

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

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

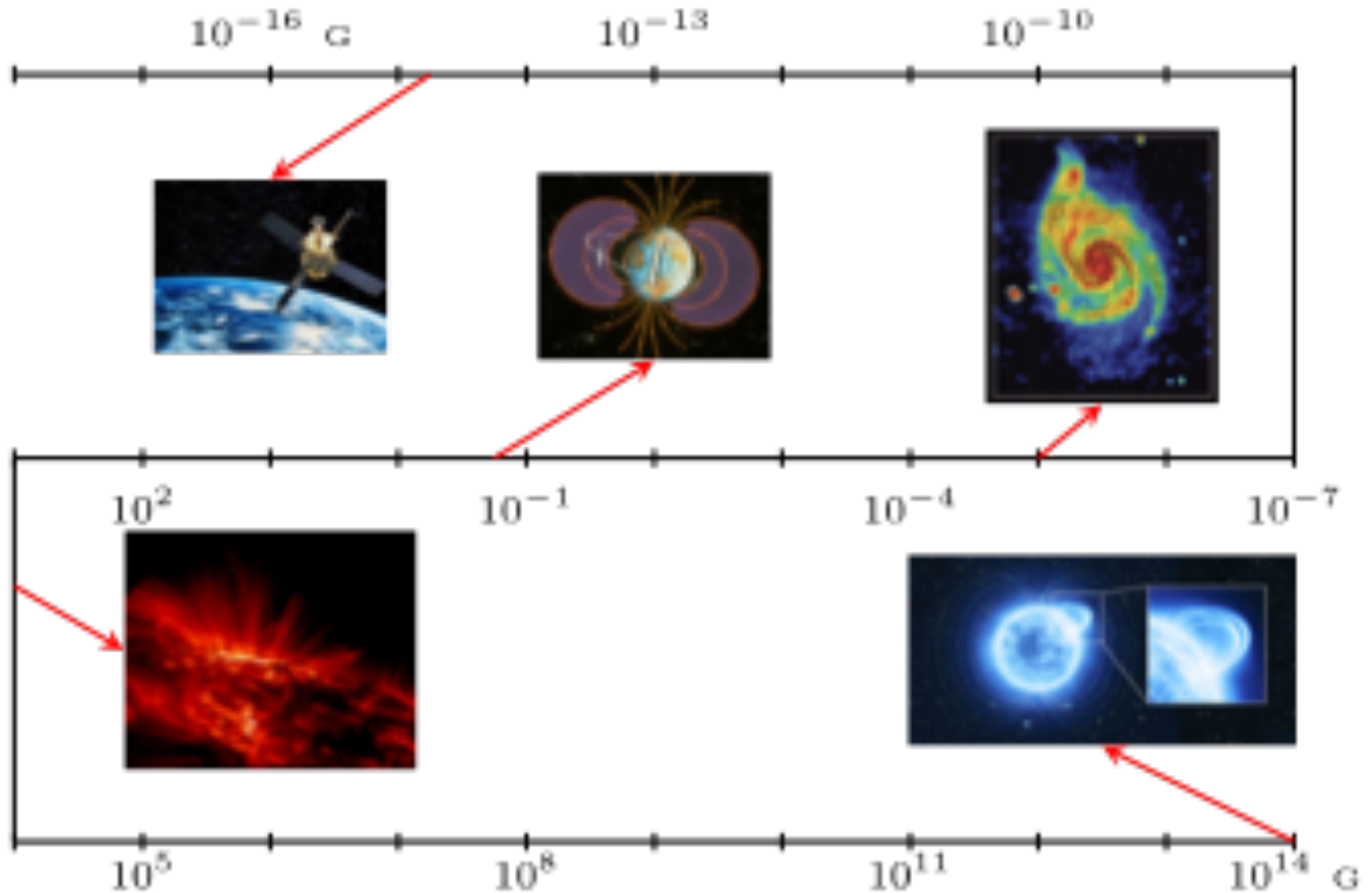
Outline

- 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(?)

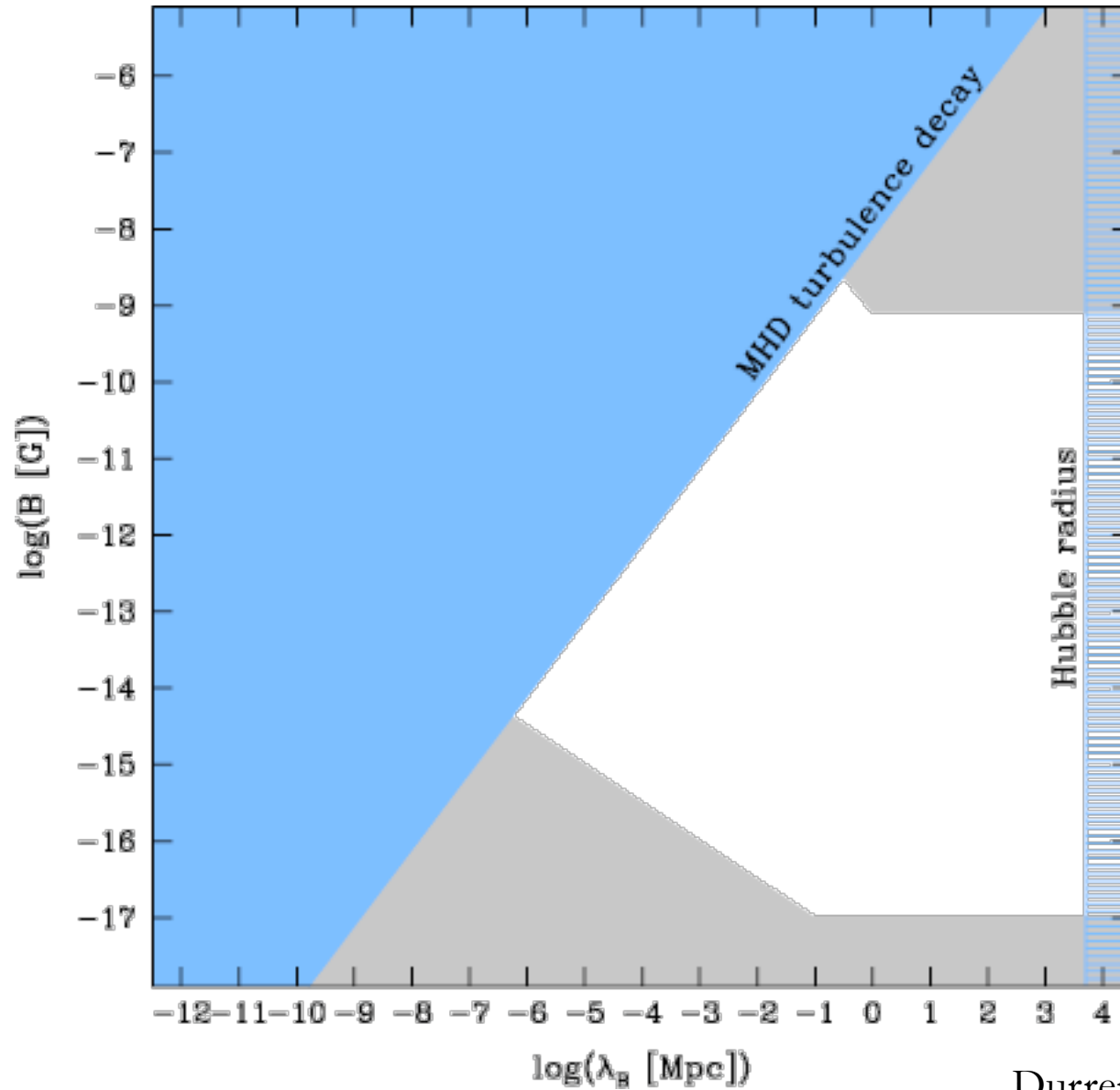
Introduction:

PRIMORDIAL MAGNETIC FIELDS

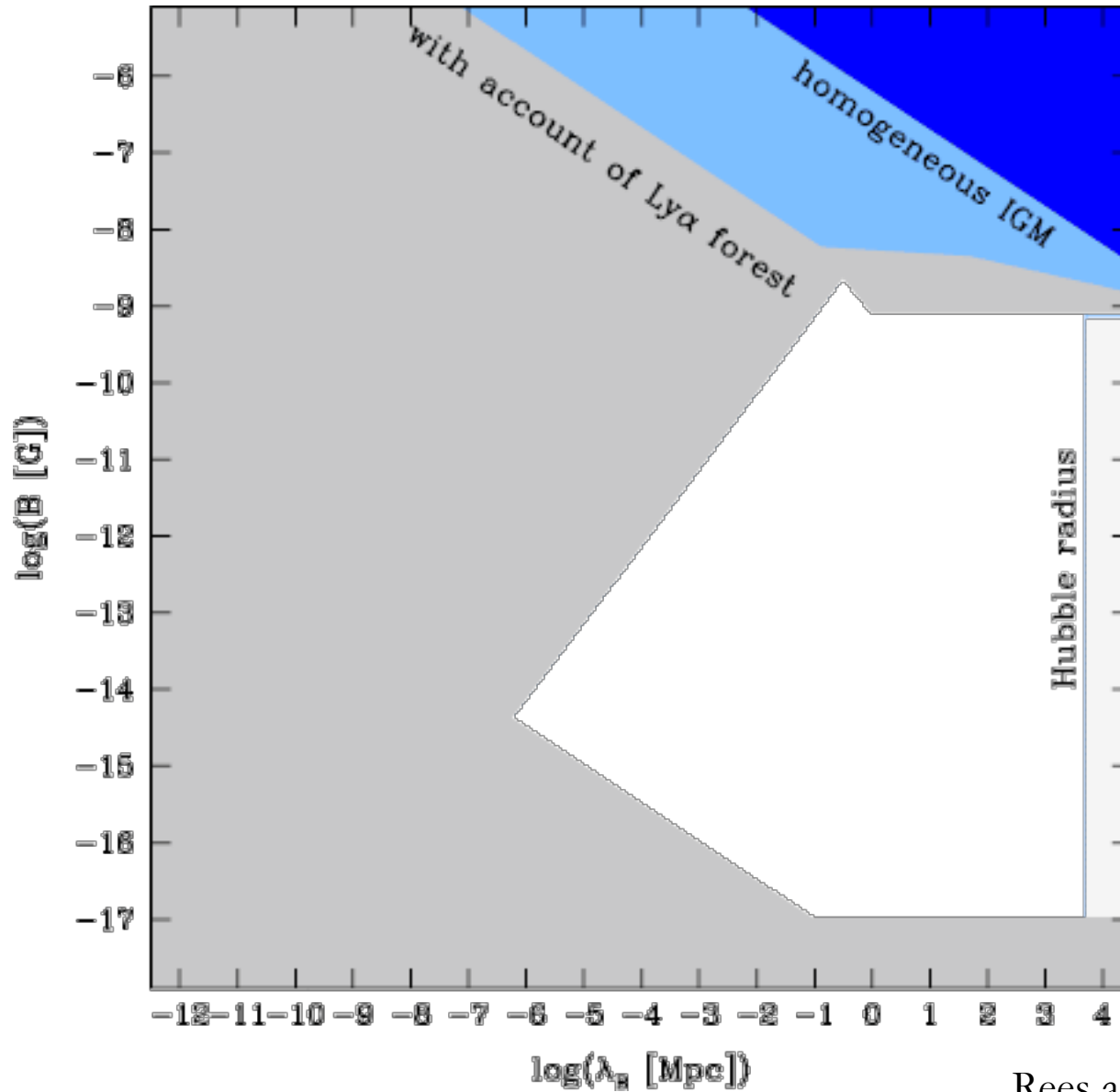
Magnetic fields: orders of magnitude



Current constraints on PMFs

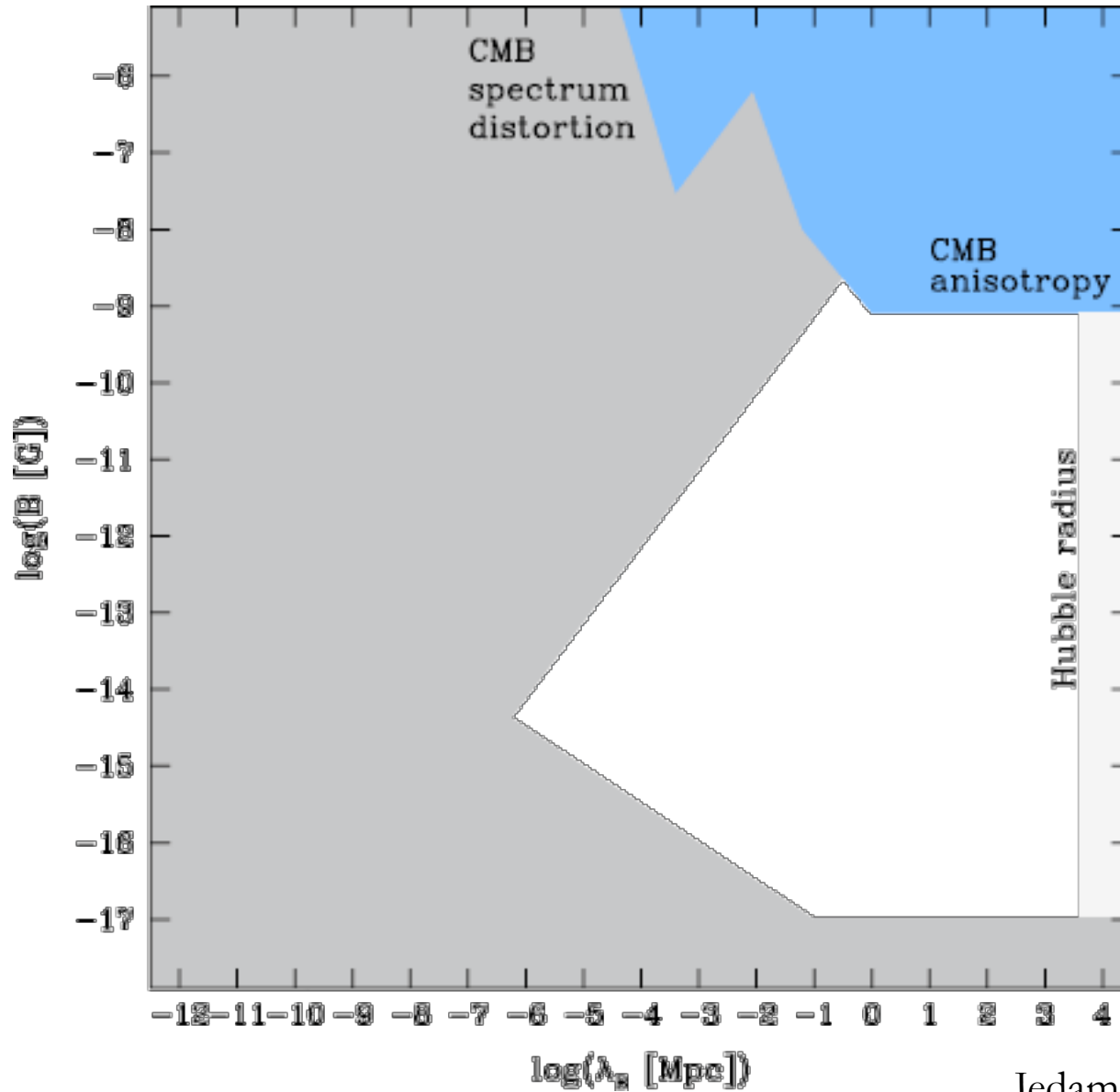


Current constraints on PMFs



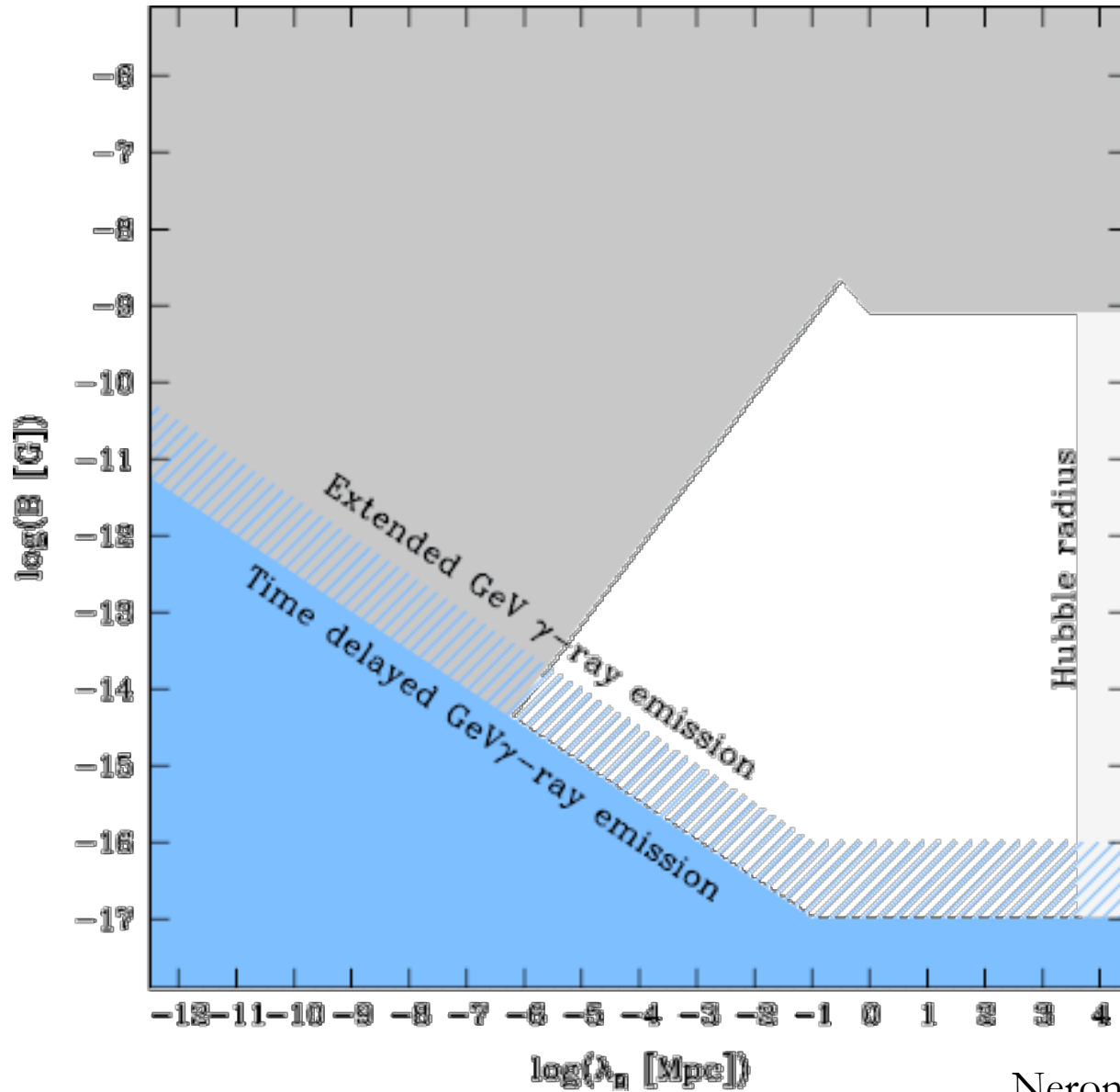
Rees and Reinhardt (1972)
Kronberg (1994)

Current constraints on PMFs



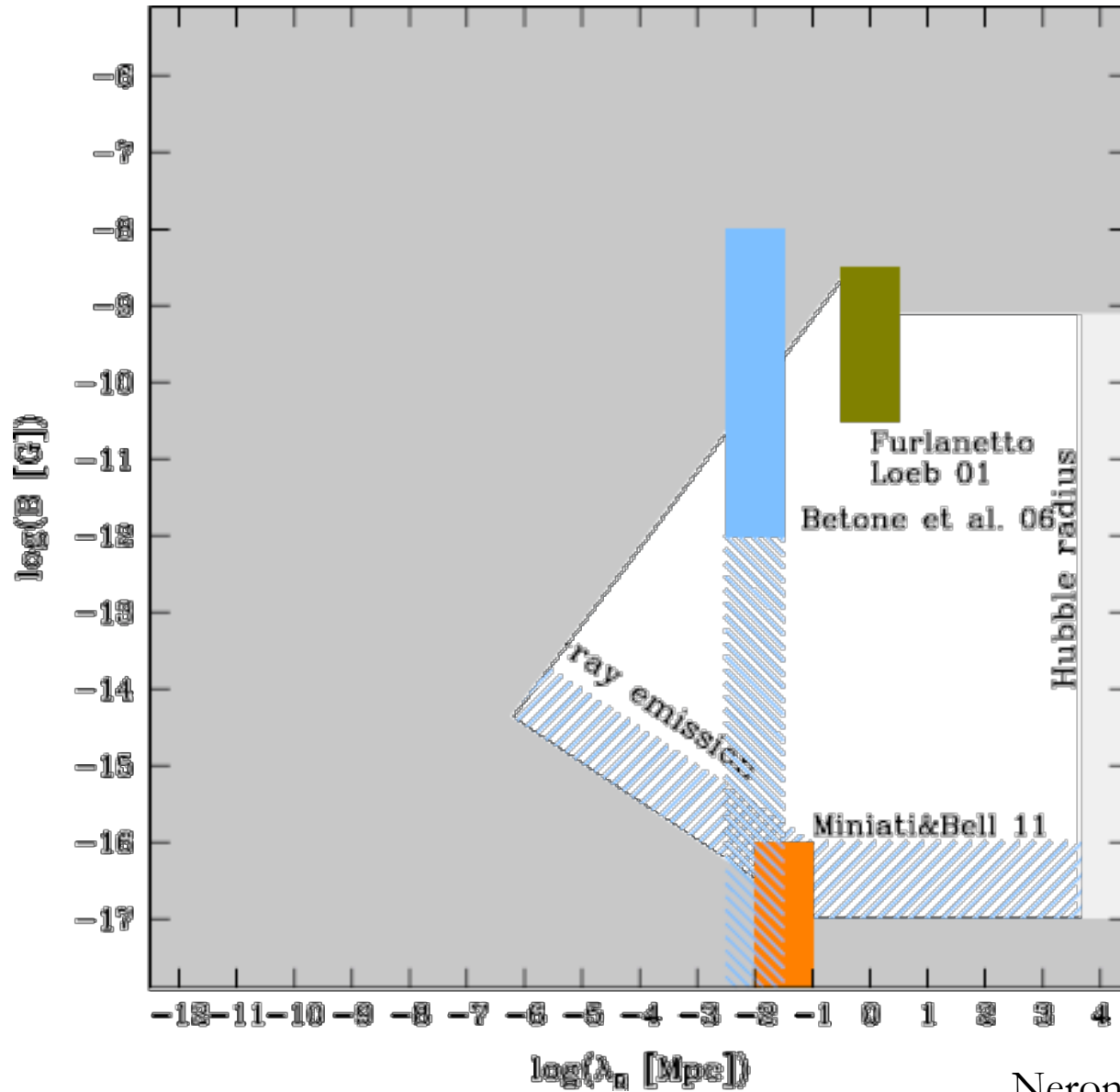
Jedamzik et. al. (2000)
Paoletti and Finelli (2011)

