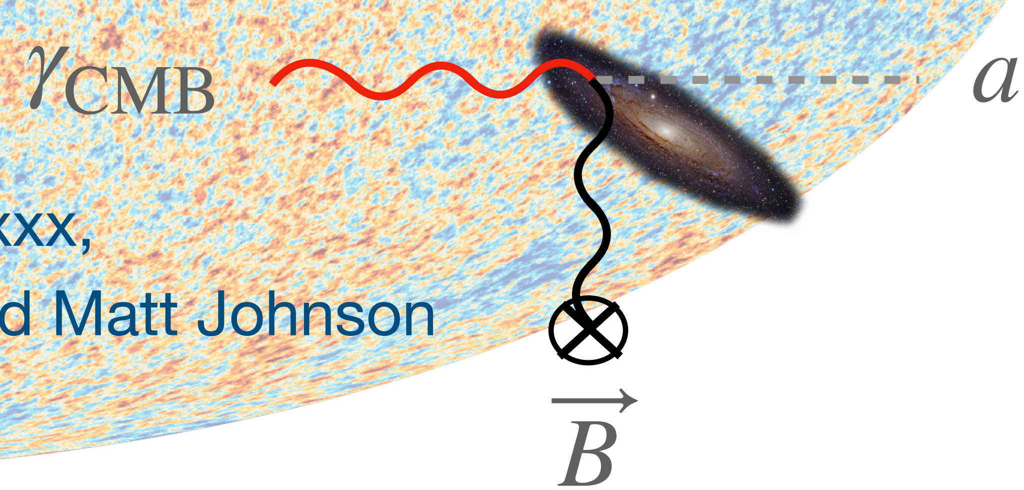
Axion screening of the CMB

Cristina Mondino

PERIMETER INSTITUTE

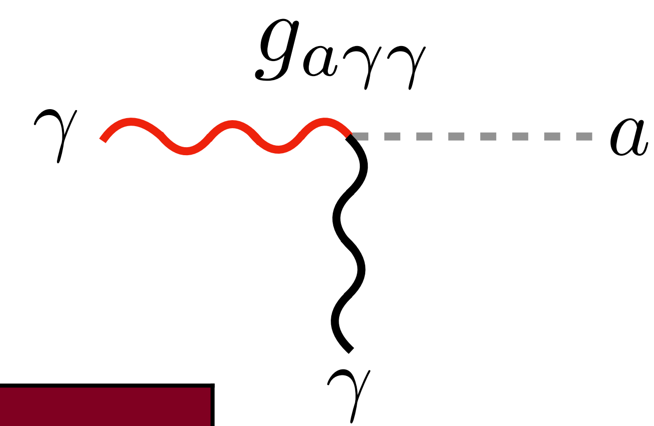


Based on arXiv:2404.xxxx,
with Dalila Pîrvu , Junwu Huang, and Matt Johnson

ALPS 2024, UZ Obergurgl, April 3rd 2024

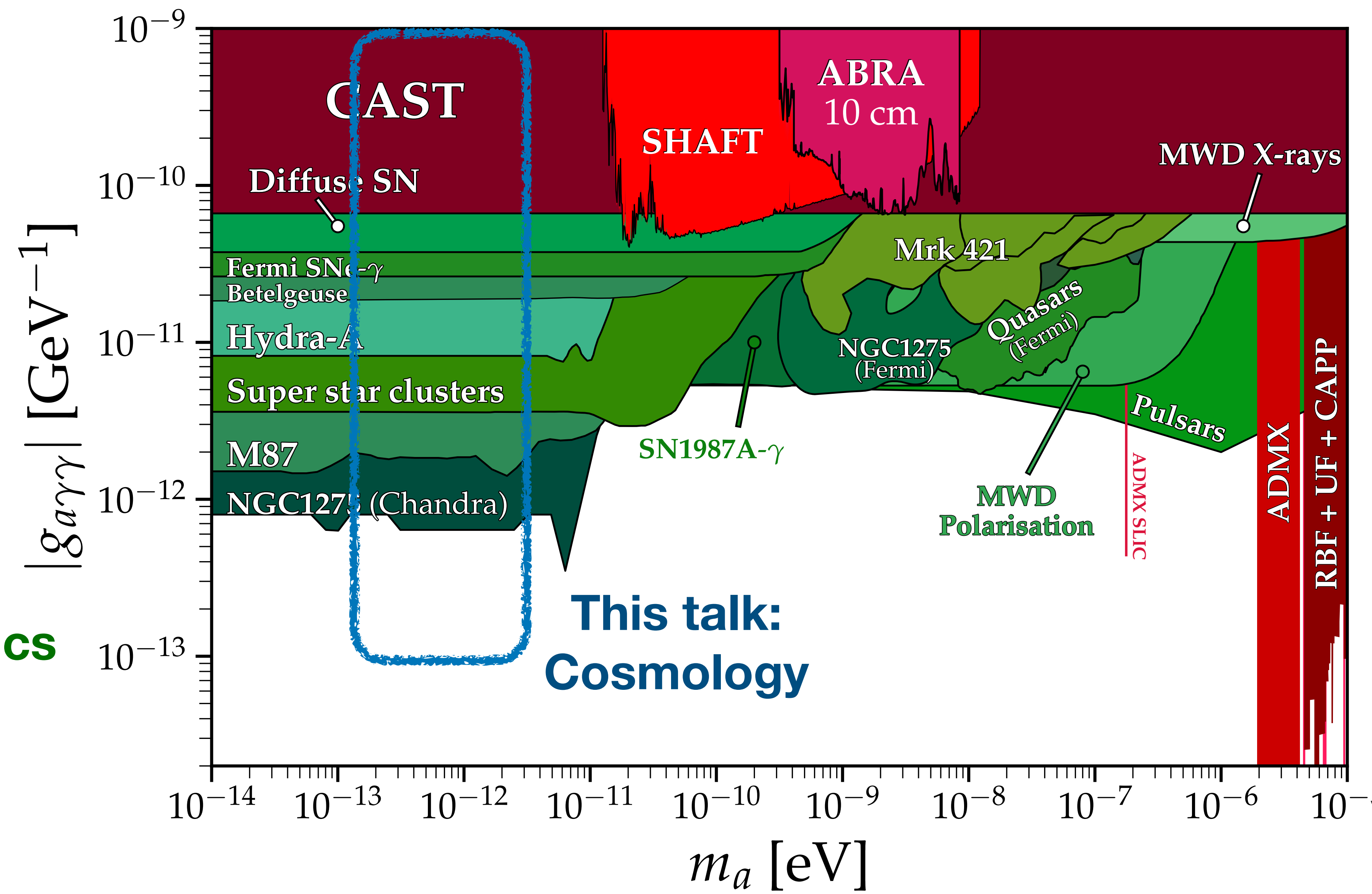
Axion ~~(Like) Particles~~

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



Laboratory

Astrophysics

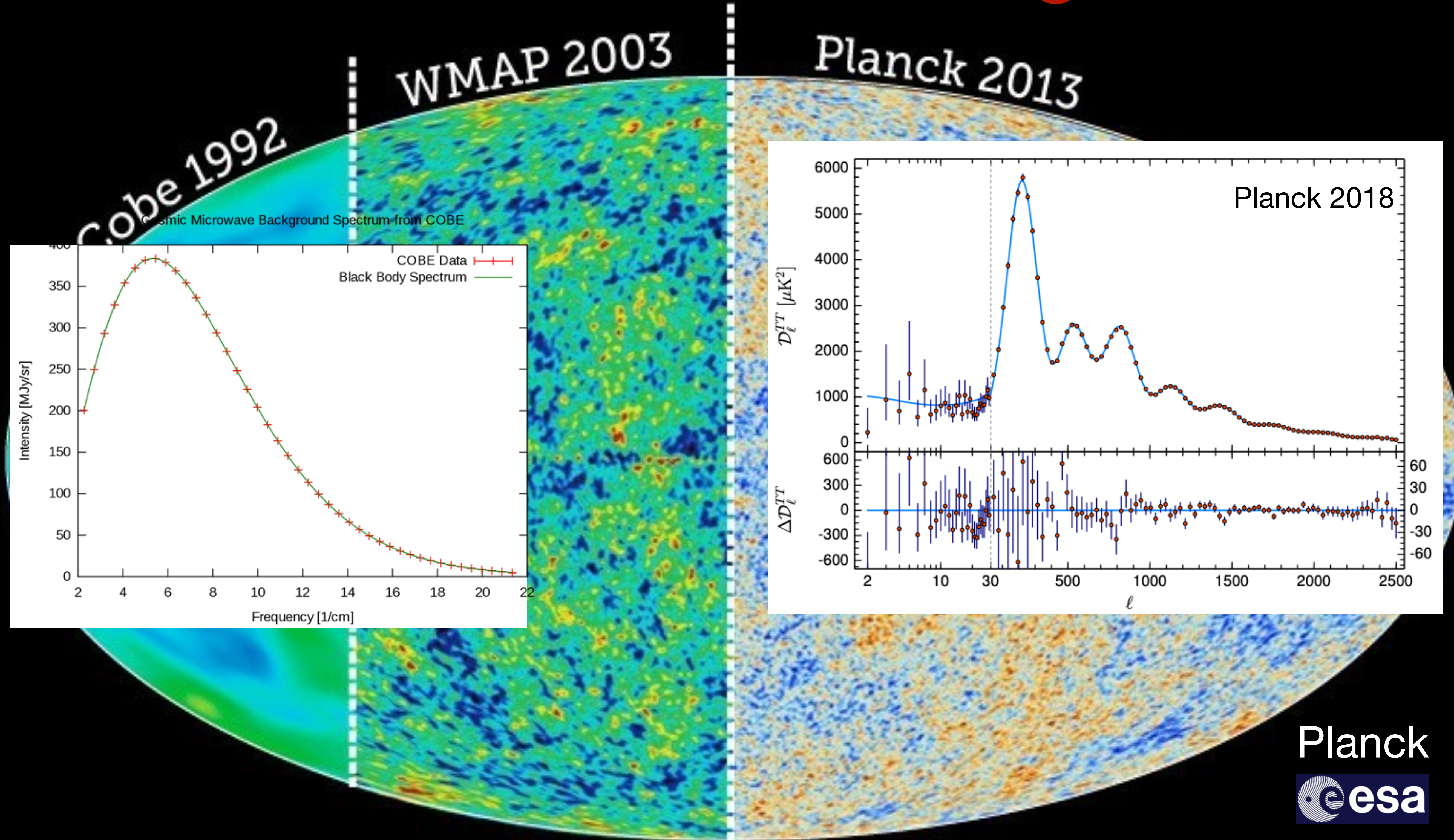


From Ciaran O'Hare (cajohare.github.io/AxionLimits/)

Outline

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

Cosmic Microwave Background



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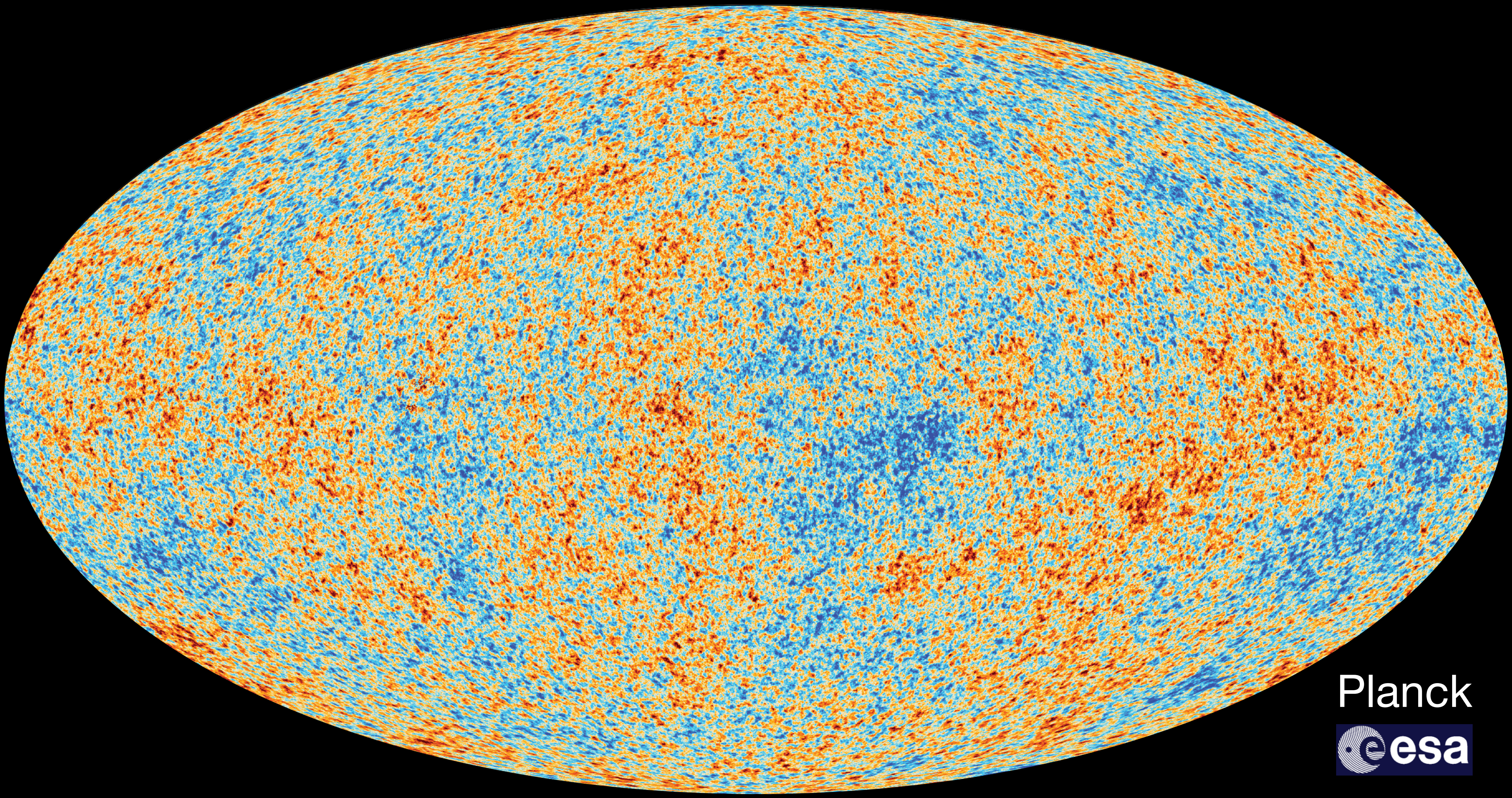
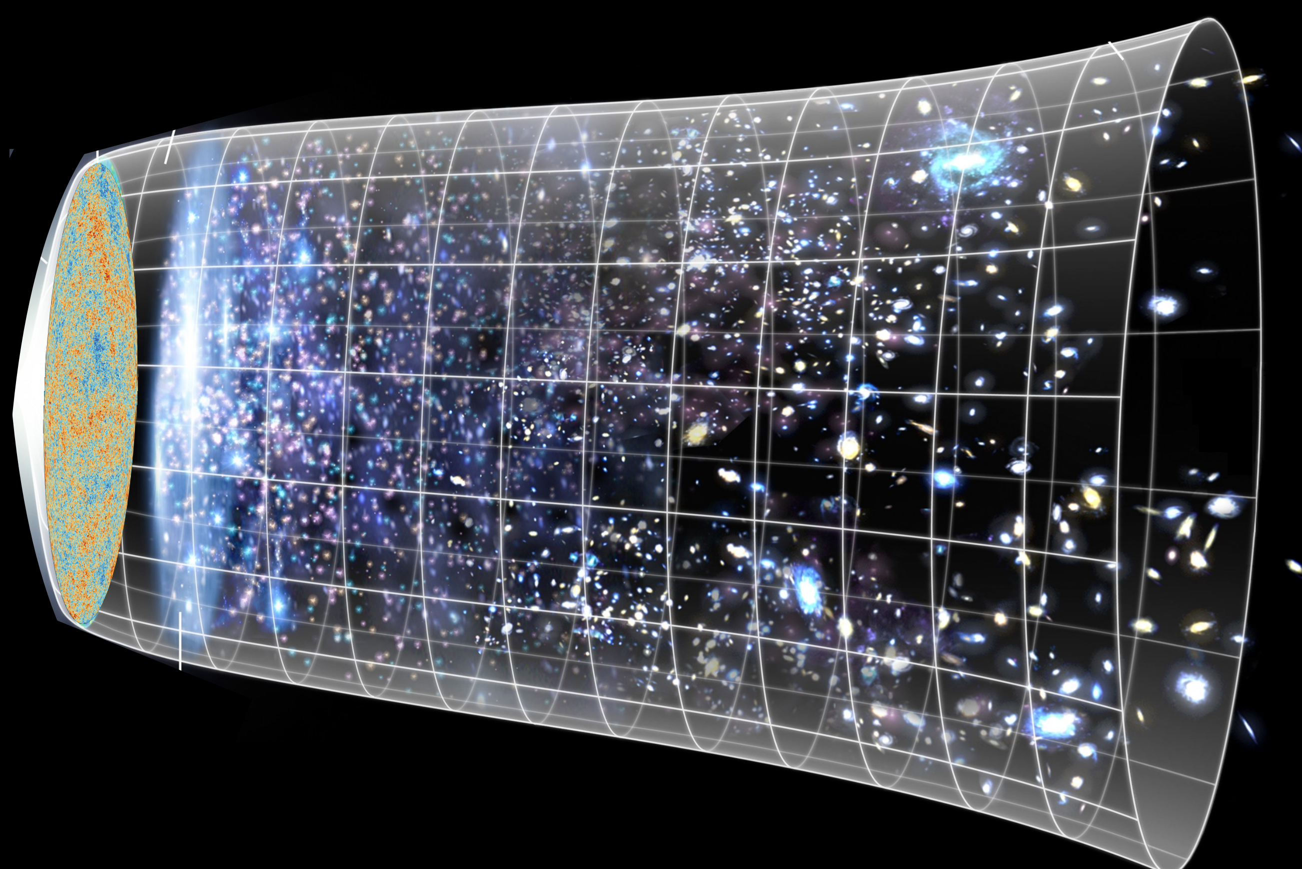
Primary CMB anisotropies



