Looking for new physics with radio signatures

Andrea Caputo

UNDARK kick-off meeting

hep-ph/2405.13882 with Carl Beadle and Sebastian Ellis

CERN

at some point in the future

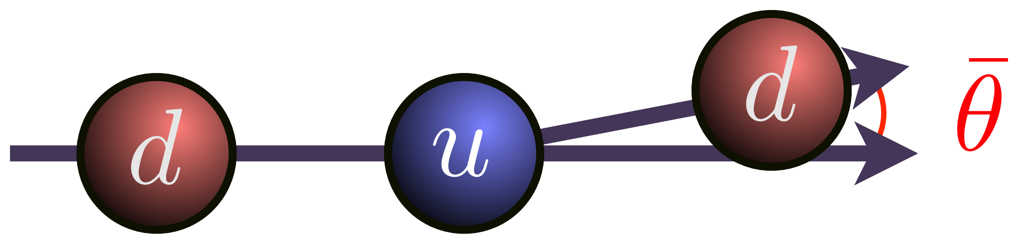
SAPIENZA UNIVERSITÀ DI ROMA

erc

Funded by the European Union

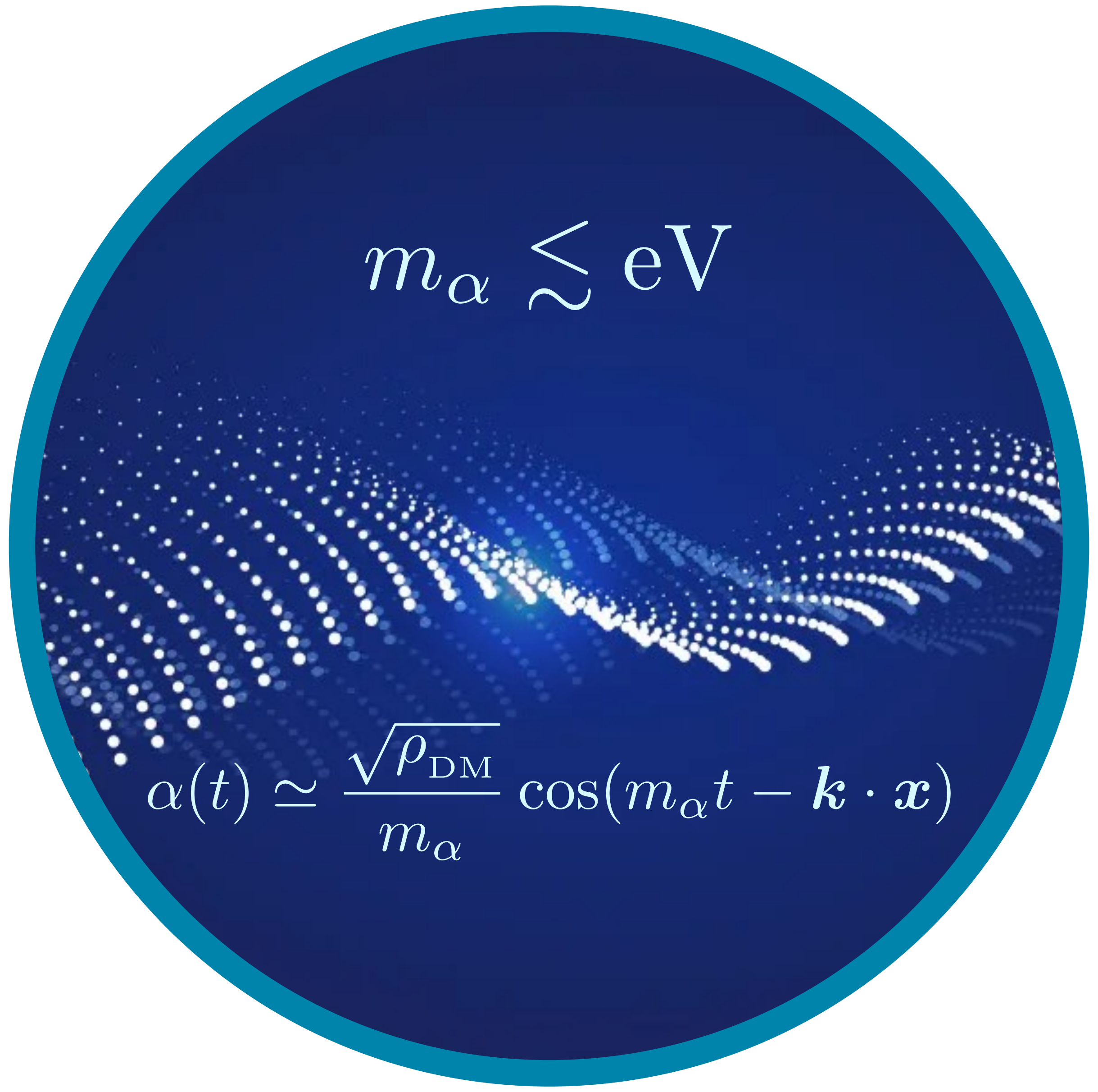
Two different targets (with some similarities)

Axions

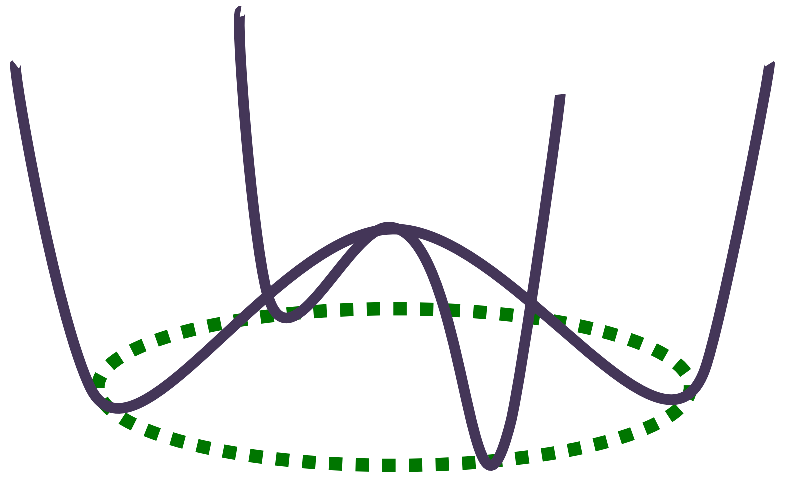


$$\mathcal{L} \supset \left(\frac{a}{f_a} + \bar{\theta}\right) \frac{g_s^2}{32\pi^2} G^a_{\mu\nu} \tilde{G}^{\mu\nu,a}$$

Peccei & Quinn (1977)
Weinberg (1978)
Wilczek (1978)



Massive Dark Photons



Proca (1936)
Stückelberg (1938)

- Misalignment — Preskill et al, Abbott & Sikivie (1983)
- Cosmic strings — Harari & Skive (1987), …, Klaer & Moore (2017), Gorghetto, Hardy & Villadoro (2018), Buschmann, Foster & Safdi (2019), Gorghetto, Hardy & Villadoro (2020), Buschmann et al (2021)
- …

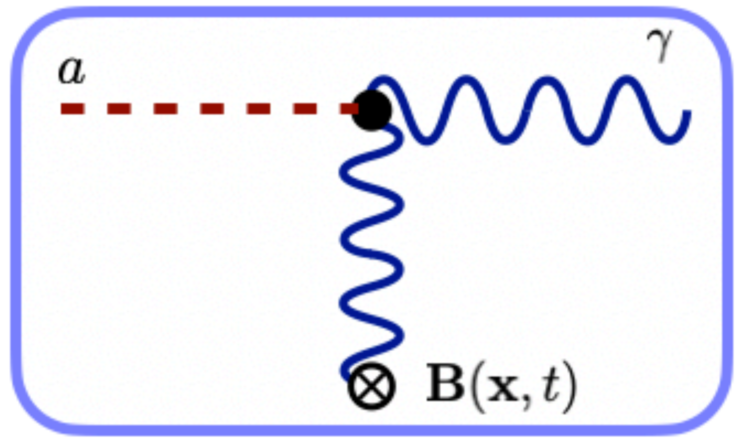
- Misalignment — Nelson & Scholtz (2011)
- Inflation — Graham, Mardon & Rajendran (2015)
- … e.g. Agrawal et al, Co et al, Dror et al, Bastero-Gil et al (all 2018)

Two different targets (with some similarities)

Dark Photon: $$\mathcal{L} \supset -\frac{1}{4}\left(F_{\mu\nu}F^{\mu\nu} - 2\epsilon F'_{\mu\nu}F^{\mu\nu} + F'_{\mu\nu}F'^{\mu\nu}\right) + \frac{1}{2}m_{A'}^2 A'_\mu A'^\mu - A_\mu \mathcal{J}^\mu$$

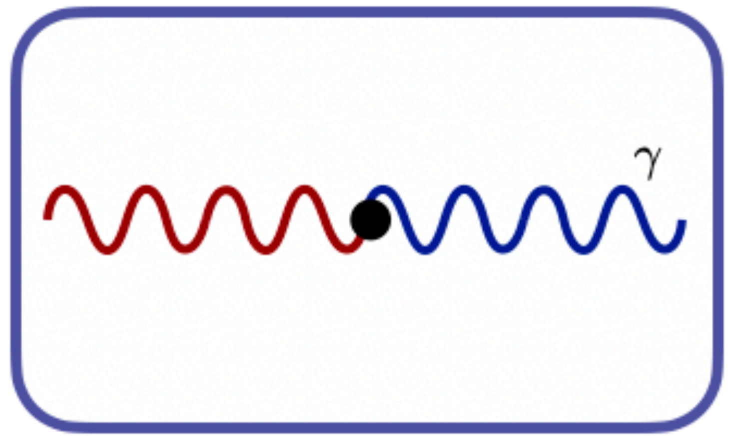
Axion: $$\mathcal{L} \supset -\frac{1}{4}\left(F_{\mu\nu}F^{\mu\nu} - 2\,\partial_\mu a\,\partial^\mu a + g_{a\gamma\gamma} a F_{\mu\nu}\tilde{F}^{\mu\nu}\right) - \frac{1}{2}m_a^2 a^2 - A_\mu \mathcal{J}^\mu$$

Axion:



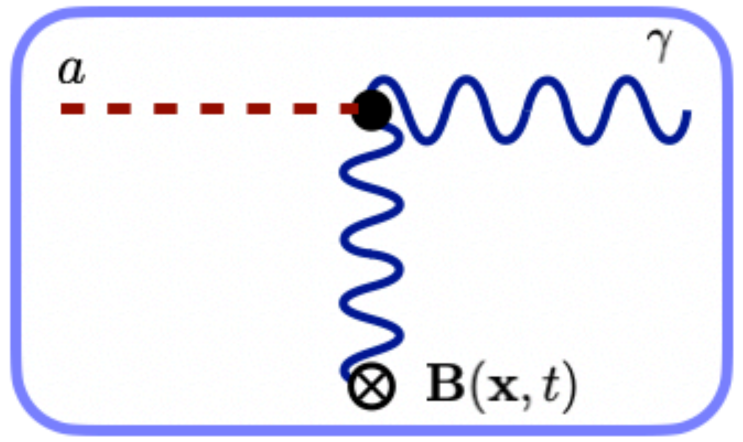
$$j_a \sim g_{a\gamma\gamma}(\partial a)F$$

Dark Photon:



$$j_{A'} \sim -\epsilon m_{A'}^2 A'$$

Axion:



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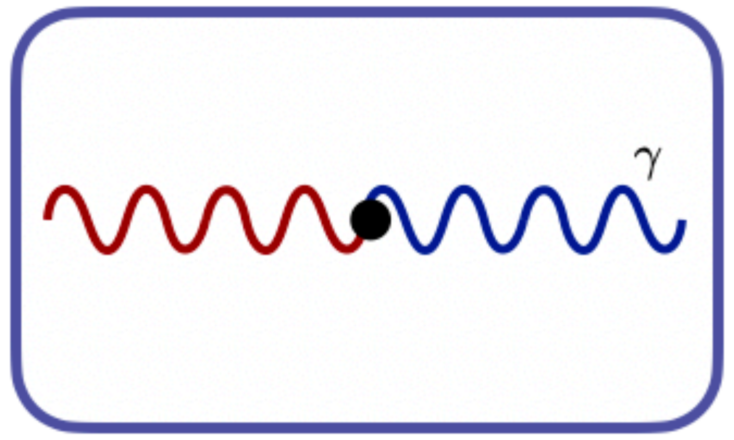

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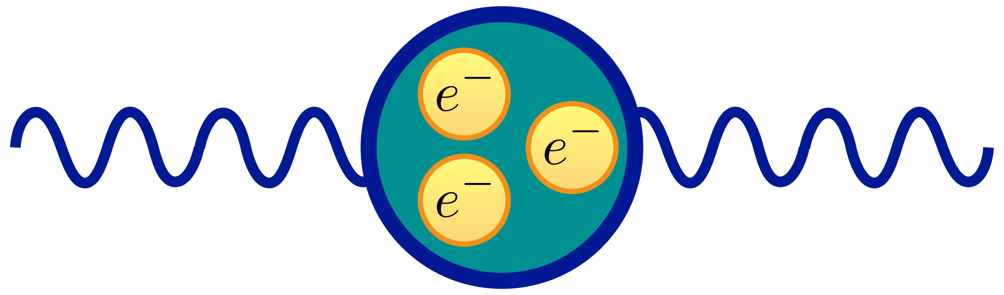
Free charges modify photon self-energy



$$\Pi^{\mu\nu} = \sum_p \Pi_p P^{\mu\nu}$$

Transverse

$$\Pi_T \sim \omega_{\rm pl}^2 \sim \frac{e^2 n_e}{m_e}$$

Longitudinal

$$\Pi_L \sim \omega_{\rm pl}^2 \left(1 - \frac{k^2}{\omega^2}\right)$$

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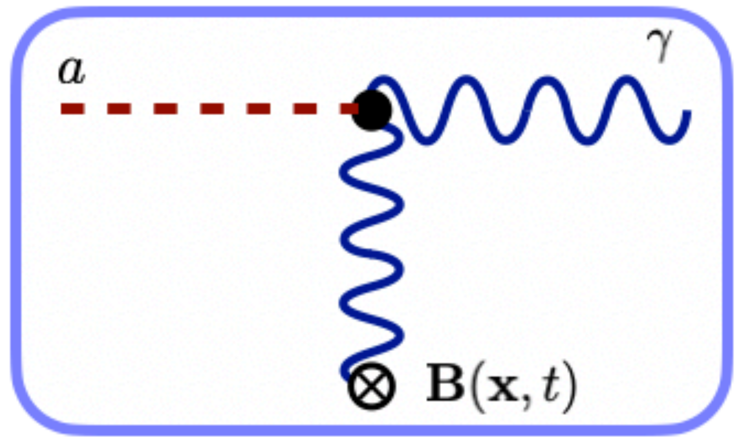

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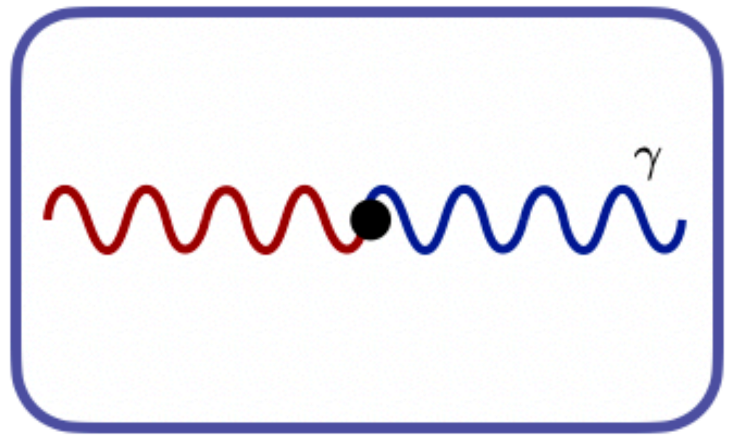

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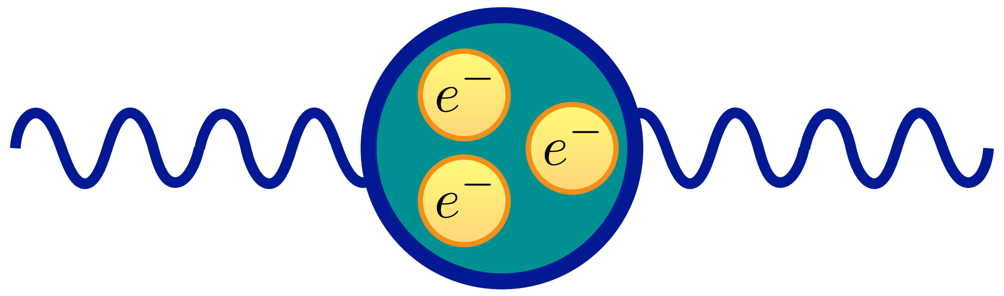

