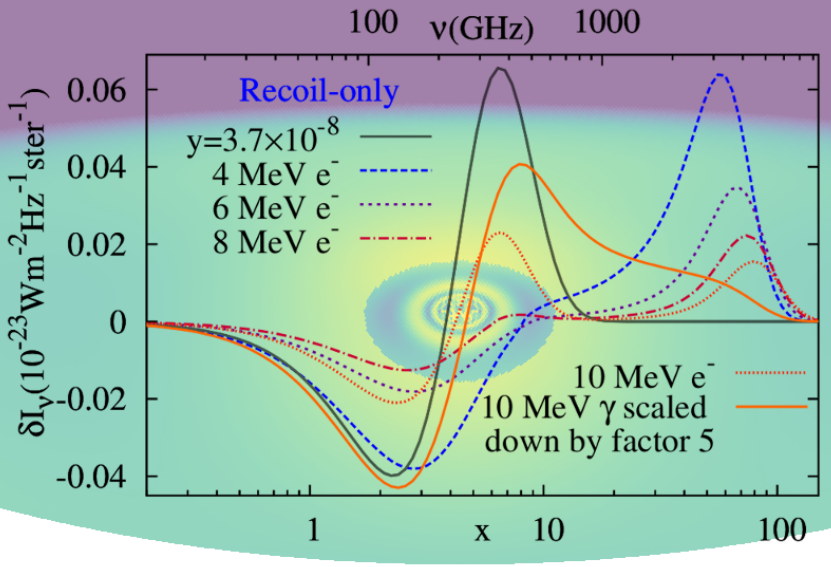
Signatures of primordial black holes and axions in the CMB

Rishi Khatri



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Signatures of axion like particles and primordial black holes in the CMB

Irrespective of whether they form a significant component of dark matter today

Signatures of axion like particles and primordial black holes in the CMB

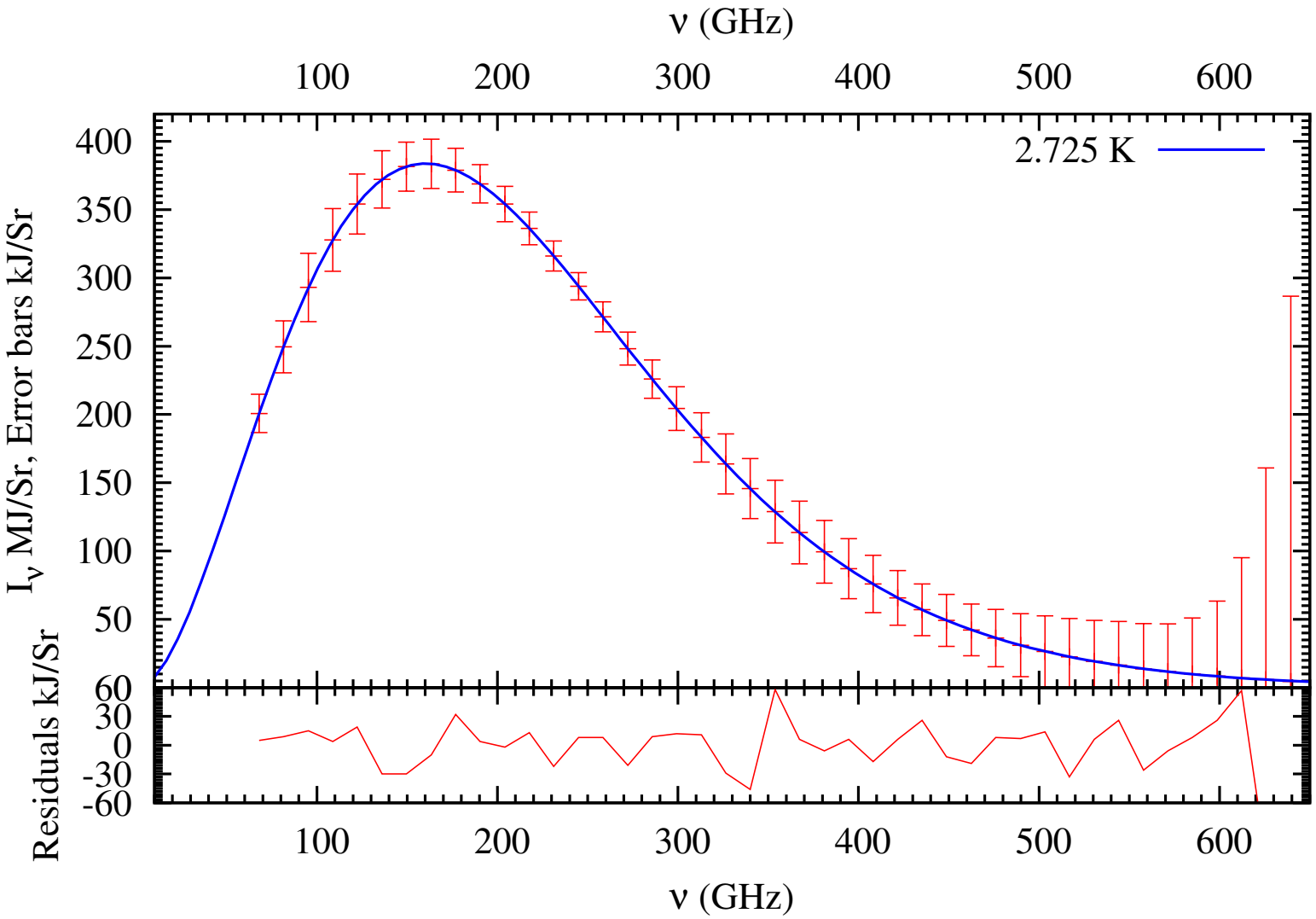
If detected $\Rightarrow$
Discovery of new fundmental physics (new fundamental particle)
Anomaly of standard cosmological model (rule out simple inflationary models)

Looking for anomalies in CMB spectrum and anisotropies
(and BBN predictions)

Standard model predicts distortions other than Sunyaev-Zeldovich effect at the level of 10^{-8} and SZ effect at level of 10^{-6}

No deviations from a Planck spectrum at $\sim 10^{-4}$

COBE-FIRAS *Fixsen et al. 1996, Fixsen and Mather 2002*



Planck and Bose-Einstein spectrum

$$I_\nu = \frac{2h\nu^3}{c^2}\frac{1}{e^{h\nu/(k_\mathrm{B}T)}-1}$$

Relativistic invariant occupation number/phase space density

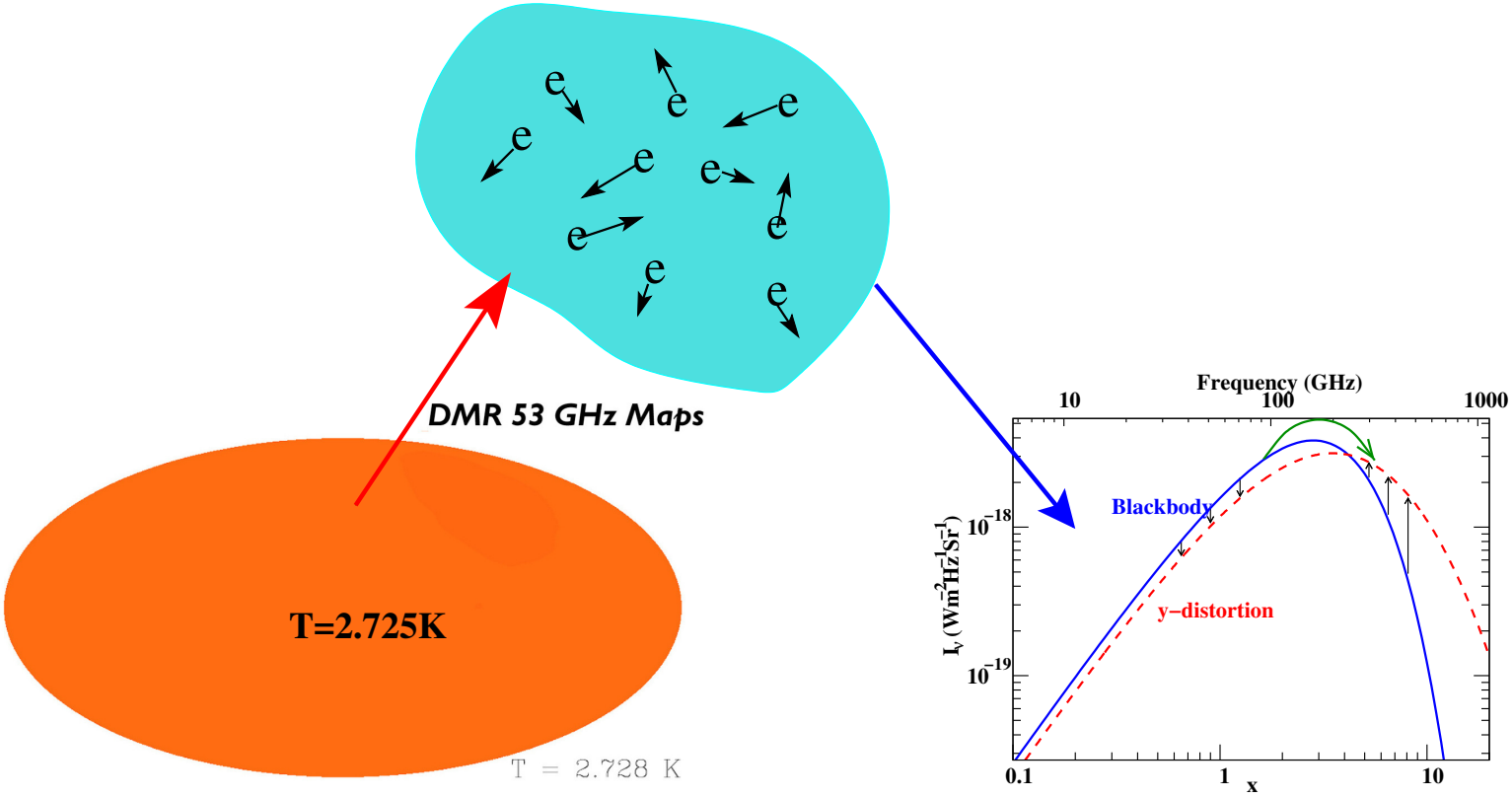
$$n(\nu) \equiv \frac{c^2}{2h\nu^3}I_\nu \quad , \quad x \equiv \frac{h\nu}{k_\mathrm{B}T}$$

$$n_\mathrm{Planck}(x) = \frac{1}{e^x-1} \quad , \quad n_\mathrm{Bose-Einstein}(x) = \frac{1}{e^{x+\mu}-1}$$

y-type (Sunyaev-Zeldovich effect) from clusters/reionization

$$y_\gamma \ll 1 \ , \ T_e \sim 10^4$$

$$y = (\tau_{\rm reionization}) \frac{k_B T_e}{m_e c^2} \sim (0.06)(1.6 \times 10^{-6}) \sim 10^{-7}$$



Efficiency of energy exchange between electrons and photons

Recoil:

$$y_\gamma = \int \mathrm{d}t c \sigma_\mathrm{T} n_\mathrm{e} \frac{k_\mathrm{B} T_\gamma}{m_\mathrm{e} c^2}, \qquad T_\gamma = 2.725(1+z)$$

Doppler effect:

$$y_e = \int \mathrm{d}t c \sigma_\mathrm{T} n_\mathrm{e} \frac{k_\mathrm{B} T_\mathrm{e}}{m_\mathrm{e} c^2}$$

In early Universe $y_\gamma \approx y_\mathrm{e}$

y: Amplitude of distortion

$$y = \int \mathrm{d}t c \sigma_\mathrm{T} n_\mathrm{e} \frac{k_\mathrm{B} \left(T_\mathrm{e} - T_\gamma\right)}{m_\mathrm{e} c^2}$$

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No. of scatterings

Doppler effect:

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No. of scatterings Energy transfer per scattering

Doppler effect:

$$y_e = \int \mathrm{d}t c \sigma_\mathrm{T} n_\mathrm{e} \frac{k_\mathrm{B} T_\mathrm{e}}{m_\mathrm{e} c^2}$$

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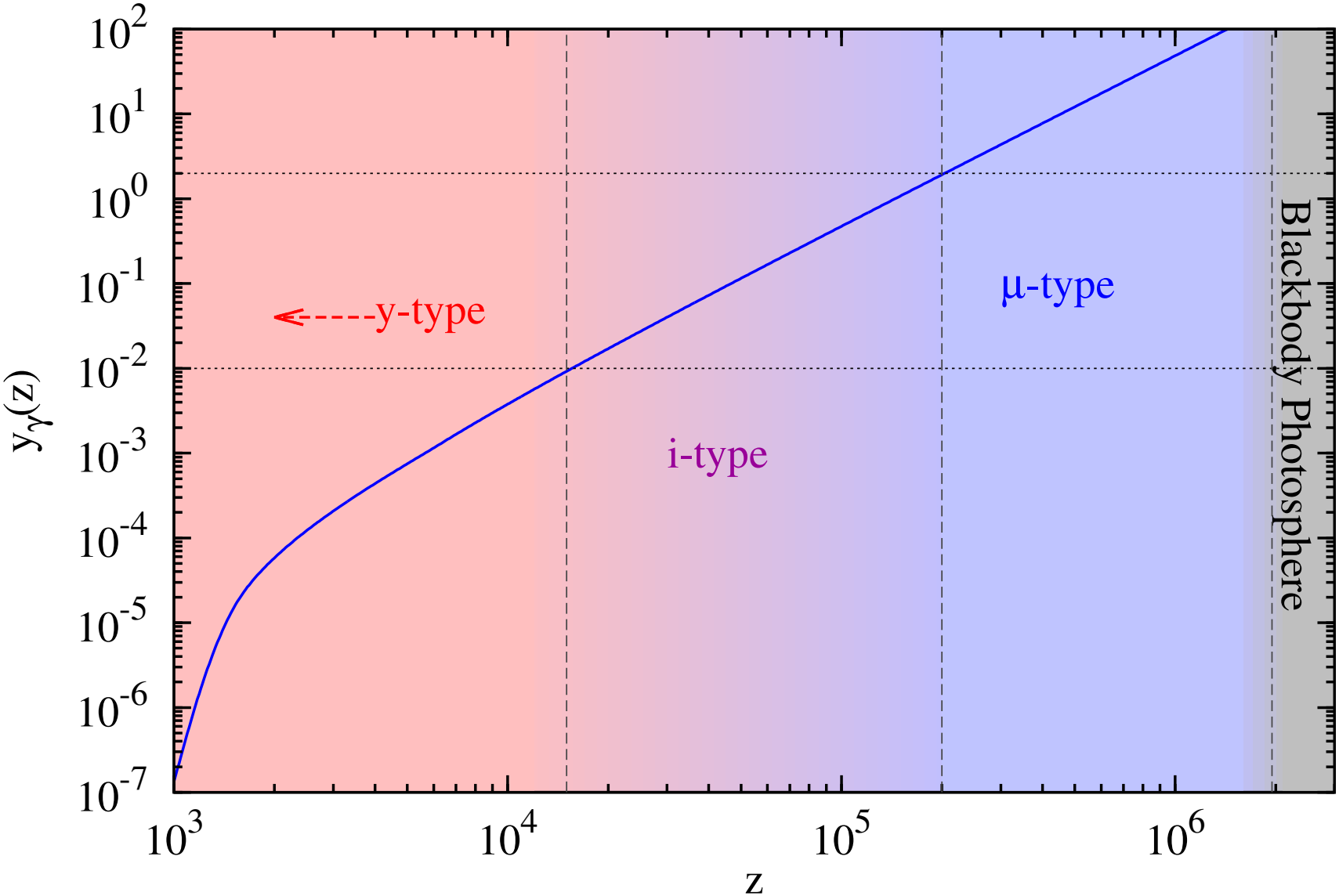
Expect rich structure of spectral distortions at $z \lesssim 10^5$

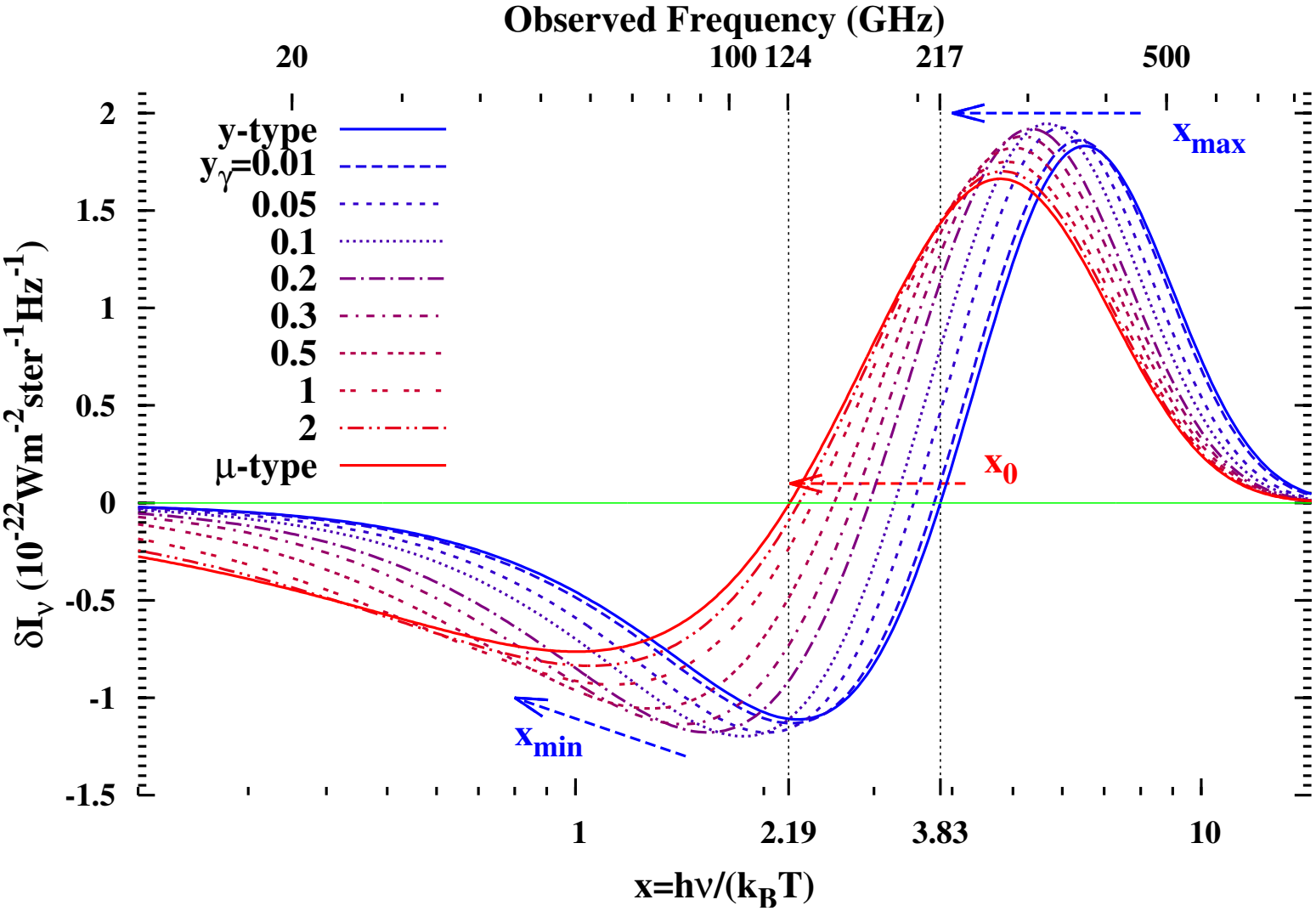
(Khatri and Sunyaev 2012, arXiv:1207.6654)