Current constraints on PMFs



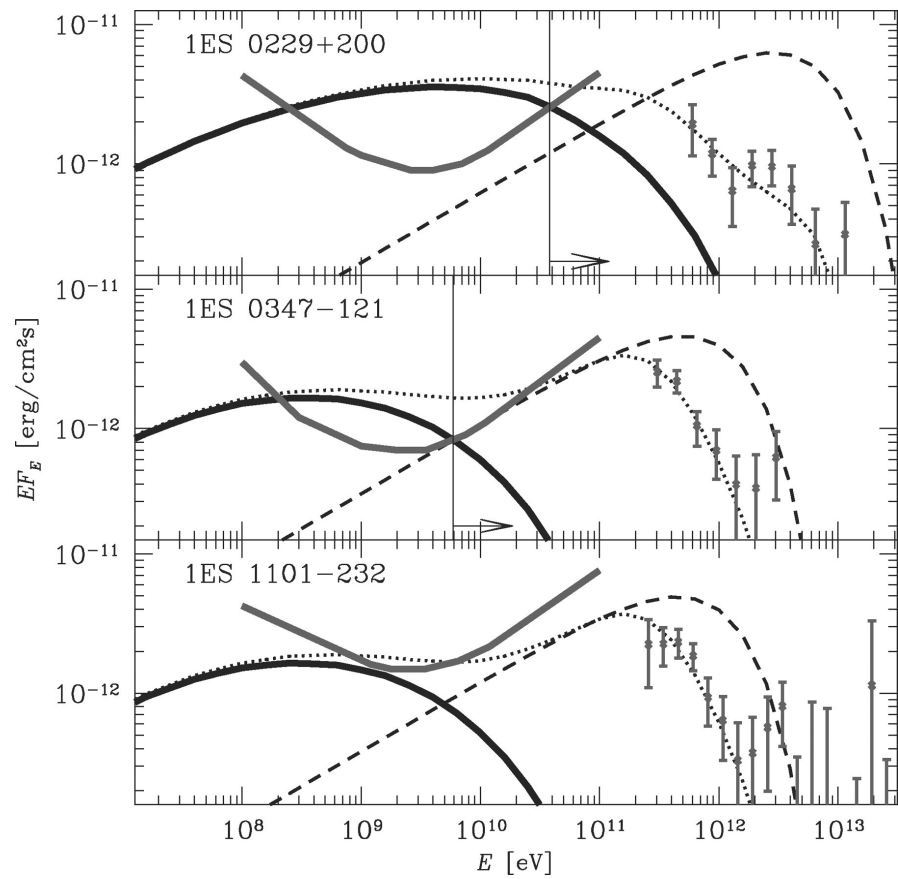
Neronov and Vovk (2010)
Tavecchio, et. al. (2011)

Current constraints on PMFs



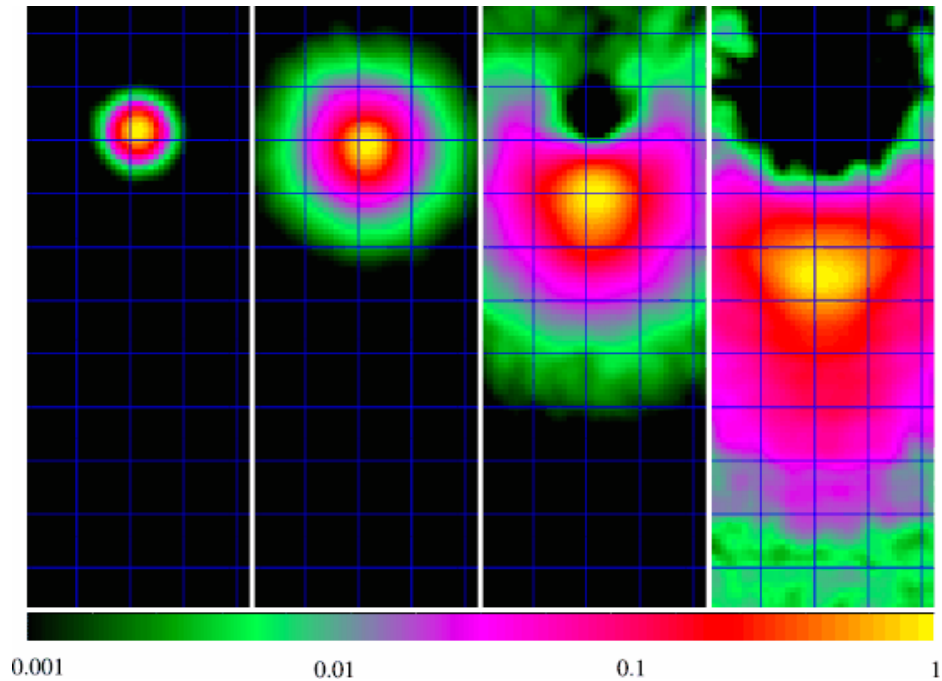
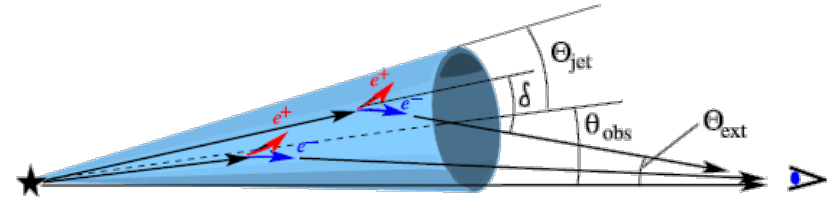
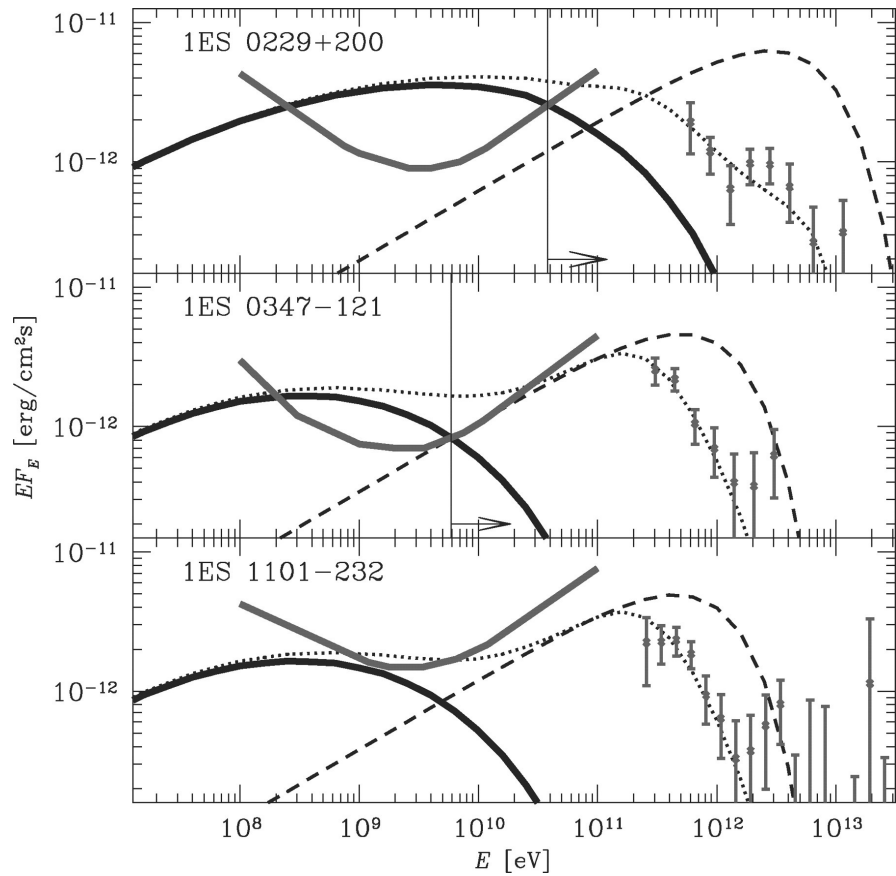
Neronov and Vovk (2010)
Tavecchio, et. al. (2011)

Current constraints on PMFs



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

Current constraints on PMFs



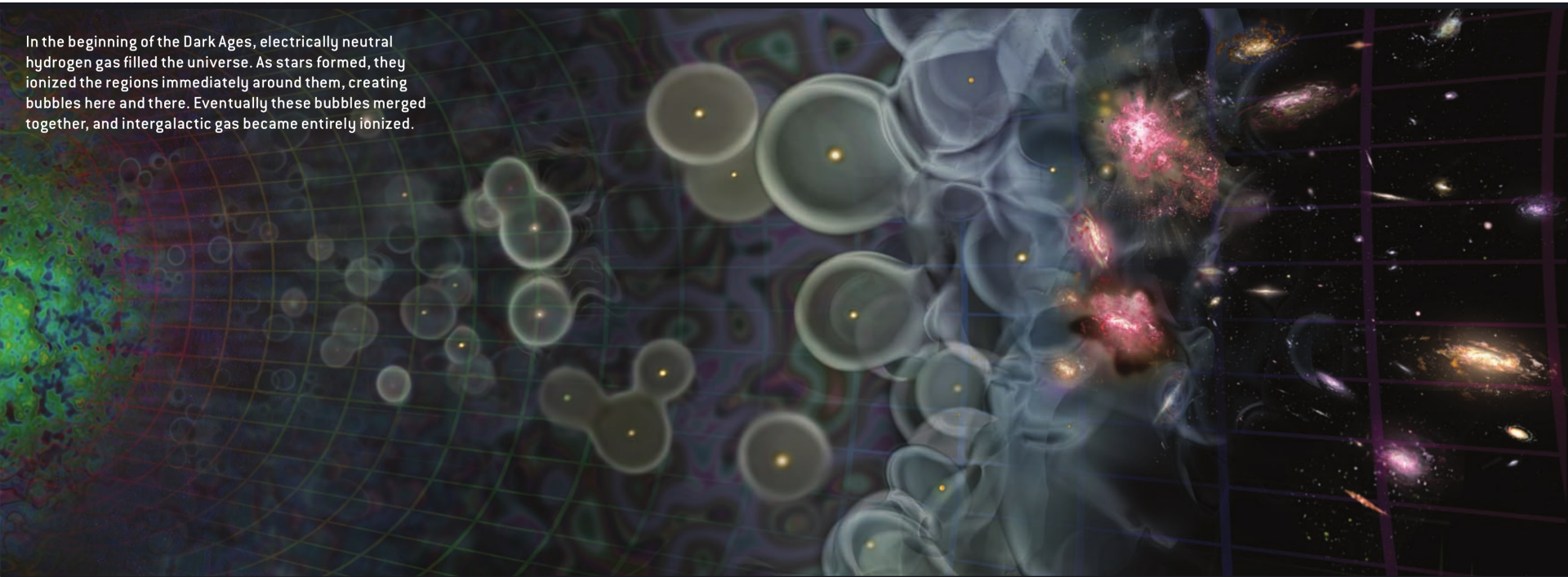
Neronov, A., and Vovk, I. (2010)

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

Introduction

21-CM TRANSITION AND APPLICATIONS TO COSMOLOGY

In the beginning of the Dark Ages, electrically neutral hydrogen gas filled the universe. As stars formed, they ionized the regions immediately around them, creating bubbles here and there. Eventually these bubbles merged together, and intergalactic gas became entirely ionized.



Time:
Width of frame:
Observed wavelength:

210 million years
2.4 million light-years
4.1 meters

All the gas is neutral. The white areas are the densest and will give rise to the first stars and quasars.

290 million years
3.0 million light-years
3.3 meters

Faint red patches show that the stars and quasars have begun to ionize the gas around them.

370 million years
3.6 million light-years
2.8 meters

These bubbles of ionized gas grow.

460 million years
4.1 million light-years
2.4 meters

New stars and quasars form and create their own bubbles.

540 million years
4.6 million light-years
2.1 meters

The bubbles are beginning to interconnect.

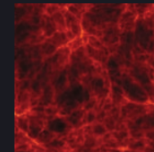
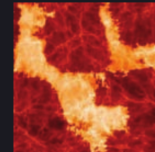
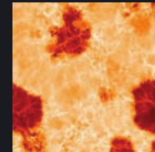
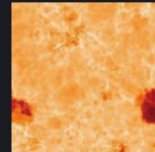
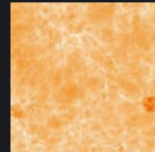
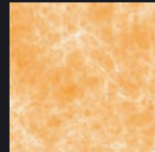
620 million years
5.0 million light-years
2.0 meters

The bubbles have merged and nearly taken over all of space.

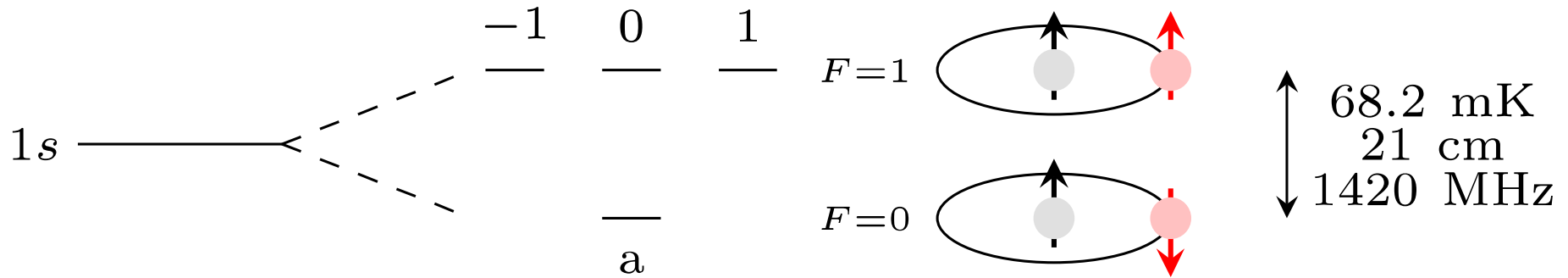
710 million years
5.5 million light-years
1.8 meters

The only remaining neutral hydrogen is concentrated in galaxies.

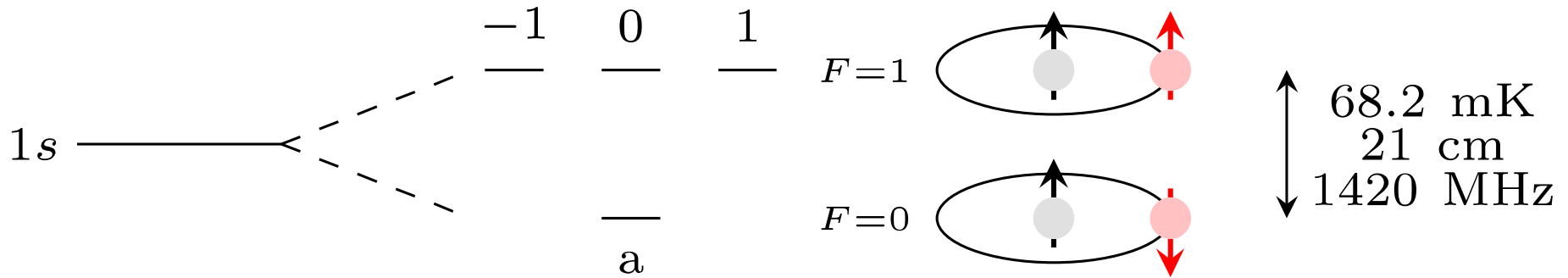
Simulated images of 21-centimeter radiation show how hydrogen gas turns into a galaxy cluster. The amount of radiation (*white is highest; orange and red are intermediate; black is least*) reflects both the density of the gas and its degree of ionization: dense, electrically neutral gas appears white; dense, ionized gas appears black. The images have been rescaled to remove the effect of cosmic expansion and thus highlight the cluster-forming processes. Because of expansion, the 21-centimeter radiation is actually observed at a longer wavelength; the earlier the image, the longer the wavelength.



The 21cm line of atomic hydrogen



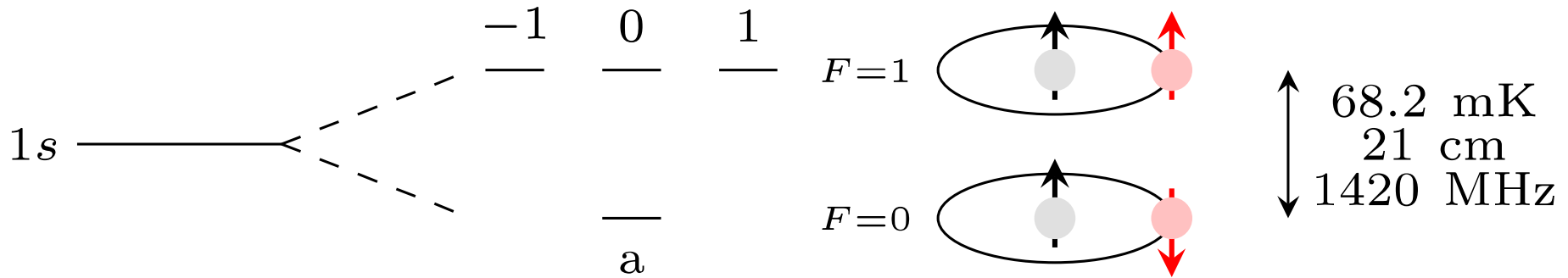
The 21cm line of atomic hydrogen



Spin-flip transition

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

The 21cm line of atomic hydrogen



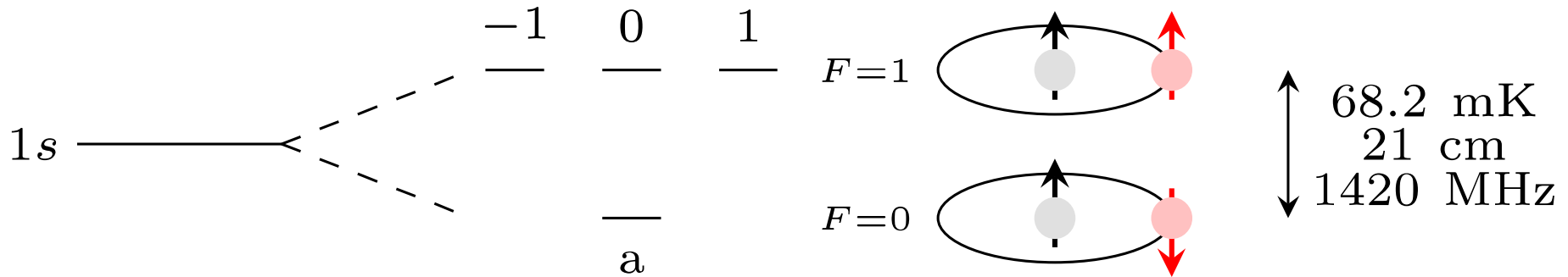
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Spin temperature:

$$\frac{n_{F=1}}{n_{F=0}} = 3 e^{-\frac{68.2 \text{ mK}}{T_s}}$$

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Observable: brightness temperature

$T_s < T_\gamma$: Absorption

$T_s > T_\gamma$: Emission

Observable: brightness temperature

Radiative transfer of the CMB through neutral gas

$T_s < T_\gamma$: Absorption

$T_s > T_\gamma$: Emission

Output brightness temperature against the CMB is

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

Observable: brightness temperature

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$T_s < T_\gamma$: Absorption

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Output brightness temperature against the CMB is

$$\begin{aligned}\delta T_b &= \frac{1}{1+z} (T|_{\text{out}} - T_\gamma) \\ &= 26.4 \text{ mK } x_{1s} \frac{T_s - T_\gamma}{T_s} \left(\frac{1+z}{10} \right)^{1/2} (1+\delta) \frac{H(z)}{\partial_{||} v_{||}}\end{aligned}$$

Observable: brightness temperature

Radiative transfer of the CMB through neutral gas

$$T_s < T_\gamma : \text{Absorption}$$

$$T_s > T_\gamma : \text{Emission}$$

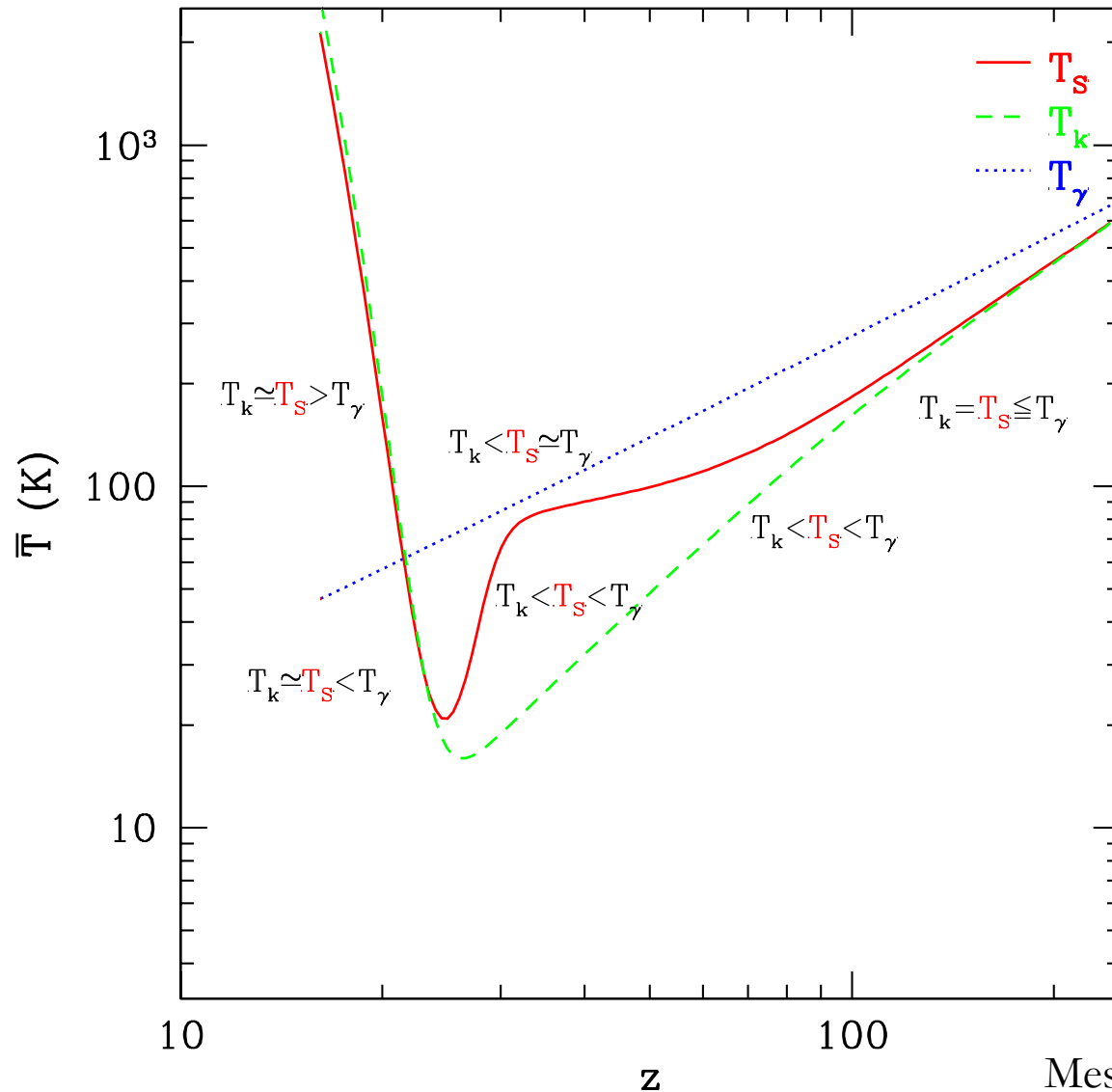
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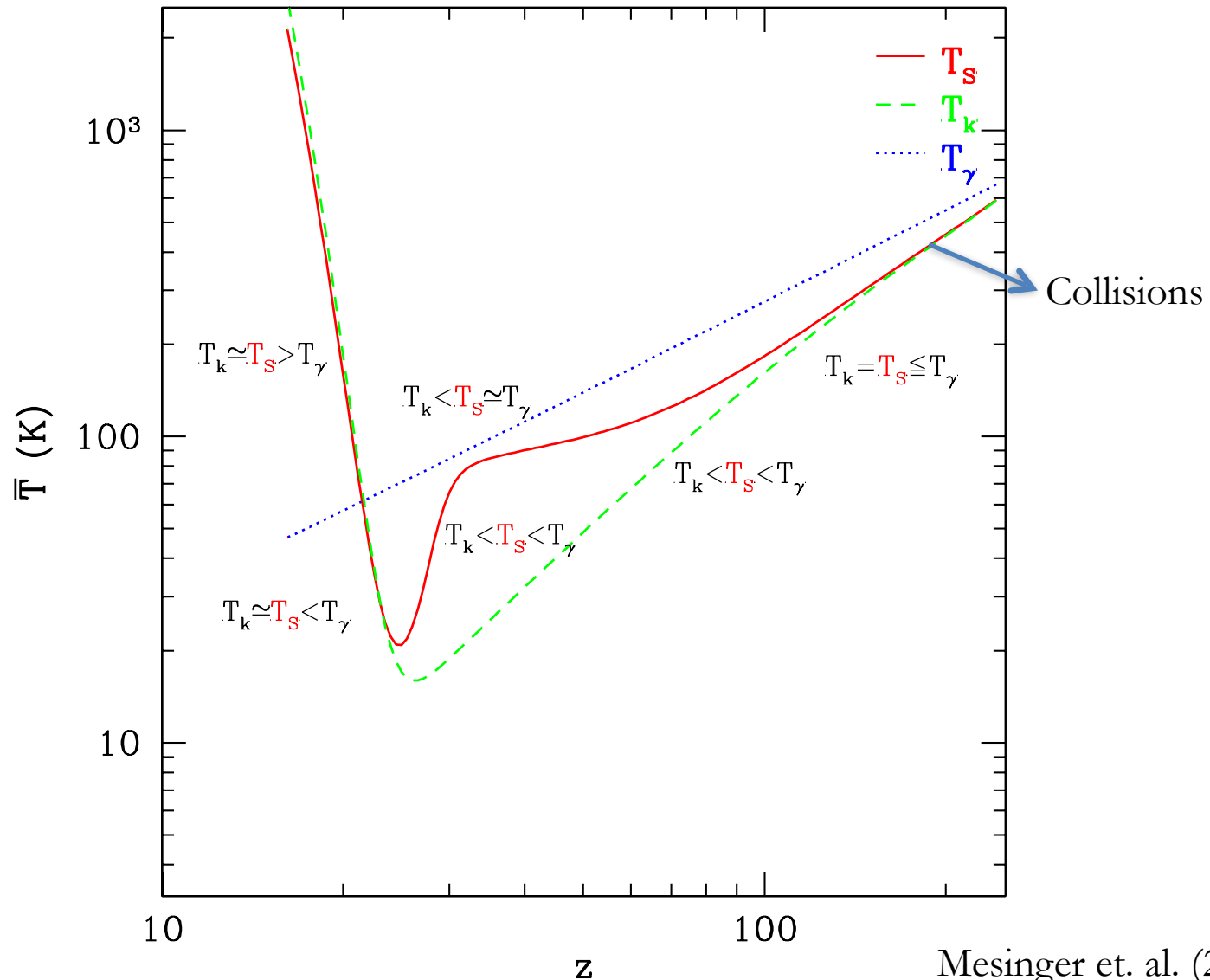
$$= 26.4 \text{ mK } \boxed{x_{1s}} \frac{T_s - T_\gamma}{\boxed{T_s}} \left(\frac{1+z}{10} \right)^{1/2} (1 + \boxed{\delta}) \frac{H(z)}{\boxed{\dot{\sigma}_{||} v_{||}}}$$