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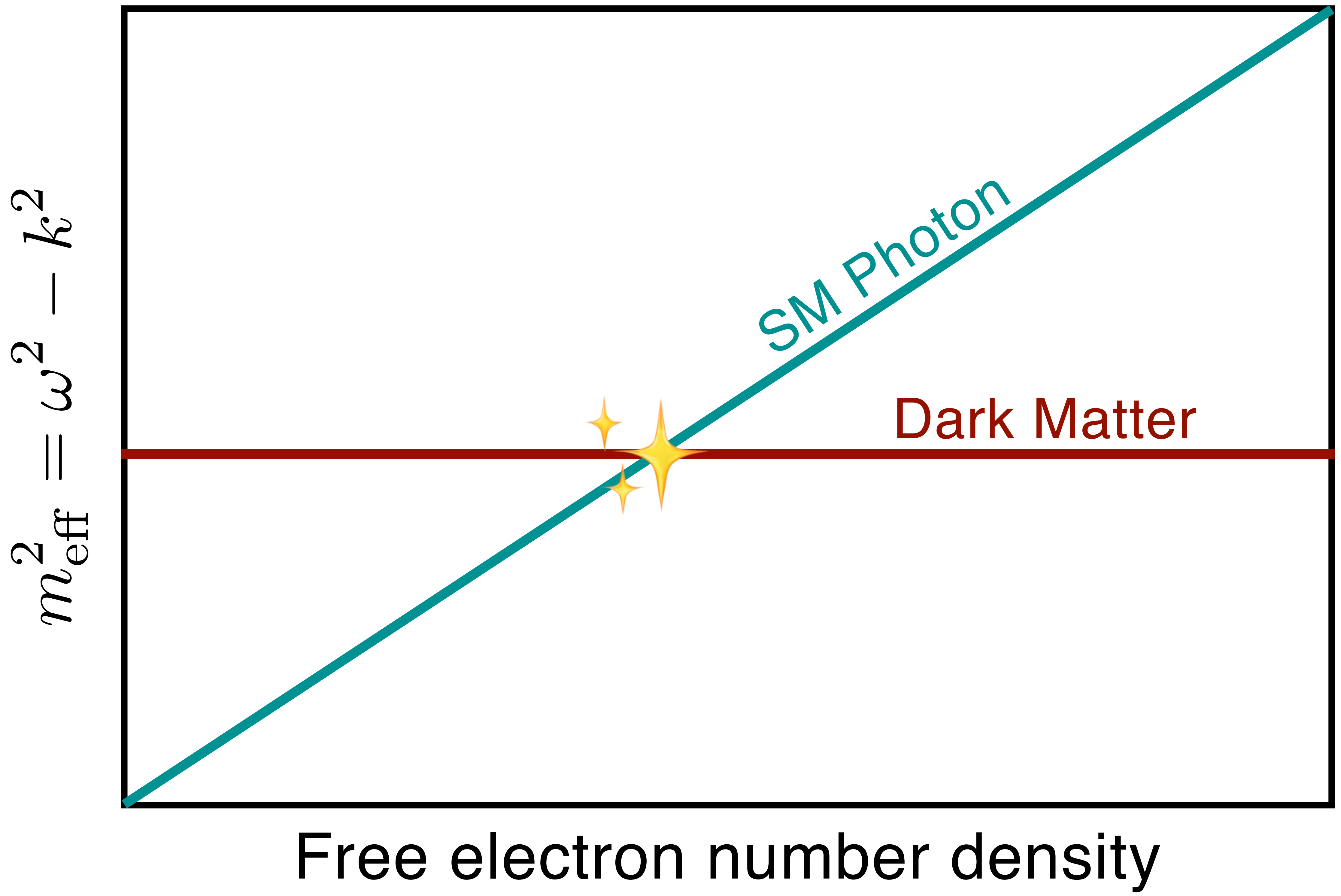

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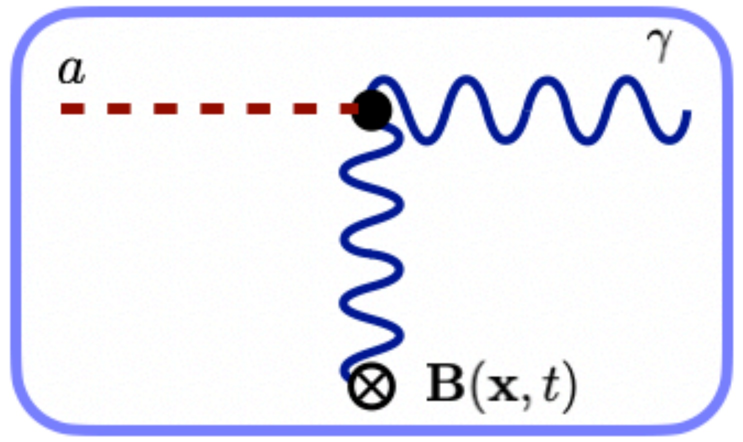

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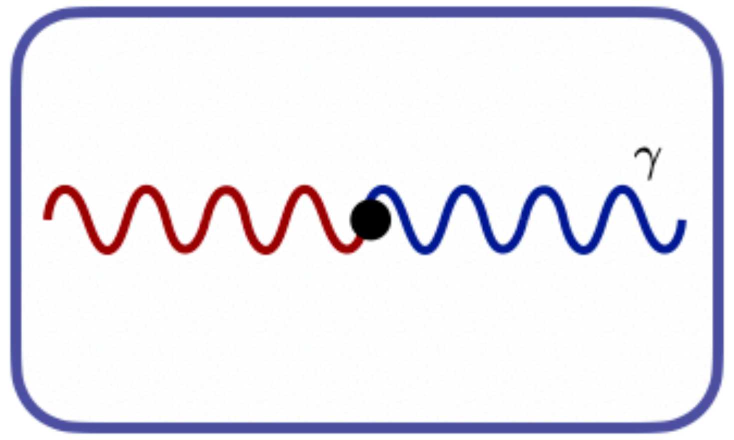

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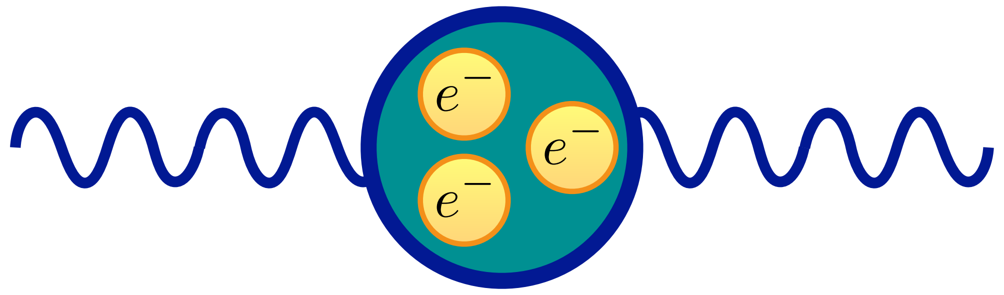

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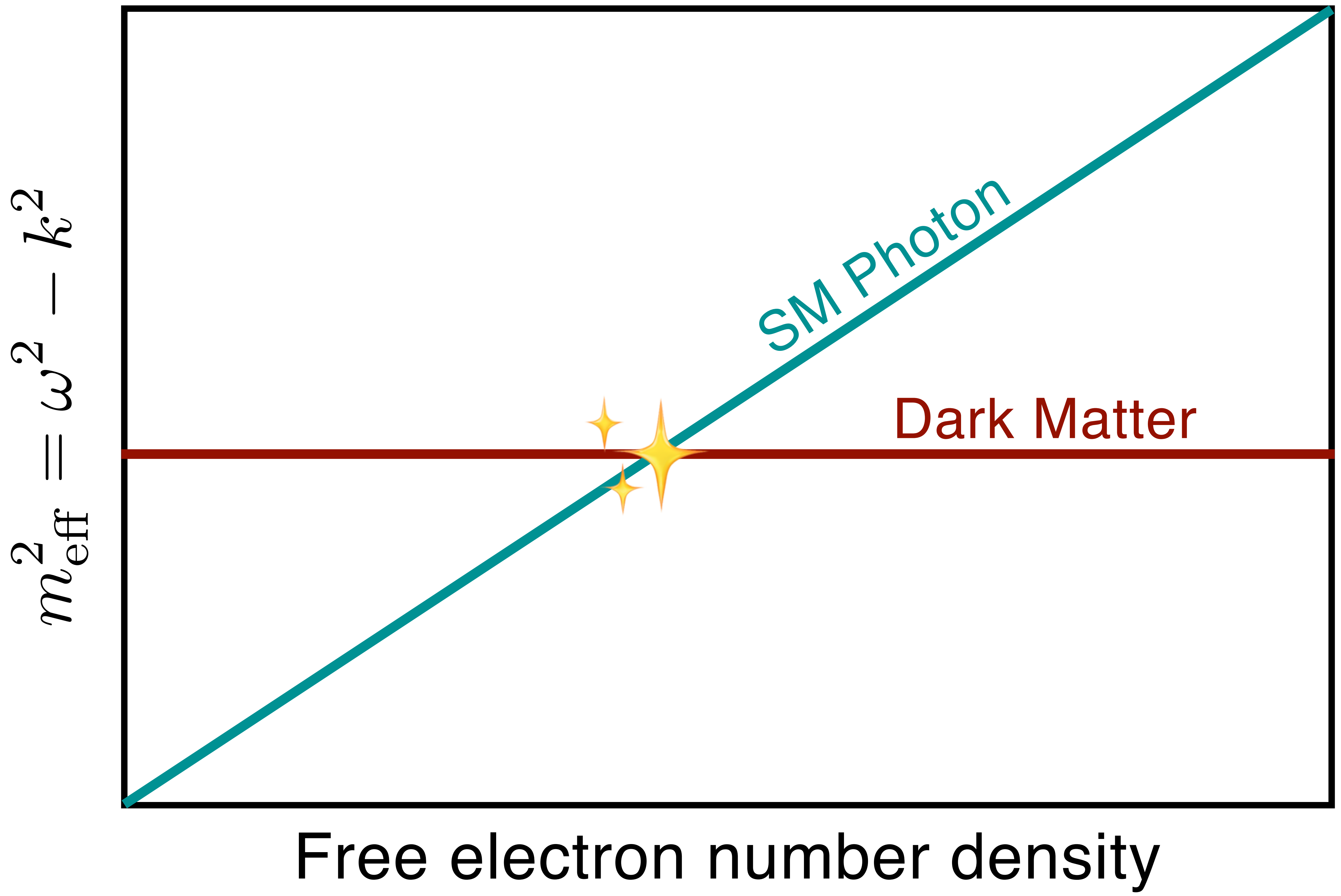
Resonance condition from two-level system



Resonant level crossing

Landau-Zener: $$P_{\alpha\to\gamma} \simeq \frac{f_{\rm pol}\pi}{v_r} g_{\rm eff}^2 m_\alpha \left|\frac{\partial \ln \omega_{\rm pl}^2}{\partial r}\right|_{r_c}^{-1}$$

Axion: $$g_{\rm eff} \to \frac{g_{a\gamma}|\boldsymbol{B}_T|}{m_a}$$

Dark Photon: $$g_{\rm eff} \to \epsilon$$

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Axion: $$g_{\rm eff} \to \frac{g_{a\gamma}|\boldsymbol{B}_T|}{m_a}$$

$$\left(\omega^2 + \nabla^2 - \begin{pmatrix} \Pi_\parallel & -g_{a\gamma\gamma}B_T\omega \\ -g_{a\gamma\gamma}B_T\omega & m_a^2 \end{pmatrix}\right)\begin{pmatrix} A_\parallel \\ a \end{pmatrix} = 0$$

$$\left(\omega^2 + \nabla^2 - \begin{pmatrix} \Pi_T & \epsilon m_{A'}^2 \\ \epsilon m_{A'}^2 & m_{A'}^2 \end{pmatrix}\right)\begin{pmatrix} \boldsymbol{A}_T \\ \boldsymbol{A}'_T \end{pmatrix} = 0$$

Dark Photon: $$g_{\rm eff} \to \epsilon$$

Couple system of equations, usually use WKB and solve linear PDE à la Raffelt-Stodolsky (1988)

Two-level system

WKB: $\omega^2 + \nabla^2 \simeq (\omega + k)(\omega - i\nabla)$

valid for $|\nabla^2 A| \ll k|\nabla A|, \ |\nabla^2 \alpha| \ll k|\nabla \alpha|$

$$\left(-i\nabla + \frac{1}{2k}\begin{pmatrix} \omega_{\rm pl}^2 - m_\alpha^2 & \Pi_{A\alpha} \\ \Pi_{A\alpha} & 0 \end{pmatrix}\right)\begin{pmatrix} A \\ \alpha \end{pmatrix} = 0$$

Good approximation for many astrophysical environments, *e.g.*:
- *axions near NSs* — Hook et al (2018), Foster et al (2020), Foster et al (2022)
- *DPs near NSs* — Hardy & Song (2022)
- *DPs in the Solar corona* — An et al (2020, 2023)

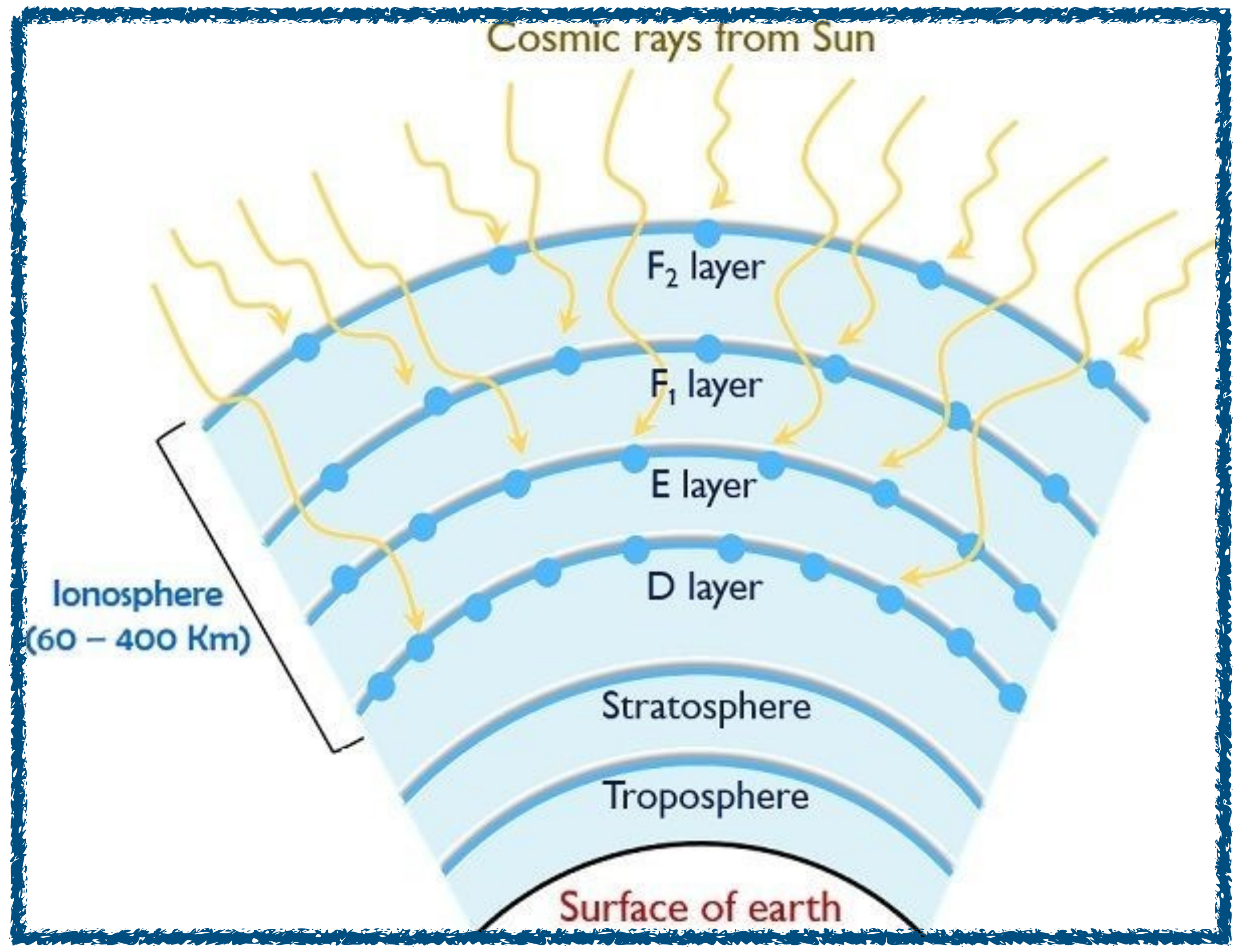
+++

Probability of conversion:

$$P_{\alpha\to A} \simeq \left| \int_0^\infty dz\, \frac{\Pi_{A\alpha}}{2k}\, e^{-i\int_0^z dz'\,(m_\alpha^2 - \omega_{\rm pl}^2)/2k} \right|$$

