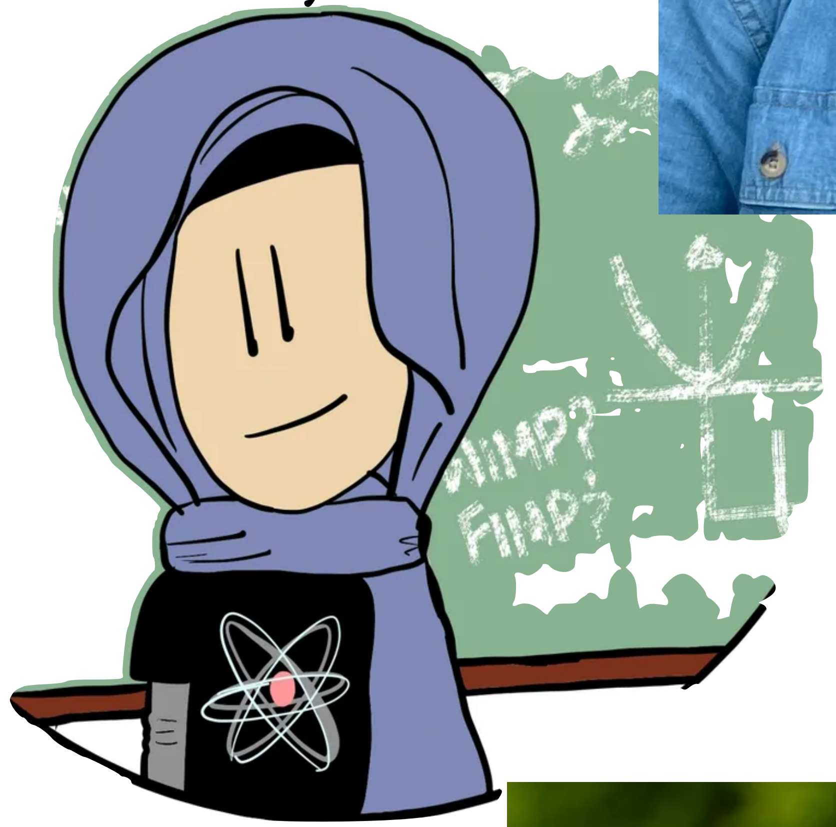
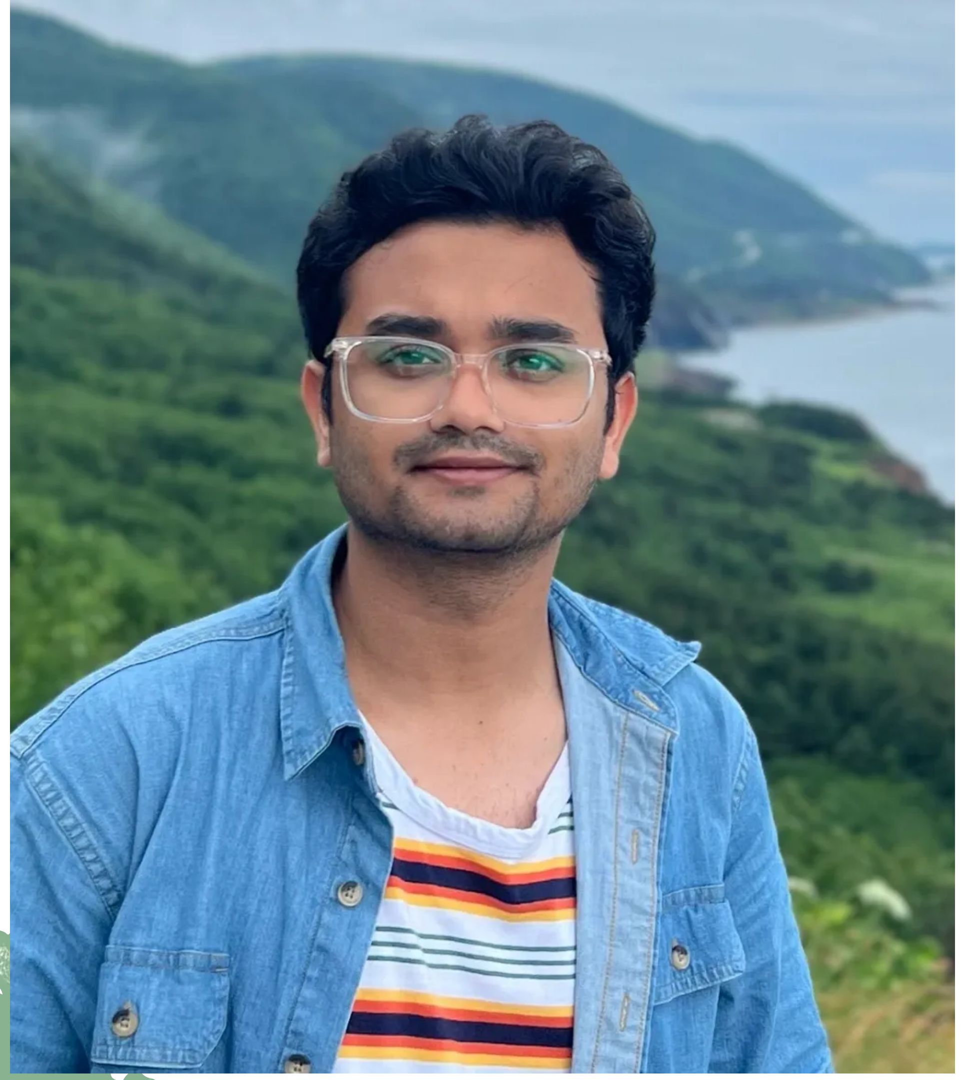
LOOKING FOR NEW PHYSICS IN THE MUD

Katelin Schutz, McGill University
Lawrence-Hitoshi-fest, September 27 2024

The importance of saying "hi"

Dr. Saniya Heeba





Nirmalya Brahma

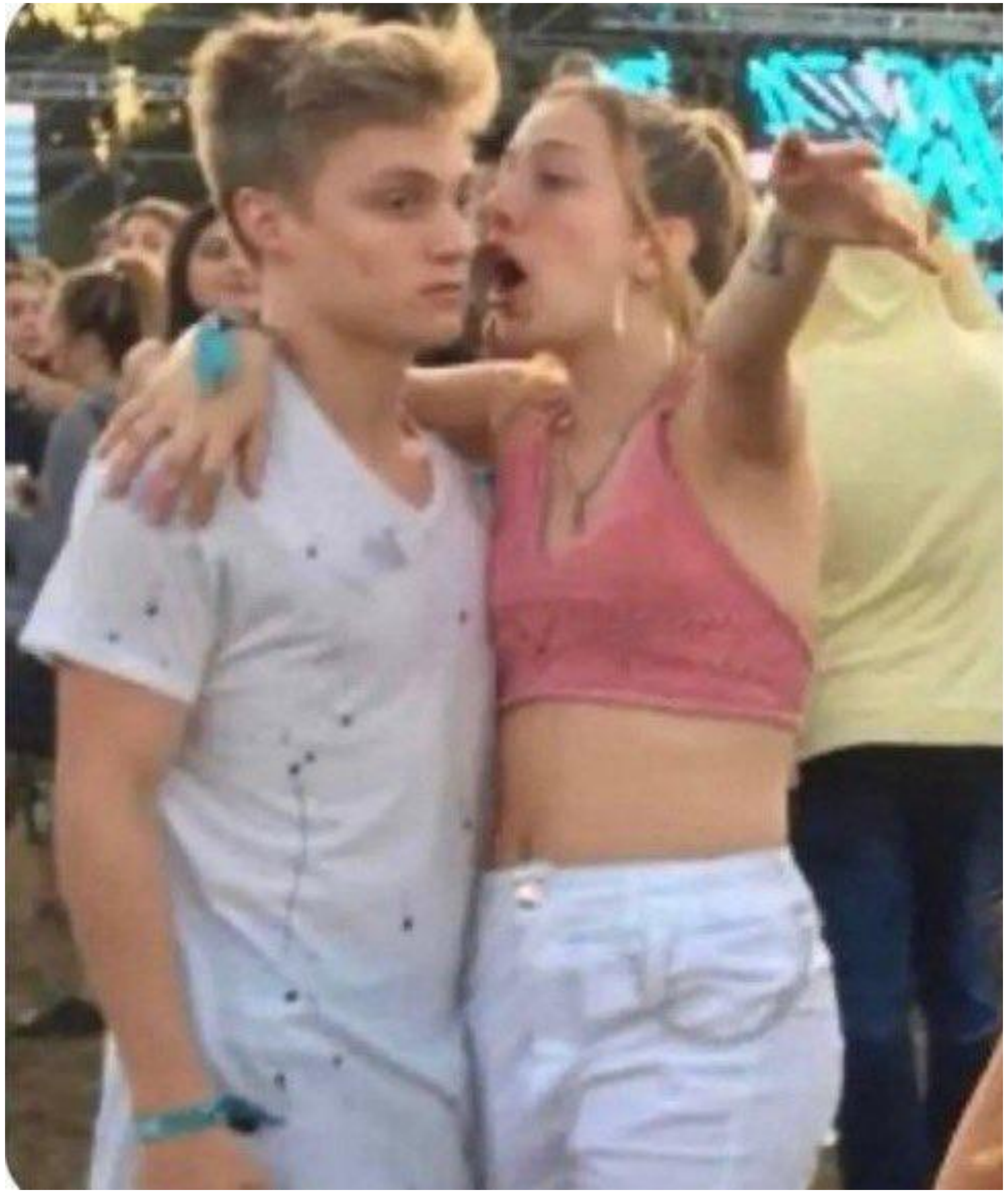
Hugo Schérer

LOOKING FOR NEW PHYSICS IN THE MUD

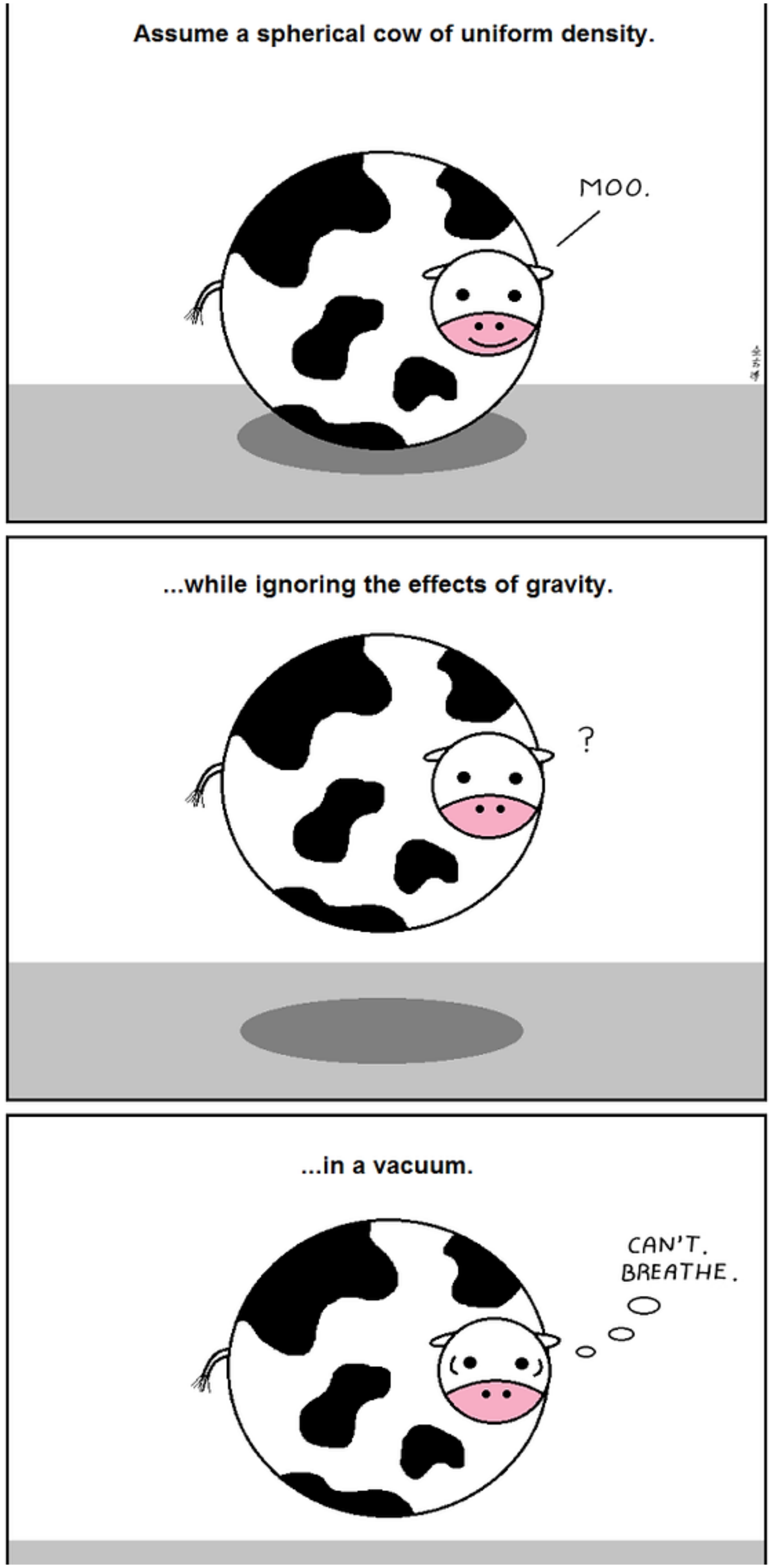
Katelin Schutz, McGill University

Lawrence-Hitoshi-fest, September 27 2024

NEWS FLASH: OUR UNIVERSE IS NOT A VACUUM!