Intermediate-type distortions *(Khatri and Sunyaev 2012)*

Solve Kompaneets equation with initial condition of $y-$type solution.

$$\frac{\partial n}{\partial y_\gamma} = \frac{1}{x^2}\frac{\partial}{\partial x}x^4\left(n+n^2+\frac{T_e}{T}\frac{\partial n}{\partial x}\right), \quad \frac{T_e}{T} = \frac{\int (n+n^2)x^4 dx}{4\int n x^3 dx}$$

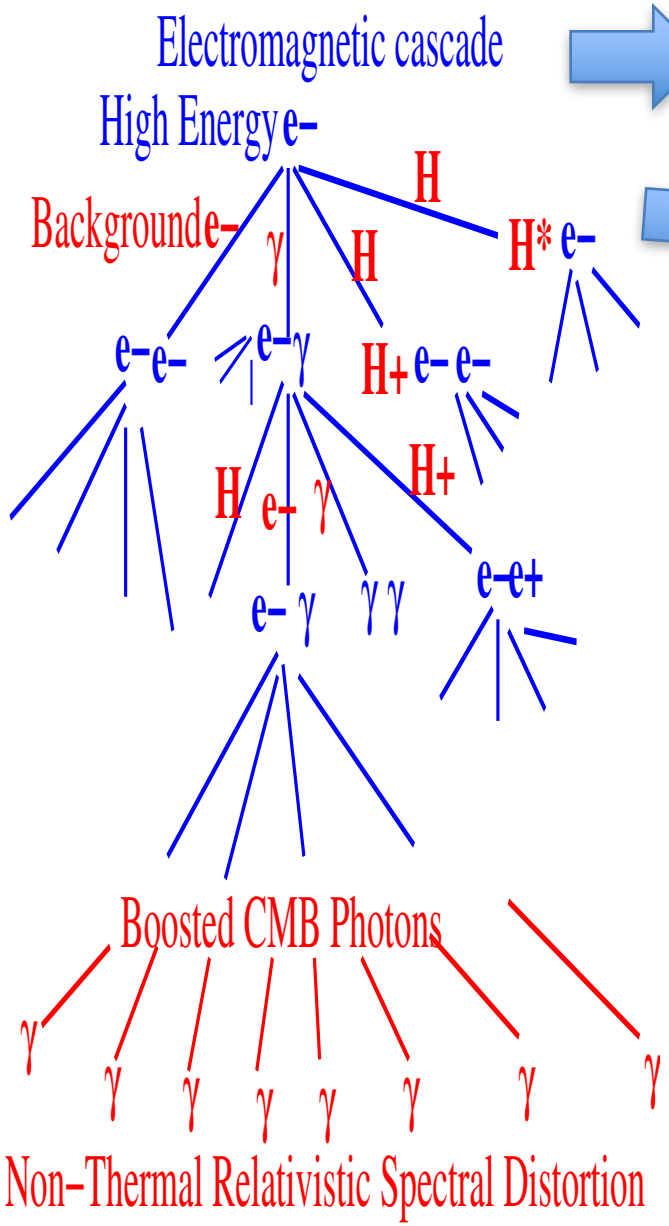


y and i-type distortions are non-relativistic solutions

Many processes in the early Universe inject relativistic particles. So far these have been studied assuming non-relativistic y-type distortions.

- Particle decay: $\frac{dQ}{dz} \propto \frac{e^{-\left(\frac{1+z_{\rm decay}}{1+z}\right)^2}}{(1+z)^4}$
  (Hu and Silk 1993, Chluba and Sunyaev 2012, Khatri and Sunyaev 2012a, 2012b)
- Cosmic strings: $\frac{dQ}{dz} \propto$ constant
  Tashiro, Sabancilar, Vachaspati 2012
- Primordial Black holes (PBH): Depends on the mass function
  Tashiro and Sugiyama 2008, Carr et al. 2010
  $\rightarrow$ non-trivial new physics during inflation to create $\mathcal{O}(1)$ fluctuations necessary to produce PBH

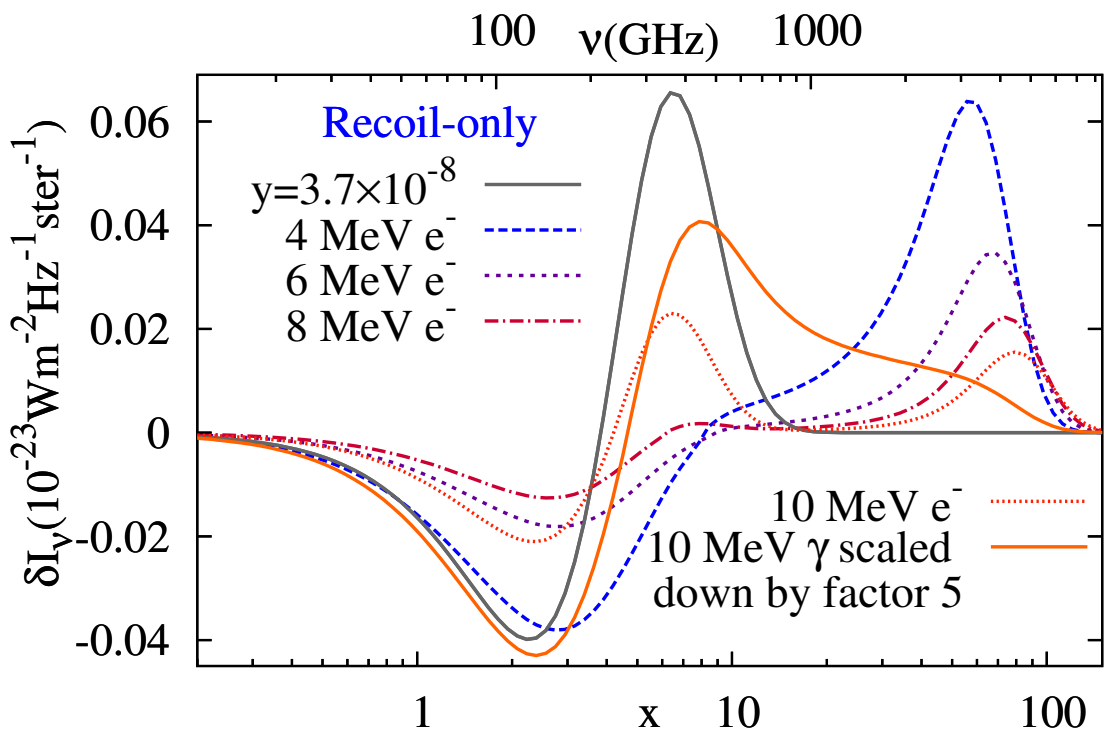
Rich information in CMB spectral distortions



Heating

Non-relativistic Compton Scattering

Spectral distortions

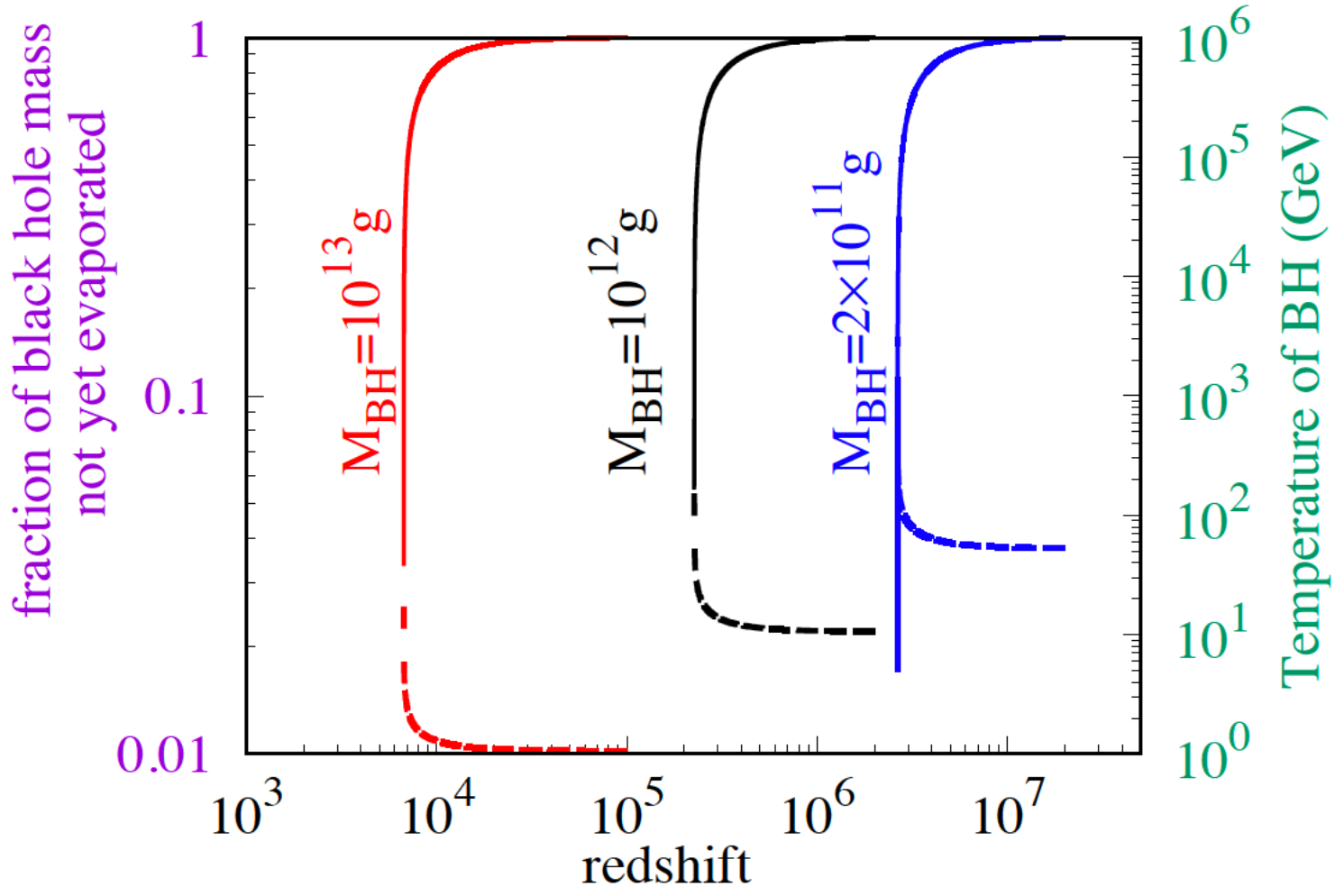


Acharya & Khatri 2019

PBH evaporating between BBN and recombination will inject relativistic particles

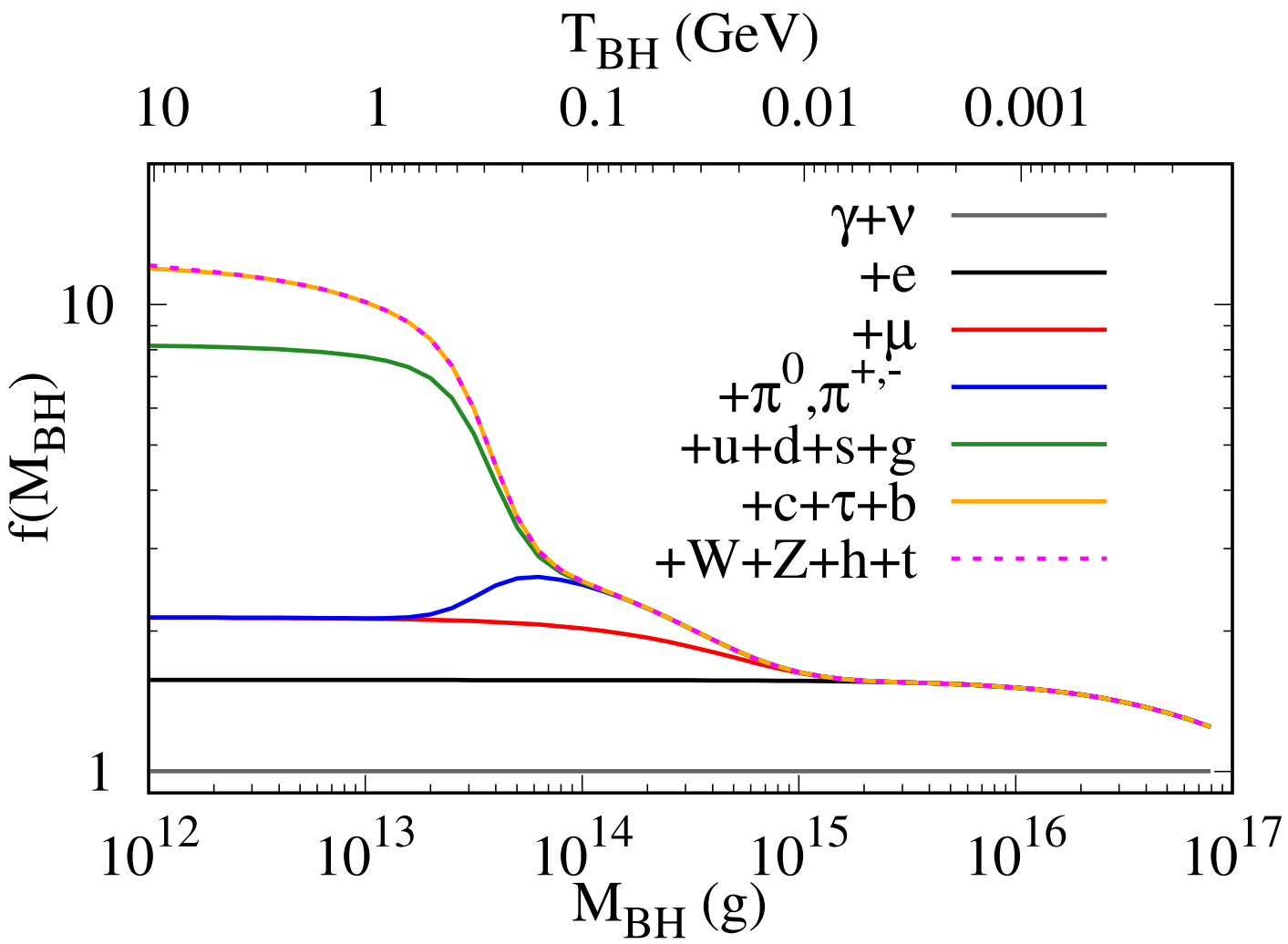
Non-relativistic solutions are not applicable

Acharya & Khatri 2020, arXiv:1912.10995



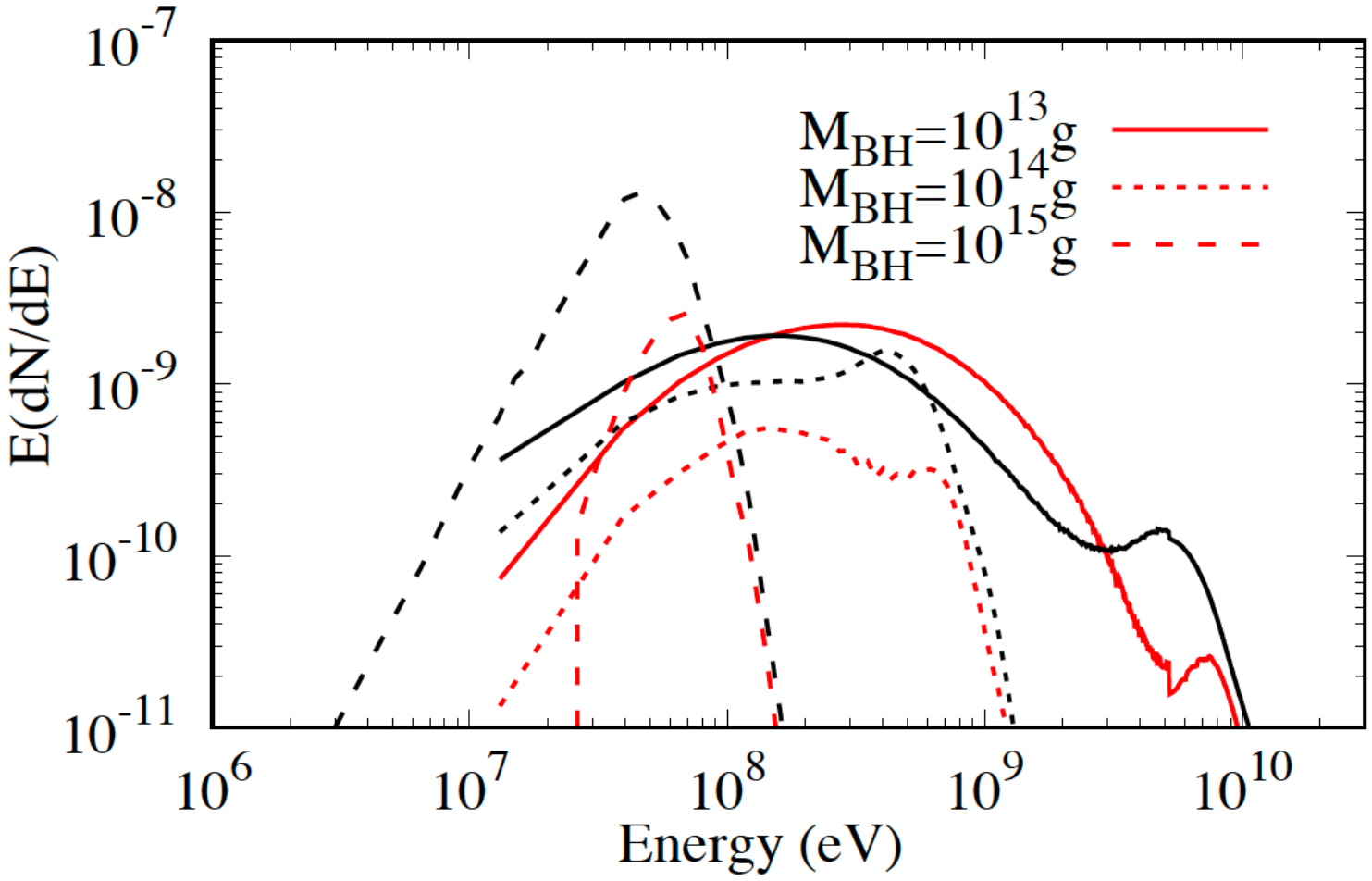
Primordial black holes can emit all standard model particles if they are hot enough

