Patchy dark screening

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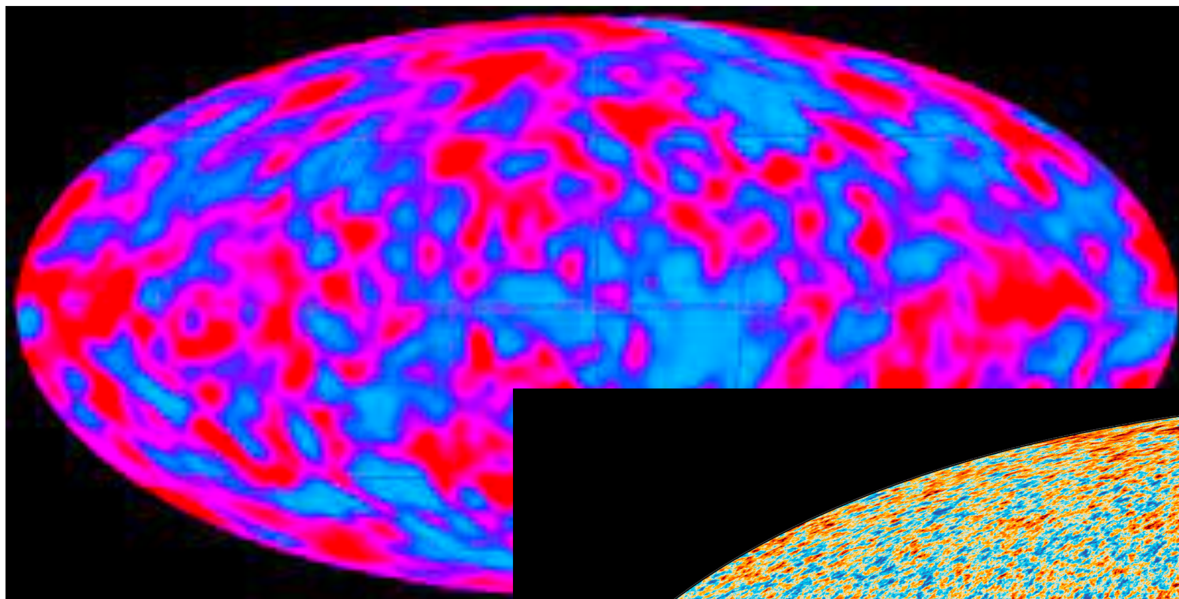
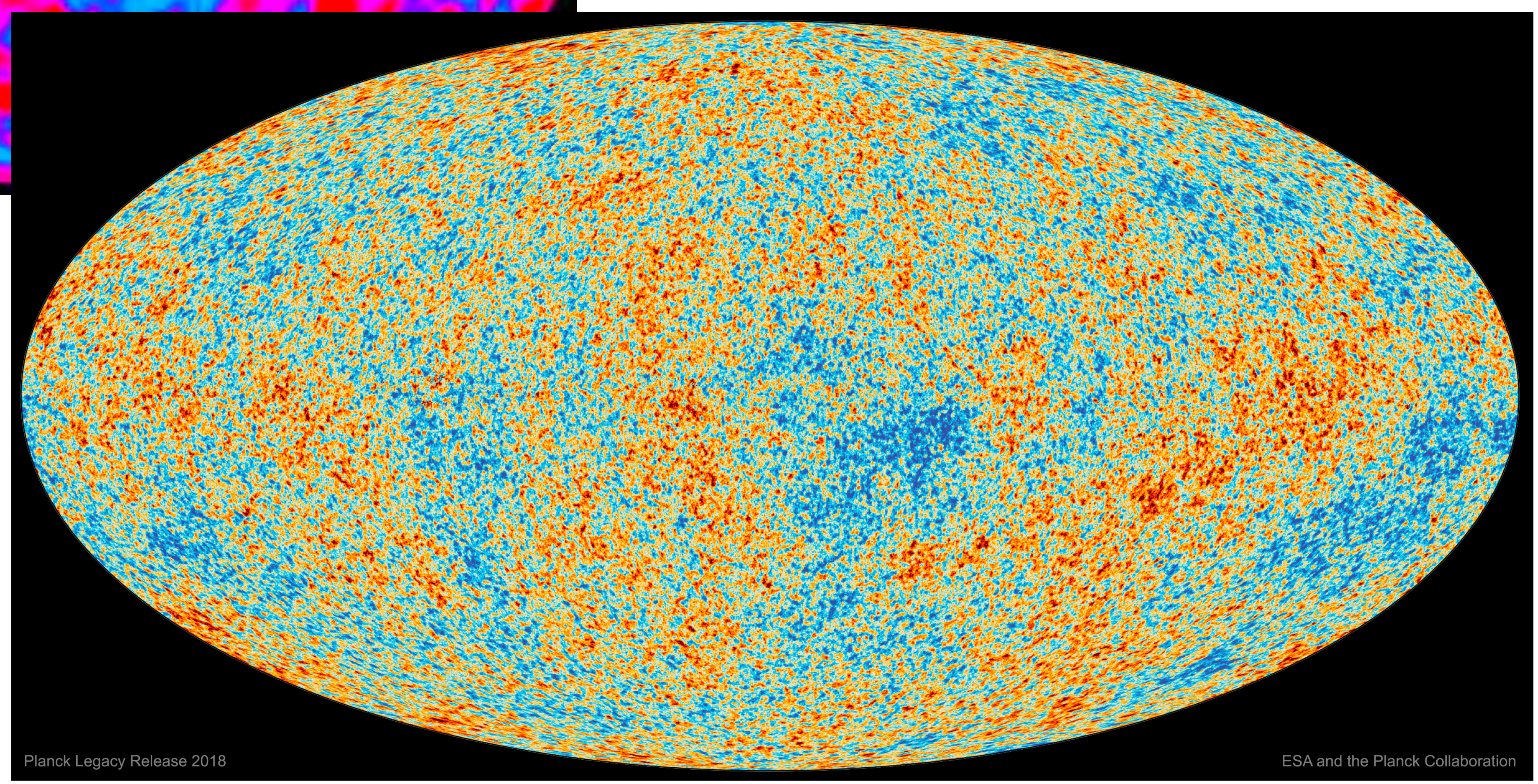
Dalila Pirvu, Junwu Huang, Matthew Johnson
2307.15124

CMB

From COBE to Planck, we have greatly improved our understanding of the Universe





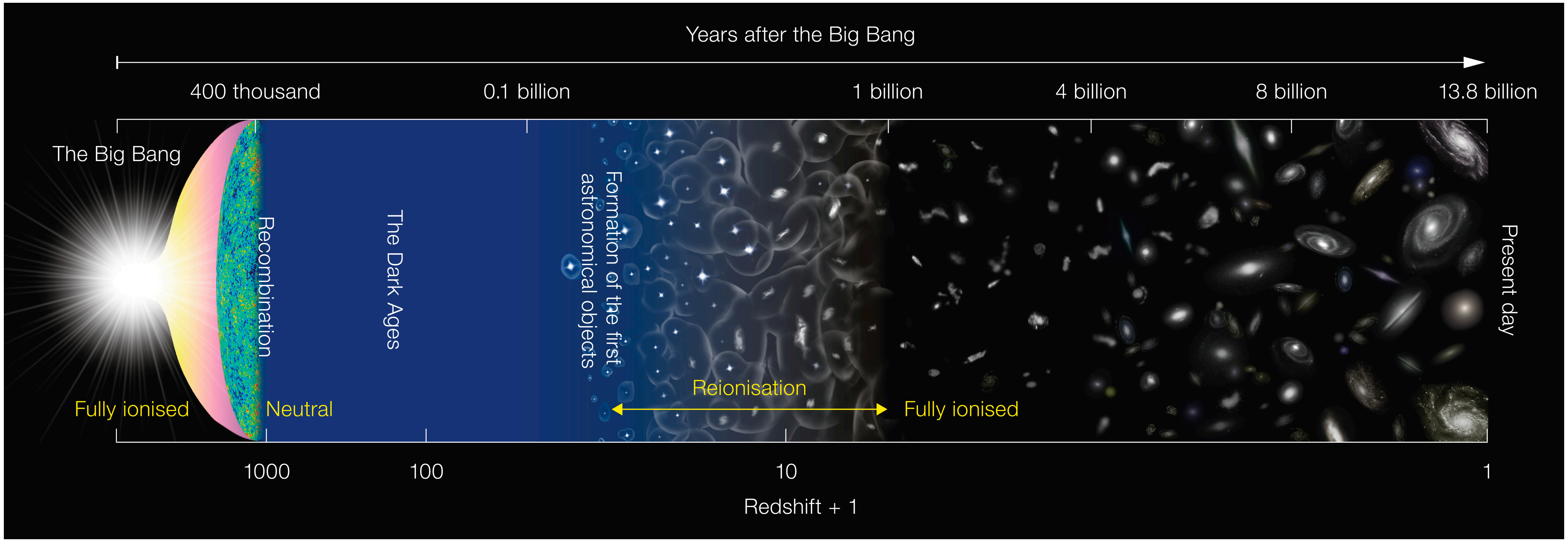
BSM in cosmology

- We have been using CMB as a tool to study DM interactions:

Background light

Effect of DM

Observer



Spectral distortion

CMB

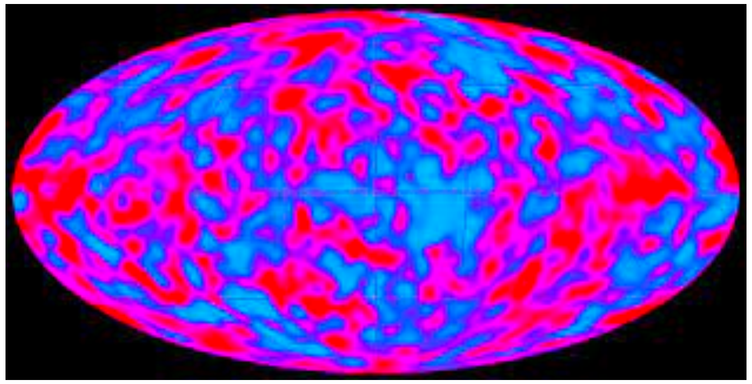
Effect of DM

Observer

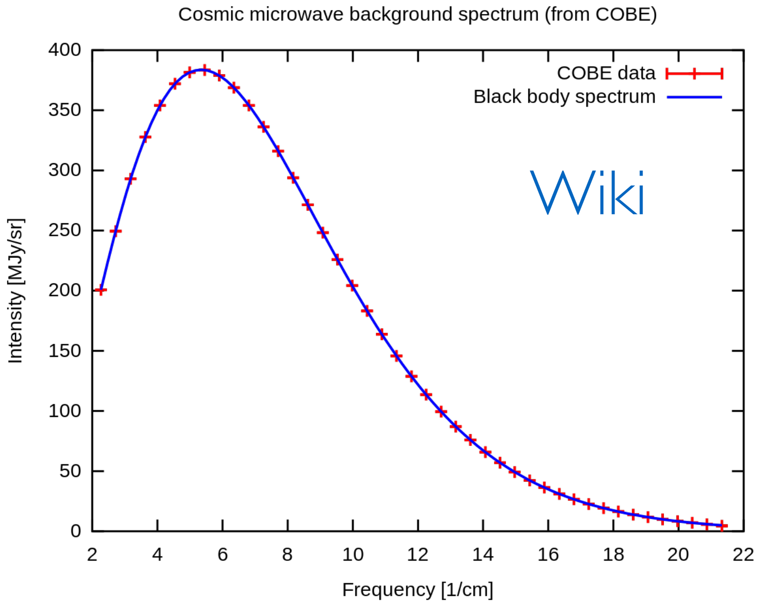
- Spectral distortion to study energy exchange:

Sunyaev, Zeldovich 1969

Standard Model: μ and y-distortion from electron scattering
Beyond Standard Model: energy injection from Dark Matter



COBE/FIRAS



CMB secondary anisotropies

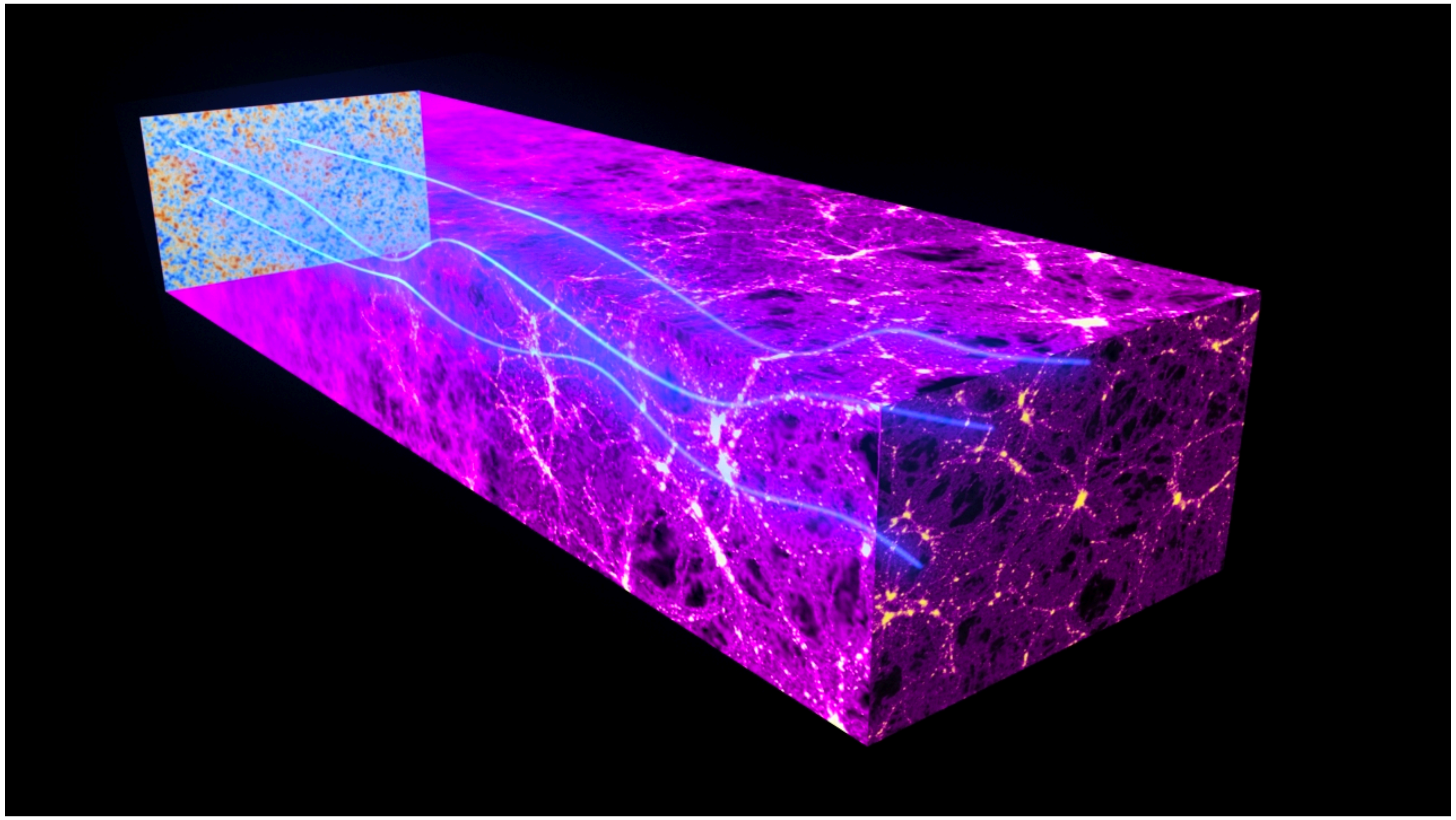
- In ΛCDM

Hu Okamoto 2001

CMB

Galaxy

Observer



CMB lensing

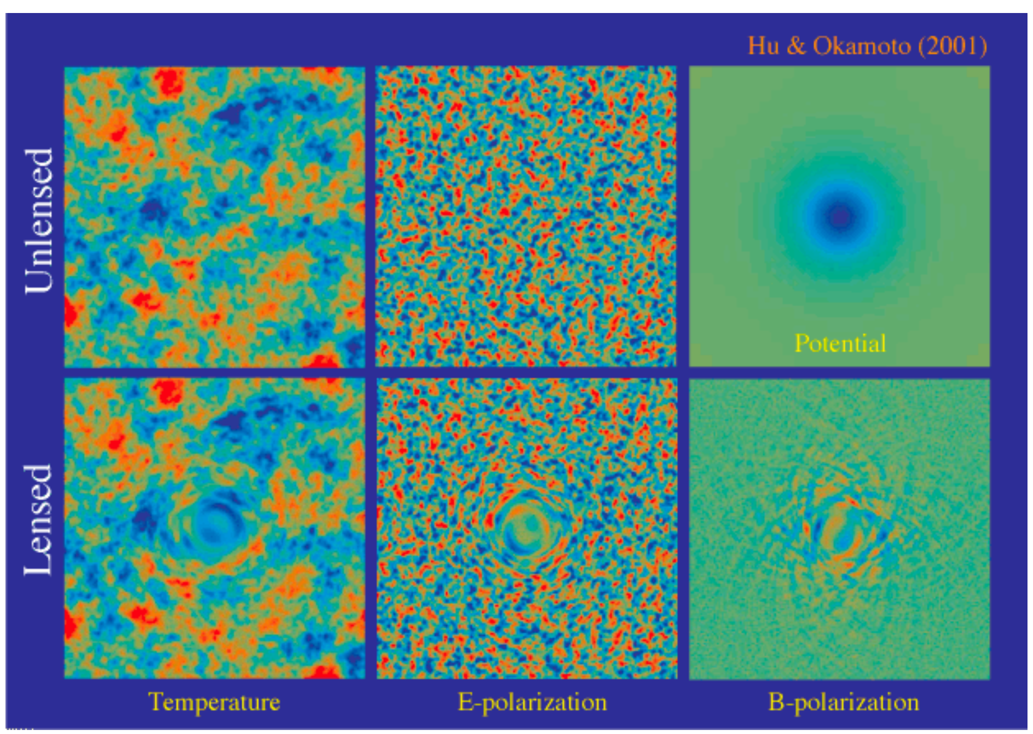
CMB secondary anisotropies

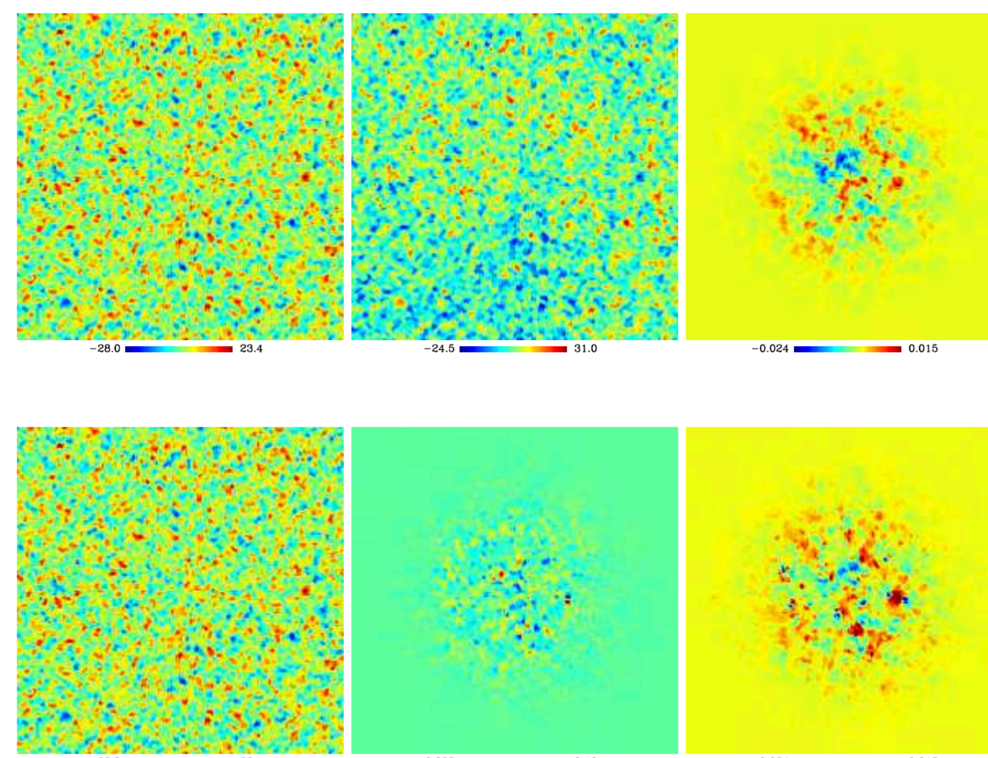
- In ΛCDM

Hu Okamoto 2001
Dvorkin Smith 2008

CMB | Galaxy | Observer

Lensing
SZ
...





DM induced secondary anisotropies

- In ΛCDM

CMB | Galaxy | Observer

Lensing
SZ
…

- WIMPs

CMB | Galaxy | Observer

DM -> Gas -> CMB photon
(Energy injection into and thermalize with SM plasma)

Tracy's talk tomorrow

Light dark sector searches

~~How much do I contribute to various SZ effect maps, etc?~~

DM or Dark sector maps generally can actually look quite different!

We can do better!

Outline

To illustrate we will discuss an example of late time dark photon to photon conversion

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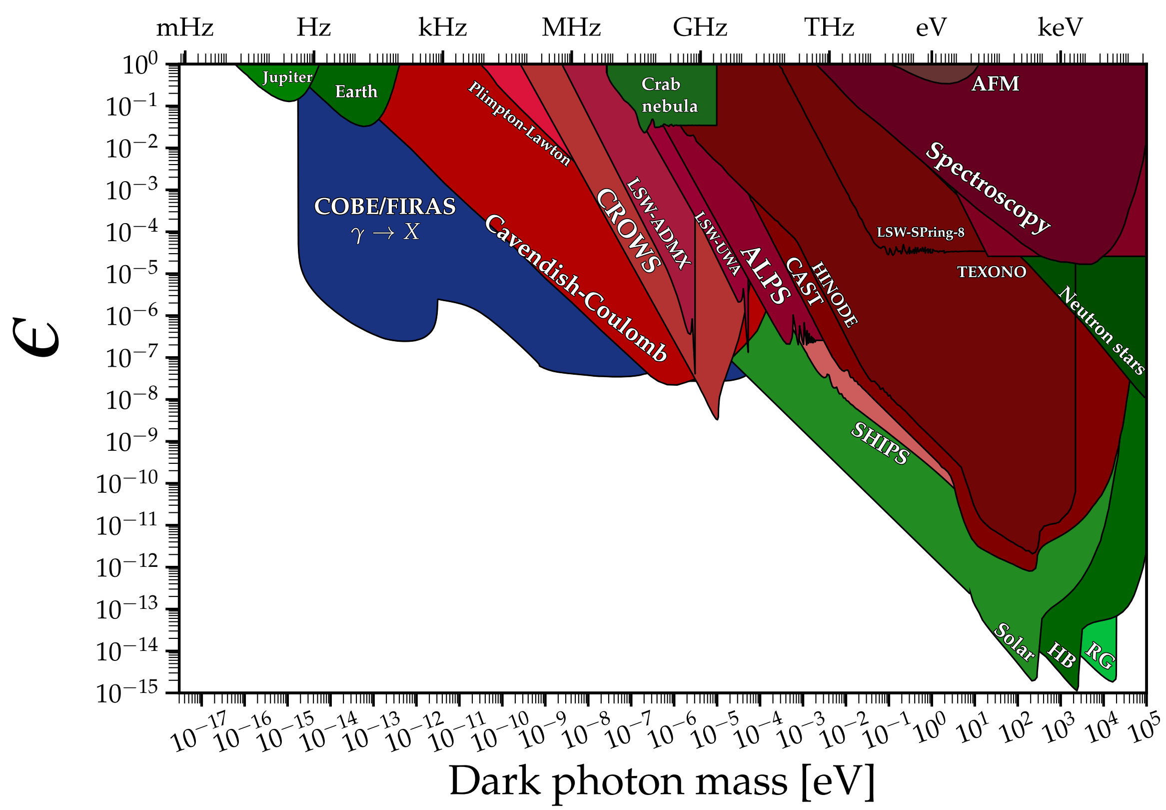
- Dark photon example:
  - Dark photon conversion
  - Halo model & Map
  - Estimators
  - Projection
  - Planck analysis
- Other particles
- Other backlight

Dark photon

Operator

- Light sector physics
  - Axion
  - Dark photon (Okun 1982, Holdom 1985)

$$\mathcal{S} = \int d^4x \left(-\frac{1}{4} F'^{\mu\nu} F'_{\mu\nu} - \frac{1}{2} m_{A'}^2 A'_\mu A'^\mu + \varepsilon F^{\mu\nu} F'_{\mu\nu} \right)$$