What happens when I go around at conferences telling people I’ve been thinking about finite-temperature field theory

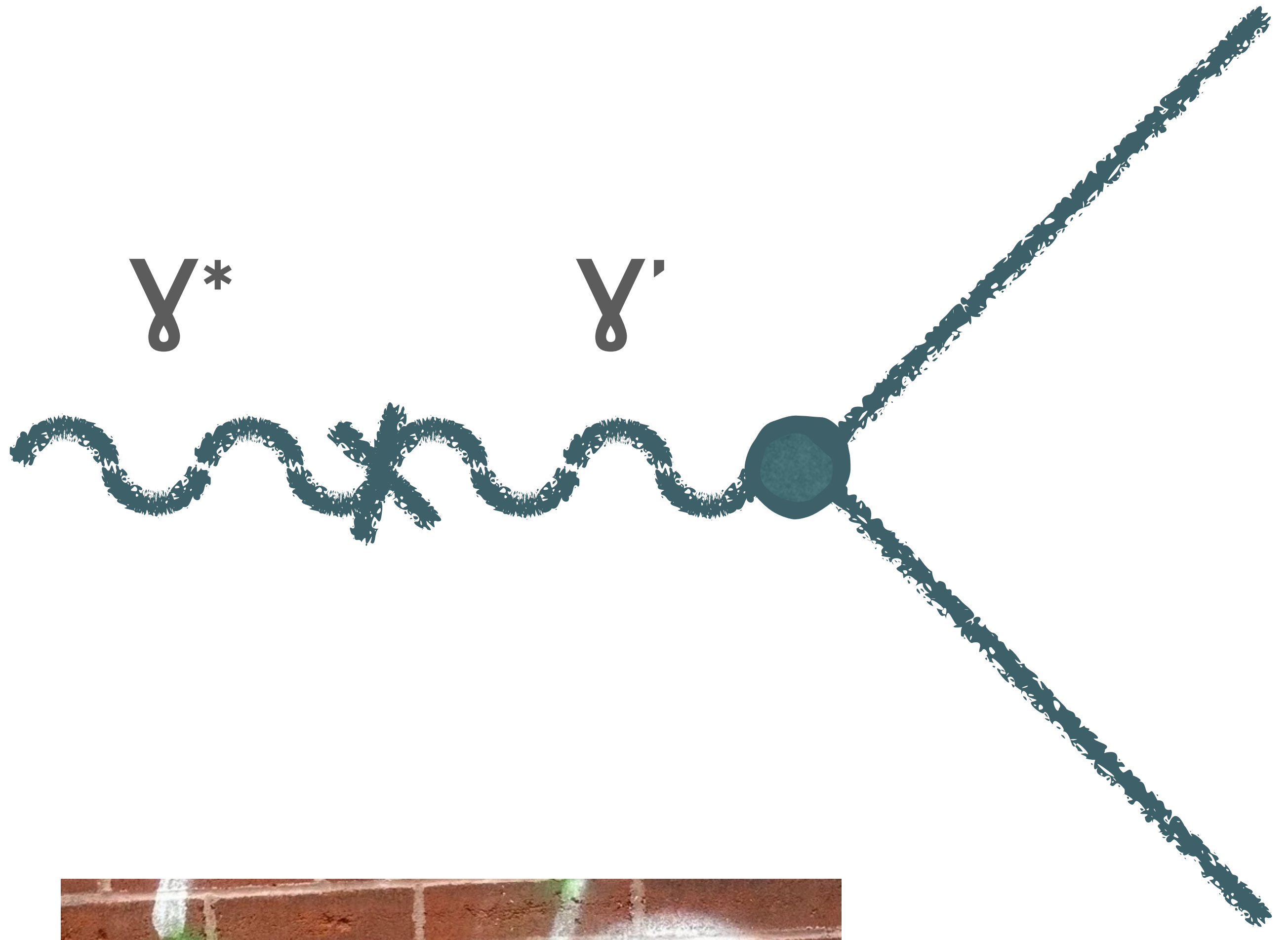


CHALLENGE OR OPPORTUNITY?

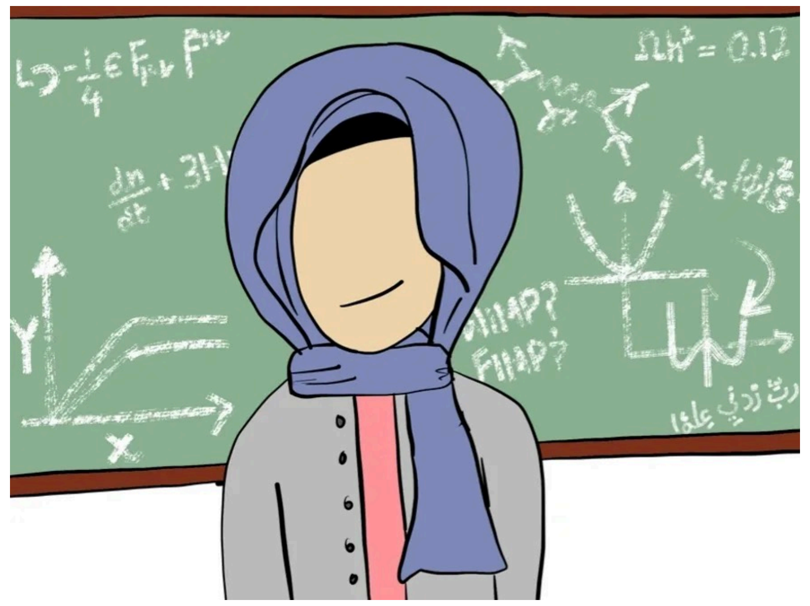
- Doing QFT in a dense medium is quite technical (apologies for the number of equations in this talk!), do we really have to deal with this?
- Yes, if we care about "long"-wavelength physics (probing system beyond individual constituents)
- Not only technical but qualitatively new way of viewing a system, new dispersion relations, new propagating modes (e.g. longitudinal photon)
- Perhaps this implies qualitatively new signatures of physics beyond the Standard Model?
- Low energies imply we could look for low-dimensional portals/operators (kinetic mixing, axions, etc.) by exploiting the medium

HOW DID I GET INTERESTED IN FTFT AS AN ASTRO-CURIOUS BSM PERSON?

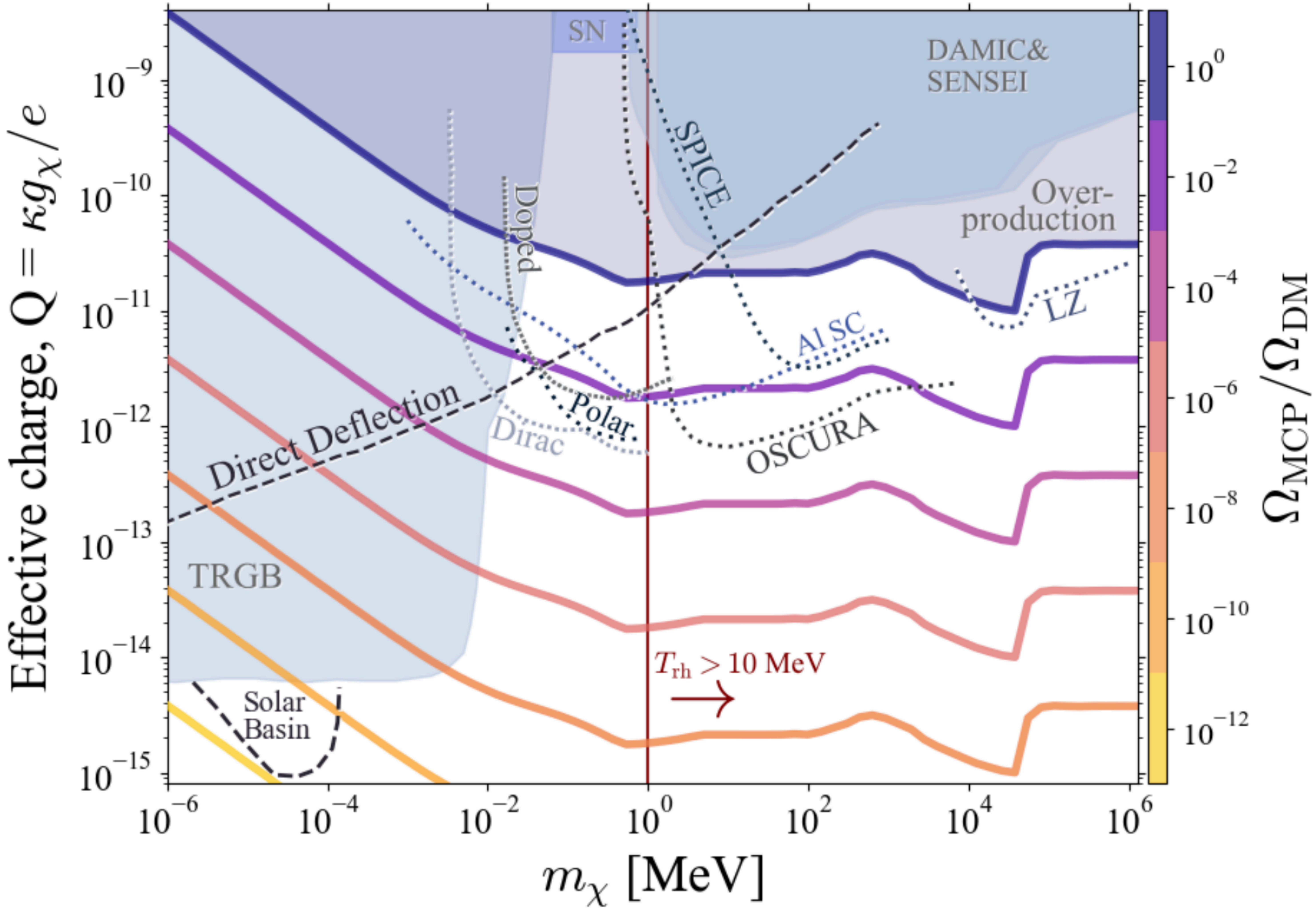
WHAT'S AT STAKE HERE FOR BSM PHYSICS?



