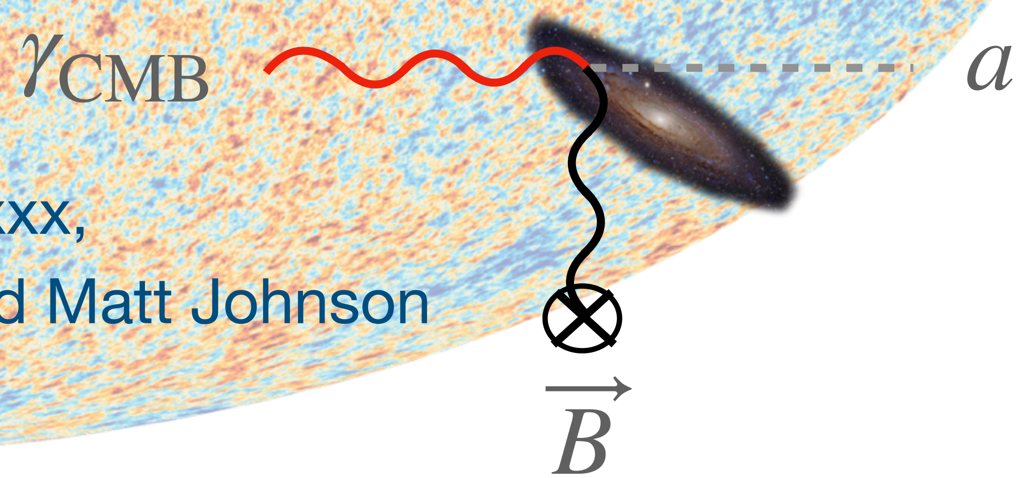
Axion screening of the CMB

Cristina Mondino

PERIMETER INSTITUTE



Based on arXiv:2405.xxxx,
with Dalila Pîrvu , Junwu Huang, and Matt Johnson

CATCH22+2 2024 — DIAS — May 3rd 2024

Axion (Like) Particles

$$\mathcal{L} \supset \frac{1}{2}\partial_\mu a \partial^\mu a - \frac{1}{2} m_a^2 a^2$$

New pseudo-scalar particle:

- Arises in several extensions of the SM
- Can solve the strong CP problem (QCD axion)
- Can be the DM or part of a dark sector
- Its mass could be small

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New pseudo-scalar particle:

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- Can be the DM or part of a dark sector
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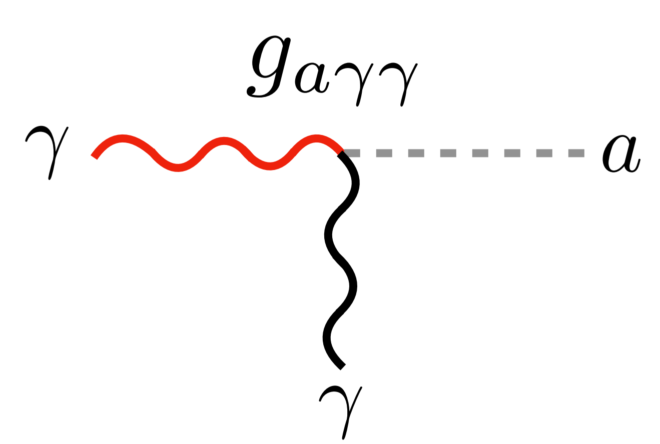
- Can couple to SM particles (gauge bosons, fermions, etc.)

$$\mathcal{L} \supset -\frac{1}{4} g_{a\gamma\gamma} a F^{\mu\nu} \tilde{F}_{\mu\nu}$$



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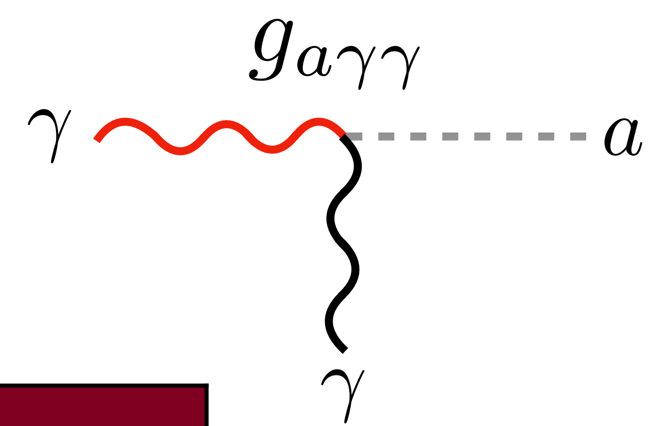
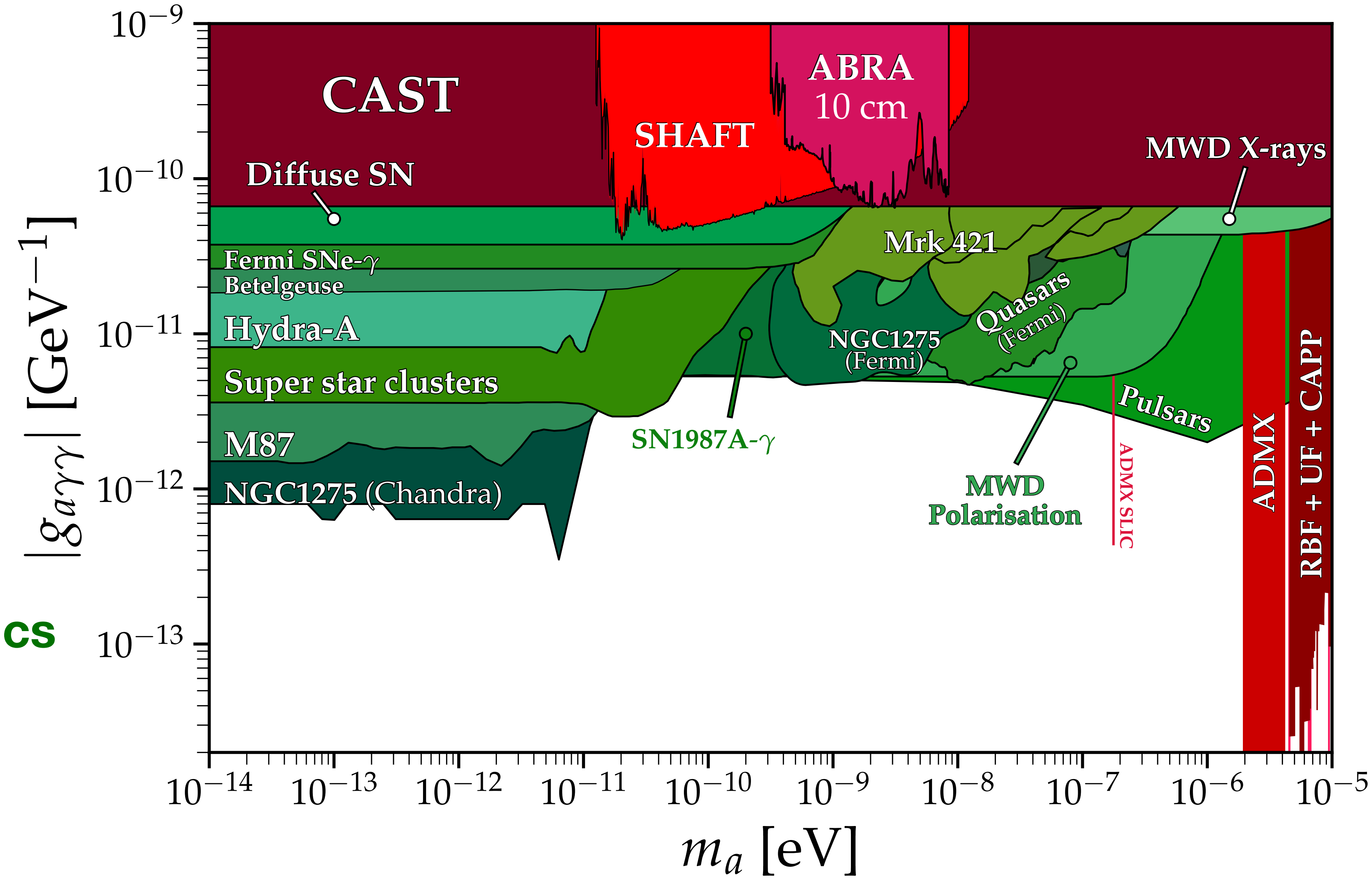


Laboratory



Astrophysics

From Ciaran O'Hare (cajohare.github.io/AxionLimits/)

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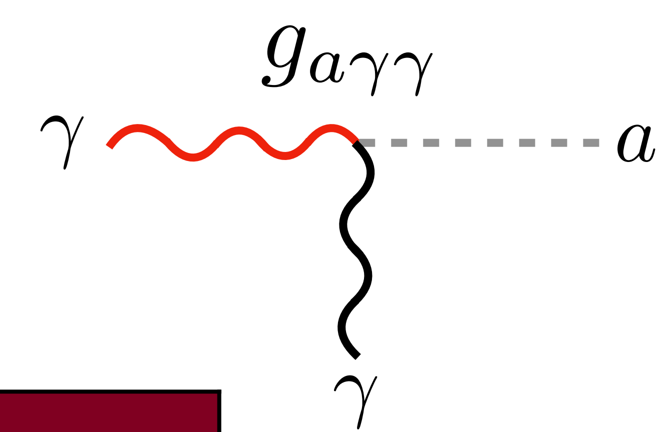

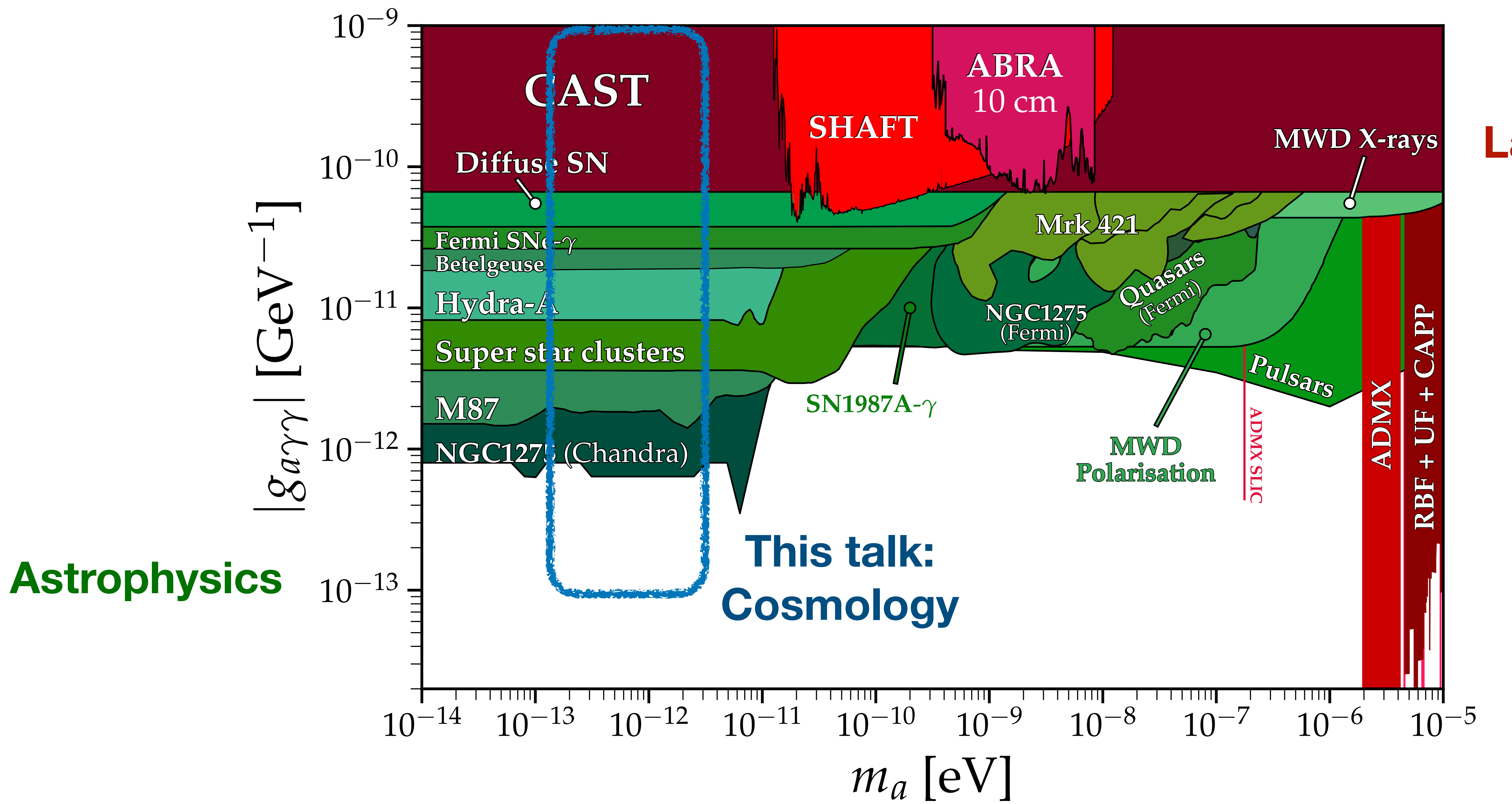

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Axion ~~(Like) Particles~~

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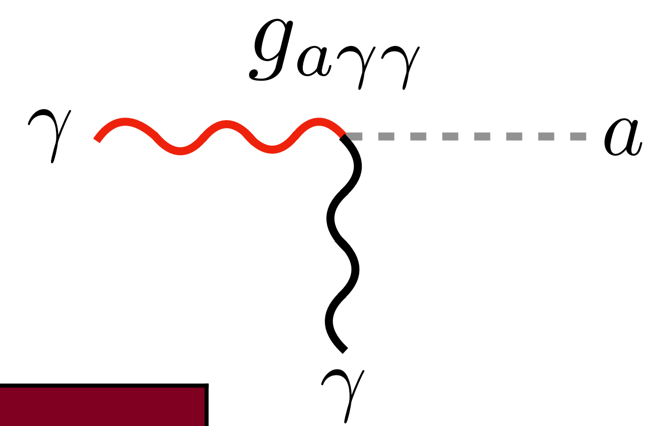

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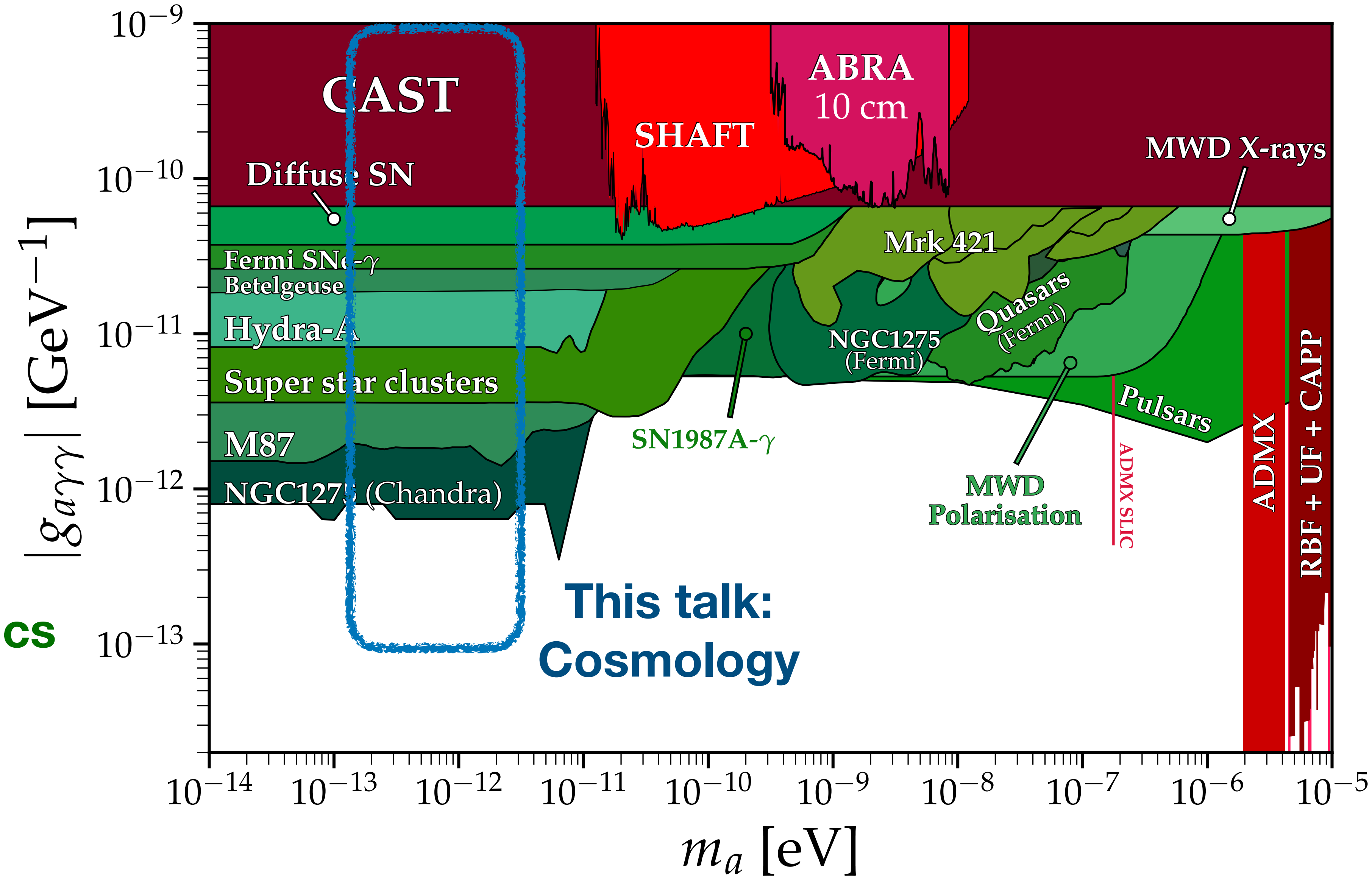

From Ciaran O'Hare (cajohare.github.io/AxionLimits/)

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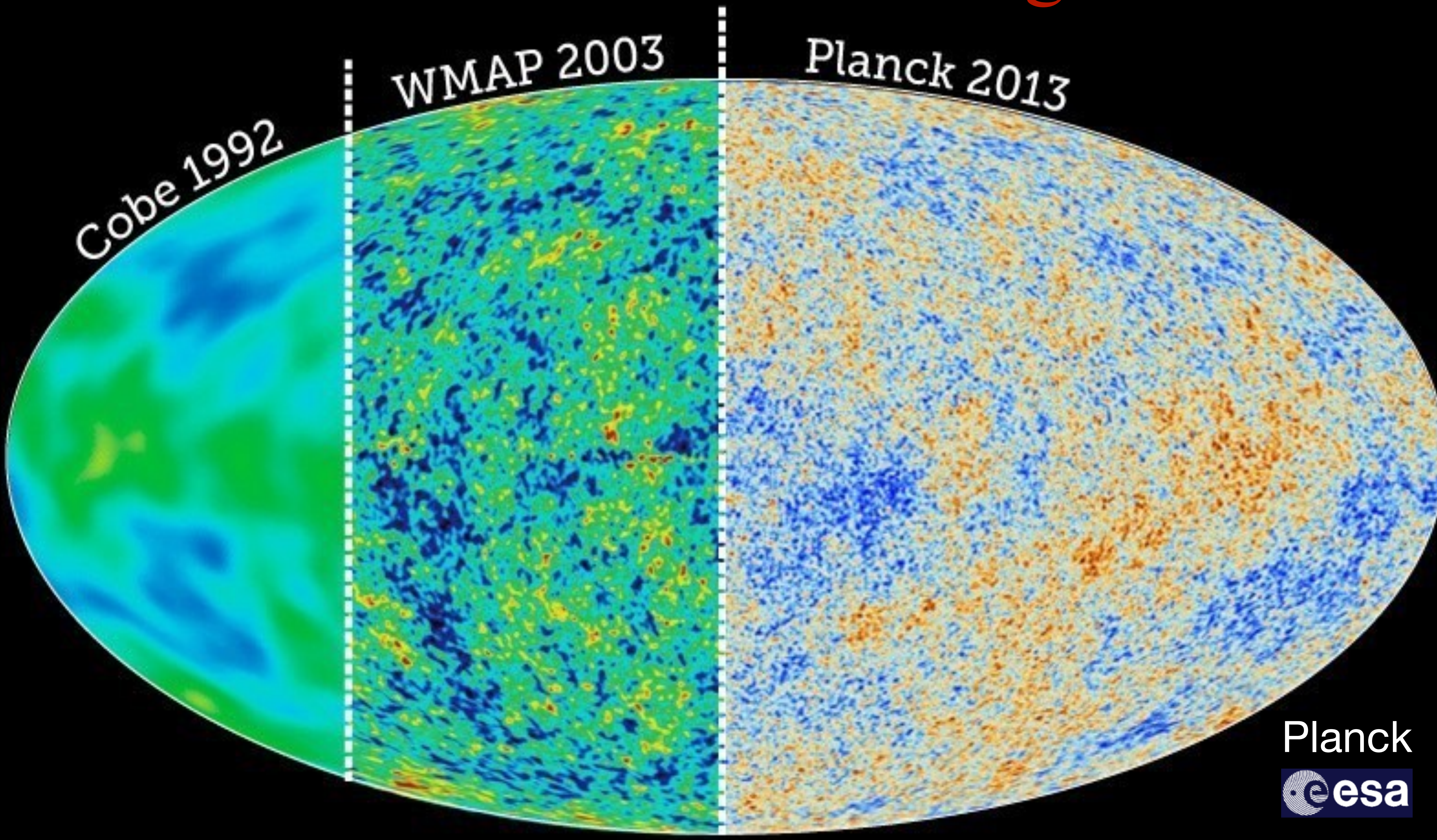
Outline

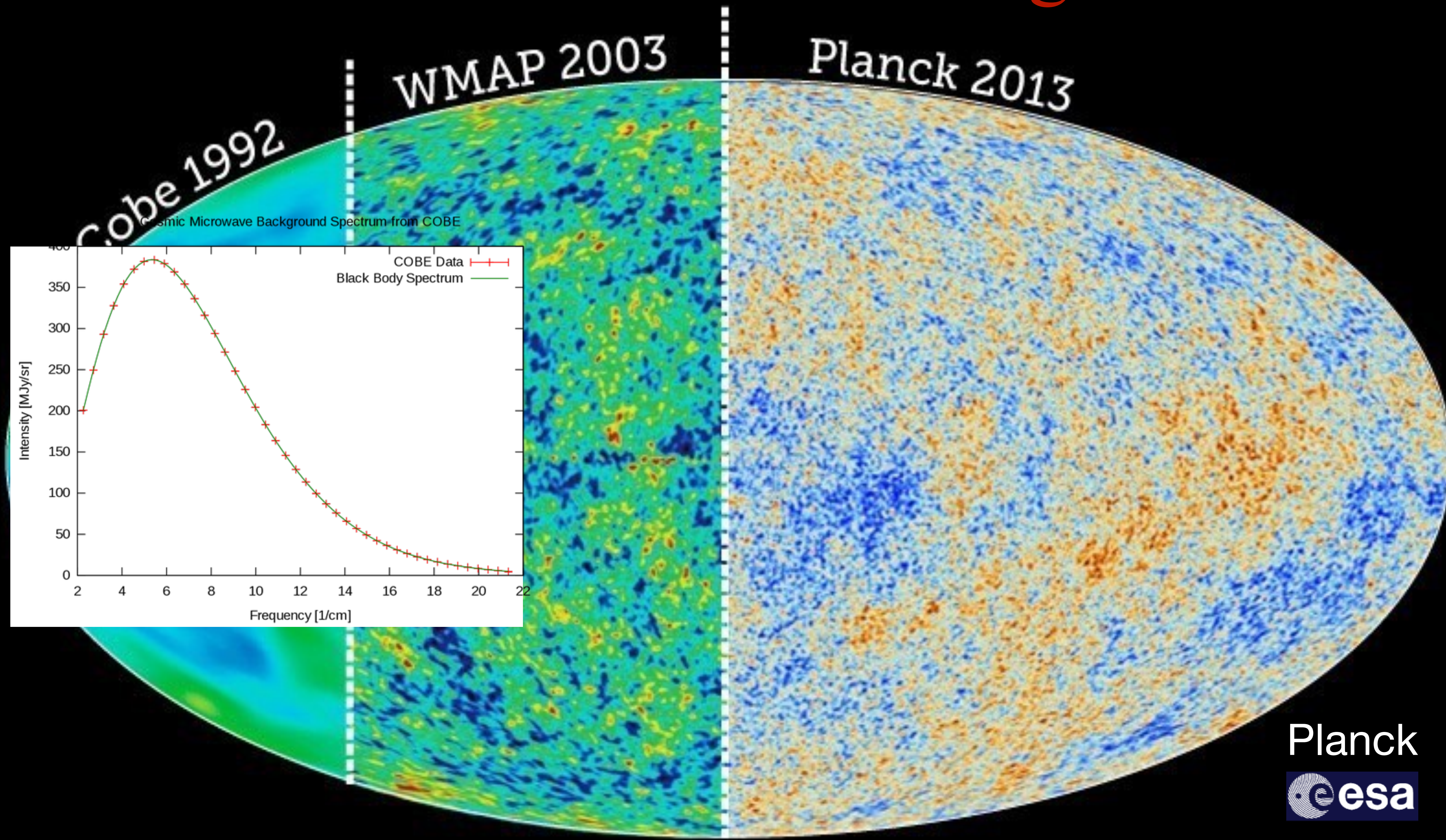
- CMB secondary anisotropies
- Photon-axion conversion inside halos
- Axion signal (temperature, polarization)
- Sensitivity projections

