation

Brightness temperature:

$$T_{\rm B}(E) = \frac{3c^3 n_{\rm H}(a_E) A_{10} h_{\rm p}^3 T_{21}}{32\pi E_{21} H(a_E)} \left.\frac{T_{\rm s} - T_\gamma}{T_s(1+z)}\right|_{\eta(a_E)} .$$

= 1 / (1+z)

spin and photon temperature

perturbations are second order

Useful approximation: $T_{\rm s} \simeq T_{\rm g} \gg T_\gamma$

Power spectrum :

$$P_{T_{\rm b}}(\mathbf{k}) = {\rm e}^{-2\tau_{\rm C}} \tilde{T}_{\rm b}^2 \left[P_0(k) + \mu^2 P_2(k) + \mu^4 P_4(k)\right]$$

$$P_0(k) \equiv x_{\rm H}^2 P_{\rm b}(k) + x_{\rm i}^2 P_{\rm ii} - 2 x_{\rm H} x_{\rm i} P_{\rm ib}(k),$$

$$P_2(k) \equiv 2\left[x_{\rm H} x_{\rm i} P_{\rm ib}(k) - x_{\rm H}^2 P_{\rm ib}(k)\right],$$

$$P_4(k) \equiv x_{\rm H}^2 P_{\rm b}(k),$$

→ **The mu-dependance can be used to extract the cosmological signal**

where $\mu \equiv \boldsymbol{k} \cdot \hat{\boldsymbol{n}}/k$ and $\widetilde{T}_{\rm b} \equiv T_{\rm b}/x_{\rm H}$

From k-space to u-space :

$$\mathbf{\Theta} = \frac{\mathbf{r}_\perp}{D_{\rm A}(z)}, \qquad F = \frac{r_\parallel}{y(z)} \qquad D_{\rm A}(z) = \int_0^z \frac{1}{H(z')} {\rm d}z'$$

$$\mathbf{u}_\perp = D_{\rm A}(z)\mathbf{k}_\perp, \qquad u_\parallel = y(z) k_\parallel \qquad y(z) = \frac{\lambda_{21}(1+z)^2}{H(z)}$$

→

$$P_{\delta T_{\rm b}}(\mathbf{u}) = \frac{P_{\delta T_{\rm b}}[\mathbf{k}(\mathbf{u})]}{D_{\rm A}^2(z) y(z)}$$

The 21cm signal to constrain DE-MG

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Beyond the w and dw/da parametrization (ref), only a very few papers:

- Archidiacono, Lopez-Honorez, Mena, 1409.1802: forecasts for early dark energy with CHIME / FFTT experiments
- Duniya, Bertacca, Maartens, 1305.4509: Clustering of quintessence with 21cm intensity mapping
- Hall, Bonvin, Challinor, 1212.0728 : CHIME experiment, f(R) model, post-reionisation $B0 < 7 \times 10^{-7}$
- Brax, Clesse, Davis, 1207.1273: f(R), chameleon, symmetron, dilaton models FFTT experiment

Tomographic approach of MG

MG Models described by two scale-independent functions of the scale factor:

The scalar field mass m and the coupling to matter β

f(R): $\beta = 1/\sqrt{6}$, $m = m_0 a^{-r}$

$r = 3(n+2)/2$

Chameleons: β **constant,** $m = m_0 a^{-r}$

$n = (2r-6)/(2r-3)$

Symmetron:

$$\beta(a) = \beta_\star \sqrt{1 - \left(\frac{a_\star}{a}\right)^3}$$

$$m(a) = m_\star \sqrt{1 - \left(\frac{a_\star}{a}\right)^3}$$ **at** $z < z_\star$

Dilaton: $m = m_0 a^{-2}$

$$\beta = \beta_0 a^3$$

1. **Background dynamics identical to LCDM**
2. **Compute linear perturbations**
3. **Compute the 21cm power spectrum at reionisation**

