Title: A new probe to axion-like particles from upcoming CMB experiments

Date: Jan 14, 2019 11:00 AM

URL: http://pirsa.org/19010069

Abstract: <p>Cosmic Microwave Background (CMB) is a powerful probe to the Universe which carries signatures of cosmic secrets over a vast range of redshifts. Along with spatial fluctuations, spectral distortions of CMB blackbody are also a rich source of cosmological information. In my talk, I will introduce a new kind of spectral distortion of CMB which can arise due to the conversion of CMB photons into Axion-Like Particles (ALPs) in the presence of an external magnetic field. This effect leads to both polarized and unpolarized spatially varying spectral distortion signal with a unique spectral shape when CMB photons undergo resonant and non-resonant conversion into ALPs in the presence of the magnetic field of Milky Way, galaxy clusters and voids. I will discuss the spatial structure of this distortion which can arise from Milky Way and galaxy clusters and will show its uniqueness from other known cosmological and astrophysical signals. I will present the first all-sky map of this distortion which is obtained using the data of Planck satellite and will discuss the capability of this new cosmological window to probe ALPs from the upcoming ground-based and space-based CMB experiments such as CMB-S4, LiteBIRD, Simons Observatory, etc.</p>

A new probe to axion-like particles from upcoming CMB experiments

Suvodip Mukherjee

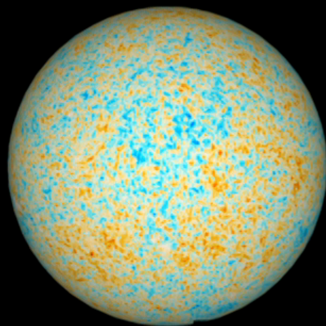
Lagrange Postdoctoral Fellow
IAP, Paris

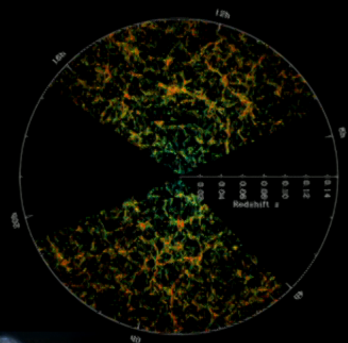
Perimeter Institute

IAP

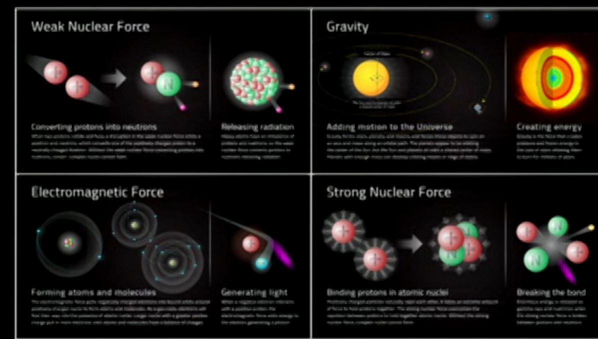
Institut Lagrange de Paris

Observational Probes



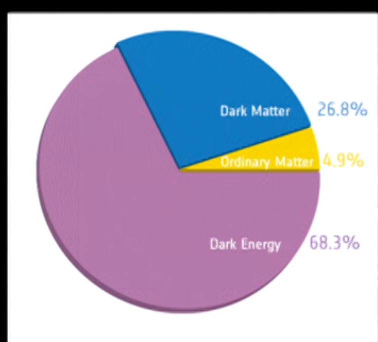


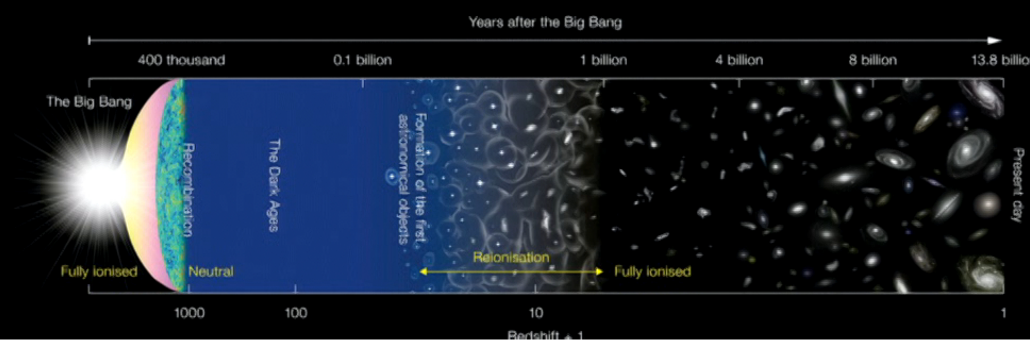
Fundamental forces



The Standard Model of Cosmology

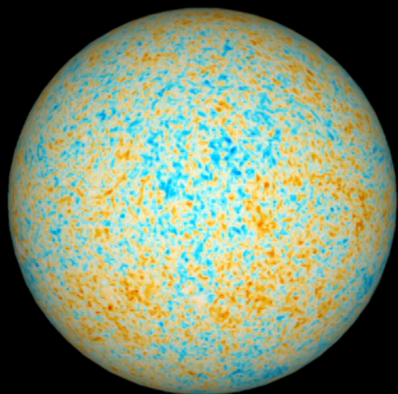
Figure courtesy: ESO

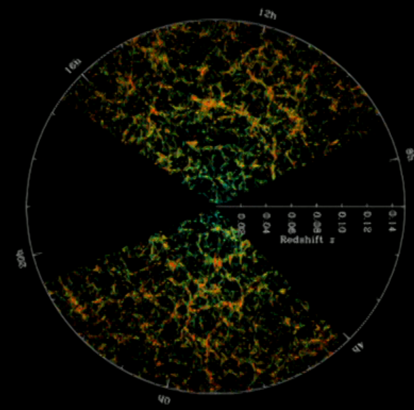


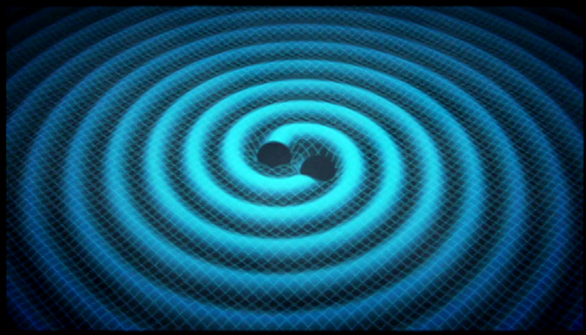


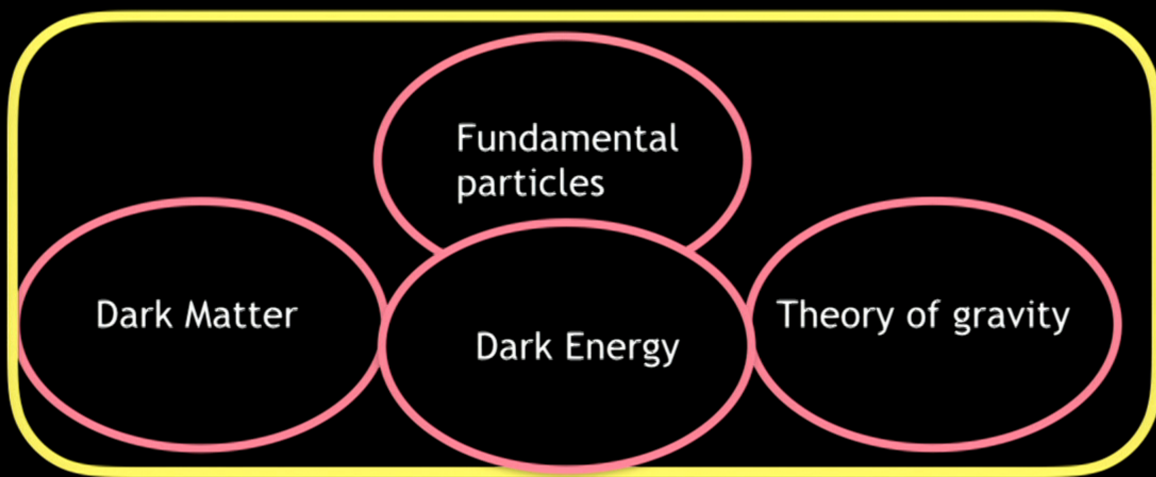
My research interest

Develop connections between cosmological probes and fundamental physics









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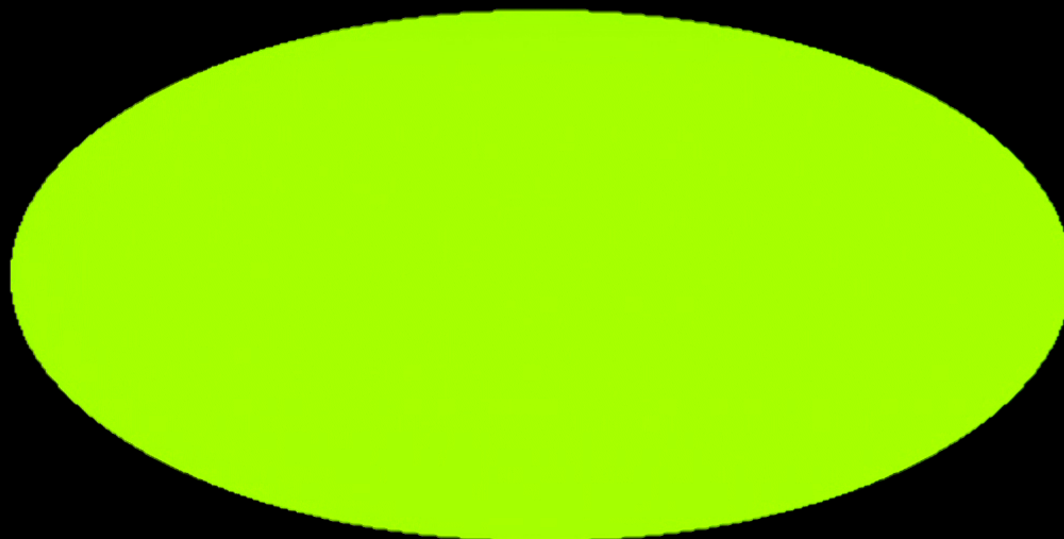
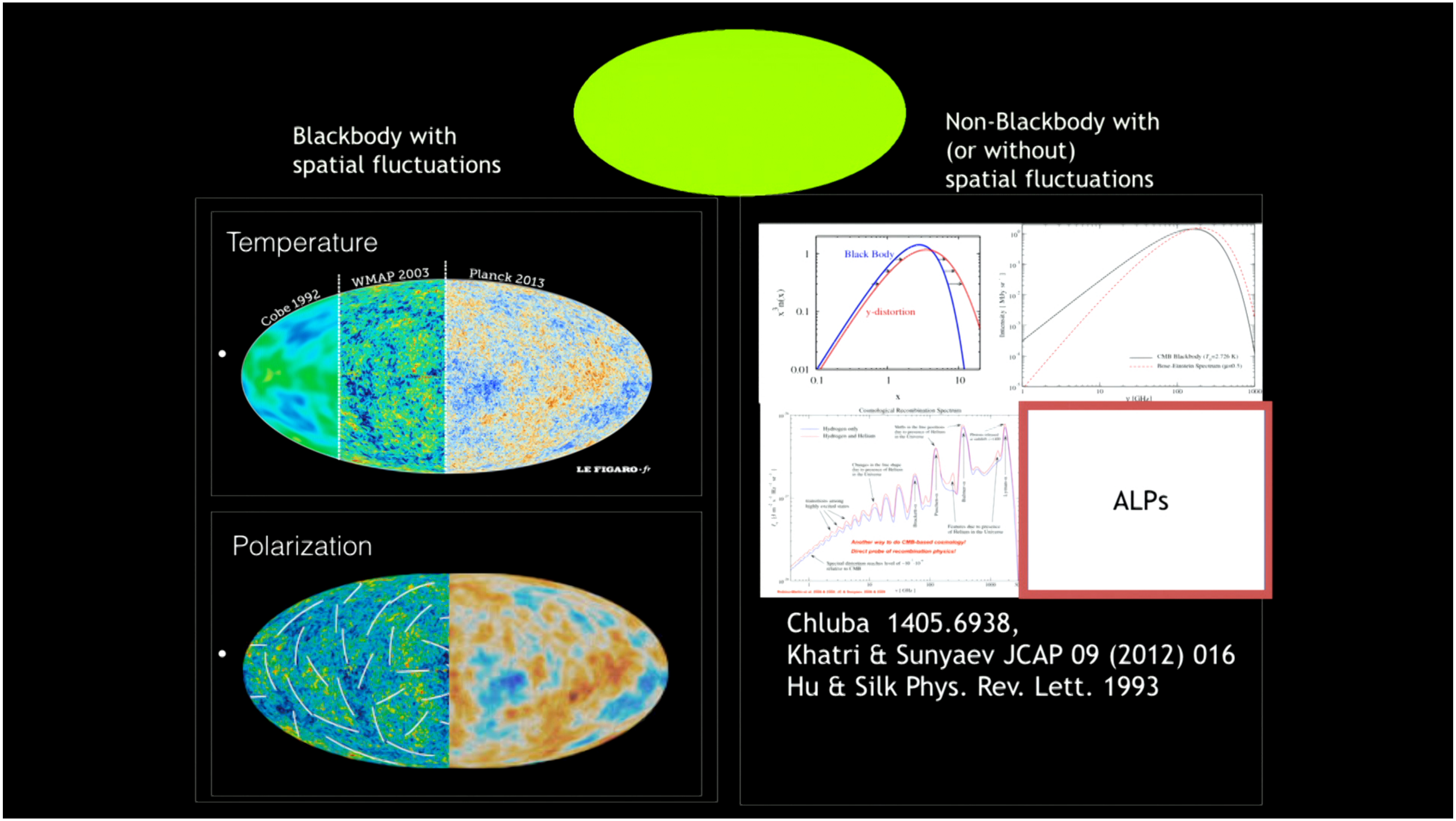
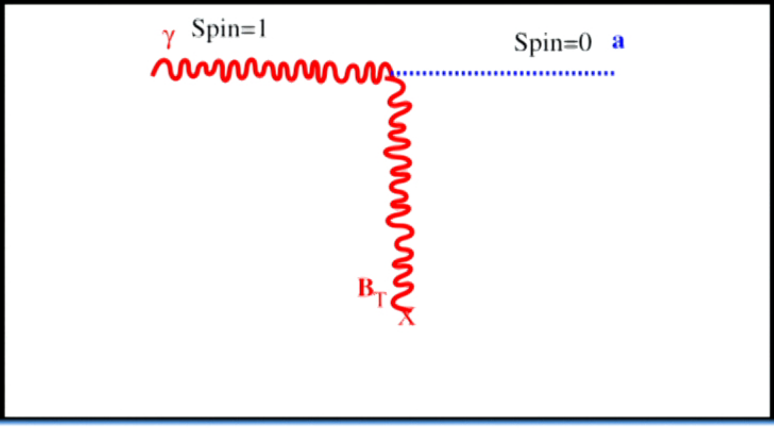
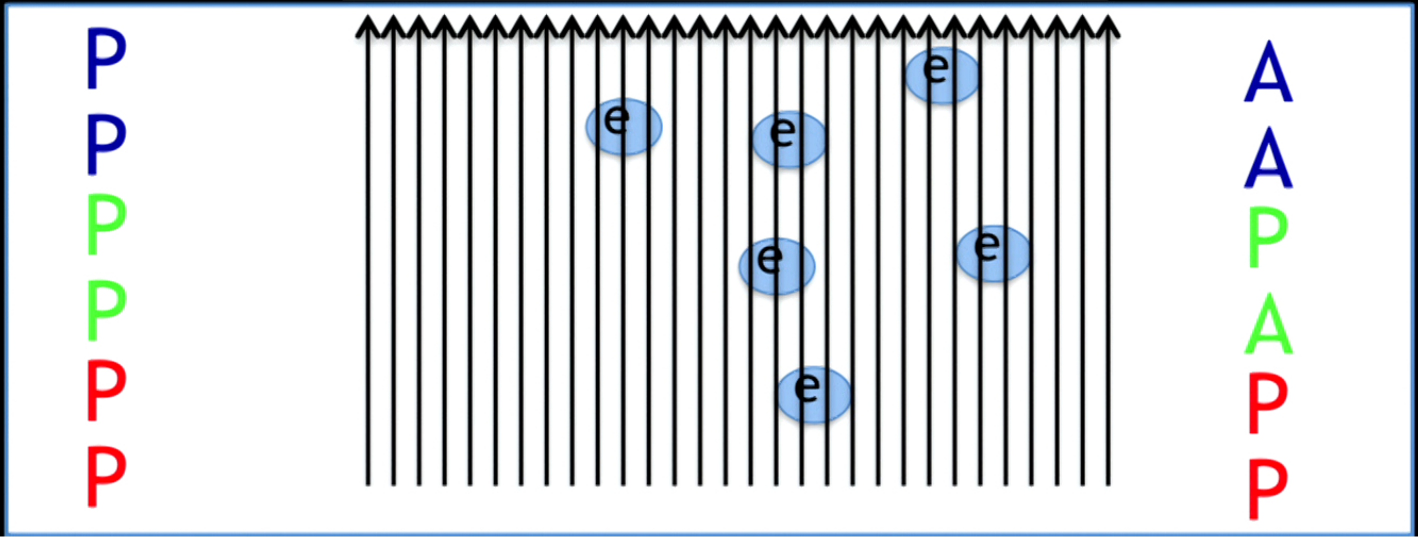
CMB Sky discovered in 1965



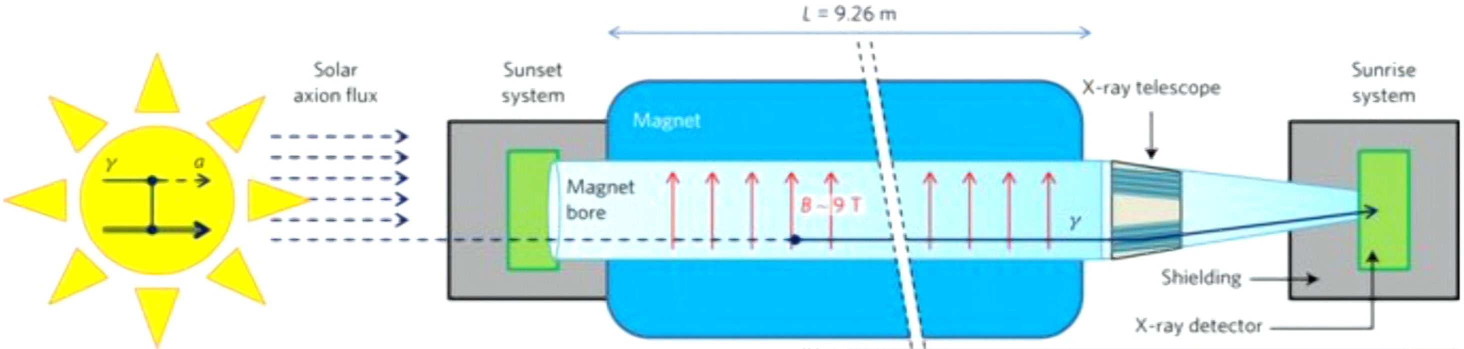

Blackbody with
spatial fluctuations
Non-Blackbody with
(or without)
spatial fluctuations
Temperature
Cobe 1992
WMAP 2003
Planck 2013
LE FIGARO.fr
Polarization
Black Body
y-distortion
ALPs
Chluba 1405.6938,
Khatri & Sunyaev JCAP 09 (2012) 016
Hu & Silk Phys. Rev. Lett. 1993

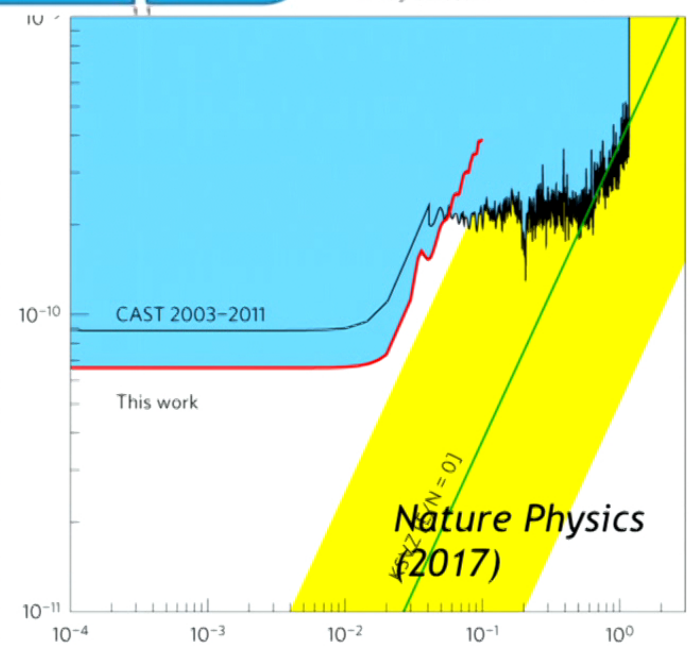
Aspects of Spectral Distortions from ALPs





