BSM AT THE ASTROPHYSICAL INTENSITY FRONTIER

Katelin Schutz, McGill University
Canada Research Chair in Astrophysics Beyond the Standard Model
EIC workshop at BNL, 22nd Nov. 2024

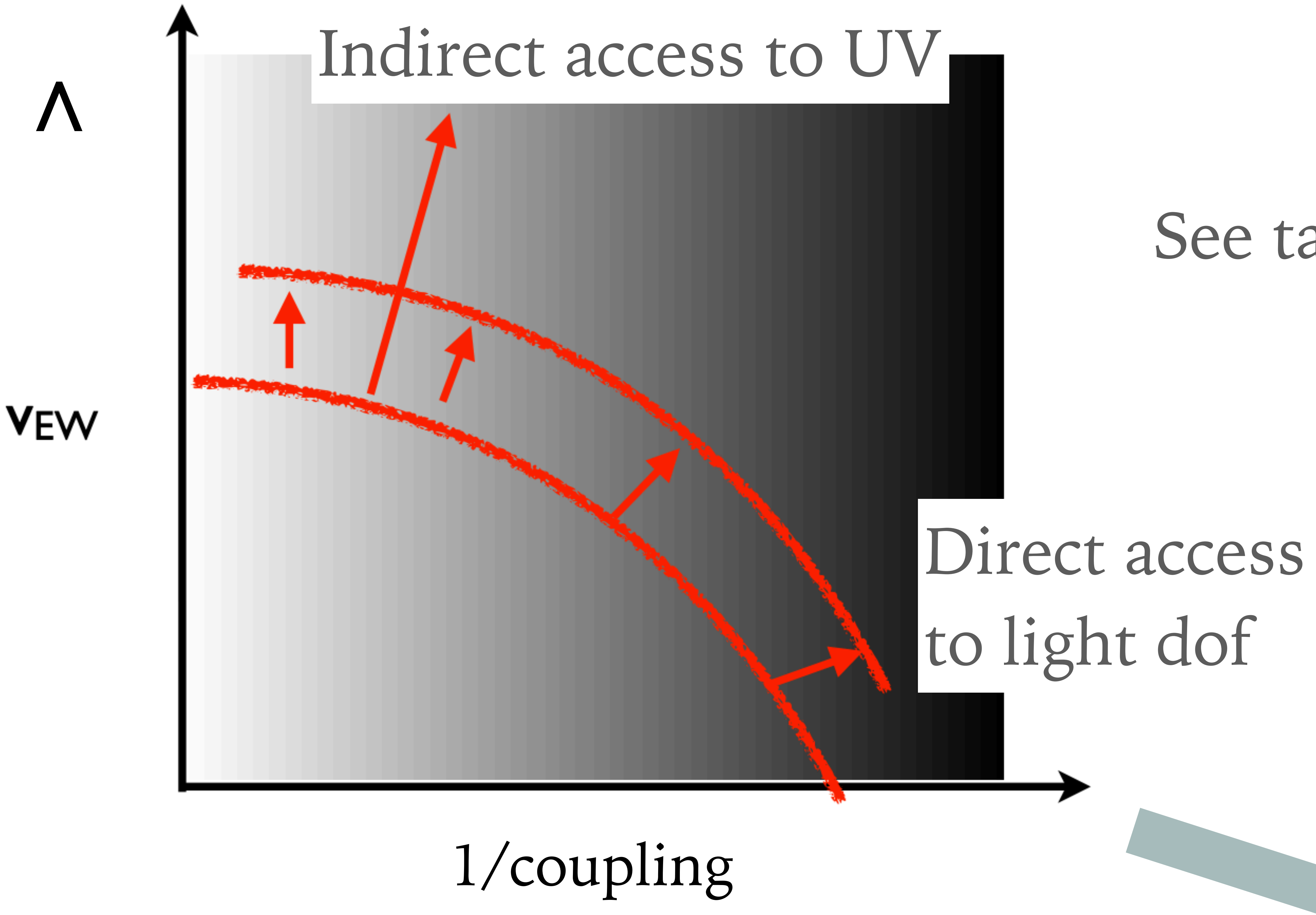
GATEKEEPING THE INTENSITY FRONTIER

“The strategy of research at the Intensity Frontier is to **generate the huge numbers of particles** needed to study rare subatomic processes” ~Symmetry Magazine

“Researchers at the Intensity Frontier investigate some of the rarest processes in nature, including **unusual interactions** of fundamental particles and **subtle effects that require large data sets to observe and measure**.” ~Argonne National Lab

“Search for rare new phenomena or difficult-to-produce new particles using medium-energy ultra-high-collision-rate accelerators, or **some other low-energy ultra-high-rate mechanism**” ~Matt Strassler

BSM AT THE “REGULAR” INTENSITY FRONTIER

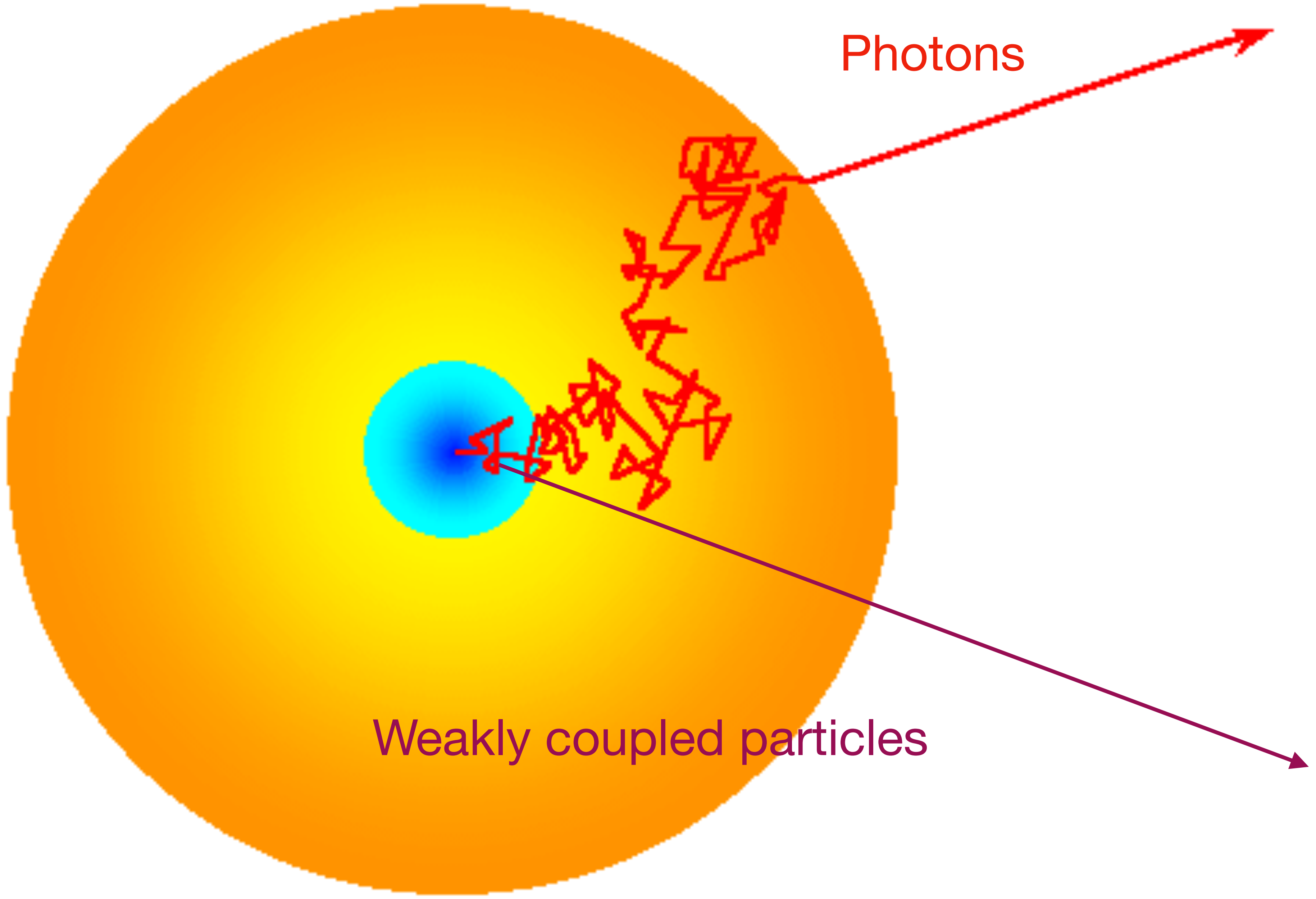


See talks by Cirigliano, Neil, Liu, Mantry++

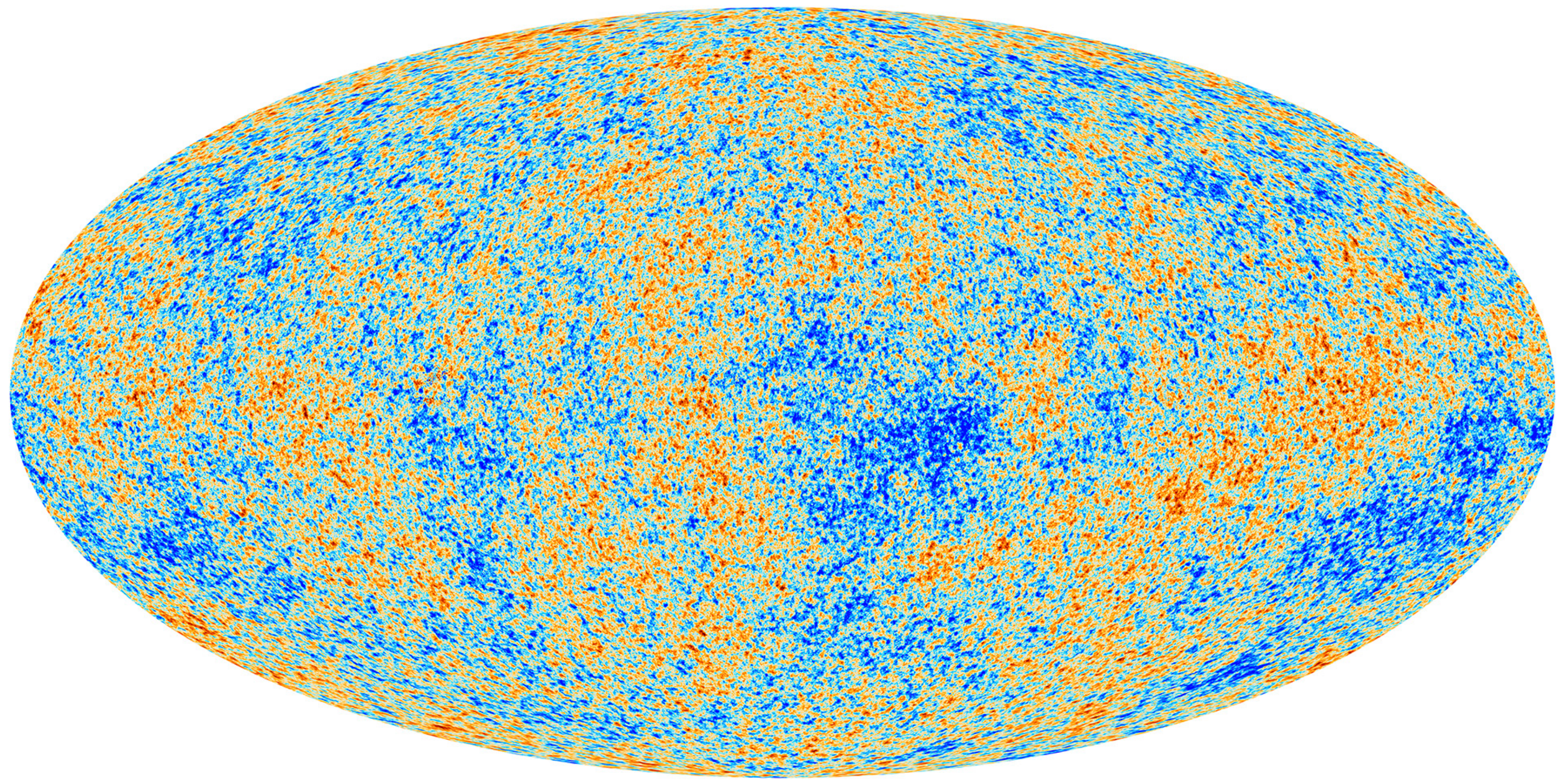
Focus of my talk

QUALITATIVE DIFFERENCES AT ASTROPHYSICS INTENSITY FRONTIER

- ✻ Not an experimental but observational science!
- ✻ Engergy is thermal, not directed as with a beam
- ✻ Processes occur in dense media that may or may not be in thermal equilibrium