Gas properties

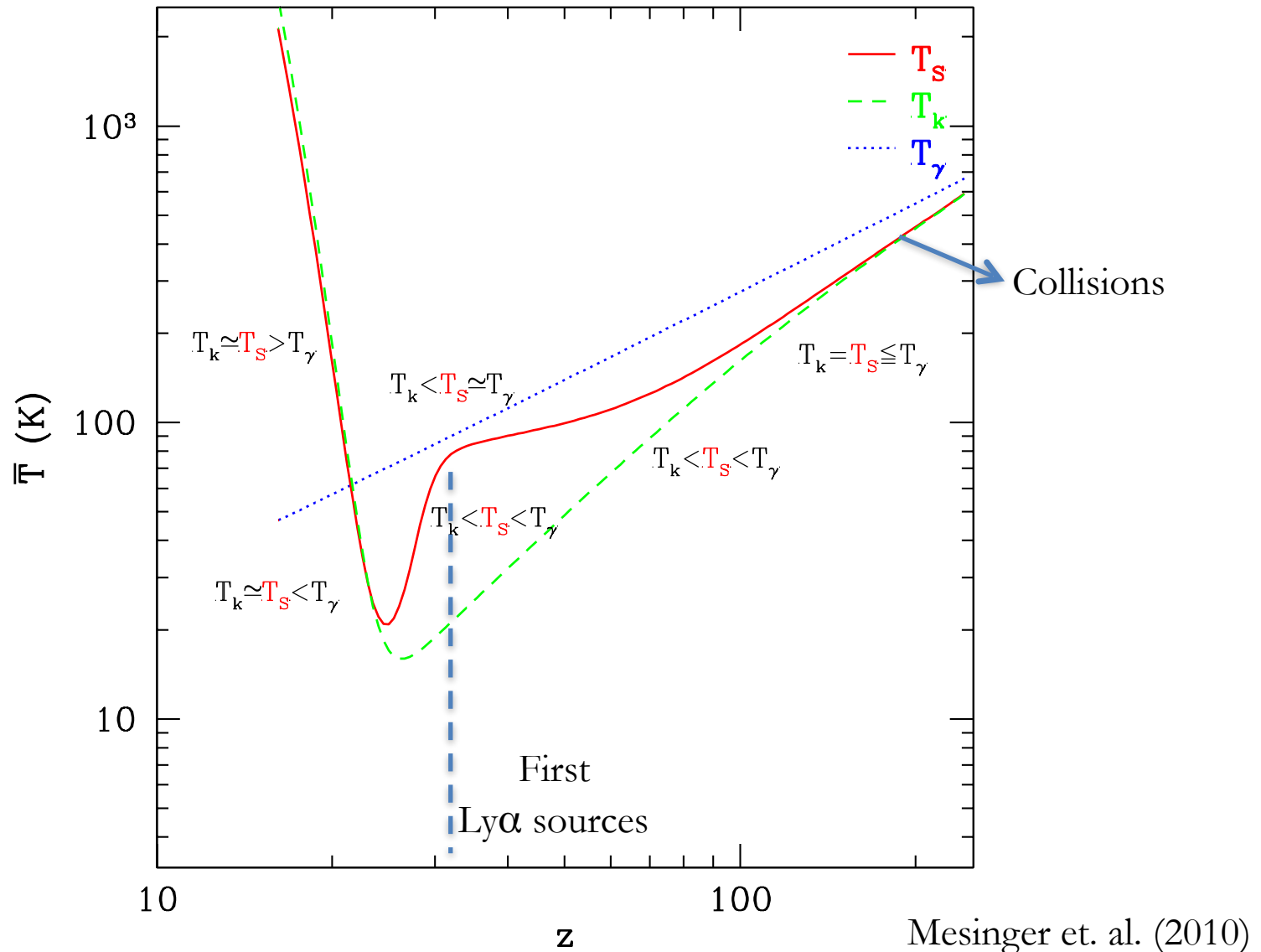
Spin temperature: evolution



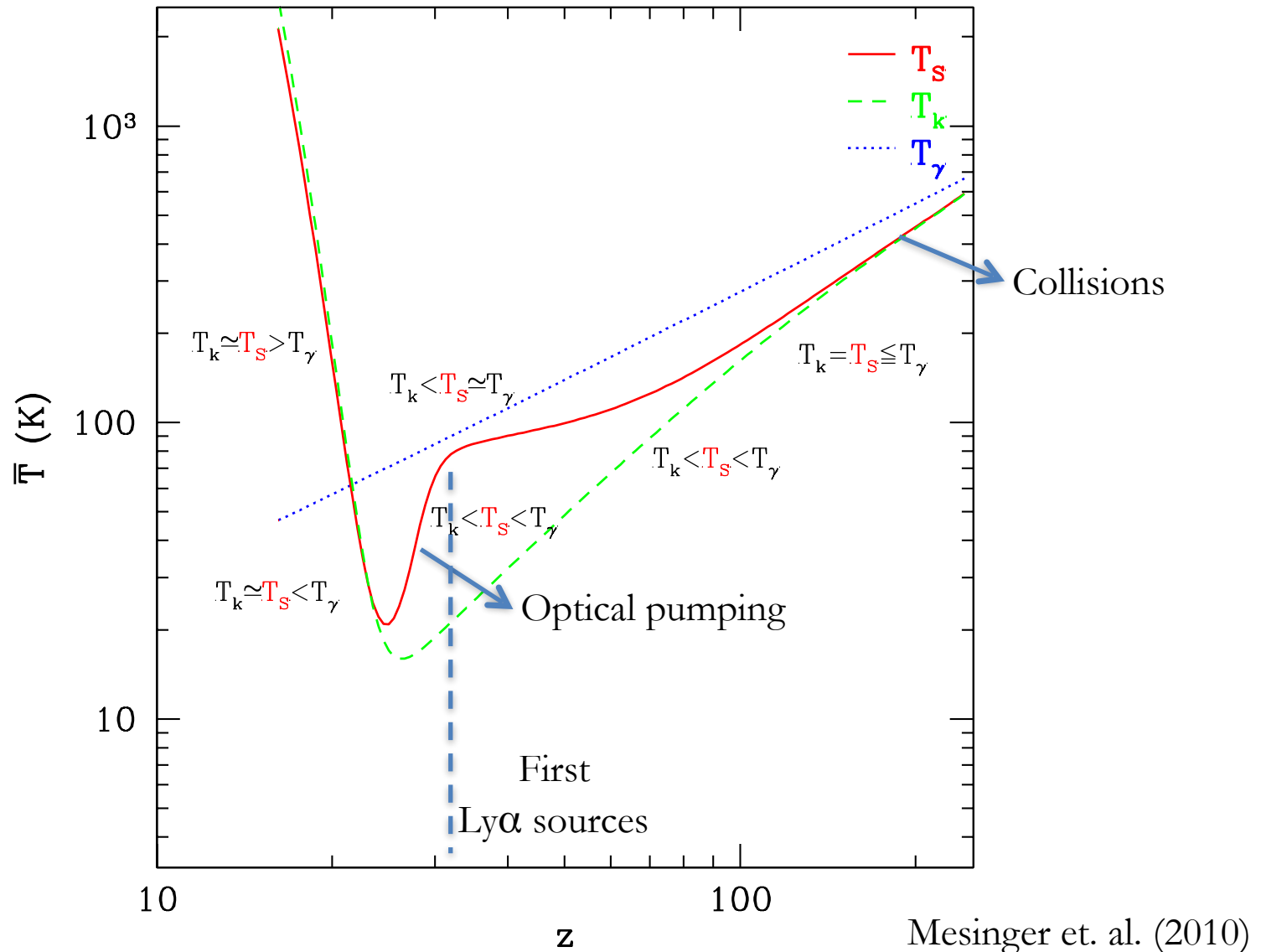
Spin temperature: evolution



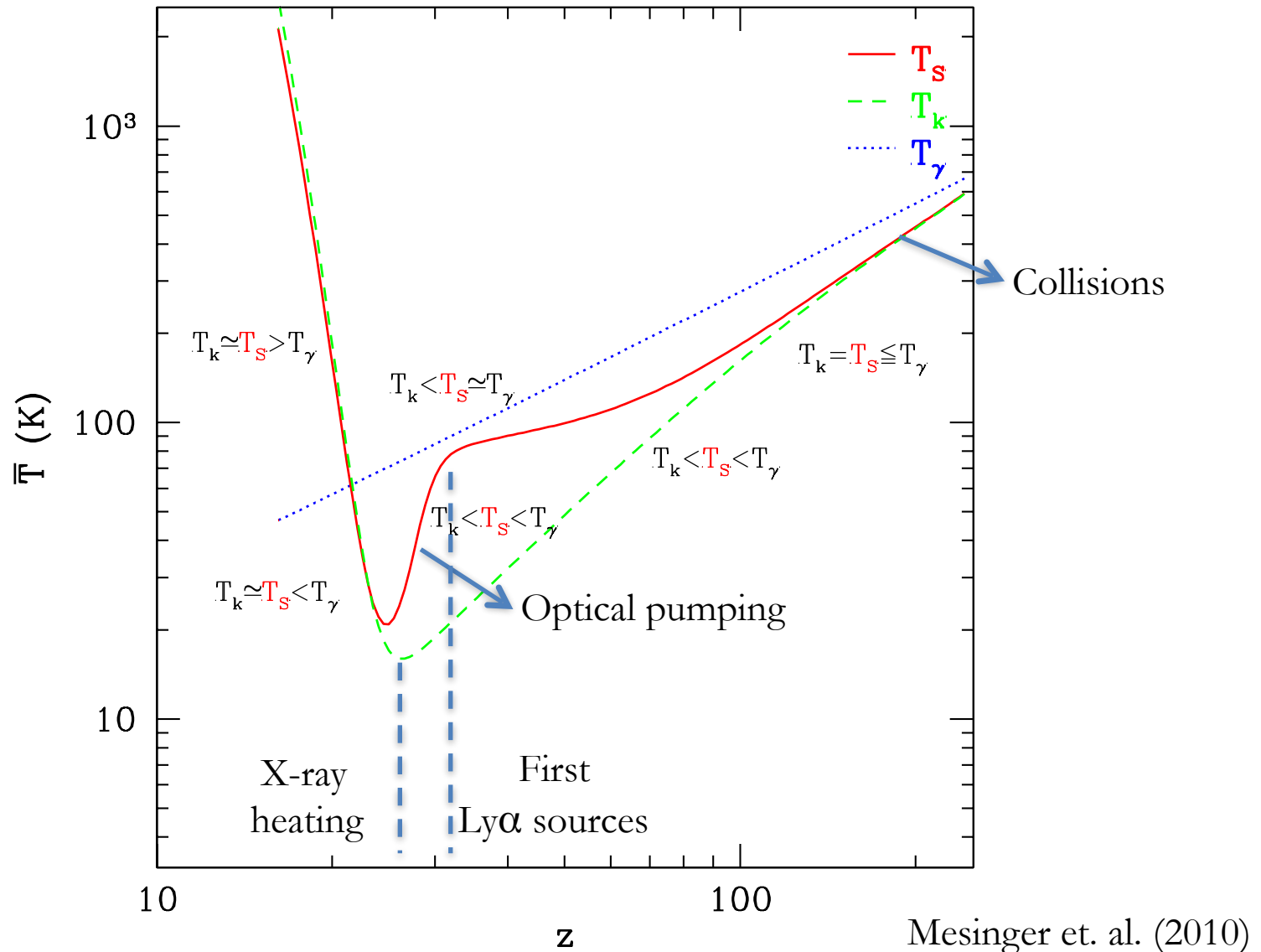
Spin temperature: evolution



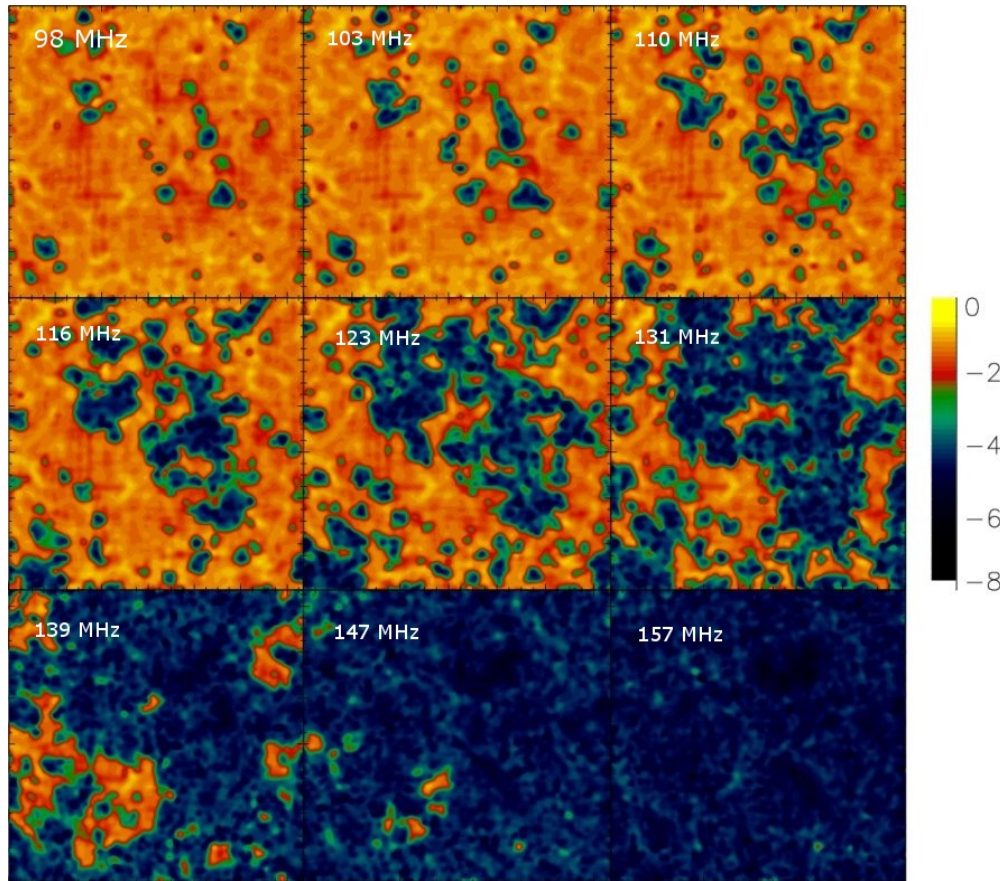
Spin temperature: evolution



Spin temperature: evolution



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.....

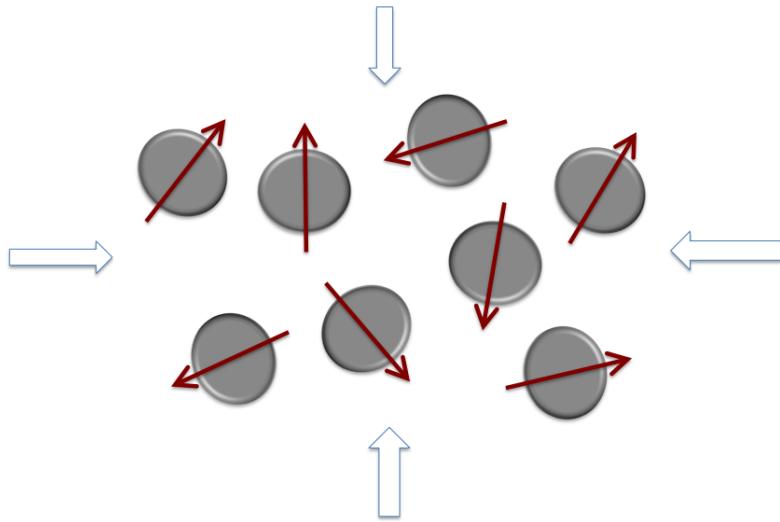
Several existing/planned low ν radio arrays aim to measure the 21cm signal from the EOR:

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

EFFECT OF MAGNETIC FIELDS

Revisiting the 21cm line

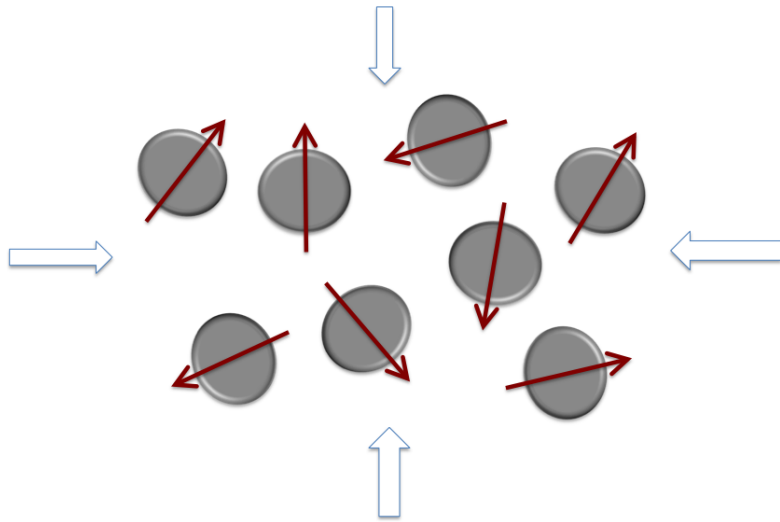
Revisiting the 21cm line



Isotropic bath of 21cm radiation.

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

Revisiting the 21cm line



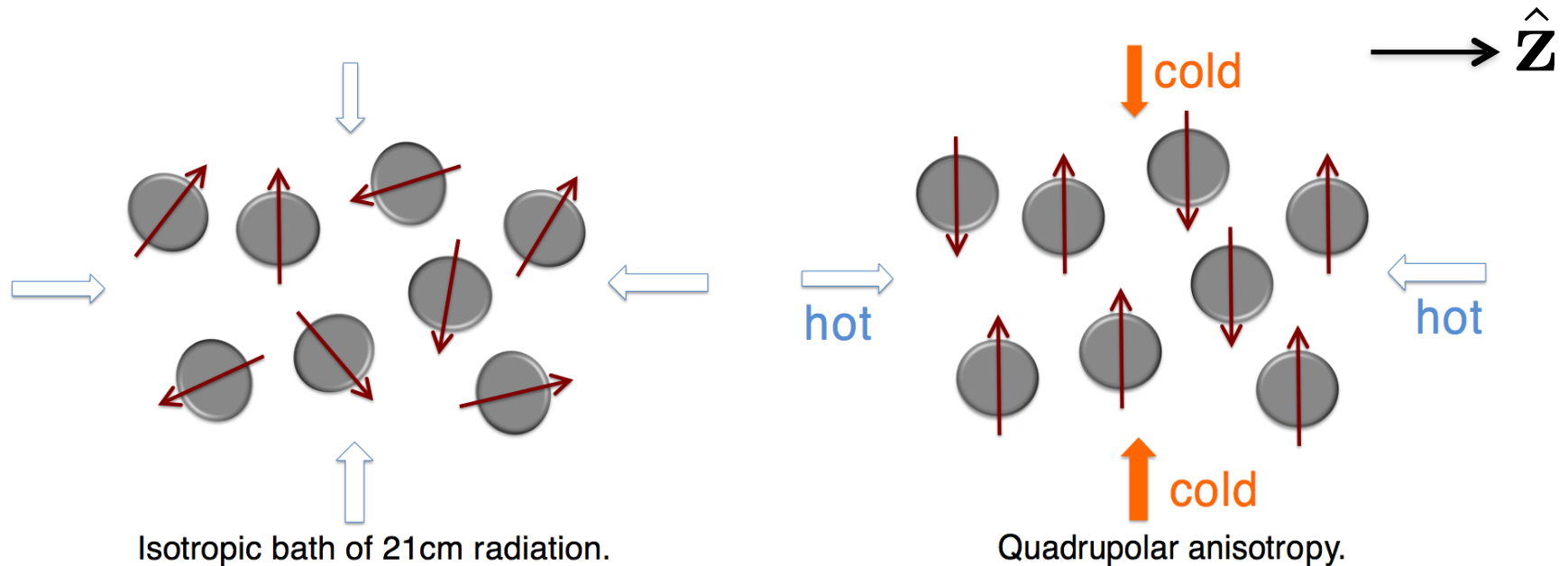
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$$\begin{array}{ccc} \mathbf{m} & -1 & 0 & 1 \\ \hline & & & \end{array}$$

$$\frac{\quad}{\mathbf{a}}$$

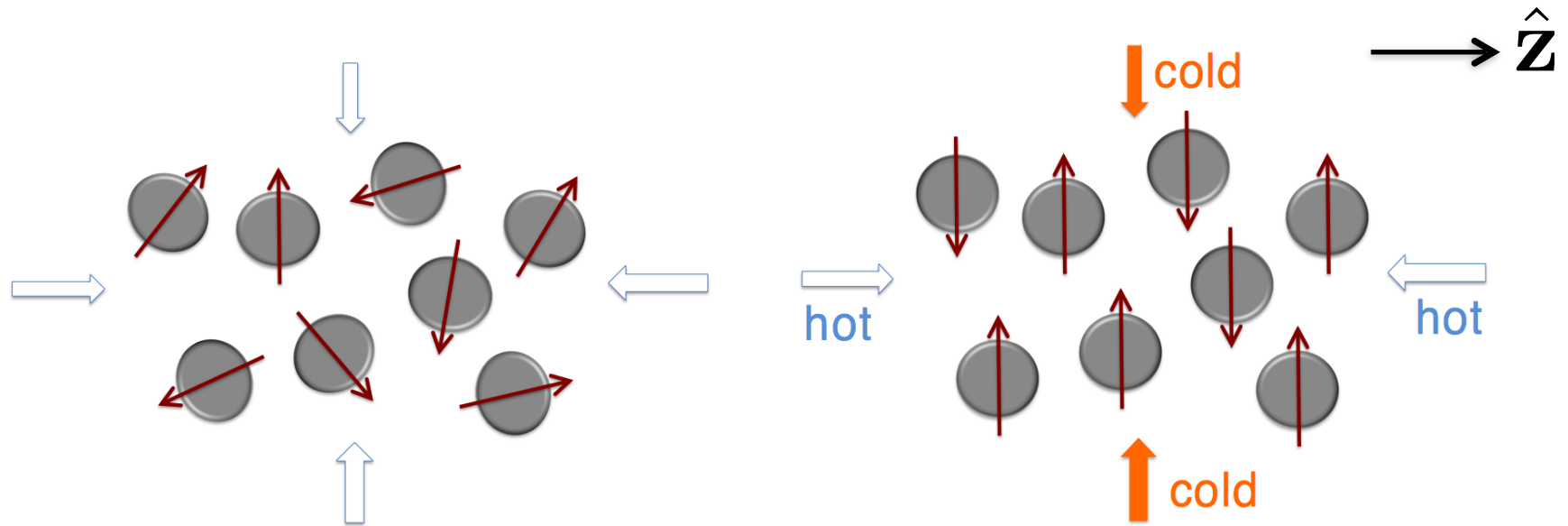
Revisiting the 21cm line



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

m	-1	0	1
	—	—	—
	—		
	a		

Revisiting the 21cm line



Isotropic bath of 21cm radiation.