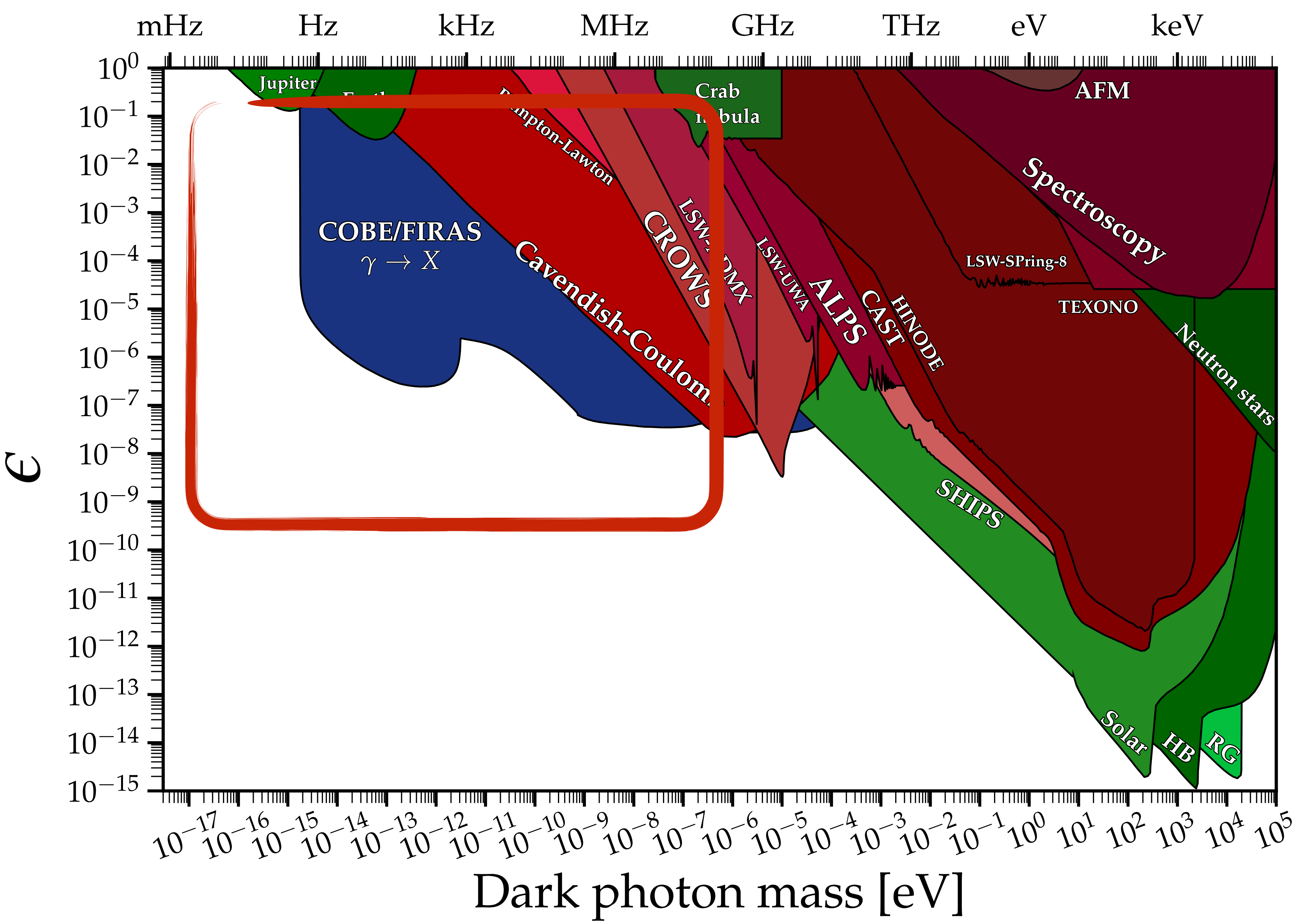
- Dark matter? :(

East, **Huang**, 2206.12432

- Mediator to the dark sector
- Low energy remnant of string theory

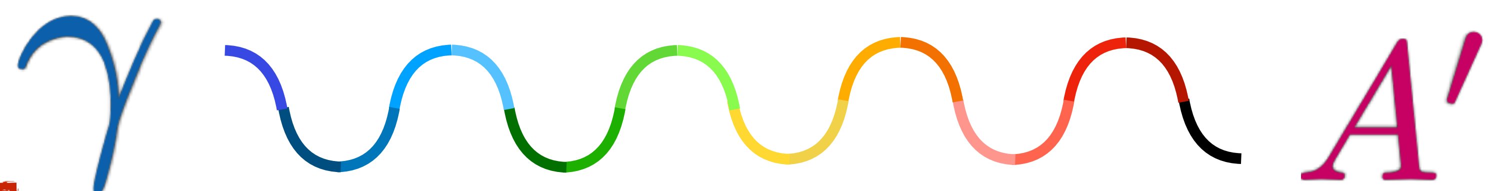
Photon disappearance

- Photon to dark photon conversion

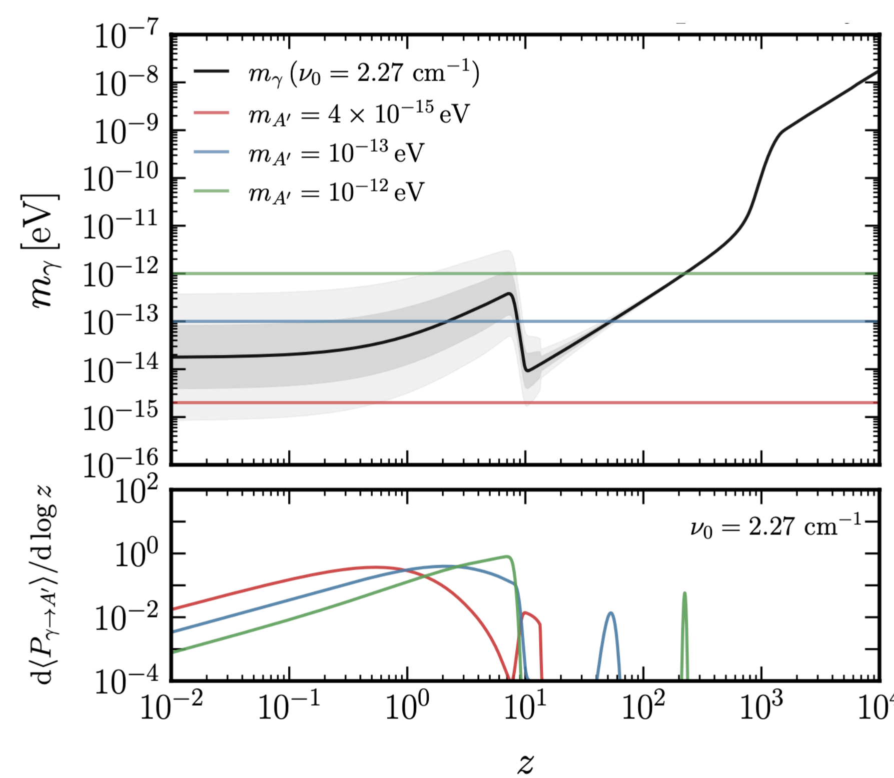


Photon disappearance

- Resonant photon to dark photon conversion
  - $\omega_p^2 = m_{A'}^2$



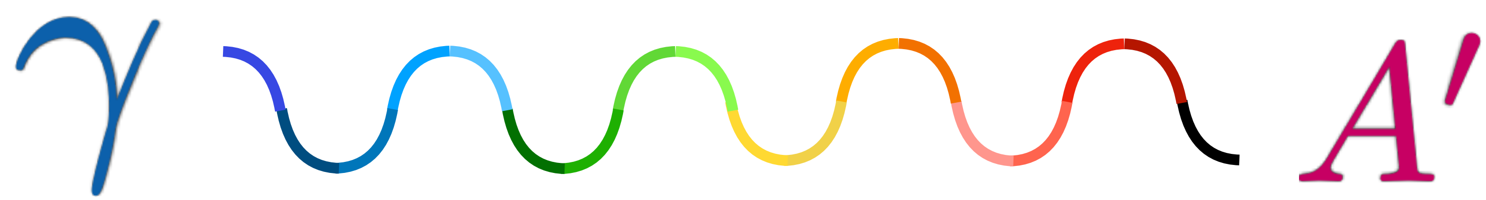
Cosmology provides natural scanners



(From Hongwan Liu)

Photon disappearance

- Resonant photon to dark photon conversion
  - $\omega_p^2 = m_{A'}^2$
  - Probability

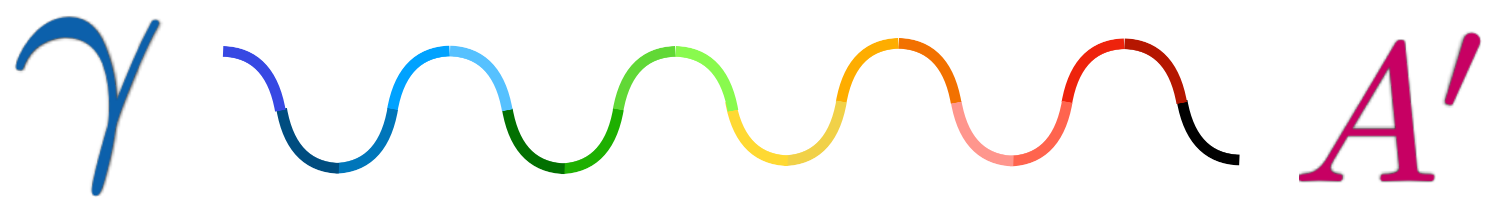


$$P_{\gamma\to A'} = \sum_{t_{\rm res}} \frac{\pi\varepsilon\, m_{A'}^2}{\omega(t_{\rm res})} \times \varepsilon \left| \frac{\mathrm{d}}{\mathrm{d}t} \ln m_\gamma^2(\vec{x}(t)) \right|_{t=t_{\rm res}}^{-1}$$

- Absorption optical depth
- $1/\omega$ frequency dependence
- Depends on the distribution of matter

Photon disappearance

- Resonant photon to dark photon conversion
  - $\omega_p^2 = m_{A'}^2$
  - Probability



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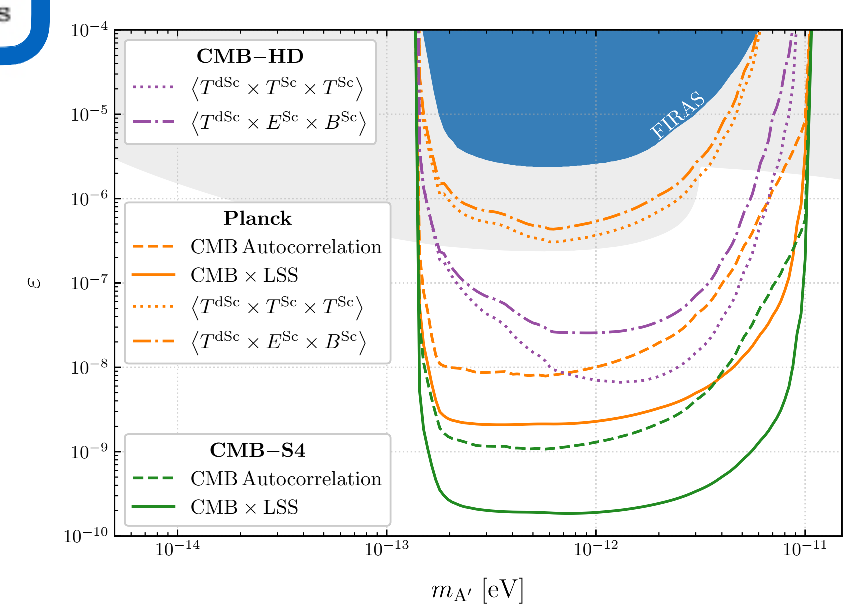
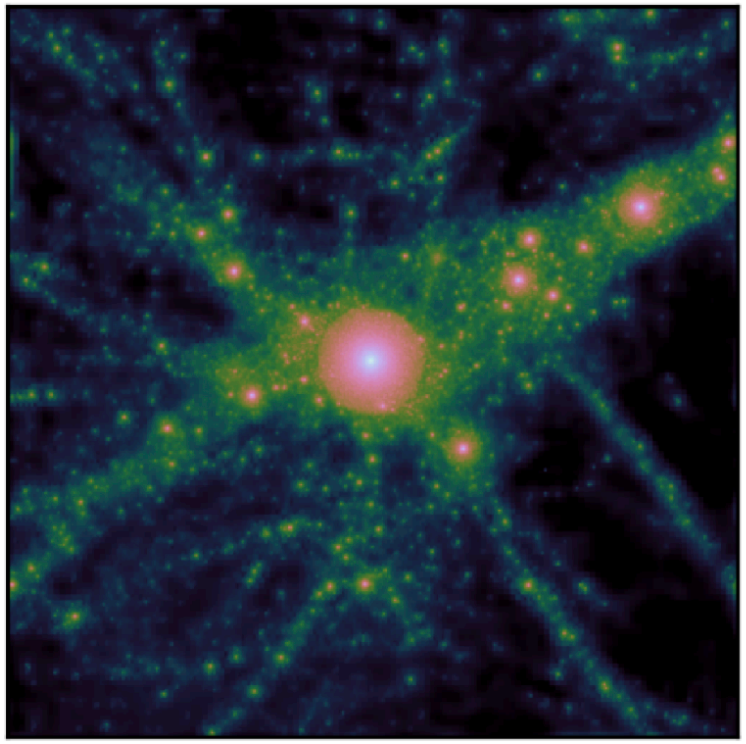
- Absorption optical depth
- $1/\omega$ frequency dependence
- Depends on the distribution of matter

Contrast with SM effects



Dark screening from Halos

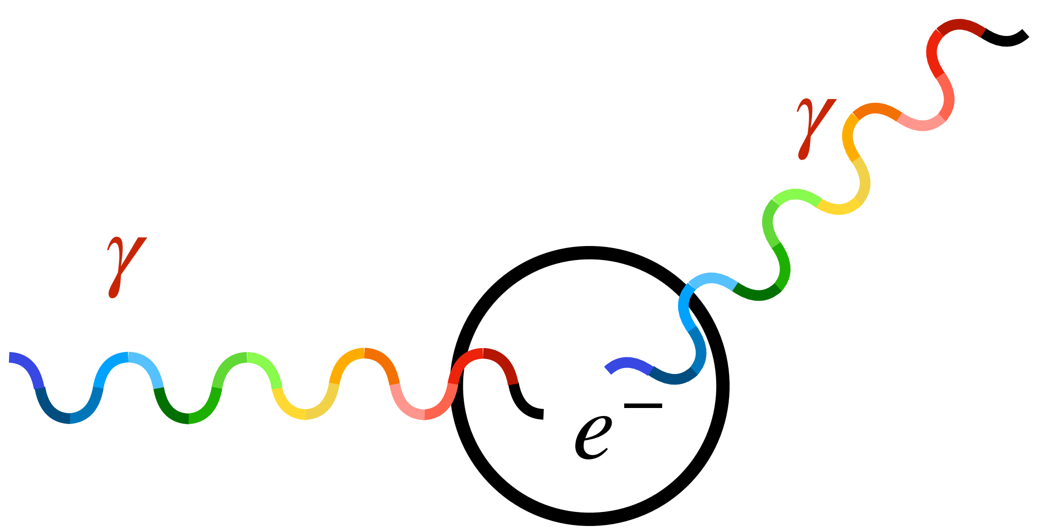


Anisotropies of $P_{\gamma\to A'}$ tracks anisotropies of matter

Thomson screening (detour)

- Thomson screening comes from Thomson scattering between CMB photon with electrons.

One halo



Optical depth τ^{Th}

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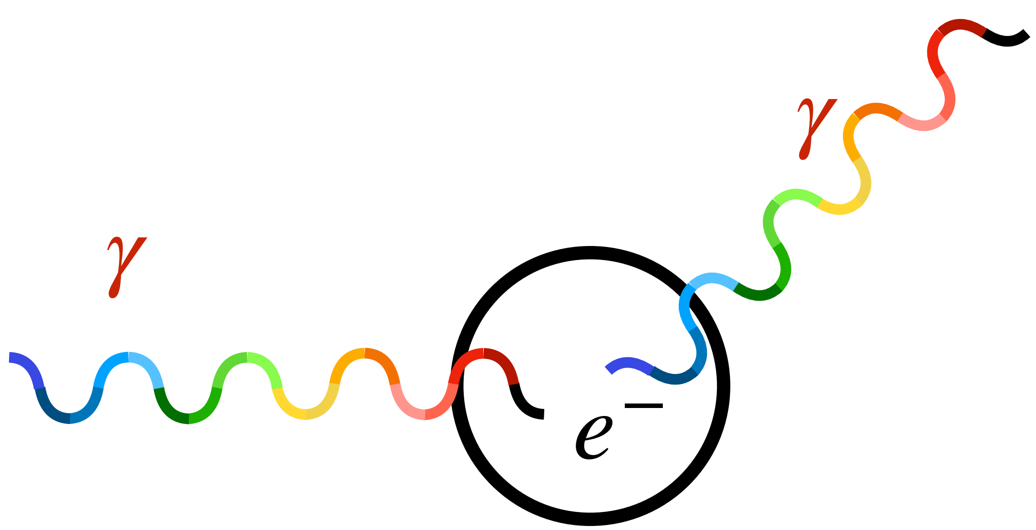
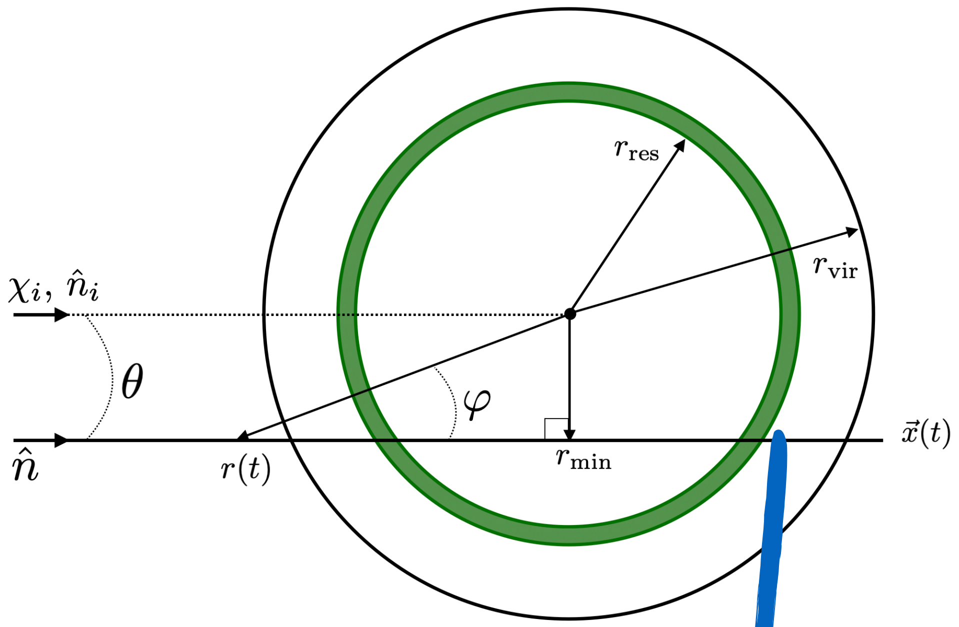


Optical depth τ^{Th}

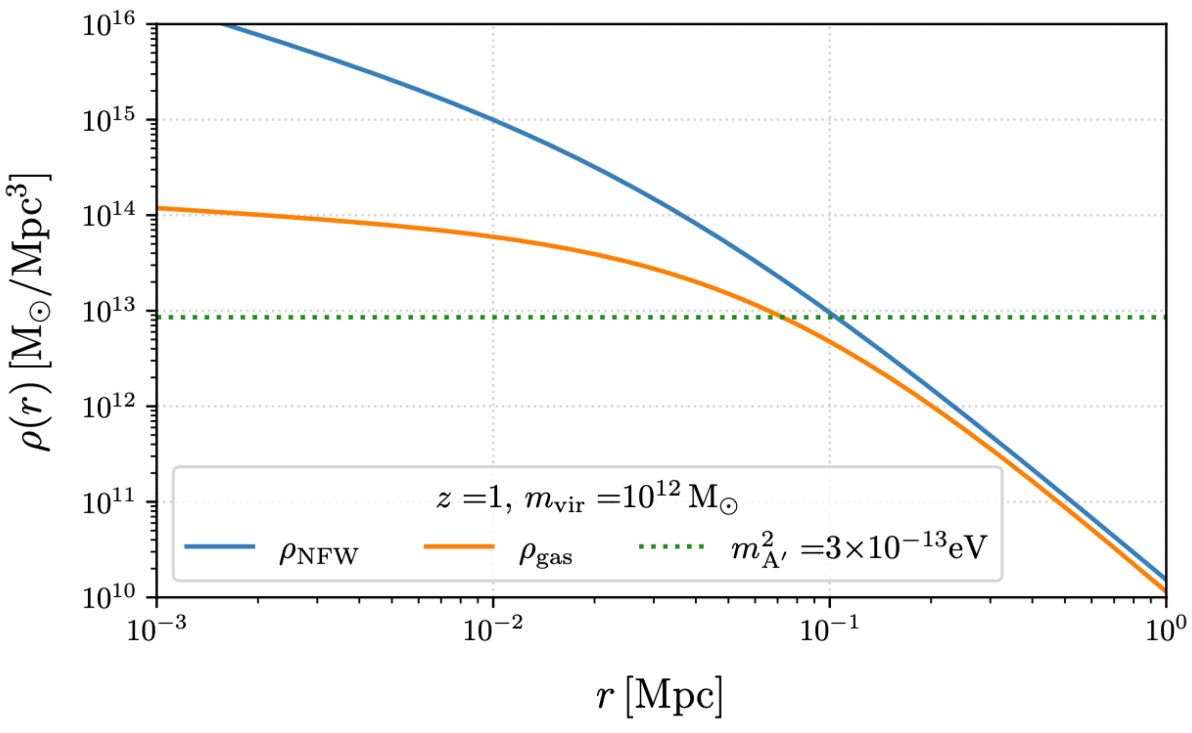
- Density distribution in halos
- Halo mass function

Photon disappearance (in Halo)

One halo



Density profile provides scanner



$$\tau(\hat{n},\omega) \equiv P_{\gamma\to \mathrm{A}'} = \sum_{t_{\rm res}} \frac{\pi\varepsilon\, m^2_{\mathrm{A}'}}{\omega(t_{\rm res})} \times \varepsilon \left| \frac{\mathrm{d}}{\mathrm{d}t} \ln m^2_\gamma(\vec{x}(t)) \right|^{-1}_{t=t_{\rm res}}$$

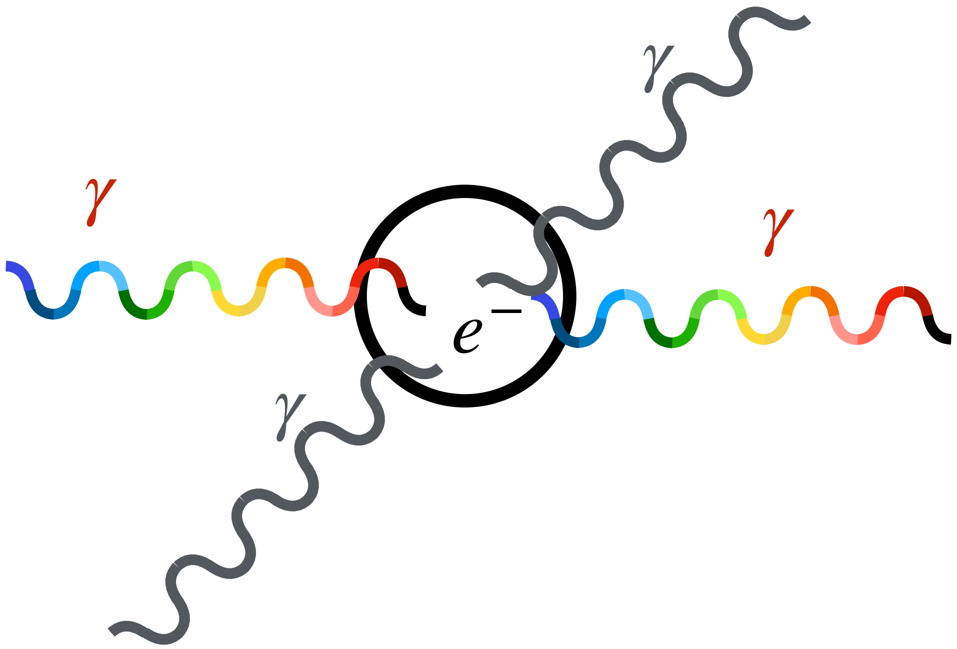
Contrast with SM

- **Absorption optical depth**
- $1/\omega$ frequency dependence
- Depends on the distribution of matter

- **Coupled to the CMB monopole!**
- Can be separated from the primordial CMB
- Correlated with LSS

Scattering

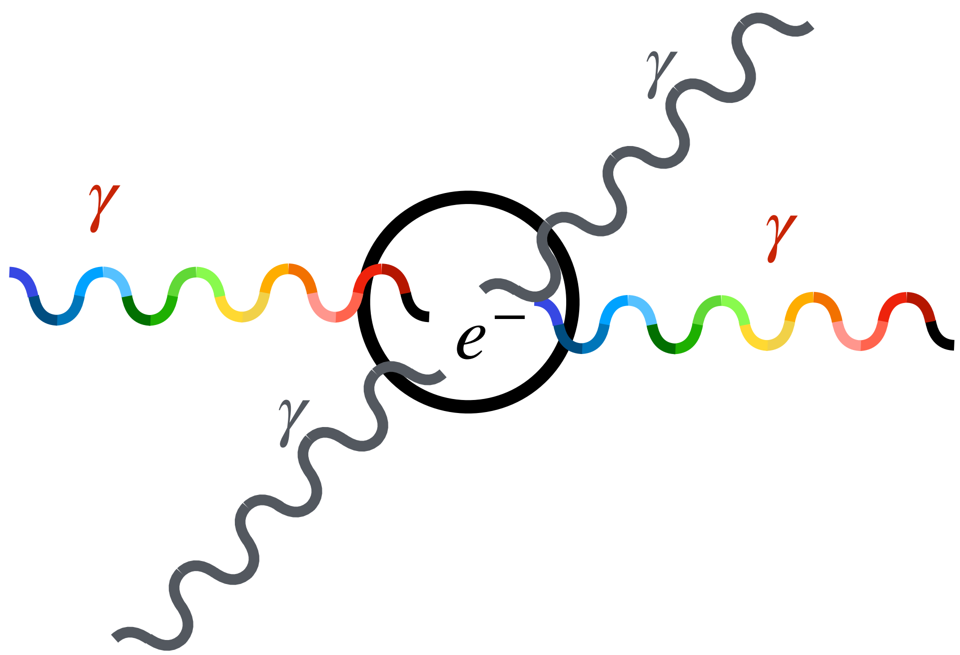
Following notations of Dvorkin & Smith 0812.1566

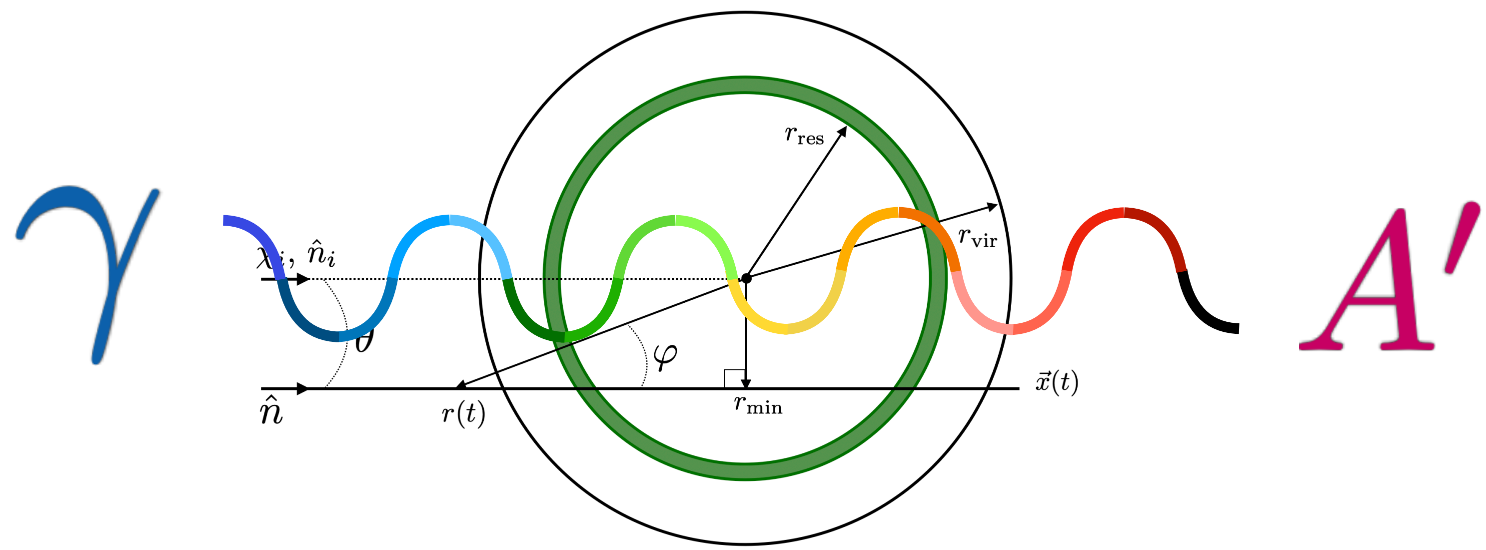


$$T^{\rm Sc}(\hat{n}) \simeq T(\hat{n}) - \tau^{\rm Th}(\hat{n})T(\hat{n})$$

Absorption

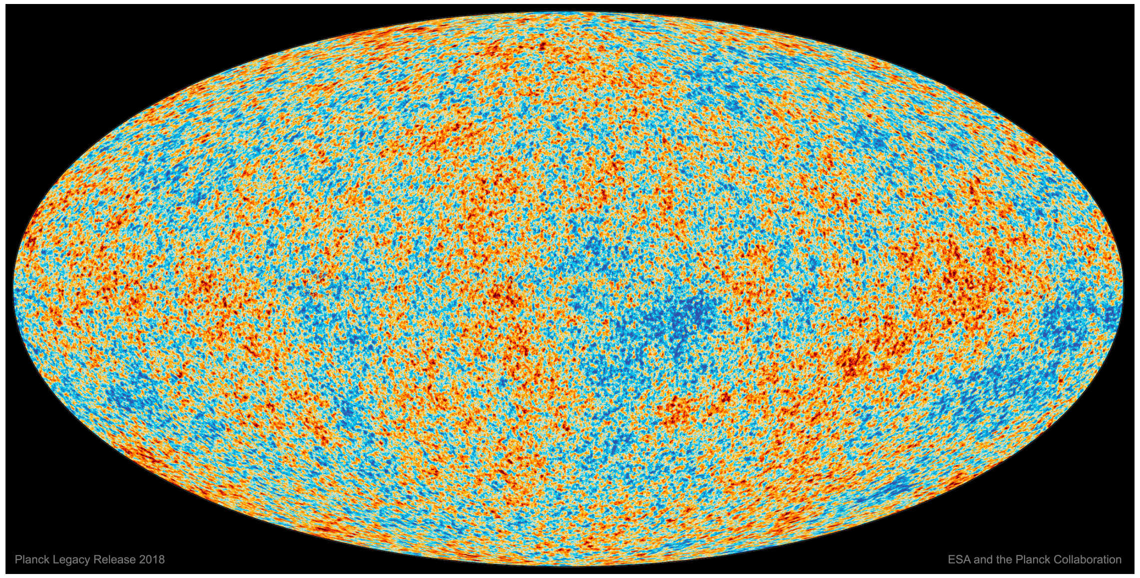
Following notations of Dvorkin & Smith 0812.1566





$$T^{\rm Sc}(\hat{n}) \simeq T(\hat{n}) - \tau^{\rm Th}(\hat{n})T(\hat{n}) \qquad T^{\rm dSc}(\hat{n},\omega) \simeq -\tau(\hat{n},\omega)\left[\bar{T} + T(\hat{n})\right]$$

