Measuring Primordial Magnetic Fields using the 21cm Signal from the Cosmic Dawn Epoch

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Schmidt Fellow

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With: Gluscević, V., Oklopčić, A., Mishra, A., Fang, X., and Hirata, C.

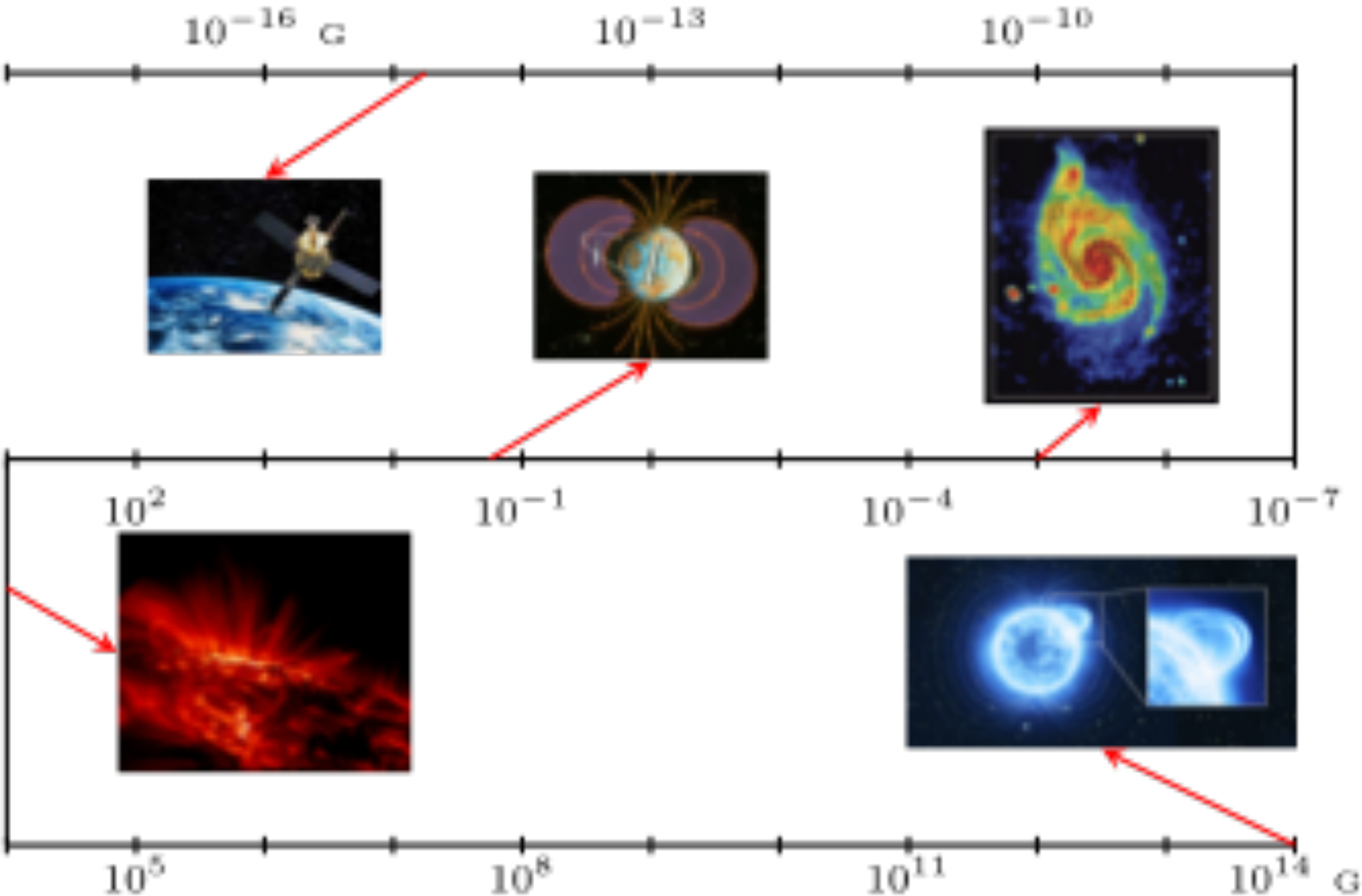
Outline

- Cosmological magnetic fields: current constraints
- The 21-cm line and cosmology
- Alignment of the triplet state
- Effect of magnetic fields
- Prospects for detection
- Gravitational waves(?)

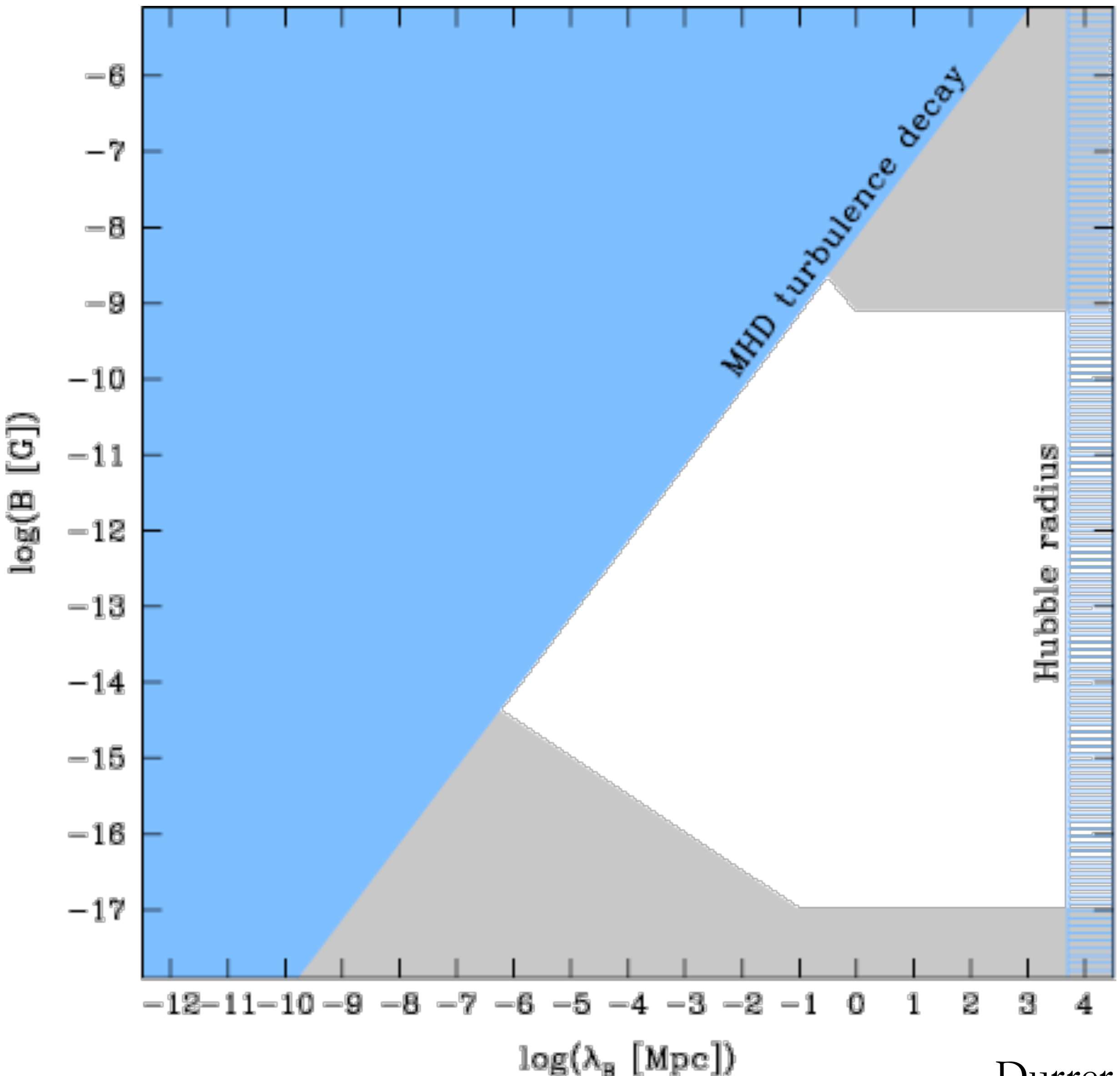
Introduction:

PRIMORDIAL MAGNETIC FIELDS

Magnetic fields: orders of magnitude

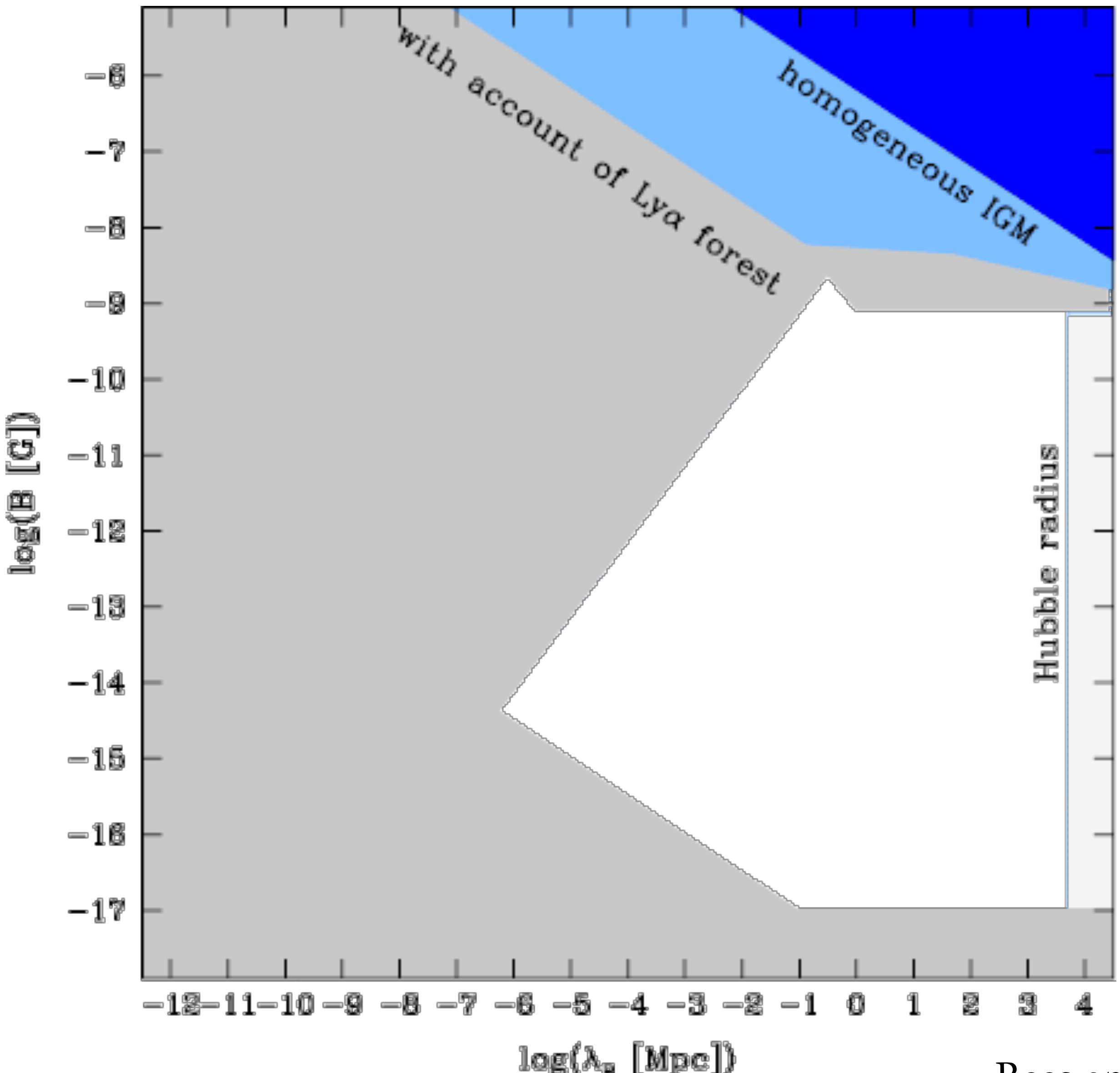


Current constraints on PMFs



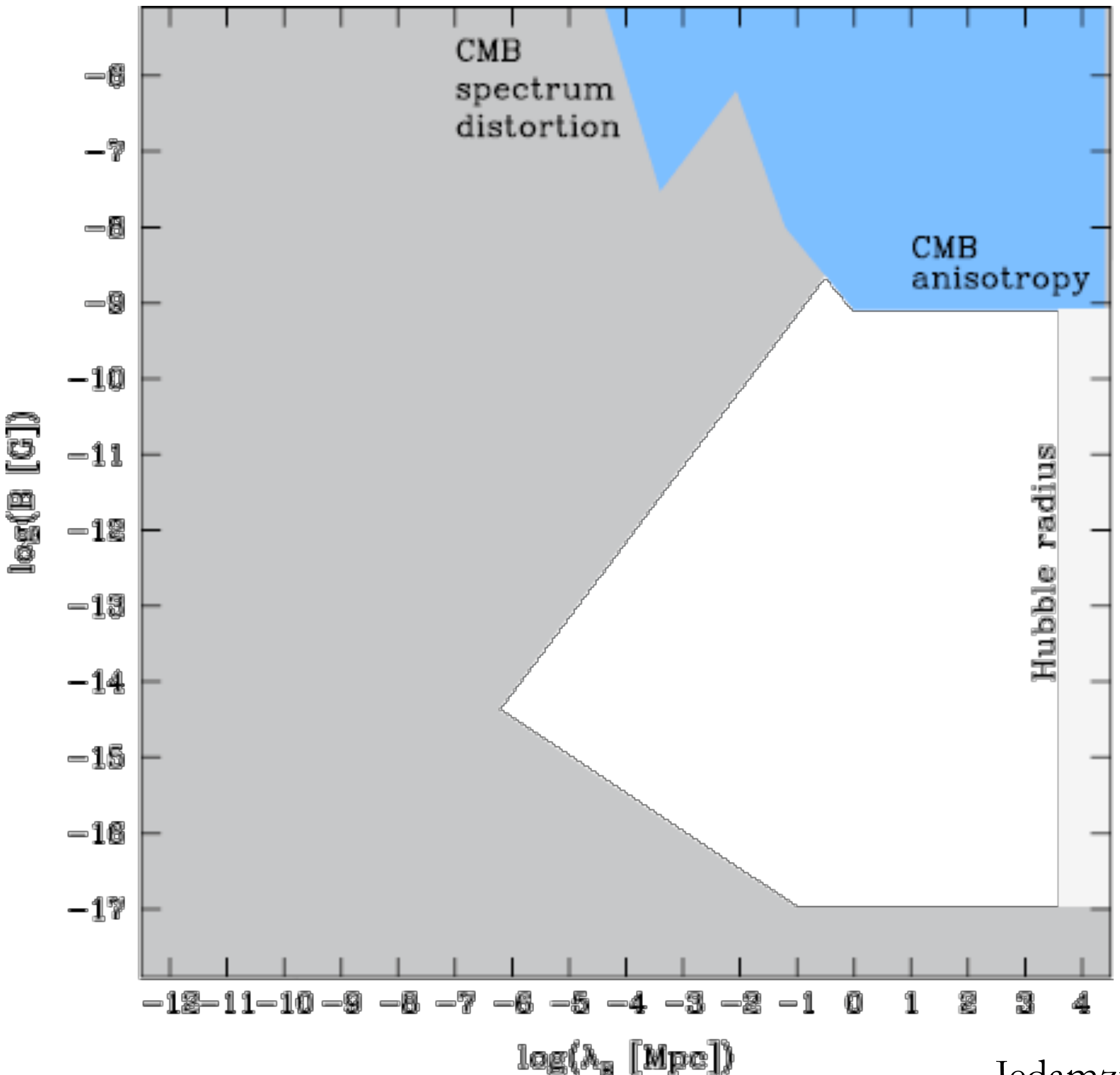
Durrer and Neronov (2014)

Current constraints on PMFs



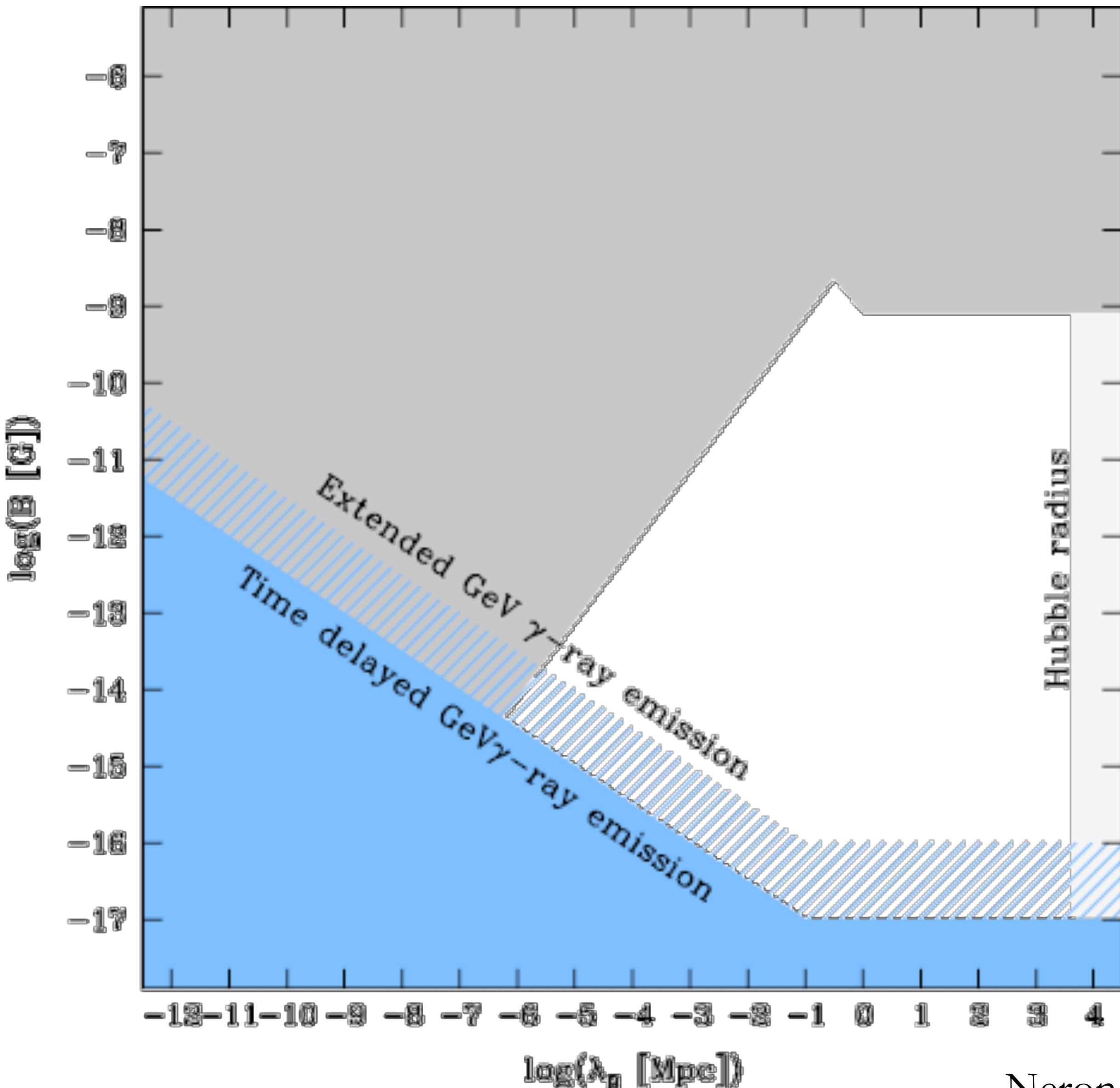
Rees and Reinhardt (1972)
Kronberg (1994)

Current constraints on PMFs



Jedamzik et. al. (2000)
Paoletti and Finelli (2011)

Current constraints on PMFs



Neronov and Vovk (2010)
Tavecchio, et. al. (2011)

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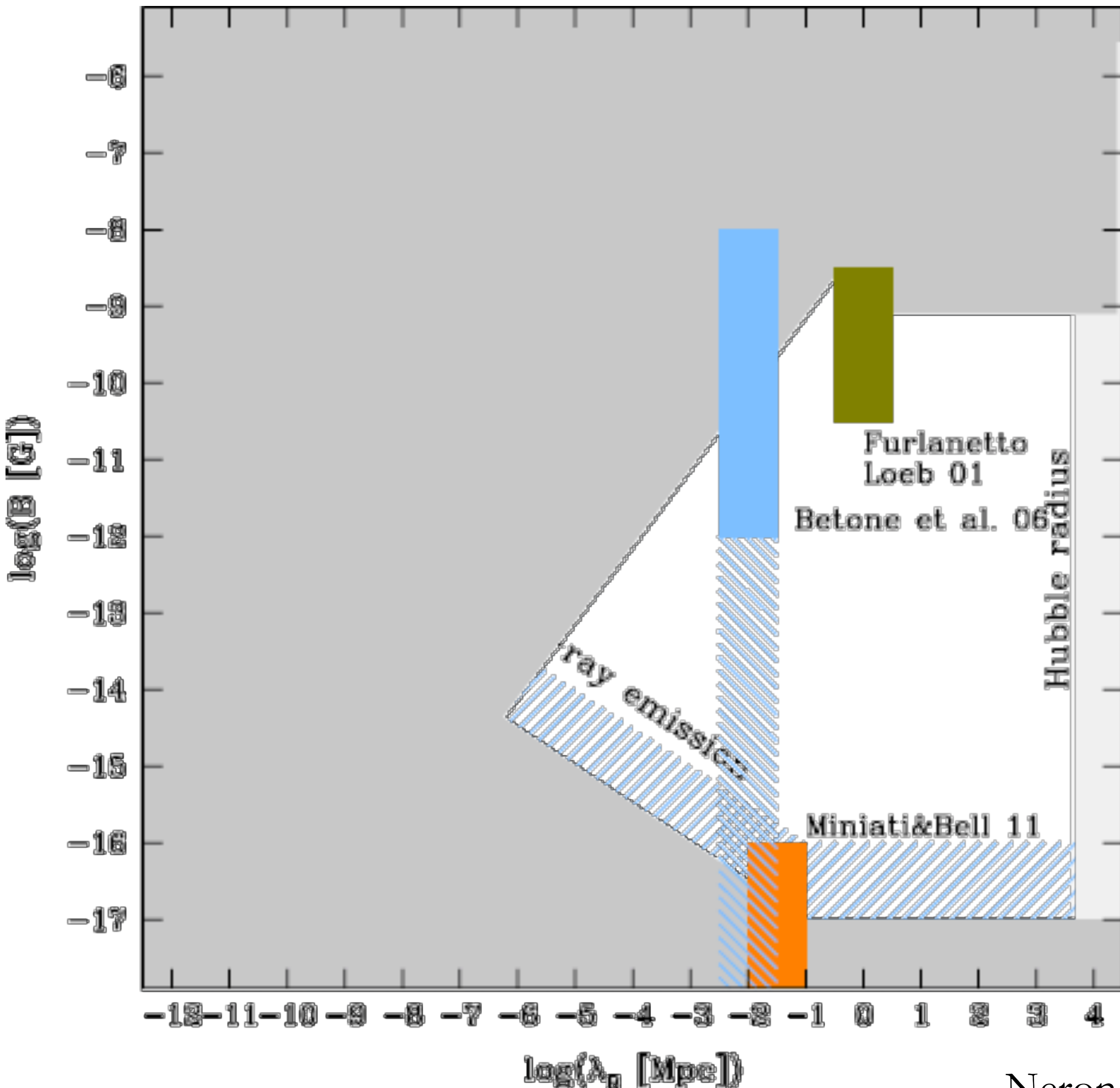

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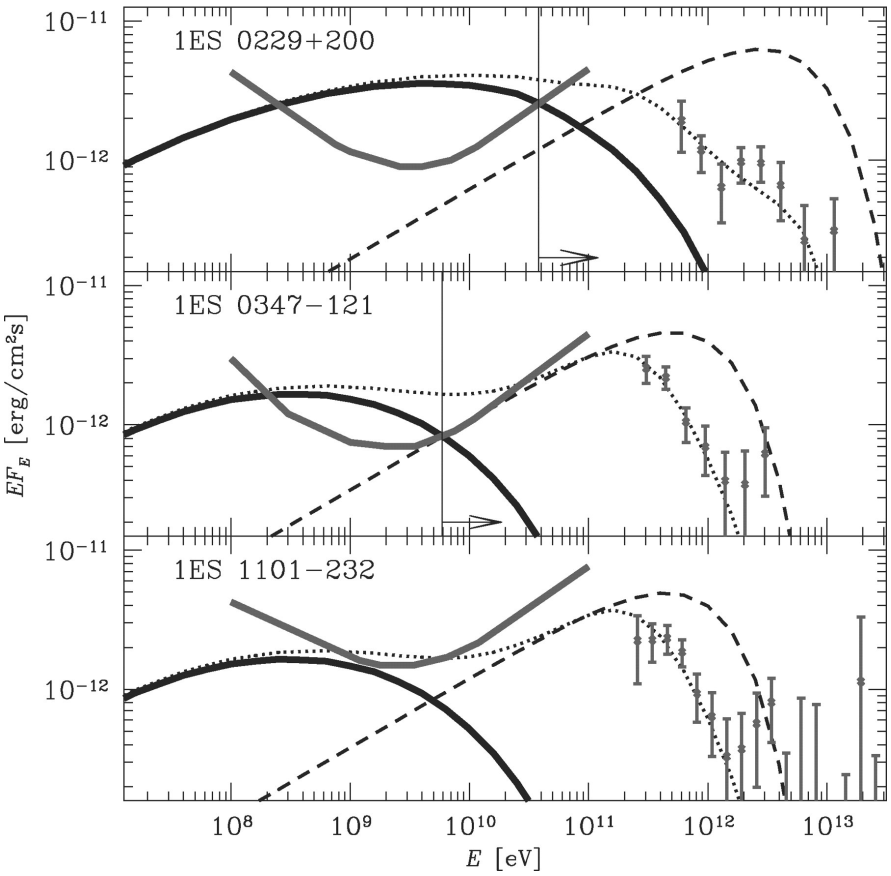

Neronov, A., and Vovk, I. (2010)

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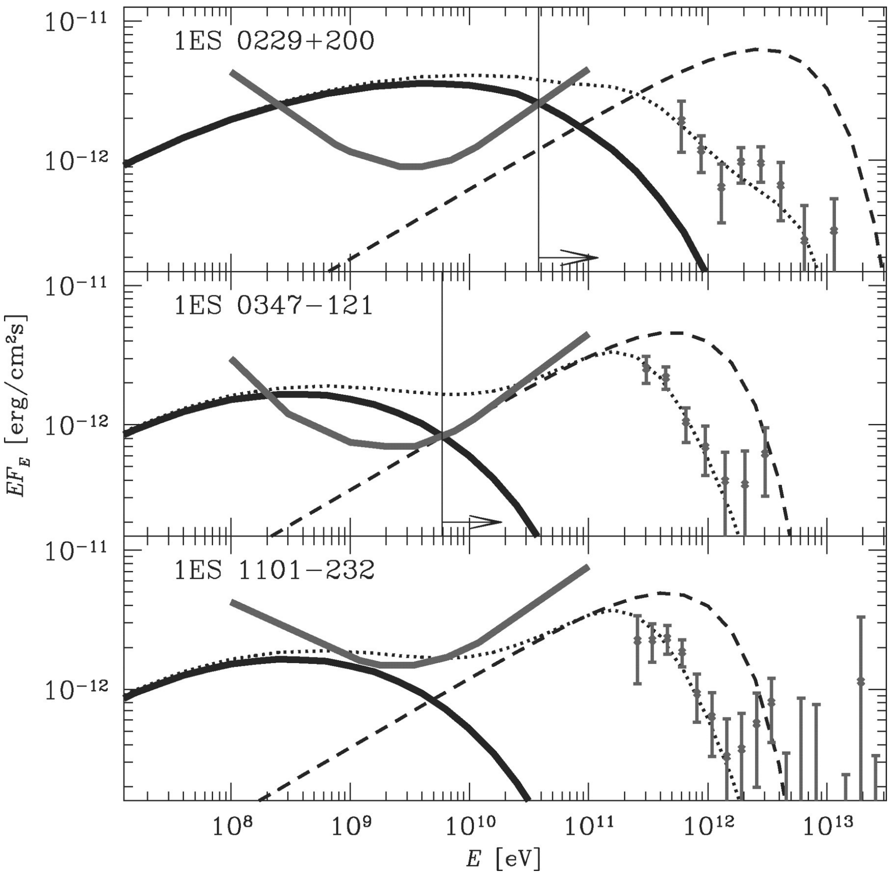