- ☑ Enormous volumes and long timescales compensate for low production rates, weak coupling can be a benefit for observability
- ☑ Lots of easy-to-observe “samples” for some kinds of astrophysical objects (e.g. stars) for collateral science opportunity
- ☑ Finite densities might provide qualitatively new channels for testing BSM physics that cannot be accessed in lab



GUIDING PRINCIPLE: BOTTOM-UP EFT

Typical astrophysical system has temperatures ranging from few keV to few MeV max! Focus on the relevant or marginal operators connecting SM to “hidden” dof (SM singlets), leads to “portal” picture:

- Higgs portal, $\epsilon_h |h|^2 |\phi|^2$
- neutrino portal, $\epsilon_\nu (hL)\psi$
- vector portal, $\epsilon_Y F^{\mu\nu} F'_{\mu\nu}$
- add vectors that gauge SM fermions e.g. $U(1)_{B-L}$
- axions (dimension-5)
- …

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- Higgs portal, $\epsilon_h |h|^2 |\phi|^2$
- neutrino portal, $\epsilon_\nu (hL)\psi$
- vector portal, $\epsilon_Y F^{\mu\nu} F'_{\mu\nu}$ focus of today (simple, illustrative, widely testable)
- add vectors that gauge SM fermions e.g. $U(1)_{B-L}$
- axions (dimension-5)
- …

“DARK PHOTON” PORTAL TO HIDDEN SECTOR

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

Kinetic mixing can come from loops of heavy particles, string theory compactifications

(small) Stueckelberg mass

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

Rotate away kinetic mixing term (“mass basis”)

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

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

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

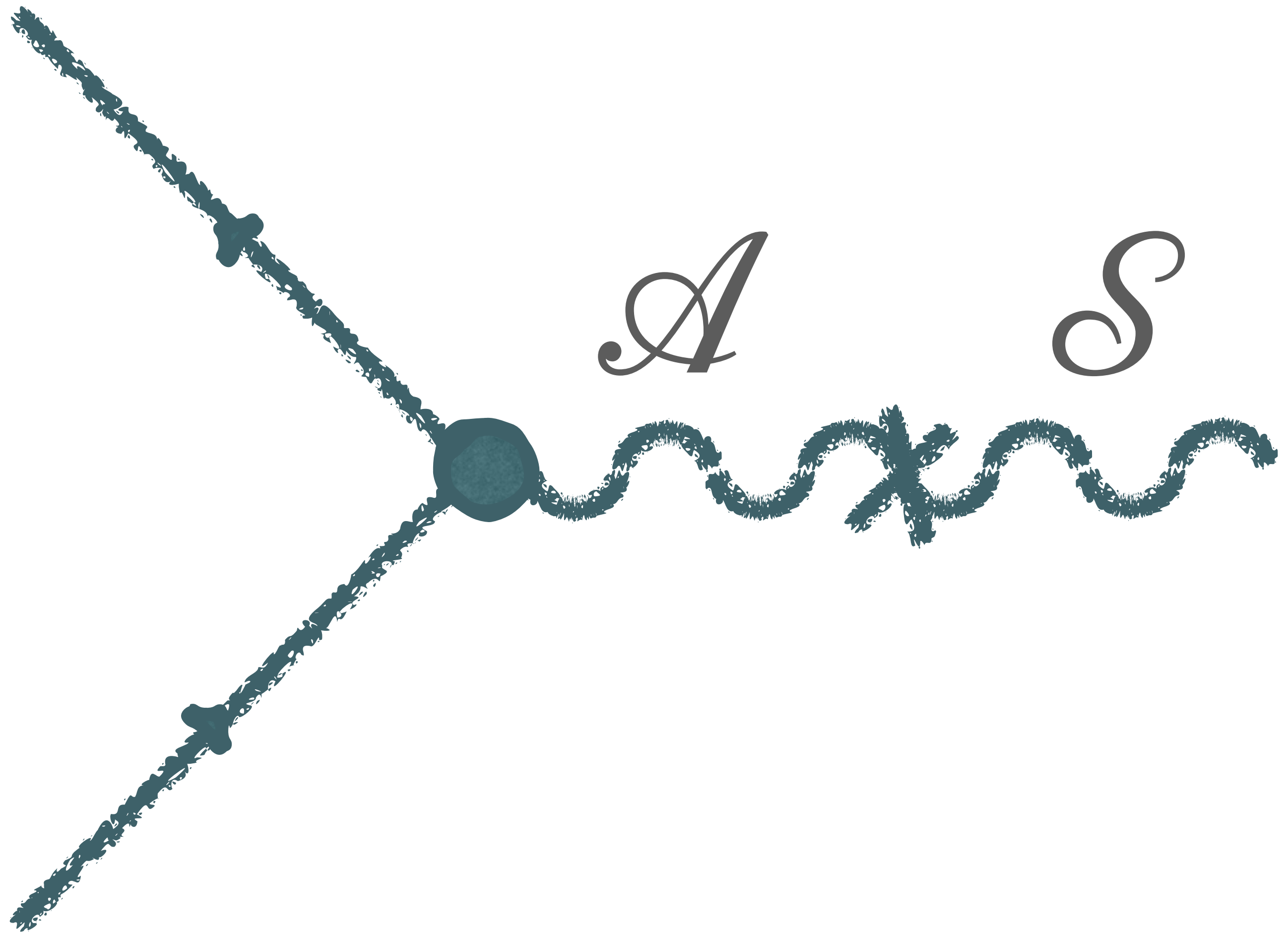
$$\mathscr{L} \supset \frac{1}{2}m_{A'}^2 \mathscr{S}_\mu(\mathscr{S}^\mu + \mathscr{A}^\mu) + ej_\mu \mathscr{A}^\mu$$

HOW IS THIS AFFECTED BY A DENSE (ASTROPHYSICAL) MEDIUM?

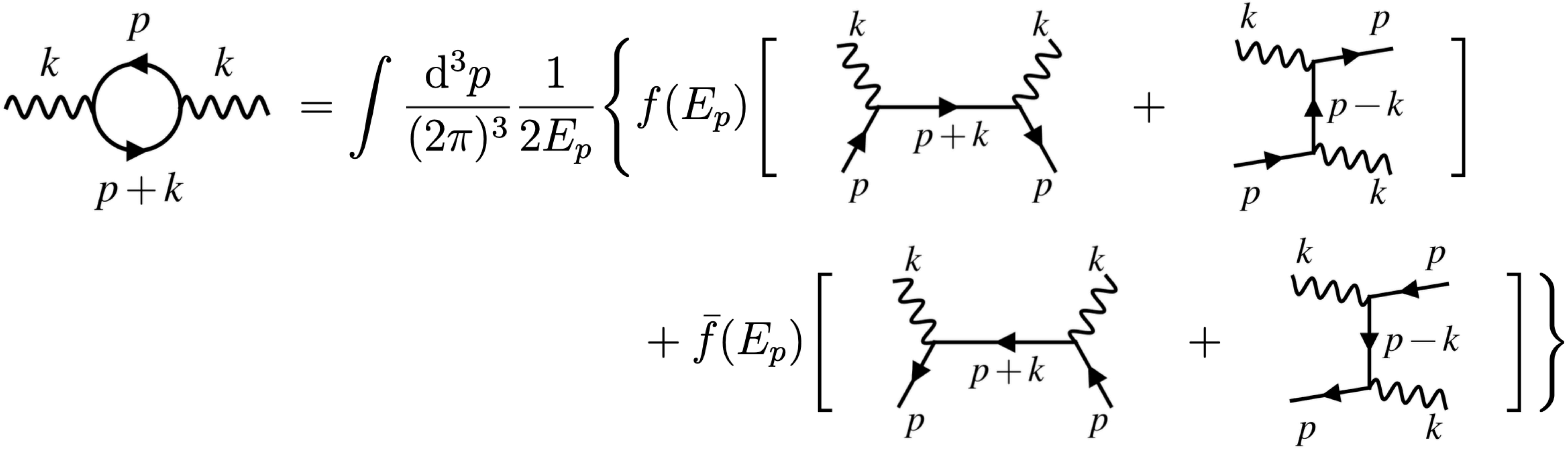
$$j_\mu = j_\mu^{\text{ext}} + j_\mu^{\text{ind}} \, , \quad j_\mu^{\text{ind}} \equiv \Pi^{\mu\nu}(\omega, k) A_\nu$$

Polarization tensor of linear response theory

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

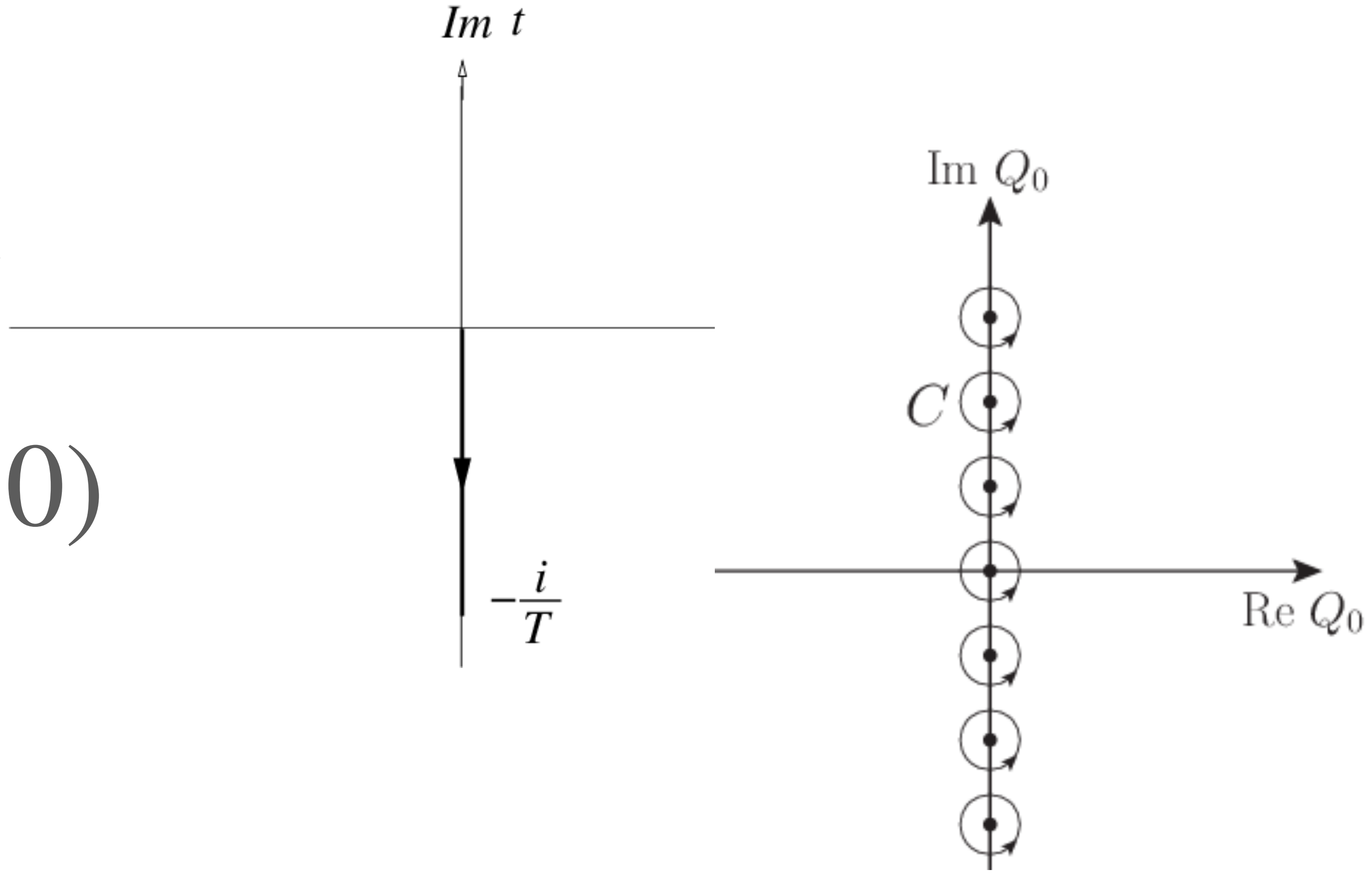


Active state is constantly getting bombarded (“dressed”) by background particles before oscillating to sterile state



$$= \int \frac{\mathrm{d}^3 p}{(2\pi)^3}\,\frac{1}{2E_p}\left\{ f(E_p)\left[\quad + \quad \right] + \bar{f}(E_p)\left[\quad + \quad \right] \right\}$$