Planck

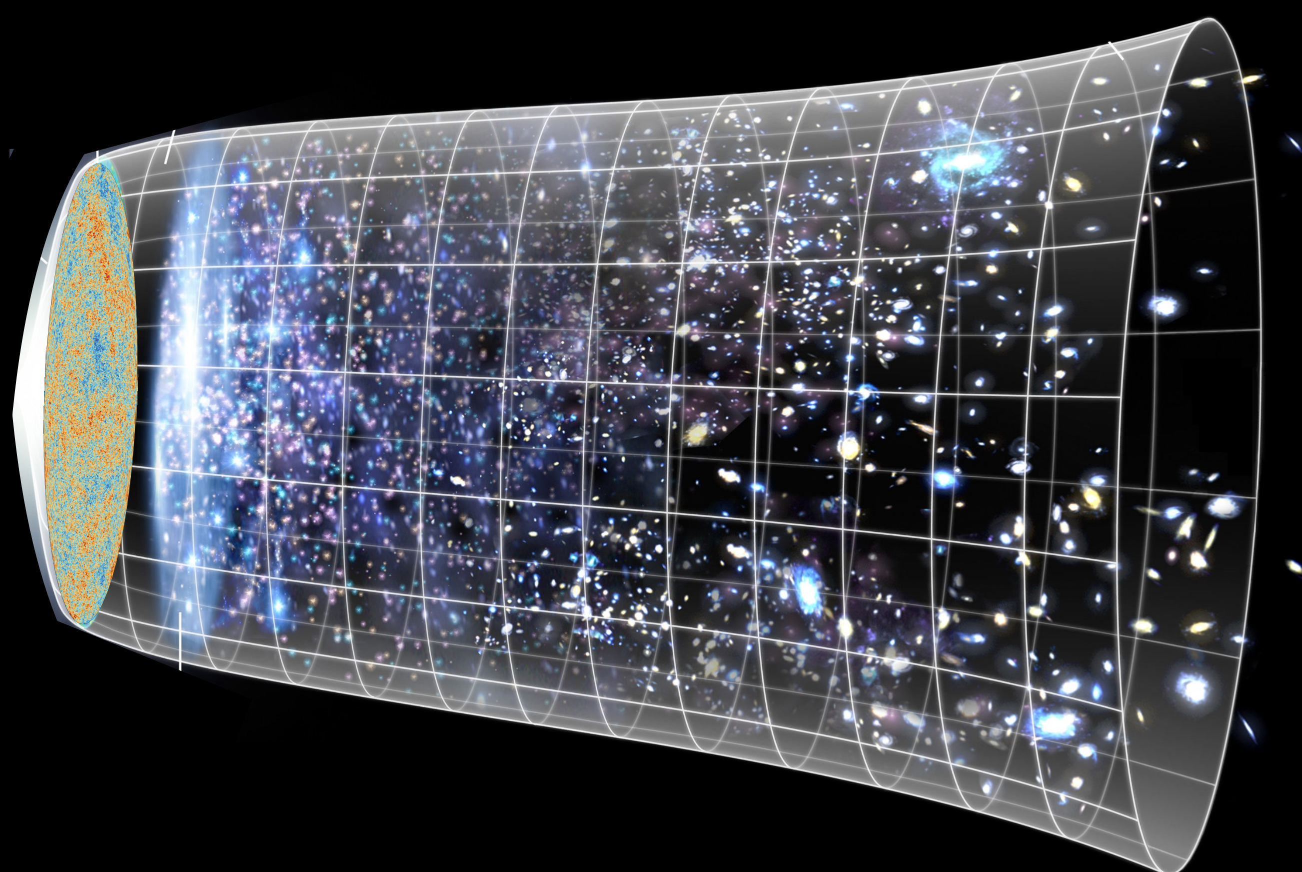
Secondary CMB anisotropies

Interactions with intervening structure → New anisotropies



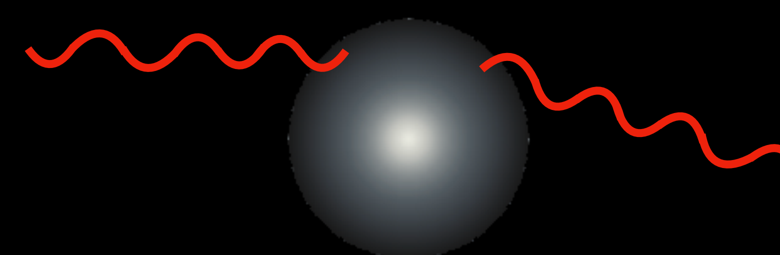
Secondary CMB anisotropies

Interactions with intervening structure → New anisotropies

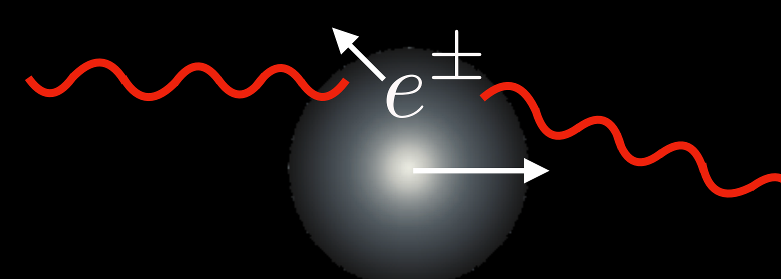


Standard Model effects:

- Lensing ✓



- Screening
- Sunyaev Zel'dovich effects ✓



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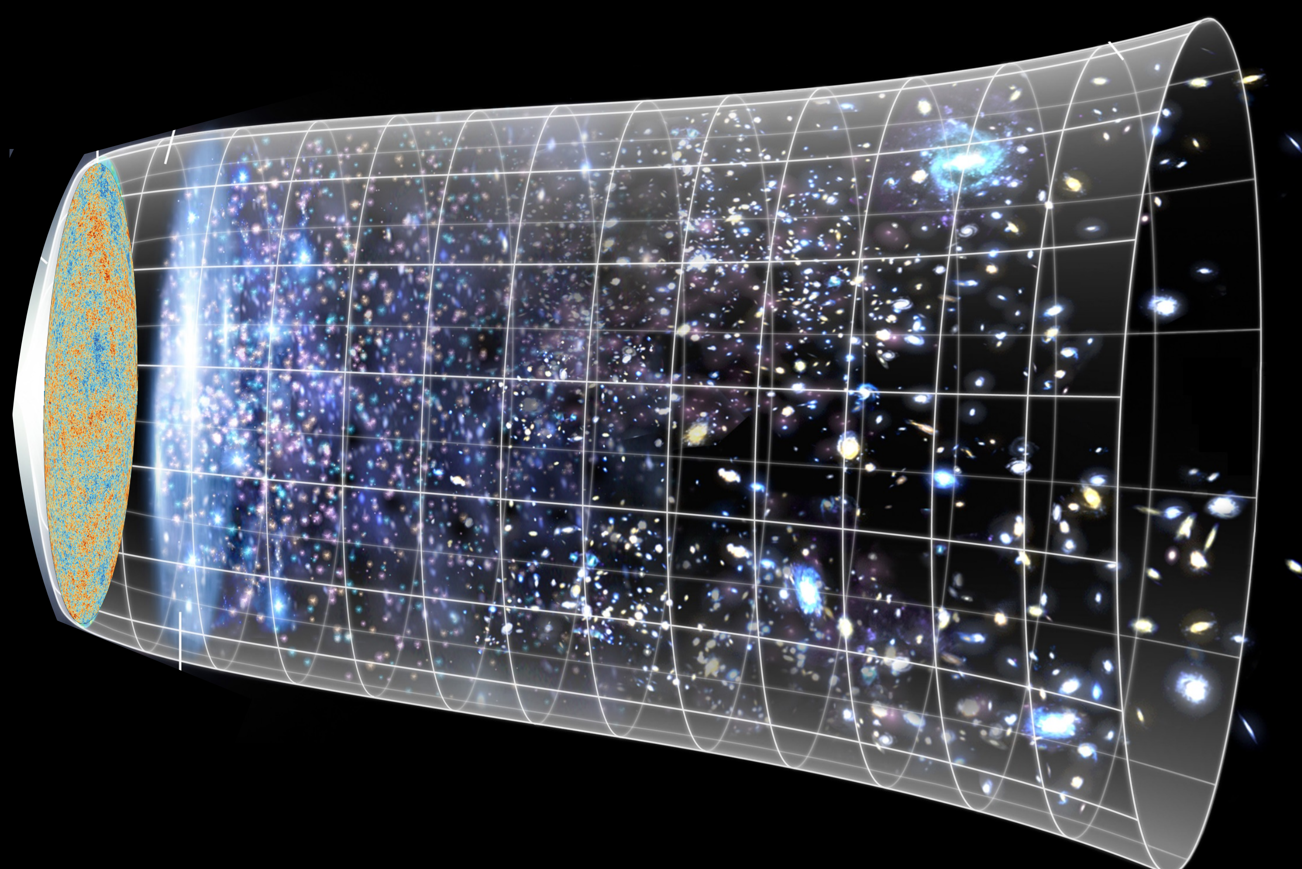
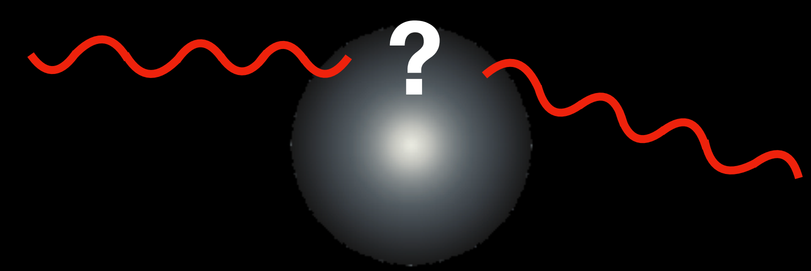
Secondary CMB anisotropies

Interactions with intervening structure → New anisotropies

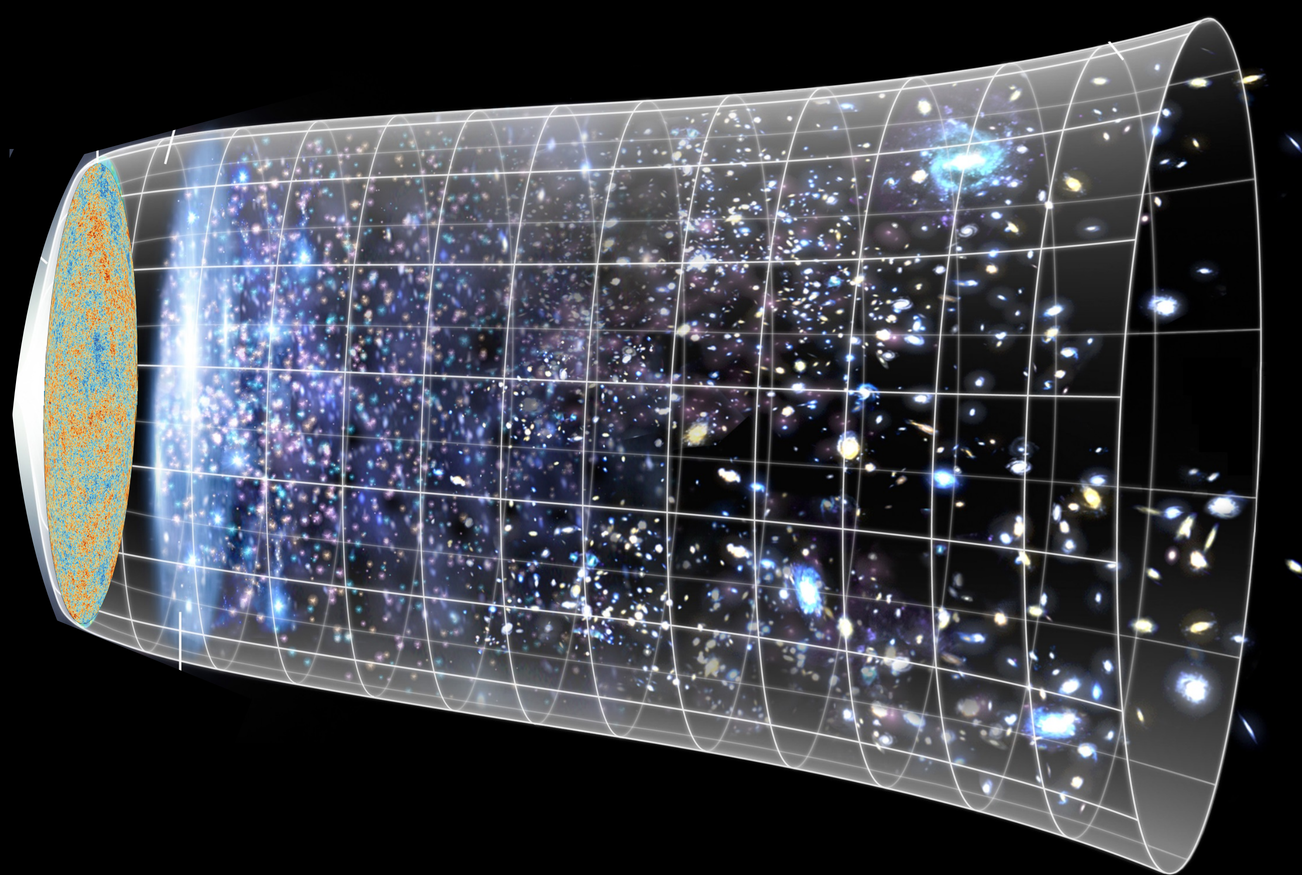


What about New Physics?

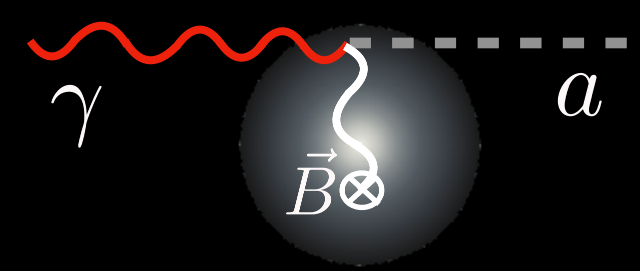


Secondary CMB anisotropies

Interactions with intervening structure → New anisotropies



What about New Physics?

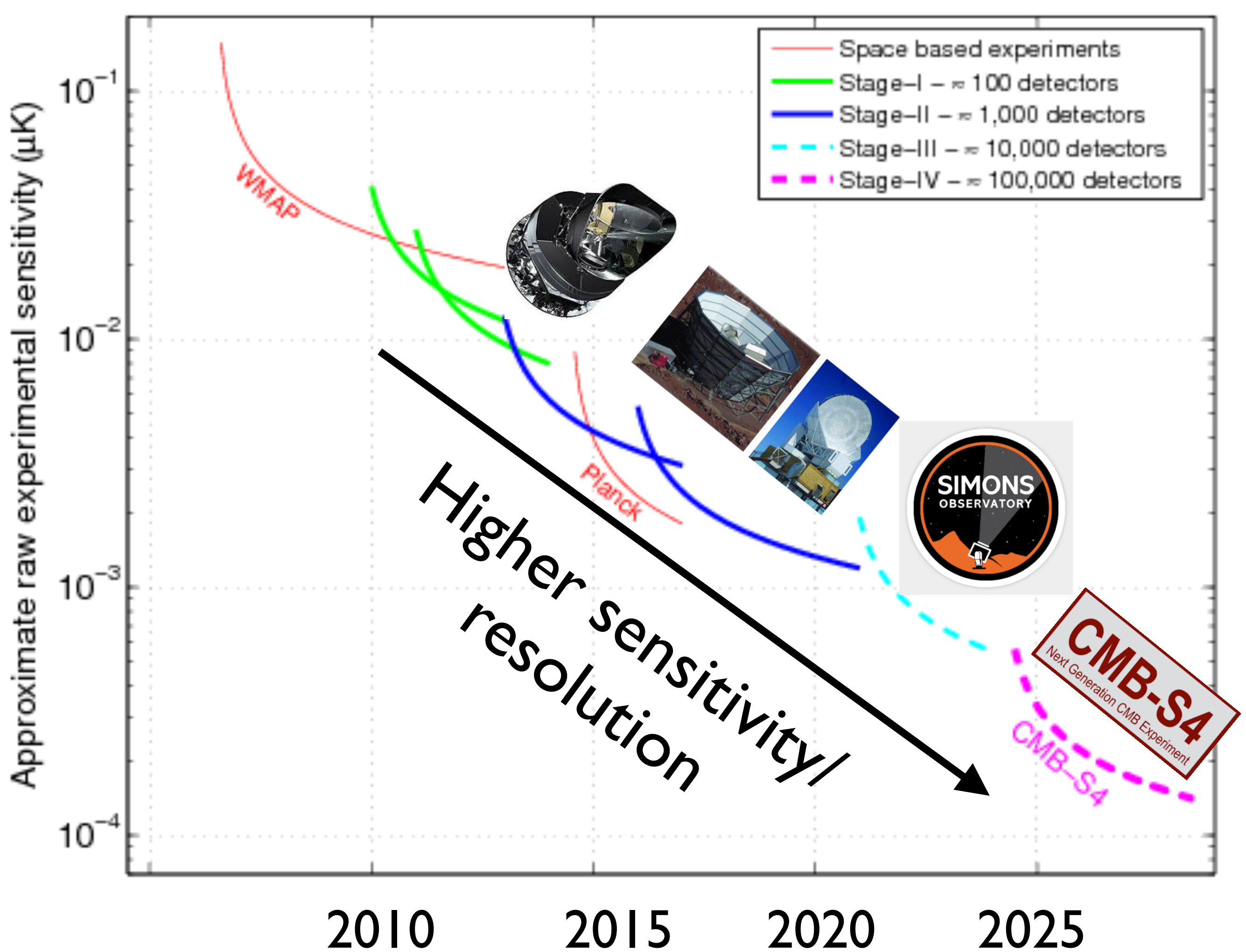


This talk: photon to axion conversion inside halos

...