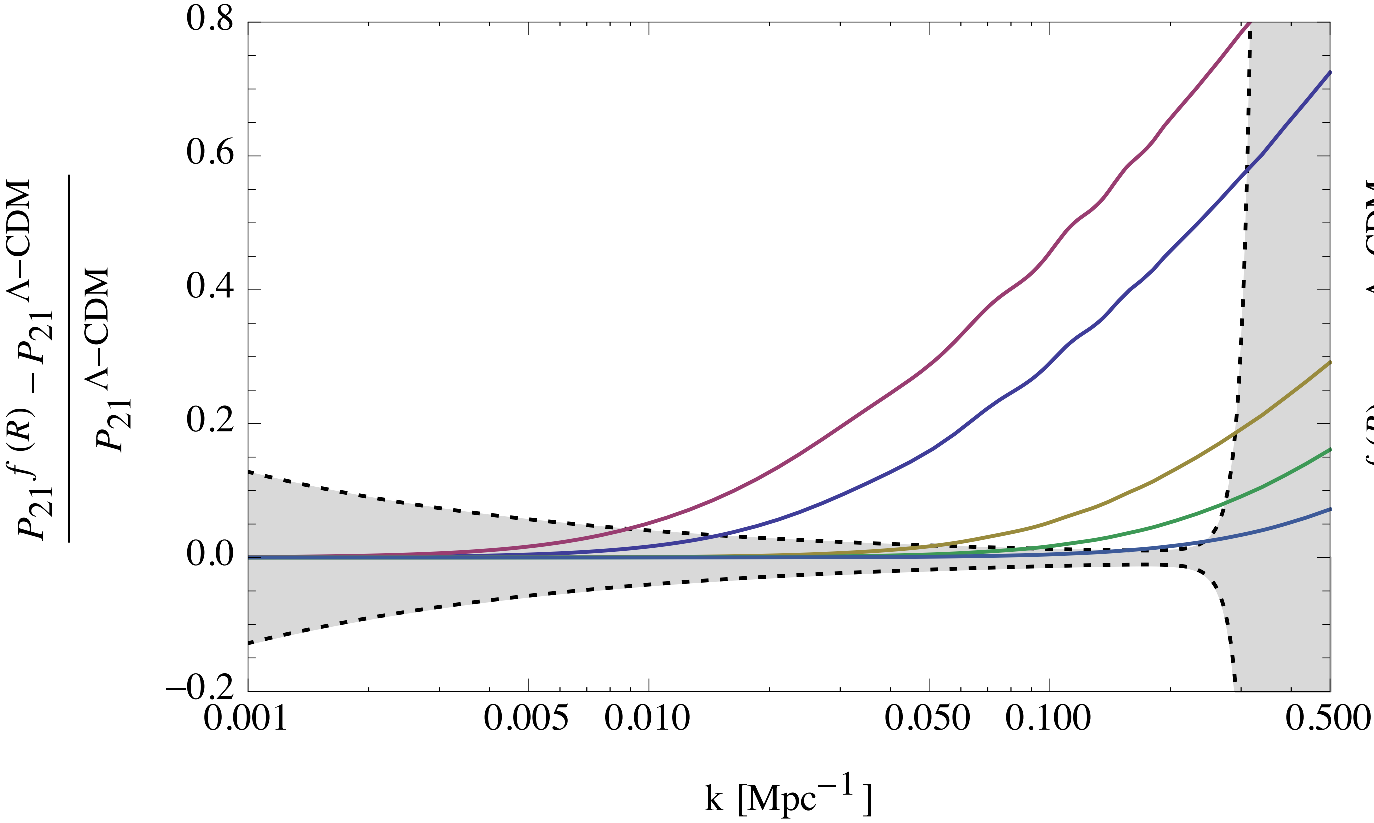
21cm experiment: Fast Fourier Transform Telescope, Tegmark, Zaldarriaga, 0805.4414