ALPs are also searched by particle physicists





Signature from the Milky Way

Mukherjee, Khatri, Wandelt
JCAP 04 (2018) 045

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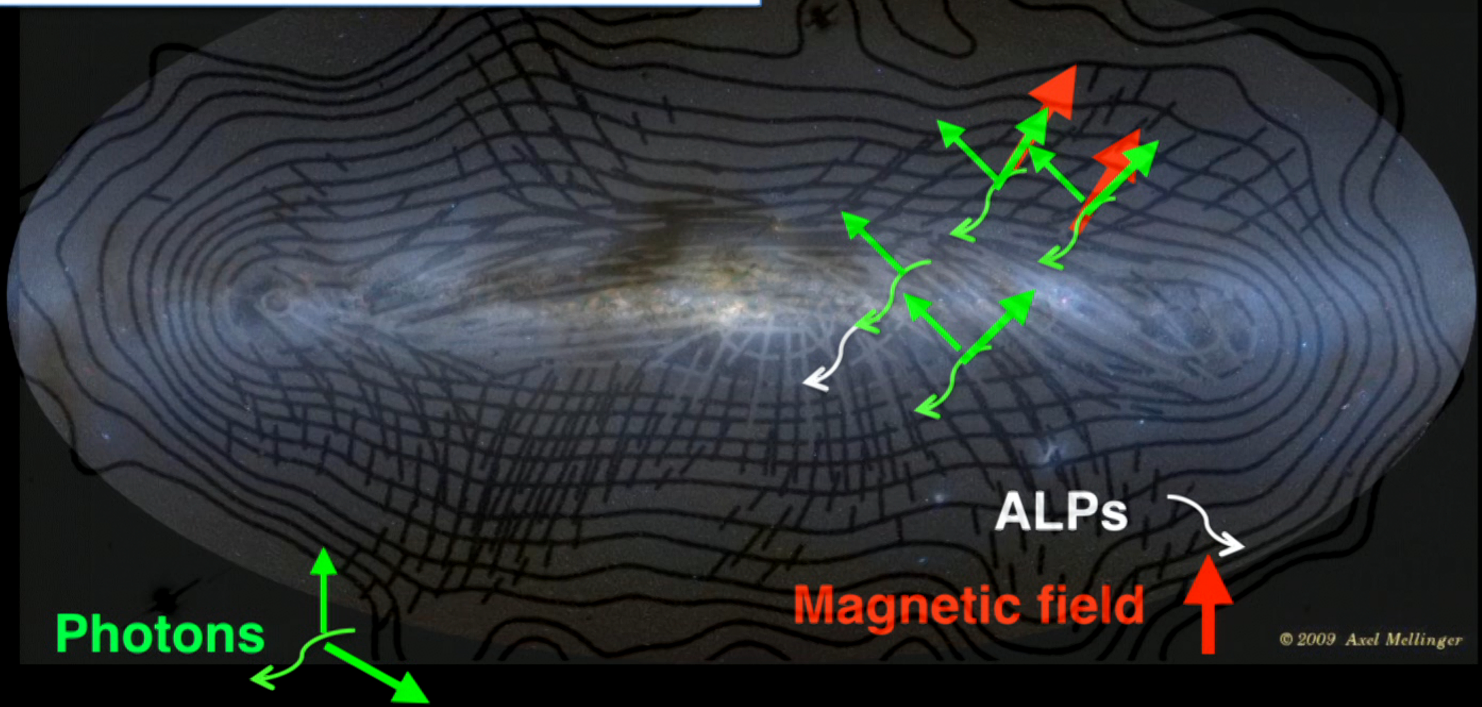
Milky Way scenario

Photons

Photon to ALPs in Milky Way

$$\mathcal{I}^{\gamma a} = \frac{\Delta I_\nu^{\gamma a}}{I_\nu} \equiv \frac{I_\nu^{\rm obs} - I_\nu}{I_\nu} = -P(\gamma \to a)$$



Photon to ALPs in Milky Way

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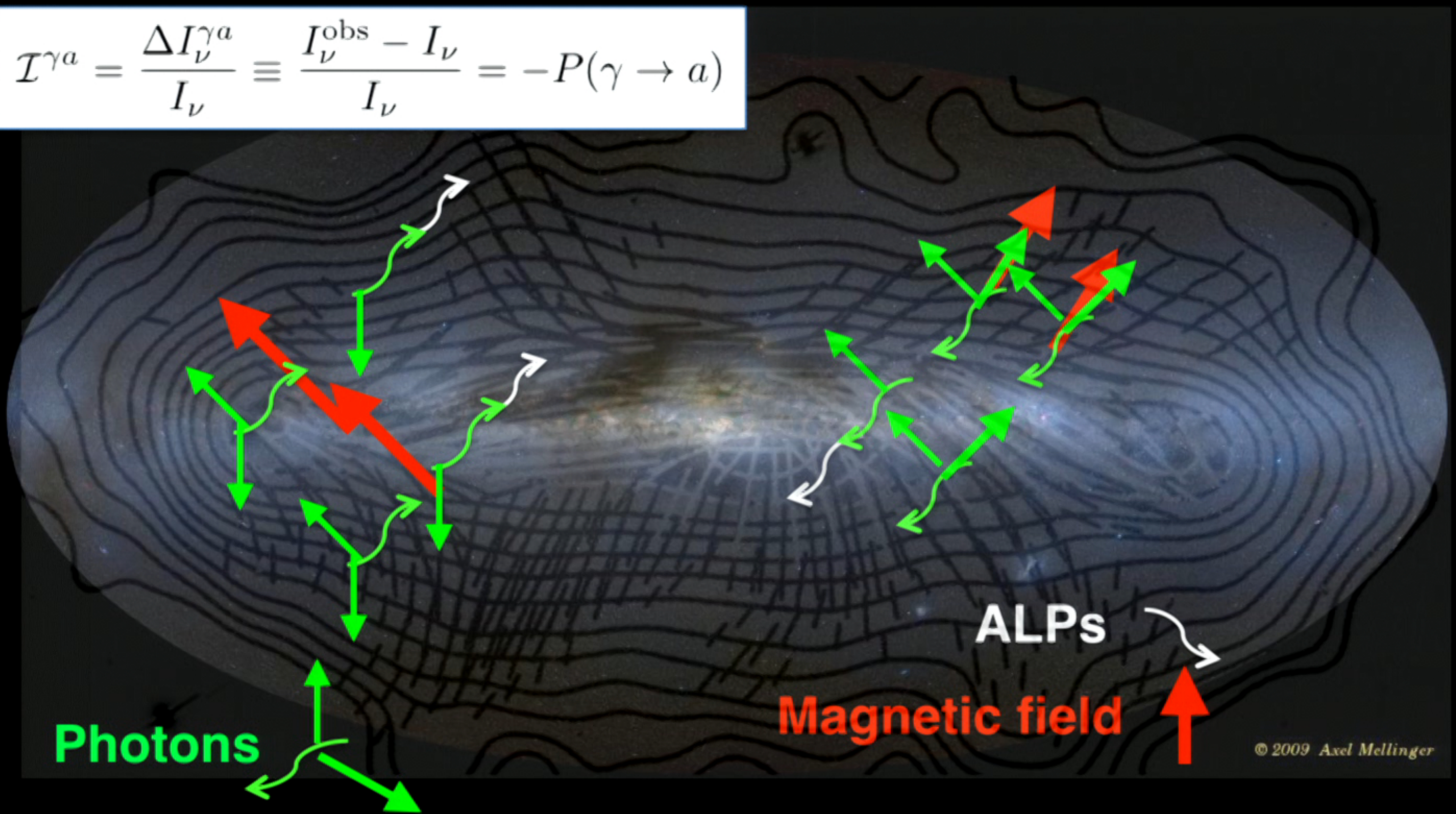

Photon to ALPs in Milky Way

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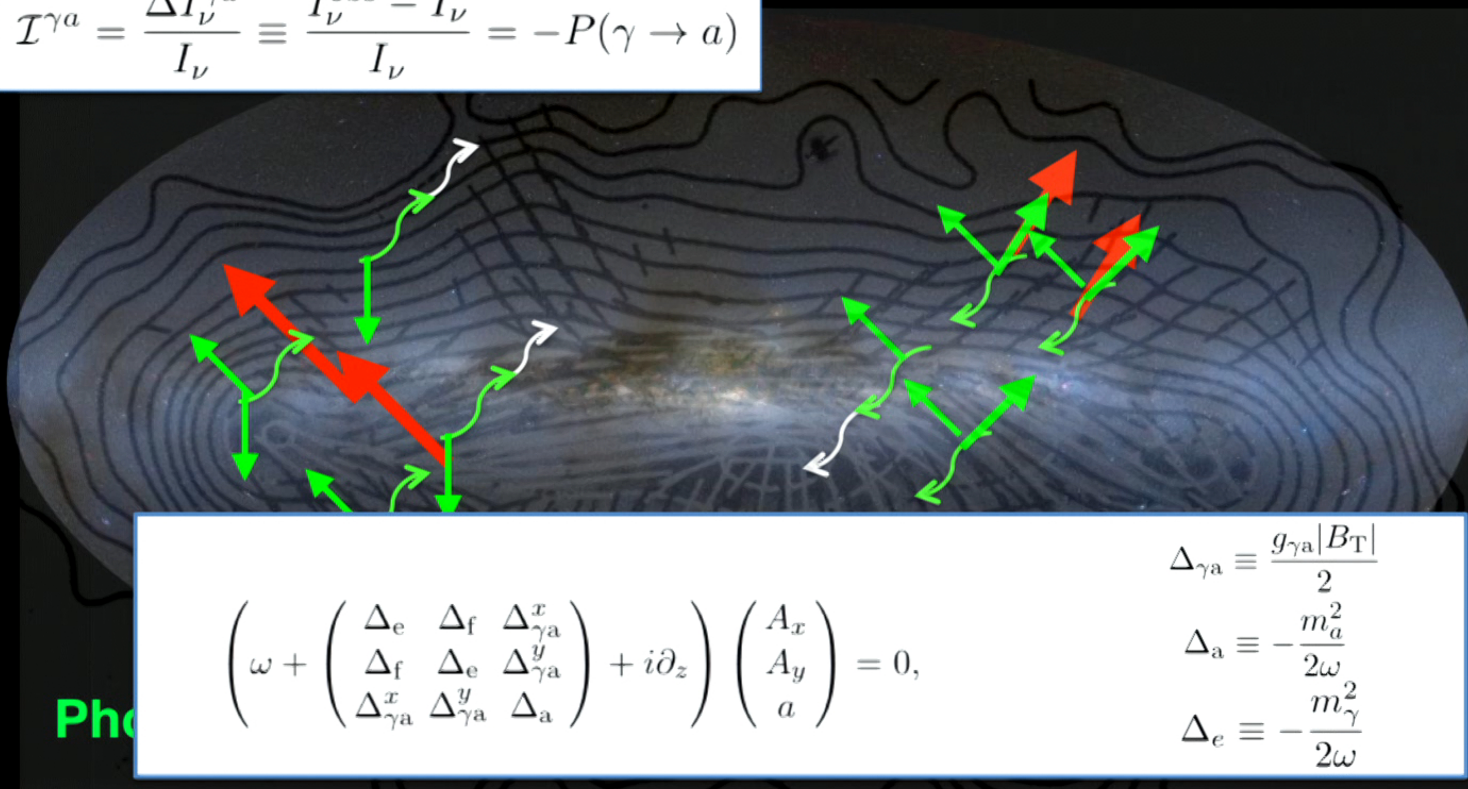

$$\left(\omega + \begin{pmatrix} \Delta_\mathrm{e} & \Delta_\mathrm{f} & \Delta_{\gamma\mathrm{a}}^x \\ \Delta_\mathrm{f} & \Delta_\mathrm{e} & \Delta_{\gamma\mathrm{a}}^y \\ \Delta_{\gamma\mathrm{a}}^x & \Delta_{\gamma\mathrm{a}}^y & \Delta_\mathrm{a} \end{pmatrix} + i\partial_z\right) \begin{pmatrix} A_x \\ A_y \\ a \end{pmatrix} = 0,$$

$$\Delta_{\gamma\mathrm{a}} \equiv \frac{g_{\gamma\mathrm{a}}|B_\mathrm{T}|}{2}$$

$$\Delta_\mathrm{a} \equiv -\frac{m_a^2}{2\omega}$$

$$\Delta_e \equiv -\frac{m_\gamma^2}{2\omega}$$

Two kinds of conversion

Resonance conversion

Happen at places where ALPs mass equals photon mass in the plasma

Non-Resonance conversion

Happens throughout the line of sight

Non-Resonant Conversion

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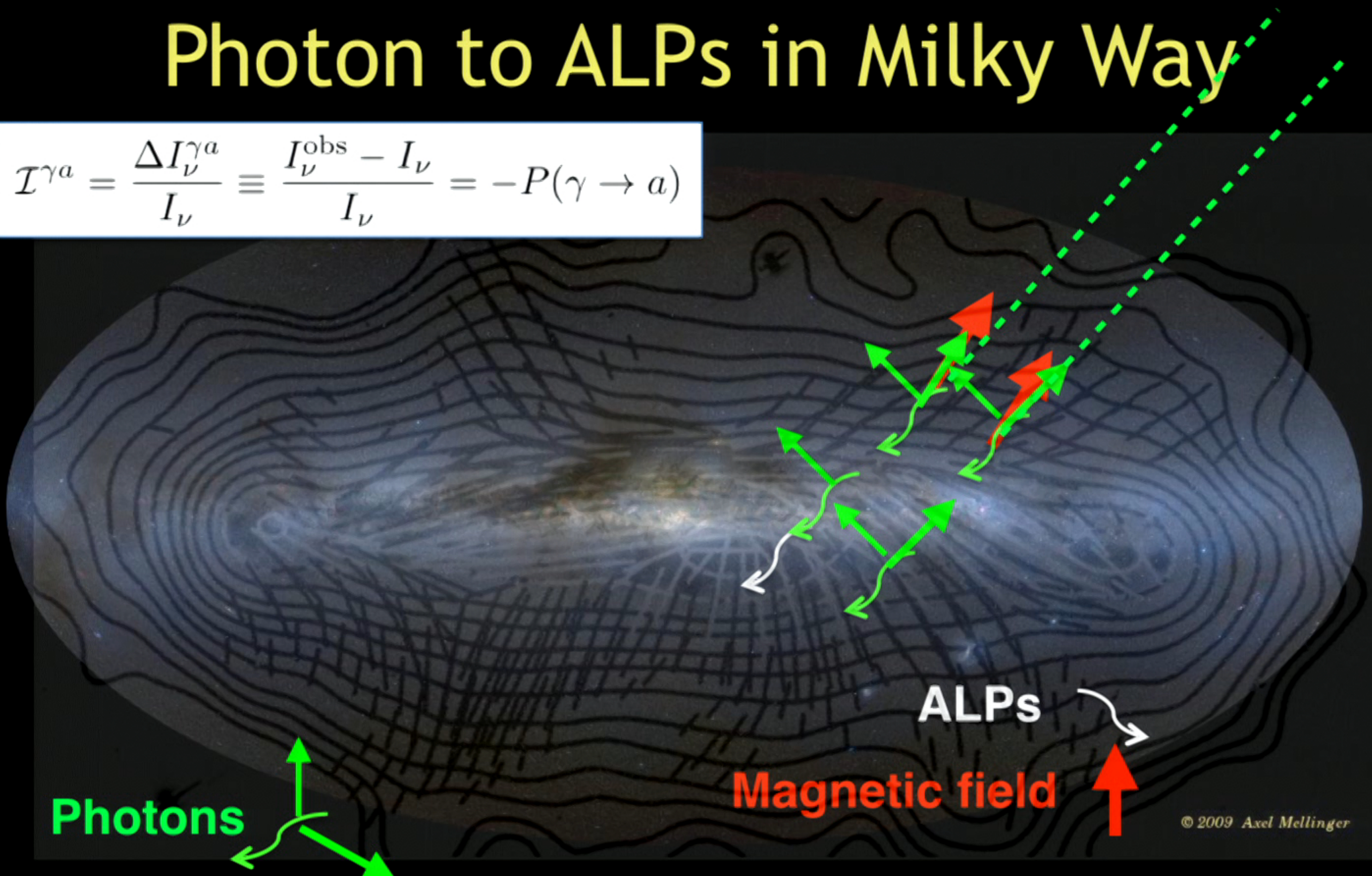
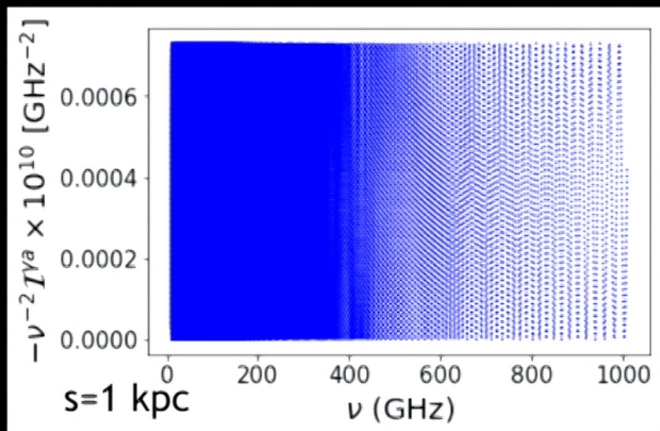
Photon to ALPs in Milky Way

$$\mathcal{I}^{\gamma a} = \frac{\Delta I_\nu^{\gamma a}}{I_\nu} \equiv \frac{I_\nu^{\mathrm{obs}} - I_\nu}{I_\nu} = -P(\gamma \to a)$$



$$\mathcal{I}^{\gamma a} = \frac{\Delta I_\nu^{\gamma a}}{I_\nu} \equiv \frac{I_\nu^{\rm obs} - I_\nu}{I_\nu} = -P(\gamma \to a)$$



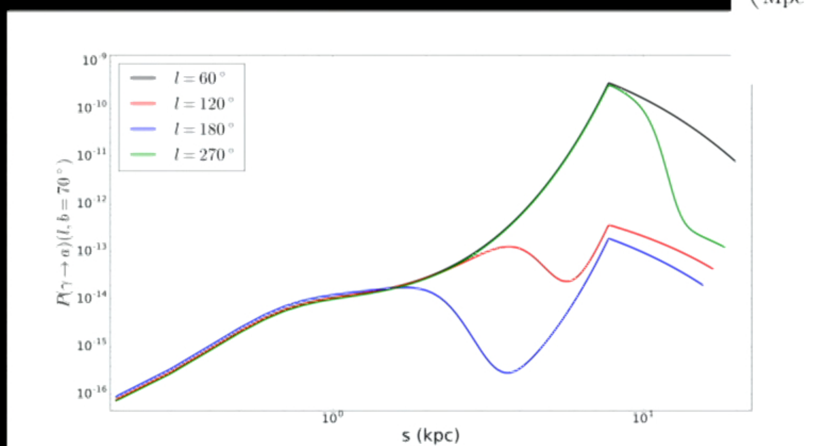
$$\left(\omega + \begin{pmatrix} \Delta_{\rm e} & \Delta_{\rm f} & \Delta^x_{\gamma{\rm a}} \\ \Delta_{\rm f} & \Delta_{\rm e} & \Delta^y_{\gamma{\rm a}} \\ \Delta^x_{\gamma{\rm a}} & \Delta^y_{\gamma{\rm a}} & \Delta_{\rm a} \end{pmatrix} + i\partial_z \right) \begin{pmatrix} A_x \\ A_y \\ a \end{pmatrix} = 0,$$

$$\left(\frac{\Delta^{x,y}_{\gamma{\rm a}}}{\rm Mpc^{-1}}\right) \equiv \frac{g_{\gamma{\rm a}}|B_{x,y}|}{2} = 15.2\left(\frac{g_{\gamma{\rm a}}}{10^{-11}{\rm Gev}^{-1}}\right)\left(\frac{B_{x,y}}{\mu{\rm G}}\right),$$

$$\left(\frac{\Delta_{\rm a}}{\rm Mpc^{-1}}\right) \equiv -\frac{m_a^2}{2\nu} = -1.9\times 10^4\left(\frac{m_{\rm a}}{10^{-14}{\rm eV}}\right)\left(\frac{100\ {\rm GHz}}{\nu}\right),$$

$$\left(\frac{\Delta_{\rm e}}{\rm Mpc^{-1}}\right) \approx \frac{\omega_{\rm p}^2}{2\nu}\left[-1 + 7.3\times 10^{-3}\frac{n_{\rm H}}{n_{\rm e}}\left(\frac{\omega}{\rm eV}\right)^2\right]$$

$$= -2.6\times 10^6\left(\frac{n_{\rm e}}{10^{-5}{\rm cm}^{-3}}\right)\left(\frac{100\ {\rm GHz}}{\nu}\right)\times\left[1 - 7.3\times 10^{-3}\frac{n_{\rm H}}{n_{\rm e}}\left(\frac{\omega}{\rm eV}\right)^2\right]$$



Electron density model :
J.M.Cordes & T.J.W.Lazio
arXiv: astro-ph/0207156
Gaensler et al.
arXiv0808.2550[astro-ph]