Why CMB secondaries?

Future CMB experiments will have better sensitivity at high resolution



From Matt Johnson

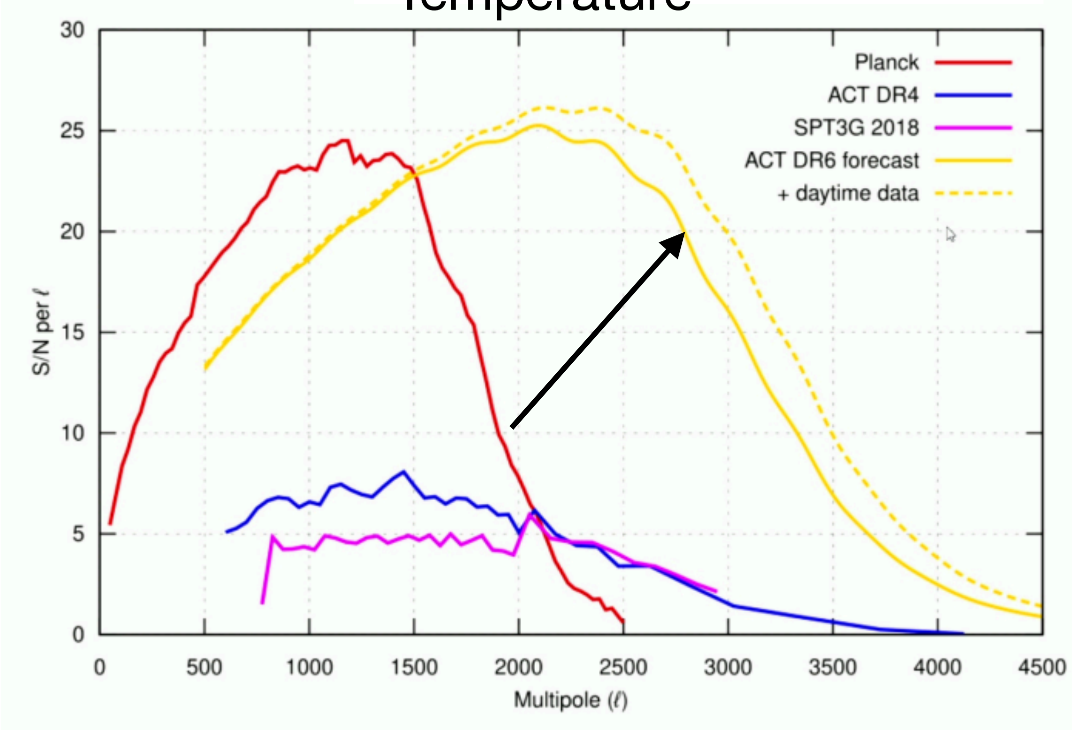
Why CMB secondaries?

Current
~~Future~~ CMB experiments will have better sensitivity at high resolution

ACT DR6 Preliminary (expected in 2024)
(from Sigurd Naess talk @ PI, Dec. 2023)

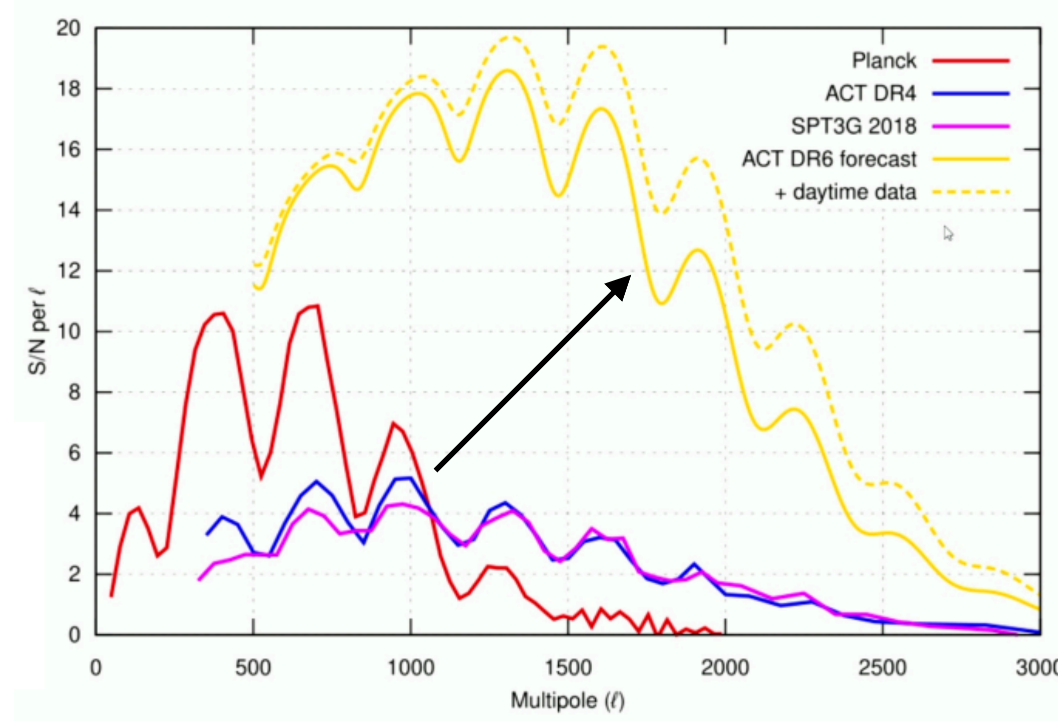
S/N improvement

Temperature



TT

Polarization



EE

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Outline

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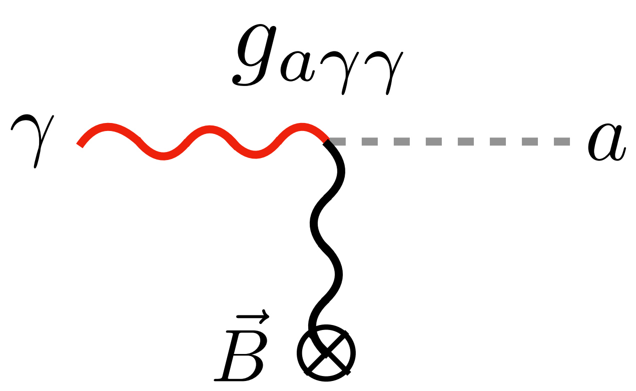
- Photon-axion conversion inside halos
- Axion signal (temperature, polarization)
- Sensitivity projections

Photon-axion conversion

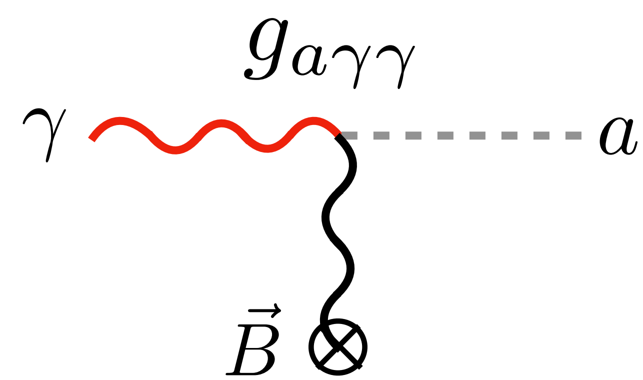
$$\mathcal{L} \supset -\frac{1}{4} g_{a\gamma\gamma} a F^{\mu\nu} \tilde{F}_{\mu\nu}$$



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

Resonant conversion



Like for neutrinos,
medium effects can be important!

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

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

resonance

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

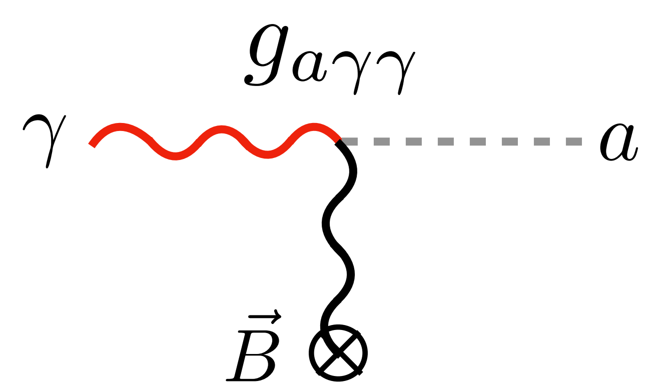
Slope of the number density profile

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

Resonant conversion

This talk:

Inside DM halos

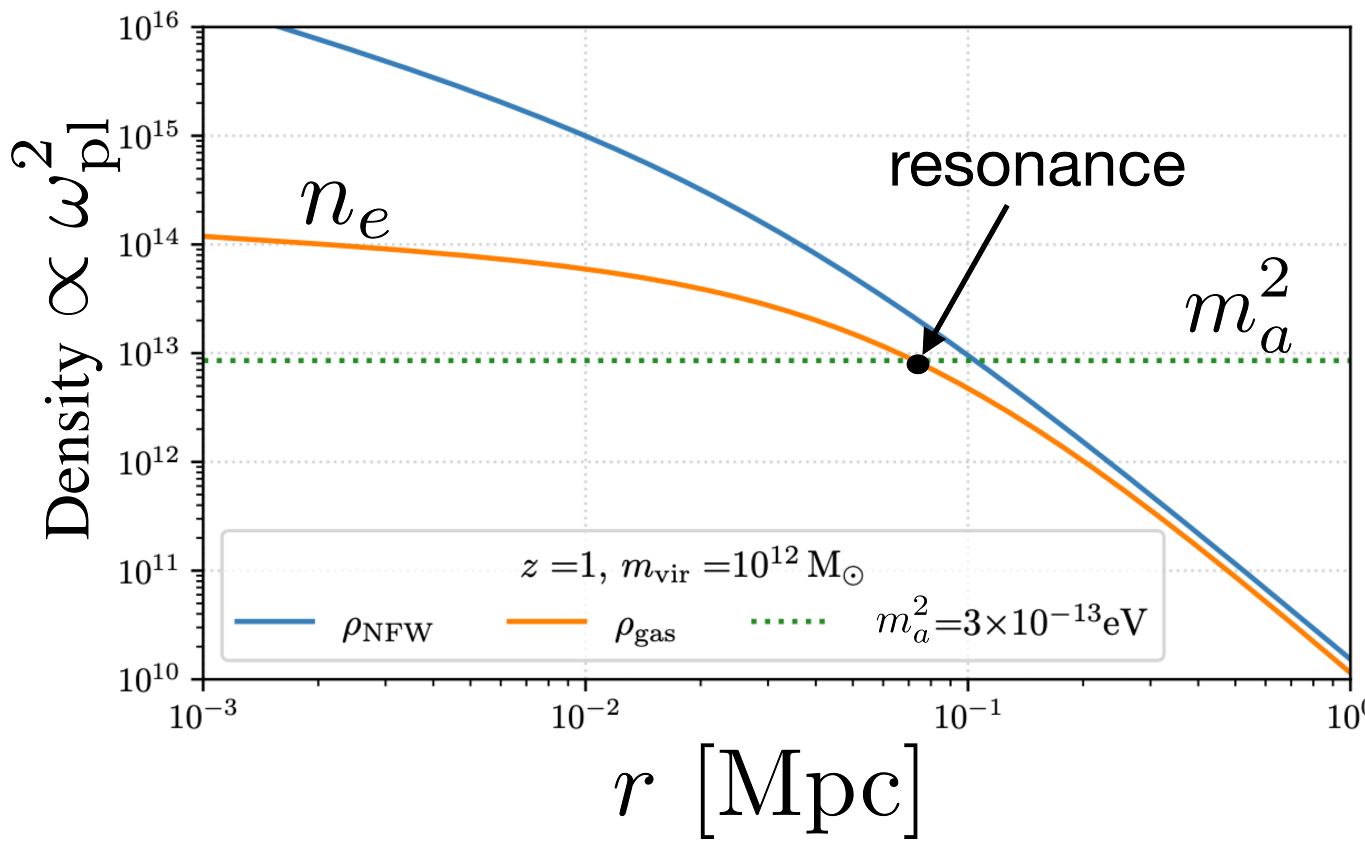


Photon plasma mass: $m_{\rm pl}^2 = \dfrac{e^2 n_e}{m_e}$

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

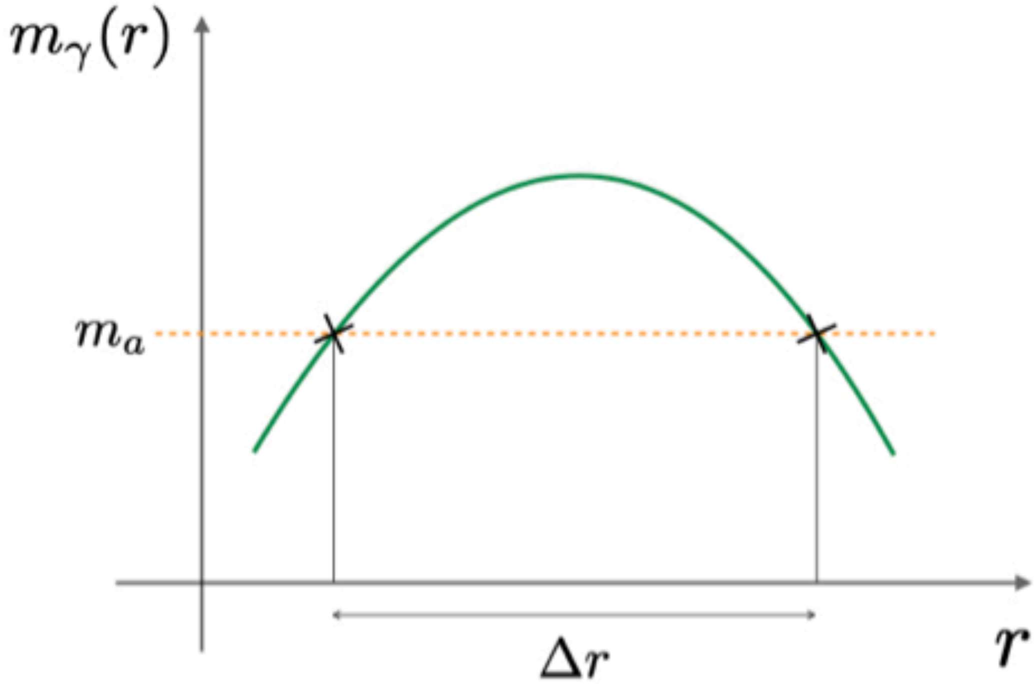
resonance

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

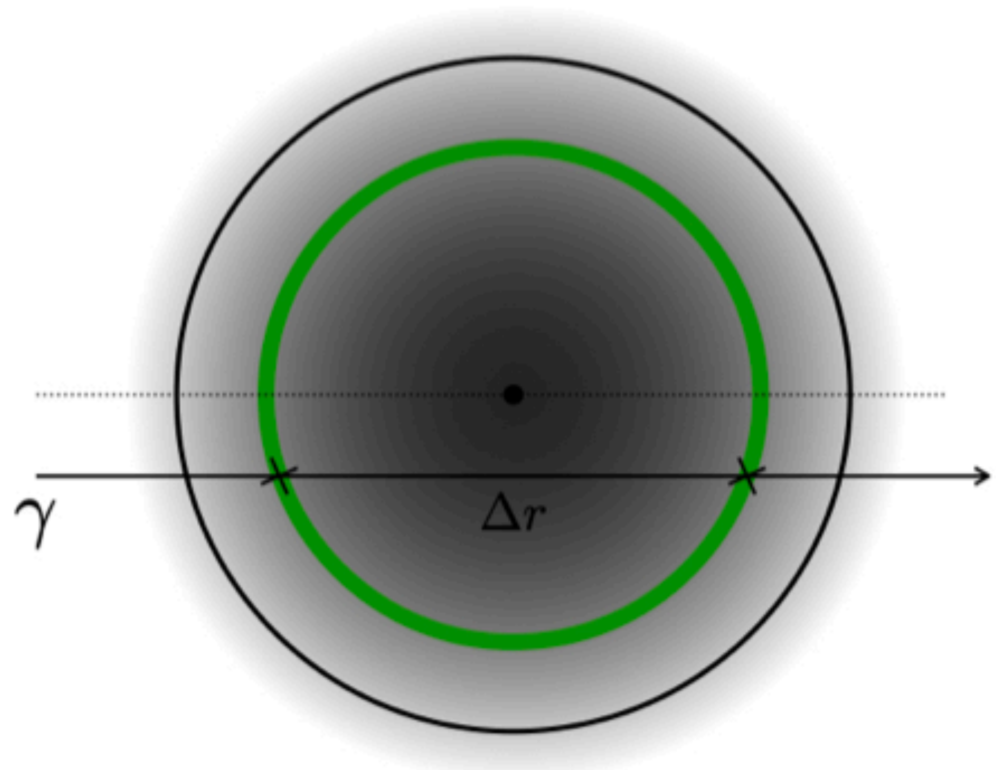


Navarro, Frenk, and White, 1996
N. Battaglia, 2016

Resonant conversion in halos



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

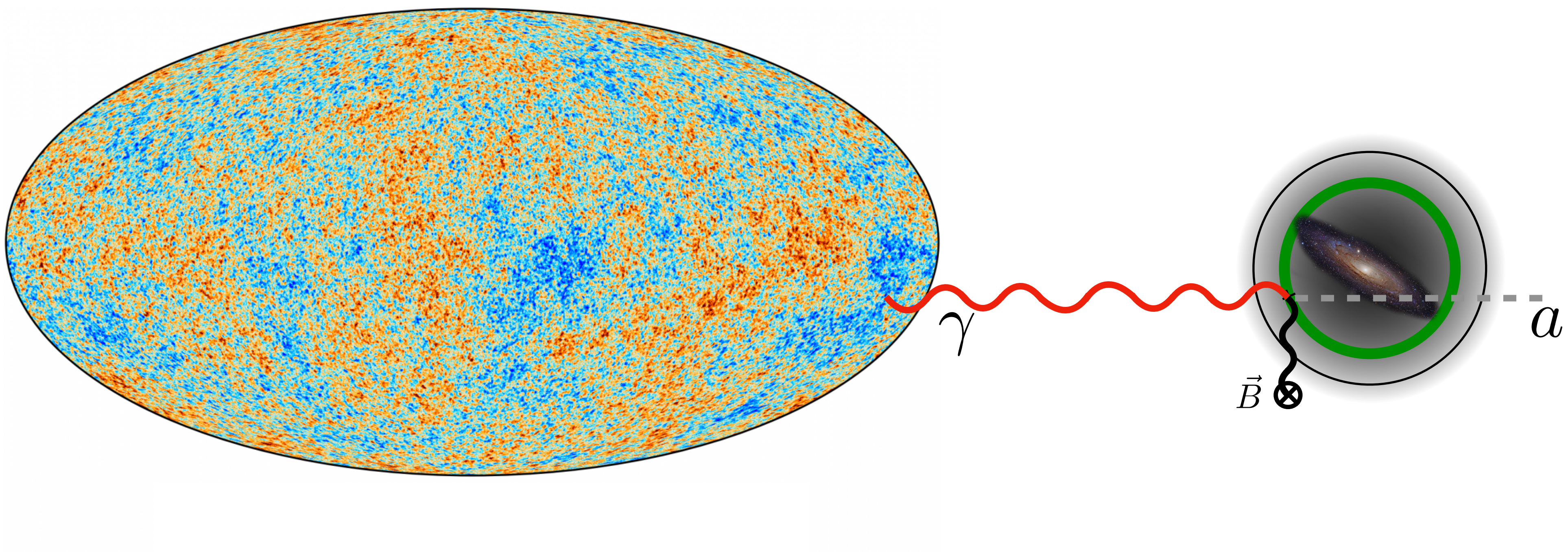


Depends on:

- **halo density profile**
- **frequency of the photon**

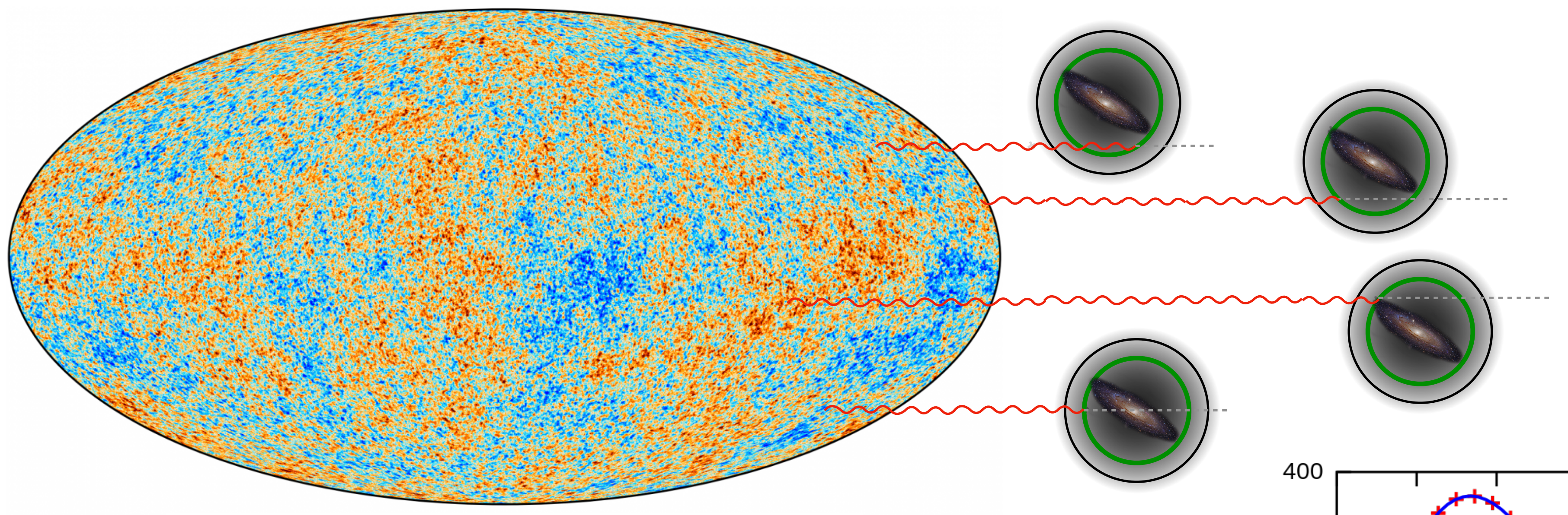
CMB photon disappearance

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

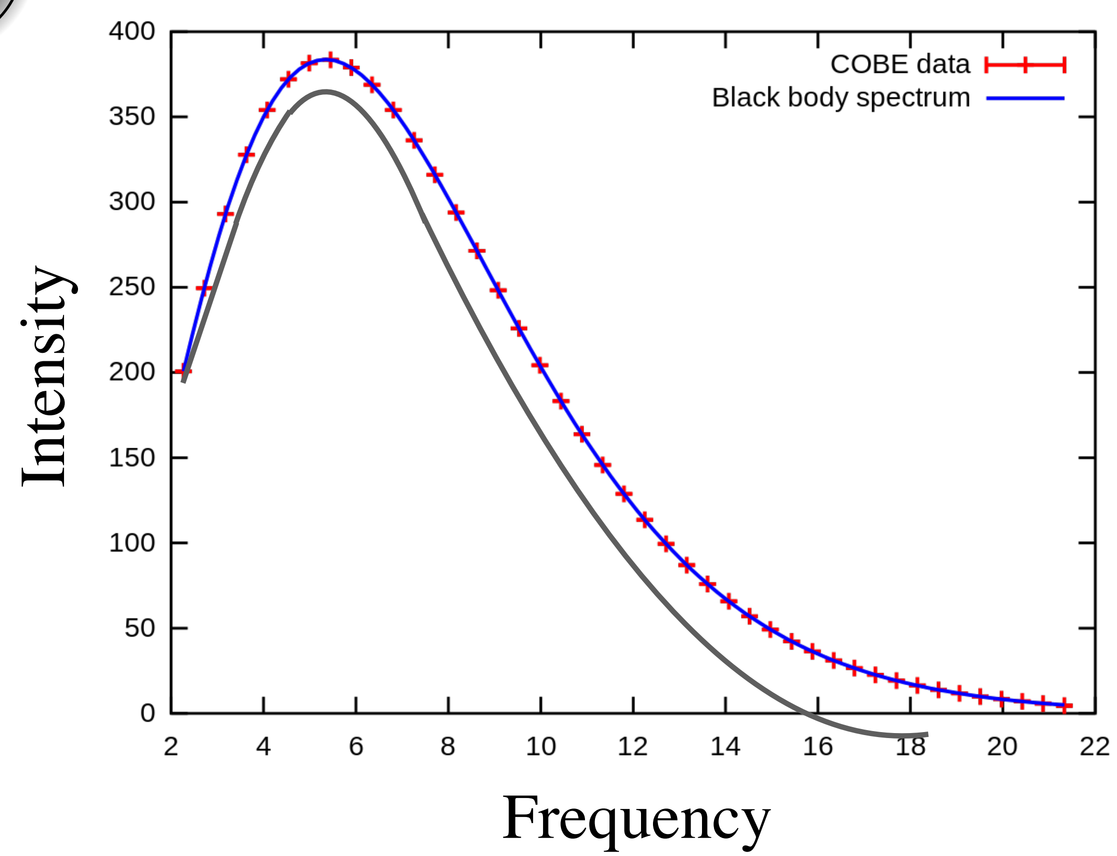


CMB photon disappearance

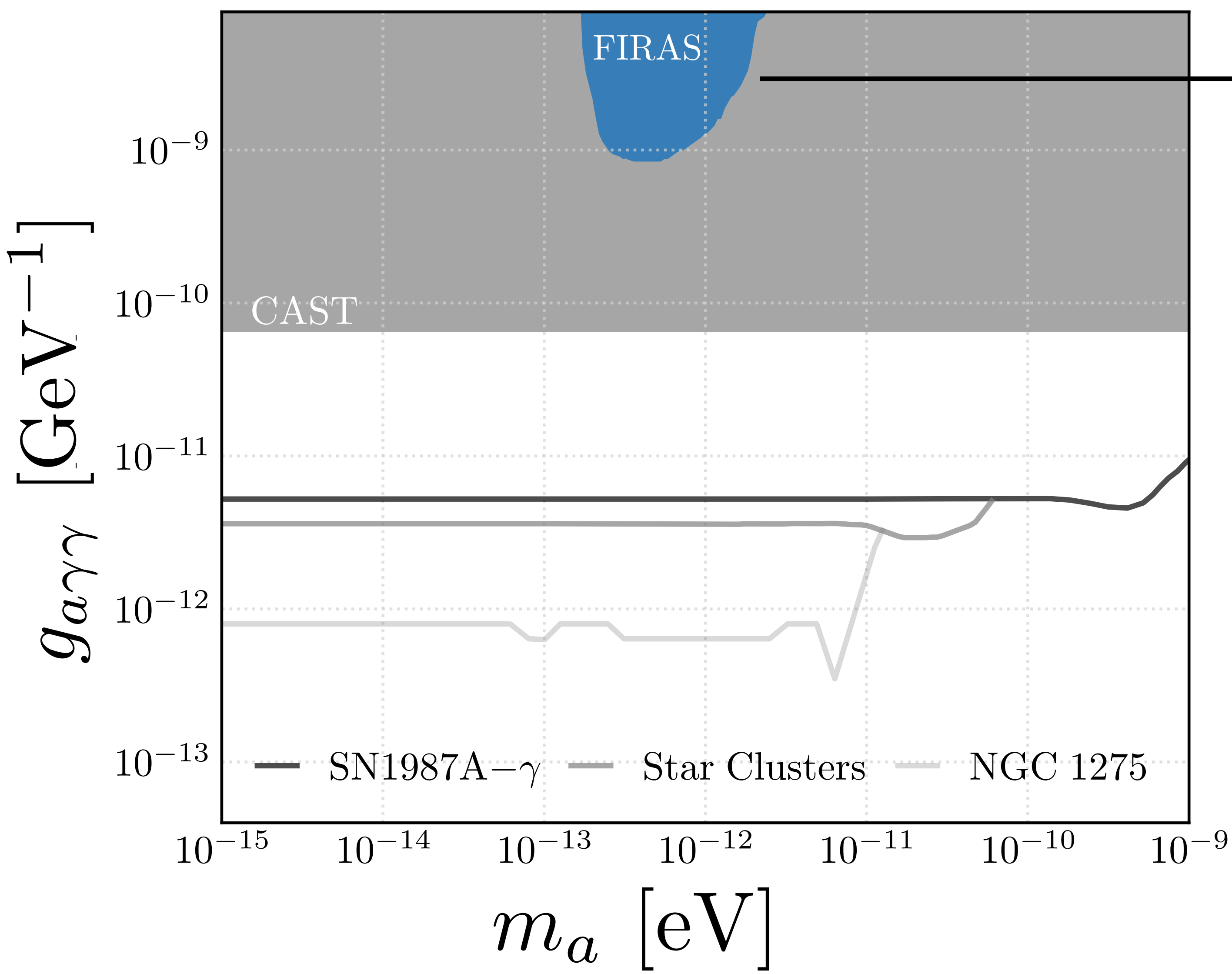
$$P^{\rm res}_{\gamma\to a} = g^2_{a\gamma\gamma} B^2 \frac{\pi\omega}{m_a^2} \left| \frac{d \ln \omega^2_{\rm pl}}{dt} \right|^{-1}_{t_{\rm res}}$$