Photon disappearance (Halo Model)



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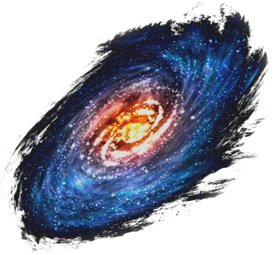
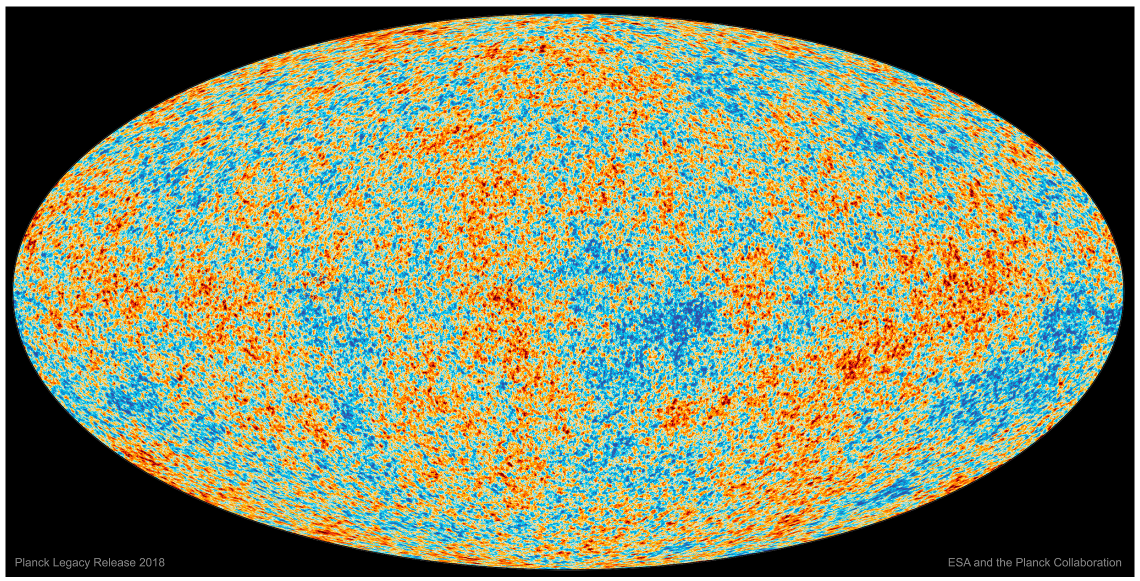


Special thanks to Marilena for the suggestions

Photon disappearance (Halo Model)



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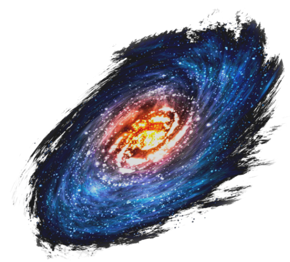
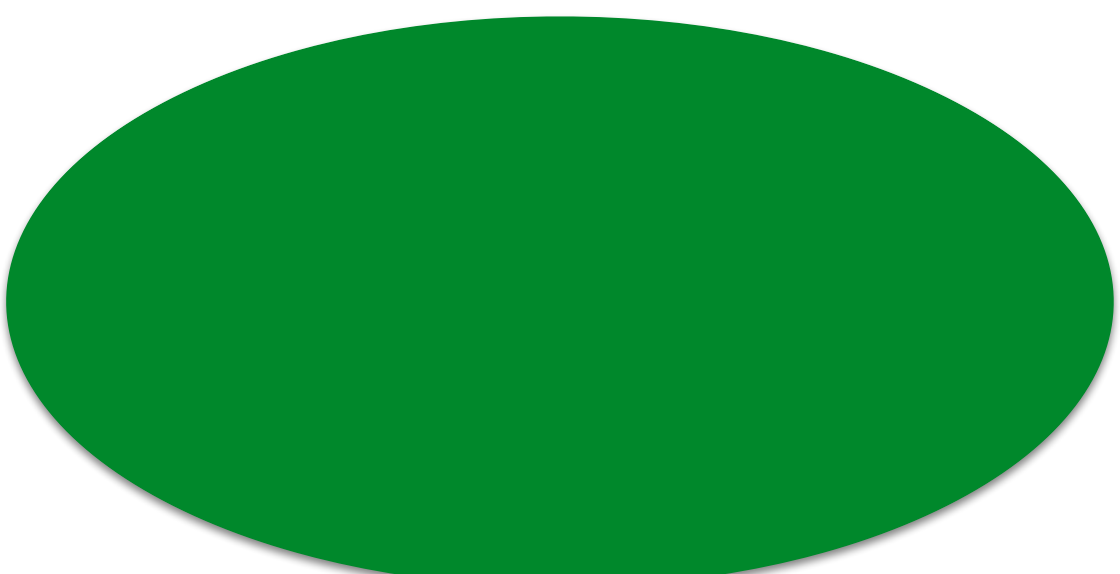
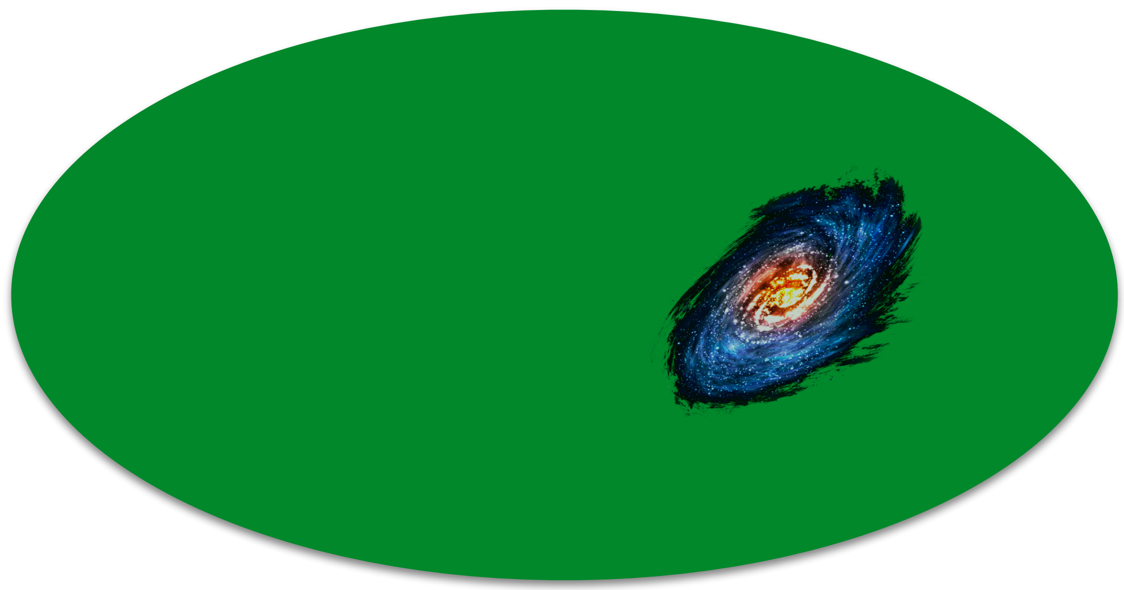


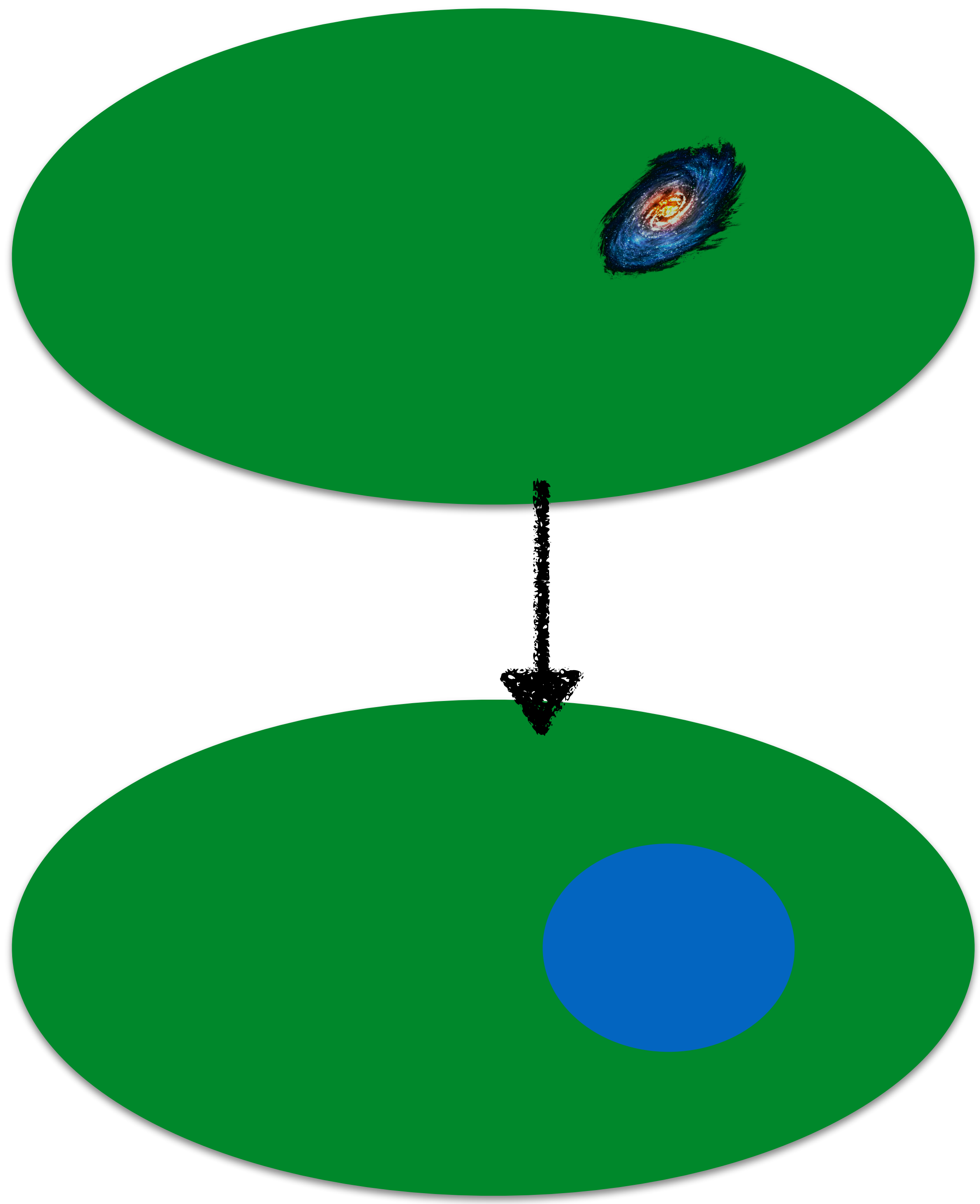


$$\bar{T} = 2.726K$$

One Halo



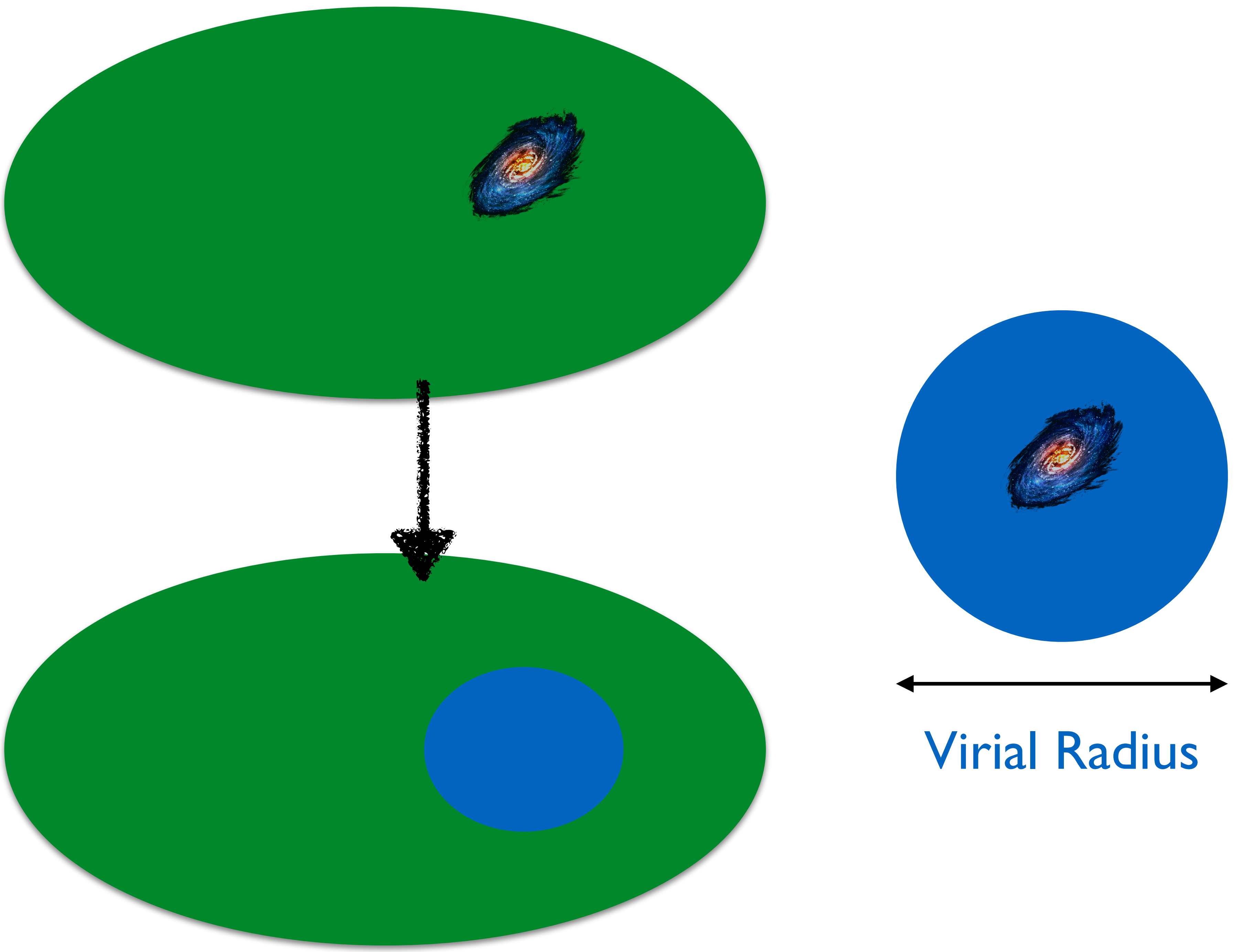
One Halo



$\bar{T} + \text{halo}$

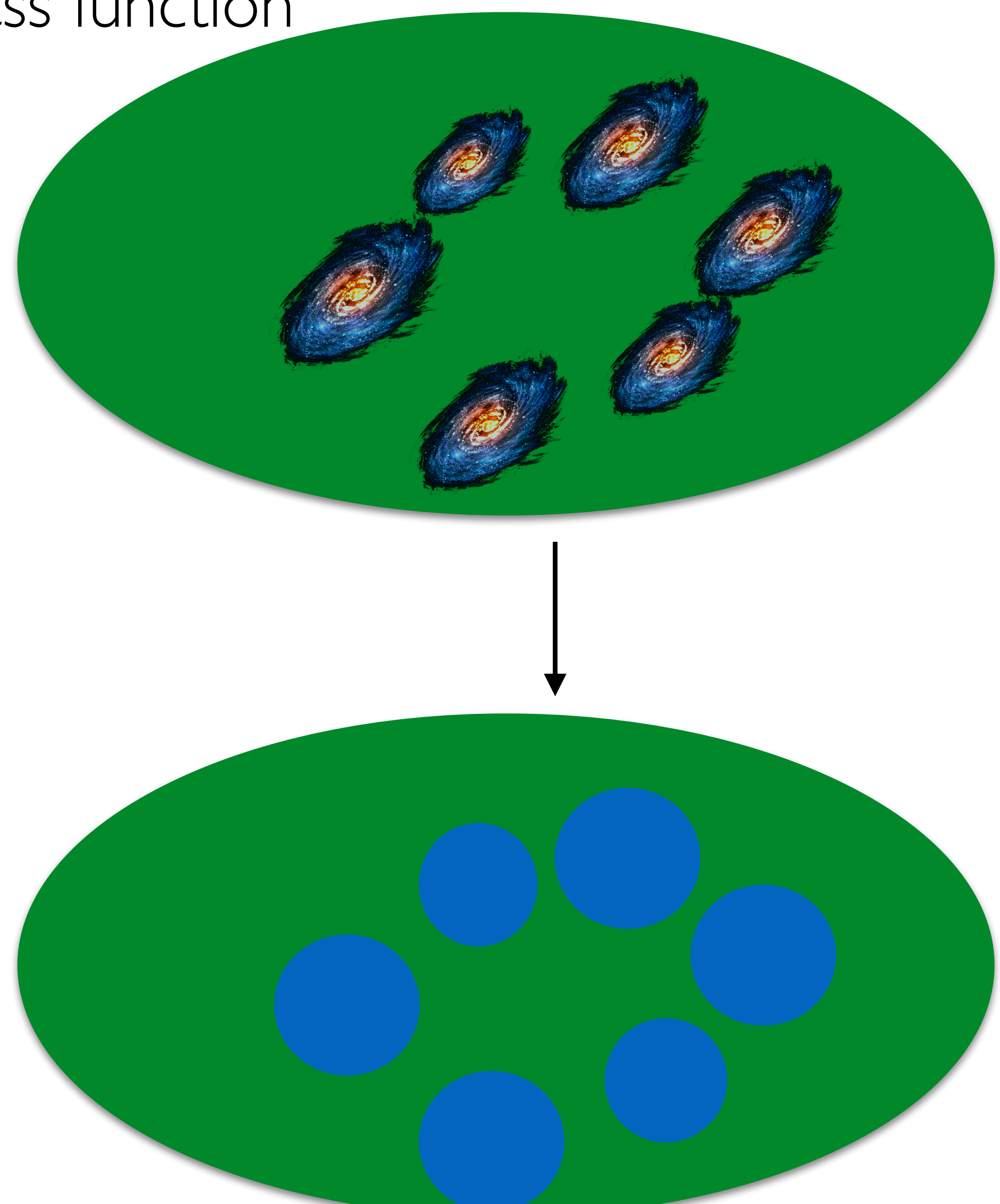
$T^{\text{dsc}}(\hat{n}) = \bar{T}\tau(\omega, \hat{n})$

One Halo



Many halos

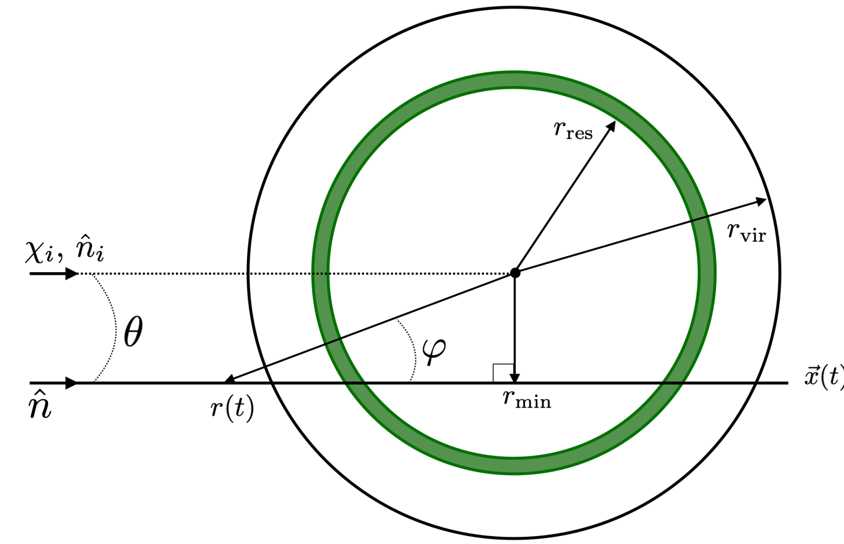
- With halo mass function



$$\bar{T} + \text{halo}$$

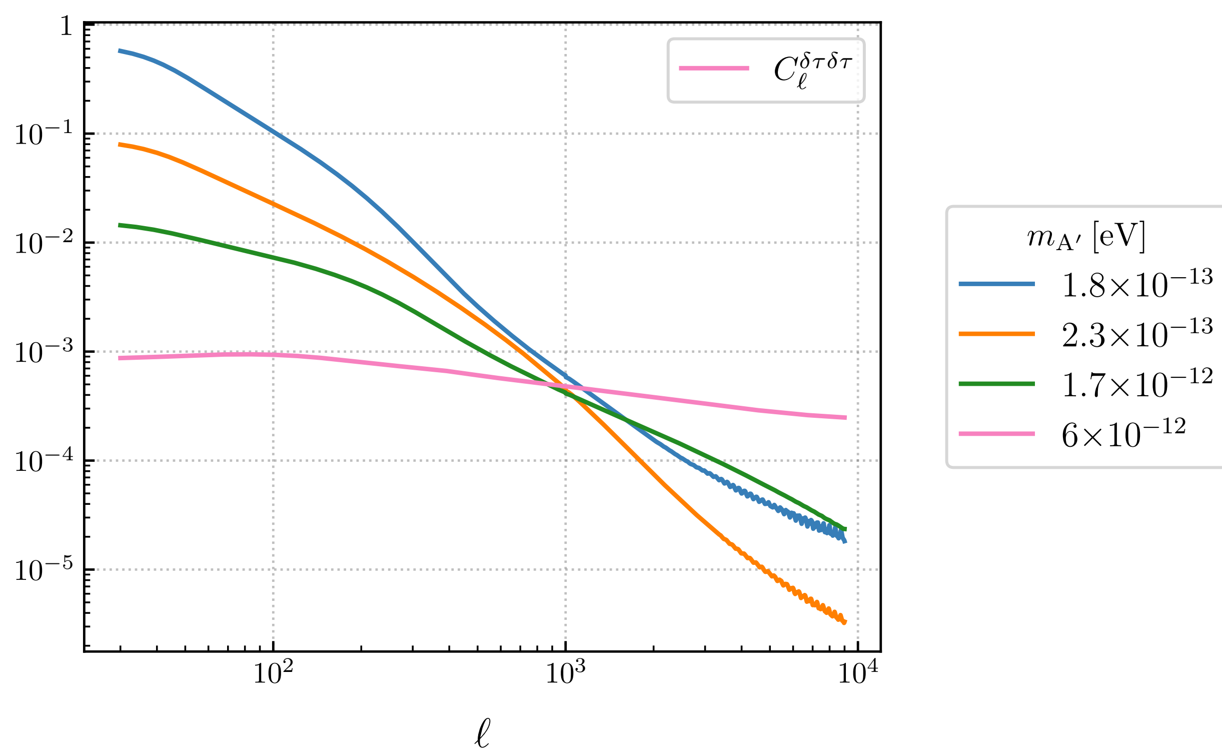
$$T^{\text{dsc}}(\hat{n}) = \bar{T}\tau(\omega, \hat{n})$$

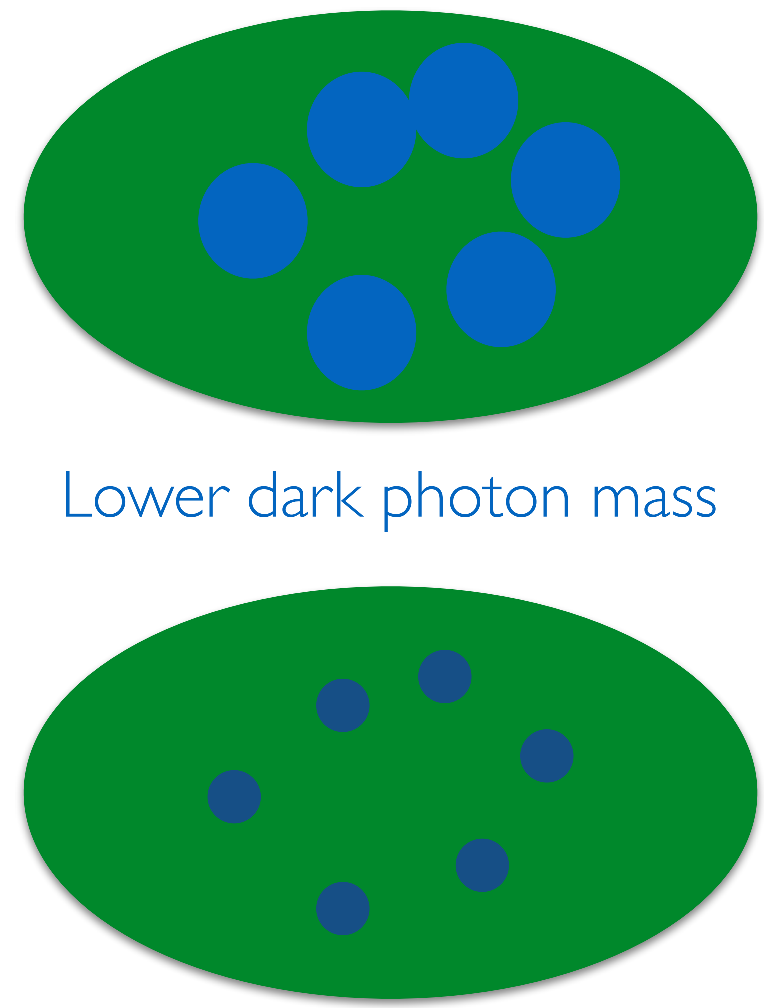
Optical depth map



- Sum over halo:

Following: Hill & Pajer 1303.4726, Roy, Battaglia+ 2201.05076

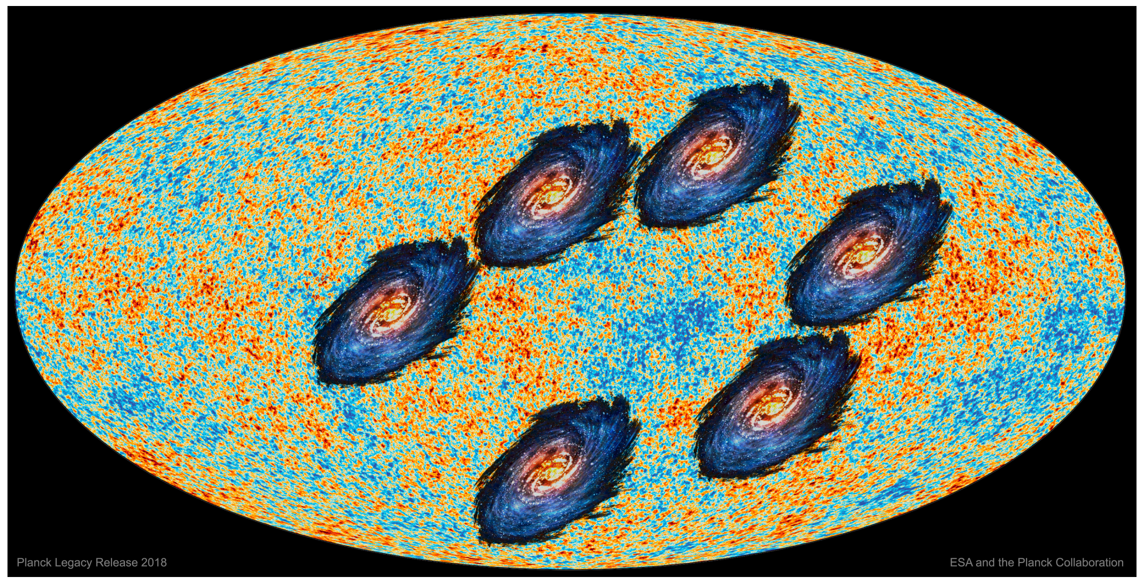




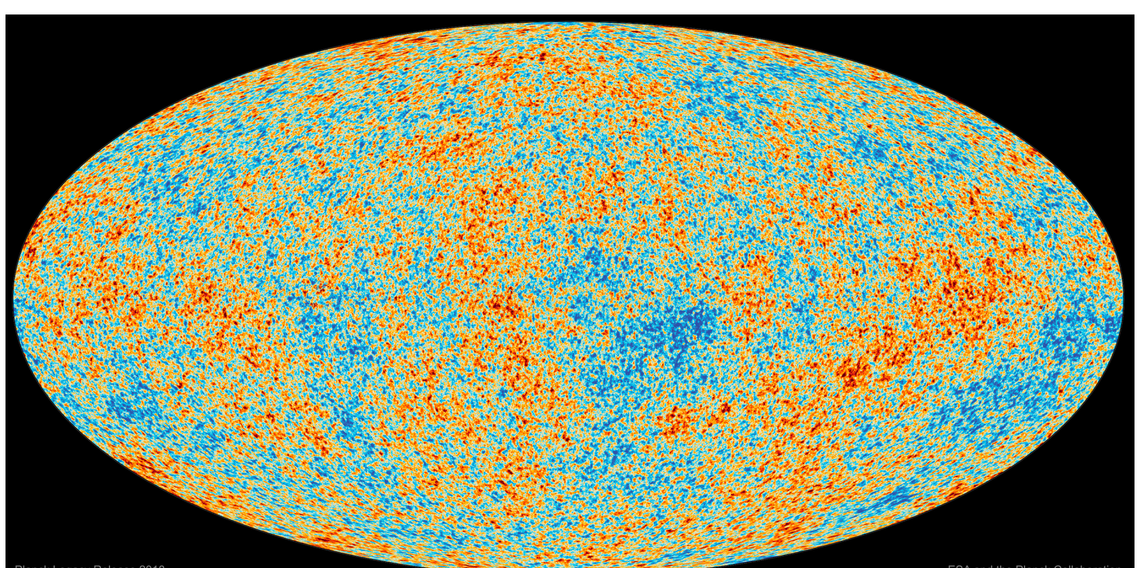
Lower dark photon mass

Higher dark photon mass

Many halos



$\bar{T} + \text{halo}$



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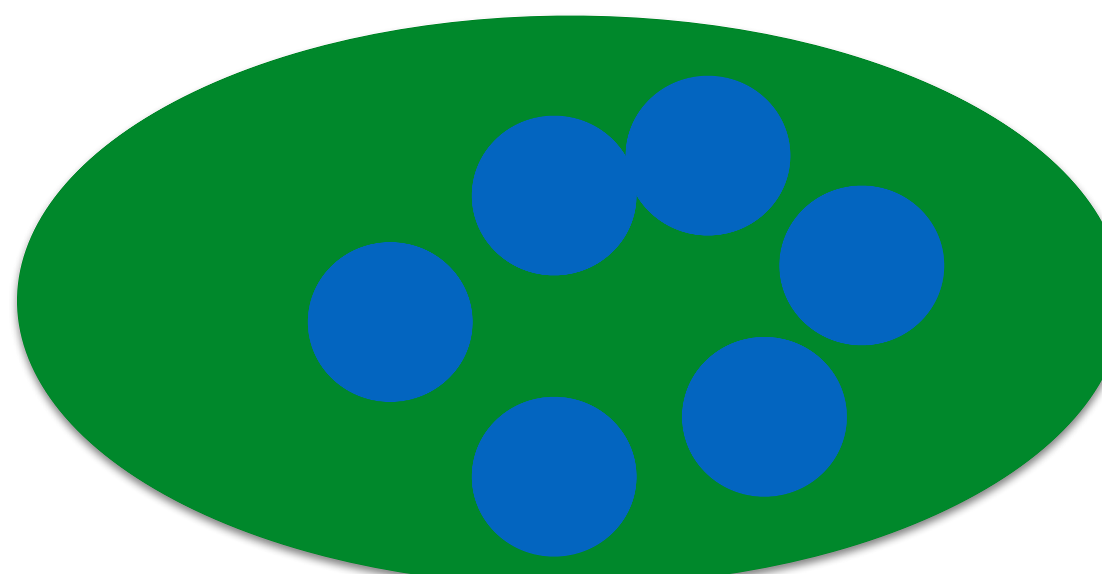
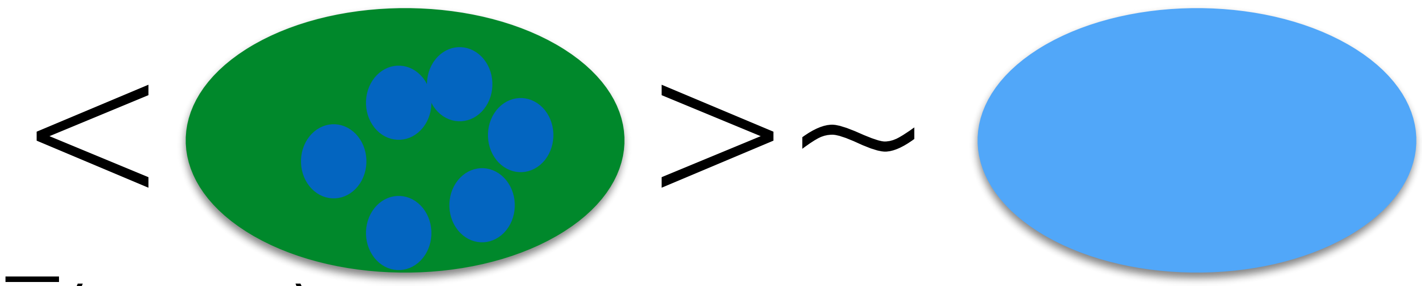


$$T^{\rm Sc}(\hat{n}) \simeq T(\hat{n}) - \tau^{\rm Th}(\hat{n})T(\hat{n})$$

$$T^{\rm dsc}(\hat{n}) = -\bar{T}\tau(\omega, \hat{n})$$

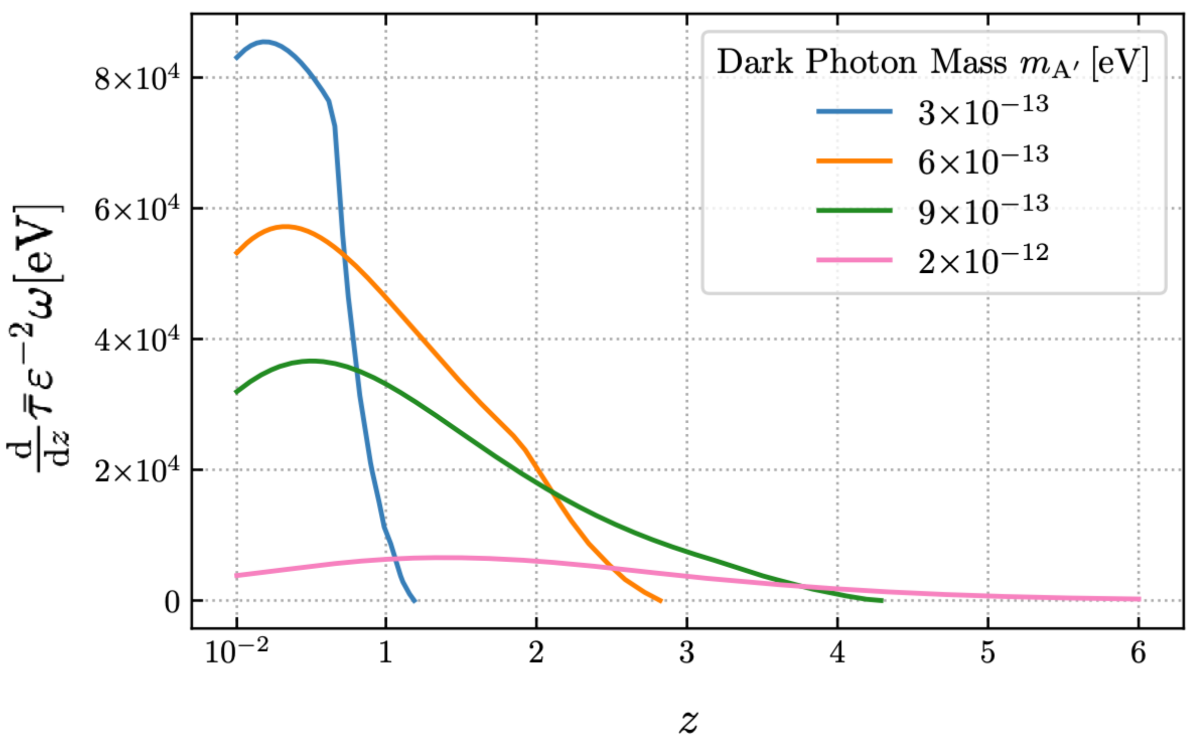
Monopole = Spectral distortion

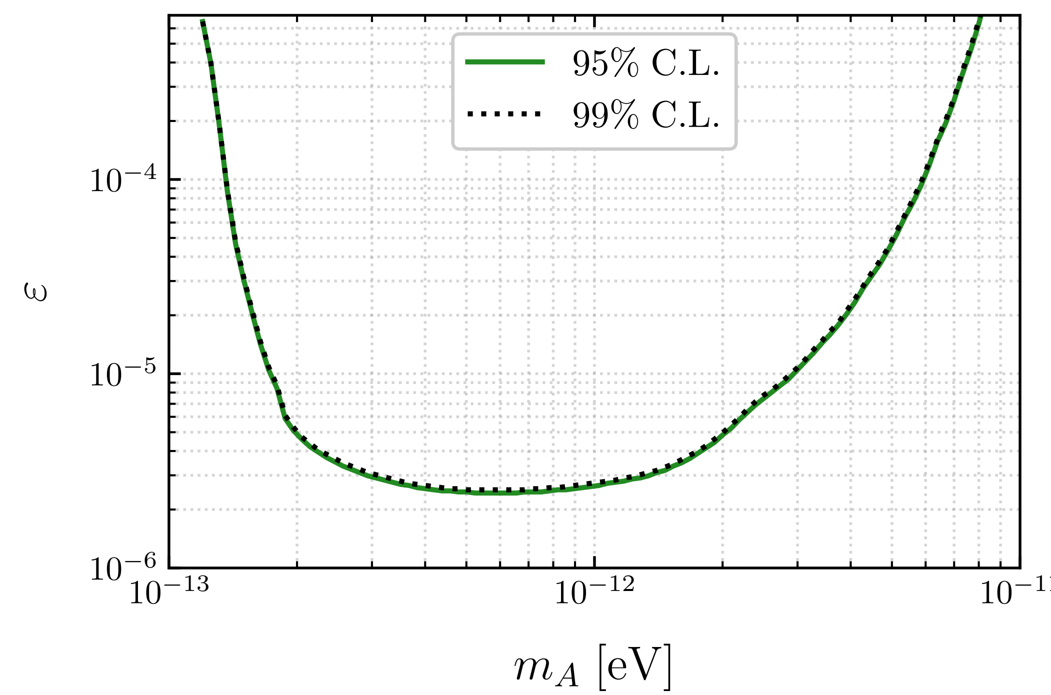
- Monopole:



$$\langle T^{\rm dsc}\rangle = \overline{T}\langle P_{\gamma\to A'}\rangle$$

- Absorption optical depth
- $1/\omega$ frequency dependence



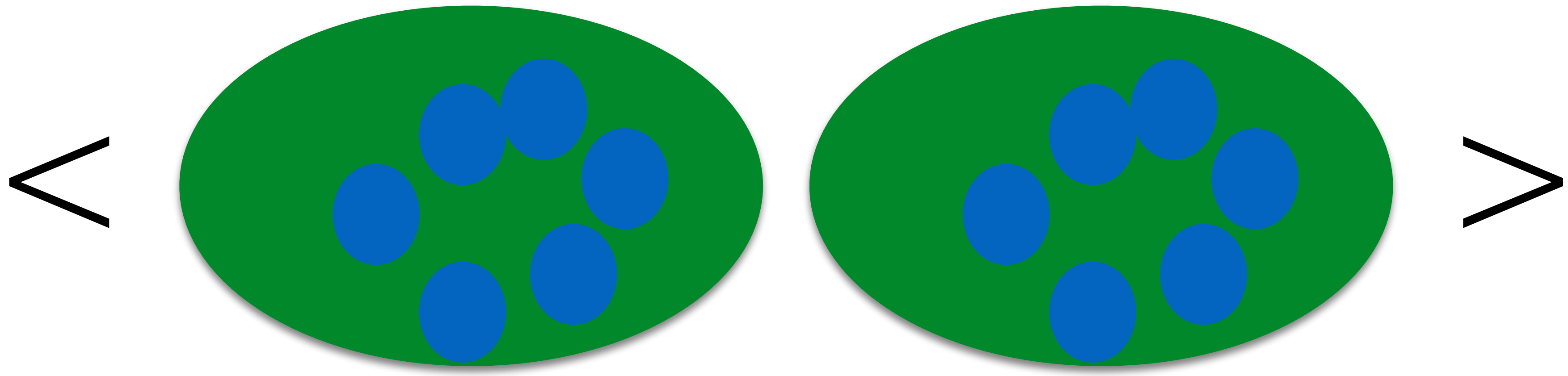


Auto-correlation

- Auto-correlation

$$\langle T^{\mathrm{dsc}} T^{\mathrm{dsc}} \rangle = \overline{T}^2 C_\ell^{\tau\tau}$$

$$T^{\mathrm{dsc}}(\hat{n}) = -\bar{T}\tau(\omega, \hat{n})$$



Auto-correlation

- Auto-correlation

$$\langle T^{\rm dsc} T^{\rm dsc} \rangle = \overline{T}^2 C_\ell^{\tau\tau}$$

- This is in contrast with Thomson screening

$$\langle T^{\rm sc} T^{\rm sc} \rangle = C_\ell^{TT} + C_\ell^{TT} C_\ell^{\tau^{\rm Th}\tau^{\rm Th}}$$

Auto-correlation

- Auto-correlation

$$\langle T^{\rm dsc} T^{\rm dsc} \rangle = \overline{T}^2 C_\ell^{\tau\tau}$$

- This is in contrast with Thomson screening

$$\langle T^{\rm sc} T^{\rm sc} \rangle = C_\ell^{TT} + C_\ell^{TT} C_\ell^{\tau^{\rm Th}\tau^{\rm Th}}$$

- Qualitatively,
  - We win by $\overline{T}^2 / C_\ell^{TT}$

Absorption VS scattering

Auto-correlation

- Auto-correlation

$$\langle T^{\rm dsc} T^{\rm dsc} \rangle = \overline{T}^2 C_\ell^{\tau\tau}$$

- This is in contrast with Thomson screening

$$\langle T^{\rm sc} T^{\rm sc} \rangle = C_\ell^{TT} + C_\ell^{TT} C_\ell^{\tau^{\rm Th}\tau^{\rm Th}}$$

- Qualitatively,
  - We win by $\overline{T}^2 / C_\ell^{TT}$
  - However $\langle T^{\rm dsc} T^{\rm dsc} \rangle \propto \varepsilon^4$

Absorption VS scattering

Cross-correlation

- Absorption optical depth
- $1/\omega$ frequency dependence
- **Depends on the distribution of matter**

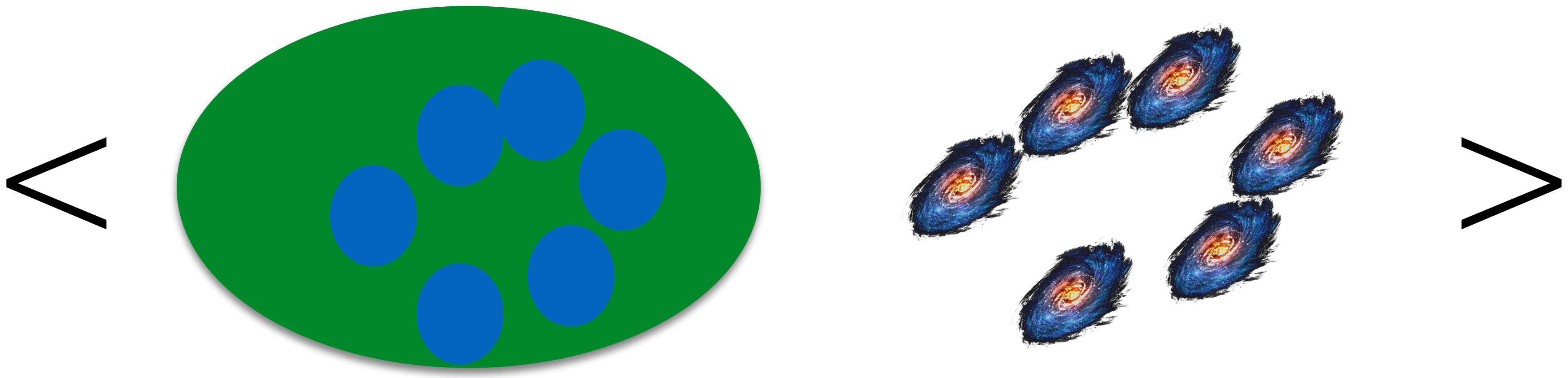
- Coupled to the CMB monopole!
- Can be separated from the primordial CMB
- **Correlated with LSS**

Cross-correlation

- Cross-correlation with LSS survey

$$\langle T^{\rm dsc}\hat{\tau}_g\rangle = \overline{T} C_\ell^{\tau\hat{\tau}^g}$$

No suppression of C_ℓ^{TT}
Scales as ε^2



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- Cross-correlation with LSS survey

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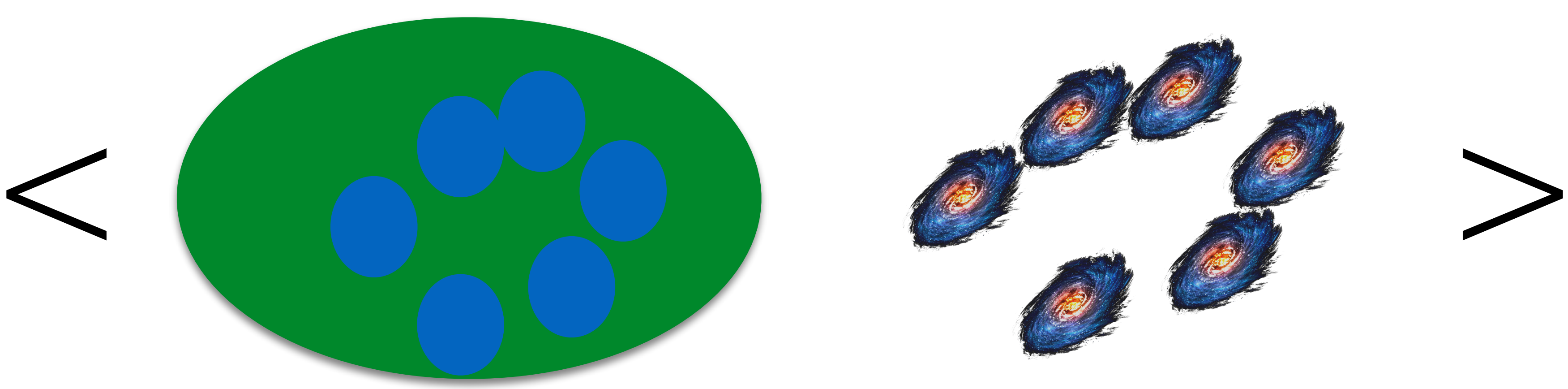


$\langle \mathrm{BSM} \times \mathrm{SM} \rangle$ type operators
$\langle \mathrm{CMB} \times \mathrm{LSS} \rangle$

Cross-correlation

- Cross-correlation with LSS survey

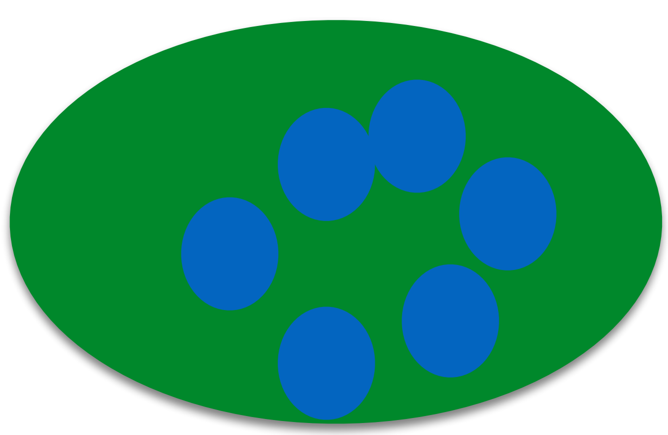
$$\langle T^{\mathrm{dsc}} \hat{\tau}_g \rangle = \overline{T} C_\ell^{\tau \hat{\tau}^g}$$

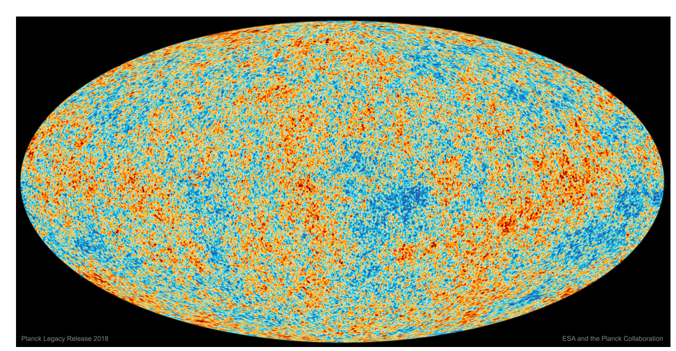
- CMB alone?

$$\langle T^{\mathrm{dsc}} T^{\mathrm{sc}} \rangle = C_\ell^{TT} C_\ell^{\tau\tau^{\mathrm{Th}}}$$

Not good!