Magnetic field model:
Jansson & Farrar
Astrophys.J. 757 (2012) 14

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Non-Resonant conversion from the random magnetic field

$$\bar{P}(\gamma \to a)(r) = \frac{1}{3}\left(1 - e^{(-3P(\gamma\to a)r/2d_0)}\right) \qquad r >> d_0$$

A. Mirizzi, G. G. Raffelt, and P. D. Serpico
Phys.Rev.D, 72(2):023501
Y. Grossman, S. Roy, and J. Zupan.
Physics Letters B, 543:23–28

$$\bar{P}(\gamma \to a) \approx \frac{P(\gamma \to \mathrm{a})R}{2s}$$
$$\approx \frac{\Delta^2_{\gamma\mathrm{a}} Rs}{2} = 10^{-9}\left(\frac{g_{\gamma\mathrm{a}}}{10^{-10}\ \mathrm{GeV}^{-1}}\right)^2\left(\frac{B_T}{1\ \mu\mathrm{G}}\right)^2\left(\frac{R}{1000\mathrm{pc}}\right)\left(\frac{s}{10^{-4}\ \mathrm{pc}}\right)$$

Resonant Conversion

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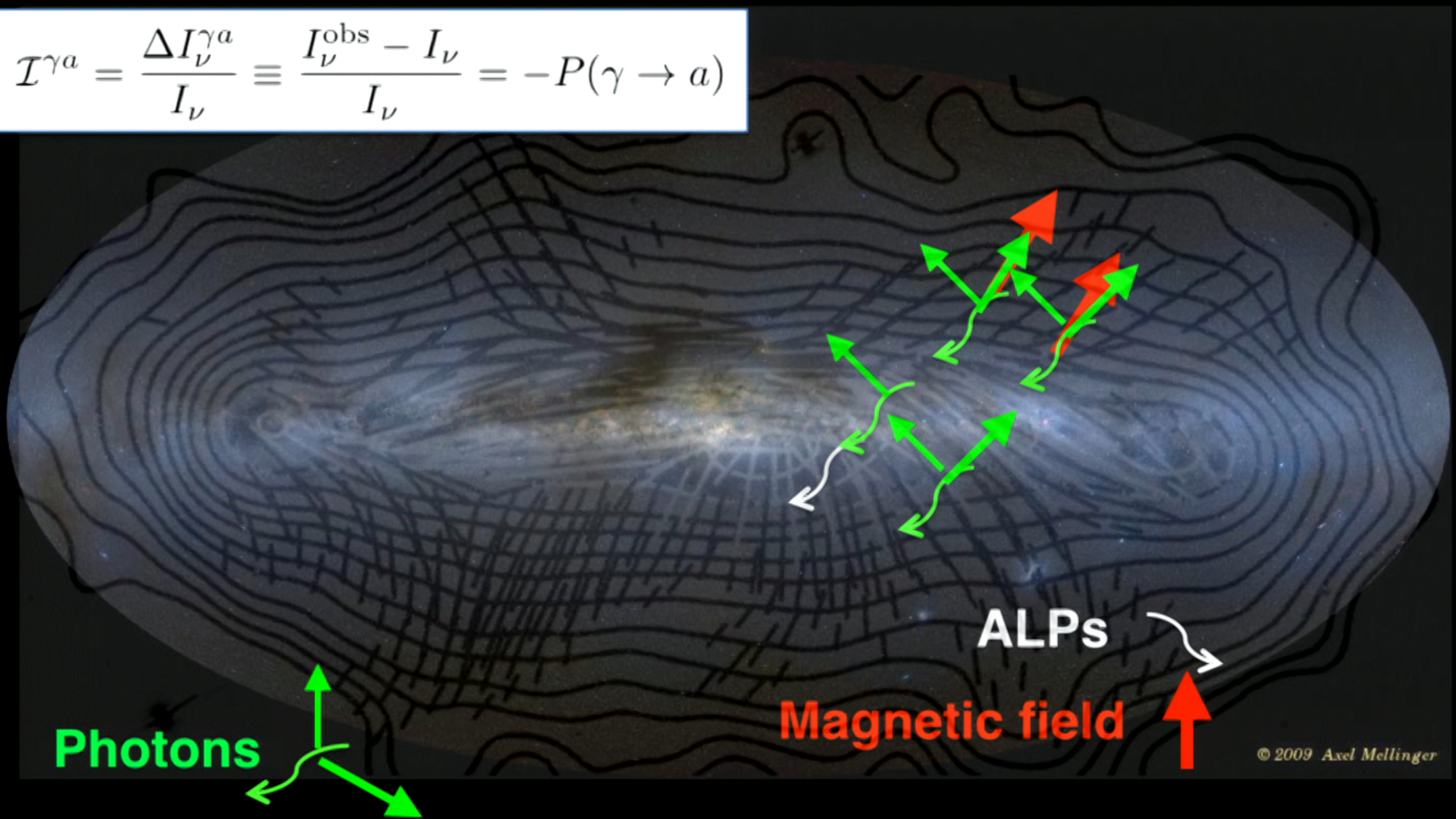
Photon to ALPs in Milky Way

$$\mathcal{I}^{\gamma a} = \frac{\Delta I_\nu^{\gamma a}}{I_\nu} \equiv \frac{I_\nu^{\rm obs} - I_\nu}{I_\nu} = -P(\gamma \to a)$$

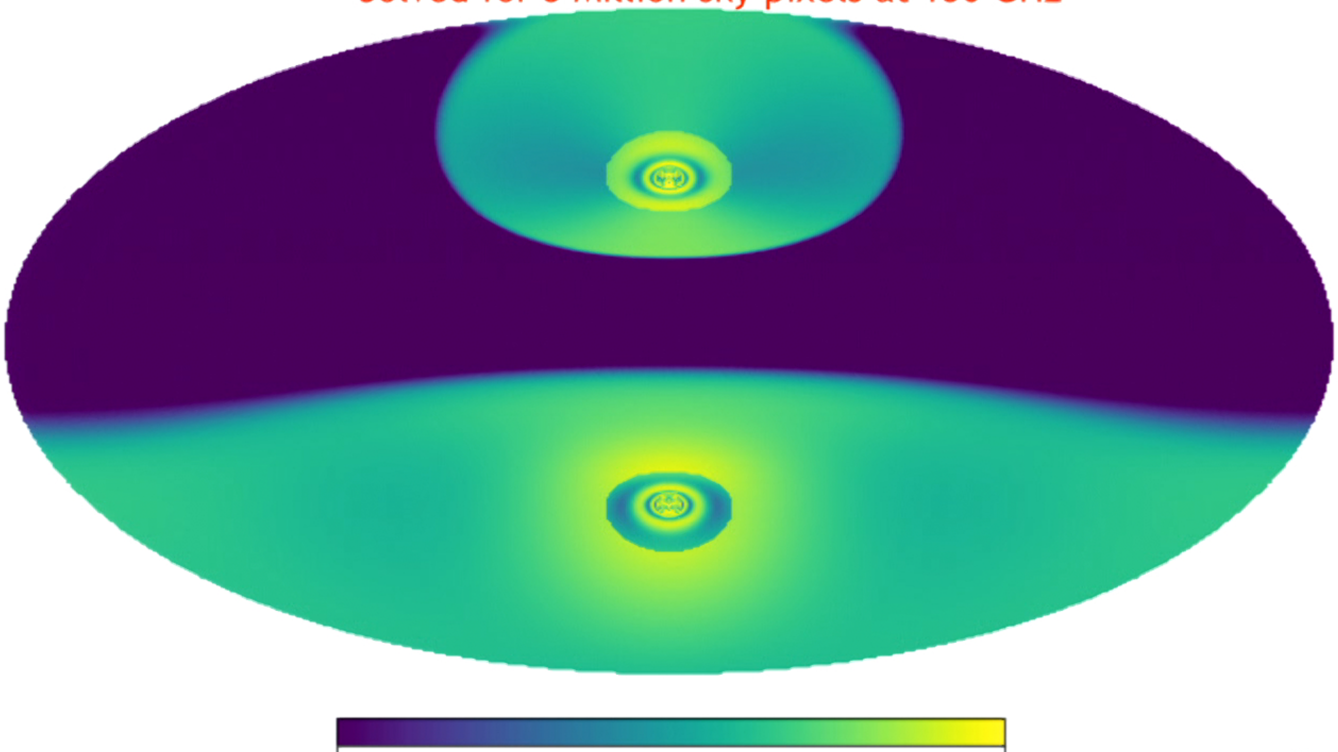


Resonant Conversion

ALPs mass: 5*10^-13 eV

Mukherjee, Khatri, Wandelt
JCAP 04 (2018) 045

Solved for 3 Million sky pixels at 150 GHz



Probability of conversion in log-scale

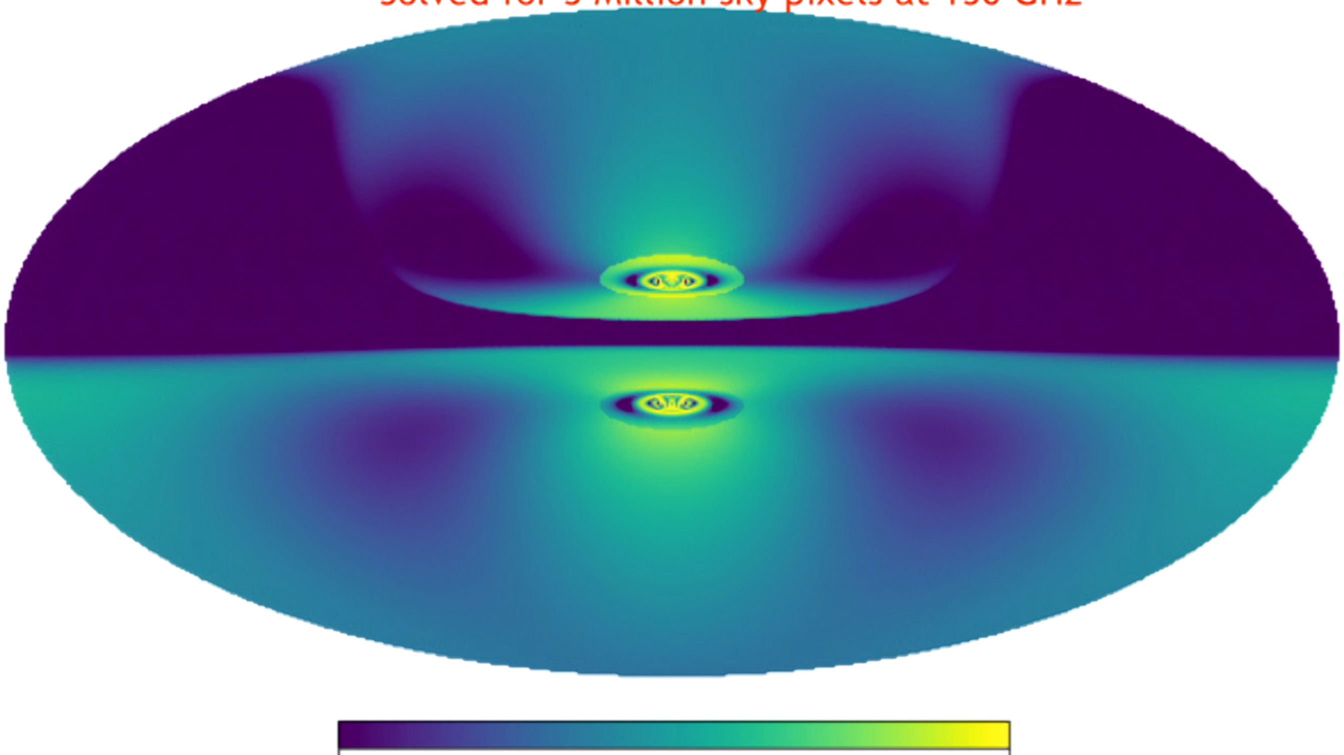
21

Resonant Conversion

ALPs mass: 5*10^-12 eV

Mukherjee, Khatri, Wandelt
JCAP 04 (2018) 045

Solved for 3 Million sky pixels at 150 GHz

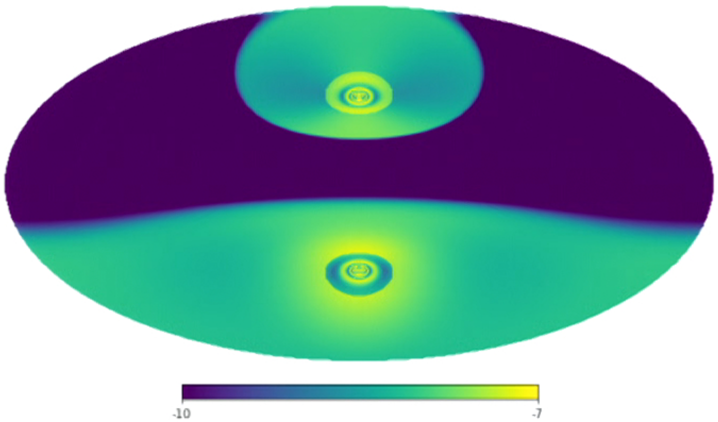


Probability of conversion in log-scale

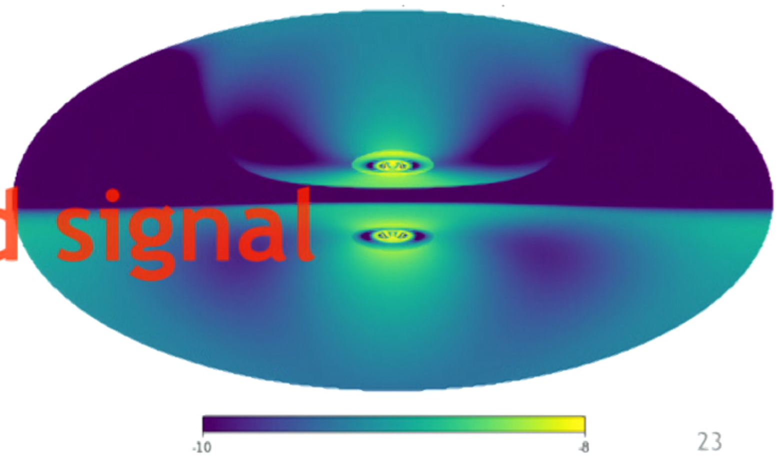
22

Resonant Conversion

ALPs mass:5*10^-13 eV



ALPs mass:5*10^-12 eV



100 % Polarized signal

Spatially fluctuating
a unique structure

What about other signals (contaminations)

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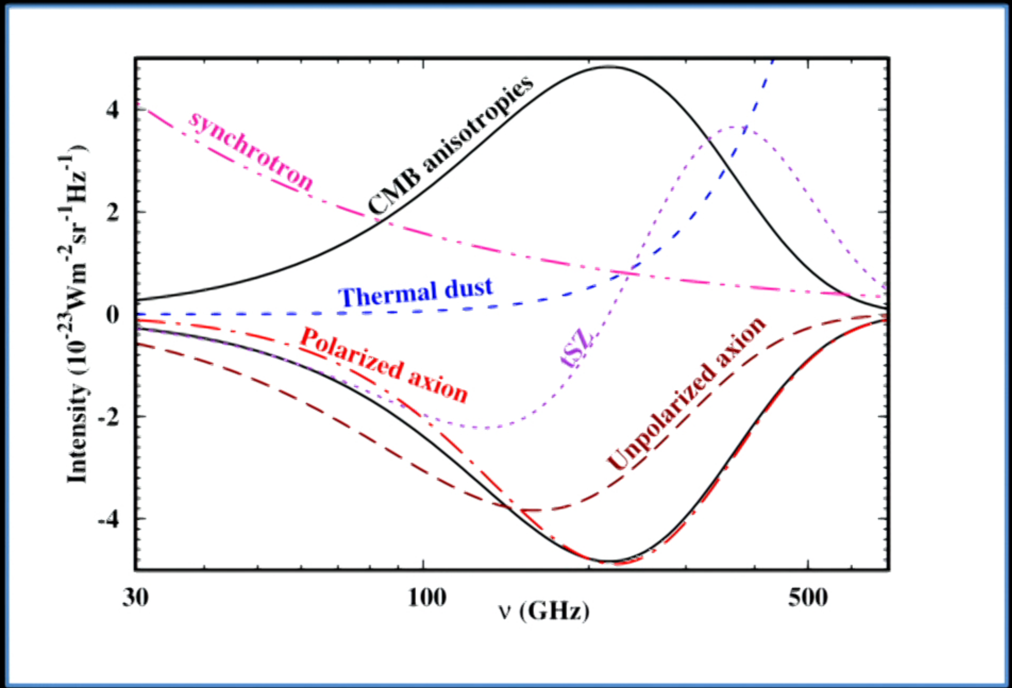
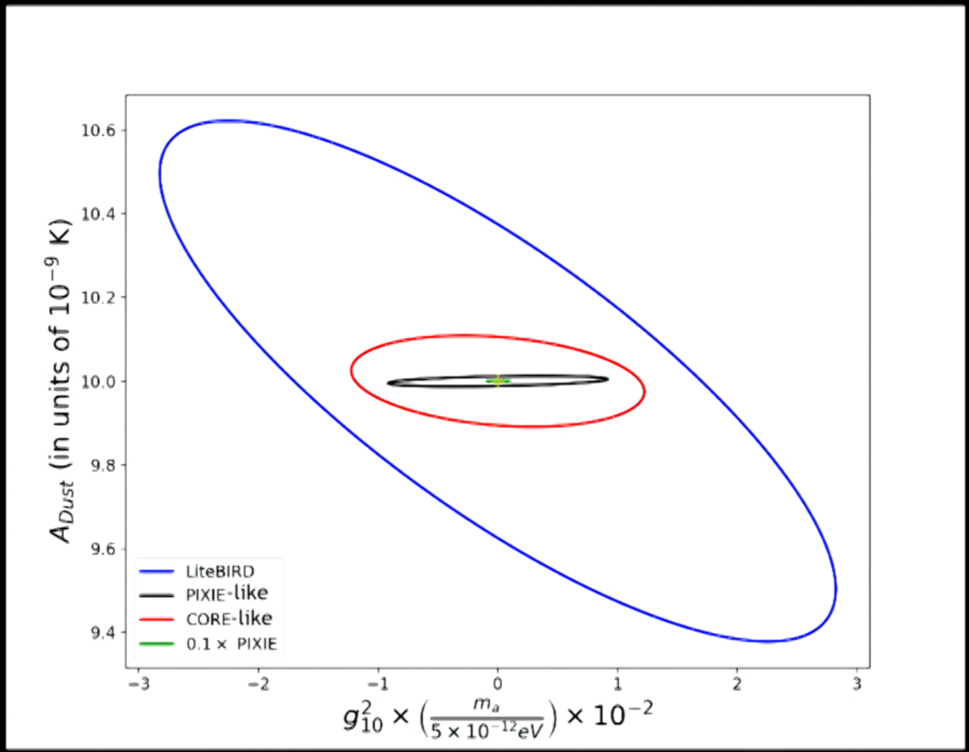
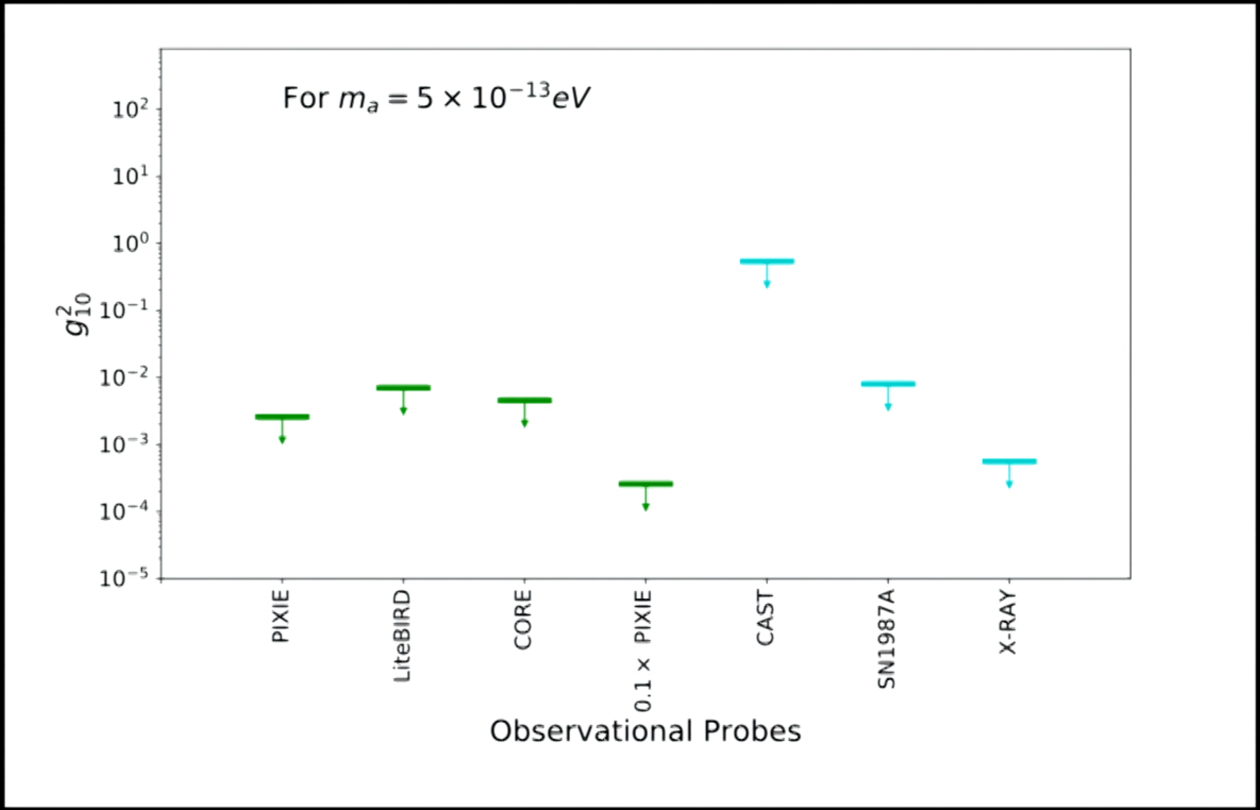
Two new signals of spectral distortions