Ella Iles



Dr. Saniya Heeba

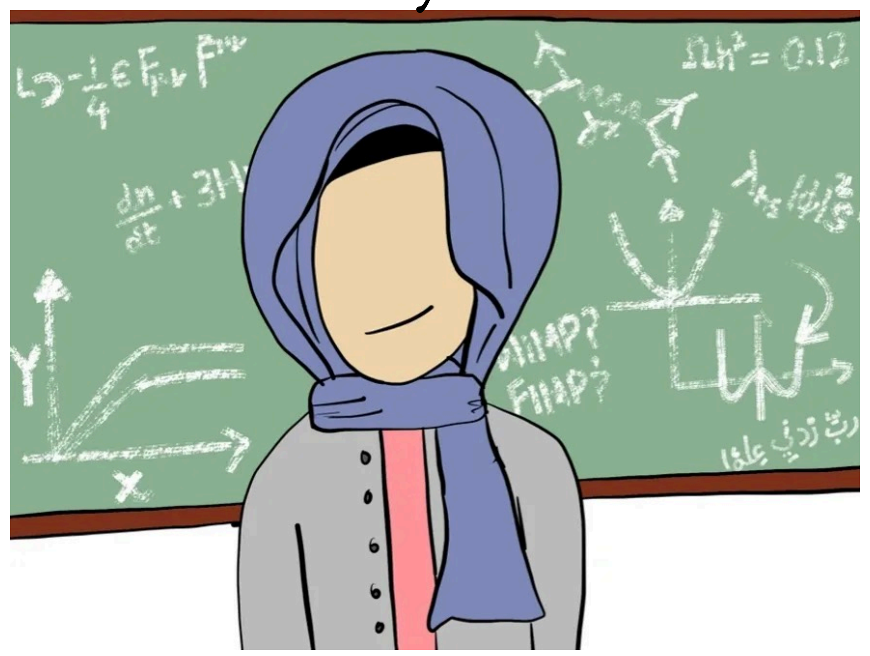


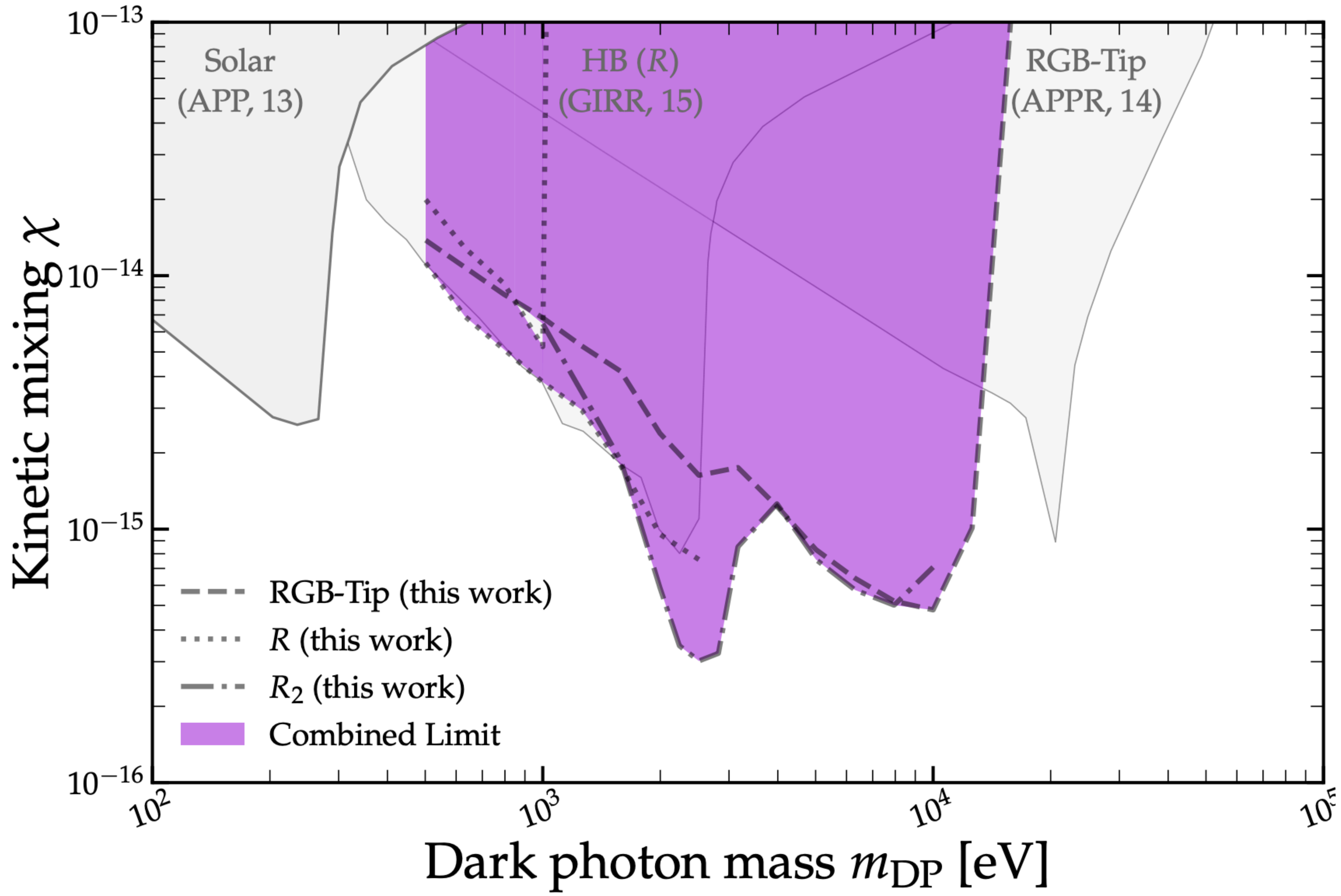
Iles, Heeba, **KS** 2407.21096

WHAT'S AT STAKE HERE FOR BSM PHYSICS?