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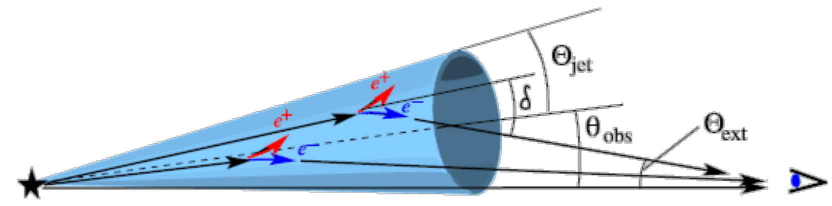
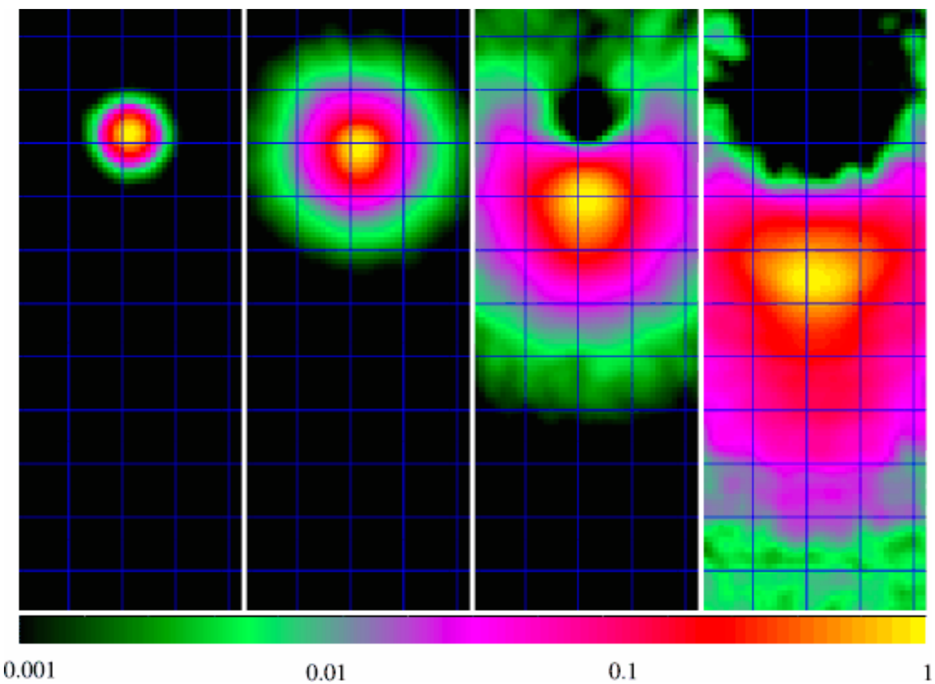
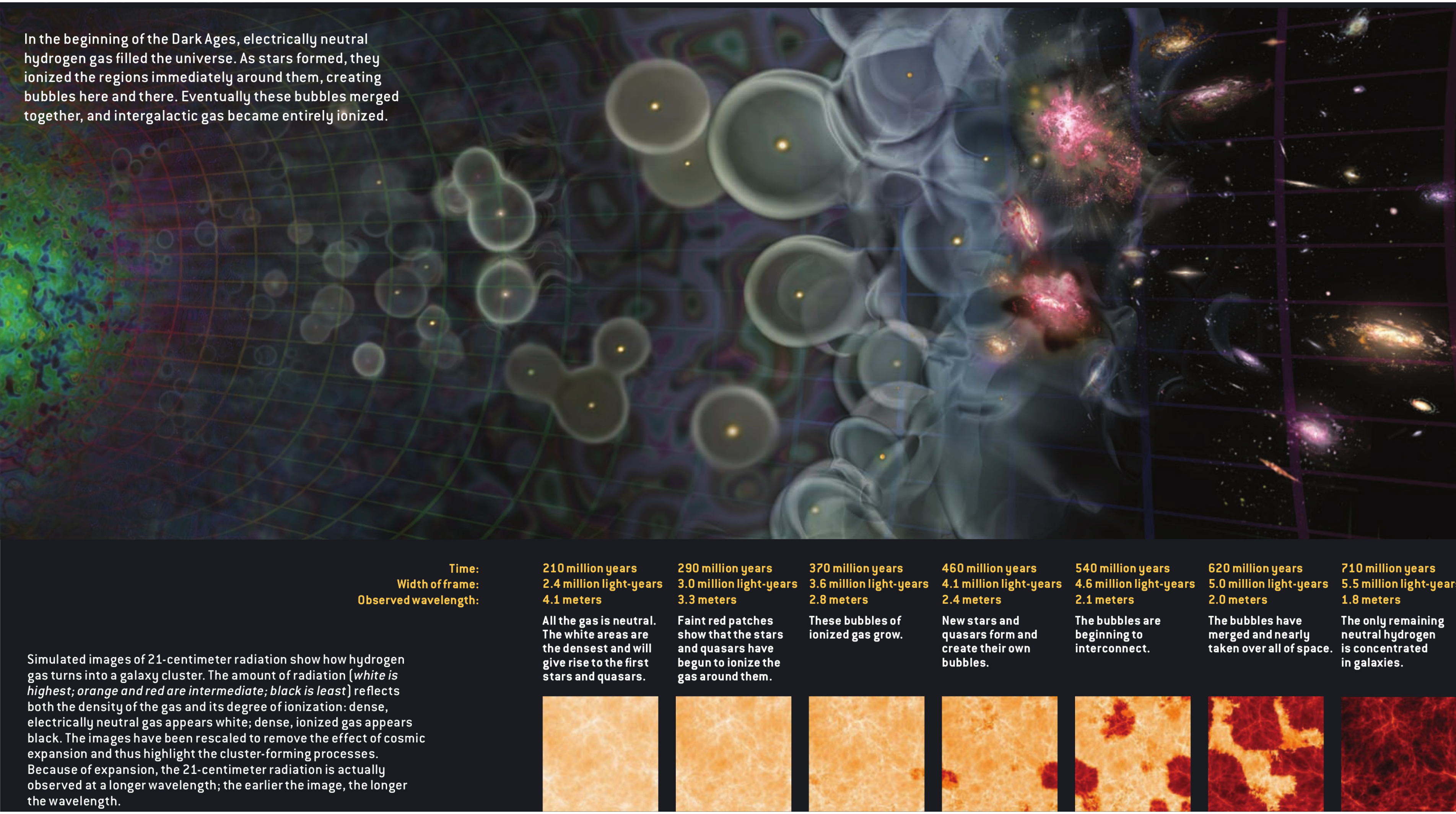




Tavecchio, F. et. al. (2011)
Broderick, A., et. al. (2012)
Chang, P., et. al. (2014)

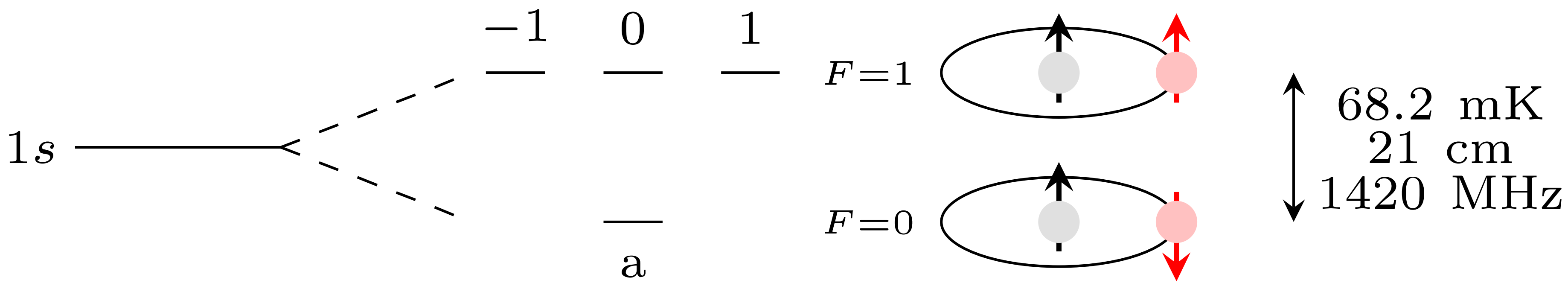
Introduction

21-CM TRANSITION AND APPLICATIONS TO COSMOLOGY



A. Loeb, Scientific American (2006)

The 21cm line of atomic hydrogen



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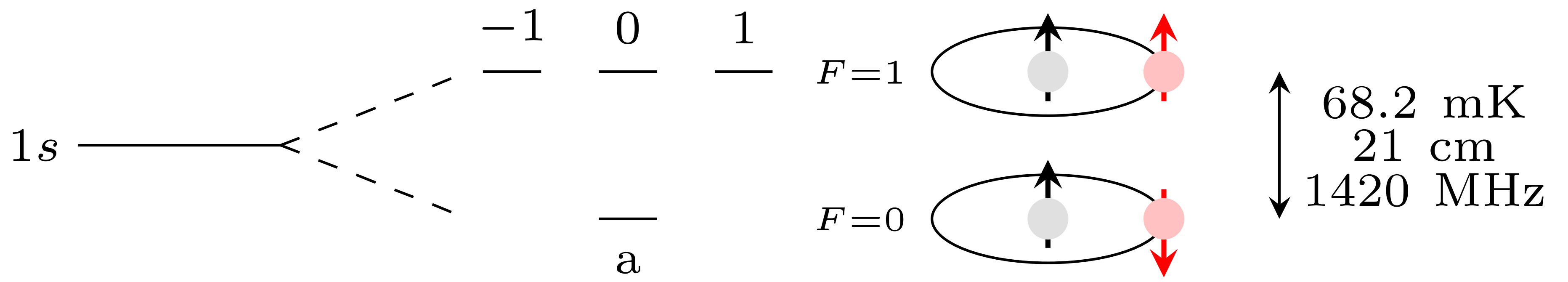
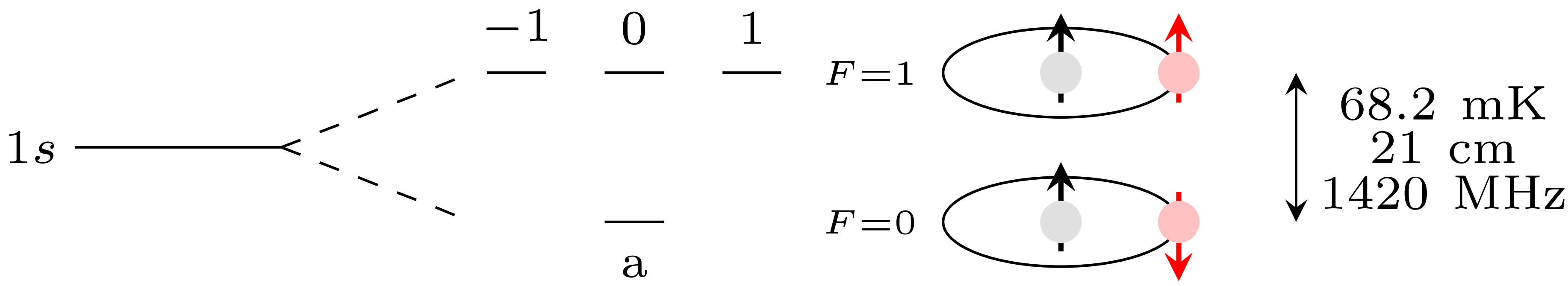


Spin-flip transition

$$A = 2.86 \times 10^{-15}\, s^{-1}$$

The 21cm line of atomic hydrogen



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Spin temperature: $$\frac{n_{F=1}}{n_{F=0}} = 3 \ e^{-\frac{68.2\,mK}{T_s}}$$

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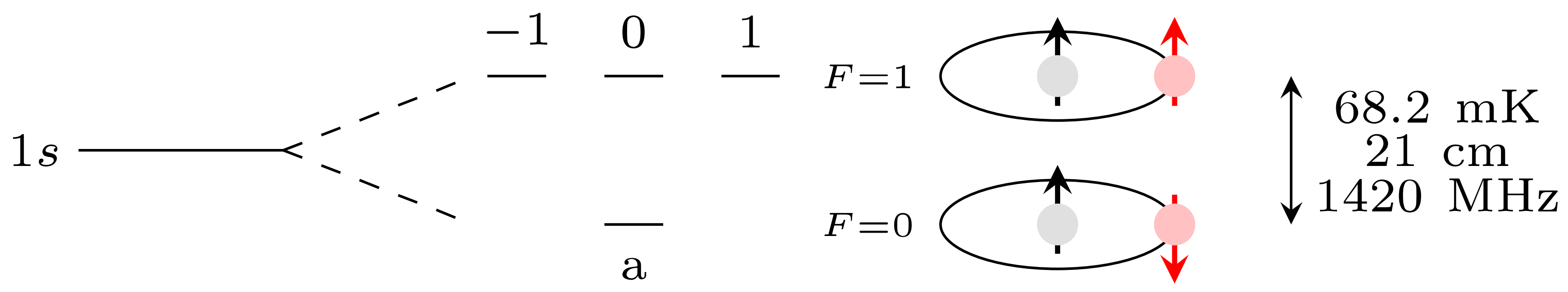

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Observable: brightness temperature

$$T_{\rm s} < T_\gamma \quad : \quad \text{Absorption}$$

$$T_{\rm s} > T_\gamma \quad : \quad \text{Emission}$$

Observable: brightness temperature

Radiative transfer of the CMB through neutral gas

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Output brightness temperature against the CMB is

$$\delta T_{\rm b} = \frac{1}{1+z}(T|_{\rm out} - T_\gamma)$$

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$$= 26.4\ {\rm mK}\ x_{\rm 1s}\frac{T_{\rm s}-T_\gamma}{T_{\rm s}}\left(\frac{1+z}{10}\right)^{1/2}(1+\delta)\frac{H(z)}{\partial_{||}v_{||}}$$

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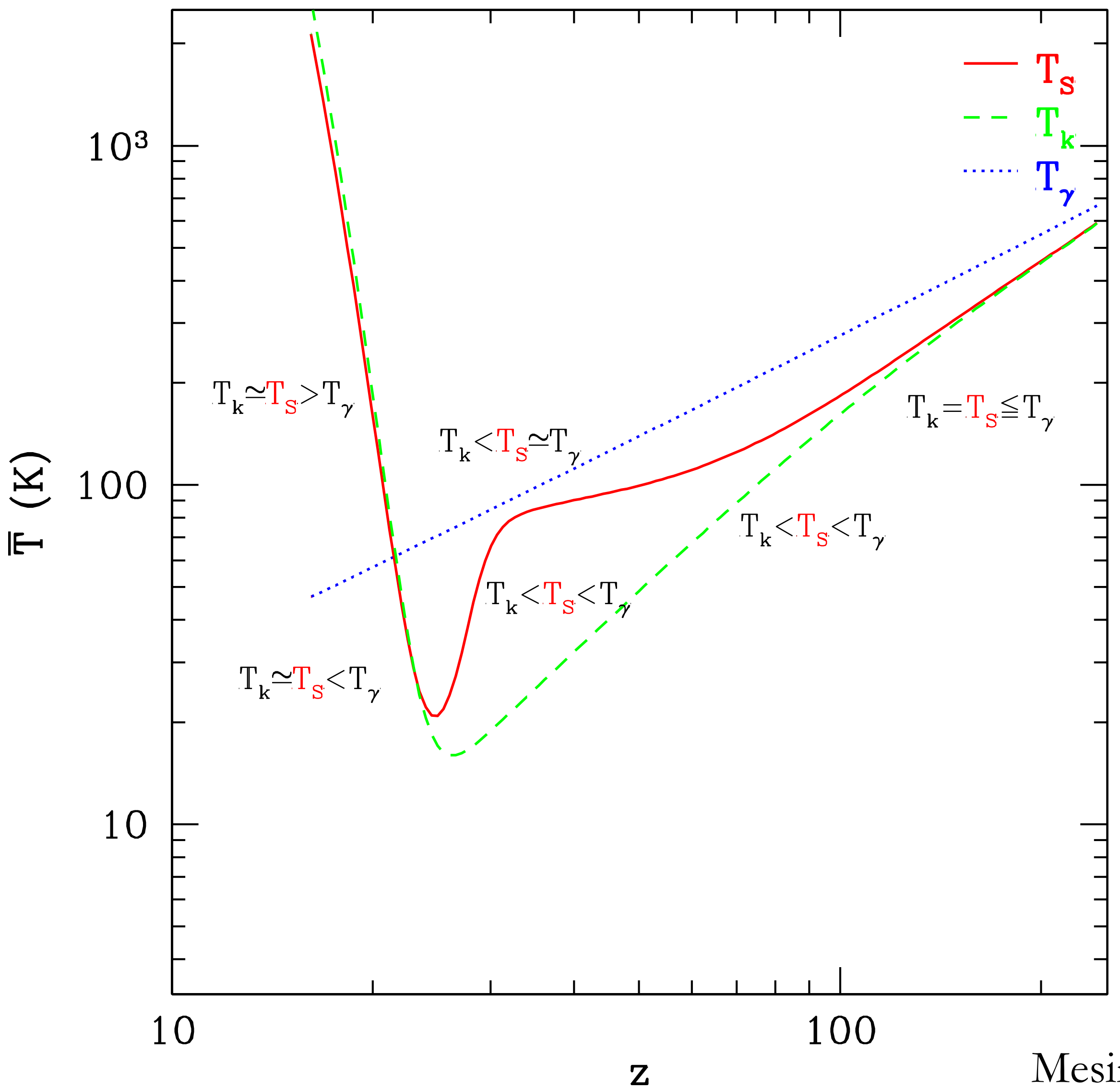
Gas properties

Spin temperature: evolution



Mesinger et. al. (2010)

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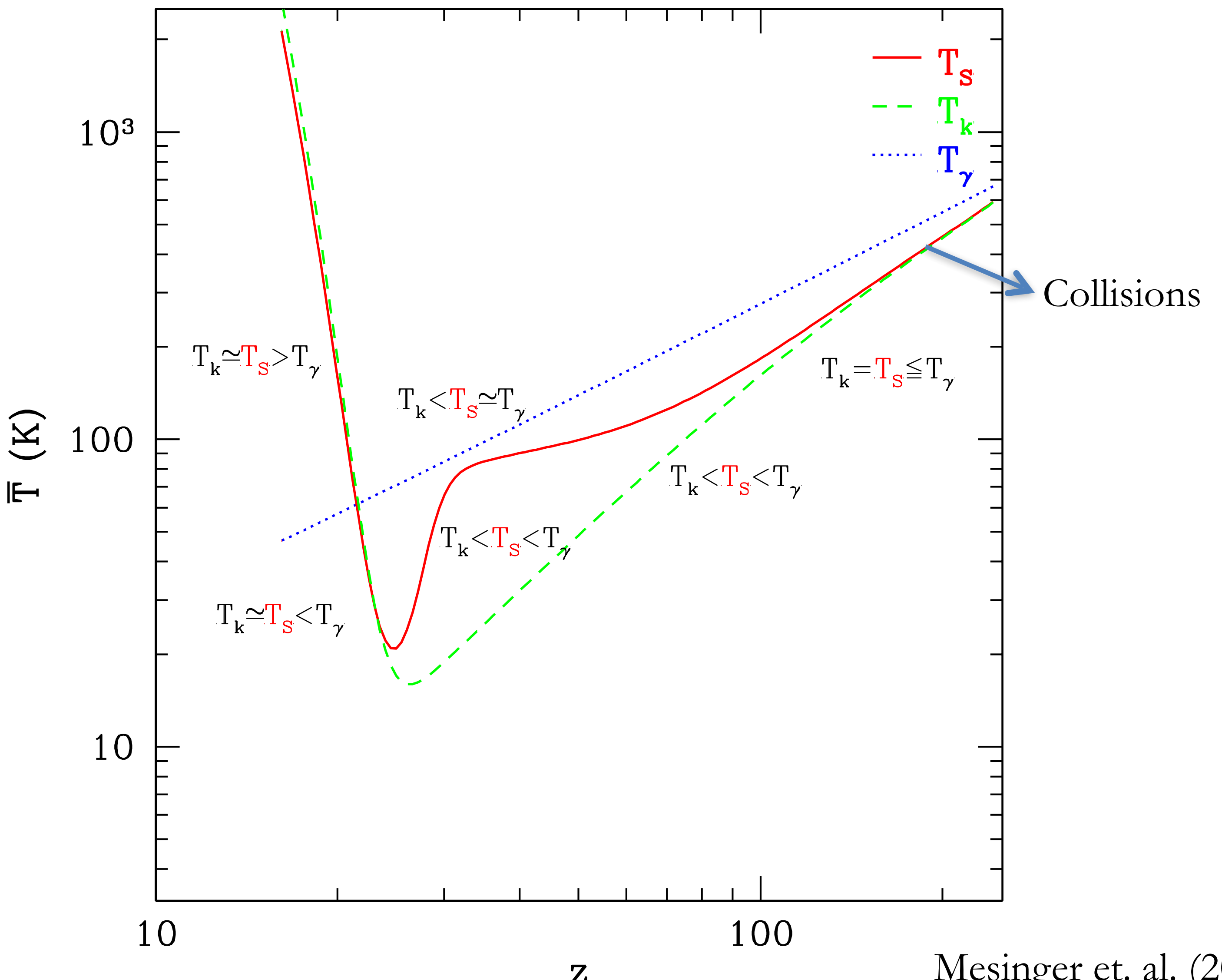

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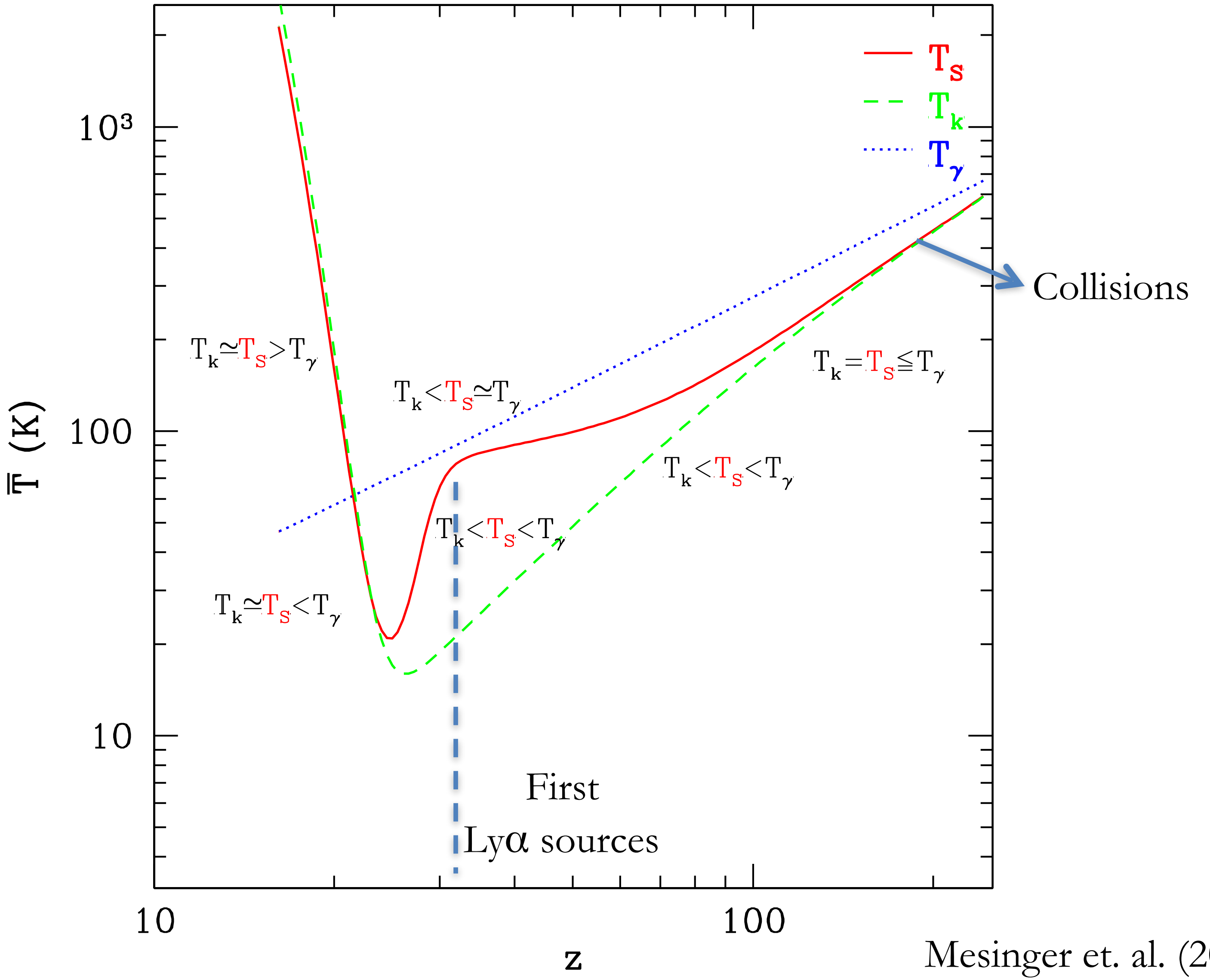