Resonant case



Resonant case



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Extragalactic sources: Voids

Mukherjee, Khatri, Wandelt
JCAP 04 (2018) 045

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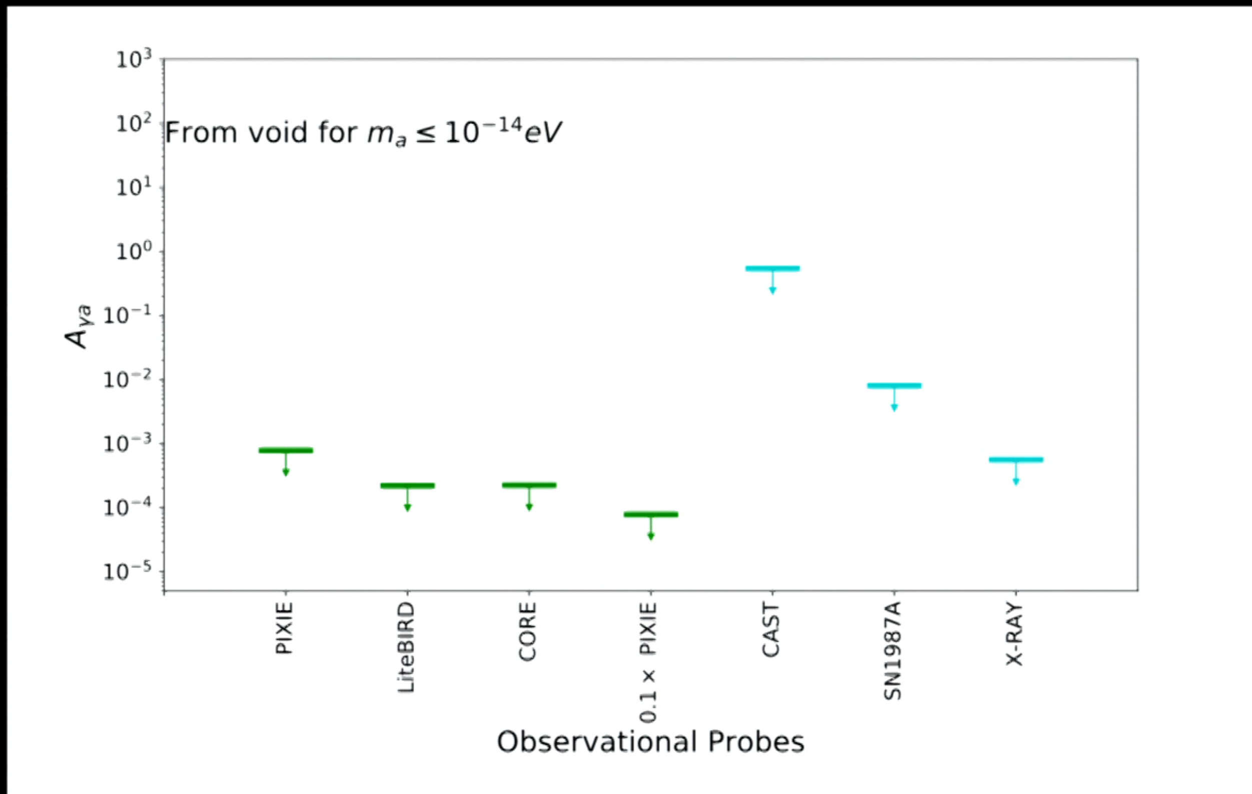
Forecast for future CMB mission after marginalizing other contaminations



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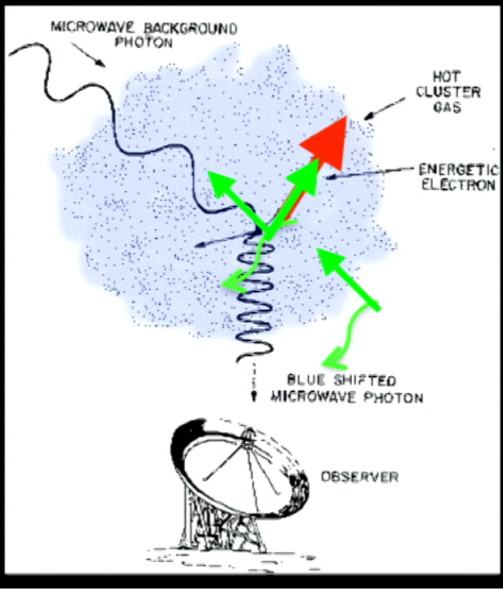
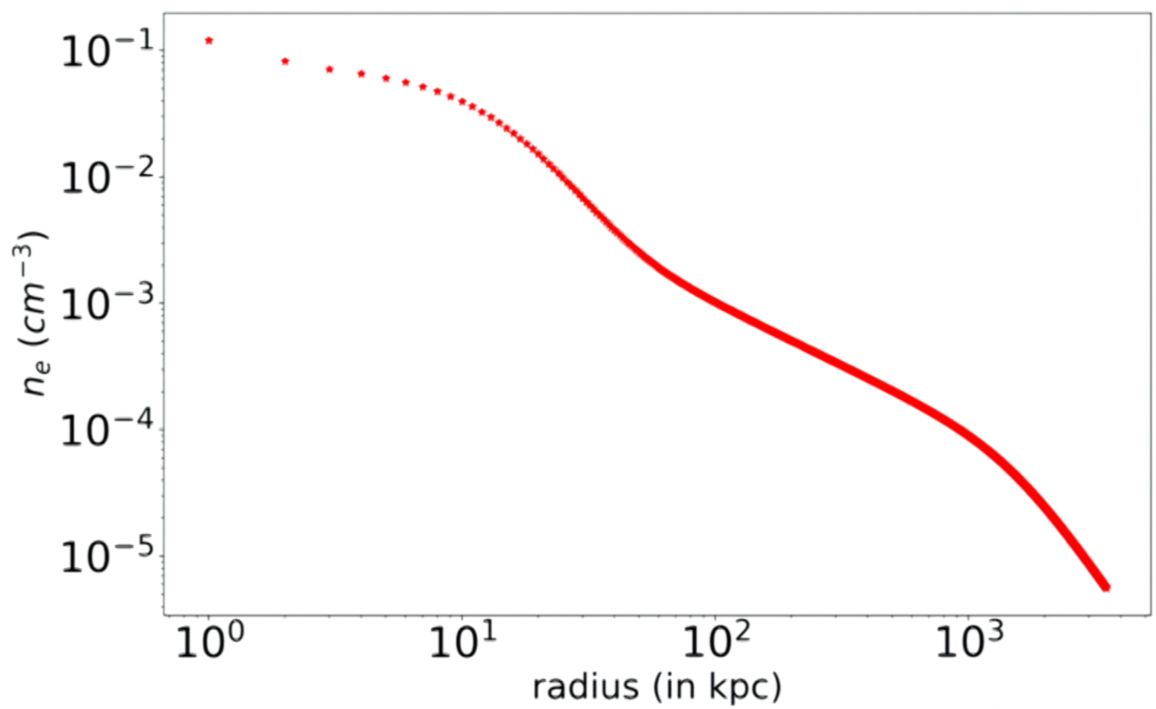
ALPs constraints from Simons Observatory and CMB-S4 using Galaxy Clusters

Mukherjee, Spergel, Khatri, Wandelt.
To be submitted



Electron density in galaxy clusters



Vikhlinin et al. 2006,
Bartalucci et al. 2017

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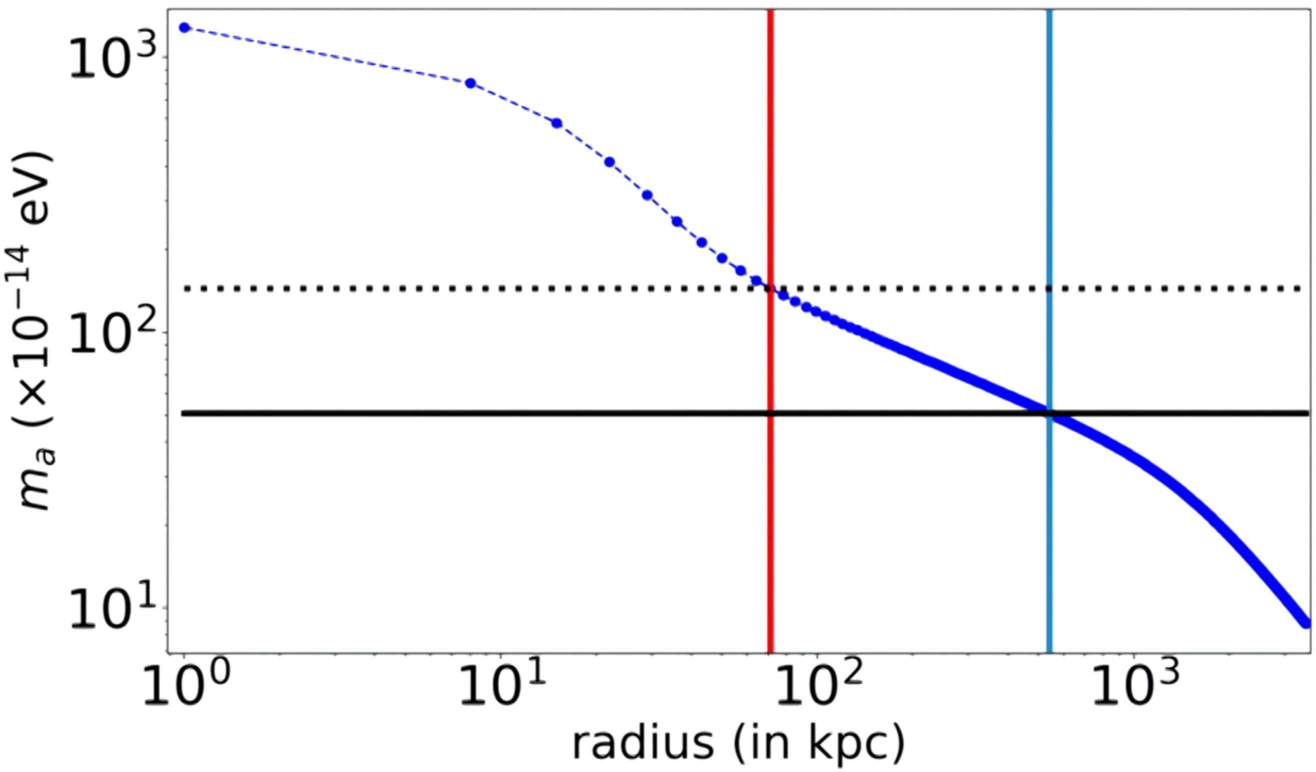
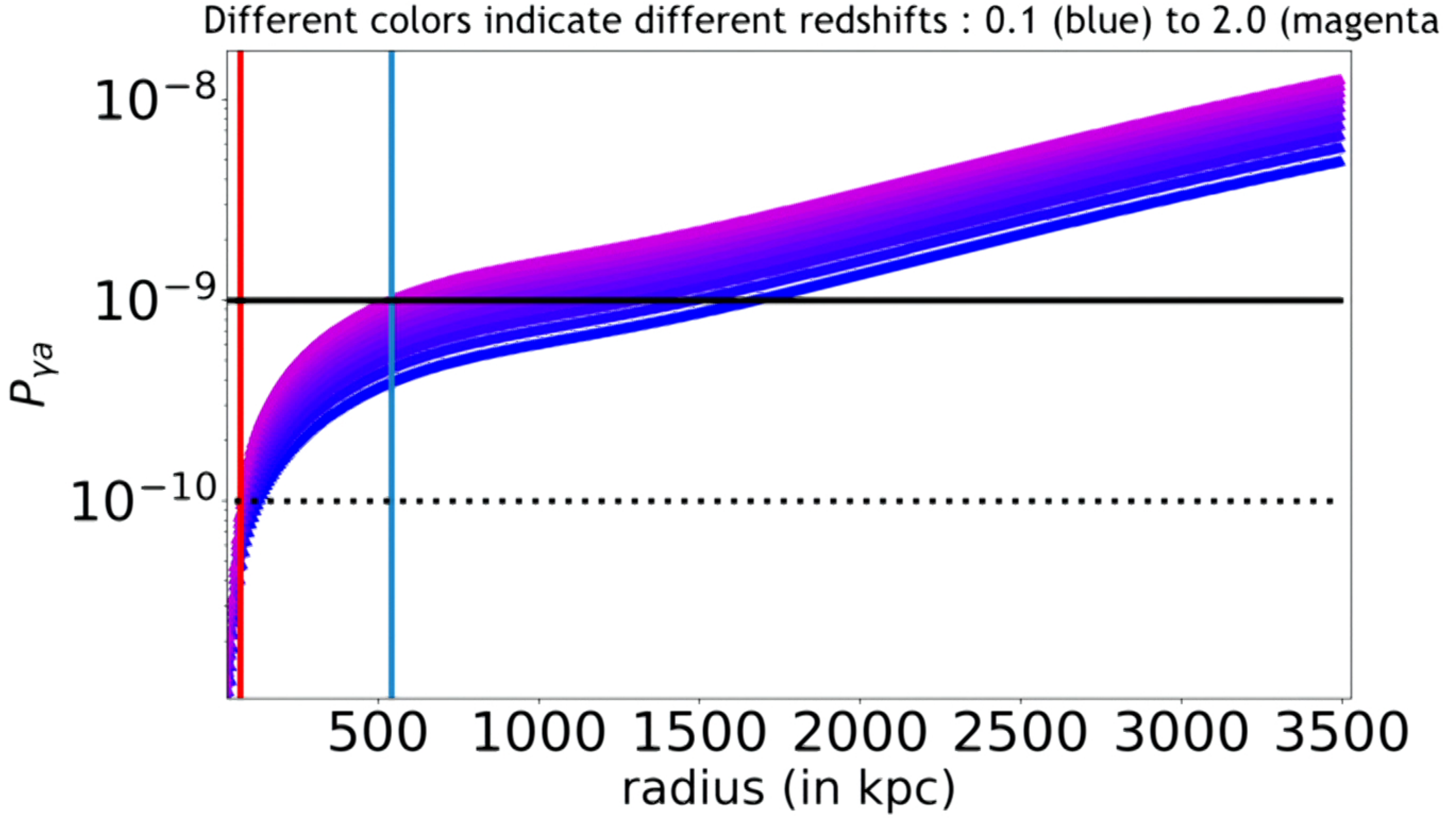
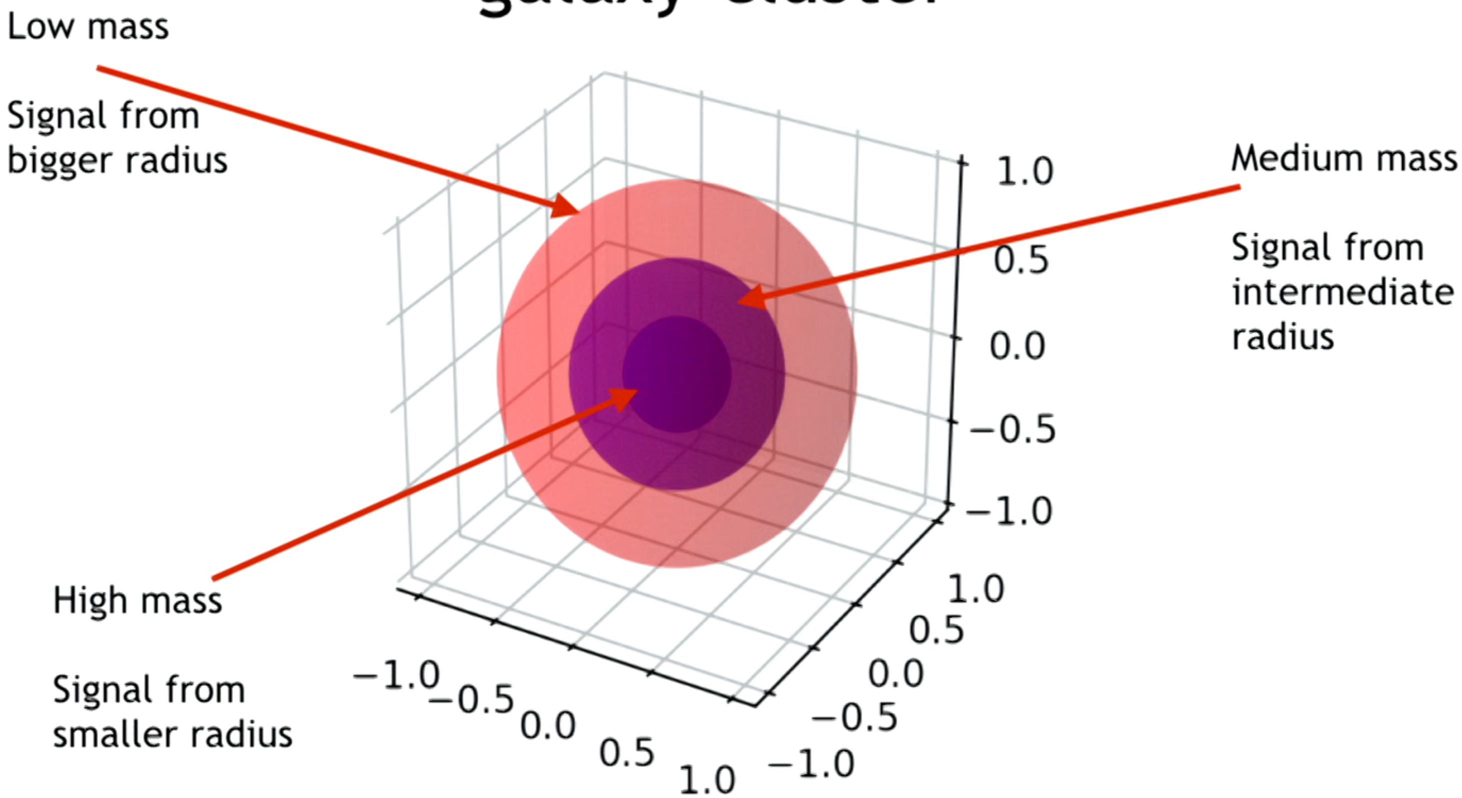
which ALP mass at which radius?



Signal profile with radius in galaxy cluster



Spatial shape of the distortion around a galaxy-cluster



A simplistic simulated sky map of ALPs signal around galaxy cluster

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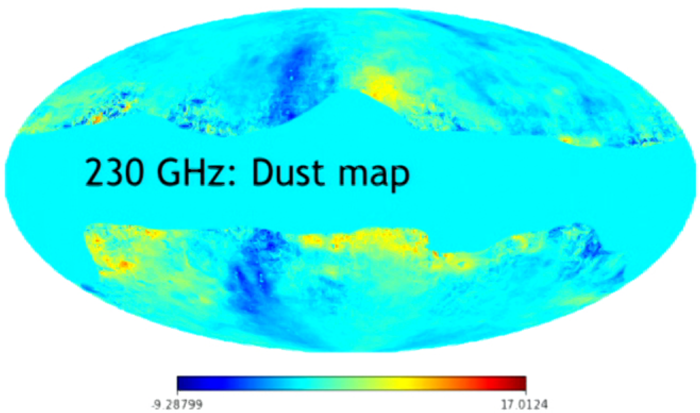
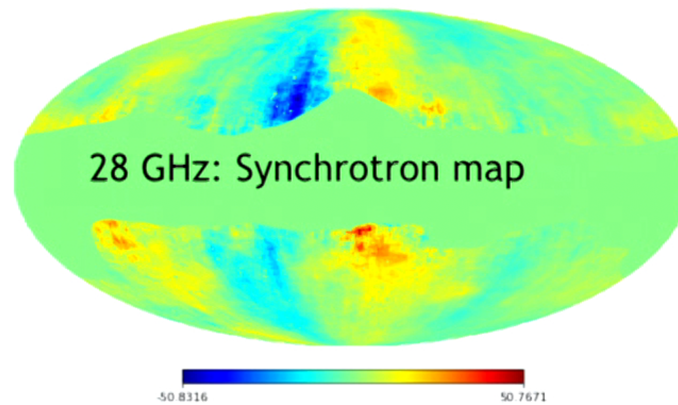
Model of the signal in the Sky

$$S_{\nu_i}(\hat{p}) = A_{\nu_i j} x_j(\hat{p}) + n_{\nu_i}(\hat{p}),$$
$$\mathbf{S}(\hat{p}) = \mathbf{A}\mathbf{x}(\hat{p}) + \mathbf{n}(\hat{p}),$$

We added simulated maps of synchrotron, dust, CMB over the ALPs signal at randomly selected cluster locations.