Cosmic Microwave Background



Planck
esa

Cosmic Microwave Background



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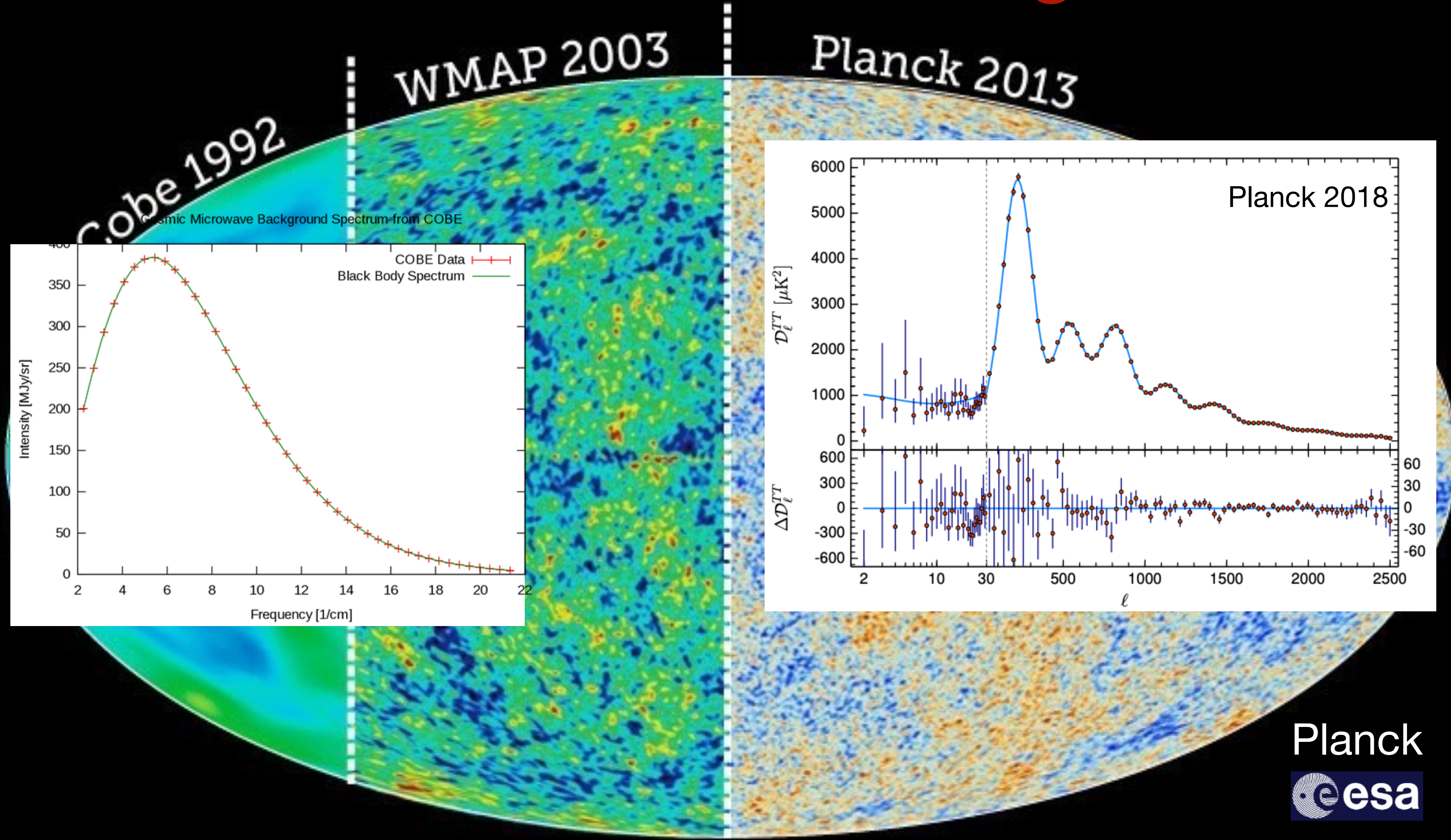

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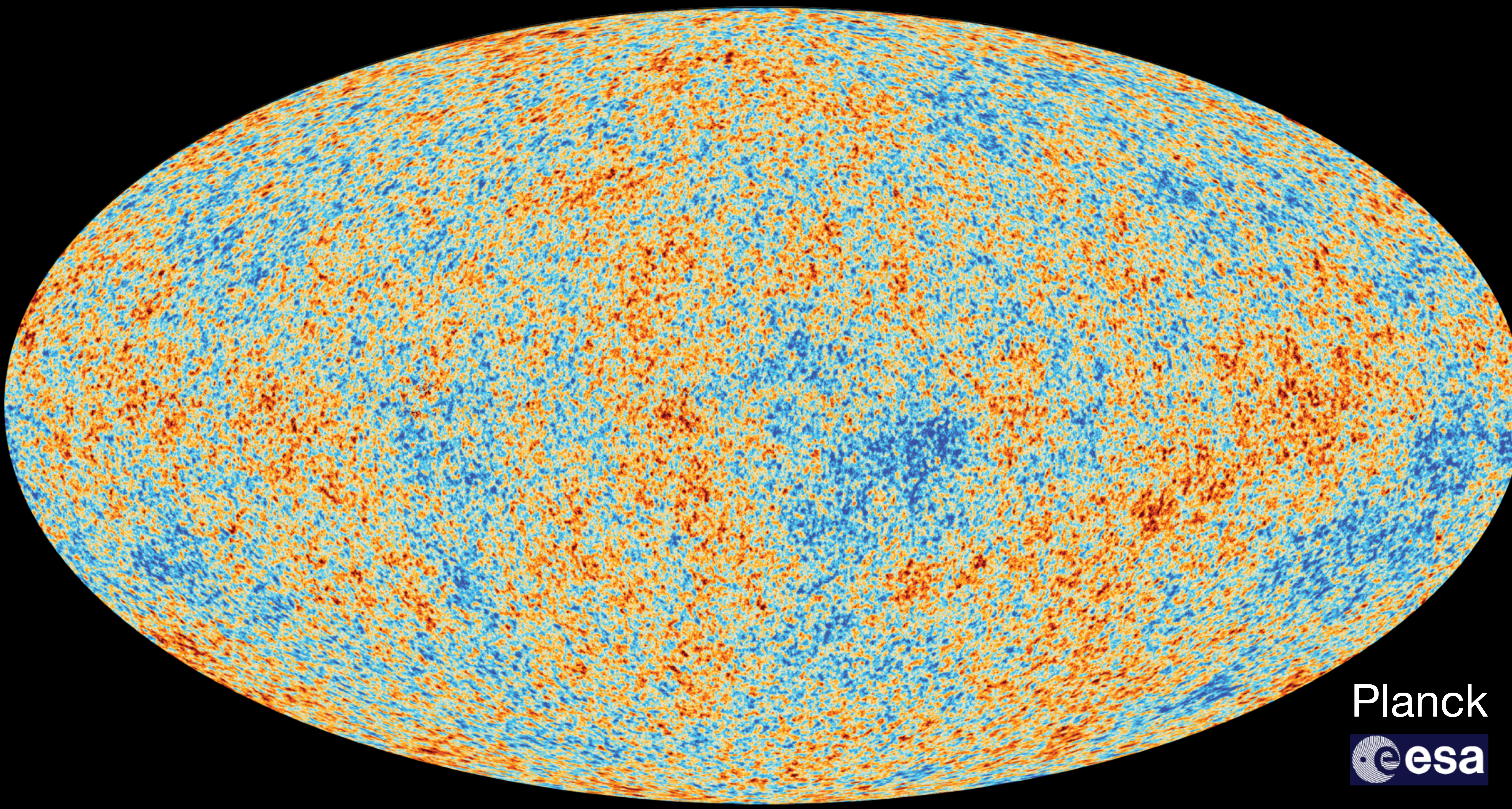
Primary CMB anisotropies



Planck

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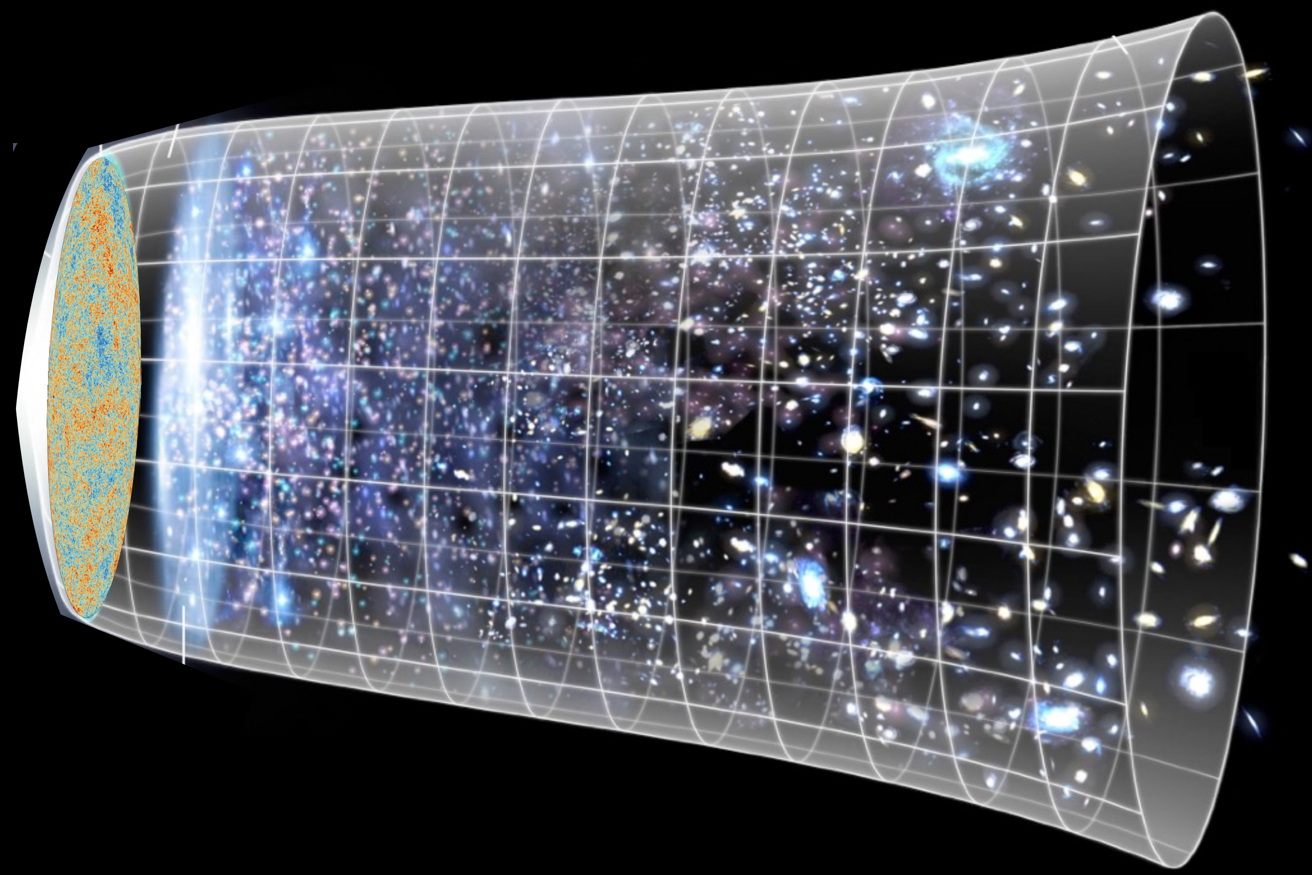
Secondary CMB anisotropies

Interactions with intervening structure ⟶ New anisotropies



Secondary CMB anisotropies

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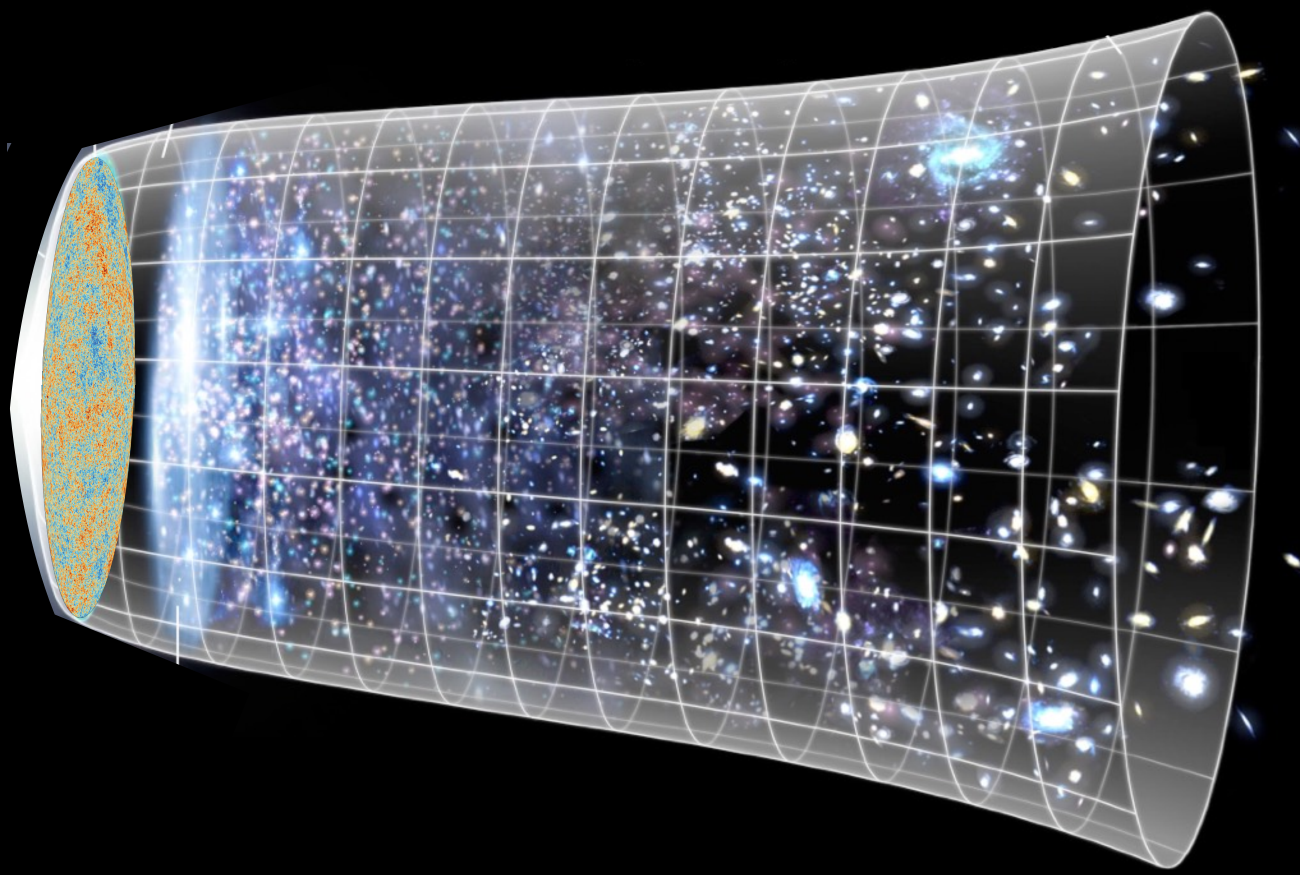
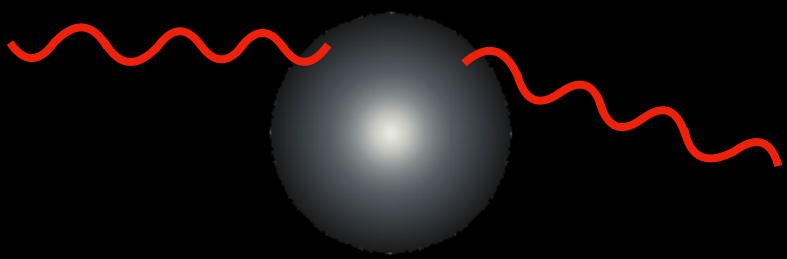


Standard Model effects:

- Lensing



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Secondary CMB anisotropies

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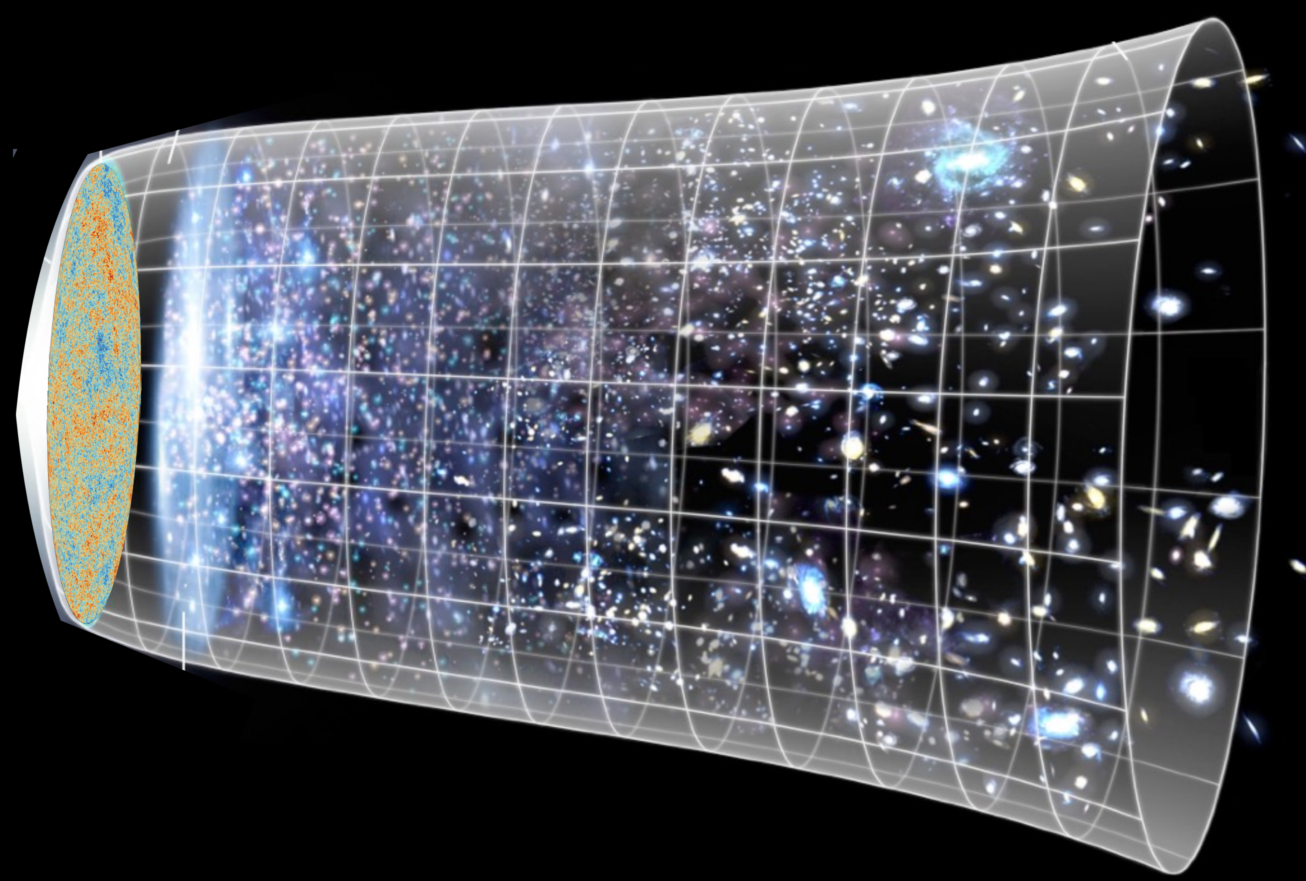

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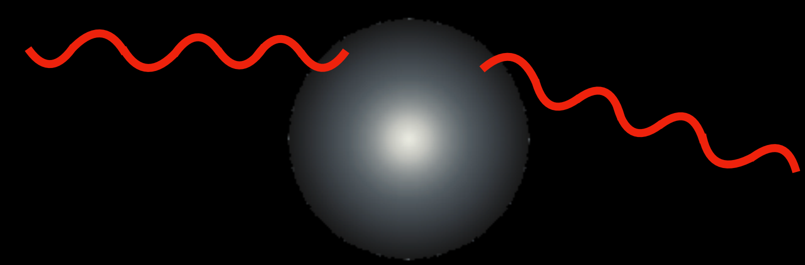
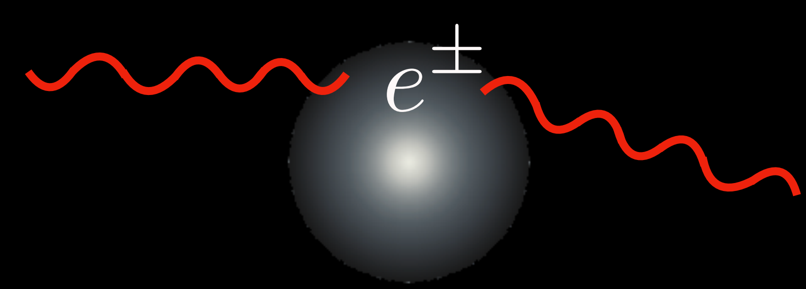