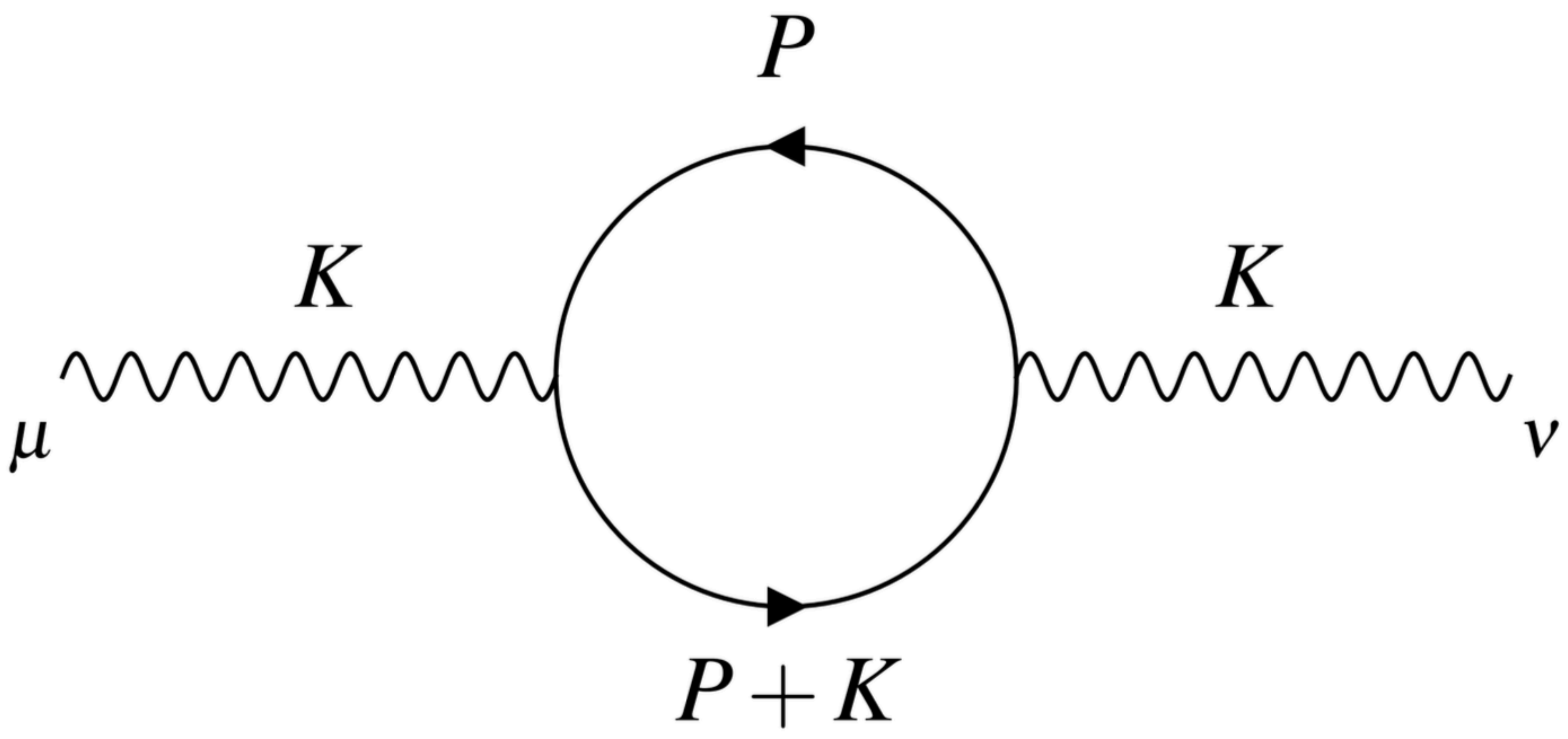
HOW DO WE COMPUTE POLARIZATION TENSORS?



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

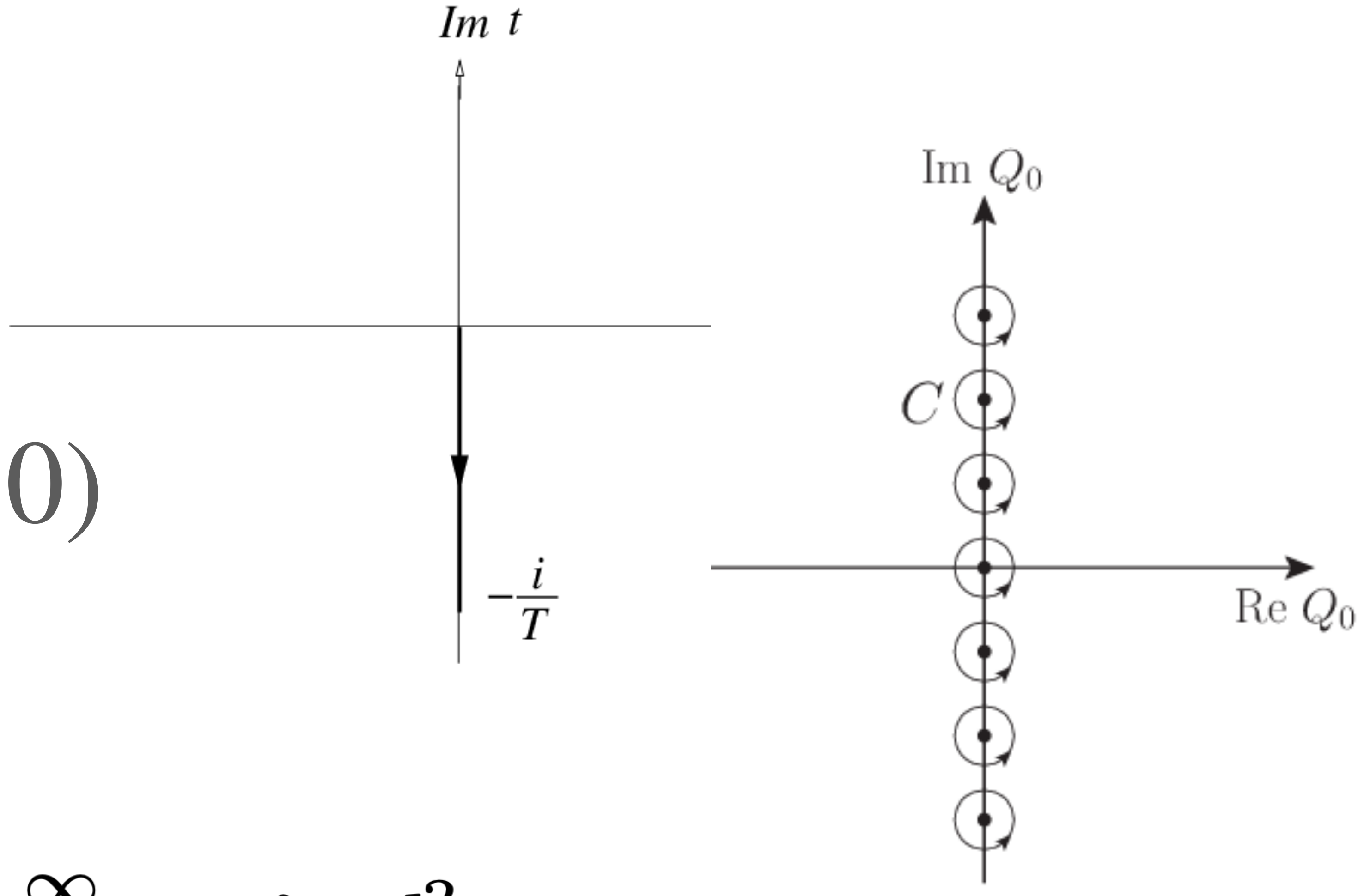
finite imaginary time interval, bosons have periodic boundary conditions, so Fourier transforming we get discrete spectrum of imaginary "Matsubara frequencies"

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



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

HOW DO WE COMPUTE POLARIZATION TENSORS?



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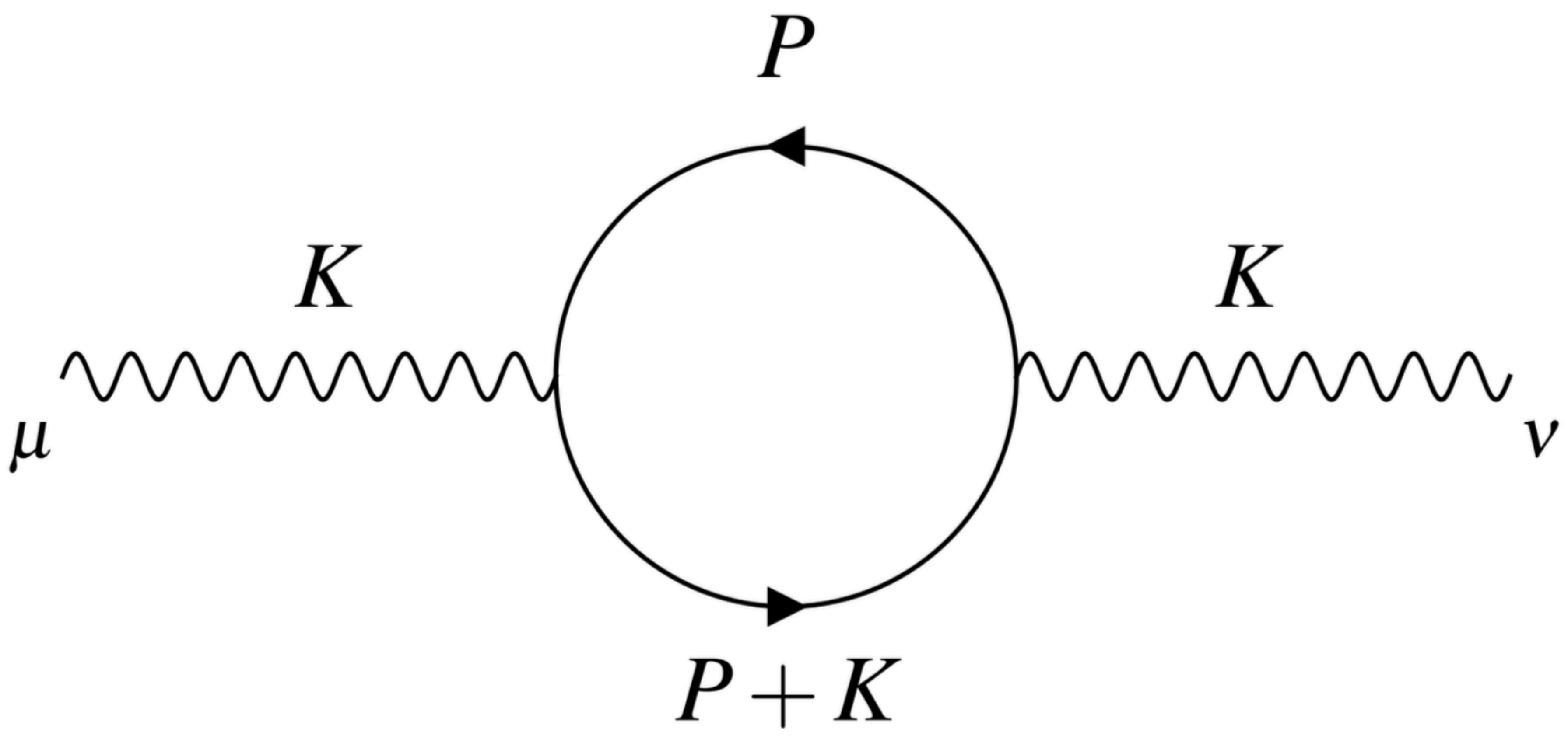

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soft photon approximation used in Braaten & Segel (1993)