$\langle$





$\rangle$

Cross-correlation

- Cross-correlation with LSS survey

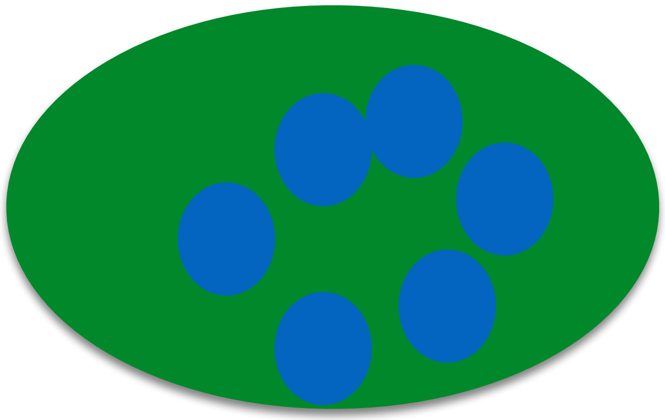
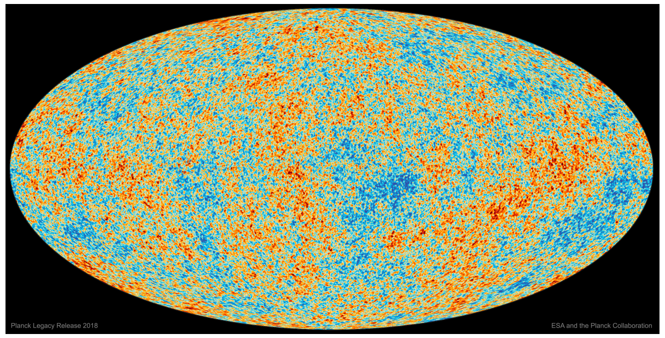
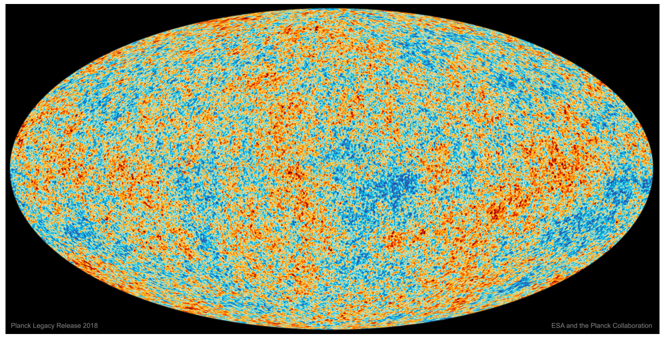
$$\langle T^{\rm dsc}\hat{\tau}_g\rangle = \overline{T}C_\ell^{\tau\hat{\tau}^g}$$

- CMB alone?

$$\langle T^{\rm dsc}T^{\rm sc}\rangle = C_\ell^{TT}C_\ell^{\tau\tau^{\rm Th}}$$

- Bispectrum:

$$\langle T^{\rm dsc}T^{\rm sc}T^{\rm sc}\rangle = \overline{T}C_\ell^{TT}C_\ell^{\tau\tau^{\rm Th}}$$

$<$    $>$

Cross-correlation

- Cross-correlation with LSS survey

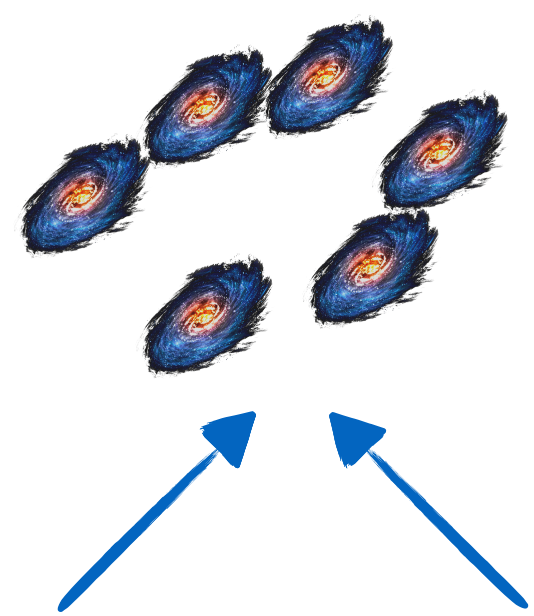
$$\langle T^{\rm dsc}\hat{\tau}_g\rangle = \overline{T} C_\ell^{\tau\hat{\tau}^g}$$

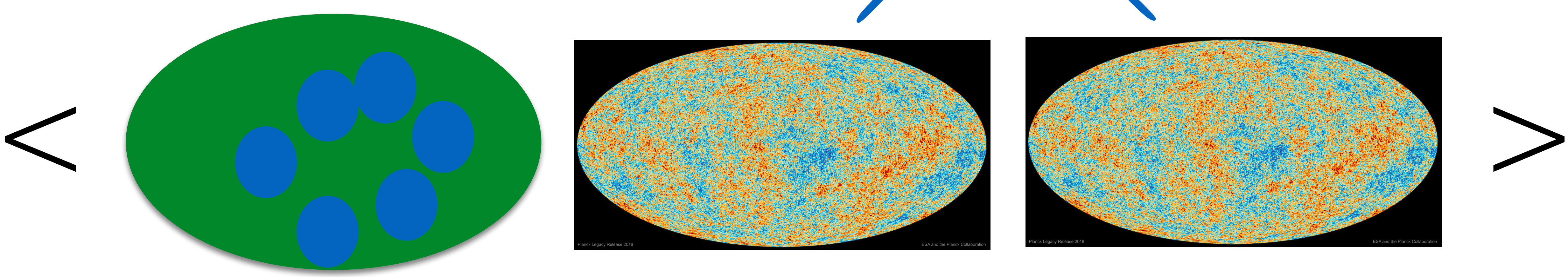
- CMB alone?

$$\langle T^{\rm dsc}T^{\rm sc}\rangle = C_\ell^{TT} C_\ell^{\tau\tau^{\rm Th}}$$

- Bispectrum:

$$\langle T^{\rm dsc}T^{\rm sc}T^{\rm sc}\rangle = \overline{T} C_\ell^{TT} C_\ell^{\tau\tau^{\rm Th}}$$





Cross-correlation

- Cross-correlation with LSS survey

$$\langle T^{\rm dsc}\hat{\tau}_g\rangle = \overline{T} C_\ell^{\tau\hat{\tau}^g}$$

- CMB alone?

$$\langle T^{\rm dsc}T^{\rm sc}\rangle = C_\ell^{TT} C_\ell^{\tau\tau^{\rm Th}}$$

- Bispectrum:

$$\langle T^{\rm dsc}T^{\rm sc}T^{\rm sc}\rangle = \overline{T} C_\ell^{TT} C_\ell^{\tau\tau^{\rm Th}}$$

Enhanced by $\bar{T}$
Scales as ε^2
Suppressed by $\tau^{\rm Th}$

Summary

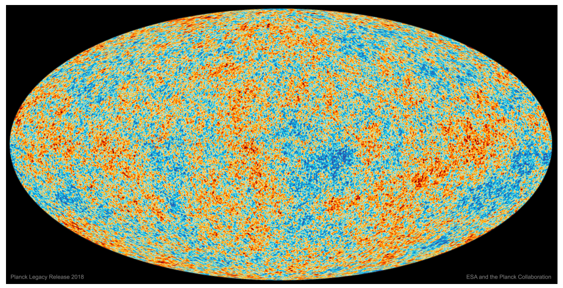
	ε	C_ℓ^{TT}	$\tau^{\rm Th}$	C_ℓ^{EE}
$\langle T^{\rm dSc}\rangle$	2	0	0	-
$\langle T^{\rm Sc}T^{\rm Sc}\rangle$	0	1	2	-
$\langle T^{\rm dSc}T^{\rm dSc}\rangle$	4	0	0	-
$\langle T^{\rm Sc}T^{\rm dSc}\rangle$	2	1	1	-
$\langle T^{\rm dSc}\hat{\tau}^{g}\rangle$	2	0	0	-
$\langle T^{\rm Sc}T^{\rm Sc}T^{\rm dSc}\rangle$	2	1	1	-
$\langle T^{\rm dSc}E^{\rm Sc}B^{\rm Sc}\rangle$	2	-	1	1

Projection & Analysis

- Absorption optical depth
- $1/\omega$ **frequency dependence**
- Depends on the distribution of matter

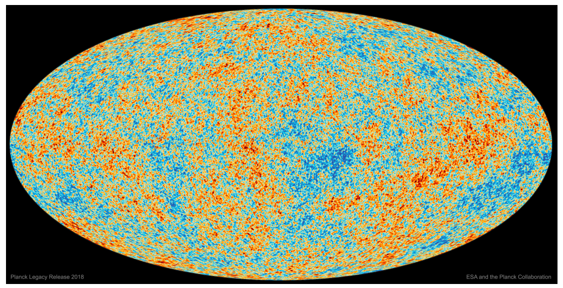
- Coupled to the CMB monopole!
- **Can be separated from the primordial CMB**
- Correlated with LSS

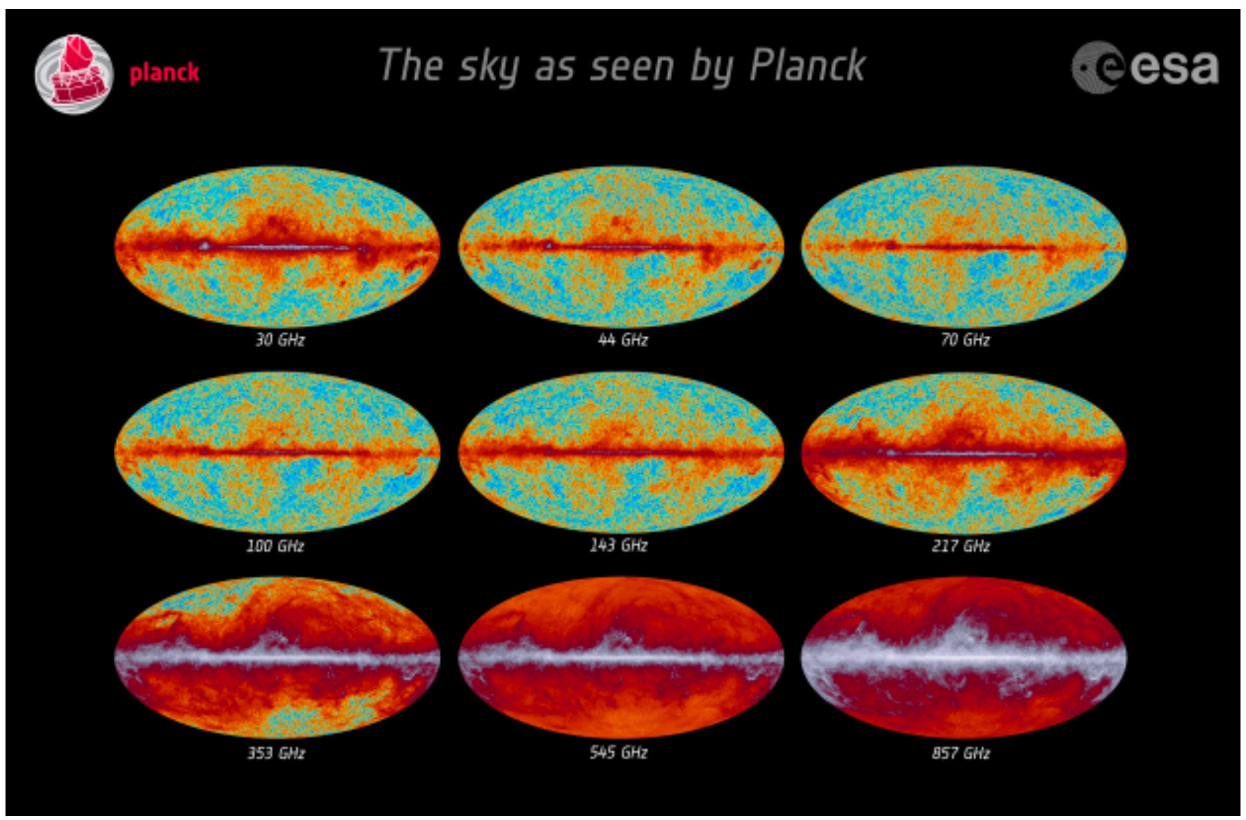
Frequency dependence



(Taken from Planck website)

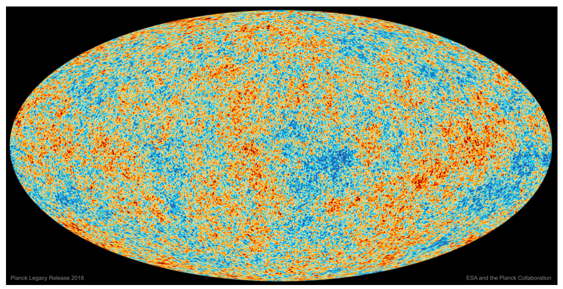
Frequency dependence

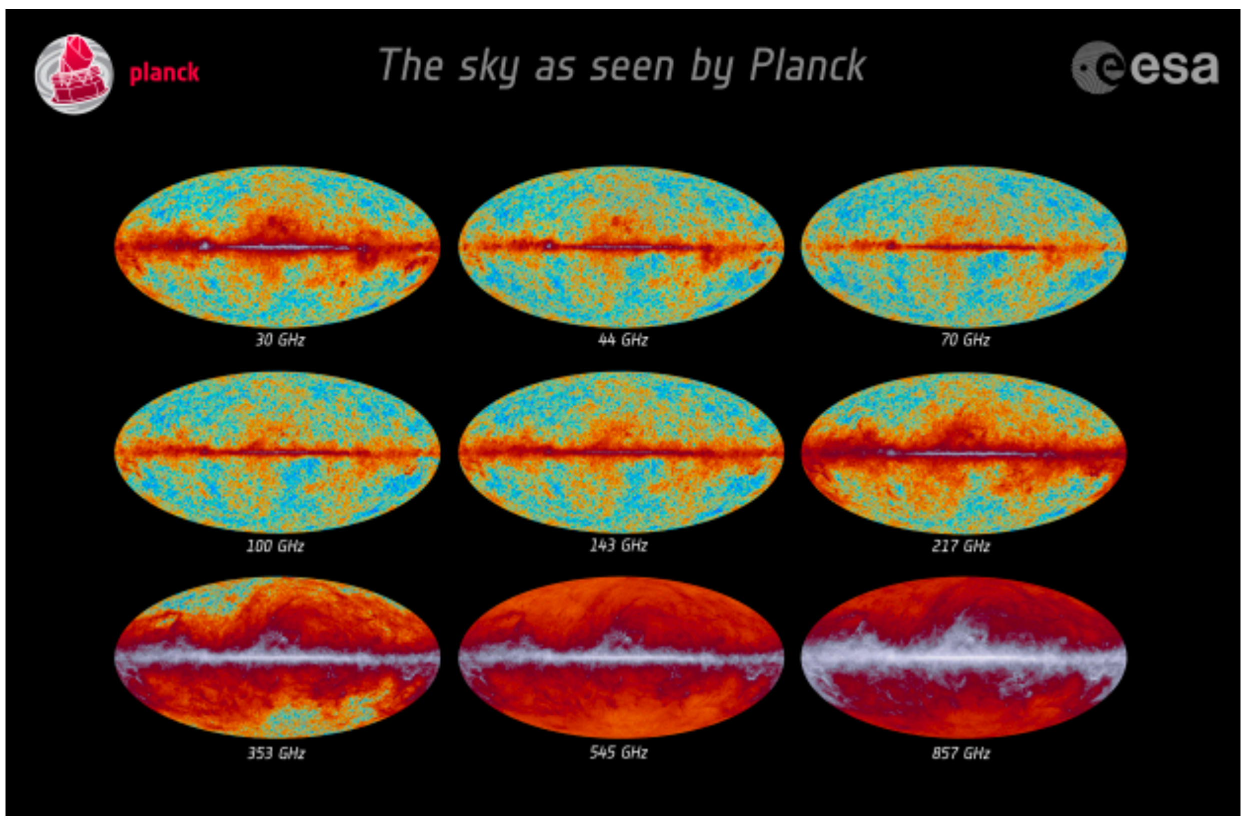




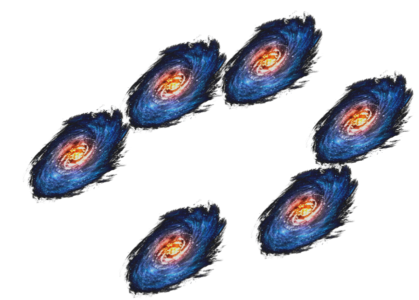
(Taken from Planck website)

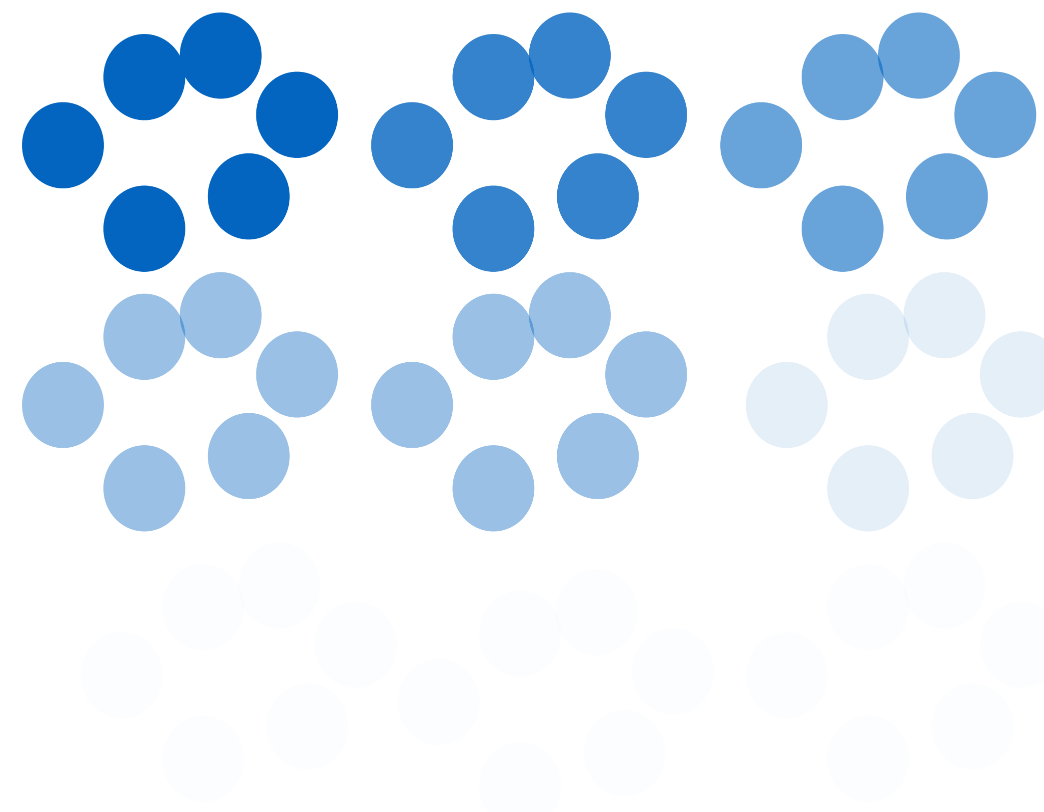
Frequency dependence





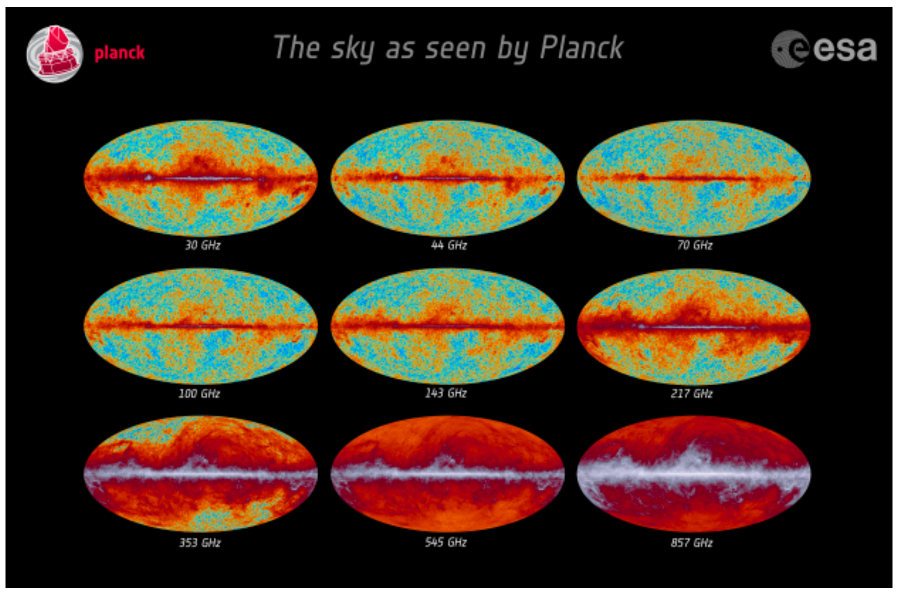
(Taken from Planck website)

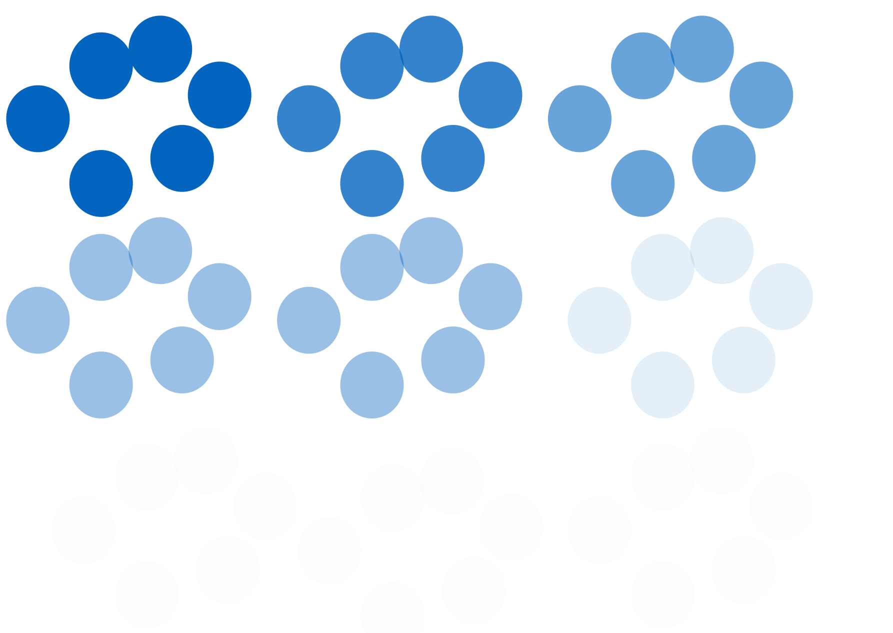


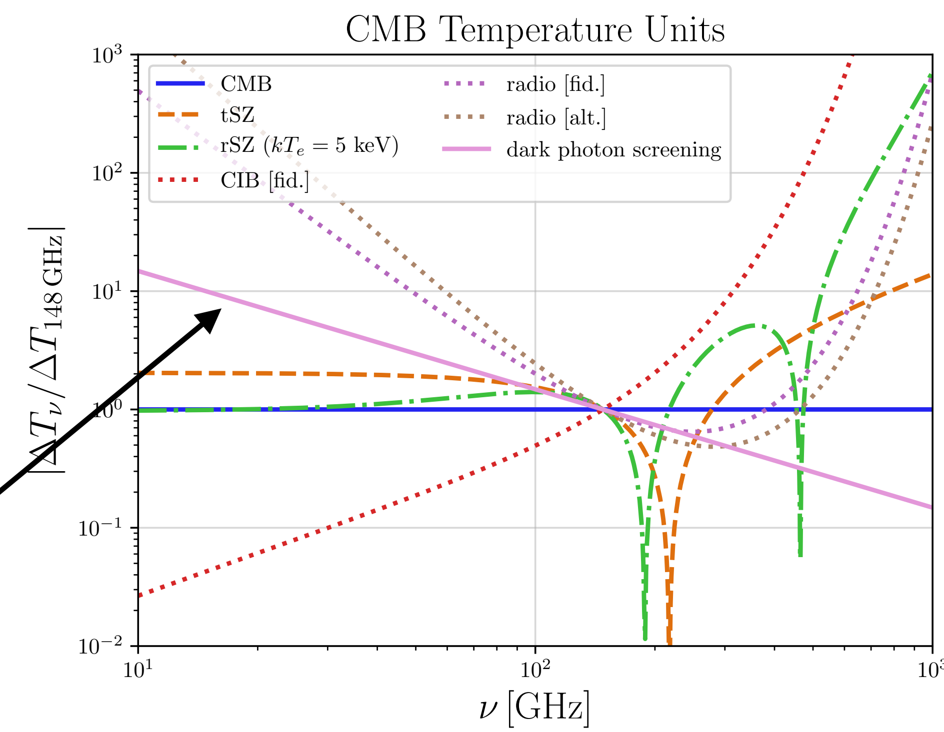


With respect to CMB frequency spectral

ILC cleaning



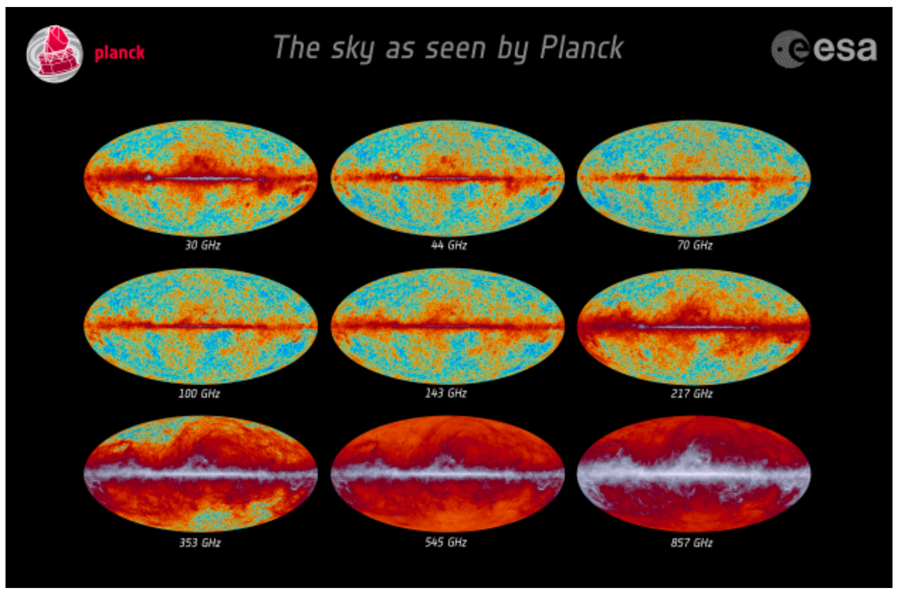


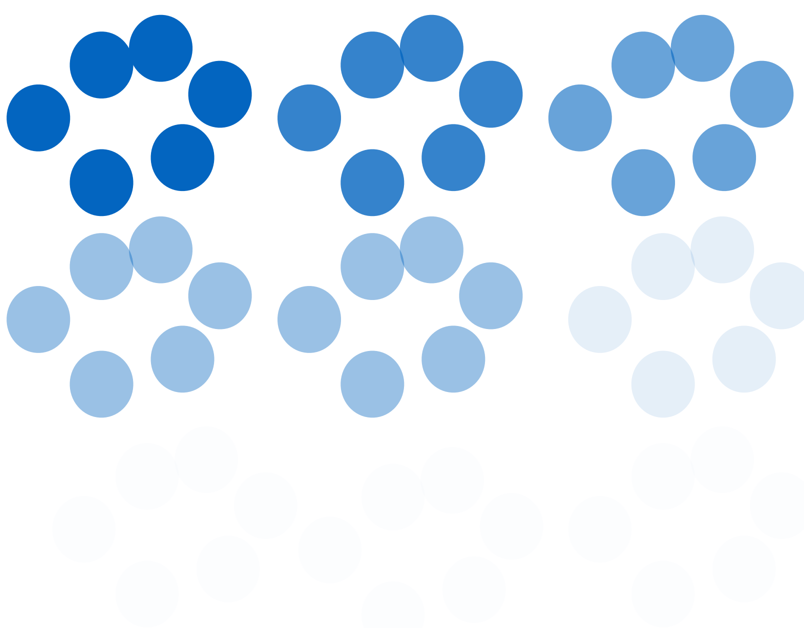


Credit: Fiona & Colin

Analysis ongoing with Fiona McCarthy, Dalila Pirvu, Colin Hill, Keir Rogers and Matt Johnson

ILC cleaning





ILC cleaning

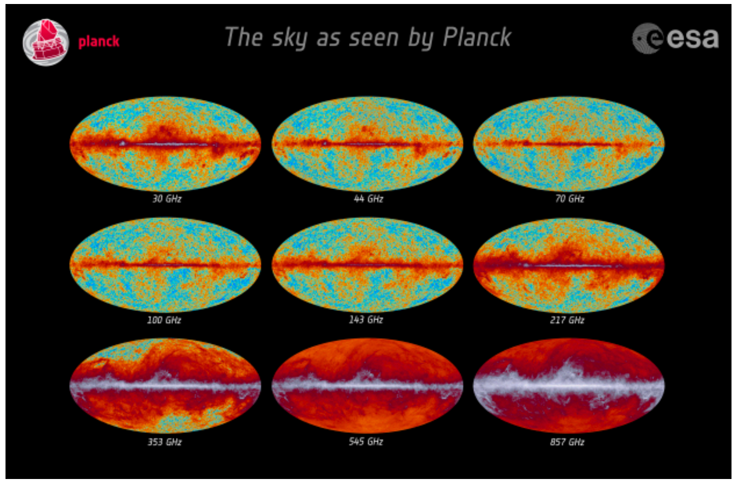
ILC cleaning

Dark screening map

$1/\omega \times$ Blackbody

CMB map

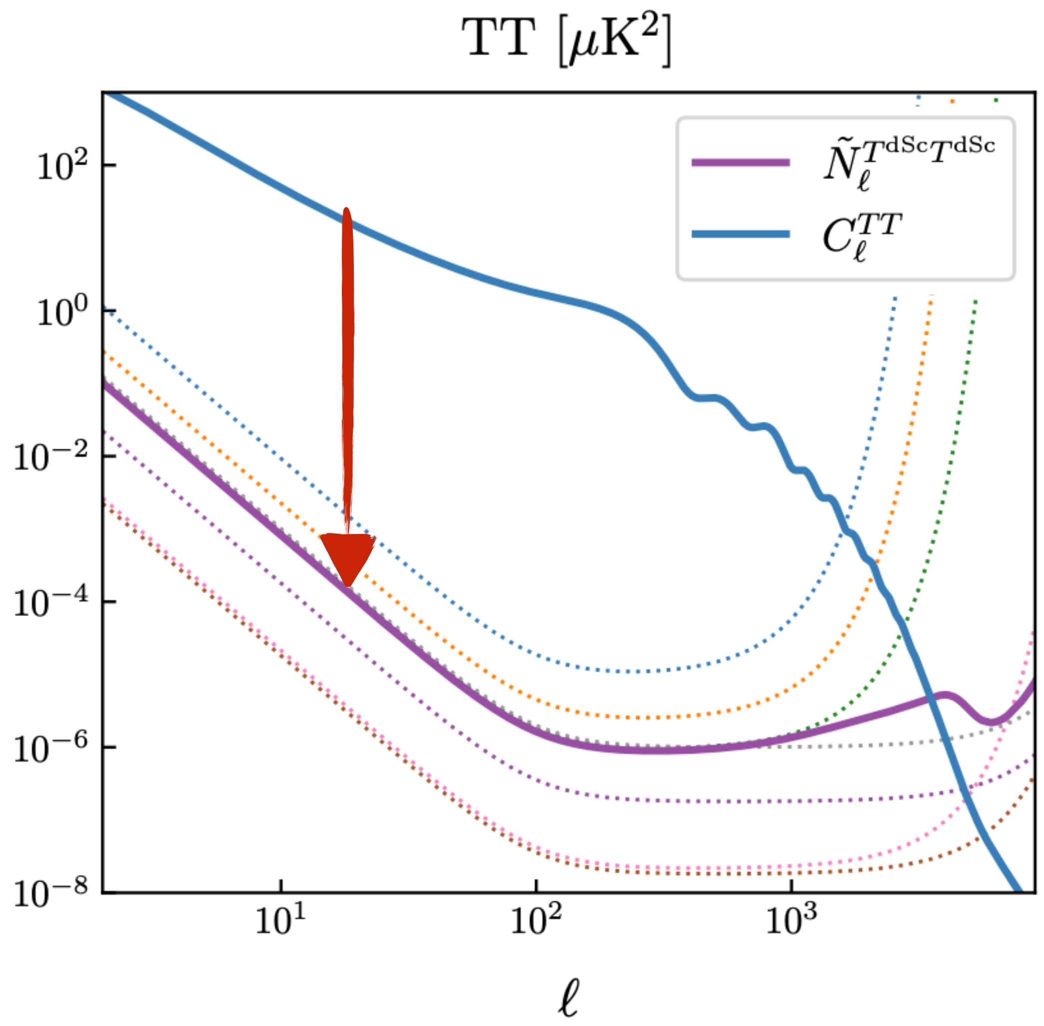
Blackbody



Weighting the different frequency maps differently!