Python Sky Model (PYSM) code
Thorne et al. (2018)

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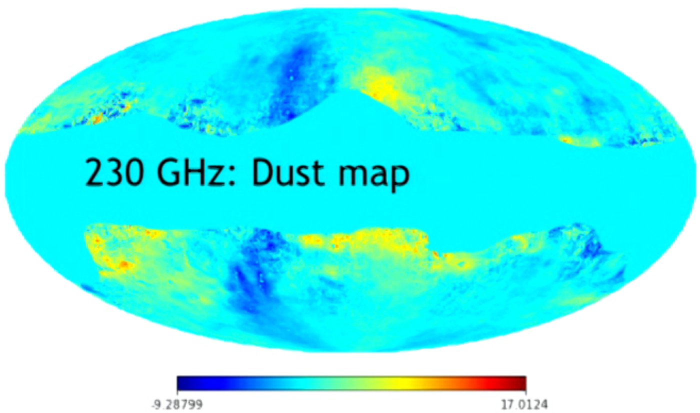
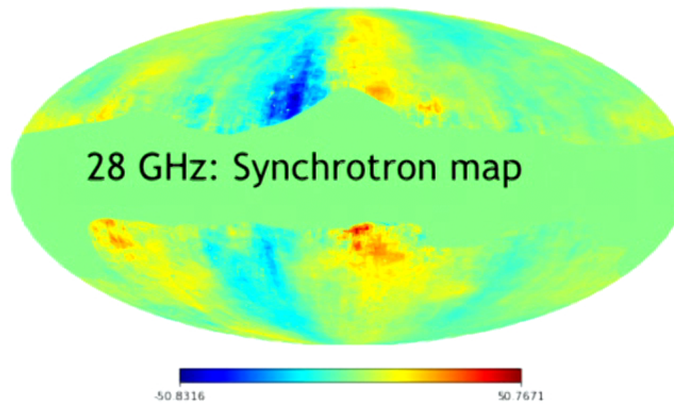




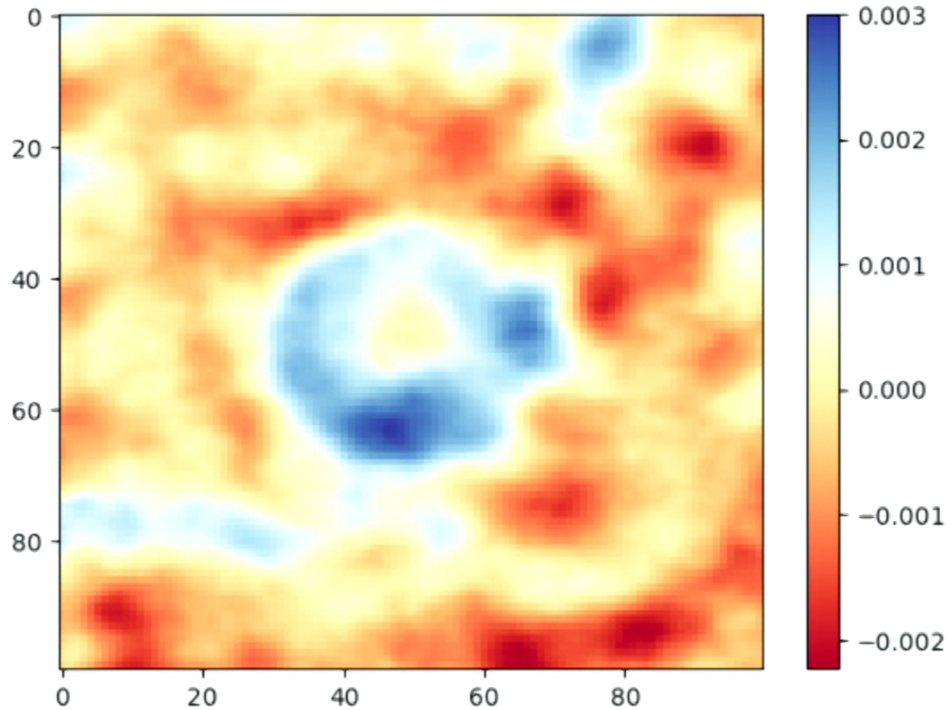
Python Sky Model (PYSM) code
Thorne et al. (2018)

Then we clean the foregrounds using component separation method: Internal Linear Combination (ILC)

$$\hat{x}_{\gamma a}(\hat{p}) = \hat{\mathcal{W}}^T_{\gamma a}\mathbf{S}(\hat{p}),$$

$$\hat{\mathbf{W}}_{\gamma a}(\nu) = \mathbf{C}_S^{-1}\mathbf{a}_{\gamma a}(\mathbf{a}^T_{\gamma a}\mathbf{C}_S^{-1}\mathbf{a}_{\gamma a})^{-1}$$

Adding 1000 clusters



Q- polarization map

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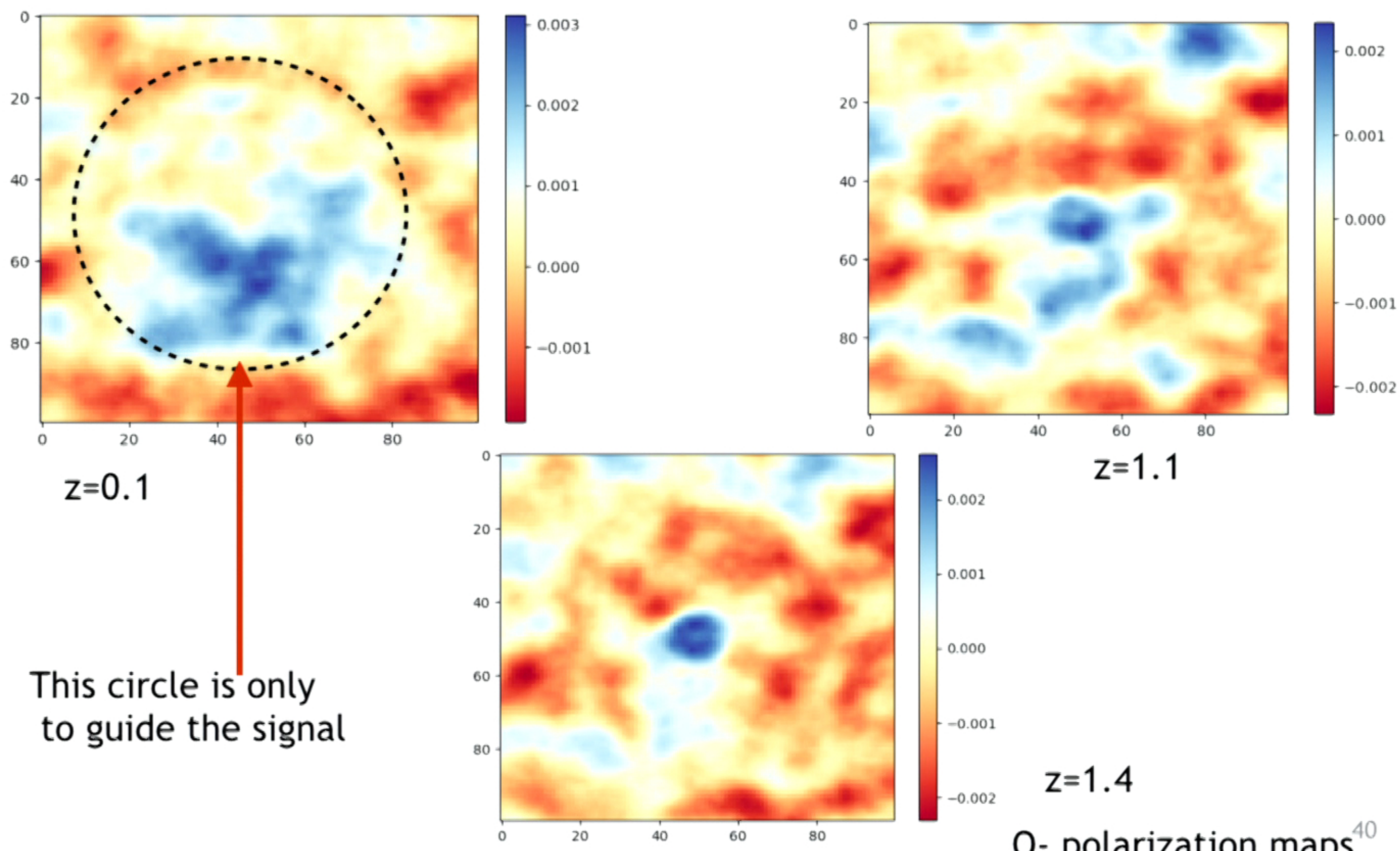
At different redshifts



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Detectability of the signal

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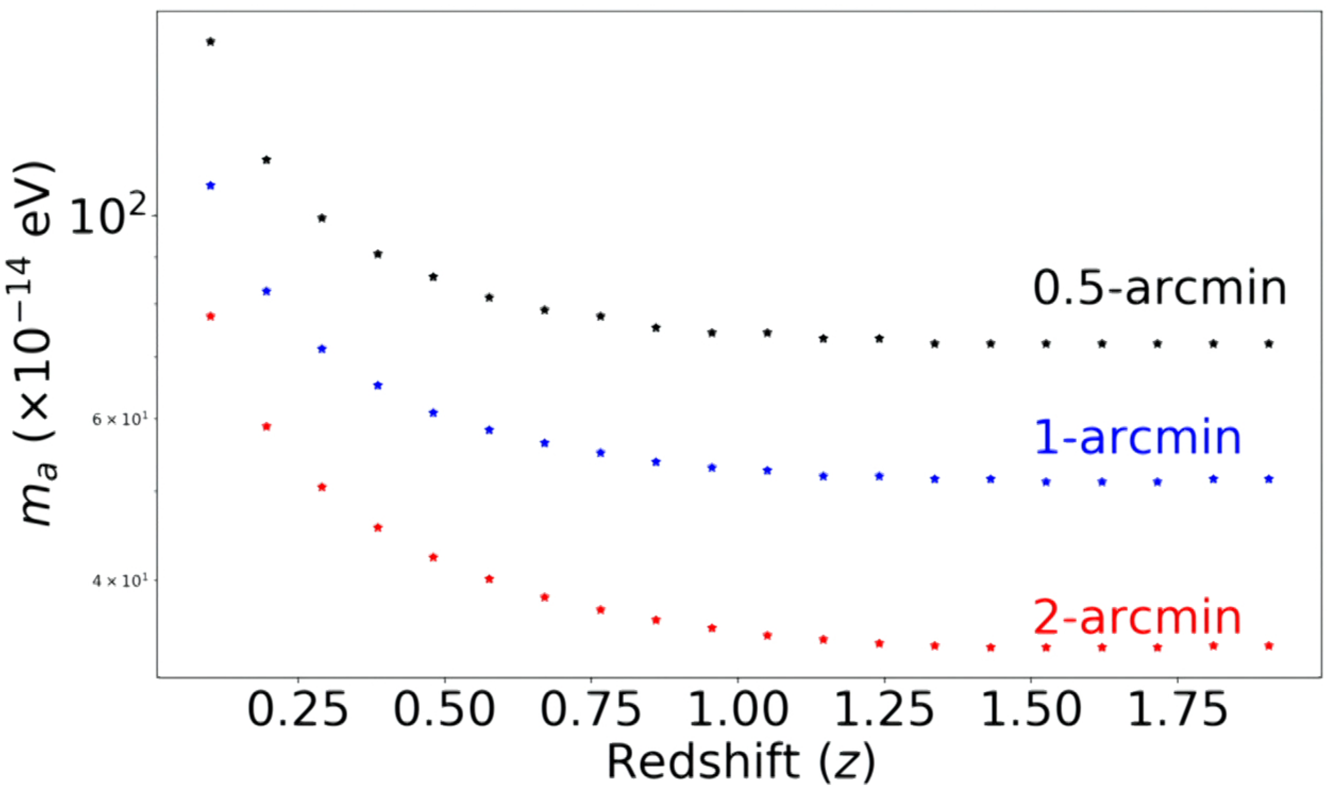
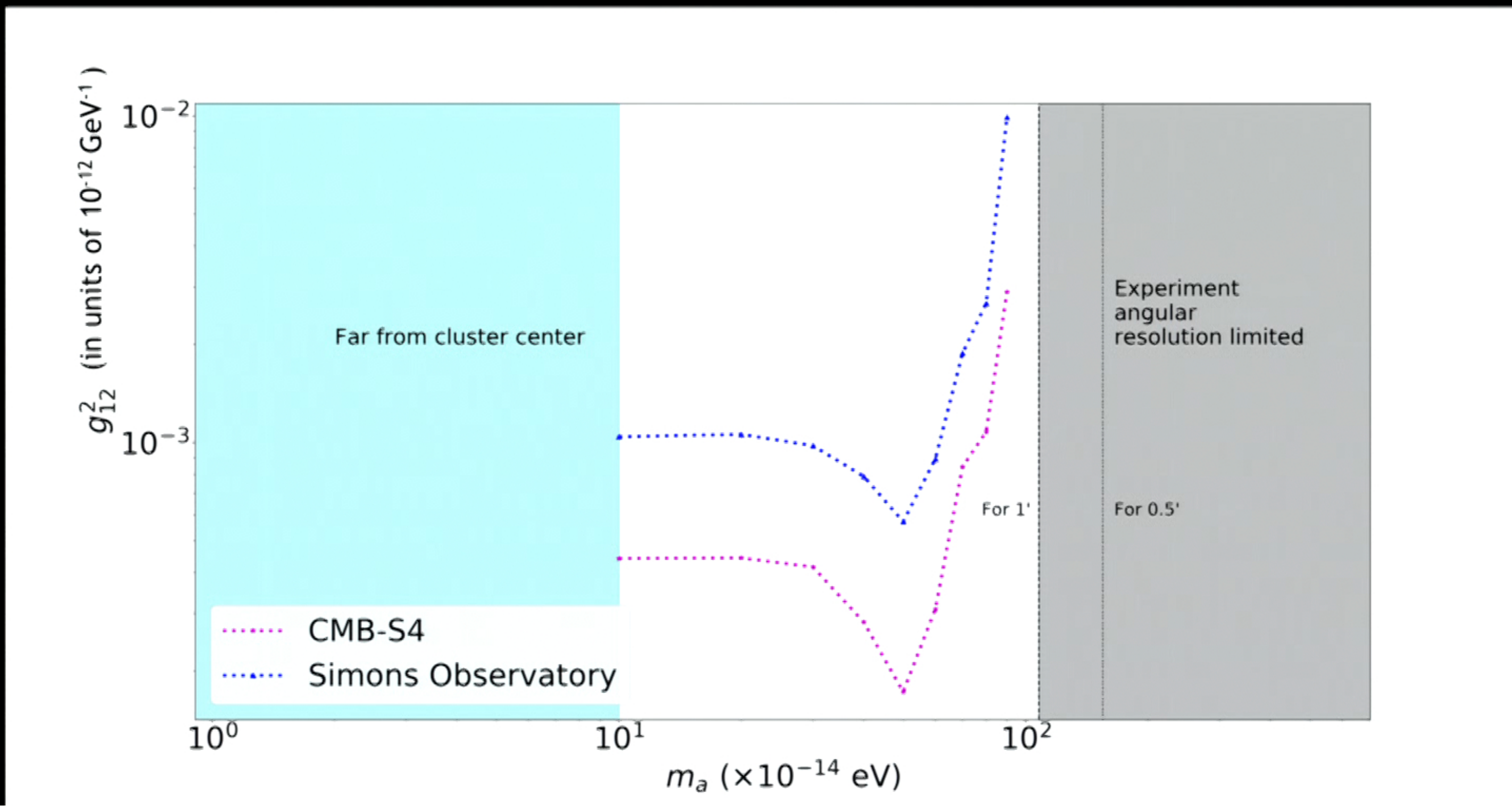
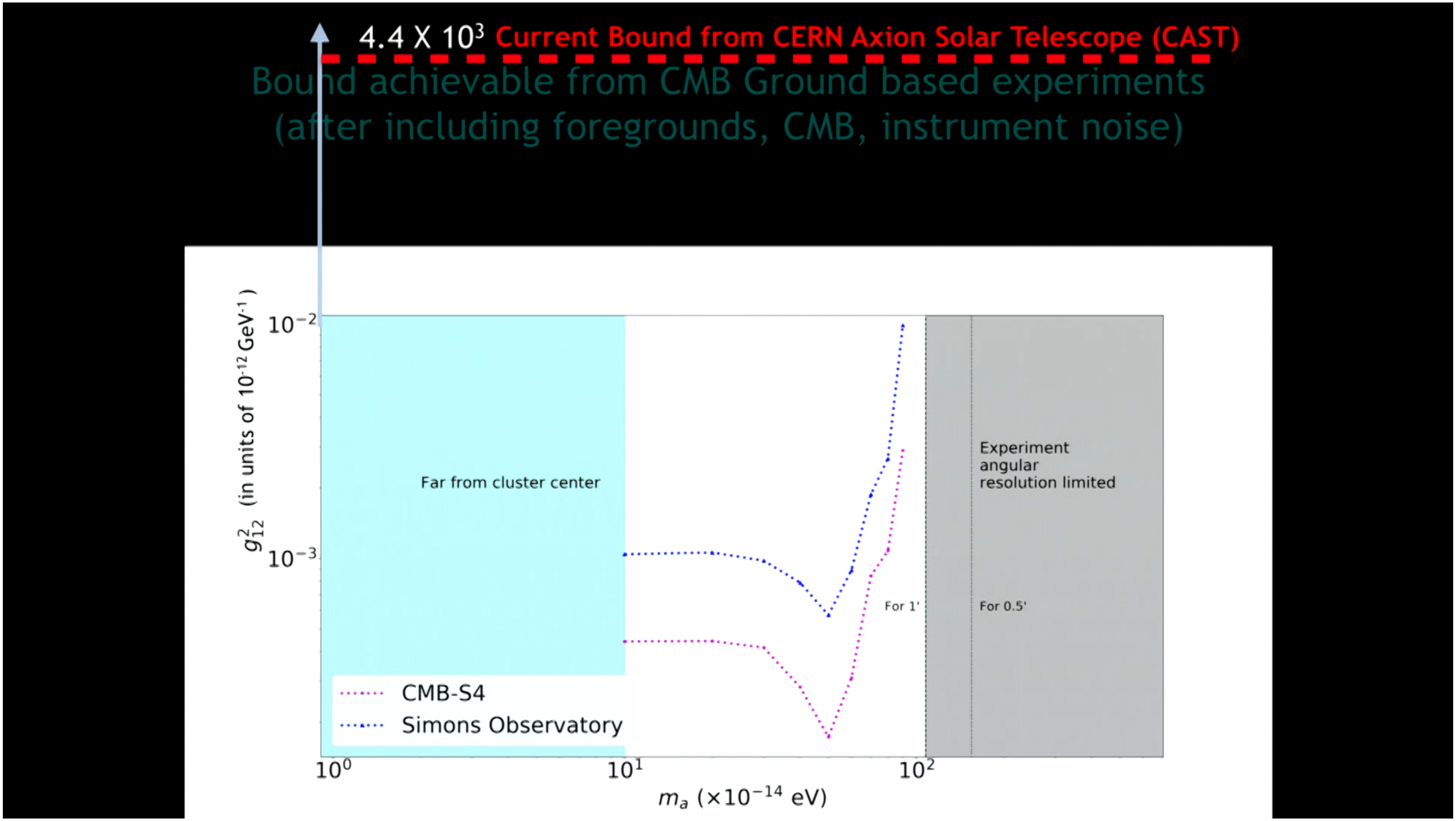
ALP mass spatially resolved



Bound achievable from CMB Ground based experiments (after including foregrounds, CMB, instrument noise)





4.4 X 10³ Current Bound from CERN Axion Solar Telescope (CAST)
Bound achievable from CMB Ground based experiments
(after including foregrounds, CMB, instrument noise)
Far from cluster center
Experiment
angular
resolution limited
For 1'
For 0.5'
CMB-S4
Simons Observatory
g_{12}^2 (in units of 10^{-12} GeV^{-1})
10^{-2}
10^{-3}
10^0
10^1
10^2
m_a ($\times 10^{-14}$ eV)

