CMB probes of neutrinos and searches for other neutrino-like particles

Marius Millea

on behalf of the CMB-S4 collaboration

BERKELEY CENTER *for* COSMOLOGICAL PHYSICS

AAS Meeting – Seattle – Jan 7, 2019

3x3 matrix parameterized by mixing angles and CP violating phase(s)

Three masses

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \overbrace{\begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix}} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix} \begin{matrix} \nearrow m_1 \\ \rightarrow m_2 \\ \searrow m_3 \end{matrix}$$

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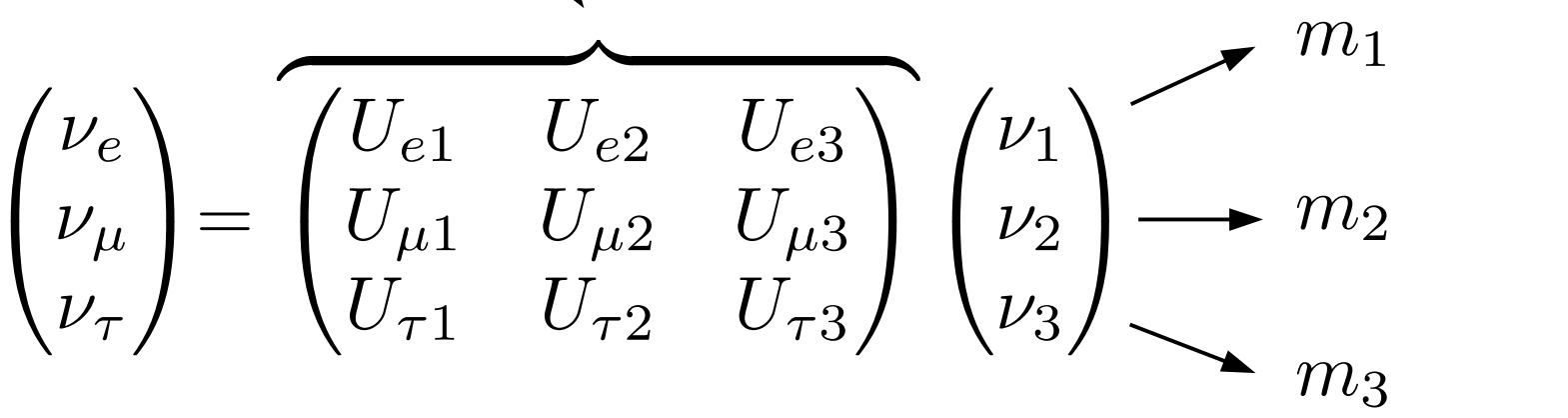
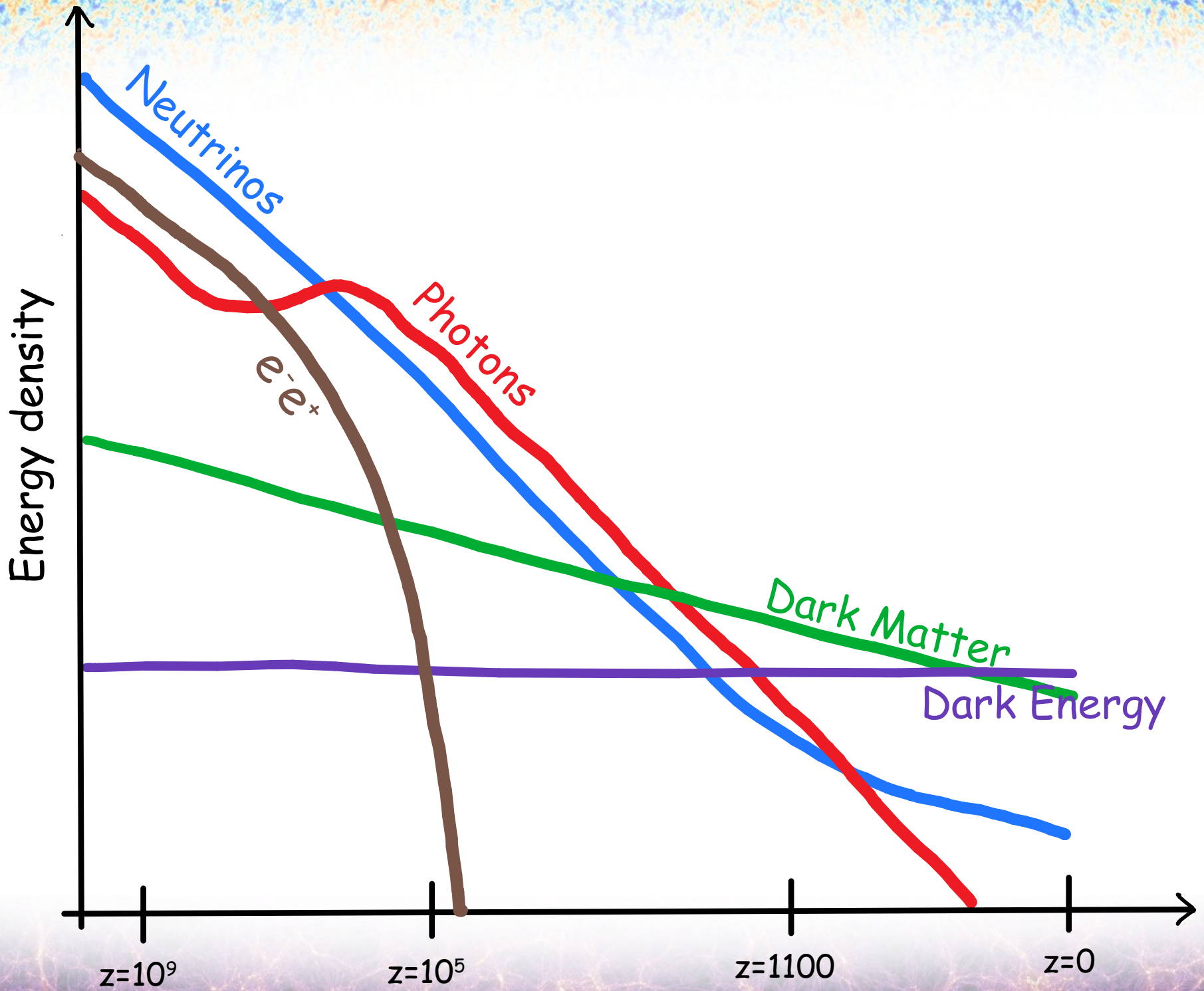
- Are there other neutrinos?
- Are neutrinos their own anti-particle?

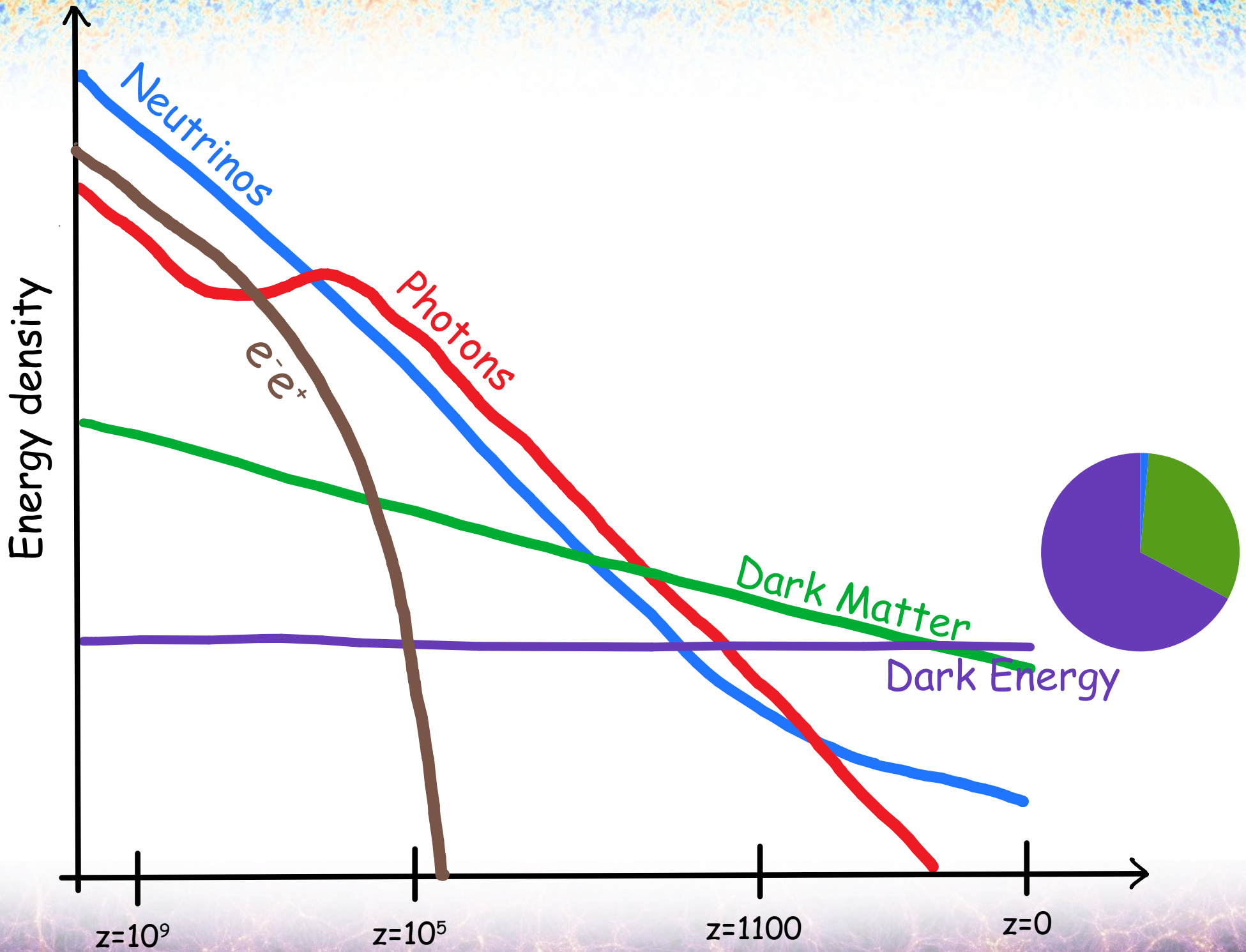
3x3 matrix parameterized by mixing angles and CP violating phase(s)

Three masses



- How do the neutrinos acquire their masses?
- Are there other neutrinos?
- Are neutrinos their own anti-particle?
- What is the order of the masses? (ie normal or inverted hierarchy)


Energy density
Neutrinos
Photons
$e^- e^+$
Dark Matter
Dark Energy
$z=10^9$
$z=10^5$
z=1100
z=0