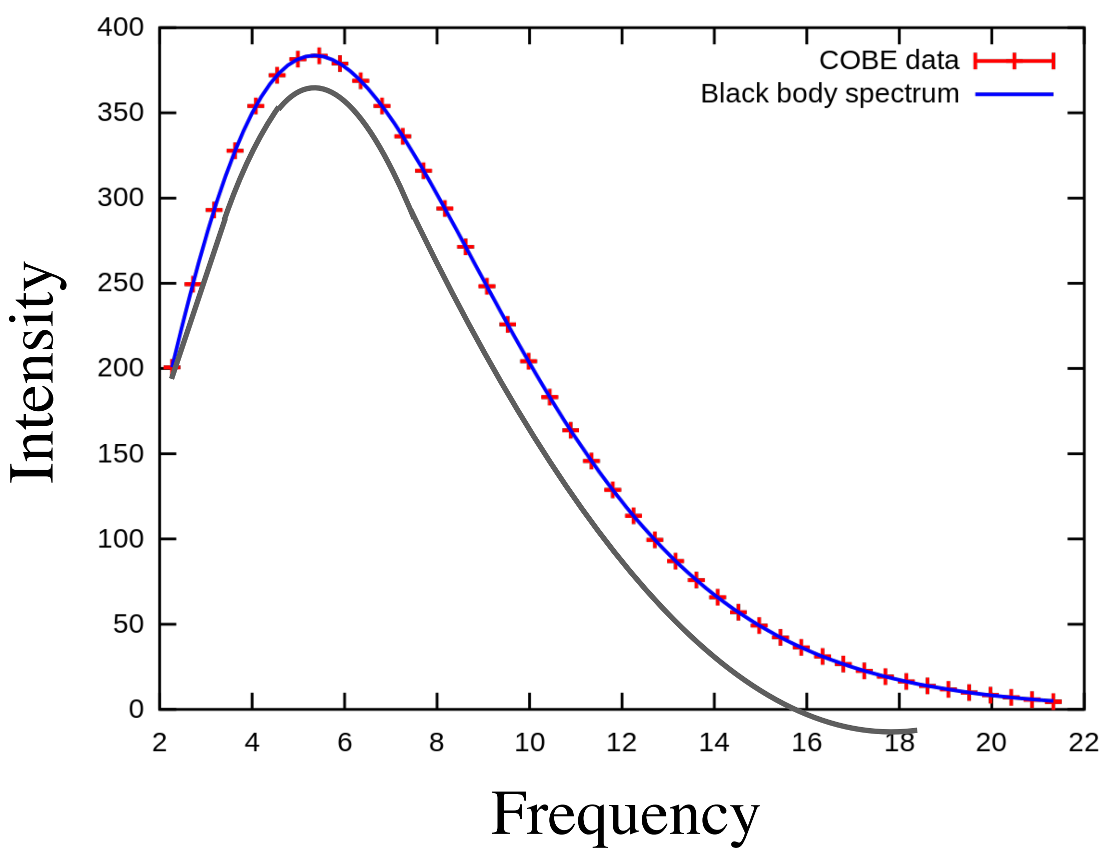
Distortion of the black body spectrum



CMB photon disappearance

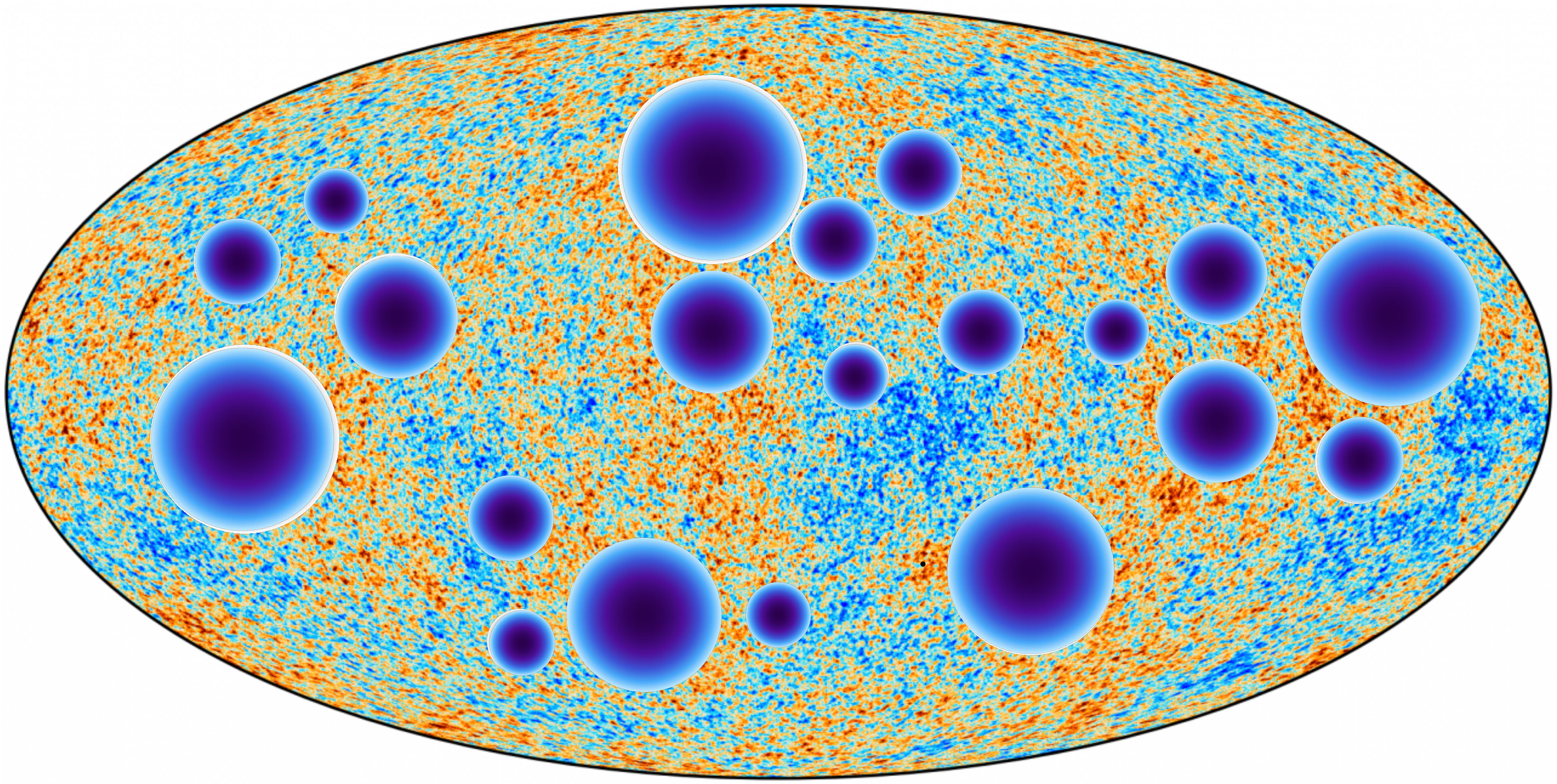


COBE/Firas constraint from spectral distortion



Anisotropic screening

The signal is not isotropic!



Anisotropic screening

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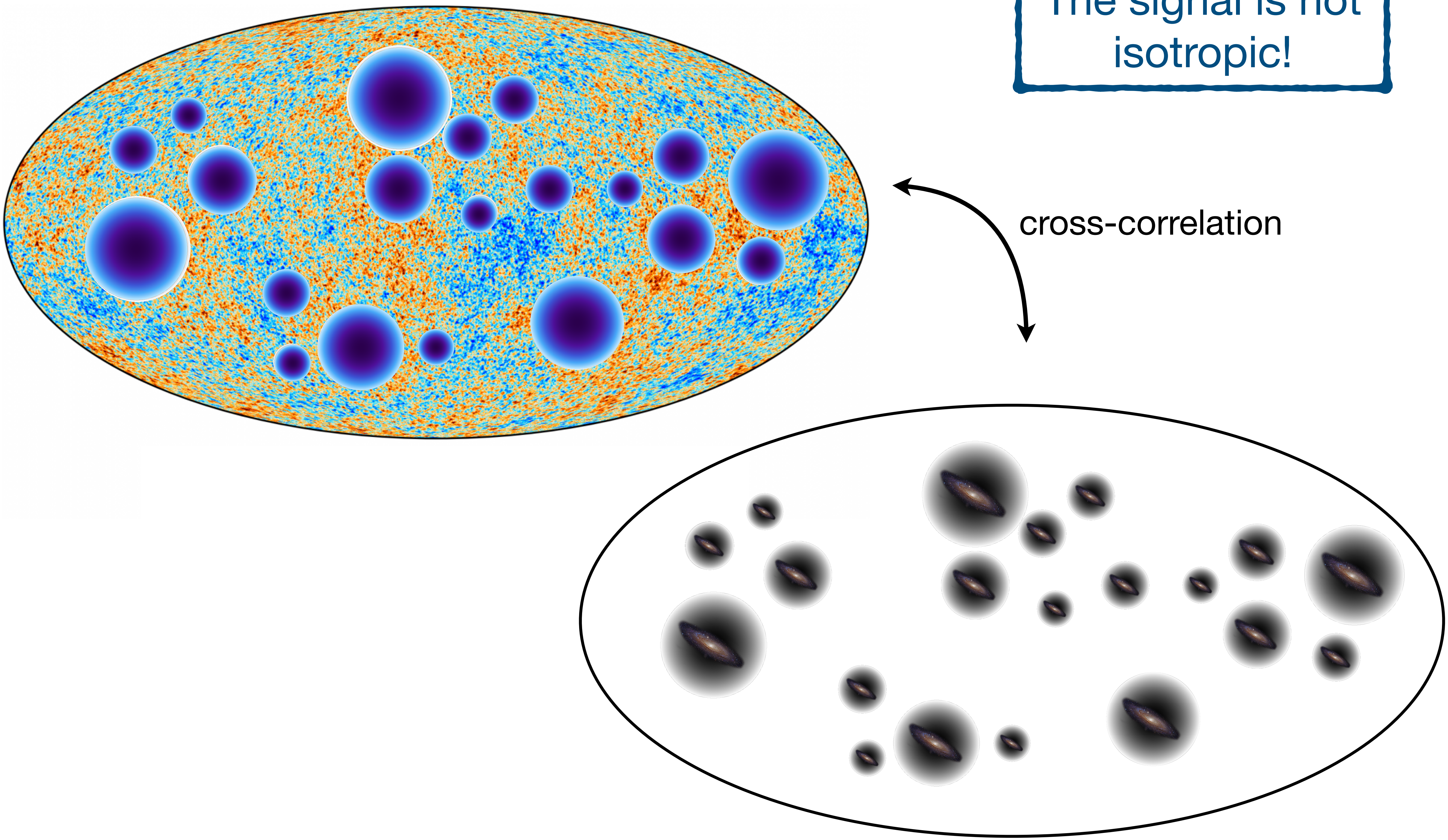

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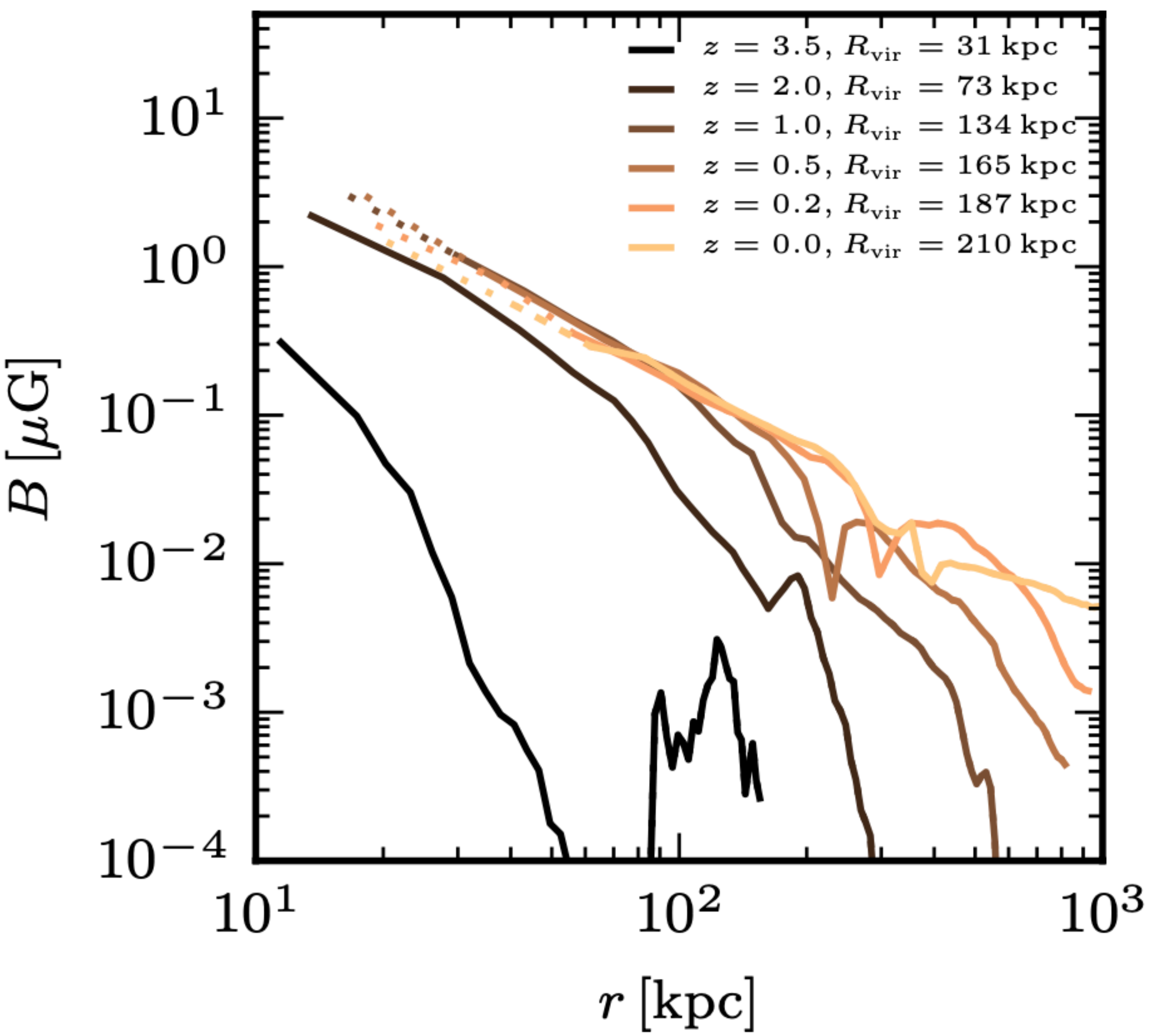
Halo B field

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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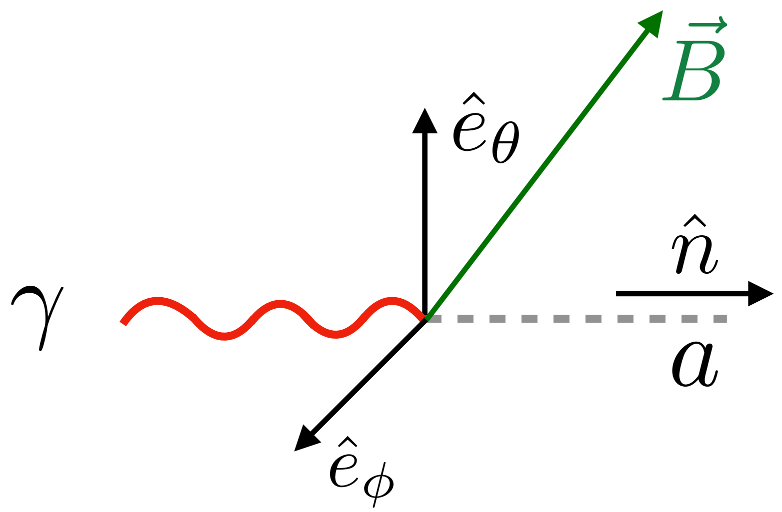
Axion screening



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

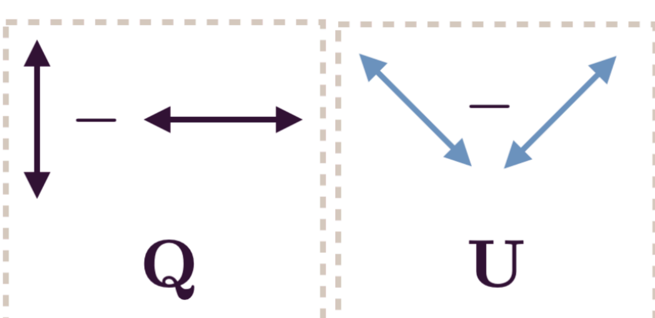
Only $B \parallel$ to the polarization direction
(CP conservation)

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

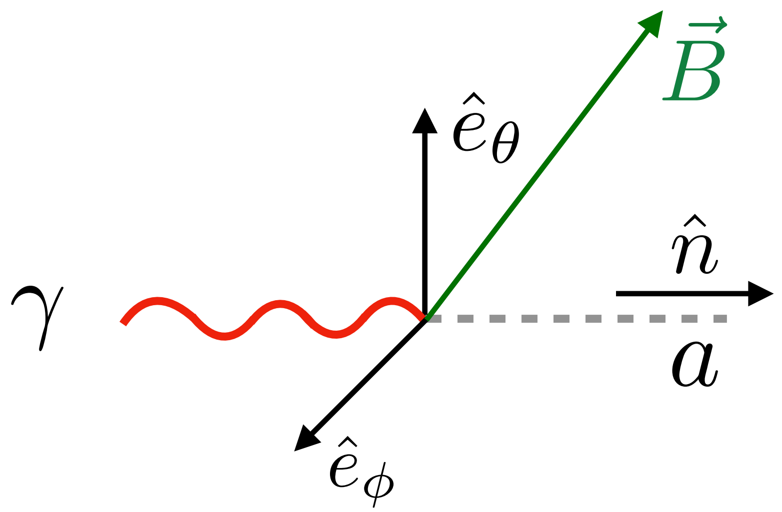
Intensity $$I_{\mathbf{axion}} \propto -I_{\mathbf{CMB}} \frac{g^2_{a\gamma\gamma}(B^2_\theta + B^2_\phi)}{2}$$

Polarization $$Q_{\rm axion} \propto -I_{\rm CMB} \frac{g^2_{a\gamma\gamma}(B^2_\theta - B^2_\phi)}{2}$$

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



Axion screening



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

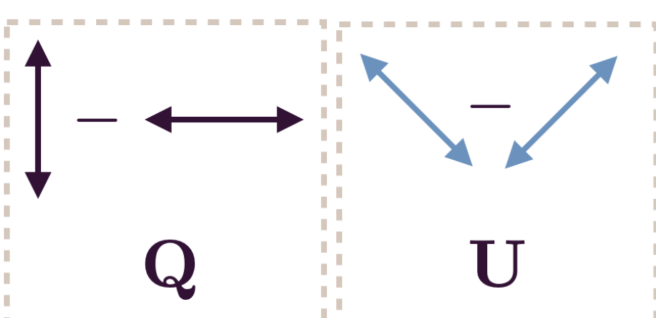
Only $B \parallel$ to the polarization direction
(CP conservation)

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

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

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

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



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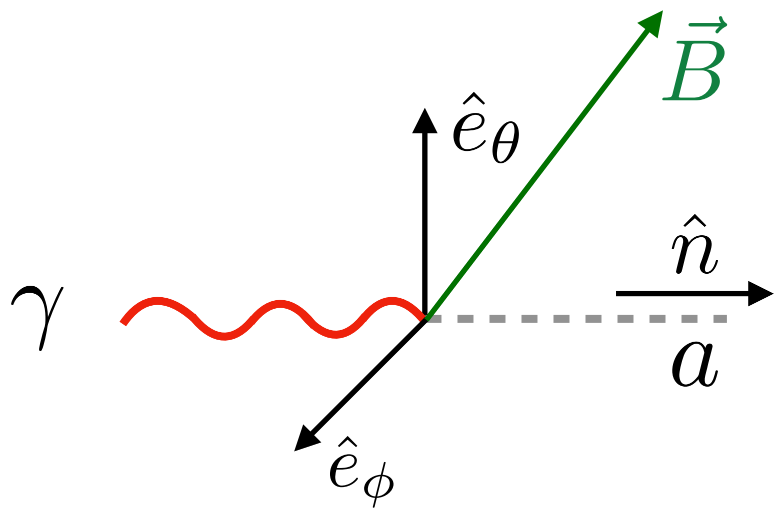
One-point function: temperature