- Screening



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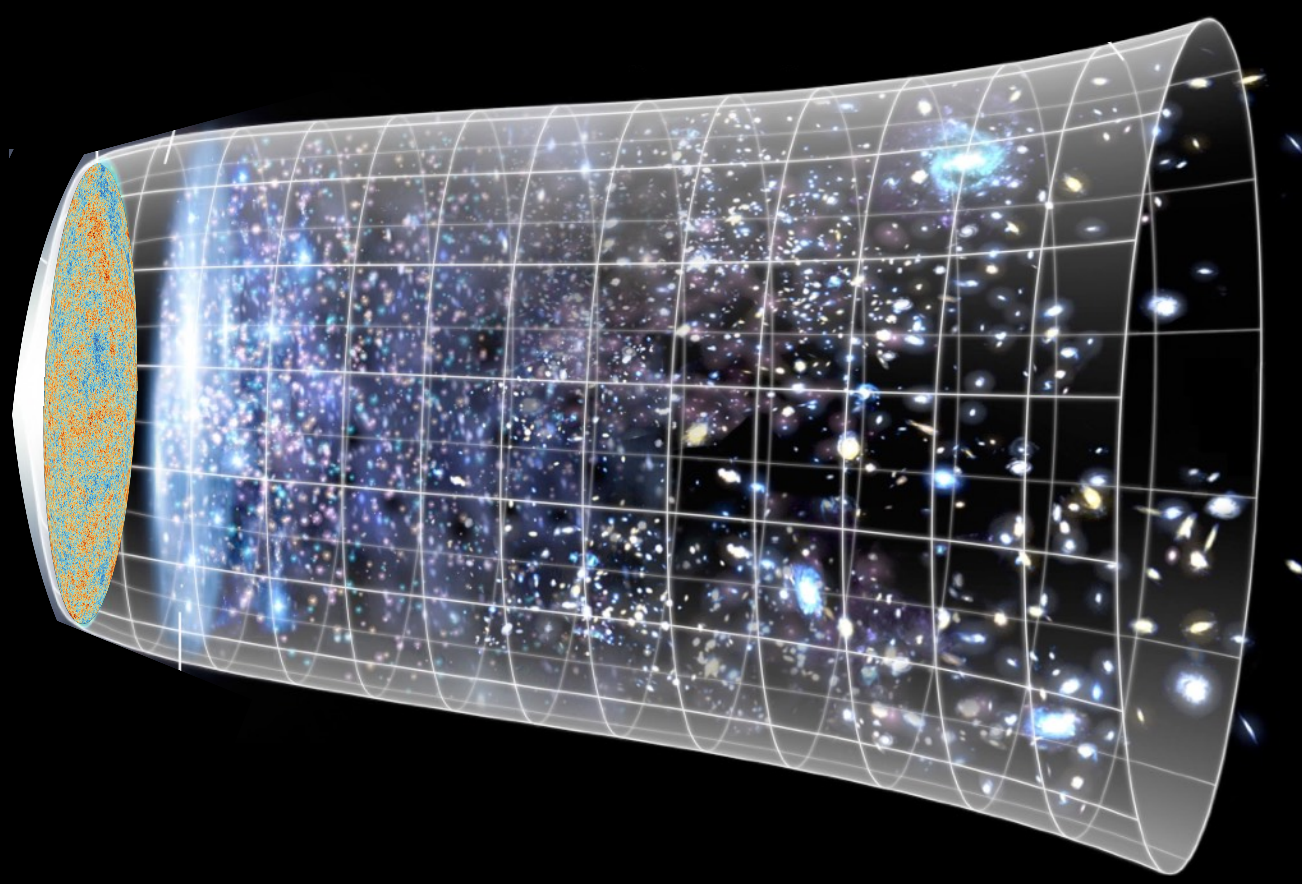

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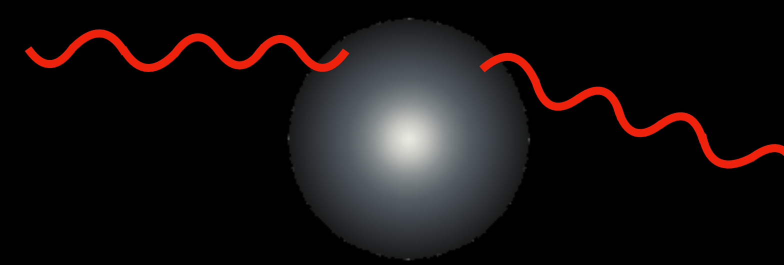
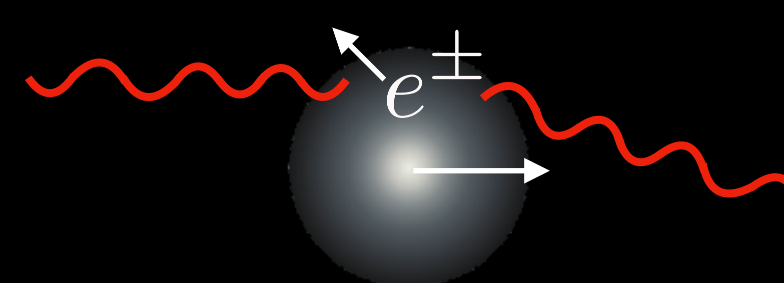
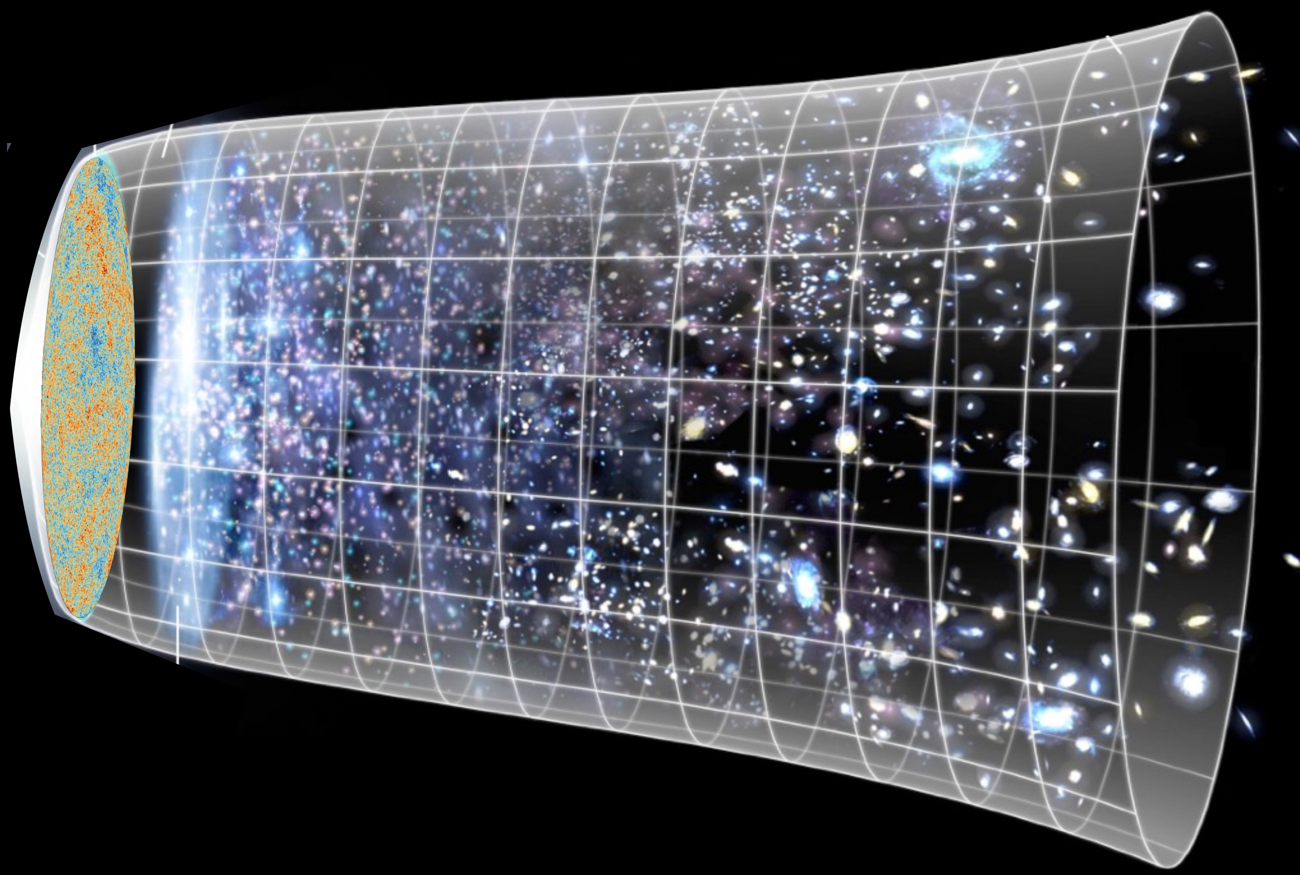


- Screening
- Sunyaev Zel'dovich effects



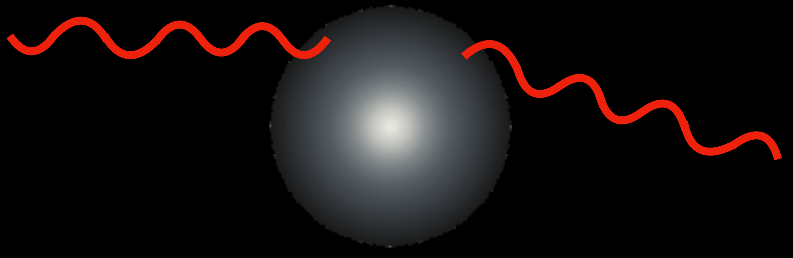
Secondary CMB anisotropies

Interactions with intervening structure → New anisotropies



Standard Model effects:

- Lensing ✓



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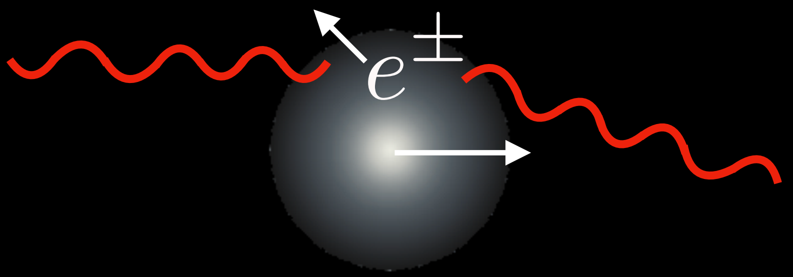

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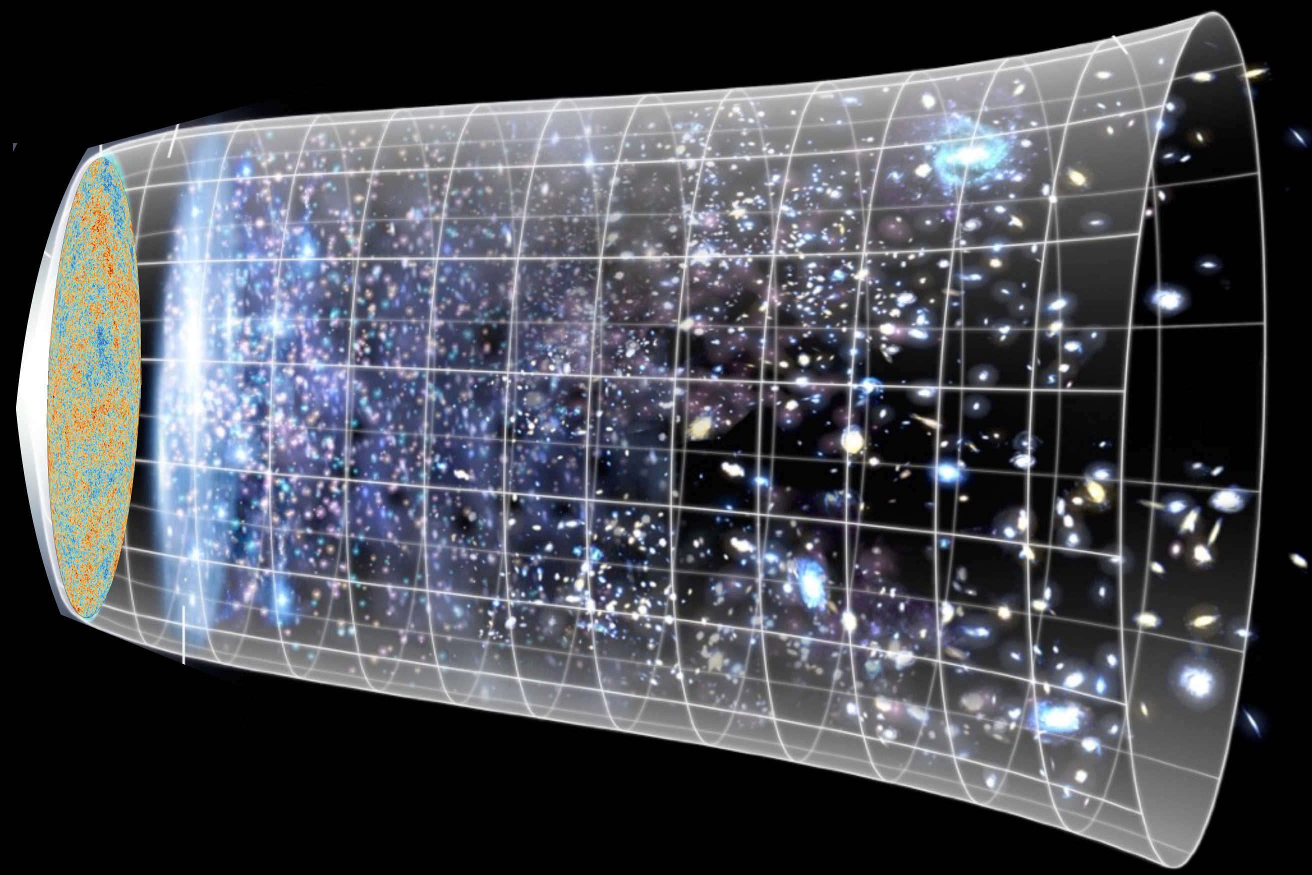
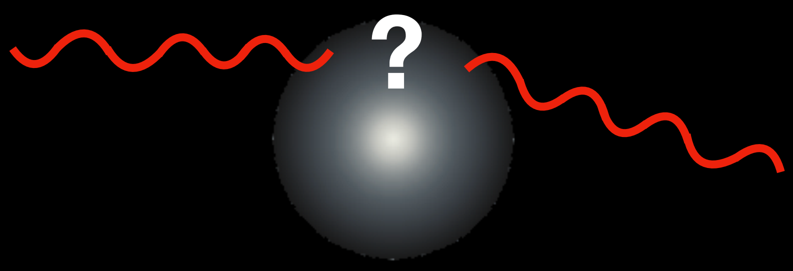
Secondary CMB anisotropies

Interactions with intervening structure → New anisotropies

What about New Physics?





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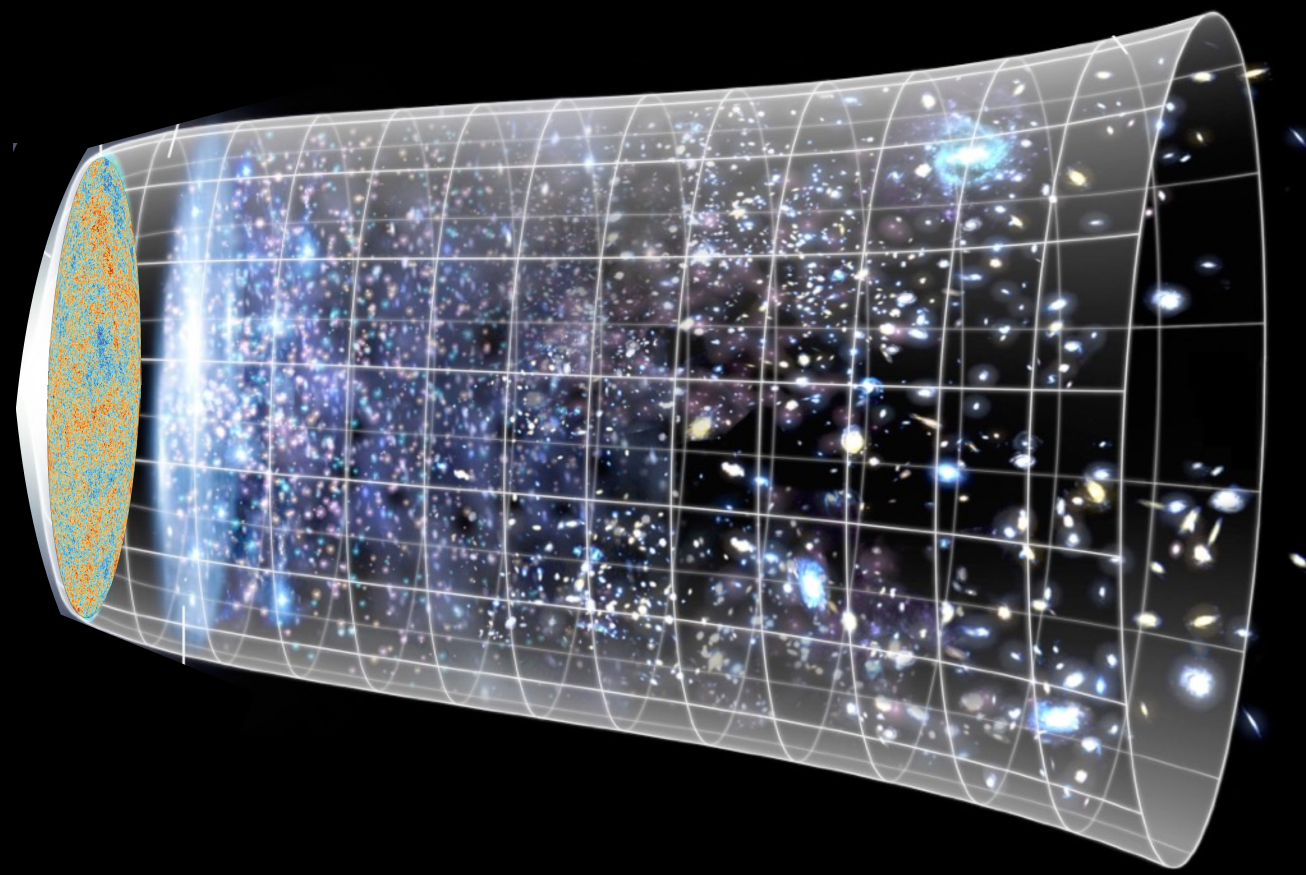

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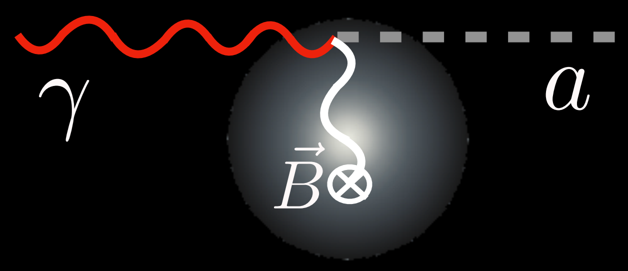
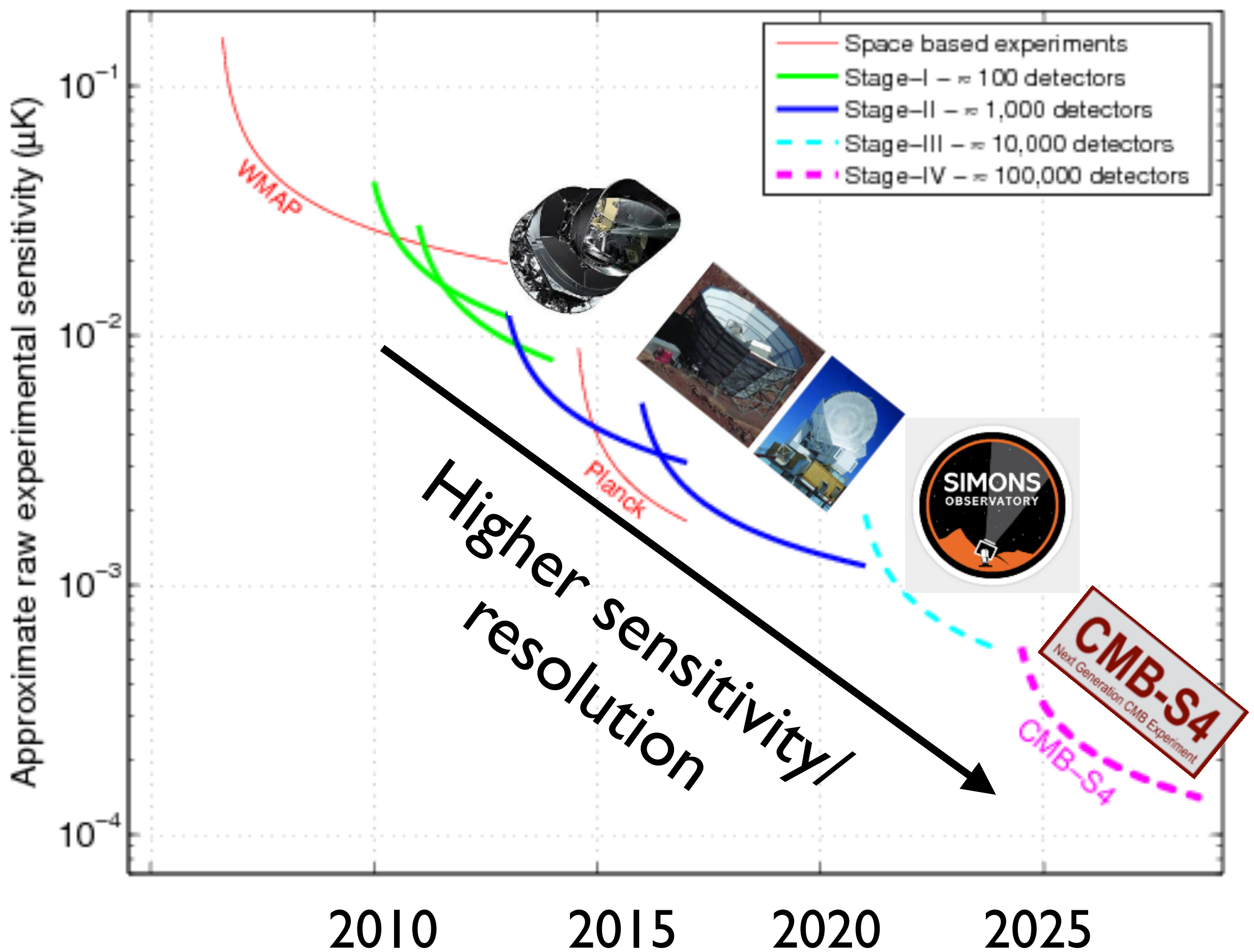


This talk: photon to axion conversion inside halos

...

Why CMB secondaries?

Future CMB experiments will have better sensitivity at high resolution



Credit: Matt Johnson

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Photon-axion conversion

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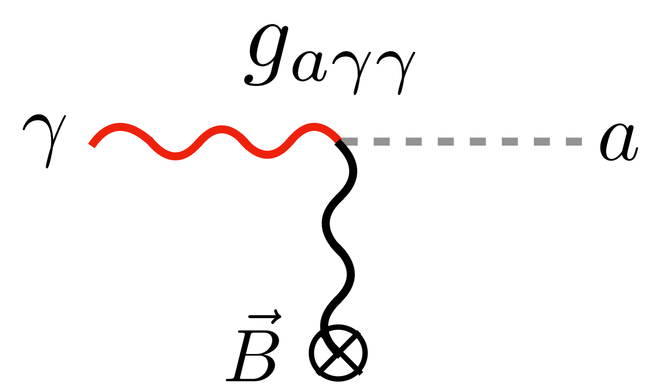
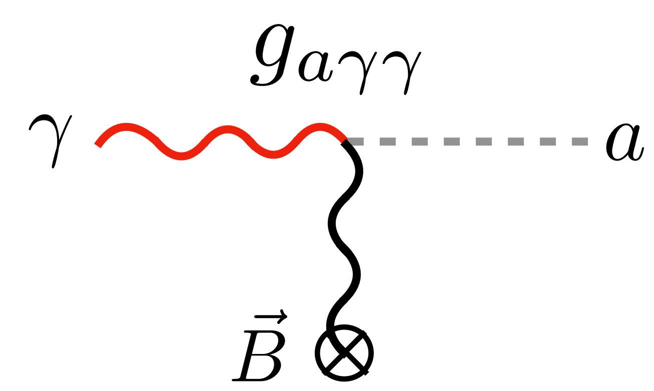


In an external *B* field, we can have photon-axion oscillations
(like neutrino oscillations)

G. Raffelt and L. Stodolsky, 1988
C. Deffayet, D. Harari, J.P. Uzan, and M. Zaldarriaga, 2002
A. Mirizzi, G. Raffelt, and P. D. Serpico, 2005

Photon-axion resonant conversion

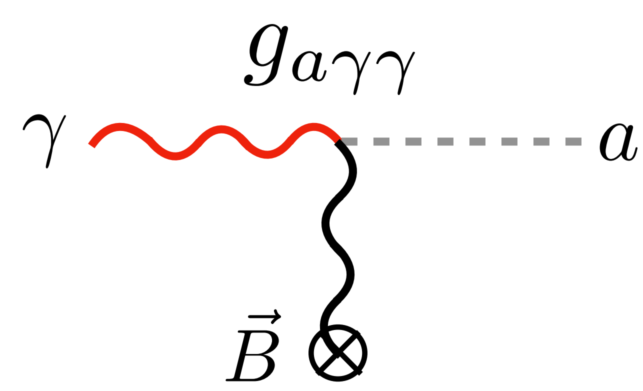
Like for neutrinos,
medium effects can be important!