Acharya and Khatri 2020, arXiv:2002.00898



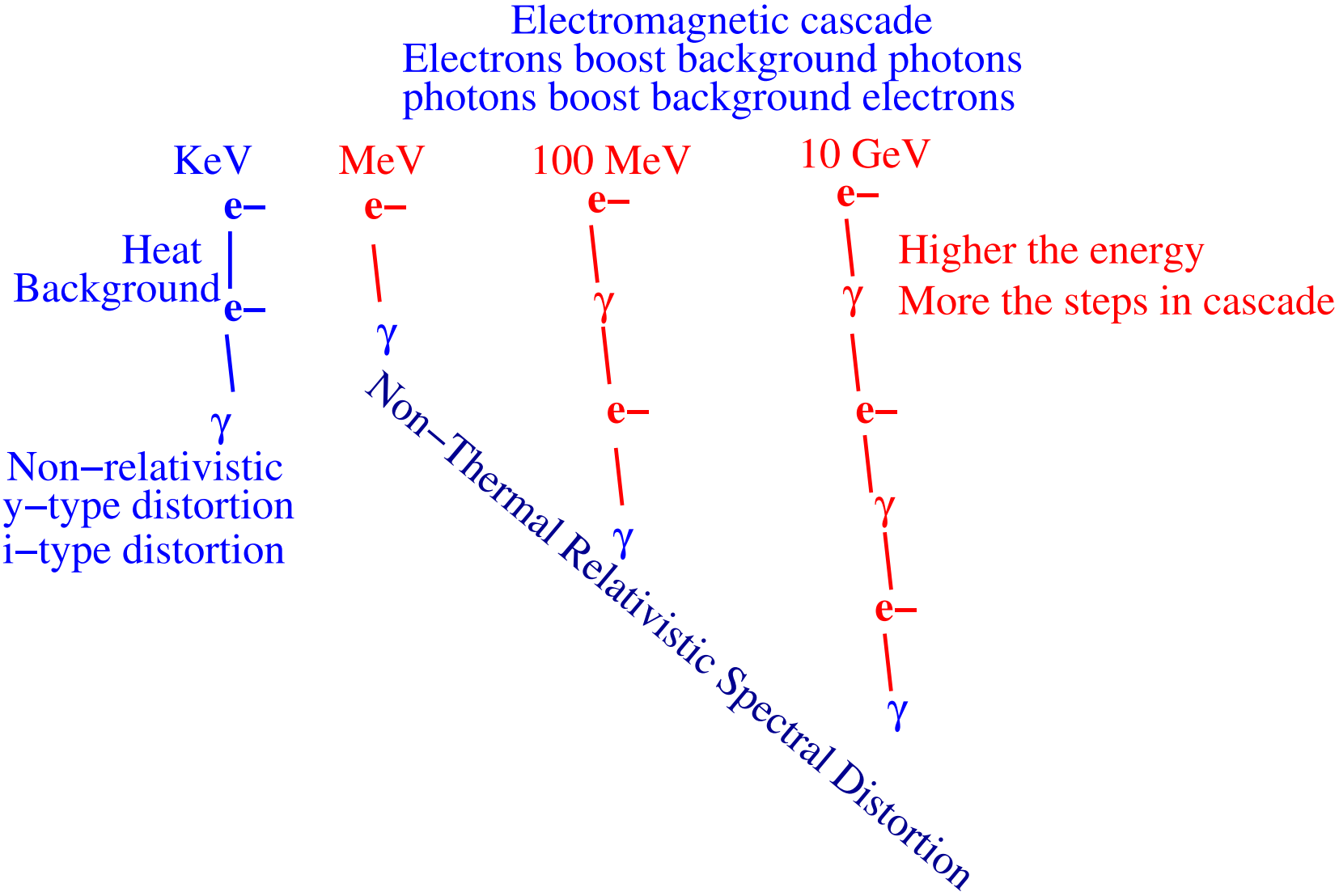
Broad spectrum of high energy electrons, positrons and photons after hadronization and decay of unstable particles triggers particle cascade

Acharya and Khatri 2020, arXiv:2002.00898



Particle cascades ⇒ Non-Thermal Relativistic Distortions (ntr-type)

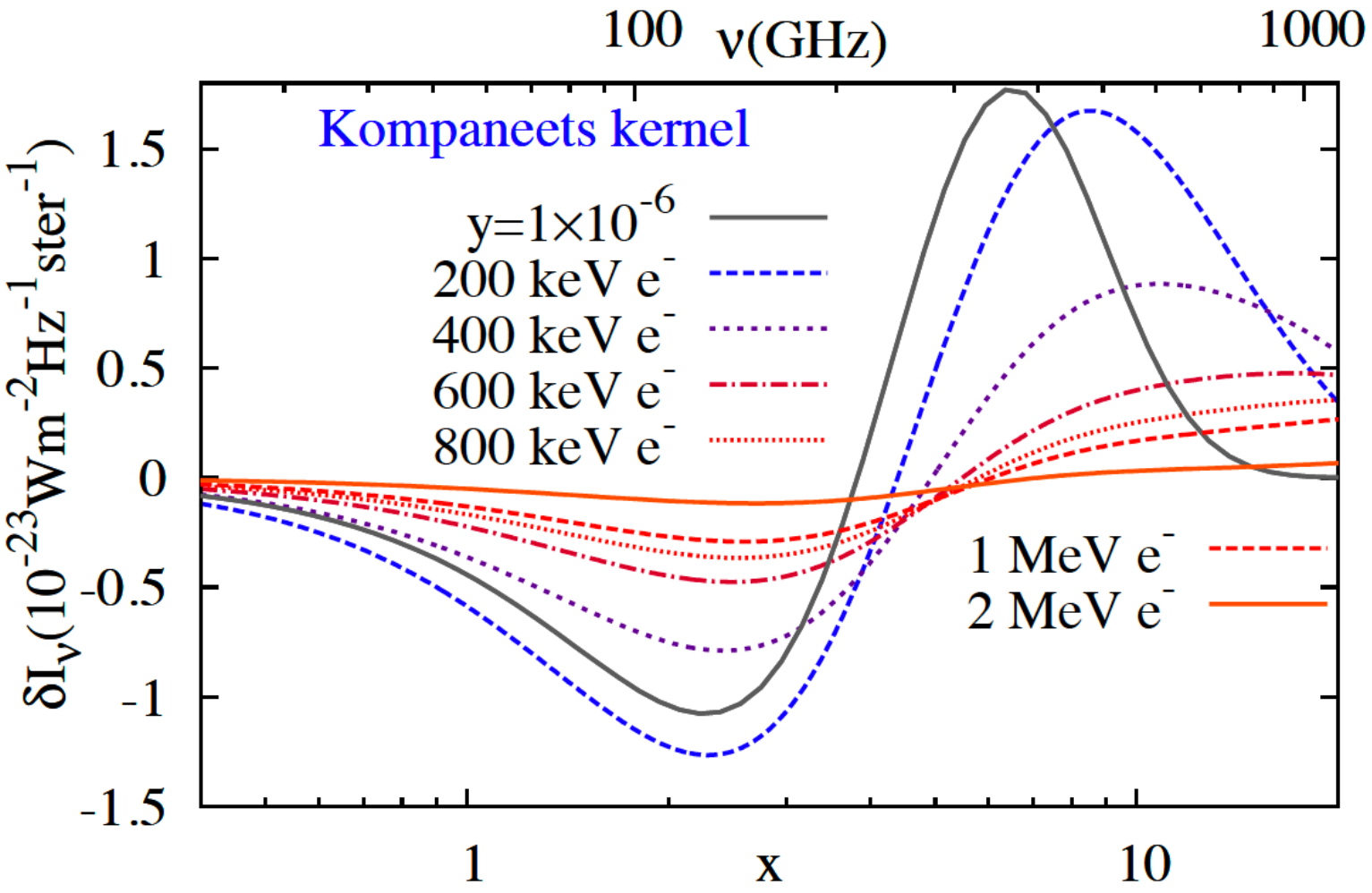
(Acharya & Khatri 2019, arXiv:1808.02897)



Rich structure of ntr-type CMB spectral distortions

electron injection at $z = 20000$

Acharya & Khatri 2019, arXiv:1808.02897



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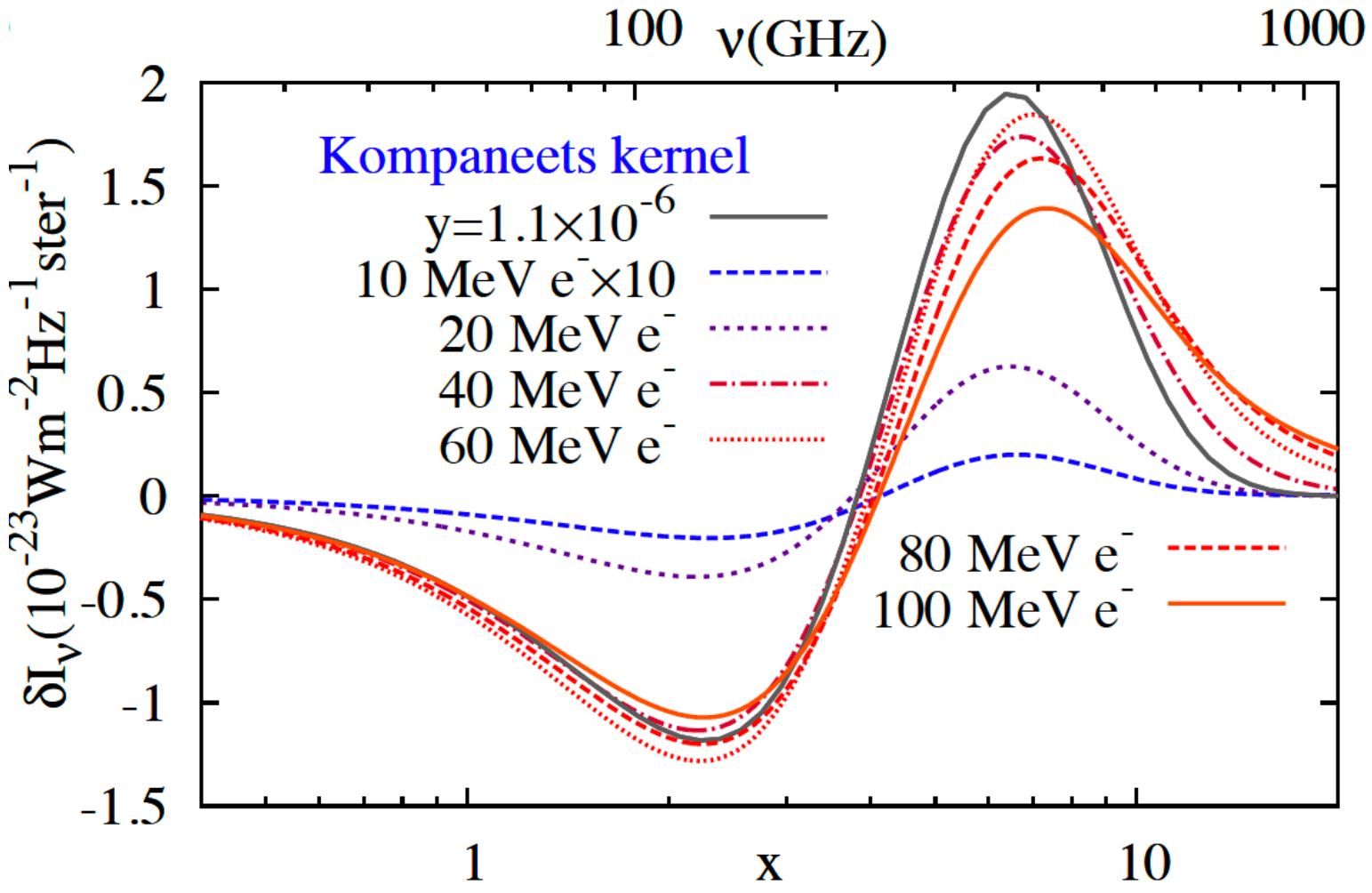
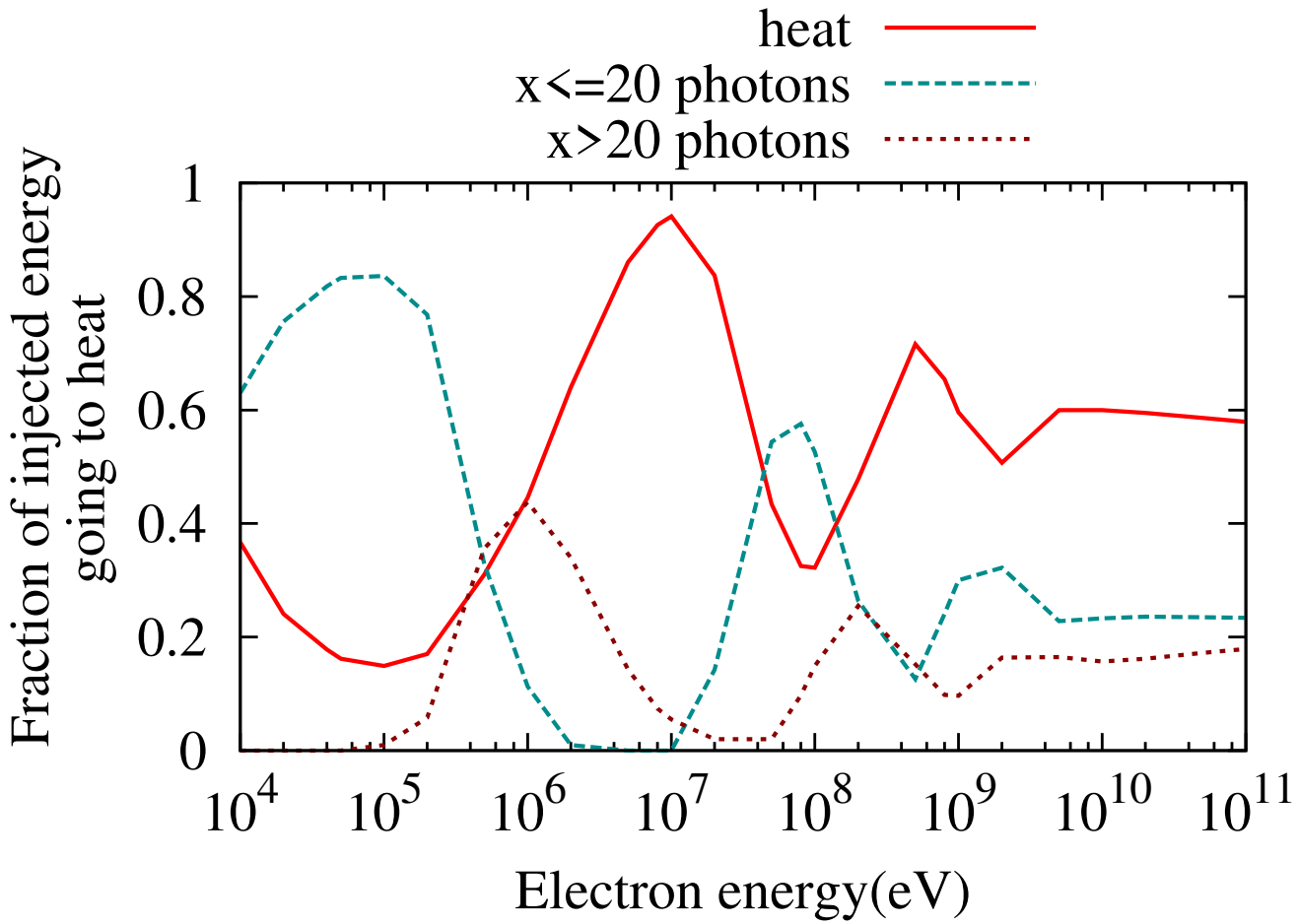


Fraction of energy going into spectral distortions is a function of energy *Acharya & Khatri 2019, arXiv:1808.02897*

Heat $\rightarrow$ non-relativistic y-type distortions (SZ effect)

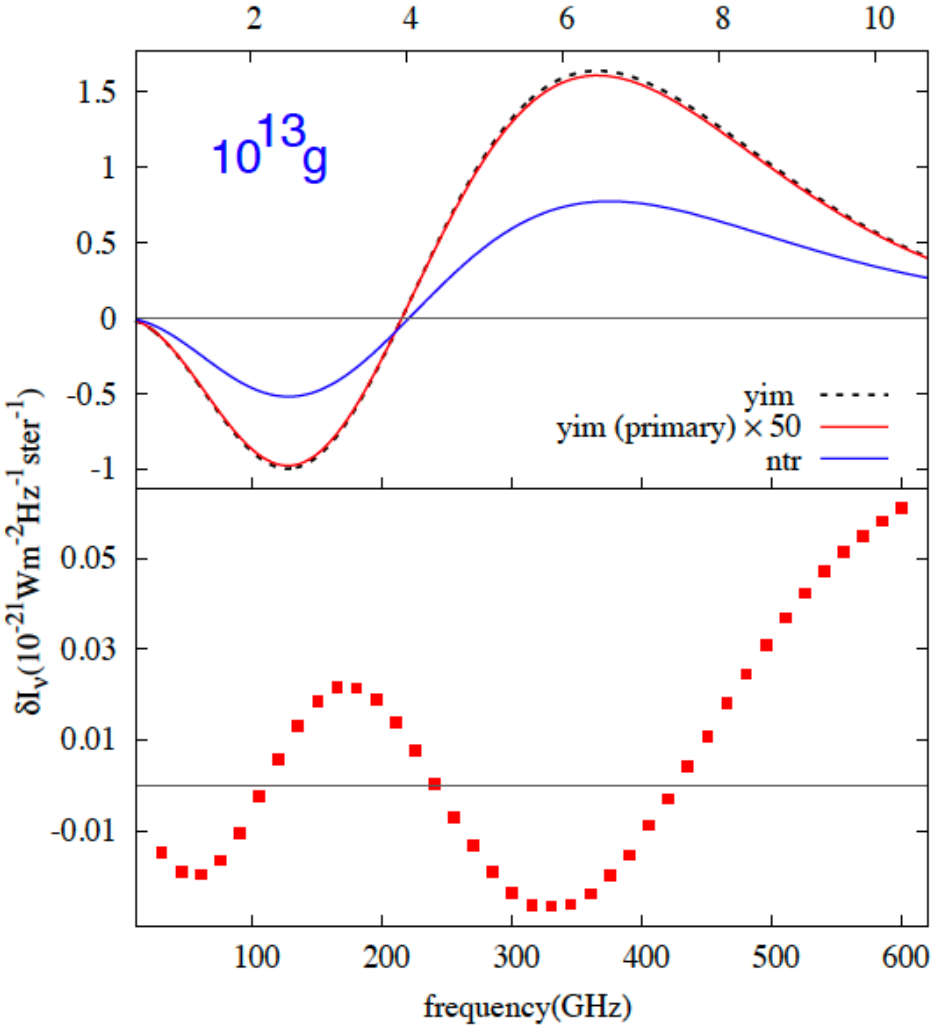
$x <= 20 \rightarrow$ non-thermal relativistic distortion (ntr-type)