Only $B \perp$ to the line of sight
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Only $B \parallel$ to the polarization direction
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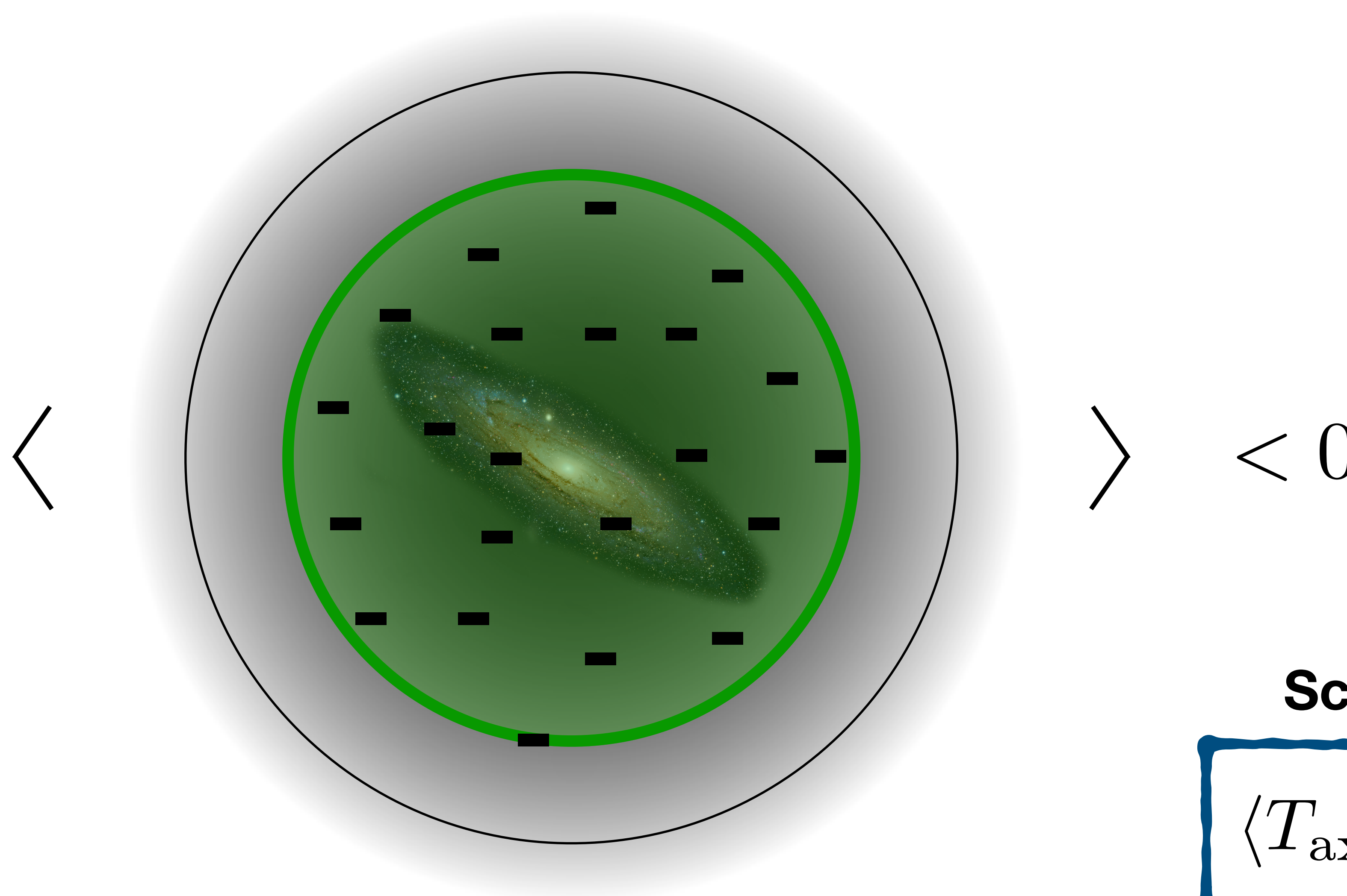
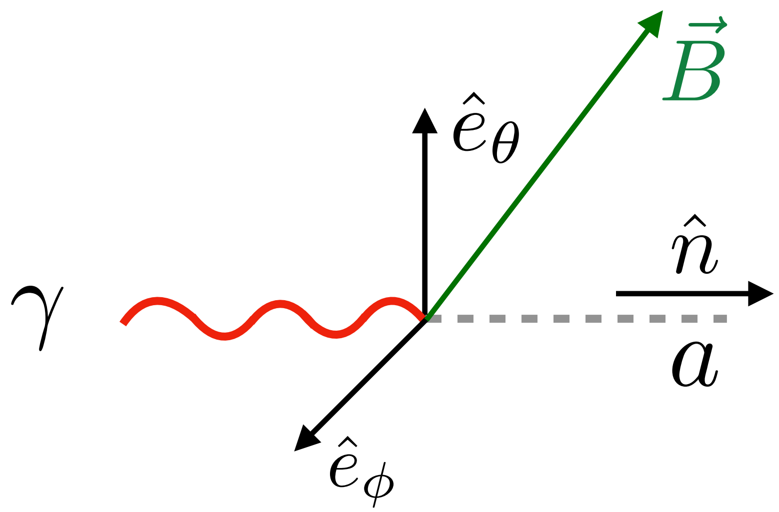


Screening

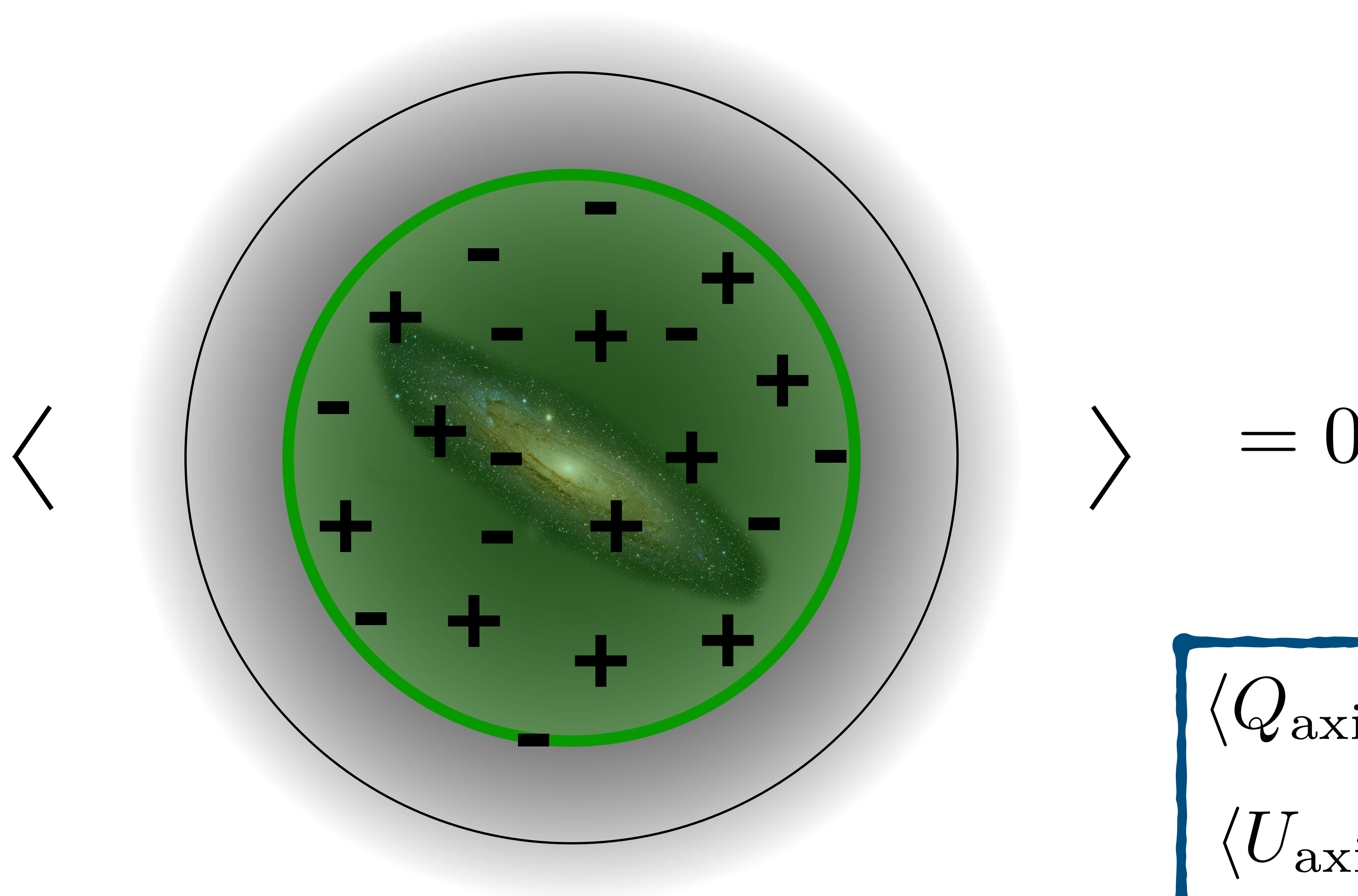
$$\langle T_{\rm axion} \rangle < 0$$

One-point function: polarization



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

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

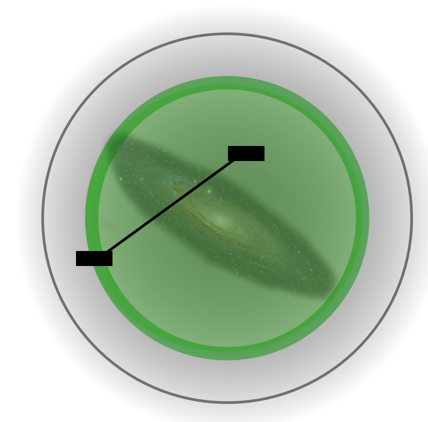


$$\langle Q_{\rm axion} \rangle = 0$$

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

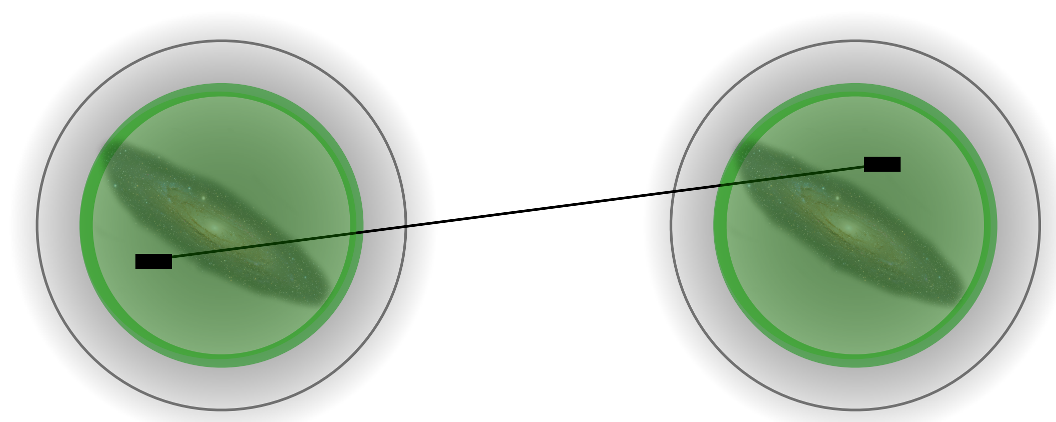
Two-point function: temperature

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

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

Small scale

(halo shape)

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

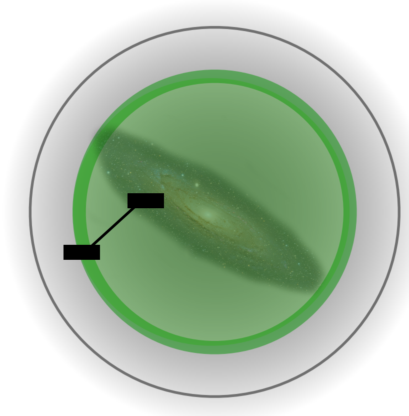
Clustering

↓

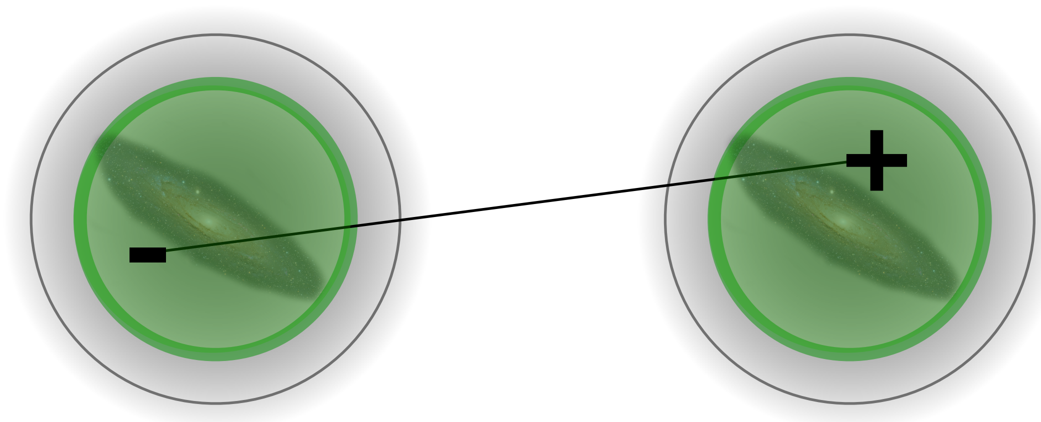
halo-halo auto-correlation (matter power spectrum)

Two-point function: polarization

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

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

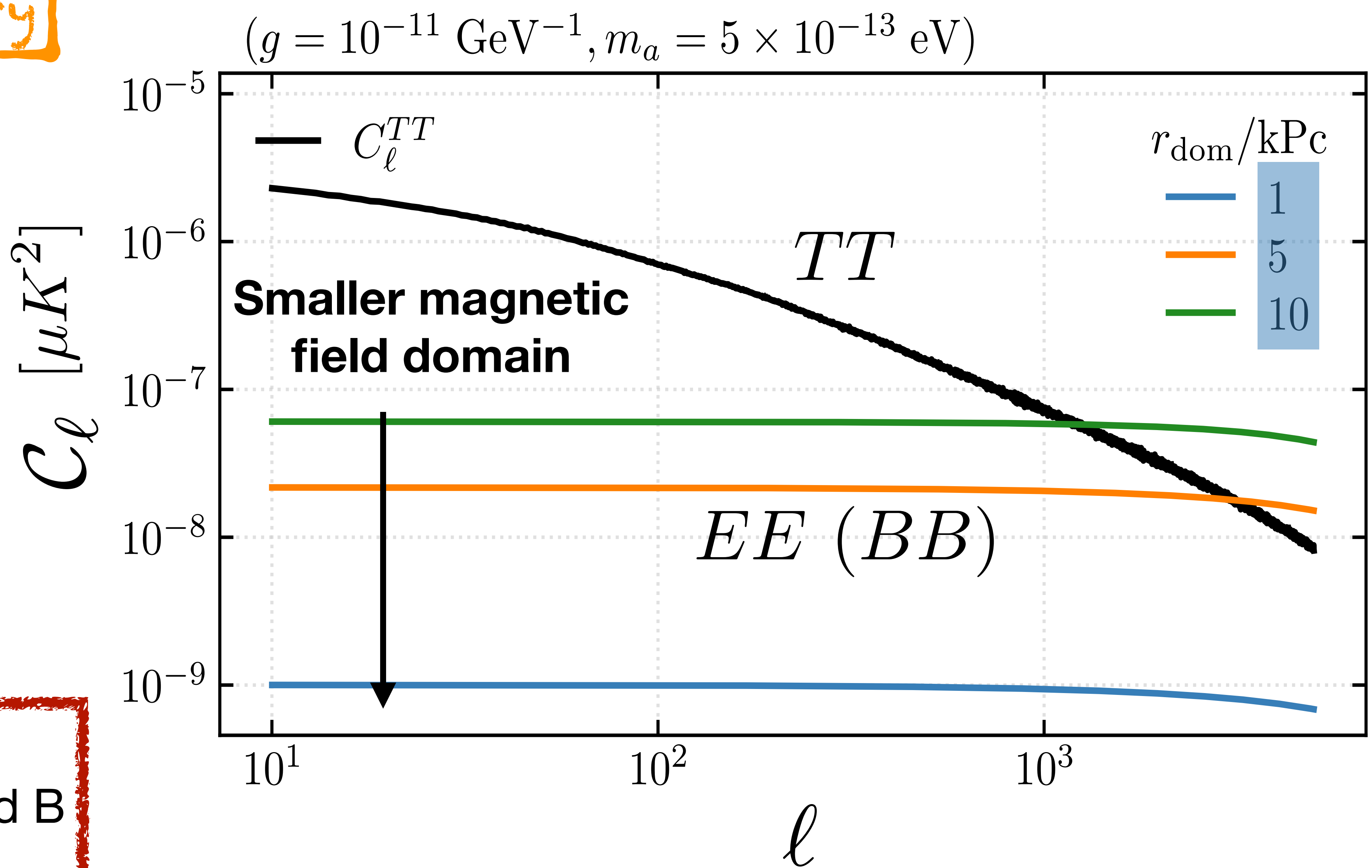
Angular size of the magnetic field coherence domain