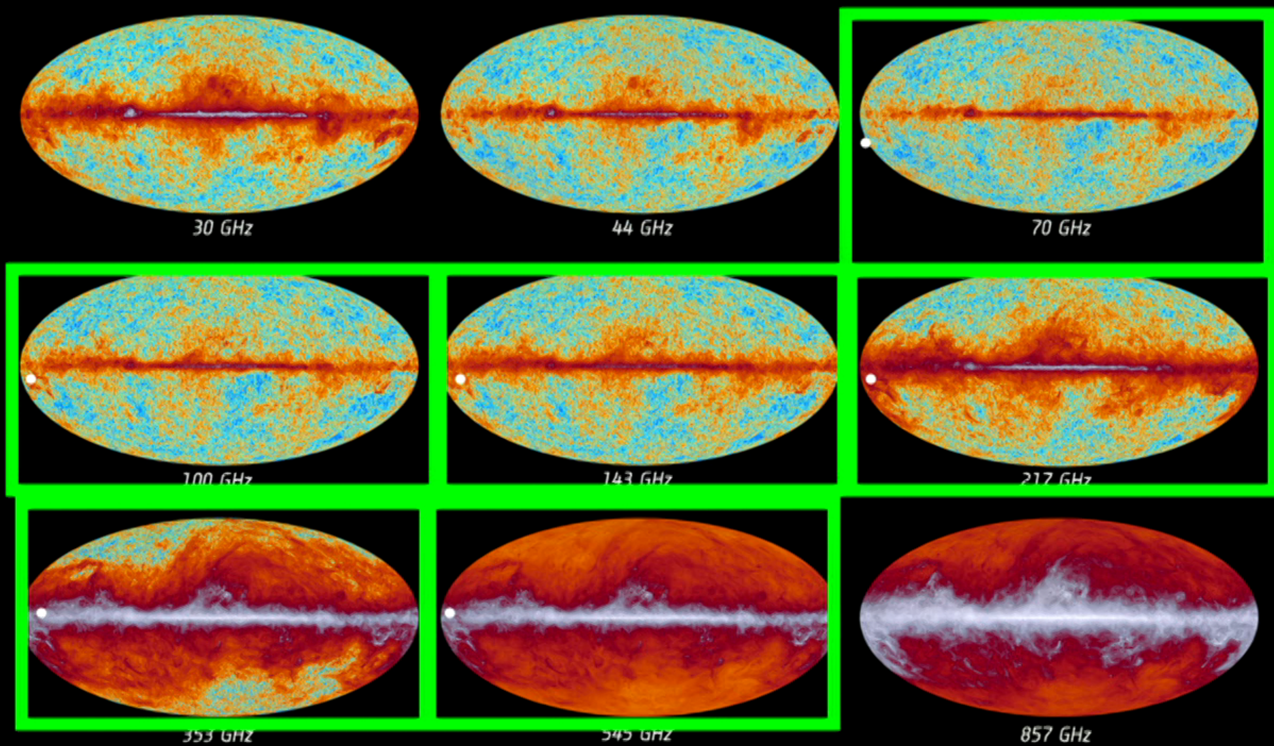
ALPs distortion map

Mukherjee, Khatri, Wandelt

arXiv:1811.11177

Using the Planck temperature data
(For the non-resonance case)

From Polarization data: In preparation
(For the resonance case)



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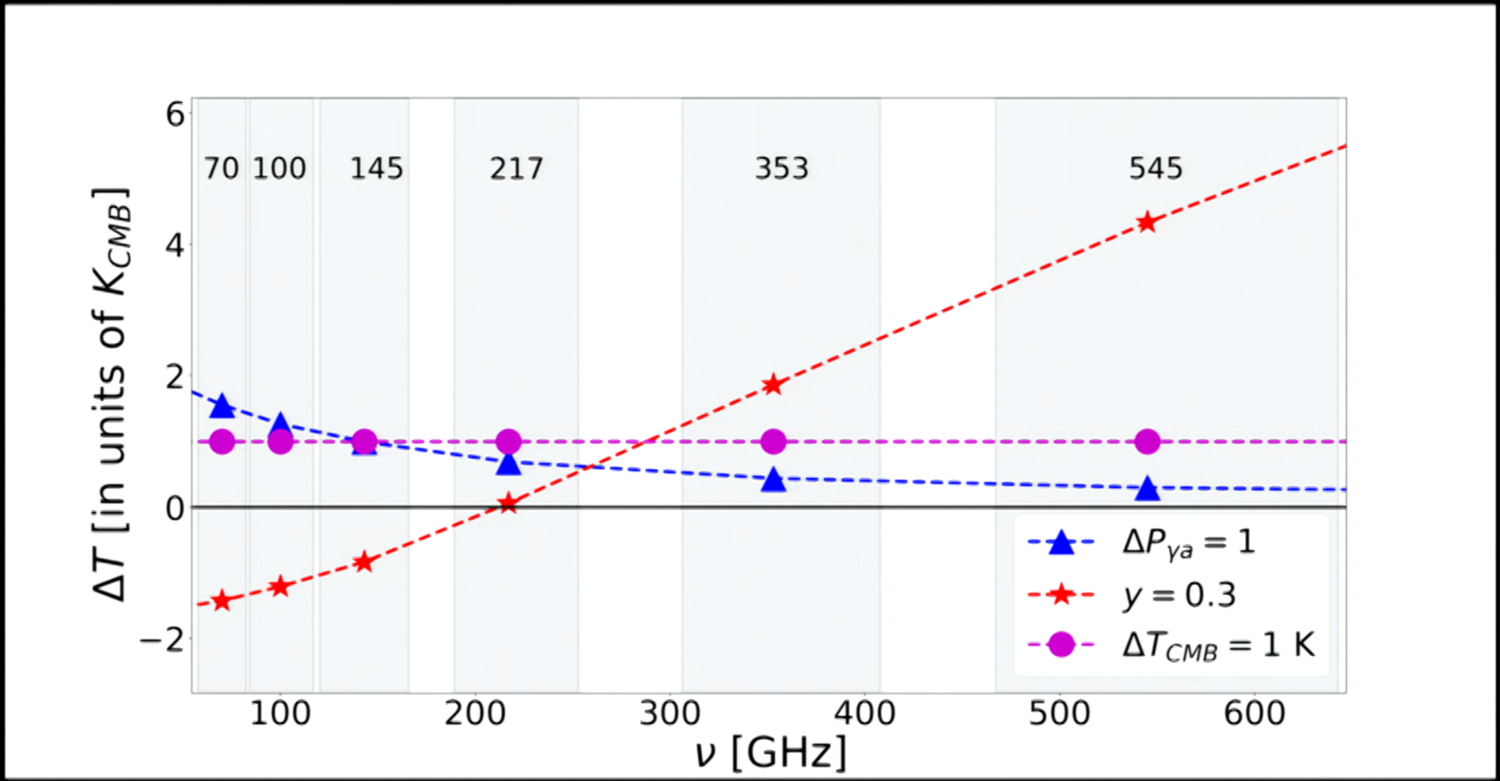
Spectrum of the distortion in the Planck frequency bands



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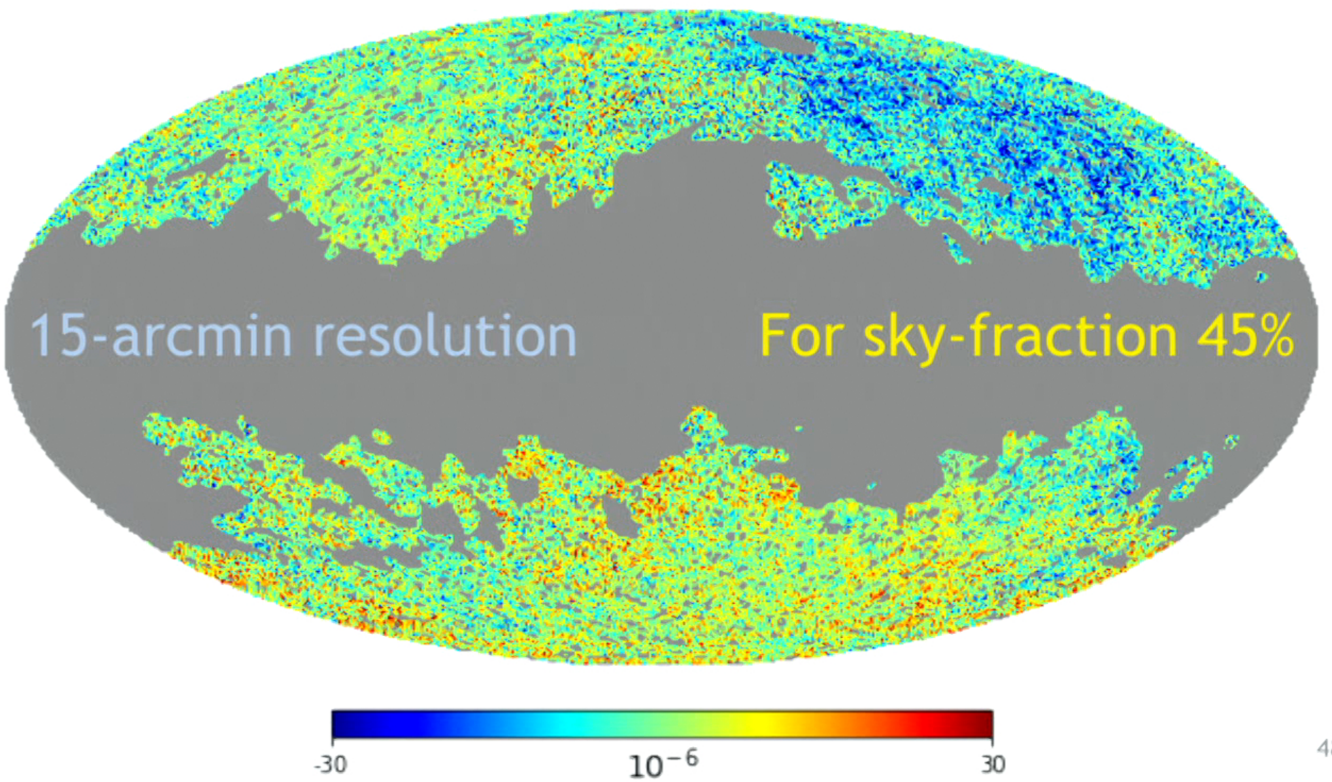
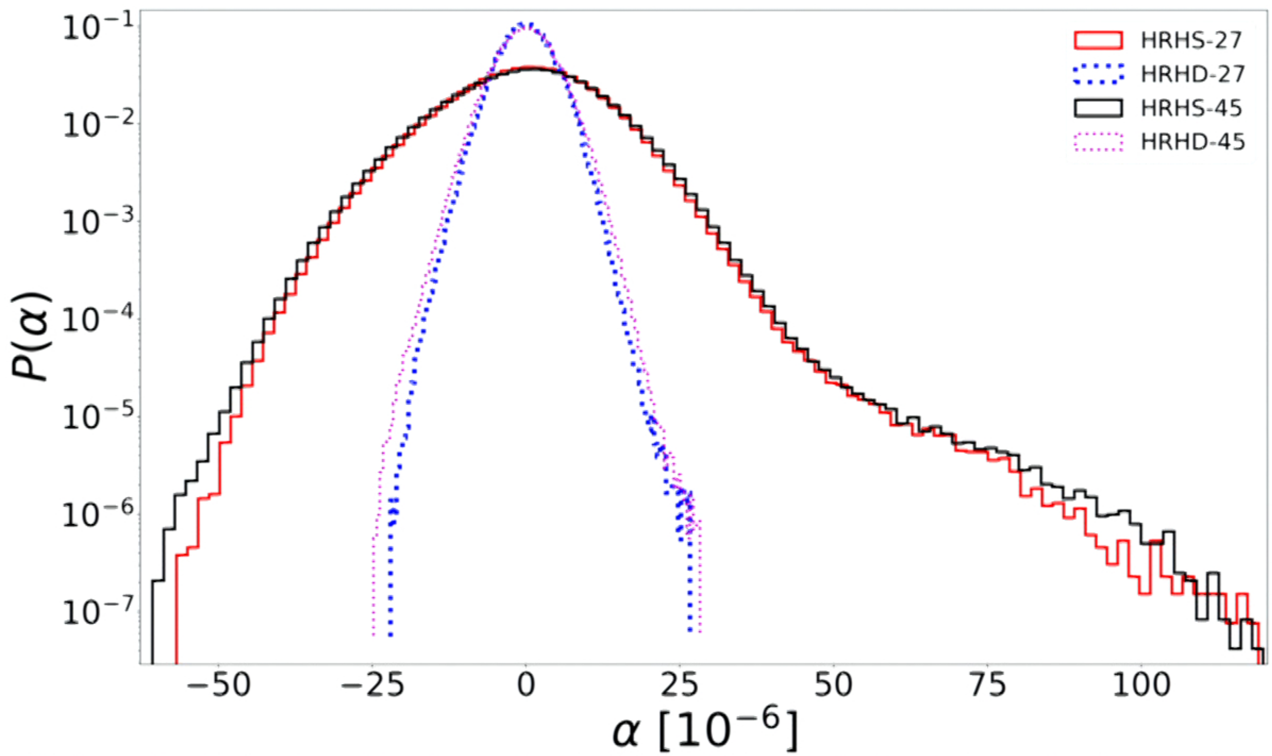
First all-sky constraints on Non-Resonant ALPs signal from Planck-data

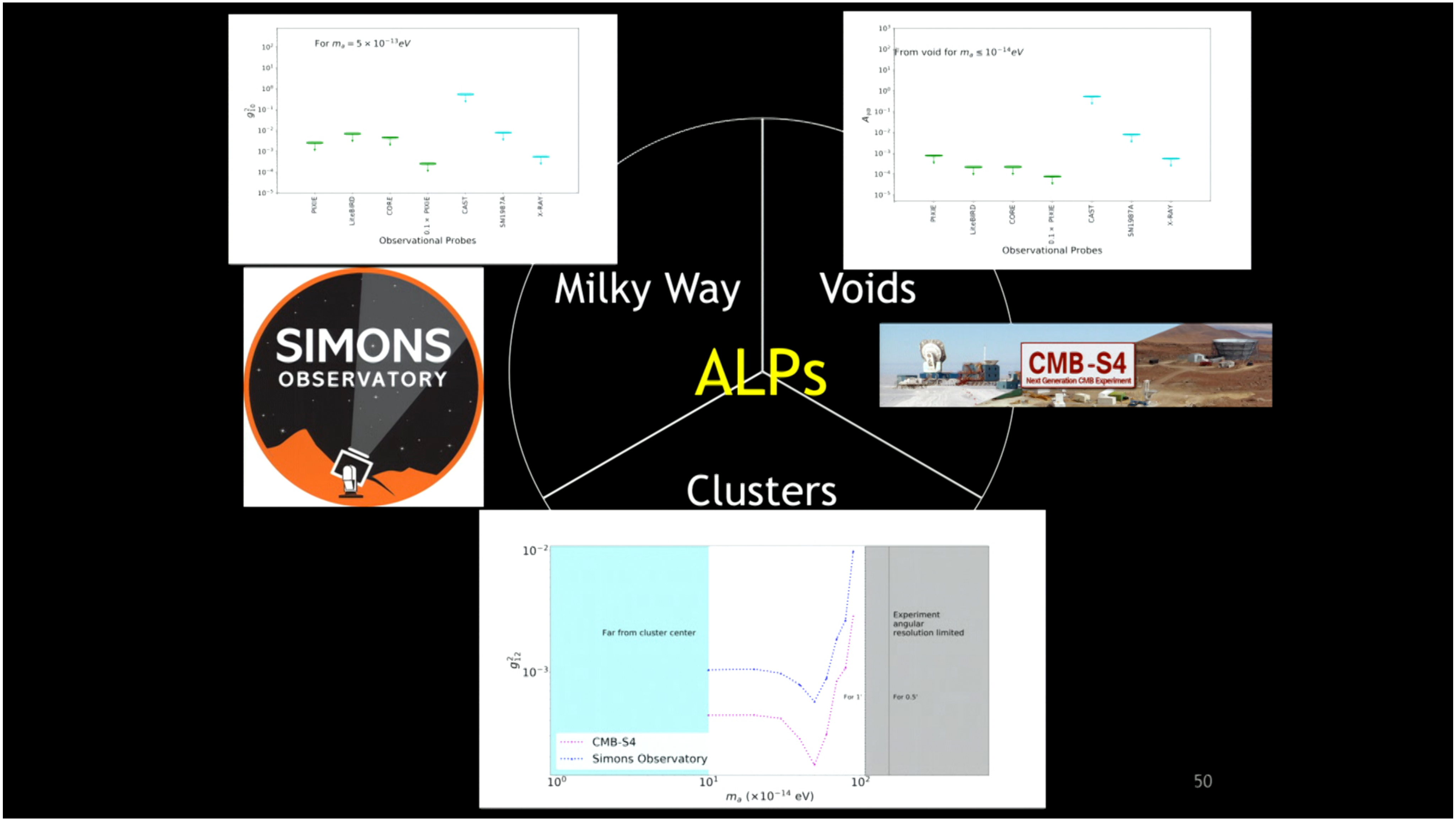
$$\hat{x}_{\gamma a}(\hat{p}) = \hat{\mathcal{W}}_{\gamma a}^T \mathbf{S}(\hat{p}),$$