USAGE OF BRAATEN & SEGEL APPROXIMATION

Decompose polarization tensor by projection

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

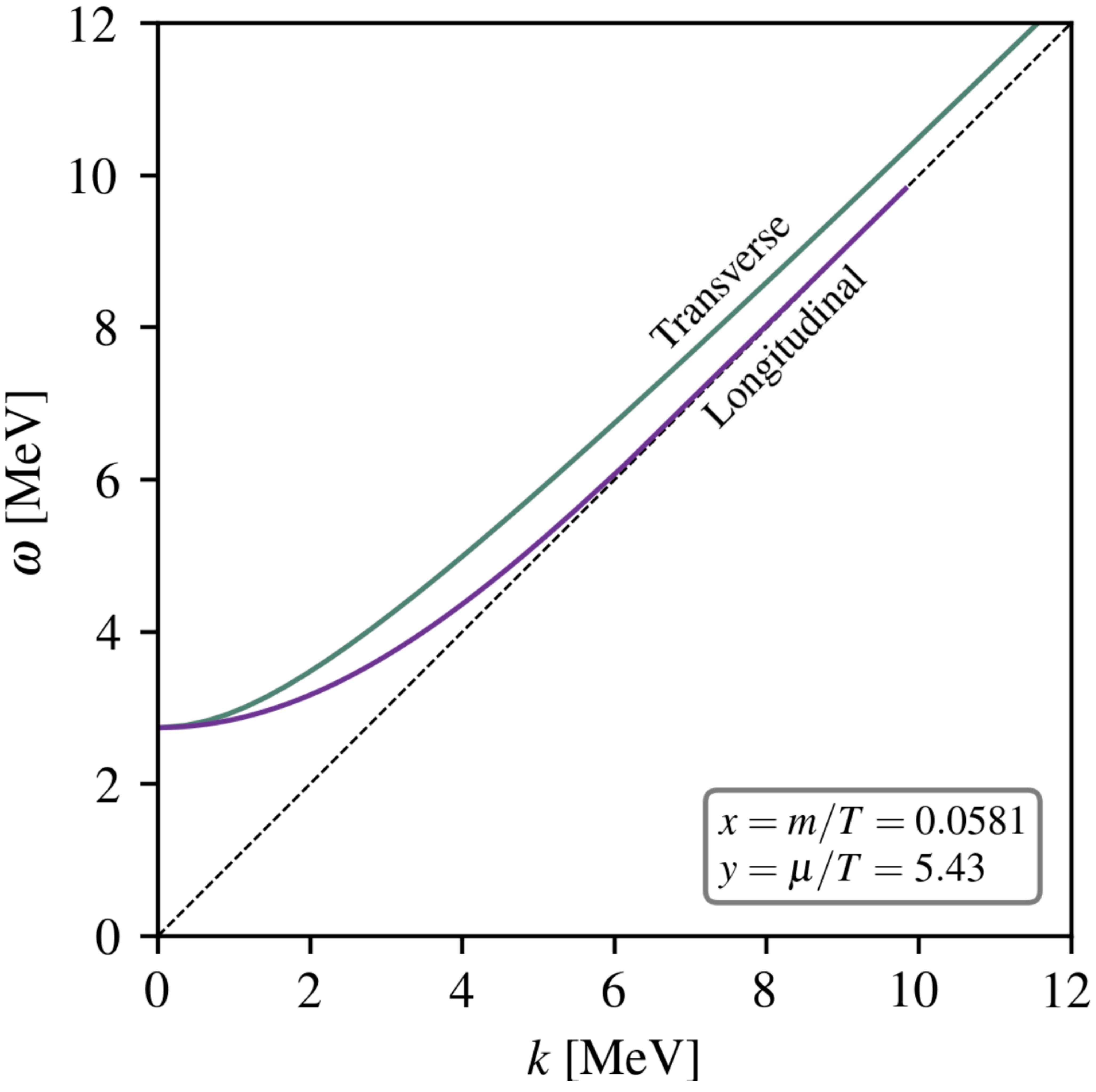
$$\Pi^{\mu\nu} = \Pi_L P_L^{\mu\nu} + \Pi_T P_T^{\mu\nu}$$

Read off dispersion relations from poles in propagator

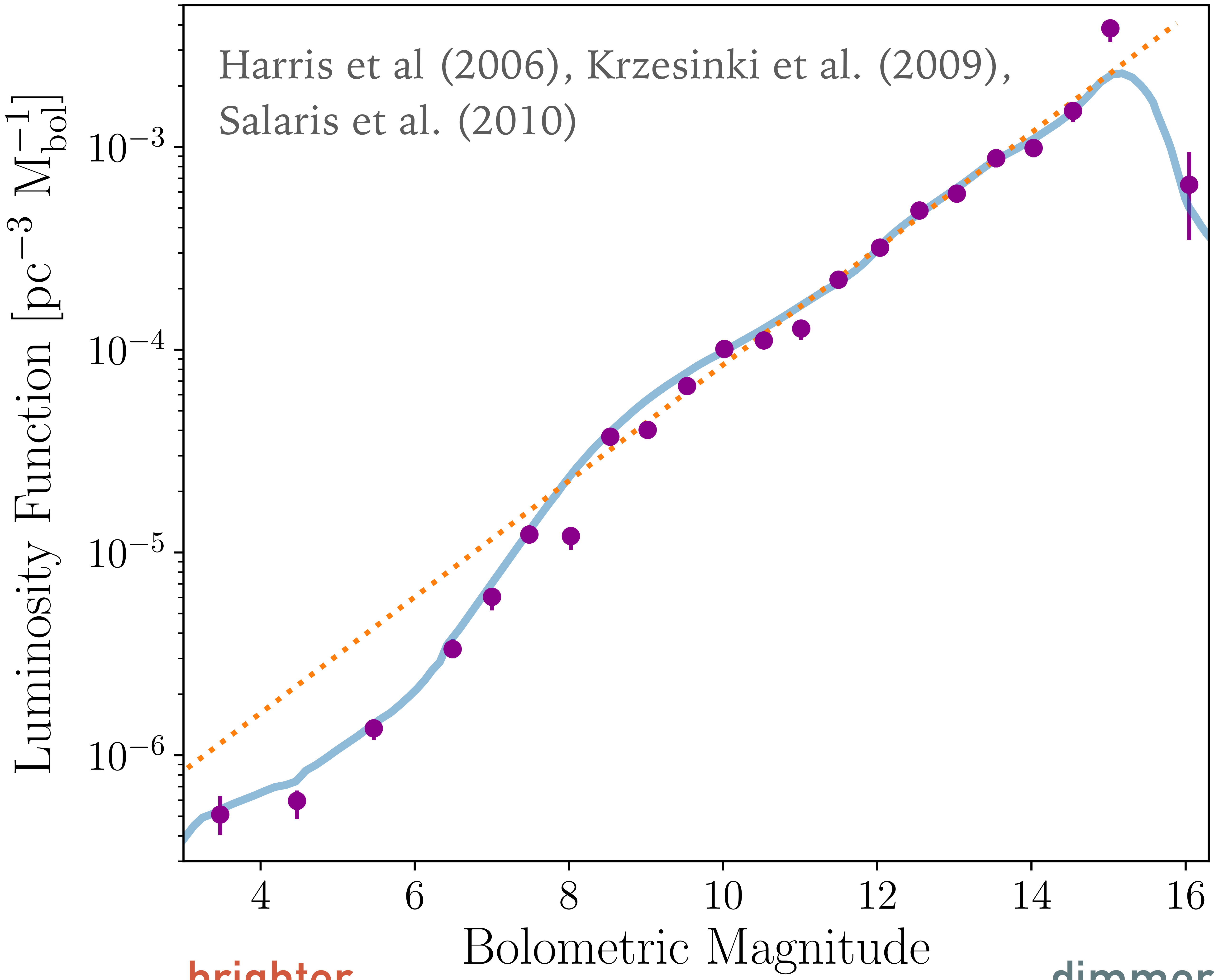
$$\omega_T^2 = k^2 + \Pi_T, \quad \omega_L = \frac{\omega_L^2}{k^2}\Pi_L$$