Photon plasma mass: $\omega_{\rm pl}^2 = \frac{e^2 n_e}{m_e}$

S. J. Parke, 1986
A. Mirizzi, J. Redondo, and G. Sigl, 2009
H. Tashiro, J. Silk, and D. J. E. Marsh, 2013

Photon-axion resonant conversion



Like for neutrinos,
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Photon plasma mass: $\omega_{\rm pl}^2 = \dfrac{e^2 n_e}{m_e}$

$$\omega_{\rm pl} = m_a$$

resonance

$$P^{\rm res}_{\gamma\to a} = g^2_{a\gamma\gamma} B^2 \frac{\pi\omega}{m_a^2} \left| \frac{d\ln\omega_{\rm pl}^2}{dt} \right|^{-1}_{t_{\rm res}}$$

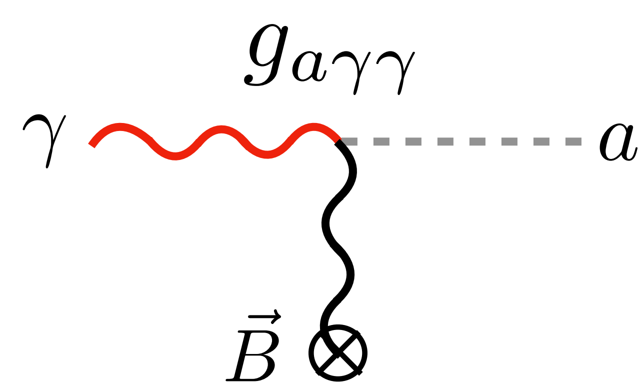
Slope of the number density profile

S. J. Parke, 1986
A. Mirizzi, J. Redondo, and G. Sigl, 2009
H. Tashiro, J. Silk, and D. J. E. Marsh, 2013

Photon-axion resonant conversion

This talk:

Inside DM halos



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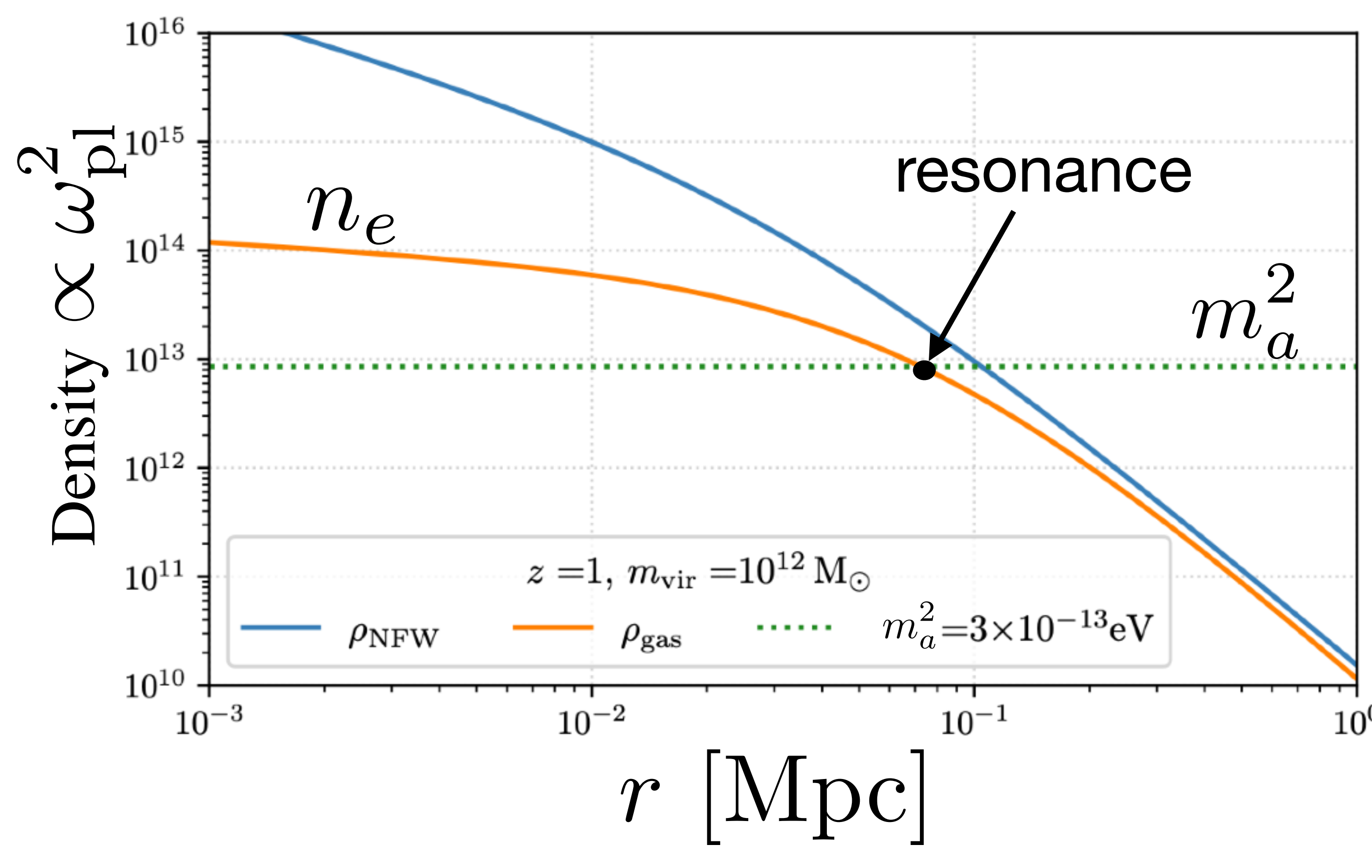

Navarro, Frenk, and White, 1996
N. Battaglia, 2016

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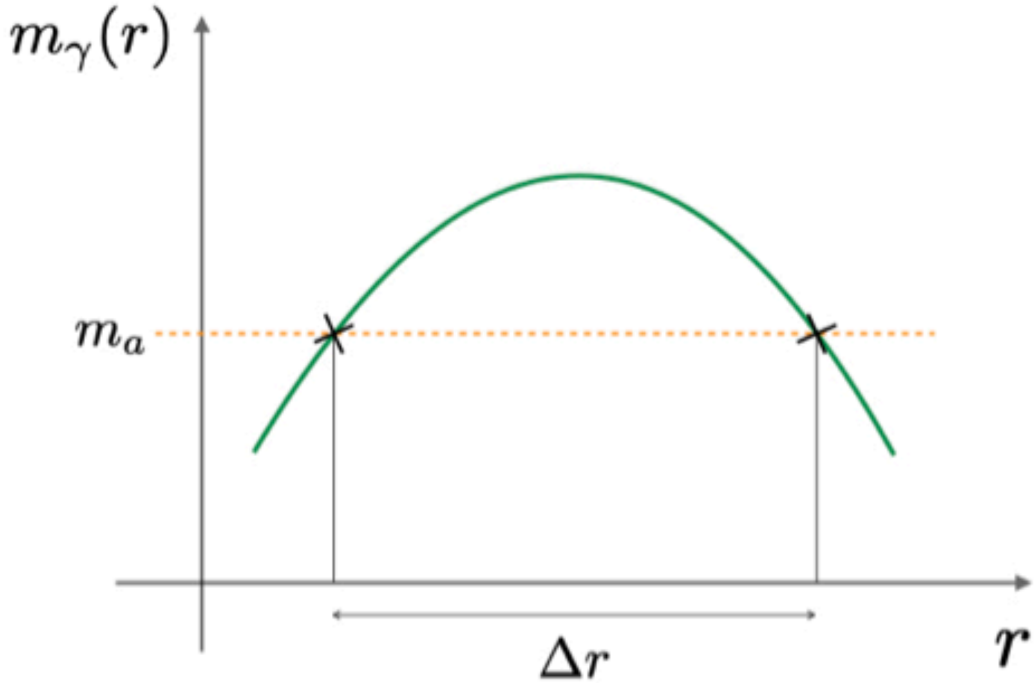
Resonant conversion in halos



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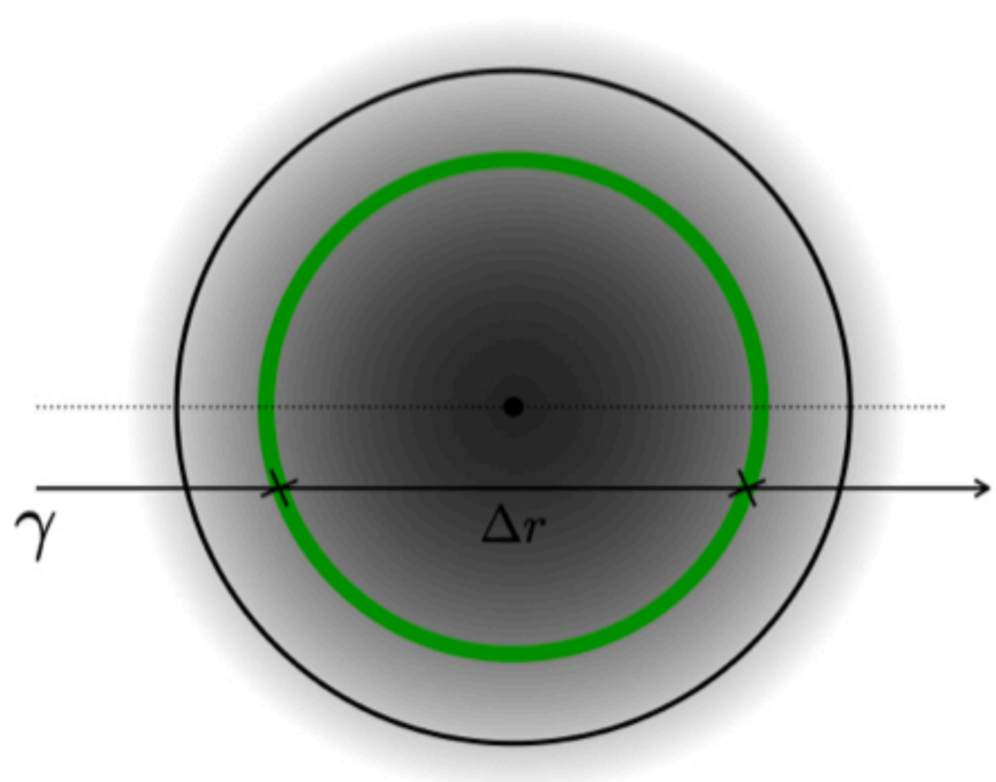

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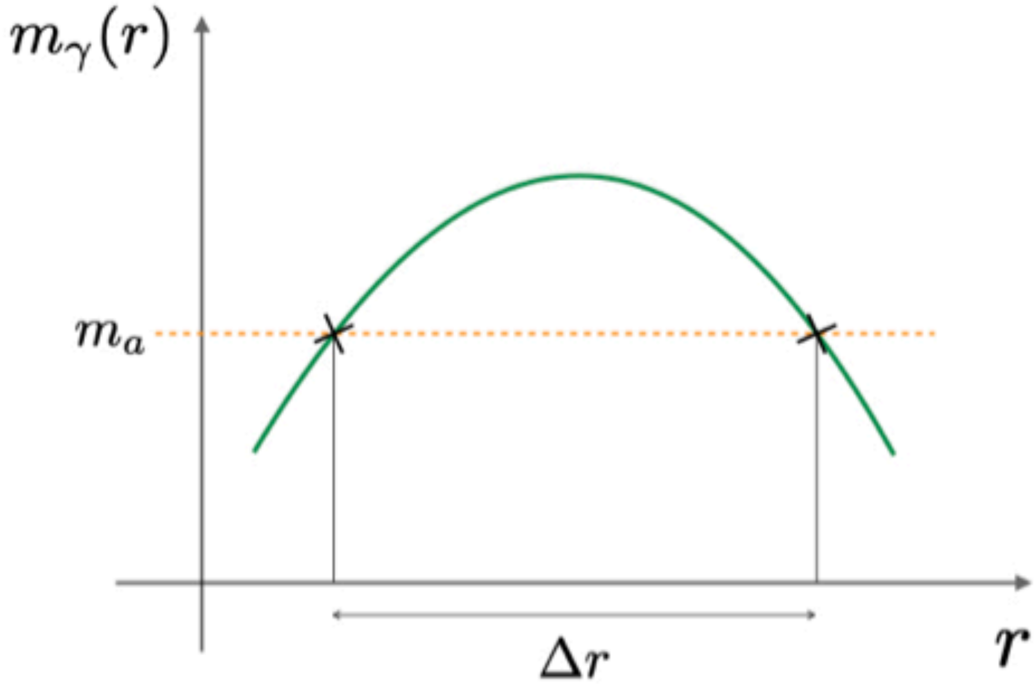

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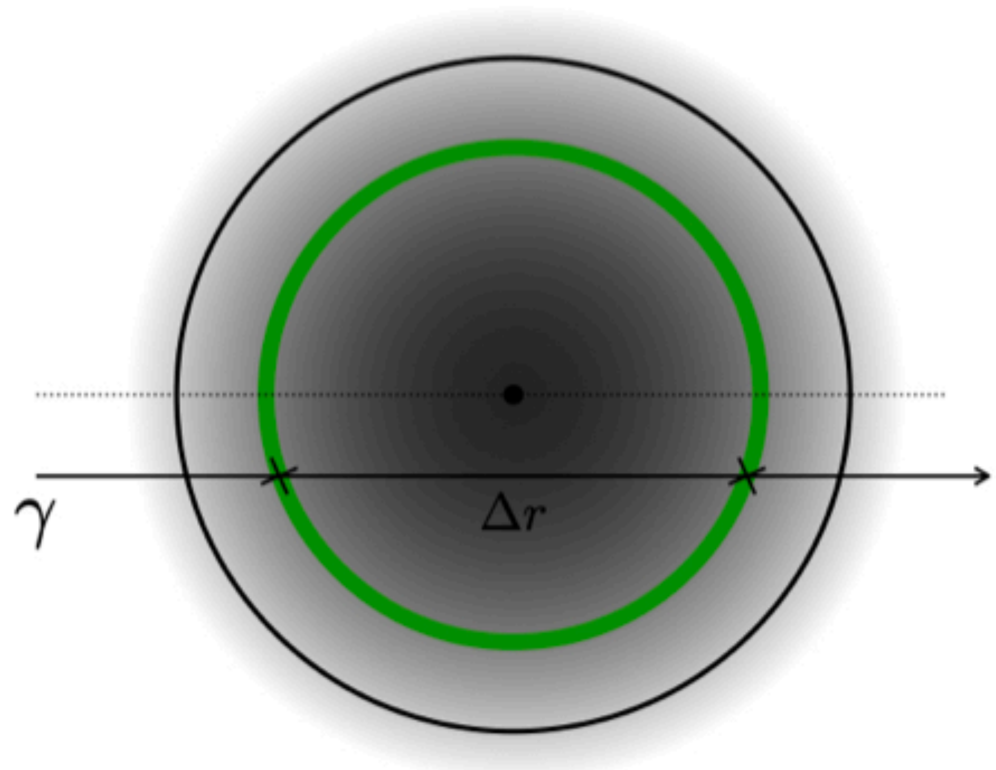
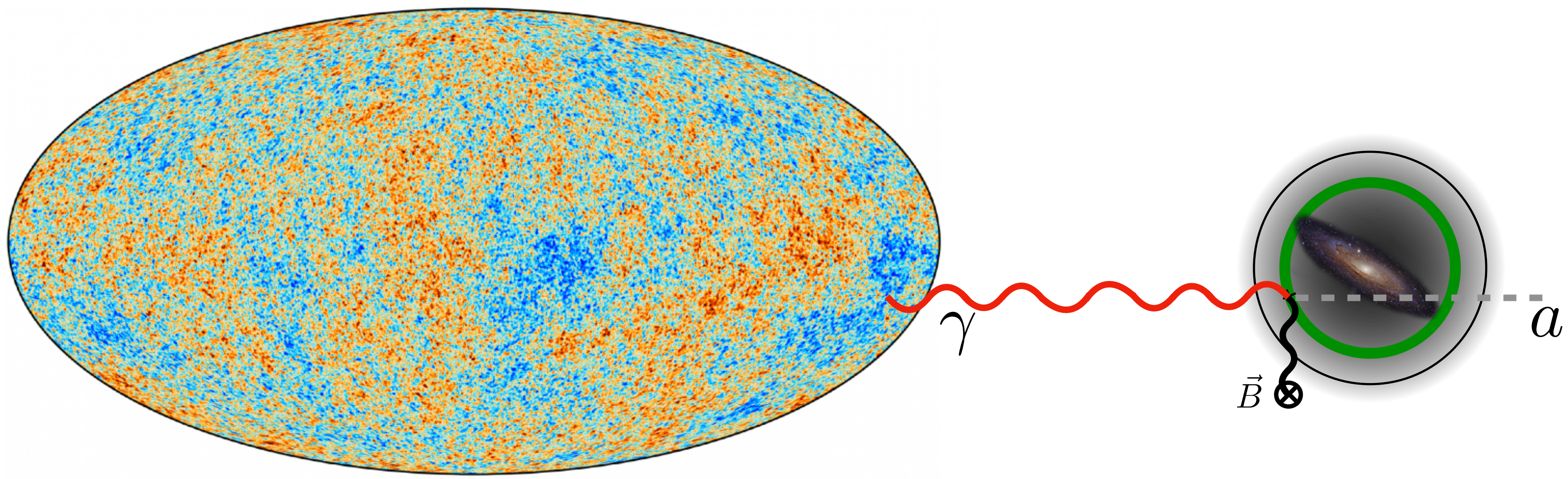


Depends on:

- halo density profile
- frequency of the photon

CMB photon disappearance

$$P^{\rm res}_{\gamma\to a} = g^2_{a\gamma\gamma} B^2 \frac{\pi\omega}{m_a^2} \left| \frac{d\ln\omega^2_{\rm pl}}{dt} \right|^{-1}_{t_{\rm res}}$$



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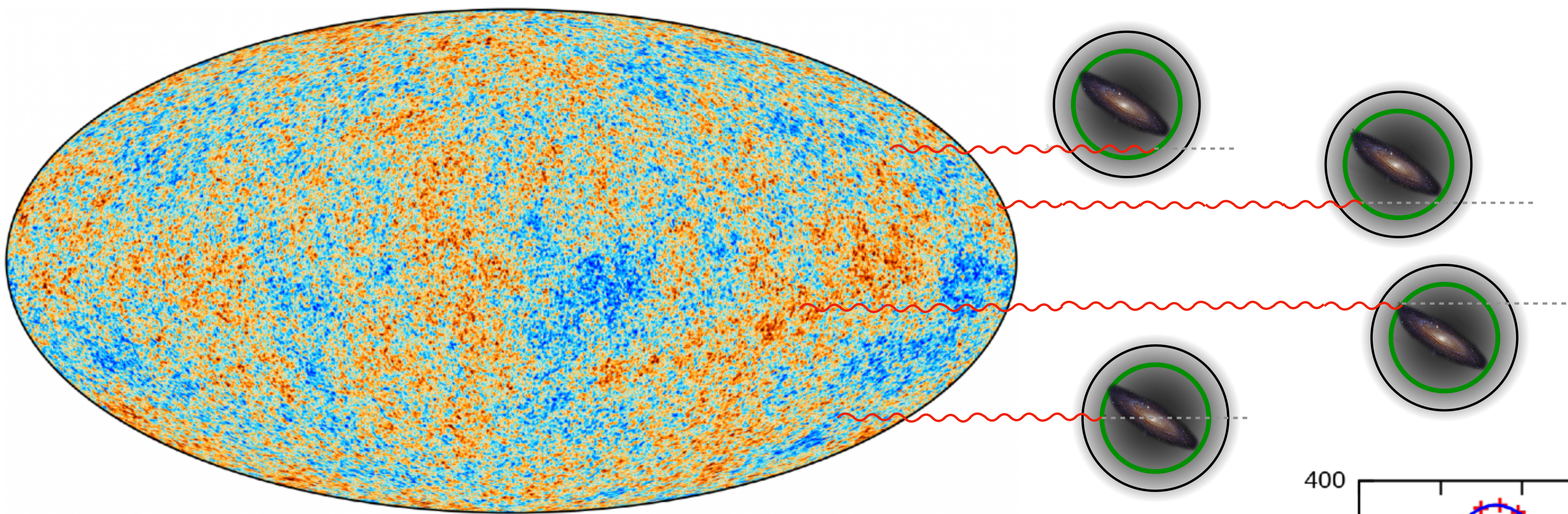