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

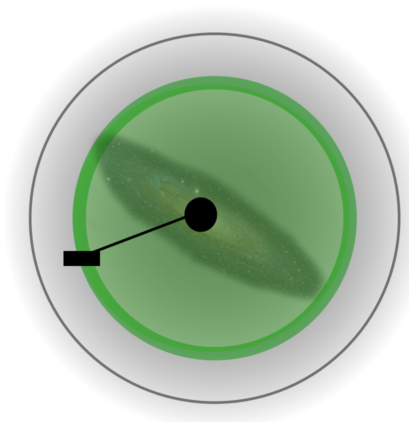


< max angular resolution

The axion signal for E and B is the same

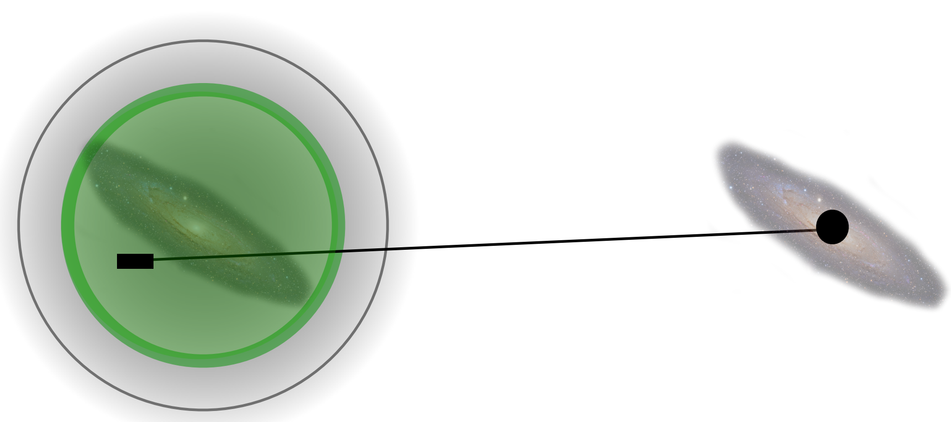
Cross-correlation: temperature

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

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

Small scale

(halo shape)

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

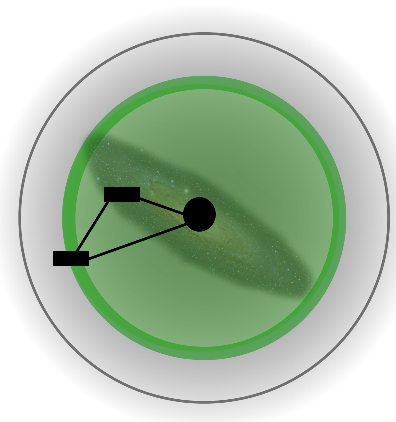
Clustering

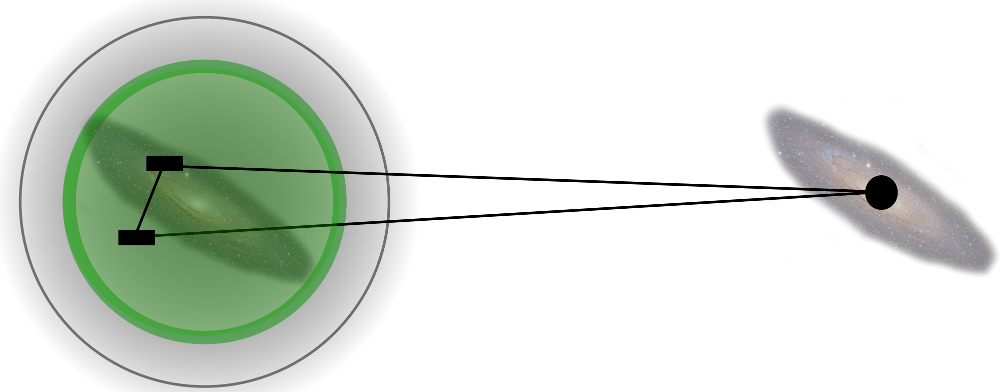
↓

halo-halo auto-correlation (matter power spectrum)

Cross-correlation: polarization

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

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

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

↓

halo-halo auto-correlation (matter power spectrum) **Clustering**

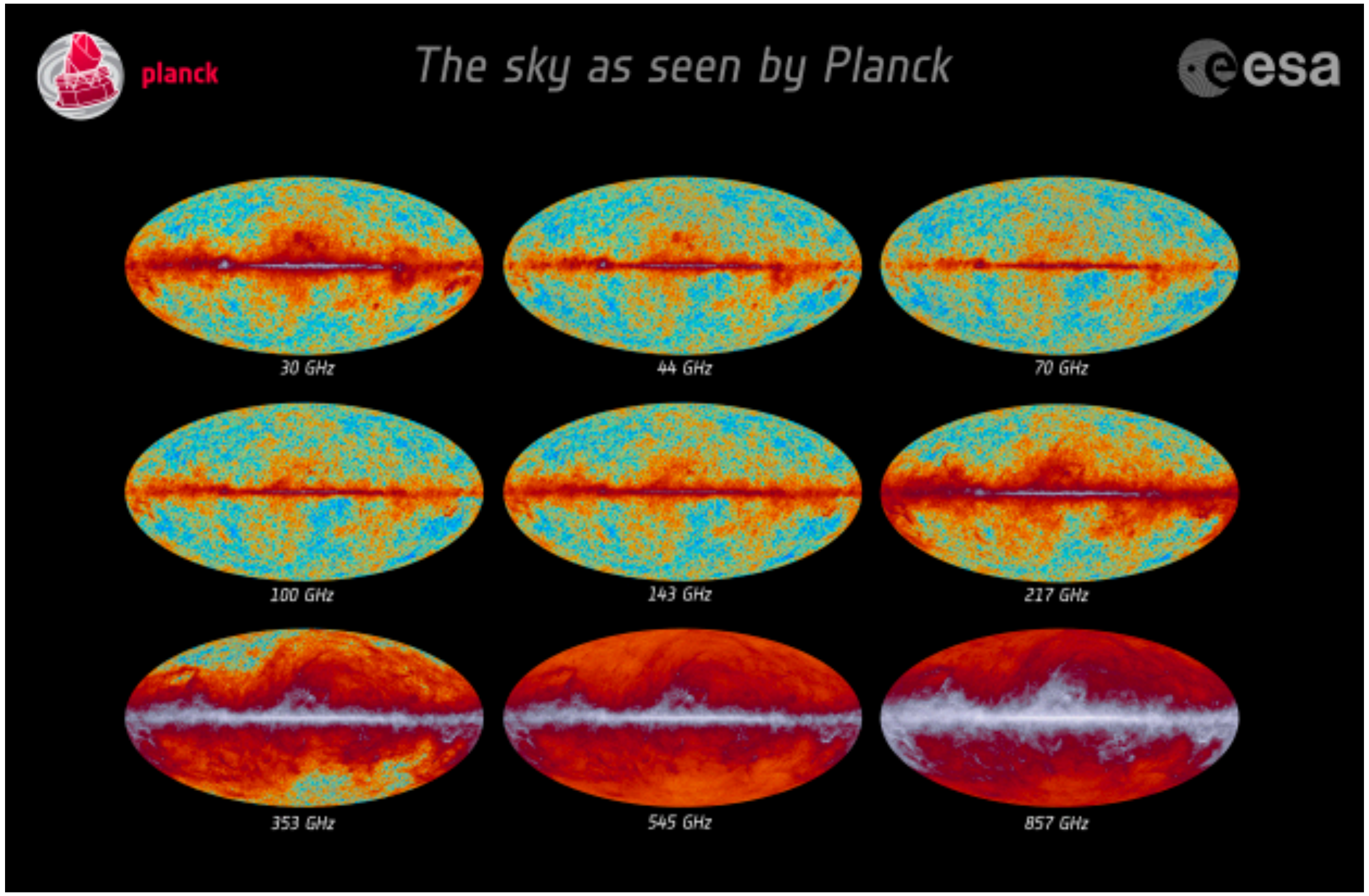
$$\langle BBg\rangle \sim \mathcal{C}_l^{BB}\mathcal{C}_l^{hh}$$

Outline

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

Internal Linear Combination (ILC)

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

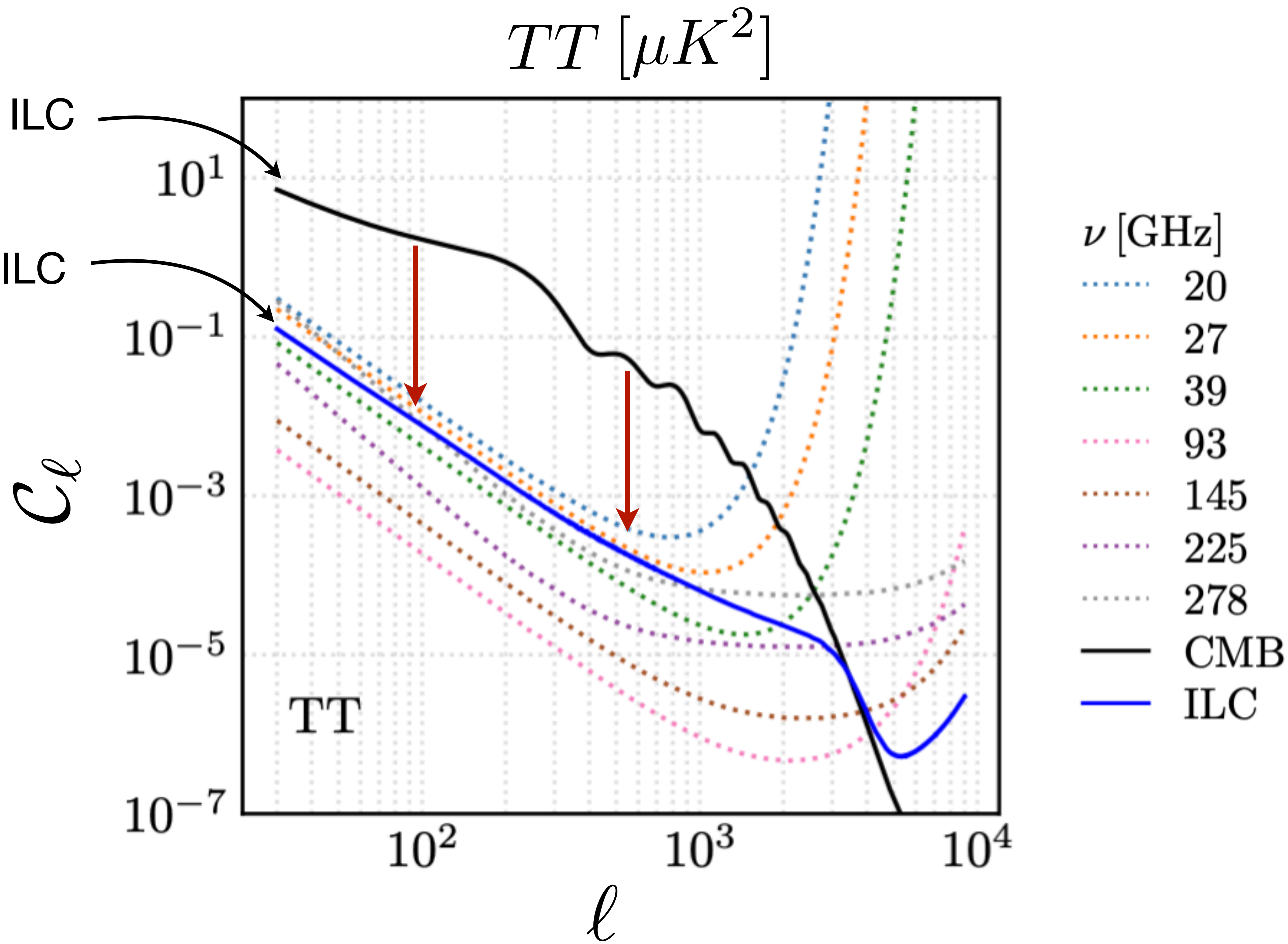


Weight different maps appropriately to minimize the noise with respect to the **frequency scaling of the signal**

ILC cleaning

Noise without ILC

Noise with ILC



We can see a signal if it is above the blue line

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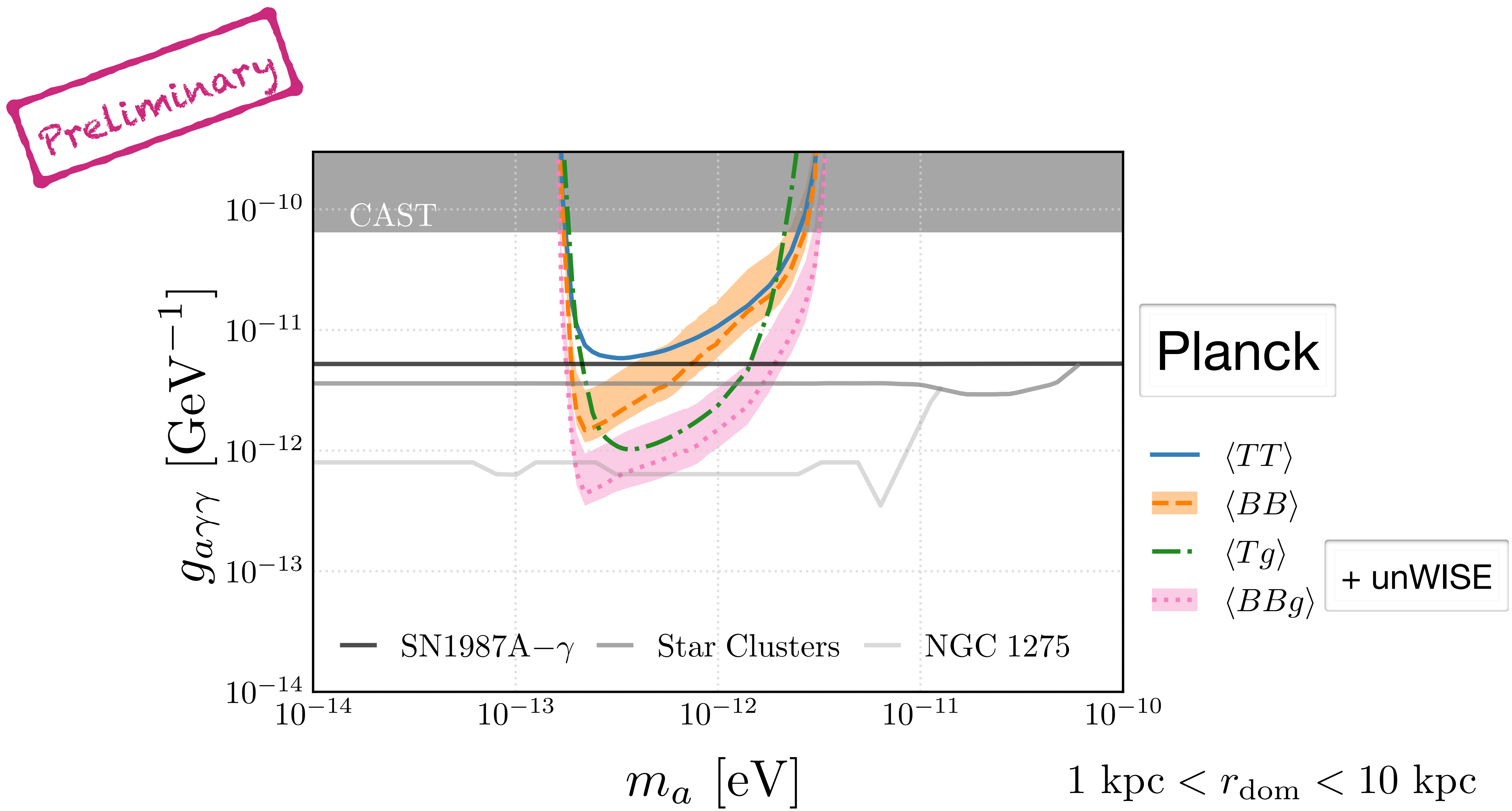
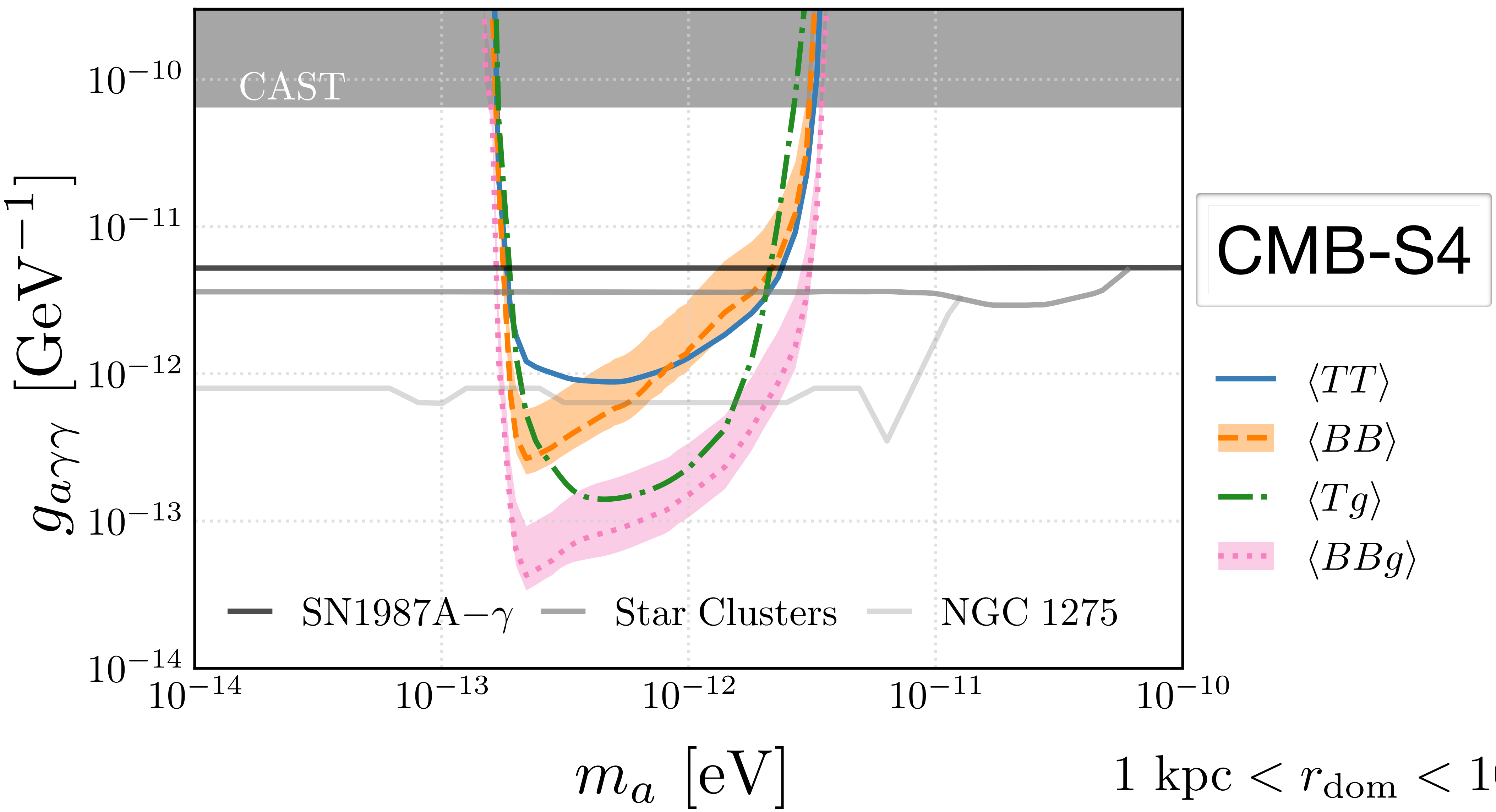
Projections: Planck + unWISE