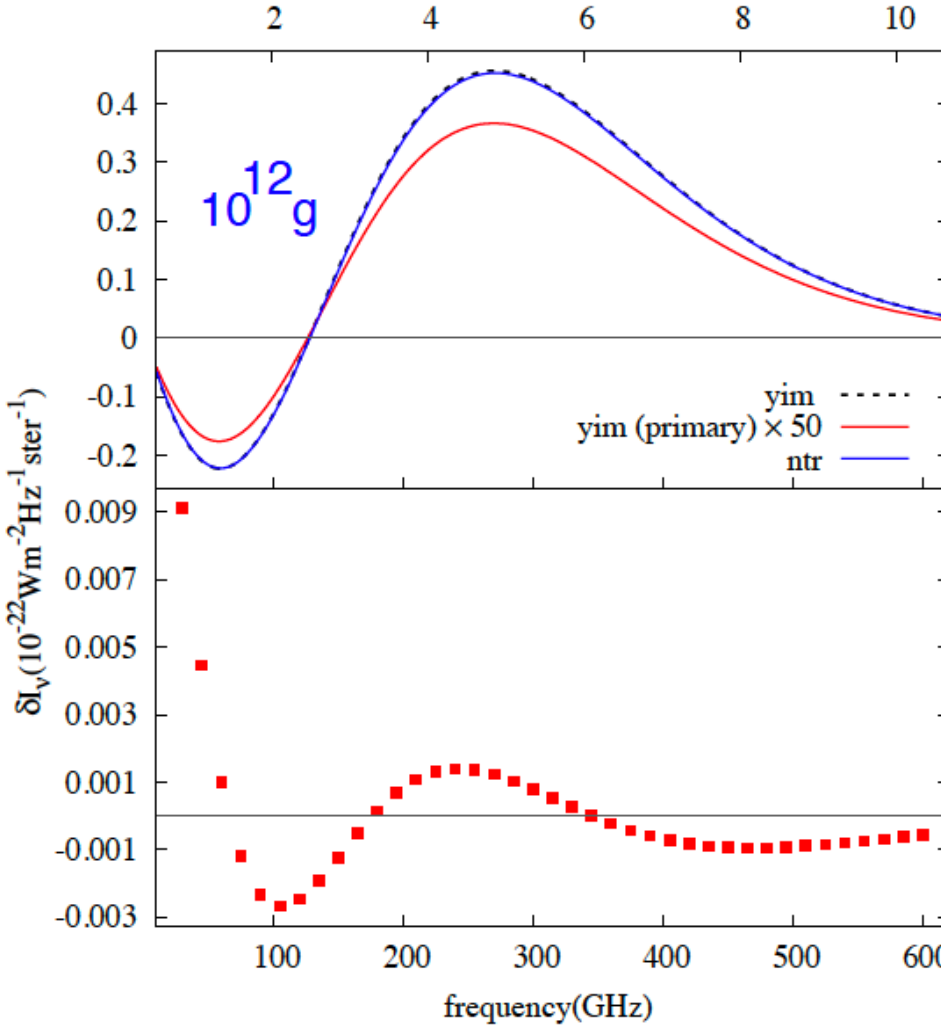
$x > 20 \rightarrow$ unobservable



CMB spectral distortions from primordial black holes

Acharya & Khatri 2020, arXiv:1912.10995

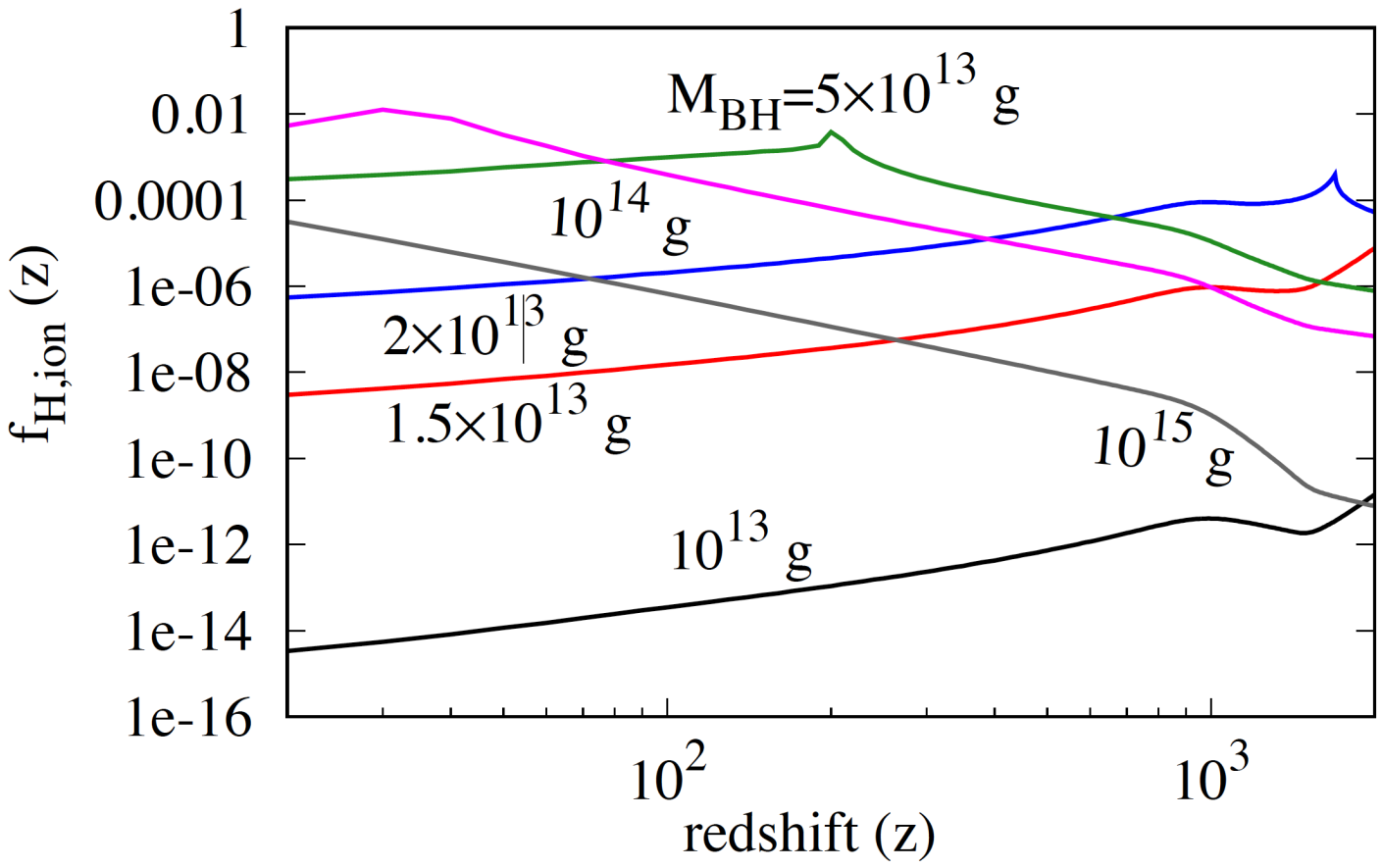


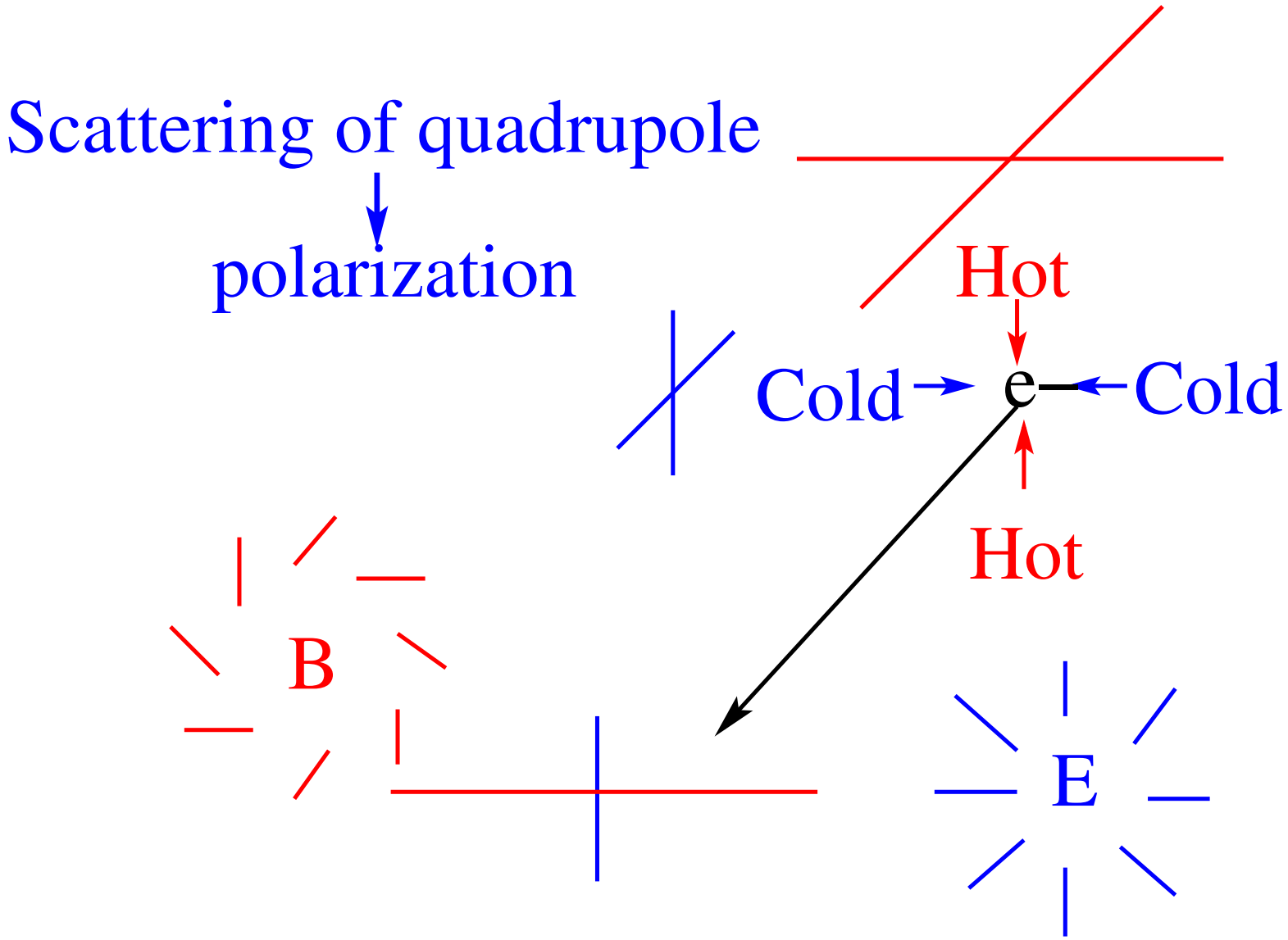


Energy injection changes the recombination history/residual electron fraction after recombination

Acharya and Khatri 2020, arXiv:2002.00898

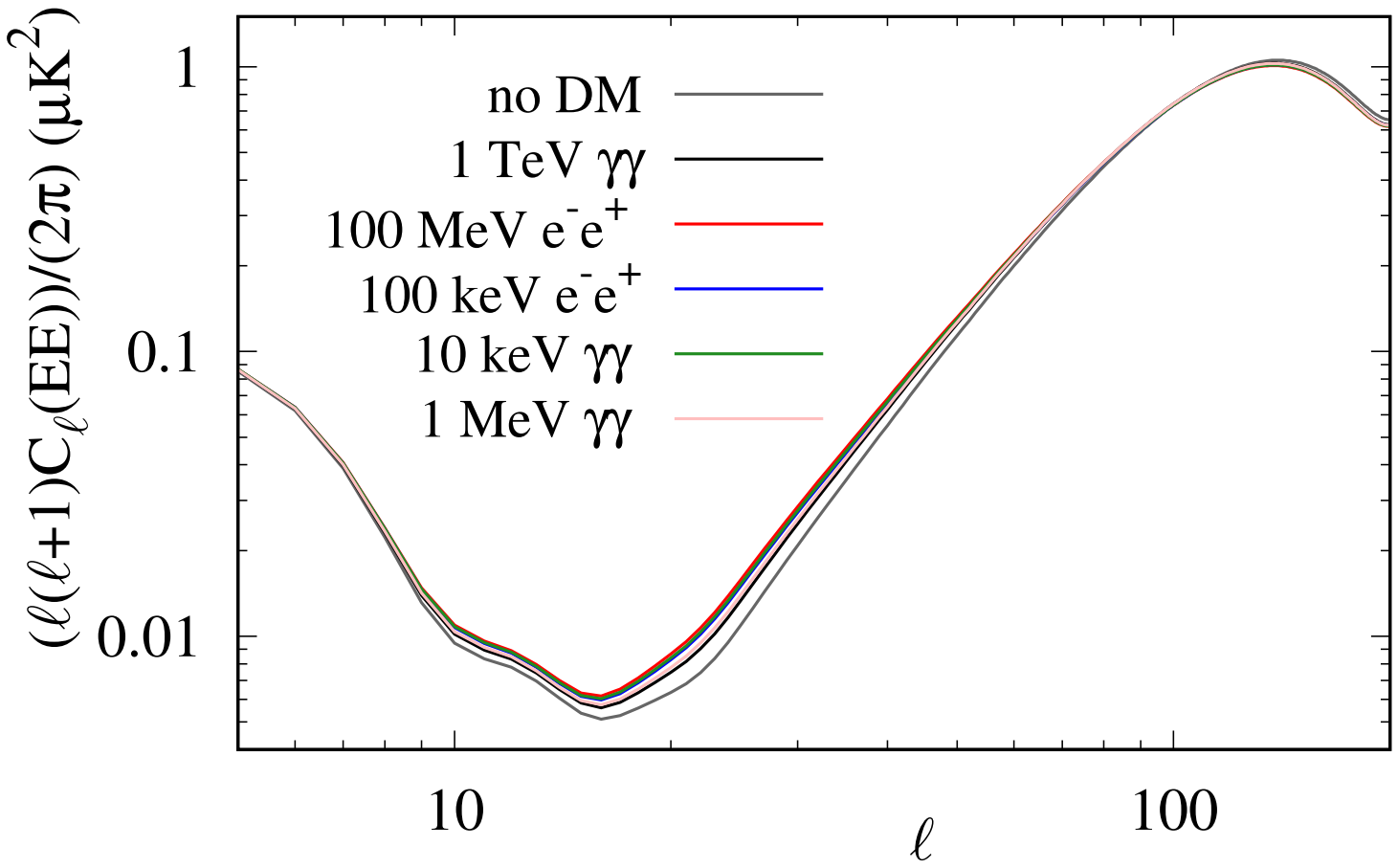
fraction of injected energy going into ionization of hydrogen




Scattering of quadrupole
polarization
Hot
Cold
e
Cold
Hot
B
E

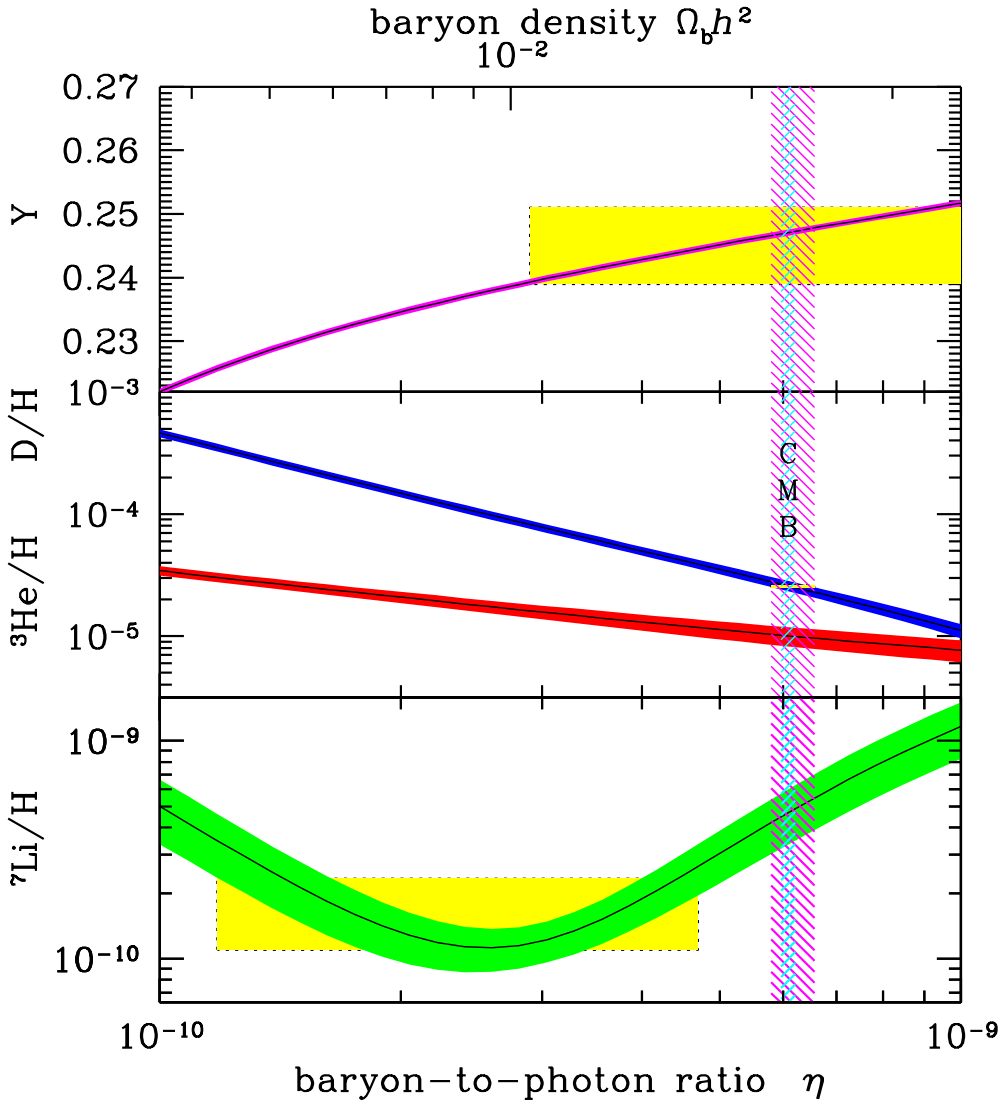
CMB E-mode polarization is enhanced from extra scatterings

Acharya and Khatri 2019, arXiv:1910.06272



Big bang nucleosynthesis

Fields, Molaro and Sarkar 2019, Particle Data Group



High energy photons can dissociate light elements produced in the BBN

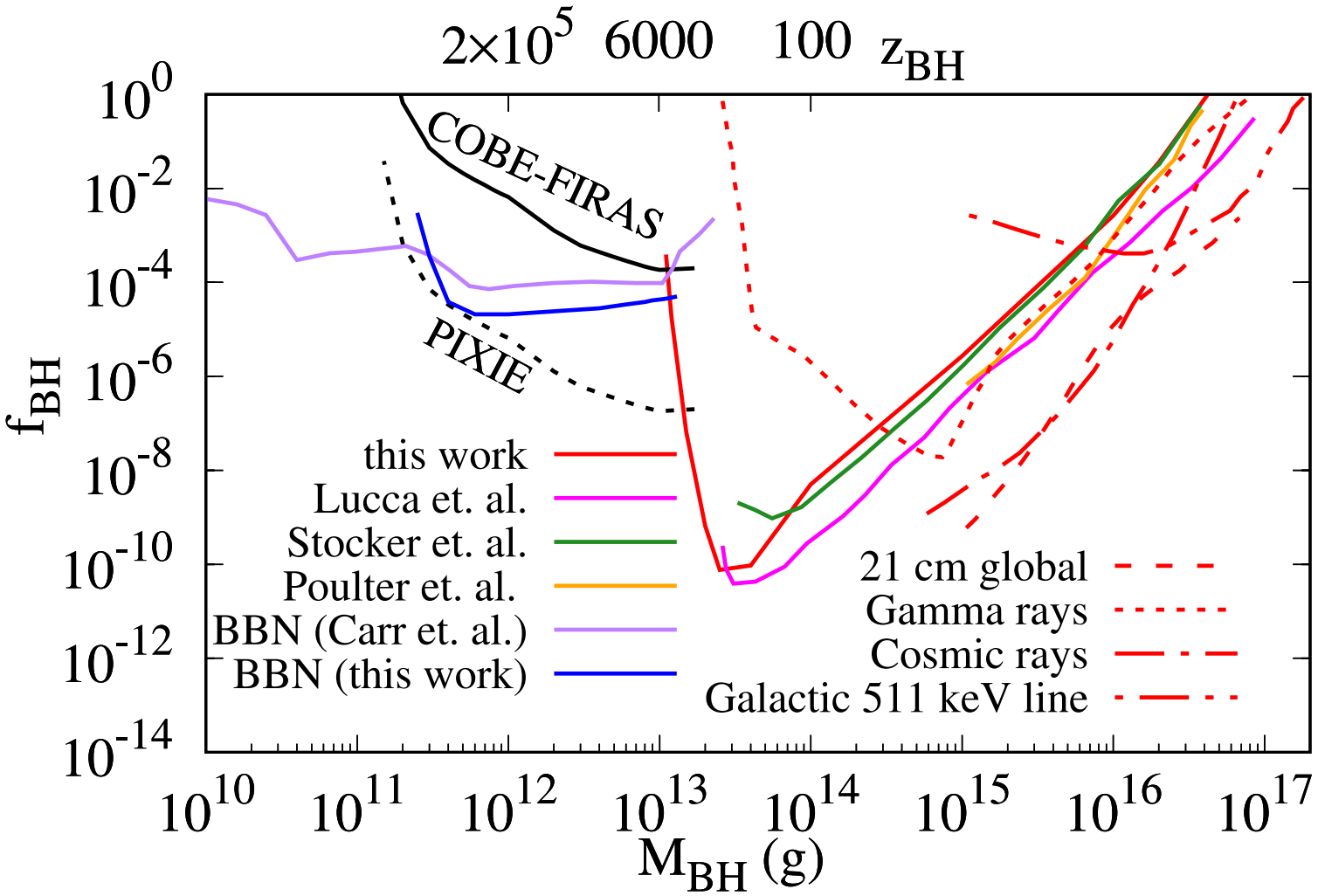
Acharya and Khatri 2019, arXiv:1910.06272