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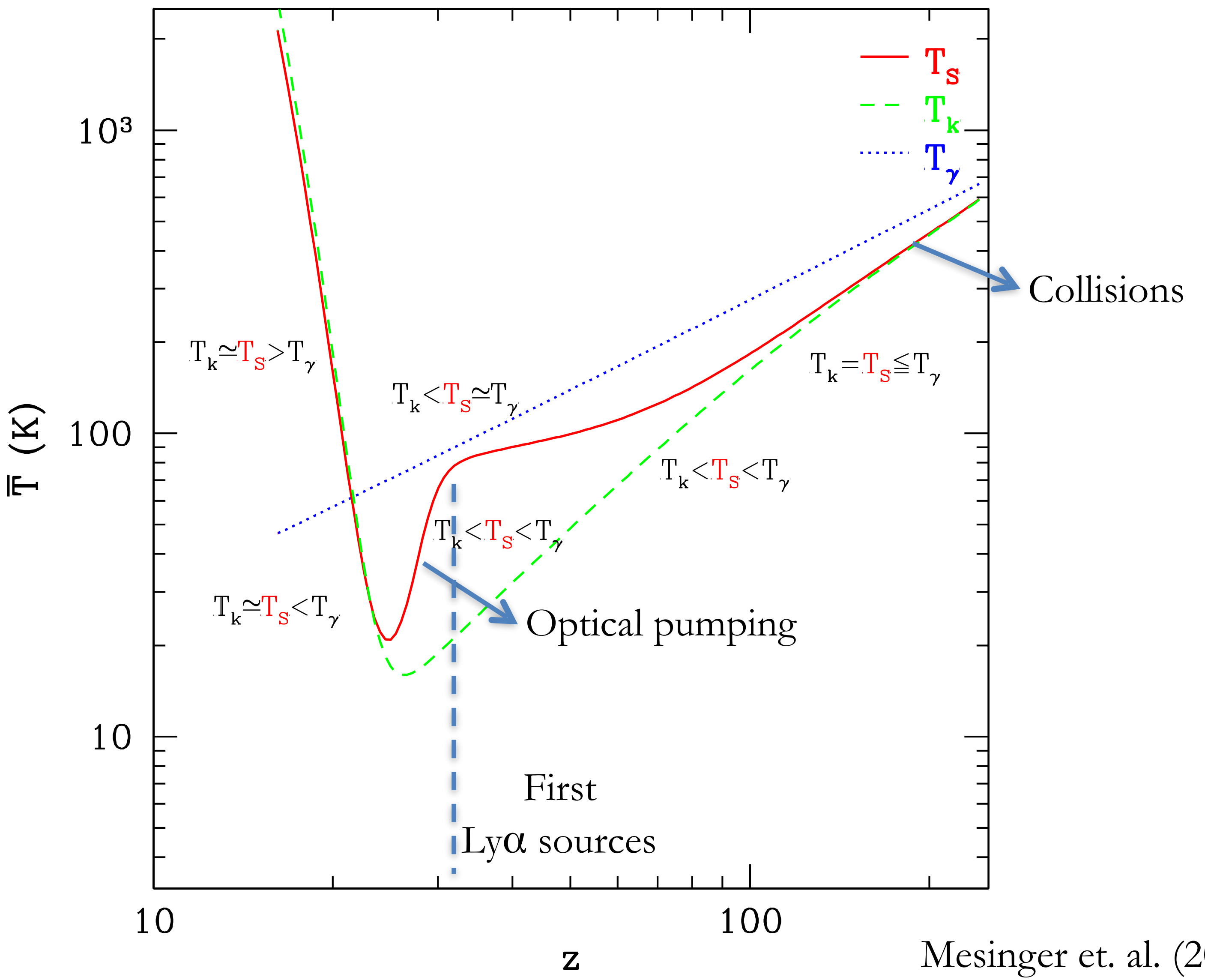

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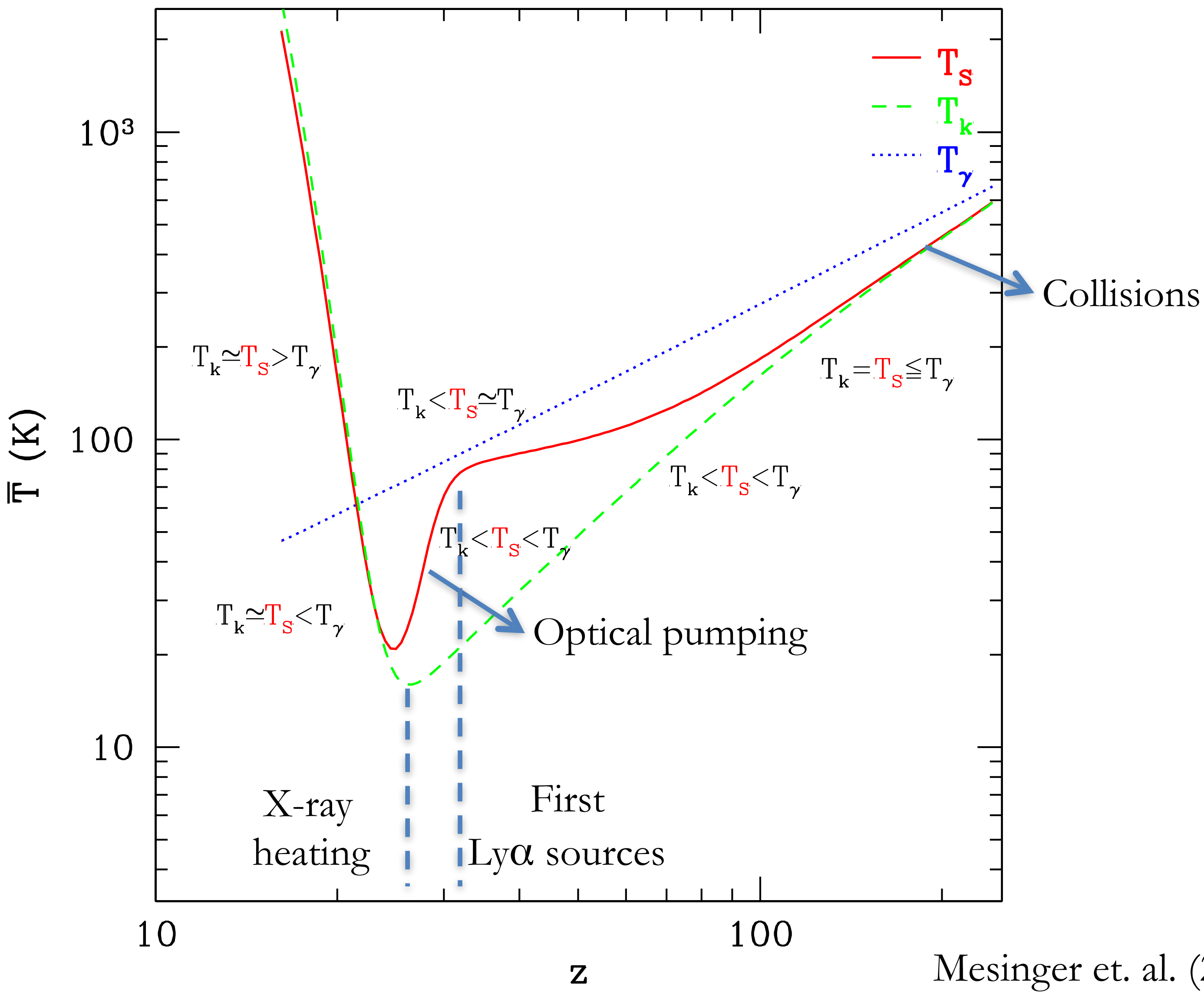
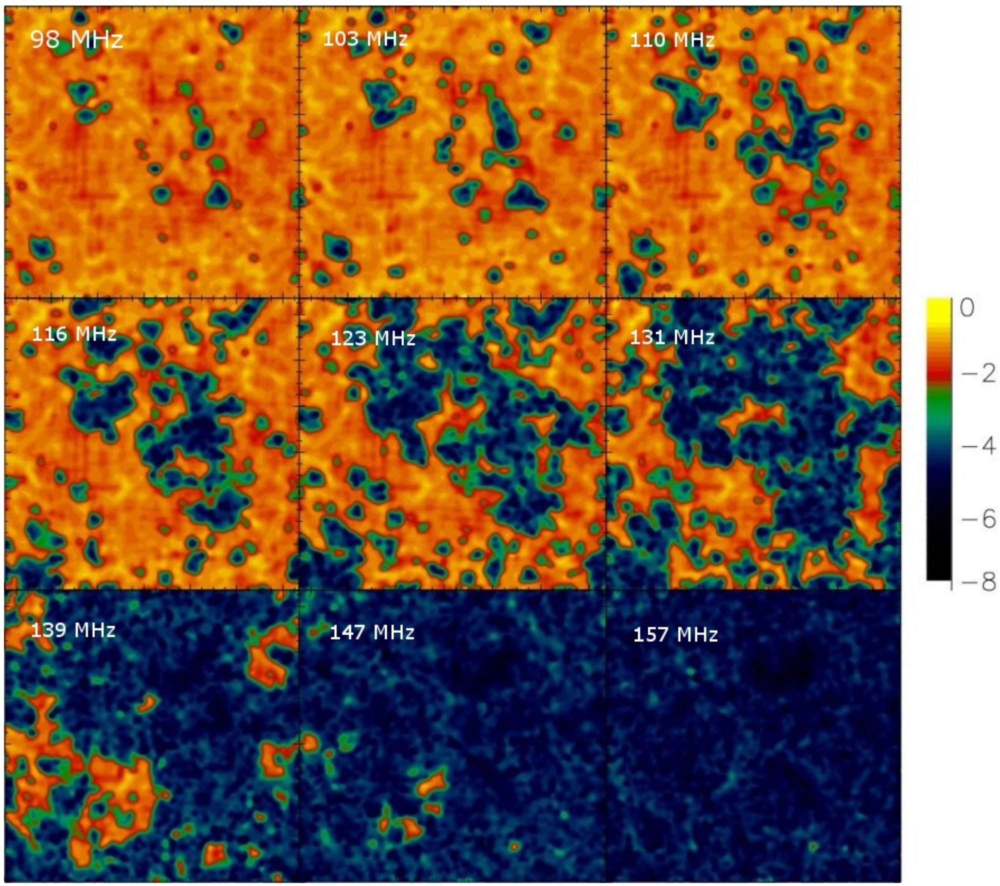


Mesinger et. al. (2010)

Brightness temperature fluctuations in the pre-reionization epoch and the EOR



Advantages for cosmology:

- 3D maps
- Small-scale information

McQuinn et. al. (2006)
Mao et . al. (2008)
Many more…..

Several existing/planned low ν radio arrays aim to measure the 21cm signal from the EOR:

GMRT, PAPER, LOFAR, MWA, LEDA, HERA, SKA …

http://mpa-garching.mpg.de

EFFECT OF MAGNETIC FIELDS

Revisiting the 21cm line

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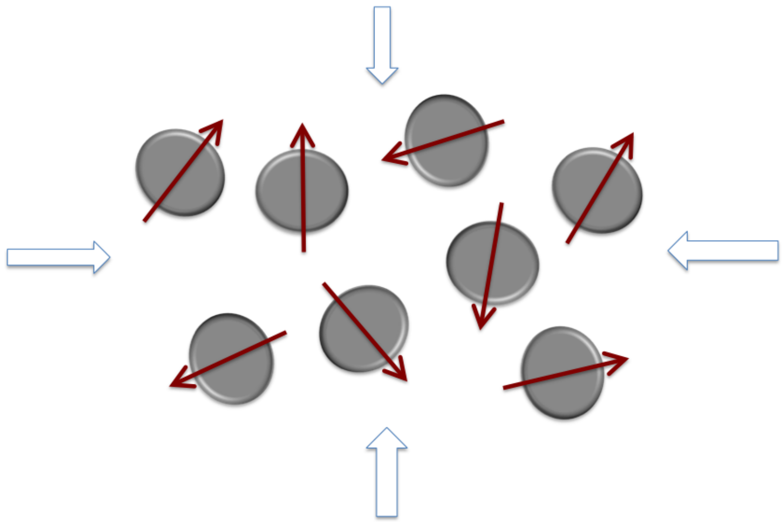

Isotropic bath of 21cm radiation.

$$\langle F_\alpha \rangle = 0 \quad \langle F_\alpha F_\beta \rangle = 0$$

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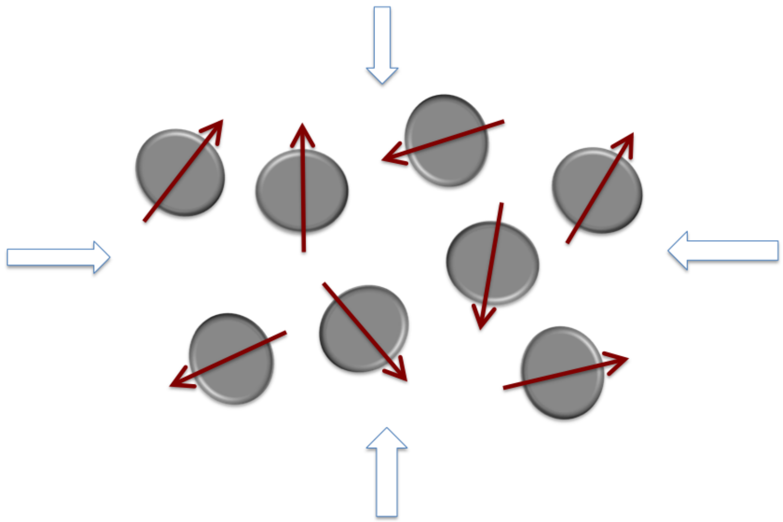

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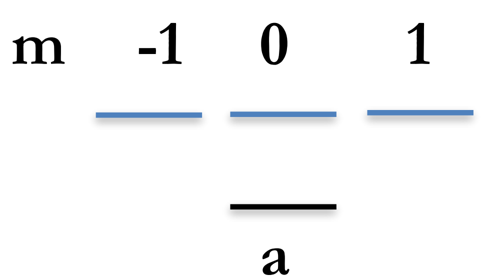

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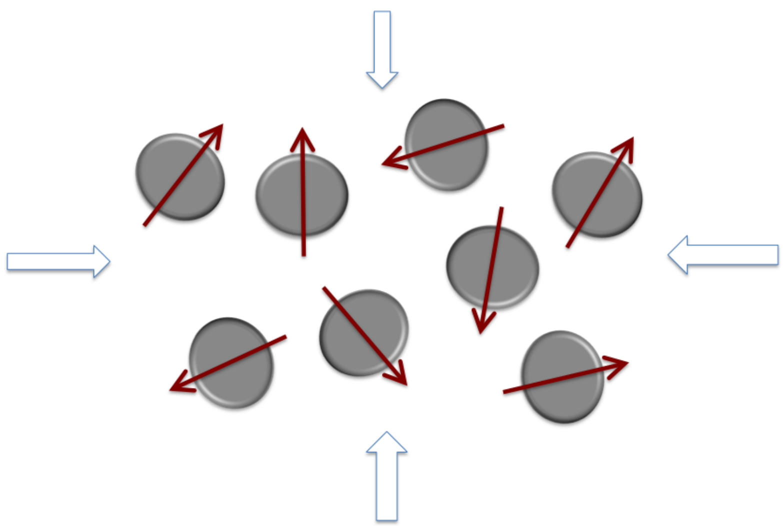

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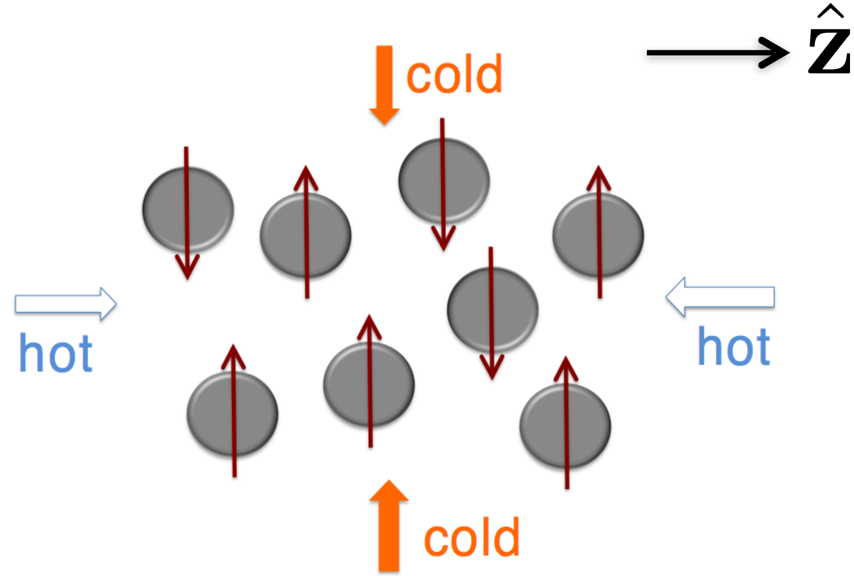
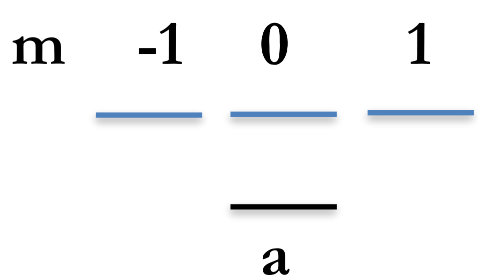


Quadrupolar anisotropy.

$$\langle F_\alpha \rangle = 0 \quad \langle F_\alpha F_\beta \rangle = 0 \quad \langle F_\alpha \rangle = 0 \quad \langle F_z F_z - \frac{1}{3} F^2 \rangle \neq 0$$



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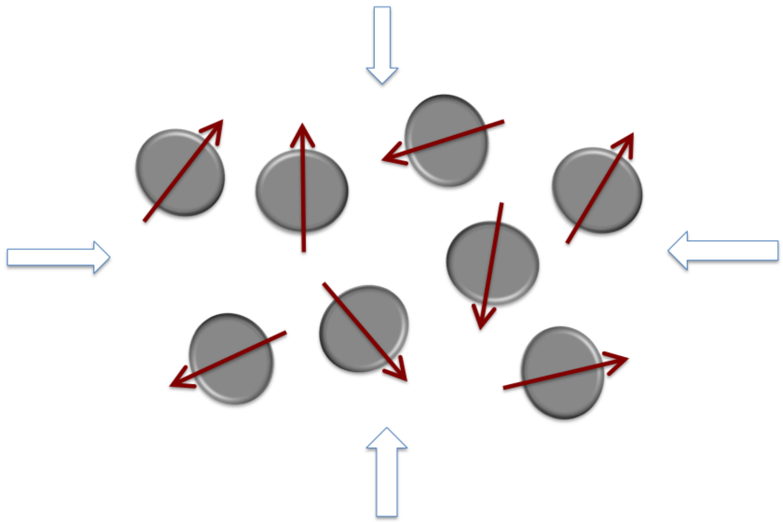

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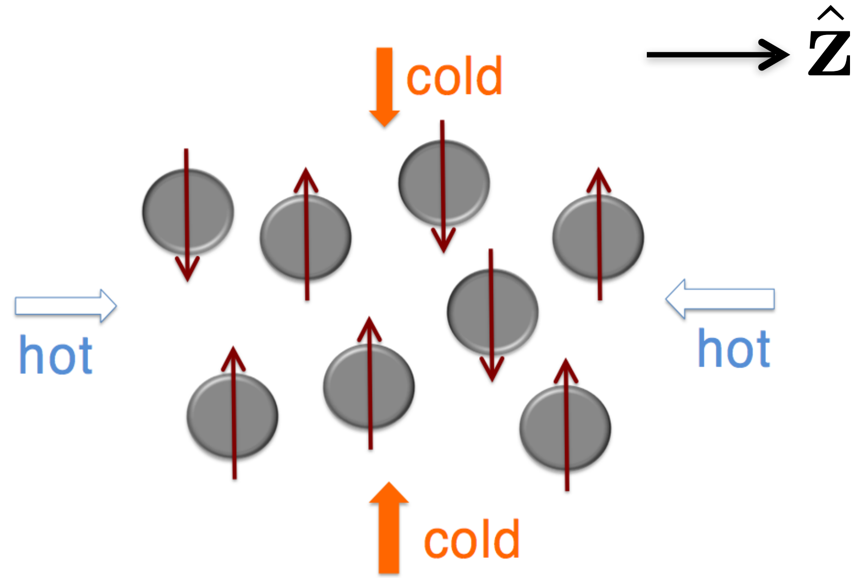

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m -1 0 1

a

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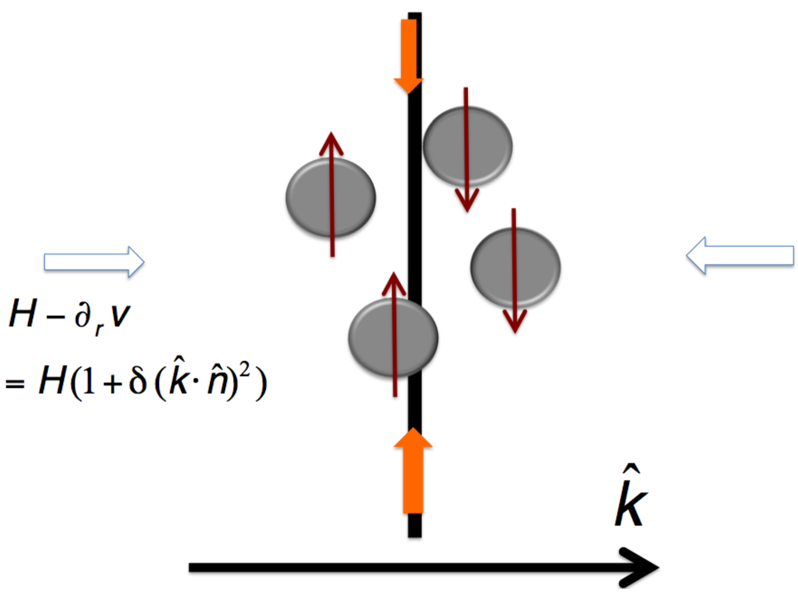
a

Anisotropies and anisotropic emission

$$\tau(\hat{\mathbf{n}}) = 9.7 \times 10^{-3} x_{1s} \left(\frac{T_\gamma}{T_s}\right) (1+\delta) \frac{H}{\partial_{||} v_{||}} \left(\frac{1+z}{10}\right)^{1/2}$$

$$\partial_{||} v_{||} = H\left(1 - \delta(\hat{\mathbf{k}} \cdot \hat{\mathbf{n}})^2\right)$$



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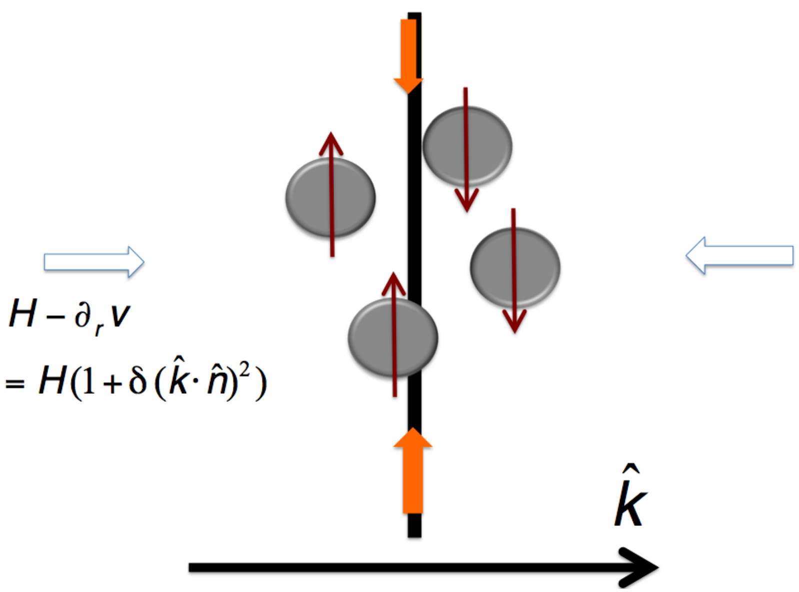
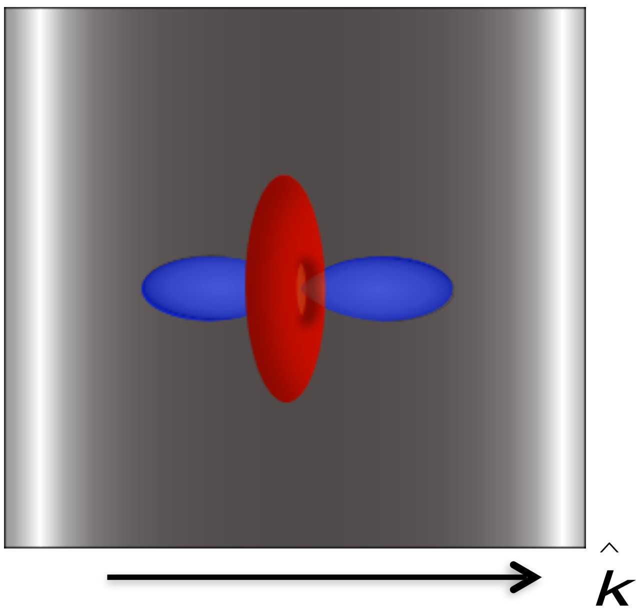
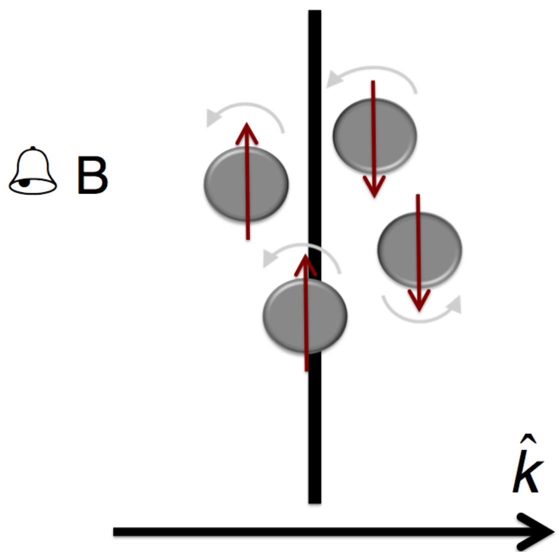
δT_b from thermal background is "one absorption/emission" $\sim \mathcal{O}(\tau)$

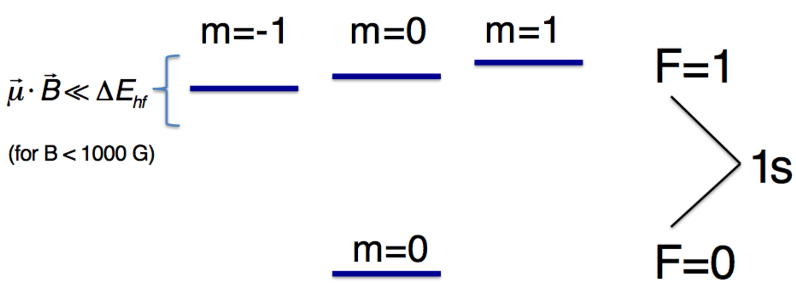
De-excitation of "aligned" moments is "two absorption/emission" $\sim \mathcal{O}(\tau^2)$





Effect of an external magnetic field





Zeeman splitting and precession.