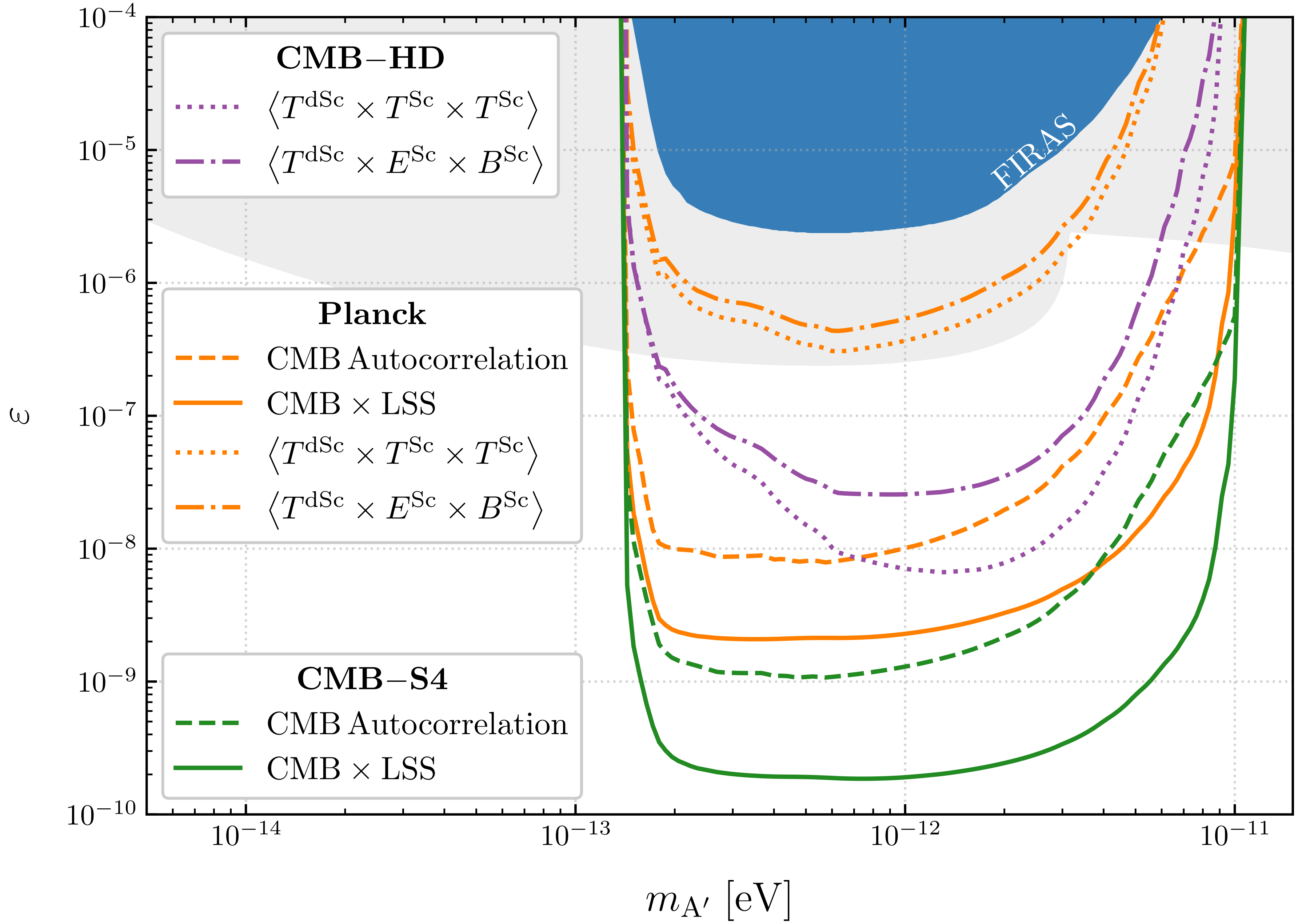
Questions about the details: Keir Rogers

ILC cleaning



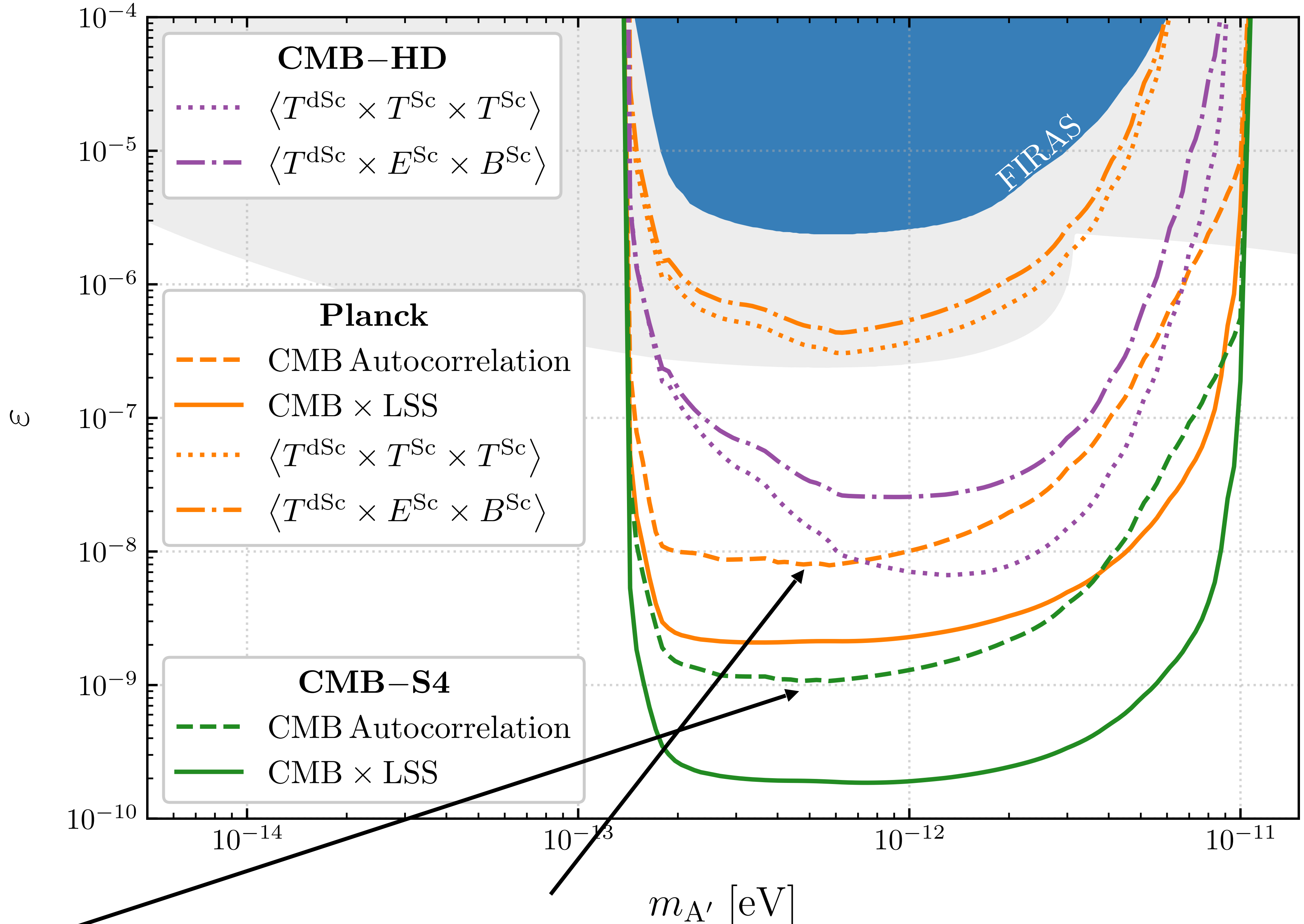
Six orders of magnitude of reduction of the noise with S4!

Summary



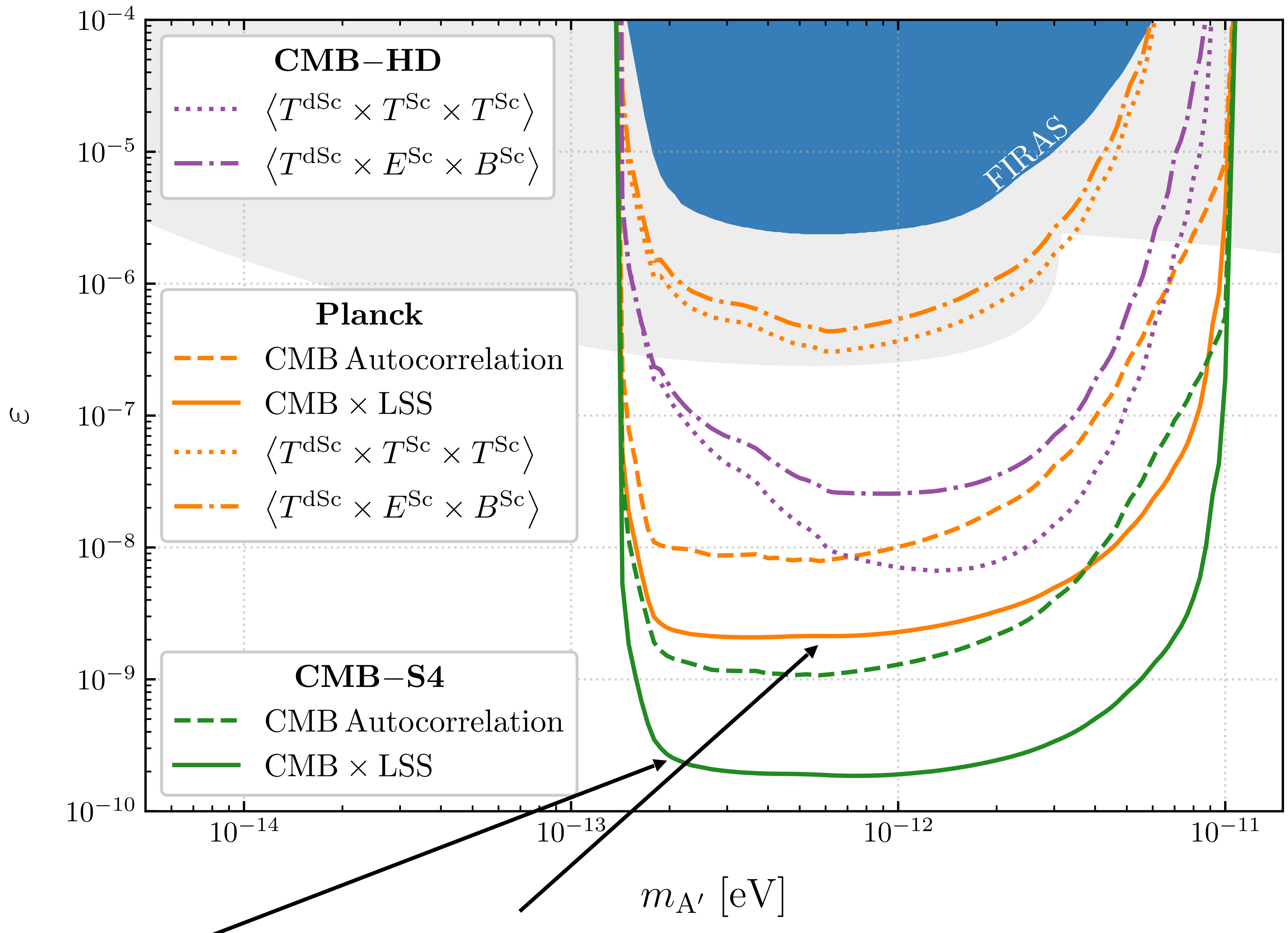
CMB−HD
$\langle T^{\rm dSc} \times T^{\rm Sc} \times T^{\rm Sc} \rangle$
$\langle T^{\rm dSc} \times E^{\rm Sc} \times B^{\rm Sc} \rangle$
Planck
CMB Autocorrelation
CMB × LSS
$\langle T^{\rm dSc} \times T^{\rm Sc} \times T^{\rm Sc} \rangle$
$\langle T^{\rm dSc} \times E^{\rm Sc} \times B^{\rm Sc} \rangle$
CMB−S4
CMB Autocorrelation
CMB × LSS
FIRAS
ε
$m_{\rm A'}$ [eV]
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-14}
10^{-13}
10^{-12}
10^{-11}

Summary



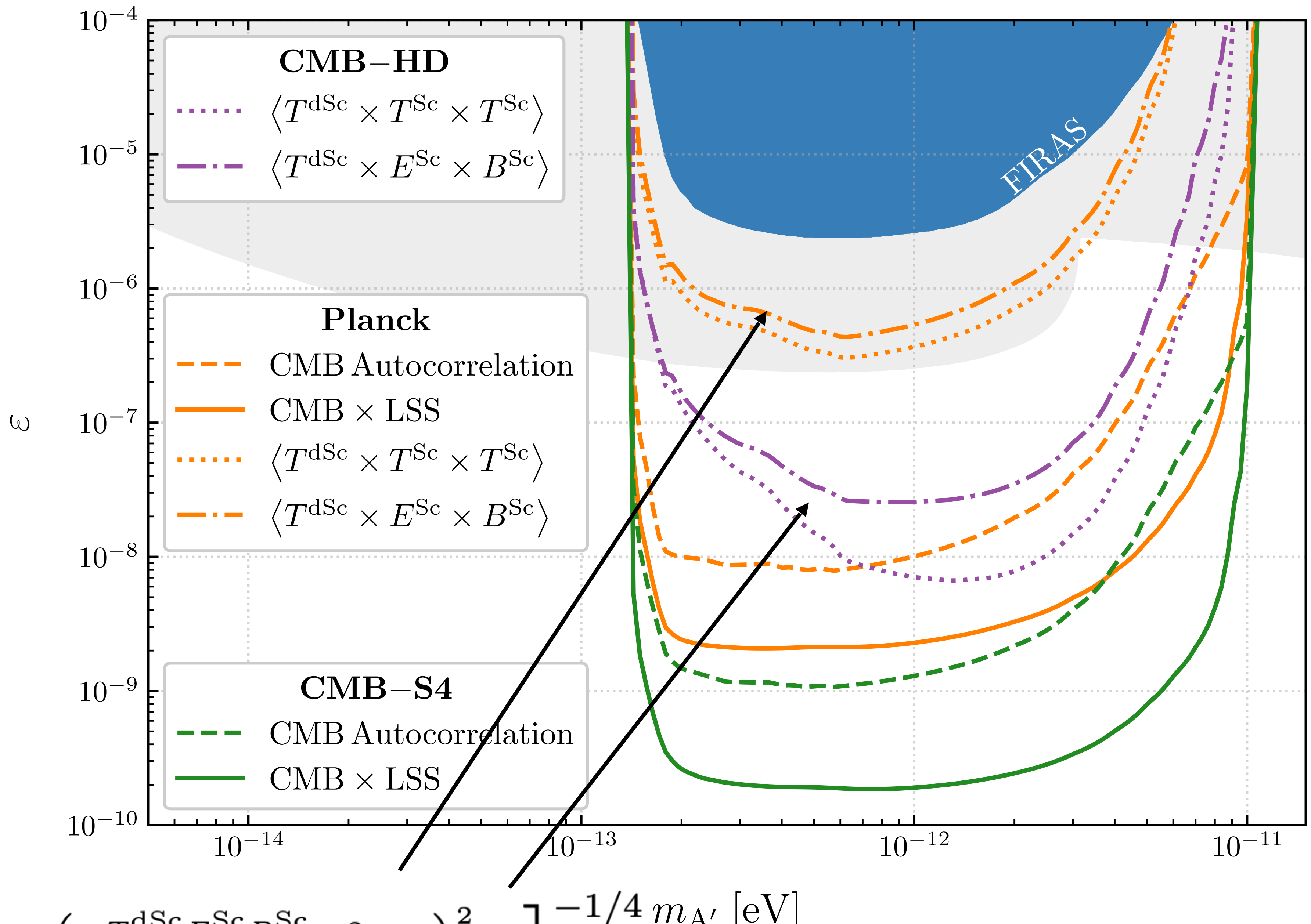
$$\sigma_\varepsilon \propto \left[\sum_\ell (2\ell+1)\left(\frac{C_\ell^{\tau\tau}(\varepsilon^4\!=\!1)}{\tilde{N}_\ell^{T^{\mathrm{dSc}}T^{\mathrm{dSc}}}}\bar{T}^2\right)^2\right]^{-1/8}$$

Summary



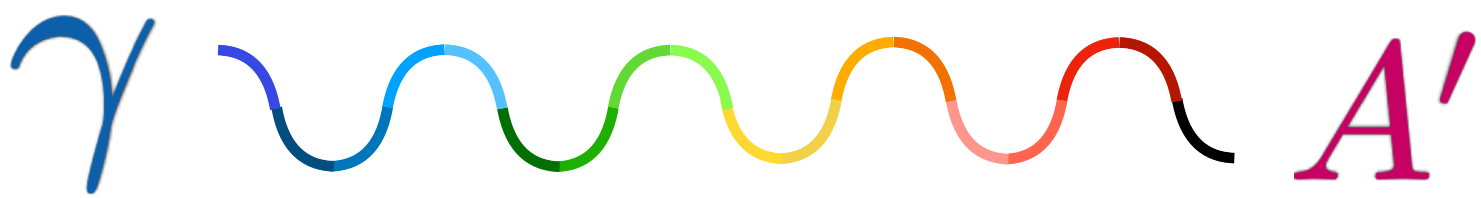
$$\sigma_\varepsilon \propto \left[\sum_\ell (2\ell+1)\ \bar{T}^2\ \frac{C_\ell^{\hat{\tau}\hat{\tau}}(\varepsilon^2{=}1)}{\tilde{N}_\ell^{T^{\rm dSc}T^{\rm dSc}}} \right]^{-1/4}$$

Summary

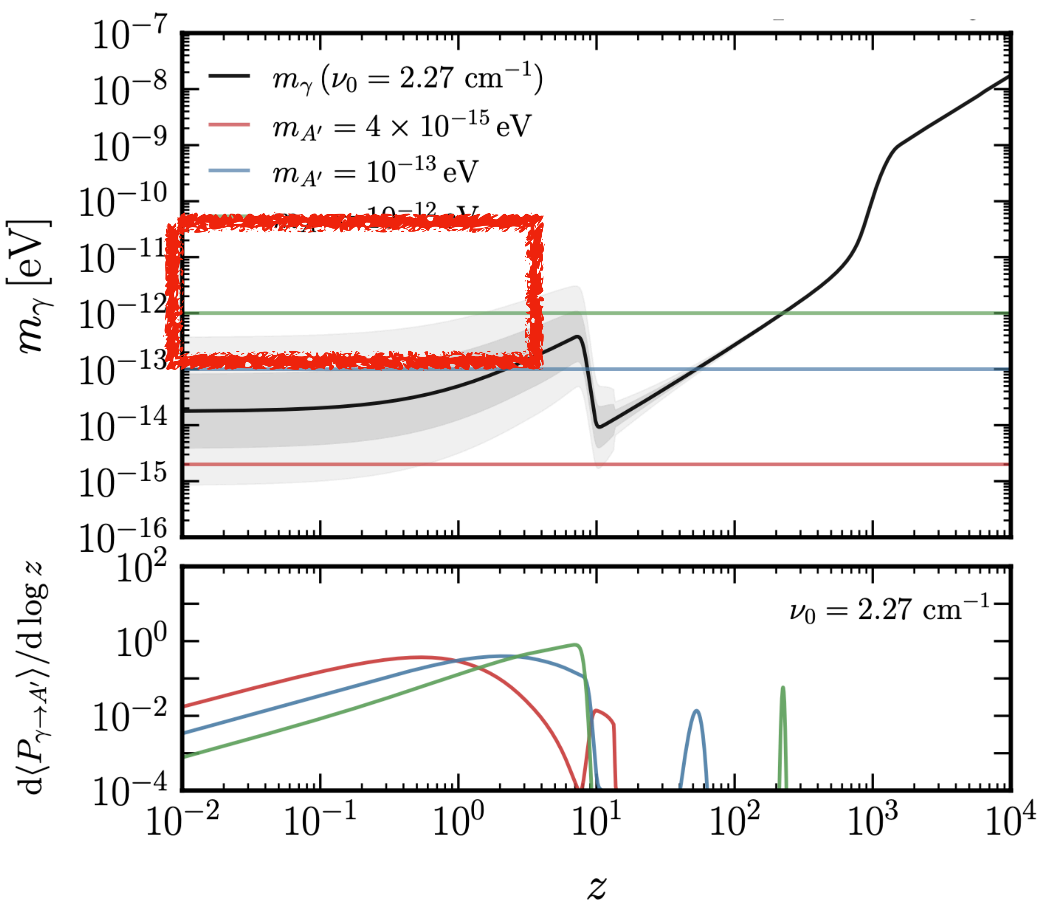


$$\sigma_\varepsilon \propto \left[\sum_{\ell\ell'\ell''} \frac{\left(B^{T^{\rm dSc}E^{\rm Sc}B^{\rm Sc}}_{\ell\ell'\ell''}(\varepsilon^2=1)\right)^2}{\tilde{C}_\ell^{T^{\rm dSc}T^{\rm dSc}}\,\tilde{C}_{\ell'}^{E^{\rm Sc}E^{\rm Sc}}\,\tilde{C}_{\ell''}^{B^{\rm Sc}B^{\rm Sc}}}\right]^{-1/4}$$

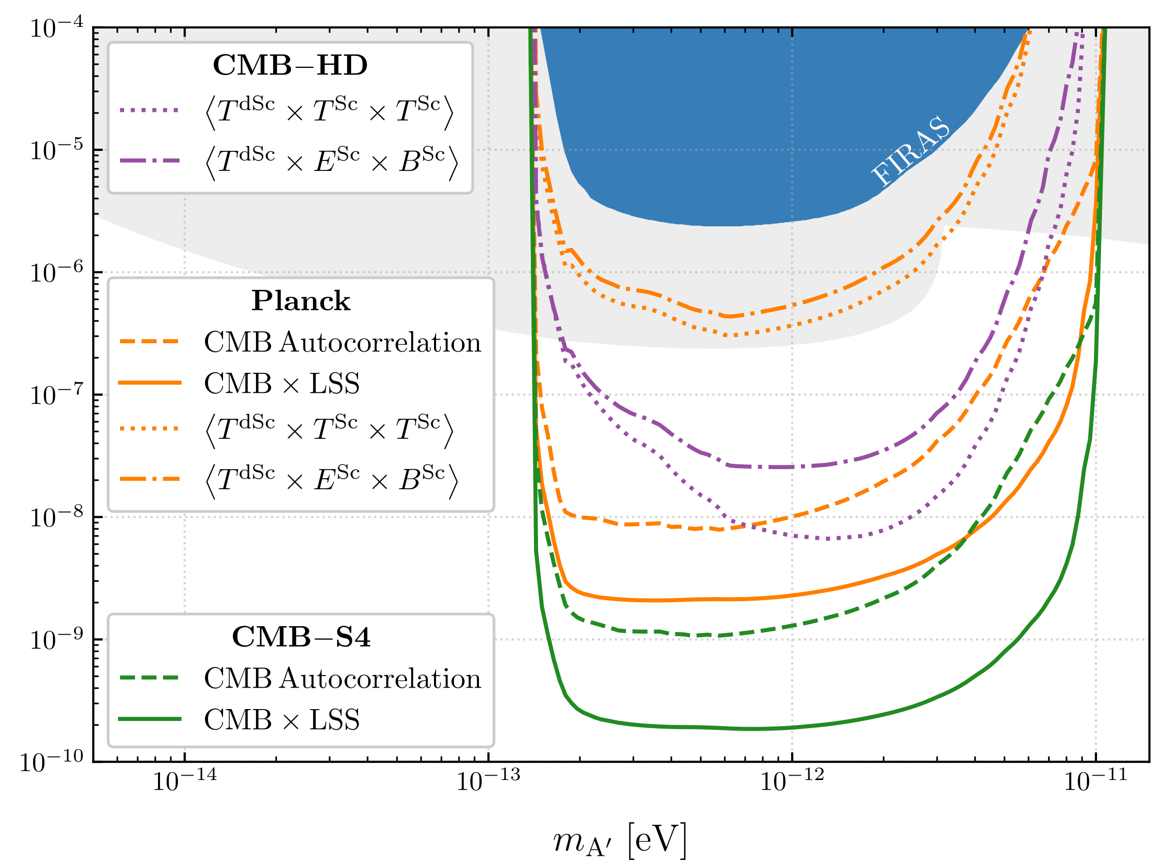
Summary



γ
A'