Reactions	photo-dissociation threshold (MeV)
^{2}H+$\gamma \rightarrow$ n+p	2.22
^{3}He+$\gamma \rightarrow$ ^{2}H+p	5.49
^{3}He+$\gamma \rightarrow$ n+p+p	7.718
^{4}He+$\gamma \rightarrow$ ^{3}H+p, ^{3}H $\rightarrow^3$ He + $e^- + \nu_e$	19.81
^{4}He+$\gamma \rightarrow$ ^{3}He+n	20.58
^{4}He+$\gamma \rightarrow$ ^{2}H+^{2}H	23.85
^{4}He+$\gamma \rightarrow$ ^{2}H+n+p	26.07

Elements	theoretical value(1σ)	observational value(1σ)
$n_{^2\mathrm{H}}/n_{\mathrm{H}}$	$(2.58 \pm 0.13) \times 10^{-5}$ [75]	$(2.53 \pm 0.04) \times 10^{-5}$ [75]
Y_p	0.24709 ± 0.00025 [75]	0.2449 ± 0.0040 [76]
$n_{^3\mathrm{He}}/n_{\mathrm{H}}$	$(10.039 \pm 0.090) \times 10^{-6}$ [75]	1.5×10^{-5} (2σ upper limit) [77]

CMB and BBN constraints on primordial black holes

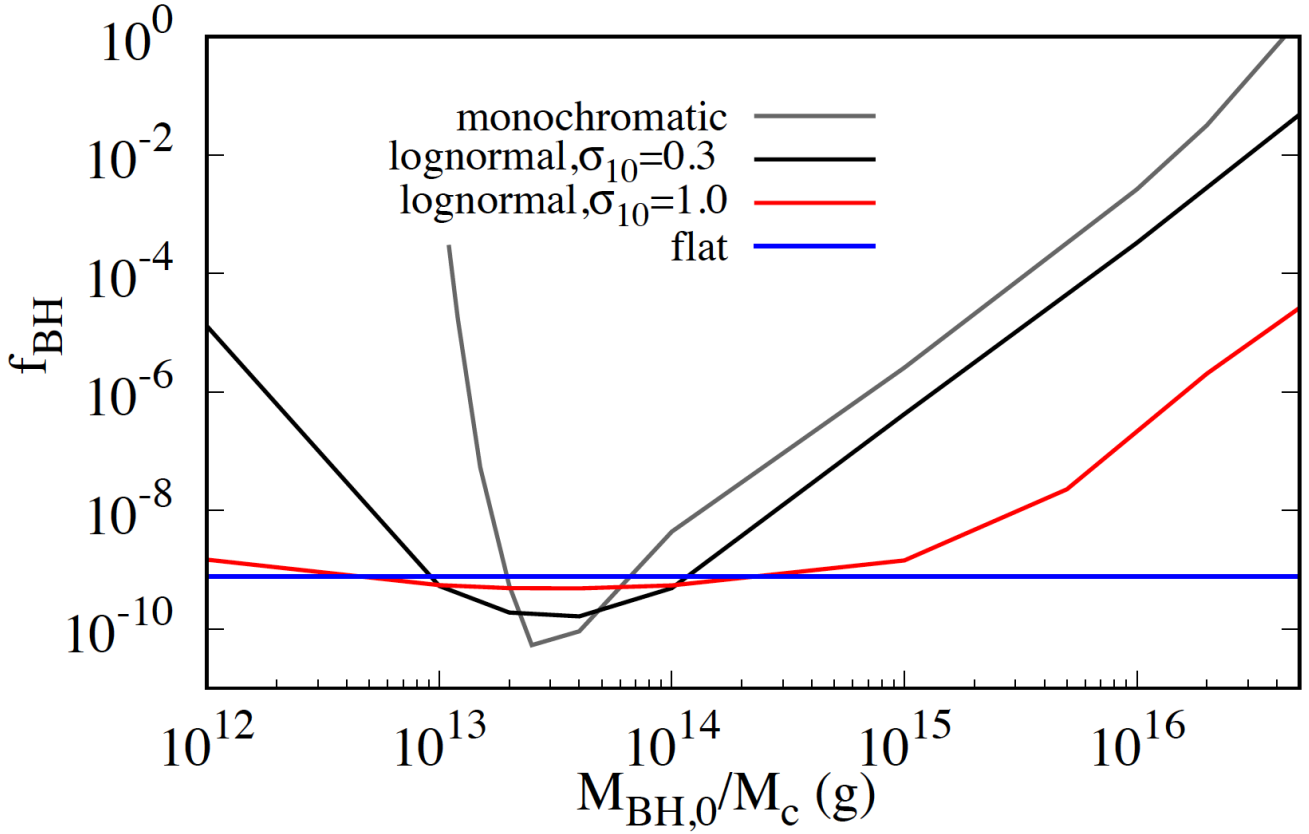
Acharya and Khatri 2020, arXiv:2002.00898



Extended mass function constraints

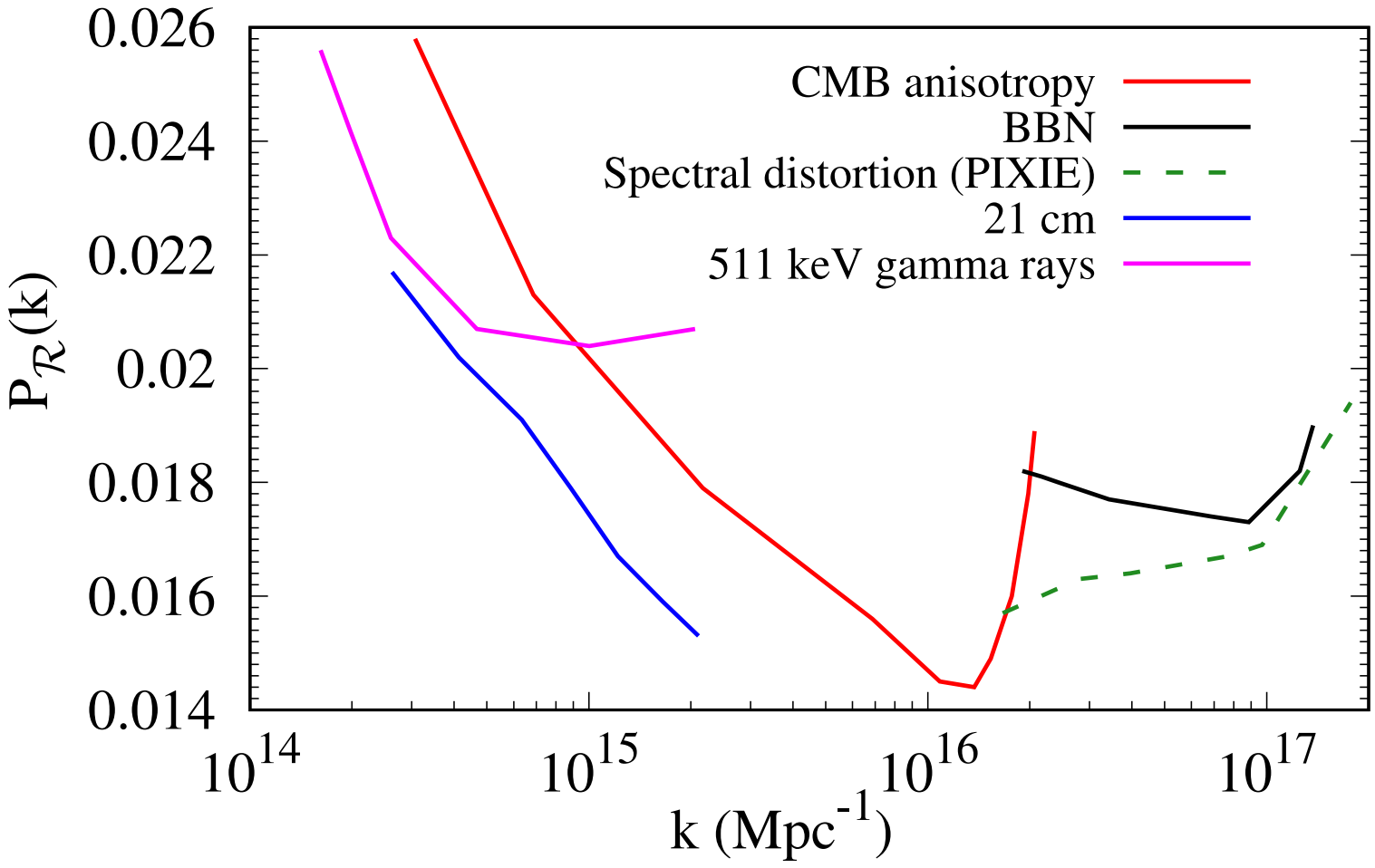
Acharya and Khatri 2020, arXiv:2002.00898

Assumes constraints can be independently combined (*Carr et al. 2017*) not strictly valid for ntr-type distortions



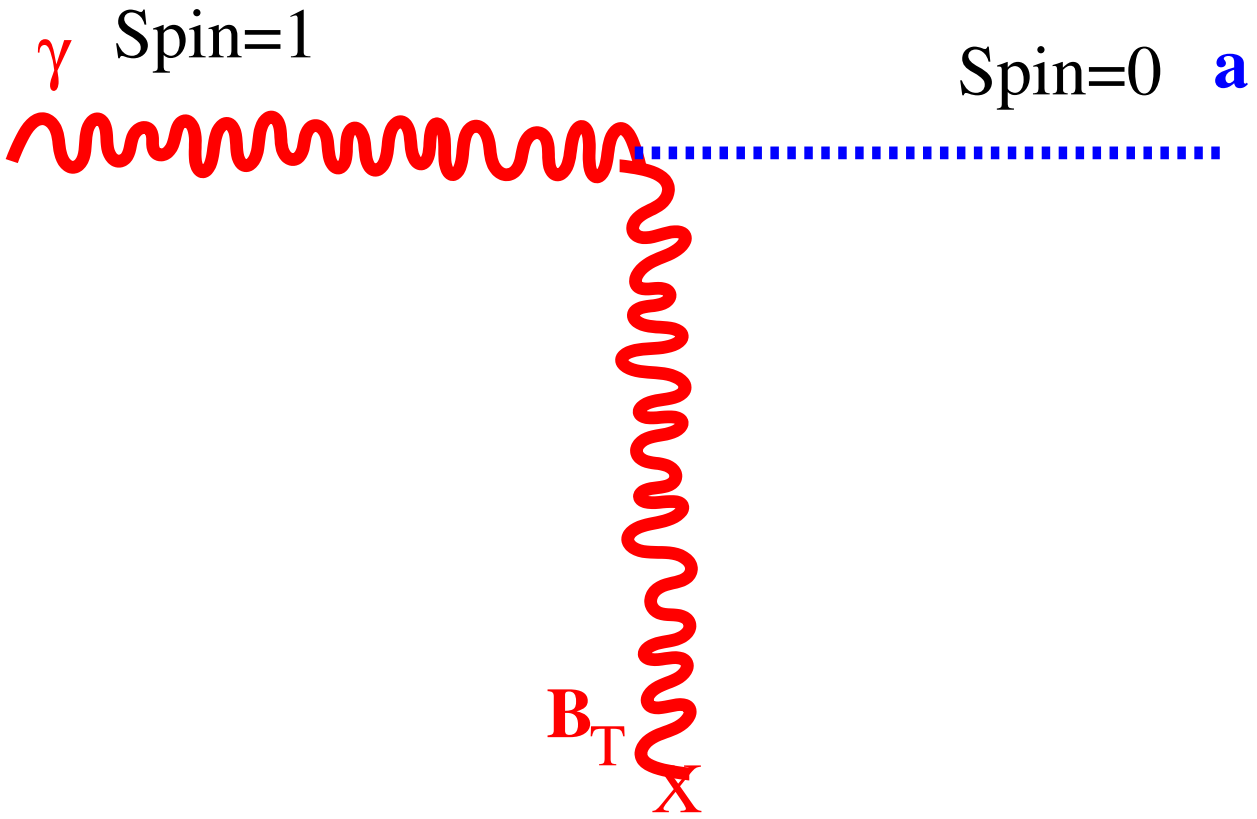
PBH constraints translate into constraints on primordial power spectrum *Acharya and Khatri 2020, arXiv:2002.00898*

Probing 40 e-folds of inflation!



Photon-axion conversion

Axion: pseudo-scalar particle with low mass and two photon coupling to photons



Photon-axion conversion

Raffelt and Stodolsky 1988
The coupling of axions to photons is given by CP conserving interaction term in Lagrangian of the form

$$\mathscr{L}_{int} = -\frac{1}{4} g_{a\gamma} F_{\mu\nu} \tilde{F}^{\mu\nu} a = g_{a\gamma} \mathbf{E}.\mathbf{B} a$$

i.e. For external transverse magnetic field **B**, only the polarization (defined by electric field) parallel to **B** would be converted to axion

Wave equation for free photon in vaccum

$$(\partial_t^2 - \nabla^2)A_{\parallel} = 0$$

with solution

$$A_{\parallel} \propto e^{i(\mathbf{k}.\mathbf{x} - \omega t)}$$

The electromagnetic wave has energy $E = \omega$ and momentum $\mathbf{k}$ with $E^2 = \omega^2 = k^2$

The presence of a medium gives photon an effective mass m_γ

Born and Wolf 1999

Refractive index $n = k/\omega$. We can identify the effective mass of photon by comparison with the relativistic relation $E^2 = p^2 + m^2$

$$n^2 - 1 = \frac{k^2 - \omega^2}{\omega^2} = \frac{-m_\gamma^2}{\omega^2}$$

Refractive index

Born and Wolf 1999

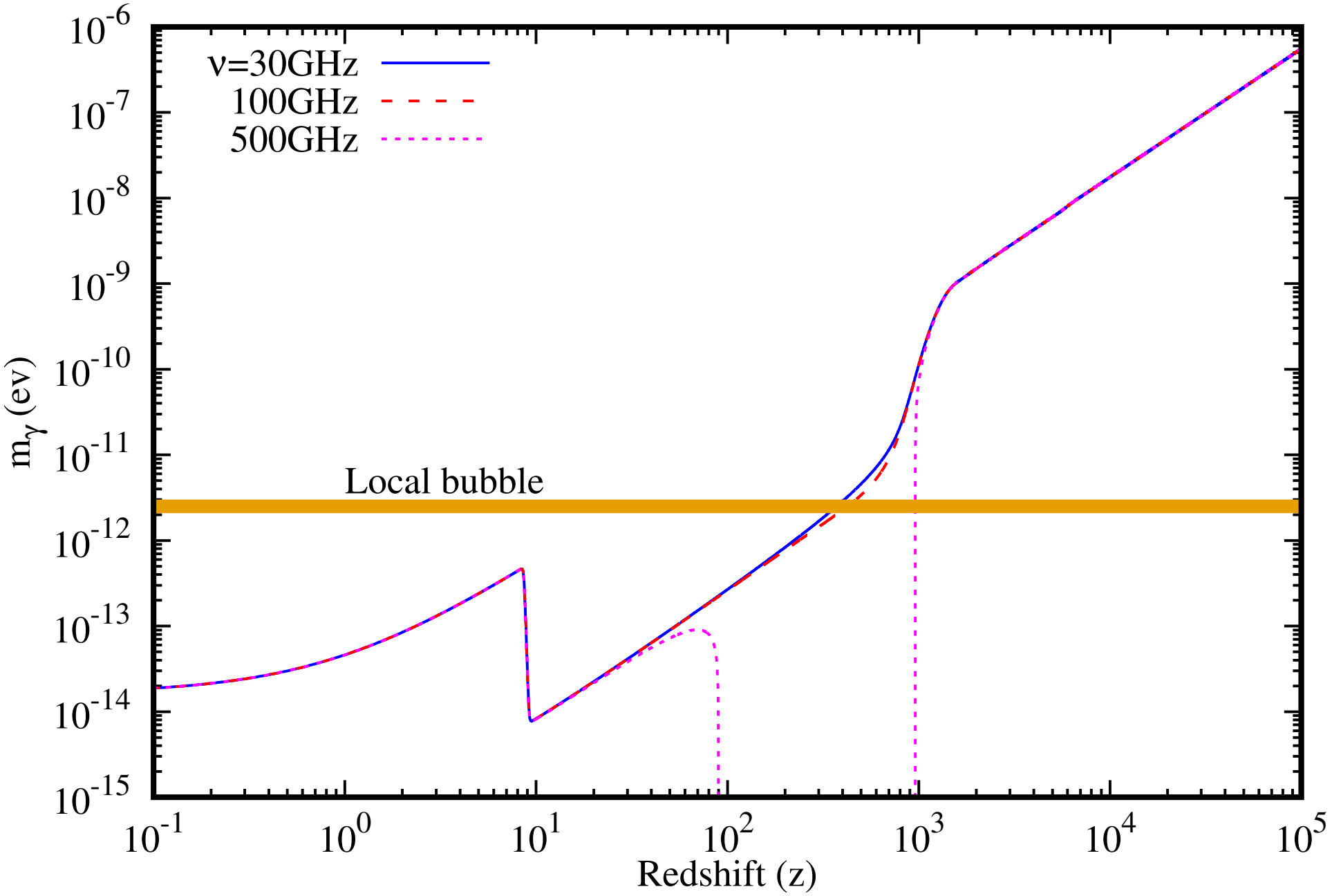
For $n \approx 1$, we have $n^2 - 1 \approx 2(n-1)$,

$$n - 1 \approx \frac{-m_\gamma^2}{2\omega^2}$$

$$\approx \frac{2\pi\alpha}{m_\mathrm{e}\omega^2}\left(-n_\mathrm{e} + n_\mathrm{H}\sum_i \frac{f_i^\mathrm{H}\omega^2}{{}^\mathrm{H}\omega_i^2 - \omega^2} + n_\mathrm{He}\sum_i \frac{f_i^\mathrm{He}\omega^2}{{}^\mathrm{He}\omega_i^2 - \omega^2}\right)$$

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

Evolution of the effective mass of the photon



Photons and axions in a medium

Raffelt and Stodolsky 1988, Raffelt 1996

$$(\partial_t^2 - \nabla^2 + m_\gamma^2)A_\parallel = g_{\gamma\mathrm{a}} B_\mathrm{T} \partial_t a$$
$$(\partial_t^2 - \nabla^2 + m_\mathrm{a}^2)a = \frac{1}{2} g_{\gamma\mathrm{a}} B_\mathrm{T} \partial_t A_\parallel$$