Quadrupolar anisotropy.

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

m	-1	0	1
	—	—	—

—
a

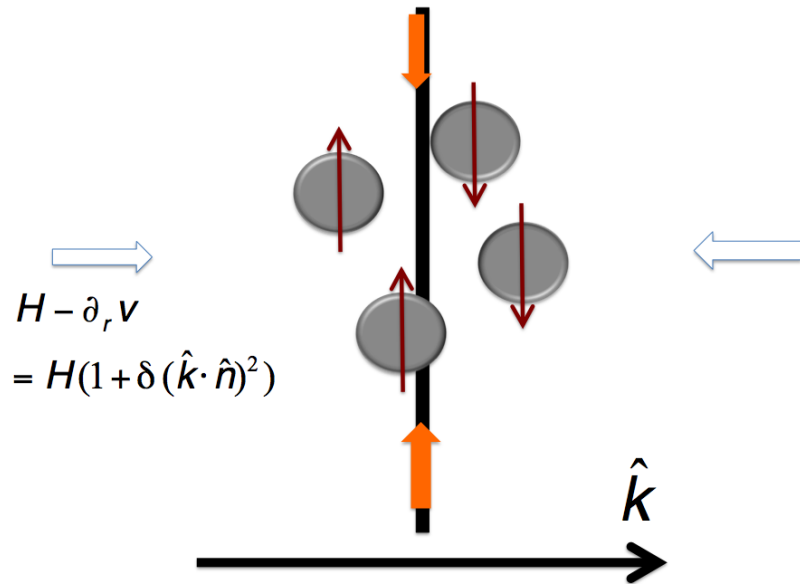
m	-1	0	1
	—	—	—

—
a

Anisotropies and anisotropic emission

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

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



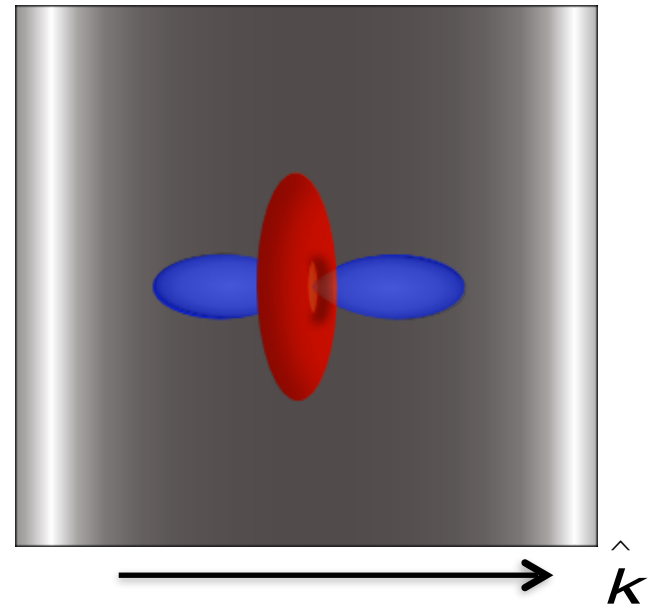
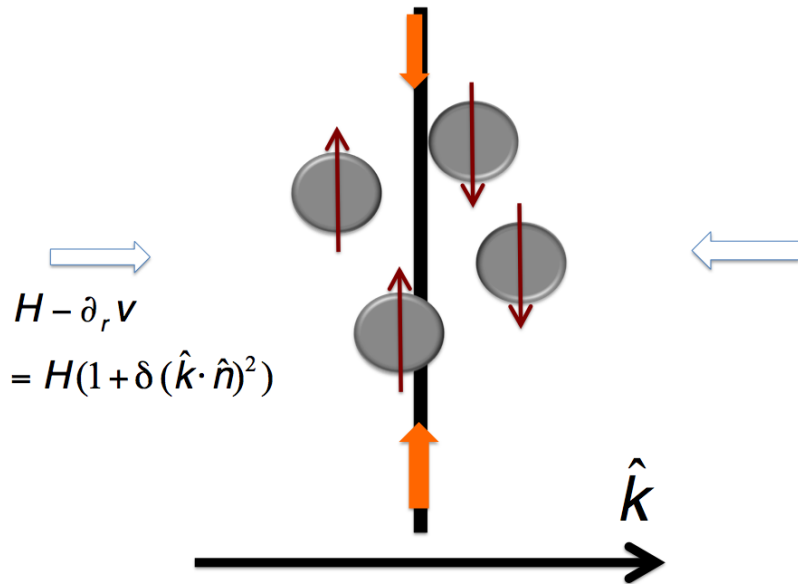
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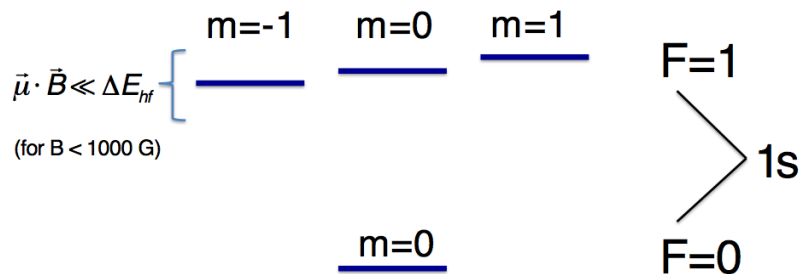
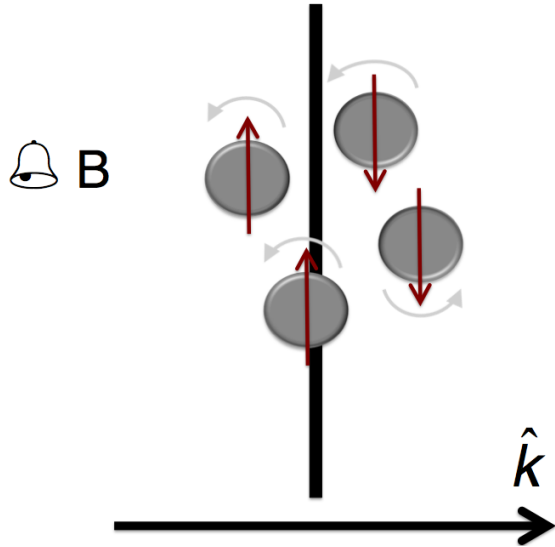
$$\partial_{\parallel} v_{\parallel} = H \left(1 - \delta (\hat{\mathbf{k}} \cdot \hat{\mathbf{n}})^2 \right)$$

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

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

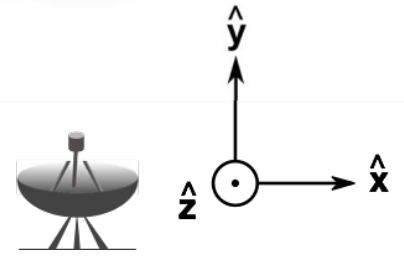
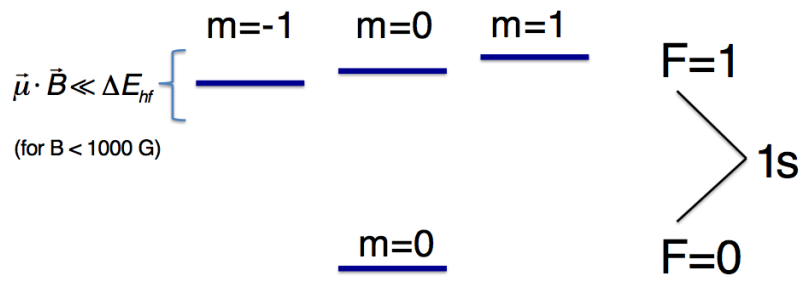
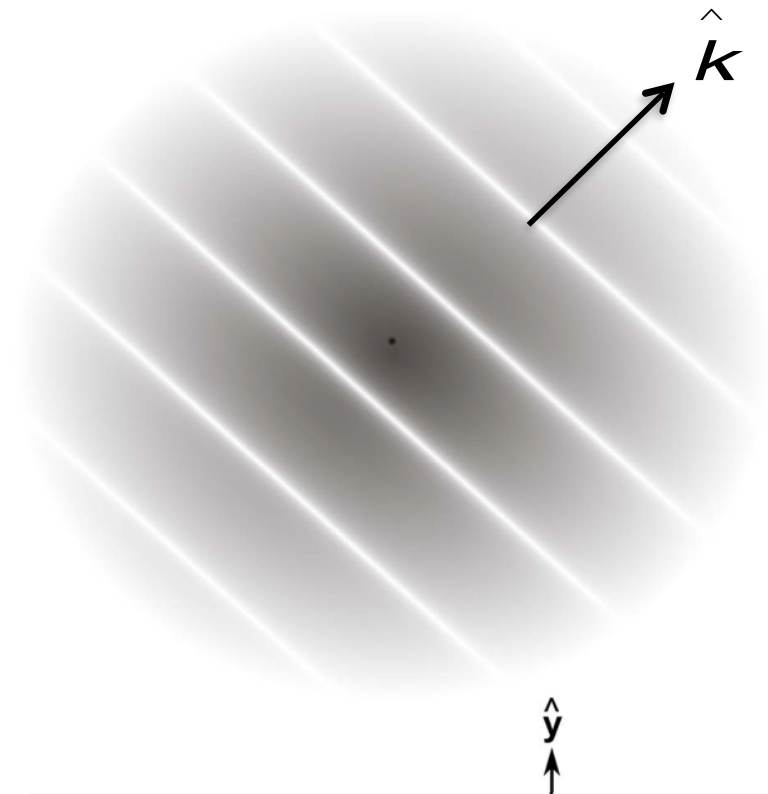
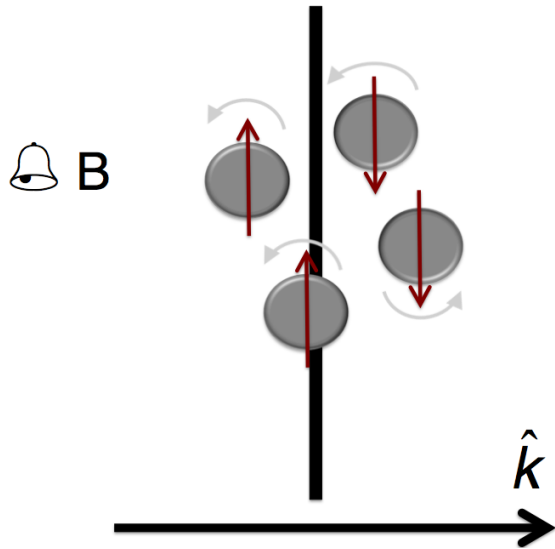


Effect of an external magnetic field



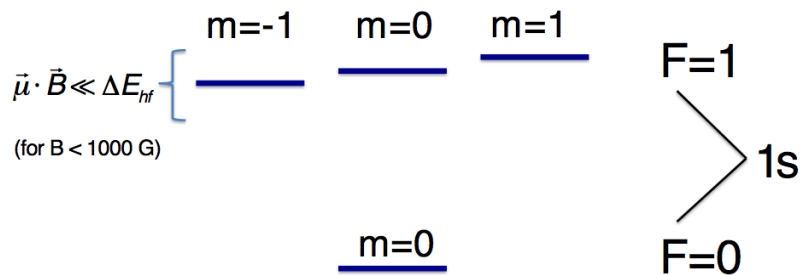
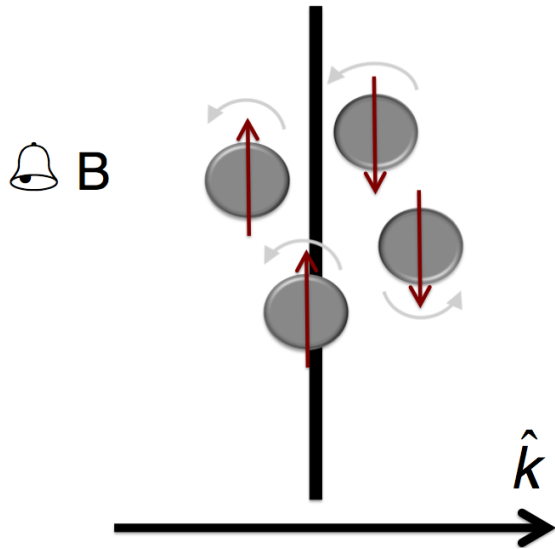
Zeeman splitting and precession.

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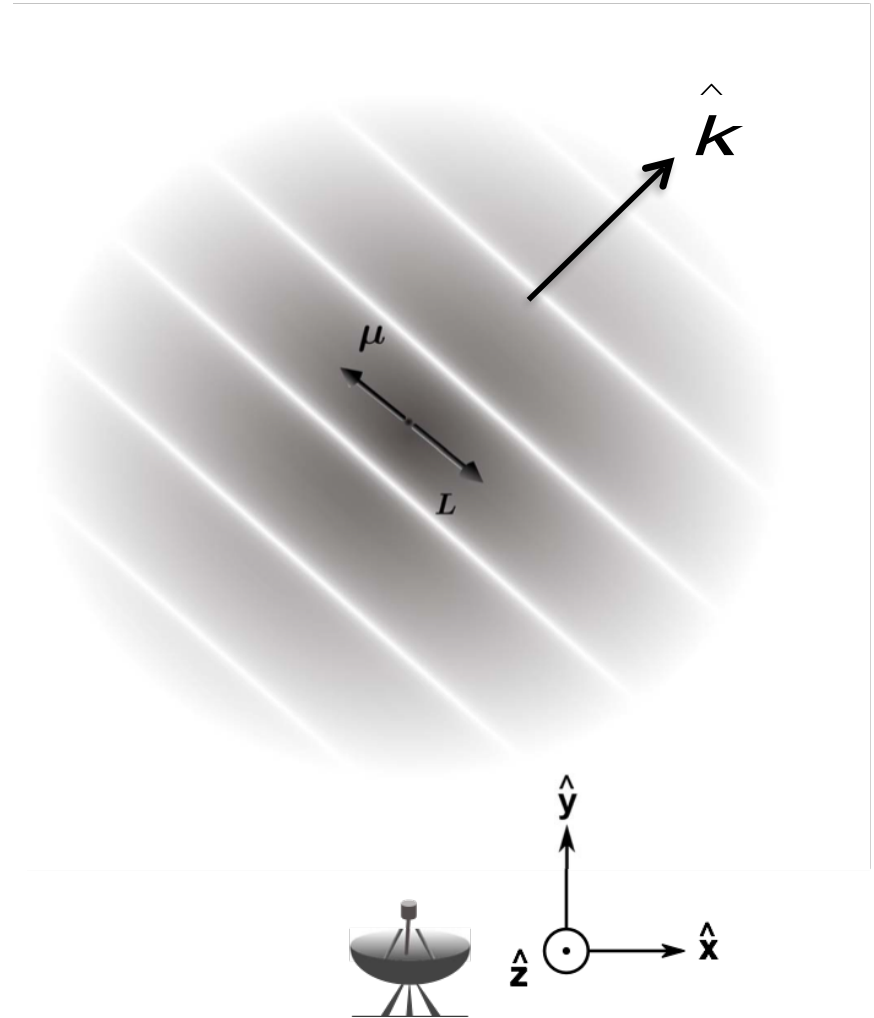


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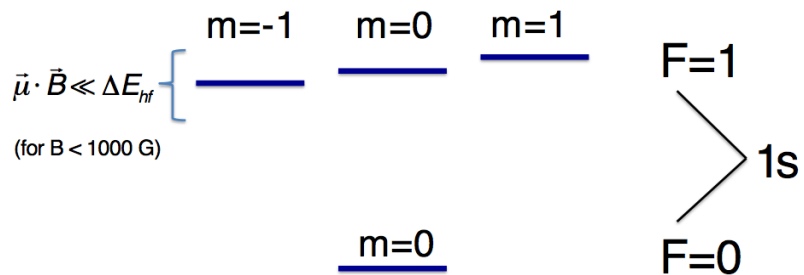
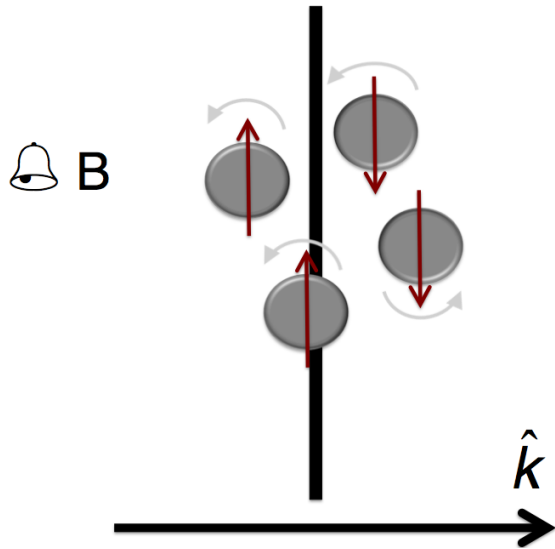
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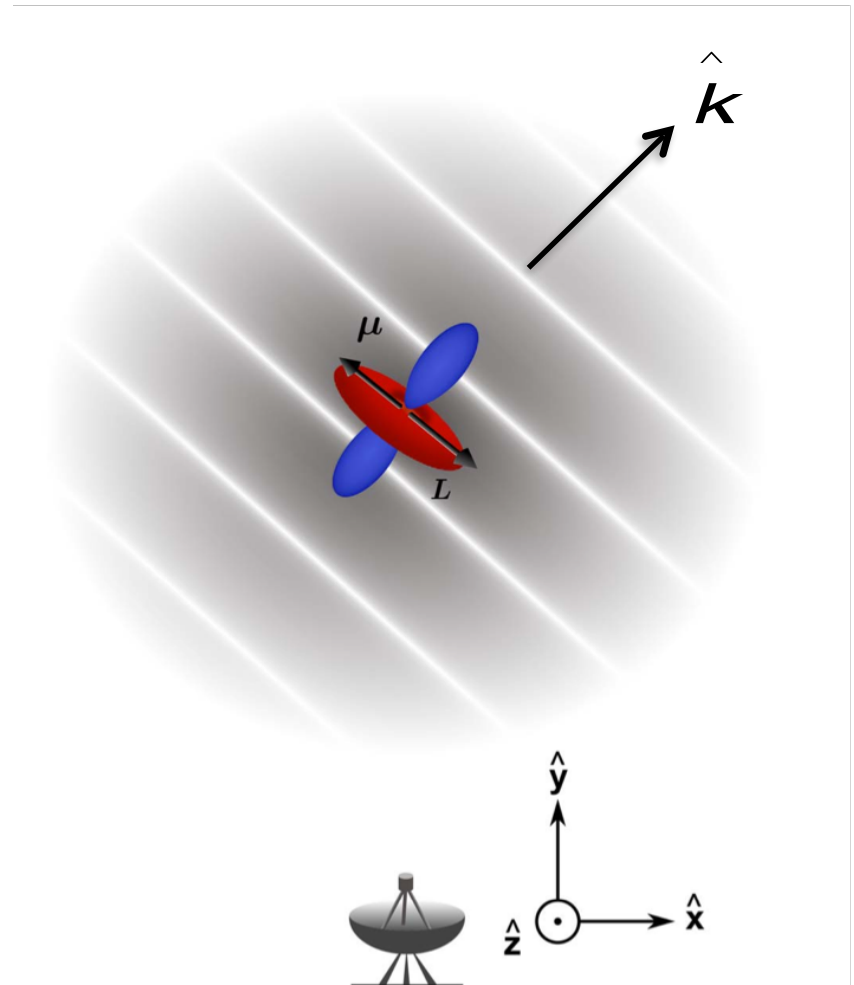
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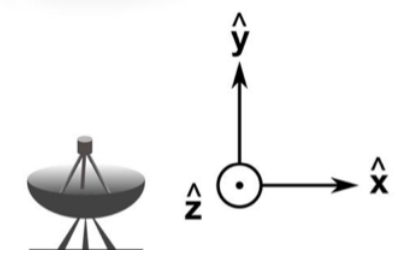
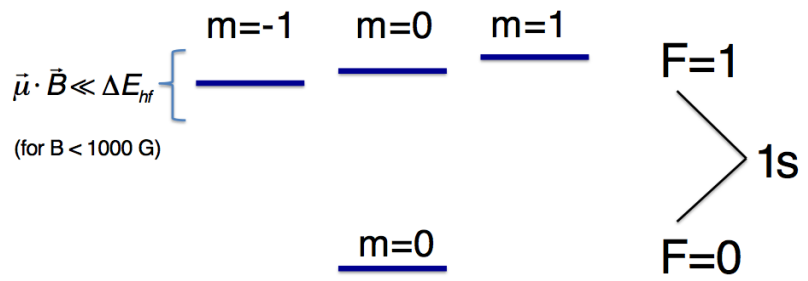
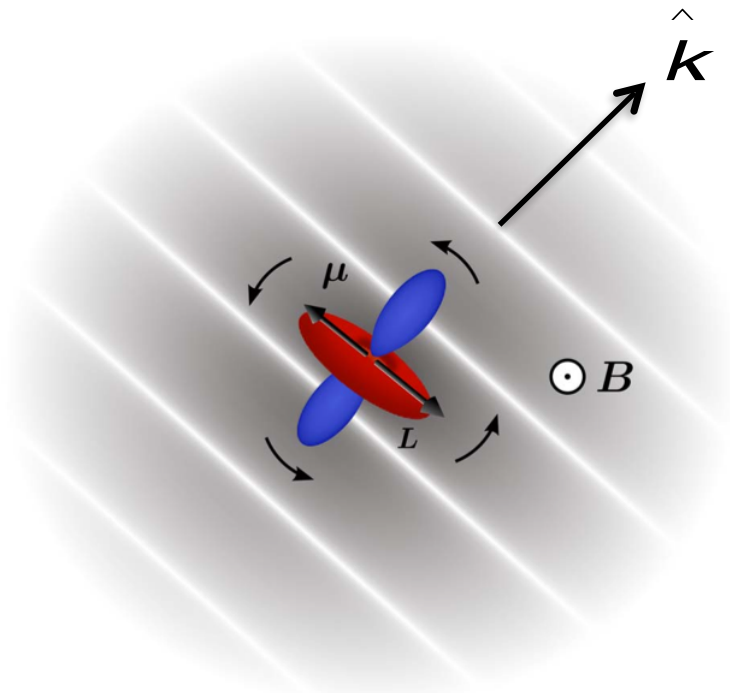
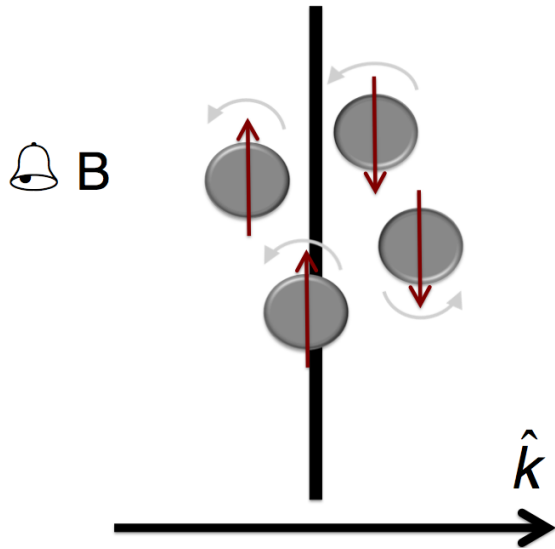
Effect of an external magnetic field