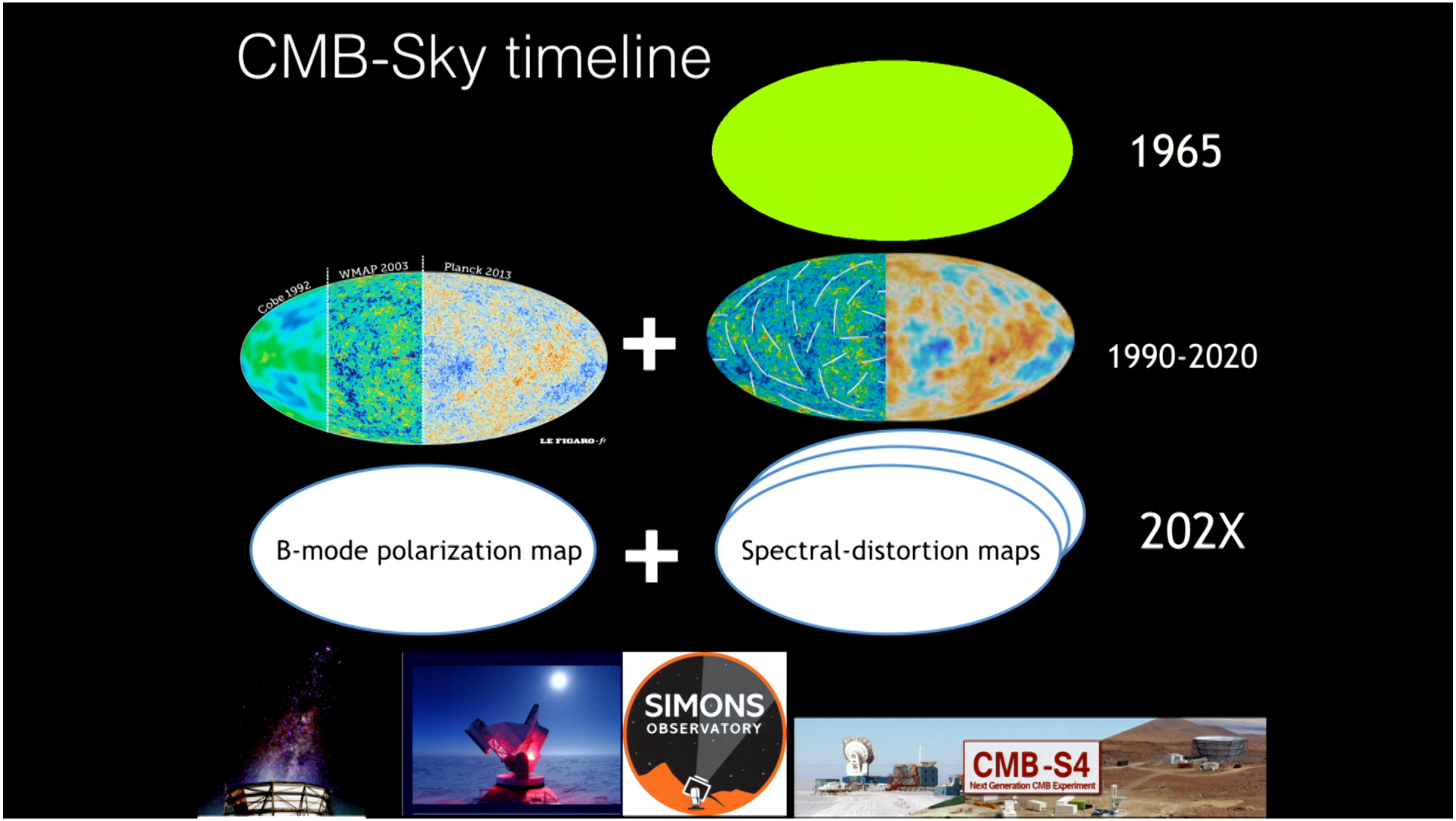


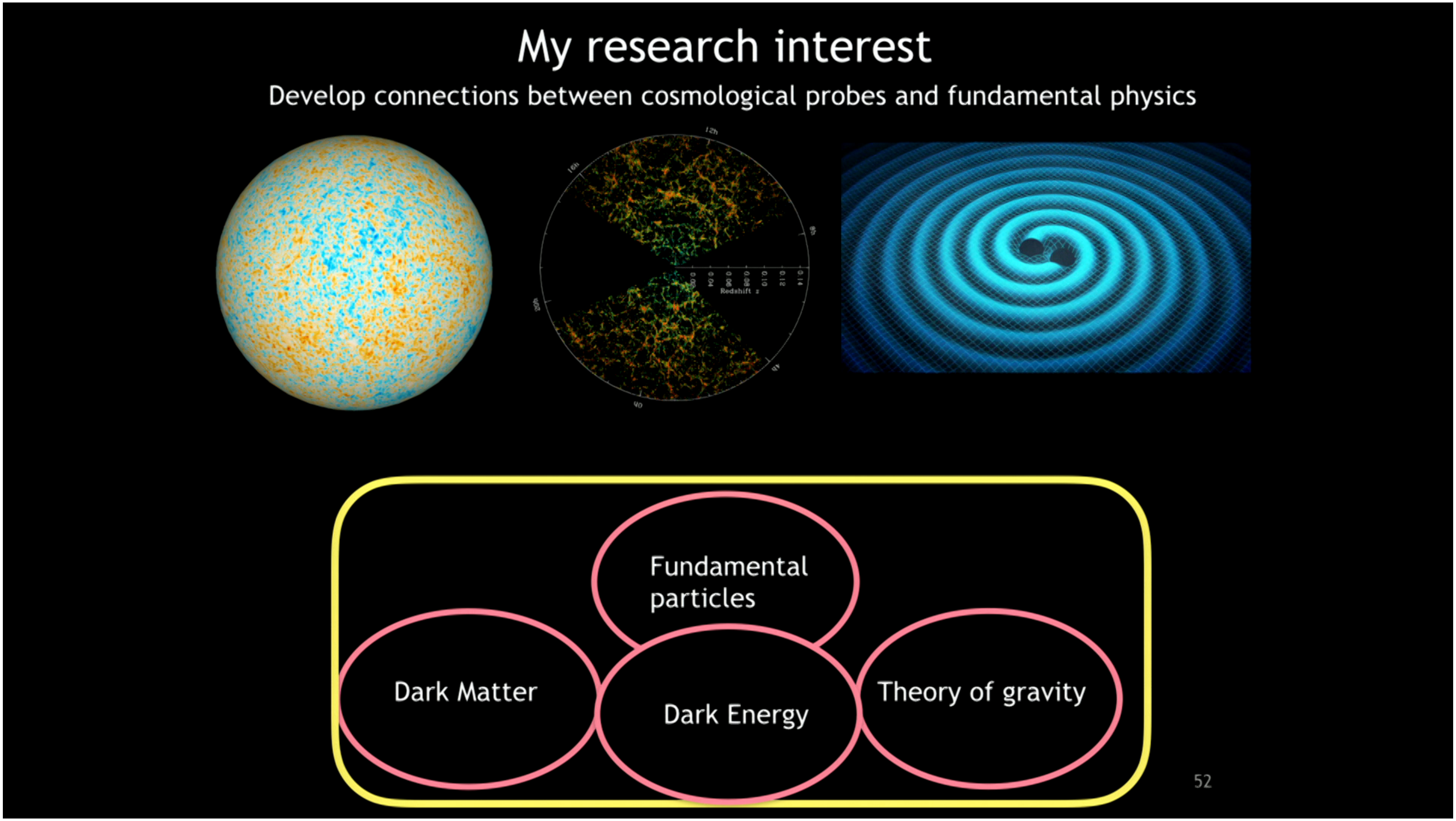
First all-sky constraints on Non-Resonant ALPs signal from Planck-data



49


For $m_a = 5 \times 10^{-13} eV$
g^2_{i0}
PIXIE
LiteBIRD
CORE
$0.1 \times$ PIXIE
CAST
SN1987A
X-RAY
Observational Probes
From void for $m_a \leq 10^{-14} eV$
$A_{\mu a}$
PIXIE
LiteBIRD
CORE
$0.1 \times$ PIXIE
CAST
SN1987A
X-RAY
Observational Probes
SIMONS
OBSERVATORY
Milky Way
Voids
ALPs
Clusters
CMB-S4
Next Generation CMB Experiment
Far from cluster center
Experiment
angular
resolution limited
For 1'
For 0.5'
g^2_{12}
CMB-S4
Simons Observatory
m_a ($\times 10^{-14}$ eV)
50


CMB-Sky timeline
1965
Cobe 1992
WMAP 2003
Planck 2013
LE FIGARO·fr
+
1990-2020
B-mode polarization map
+
Spectral-distortion maps
202X
SIMONS
OBSERVATORY
CMB-S4
Next Generation CMB Experiment


My research interest
Develop connections between cosmological probes and fundamental physics
Fundamental particles
Dark Matter
Dark Energy
Theory of gravity
52

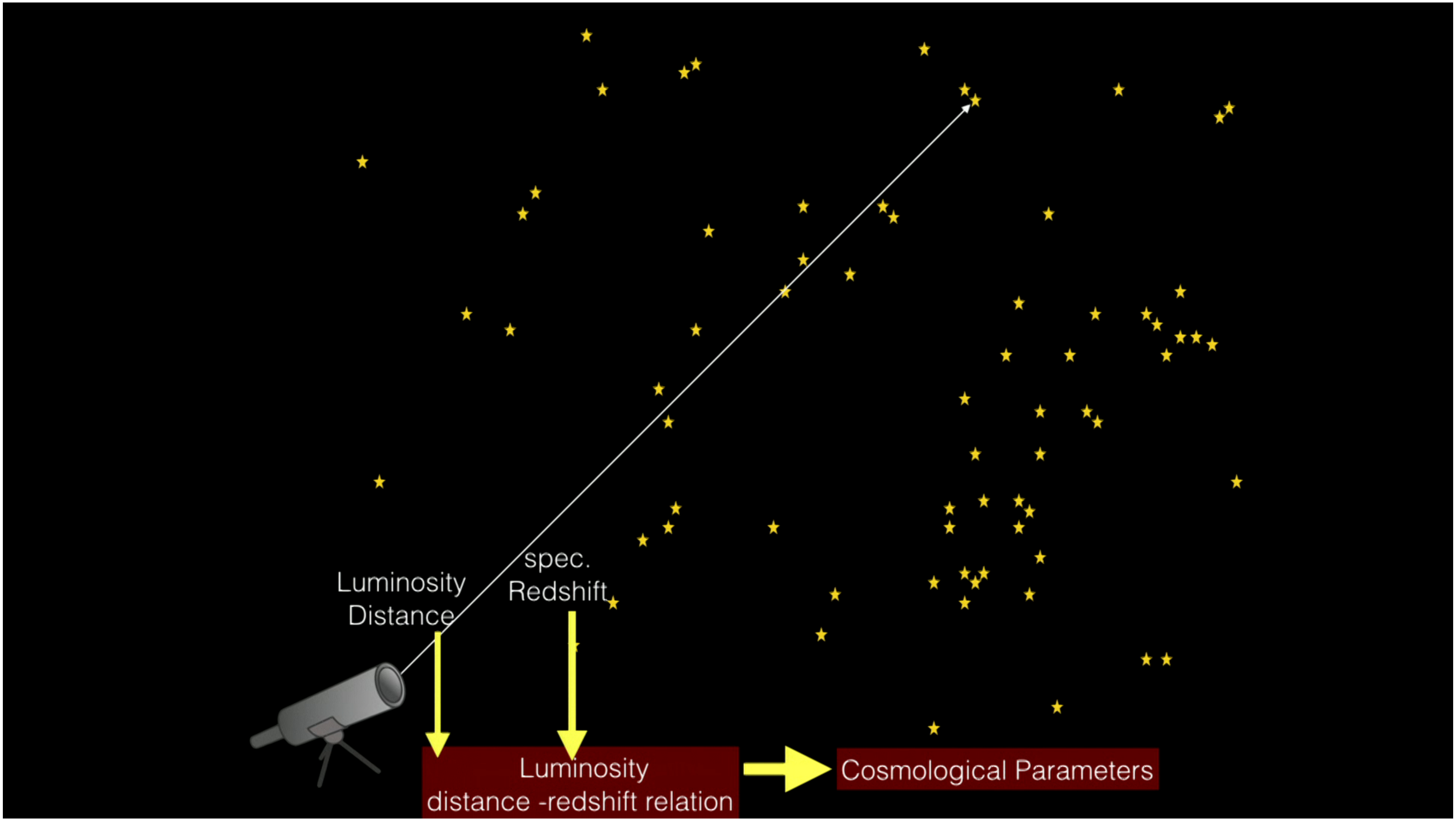
Cosmology with redshift unknown supernovae

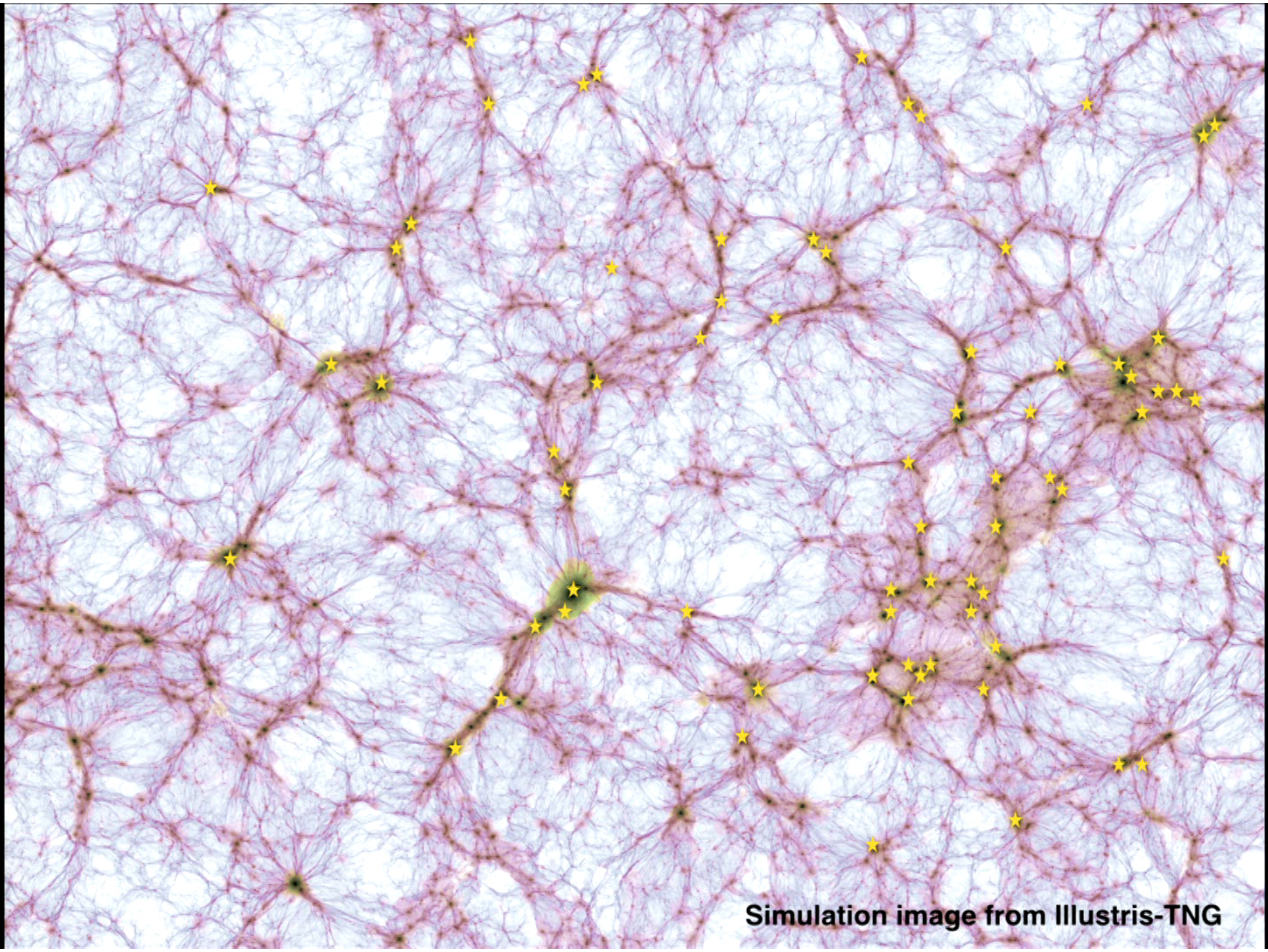
Mukherjee and Wandelt
arXiv:1808.06615

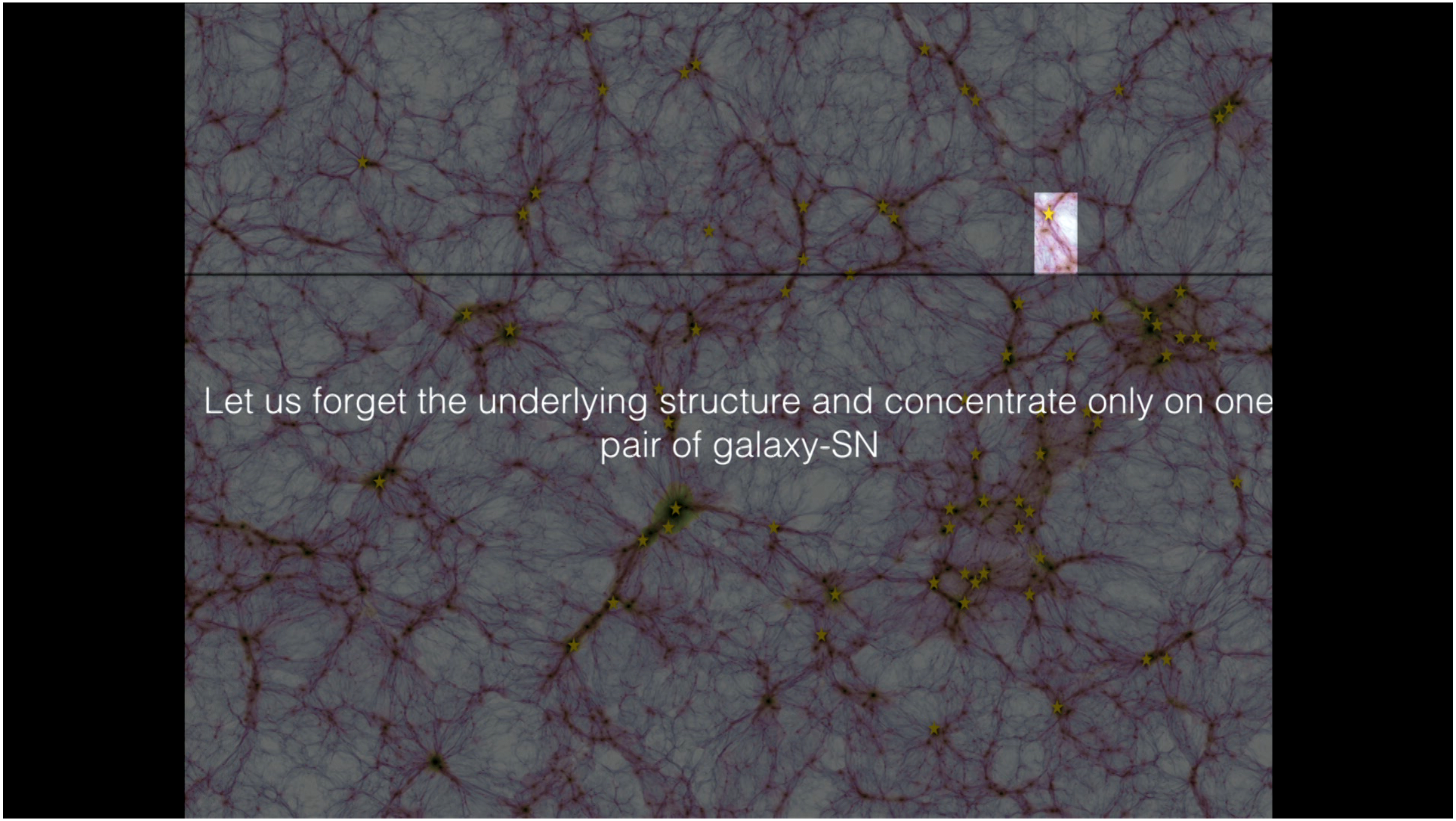
Upcoming surveys are going to measure

10^4-10^5 SN every year

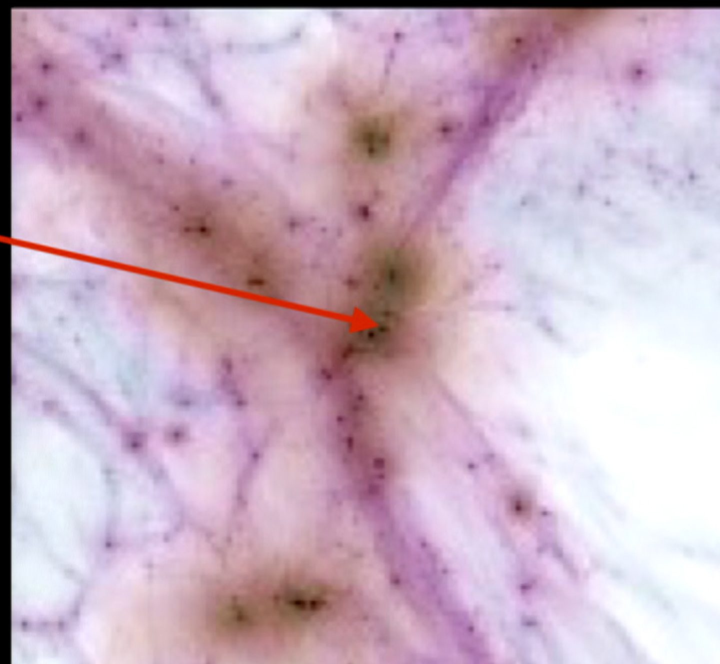
These will primarily rely on photometric redshift measurements


spec.
Redshift
Luminosity
Distance
Luminosity
distance -redshift relation
Cosmological Parameters

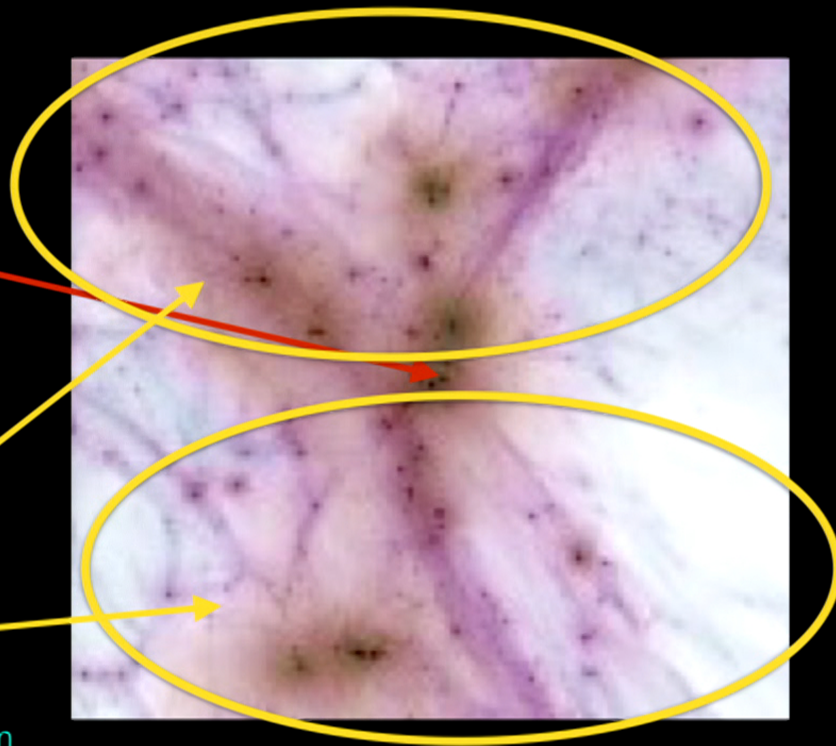

Simulation image from Illustris-TNG


Let us forget the underlying structure and concentrate only on one pair of galaxy-SN