Yields the Landau-Zener formula

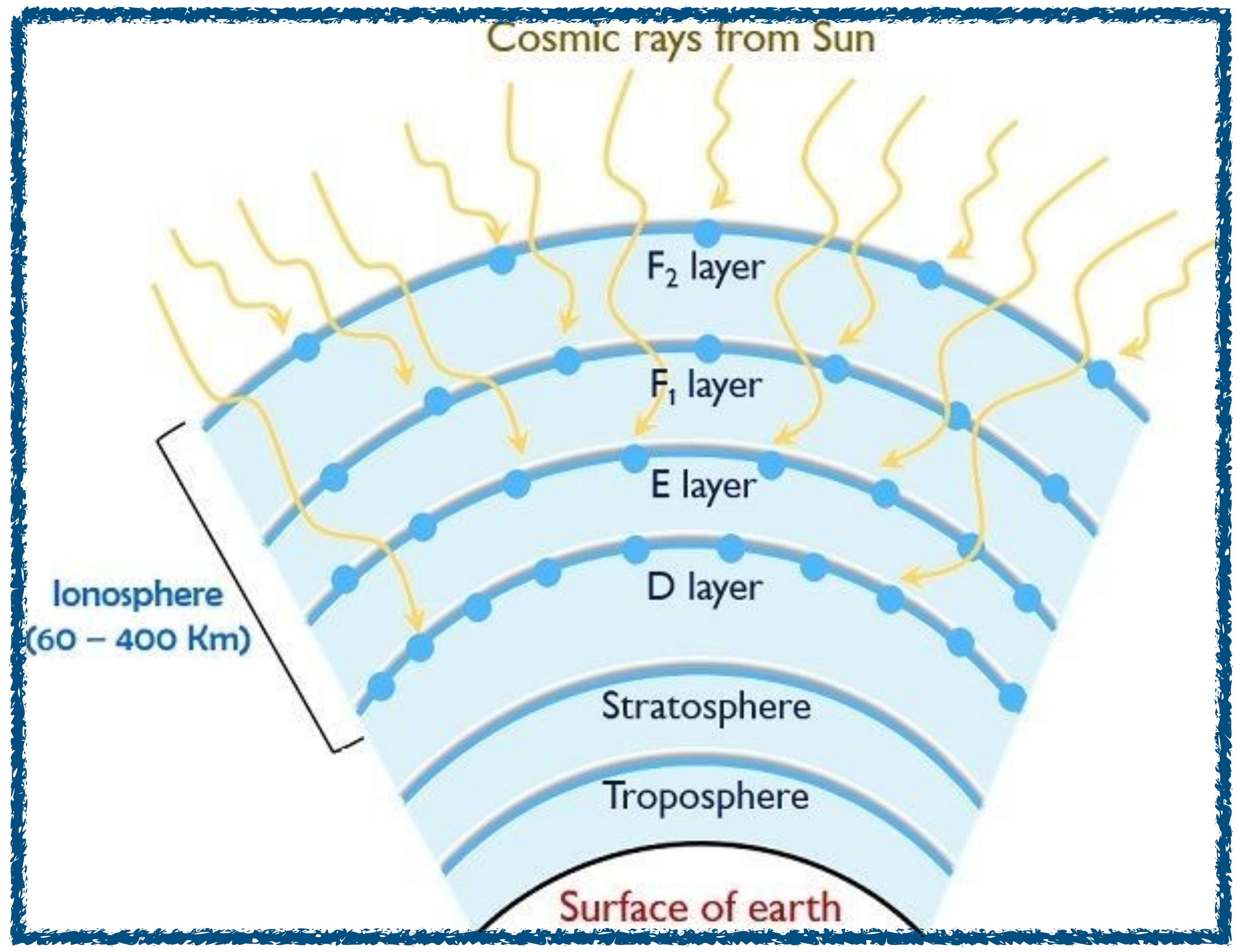
The Ionosphere

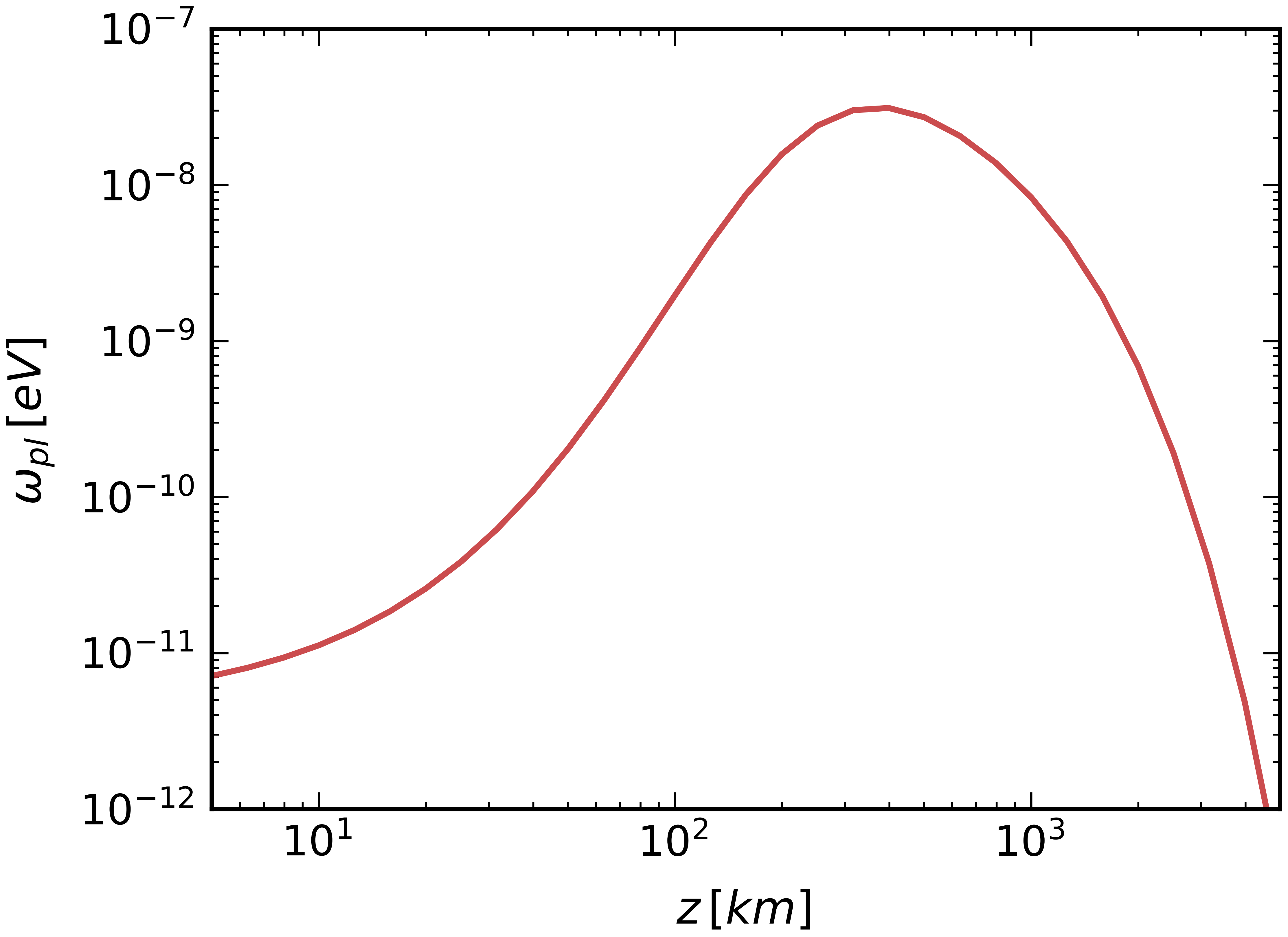


Created by ionising UV & X-ray radiation.

The Ionosphere

Created by ionising UV & X-ray radiation.





Chapman model:

- Scale height H
- Max. free electron n_e
- Max. height $r_{\rm max}$

Scale height sets variational length scale:

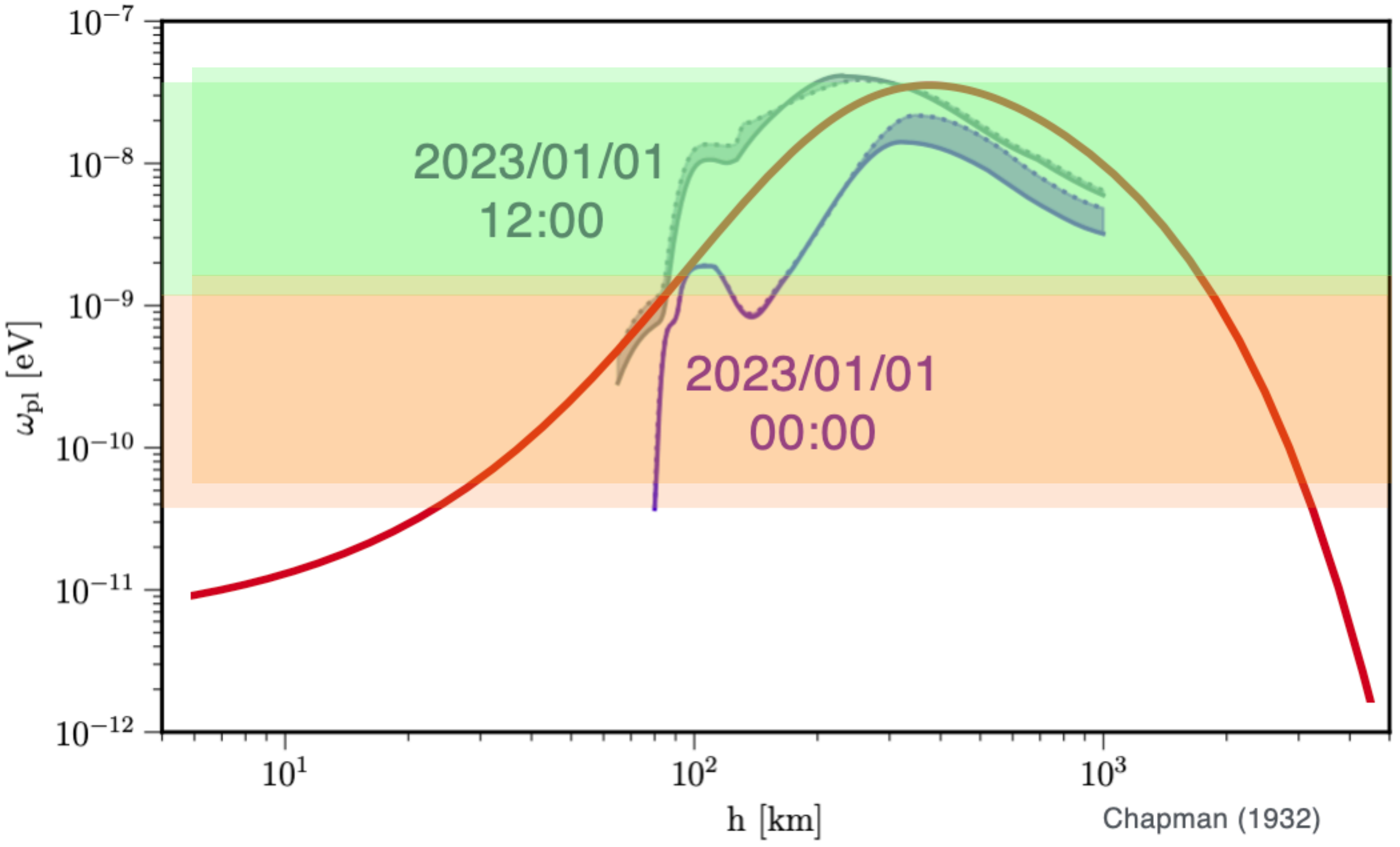
$$\left|\frac{\partial \ln \omega_{\rm pl}^2}{\partial r}\right|_{r_c}^{-1} \gtrsim 2H$$

The *real* Ionosphere

For decade in mass, Chapman is a reasonable middle ground

Low masses, poor approximation

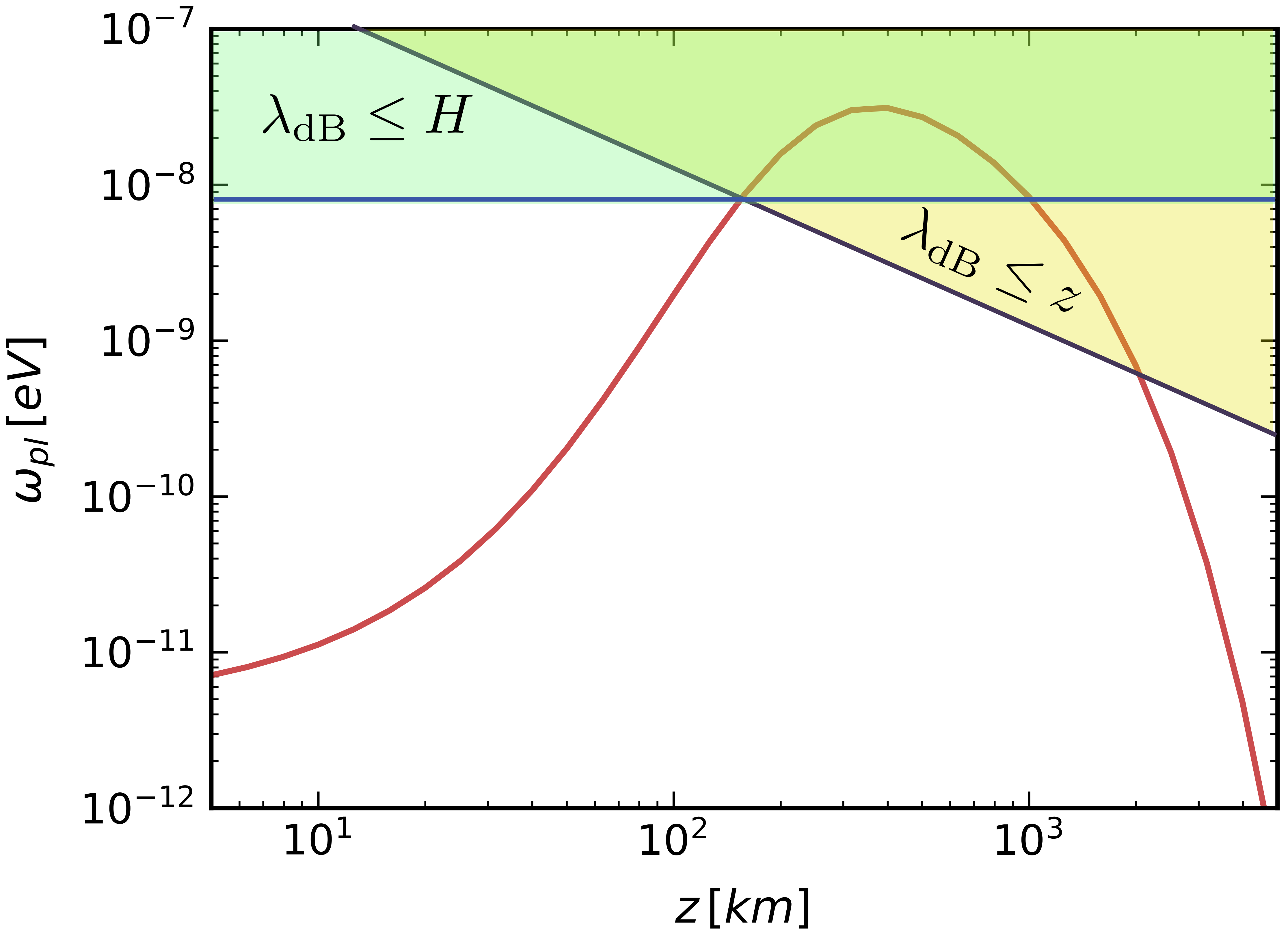
Real ionosphere *steeper*



Data from International Ref. Ionosphere (IRI) https://kauai.ccmc.gsfc.nasa.gov/instantrun/iri

Chapman scale height $H \sim 100\,\mathrm{km}$

Over most parameter space, WKB
not valid



Presence of local maximum also problematic

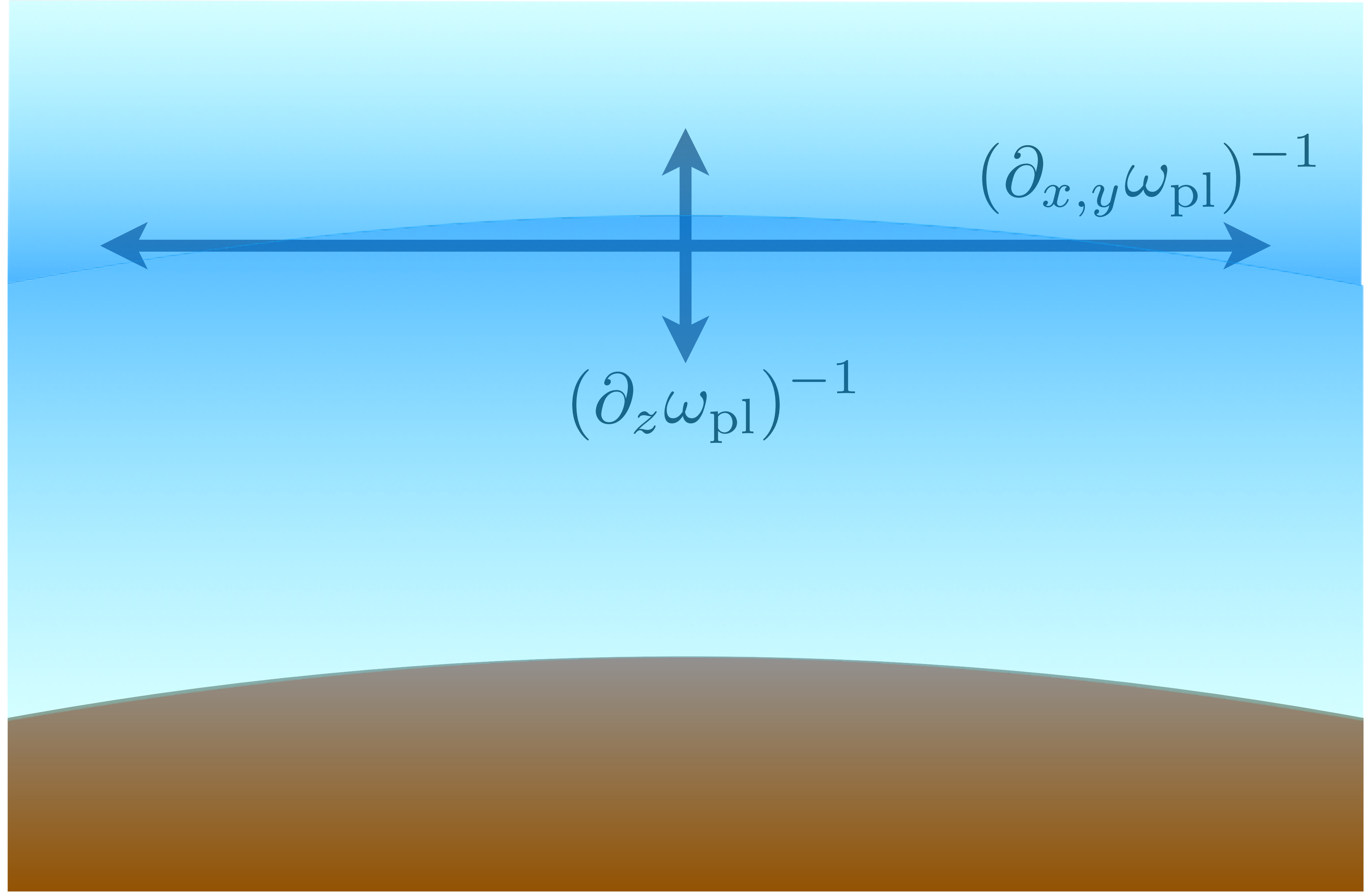
local extrema: Brahma et al (2023)

Back to initial equations

Need to solve full 2nd order equation $$\left(\omega^2 + \nabla^2 - \begin{pmatrix} \Pi_{AA} & \Pi_{A\alpha} \\ \Pi_{A\alpha} & m_\alpha^2 \end{pmatrix}\right) \begin{pmatrix} A \\ \alpha \end{pmatrix} = 0$$

Transverse variation length-scale long — model as 1D

$$\left[\partial_z^2 + \omega^2 - \frac{\omega^2}{\omega^2 + i\nu(z)\omega}\,\omega_{\rm pl}^2\,(z)\right]\boldsymbol{E}_T\,(z) = \Pi_{A\alpha}\partial_t\alpha\,(z)$$