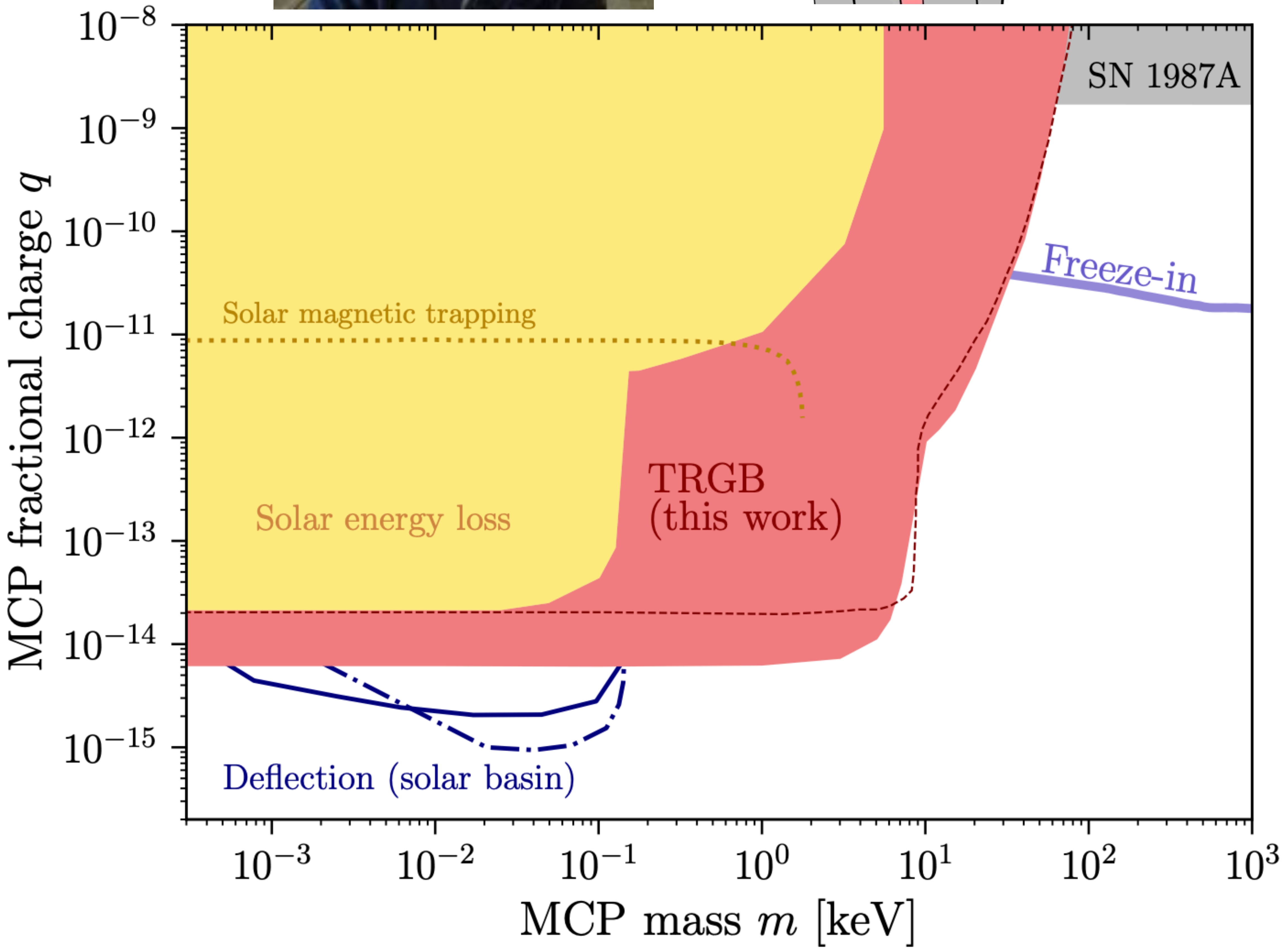
Audrey Fung

Dr. Saniya Heeba



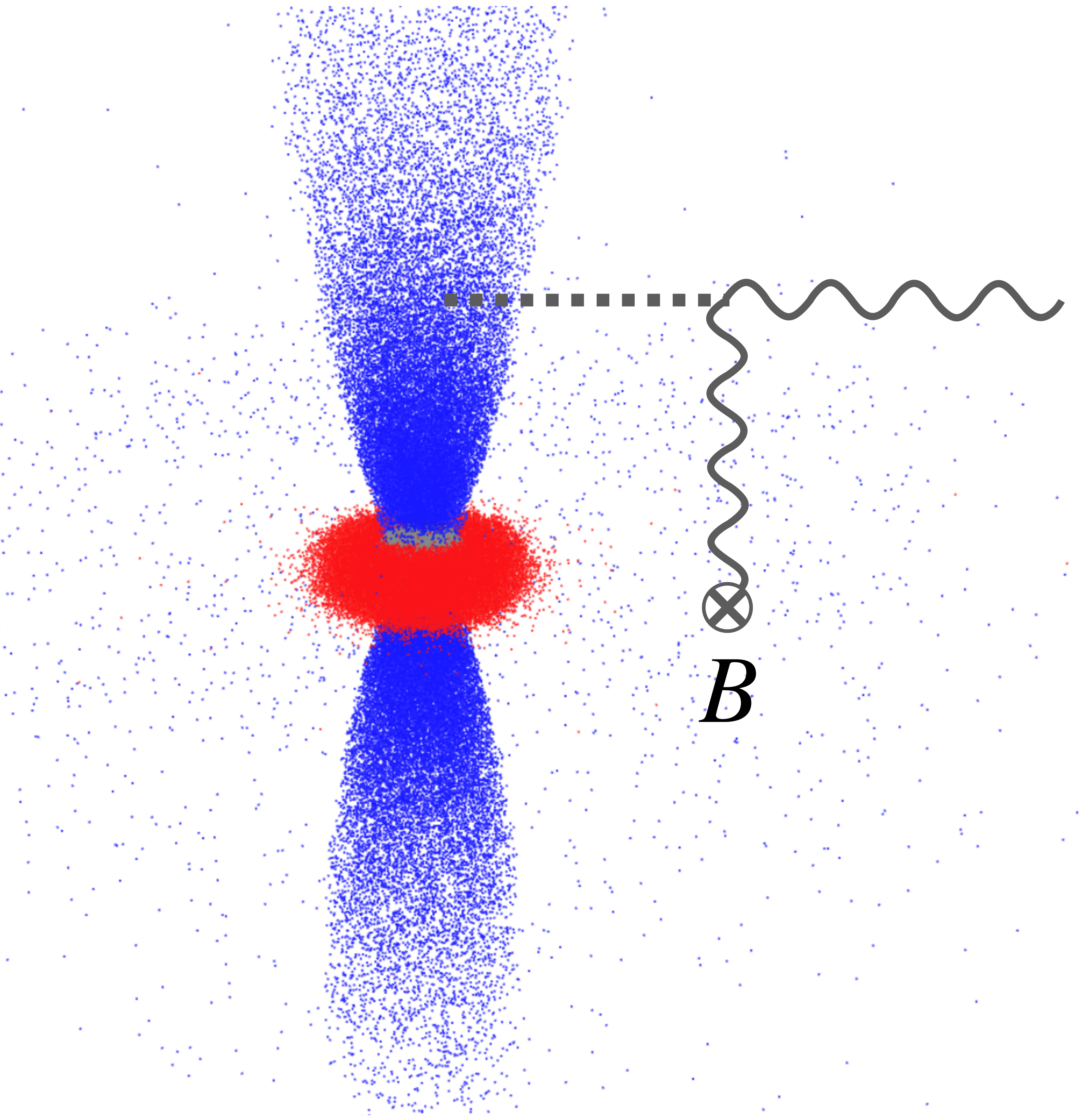


Dolan et al. 2022

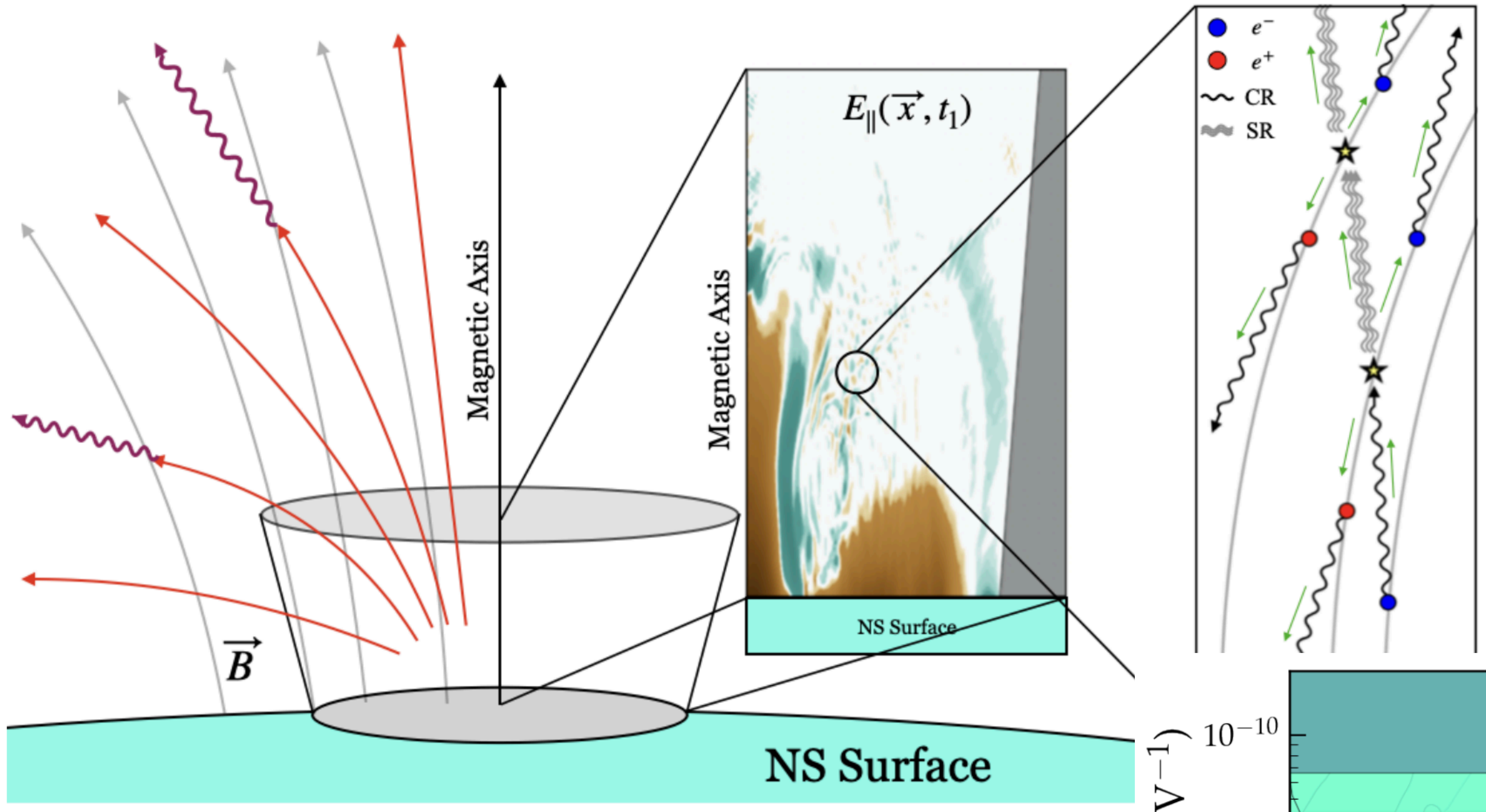


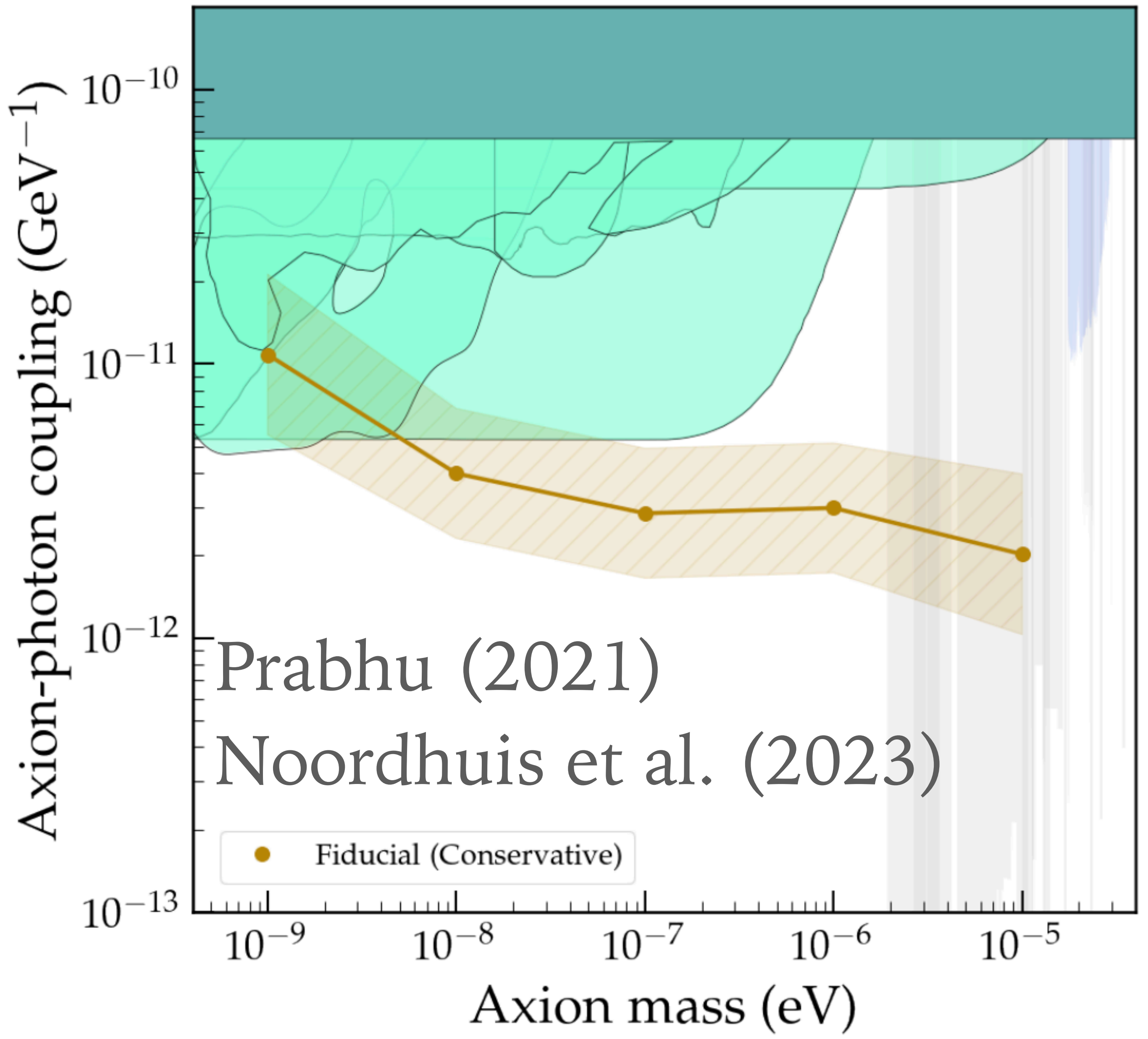
Fung, Heeba, Liu, Muralidharan, **KS**, Vincent (2024)

WHAT'S AT STAKE HERE FOR BSM PHYSICS?



Hook, Kahn, Safdi, Sun (2018),
Safdi, Sun, Chen (2018)





Prabhu (2021)
Noordhuis et al. (2023)

HOW MIGHT THESE NEW SIGNATURES ARISE?

Dark photons in vacuum: $\mathscr{L} = -\frac{1}{4}F^2 - \frac{1}{4}F'^2 + \frac{1}{2}\kappa FF' + \frac{1}{2}m_{A'}^2 A'^2 + ej_\mu A^\mu, \quad \kappa \ll 1$

$A_1 = A - \kappa A', \quad A_2 = A'$

Rotate away kinetic mixing term
("mass basis")

$$\mathscr{L} \supset \frac{1}{2}m_{A'}^2 A_2^2 + ej_\mu(A_1^\mu + \kappa A_2^\mu)$$

$\mathscr{A} = A, \quad \mathcal{S} = A' - \kappa A$

Rotate away kinetic mixing term
("active/sterile basis" analog of neutrinos)

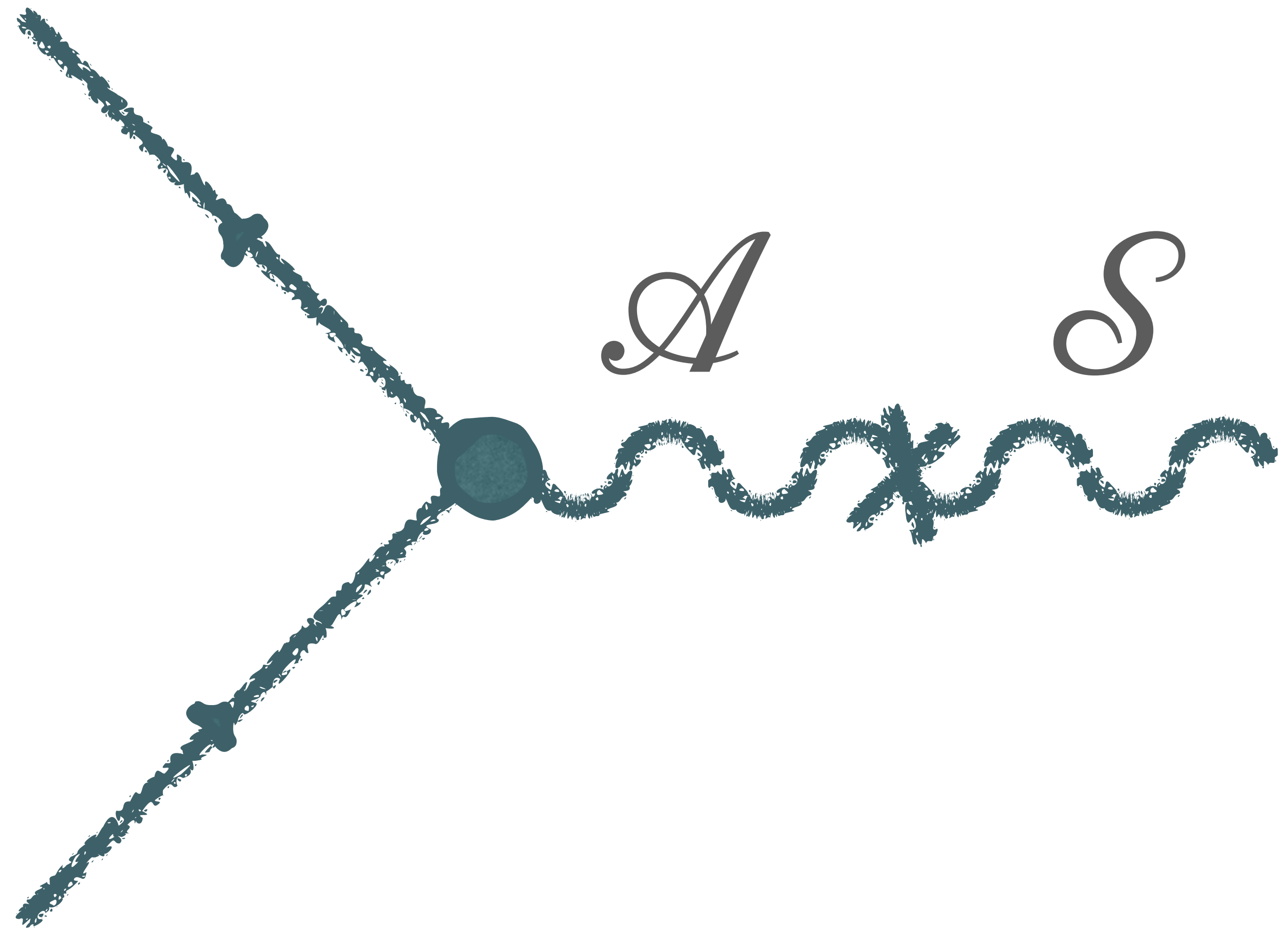
$$\mathscr{L} \supset \frac{1}{2}m_{A'}^2 \mathcal{S}_\mu(\mathcal{S}^\mu + \mathscr{A}^\mu) + ej_\mu\mathscr{A}^\mu$$

HOW IS THIS AFFECTED BY AN AMBIENT MEDIUM?

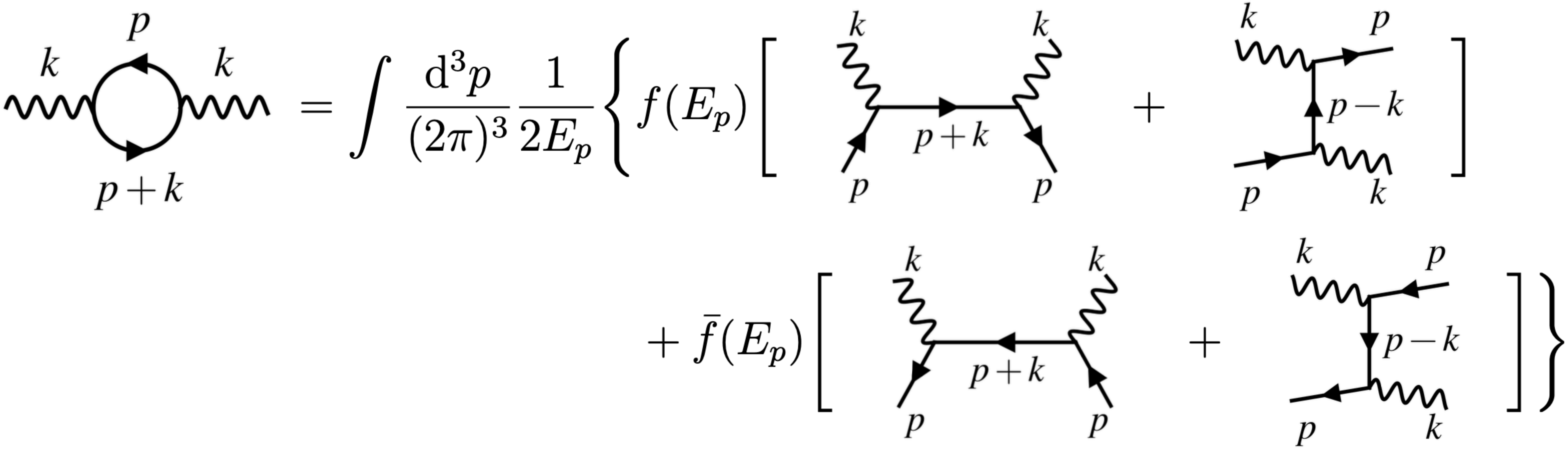
$$j_\mu = j_\mu^{\text{ext}} + j_\mu^{\text{ind}} \,, \quad j_\mu^{\text{ind}} \equiv \Pi^{\mu\nu}(\omega, k) A_\nu$$

Polarization tensor of linear response theory

$$\mathscr{L} \supset \frac{1}{2} m_{A'}^2 \mathscr{S}_\mu (\mathscr{S}^\mu + \mathscr{A}^\mu) + \mathscr{A}_\mu \Pi^{\mu\nu} \mathscr{A}_\nu + e j_\mu^{\text{ext}} \mathscr{A}^\mu$$



Active state is constantly getting bombarded ("dressed") by background particles before oscillating to sterile state