Identifying the host galaxy of the supernovae

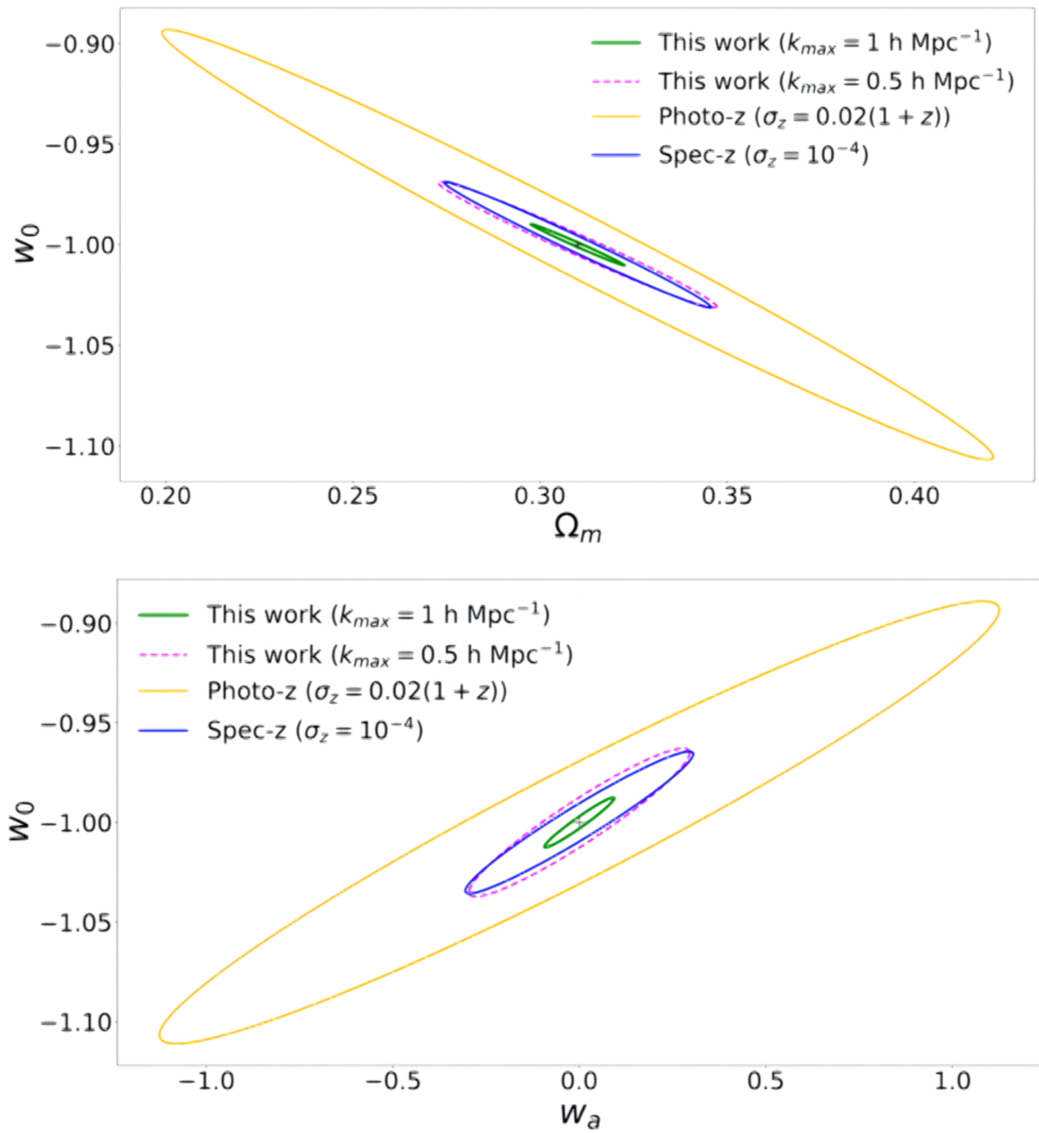


Cross-correlation of galaxies and supernovae



Identifying the host galaxy
of the supernovae

More galaxies!!
What can we get from them


This work ($k_{max} = 1$ h Mpc^{-1})
This work ($k_{max} = 0.5$ h Mpc^{-1})
Photo-z ($\sigma_z = 0.02(1+z)$)
Spec-z ($\sigma_z = 10^{-4}$)
w_0
−0.90
−0.95
−1.00
−1.05
−1.10
0.20
0.25
0.30
0.35
0.40
Ω_m
This work ($k_{max} = 1$ h Mpc^{-1})
This work ($k_{max} = 0.5$ h Mpc^{-1})
Photo-z ($\sigma_z = 0.02(1+z)$)
Spec-z ($\sigma_z = 10^{-4}$)
w_0
−0.90
−0.95
−1.00
−1.05
−1.10
−1.0
−0.5
0.0
0.5
1.0
w_a

Cosmology with Gravitational Waves : Going beyond standard sirens

Mukherjee, Wandelt, Silk
under review in
Nature-Astronomy

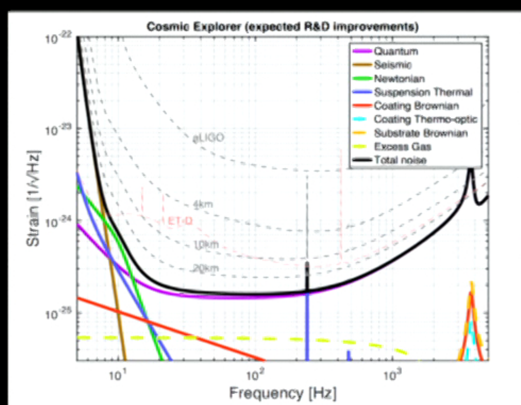


Image: LIGO collaboration
1607.08697

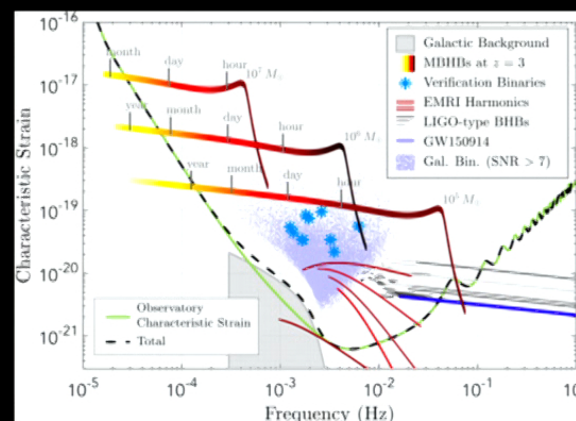


Image: LISA Science Proposal

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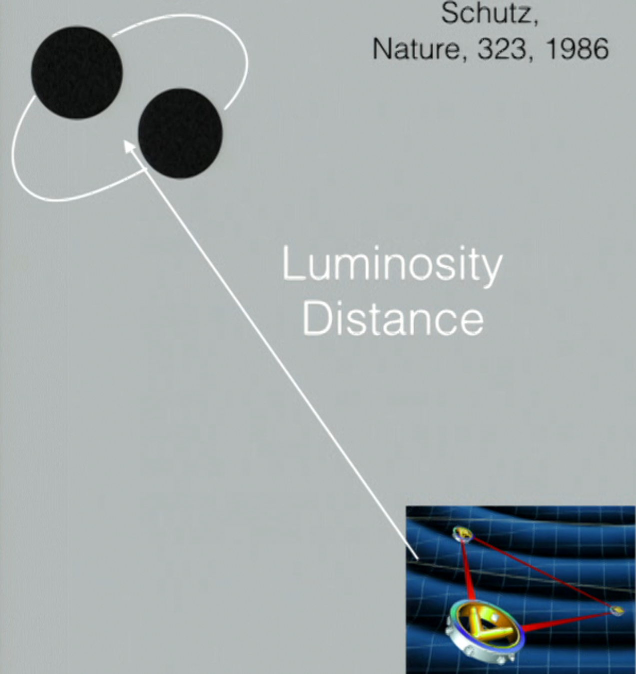
Cosmology with GW

Standard Sirens: Distance Ladder

Schutz,
Nature, 323, 1986



Cosmic Density field

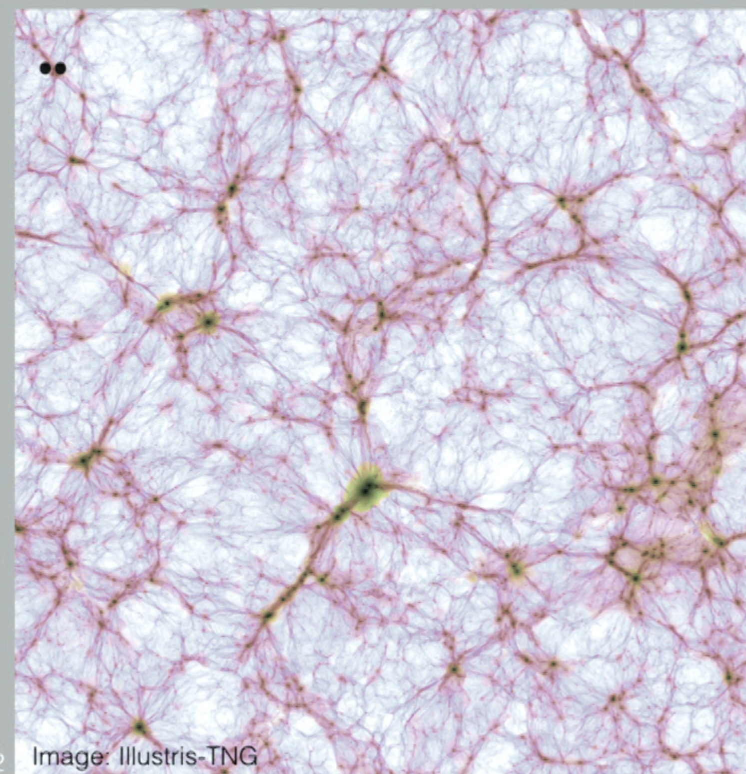


Image: Illustris-TNG

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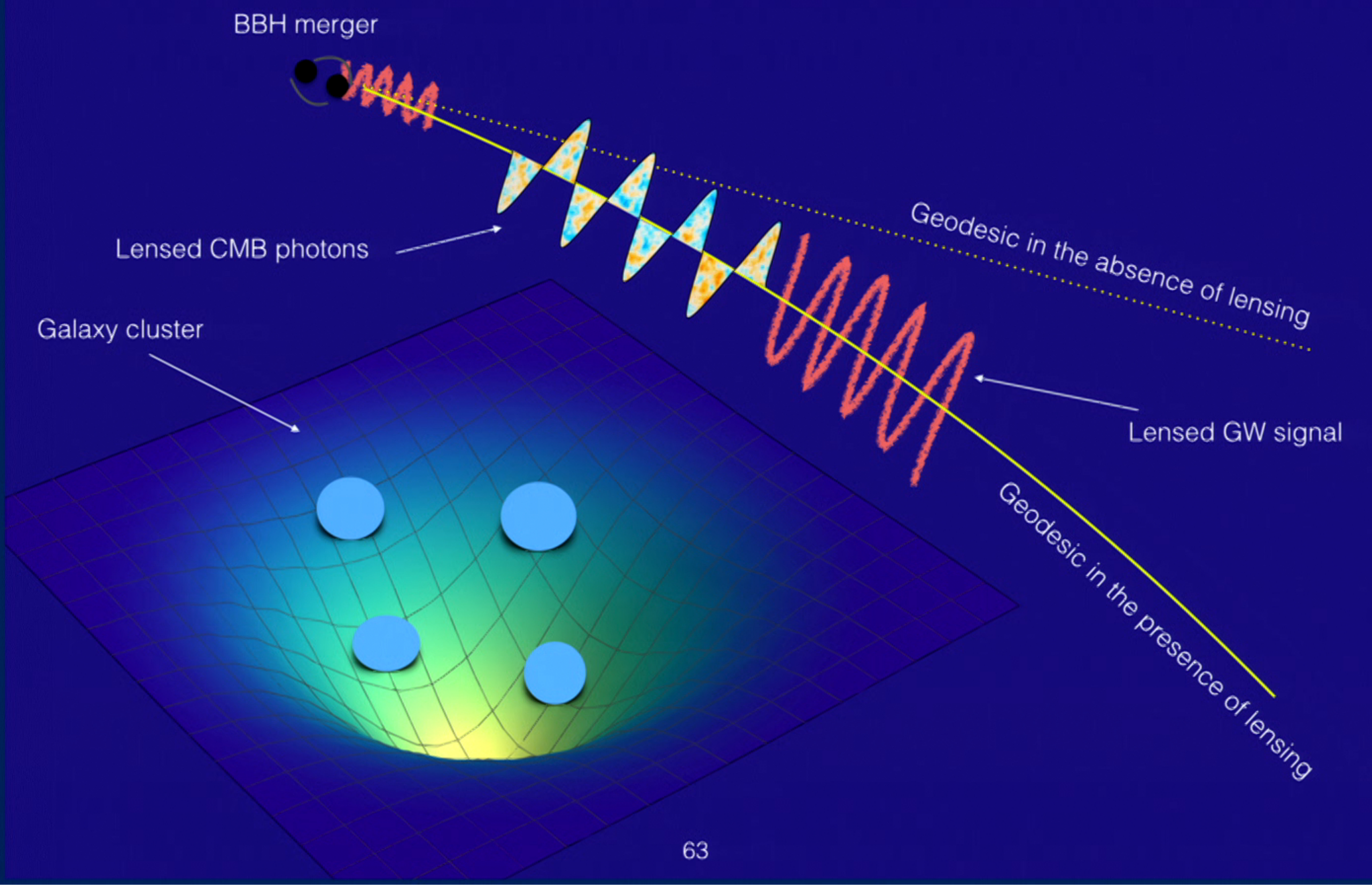
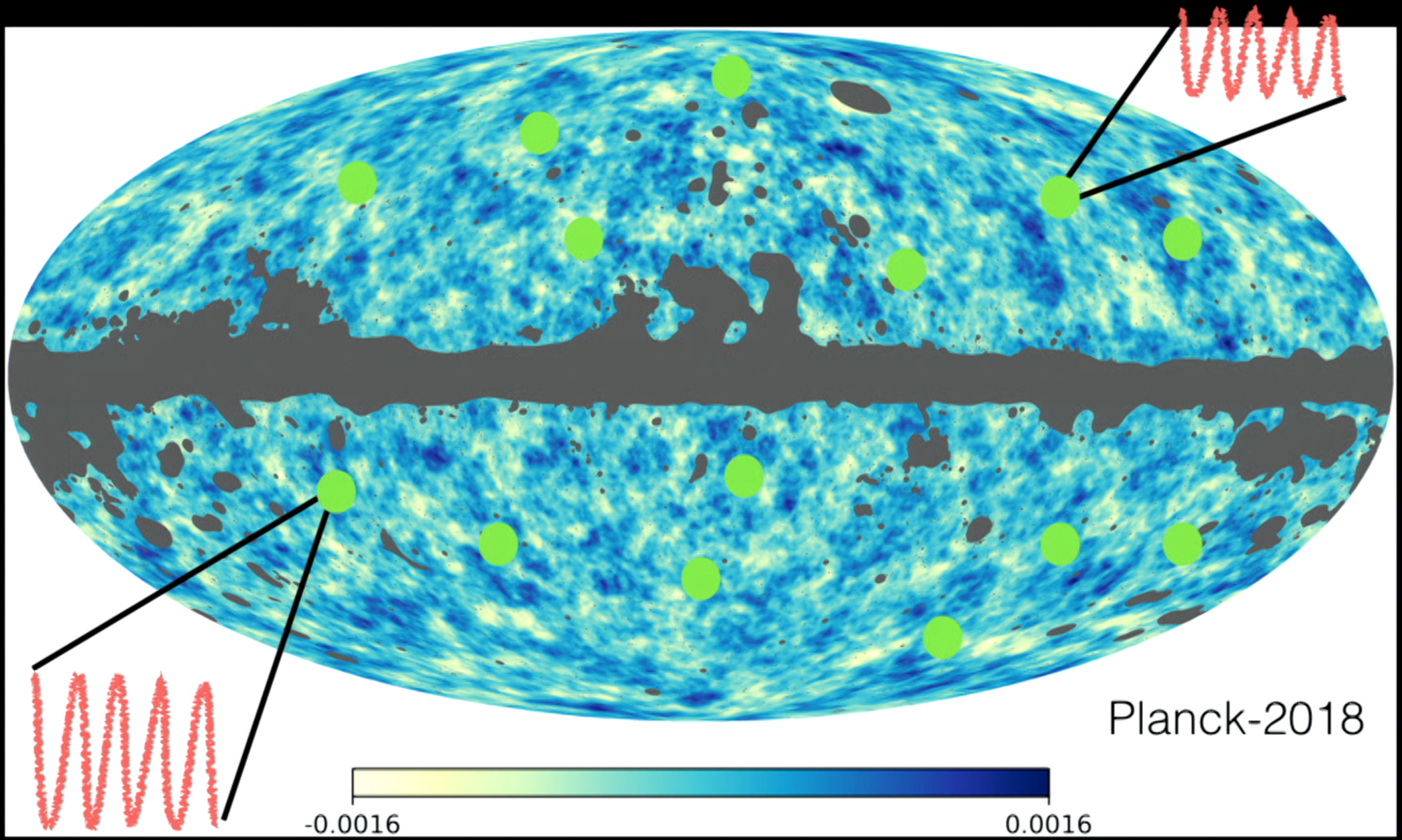
Probing GW lensing using CMB-GW correlation

Mukherjee, Wandelt, Silk (2018)



63



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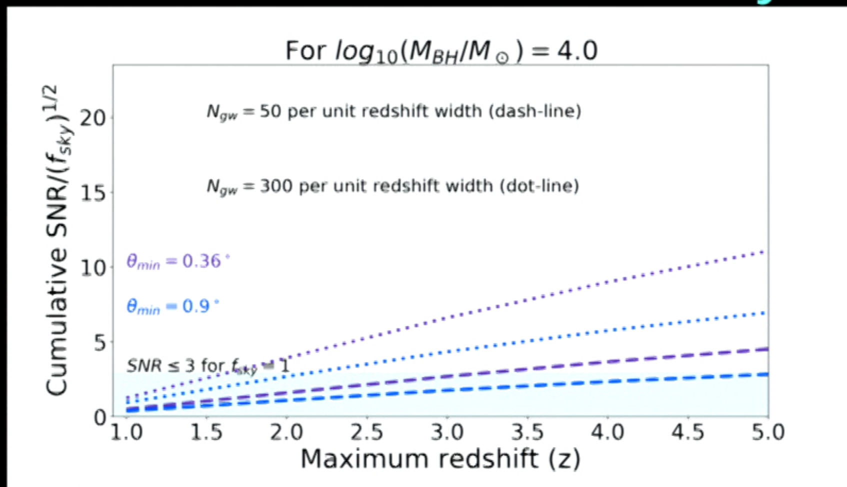
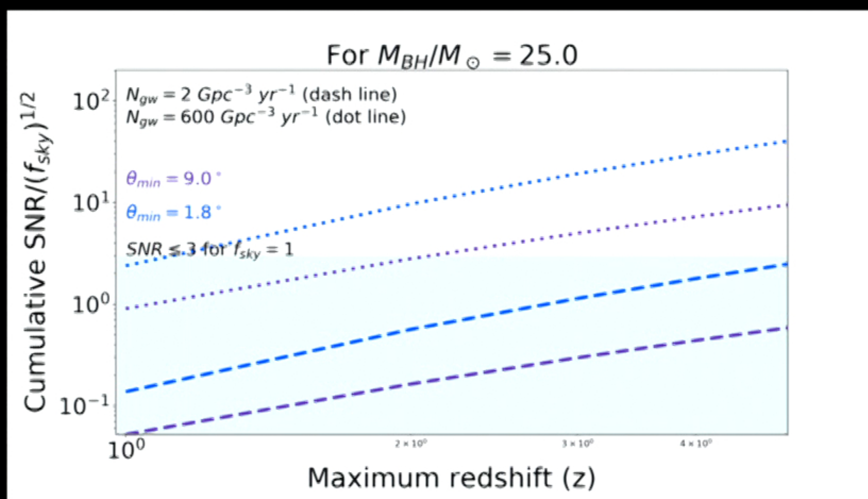
Discovery space

Mukherjee, Wandelt, Silk (2018)



LISA



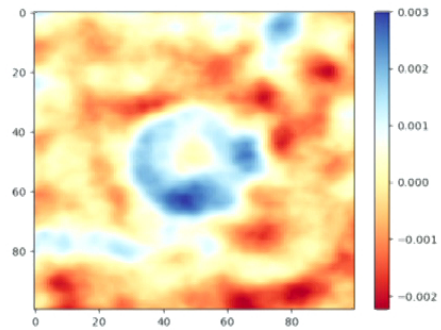
Cosmic Explorer

Diverse scientific scopes

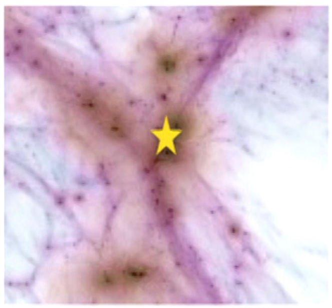
- Concordant trajectory between electromagnetic waves and gravitational waves
- A probe to the theories of extra-dimensions of spacetime (Deffayet & Menou 2007, LIGO-VIRGO Coll. (2018))
- A probe to the alternative theories of gravity

(Saltas et al. 2014,Nishizawa 2018)

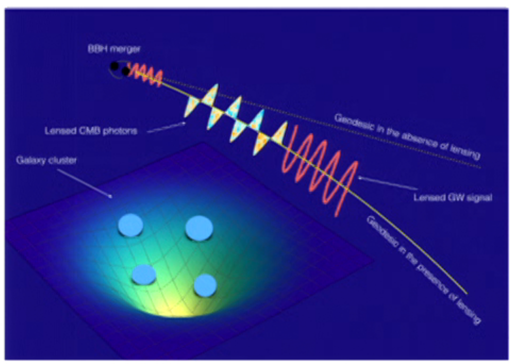
A Few New Frontiers in Cosmology



Simons Observatory
CMB-S4



LSST
EUCLID
DESI



adv-LIGO
LISA
Cosmic Explorer

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