Energy density
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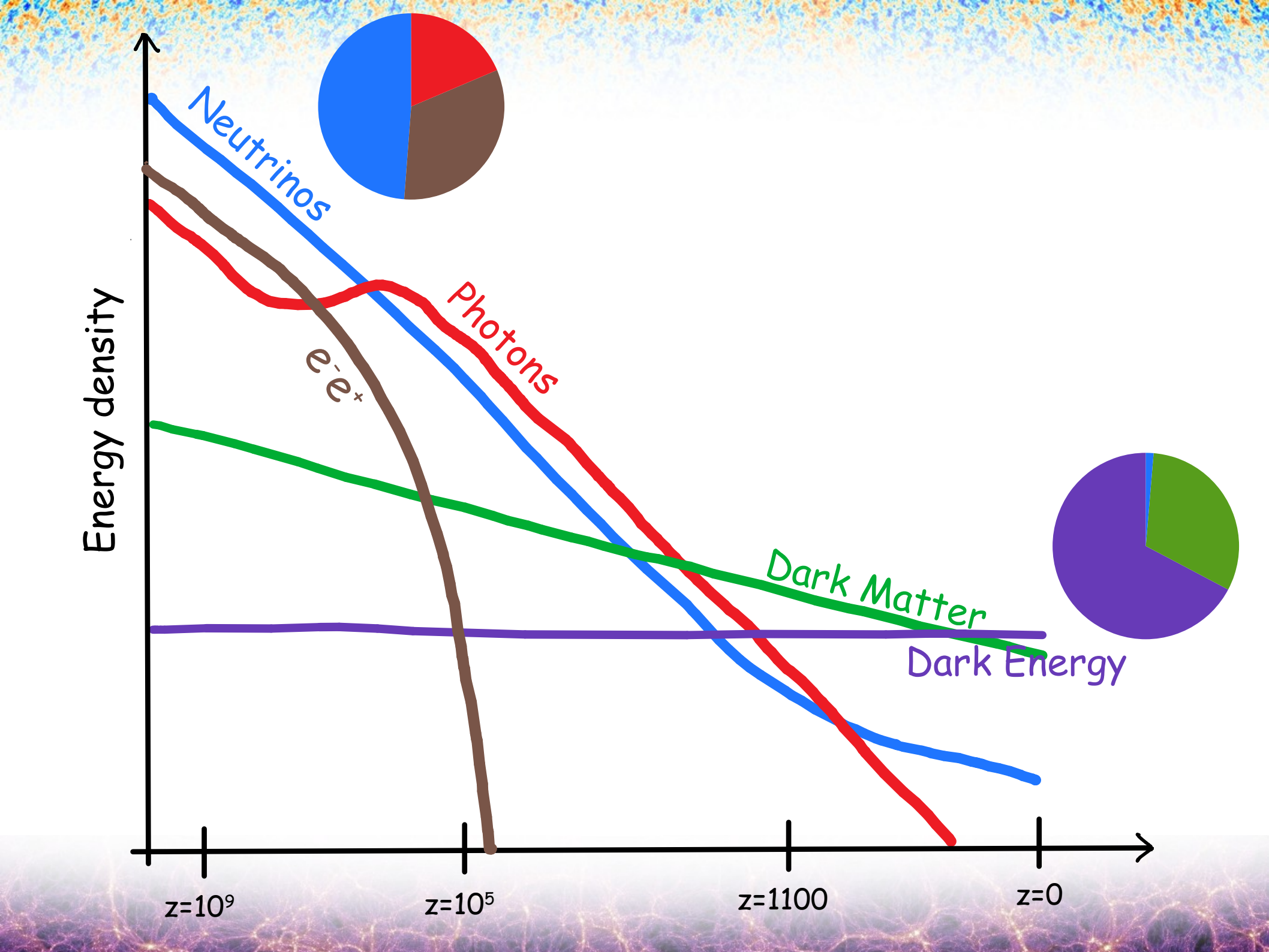
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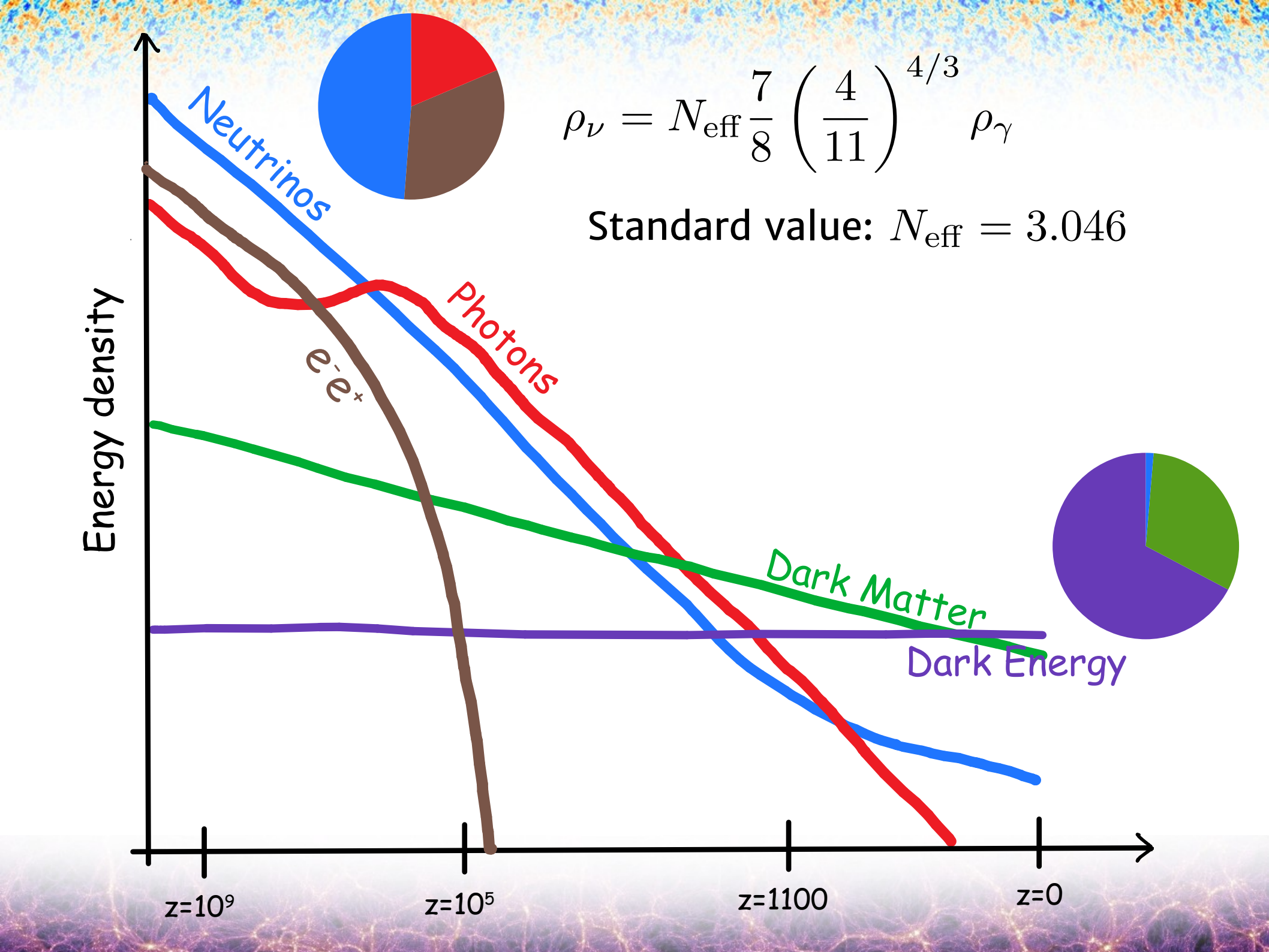
$\rho_\nu = N_{\rm eff} \frac{7}{8} \left(\frac{4}{11}\right)^{4/3} \rho_\gamma$
Standard value: $N_{\rm eff} = 3.046$
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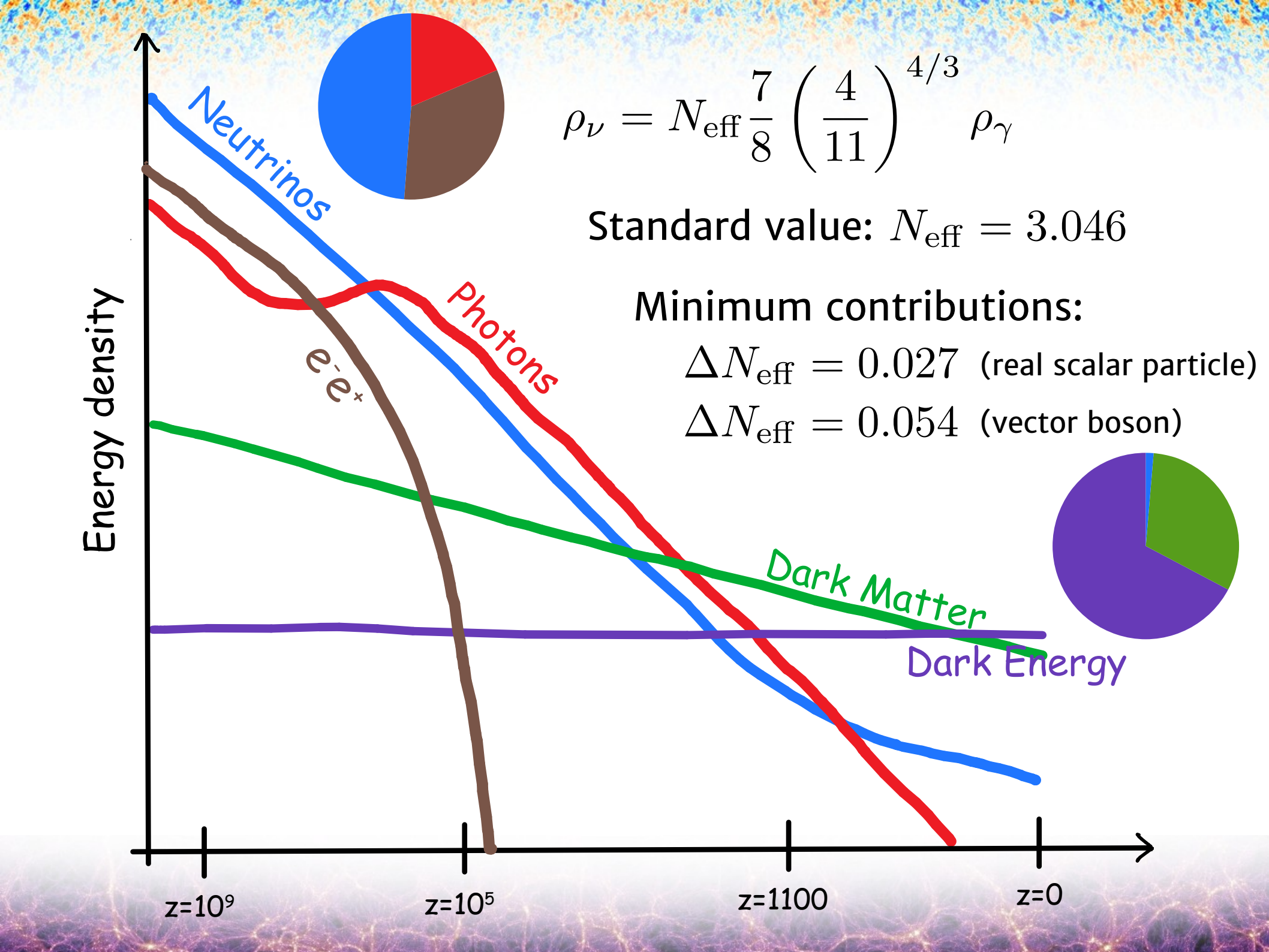