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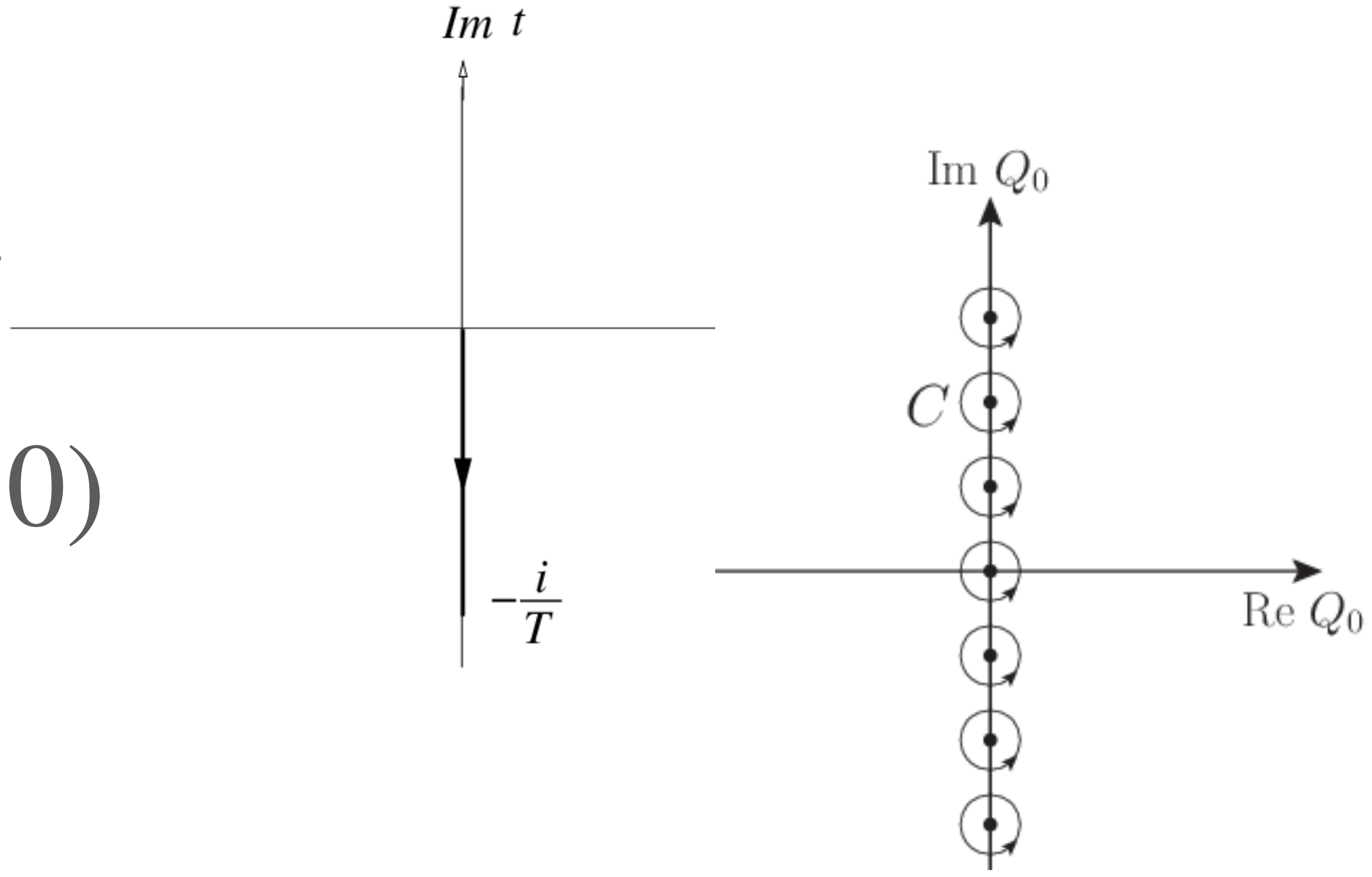
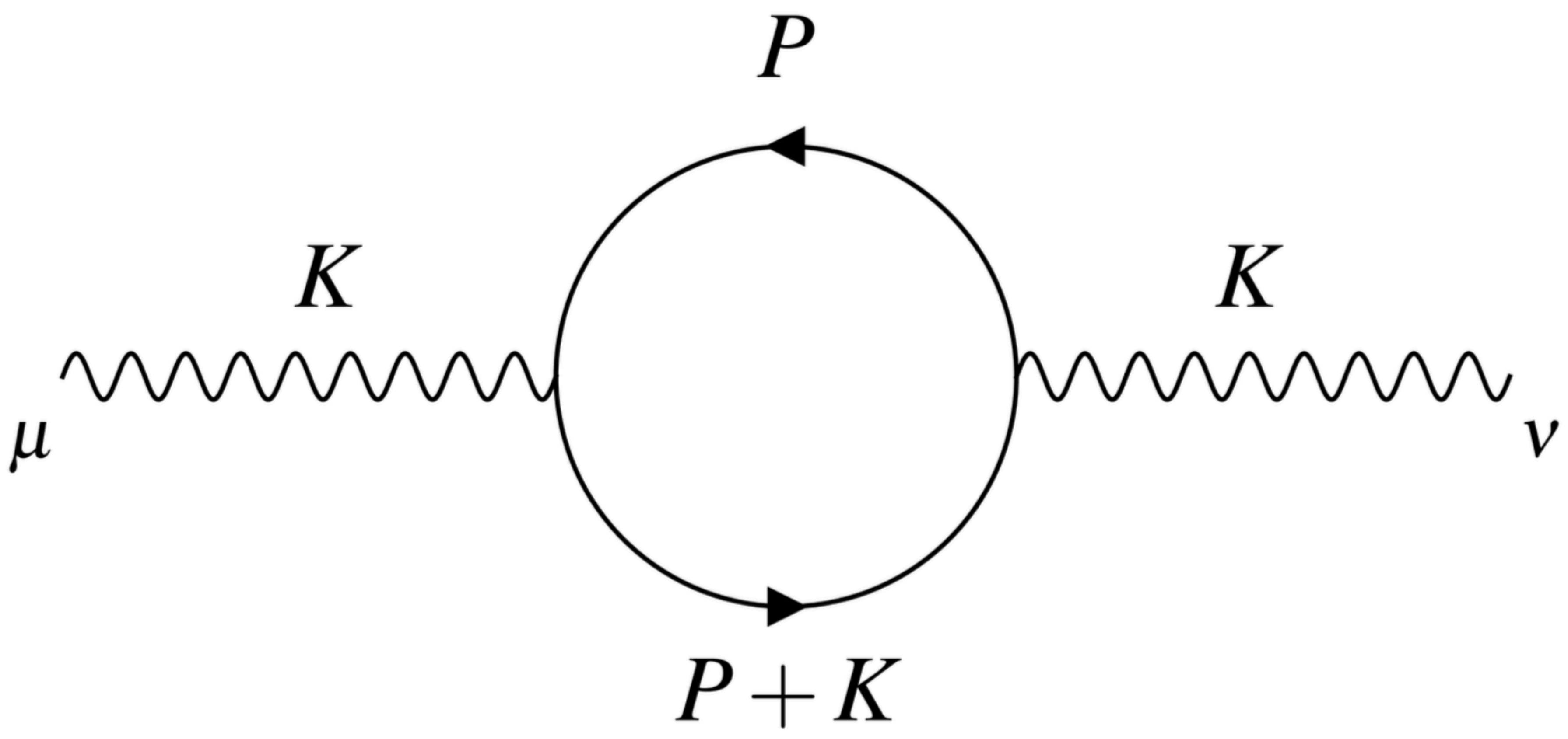
HOW DO WE COMPUTE POLARIZATION TENSORS?



If system is in thermal equilibrium, $\rho = e^{-H\beta} = e^{-iH\Delta t} = U(-i\beta, 0)$

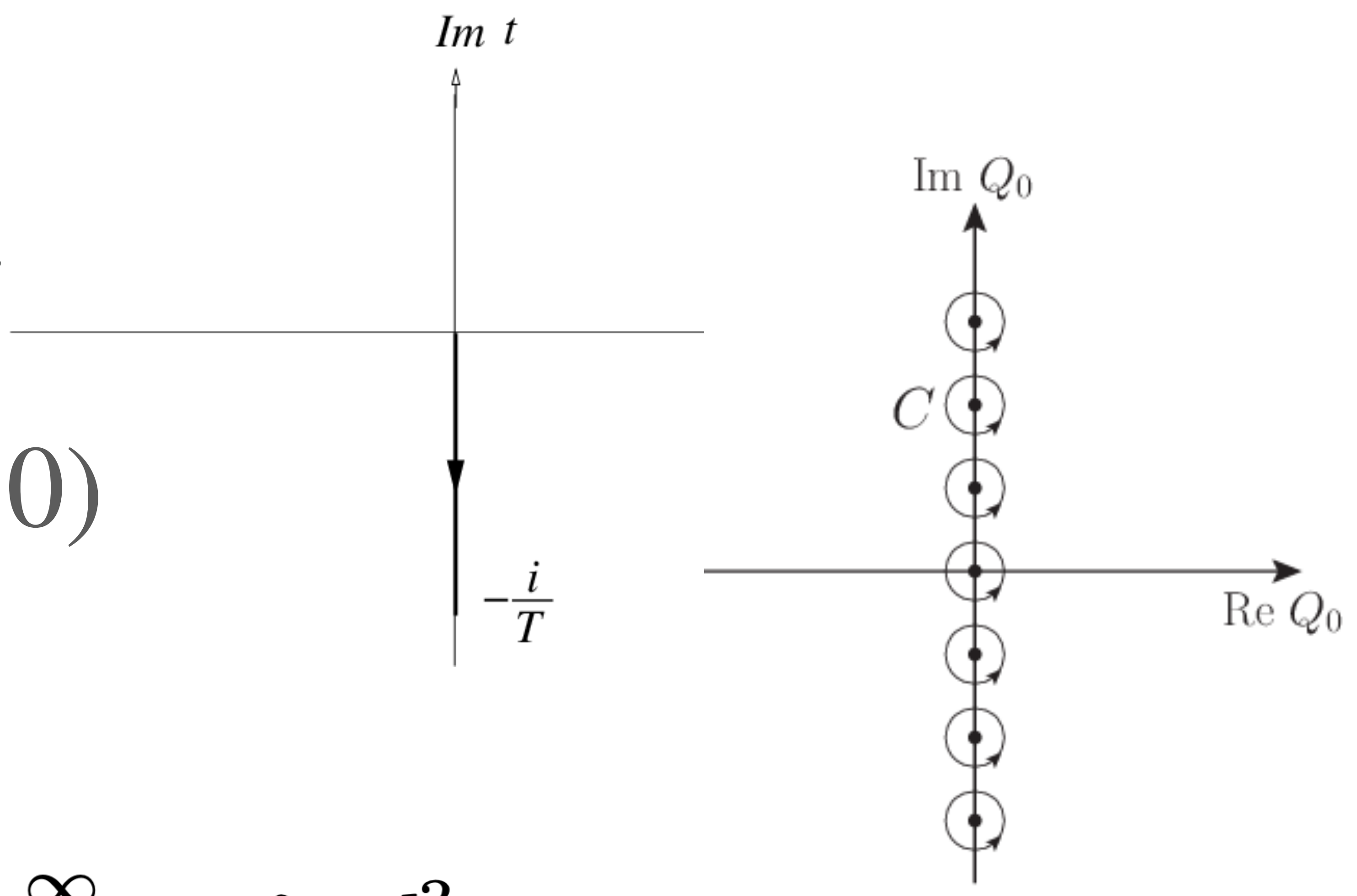
finite imaginary time interval, bosons have periodic boundary conditions, so Fourier transforming we get discrete spectrum of imaginary "Matsubara frequencies"

$$\int \frac{d^4p}{(2\pi)^4} M(p_0) \to \frac{i}{\beta} \sum_{n=-\infty}^{\infty} \int \frac{d^3p}{(2\pi)^3} M(p_0 = i\omega_n)$$



$$= 16\pi\alpha \int \frac{\mathrm{d}^3p}{(2\pi)^3} \frac{1}{2E_p} \left[f(E_p) + \bar{f}(E_p)\right] \times \frac{(p\cdot k)(k^\mu p^\nu + k^\nu p^\mu) - (k^2)p^\mu p^\nu - (p\cdot k)^2 \eta^{\mu\nu}}{(p\cdot k)^2 - \frac{1}{4}(k^2)^2}$$

HOW DO WE COMPUTE POLARIZATION TENSORS?