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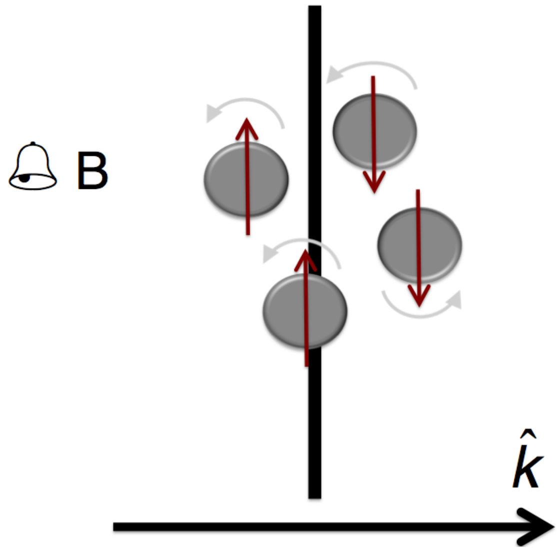

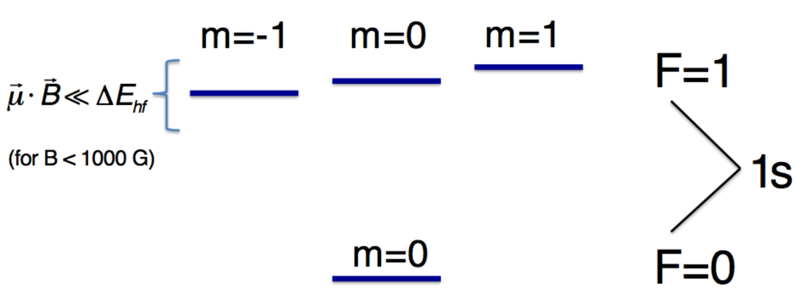

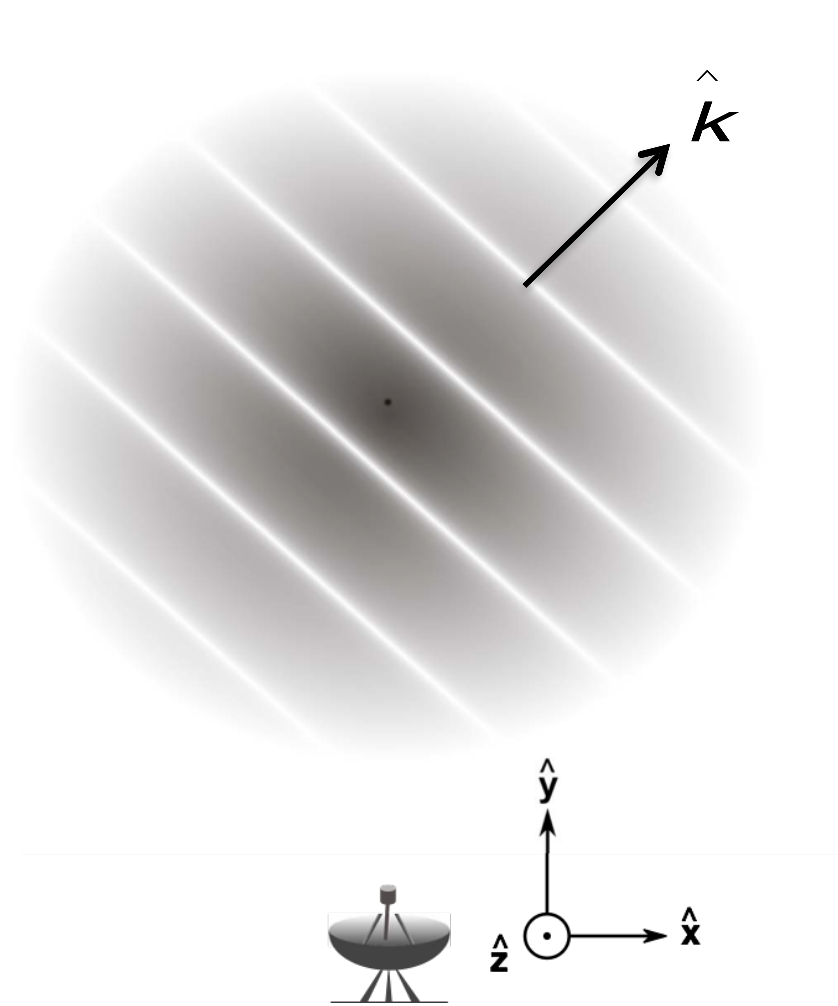

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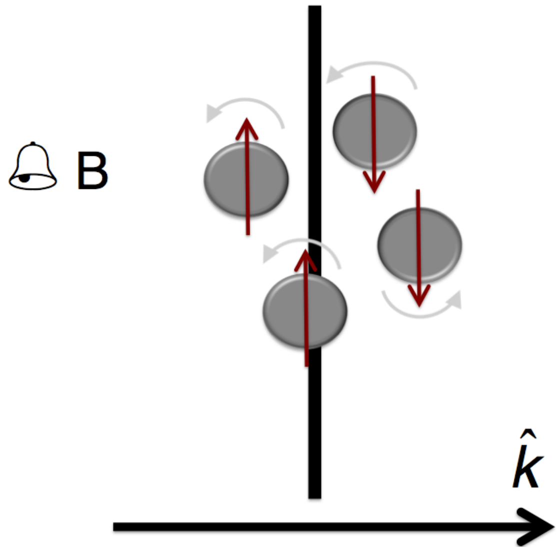

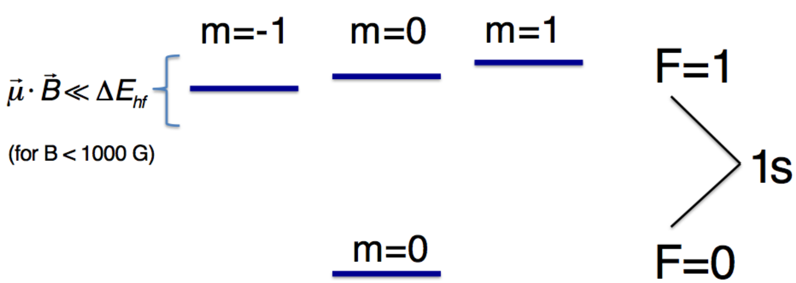

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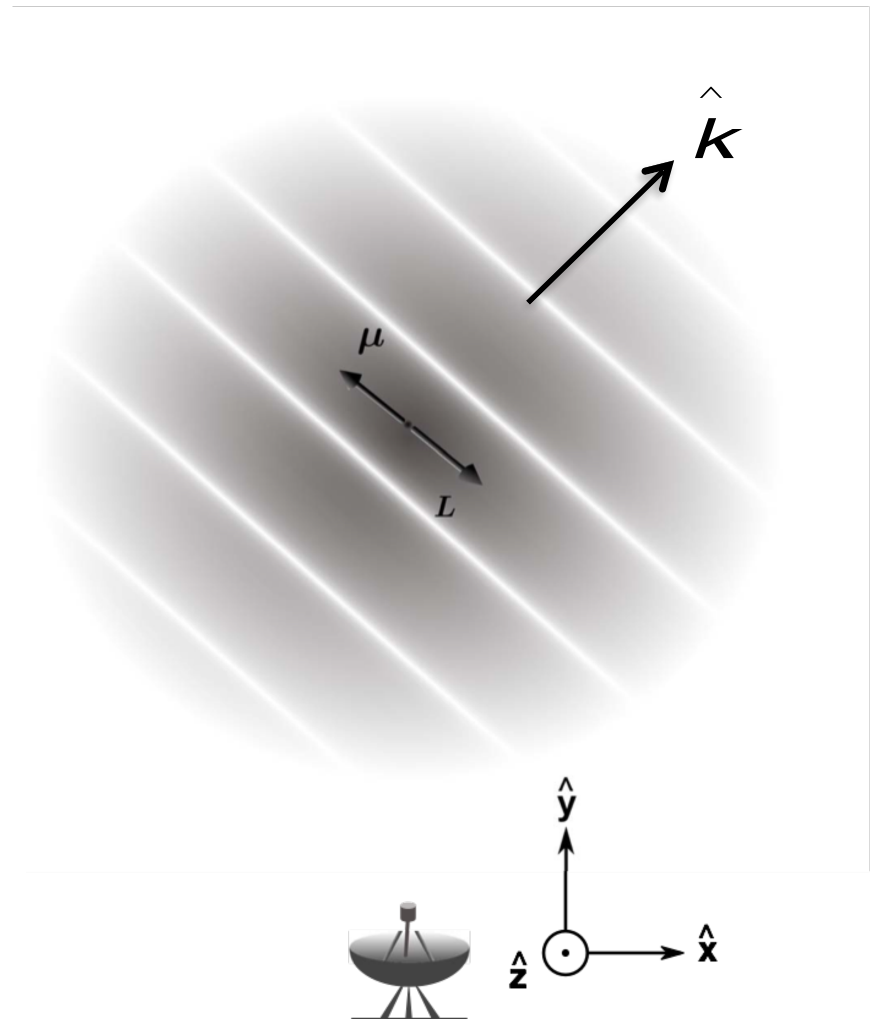

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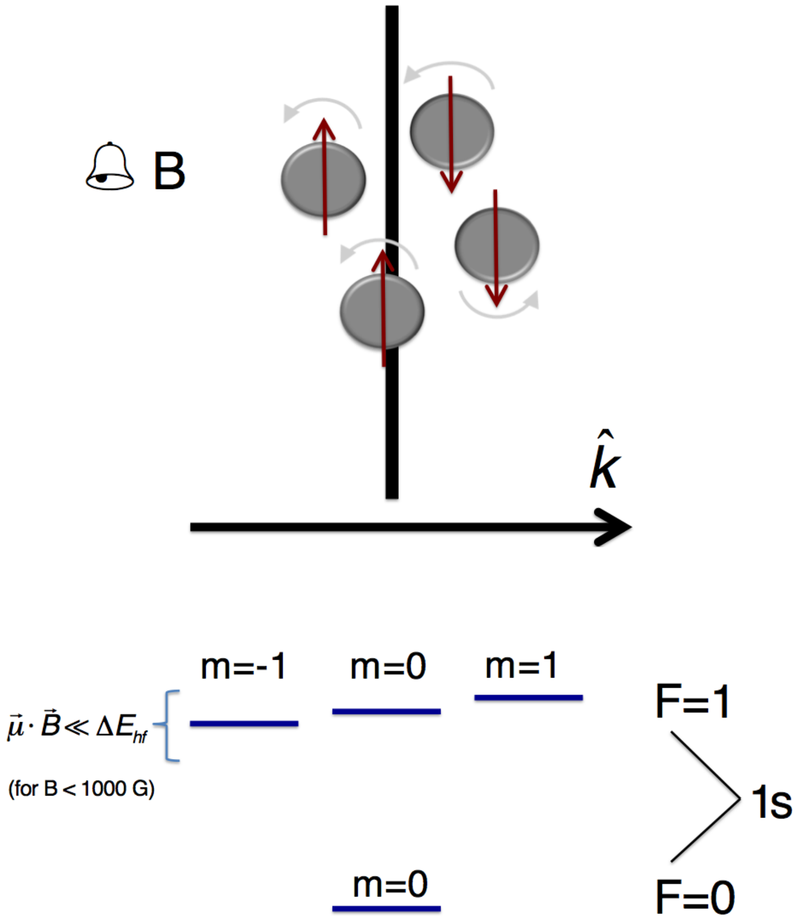

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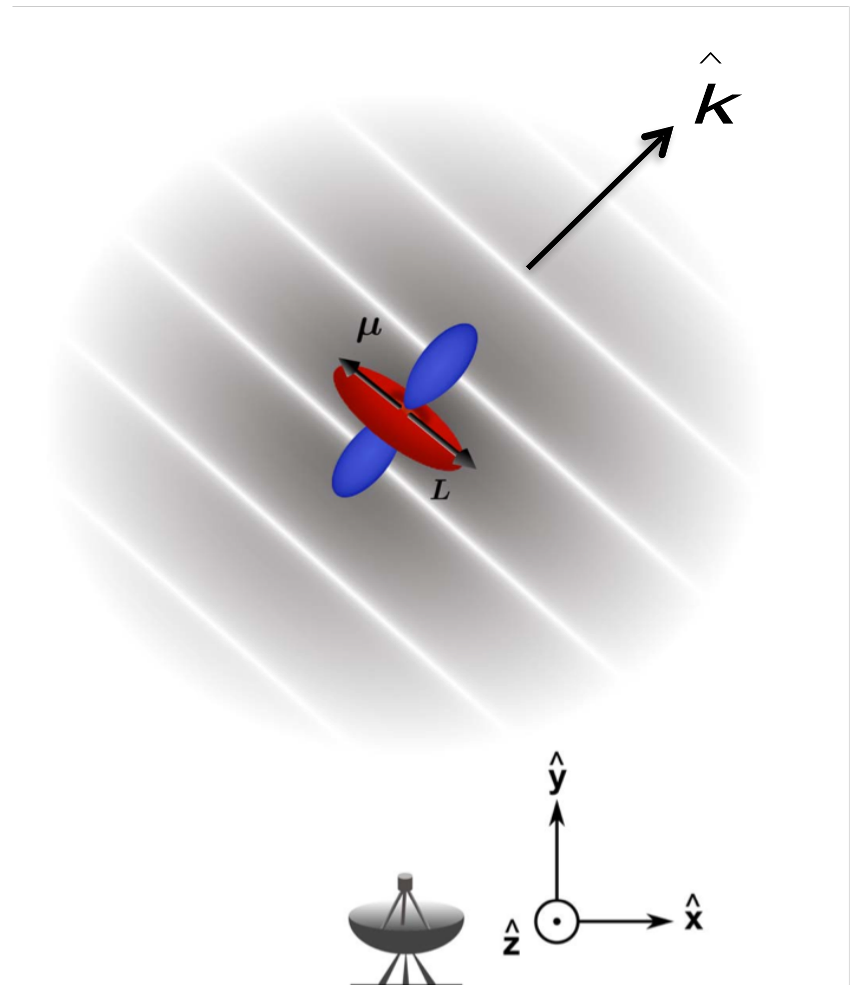

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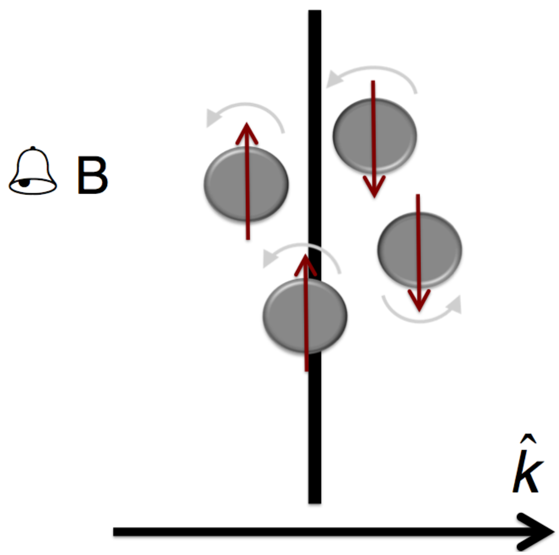

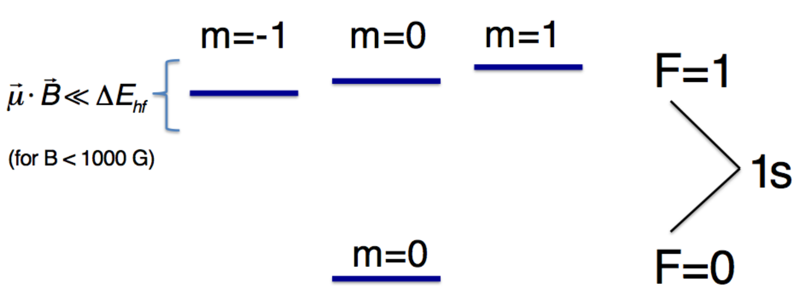

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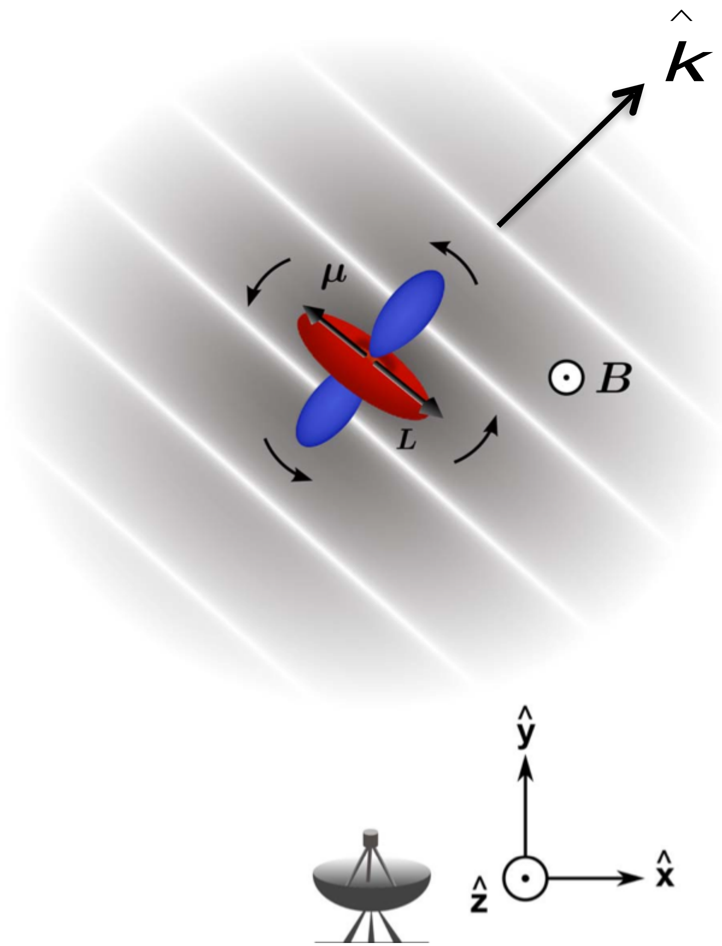

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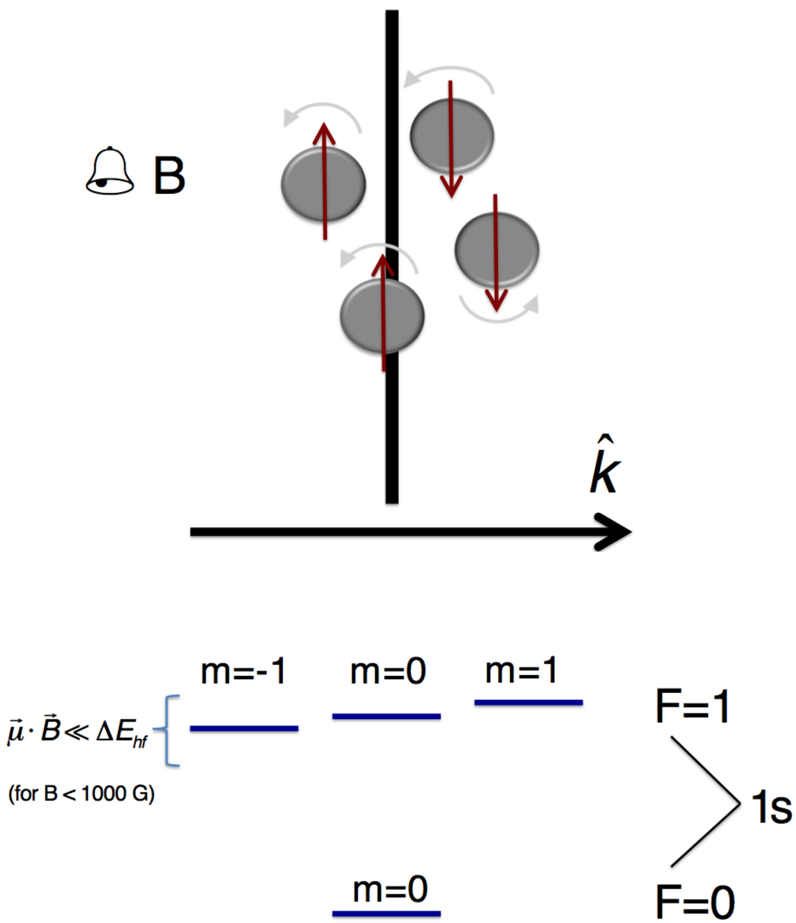

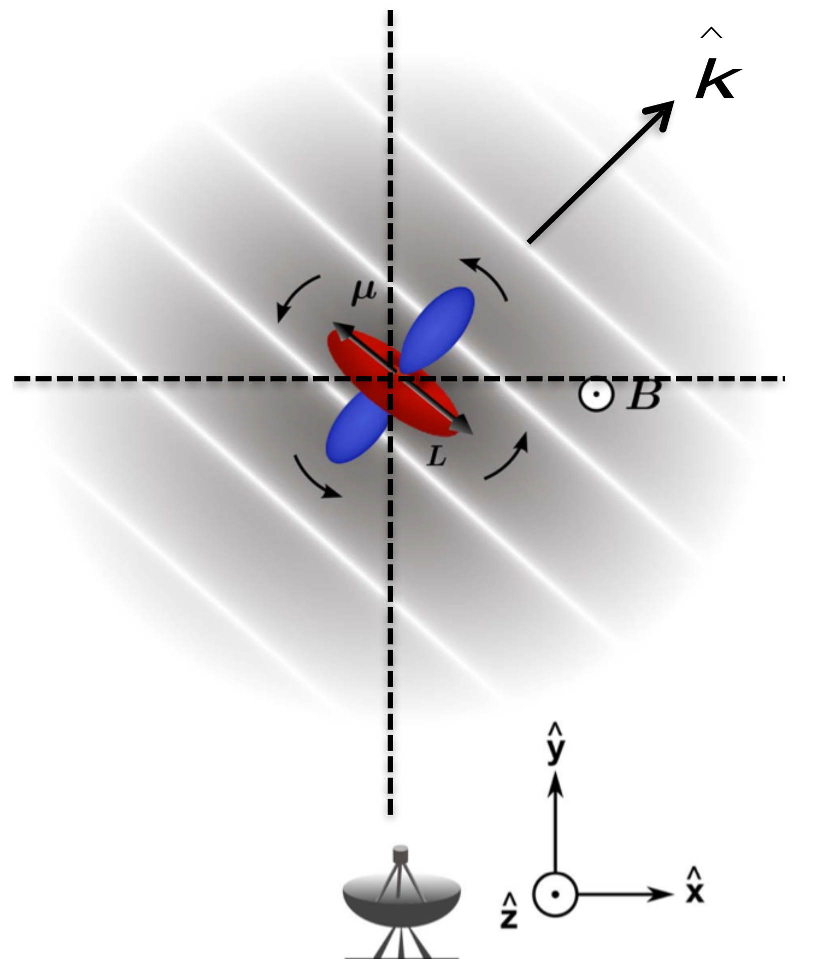

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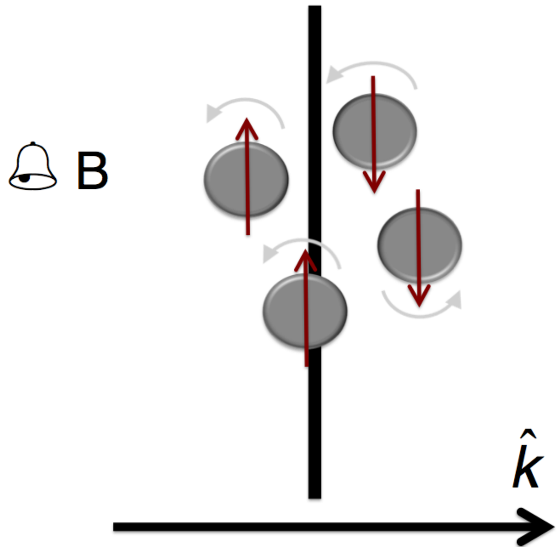

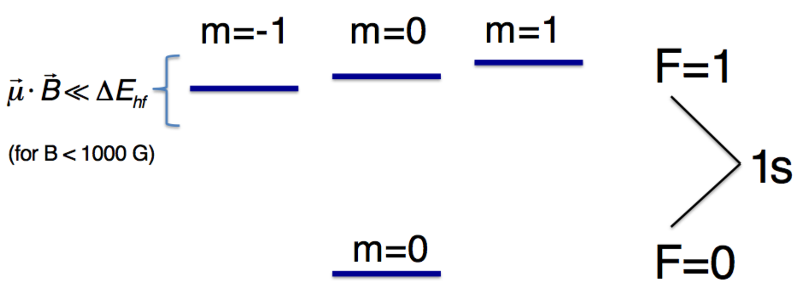

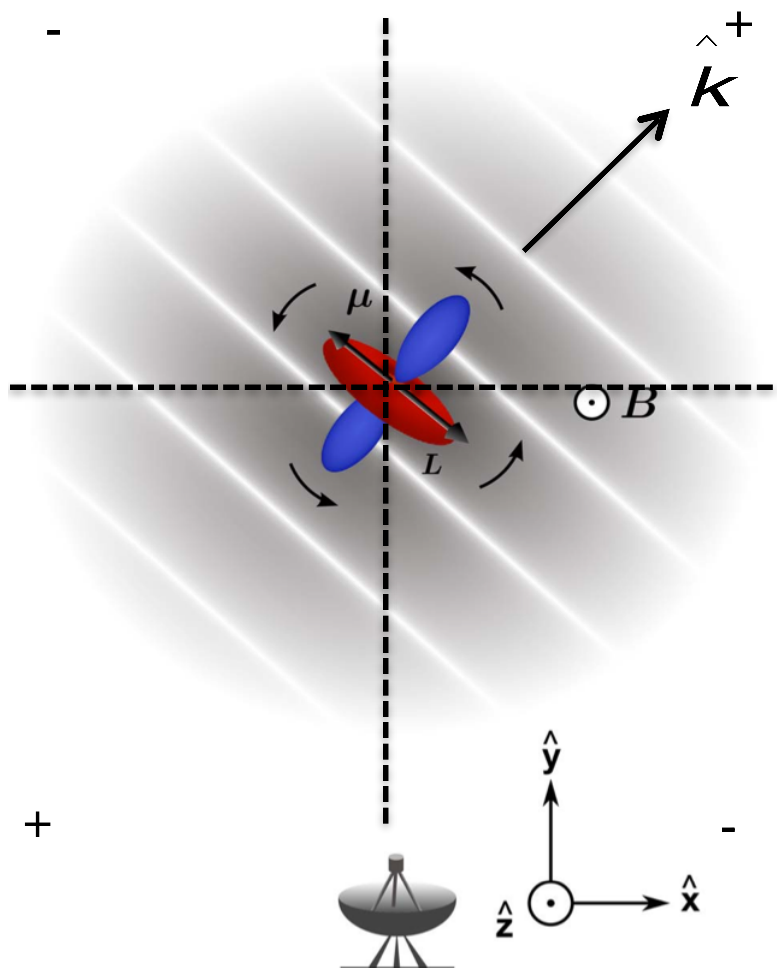

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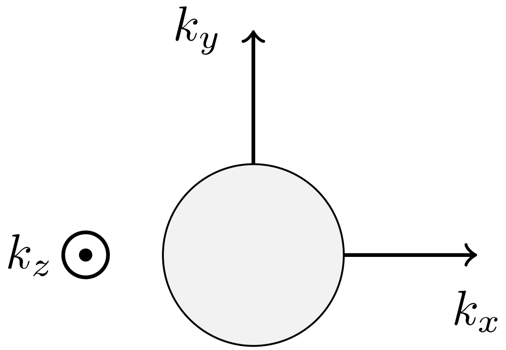
Effect on 21cm observables



(a)

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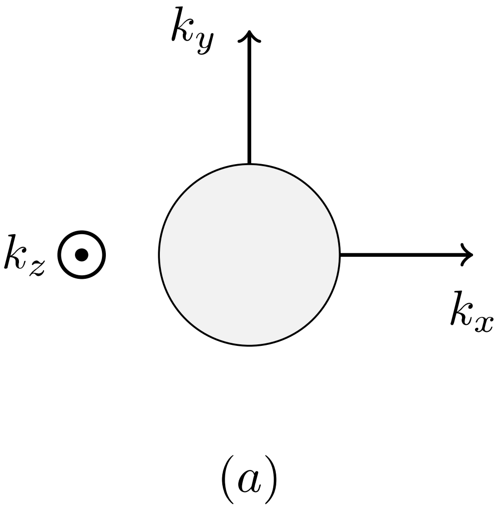