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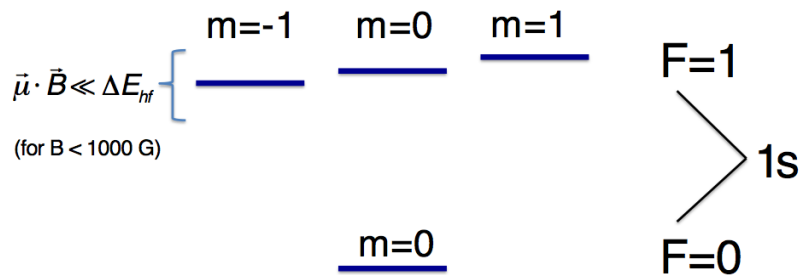
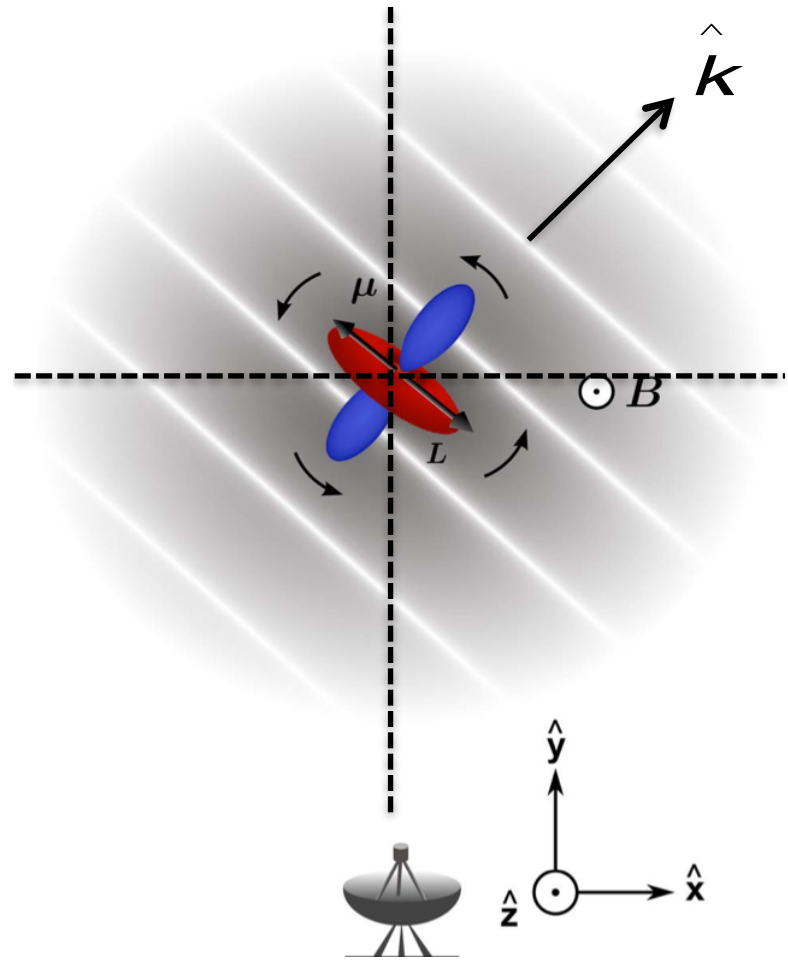
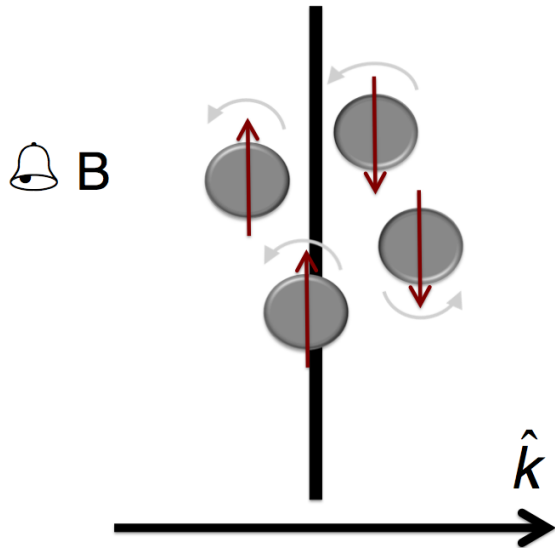


Effect of an external magnetic field



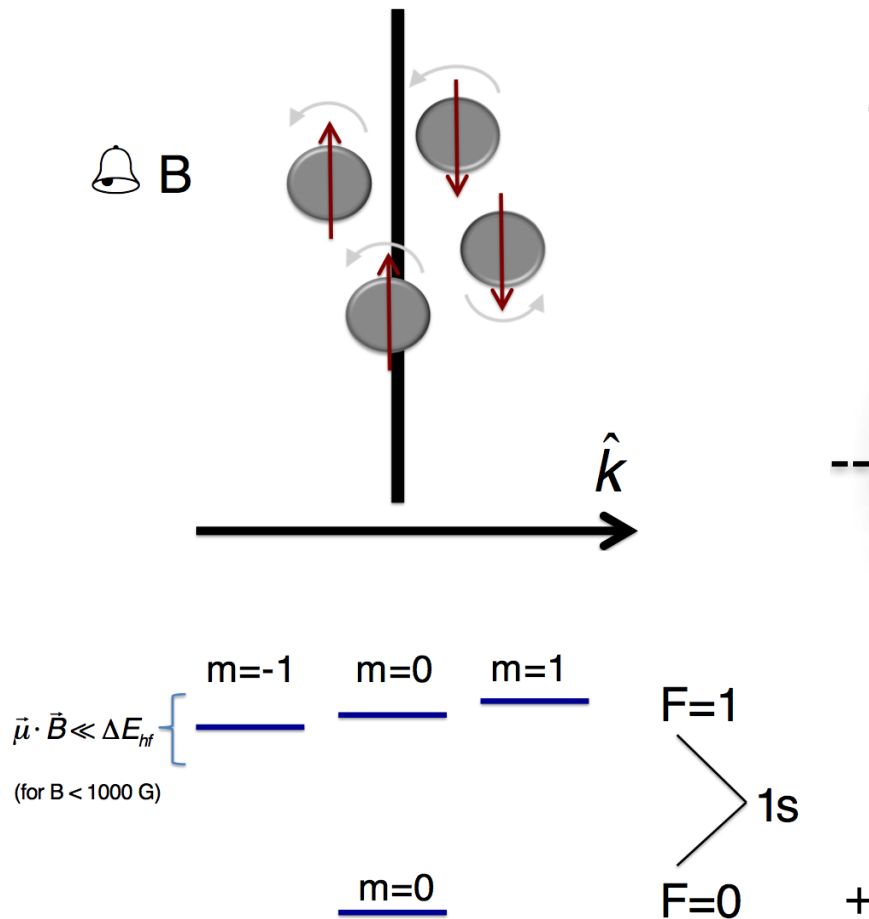
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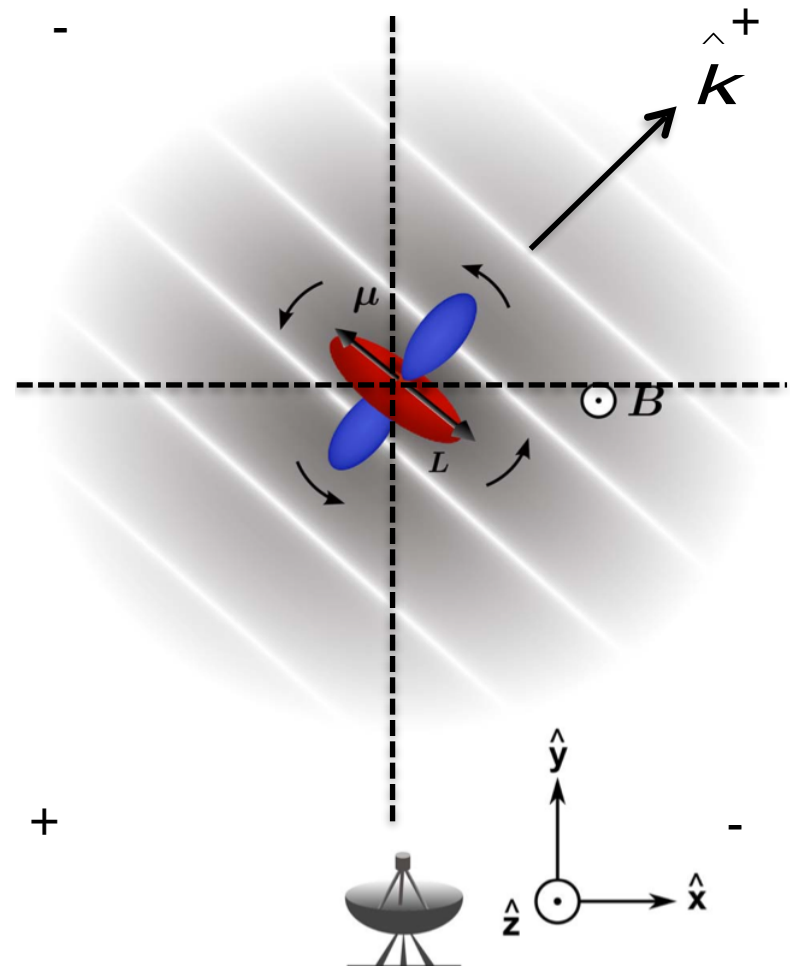


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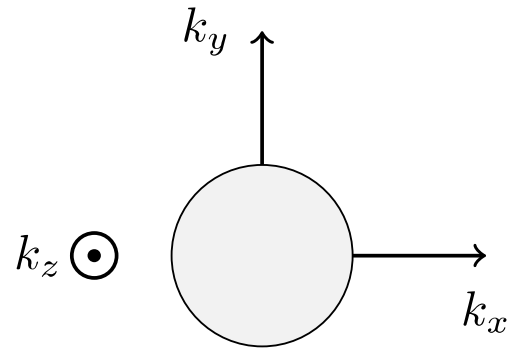
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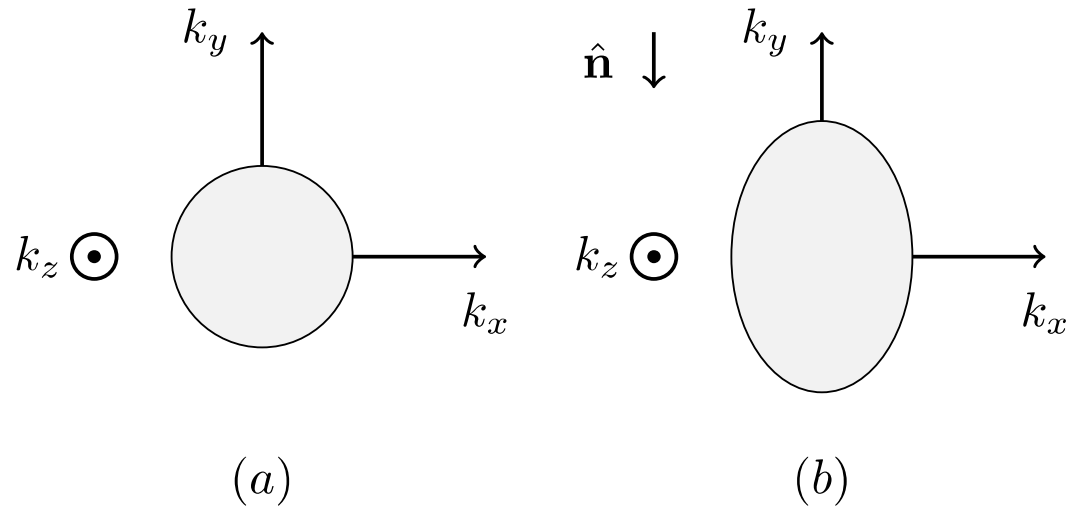
Effect on 21cm observables



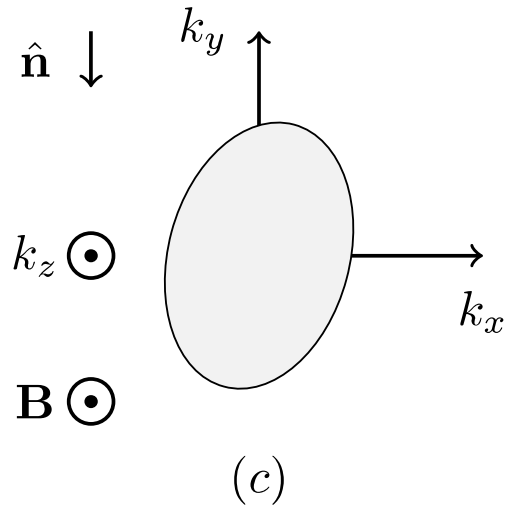
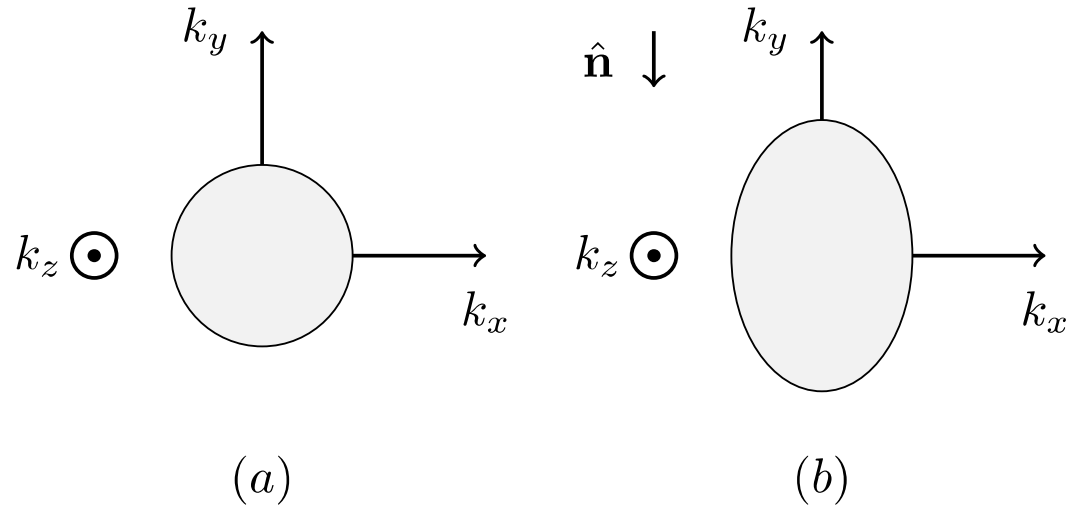
(a)

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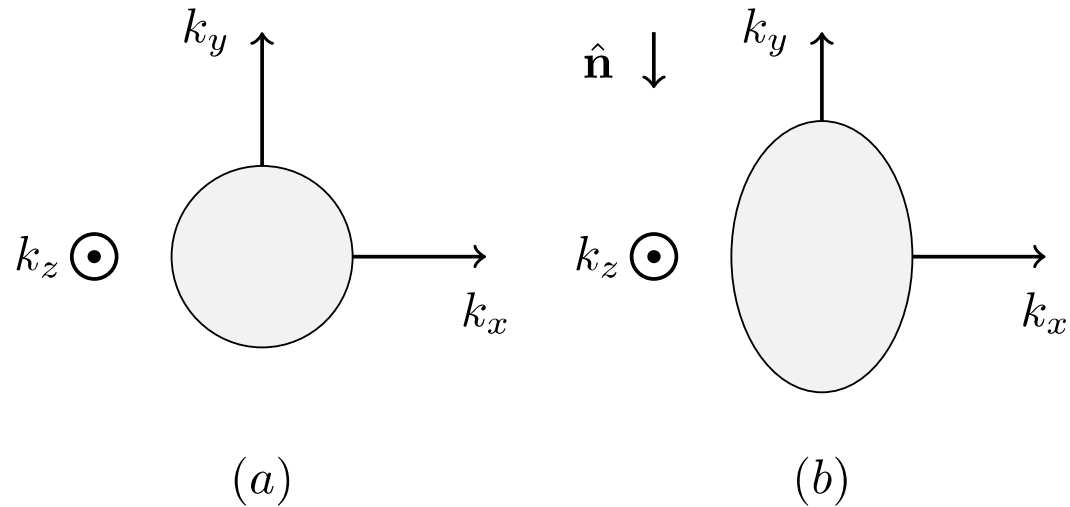
Effect on 21cm observables



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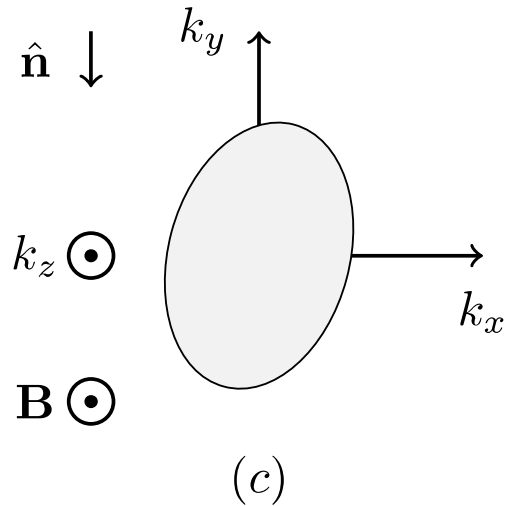
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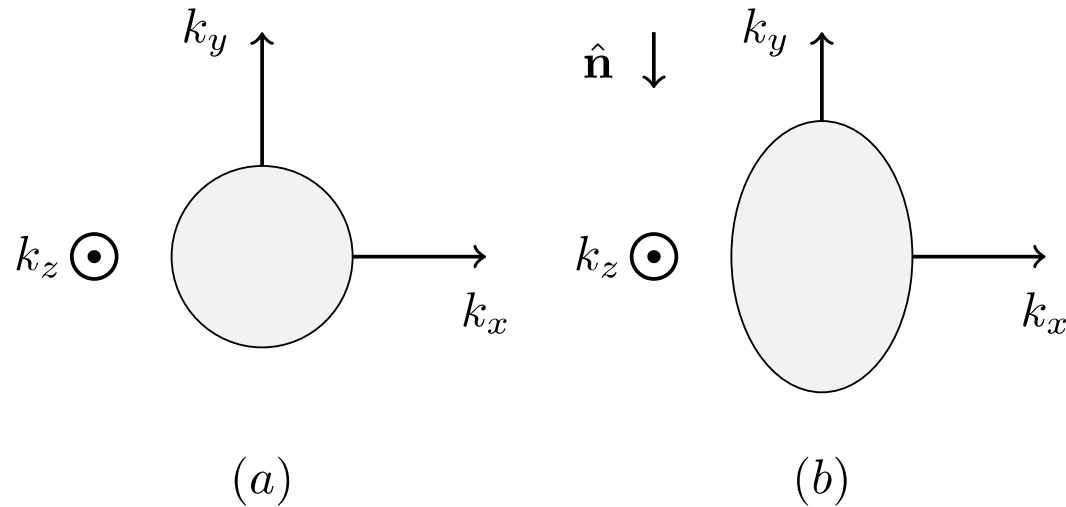
Triplet lifetime:

$$t_d = \frac{1}{A} \frac{68.2 \text{ mK}}{T_\gamma}$$

$$= 1.3 \times 10^4 \left(\frac{20}{1+z} \right) \text{ Yr}$$



Effect on 21cm observables



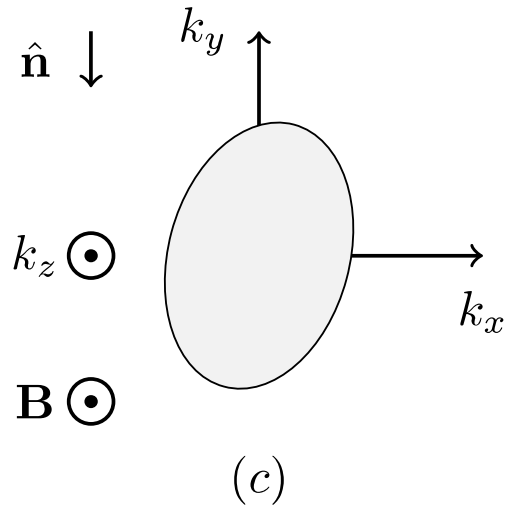
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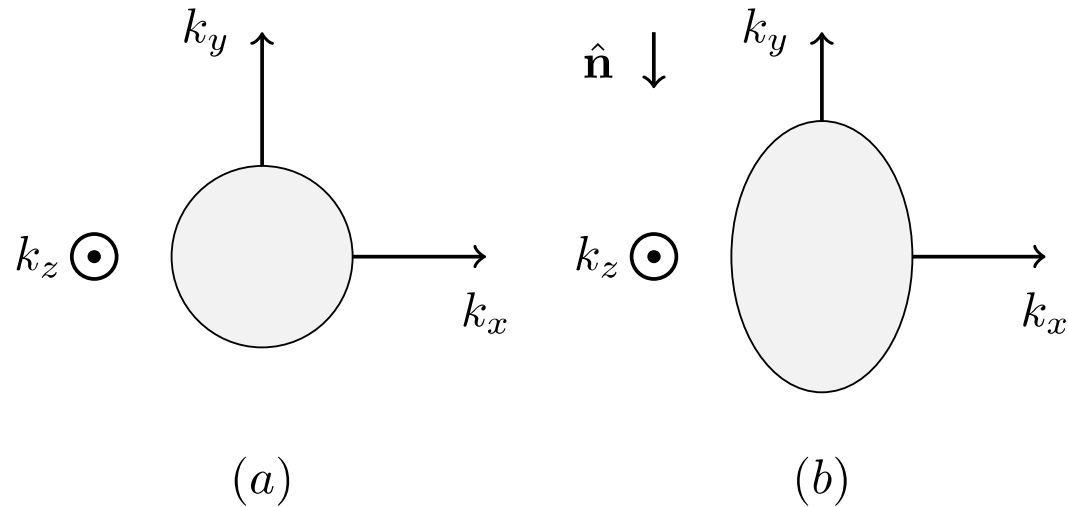
$$= 1.3 \times 10^4 \left(\frac{20}{1+z} \right) \text{ Yr}$$

Precession rate:

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



Effect on 21cm observables



Triplet lifetime:

$$t_d = \frac{1}{A} \frac{68.2 \text{ mK}}{T_\gamma}$$

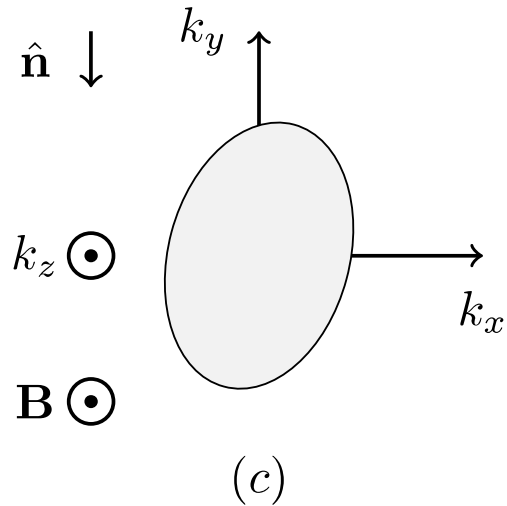
$$= 1.3 \times 10^4 \left(\frac{20}{1+z} \right) \text{ Yr}$$

Precession rate:

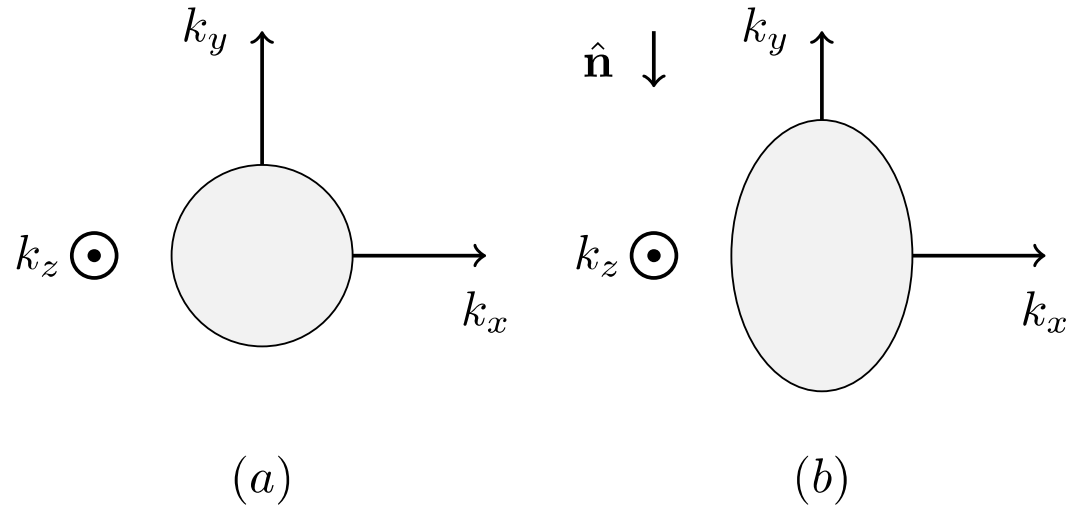
$$\gamma_e = 1.8 \times 10^7 \text{ s}^{-1} \text{ G}^{-1}$$