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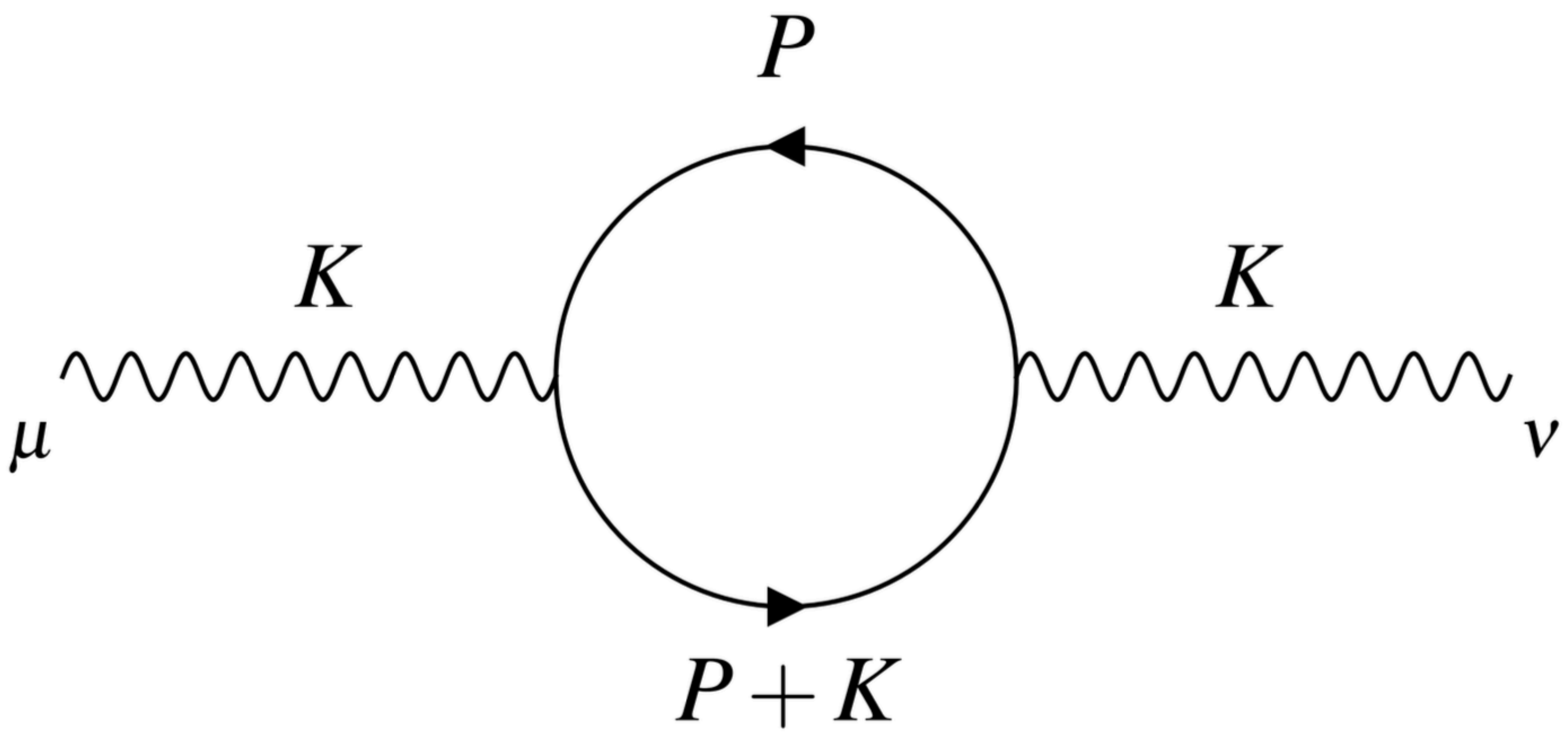


$$= 16\pi\alpha \int \frac{\mathrm{d}^3p}{(2\pi)^3} \frac{1}{2E_p} \left[f(E_p) + \bar{f}(E_p) \right] \times \frac{(p\cdot k)(k^\mu p^\nu + k^\nu p^\mu) - (k^2) p^\mu p^\nu - (p\cdot k)^2 \eta^{\mu\nu}}{(p\cdot k)^2 - \cancel{\frac{1}{4}(k^2)^2}}$$

soft photon approximation used in Braaten & Segel (1993)

USAGE OF BRAATEN & SEGEL APPROXIMATION

Decompose polarization tensor by projection

$$P_L^{\mu\nu} = \epsilon_L^\mu \epsilon_L^\nu, \quad P_T = \epsilon_{T1}^\mu \epsilon_{T1}^\nu + \epsilon_{T2}^\mu \epsilon_{T2}^\nu$$

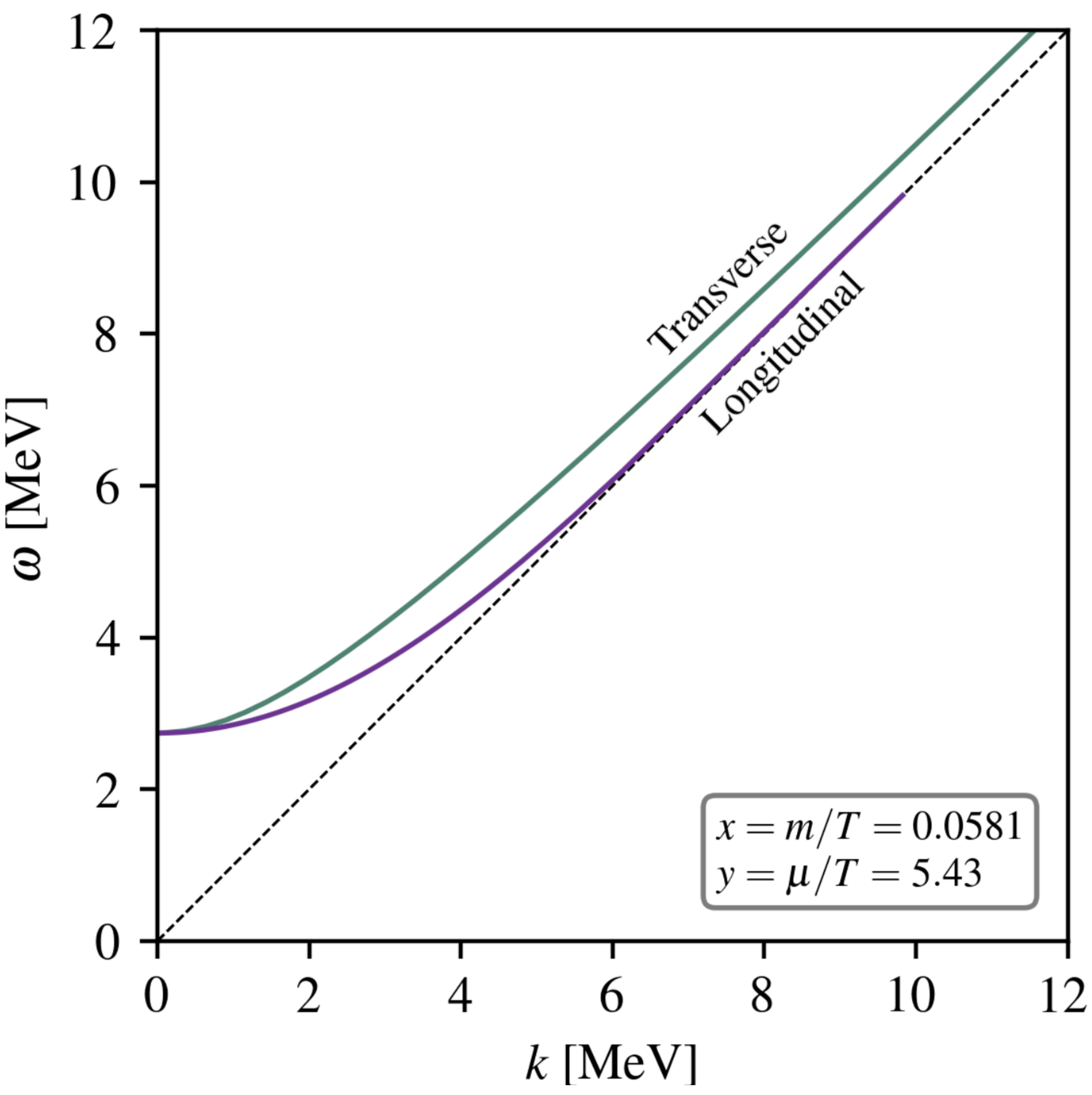
$$\Pi^{\mu\nu} = \Pi_L P_L^{\mu\nu} + \Pi_T P_T^{\mu\nu}$$

Read off dispersion relations from poles in propagator

$$\omega_T^2 = k^2 + \Pi_T, \quad \omega_L = \frac{\omega_L^2}{k^2}\Pi_L$$

$$\Pi_L^{\mathrm{On}} = \frac{3\omega_p^2}{v_*^2}\left(\frac{1-n^2}{n^2}\right)\left[\frac{1}{2nv_*}\log\left(\frac{1+nv_*}{1-nv_*}\right) - 1\right]$$

$$\Pi_T^{\mathrm{On}} = \frac{3\omega_p^2}{2v_*^2}\left[\frac{1}{n^2} - \left(\frac{1-n^2v_*^2}{n^2}\right)\frac{1}{2nv_*}\log\left(\frac{1+nv_*}{1-nv_*}\right)\right]$$



USAGE OF BRAATEN & SEGEL APPROXIMATION

Hugo Schérer

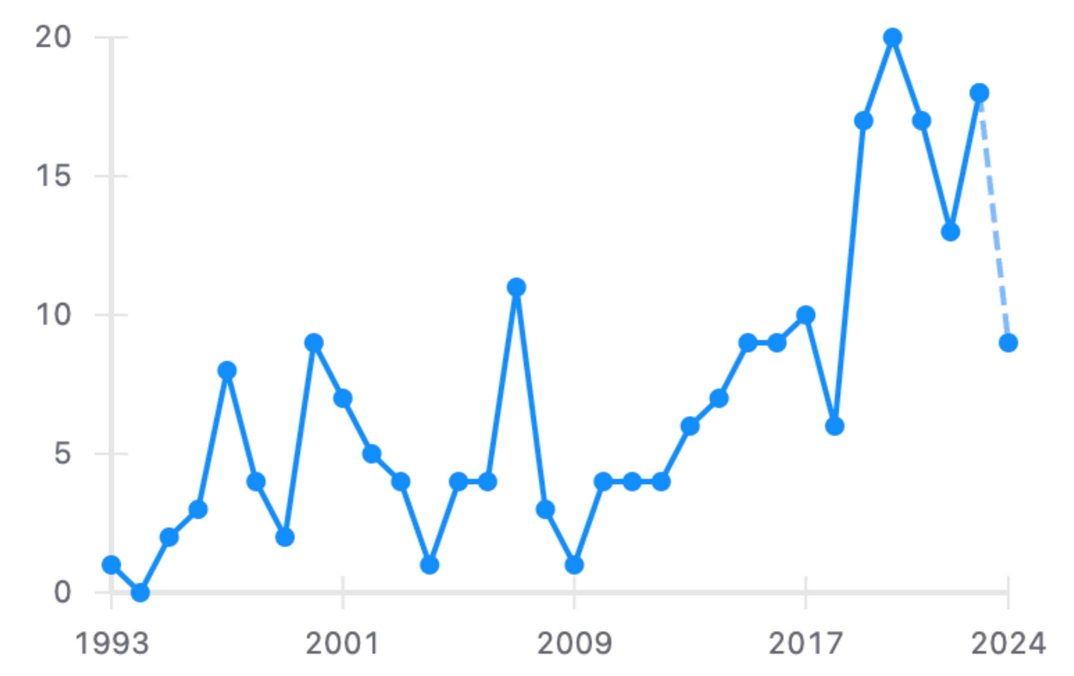
Neutrino energy loss from the plasma process at all temperatures and densities

Eric Braaten (Northwestern U.), Daniel Segel (Northwestern U.)
Jan, 1993

38 pages
Published in: *Phys.Rev.D* 48 (1993) 1478-1491
e-Print: hep-ph/9302213 [hep-ph]
DOI: 10.1103/PhysRevD.48.1478
Report number: NUHEP-TH-93-1
View in: OSTI Information Bridge Server, ADS Abstract Service

pdf cite claim reference search 222 citations

Citations per year



Raffelt's book, "Stars as Laboratories for fundamental physics"

This version (08 July 2023) with some errata fixed
See also new Appendix E

6.3.4 Lowest-Order QED Calculation of the Polarization Tensor

This section was aiming at the dispersion relations of transverse and longitudinal plasmons, following Braaten and Segel (1993) [4] who provided beautiful analytic approximations. The expressions for the polarization tensor that obtain after dropping $(K^2)^2/4$ in Eq. (6.36) are accurate to lowest order in α only in the neighborhood of $\omega \sim k$ and thus are only useful to find the dispersion relations. *They should not be used in the off-shell regime.* After dropping this term, Braaten and Segel arrive at their Eqs. (A16) and (A17), corresponding to Eqs. (6.37)

RESULT WITHOUT ASSUMING ON-SHELL

$$\Pi_L = \omega_p^2\Bigg[-\frac{2K^2}{k^2v_*^2} + \frac{K^2}{4E_*^2v_*^3}\log\left(\frac{1+v_*}{1-v_*}\right) + \frac{\omega K^2\big(3+(\omega^2-3k^2)/4E_*^2\big)}{4k^3v_*^3}\log\left|\frac{(\omega+kv_*)^2-(K^2)^2/4E_*^2}{(\omega-kv_*)^2-(K^2)^2/4E_*^2}\right|$$

$$-\frac{E_*K^2(1+3K^2/4E_*^2)}{2k^3v_*^3}\log\left|\frac{\omega^2-(kv_*-K^2/2E_*)^2}{\omega^2-(kv_*+K^2/2E_*)^2}\right| - \frac{(1-v_*^2+K^2/2E_*^2)}{2v_*^3}\sqrt{\left|\frac{4m^2}{K^2}-1\right|}C\Bigg]$$

$$\Pi_T = \omega_p^2\Bigg[\frac{k^2+2\omega^2}{2k^2v_*^2} + \frac{K^2}{4E_*^2v_*^3}\log\left(\frac{1+v_*}{1-v_*}\right) - \frac{\omega\big(3(\omega^2-k^2v_*^2)+(\omega^2+3k^2)K^2/4E_*^2\big)}{8k^3v_*^3}\log\left|\frac{(\omega+kv_*)^2-(K^2)^2/4E_*^2}{(\omega-kv_*)^2-(K^2)^2/4E_*^2}\right|$$