$1\ \mathrm{kpc} < r_{\mathrm{dom}} < 10\ \mathrm{kpc}$

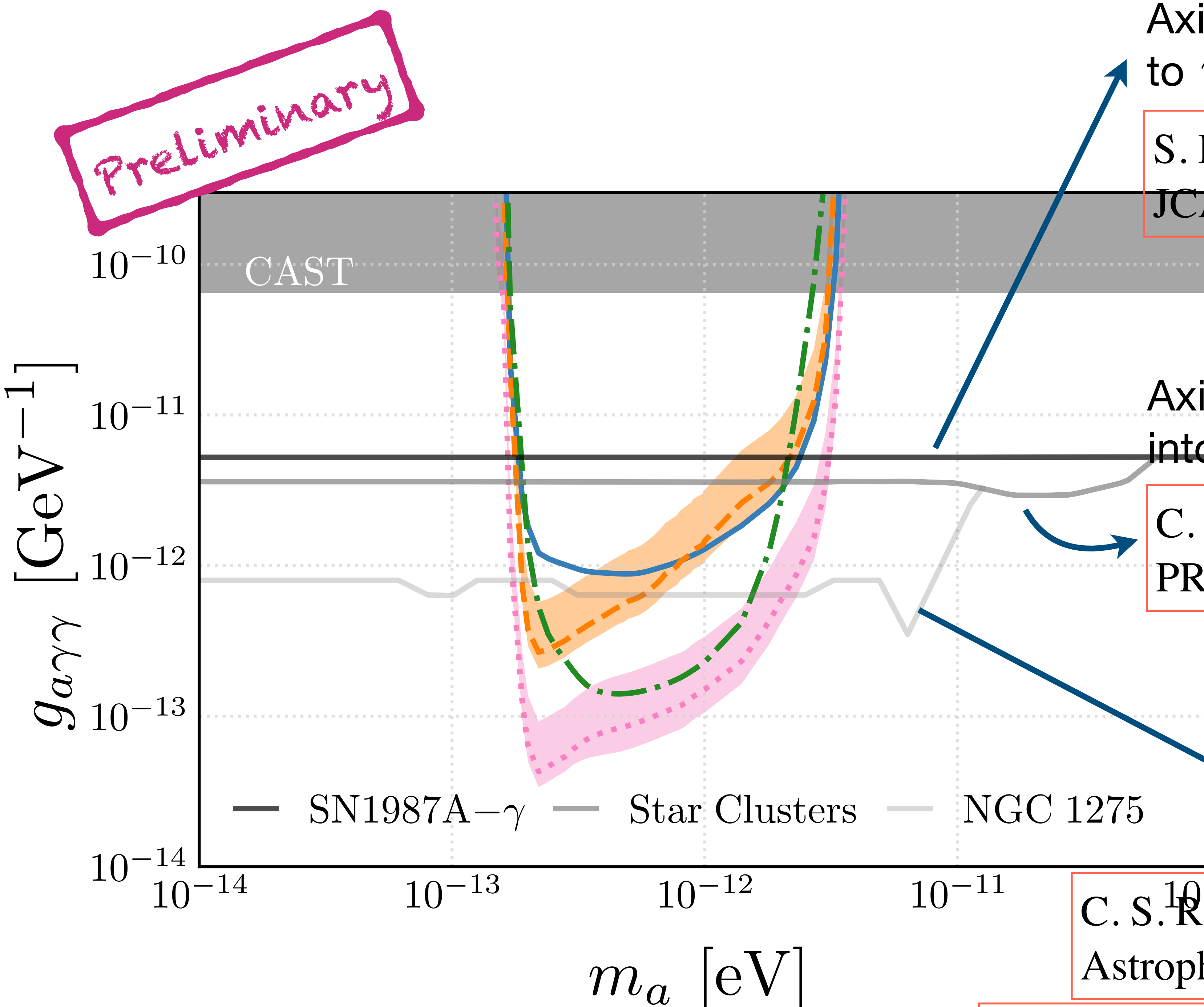
Projections: CMB-S4 + unWISE

Preliminary



$1\ \mathrm{kpc} < r_{\mathrm{dom}} < 10\ \mathrm{kpc}$

Astro bounds



Axions produced in SN1987A converting to γ-rays within the MW B field

S. Hoof, L. Schulz,
JCAP, 03 (2023) 054, arXiv:2212.09764

Axions produced in stars converting into X-ray within the MW B field

C. Dessert, J. Foster, B. R. Safdi,
PRL 125 (2020) 16, arXiv:2008.03305

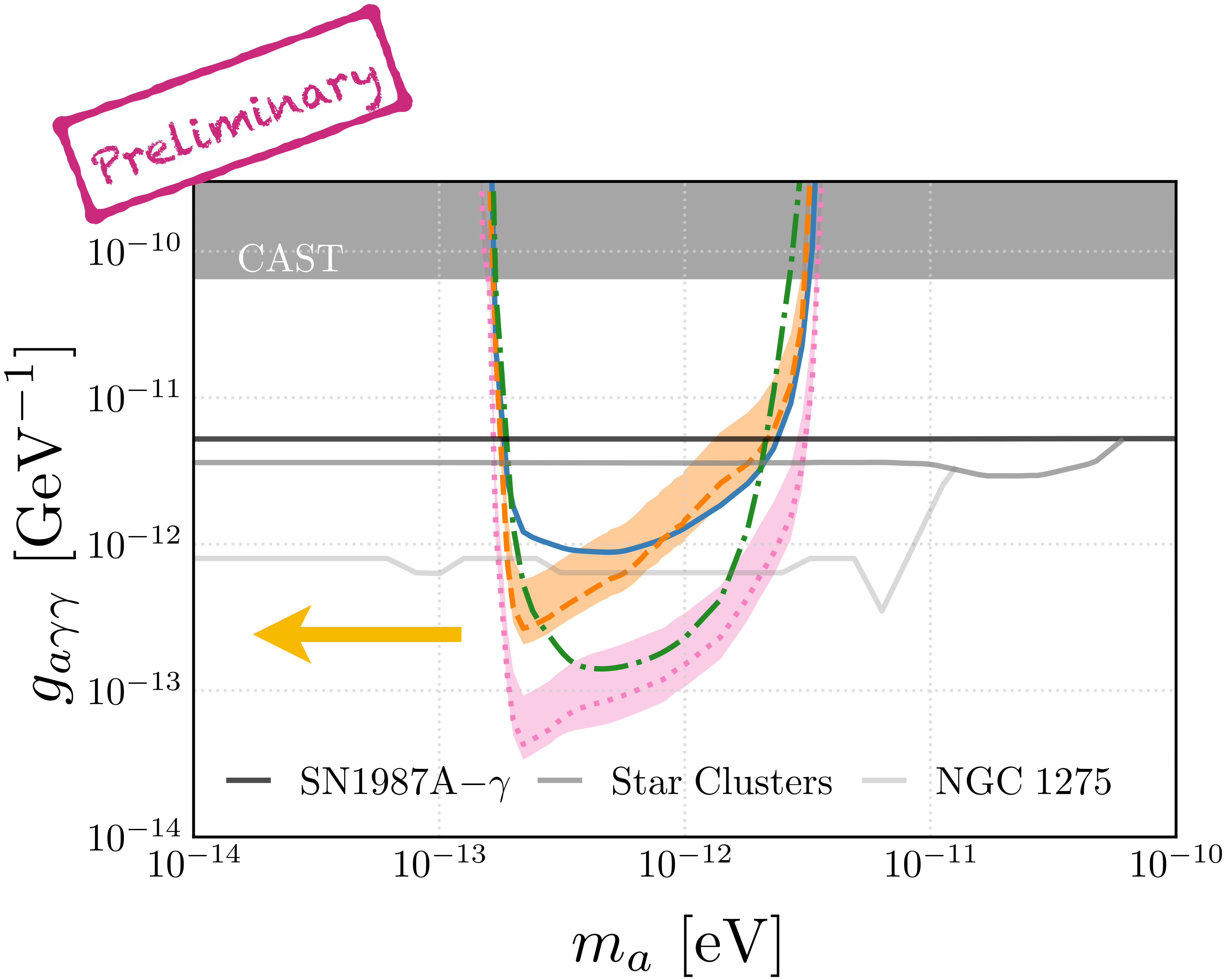
Distortions of X-ray spectra of cluster-hosted quasars

C. S. Reynolds, M.C.D. Marsh et al.,
Astrophys. J. 890, 59 (2020), arXiv:1907.05475

M. Libanov, S. Troitsky,
Phys. Lett. B, 802, 135252 (2020), arXiv:1908.03074

Large systematics from B field modeling?

Probing smaller masses?

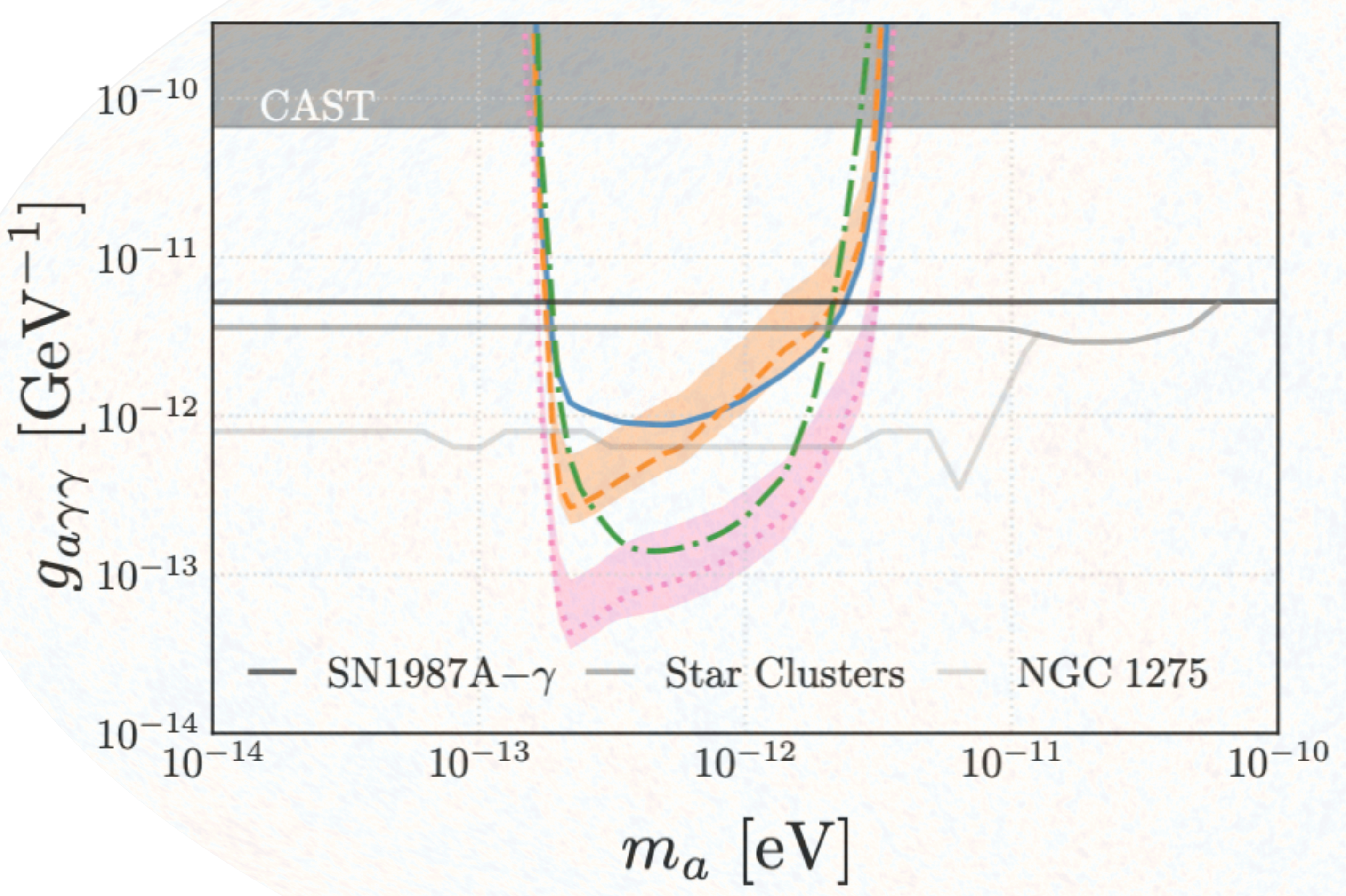


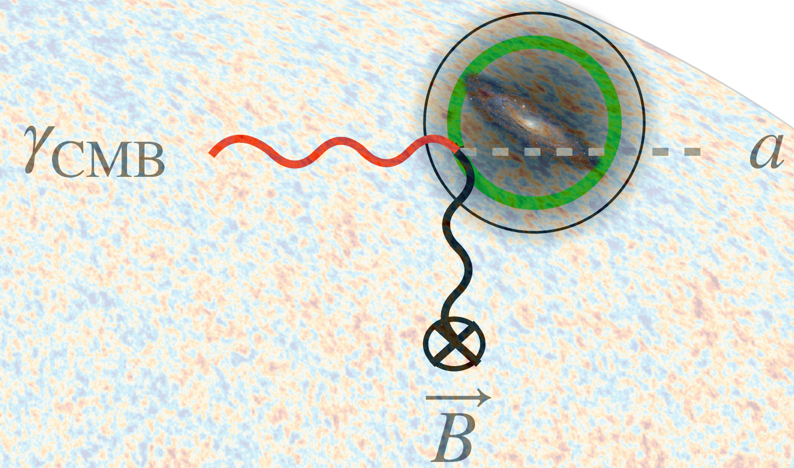
- Resonant conversion outside halos
- Non-resonant conversion

$$P_{\gamma\to a} \sim \frac{g_{a\gamma\gamma}^2 B^2 \omega^2}{\omega_{\rm pl}^4}$$

Still anisotropic

Summary





New Physics can induce secondary anisotropies

example from this talk: axions on the CMB

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

+ Sam Goldstein, Colin Hill, Fiona McCarthy

With Dalila Pîrvu , Junwu Huang, and Matt Johnson