$m_\gamma\,(\nu_0 = 2.27\ \mathrm{cm}^{-1})$
$m_{A'} = 4 \times 10^{-15}\,\mathrm{eV}$
$m_{A'} = 10^{-13}\,\mathrm{eV}$
m_γ [eV]
$\nu_0 = 2.27\ \mathrm{cm}^{-1}$
$\mathrm{d}\langle P_{\gamma\to A'}\rangle/\mathrm{d}\log z$
z



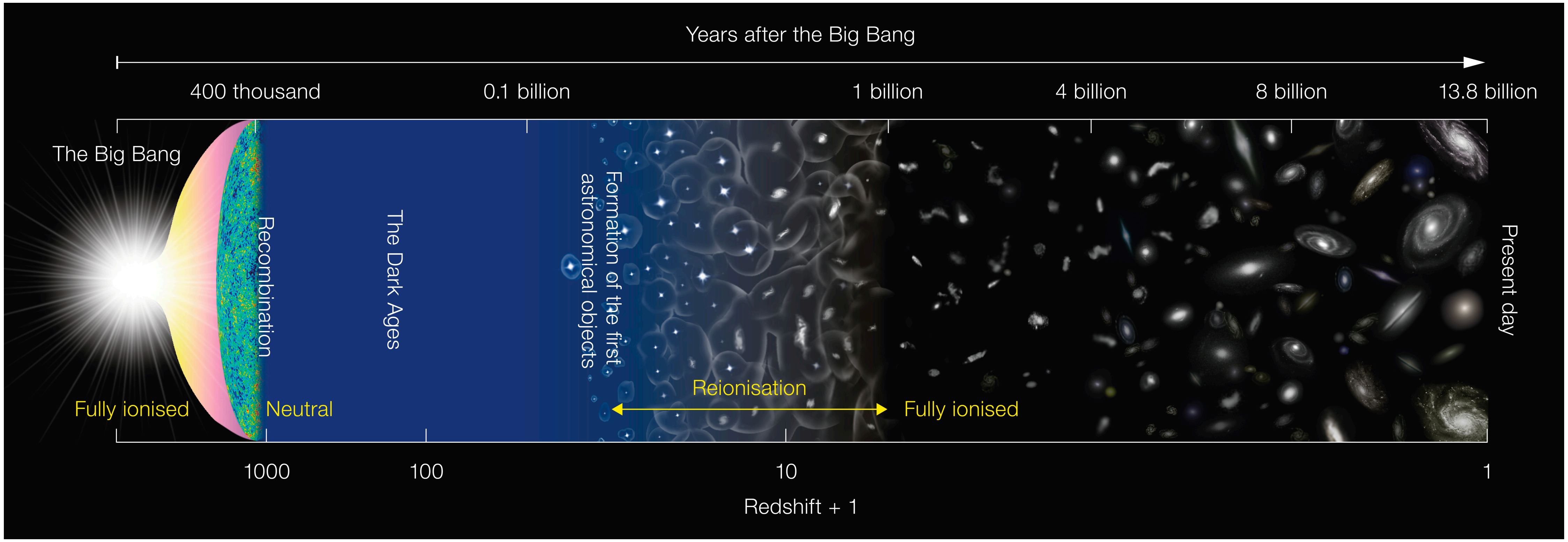
CMB−HD
$\langle T^{\mathrm{dSc}} \times T^{\mathrm{Sc}} \times T^{\mathrm{Sc}}\rangle$
$\langle T^{\mathrm{dSc}} \times E^{\mathrm{Sc}} \times B^{\mathrm{Sc}}\rangle$
Planck
CMB Autocorrelation
CMB × LSS
$\langle T^{\mathrm{dSc}} \times T^{\mathrm{Sc}} \times T^{\mathrm{Sc}}\rangle$
$\langle T^{\mathrm{dSc}} \times E^{\mathrm{Sc}} \times B^{\mathrm{Sc}}\rangle$
CMB−S4
CMB Autocorrelation
CMB × LSS
FIRAS
$m_{\mathrm{A}'}$ [eV]

Thank you!

Background light

Effect of Dark Sector

Observer



CMB, 21cm, LIM…

Dark photon, axion, freeze-in…

Halos, Voids, Bubbles…

$\langle \mathrm{BSM} \cdot \mathrm{SM} \rangle$

Thank you!

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Job type: Faculty

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Have questions?

Contact
Amanda Ferneyhough

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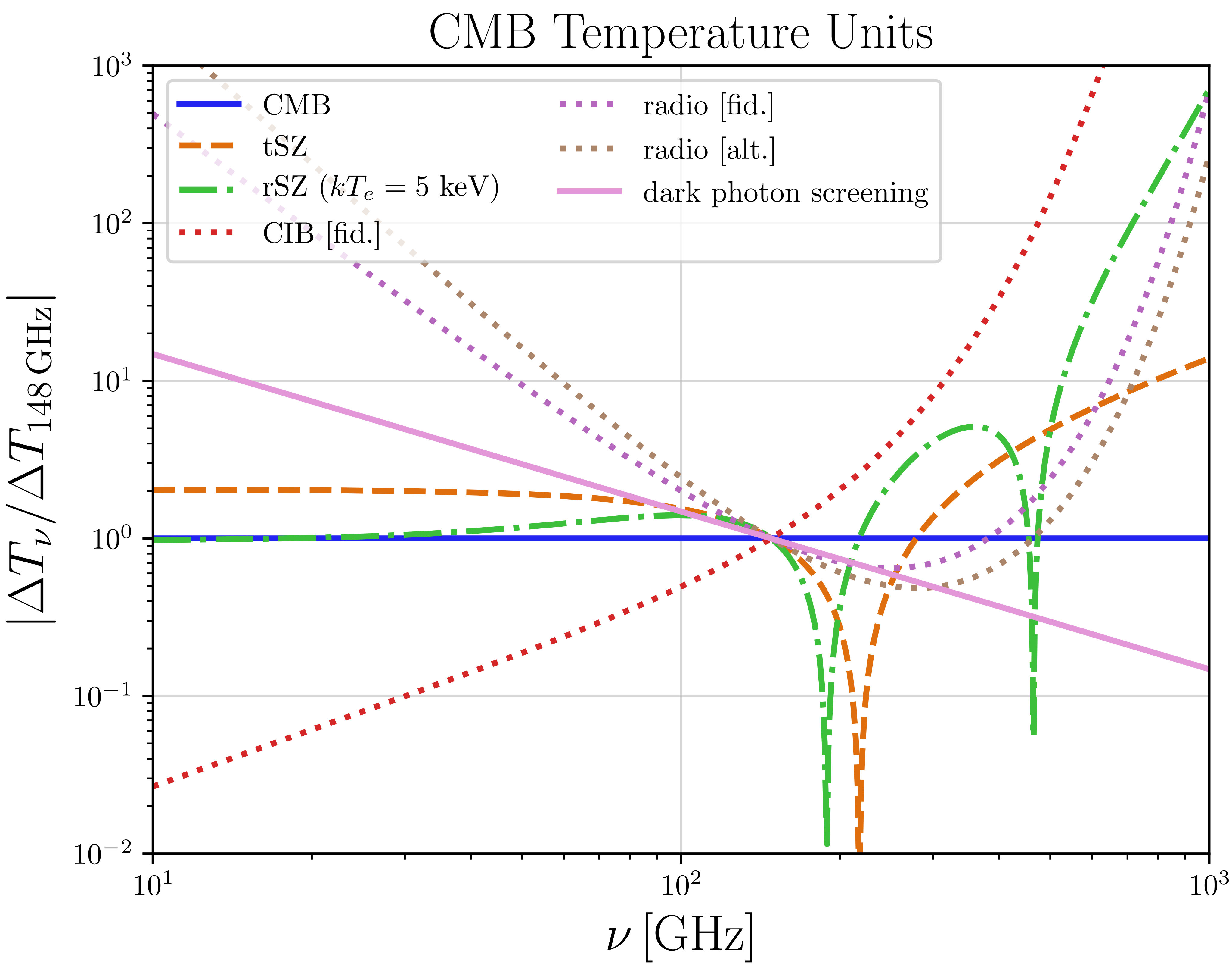
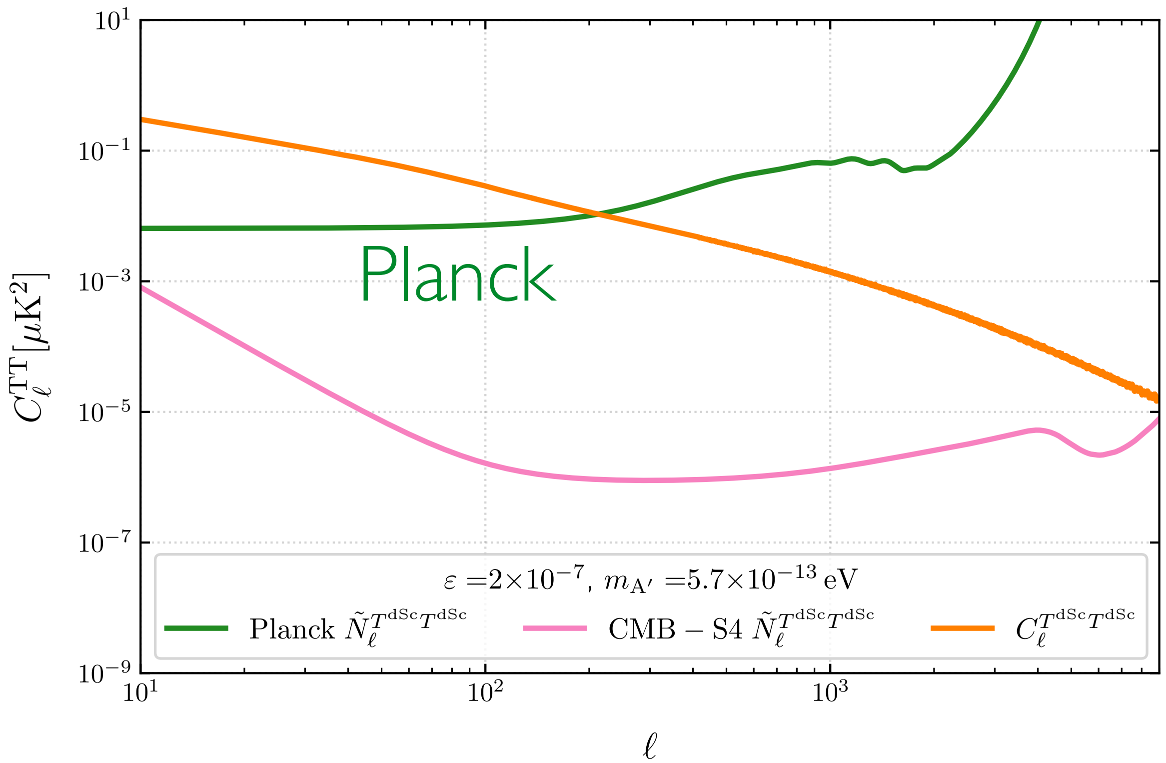
Questions shall go to Kendrick Smith or Neal Dalal

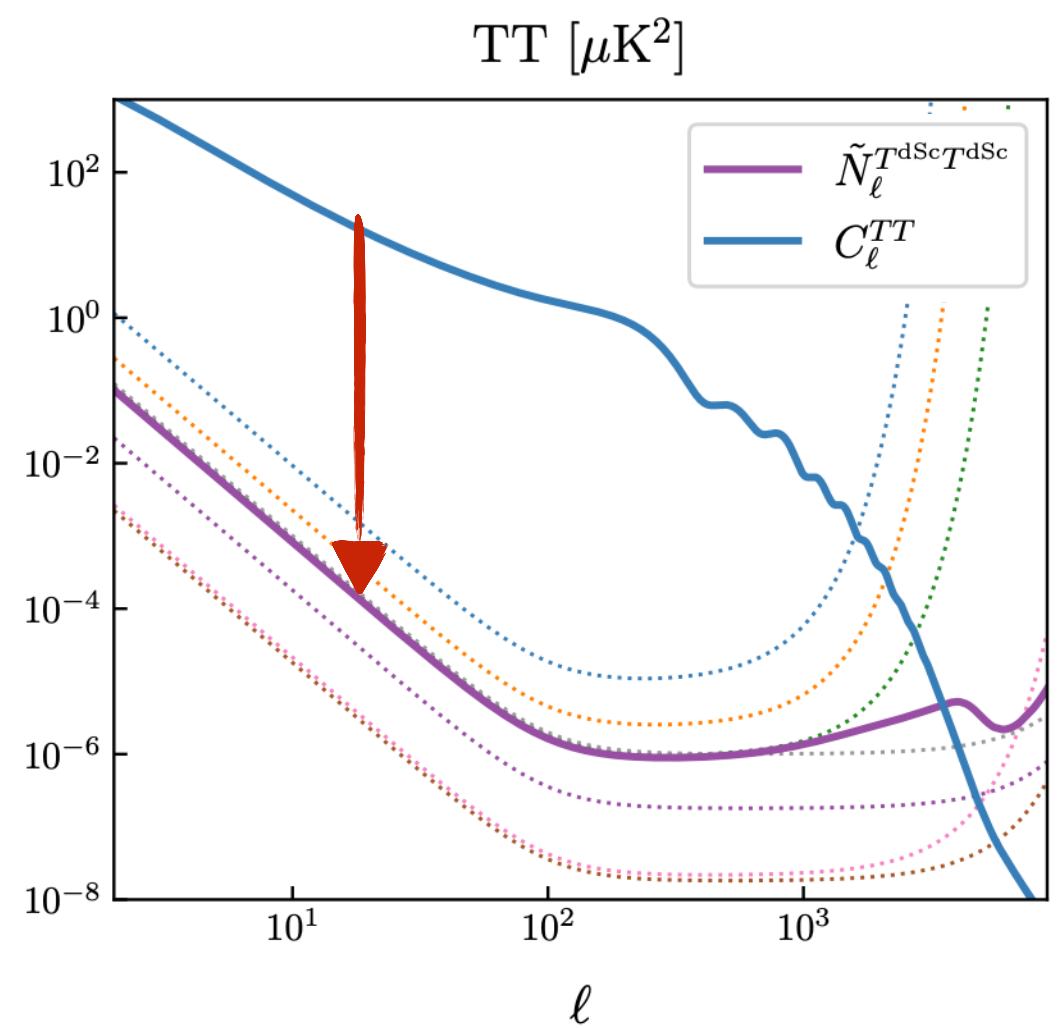
Back up



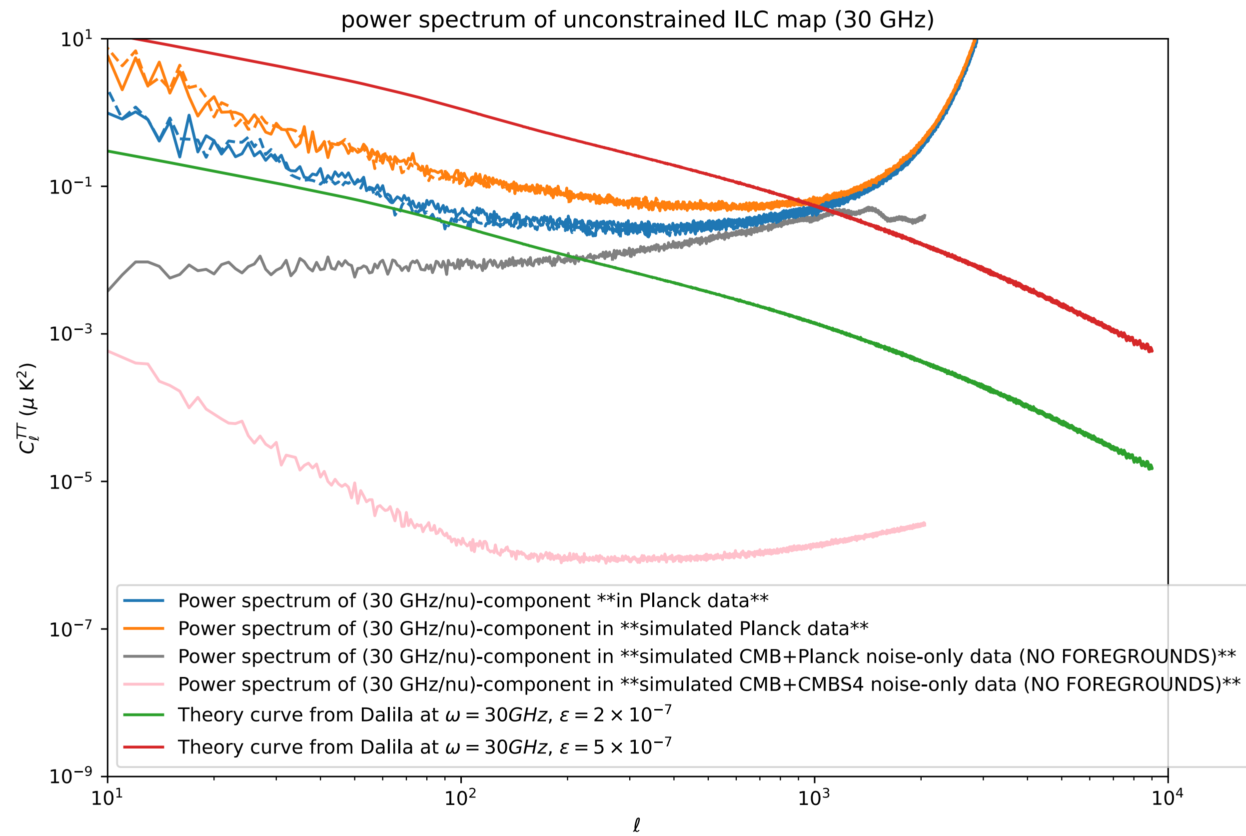
CMB Temperature Units
CMB
tSZ
rSZ ($kT_e = 5$ keV)
CIB [fid.]
radio [fid.]
radio [alt.]
dark photon screening
$|\Delta T_\nu / \Delta T_{148\,\mathrm{GHz}}|$
ν [GHz]
10^{-2}
10^{-1}
10^{0}
10^{1}
10^{2}
10^{3}
10^{1}
10^{2}
10^{3}

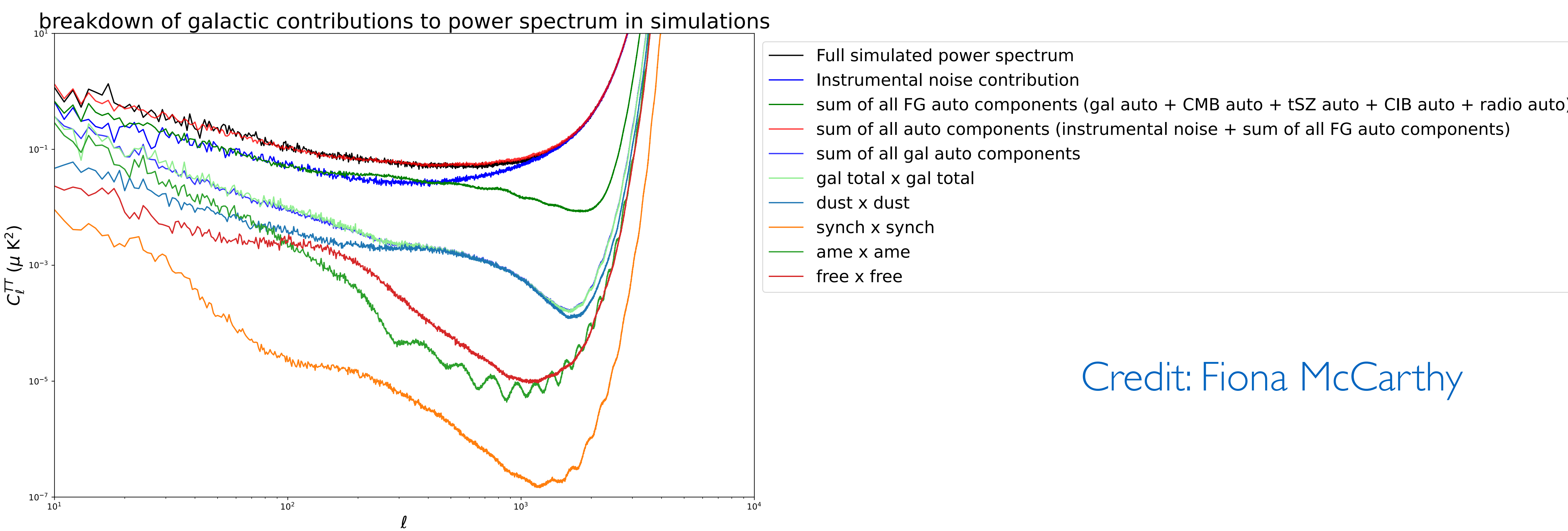
ILC cleaning





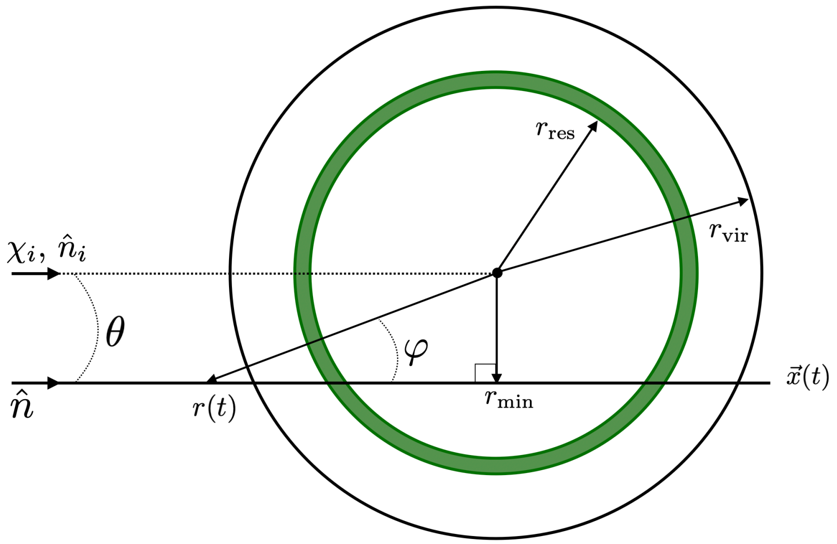
Six orders of magnitude of reduction of the noise with S4!