Precession through unit angle

$$B_{\text{th}} = 1.4 \times 10^{-19} \left(\frac{1+z}{20} \right) \text{ G}$$



Effect on 21cm observables



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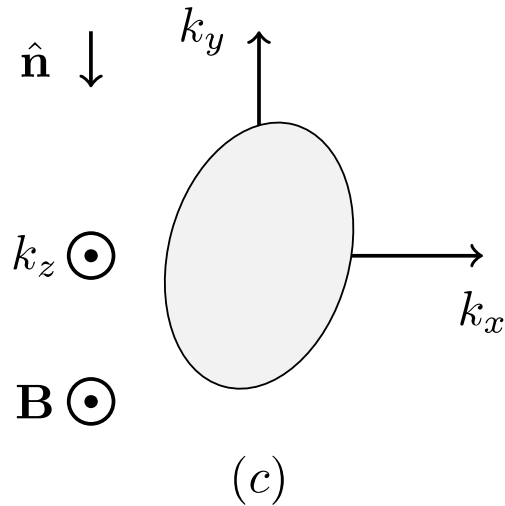
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$$\delta T_b(\hat{\mathbf{n}}) = \left(1 - \frac{T_\gamma}{T_s} \right) x_{1s} \left(\frac{1+z}{10} \right)^{1/2}$$

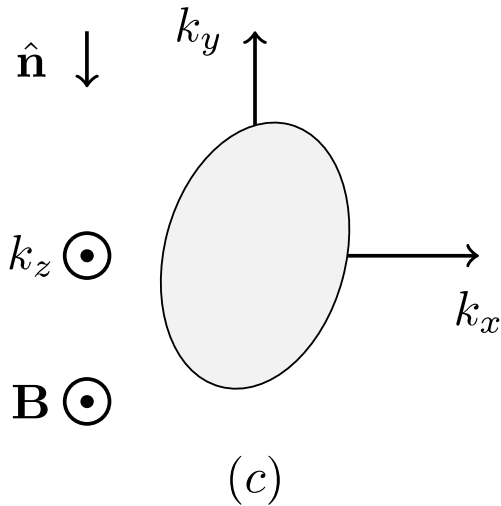
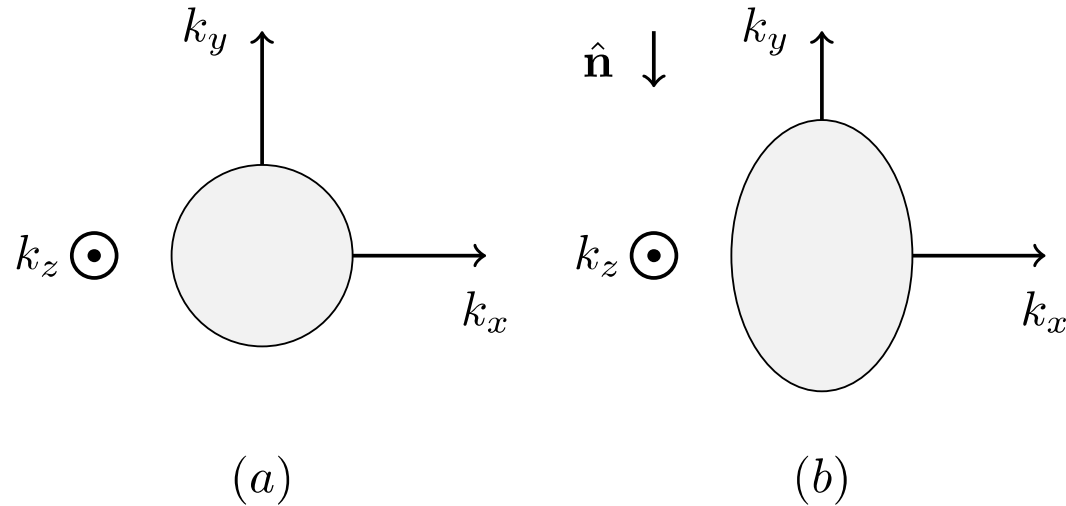
$$\times \left[26.4 \text{ mK} \left\{ 1 + \left(1 + (\hat{\mathbf{k}} \cdot \hat{\mathbf{n}})^2 \right) \delta \right\} \right.$$

$$- 0.128 \text{ mK} \left(\frac{T_\gamma}{T_s} \right) x_{1s} \left(\frac{1+z}{10} \right)^{1/2}$$

$$\times \left\{ 1 + 2 \left(1 + (\hat{\mathbf{k}} \cdot \hat{\mathbf{n}})^2 \right) \delta \right.$$

$$\left. \left. - \frac{\delta}{15} \sum_m \frac{4\pi}{5} \frac{Y_{2m}(\hat{\mathbf{k}}) [Y_{2m}(\hat{\mathbf{n}})]^*}{1 + x_{\alpha,(2)} + x_{c,(2)} - imx_B} \right\} \right]$$

Effect on 21cm observables



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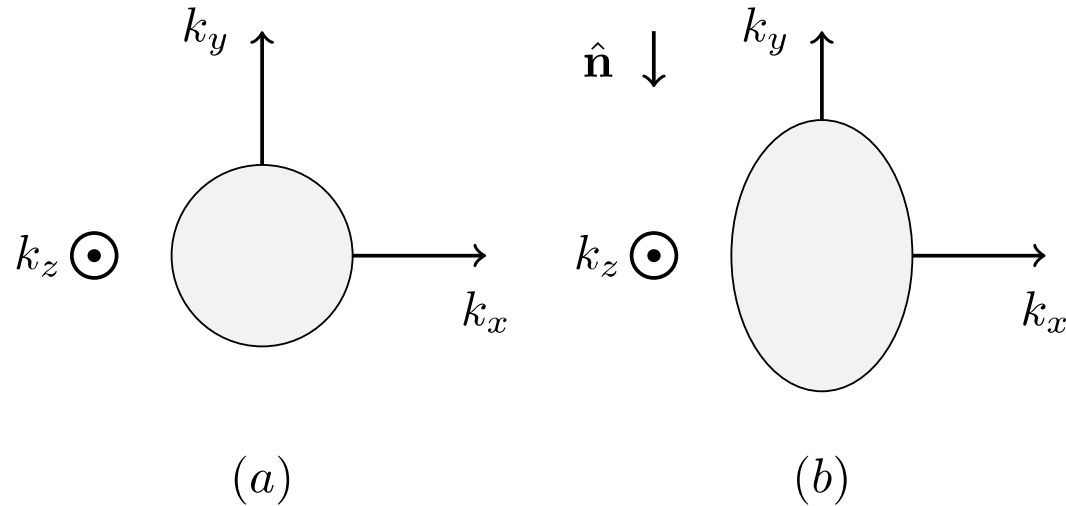
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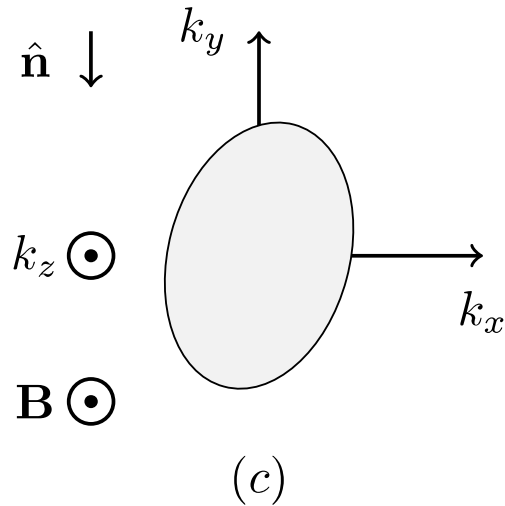
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Effect on 21cm observables



(a)

(b)



(c)

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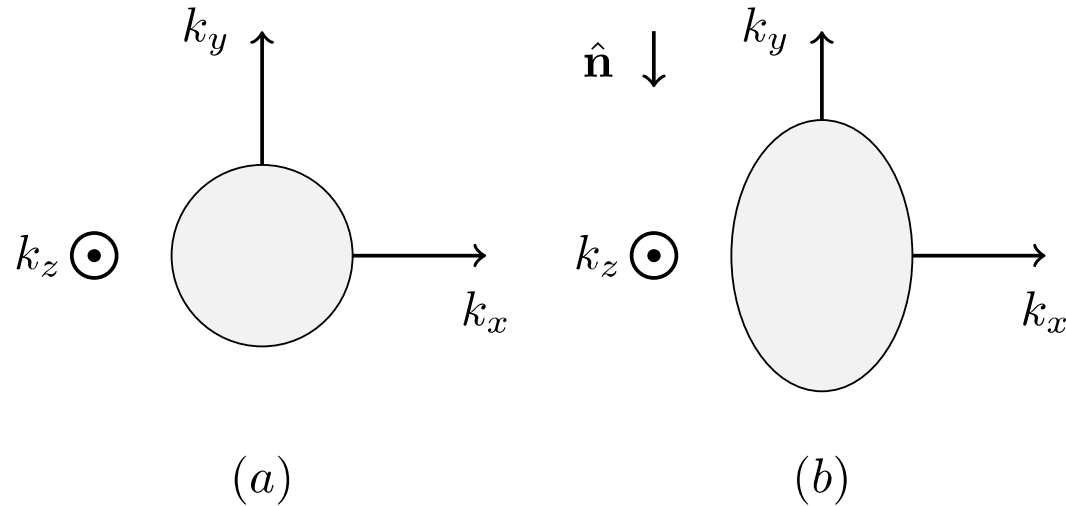
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Effect on 21cm observables



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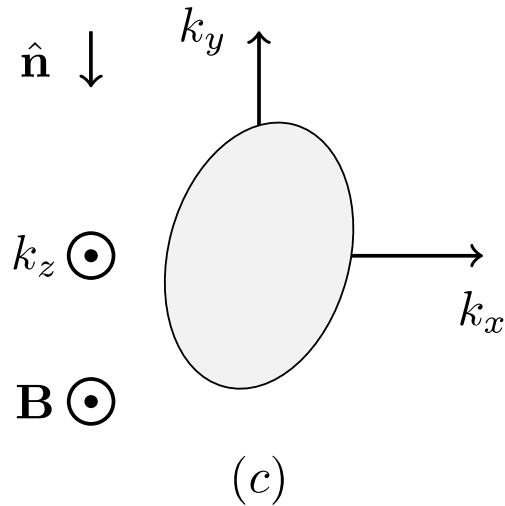
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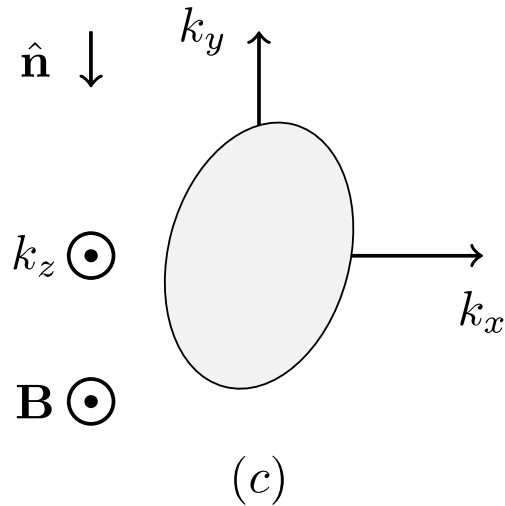
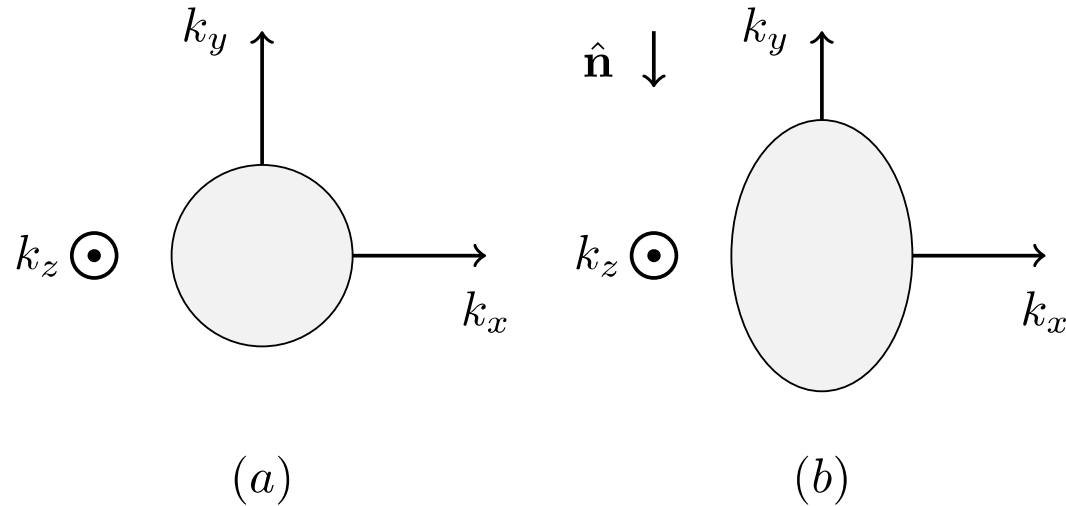
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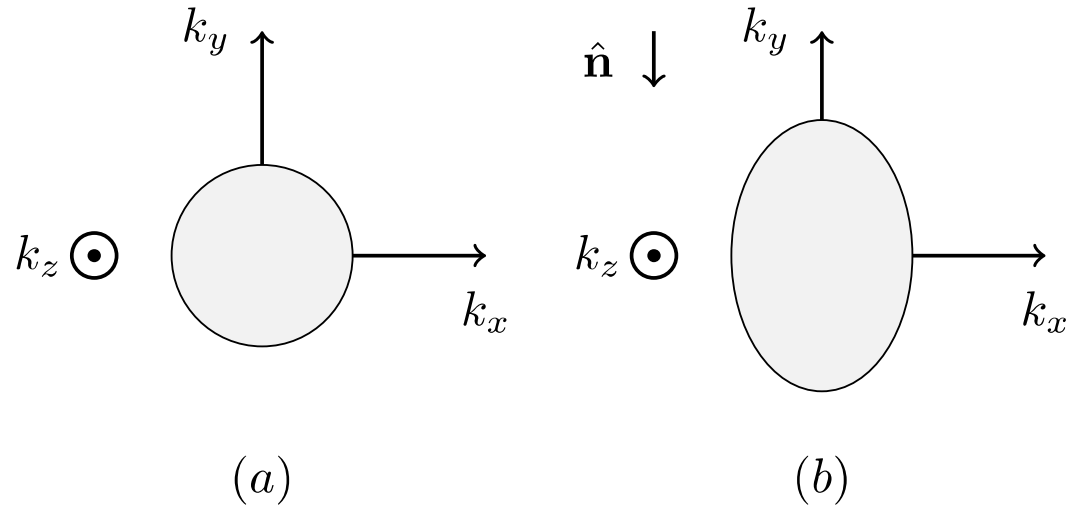
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atomic physics

Effect on 21cm observables



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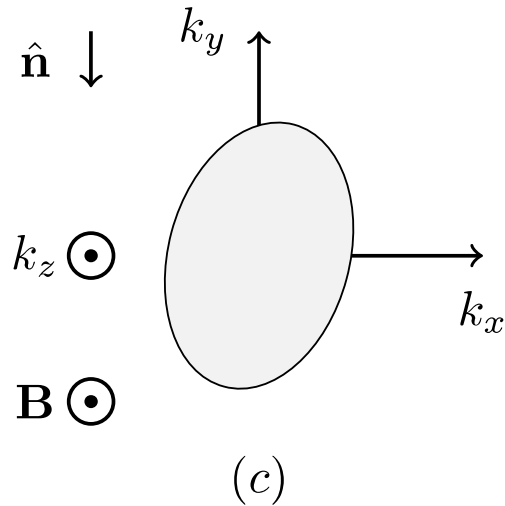
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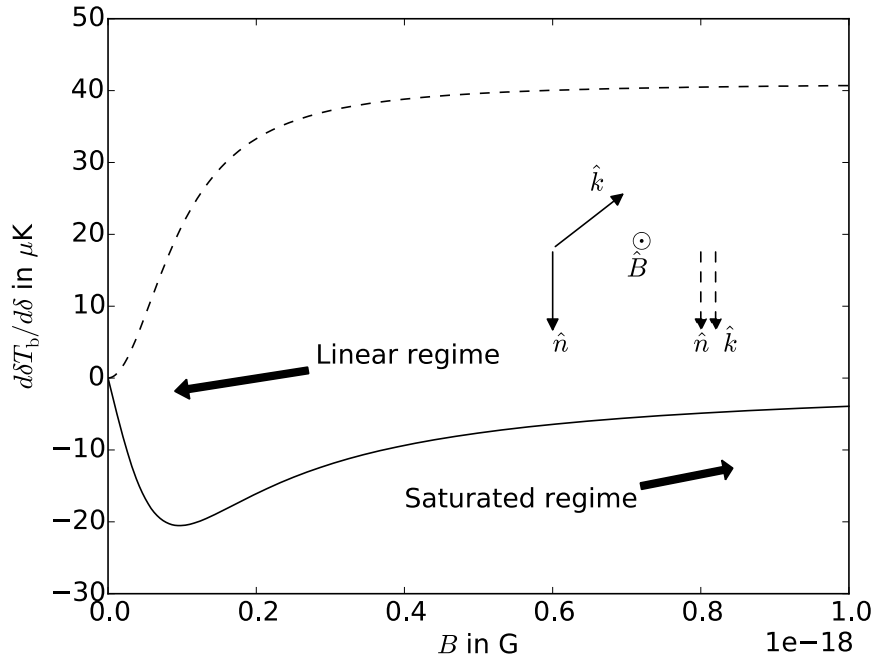
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atomic physics Precession

Limiting cases: field strengths



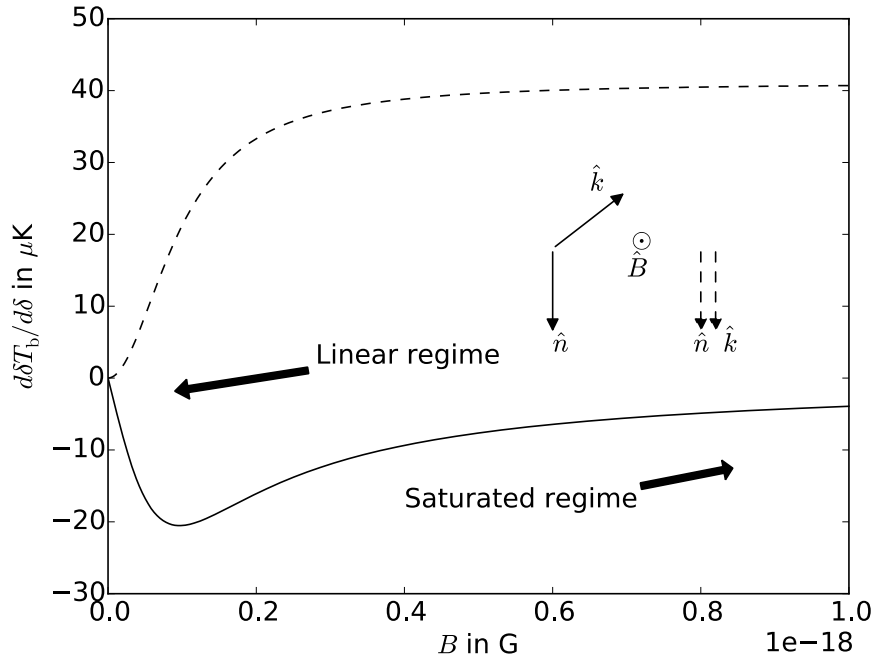
Strong field, saturated:

$$\begin{aligned} & \delta T_b(\hat{n})|_{x_B \rightarrow \infty} - \delta T_b(\hat{n})|_{x_B=0} \\ &= 8.53 \mu\text{K} \times P_2(\hat{k} \cdot \hat{B}) P_2(\hat{n} \cdot \hat{B}) \\ & \times \left(1 - \frac{T_\gamma}{T_s}\right) x_{1s}^2 \left(\frac{1+z}{10}\right) \left(\frac{T_\gamma}{T_s}\right) \frac{\delta}{1 + x_{\alpha,(2)} + x_{c,(2)}} \end{aligned}$$

Weak field, linear with B:

$$\begin{aligned} \frac{d\delta T_b}{dB}(\hat{n}) &= 1.786 \times 10^{17} \frac{\text{mK}}{\text{G}} [\hat{B} \cdot (\hat{k} \times \hat{n})](\hat{n} \cdot \hat{k}) \\ & \times \left(1 - \frac{T_\gamma}{T_s}\right) x_{1s}^2 \left(\frac{T_\gamma}{T_s}\right) \frac{\delta}{(1 + x_{\alpha,(2)} + x_{c,(2)})^2} \end{aligned}$$

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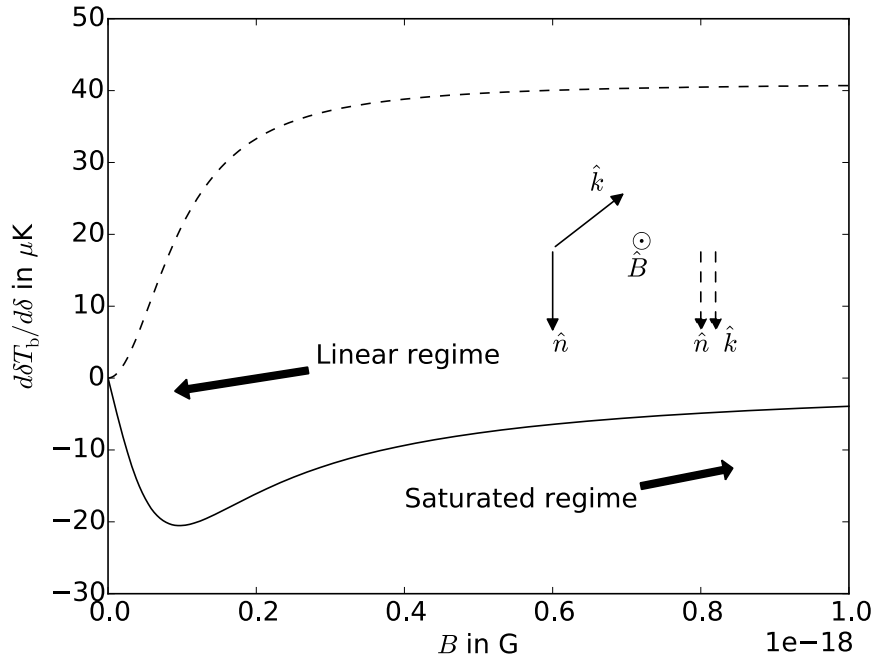
Precession by $\pi/2$

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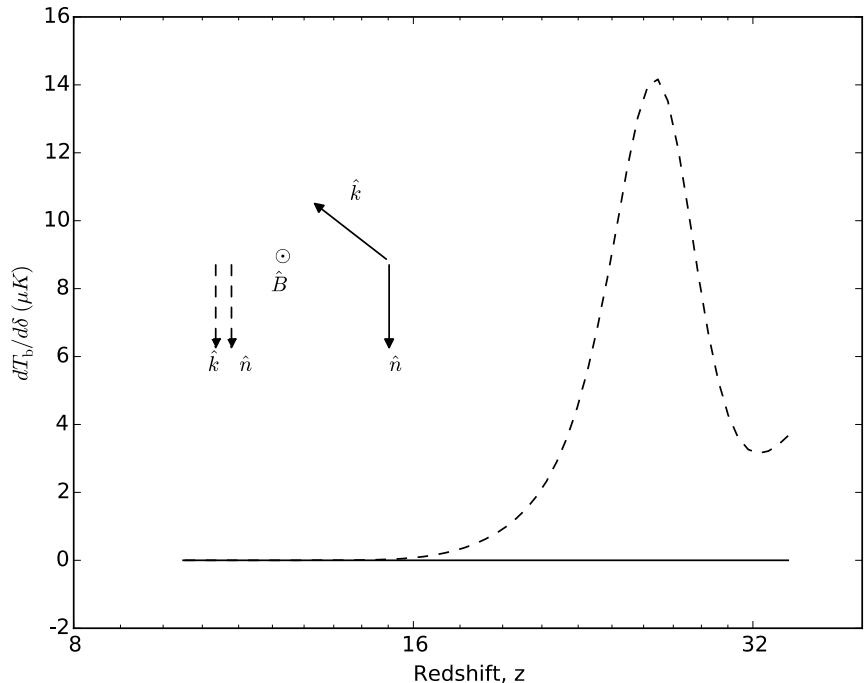
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Precession about B