For solutions $\propto e^{i(\mathbf{k}.\mathbf{x} - \omega t)}$ in the relativistic approximation $m_\gamma \ll \omega, \omega \approx k$

$$\partial_t^2 - \nabla^2 \longrightarrow k^2 - \omega^2 = (k-\omega)(k+\omega) \approx 2\omega(k-\omega)$$

Linearized photon-axion system

Photon with energy ω propagating in the z direction

$$\left(\omega + \begin{pmatrix} \Delta_{\mathrm{e}} & \Delta_{\gamma\mathrm{a}} \\ \Delta_{\gamma\mathrm{a}} & \Delta_{\mathrm{a}} \end{pmatrix} + i\partial_z\right)\begin{pmatrix} A_{\parallel} \\ a \end{pmatrix} = 0$$

$$\Delta_{\mathrm{e}} = \frac{-m_{\gamma}^2}{2\omega}, \Delta_{\mathrm{a}} = \frac{-m_{\mathrm{a}}^2}{2\omega}, \Delta_{\gamma\mathrm{a}} = \frac{1}{2} g_{\gamma\mathrm{a}} B_{\mathrm{T}}$$

This is Schrödinger equation that describes the evolution of photons/axions with energy ω through a changing medium

Interpret $A_{||}, a$ as probability amplitudes

The rotation by mixing angle θ diagnoalizes the mass matrix

$$M^2_{\rm eff} = \begin{pmatrix} \Delta_{\rm e} & \Delta_{\gamma {\rm a}} \\ \Delta_{\gamma {\rm a}} & \Delta_{\rm a} \end{pmatrix}$$

$$M^2 = R M^2_{\rm eff} R^T$$

$$R = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix}$$

The solution

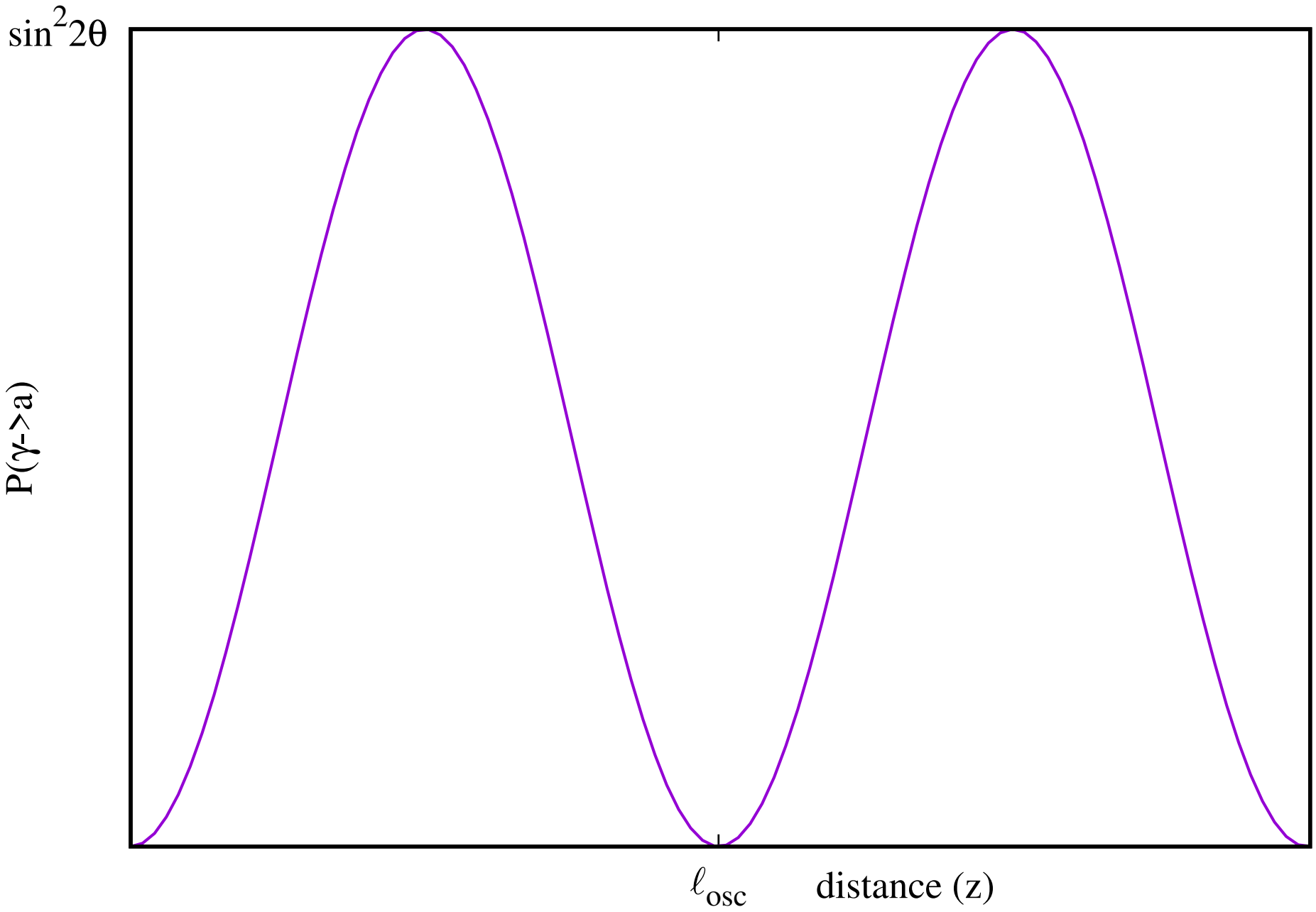
$$P(\gamma \to a) = \frac{(\Delta_{\gamma a} z)^2}{(\Delta_{\rm osc} z/2)^2} \sin^2(\Delta_{\rm osc} z/2)$$

$$\equiv \sin^2(2\theta) \sin^2(\Delta_{\rm osc} z/2)$$

$$\Delta_{\rm osc}^2 = (\Delta_{\rm e} - \Delta_{\rm a})^2 + 4\Delta_{\gamma a}^2$$

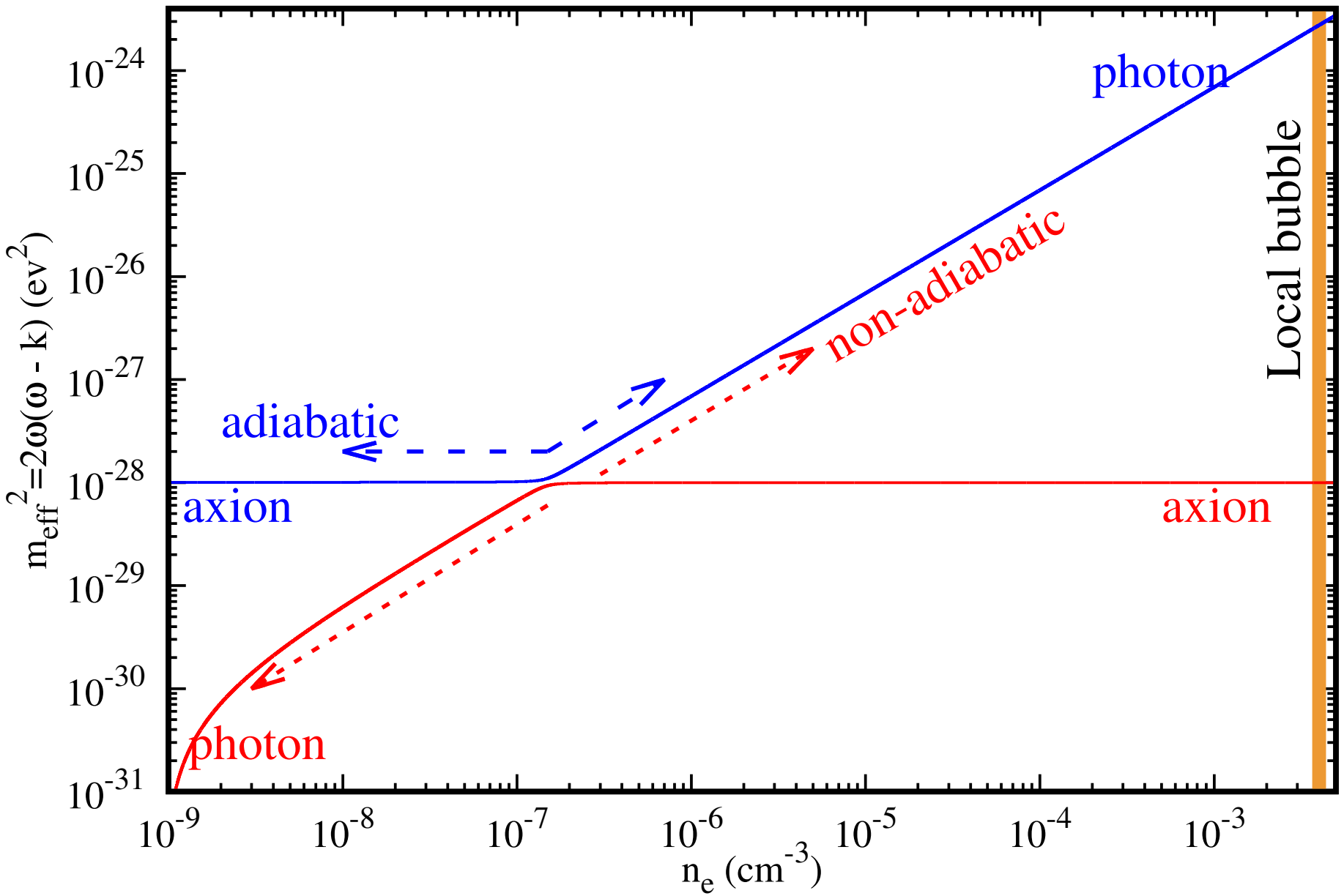
$$l_{\rm osc} = \frac{2\pi}{\Delta_{\rm osc}}$$

photon-axion oscillations



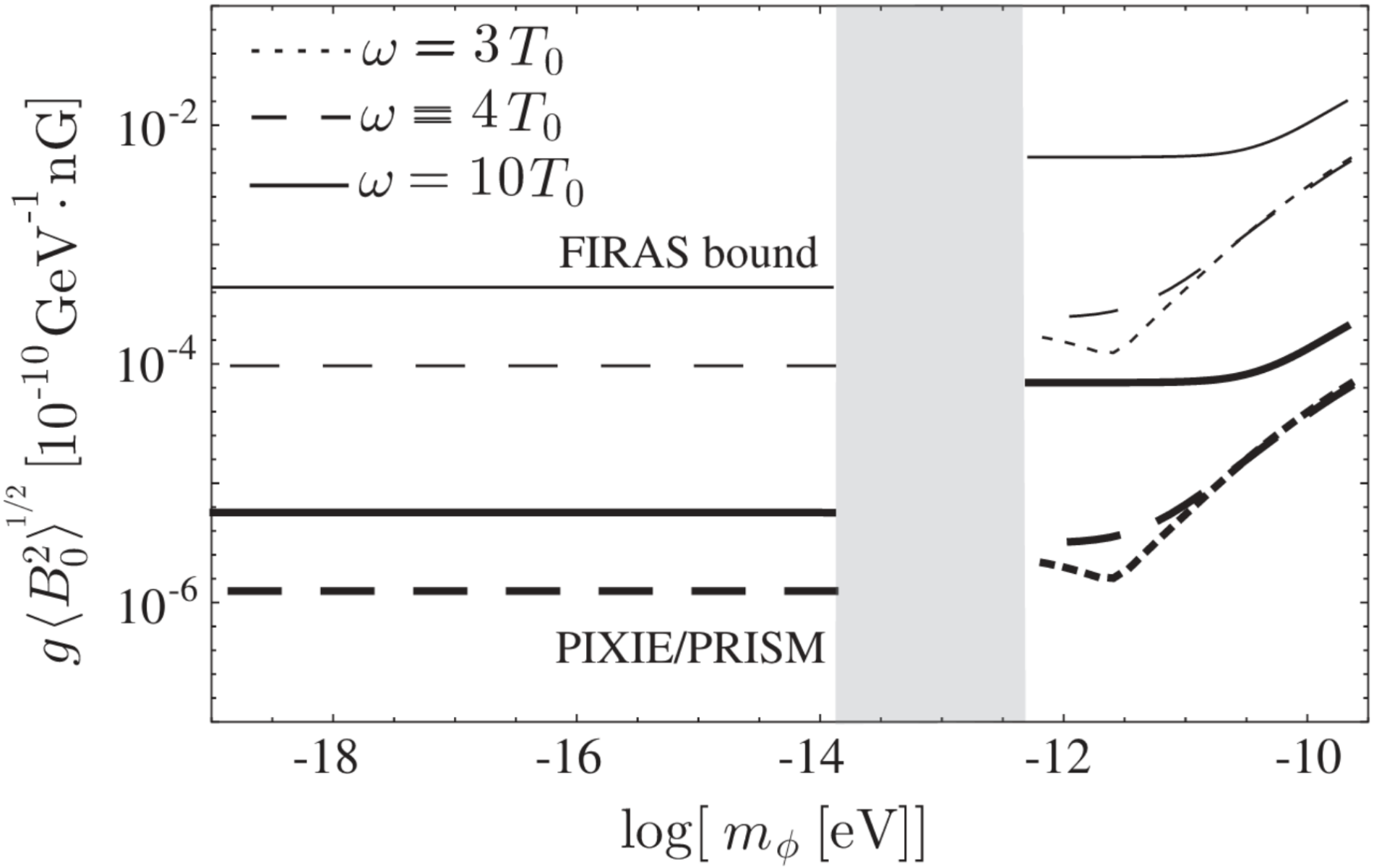
Dispersion relations $\det(\omega - k + M^2_{\rm eff}) = 0$

quadratic equation for $\omega - k$. Resonance at $m_\gamma = m_{\rm a}$.

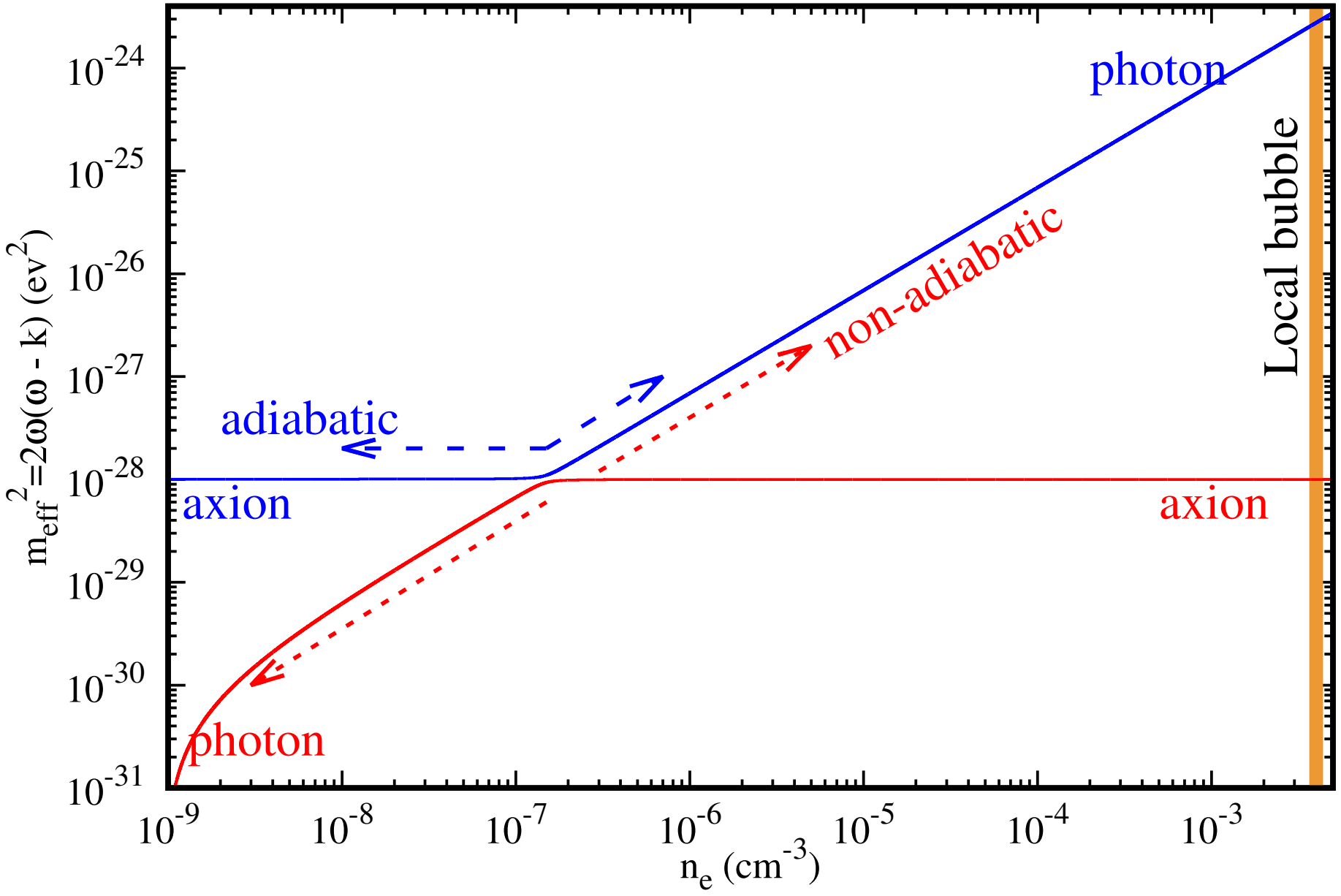


Constraints on smaller masses

Tashiro, Silk and Marsh 2013



Non-adiabatic resonances alone cannot close a window



Adiabatic and non-adiabatic resonances *Mukherjee, Khatri & Wandelt 2018, arXiv:1801.09701*

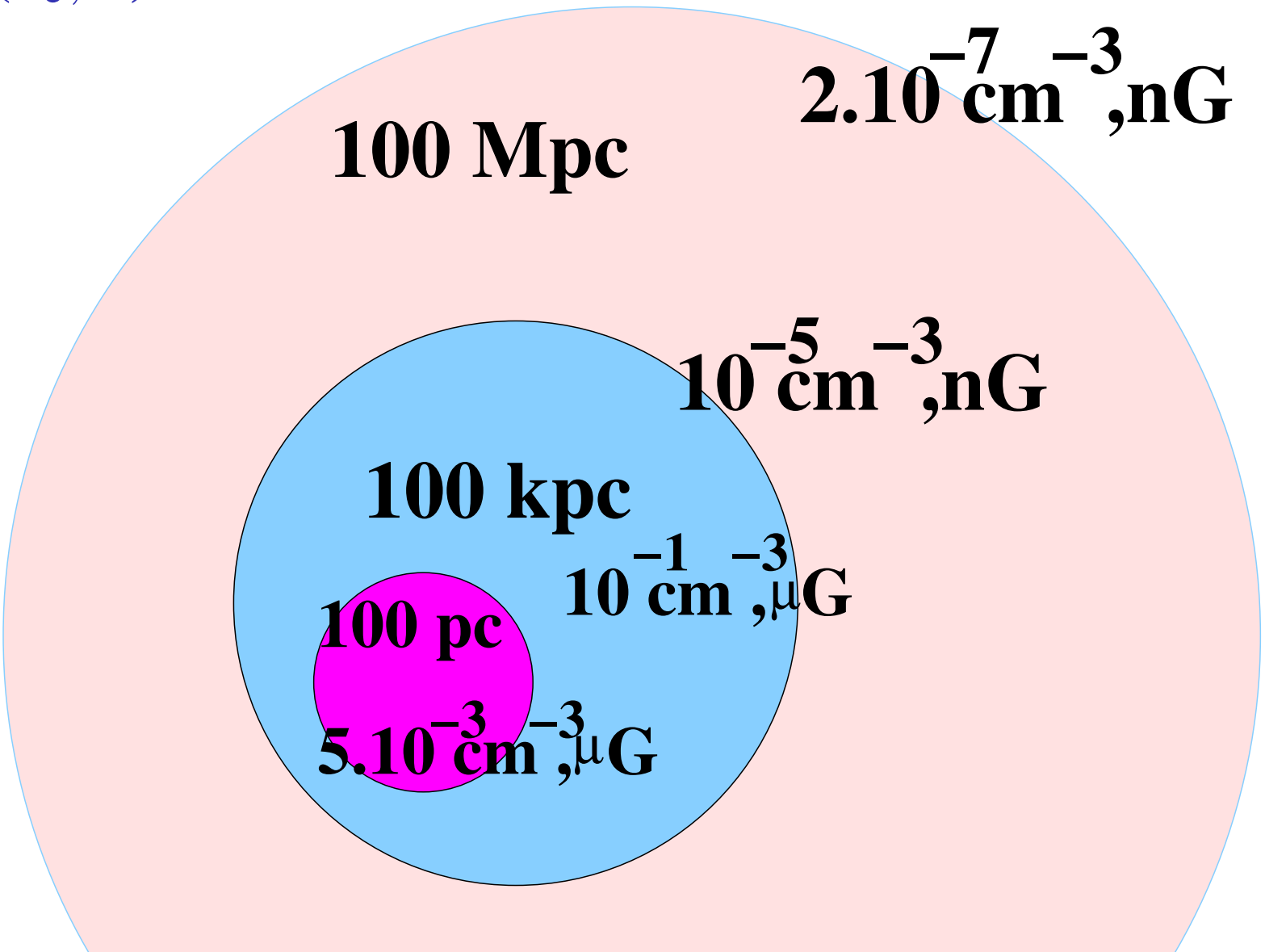
Need *odd* number of adiabatic resonances for complete conversion and ruling out axion in some mass range.