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

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



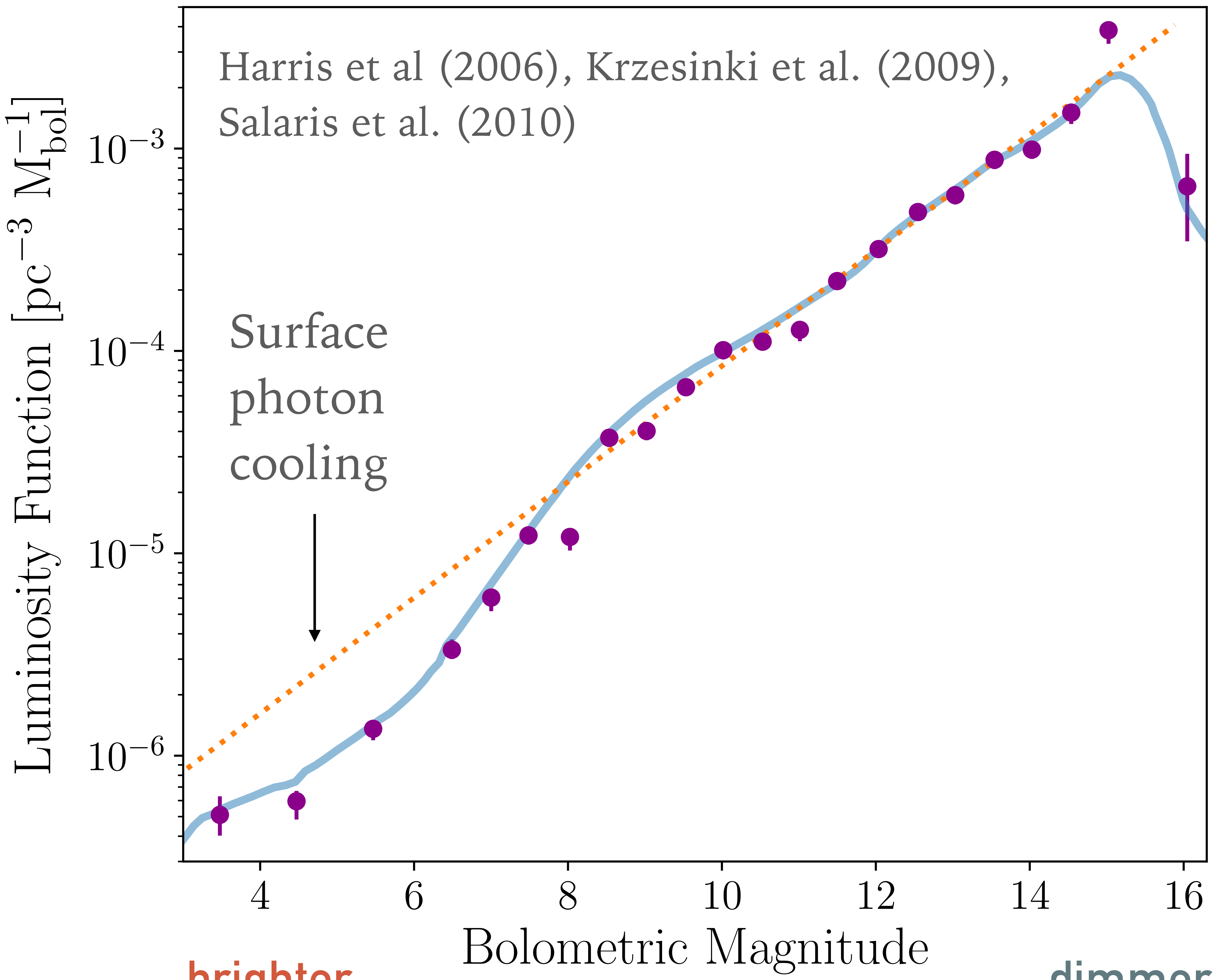
WHITE DWARF COOLING AND POPULATION



← **brighter**
hotter

dimmer →
cooler

WHITE DWARF COOLING AND POPULATION



← brighter
hotter

dimmer →
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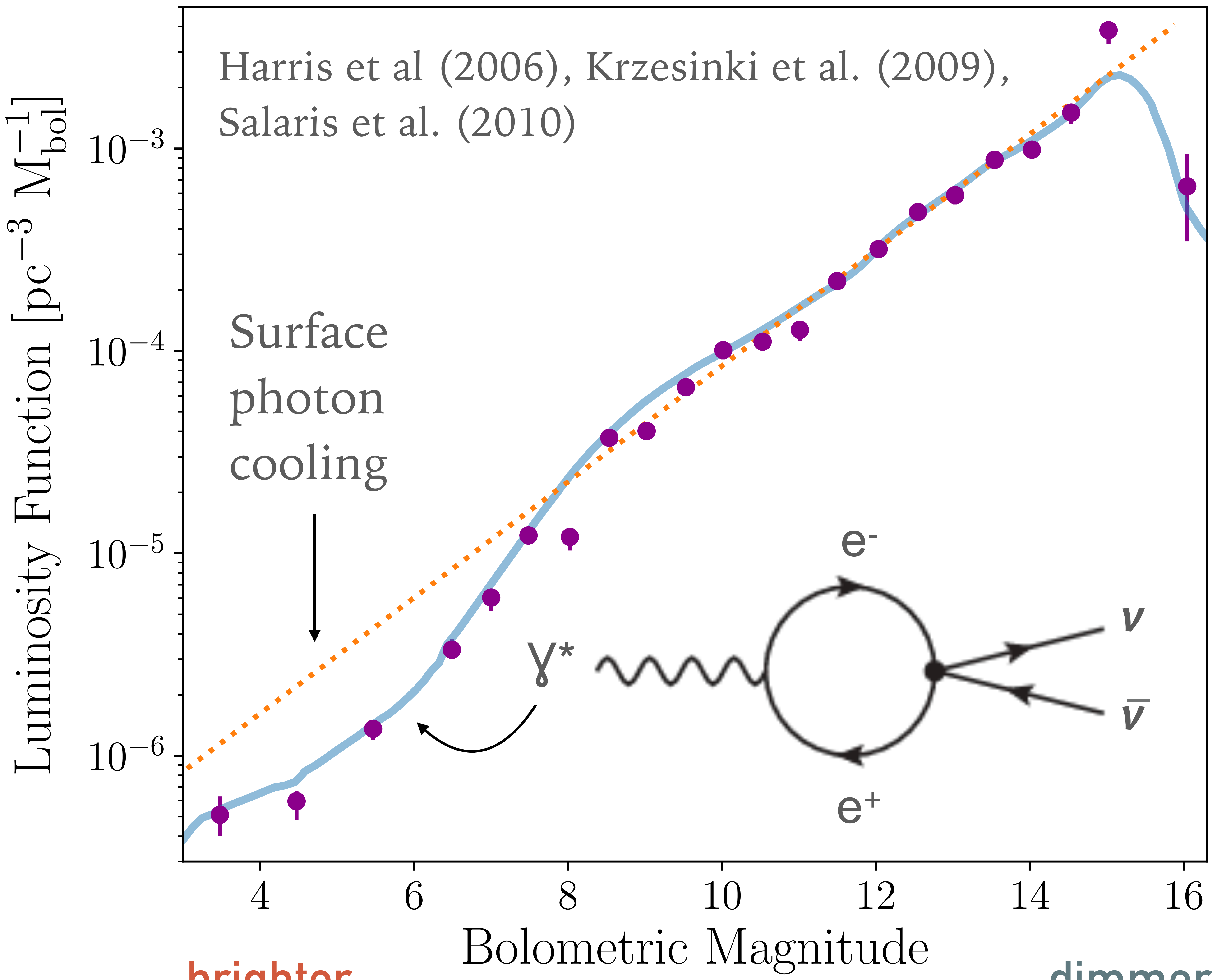
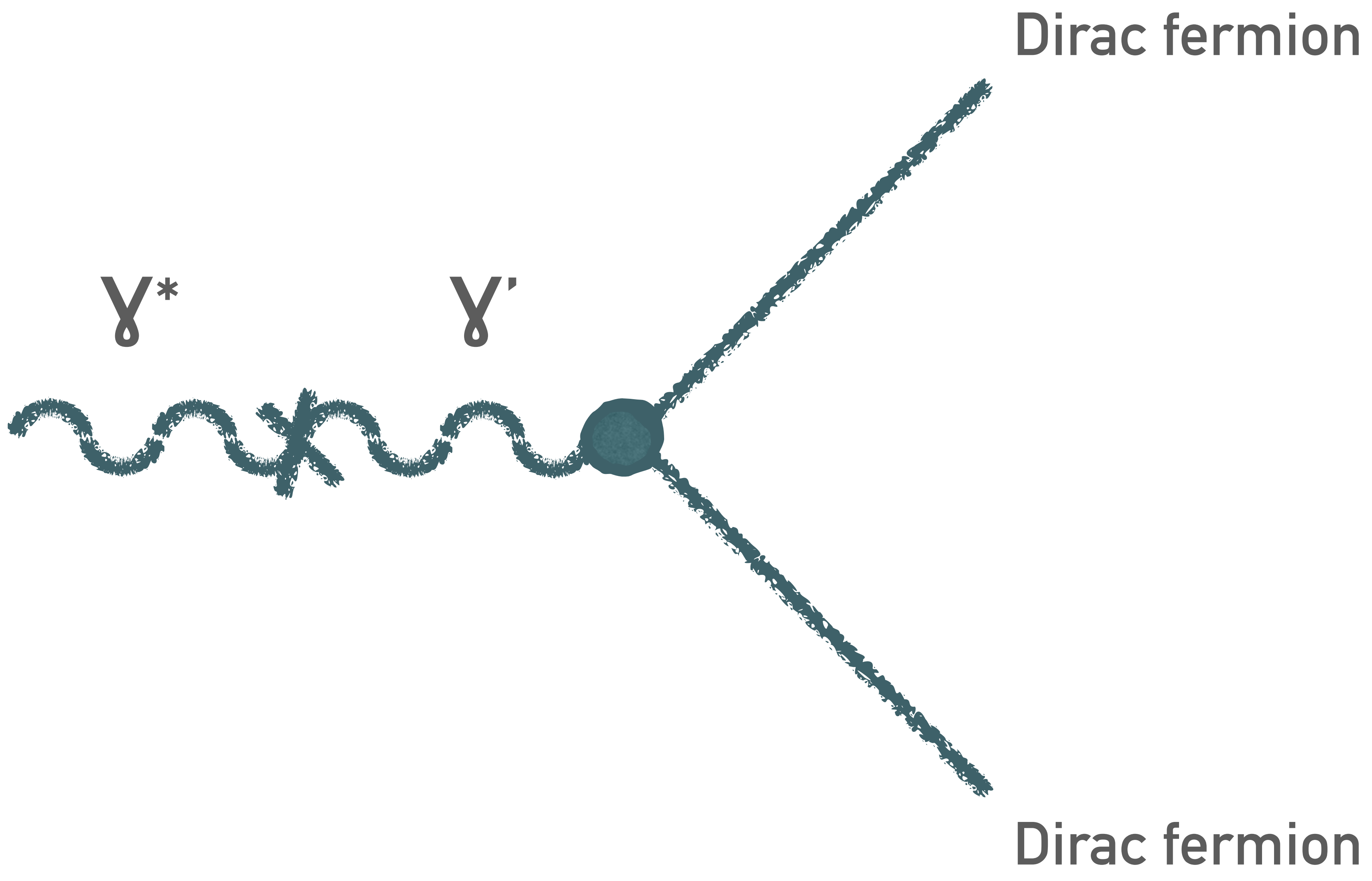
WHITE DWARF COOLING AND POPULATION



← brighter hotter

dimmer cooler →

PLASMON DECAYS FOR BSM



$$\mathscr{L} \supset \frac{\kappa}{2} F'_{\mu\nu}F^{\mu\nu} + \frac{1}{2} m_{A'}^2 A'_\mu A'^{\mu} + g_\chi \bar{\chi}\gamma^\mu\chi A'_\mu$$

Kinetic mixing can come from loops of heavy particles, string theory compactifications

(small) Stueckelberg mass

Dirac fermion charged under U(1)’

In a medium, rotating to “millicharge basis”

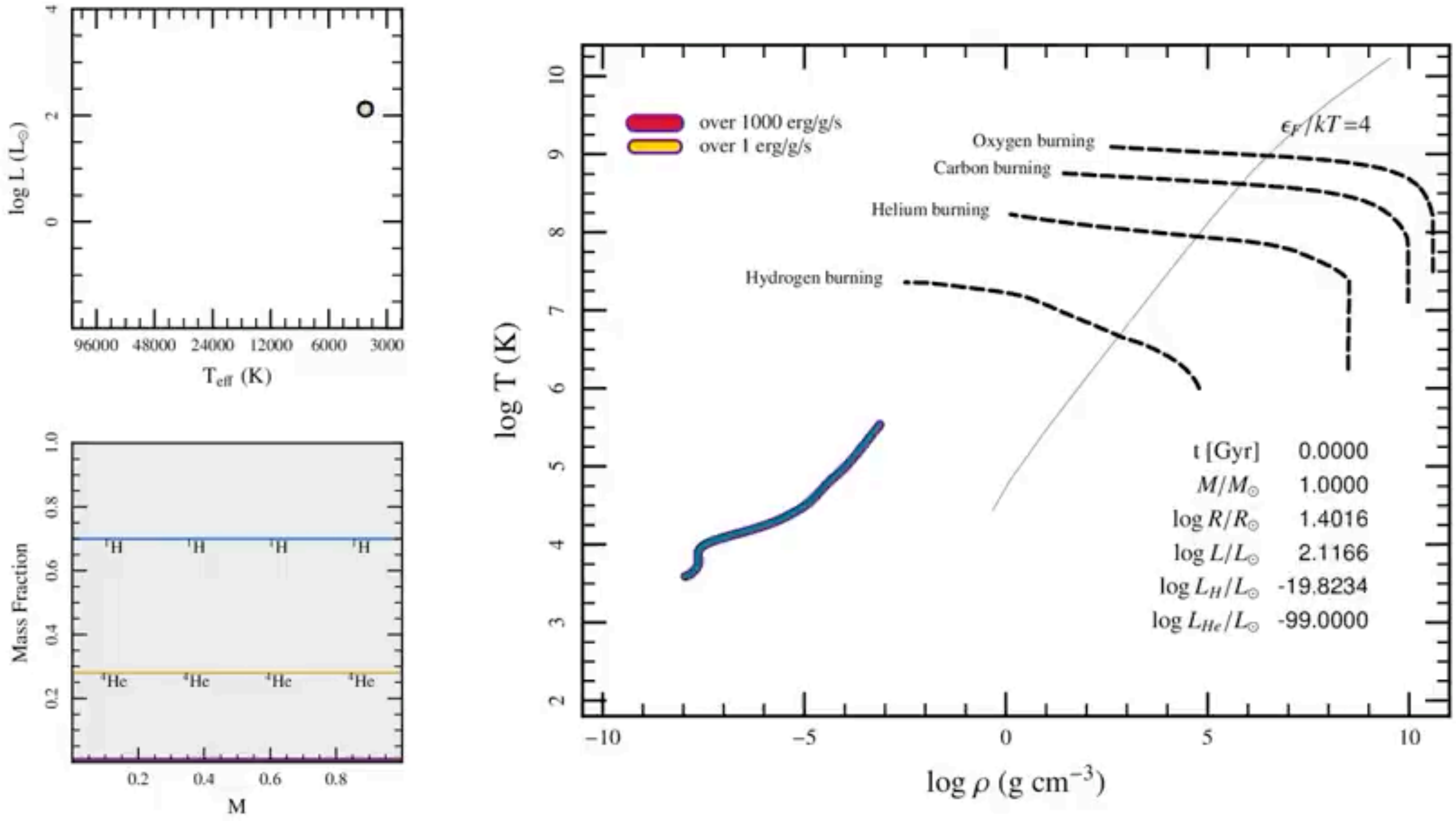
$$\mathscr{L} \supset J^\mu_{EM}\left(eA_\mu\right) + g_\chi\bar{\chi}\gamma^\mu\chi\left(A'_\mu+\kappa A_\mu\right) + \textit{higher order in } \frac{m_{A'}^2}{\pi_{L,T}}$$

Particle charged under dark U(1) appears to be “millicharged” under E&M, $Q = g_\chi \kappa/e$