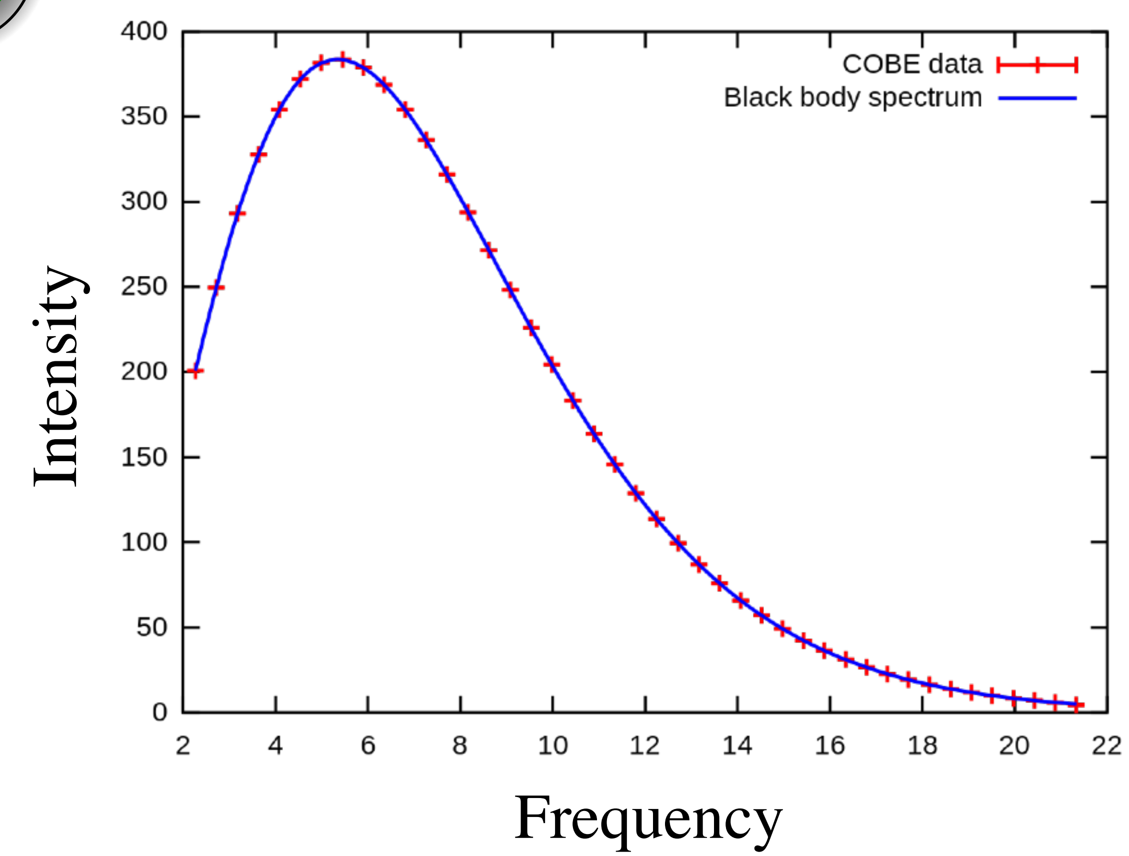

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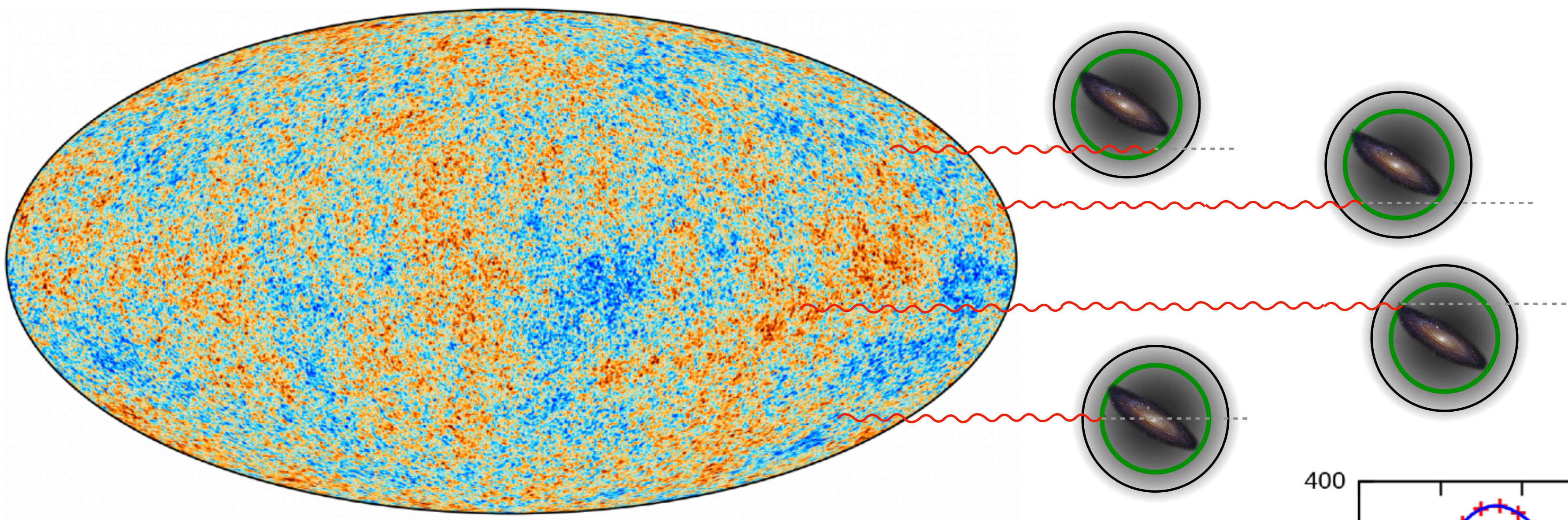
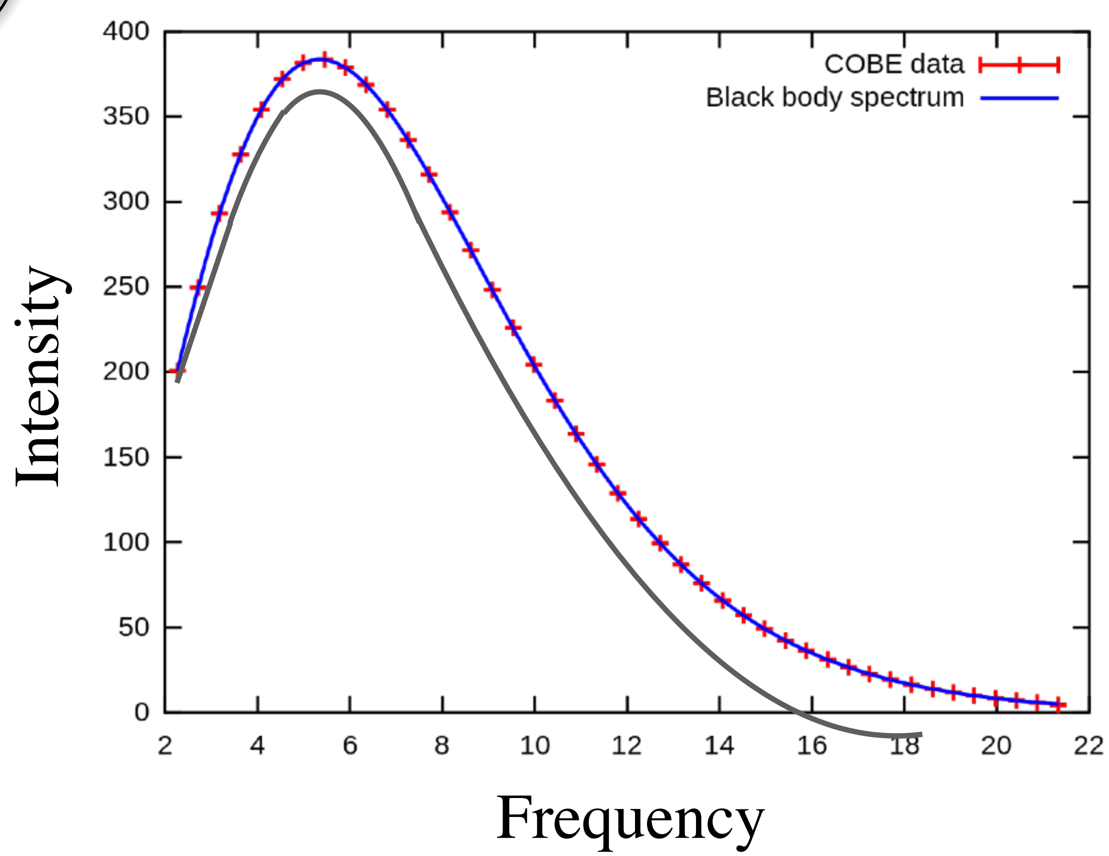


Distortion of the black body spectrum



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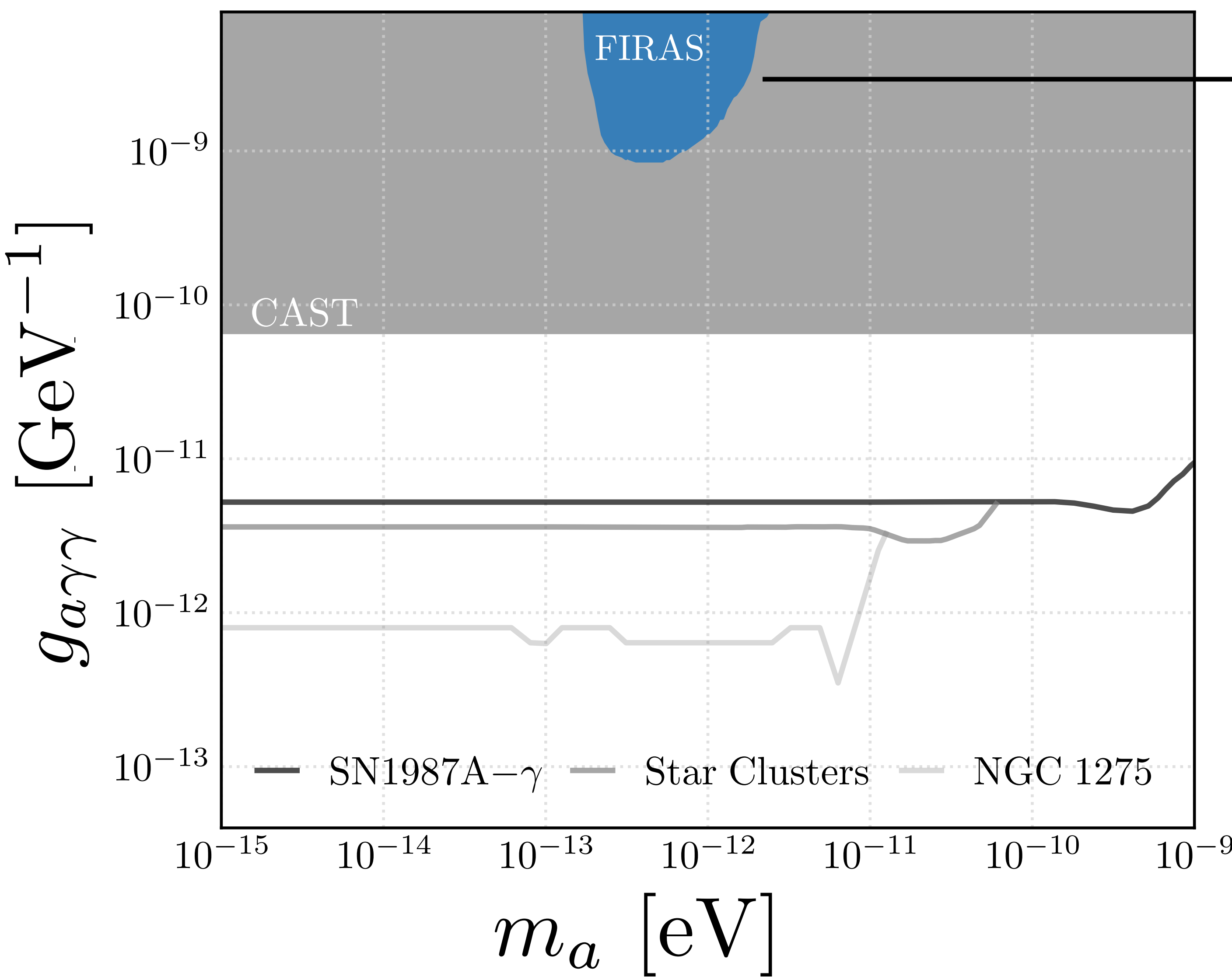
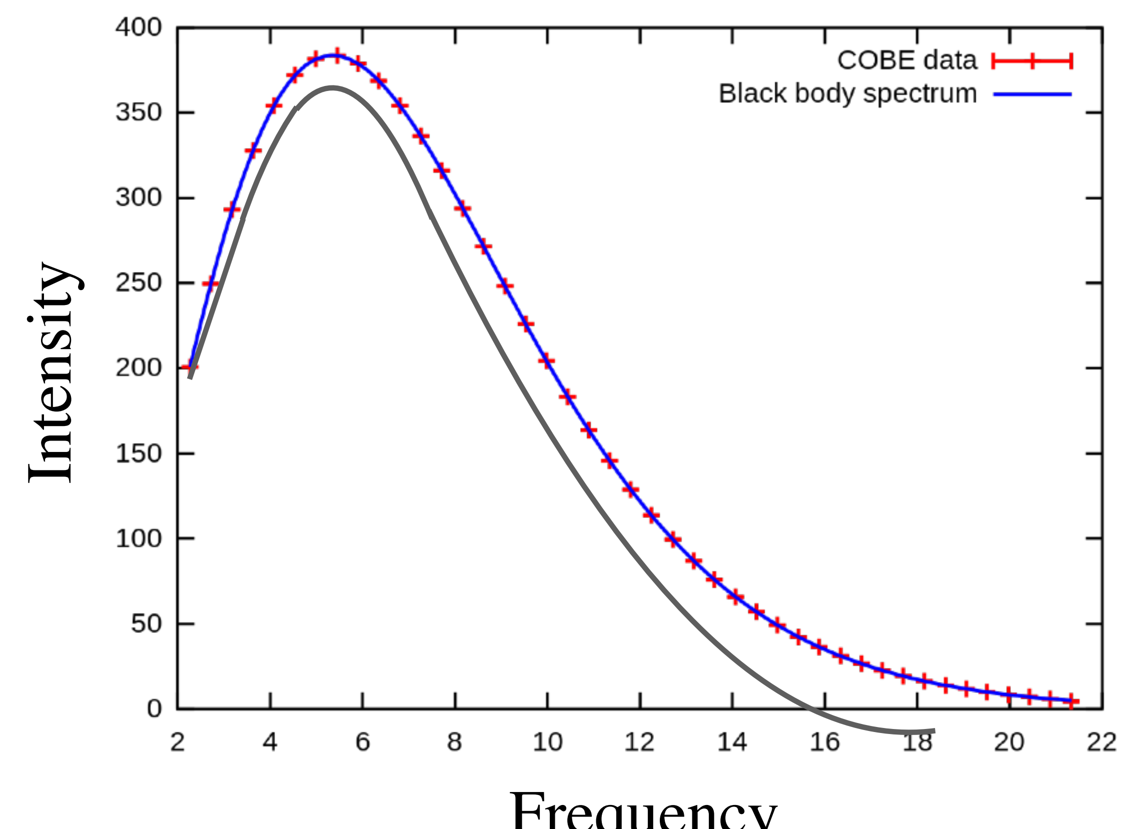
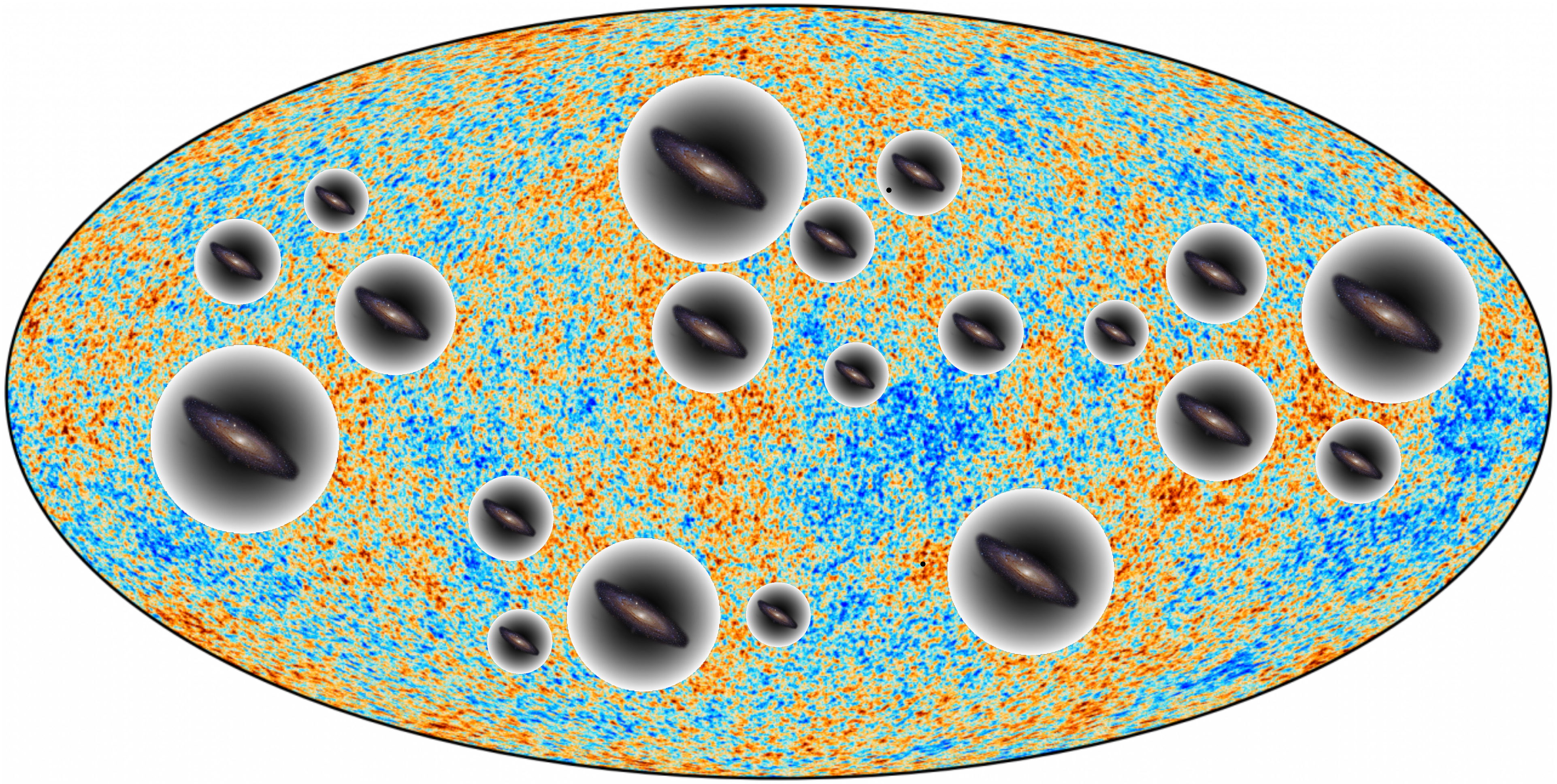


COBE/Firas constraint from spectral distortion



Anisotropic screening

The signal is not isotropic!



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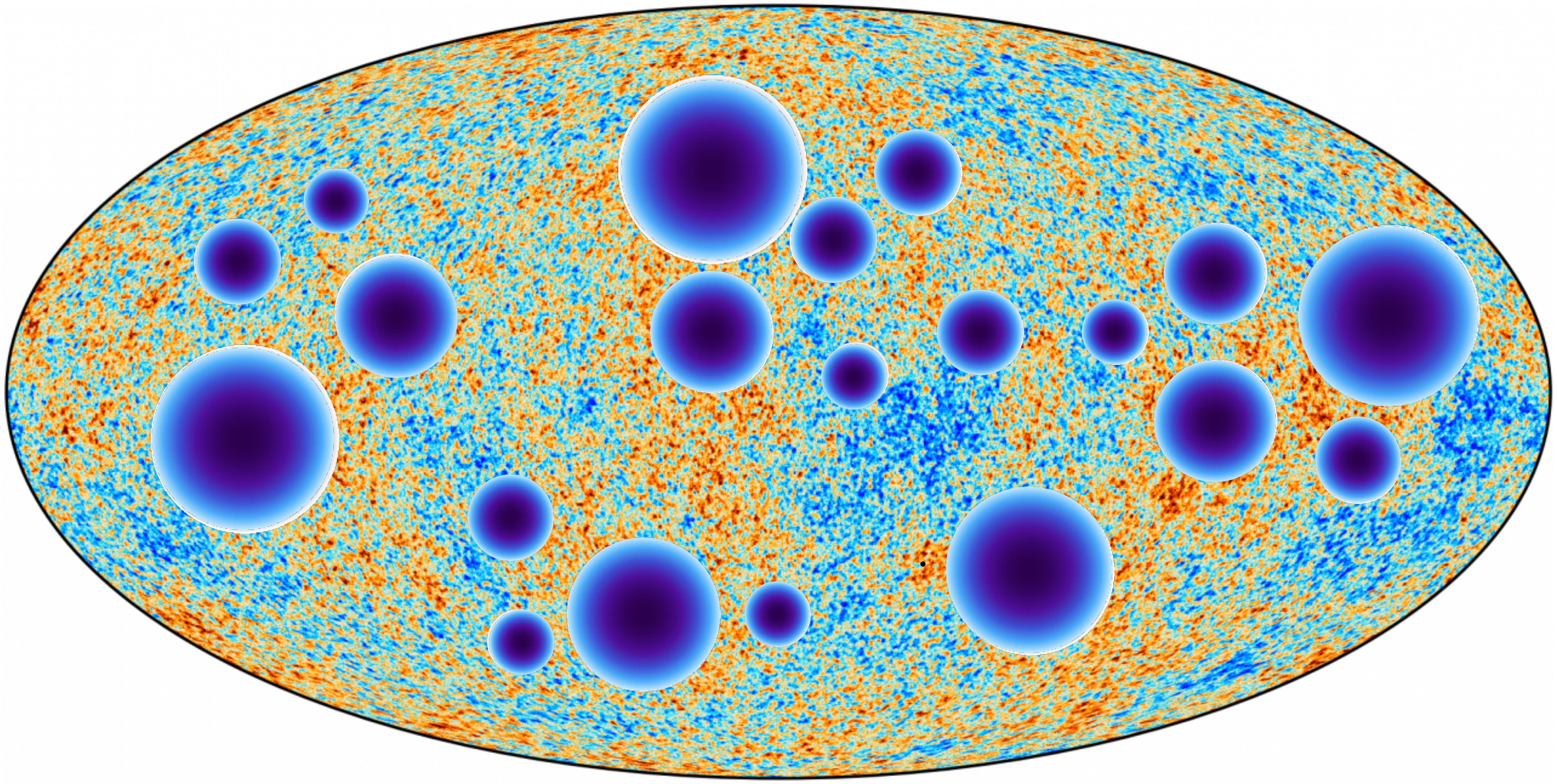

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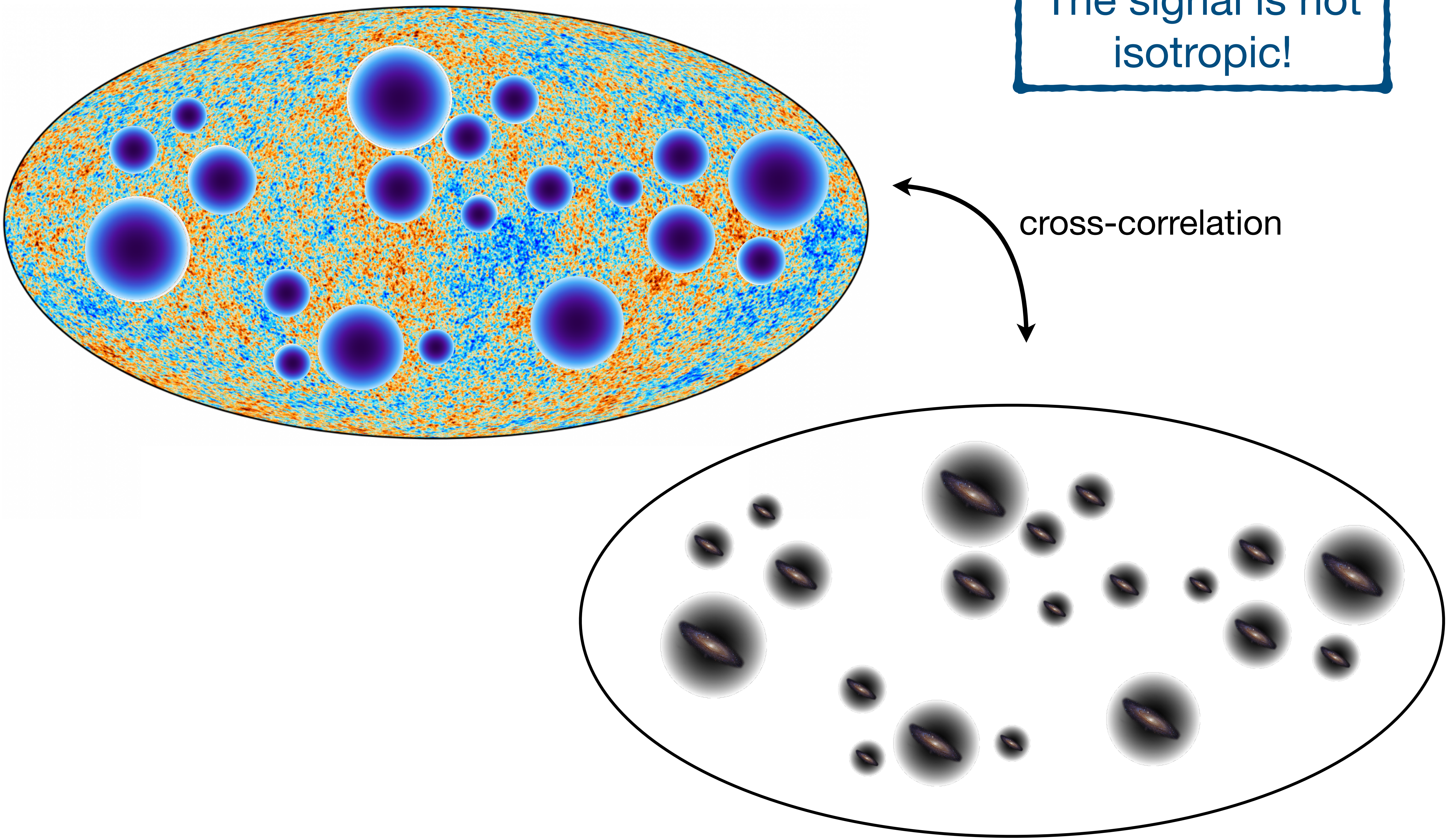