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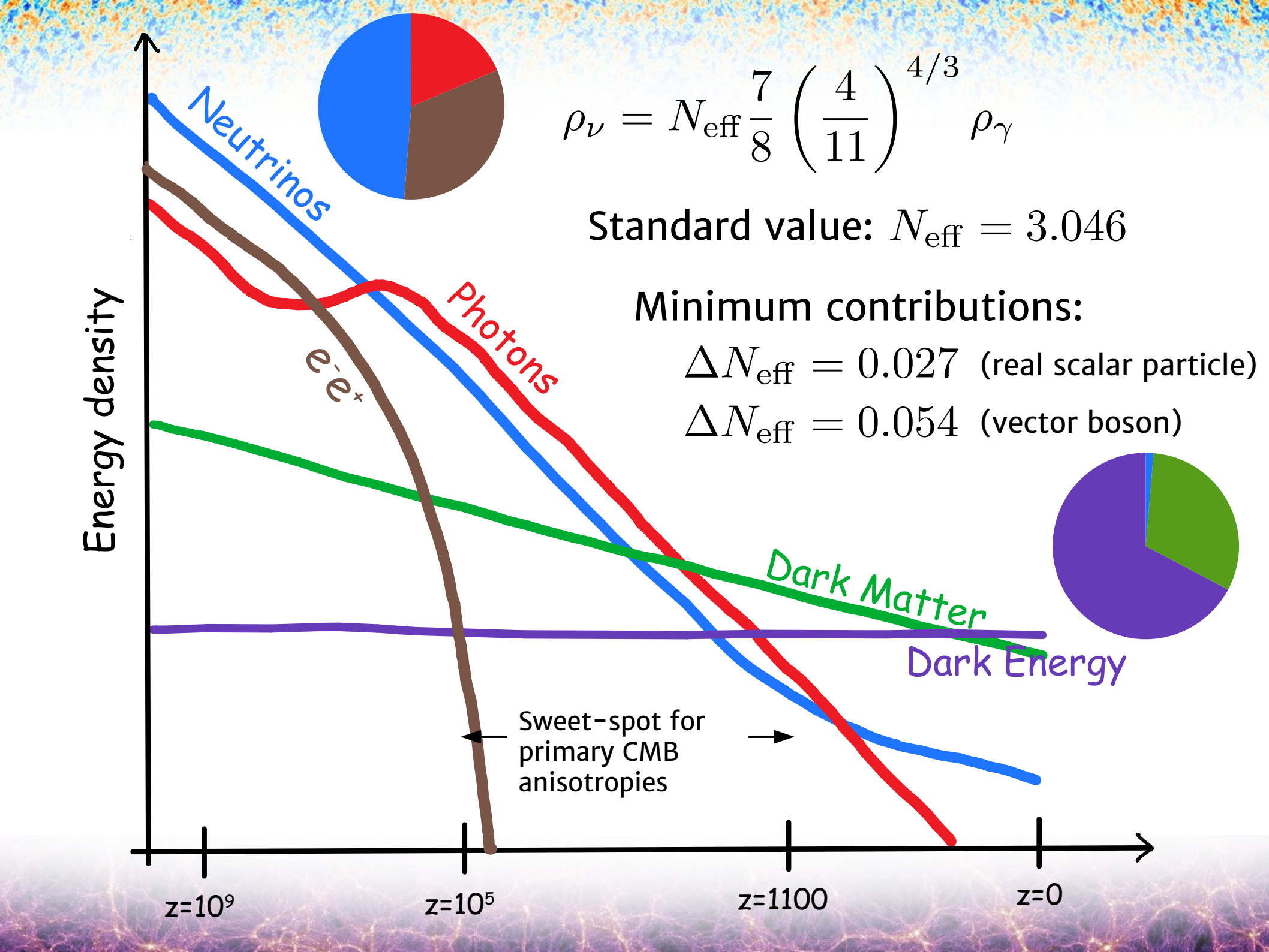
Minimum contributions:

$\Delta N_{\rm eff} = 0.027$ (real scalar particle)

$\Delta N_{\rm eff} = 0.054$ (vector boson)



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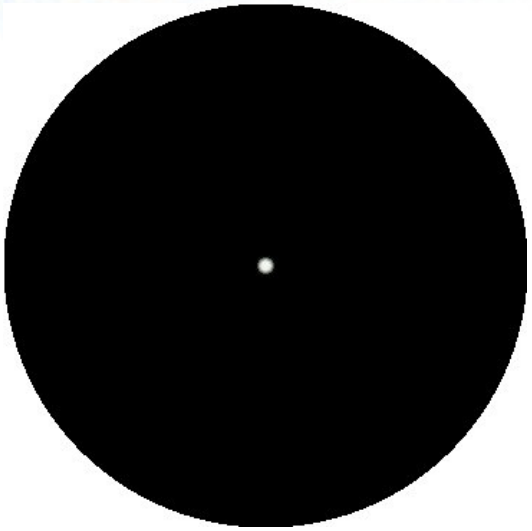
Animation: Adam D. Hinks

Acoustic waves:



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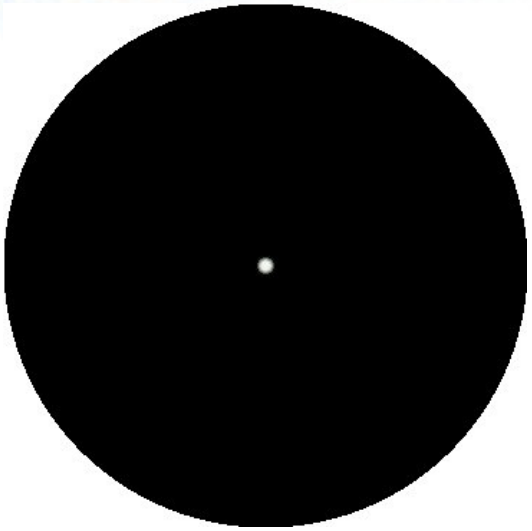
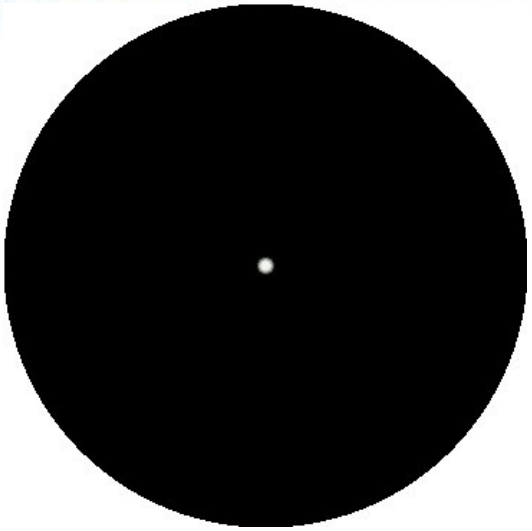


Neutrinos

Photon-electron plasma

Animation: Adam D. Hinks

Acoustic waves:



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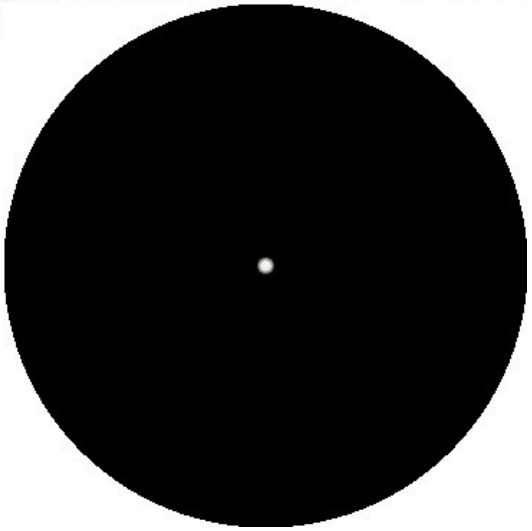


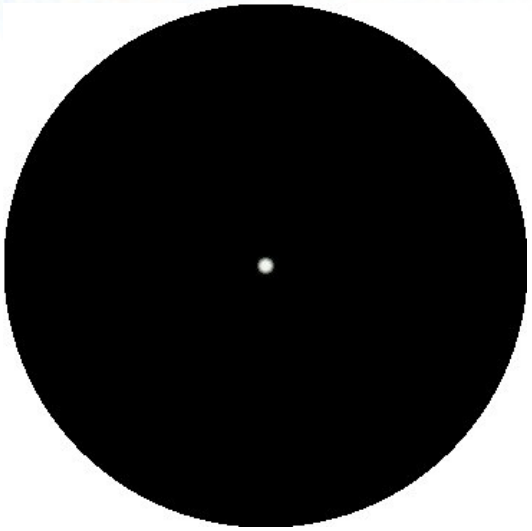
Neutrinos

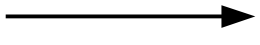
Photon-electron plasma

Gravitational pull

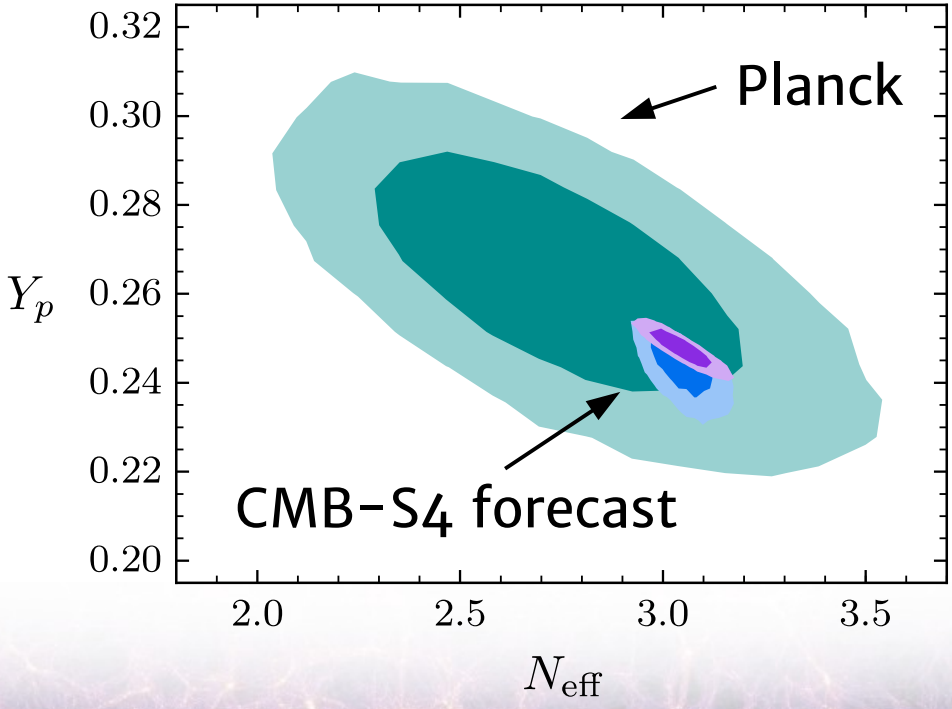
Animation: Adam D. Hinks

Acoustic waves:

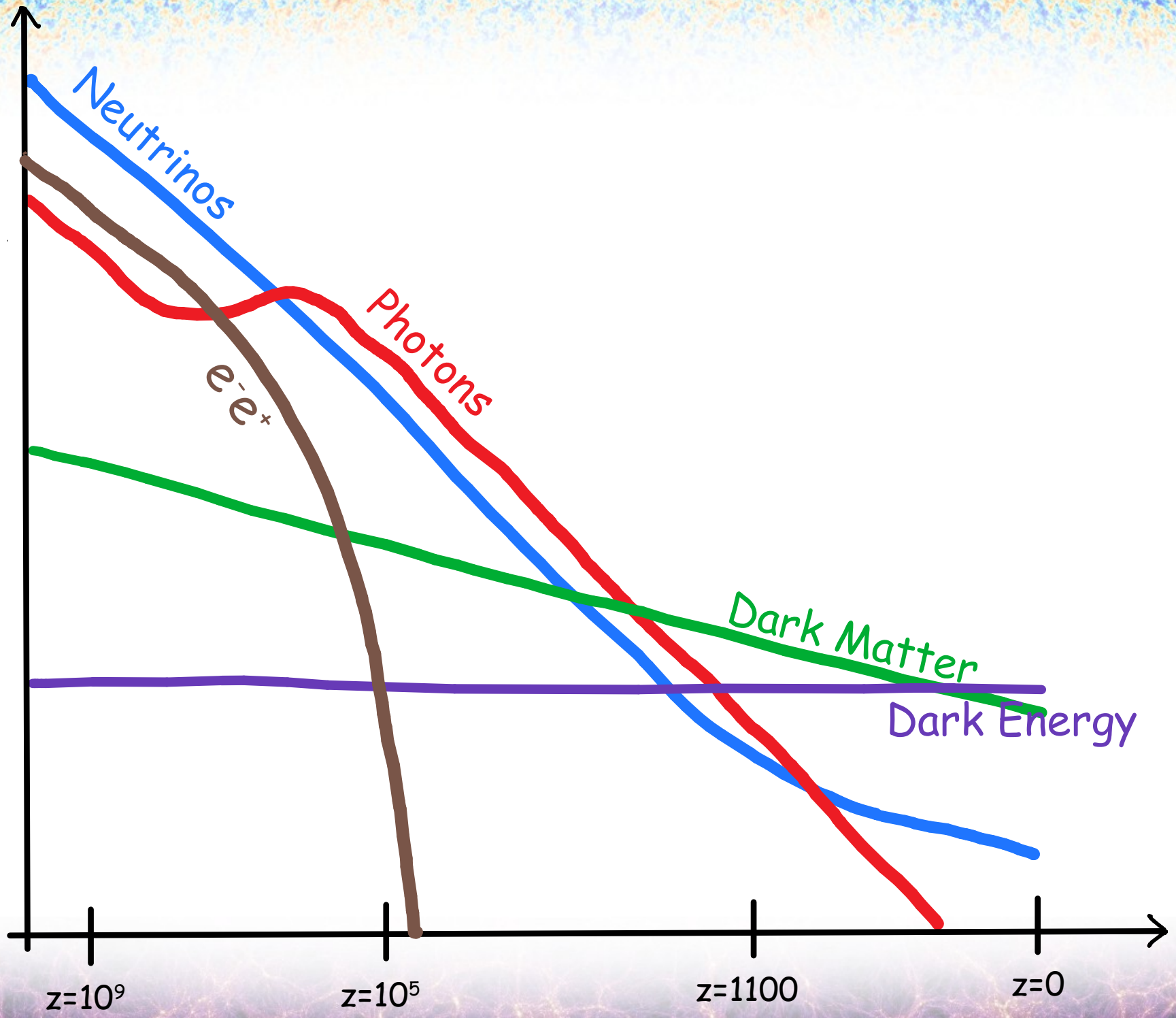




Expect much improved constraints from CMB-S4:



Baumann, Green, Myers, Wallisch (2015)


Neutrinos
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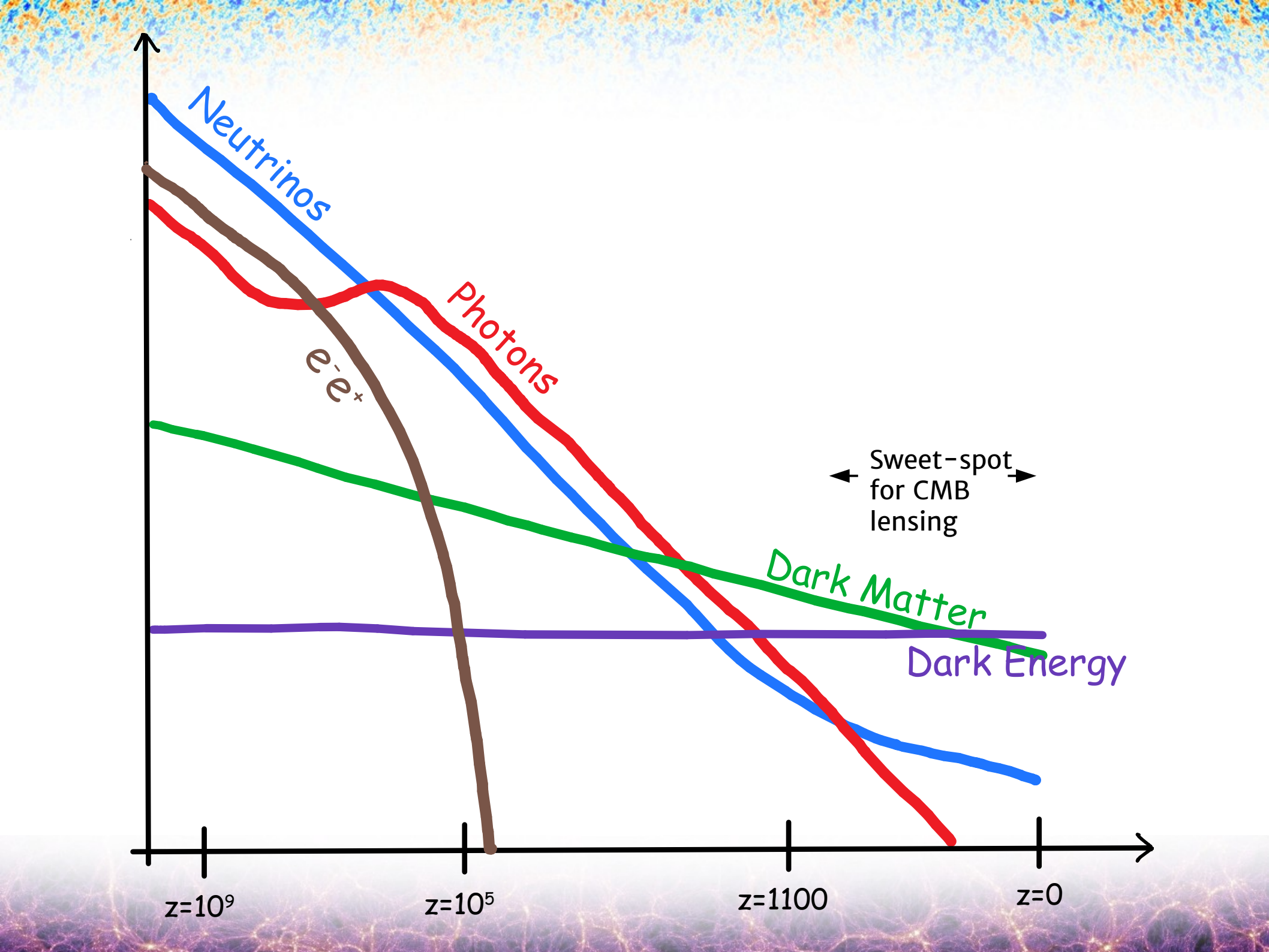
Neutrinos
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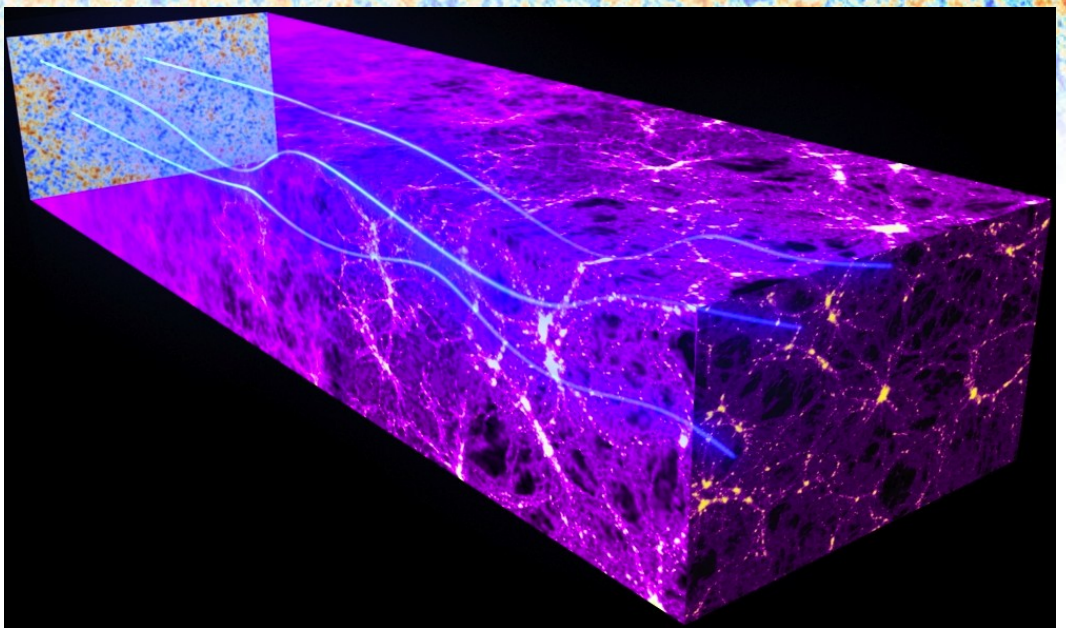