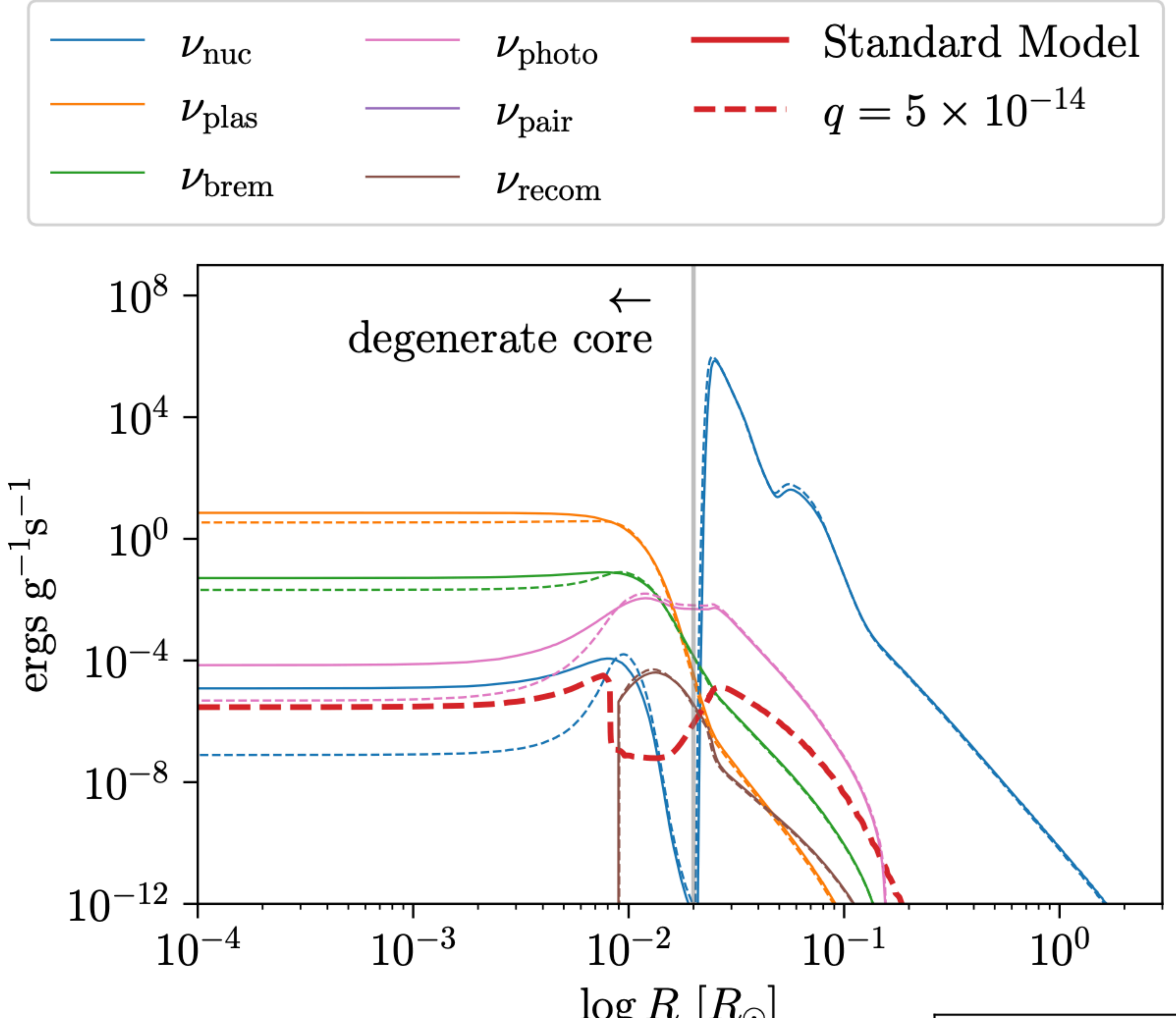
Photon form factors (effective “mass squared”) depend on kinematics, medium properties

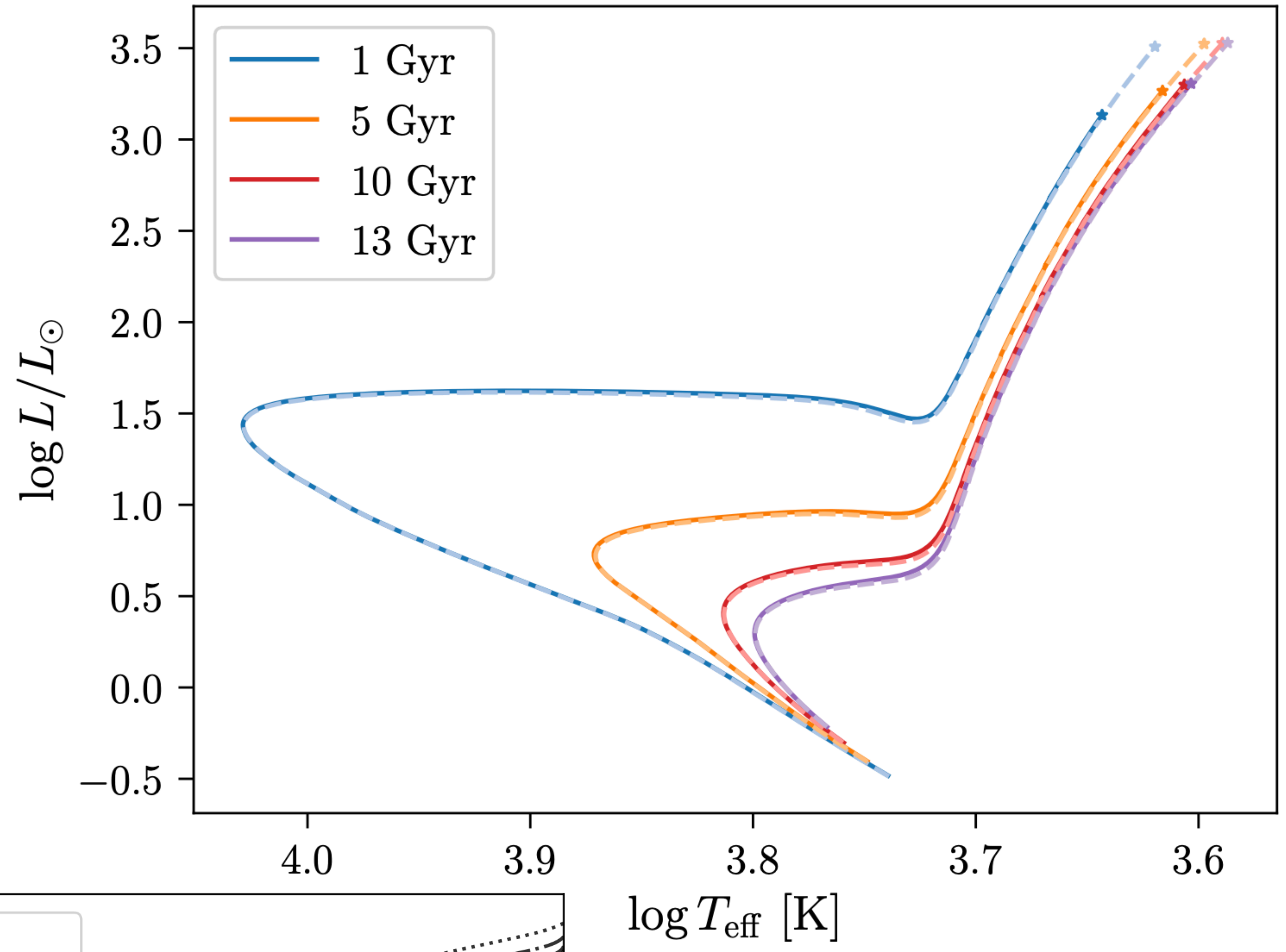
LOOKING FOR MILLICHARGED PARTICLES IN STARS