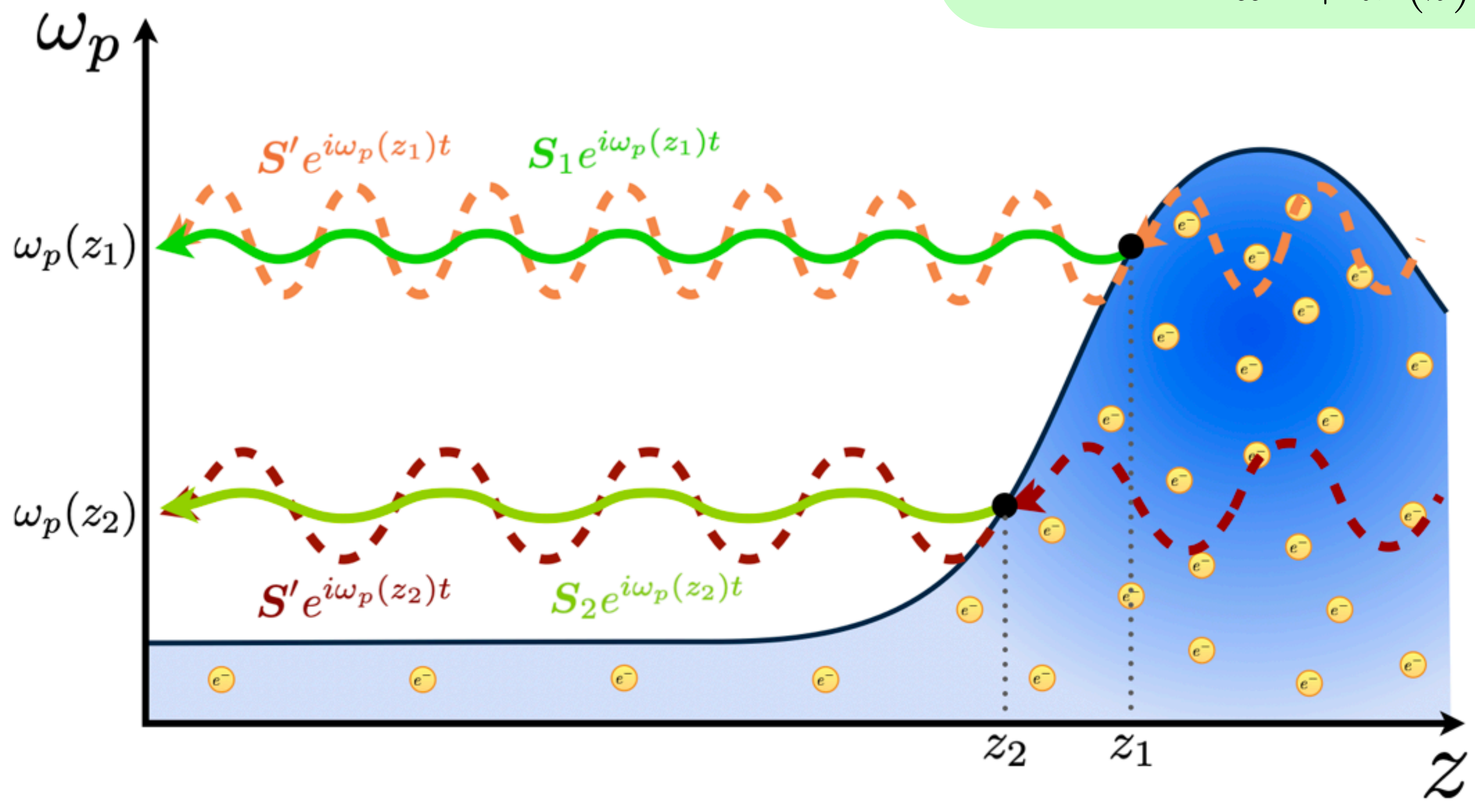


Ionosphere as a driven cavity

Ionosphere cavity:

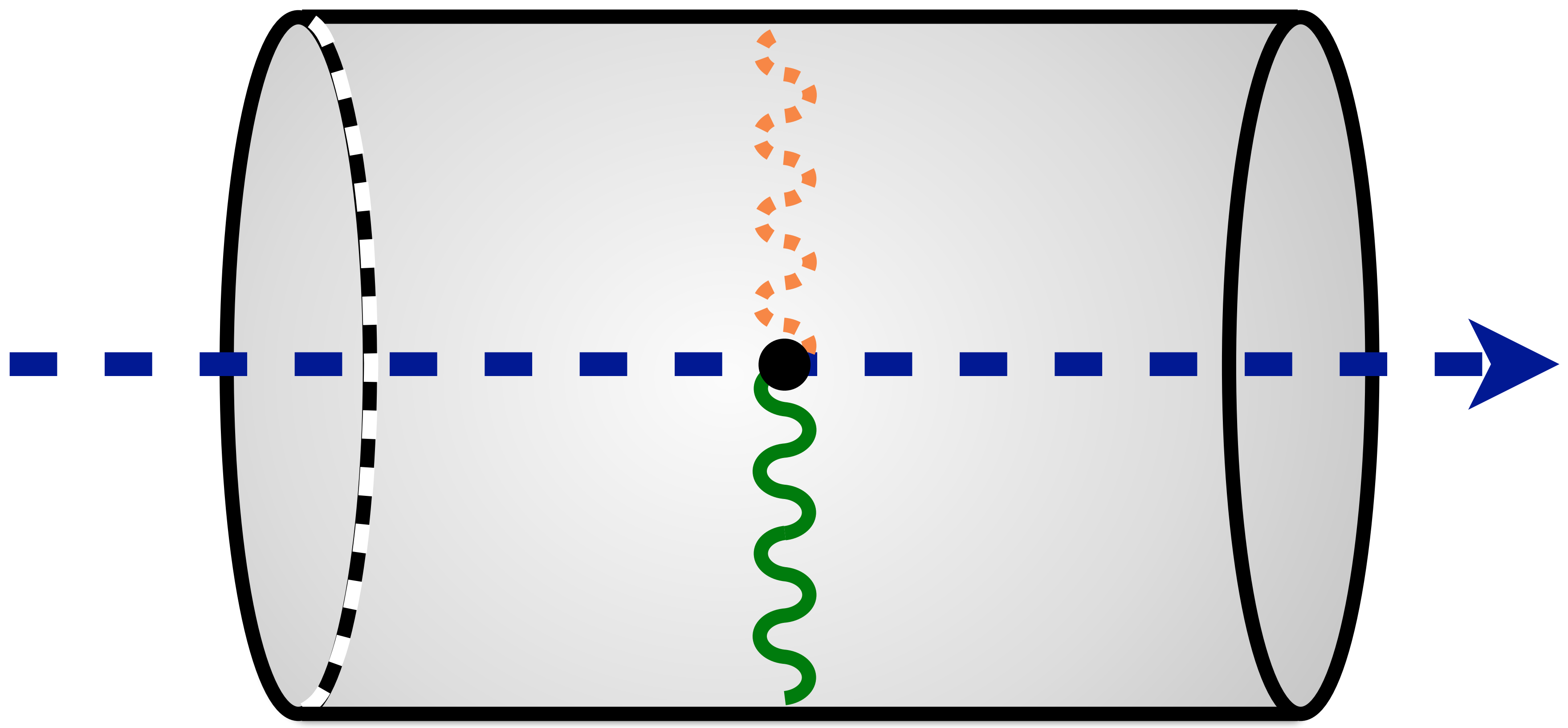
$$\left[\nabla^2 + \omega^2 \left(1 - \frac{1}{\omega^2 + i\nu\,\omega}\,\omega_p^2\right)\right] \mathbf{E}_T = i\, g_{\rm eff}\, m_{\rm DM}^2\, \omega\, \mathbf{V}$$

$$\varepsilon(z) \sim 1 - \frac{\omega_{\rm pl}^2(z)}{\omega^2 + i\nu(z)\omega}$$



Actual cavity:

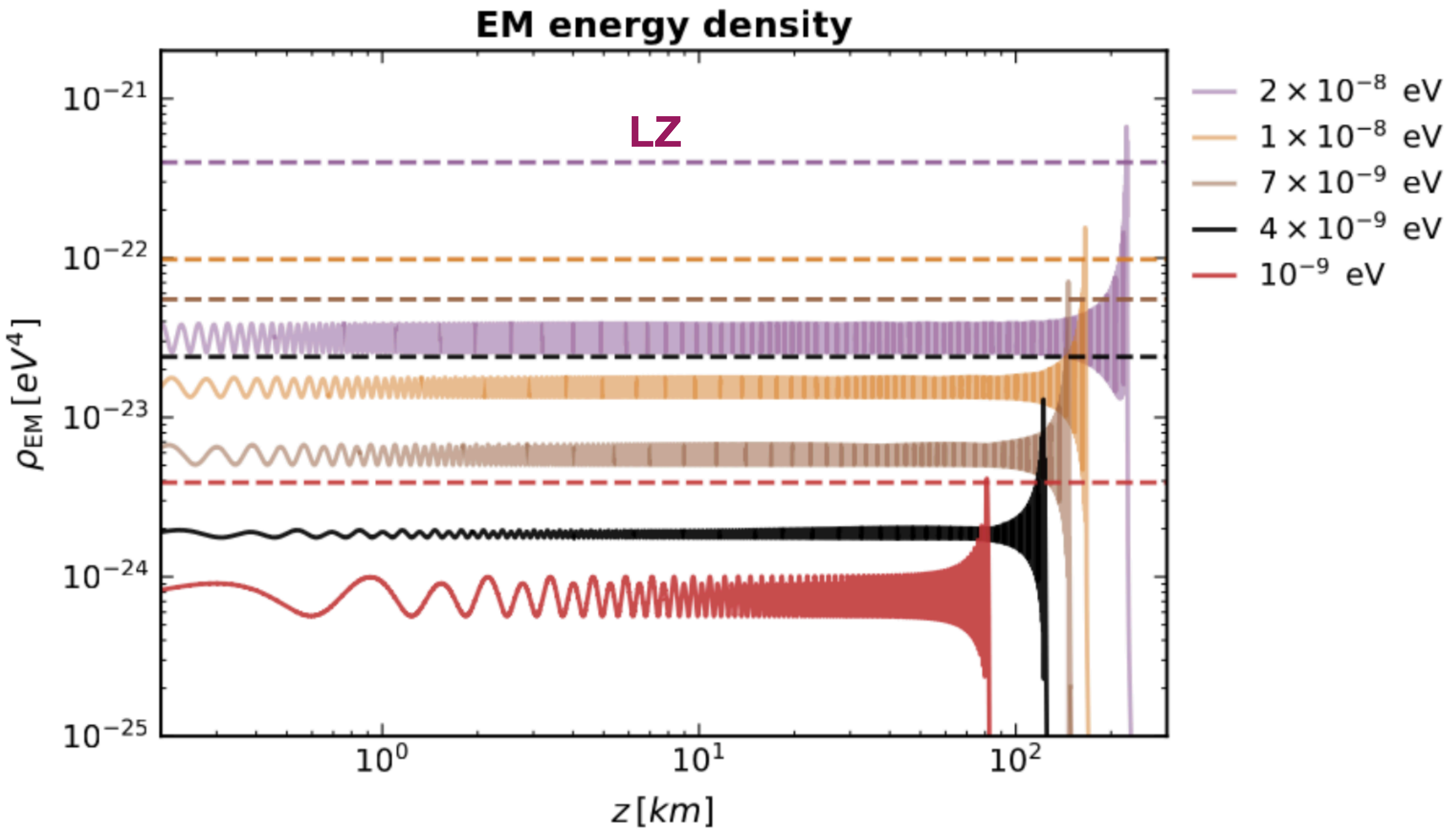
$$(\nabla^2 - \mu\varepsilon\partial_t^2)\boldsymbol{E} = \mu\partial_t \boldsymbol{j}_\alpha$$



Our signal

Numerical solution w/ Thomas Algorithm for tridiagonal matrix

```python
def TDMASolveNew(a, b, c, d):

    cprime = np.zeros(len(c), dtype = 'complex_')
    dprime = np.zeros(len(d), dtype = 'complex_')

    for i in range(len(c)-1):
        if i ==0:
            cprime[i] = c[i]/b[i]
            dprime[i] = d[i]/b[i]
        else:
            cprime[i] = c[i]/(b[i]-a[i] * cprime[i-1])
            dprime[i] = (d[i]-a[i]*dprime[i-1])/ (b[i] - a[i]*cprime[i-1])

    Er = np.zeros(len(b), dtype = 'complex_')

    for i in reversed(range(len(c)-1)):

        if i == len(c)-1:
            Er[i] = 0#Er[i] = dprime[i]
        elif i == 0:
            Er[i] = 0
        else:
            Er[i] = dprime[i] - cprime[i] * Er[i+1]

    return Er
```



hep-ph/2405.13882 Carl Beadle, AC and Sebastian Ellis

$$\rho_{\rm EM} \simeq \frac{3\times10^{-23}\,{\rm eV}^4\left(\frac{g_{\rm eff}}{10^{-10}}\right)^2}{1+\exp\left[-\left(\frac{m_\alpha}{2.3\times10^{-9}{\rm eV}}-3.8\right)\right]}$$

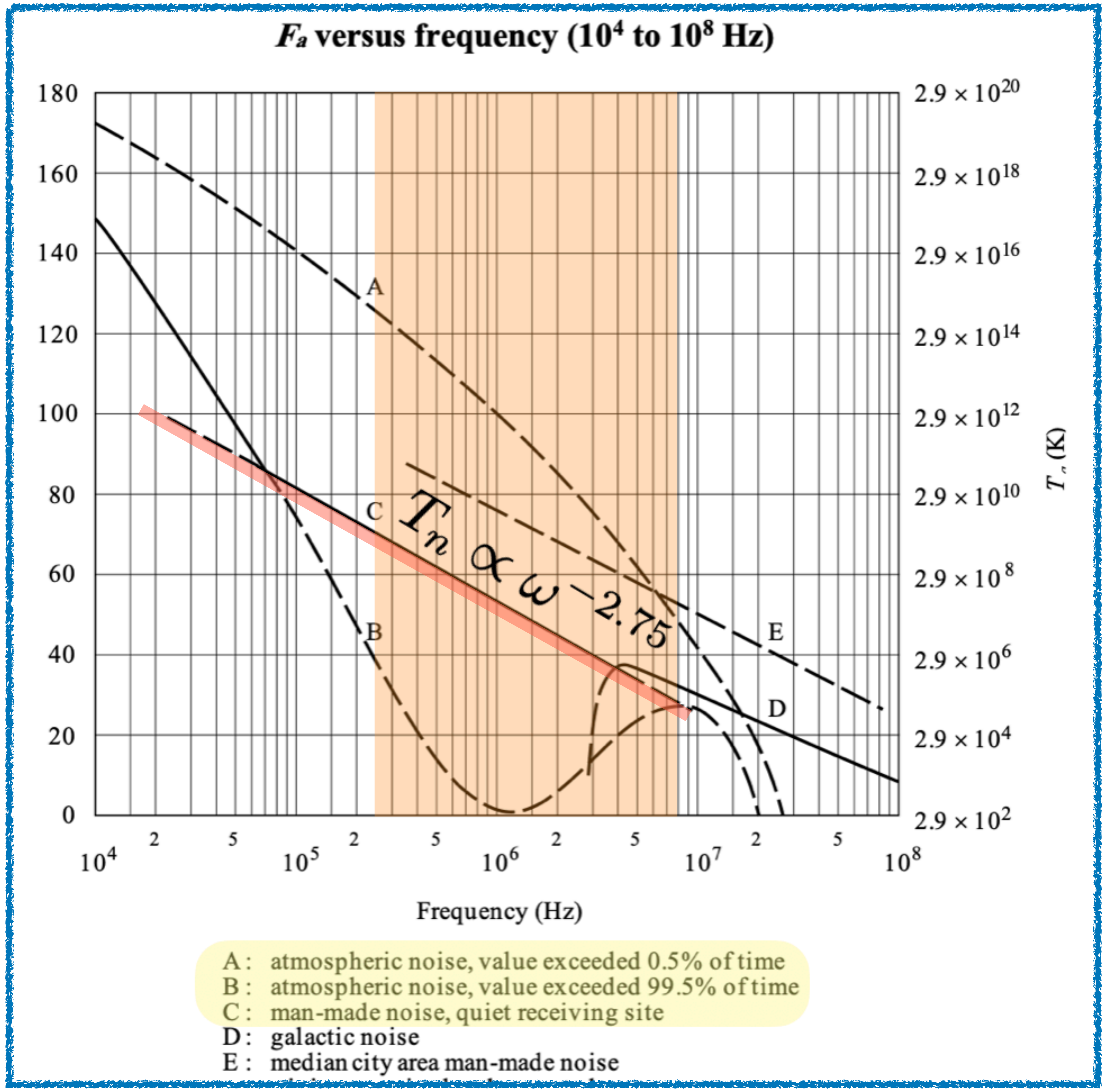
Our noise

ITU provides us with estimates for our noise

$$10^5\,\mathrm{K} \lesssim T_n \lesssim 10^9\,\mathrm{K}$$

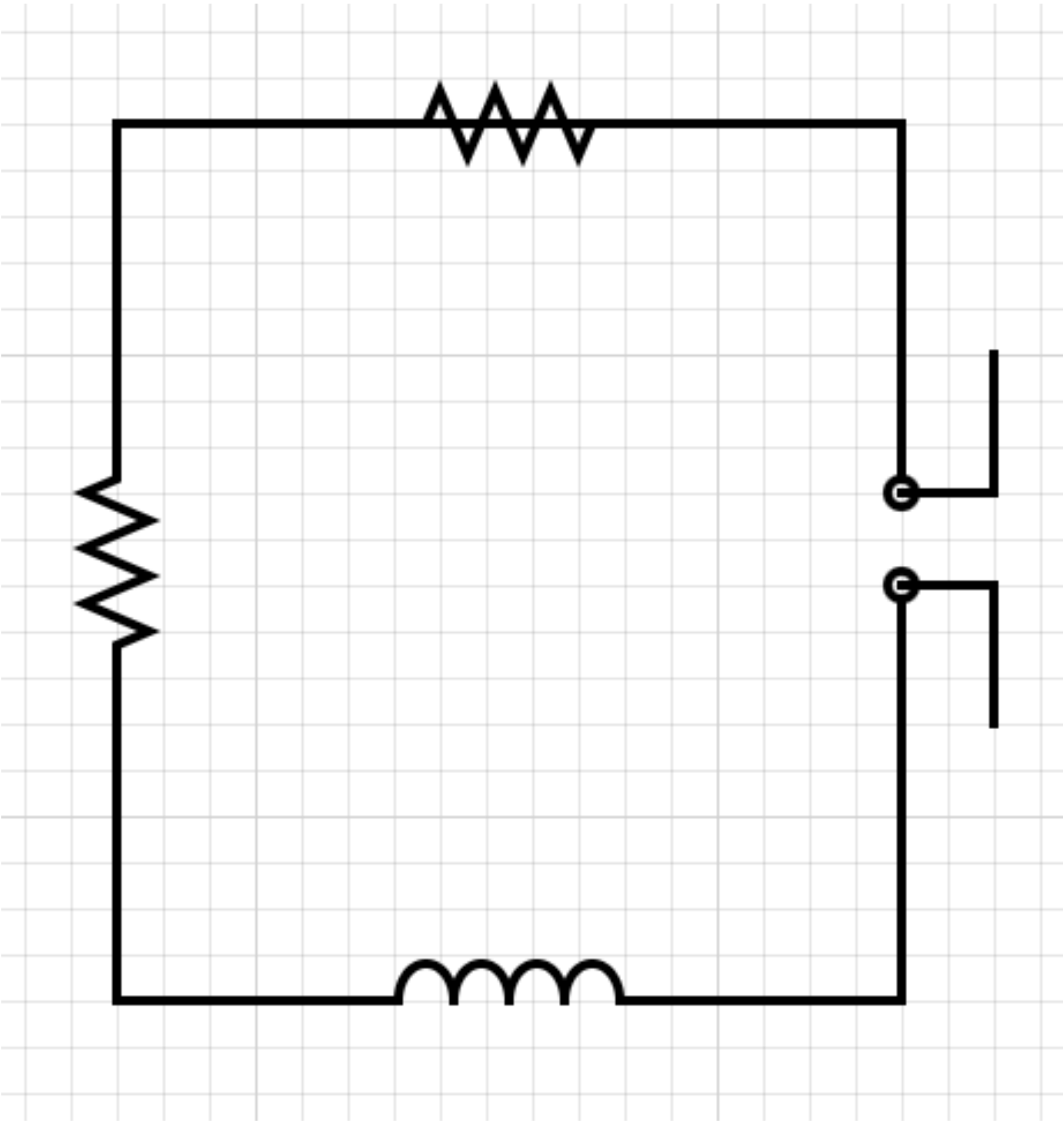
We can map from temperature to a noise PSD using:

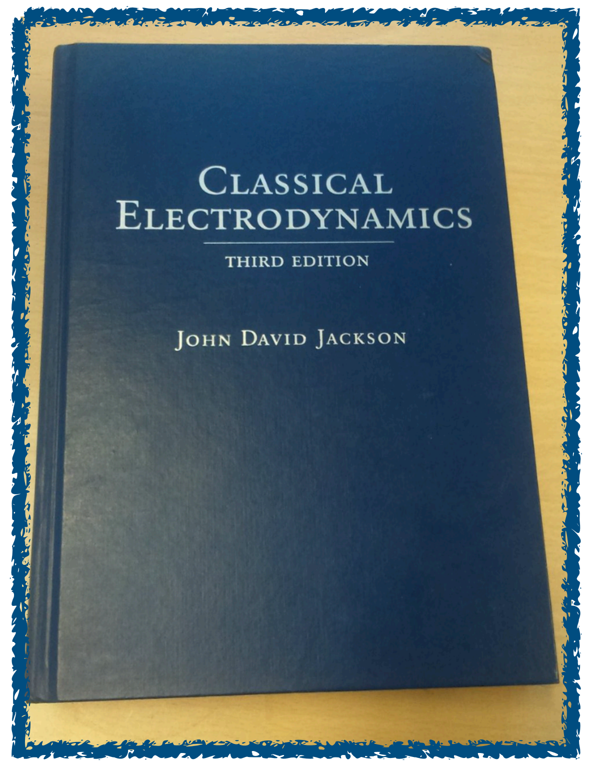
$$S_n(\nu) \approx \frac{32}{3}\pi^2\nu^2 T_n(\nu)$$



Antenna

We model a prospective antenna and read-out as a simple RLC-circuit





$$P_L = \int \mathrm{d}\omega \, \frac{\omega^2 \, h^2}{R_L \, L^2 \left[\left(\omega^2 - \omega_0^2\right)^2 + \omega^2 \, \Delta\nu^2 \right]} S_E\left(\omega\right)$$

$$\omega_0^2 \equiv \frac{1}{C_A L}$$

$$\Delta\nu \equiv \frac{R_A + R_L}{L}$$

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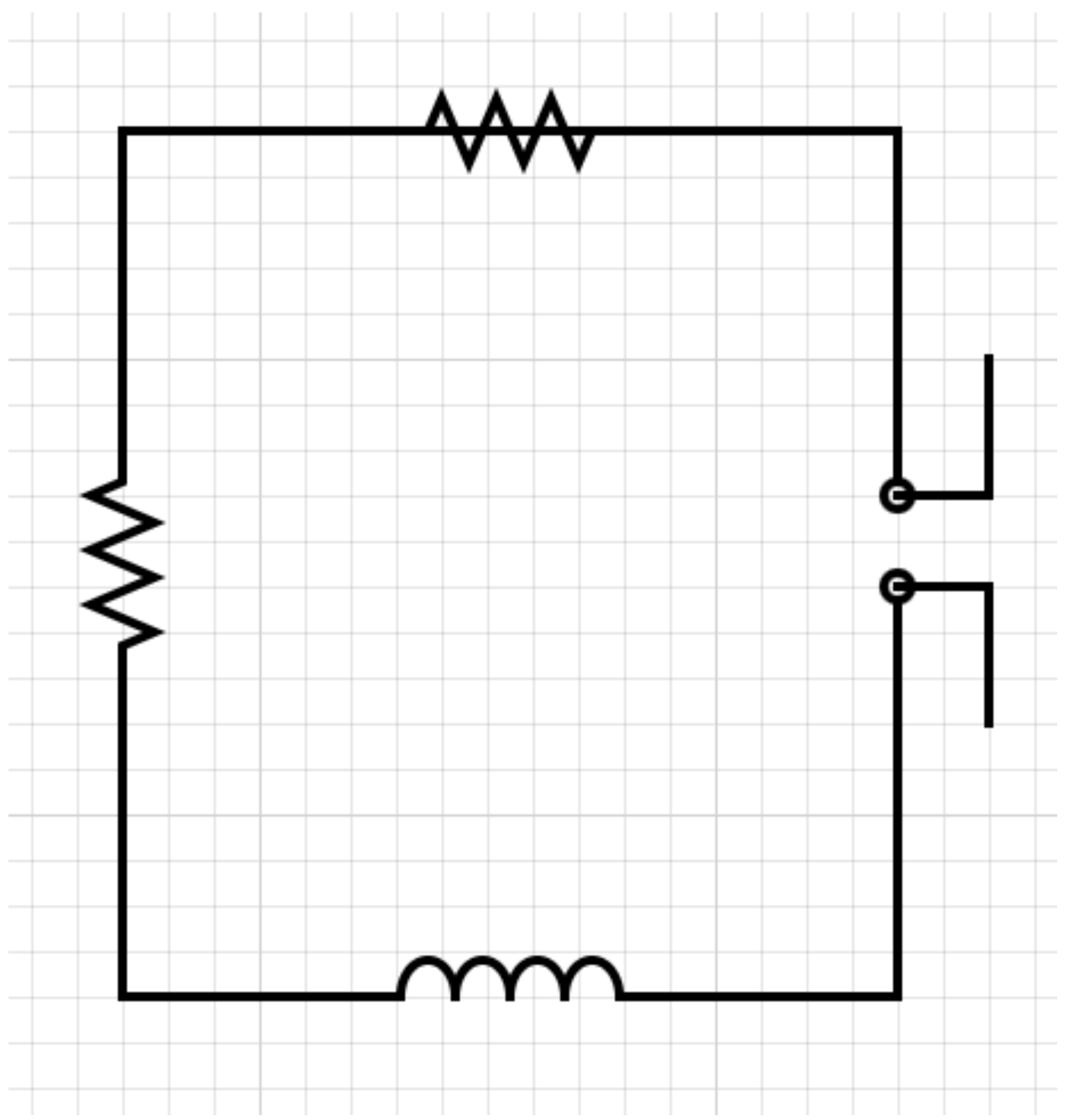

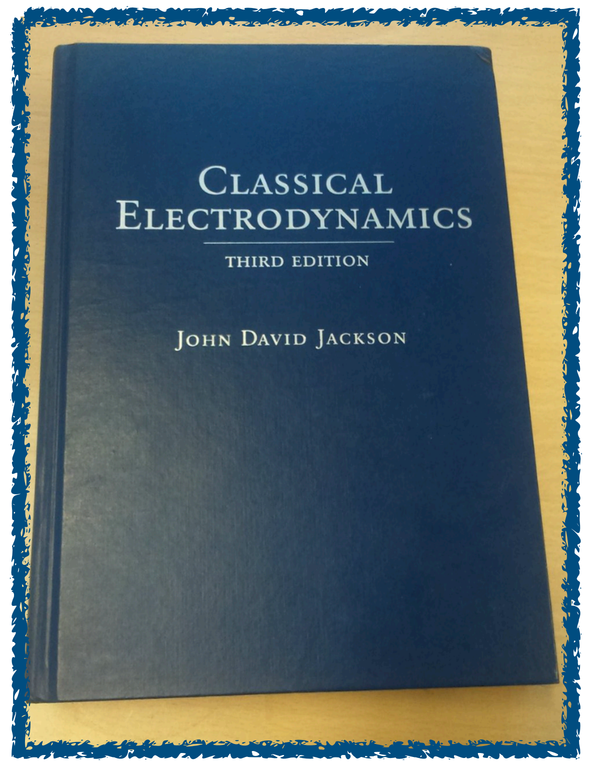

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$$\omega_0^2 \equiv \frac{1}{C_A L}$$

$$\Delta\nu \equiv \frac{R_A + R_L}{L}$$

$$\Delta\nu \sim 10\,\mathrm{kHz} \times \left(\frac{h}{1\,\mathrm{m}}\right) \left(\frac{m_\alpha}{10^{-8}}\right)^2 \left(\frac{R}{10\,\mathrm{ohm}}\right)$$

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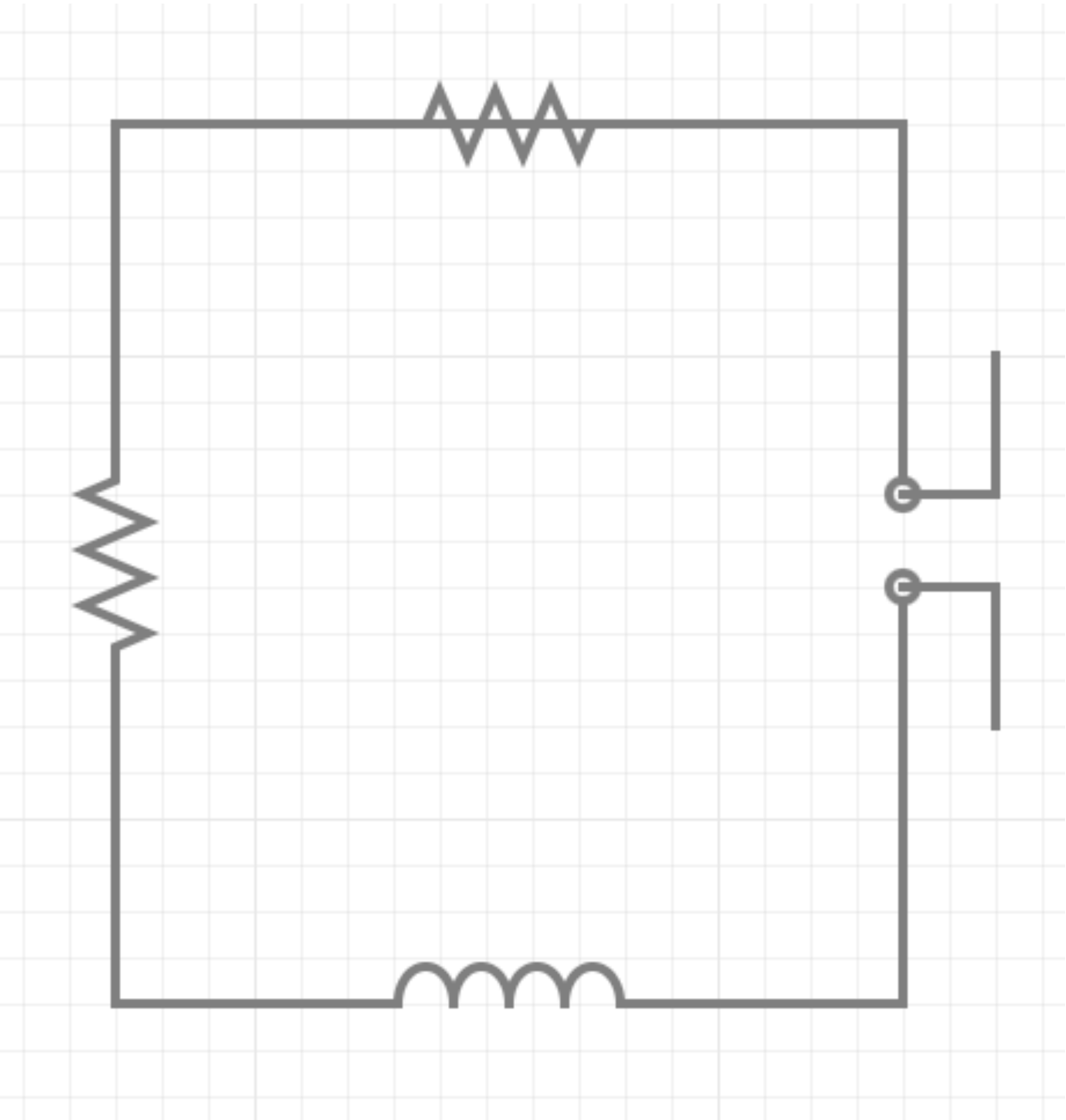
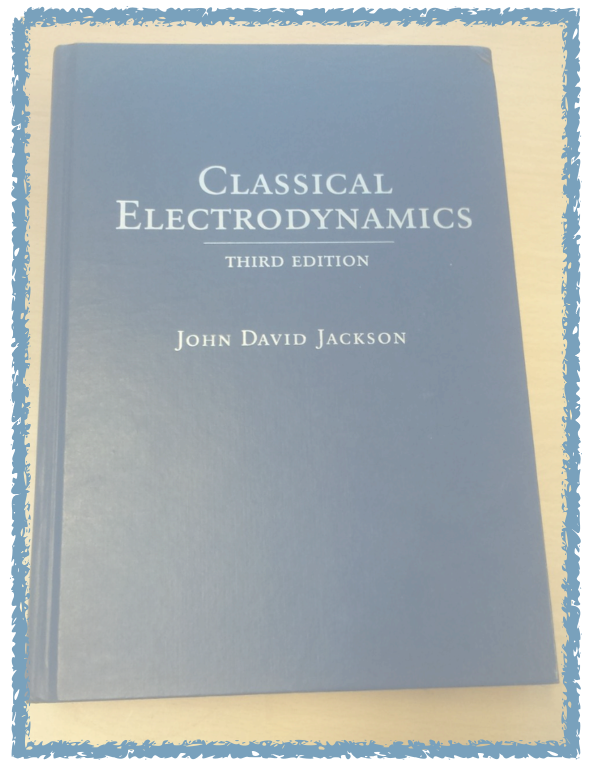
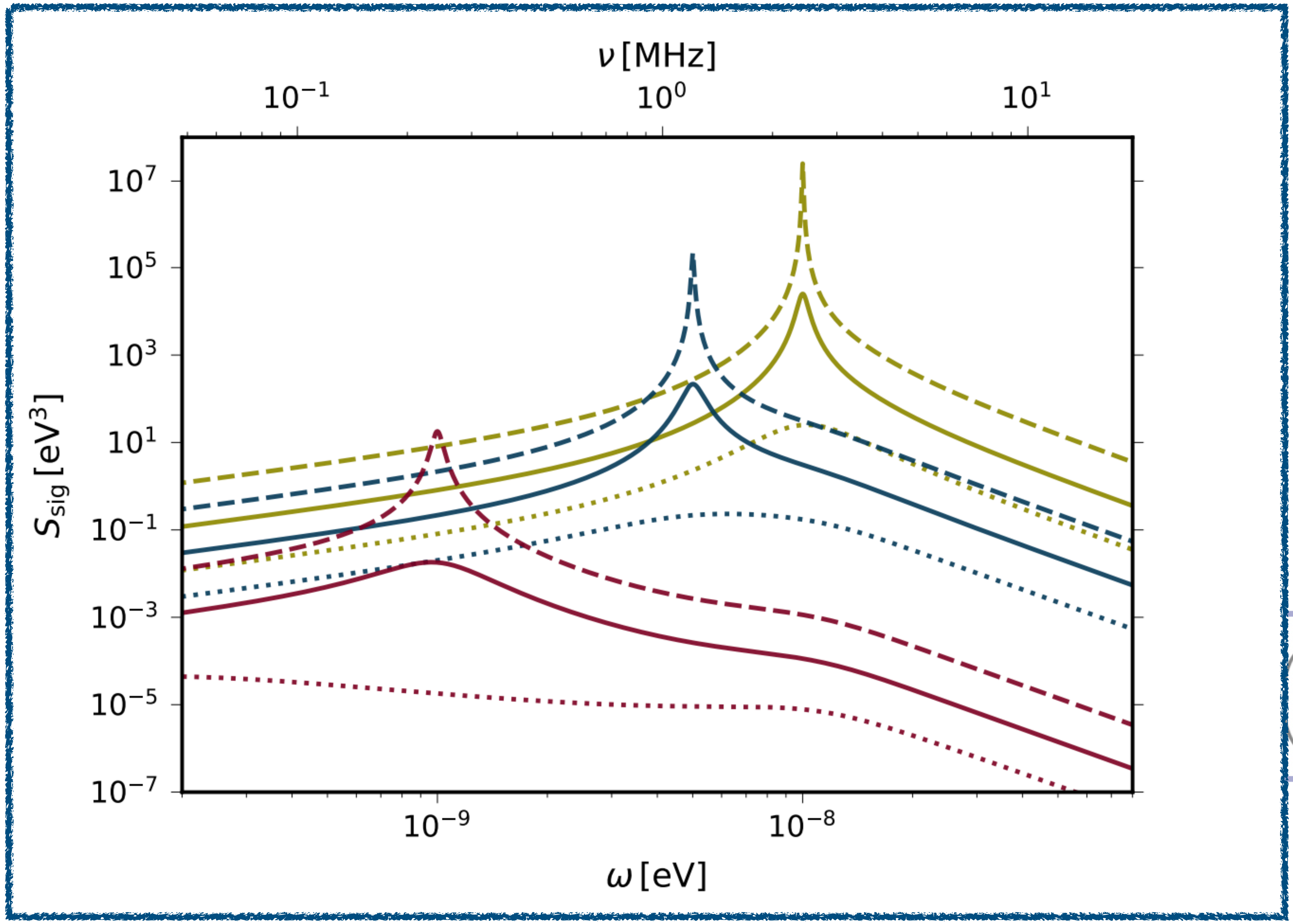