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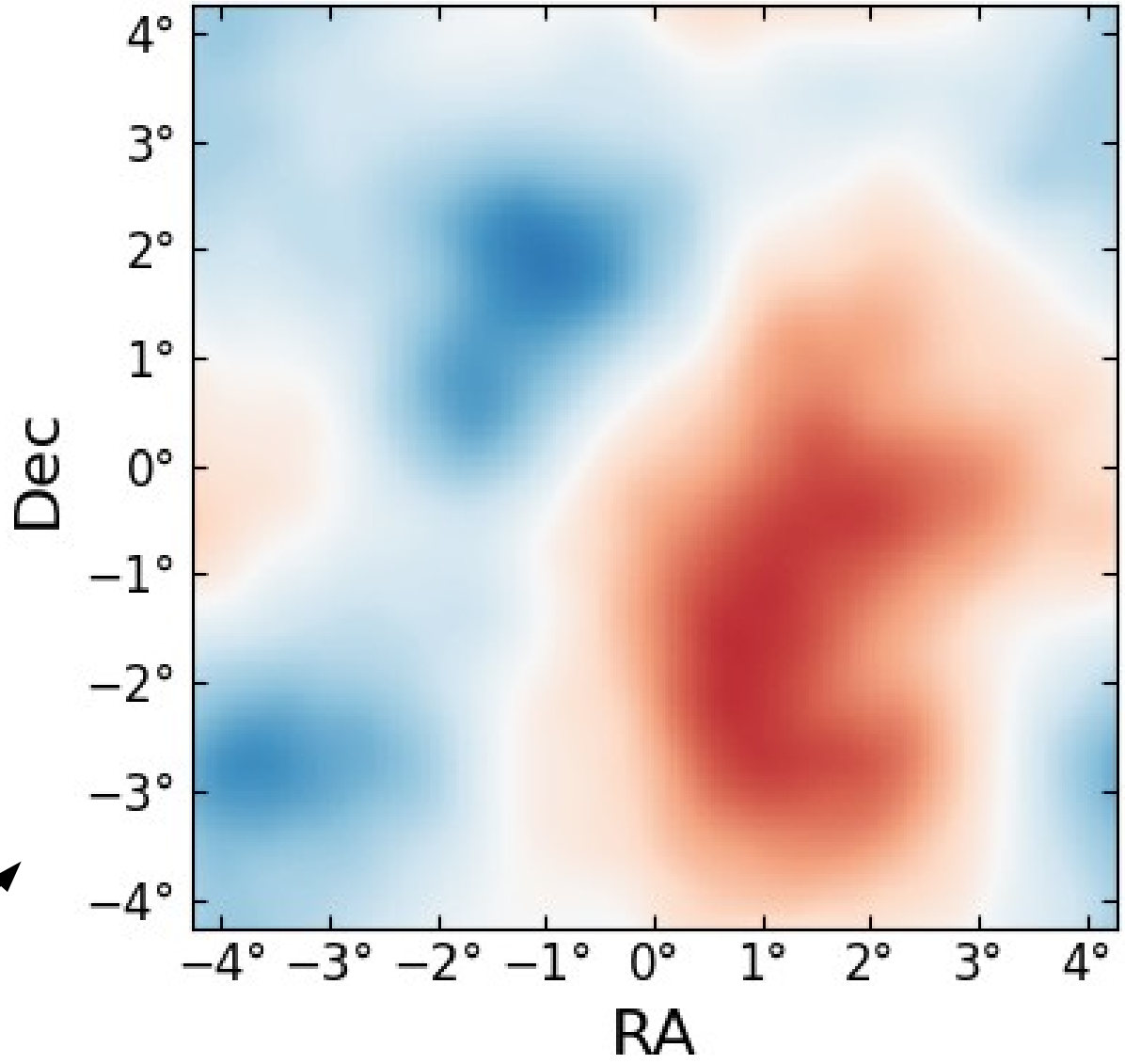
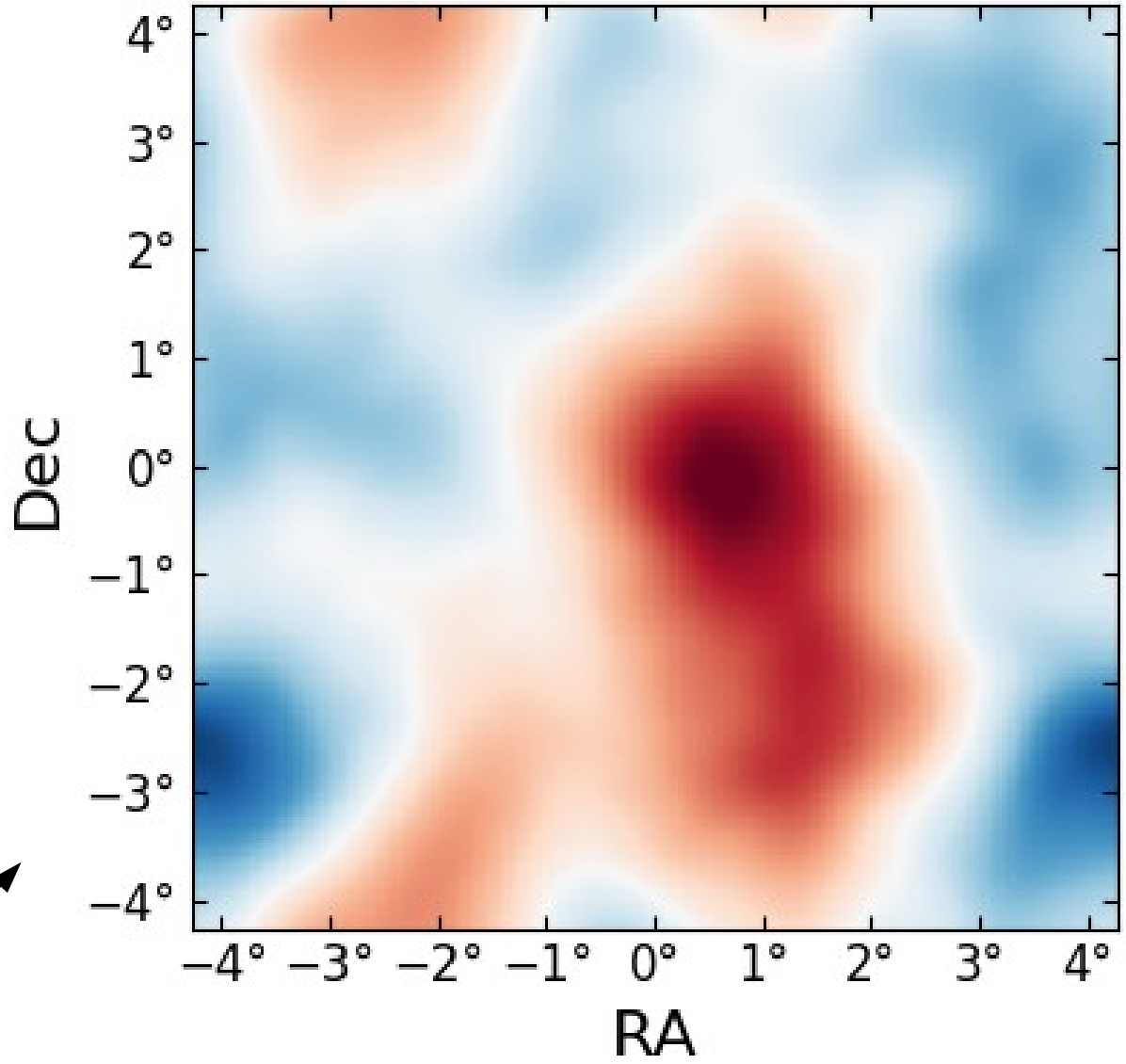
Planck temperature data



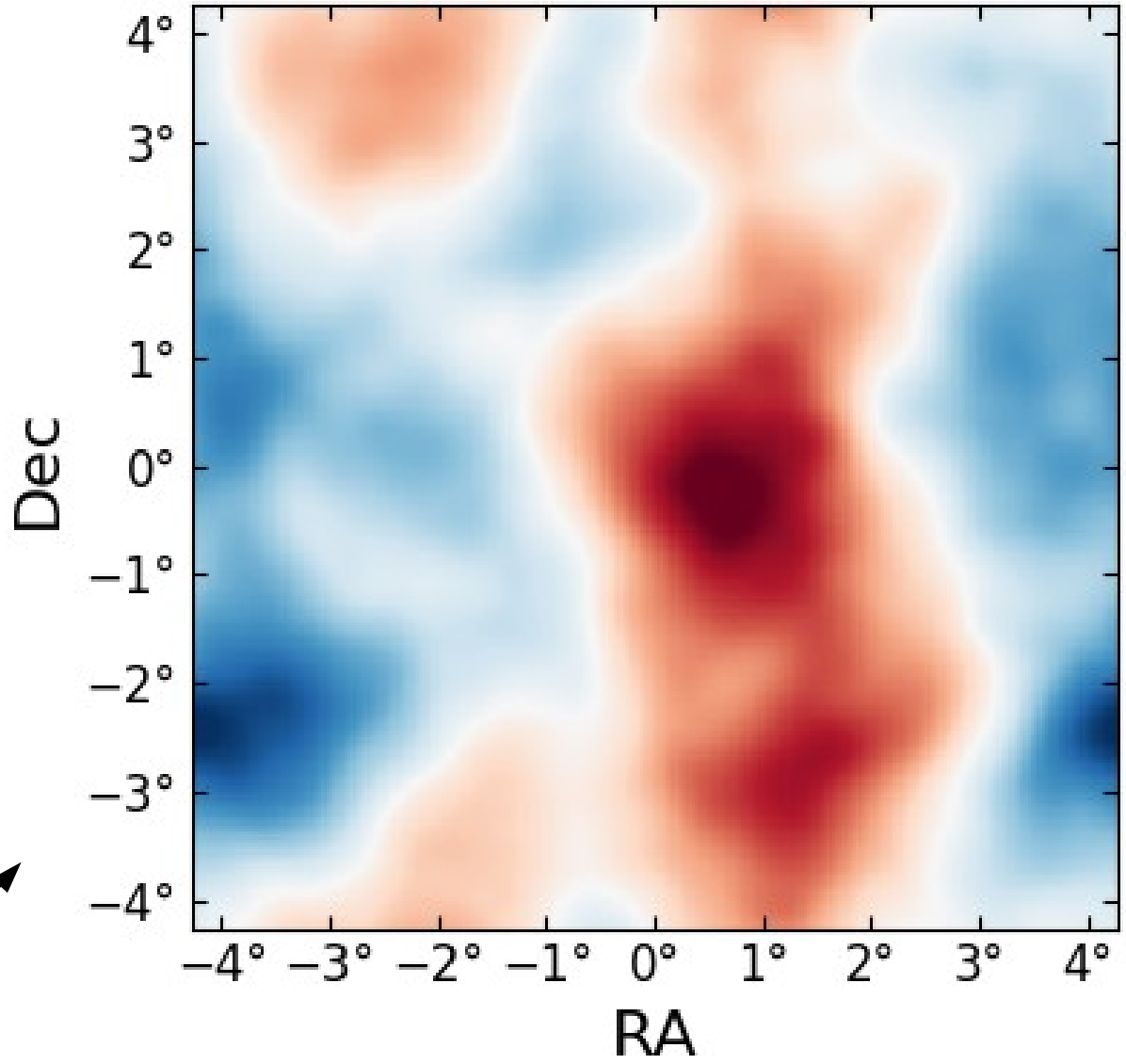
Lensing potential, ϕ, reconstructed from simulated CMB data