1km x 1km array of dipole antennas

Signatures of MG on the 21cm spectrum

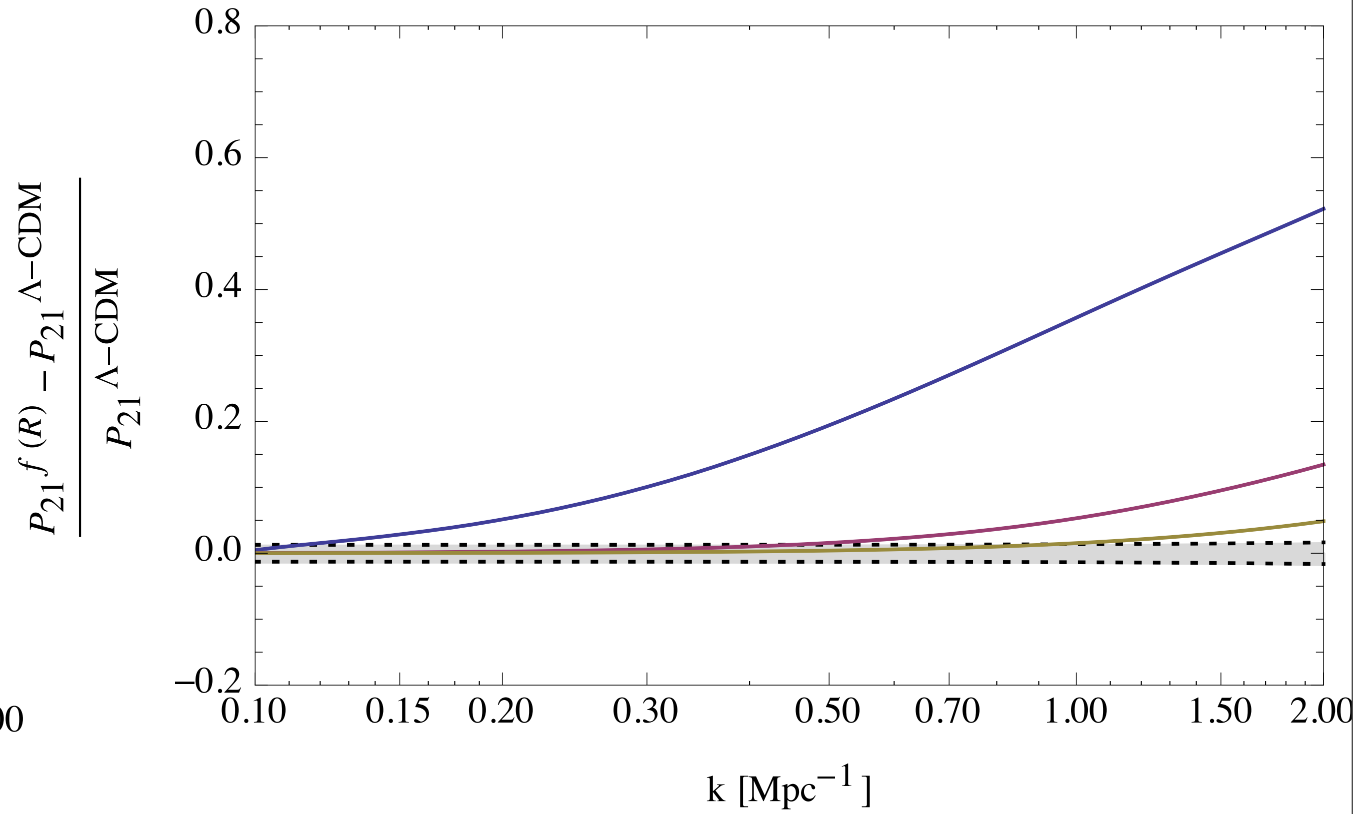
f(R)

$z = 11 \qquad x_{\mathrm{H}} = 0.9,$



$\mu = 0$ (i.e. for modes orthogonal to the line of sight)

m_0 is respectively $5\times10^{-5}\mathrm{Mpc}^{-1}$ (red), $10^{-4}\mathrm{Mpc}^{-1}$ (dark blue) $5\times10^{-4}\mathrm{Mpc}^{-1}$ (yellow), $10^{-3}\mathrm{Mpc}^{-1}$ (green) and $2\times10^{-3}\mathrm{Mpc}^{-1}$ (blue)