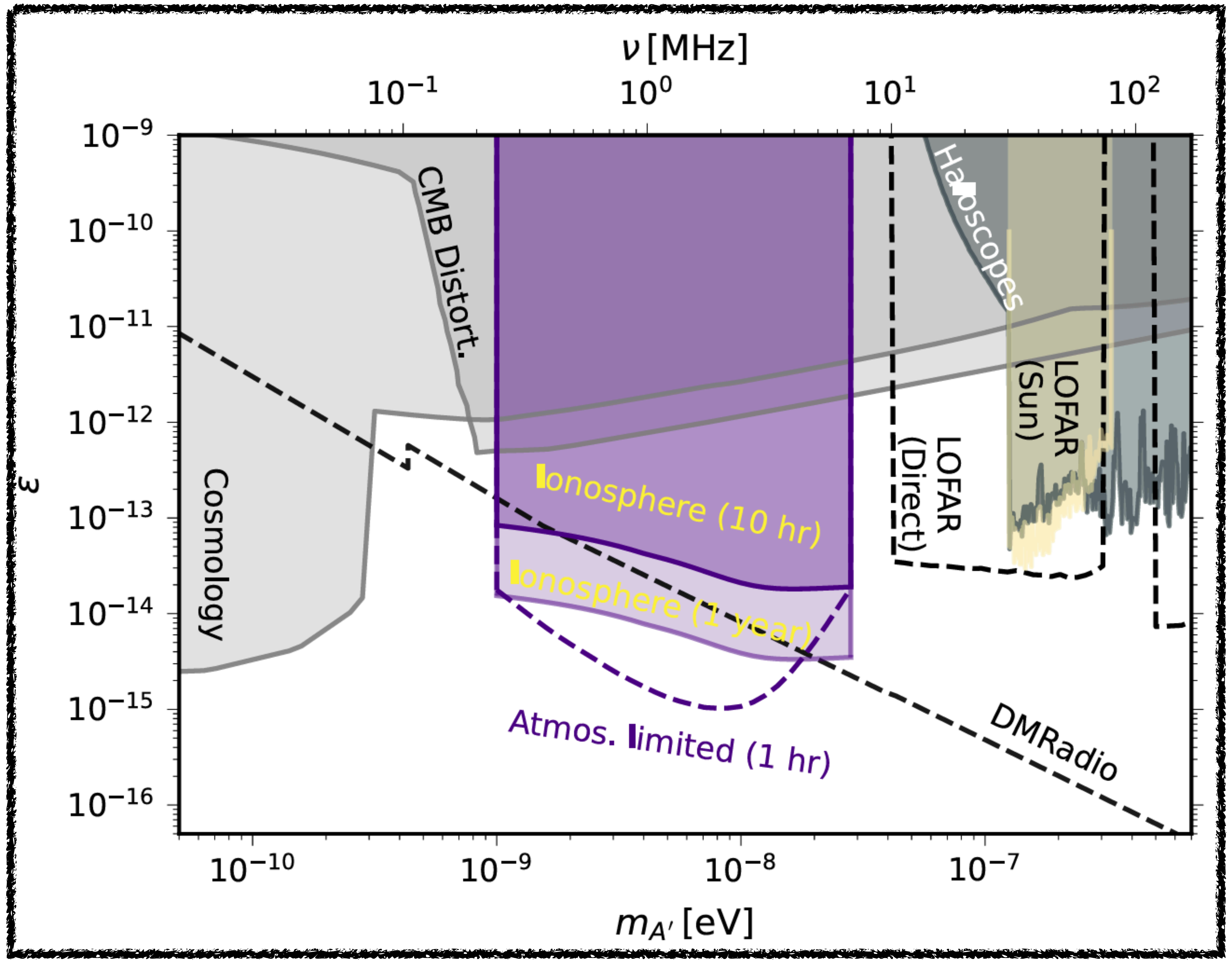


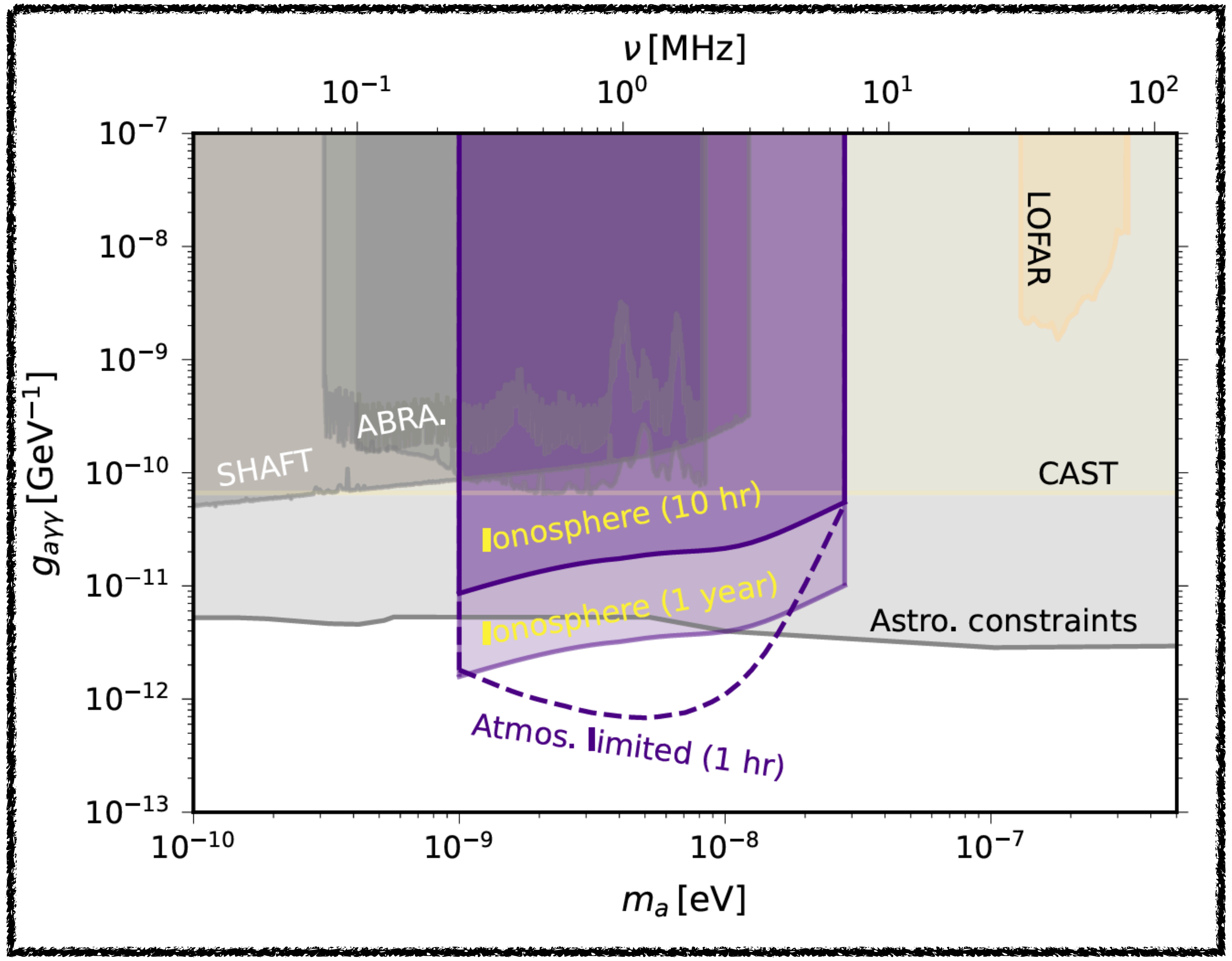
$\left(\frac{R}{10\,\mathrm{ohm}}\right)$

Our results

$$\mathrm{SNR}^2 \simeq t_{\rm int} \int_0^\infty d\nu \left(\frac{\mathcal{S}_{\rm sig}(\omega)}{\mathcal{S}_n(\omega)} \right)^2$$

$$\mathcal{S}_{\rm sig}(\omega) \sim \rho_{\rm EM} f(\omega)$$





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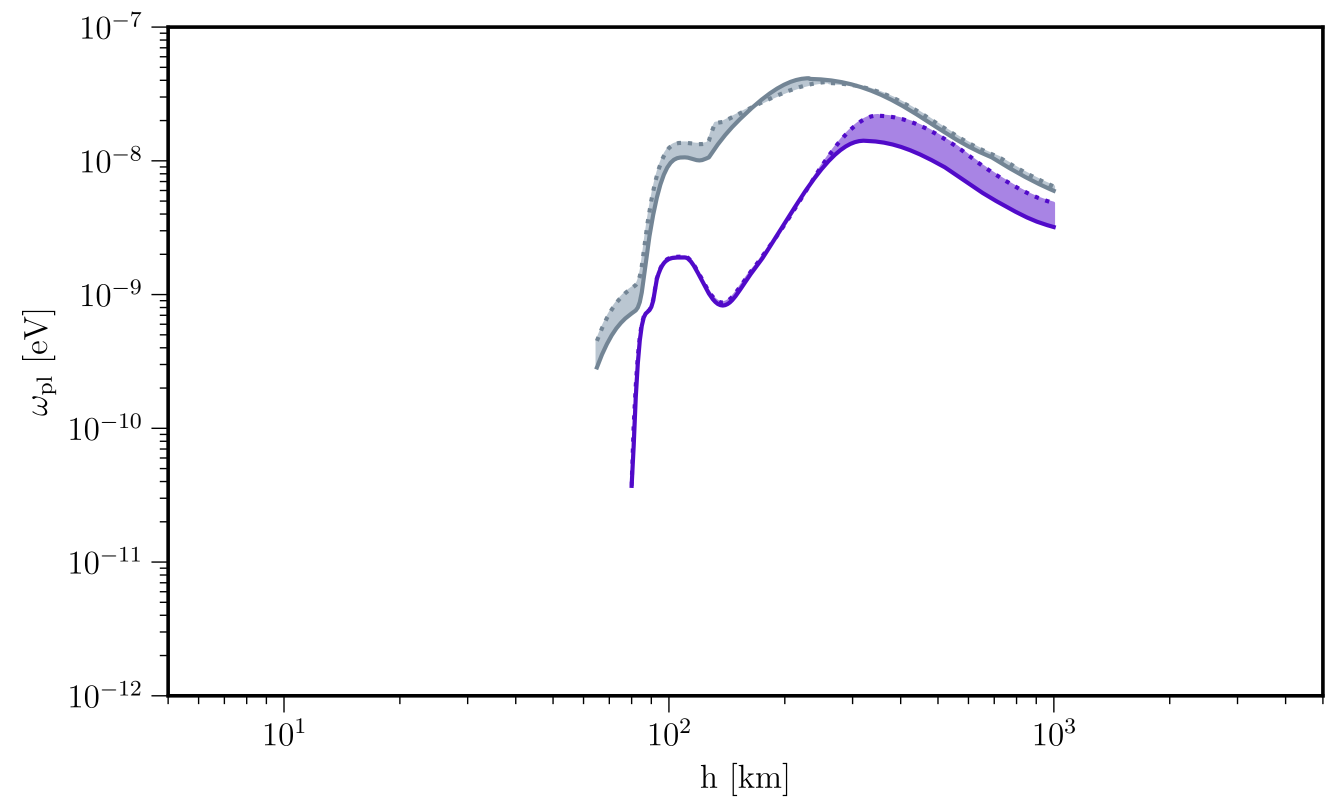
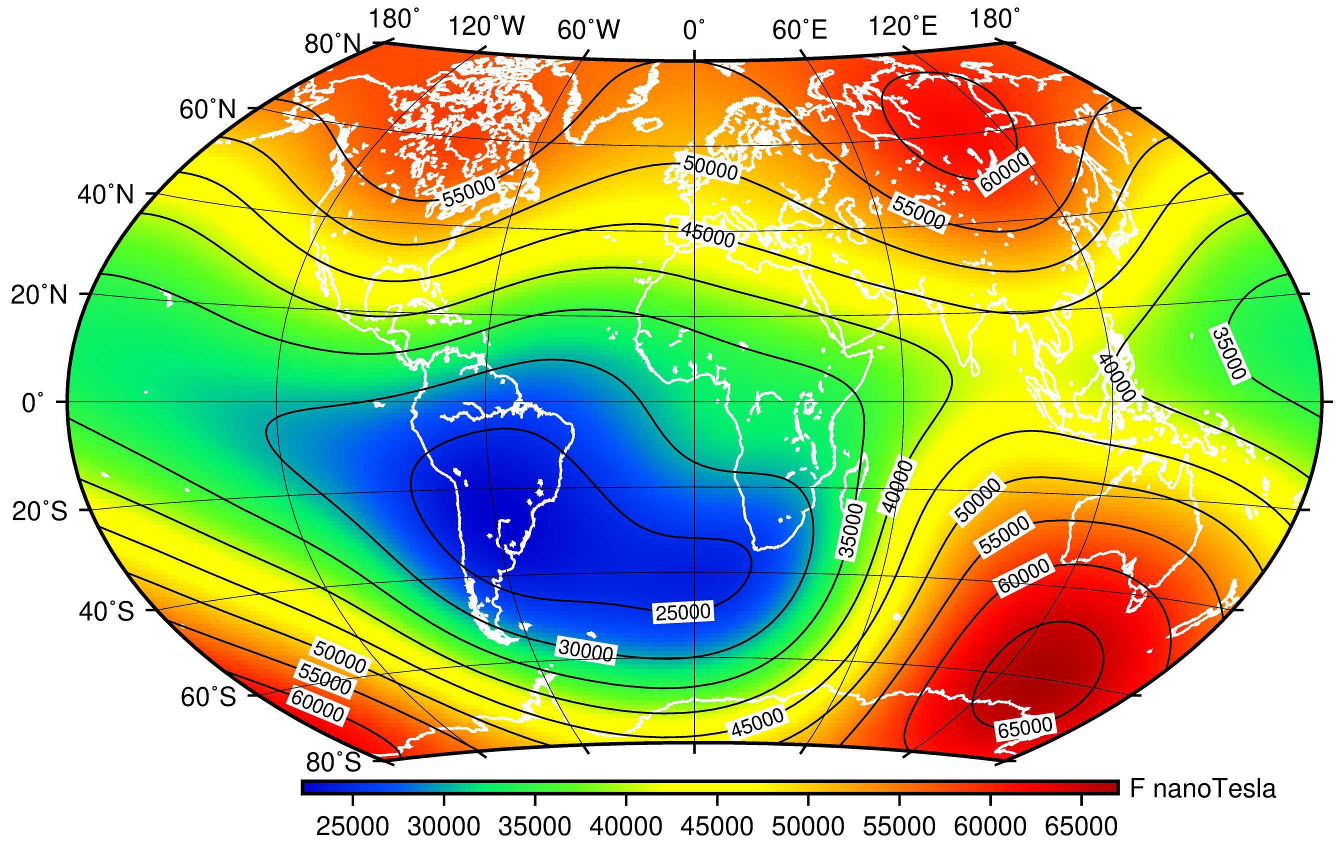
Next steps



Chapman can be replaced with real ionosphere data



https://geomag.bgs.ac.uk/education/earthmag.html

Magnetic field modelling

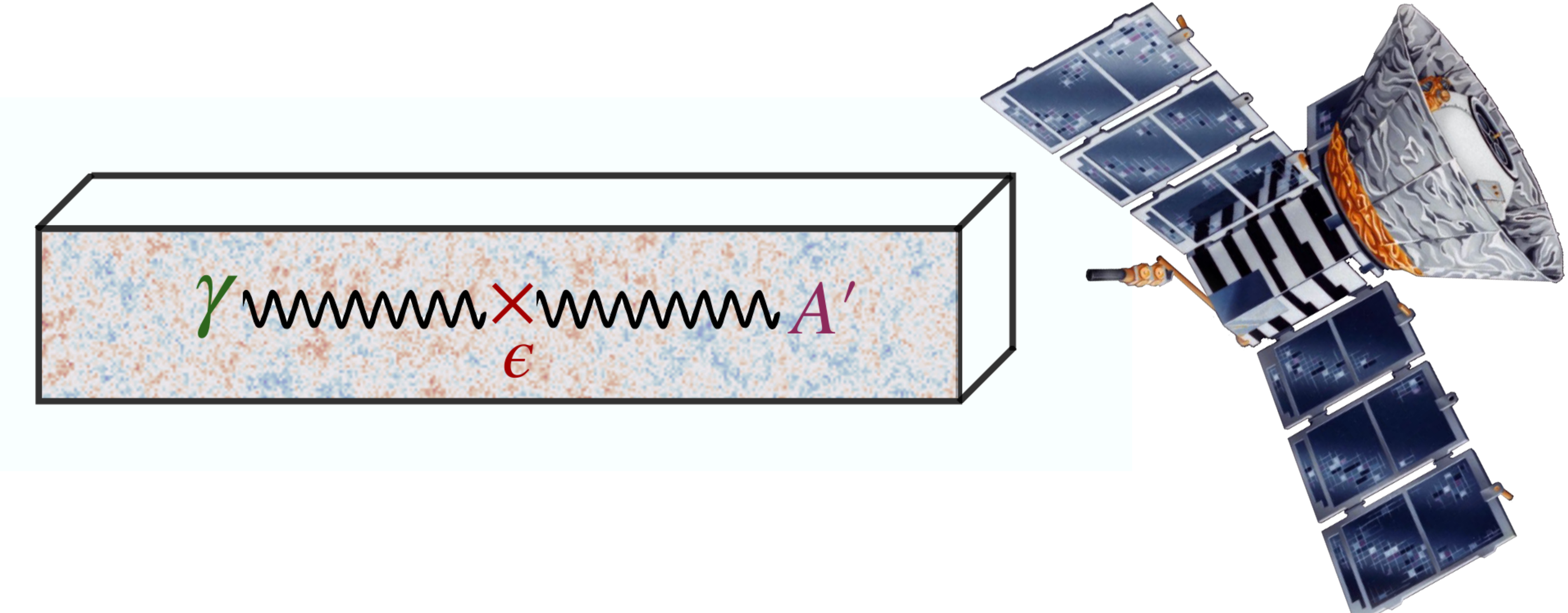
Accounting for diurnal variation in both plasma and ***B***

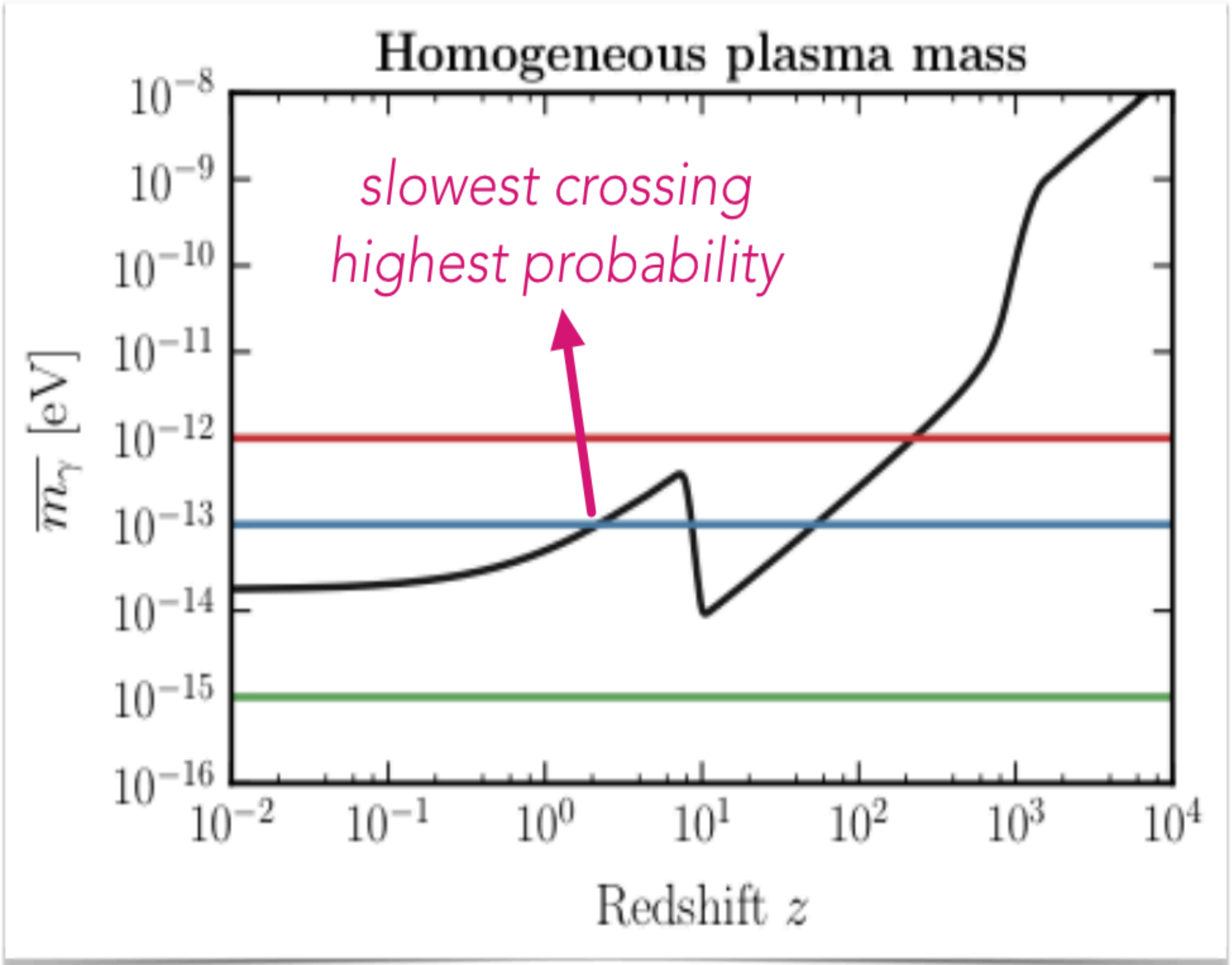
Move on to operate a prototype or use some existing data [McGill and Stanford groups interested]


Gracias!