SELF-CONSISTENT STELLAR EVOLUTION WITH MESA

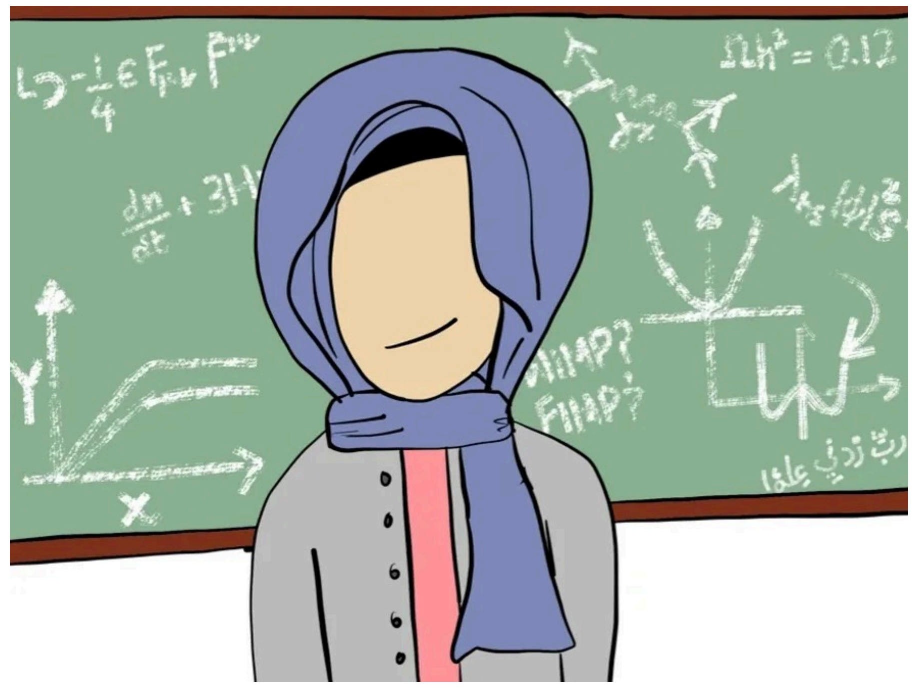


MESA SIMULATIONS WITH MILLICHARGES FROM PLASMON DECAY



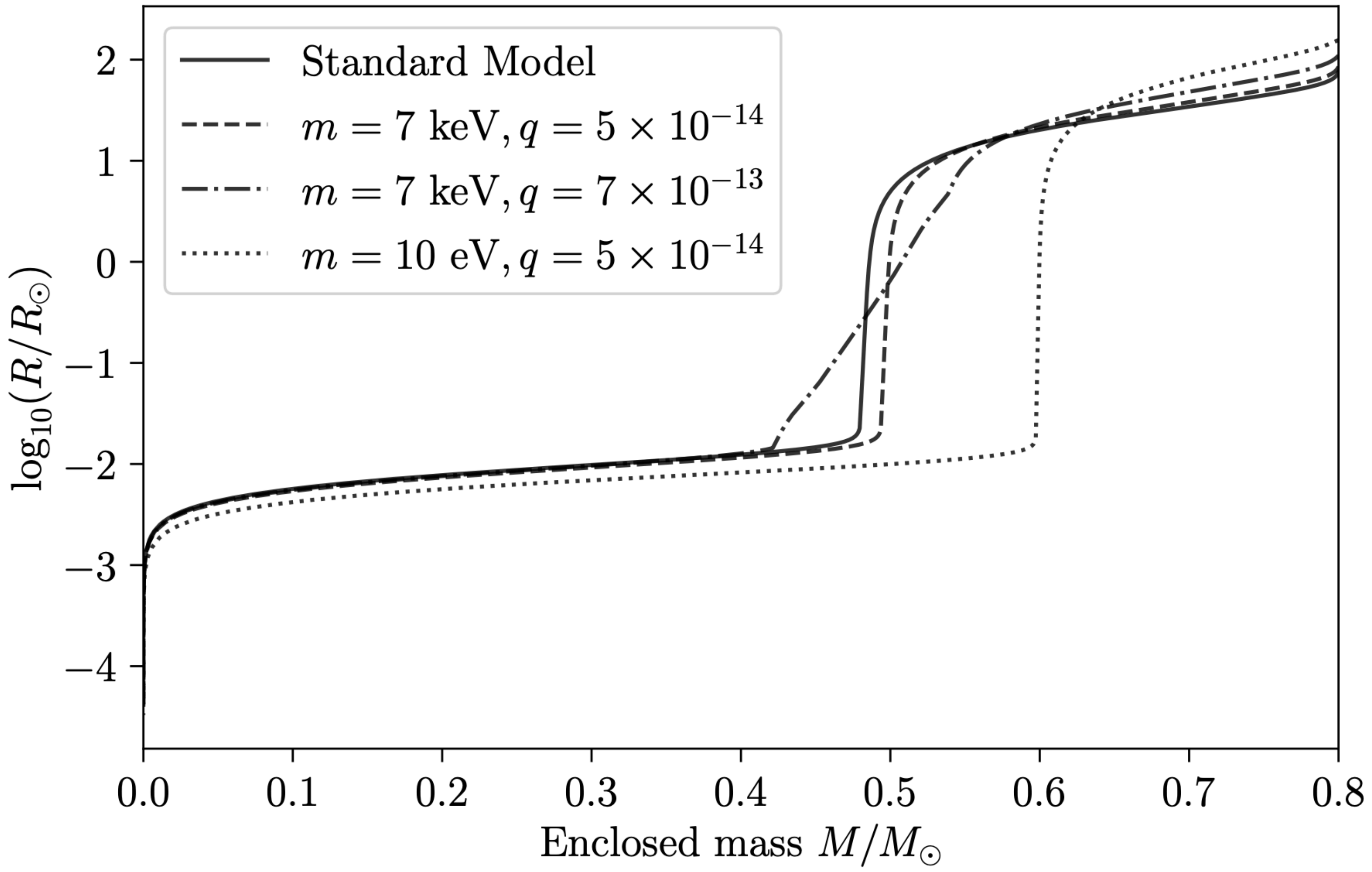


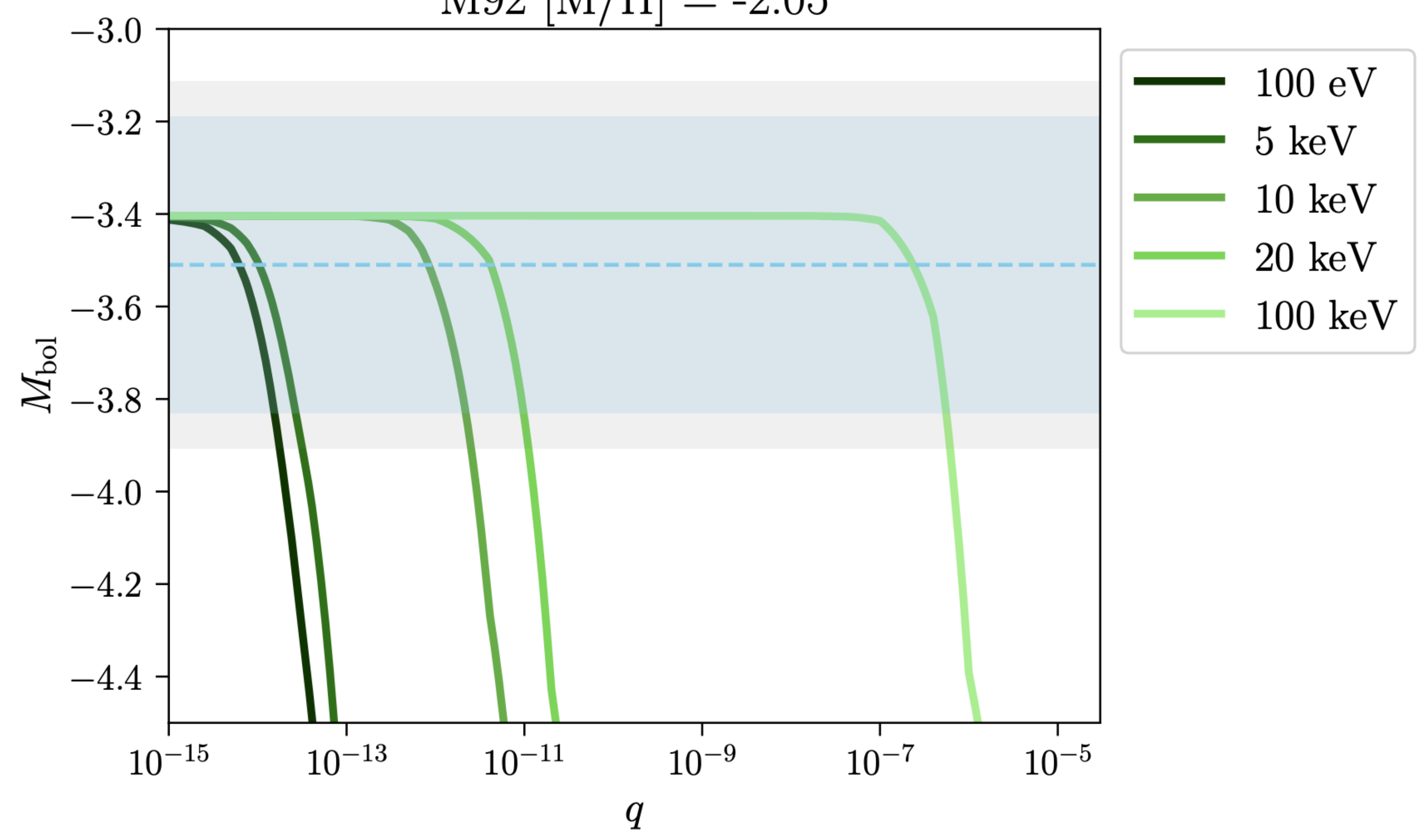
Audrey Fung

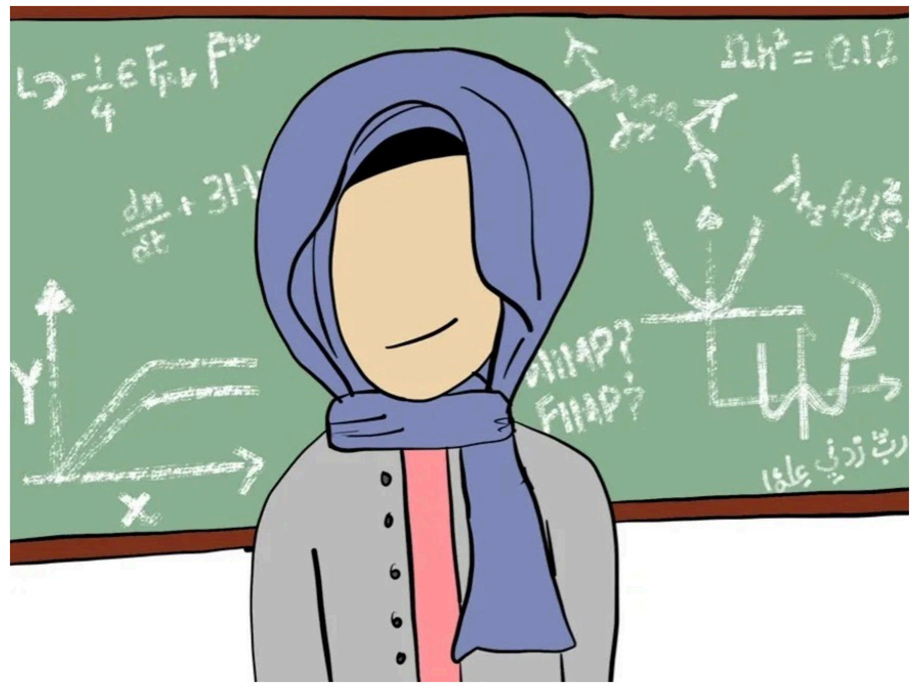


Dr. Saniya Heeba

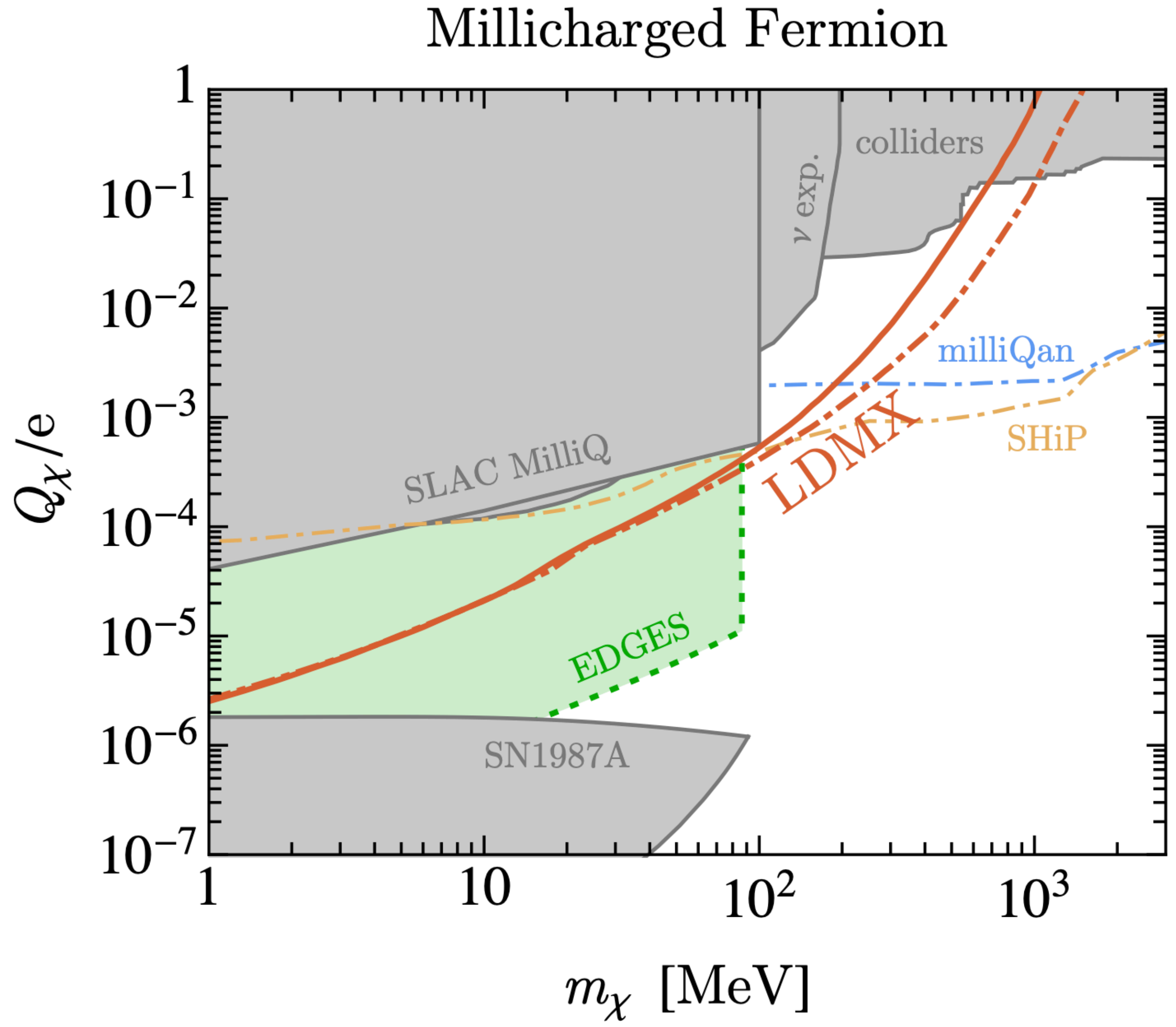
Fung, Heeba, Liu, Muralidharan, **KS**, Vincent (2024)