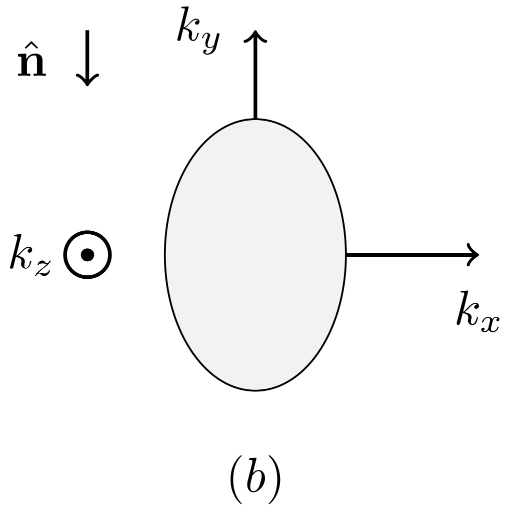

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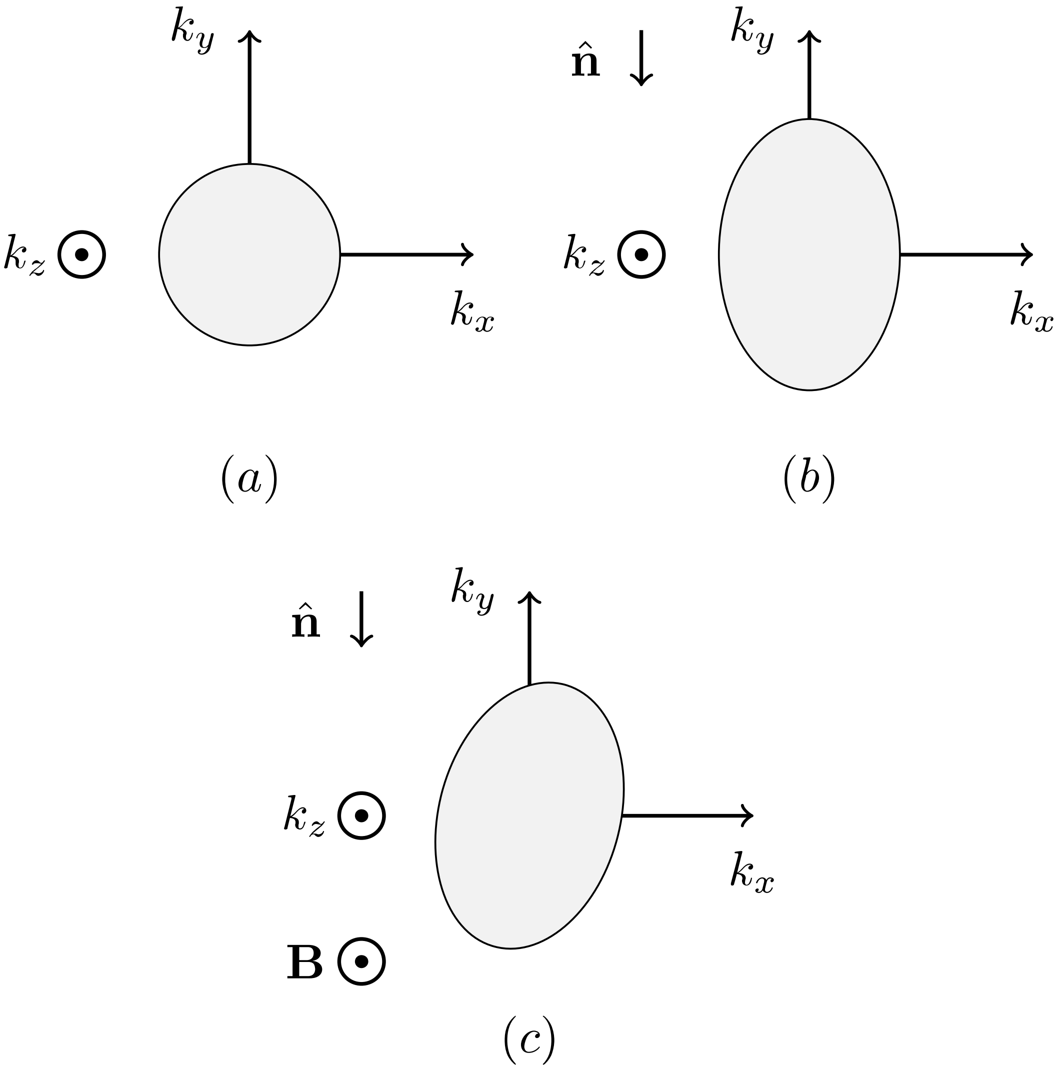
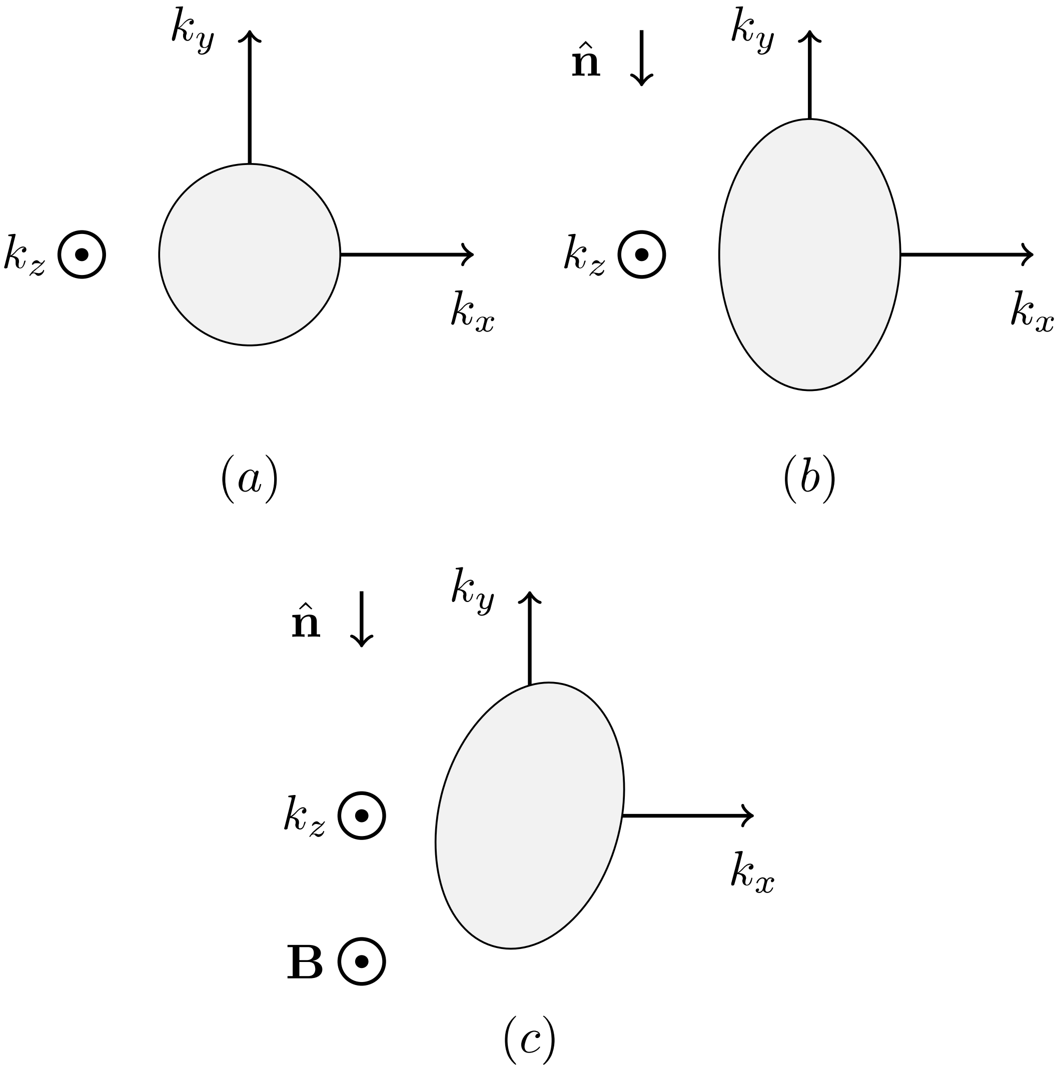


Venumadhav, T., et. al. (2014)

Effect on 21cm observables



Triplet lifetime:

$$t_{\rm d} = \frac{1}{A}\frac{68.2\ \rm mK}{T_\gamma}$$
$$= 1.3 \times 10^4 \left(\frac{20}{1+z}\right) \rm Yr$$

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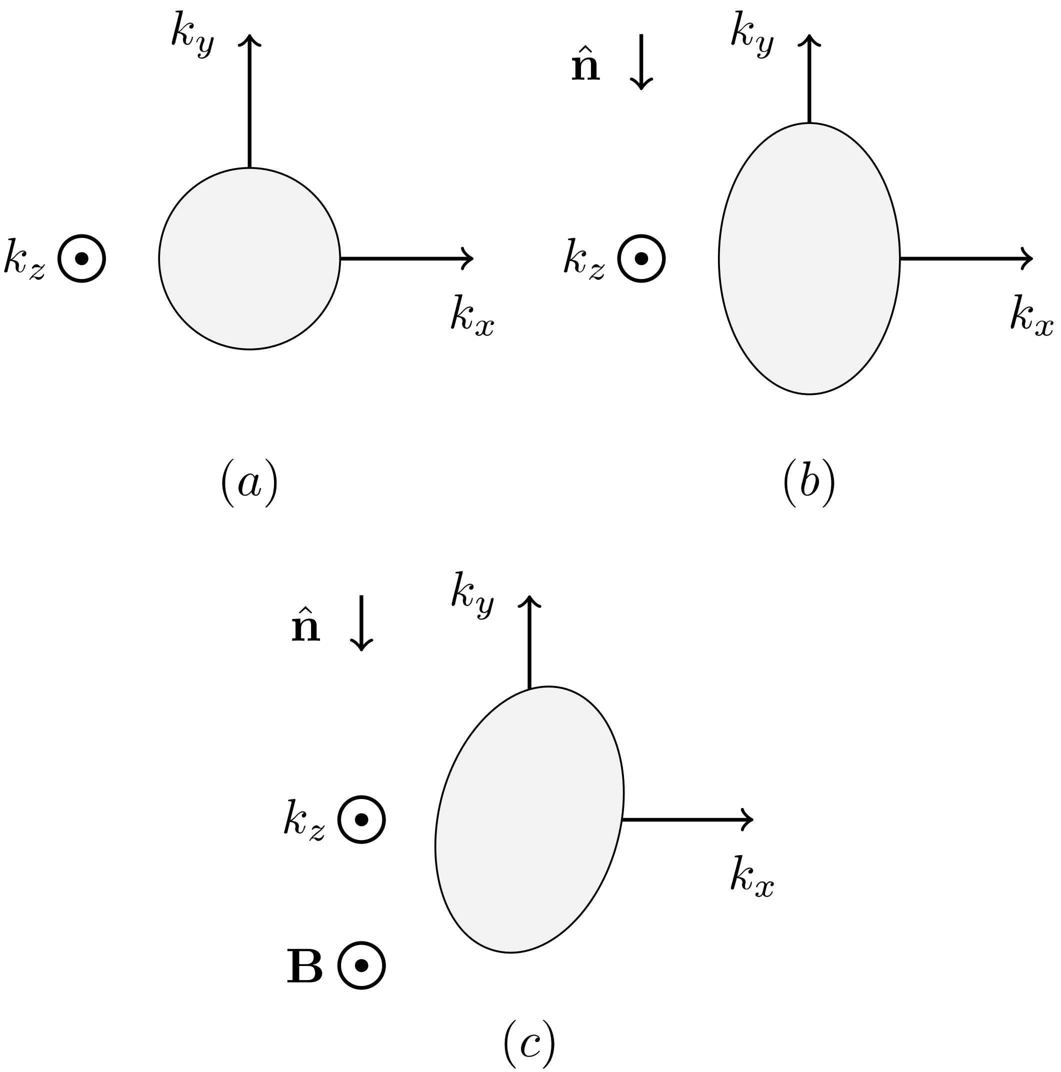

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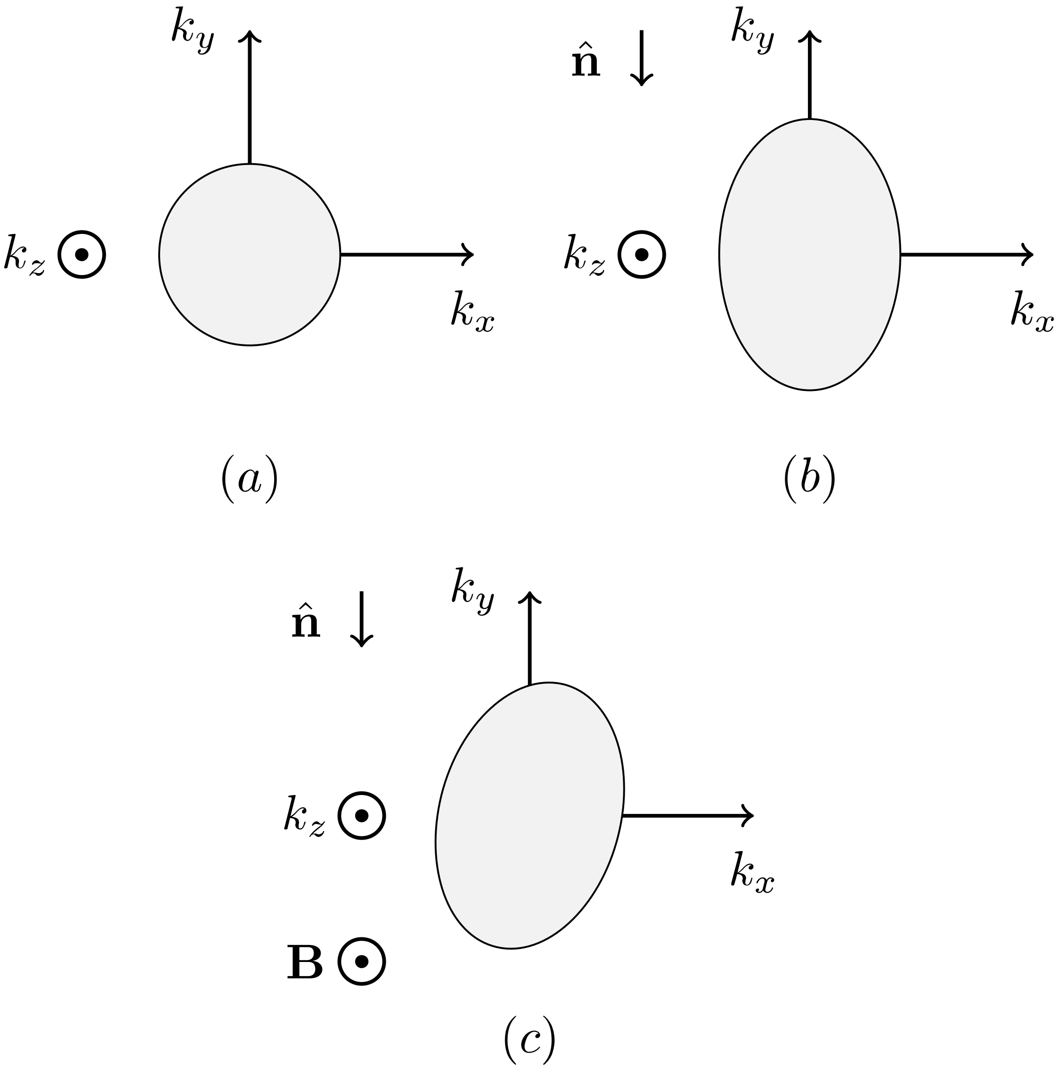
Precession rate:

$$\gamma_e = 1.8 \times 10^7 \mathrm{s}^{-1}\mathrm{G}^{-1}$$

Venumadhav, T., et. al. (2014)

Effect on 21cm observables



Triplet lifetime:

$$t_{\rm d} = \frac{1}{A}\frac{68.2\ \mathrm{mK}}{T_\gamma}$$
$$= 1.3 \times 10^4 \left(\frac{20}{1+z}\right) \mathrm{Yr}$$

Precession rate:

$$\gamma_e = 1.8 \times 10^7 \mathrm{s}^{-1}\mathrm{G}^{-1}$$

Precession through unit angle

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Venumadhav, T., et. al. (2014)

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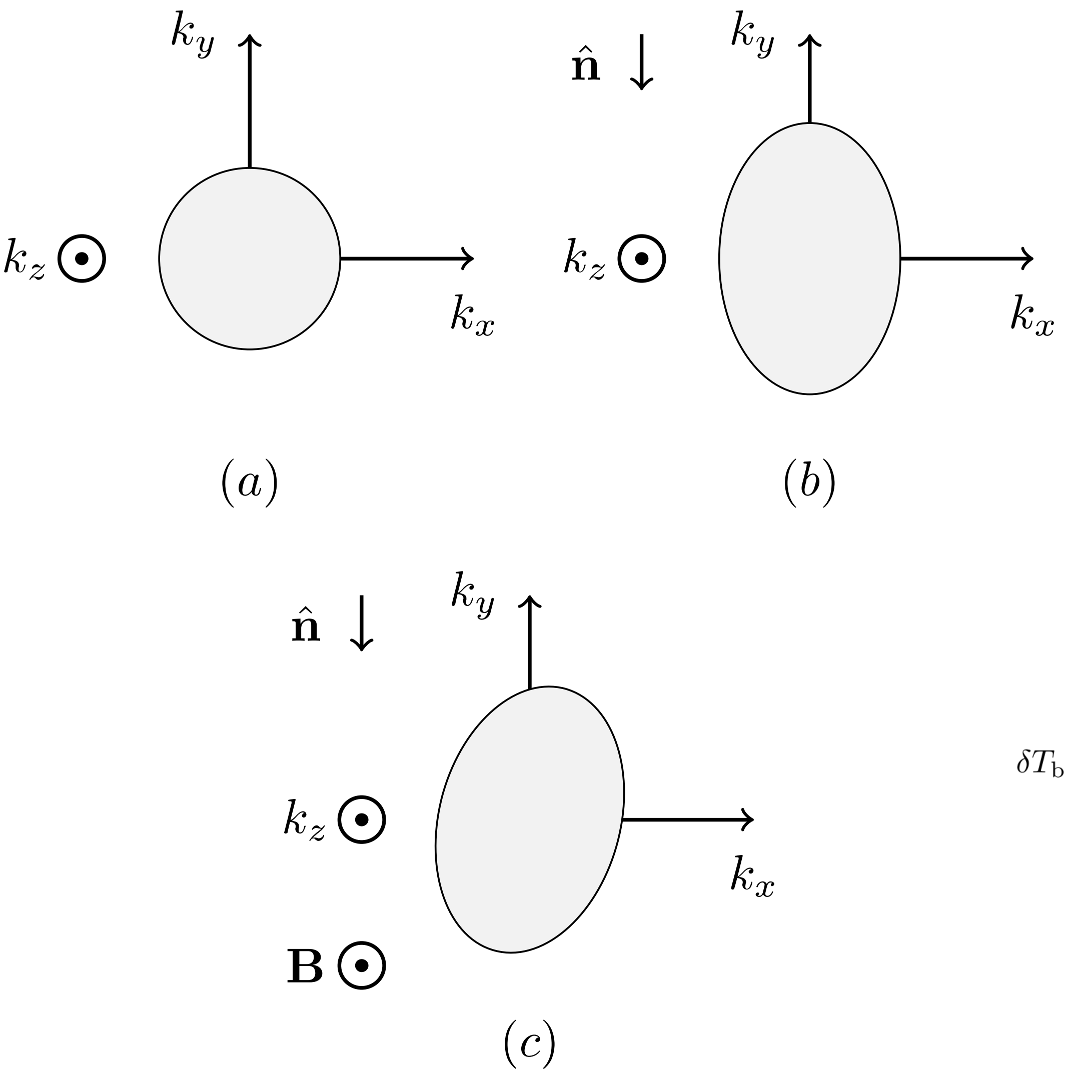

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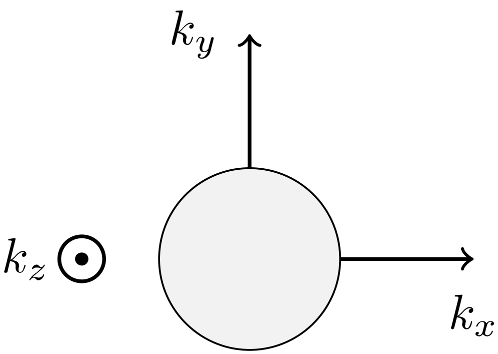
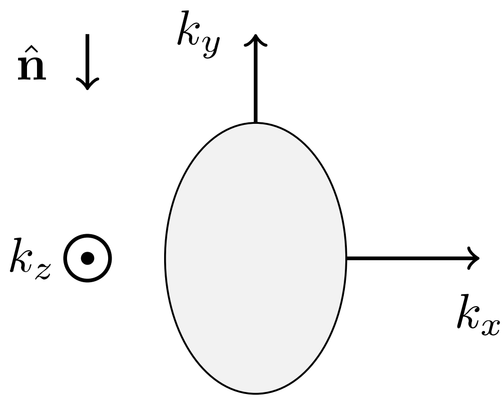
$$\delta T_{\rm b}(\hat{\mathbf{n}}) = \left(1 - \frac{T_\gamma}{T_{\rm s}}\right) x_{1\rm s} \left(\frac{1+z}{10}\right)^{1/2}$$
$$\times \Bigg[26.4 \text{ mK}\left\{1 + \left(1 + (\hat{\boldsymbol{k}}\cdot\hat{\boldsymbol{n}})^2\right)\delta\right\}$$
$$- 0.128 \text{ mK} \left(\frac{T_\gamma}{T_{\rm s}}\right) x_{1\rm s} \left(\frac{1+z}{10}\right)^{1/2}$$
$$\times \left\{1 + 2\left(1 + (\hat{\boldsymbol{k}}\cdot\hat{\boldsymbol{n}})^2\right)\delta\right.$$
$$\left. - \frac{\delta}{15}\sum_m \frac{4\pi}{5} \frac{Y_{2m}(\hat{\boldsymbol{k}})\left[Y_{2m}(\hat{\boldsymbol{n}})\right]^*}{1 + x_{\alpha,(2)} + x_{\rm c,(2)} - imx_{\rm B}}\right\}\Bigg]$$

Venumadhav, T., et. al. (2014)

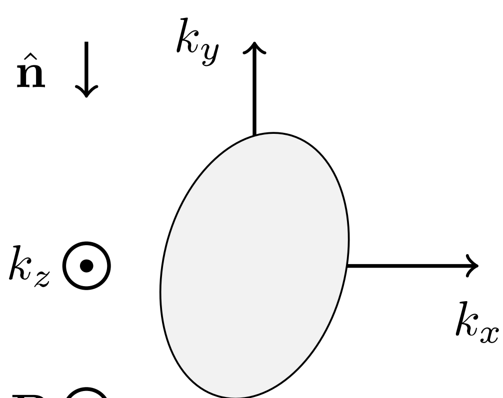
Effect on 21cm observables



(a)



(b)



(c)

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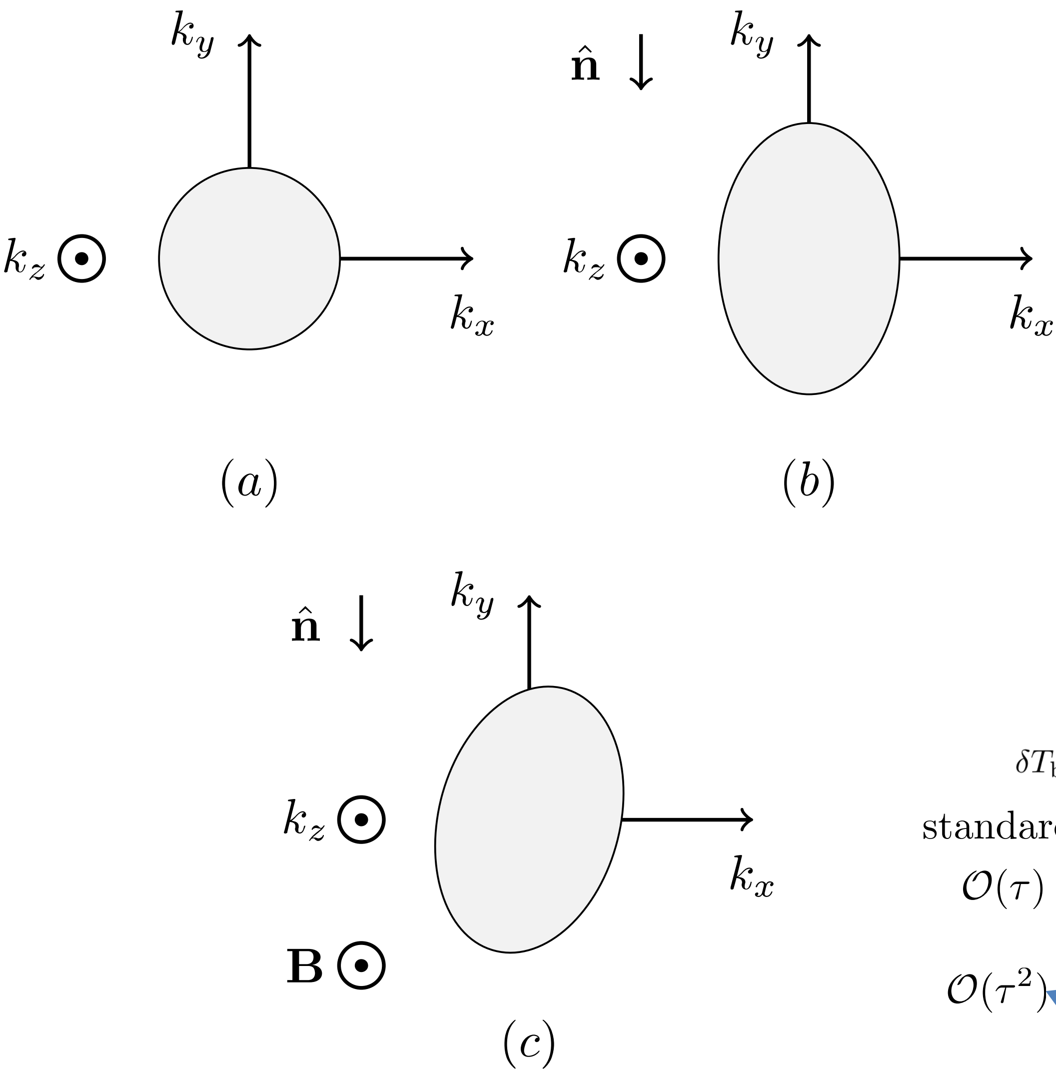
standard, $\mathcal{O}(\tau)$

Venumadhav, T., et. al. (2014)

Effect on 21cm observables



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$\mathcal{O}(\tau^2)$

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Venumadhav, T., et. al. (2014)