What if Dark Photons [or axions] are not dark matter?

We can use the inverse process: instead of dark photons into photons, we can convert photons into dark photons [or axions]



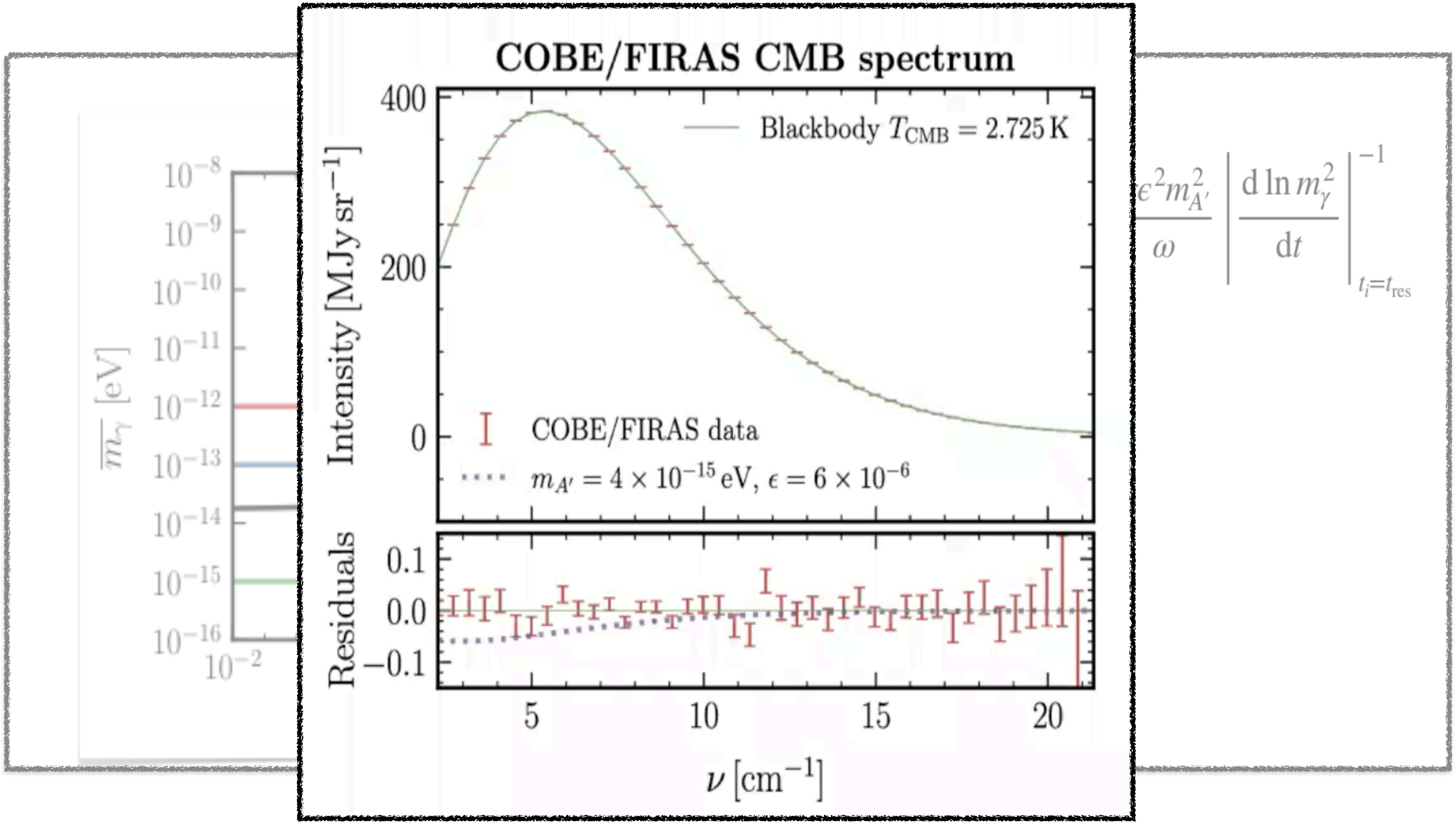


$$P_{\gamma\to A'} = \sum_i \frac{\pi \epsilon^2 m_{A'}^2}{\omega} \left| \frac{\mathrm{d} \ln m_\gamma^2}{\mathrm{d}t} \right|^{-1}_{t_i = t_{\mathrm{res}}}$$

1 crossing

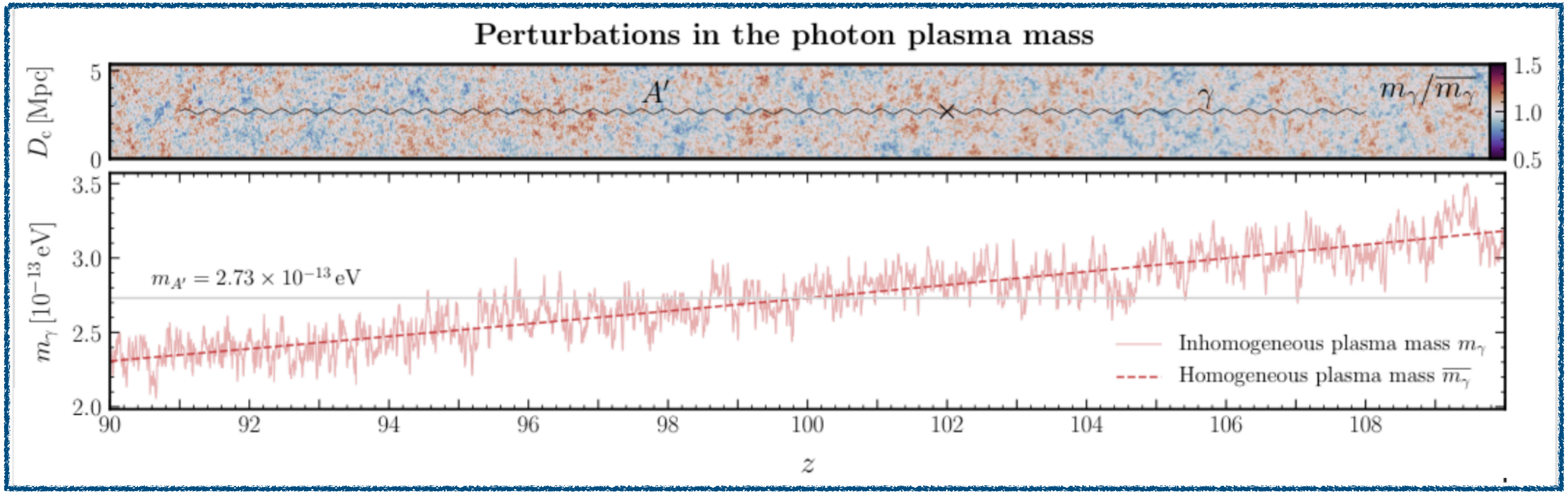
3 crossings

0 crossings



Use precise spectral measurements to look for new physics!

We developed a formalism to treat inhomogeneities in the plasma



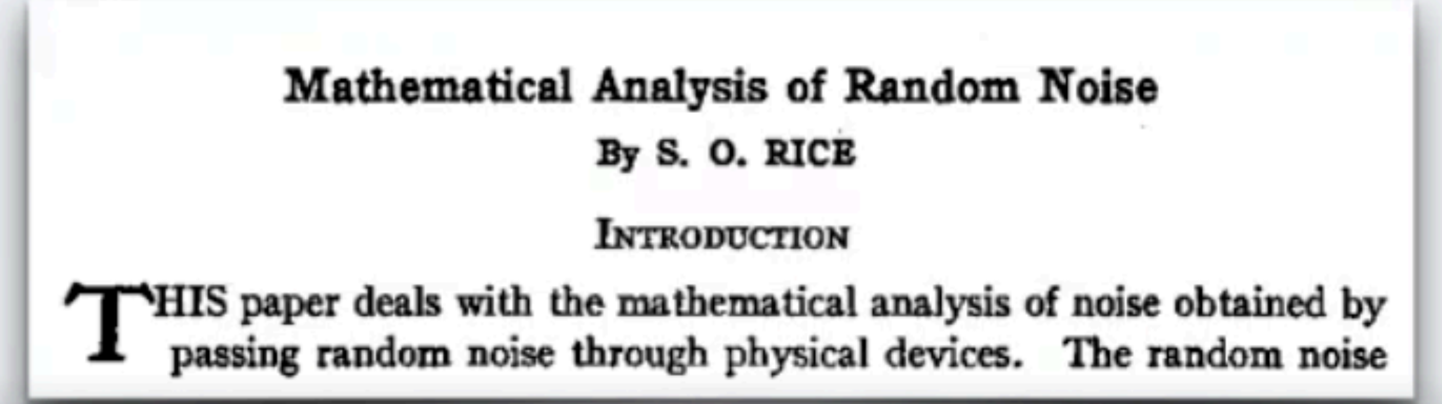
AC, H. Liu, S. Mishra-Sharma & J. T. Ruderman

Phys.Rev.Lett. 125 (2020) 22, 221303

Phys.Rev.D 102 (2020) 10, 103533

$$\langle P_{\gamma\to A'}\rangle = \int \mathrm{d}t\, f(m_\gamma^2 = m_{A'}^2; t)\,\frac{\pi\epsilon^2 m_{A'}^4}{\omega(t)}$$

Rice's Formula (1944)

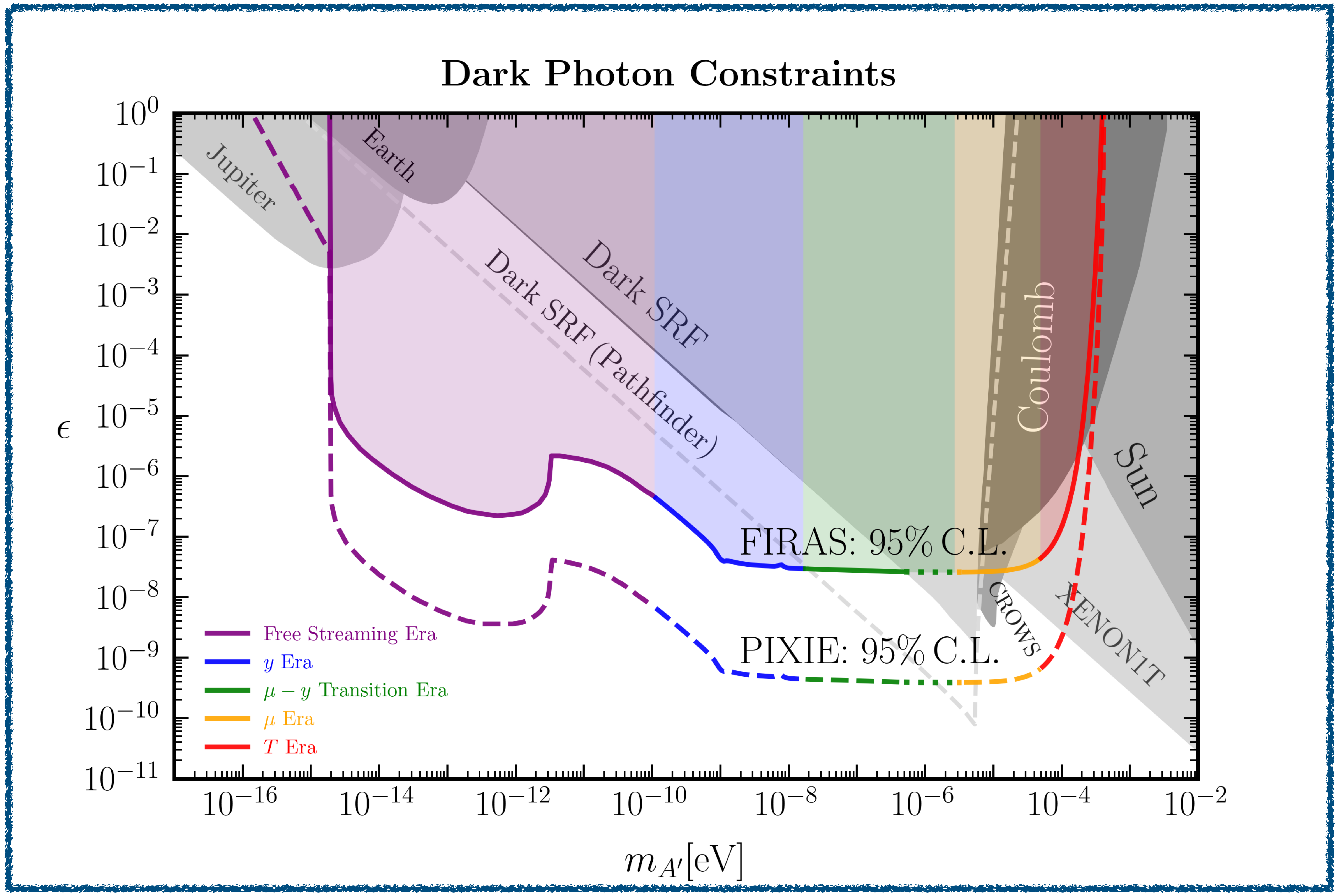


Mathematical Analysis of Random Noise

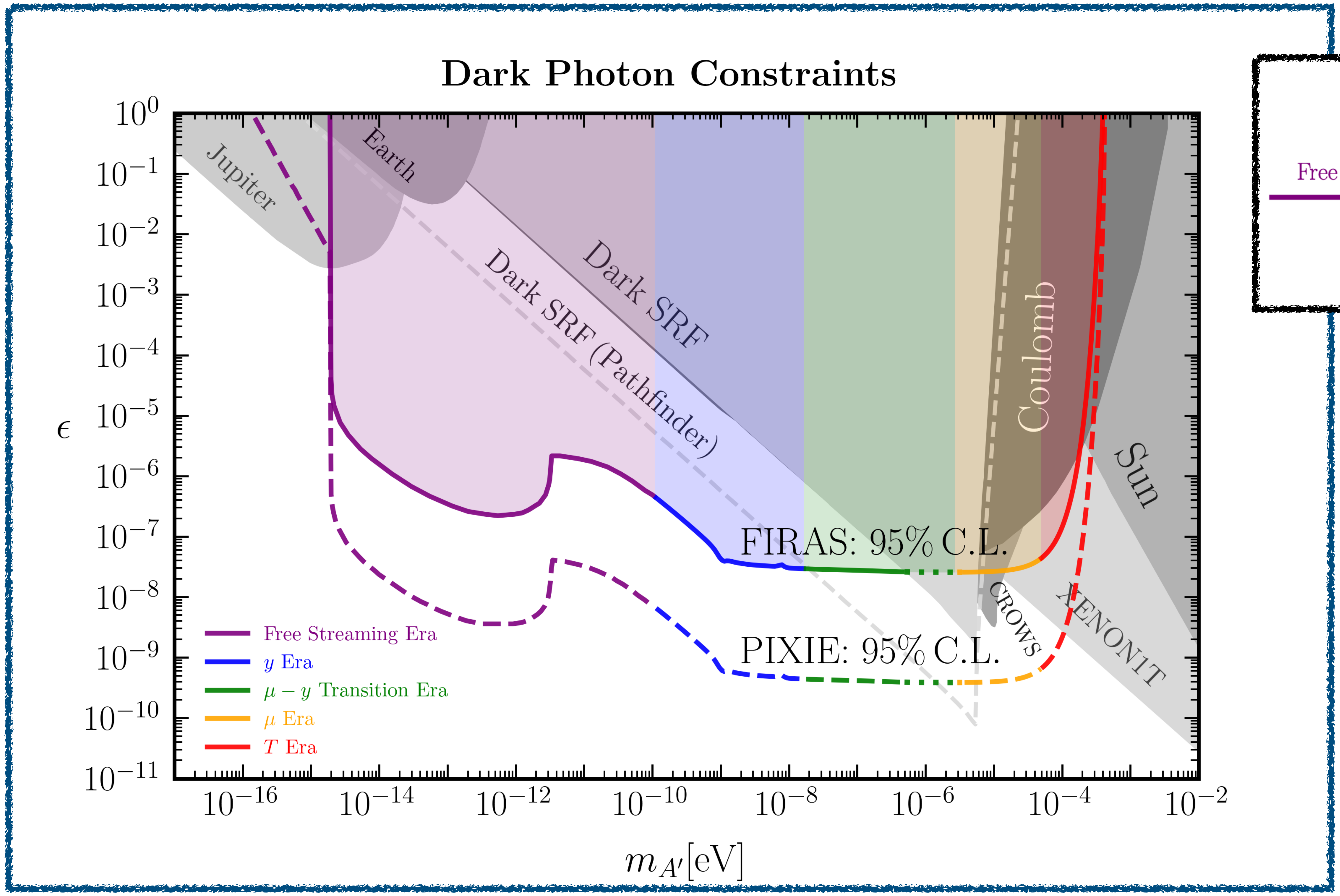
By S. O. RICE

INTRODUCTION

THIS paper deals with the mathematical analysis of noise obtained by passing random noise through physical devices. The random noise



hep-ph/2405.XXXXX, Giorgi Arsenadze, AC, Xucheng Gan, Hongwan Liu and Josh Ruderman