Current generation polarization data



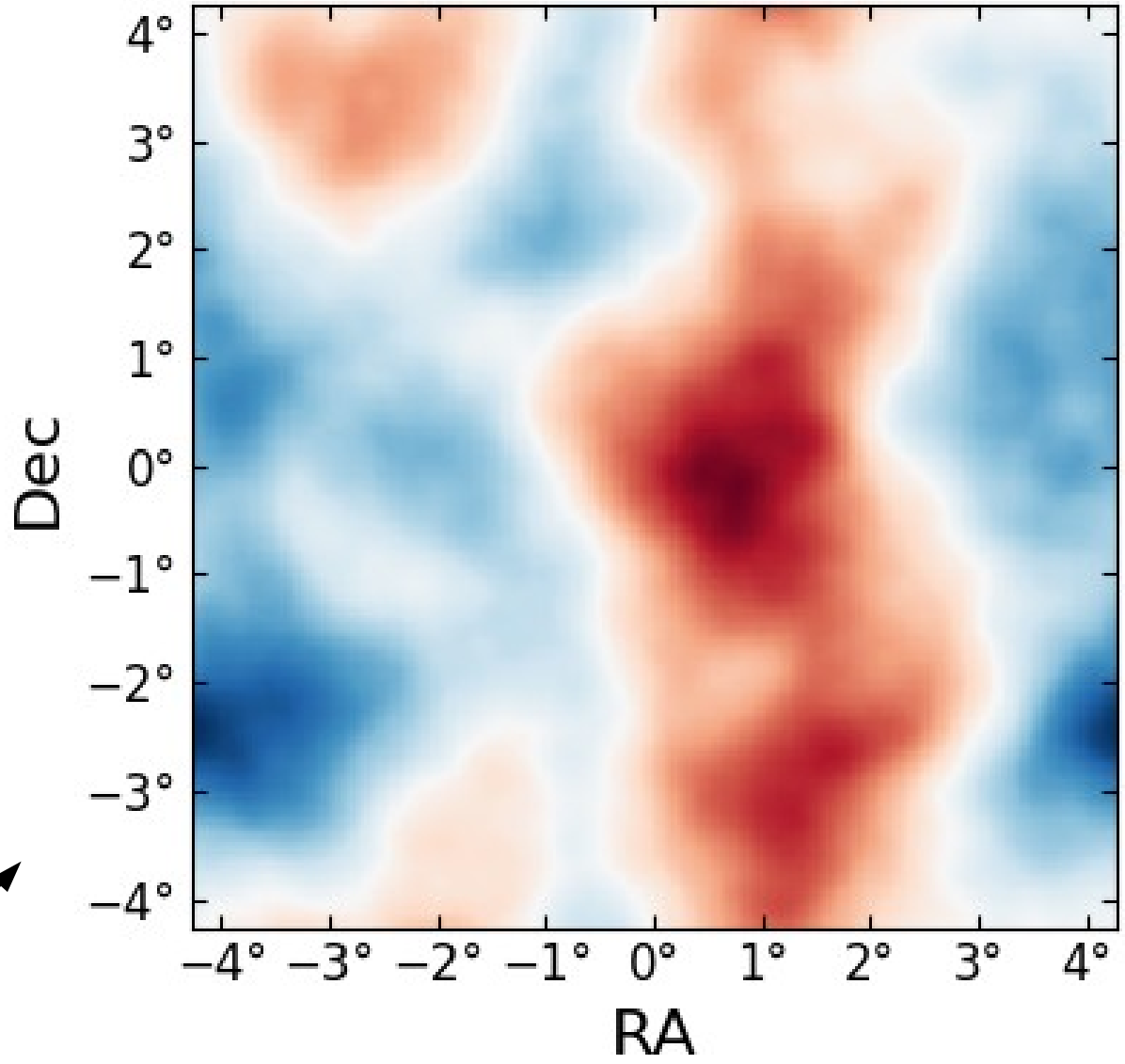
Lensing potential, ϕ, reconstructed from simulated CMB data

CMB-S4 polarization data



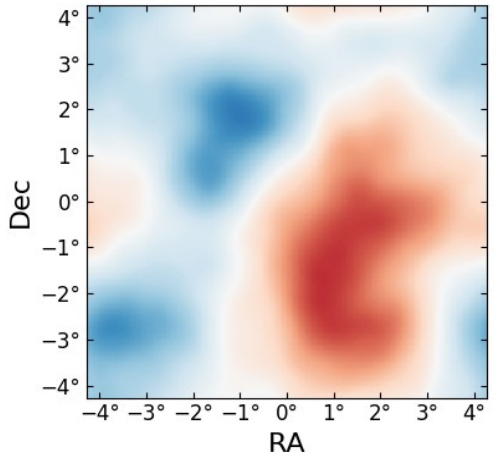
Lensing potential, ϕ, reconstructed from simulated CMB data

Simulation truth

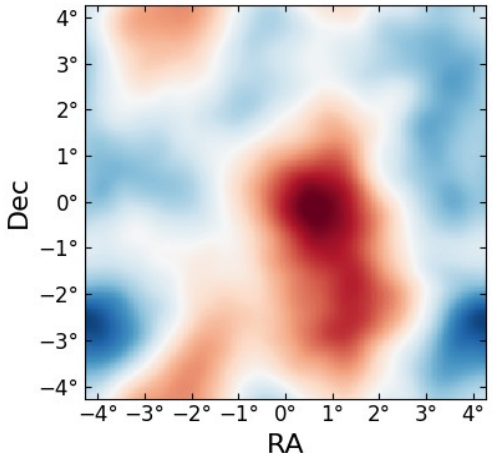


Lensing potential, ϕ, reconstructed from simulated CMB data

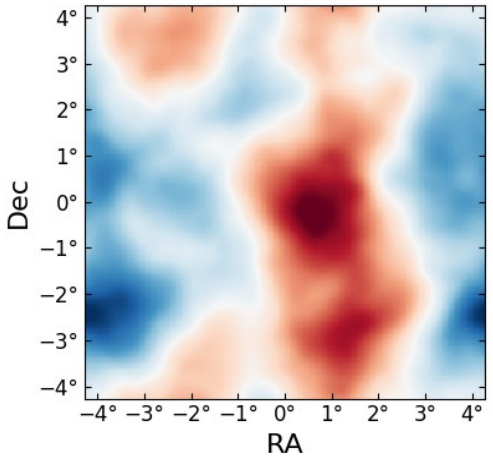
Planck



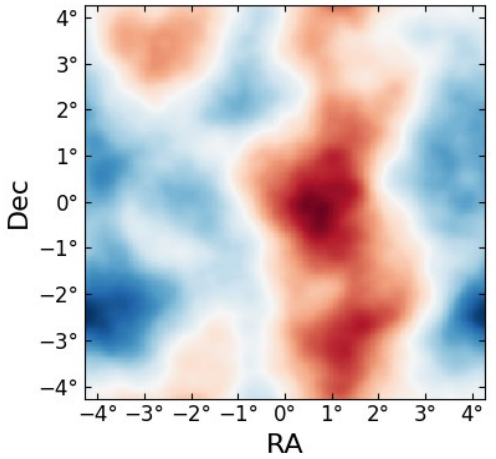
Current-gen



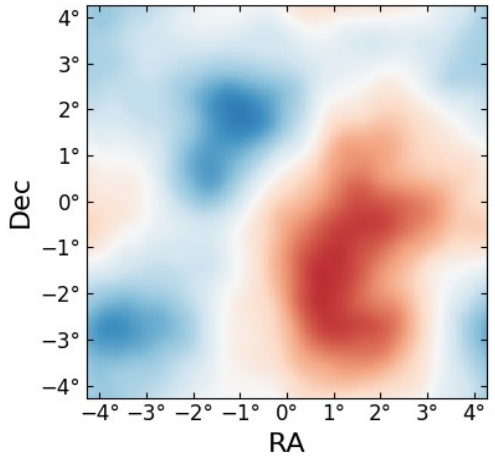
CMB-S4



Truth



Planck



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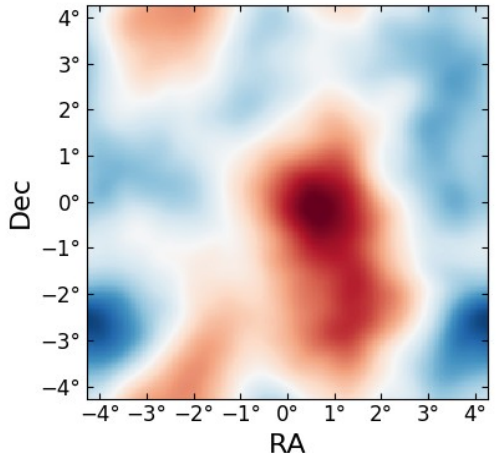
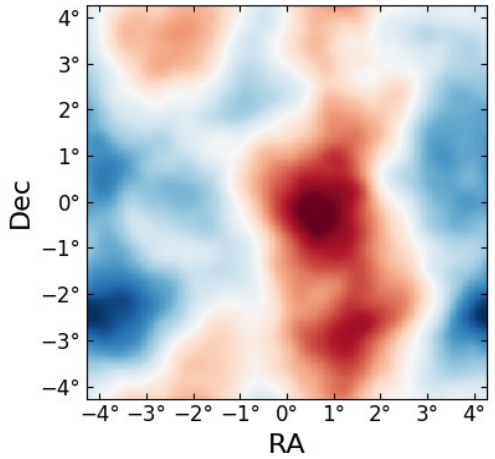
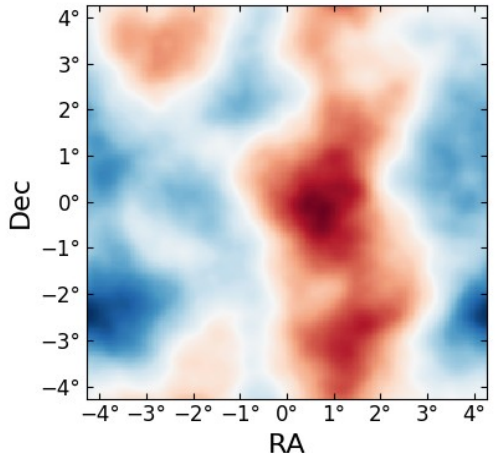