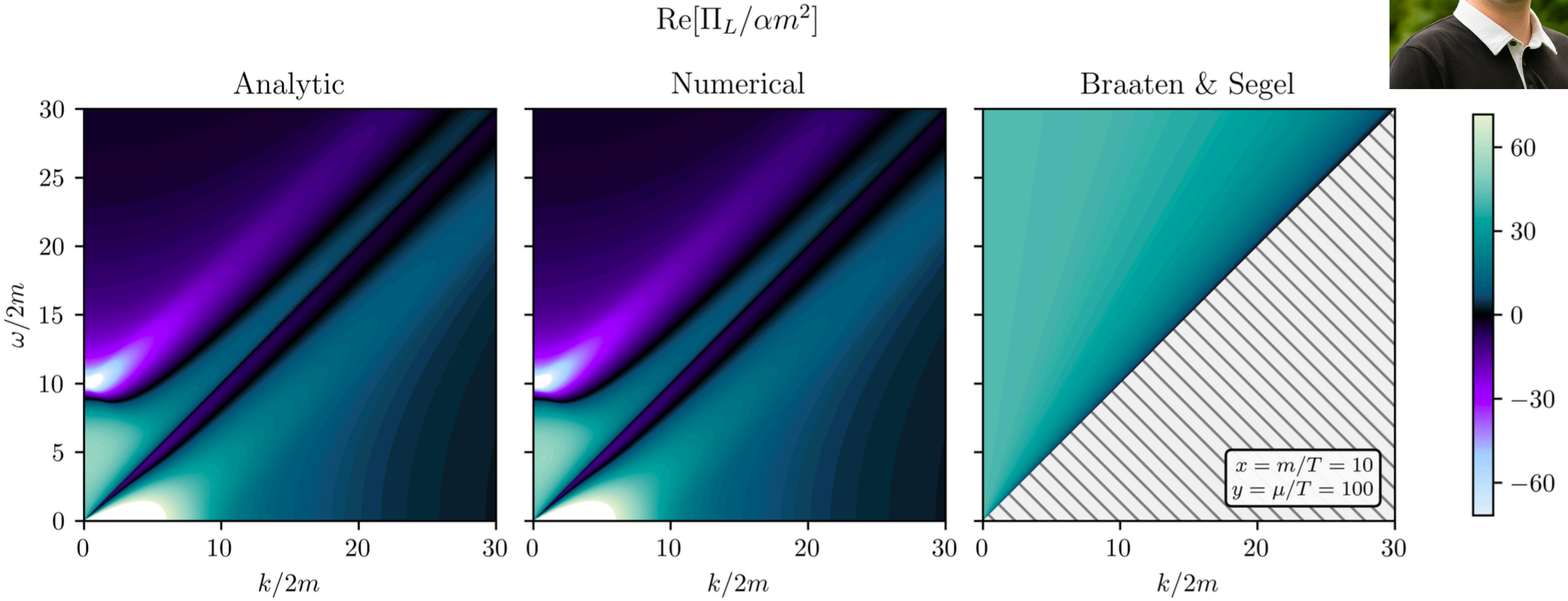
$$+\frac{E_*\big(3(\omega^2-v_*^2k^2)-2K^2+3(\omega^2+k^2)K^2/4E_*^2\big)}{4k^3v_*^3}\log\left|\frac{\omega^2-(kv_*-K^2/2E_*)^2}{\omega^2-(kv_*+K^2/2E_*)^2}\right| - \frac{(1-v_*^2+K^2/2E_*^2)}{2v_*^3}\sqrt{\left|\frac{4m^2}{K^2}-1\right|}C\Bigg]$$

where

$$C = \begin{cases} \tan^{-1}\left(\dfrac{((K^2)^2/4m^2+k^2)v_*-\omega k}{((K^2)^2/4m^2)\sqrt{4m^2/K^2-1}}\right) + \tan^{-1}\left(\dfrac{((K^2)^2/4m^2+k^2)v_*+\omega k}{((K^2)^2/4m^2)\sqrt{4m^2/K^2-1}}\right) & n<1 \text{ and } \xi<1 \\ \dfrac{1}{2}\log\left|\dfrac{\left(v_*((K^2)^2/4m^2+k^2)+((K^2)^2/4m^2)\sqrt{1-4m^2/K^2}\right)^2-\omega^2k^2}{\left(v_*((K^2)^2/4m^2+k^2)-((K^2)^2/4m^2)\sqrt{1-4m^2/K^2}\right)^2-\omega^2k^2}\right| & n>1 \text{ or } \xi>1 \end{cases}$$

Schérer, **KS** 2405.18466

HOW WELL DOES THE APPROXIMATION DO?



This is secretly the finite-T Lindhard formula for the longitudinal dielectric!!!!

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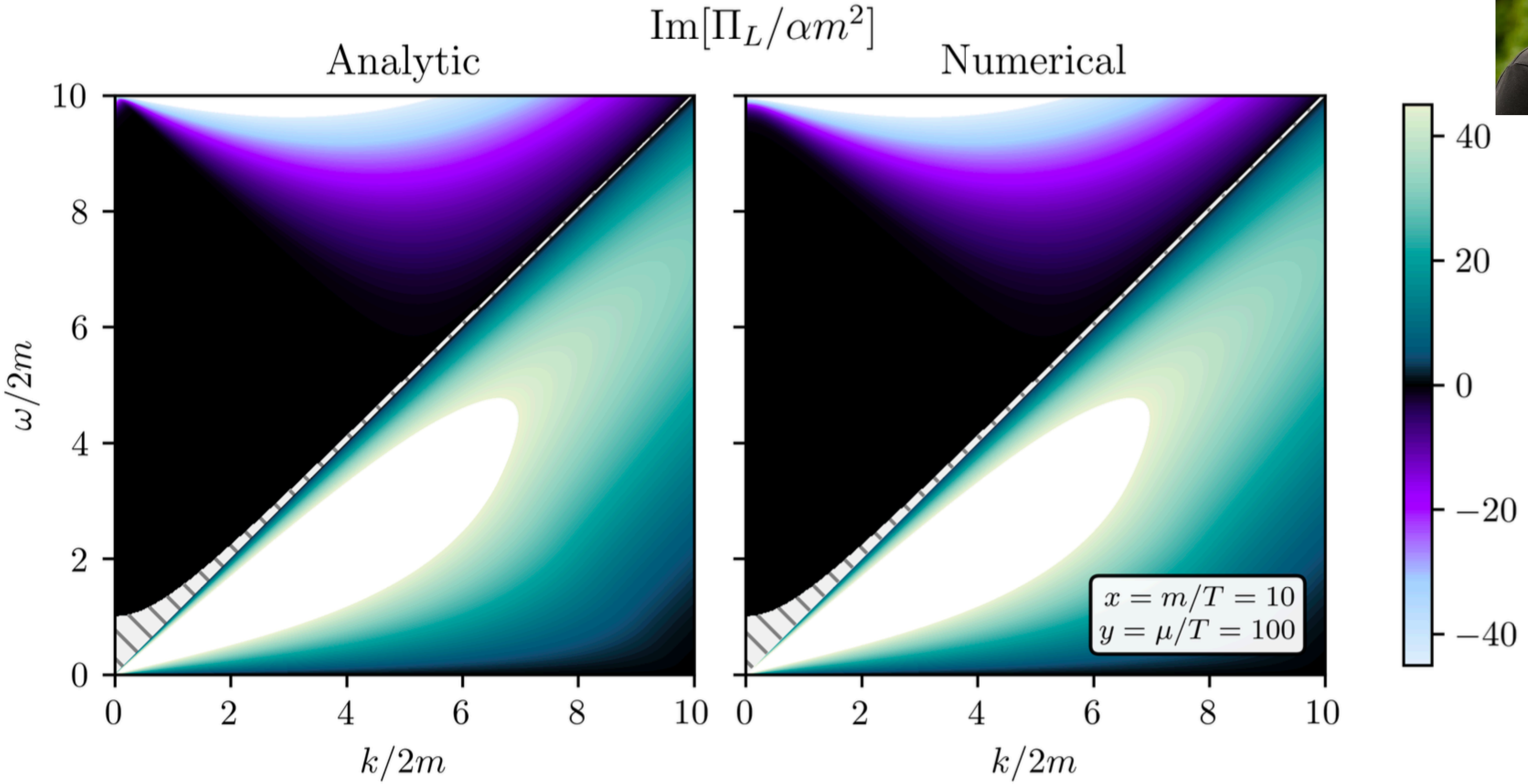
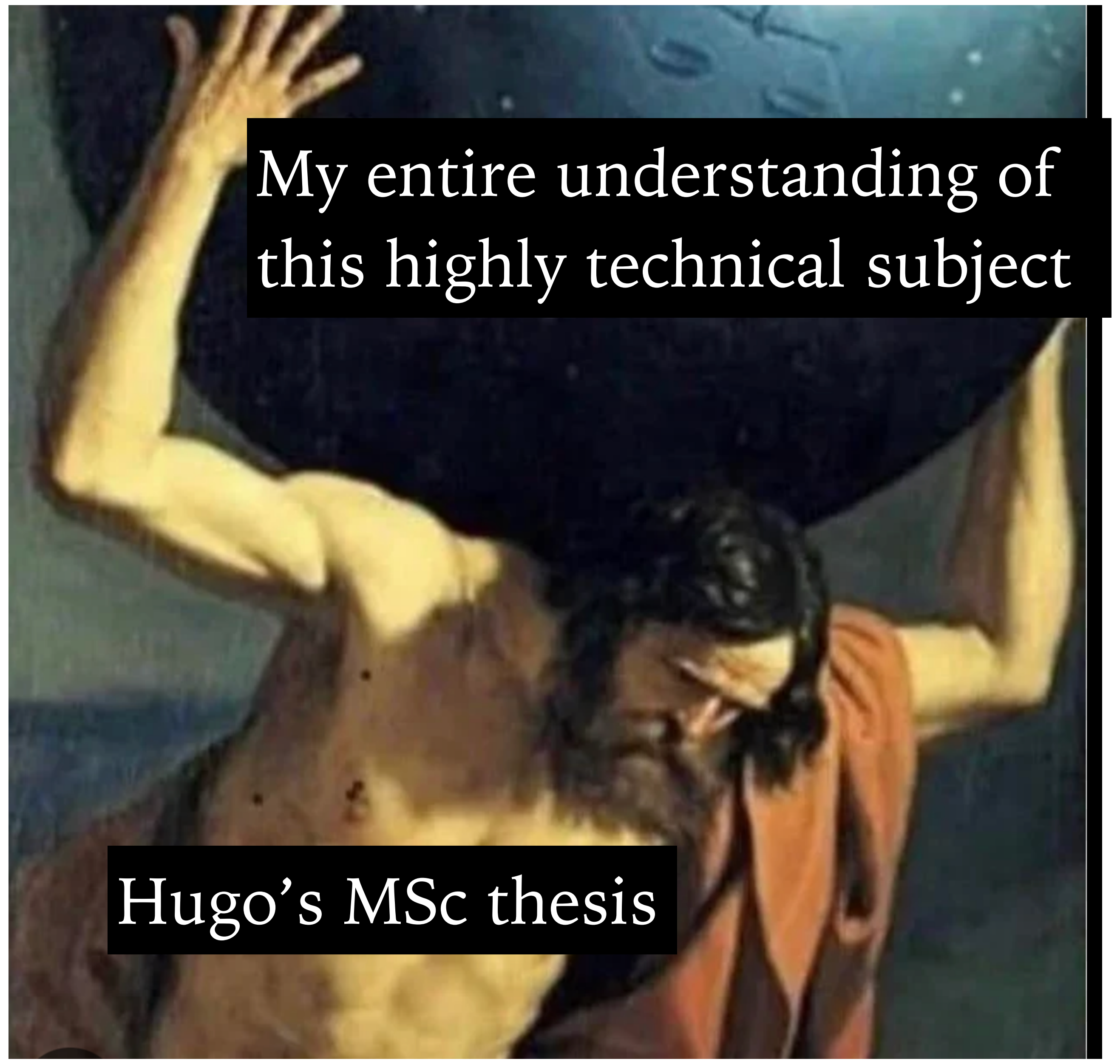
HOW WELL DOES THE APPROXIMATION DO?