$k_{\perp} = 0.1\mathrm{Mpc}^{-1}$

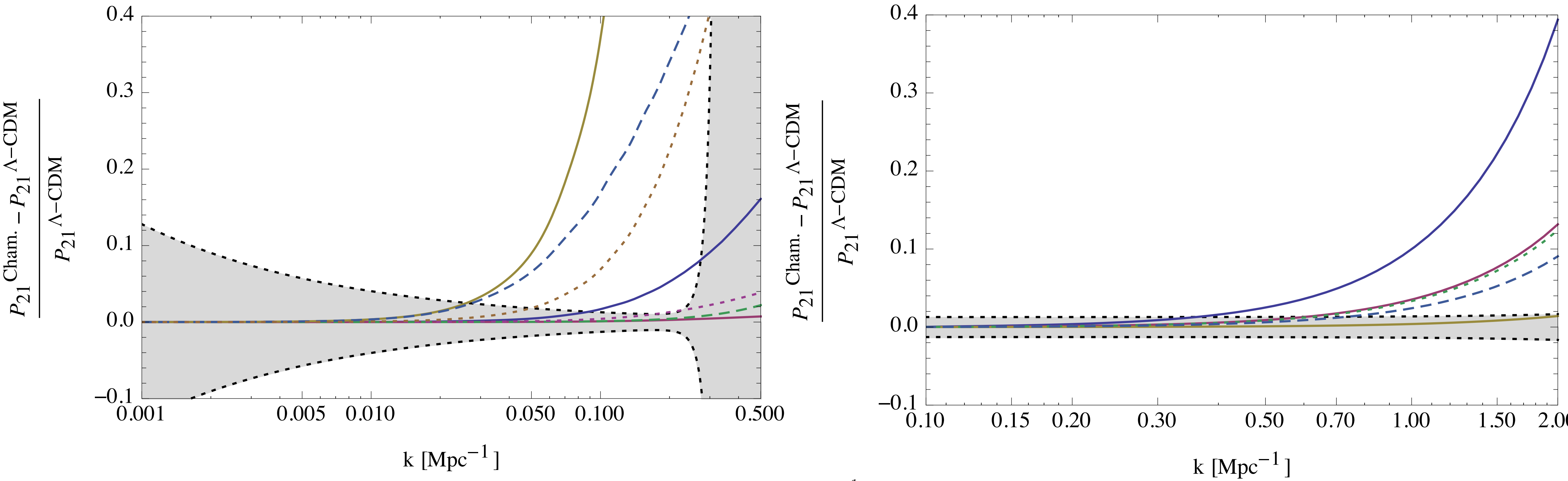
$2\times10^{-3}\mathrm{Mpc}^{-1}$ (blue), $10^{-2}\mathrm{Mpc}^{-1}$ (red) and $2\times10^{-2}\mathrm{Mpc}^{-1}$ (yellow)

- $m_0 \simeq 2\times10^{-2}\mathrm{Mpc}^{-1}$ **could be detected, for modes almost parallel to the line of sight**
- **Typically one order of magnitude better than LSS constraints (linear regime)**
- **Competitive with solar system constraints, but less stringent than galaxy constraints**

Signatures of MG on the 21cm spectrum

Chameleon/Dilaton

$z = 11 \qquad x_{\mathrm{H}} = 0.9,$



$m_0 = 10^{-3}\mathrm{Mpc}^{-1}$, $\beta_0 = 1/\sqrt{6}$, $r = 3$ and $s = 0$ (blue)

$s = 0.5$ (top yellow)

$s = -0.5$ (bottom red)

Dashed curves are for $r = 3.5$ (bottom green)

dotted curves are for $\beta_0 = 2/\sqrt{6}$ (top yellow) and $\beta_0 = 1/(2\sqrt{6})$ (bottom red)

$m_0 = 0.1\mathrm{Mpc}^{-1}$, $r = 3$, $s = 0$ and $\beta_0 = 5$ (top blue), $\beta_0 = 3$ (red) and $\beta_0 = 1$ (bottom yellow)

dotted curve is for $m_0 = 0.1\mathrm{Mpc}^{-1}$, $s = 0$, $\beta_0 = 5$ and $r = 3.2$