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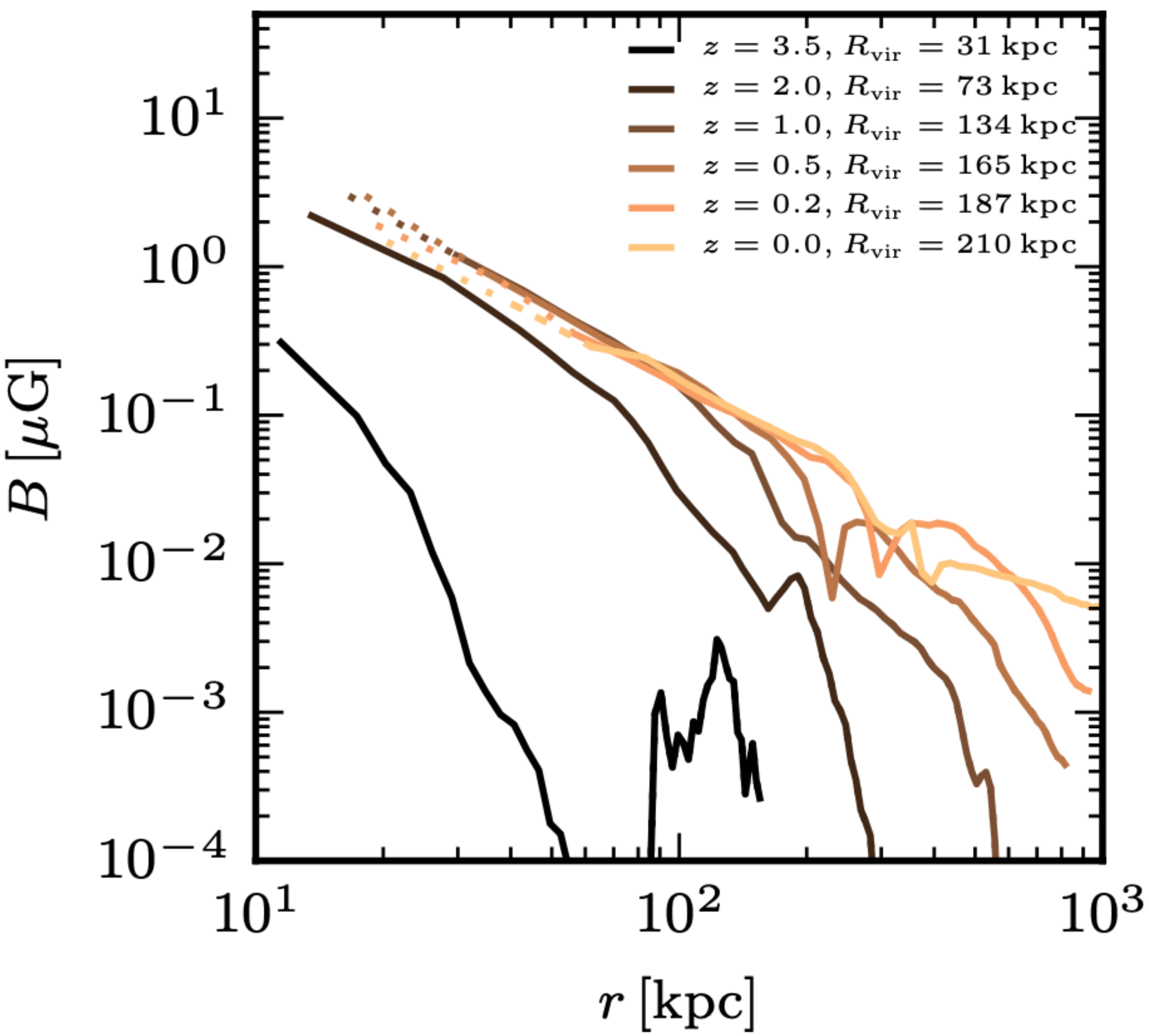
Halo B field

Auriga: high resolution cosmological magnetohydrodynamical simulations

B field profile



R. Pakmor et al.,
Magnetising the circumgalactic medium of disk galaxies
MNRAS, 498, 3, 3125 (2020), arXiv:1911.11163

$$M_{\rm halo} = 10^{12}\ M_\odot$$

R. Pakmor et al.,
Magnetic field amplification in cosmological zoom simulations from dwarf galaxies to galaxy groups
arXiv:2309.13104

$$10^{10}\ M_\odot < M_{\rm halo} < 10^{13}\ M_\odot$$

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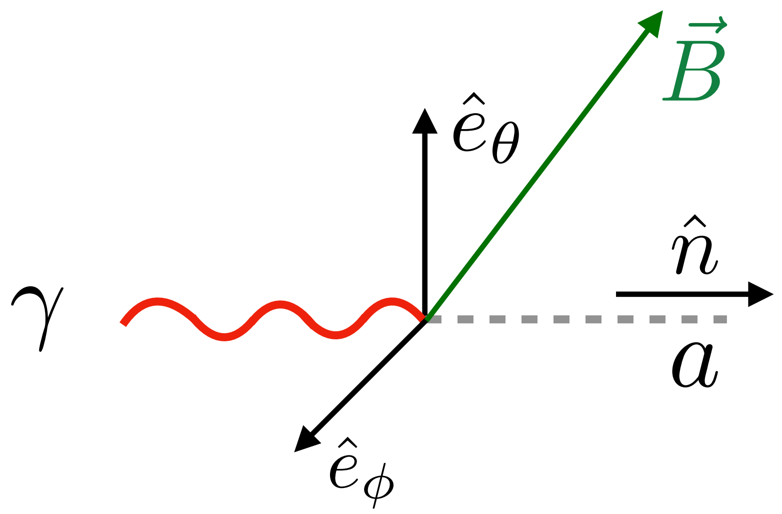
Axion screening



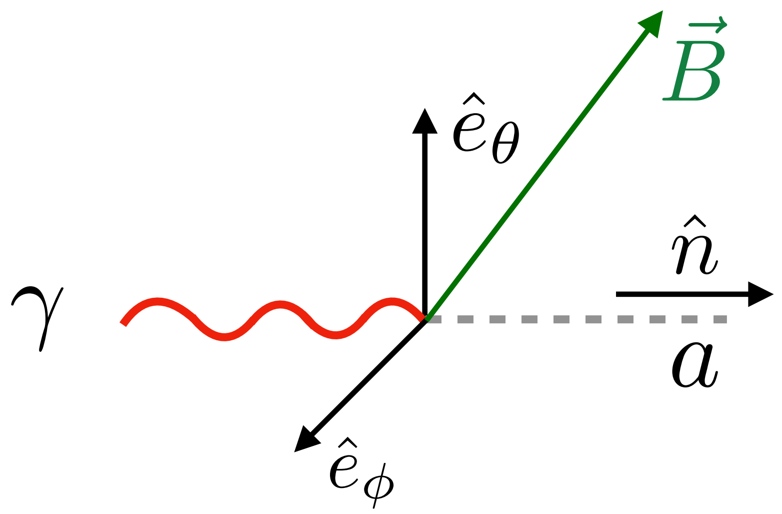
Only $B \perp$ to the line of sight
(angular momentum conservation)

Only B $||$ to the polarization direction
(CP conservation)

$$P_{\gamma\to a} \propto g_{a\gamma\gamma}^2 B^2$$

Intensity $$I_{\rm axion} = -I_{\rm CMB} P_{\gamma\to a}$$

Axion screening



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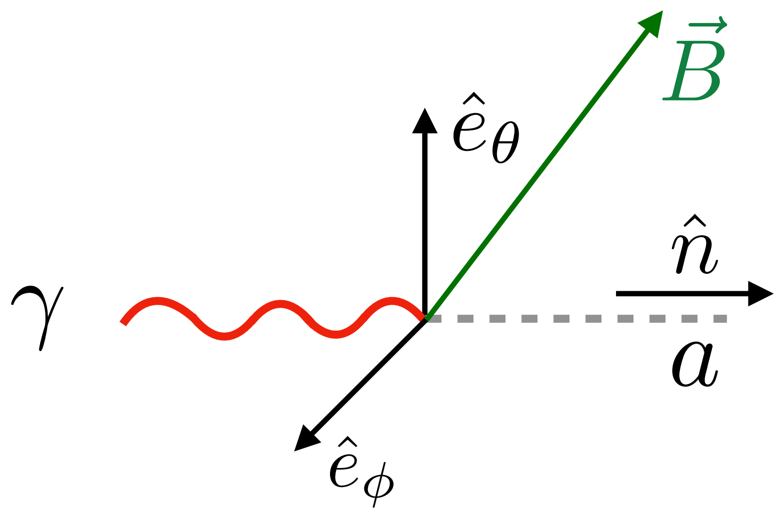
Axion screening



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Intensity
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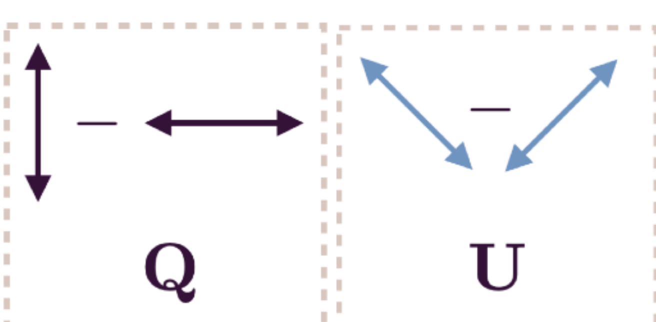
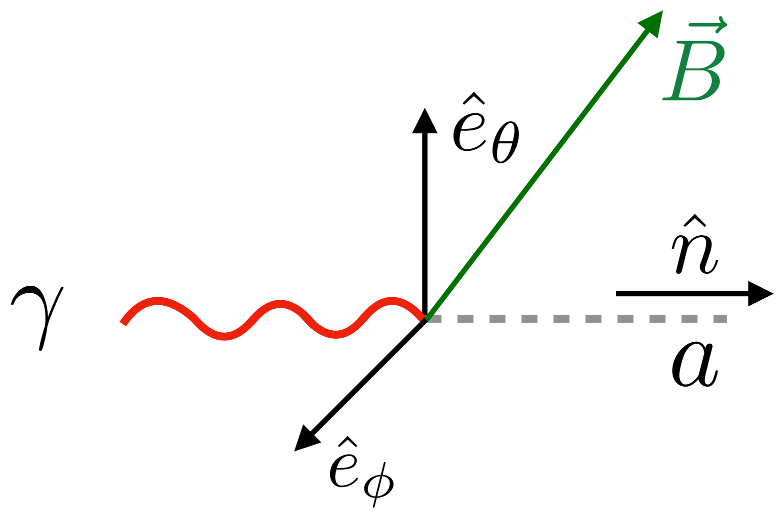
Polarization
$$Q_{\rm axion} \propto -I_{\rm CMB} \frac{g_{a\gamma\gamma}^2 (B_\theta^2 - B_\phi^2)}{2}$$

$$U_{\rm axion} \propto -I_{\rm CMB} g_{a\gamma\gamma}^2 (B_\theta B_\phi)$$



Axion screening



Only $B \perp$ to the line of sight
(angular momentum conservation)

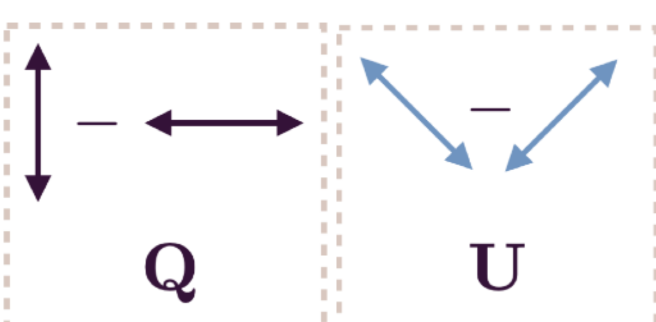
Only $B \,||$ to the polarization direction
(CP conservation)

$$P_{\gamma \to a} \propto g_{a\gamma\gamma}^2 B^2$$

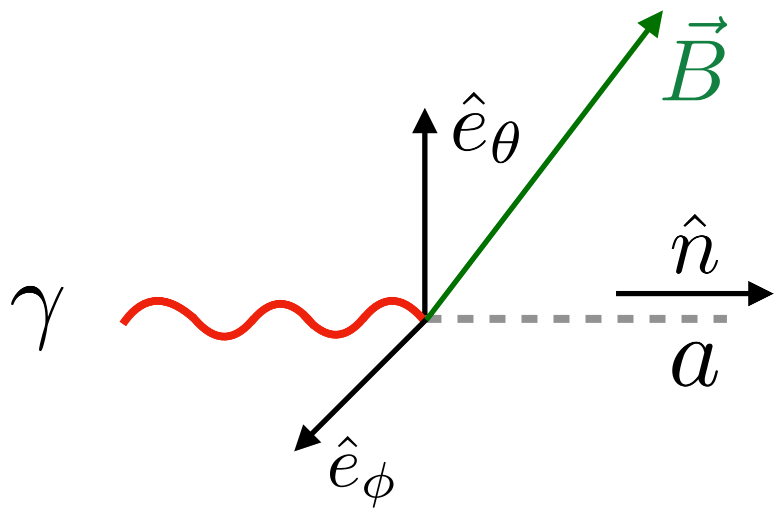
Temperature $$T_{\rm axion} \propto -\bar{T} \frac{g_{a\gamma\gamma}^2 (B_\theta^2 + B_\phi^2)}{2}$$

Polarization $$Q_{\rm axion} \propto -\bar{T} \frac{g_{a\gamma\gamma}^2 (B_\theta^2 - B_\phi^2)}{2}$$

$$U_{\rm axion} \propto -\bar{T} g_{a\gamma\gamma}^2 (B_\theta B_\phi)$$

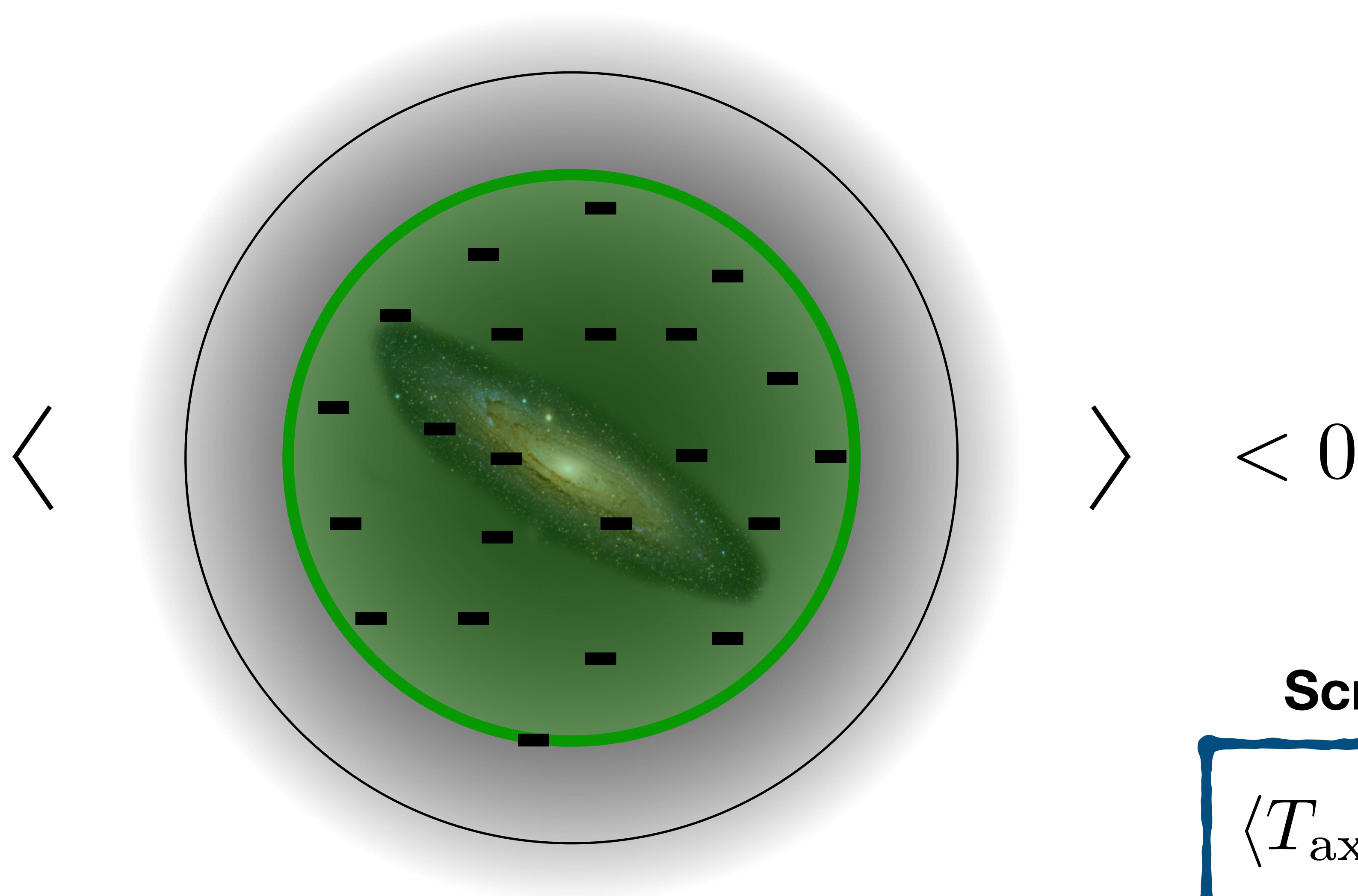


One-point function: temperature



Only $B \perp$ to the line of sight
(angular momentum conservation)

Only $B \parallel$ to the polarization direction
(CP conservation)



Screening

$\langle T_{\rm axion} \rangle < 0$

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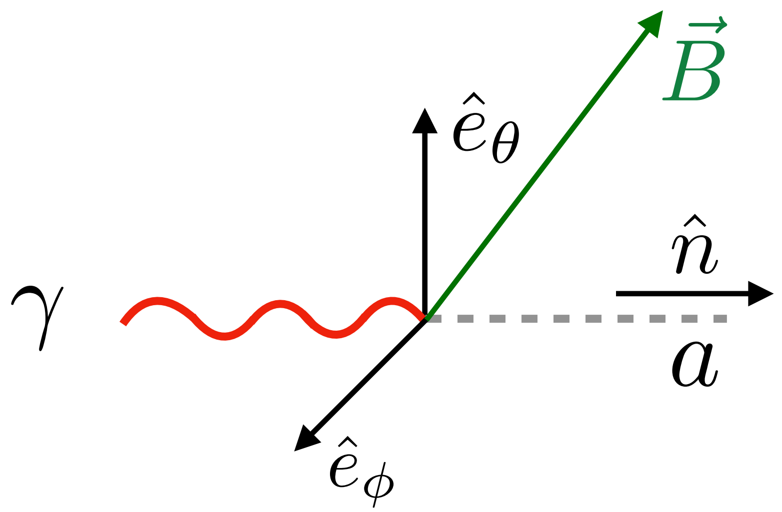
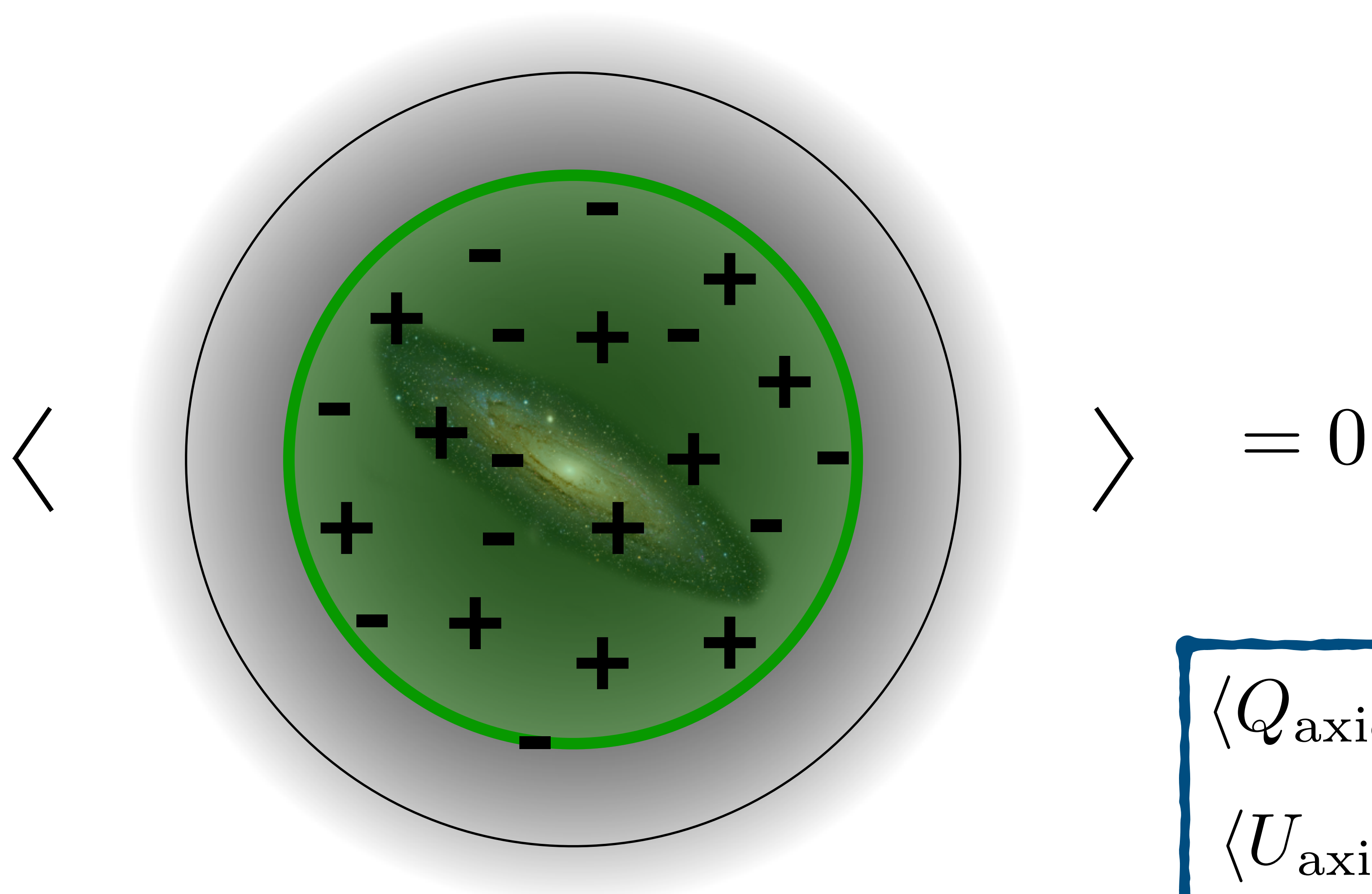
One-point function: polarization



Only $B \perp$ to the line of sight
(angular momentum conservation)

Only $B \,||\,$ to the polarization direction
(CP conservation)



$$\langle Q_{\mathrm{axion}} \rangle = 0$$

$$\langle U_{\mathrm{axion}} \rangle = 0$$

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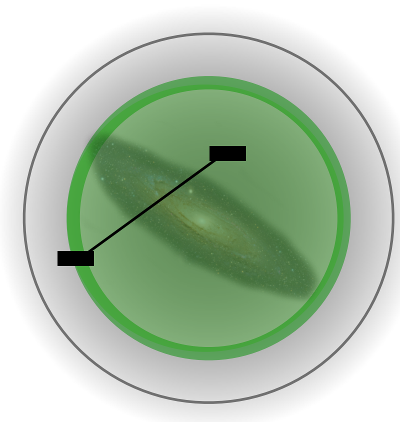
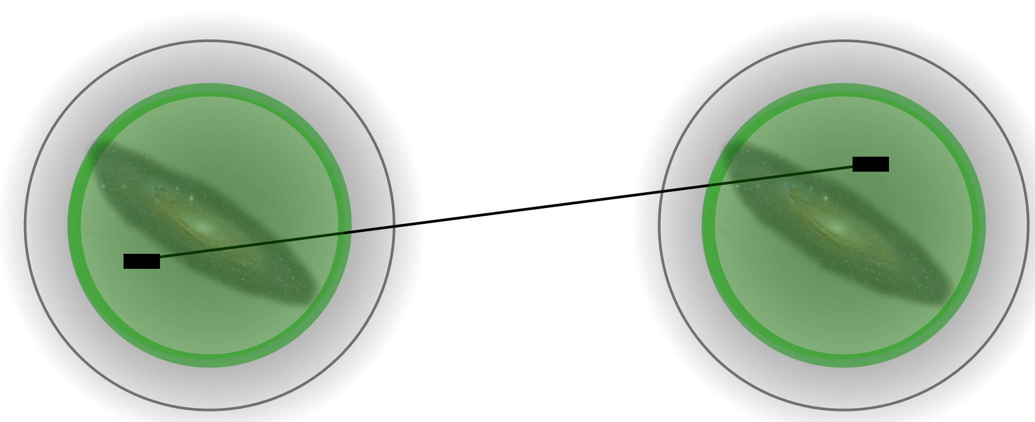
Two-point function: temperature

$$\langle T_{\rm axion}(\hat{n}_1) T_{\rm axion}(\hat{n}_2)\rangle \propto g_{a\gamma\gamma}^4 B^4 \bar{T}^2$$

1-halo term $\langle$  $\rangle \neq 0$ **Small scale** (halo shape)