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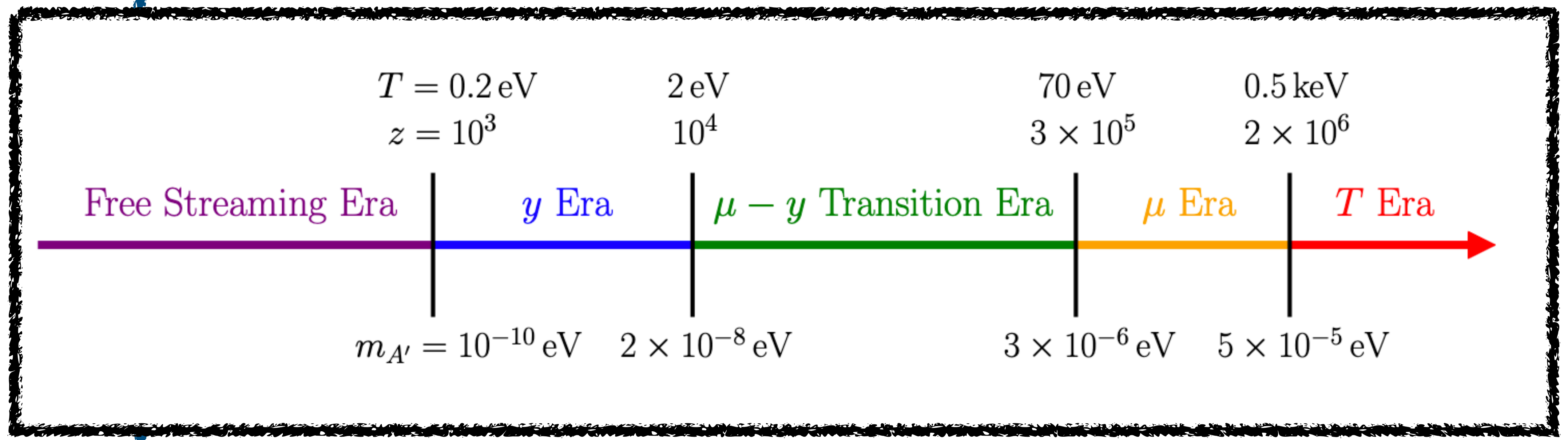


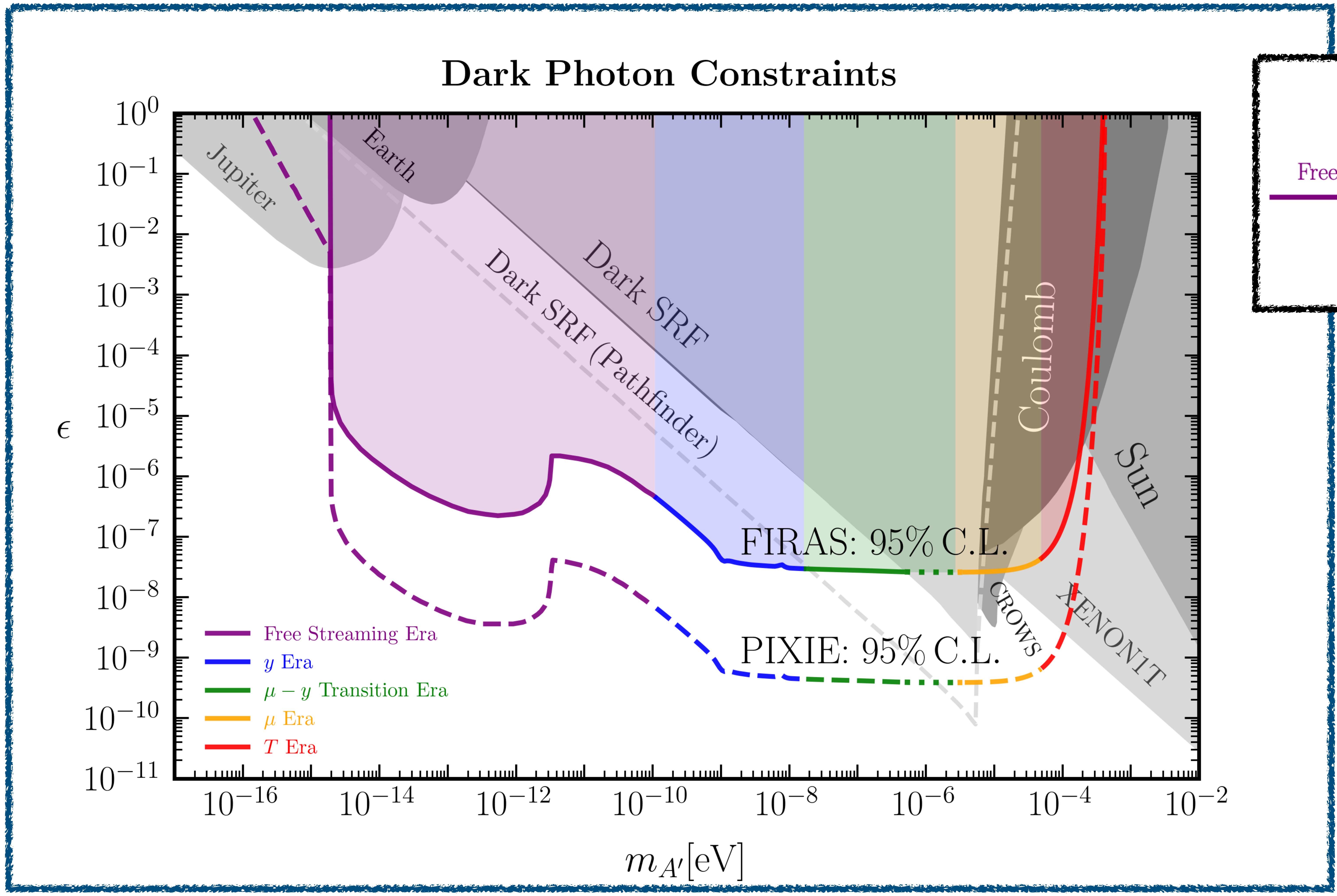
Compton Scattering (CS): $e^- + \gamma \leftrightarrow e^- + \gamma\,,$

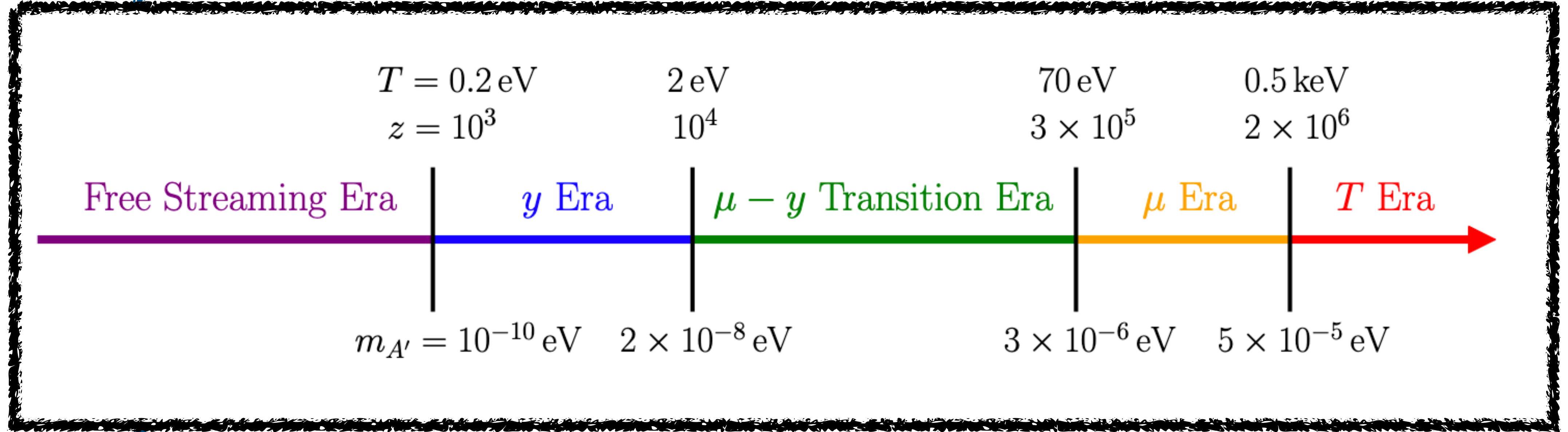
Double Compton Scattering (DCS): $e^- + \gamma \leftrightarrow e^- + \gamma + \gamma\,,$

Bremsstrahlung (BR): $e^- + X \leftrightarrow e^- + X + \gamma\,.$

The efficiency of these processes determine the type of distortions we can induce

$$f_\gamma(x) = \bar{f}_\gamma(x) + \Delta f_\gamma(x)$$





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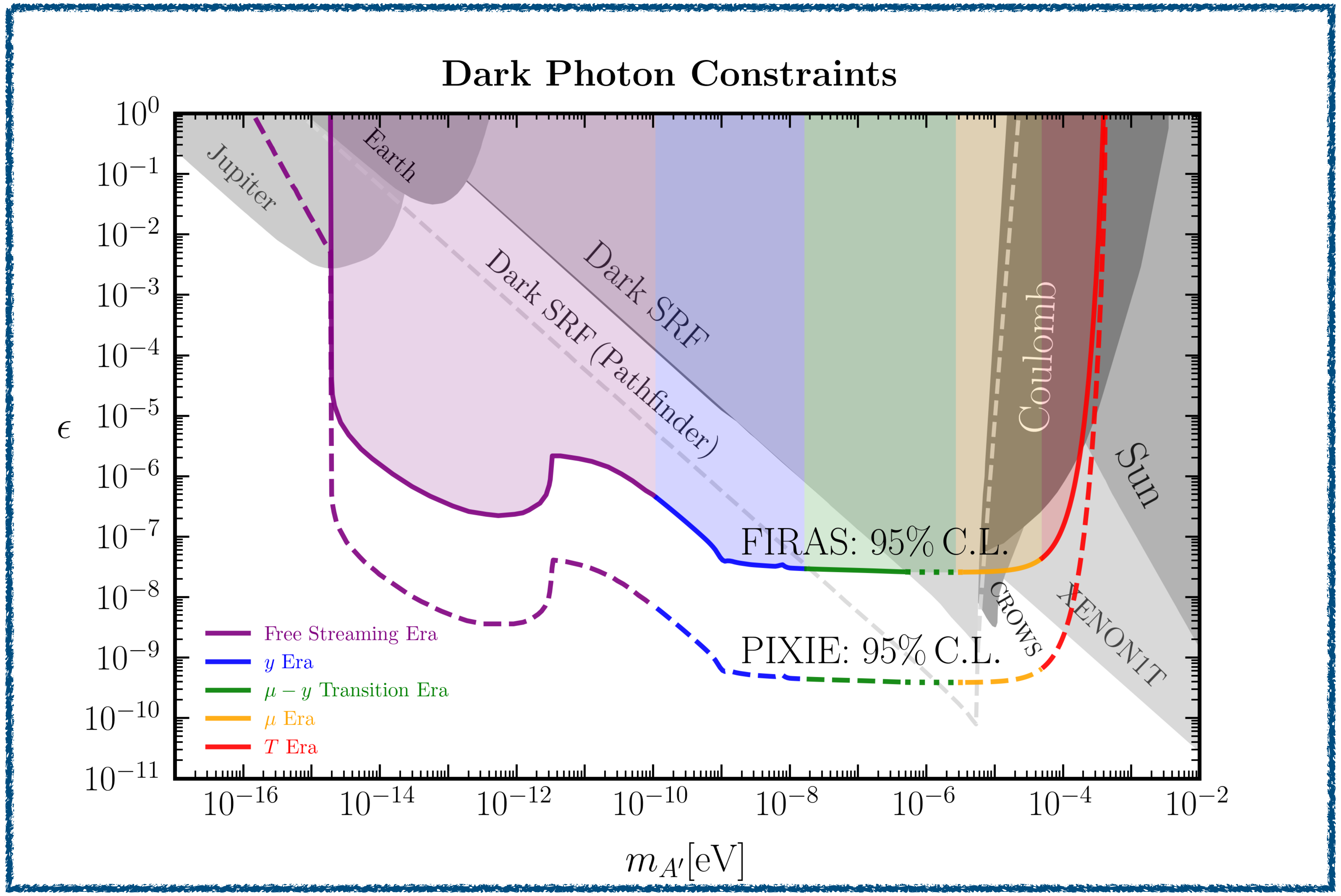
Green's function

$$I_\gamma(\omega_0; T_0) = \frac{dP_\gamma}{dA\, d\Omega\, d\nu_0} = \frac{\omega_0^3}{2\pi^2} f_\gamma(\omega_0, T_0)$$

$$\Delta I_\gamma(x; T_0) = -\int dx' \frac{1}{\bar{n}_\gamma} \frac{d\bar{n}_\gamma}{dx'} P_{\gamma \to A'} G(x; x', z'_{\rm res}; T_0)$$

Jens Chluba, 2015



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With the intensity variation at hands, we can compare our predictions with data

$$\log \mathcal{L}(\text{data}|m_{A'},\epsilon) = \max_{T_0}\left\{-\frac{1}{2}\left[\boldsymbol{\Delta I}_\gamma(m_{A'},\epsilon;T_0) - \boldsymbol{\mathcal{R}}\right]^T \cdot \boldsymbol{\mathcal{C}}^{-1} \cdot \left[\boldsymbol{\Delta I}_\gamma(m_{A'},\epsilon;T_0) - \boldsymbol{\mathcal{R}}\right]\right\}$$

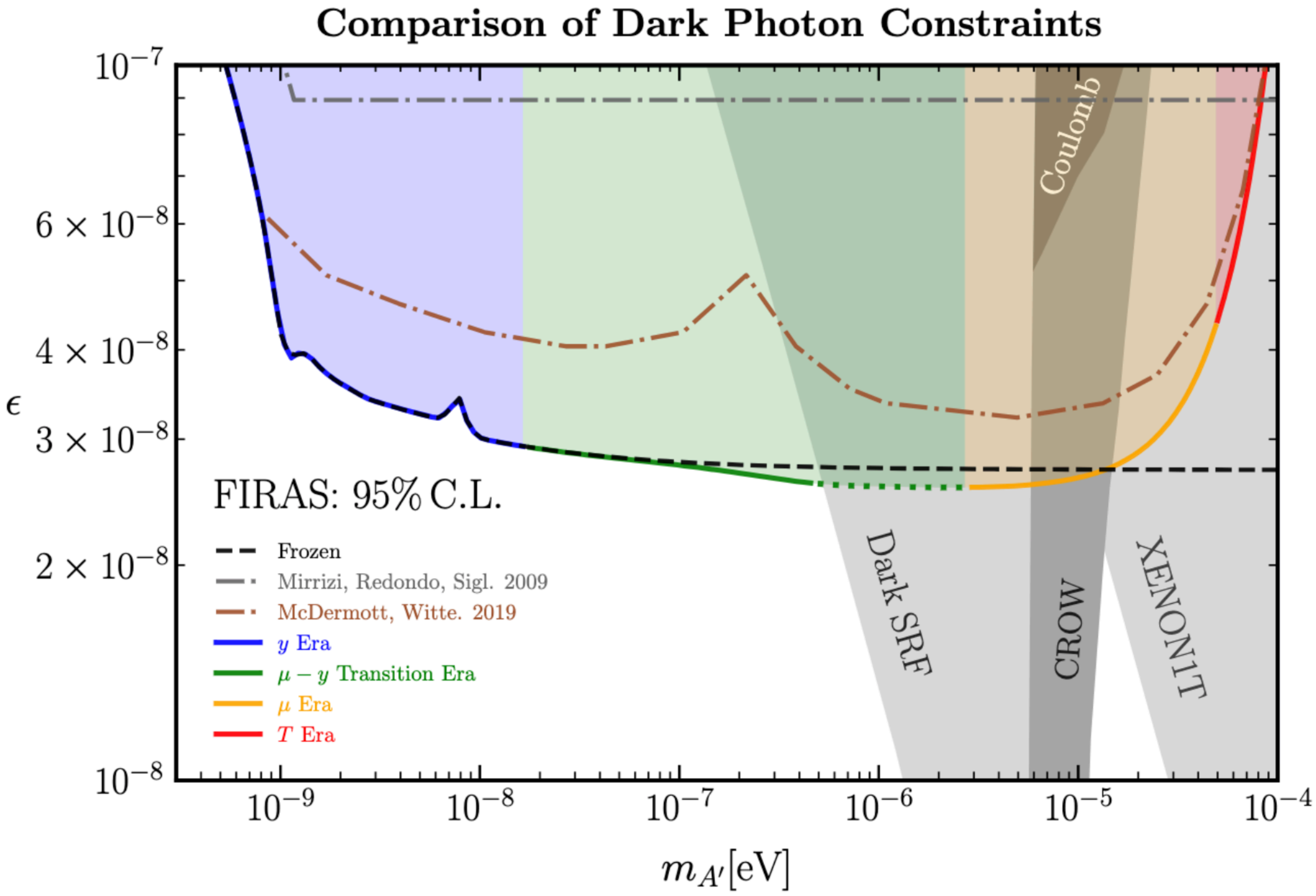
$$\text{TS}\,(m_{A'},\epsilon) = 2\left[\log \mathcal{L}(\text{data}|m_{A'},\epsilon) - \min_{\epsilon} \log \mathcal{L}(\text{data}|m_{A'},\epsilon)\right]$$

The Cosmic Microwave Background Spectrum from the Full *COBE** FIRAS Data Set

D. J. Fixsen[1], E. S. Cheng[2], J. M. Gales[1], J. C. Mather[2], R. A. Shafer[2], and E. L. Wright[3]

The Astrophysical Journal, Volume 473, Number 2
Citation D. J. Fixsen *et al* 1996 *ApJ* **473** 576
DOI 10.1086/178173

We are not the first ones to do this analysis, but the most accurate up to date



Possible future directions

Axion case, modelling [possible] extra-galactic magnetic fields

Look at anisotropies and use cross-correlation with other maps
[see also McCarthy et al. (2024), Pirvu et al. (2023)]

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