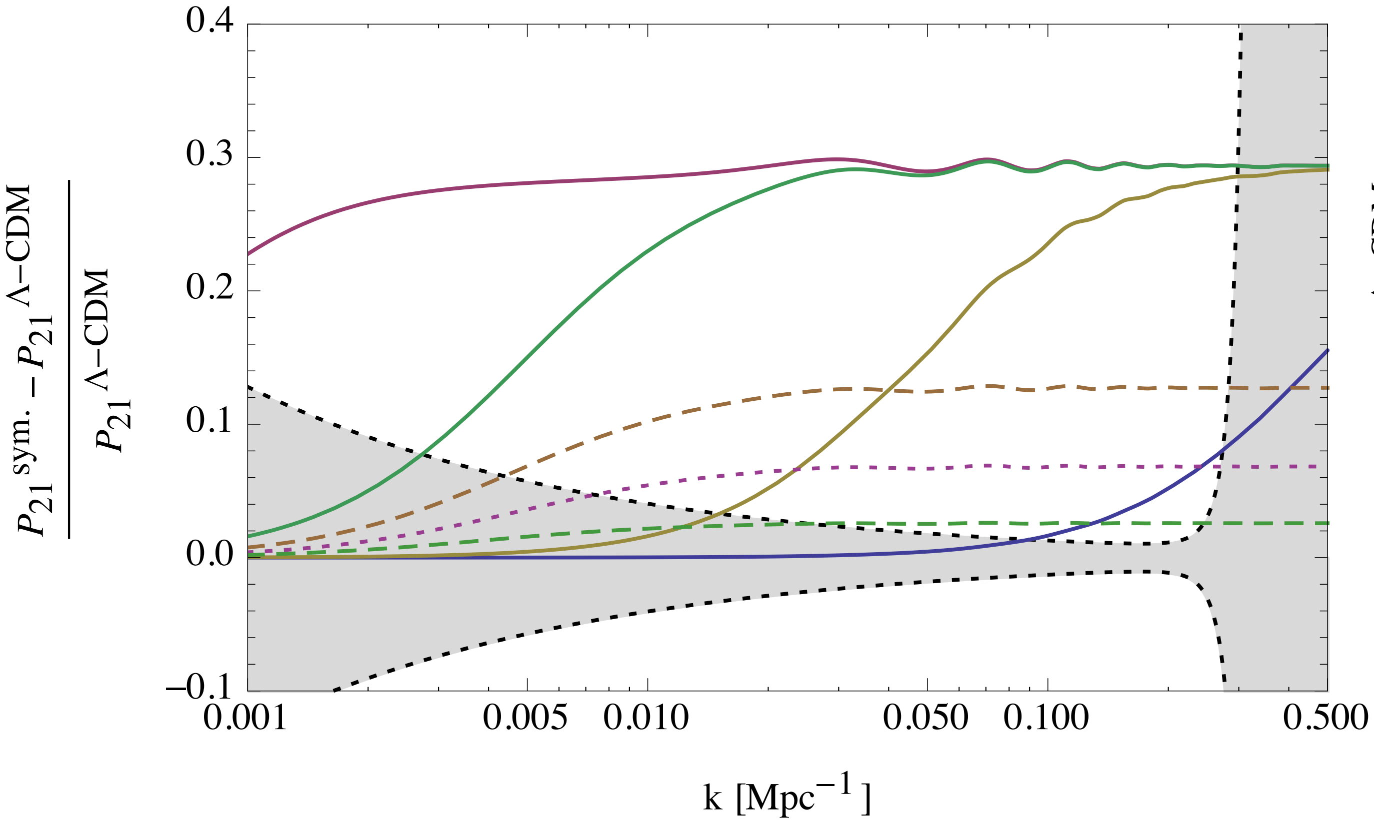
dashed curve is for $s = 0.5$ $r = 3$, $\beta_0 = 5$ and $m_0 = 0.8\mathrm{Mpc}^{-1}$