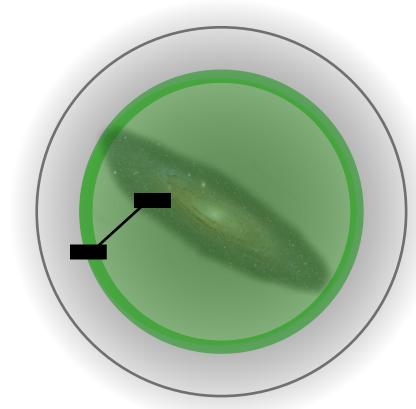
2-halo term $\langle$  $\rangle \neq 0$ **Clustering**

↓

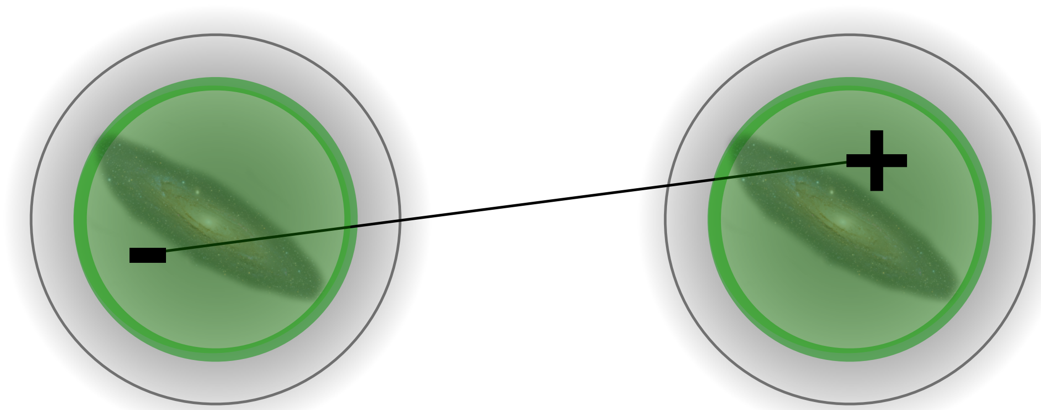
halo-halo auto-correlation (matter power spectrum)

Two-point function: polarization

$$\langle Q_{\rm axion}(\hat{n}_1) Q_{\rm axion}(\hat{n}_2)\rangle \propto g_{a\gamma\gamma}^4 B^4 \bar{T}^2$$

1-halo term $\Big\langle$  $\Big\rangle \propto e^{-|\hat{n}_1 - \hat{n}_2|^2/(2\sigma_d^2)}$

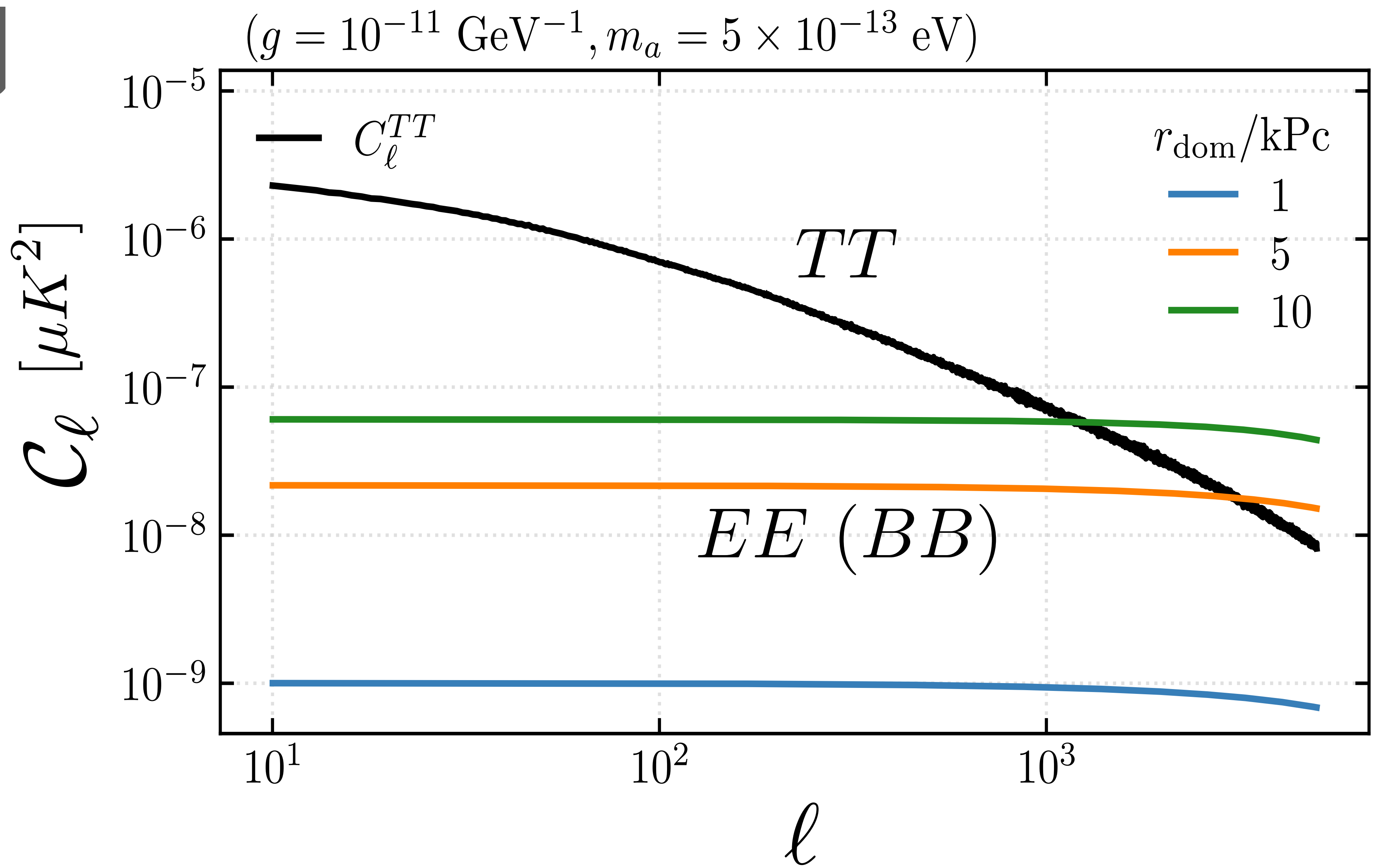
Angular size of the magnetic field coherence length

2-halo term $\Big\langle$  $\Big\rangle = 0$

Two-point function: polarization

$$\langle Q_{\rm axion}(\hat{n}_1) Q_{\rm axion}(\hat{n}_2)\rangle \propto g^4_{a\gamma\gamma} B^4 \bar{T}^2$$

Preliminary



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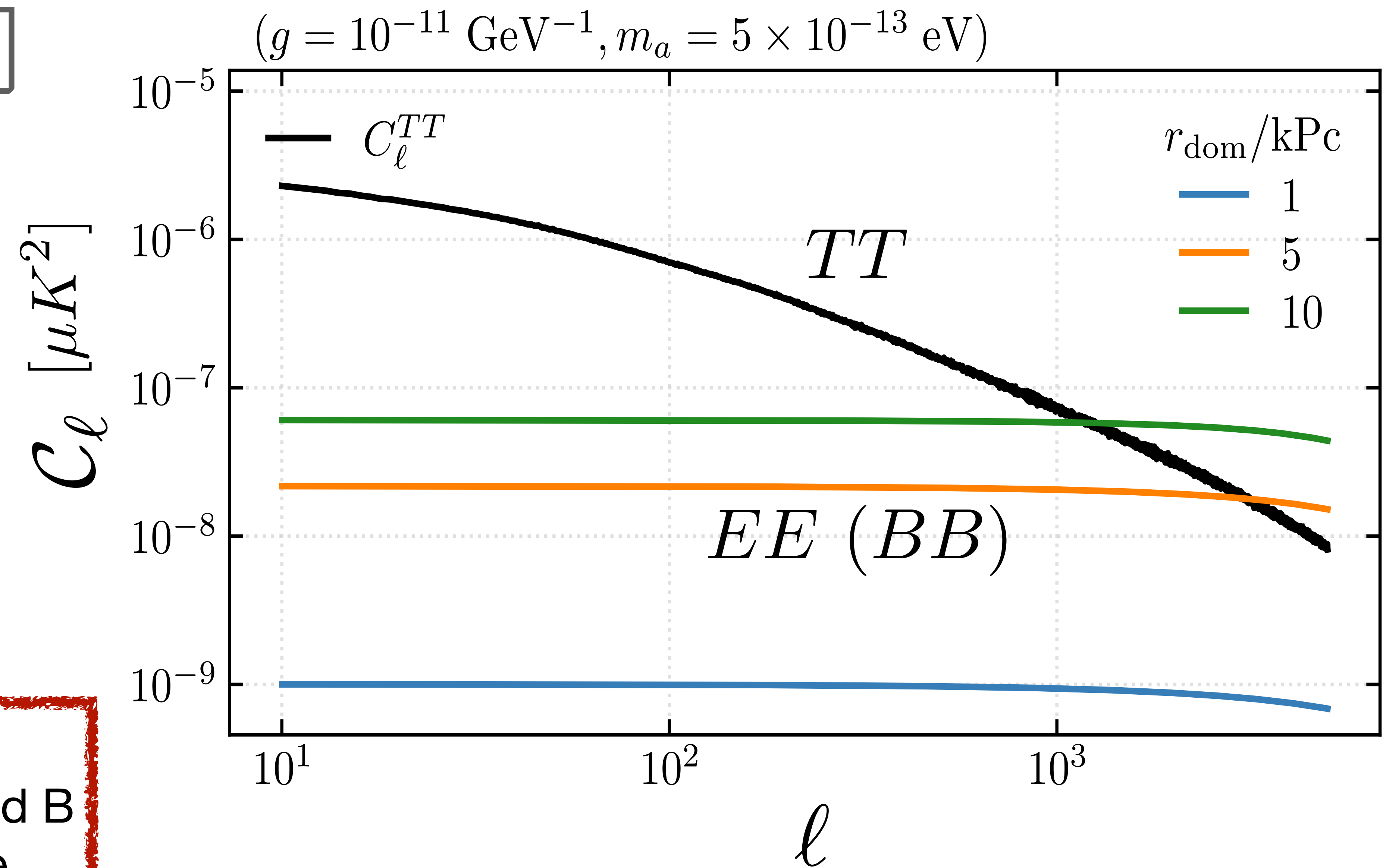
Two-point function: polarization

$$\langle Q_{\rm axion}(\hat{n}_1) Q_{\rm axion}(\hat{n}_2)\rangle \propto g_{a\gamma\gamma}^4 B^4 \bar{T}^2$$

Preliminary



The axion signal for E and B is the same

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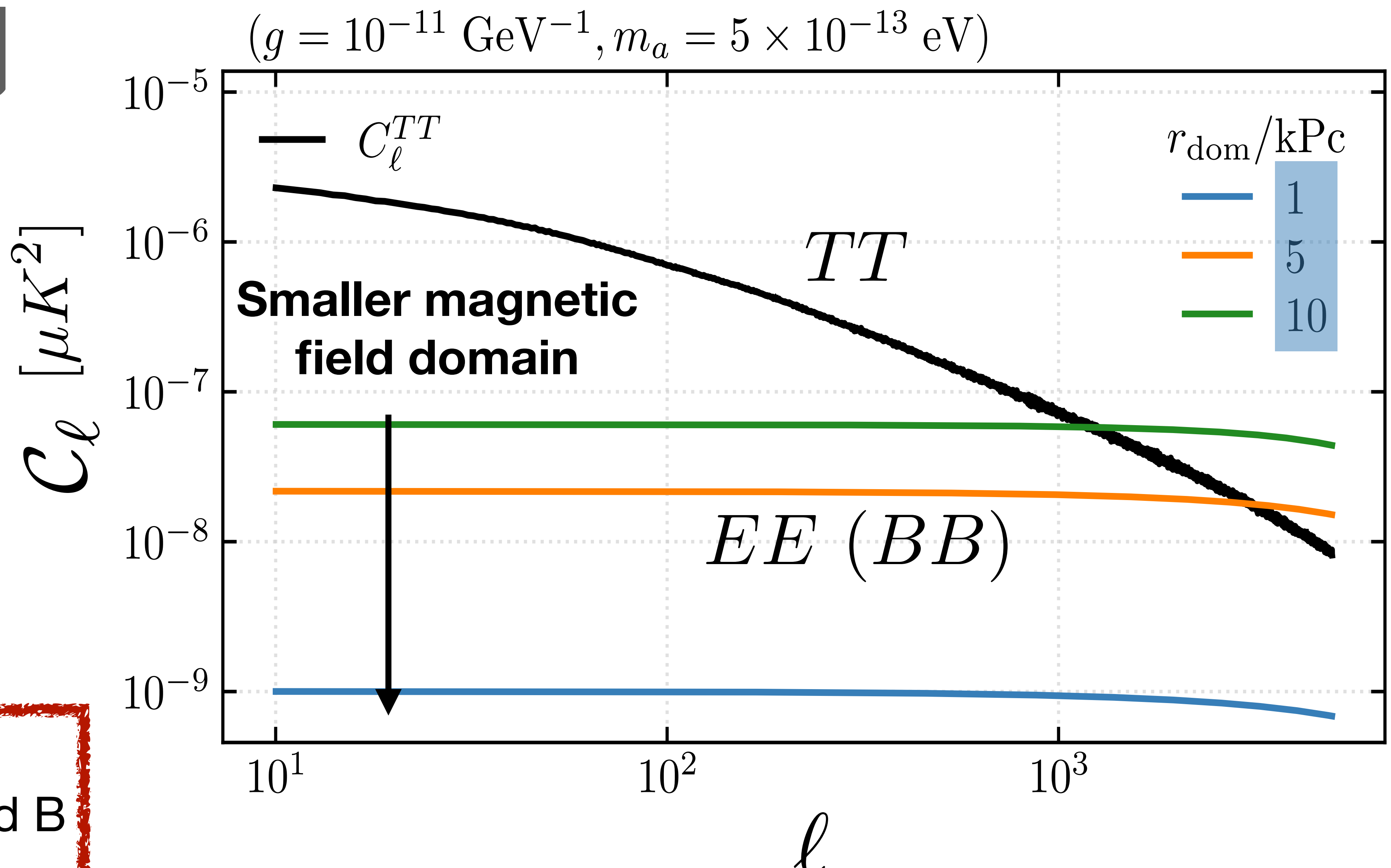
Two-point function: polarization

$$\langle Q_{\text{axion}}(\hat{n}_1) Q_{\text{axion}}(\hat{n}_2)\rangle \propto g_{a\gamma\gamma}^4 B^4 \bar{T}^2$$

Preliminary



< max angular resolution

The axion signal for E and B is the same

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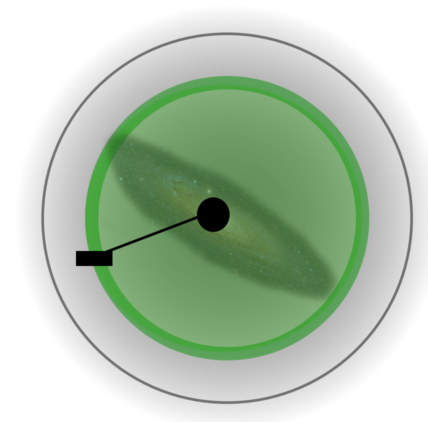
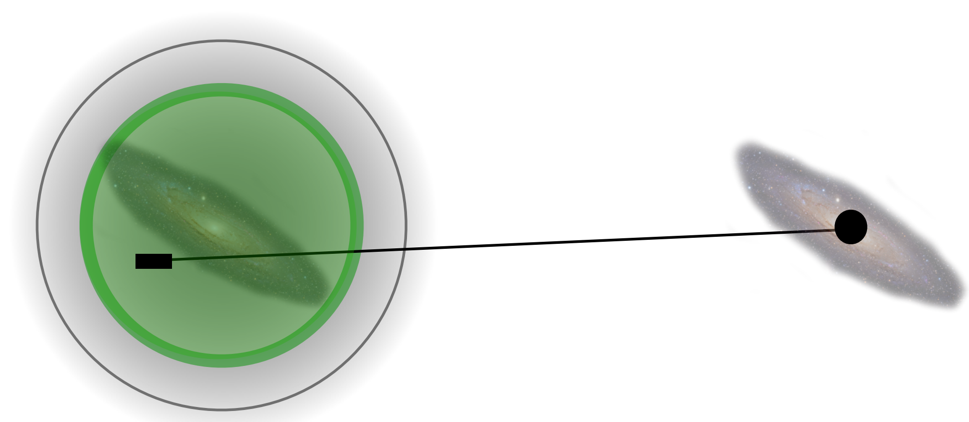
Cross-correlation: temperature

$$\langle T_{\rm axion}(\hat{n}_1)g(\hat{n}_2)\rangle \propto g^2_{a\gamma\gamma}B^2\bar{T}$$

1-halo term $\langle$  $\rangle \neq 0$

Small scale
(halo shape)

2-halo term $\langle$  $\rangle \neq 0$

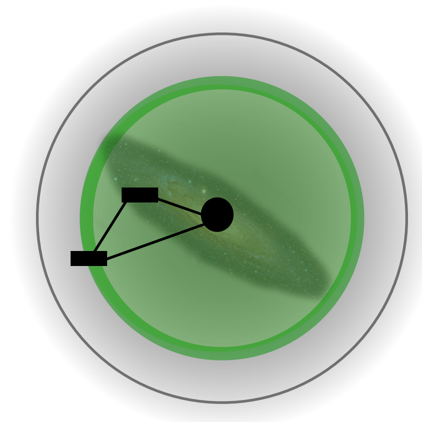
Clustering

↓

halo-halo auto-correlation (matter power spectrum)

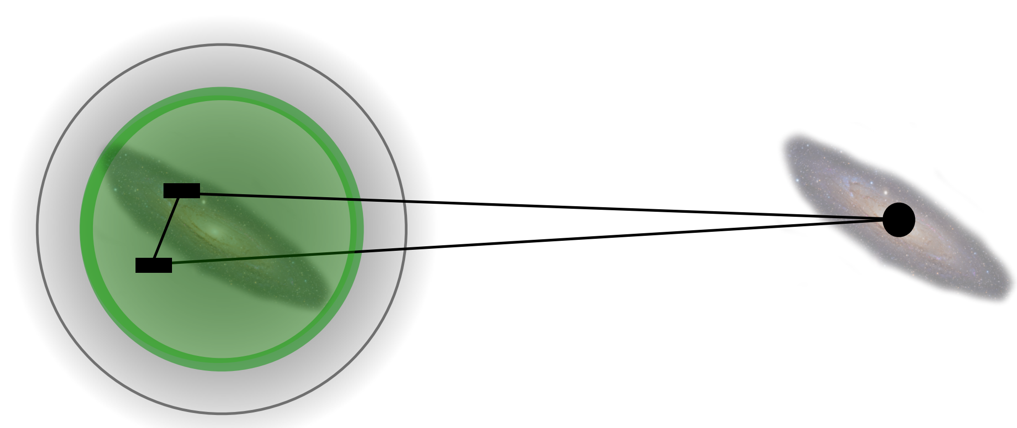
Polarization-LSS bispectrum

$$\langle Q_{\rm axion}(\hat{n}_1) Q_{\rm axion}(\hat{n}_2) g(\hat{n}_3) \rangle \propto g^4_{a\gamma\gamma} B^4 \bar{T}^2$$

1-halo term $\langle$  $\rangle \neq 0$

Small scale

(halo shape)

2-halo term $\langle$  $\rangle \neq 0$

Clustering

↓

halo-halo auto-correlation (matter power spectrum)

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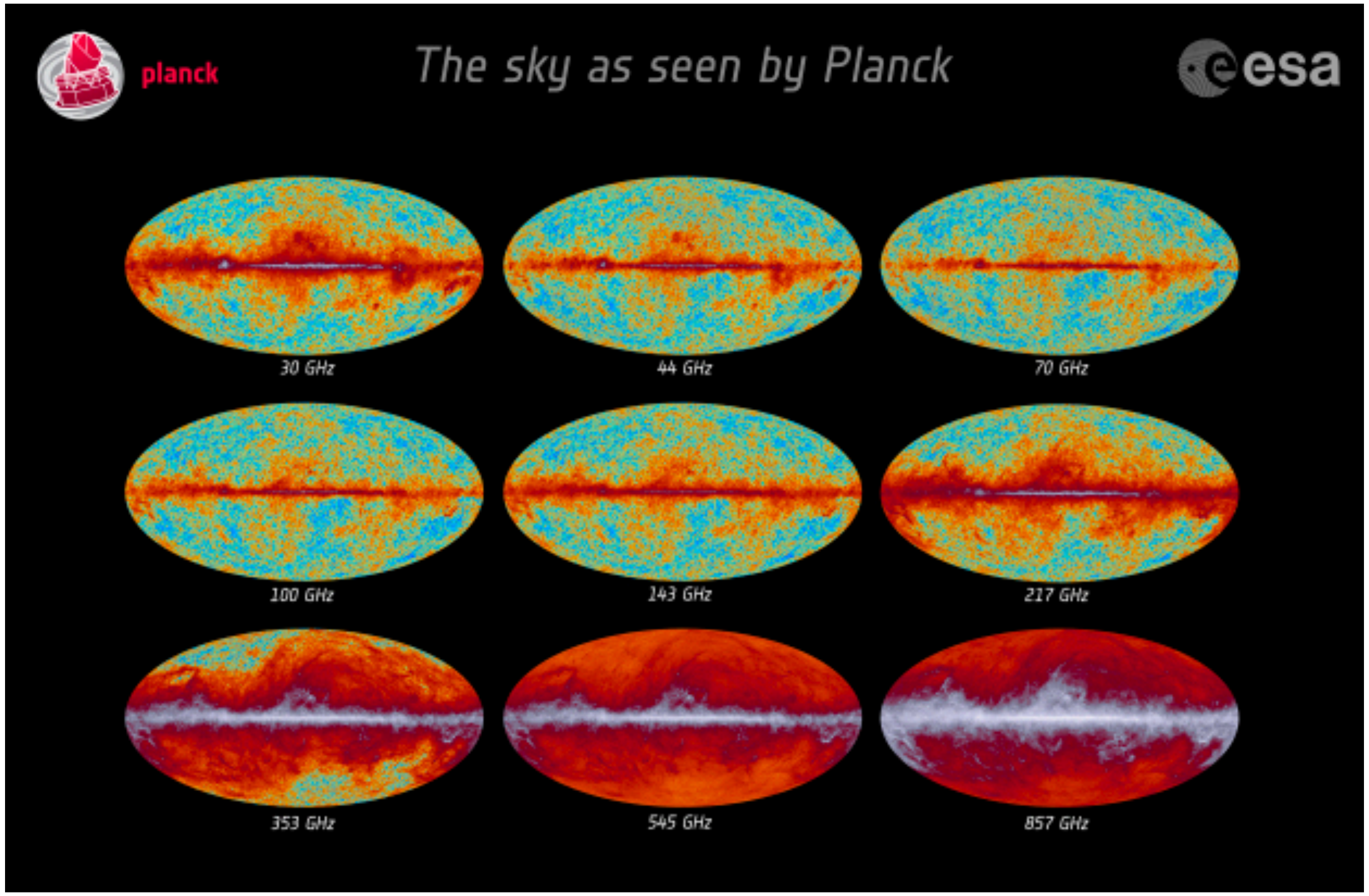
Outline

- CMB secondary anisotropies
- Photon-axion conversion inside halos
- Axion signal (temperature, polarization)
- Sensitivity projections

Internal Linear Combination (ILC)

$$T_{\rm axion}(\hat{n}) = -\frac{1-e^{-\omega/\bar{T}}}{\omega/\bar{T}}\bar{T}P_{\gamma\to\omega}(\hat{n},\omega) \propto \frac{1-e^{-\omega/\bar{T}}}{\omega/\bar{T}}\omega$$



Weight different maps appropriately to minimize the noise with respect to the **frequency scaling of the signal**