The window from $10^{-14} m_{\rm a} < 10^{-12}$ eV is not ruled out.

Photon-axion conversion in MilkyWay magnetic field

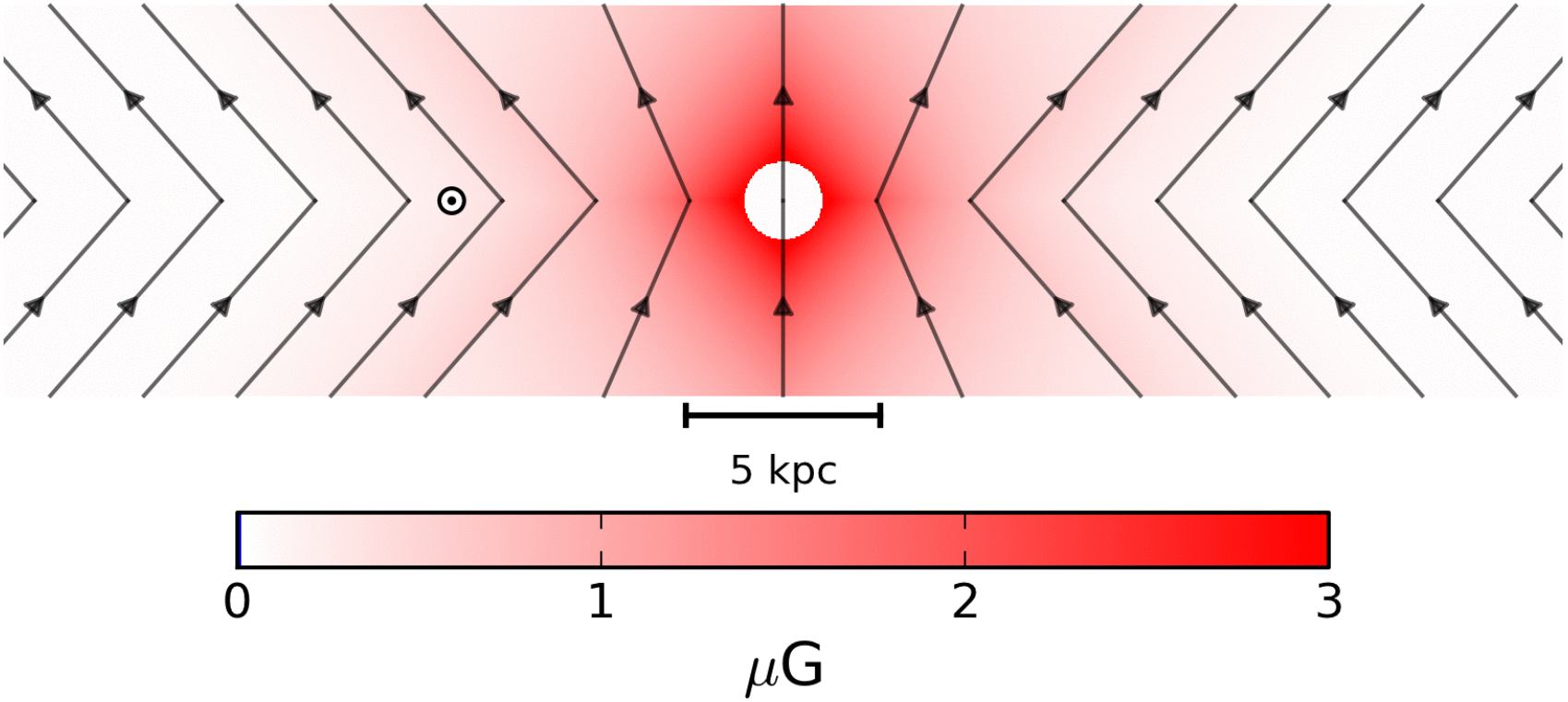
Mukherjee, Khatri & Wandelt 2018, arXiv:1801.09701

$(n_{\rm e}, B)$

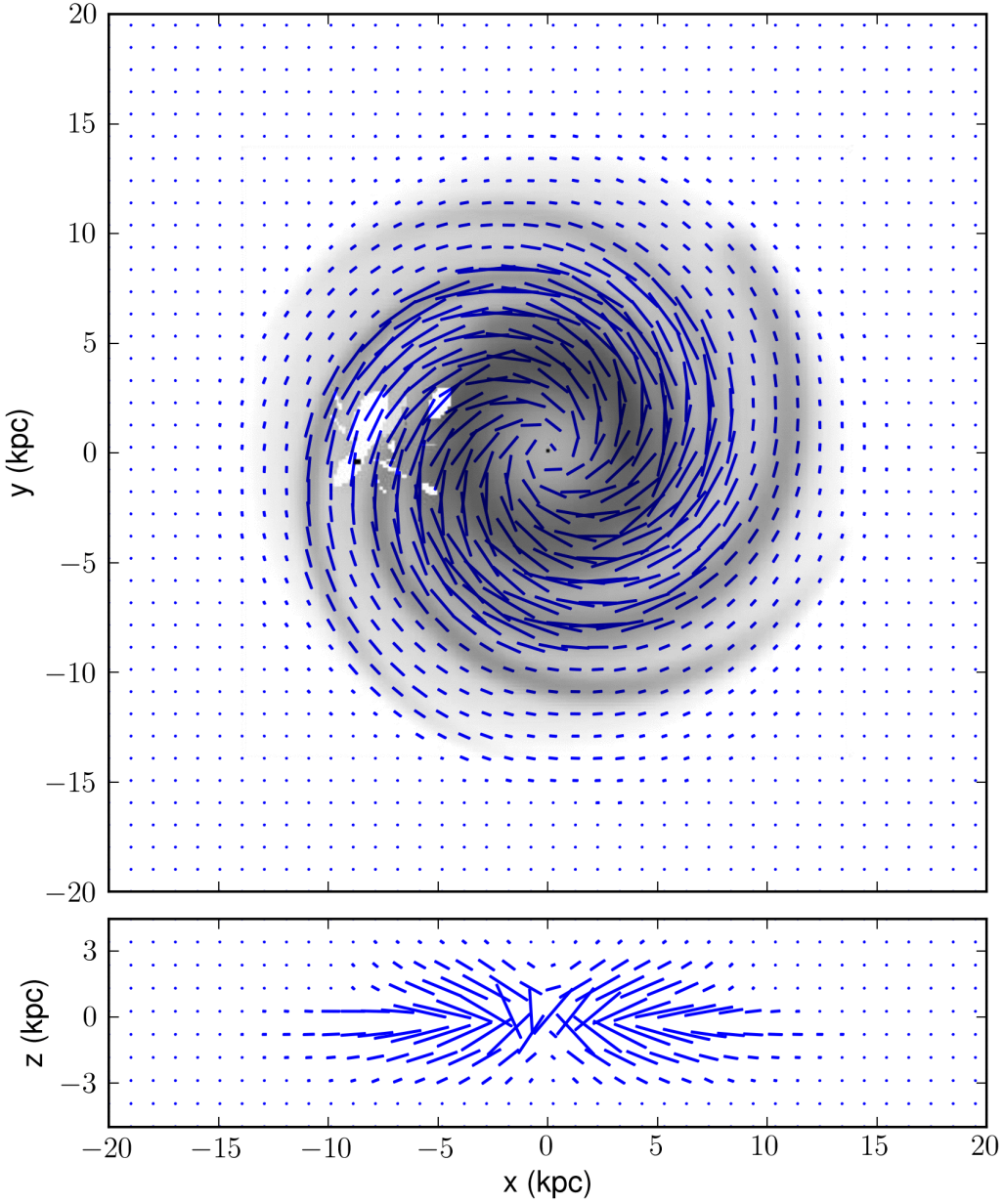


Galactic magnetic field: Poloidal field

Jansson& Farrar 2012

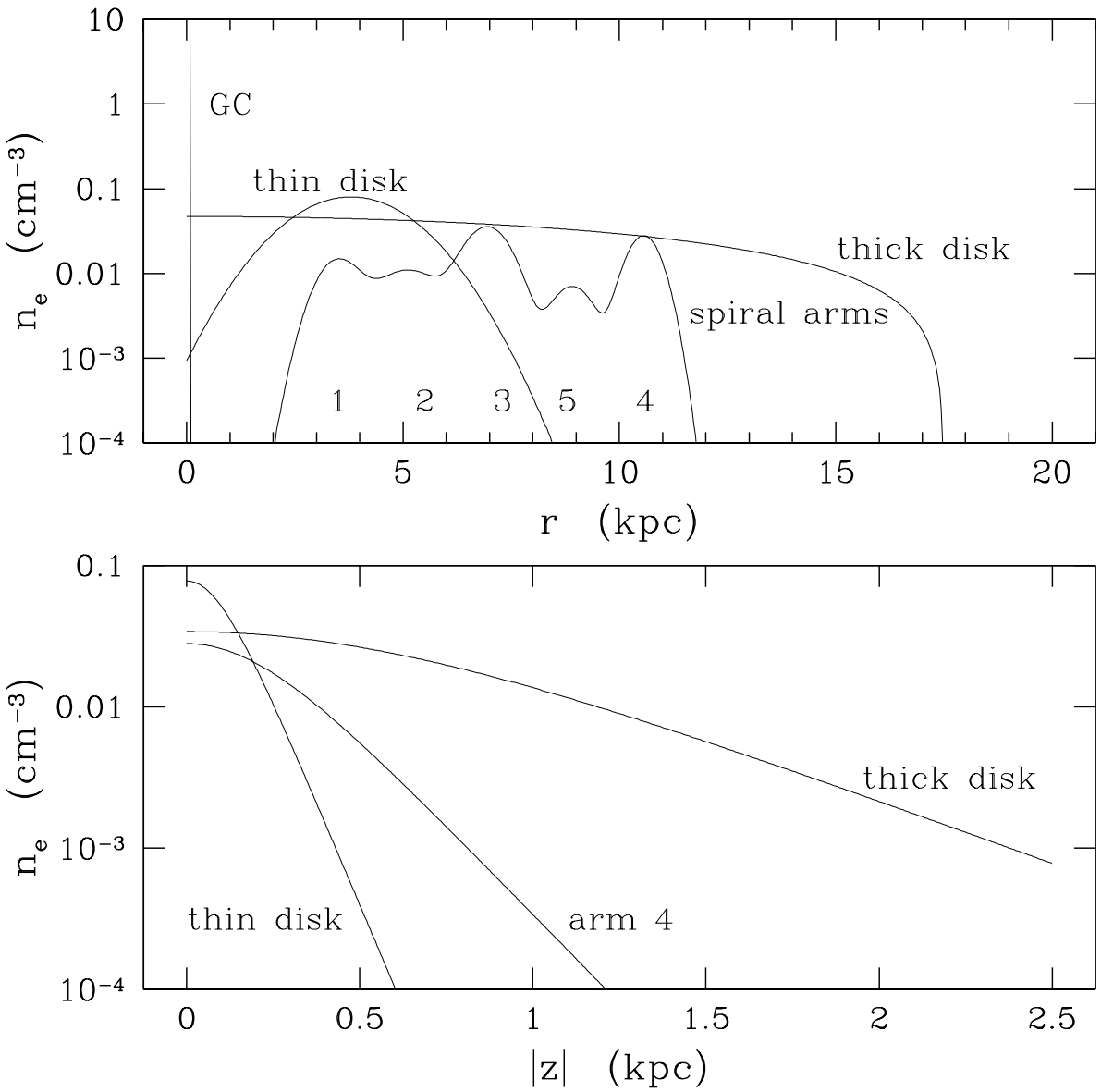


Galactic magnetic field: Toroidal field



Jansson& Farrar 2012

Galactic electron density



Cordes& Lazio 2001

Resonance in the galaxy for $10^{-14} \lesssim m_{\rm a} 10^{-11}$eV

The magnitude of transverse magnetic field at resonance point decides the conversion probability

The direction of magnetic field gives the polarization of the photon that disappears

$$\Delta I = -P(\gamma \to {\rm a}) I$$

$$P(\gamma \to {\rm a}) \propto \omega$$

Non-resonant conversion in stochastic/turbulent magnetic fields in our Galaxy, voids and galaxy clusters

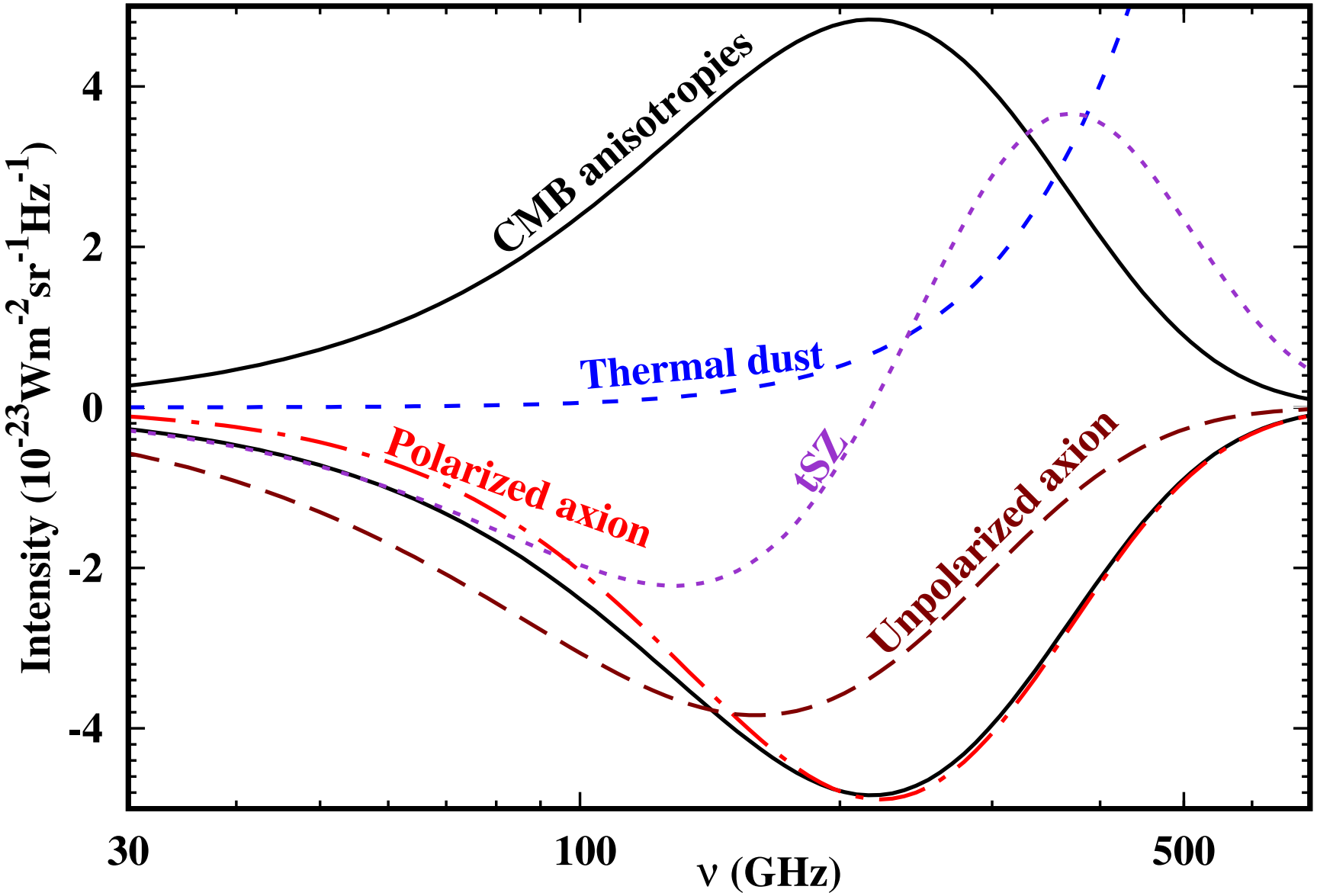
Analytical solution in the limit of uncorrelated domains
(*Grossman, Roy, & Zupan 2002*)
Example application to voids
(*Mukherjee, Khatri & Wandelt 2018, arXiv:1801.09701*)

$$\bar{P}(\gamma \to a) \approx \frac{\Delta_{\gamma a}^2 R s}{2} = 10^{-4} \left(\frac{g_{\gamma a}}{10^{-10}\ \mathrm{GeV}^{-1}} \right)^2 \left(\frac{B_T}{1\ \mathrm{nG}} \right)^2 \left(\frac{R}{1\ \mathrm{Gpc}} \right) \left(\frac{s}{10\ \mathrm{pc}} \right)$$

Non-resonant conversion probability in stochastic magnetic fields is independent of frequency