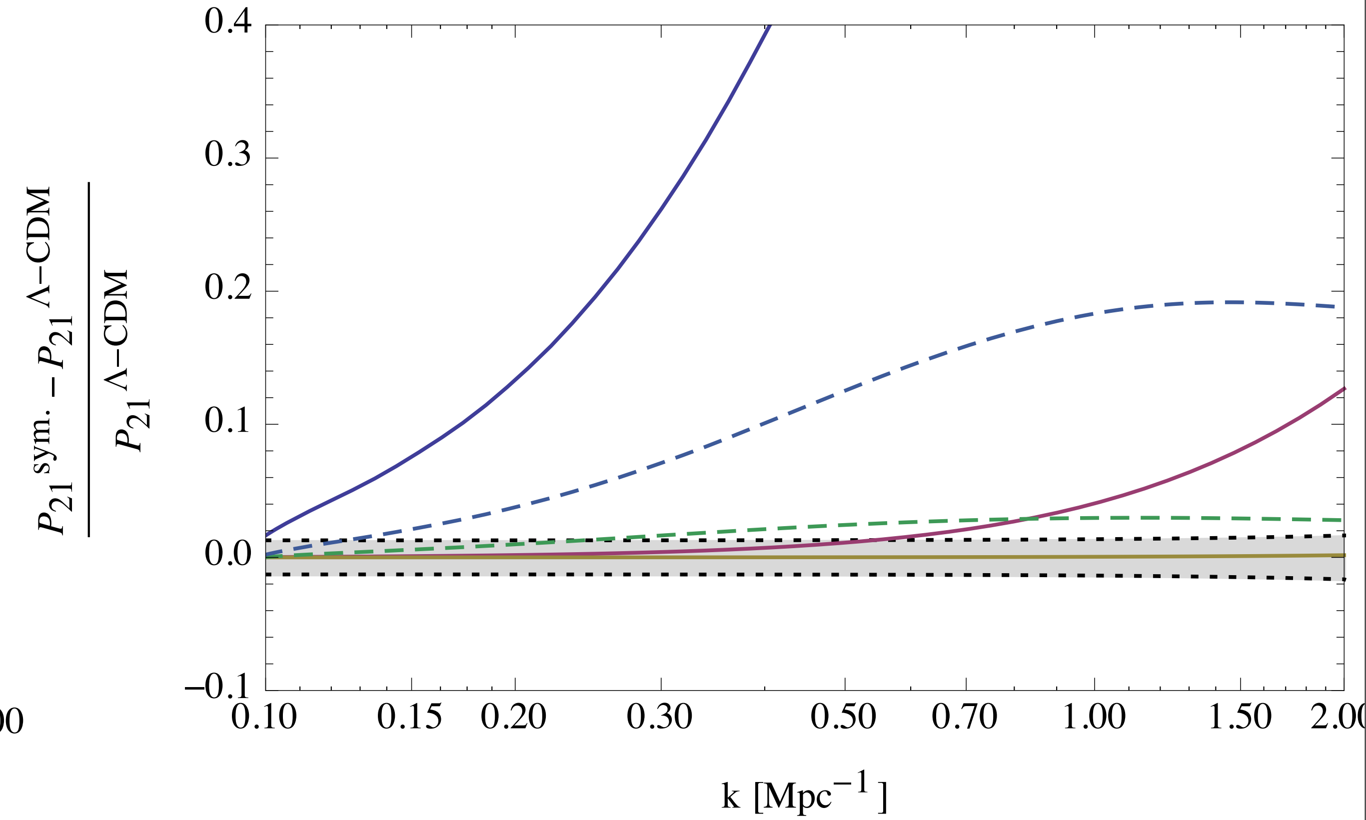
- **Dilaton: at reionisation, coupling to matter about 1000 times lower than today, so there is no visible signature in the 21cm spectrum**
- **Chameleon: Imposing $s = 0$ and $r = 3$ with $m_0 = 0.1\mathrm{Mpc}^{-1}$, observable signatures down to $\beta_0 \approx 2$ for modes almost parallel to the line of sight**

Signatures of MG on the 21cm spectrum

Symmetron

$z = 11 \qquad x_H = 0.9,$





Plain curves are for $z_\star = 20,\ \beta_0 = 1$

$m_0 = 10^{-2}\text{Mpc}^{-1}$ (red), 0.1Mpc^{-1} (green), 1Mpc^{-1} (yellow) 10Mpc^{-1} (blue)

dashed curves are for $\beta_0 = 1,\ m_0 = 0.1\text{Mpc}^{-1}$ with $z_\star$ varying $z_\star = 17$ $z_\star = 14$

$z_\star = 20,\ \beta_0 = 1$ and $m_0 = 10/100/1000\ \text{Mpc}^{-1}$ (respectively the blue, red and yellow plain curves) and $z_\star = 12$

The two dashed curves are for $\beta_0 = 1,\ m_0 = 10\ \text{Mpc}^{-1}$, $z_\star = 14$

- **For $\beta_0 \simeq 1$, the symmetron could be detected by FFTT up to $z_* \simeq 14$**
- **The 21cm signal probe different ranges of parameters than LSS at lower redshifts**
- **Smaller linear scales, and thus larger values of m_0 can be probed**
- **About 3 order of magnitudes better than local tests**

Conclusion and perspectives

* Signatures of MG on the 21cm power spectrum at reionization :
  * The 21cm is complementary to LSS and local tests
  * Probes high redshifts (interesting for symmetron)
  * Smaller scales accessible in the linear regime, importance of parallel modes
  * BUT: Assumptions about reionisation
* Perspectives :
  * MCMC-multiple redshift analysis
  * Other models, other experiments (SKA, CHIME)
  * Other periods : dark ages, post-reionisation