PROSPECTS FOR DETECTION

Survey Geometry

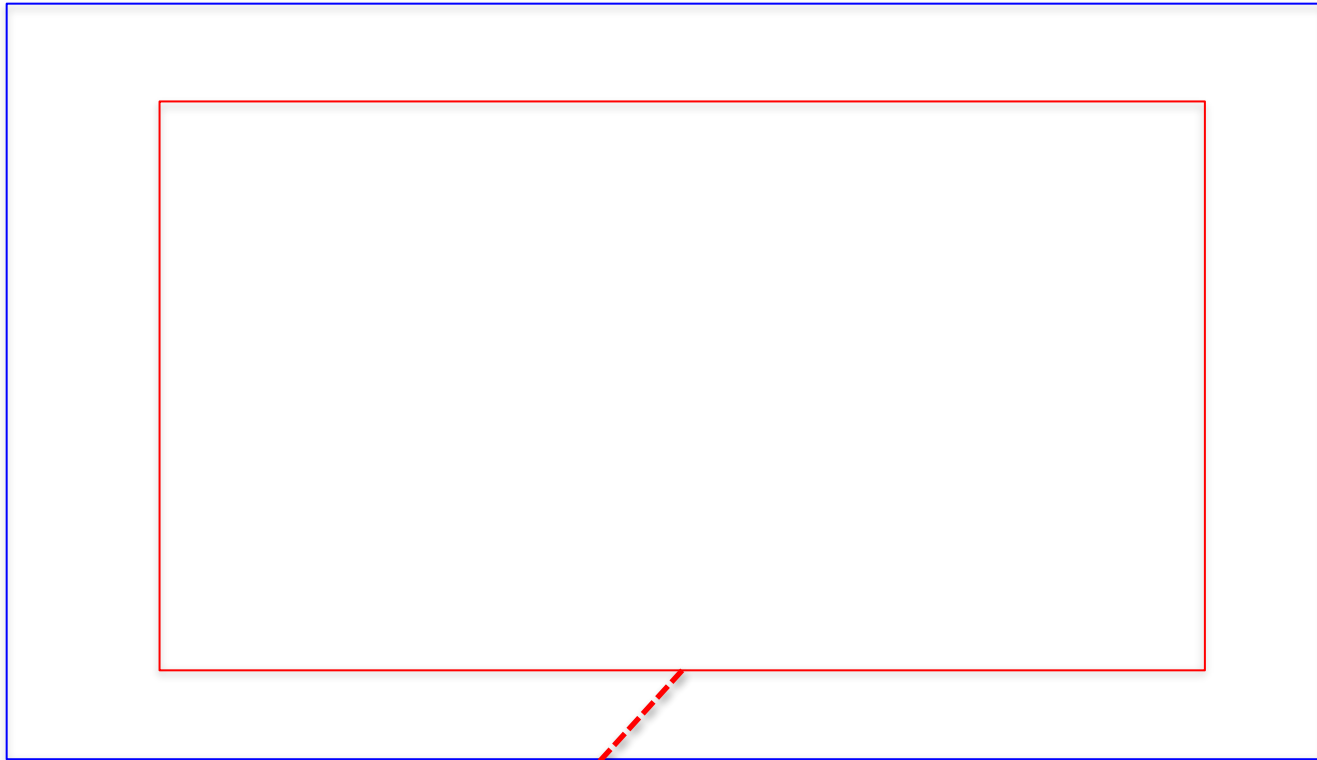
Survey Geometry



L_s

A dashed blue arrow originates from the bottom-right corner of the rectangular box and points towards the label L_s .

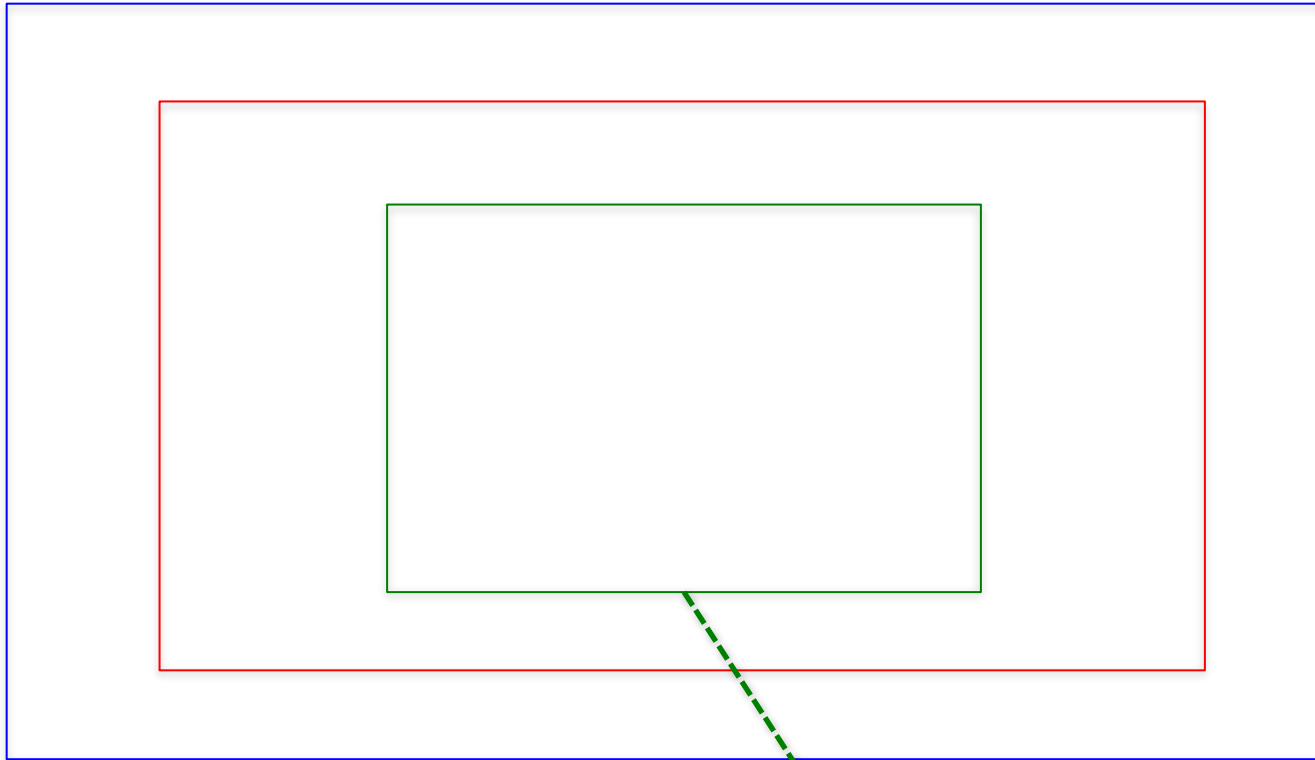
Survey Geometry



L_s

k_B^{-1}

Survey Geometry

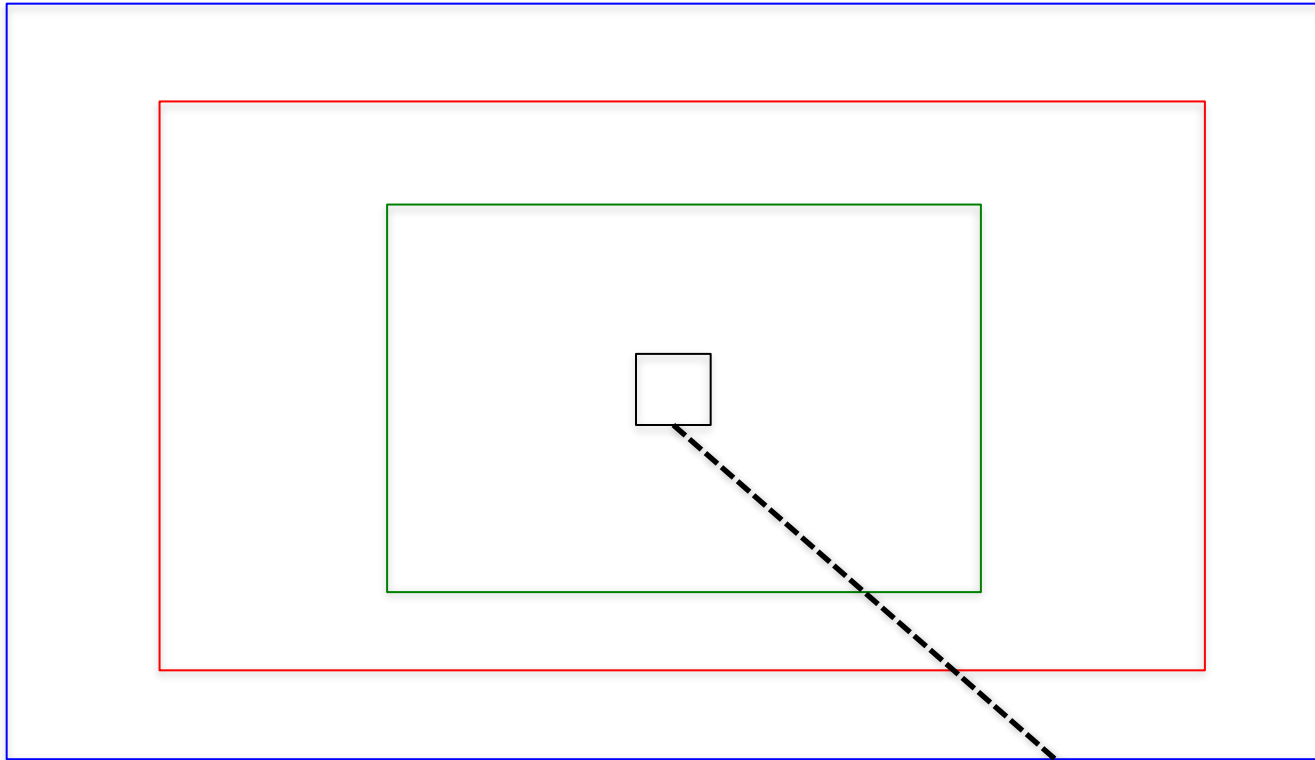


L_s

k_B^{-1}

k_{LSS}^{-1}

Survey Geometry



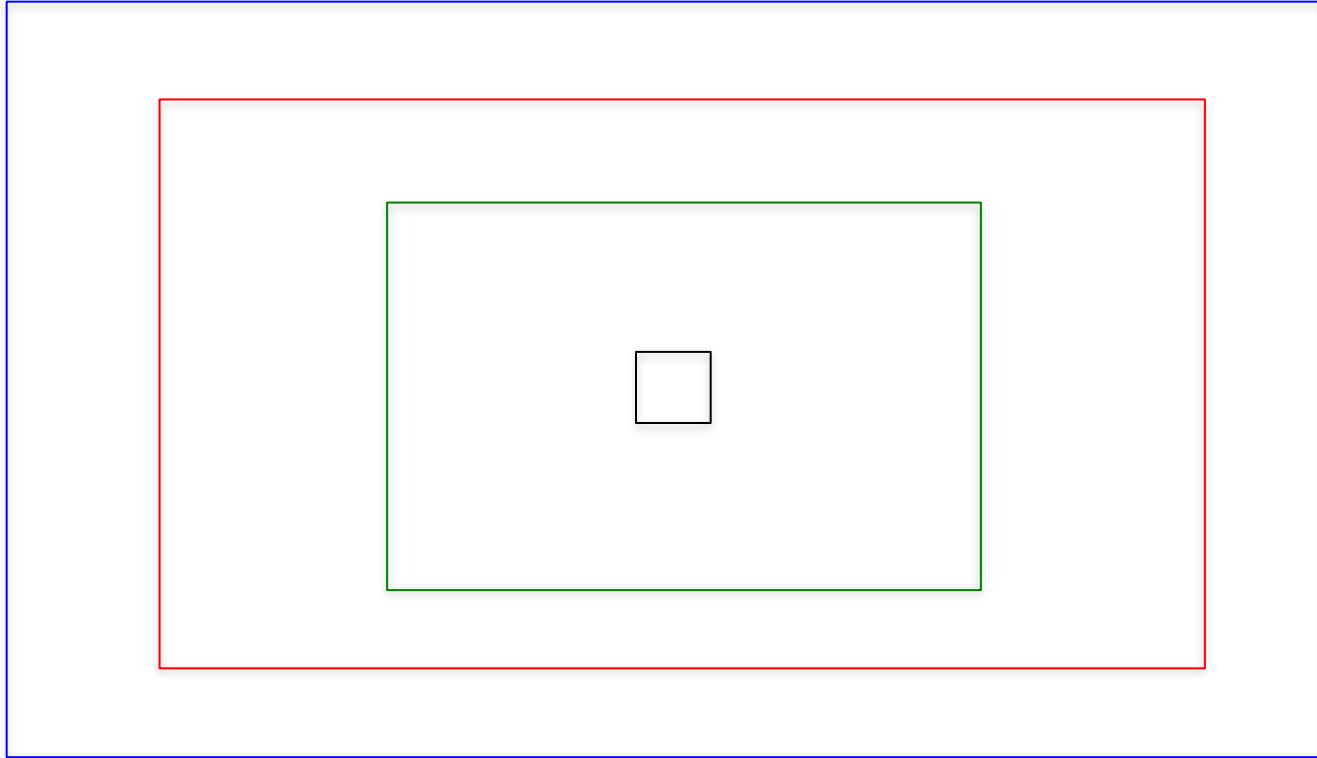
L_s

k_B^{-1}

k_{LSS}^{-1}

k_{\max}^{-1}

Survey Geometry



L_s

k_B^{-1}

k_{LSS}^{-1}

k_{\max}^{-1}

Detectability



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

Detectability



No signal - variance

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

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

Credit: Swinburne Astronomy Productions/
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Detectability



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Unsaturated case

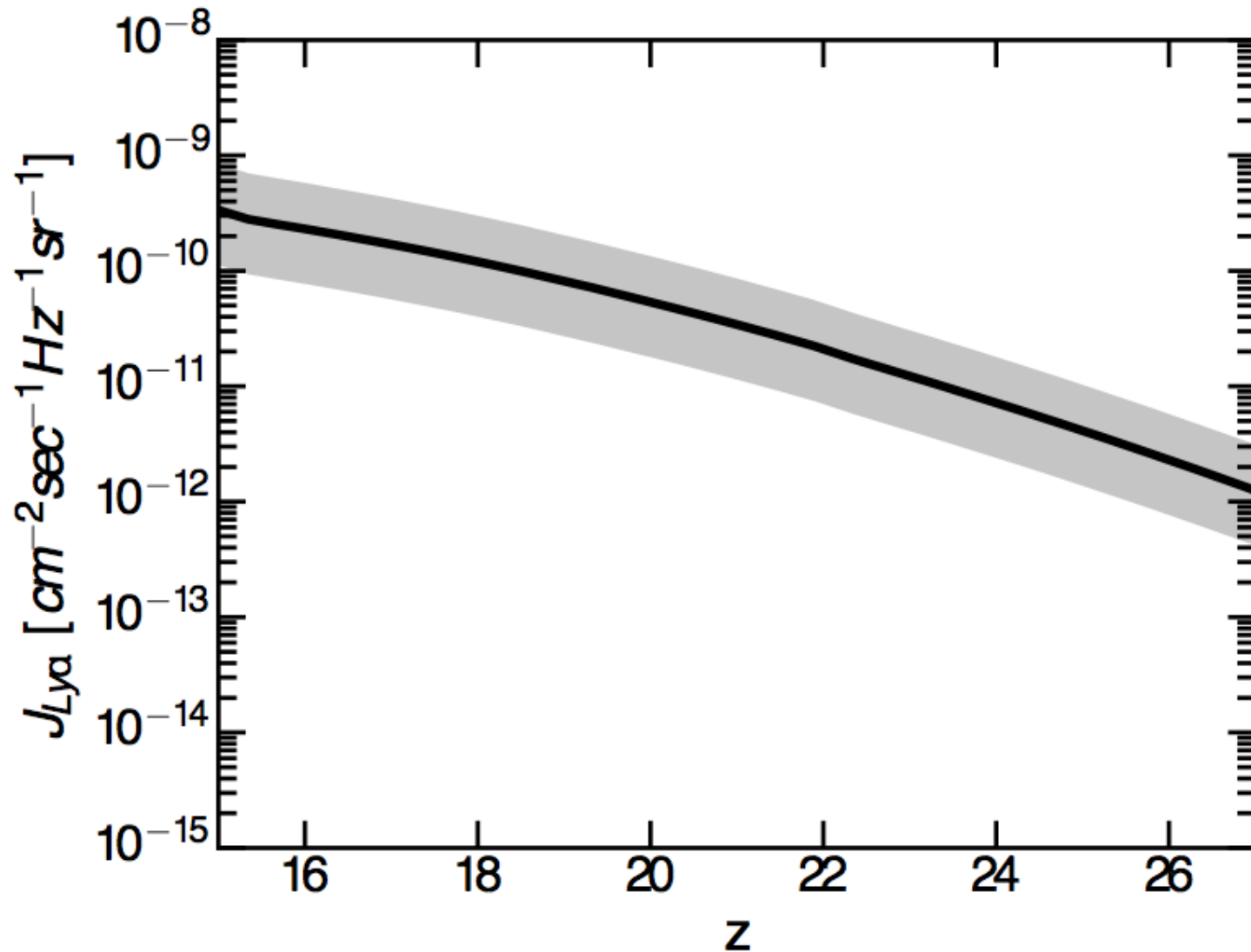
$$\sigma_{B_0}^{-2}(z) = \int dV_{\text{patch}}(z) \frac{k^2 dk d\phi_k \sin \theta_k d\theta_k}{(2\pi)^3} \left(\frac{\partial P_S / \partial B_0}{P_N + P_S} \right)^2$$

Saturated case

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

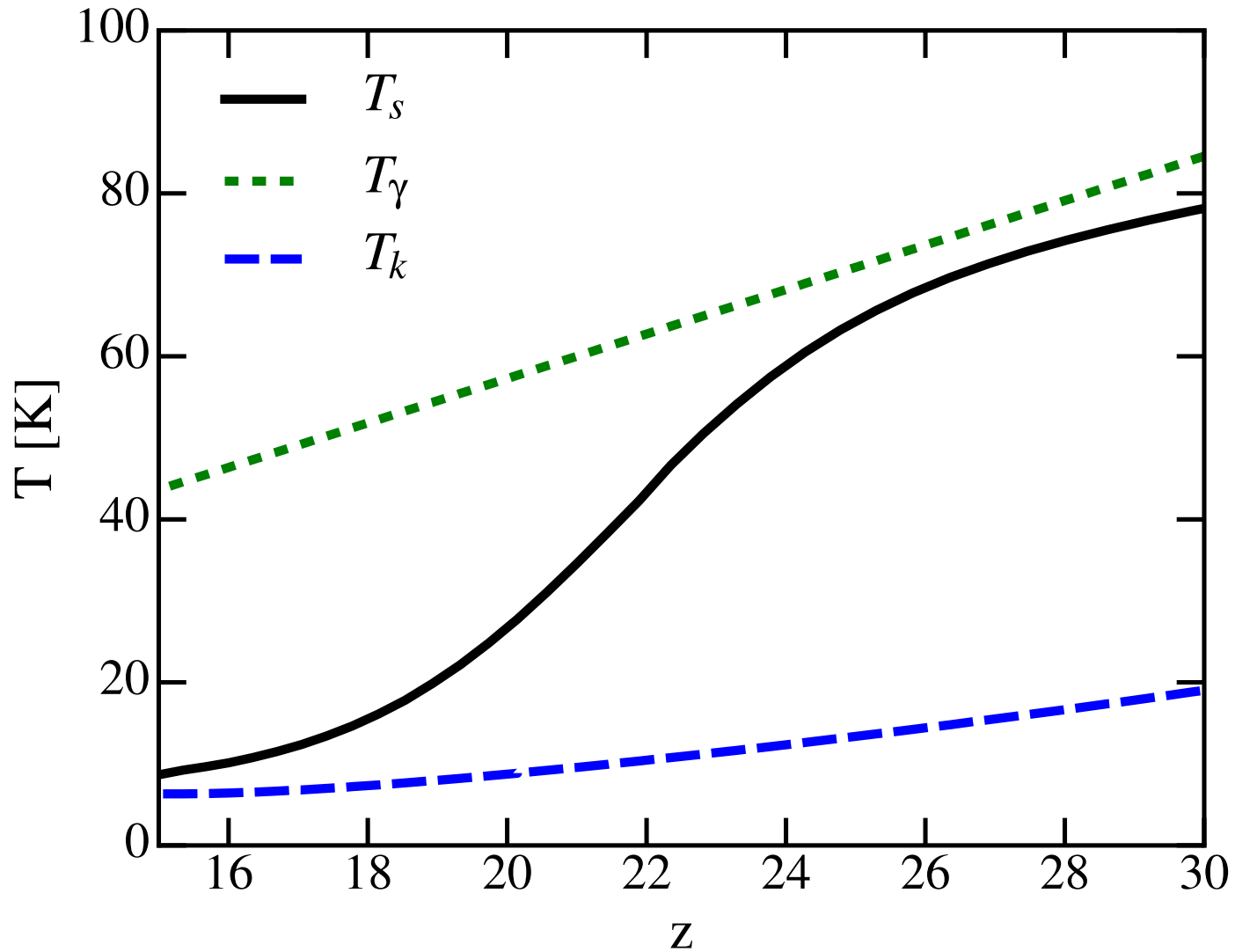
Credit: Swinburne Astronomy Productions/
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Input parameters

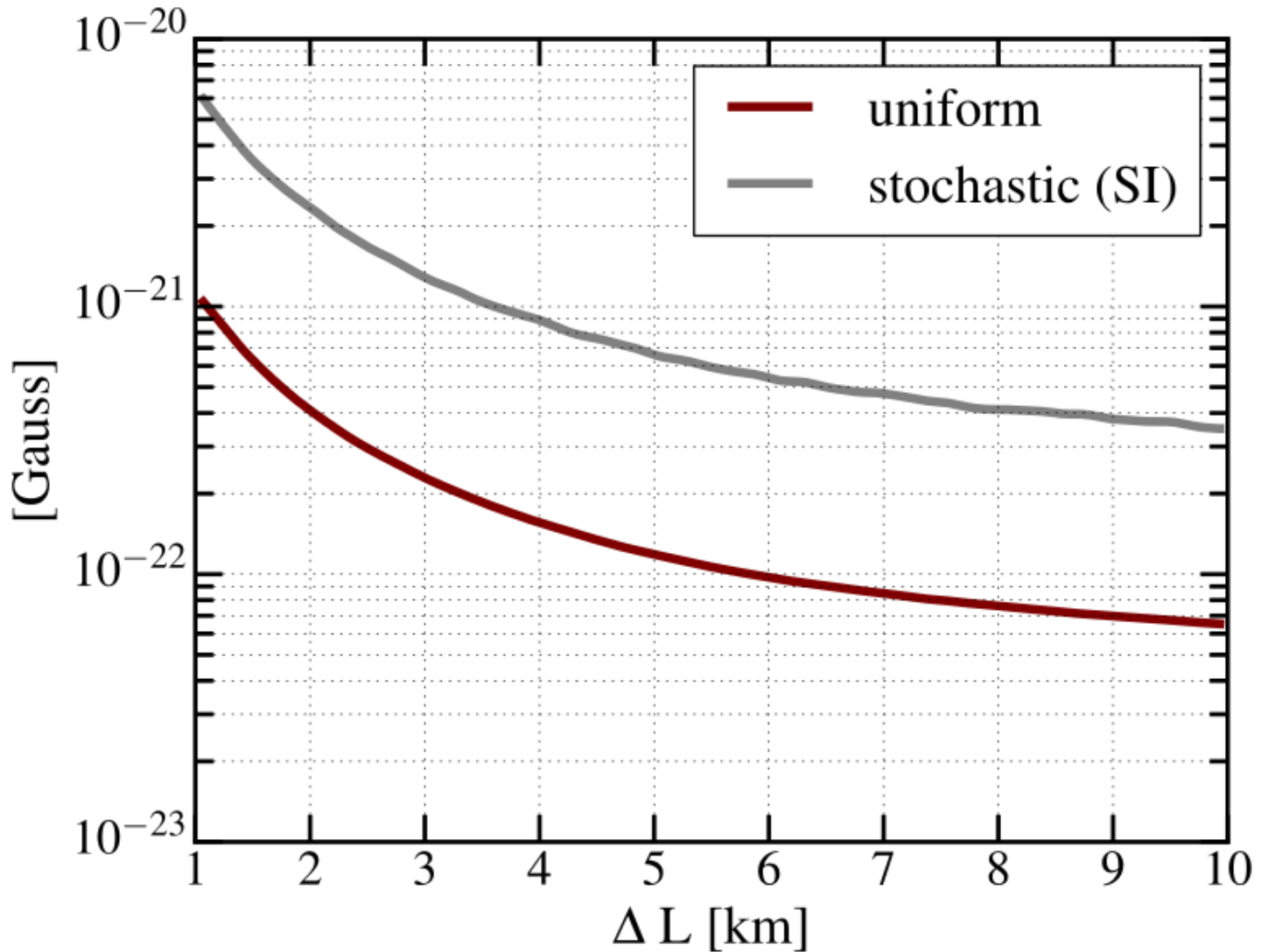


Gluscević, V., Venumadhav, T., et. al. (2016)