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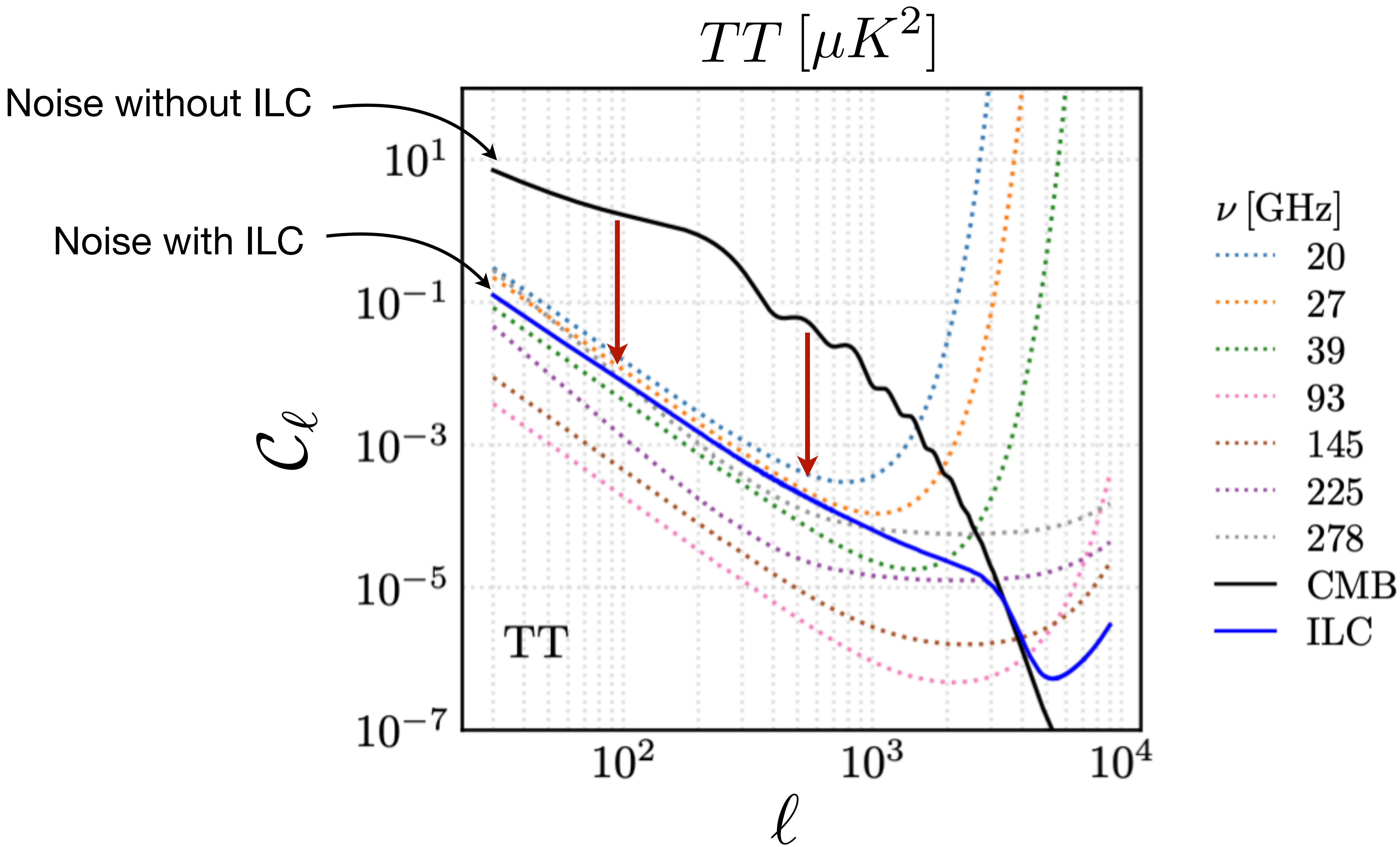
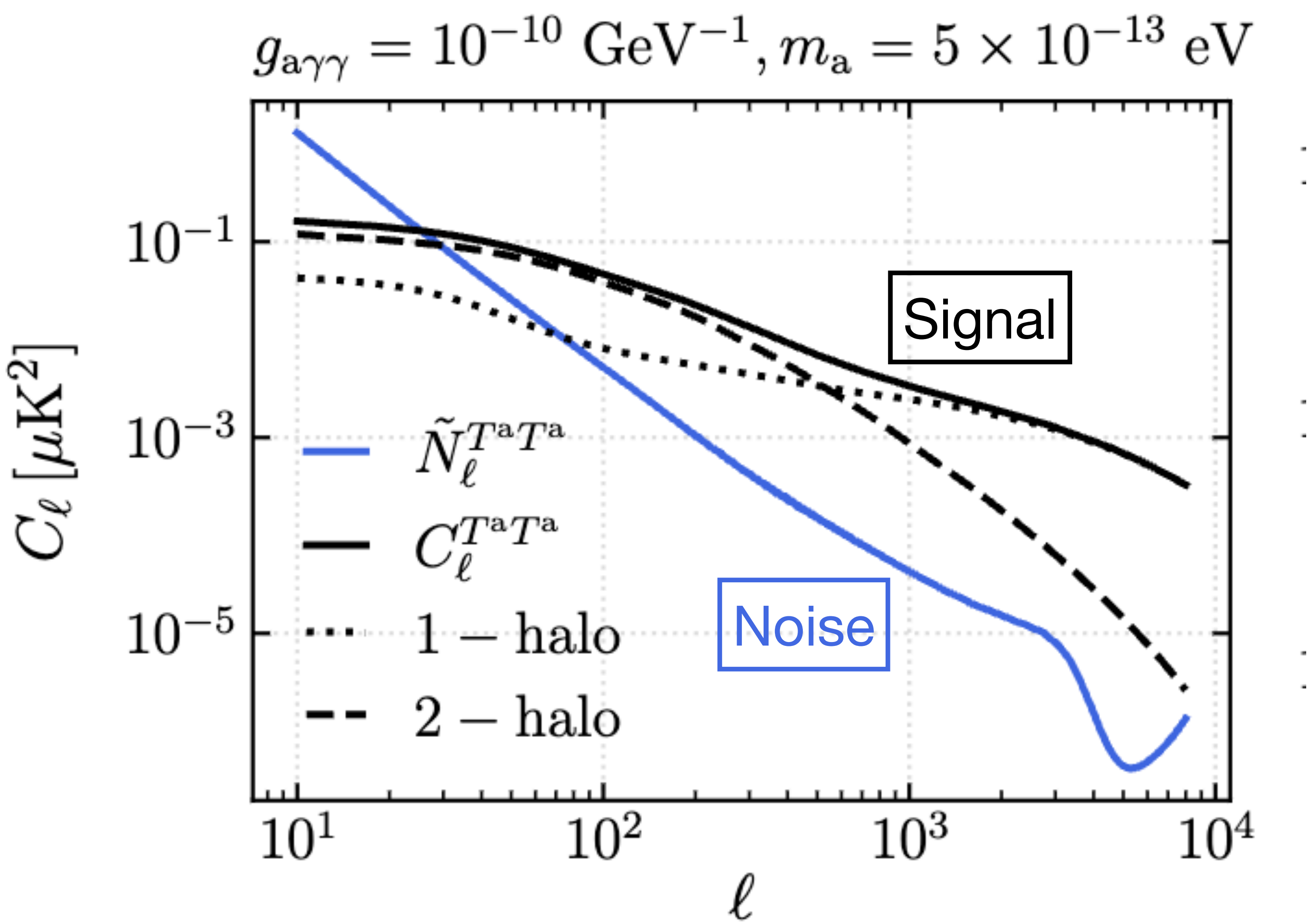
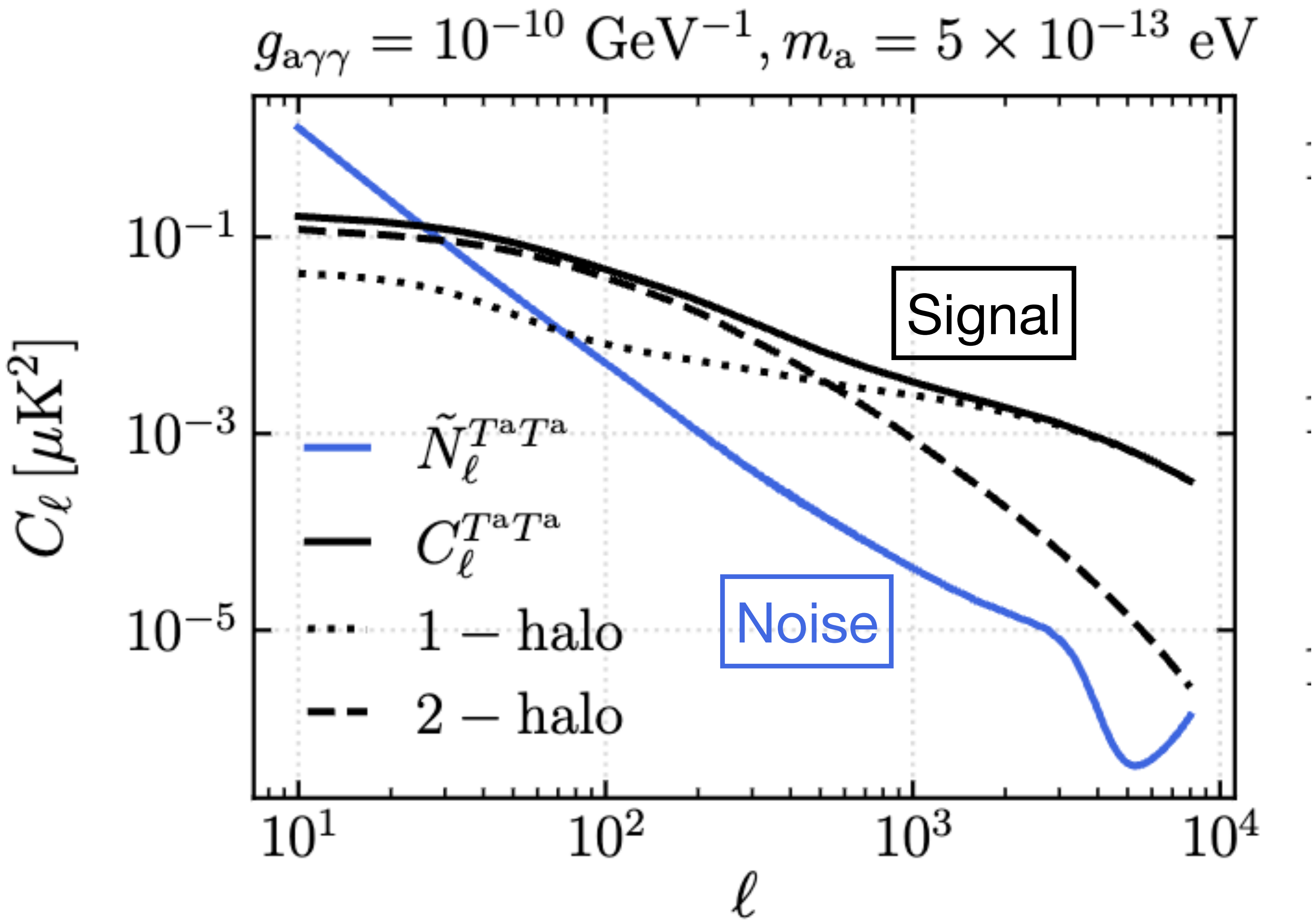
ILC cleaning



Signal-to-Noise Ratio

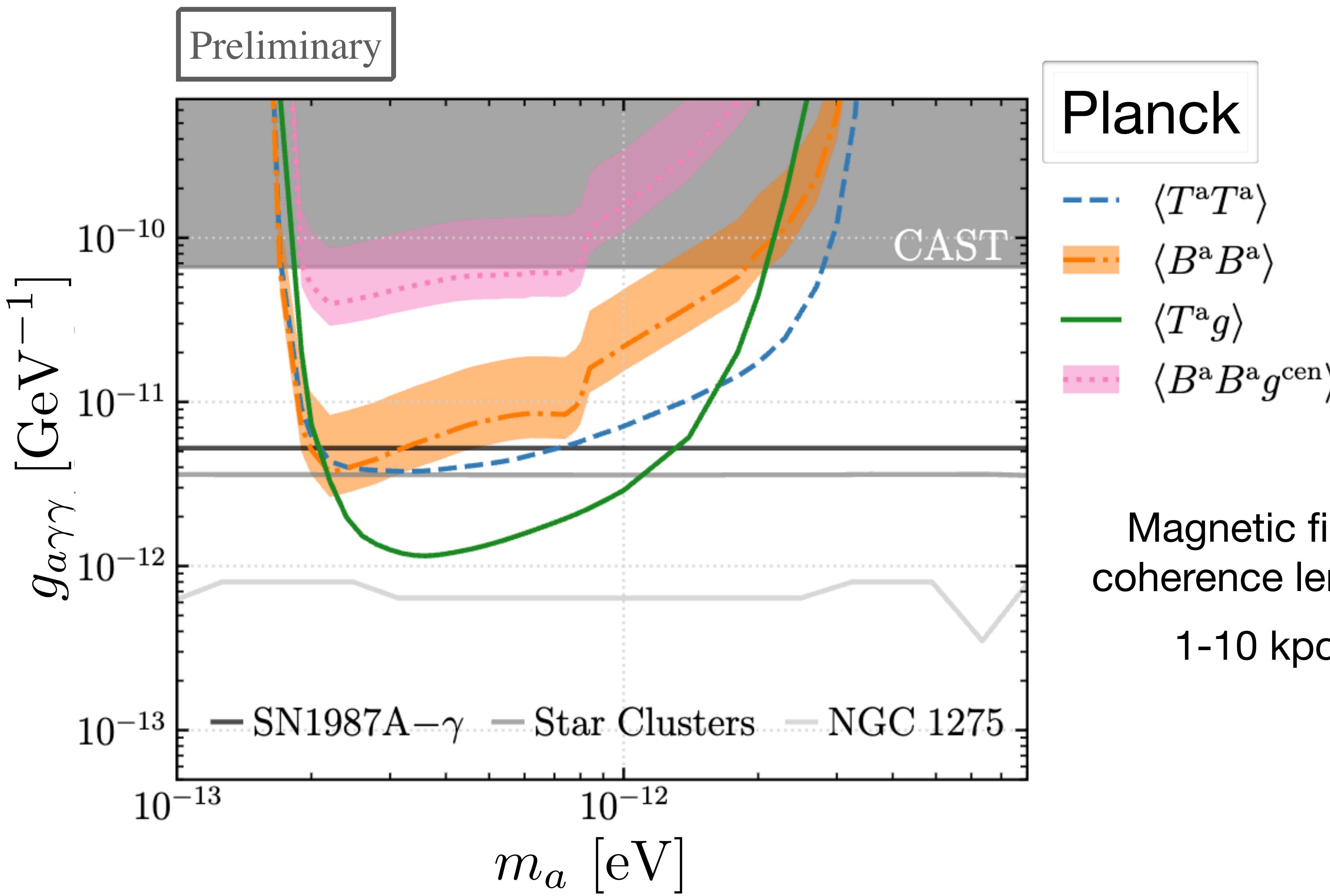


Signal-to-Noise Ratio



$$\mathrm{SNR}^2 = \sum_\ell \frac{2\ell+1}{2}\left[\frac{C_\ell^{T^aT^a}}{N_\ell^{T^aT^a}}\right]^2 \qquad C_\ell^{T^aT^a} \propto g_{a\gamma\gamma}^4$$

Projections: Planck + unWISE



Magnetic field coherence length:

1-10 kpc

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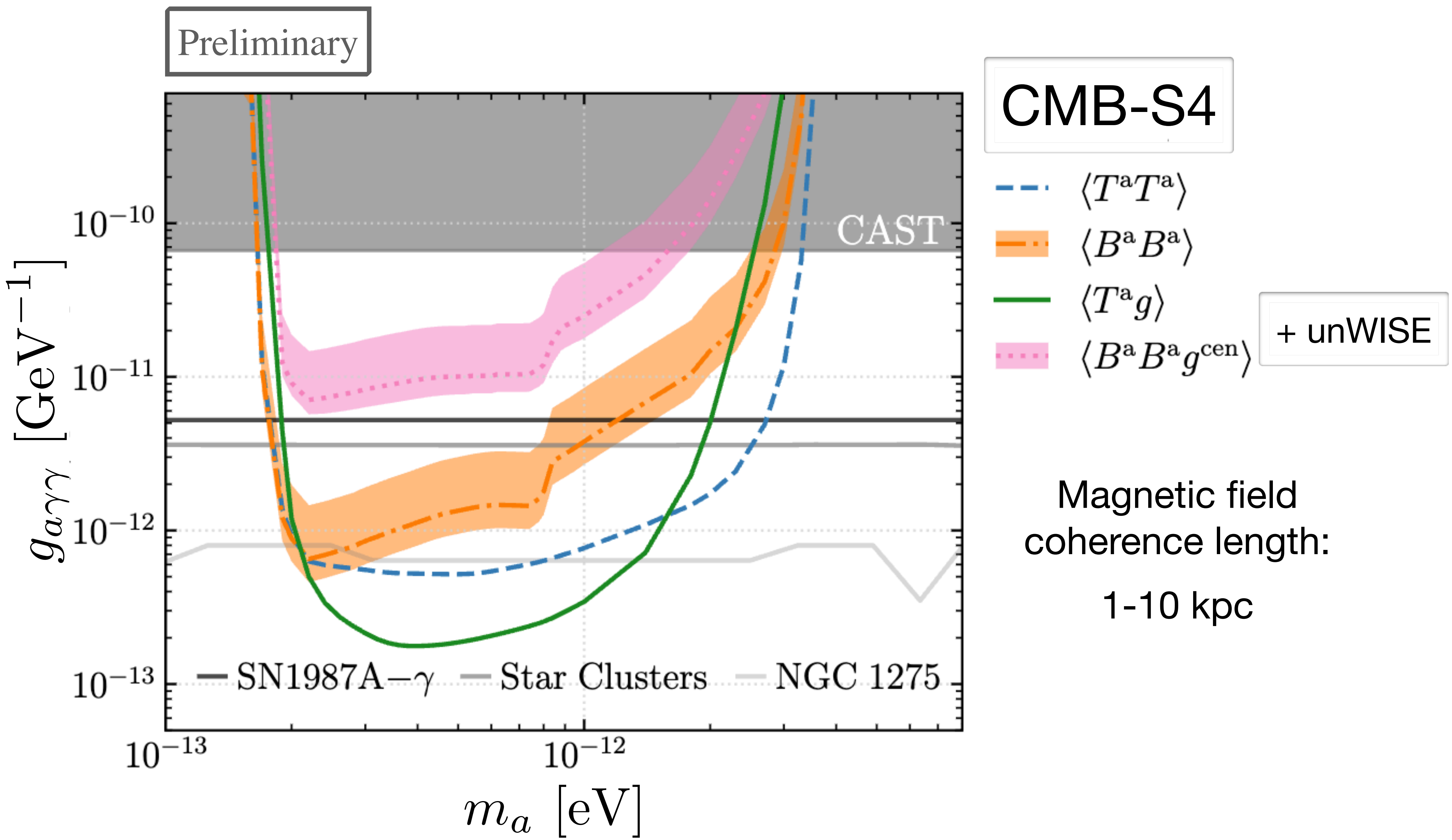
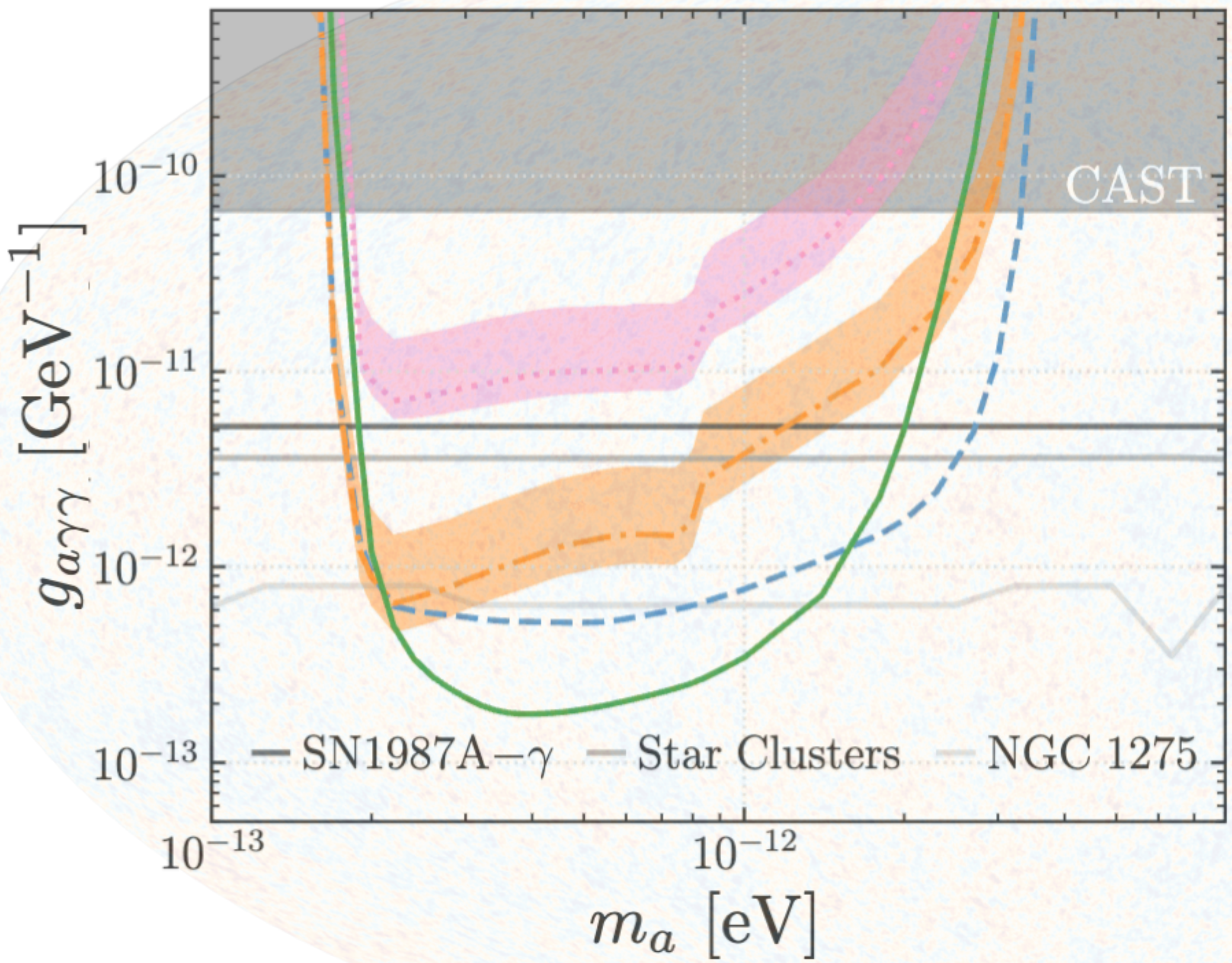
Projections: Planck + unWISE

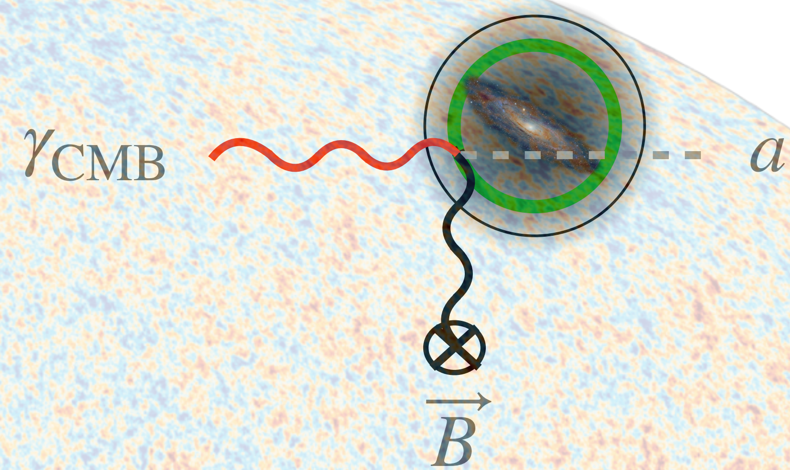


Magnetic field coherence length:

1-10 kpc

Summary





New Physics can induce secondary anisotropies

example from this talk: axions on the CMB

Next: analysis with Planck+unWISE, (soon) ACT DR6

With Sam Goldstein, Fiona McCarthy, Colin Hill

With Dalila Pîrvu , Junwu Huang, and Matt Johnson

Cristina Mondino