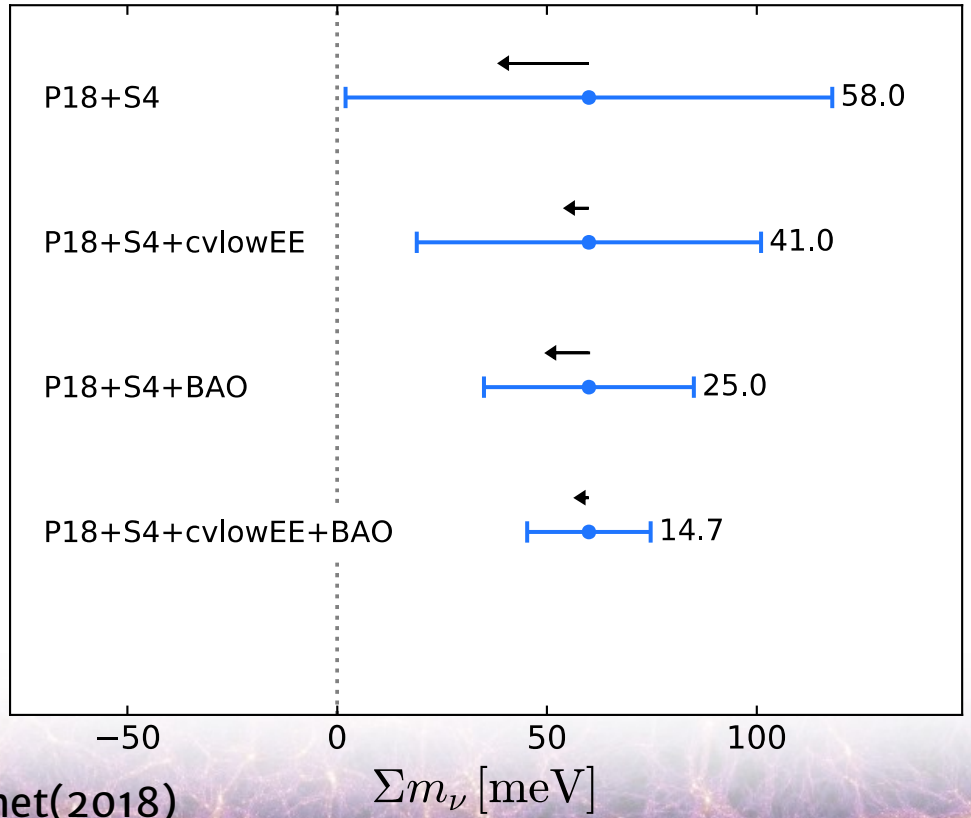
CMB-S4



Truth

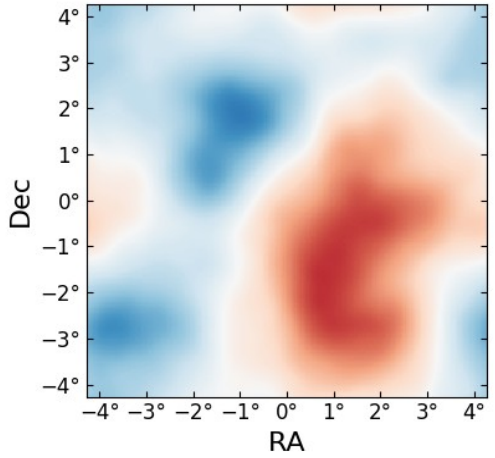


Forecasted neutrino mass constraints:

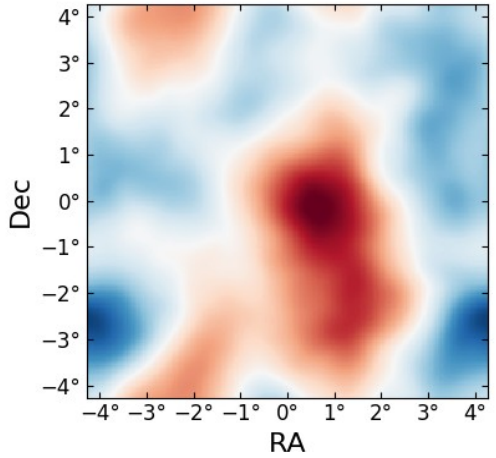


MM & Bouchet(2018)

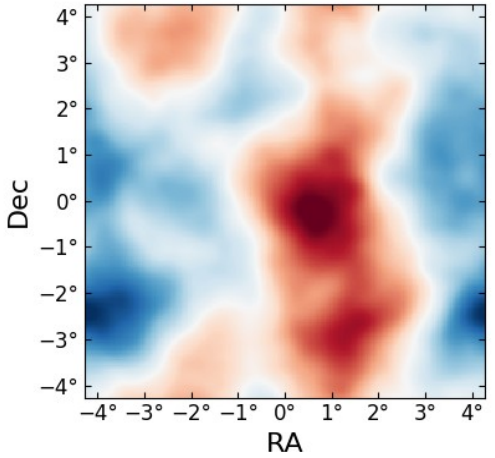
Planck



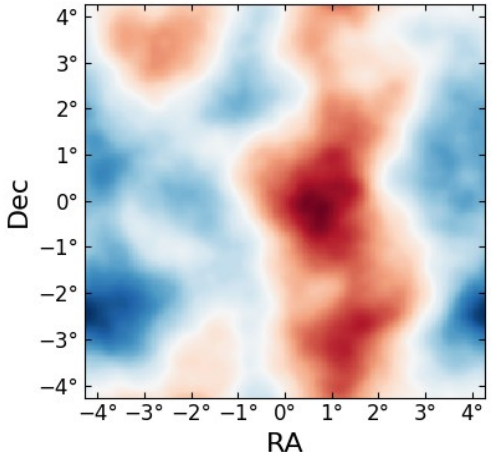
Current-gen



CMB-S4



Truth



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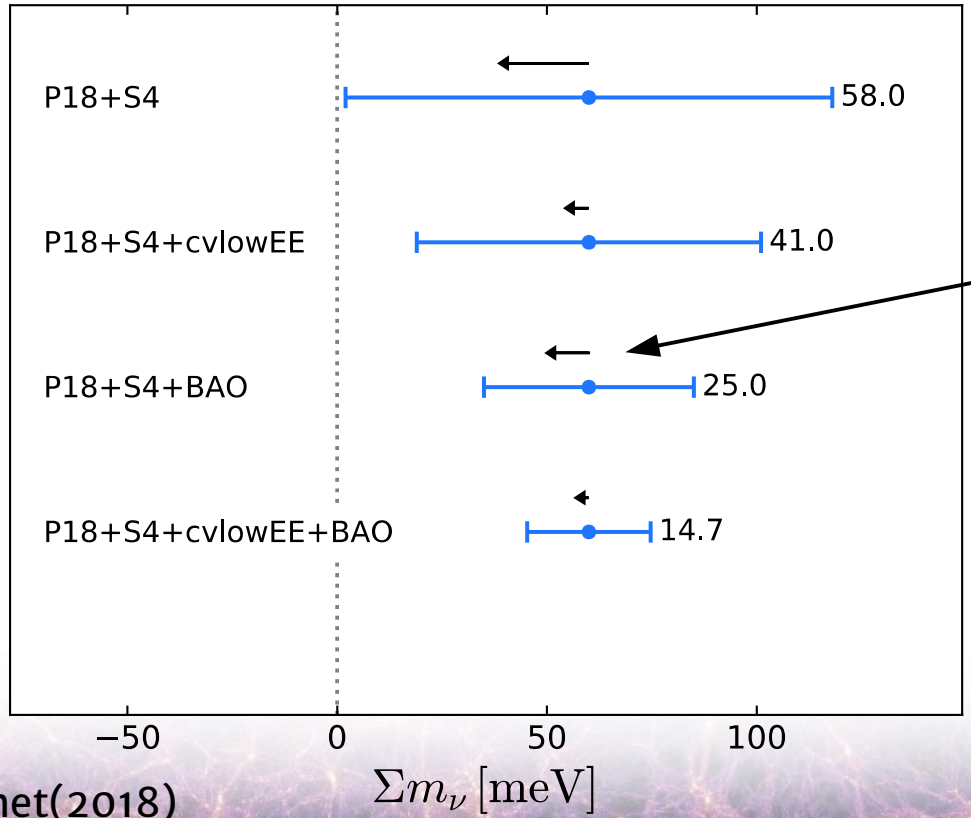

Arrows indicate uncertainty due to details of non-instantaneous reionization, which could be reduced with various external measurements.

MM & Bouchet(2018)