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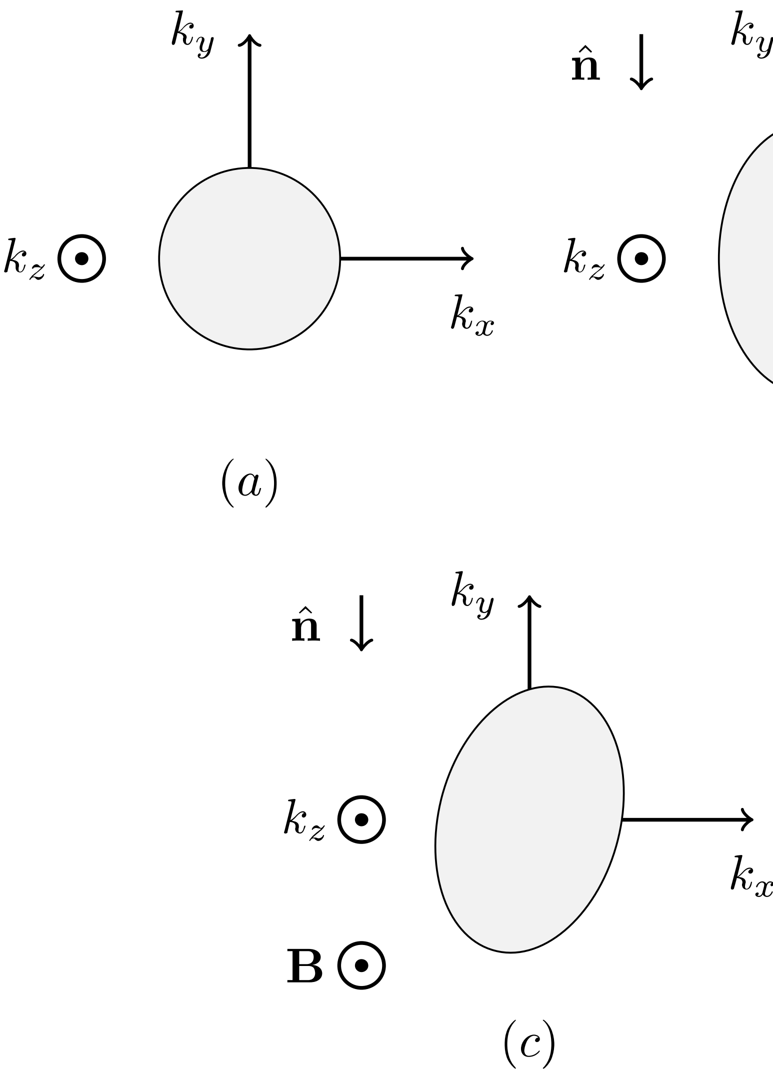

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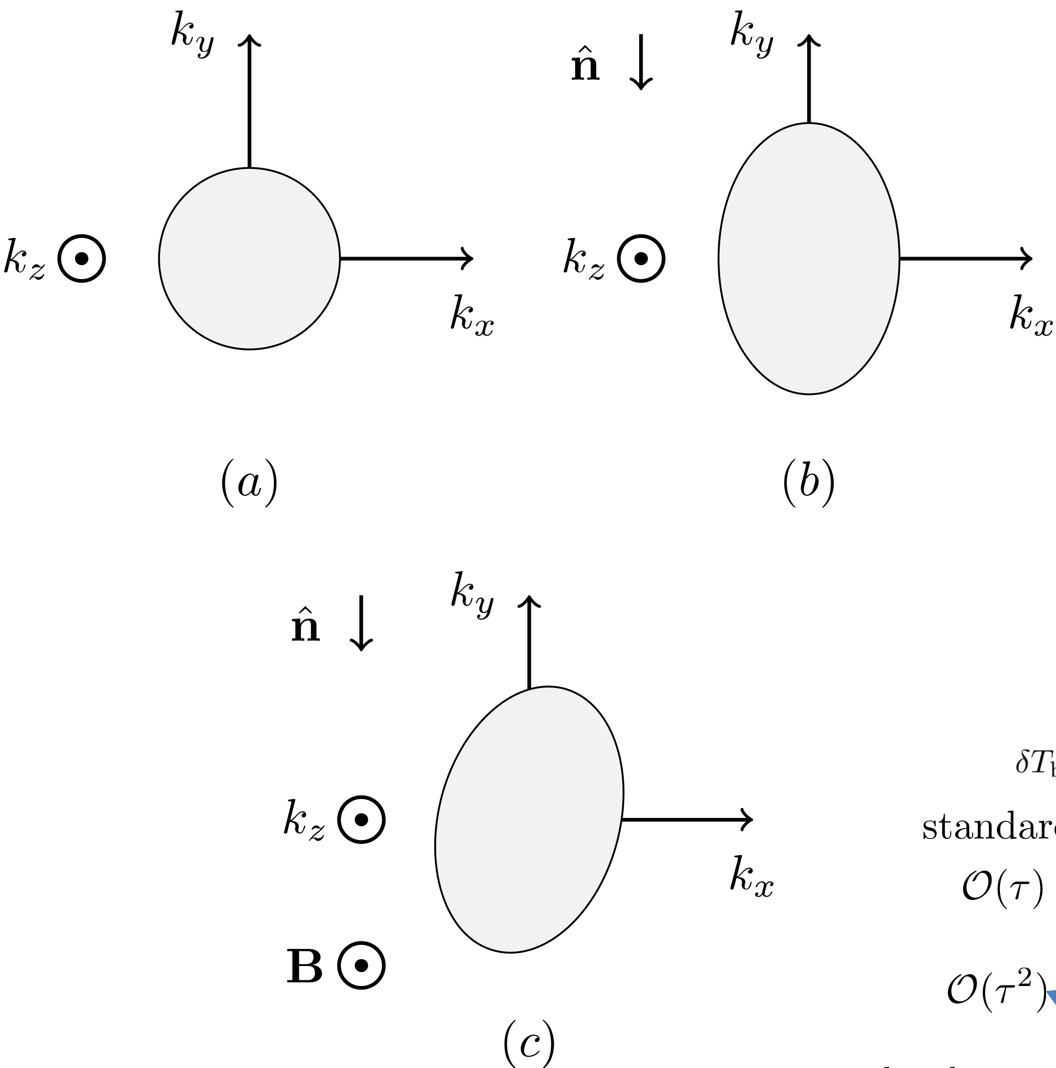
$\mathcal{O}(\tau^2)$

break symm about $\hat{\mathbf{n}}$

Venumadhav, T., et. al. (2014)

Effect on 21cm observables



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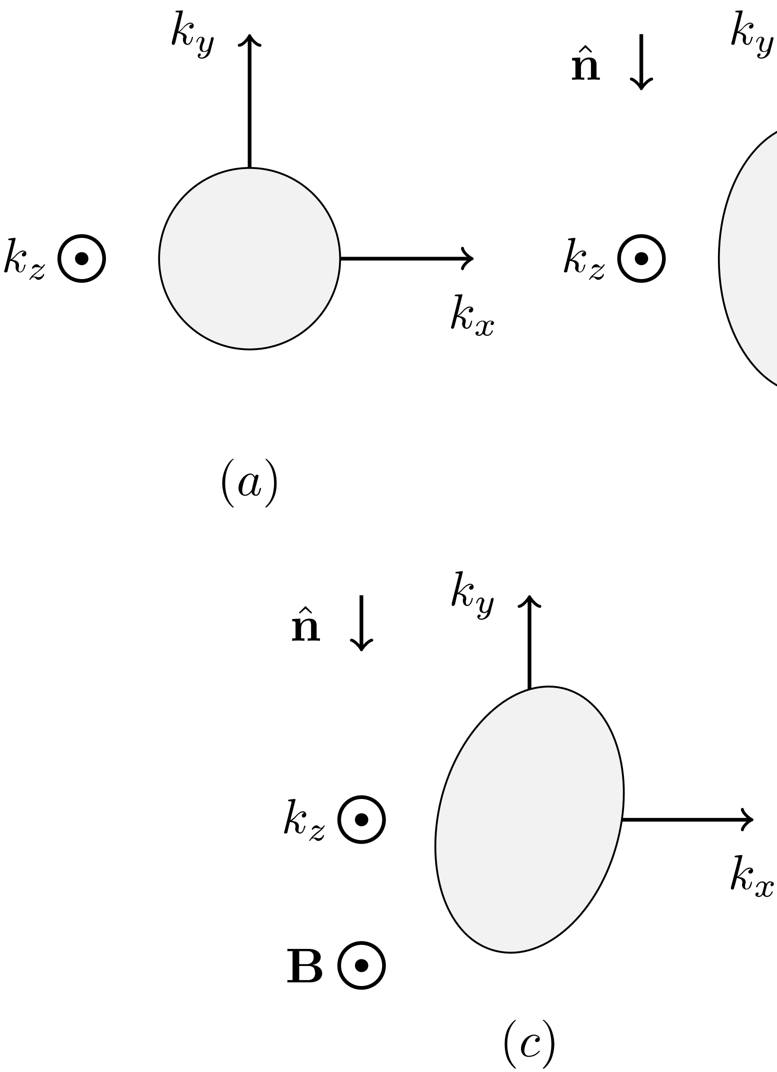
atomic physics

Venumadhav, T., et. al. (2014)

Effect on 21cm observables



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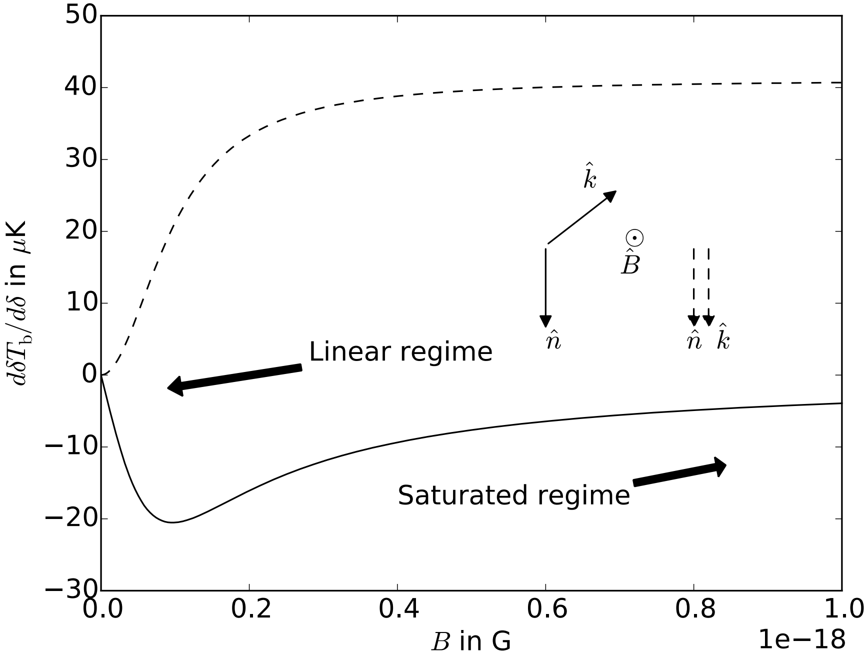
atomic physics

Precession

Venumadhav, T., et. al. (2014)

Limiting cases: field strengths



Strong field, saturated:

$$\delta T_{\rm b}(\hat{\boldsymbol{n}})|_{x_{\rm B}\to\infty} - \delta T_{\rm b}(\hat{\boldsymbol{n}})|_{x_{\rm B}=0}$$
$$= 8.53\ \mu{\rm K} \times P_2(\hat{\boldsymbol{k}}\cdot\hat{\boldsymbol{B}})P_2(\hat{\boldsymbol{n}}\cdot\hat{\boldsymbol{B}})$$
$$\times \left(1-\frac{T_\gamma}{T_{\rm s}}\right)x_{1{\rm s}}^2\left(\frac{1+z}{10}\right)\left(\frac{T_\gamma}{T_{\rm s}}\right)\frac{\delta}{1+x_{\alpha,(2)}+x_{{\rm c},(2)}}$$

Weak field, linear with B:

$$\frac{{\rm d}\delta T_{\rm b}}{{\rm d}B}(\hat{\boldsymbol{n}}) = 1.786\times10^{17}\ \frac{\rm mK}{\rm G}\ [\hat{\boldsymbol{B}}\cdot(\hat{\boldsymbol{k}}\times\hat{\boldsymbol{n}})](\hat{\boldsymbol{n}}\cdot\hat{\boldsymbol{k}})$$
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Venumadhav, T., et. al. (2014)

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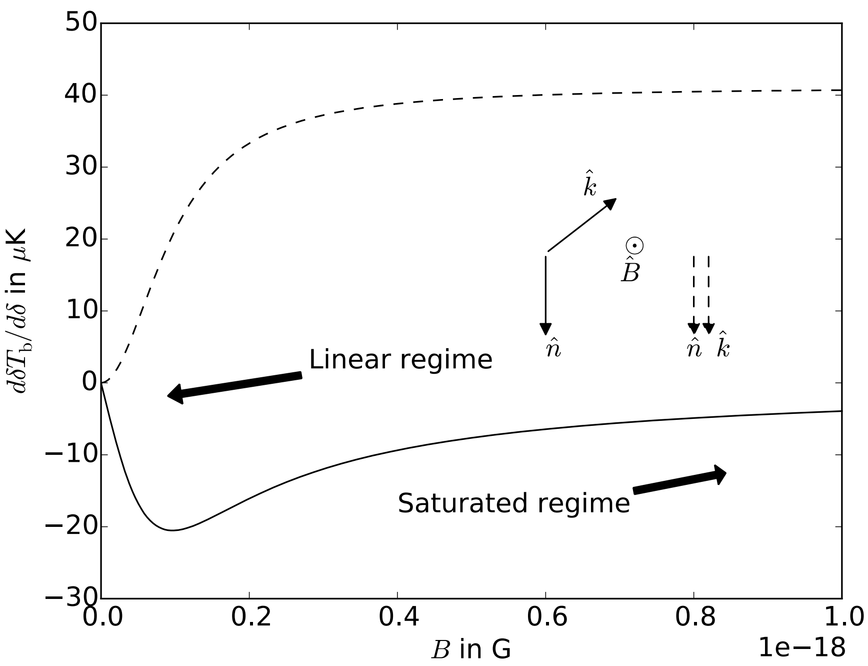

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Precession by π/2

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Precession about B

Venumadhav, T., et. al. (2014)

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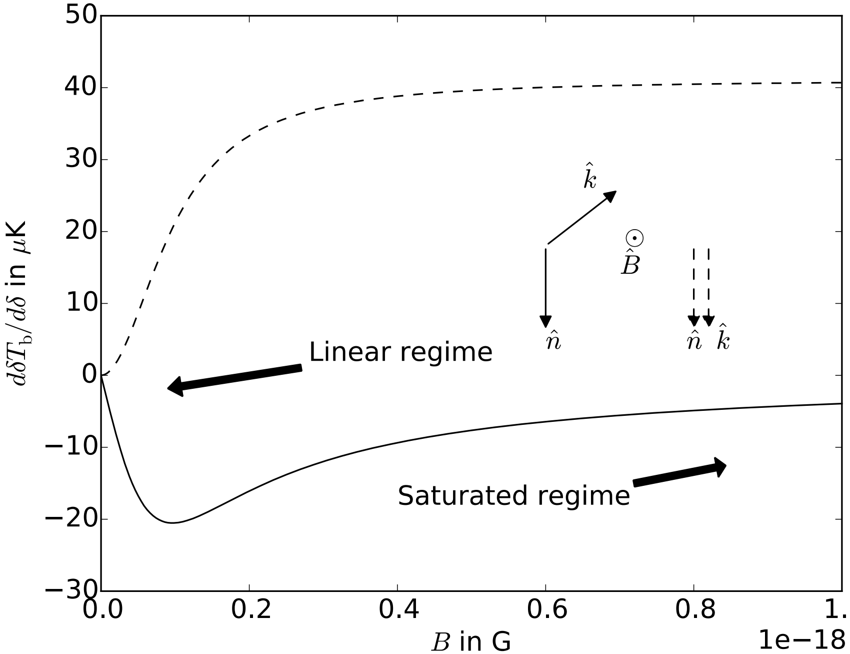

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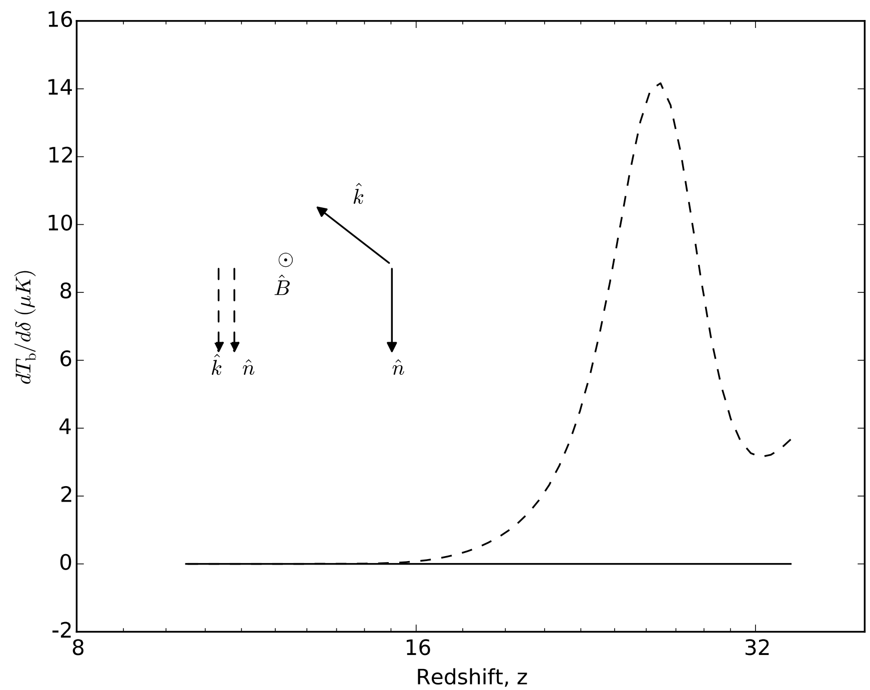

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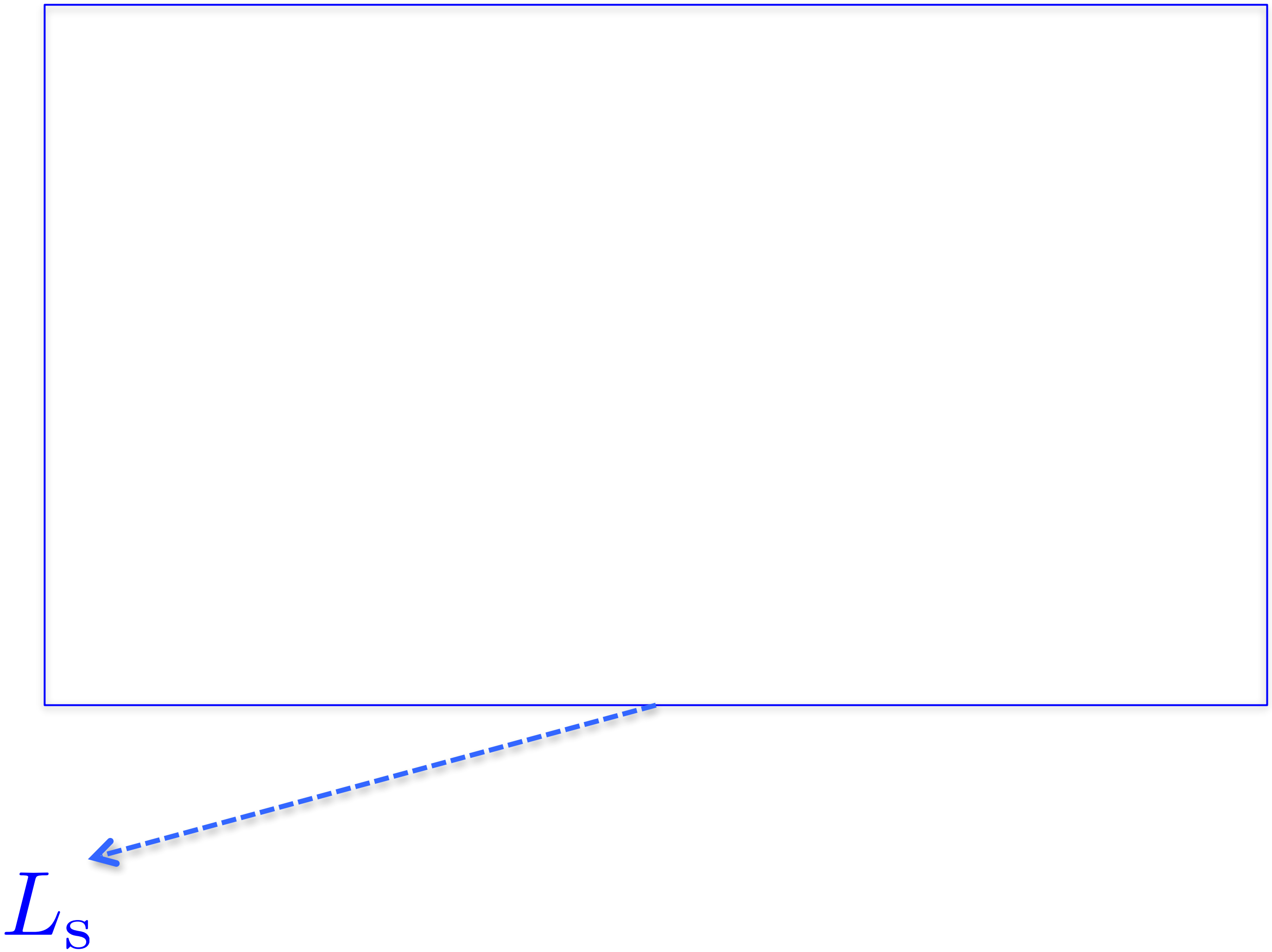
Precession about B

Venumadhav, T., et. al. (2014)

PROSPECTS FOR DETECTION

Survey Geometry

Survey Geometry



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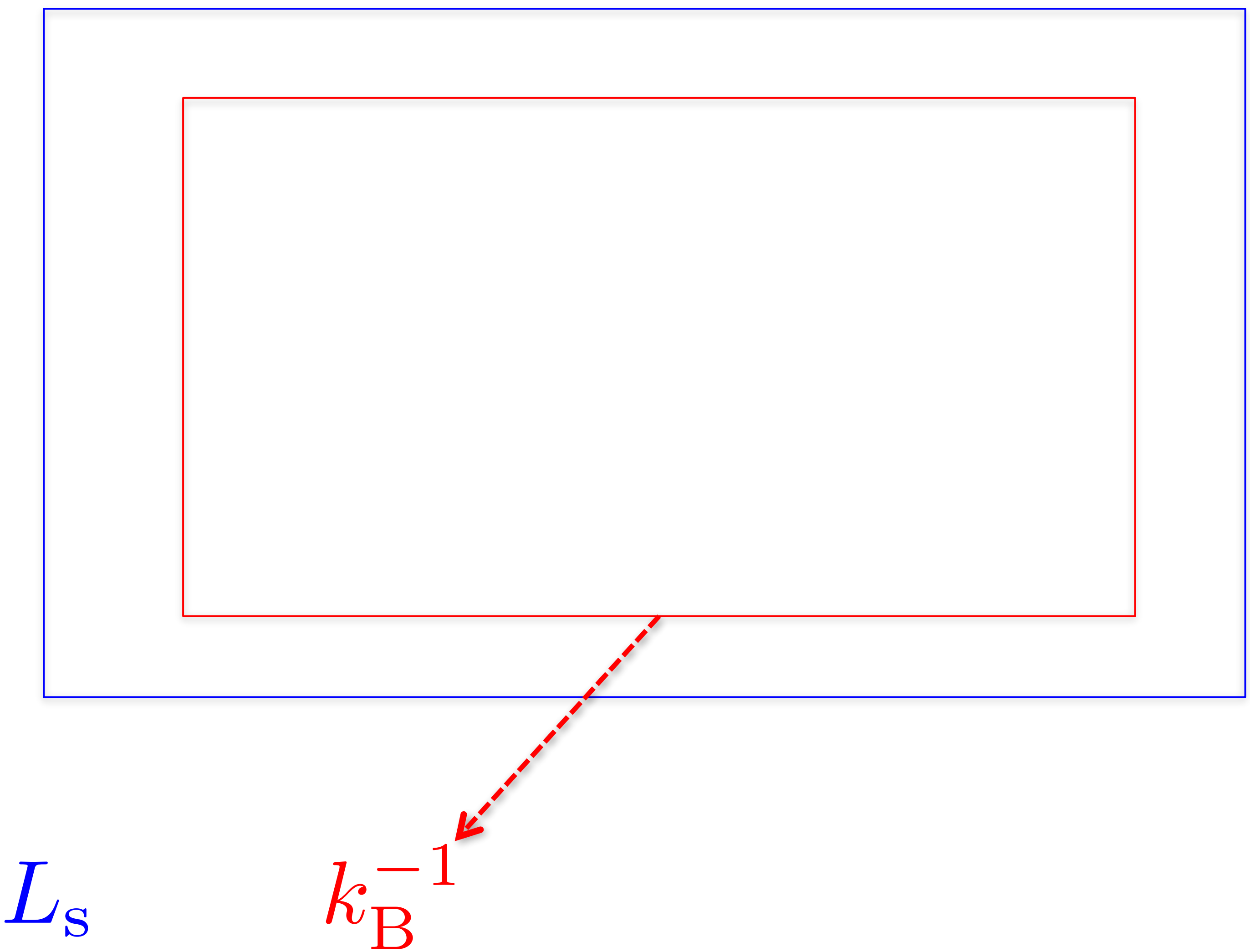

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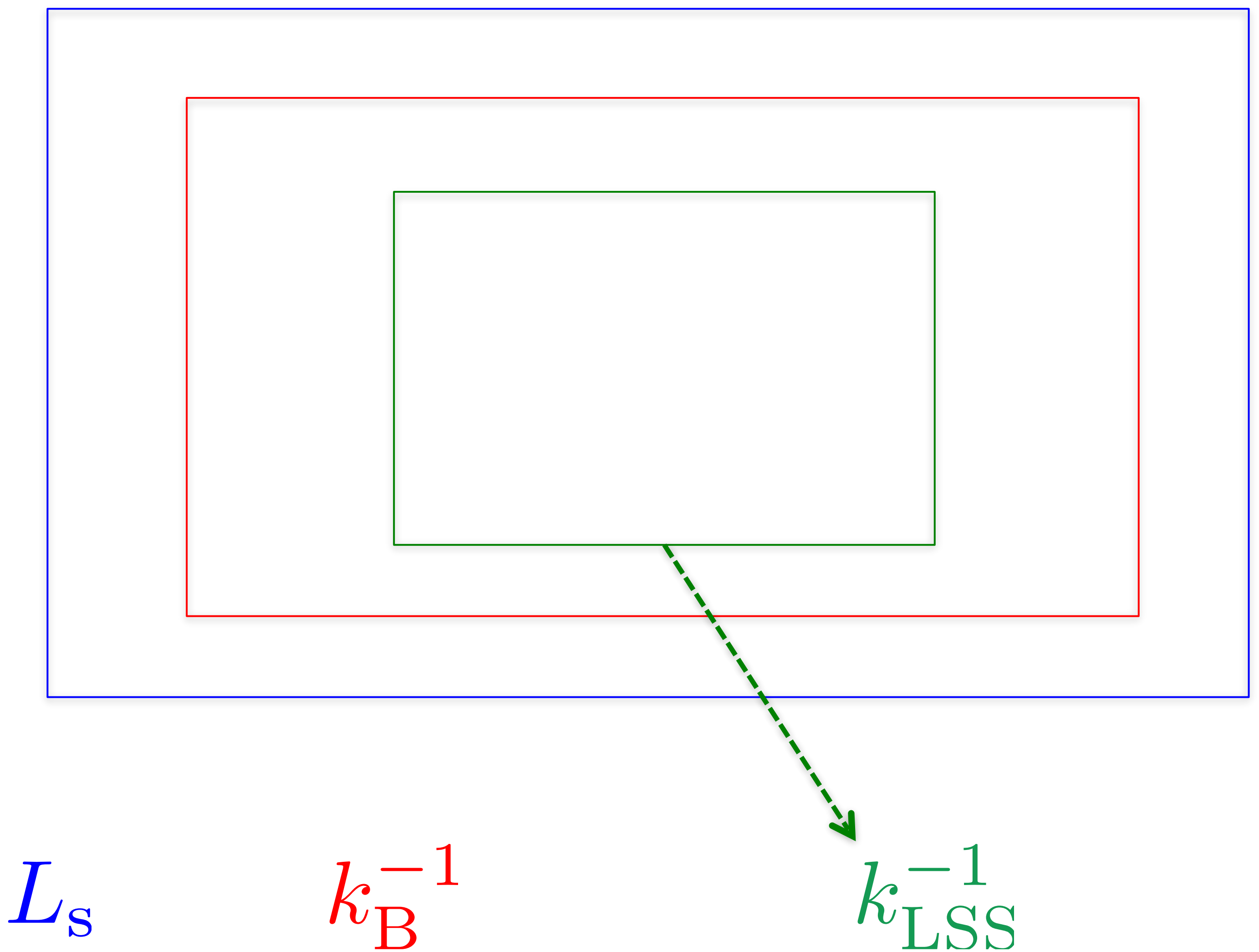