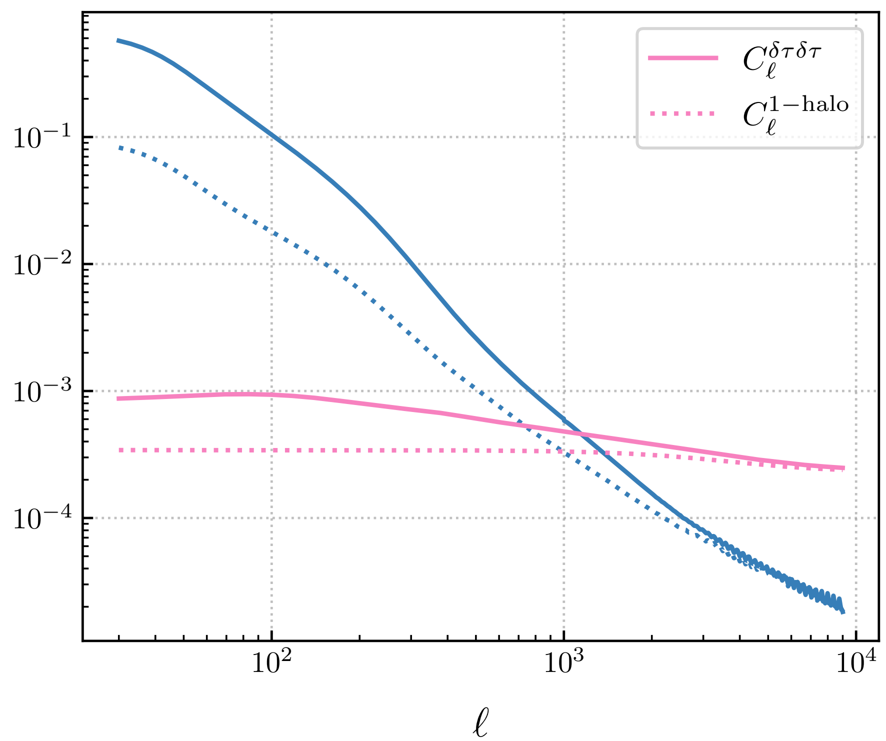


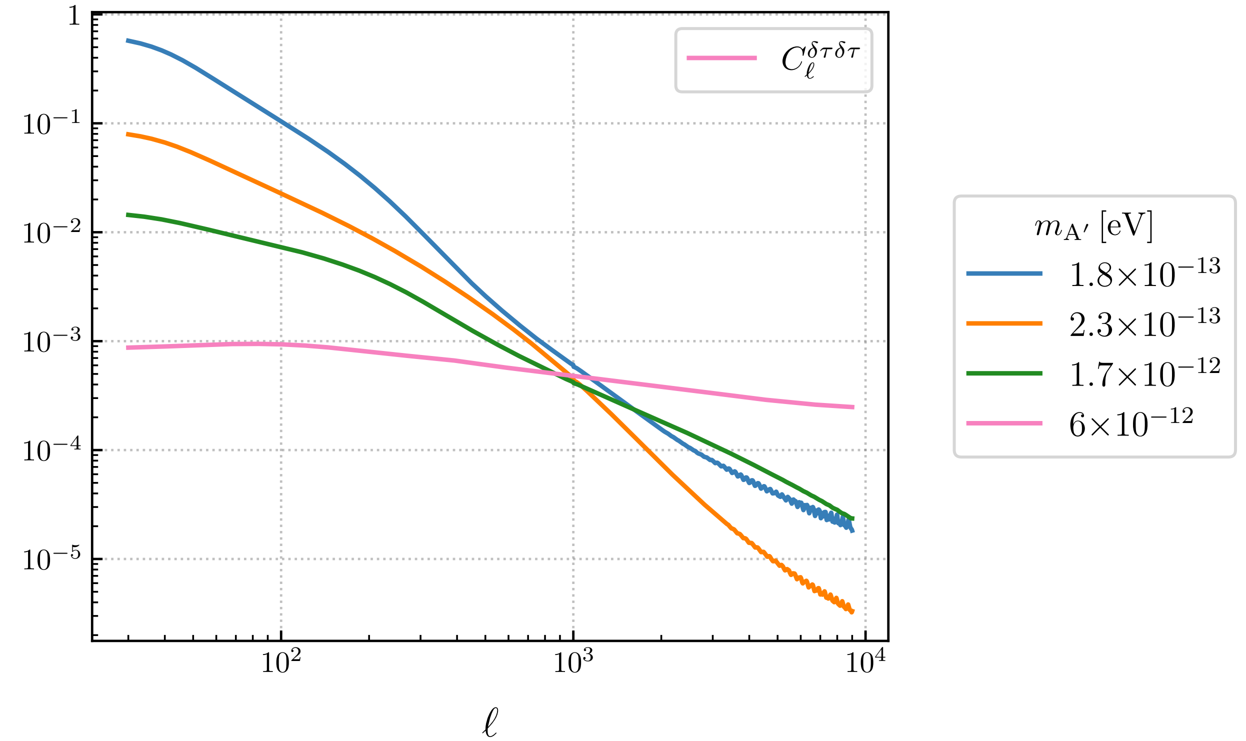
Credit: Fiona McCarthy

Optical depth map



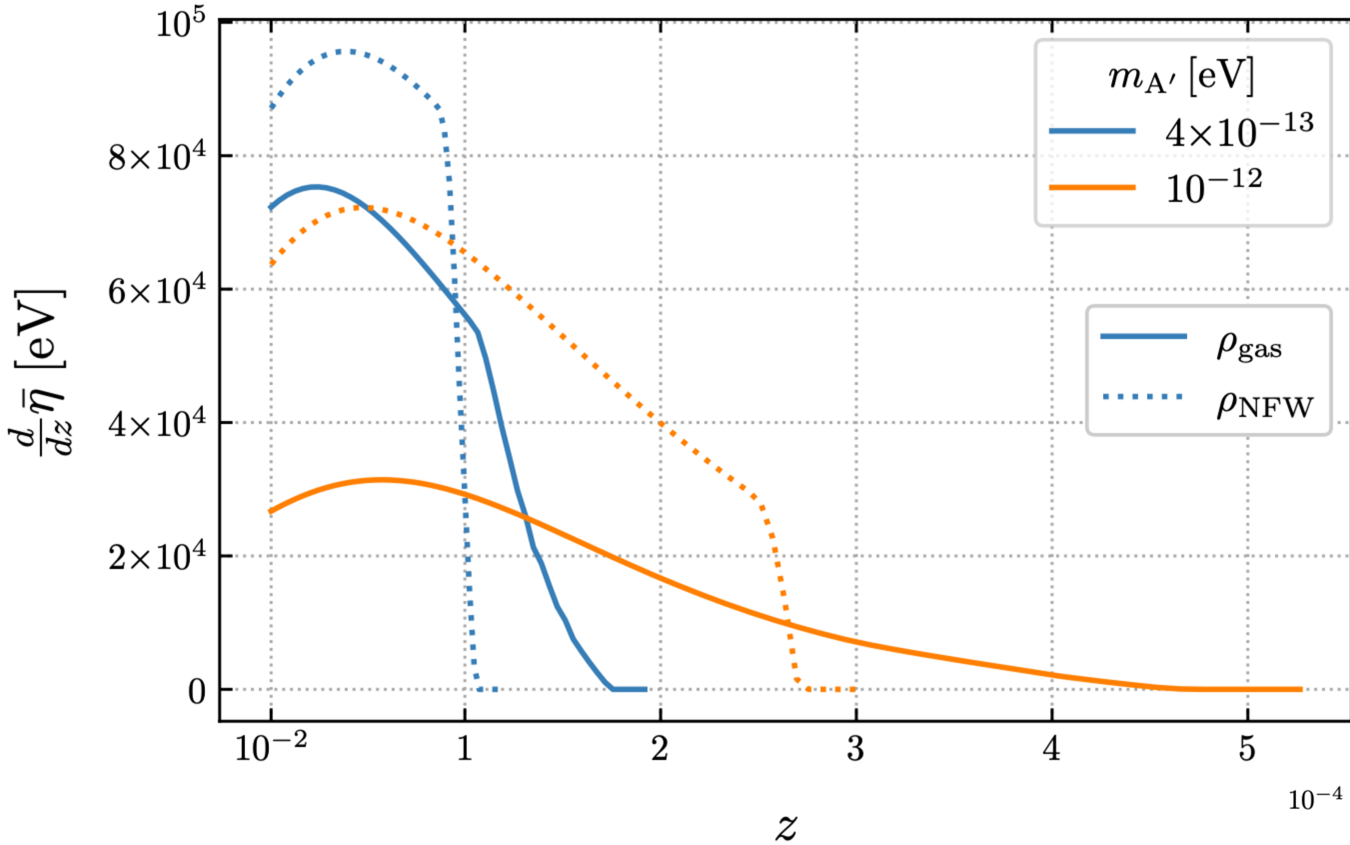
- Sum over halo:

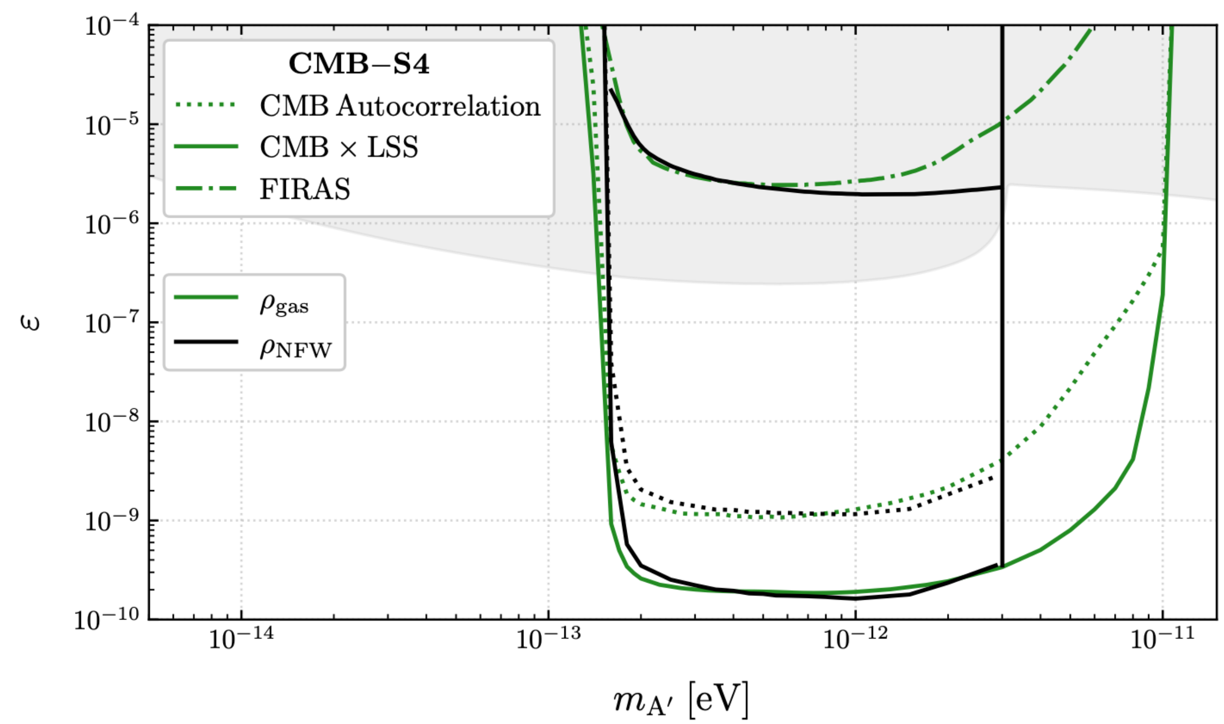




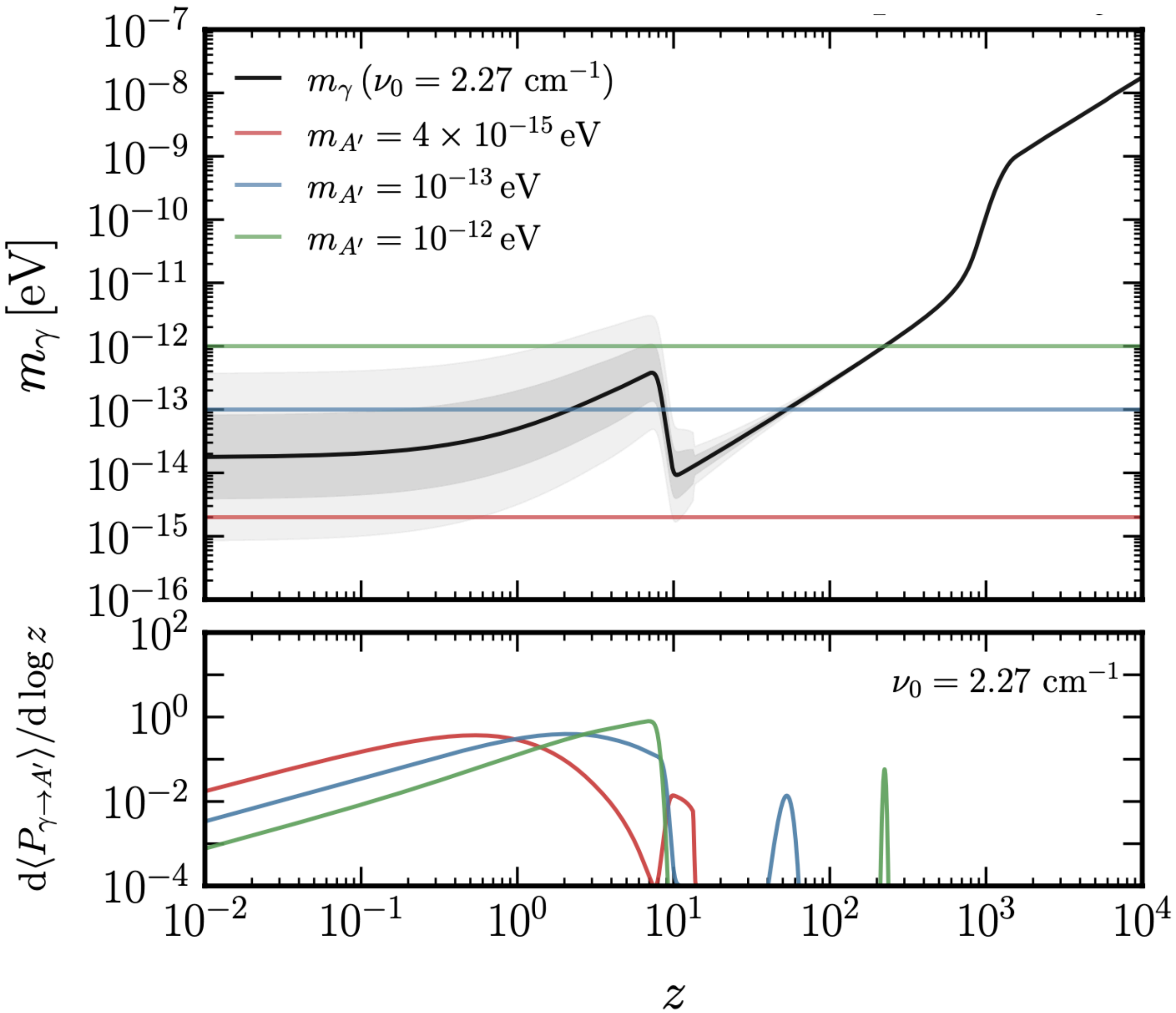
Hill & Pajer 1303.4726
Roy, Battaglia+ 2201.05076

Density profiles?

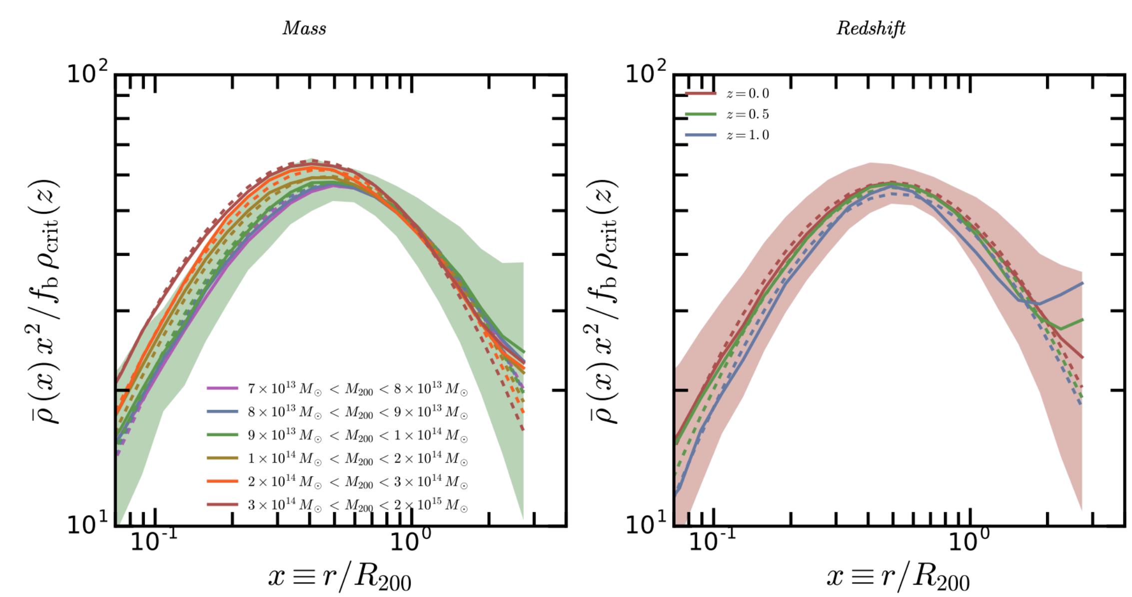




How to go to other masses?

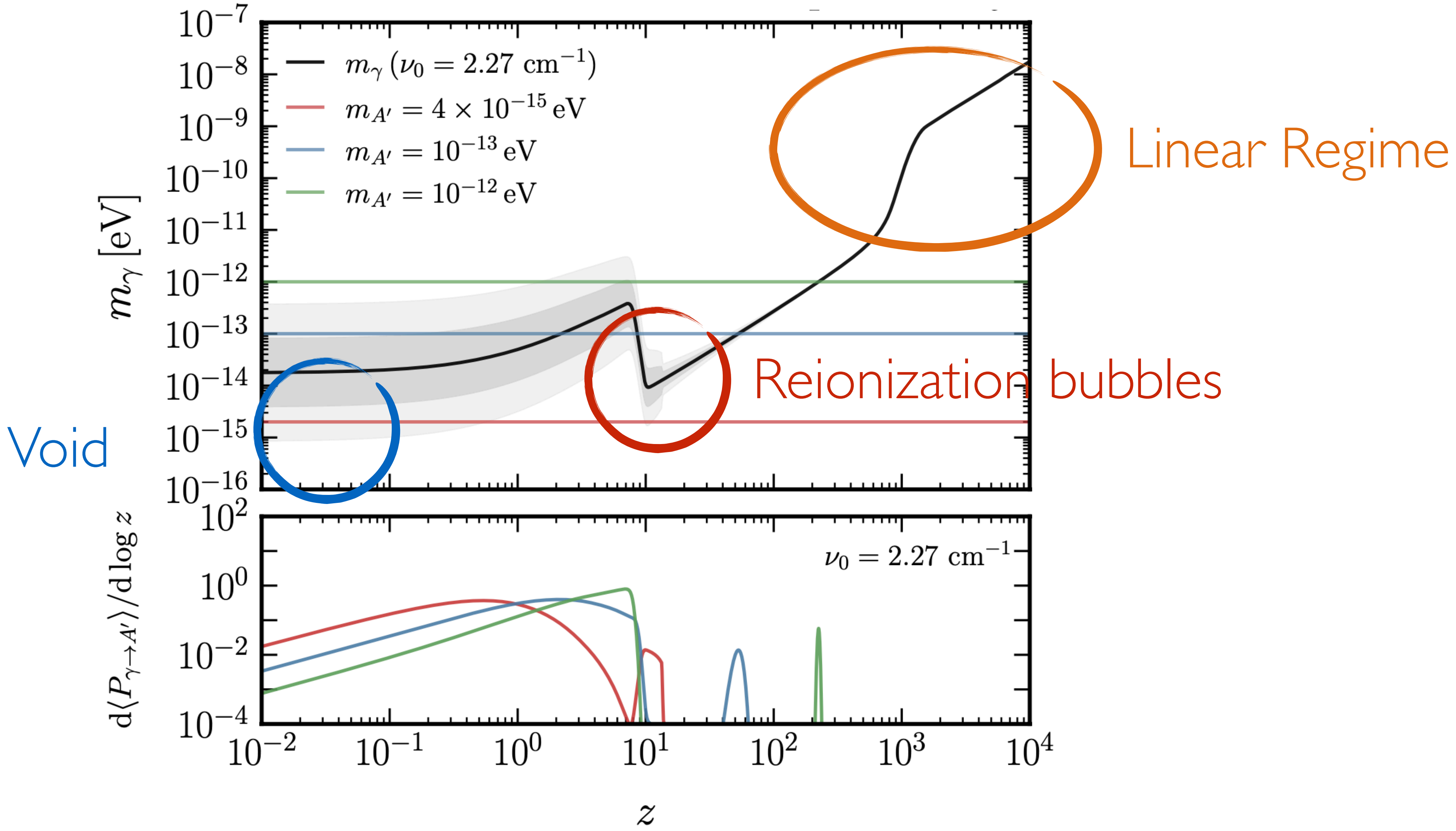


Shrinking the uncertainties of electron density profile beyond the Virial radius

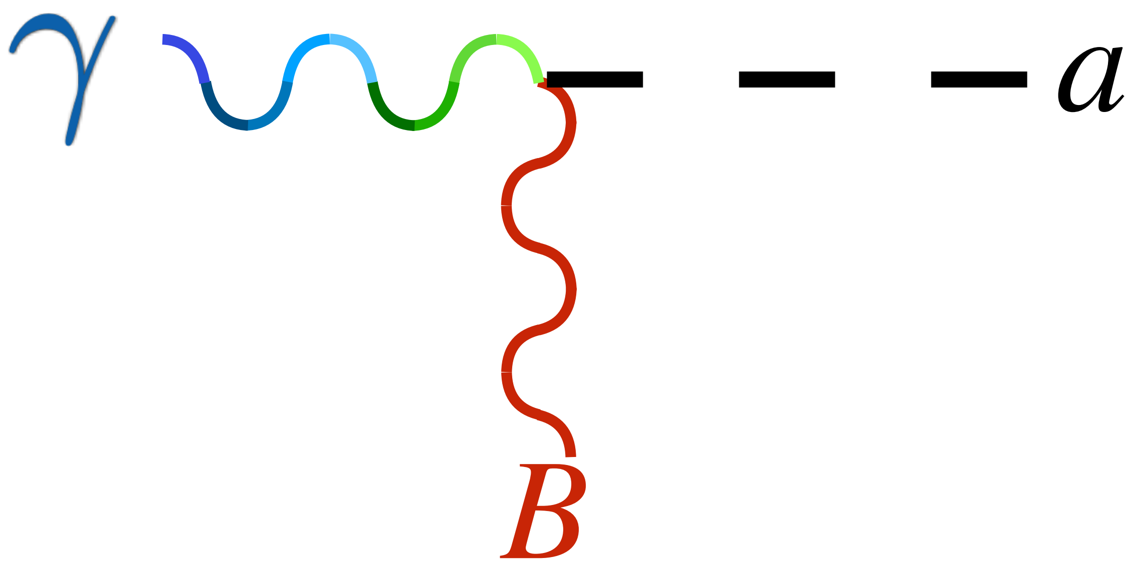


Battaglia 1607.02442

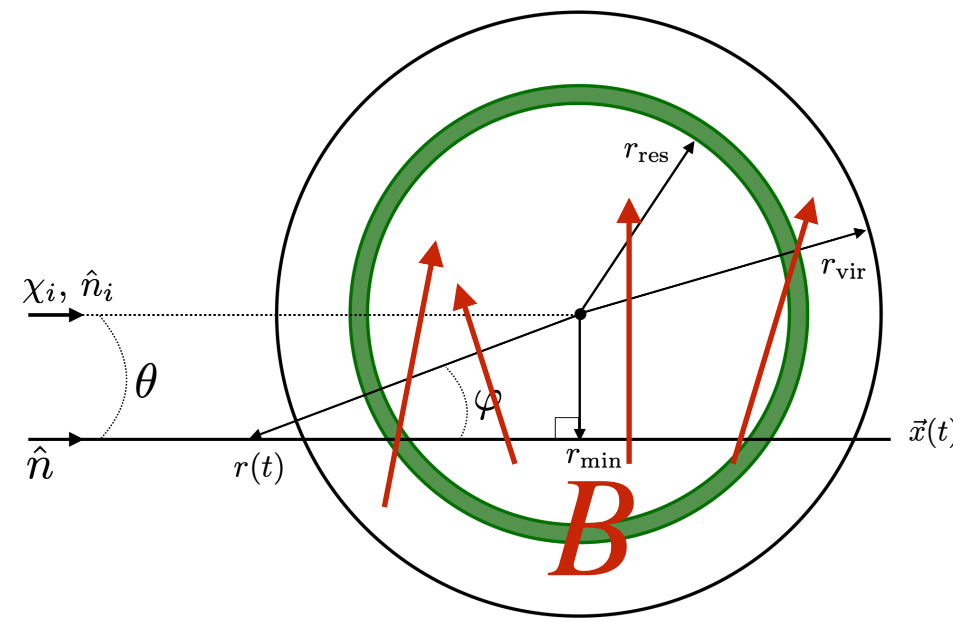
How to go to other masses?



Axion case



γ
a
B



$r_{\rm res}$
$r_{\rm vir}$
χ_i, $\hat{n}_i$
θ
φ
$\hat{n}$
$r(t)$
$r_{\rm min}$
$\vec{x}(t)$
B

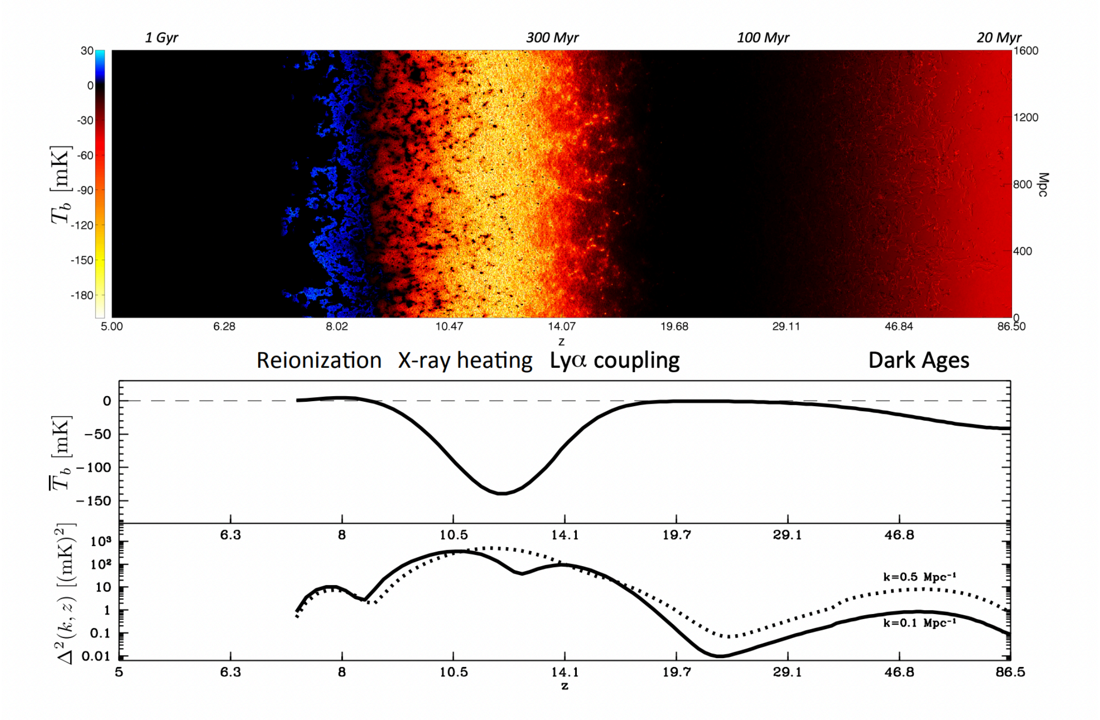
Beyond CMB

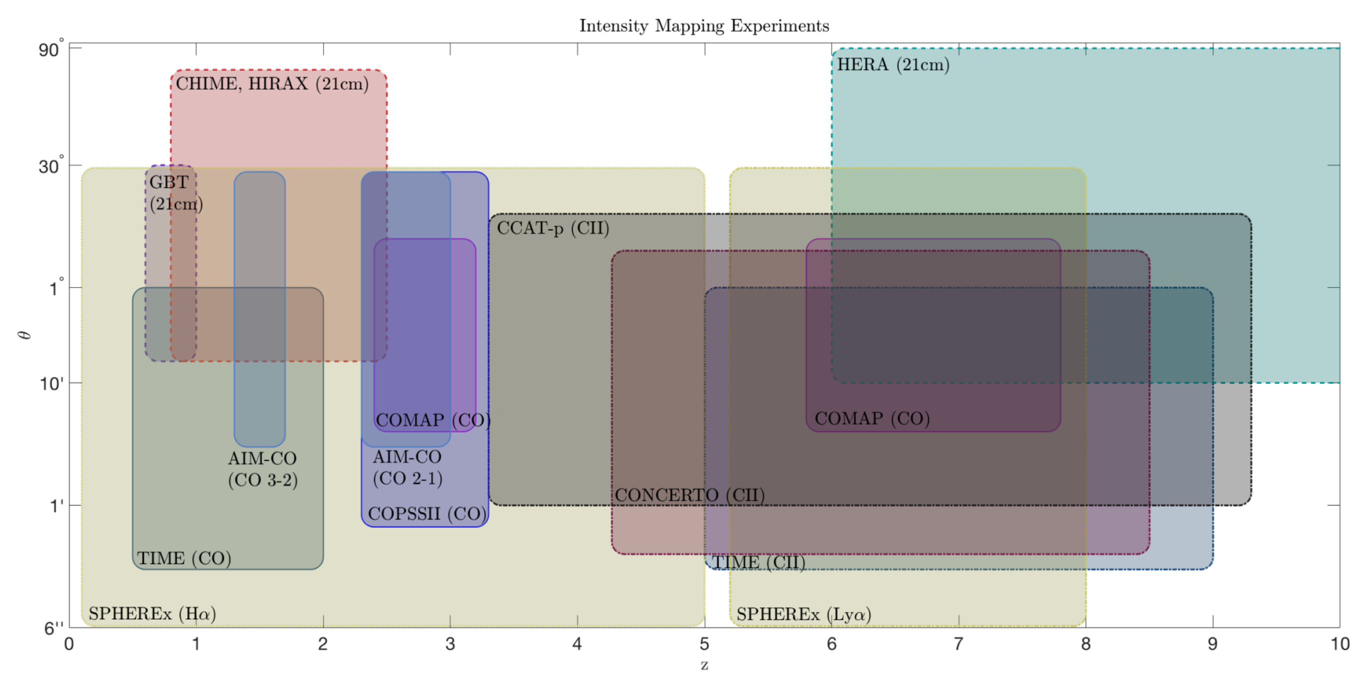
Frequency scaling

- Dark photon: $P \propto 1/\omega$
- Axion: $P \propto \omega$

Though CMB is the best measured, going to higher or lower frequencies might be better in the future!

21cm & LIM





$P \propto 1/\omega$

$P \propto \omega$