Spectrum of the polarized disortion in CMB from resonant axion conversion

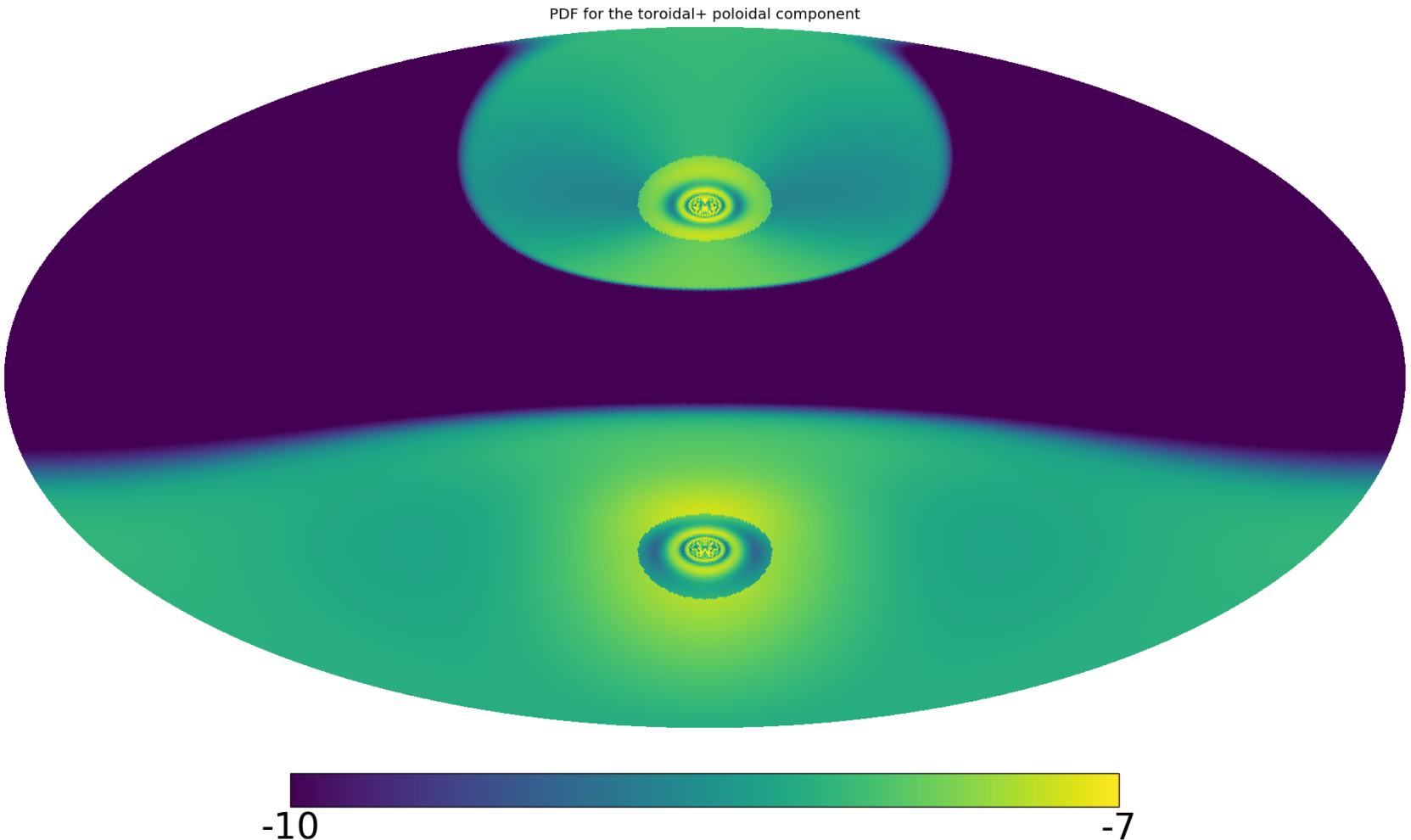
Mukherjee, Khatri & Wandelt 2018, arXiv:1801.09701



The pattern of distortion on sky strongly anisotropic: Unique signature correlated with electron distribution and magnetic field structure

Mukherjee, Khatri & Wandelt 2018, arXiv:1801.09701

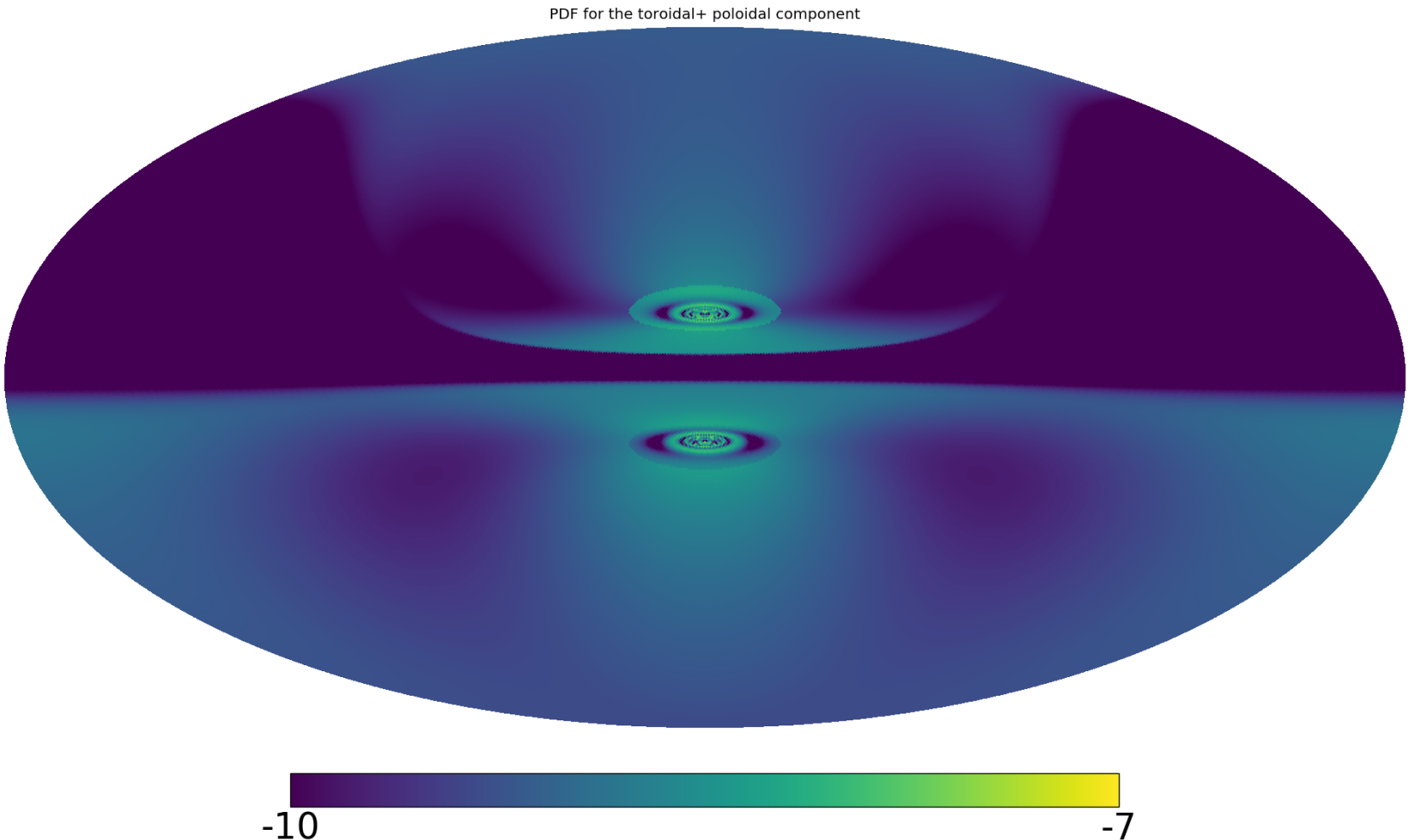
$m_{\rm a} = 5 \times 10^{-13}$ eV



The pattern of distortion on sky strongly anisotropic: Unique signature correlated with electron distribution and magnetic field structure

Mukherjee, Khatri & Wandelt 2018, arXiv:1801.09701

$m_{\rm a} = 5 \times 10^{-12}$ eV



Planck 2015 map of photon-axion conversion probability

Non-resonant $P_{\gamma \to a} \lesssim 10^{-5}$
(*Mukherjee, Khatri & Wandelt 2019, arXiv:1811.11177*)

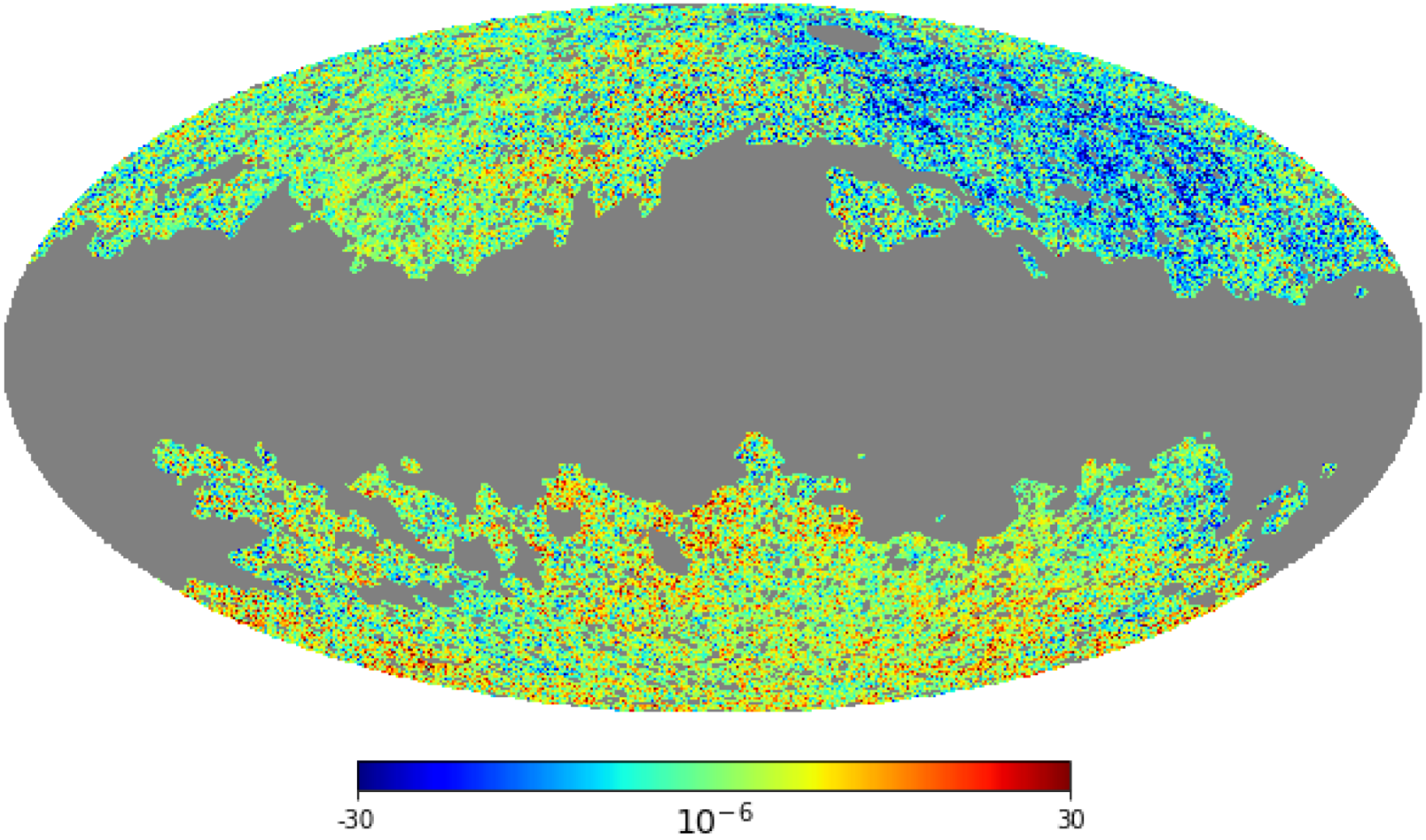
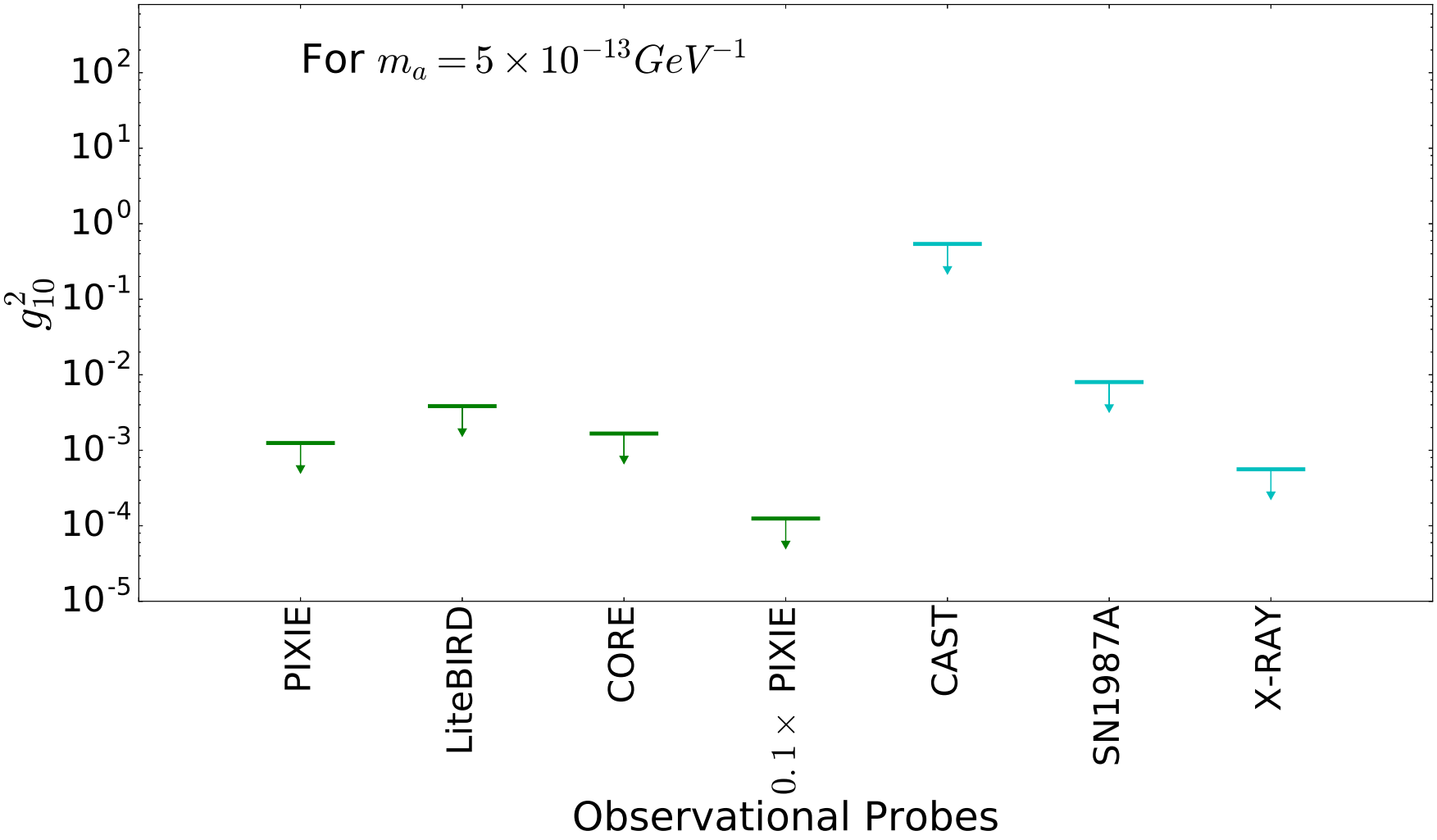


Figure 1: Internal Linear Combination Map of Axion Spectral Distortion (ASD) amplitude $P(\gamma \to a)$

Predictions for future expermiments: resonant conversion in the Galaxy

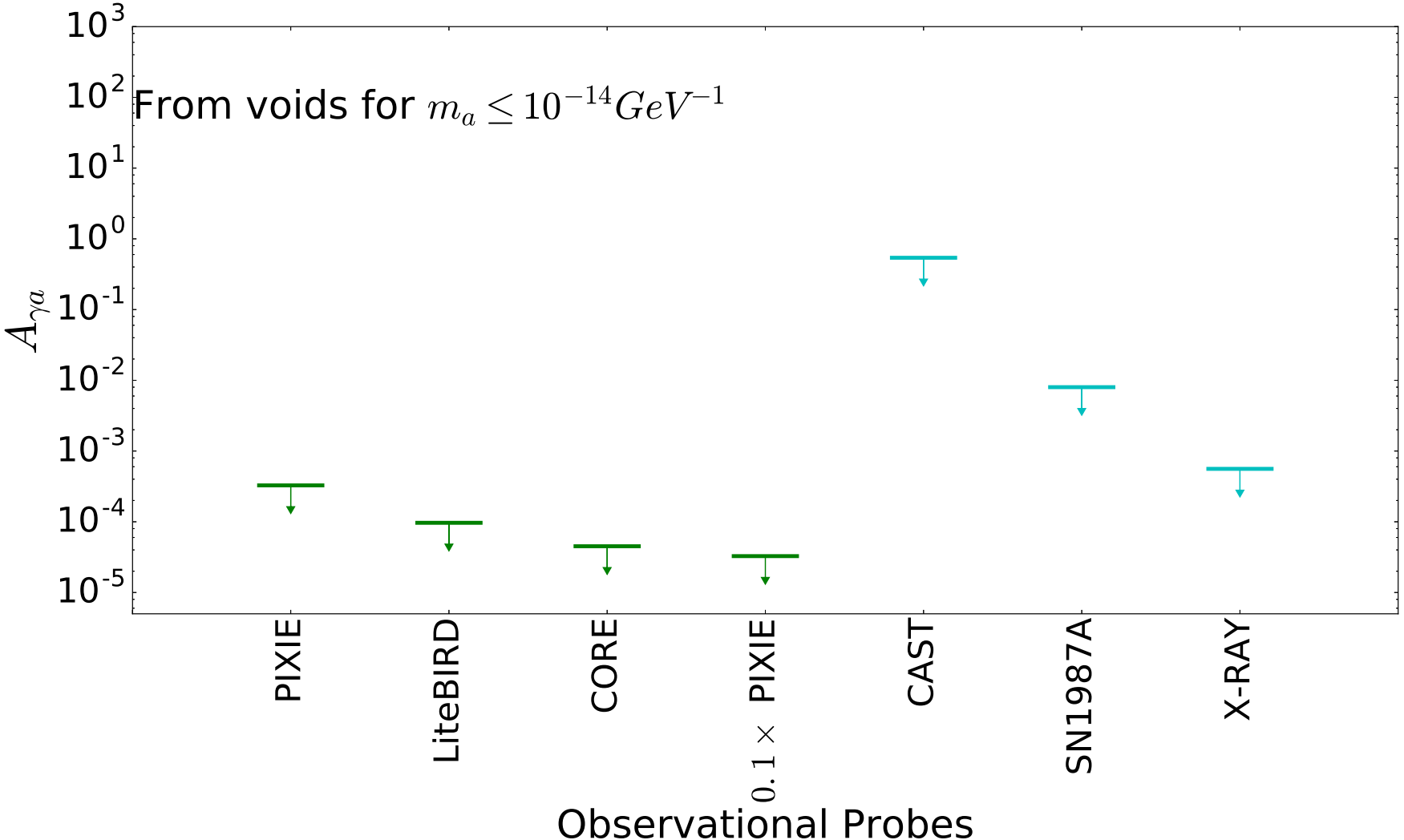
Mukherjee, Khatri & Wandelt 2018, arXiv:1801.09701



Predictions for future expermiments: non-resonant conversion in the voids

Mukherjee, Khatri & Wandelt 2018, arXiv:1801.09701

$$A_{\gamma a} \equiv \left(\frac{g_{\gamma a} B_T^{\rm rms}}{10^{-10}\ {\rm GeV}^{-1}\ {\rm nG}} \right)^2$$



New interesting signals in the CMB from axion like particles and primordial black holes

- Qualiatively new information about properties of primordial black holes in the shape of the CMB spectral distortions
- Important to take into account evolution of relativistic particle cascades for accurate constraints
- Conversion of CMB photons in the Galactic magnetic field and nearby voids can leave interesting anisotropic polarized and unpolarized spectral distortion signatures in the CMB