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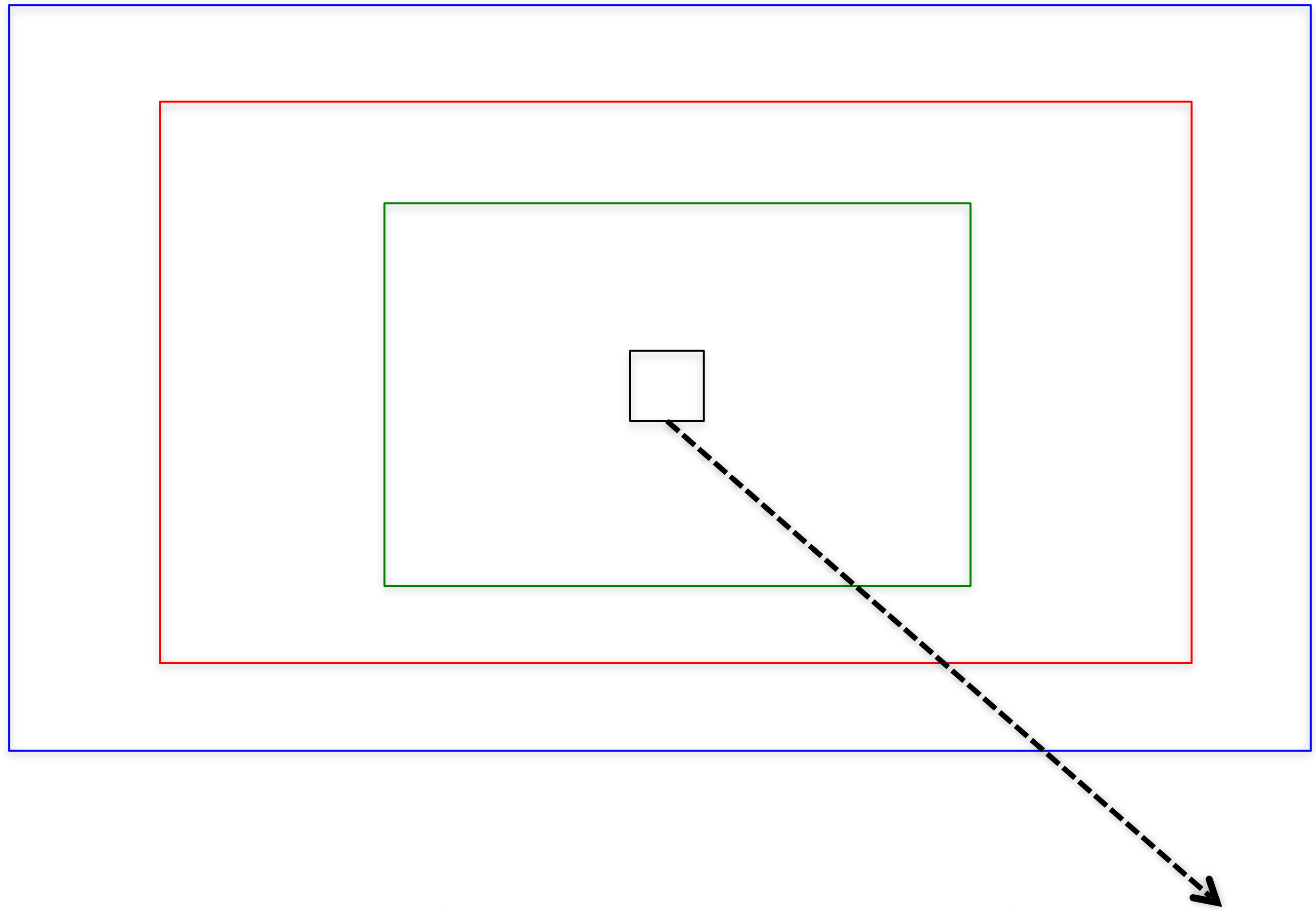
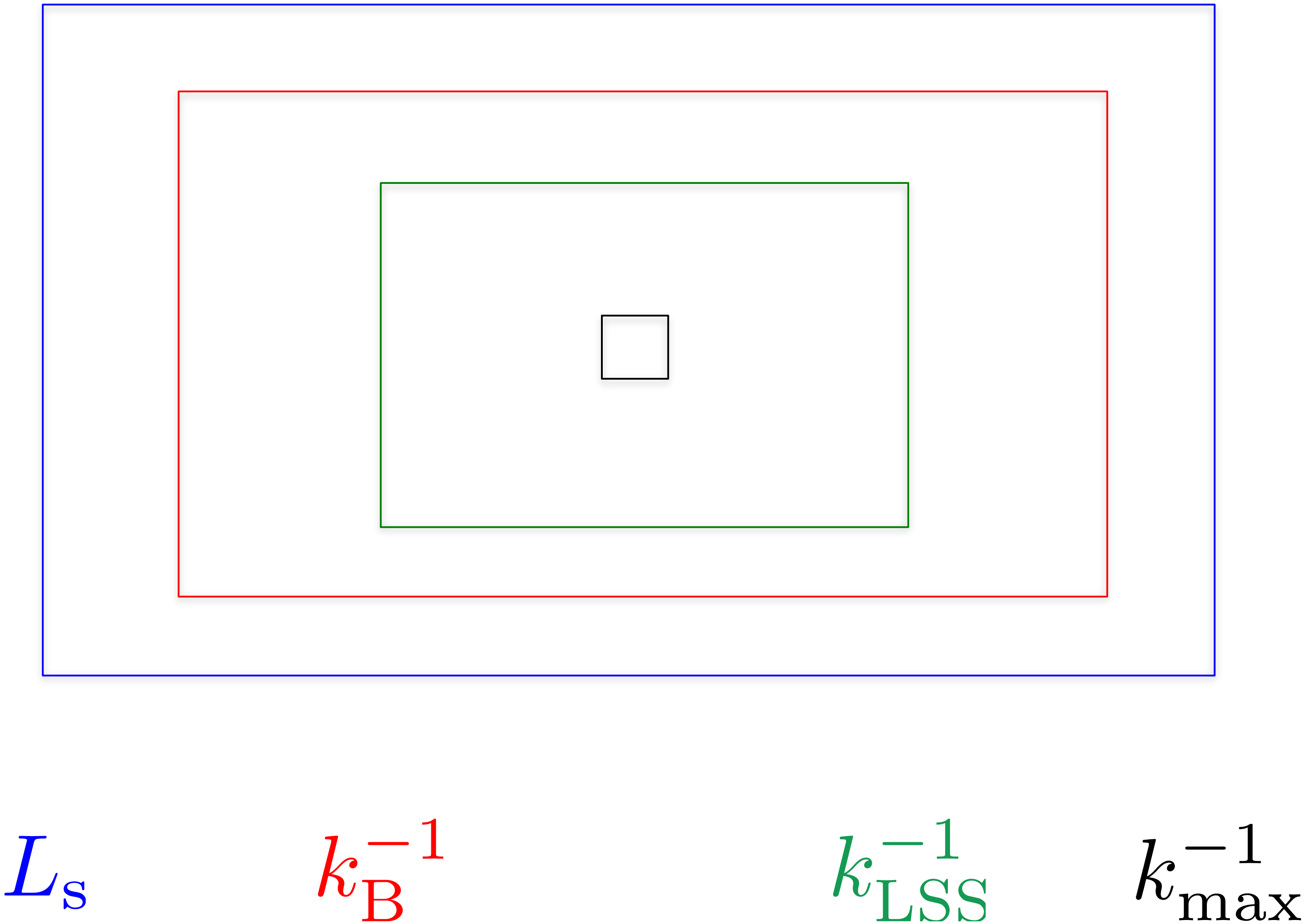
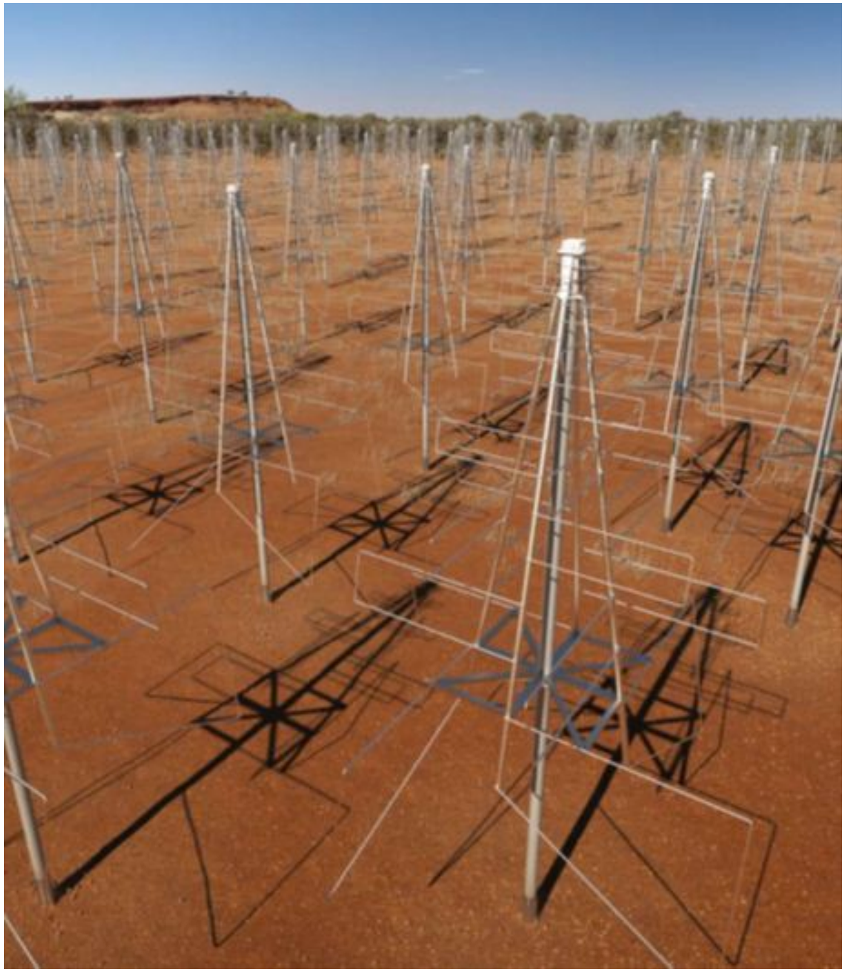


L_s k_B^{-1} k_{LSS}^{-1} k_{max}^{-1}

Survey Geometry

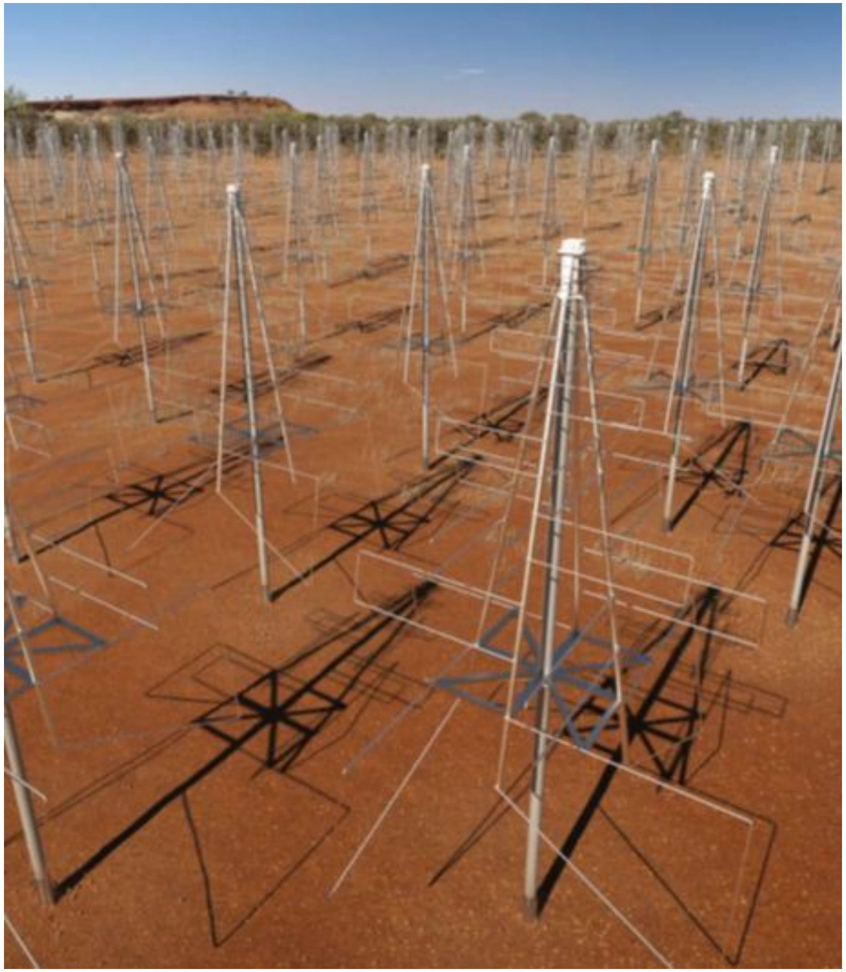


Detectability



Credit: Swinburne Astronomy Productions/
ICRAR/U. Cambridge/ASTRON.

Detectability



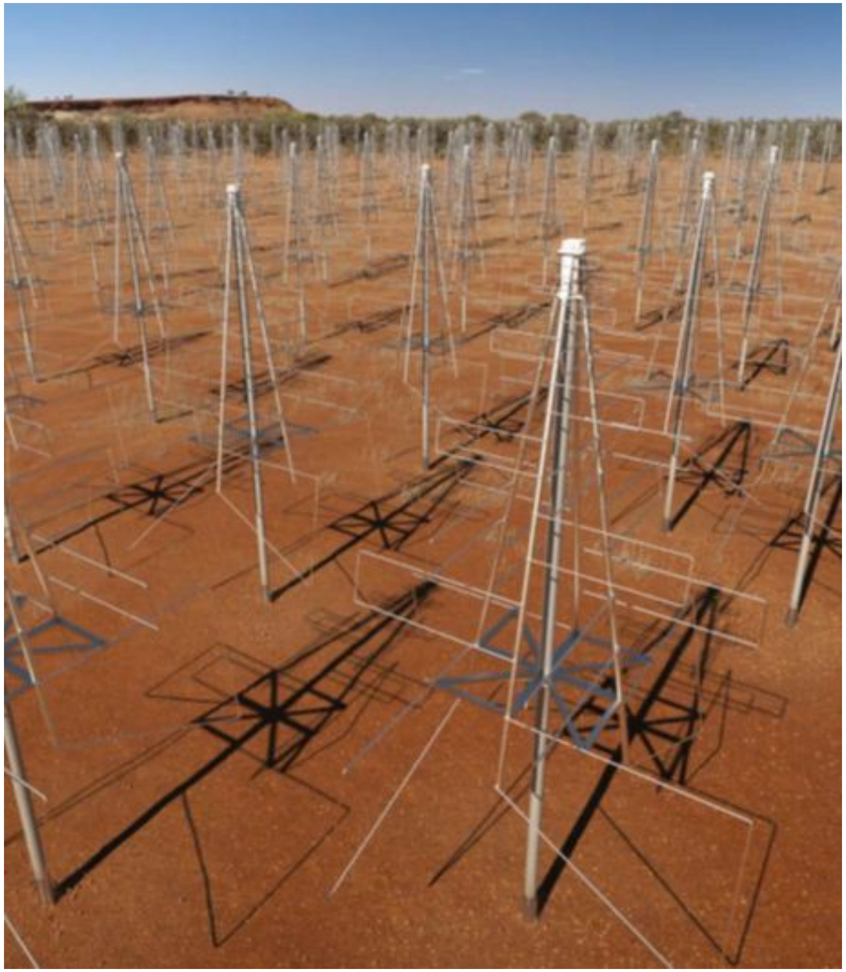
Credit: Swinburne Astronomy Productions/ ICRAR/U. Cambridge/ASTRON.

No signal - variance

$$P^N(\vec{k}) = \frac{\lambda^4 c(1+z)^2 \chi^2(z)}{\Omega_{\rm beam} t_1 H(z) \nu_{21}} \frac{T_{\rm sky}^2}{A_e^2 n_{\rm base}(\vec{k})}$$

$$T_{\rm sky} = 60 \left(\frac{21}{100}(1+z) \right)^{2.55} \quad [\mathrm{K}]$$

Detectability



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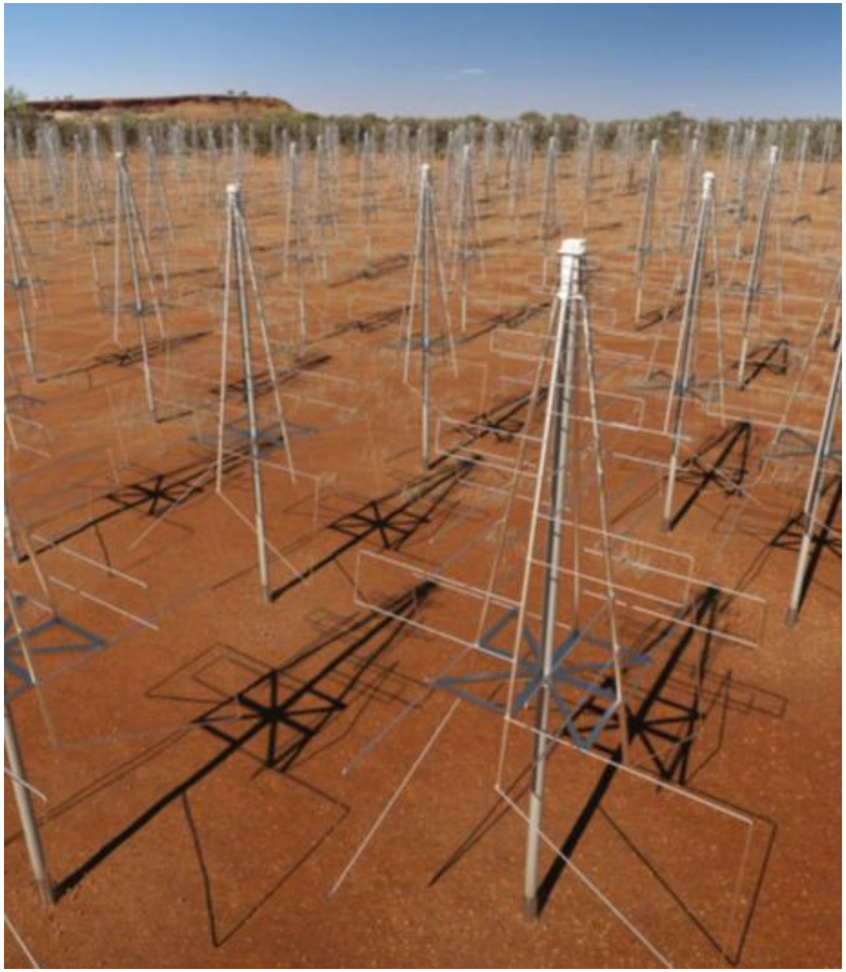

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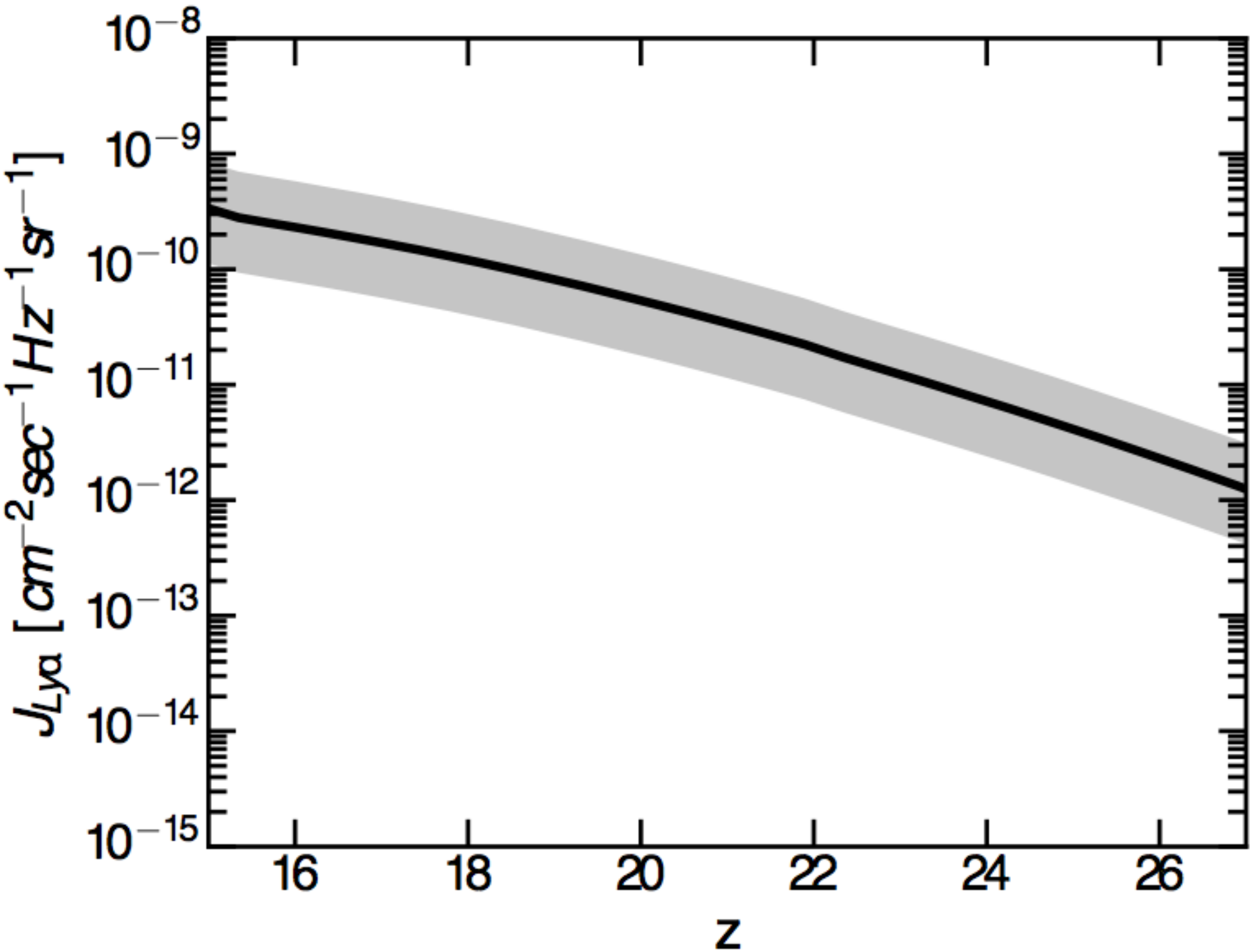
Unsaturated case

$$\sigma_{B_0}^{-2}(z) = \int dV_{\rm patch}(z)\frac{k^2 dk d\phi_k \sin\theta_k d\theta_k}{(2\pi)^3}\left(\frac{\partial P_{\rm S}/\partial B_0}{P_{\rm N}+P_{\rm S}}\right)^2$$

Saturated case

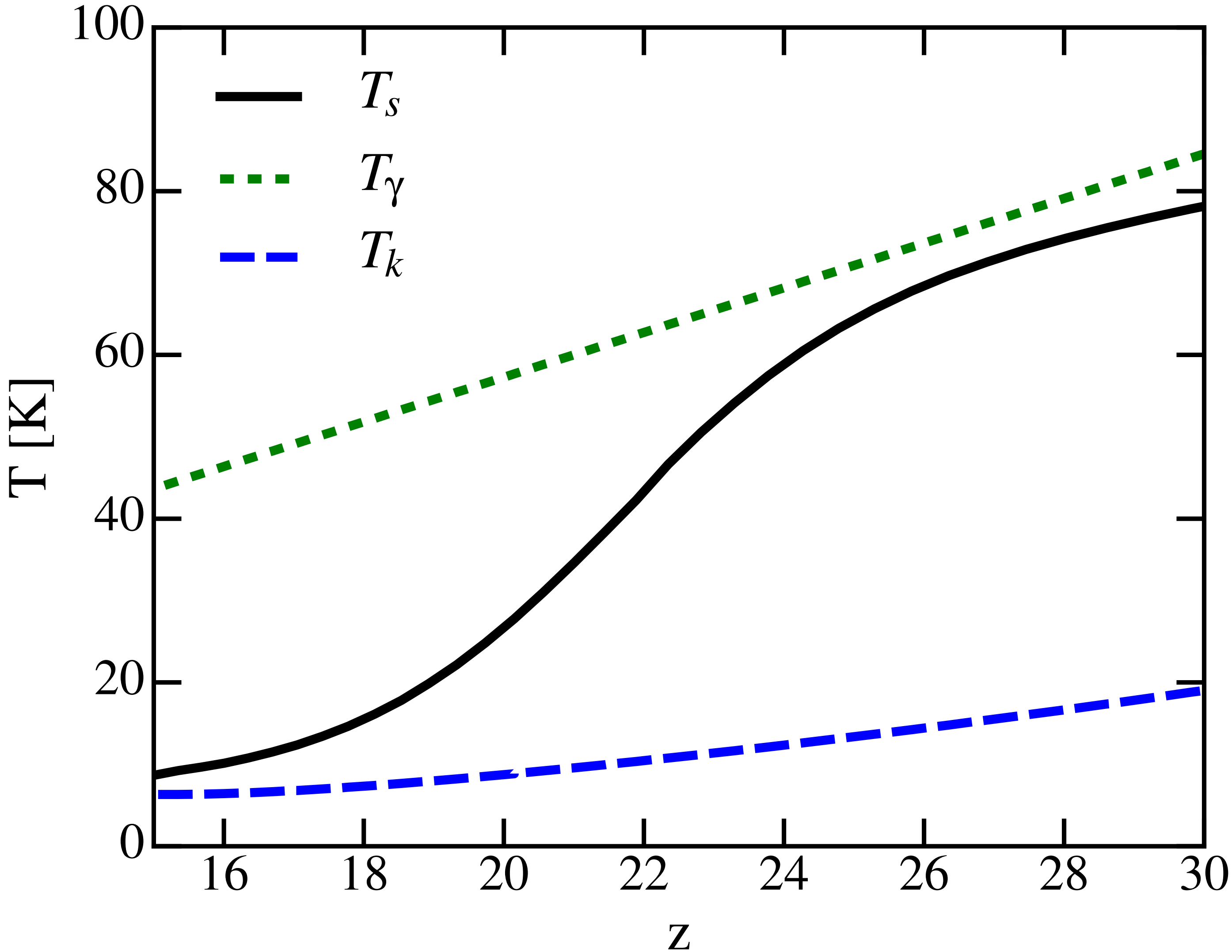
$$P = (1-\xi)P\Big|_{B=0} + \xi P\Big|_{B\to\infty}$$