Cosmology

$$\Sigma m_\nu = m_1 + m_2 + m_3$$

Oscillations

$$\Delta m^2_{ij} = m^2_i - m^2_j$$

Beta-decay

$$\langle m_\beta \rangle = \sqrt{\sum_{i=1}^{3} |U_{ei}|^2 m_i}$$

Double beta-decay

$$\langle m_{\beta\beta} \rangle = \sum_{i=1}^{3} |U_{ei}|^2 m_i \epsilon_i$$

A unique and independent probe of neutrino model parameters

Cosmology

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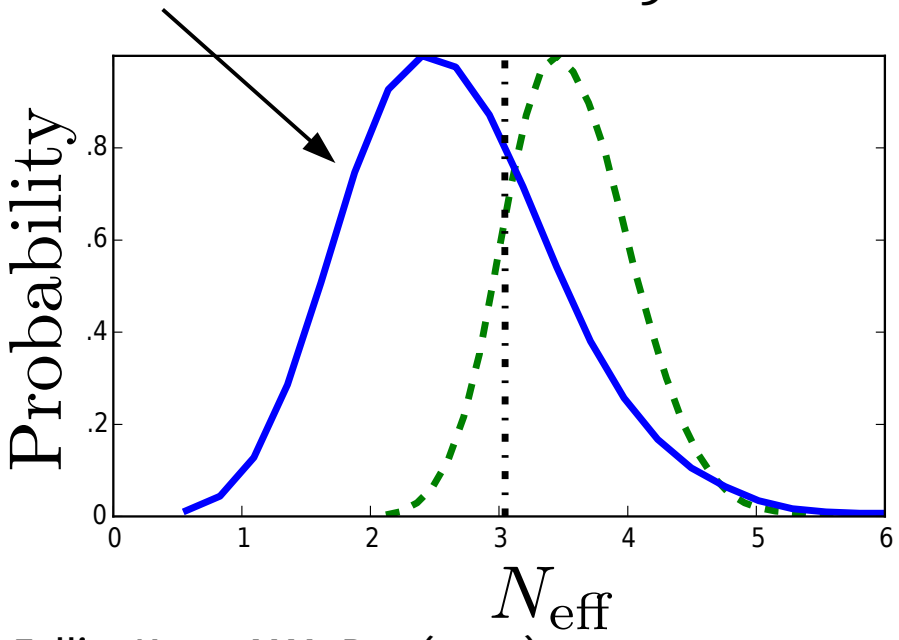
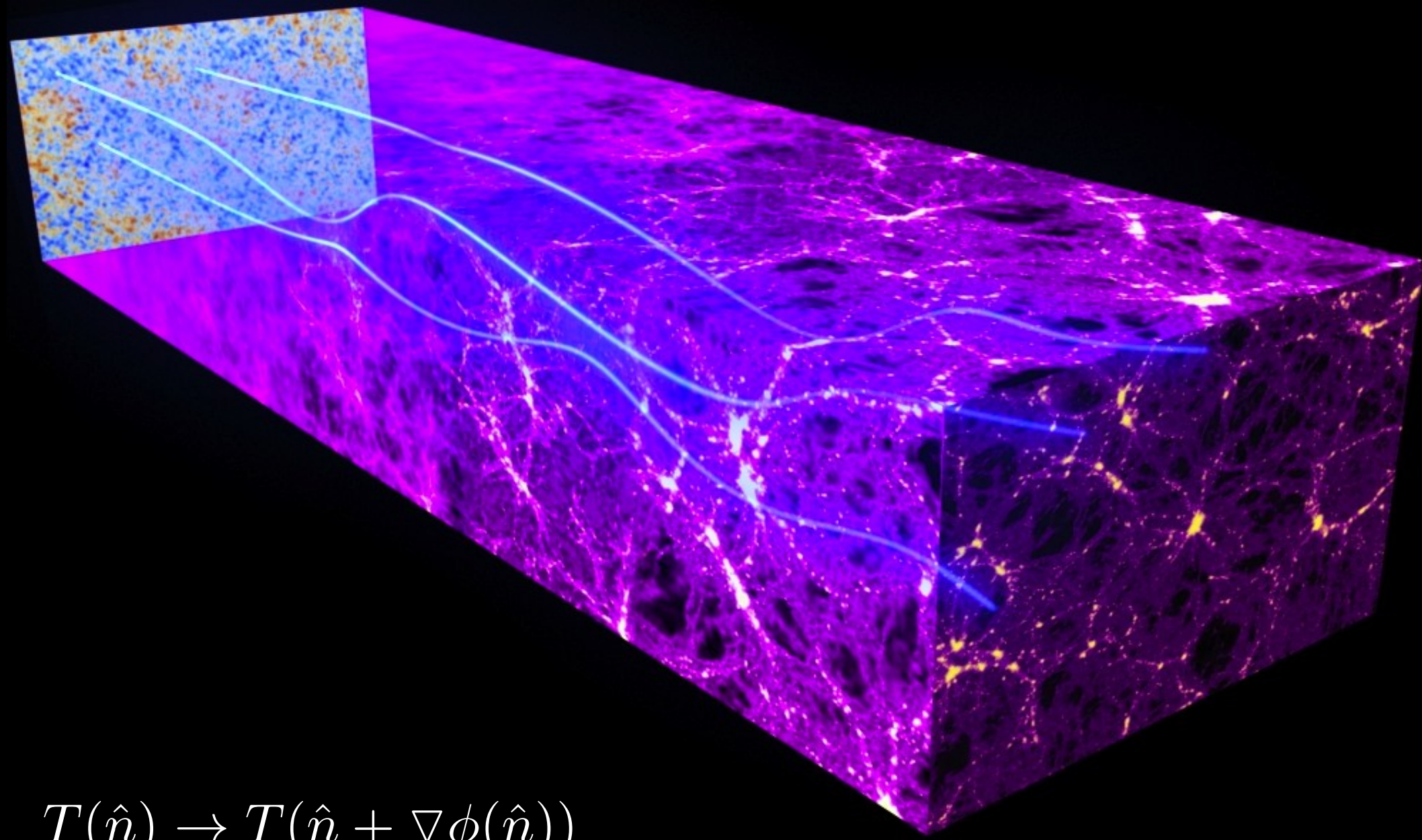
Thank you for listening!

This effect first detected in 2015 with Planck:

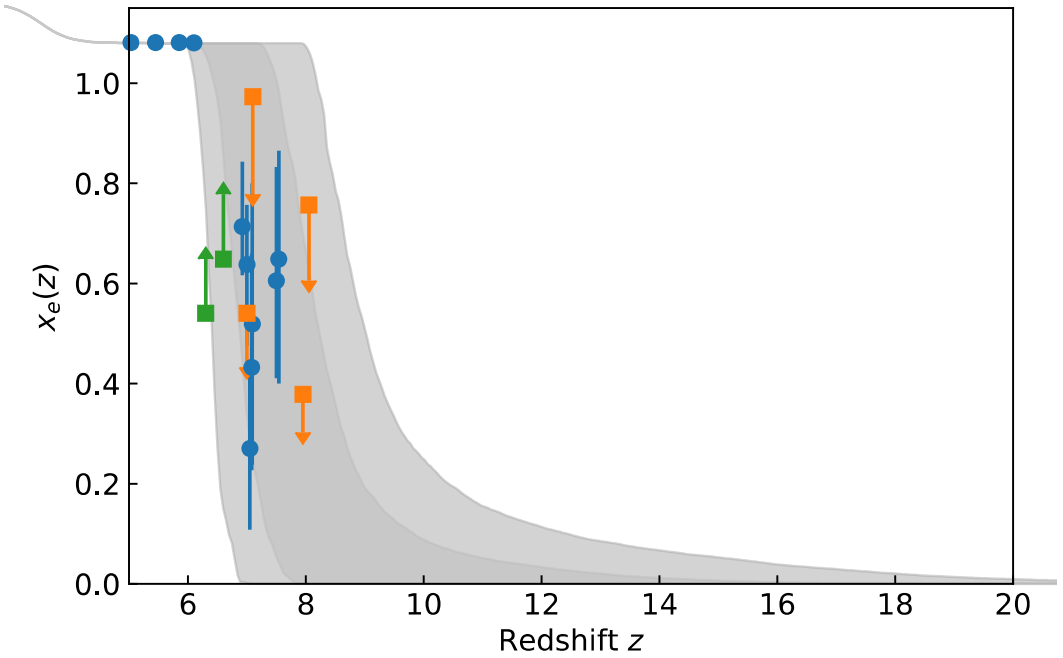


Follin, Knox, MM, Pan (2015)

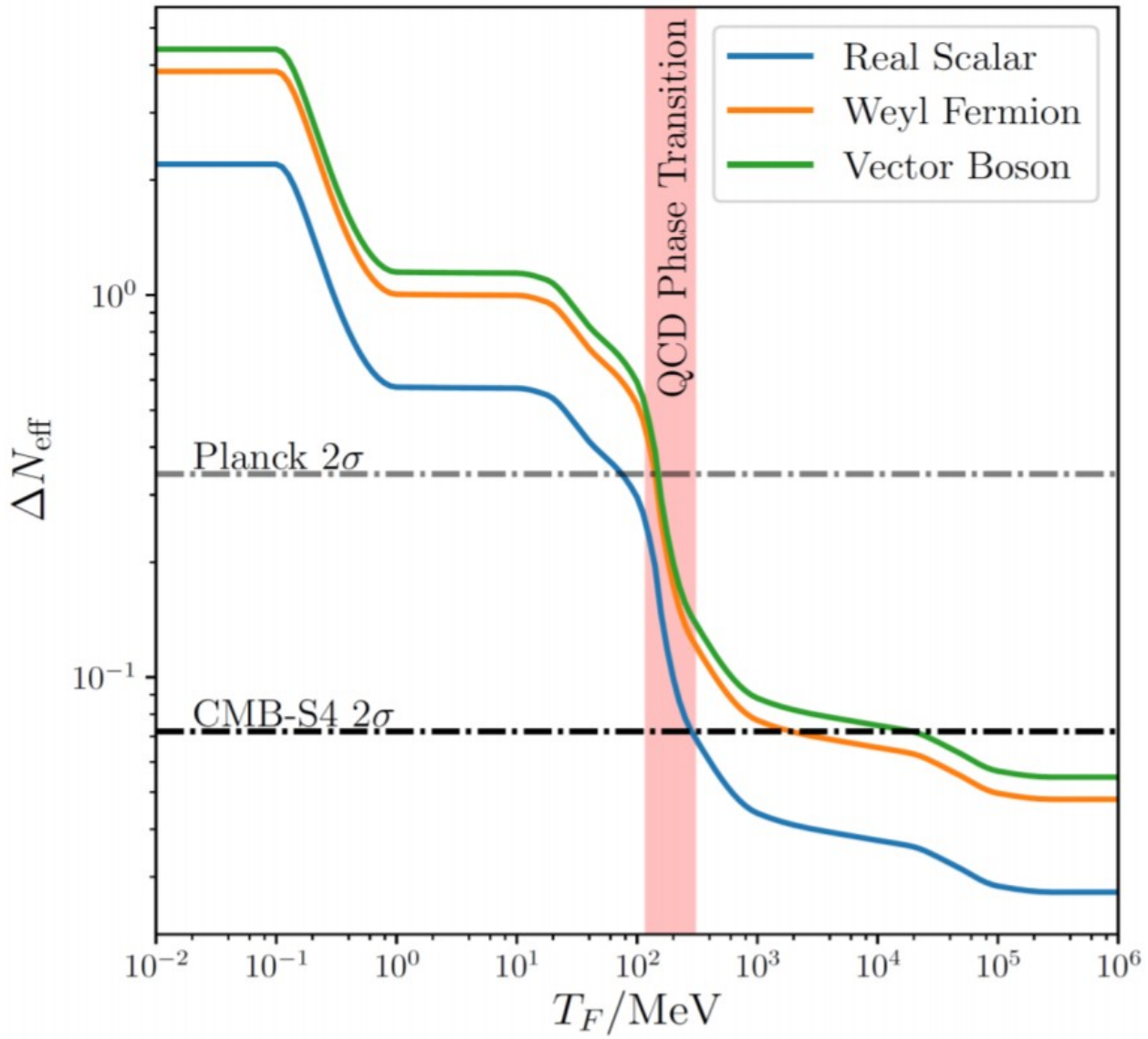


$$T(\hat{n}) \rightarrow T(\hat{n} + \nabla\phi(\hat{n}))$$

$$\phi(\hat{n}) = -2\int_0^{\chi_*} d\chi \frac{f_K(\chi_* - \chi)}{f_K(\chi_*) f_K(\chi)} \Psi(\chi\hat{n}; \eta_0 - \chi)$$


1.0
0.8
0.6
0.4
0.2
0.0
$x_e(z)$
6
8
10
12
14
16
18
20
Redshift z

Conclusions


Real Scalar
Weyl Fermion
Vector Boson
QCD Phase Transition
Planck 2σ
CMB-S4 2σ
$\Delta N_{\rm eff}$
10^0
10^{-1}
10^{-2}
10^{-1}
10^0
10^1
10^2
10^3
10^4
10^5
10^6
T_F/MeV