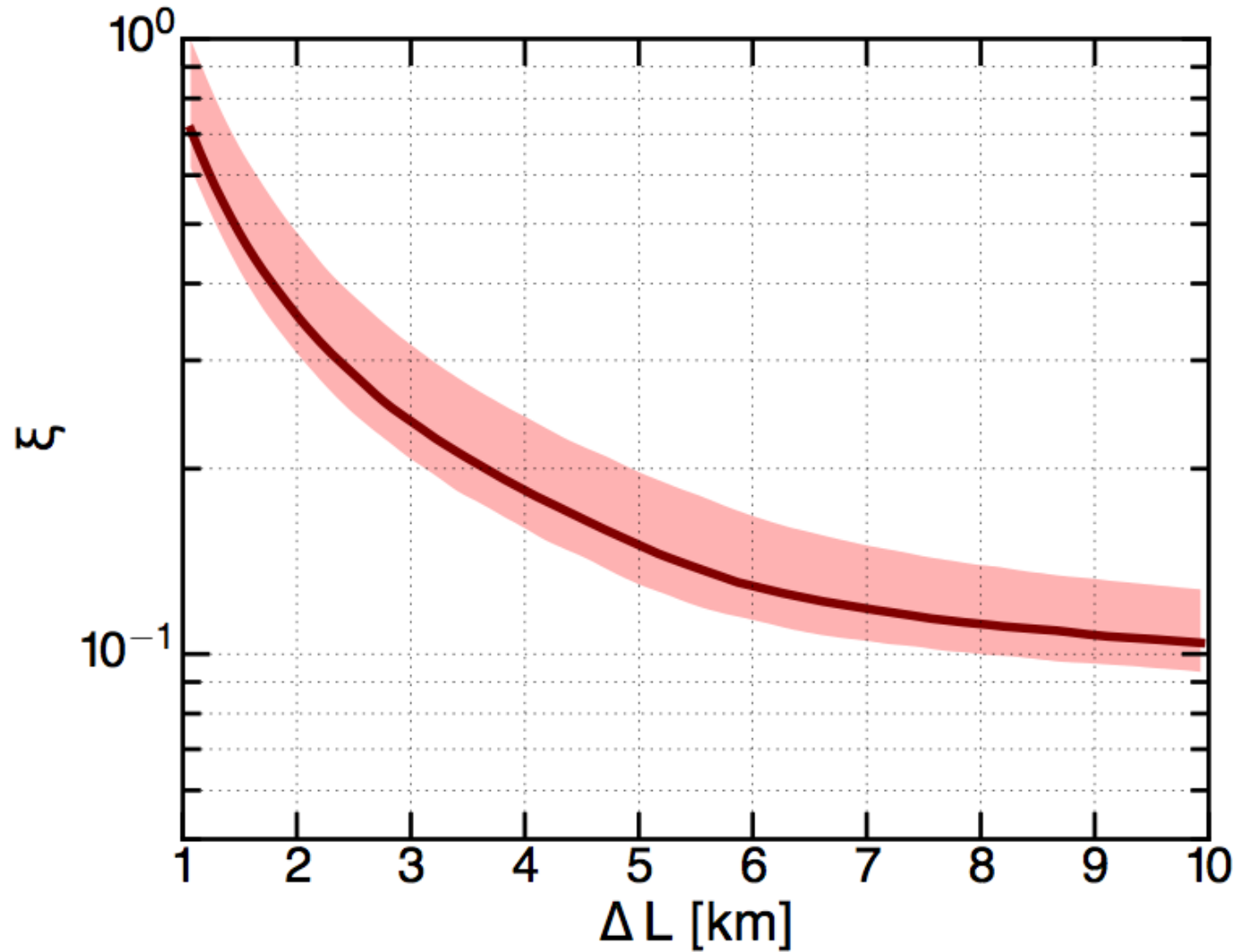
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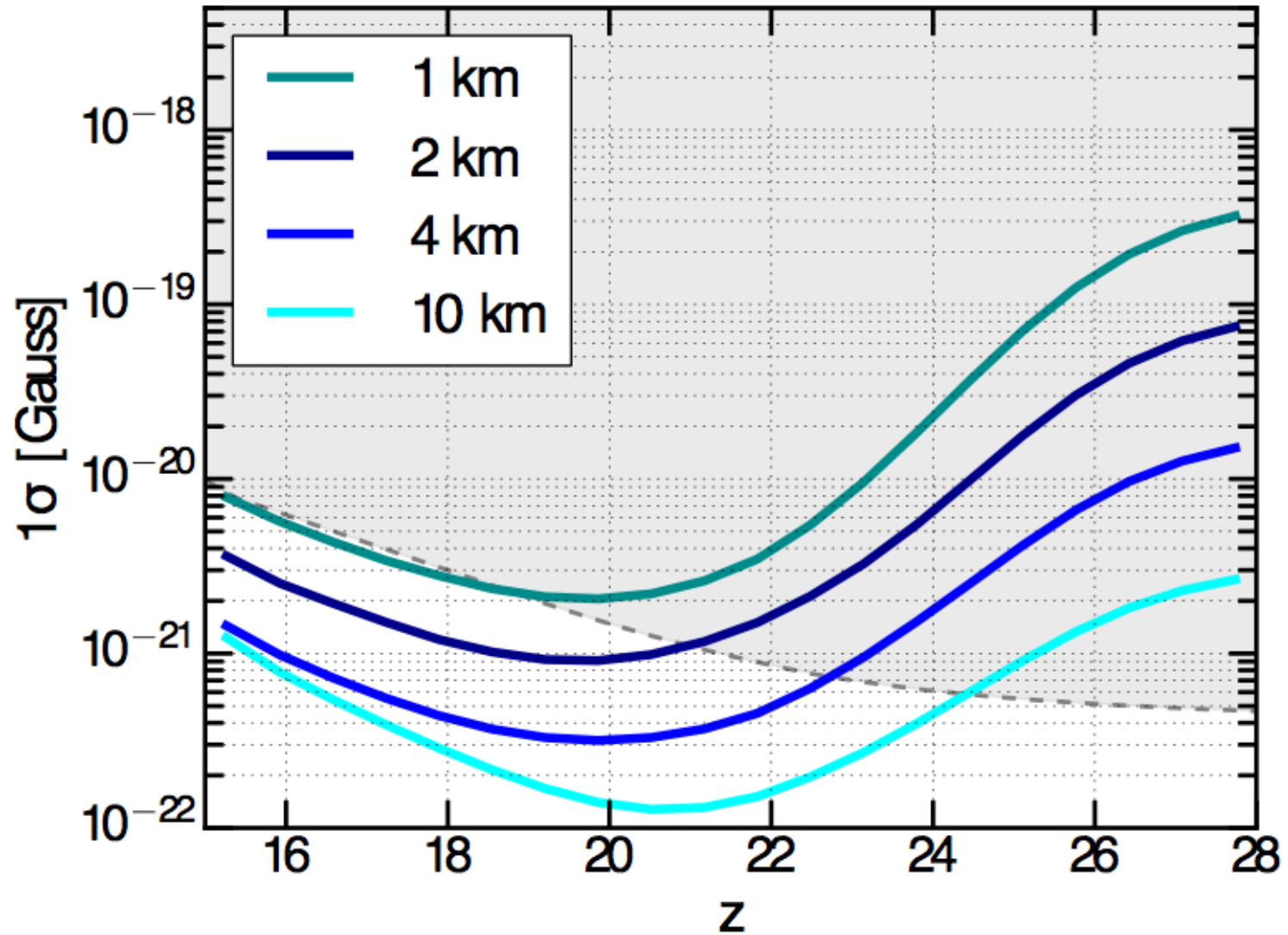
Detectability - Unsaturated



Detectability - Saturated



Detectability - Redshift



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 $\gtrsim 1 \text{ km}^2$ is **in principle** sensitive to a Gauss comoving field within one year of integration time.

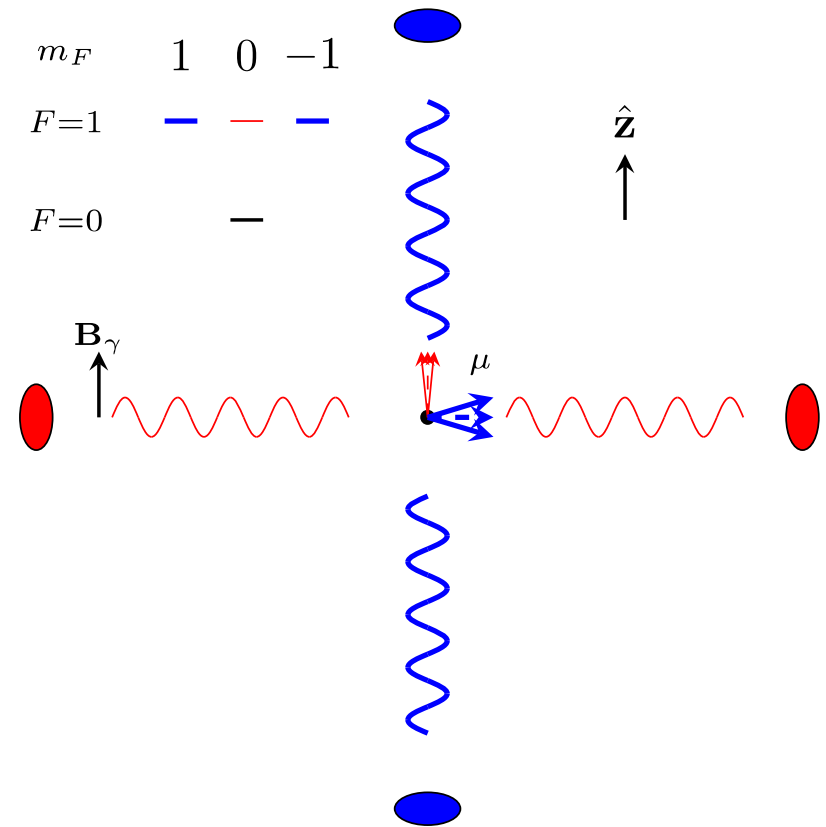
Future work towards its applicability:

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

PRIMORDIAL GRAVITATIONAL WAVES

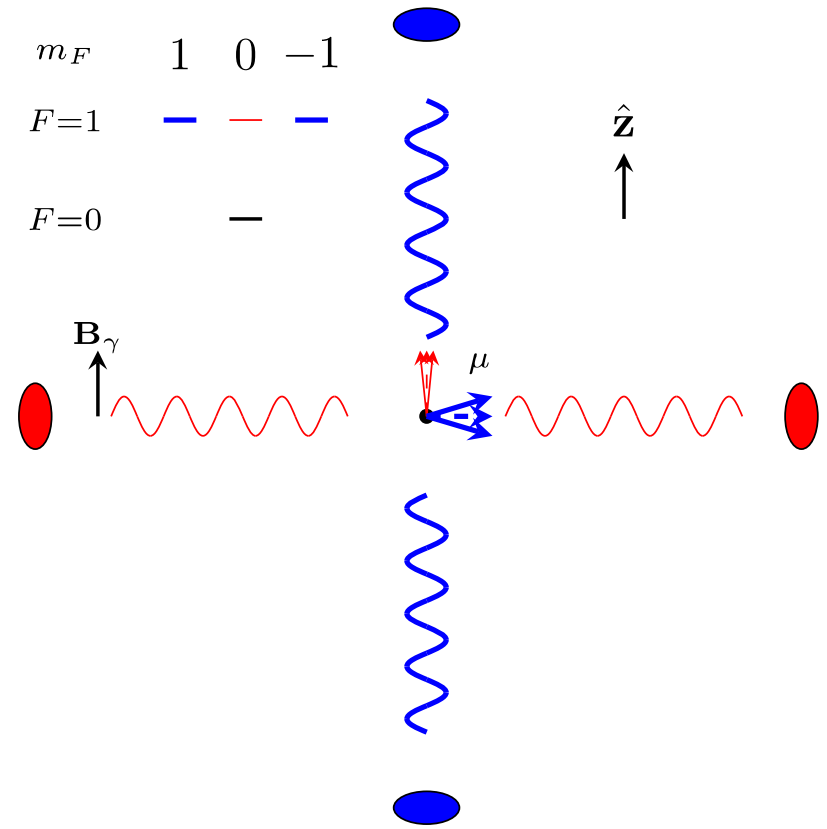
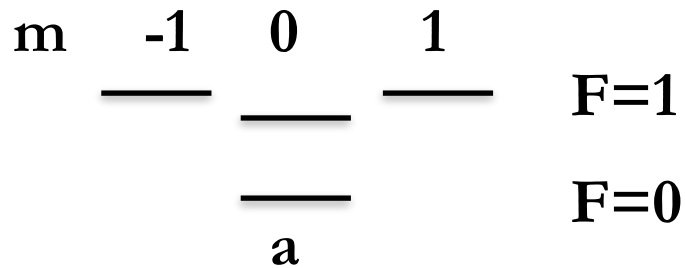
What about CMB anisotropies?

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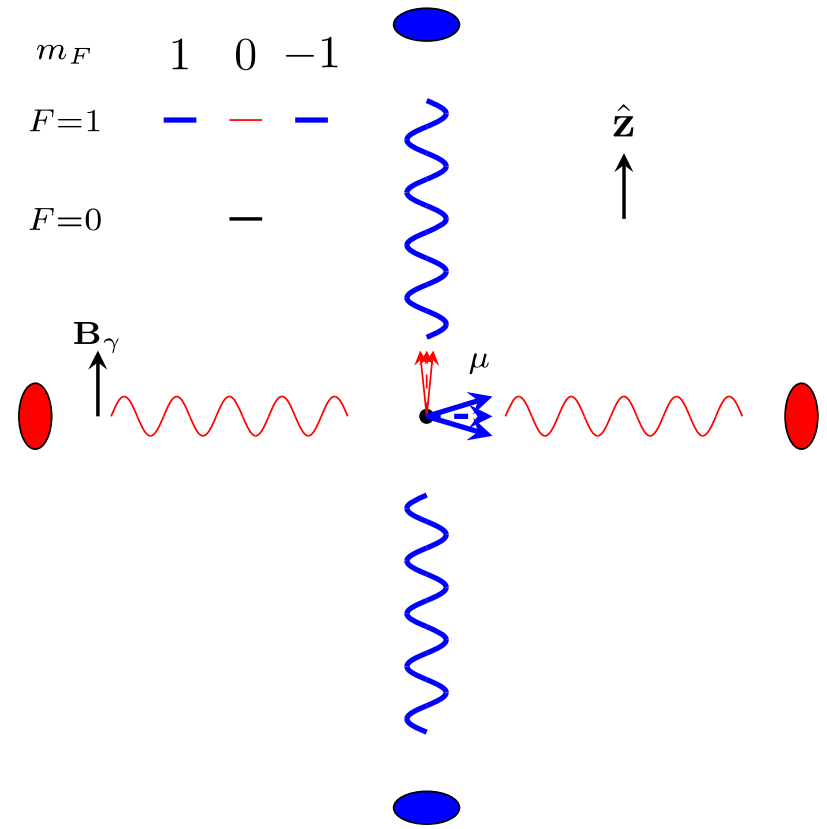
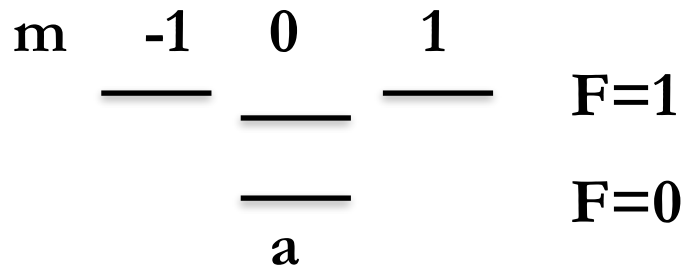
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- Off resonant, finite temperature correction to the energy levels.
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$$\frac{\Delta E_{11} - \Delta E_{10}}{\hbar} = -4.4 \times 10^{-10} \text{ s}^{-1} \left(\frac{T_\gamma}{60 \text{ K}} \right)^2 a_{20, \text{CMB}}$$

From alignment to orientation

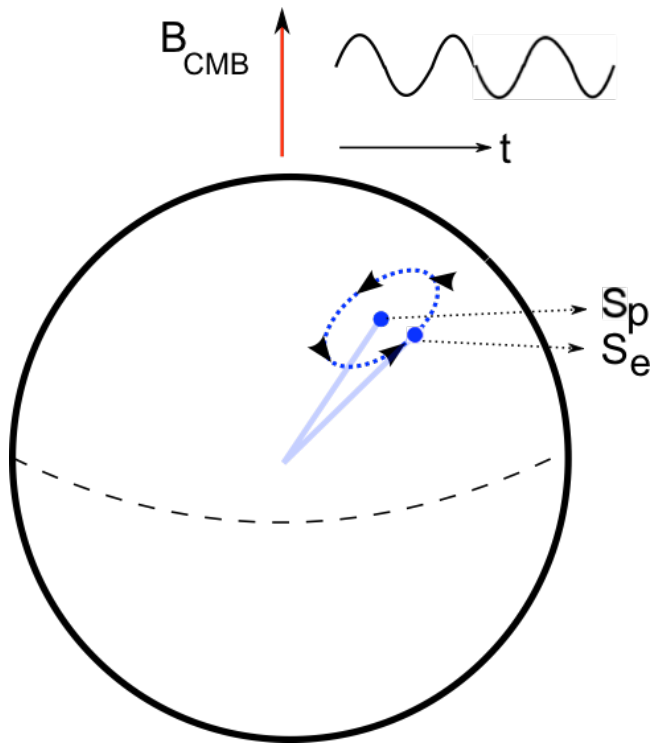
- In the presence of “alignment” or spin-polarization (due to fluctuations in the gas), and the energy level correction due to CMB quadrupoles, atoms tend to get “oriented”.

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

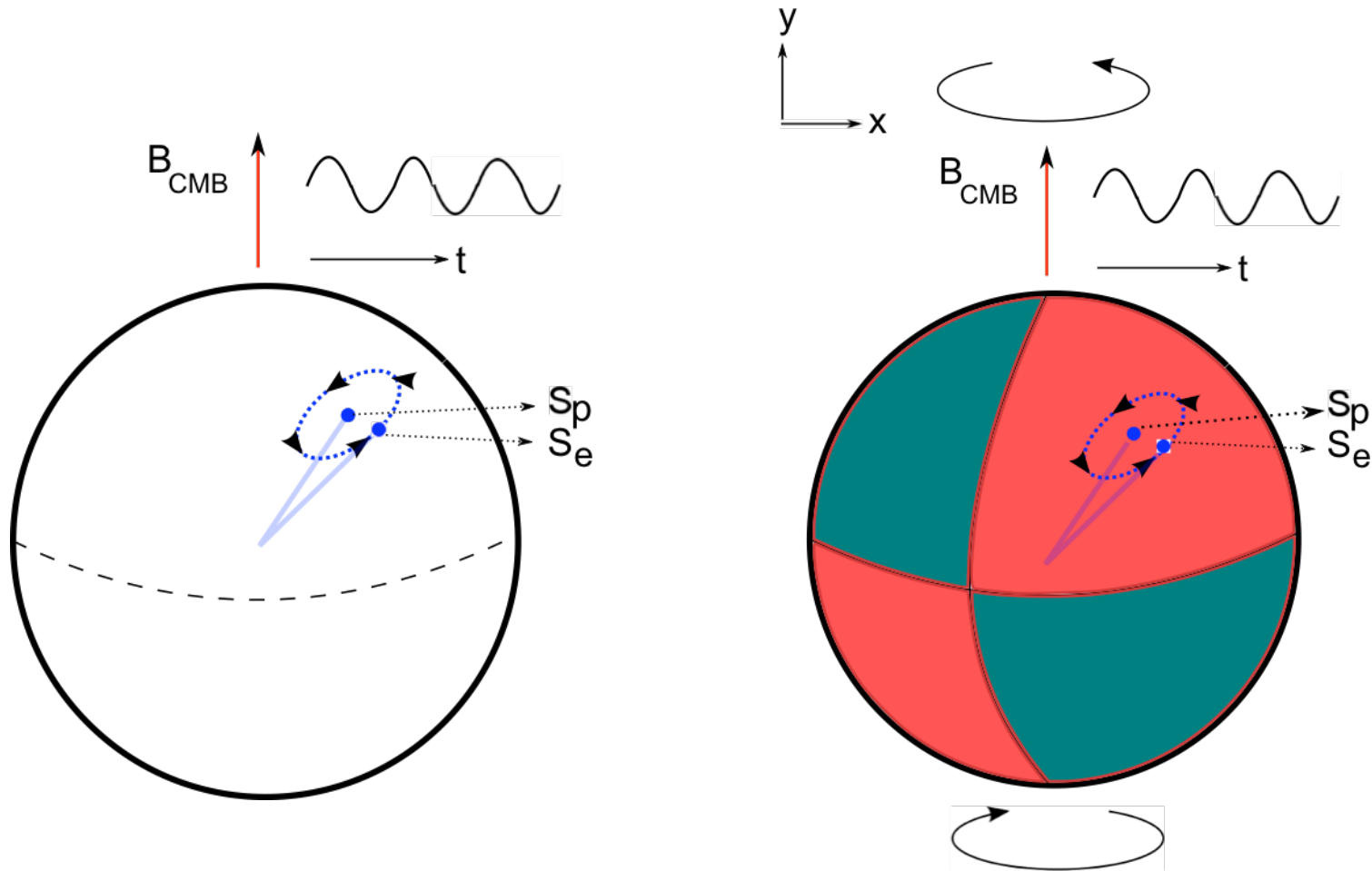
- Oriented atoms emit circularly polarized radiation.

Why do spins develop a net orientation?

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Why do spins develop a net orientation?



Using V to look at the CMB quadrupole

$$\begin{aligned} \frac{\partial V_{\text{obs}}}{\partial \delta} = & -8.6 \text{ mK} \left(\frac{1+z}{20} \right)^2 \frac{T_\gamma}{T_s} \left(1 - \frac{T_\gamma}{T_s} \right) \\ & \times \frac{1}{(1 + 0.75x_{\alpha,(2)})(1 + x_{\alpha,(2)} + x_{c,(2)})} \\ & \times \text{Im}[a_{21}Y_{21}(\hat{\mathbf{k}}) + 2a_{22}Y_{22}(\hat{\mathbf{k}})] \end{aligned}$$

Using V to look at the CMB quadrupole

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

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

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

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