Input parameters



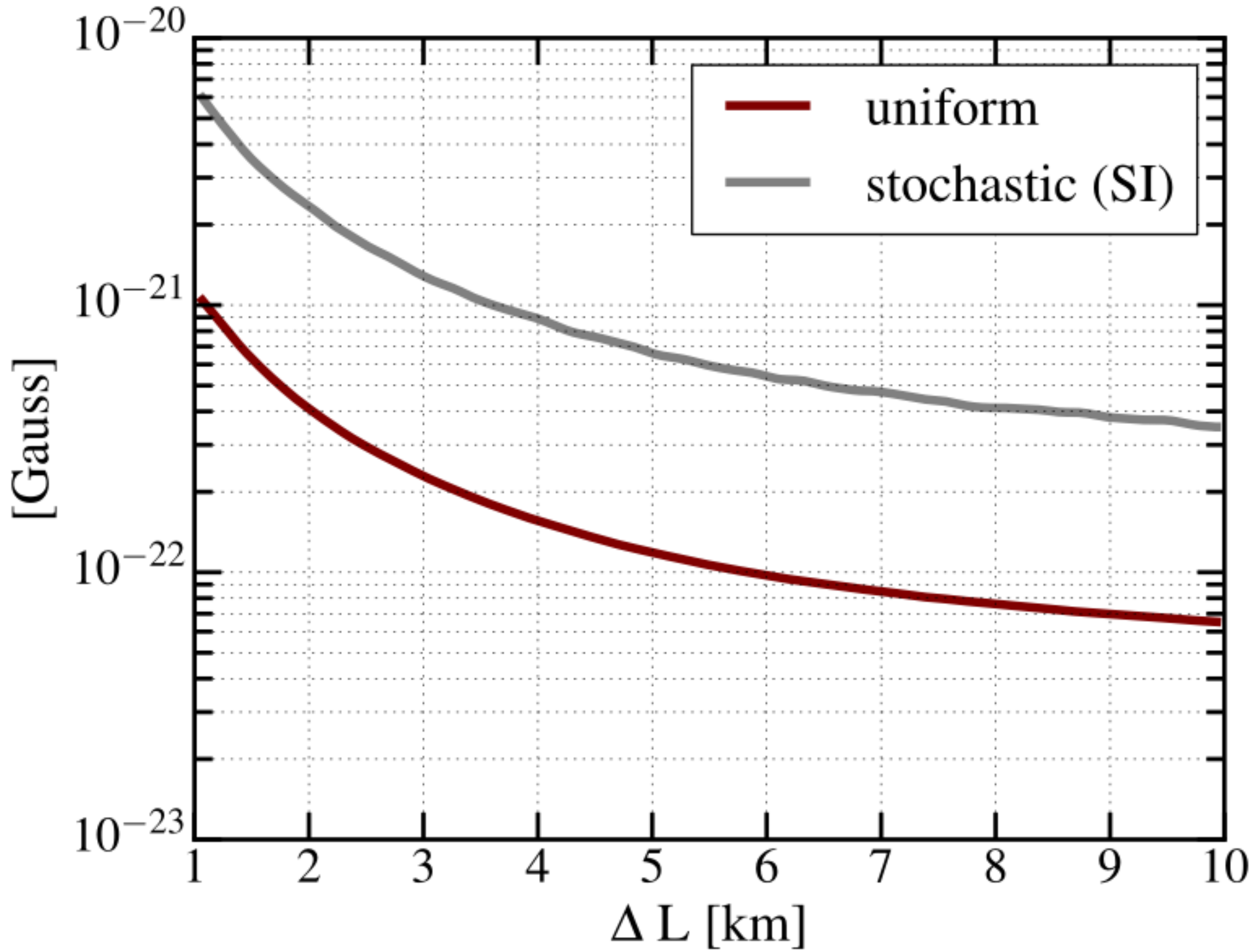
Gluscević, V., Venumadhav, T., et. al. (2016)

Input parameters



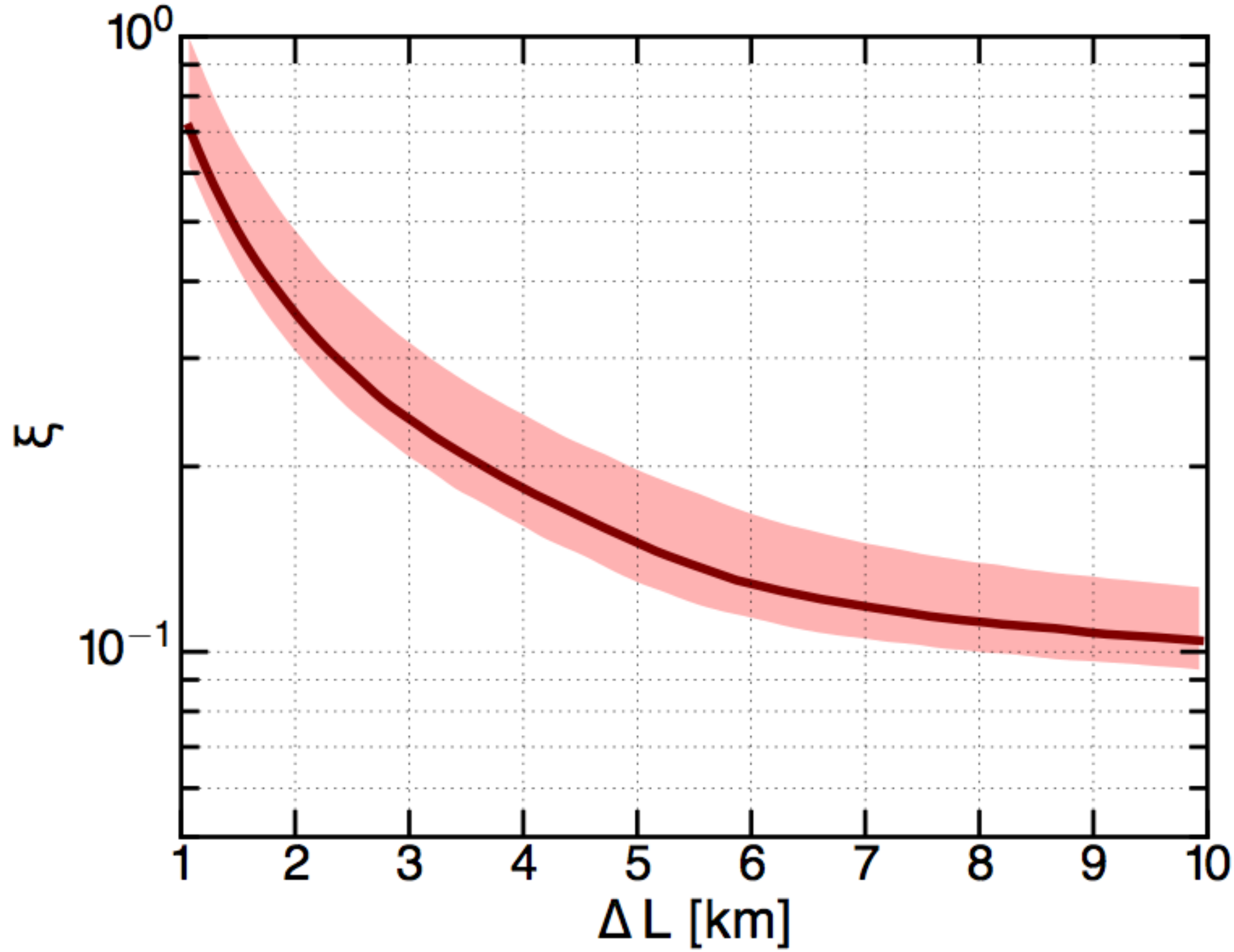
Gluscević, V., Venumadhav, T., et. al. (2016)

Detectability - Unsaturated



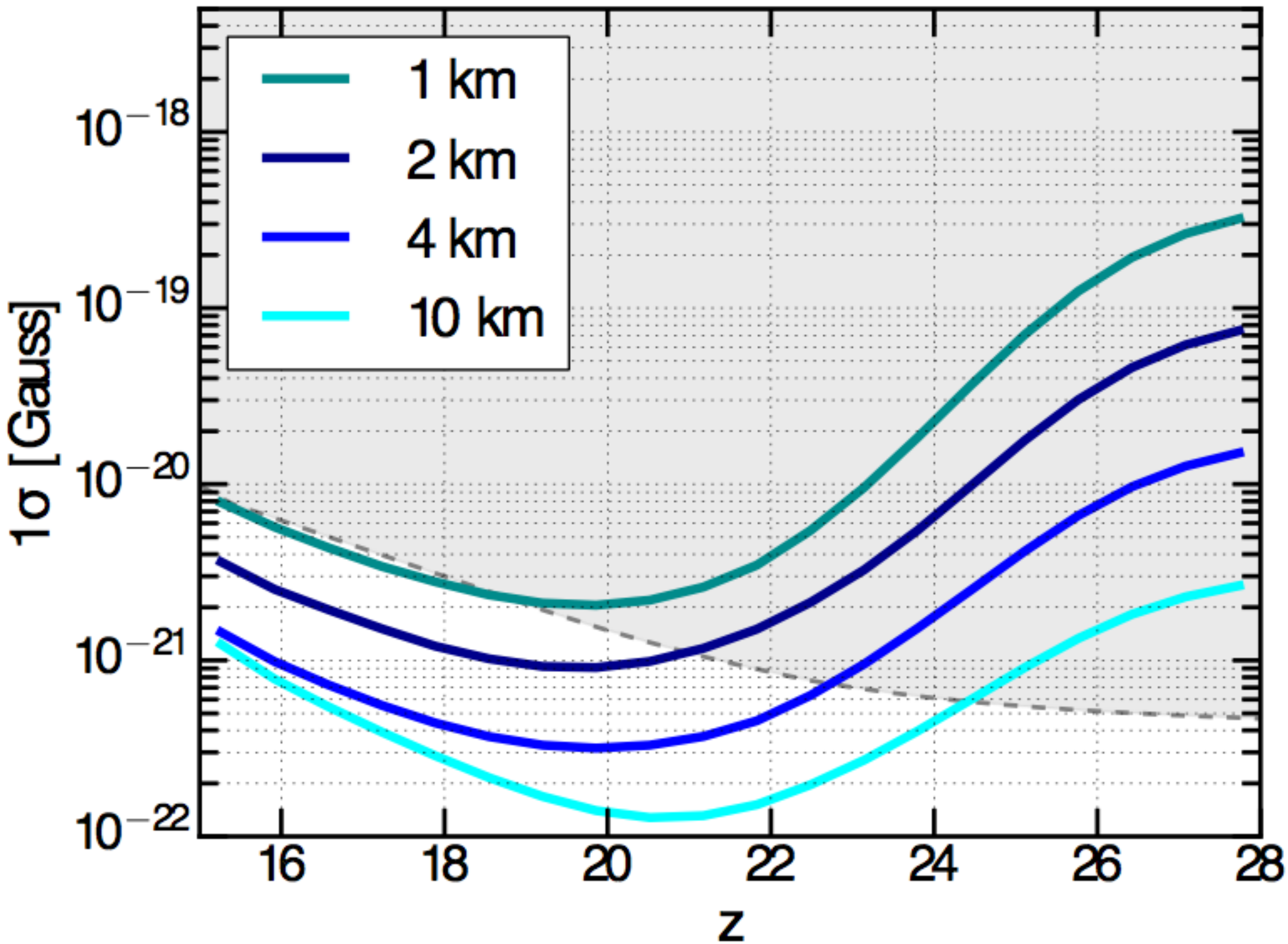
Gluscević, V., Venumadhav, T., et. al. (2016)

Detectability - Saturated



Gluscević, V., Venumadhav, T., et. al. (2016)

Detectability - Redshift



Gluscević, V., Venumadhav, T., et. al. (2016)

Conclusions

High-resolution maps of the 21-cm line from the epoch of reionization and earlier offer the possibility of directly probing primordial magnetic fields.

An array of dipole antennas in a compact–grid configuration with a collecting area $\gtrsim 1\ \mathrm{km}^2$ is **in principle** sensitive to a 10^{-21} Gauss comoving field within one year of integration time.

Future work towards its applicability:

- Foreground subtraction removes information.
- Optimal design of future experiments?
- Sensitivity to particular models of magnetic fields?

PRIMORDIAL GRAVITATIONAL WAVES

What about CMB anisotropies?

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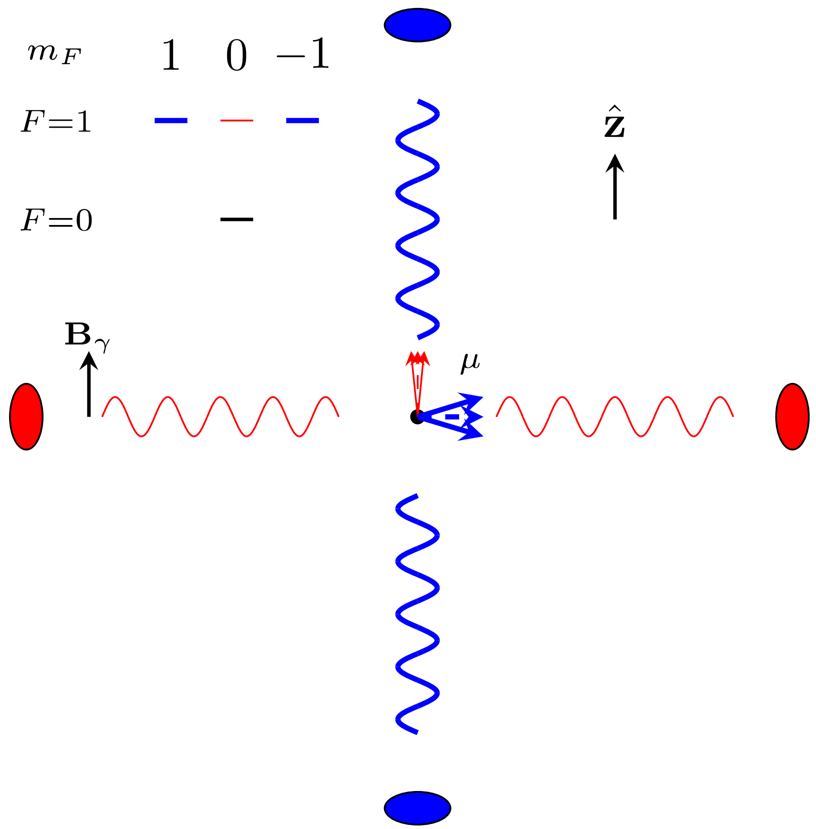
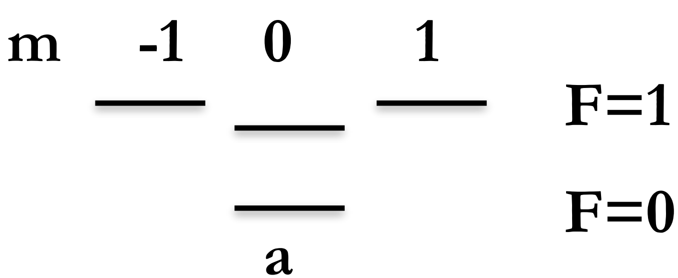
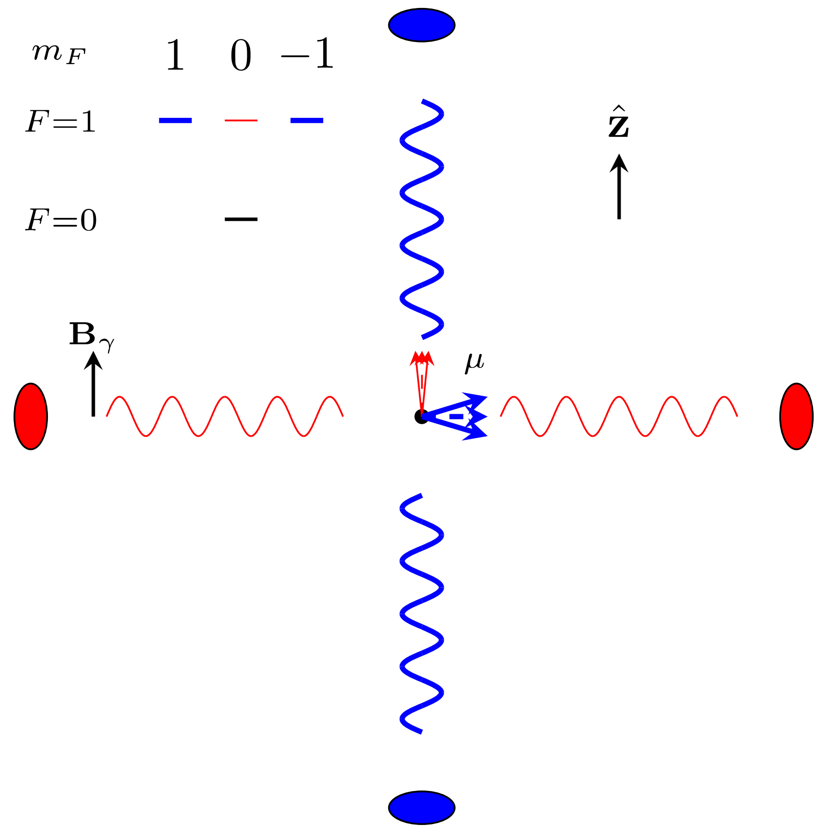


What about CMB anisotropies?

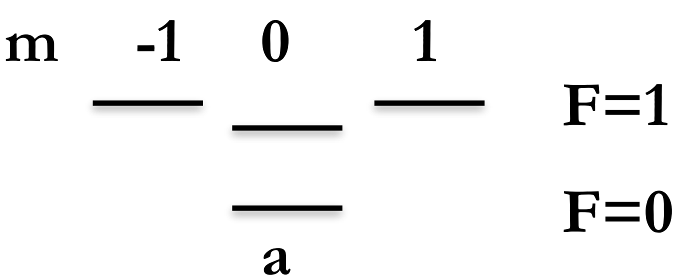
- Off resonant, finite temperature correction to the energy levels.
- Dynamical stark effect.

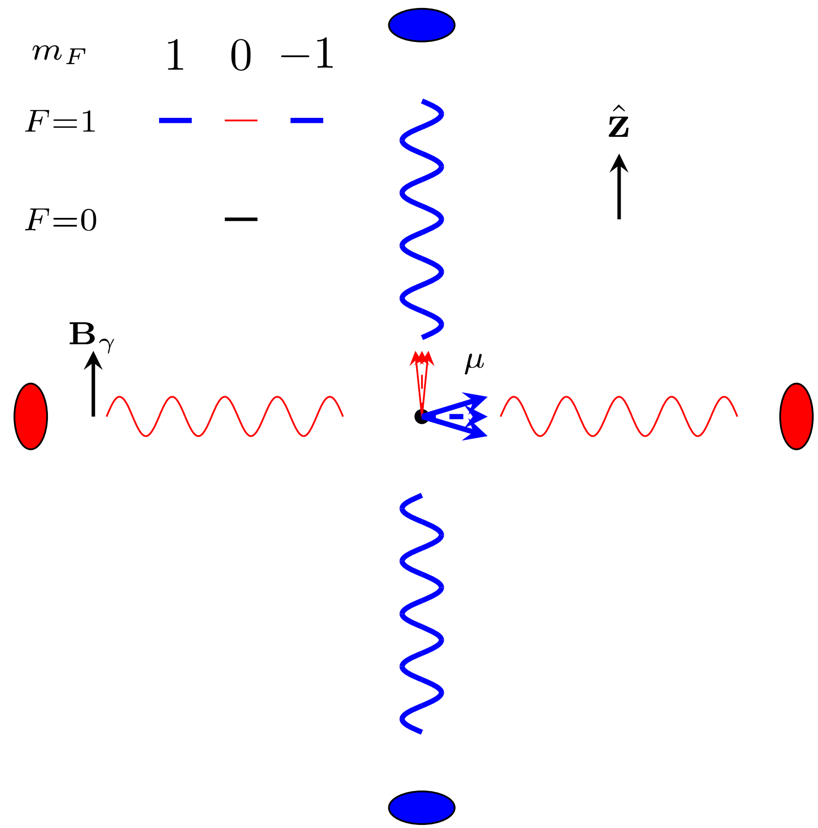




What about CMB anisotropies?

- Off resonant, finite temperature correction to the energy levels.
- Dynamical stark effect.





$$\frac{\Delta E_{11} - \Delta E_{10}}{\hbar} = -4.4 \times 10^{-10}\ \mathrm{s}^{-1} \left(\frac{T_\gamma}{60\ \mathrm{K}}\right)^2 a_{20,\mathrm{CMB}}$$

From alignment to orientation

- In the presence of “alignment” or spin-polarization (due to fluctuations in the gas), and the energy level correction due to CMB quadrupoles, atoms tend to get “oriented”.

$$\langle F_\alpha F_\beta \rangle \rightarrow \langle \mathbf{F} \rangle$$

- Oriented atoms emit circularly polarized radiation.

Why do spins develop a net orientation?

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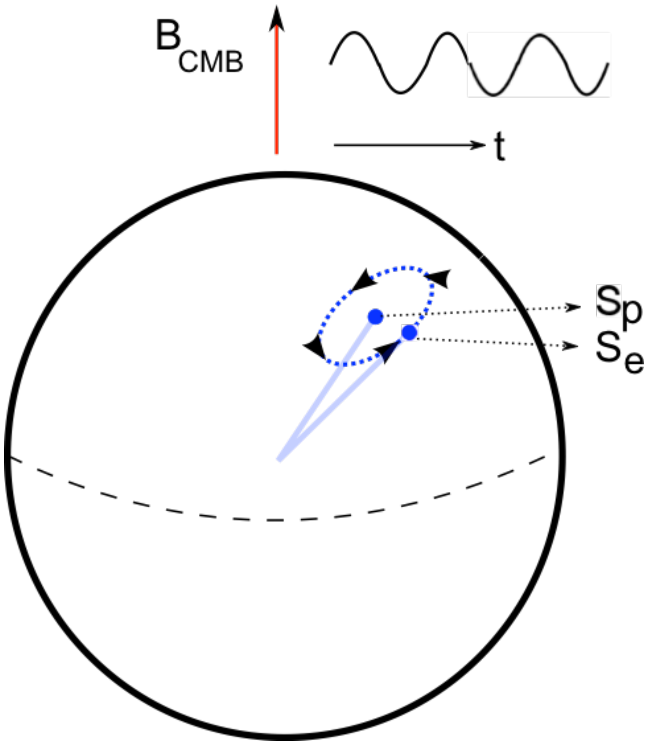

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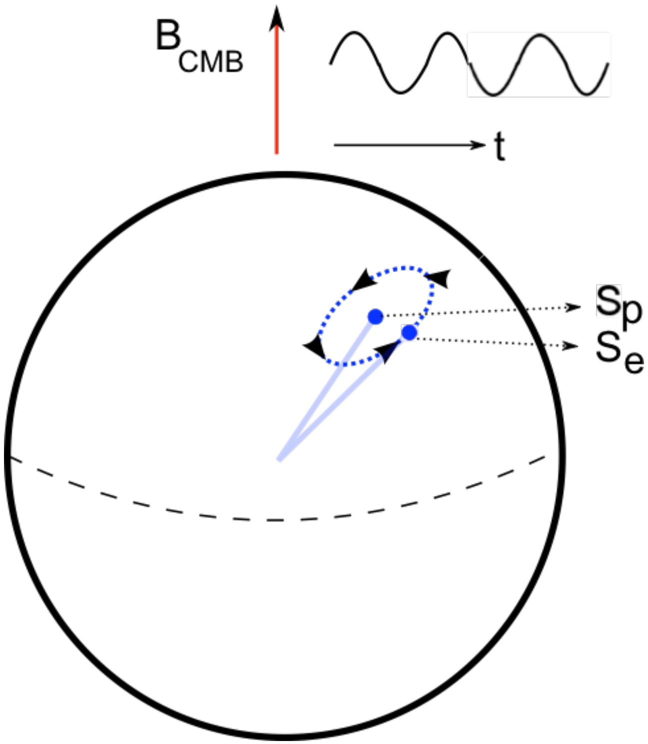

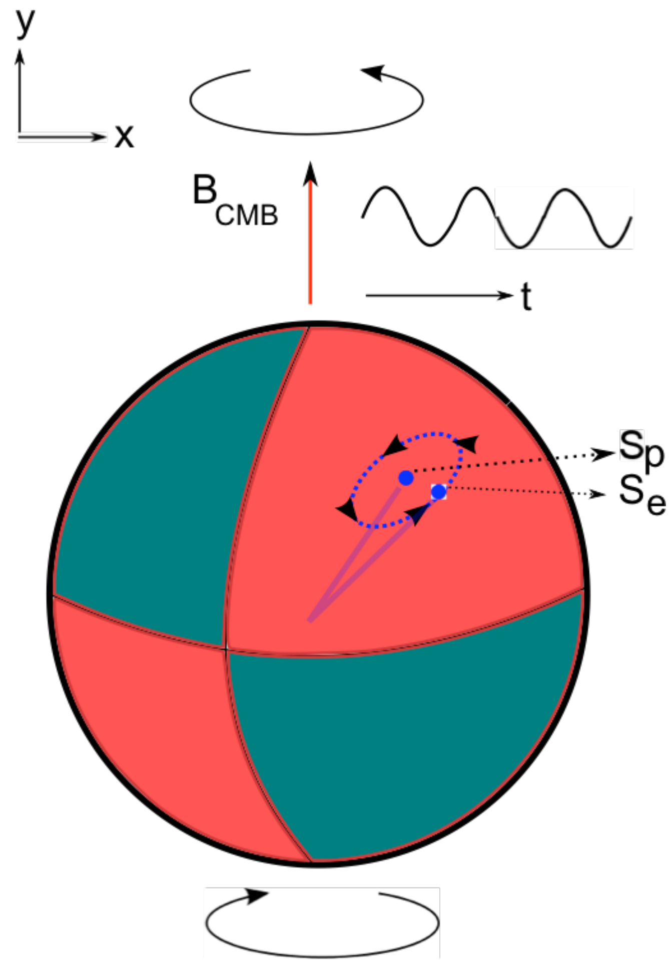

Using V to look at the CMB quadrupole

$$\frac{\partial V_{\rm obs}}{\partial \delta} = -8.6\ {\rm mK} \left(\frac{1+z}{20}\right)^2 \frac{T_\gamma}{T_{\rm s}} \left(1 - \frac{T_\gamma}{T_{\rm s}}\right)$$

$$\times \frac{1}{(1+0.75x_{\alpha,(2)})(1+x_{\alpha,(2)}+x_{{\rm c},(2)})}$$

$$\times\, {\rm Im}[a_{21}Y_{21}(\hat{\mathbf{k}}) + 2a_{22}Y_{22}(\hat{\mathbf{k}})]$$

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- TV correlations can be used to reconstruct the local CMB quadrupole at the atom's location.

$$P_{TV}(k) = \frac{\partial T_{\rm obs}}{\partial \delta}(k) \frac{\partial V_{\rm obs}}{\partial \delta}(k) P_\delta(k)$$

Reconstructing gravitational waves

- The "derived data products" from the analysis are maps of the CMB quadrupole components,

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- Components with magnetic parity only arise due to (primordial) gravitational waves

$$b^{B,q}_{\ell m}(\chi) = \frac{1}{2i}\left[b_{q\ell m}(\chi) - b_{-q,\ell m}(\chi)\right]$$