Schérer, **KS** 2405.18466

IF YOU WANT A PEDAGOGICAL REFERENCE TO LEARN MORE IN DETAIL



McGill

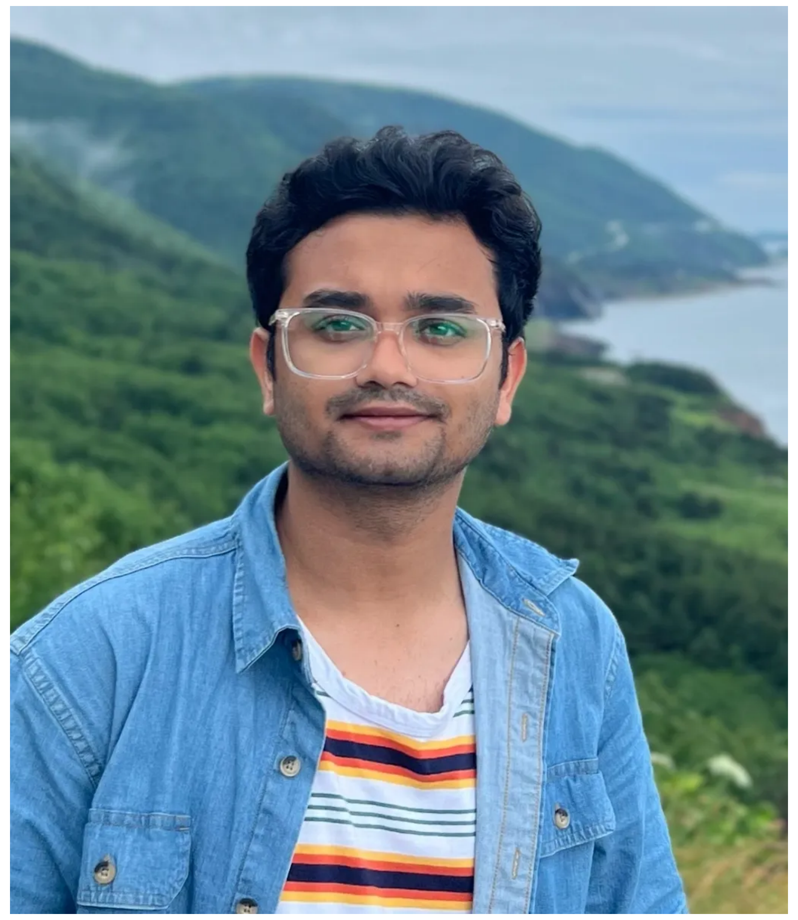
Finite temperature field theory for the masses

Hugo Schérer

Department of Physics
McGill University, Montréal

April, 2024

CRUCIAL CAVEAT: ALL OF THIS ASSUMES AN ISOTROPIC PLASMA!



Nirmalya Brahma

MOST ASTROPHYSICAL SYSTEMS HAVE MAGNETIC FIELDS— NOT ISOTROPIC!

HOW DOES ANISOTROPY PLAY A ROLE?

Brahma, **KS** 2409.monday

EOM $(K^2(g^{\mu\nu} - K^\mu k^\nu / K^2) + \Pi^{\mu\nu})A_\nu = 0$

Project onto e.g. transverse subspace

$$(\epsilon^T_\mu)^*(K^2(g^{\mu\nu} - K^\mu k^\nu / K^2) - \Pi^{\mu\nu})\epsilon^T_\nu A_T = (\omega^2 - k^2 - (\epsilon^T_\mu)^*\Pi^{\mu\nu}\epsilon^T_\nu)A_T = 0$$

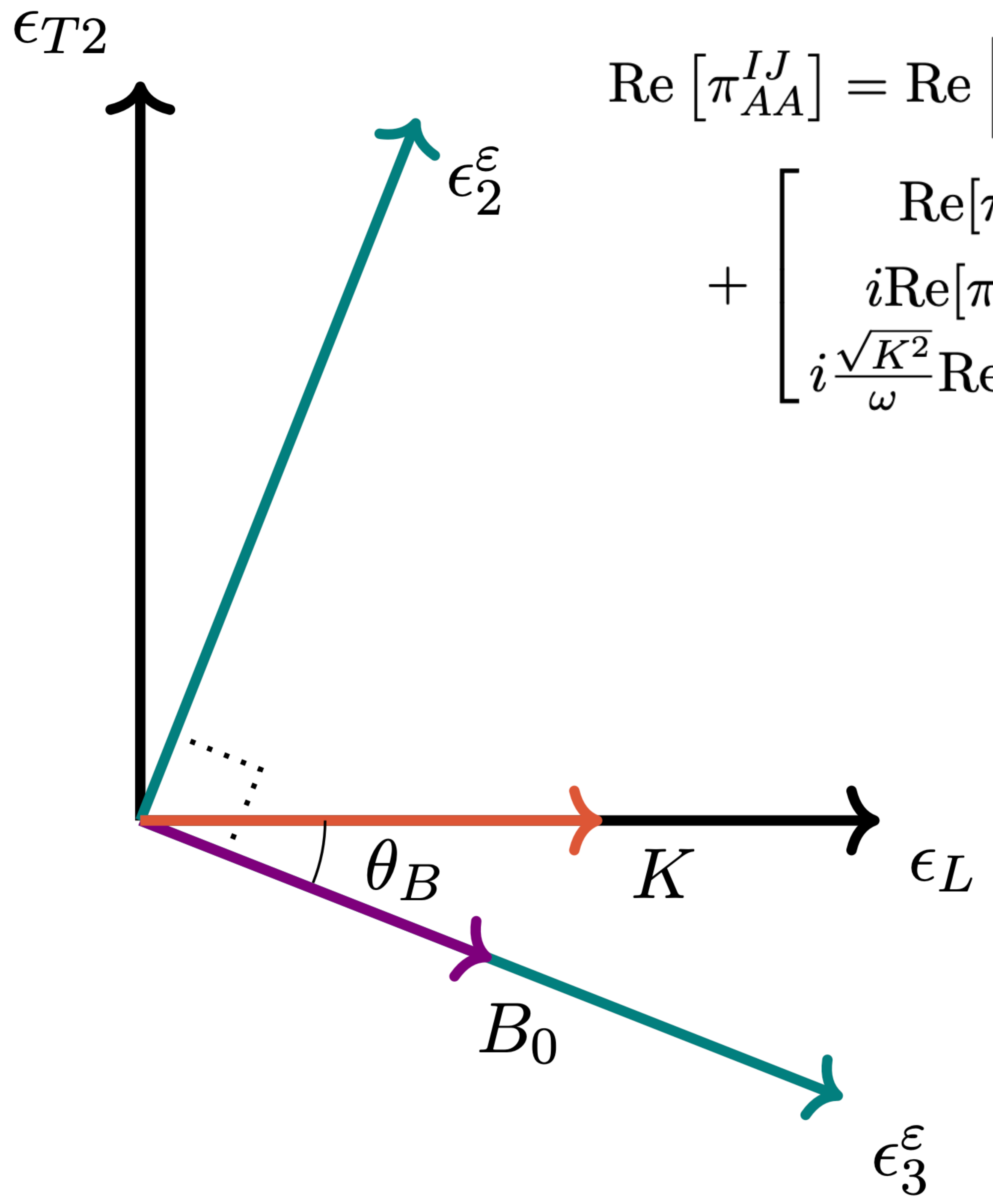
Π_T if plasma is isotropic

in general, for modes I, J $\pi^{IJ} = (\epsilon^I_\mu)^*\Pi^{\mu\nu}\epsilon^J_\nu$ is the mode mixing matrix

in isotropic plasmas, $\pi^{IJ} = \mathrm{diag}(\Pi_L, \Pi_T, \Pi_T)$ so transverse and longitudinal modes are the normal modes of the system!!

PLASMA NORMAL MODES

Brahma, **KS** 2409.monday



$$\mathrm{Re}\left[\pi^{IJ}_{AA}\right] = \mathrm{Re}\left[-(\epsilon^I)^* \cdot \hat{\Pi}^{BV} \cdot \epsilon^J\right]$$

$$+\begin{bmatrix} \mathrm{Re}[\pi_\perp] & -i\mathrm{Re}[\pi_\times]c_\theta & -i\frac{\sqrt{K^2}}{\omega}\mathrm{Re}[\pi_\times]s_\theta \\ i\mathrm{Re}[\pi_\times]c_\theta & \mathrm{Re}[\pi_\perp]c_\theta^2 + \mathrm{Re}[\pi_\parallel]s_\theta^2 & \frac{\sqrt{K^2}}{\omega}\left(\mathrm{Re}[\pi_\perp] - \mathrm{Re}[\pi_\parallel]\right)c_\theta s_\theta \\ i\frac{\sqrt{K^2}}{\omega}\mathrm{Re}[\pi_\times]s_\theta & \frac{\sqrt{K^2}}{\omega}\left(\mathrm{Re}[\pi_\perp] - \mathrm{Re}[\pi_\parallel]\right)c_\theta s_\theta & \frac{K^2}{\omega^2}\left(\mathrm{Re}[\pi_\parallel]c_\theta^2 + \mathrm{Re}[\pi_\perp]s_\theta^2\right) \end{bmatrix}$$

where $\mathrm{Re}[\pi_i(\omega, B)] = \frac{e^3 B}{4\pi}\sum_{n=0}^{\infty}\pi_i^{(n)}(\omega, B), \quad i = \perp, \parallel, \times$

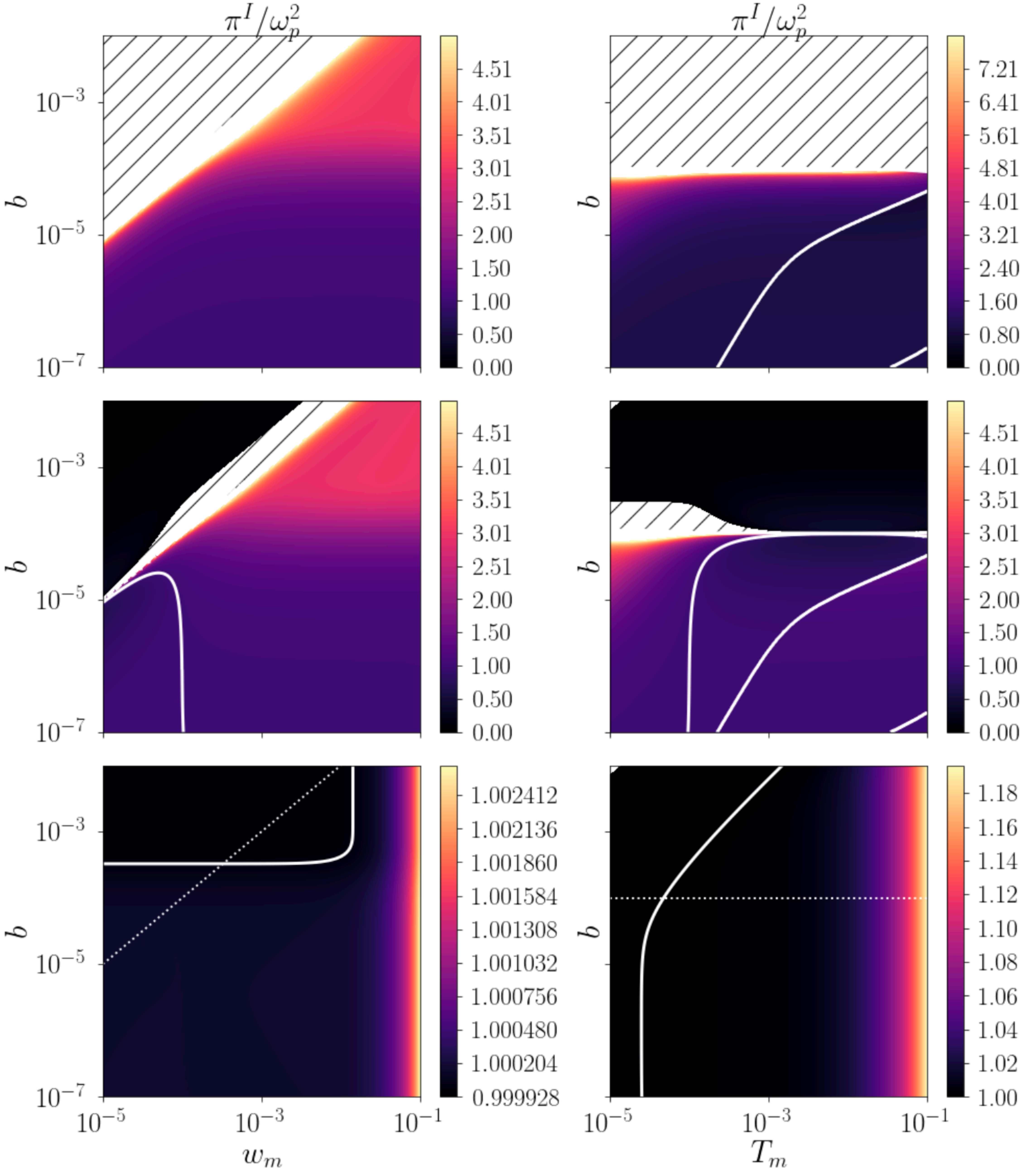
e.g. $\pi_\parallel^{(n)} = \int \frac{dq_{\parallel,b}}{2\pi}\frac{f_e\left(E_q^n\right) + f_{\bar{e}}\left(E_q^n\right)}{2E_q^n}\frac{\left(2-\delta_0^n\right)4m_e^2 + \left(1-\delta_0^n\right)16neB}{\left(E_q^n\right)^2 - \frac{\omega^2}{4}}$

energy of nth Landau level $E_q^n \equiv \sqrt{q_{\parallel,b}^2 + m_e^2 + 2neB}$

PLASMA NORMAL MODES- CLASSICAL

- “mass” of normal modes is not just simply the plasma frequency!
- In some parts of phase space, the eigenvalue of the mixing matrix is negative — no mixing with BSM particles is possible!
- As photons propagate in astrophysical media, temperatures and plasma frequencies scan a wide range of values, normal modes will rotate — lots of opportunities to hit resonances!

Brahma, **KS** 2409.monday



CONCLUSIONS

- There's a lot of variety in the universe! Many temperatures and densities to probe different energy scales
- We've developed some hammers… what are the nails? Mix and match different astro systems, models, observables, etc.
- When you create a group atmosphere where people feel welcomed and supported, you can do hard things (finite-temperature QFT!)
- Thanks for the memories and inspiration!

me at Comal 45 minutes after walking across stage in 2019

me at Comal last night