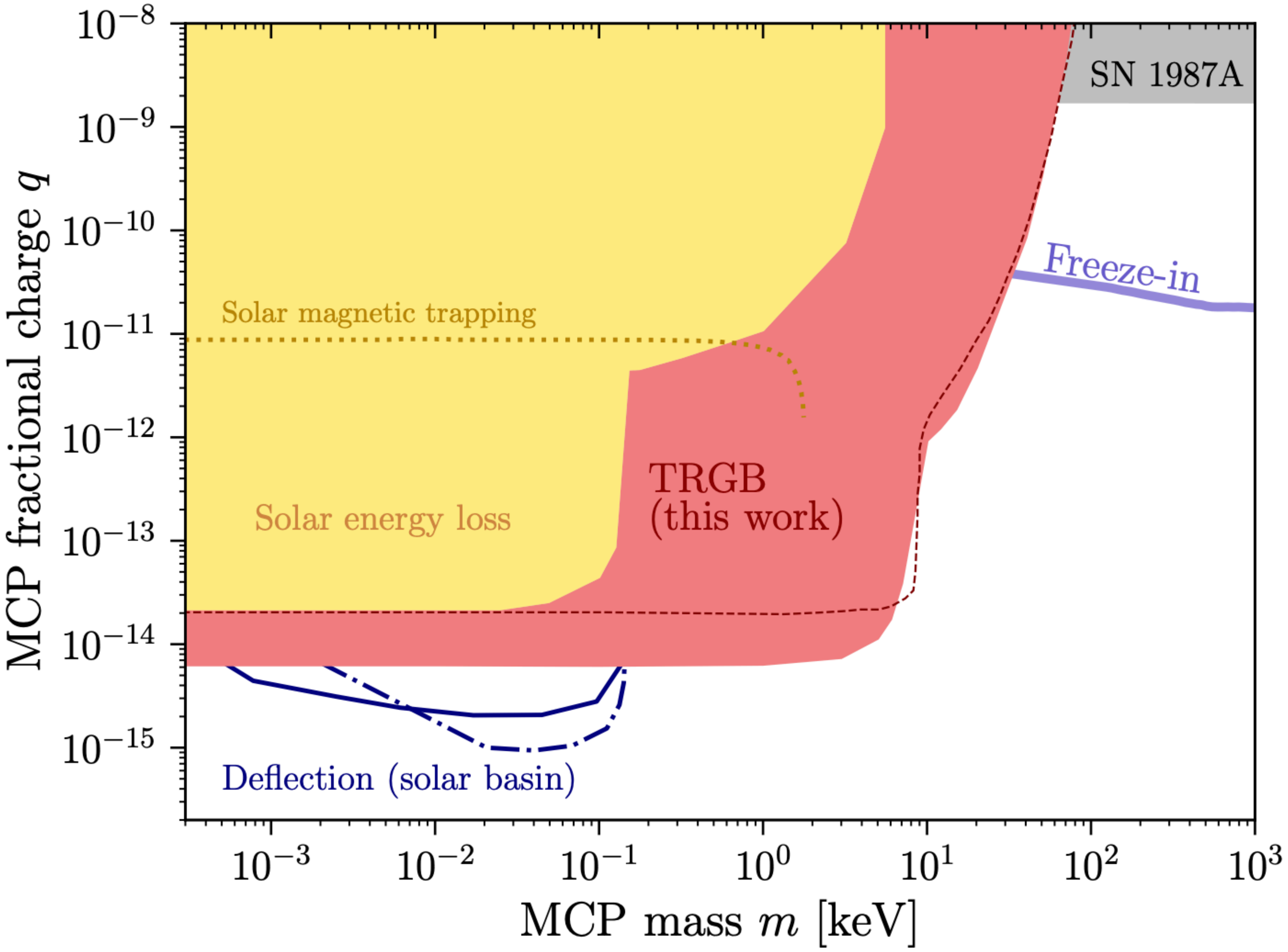




Fung, Heeba, Liu, Muralidharan, **KS**, Vincent (2024)

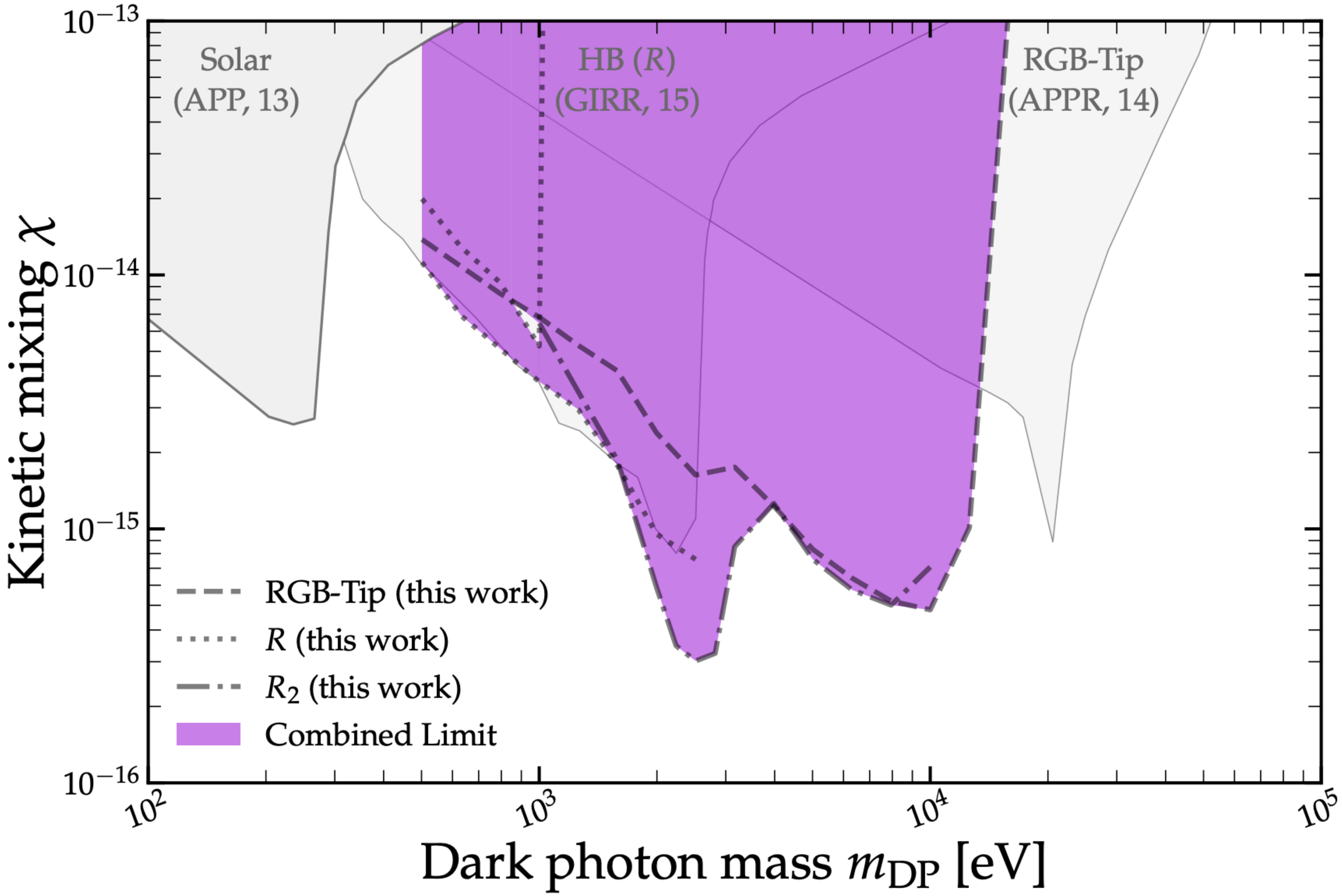


contrast with terrestrial searches e.g. Berlin et al. (2019)

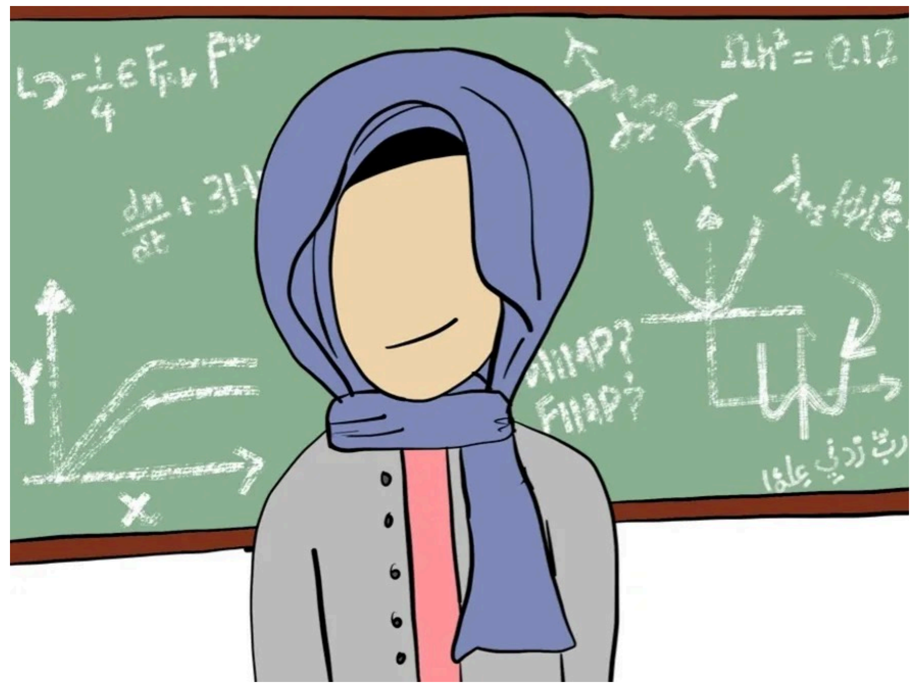


High degree of complementarity with “regular” intensity frontier!

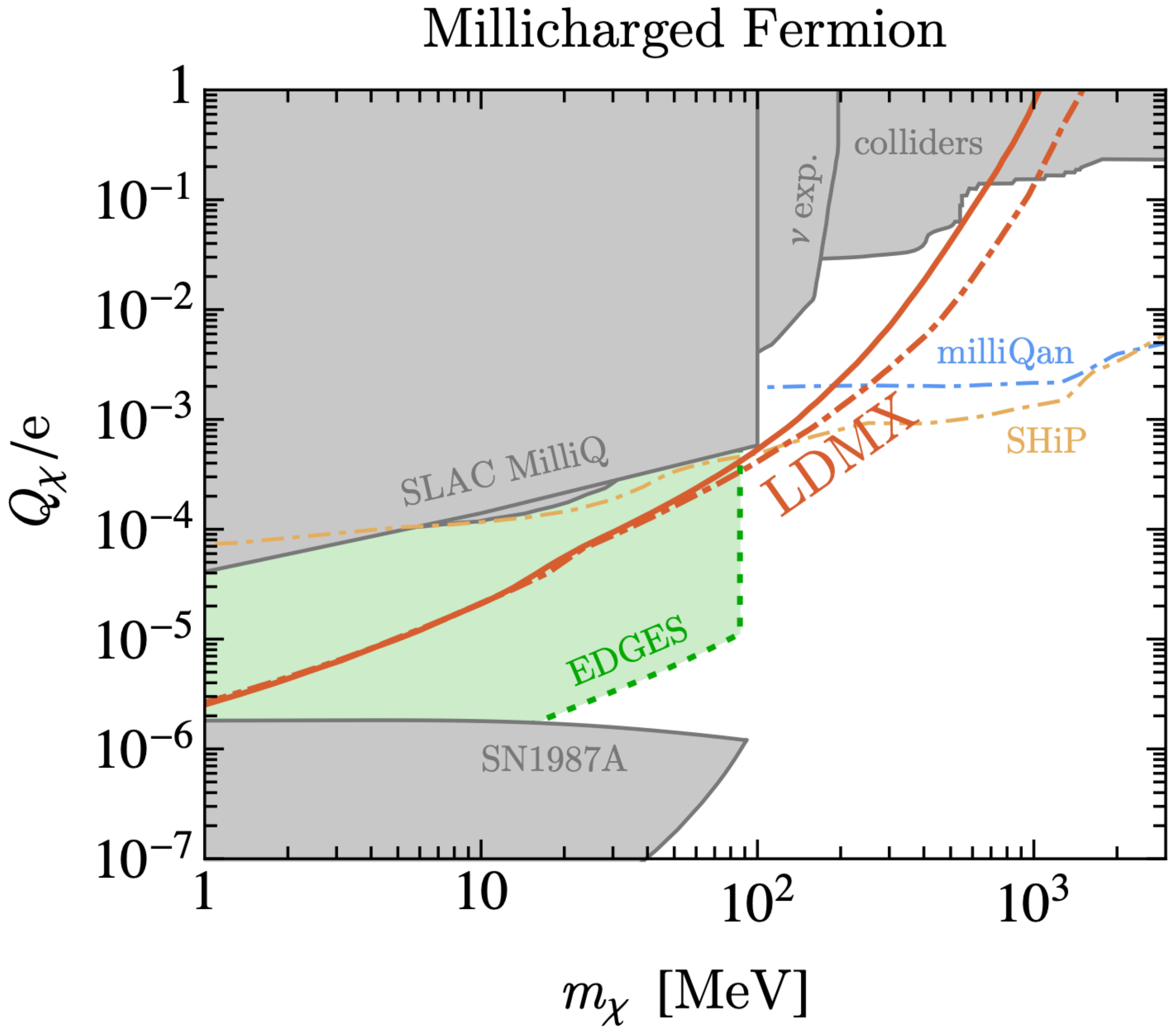
CAN DO ANALOGOUS SEARCH FOR DARK PHOTONS



Dolan et al. 2022



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



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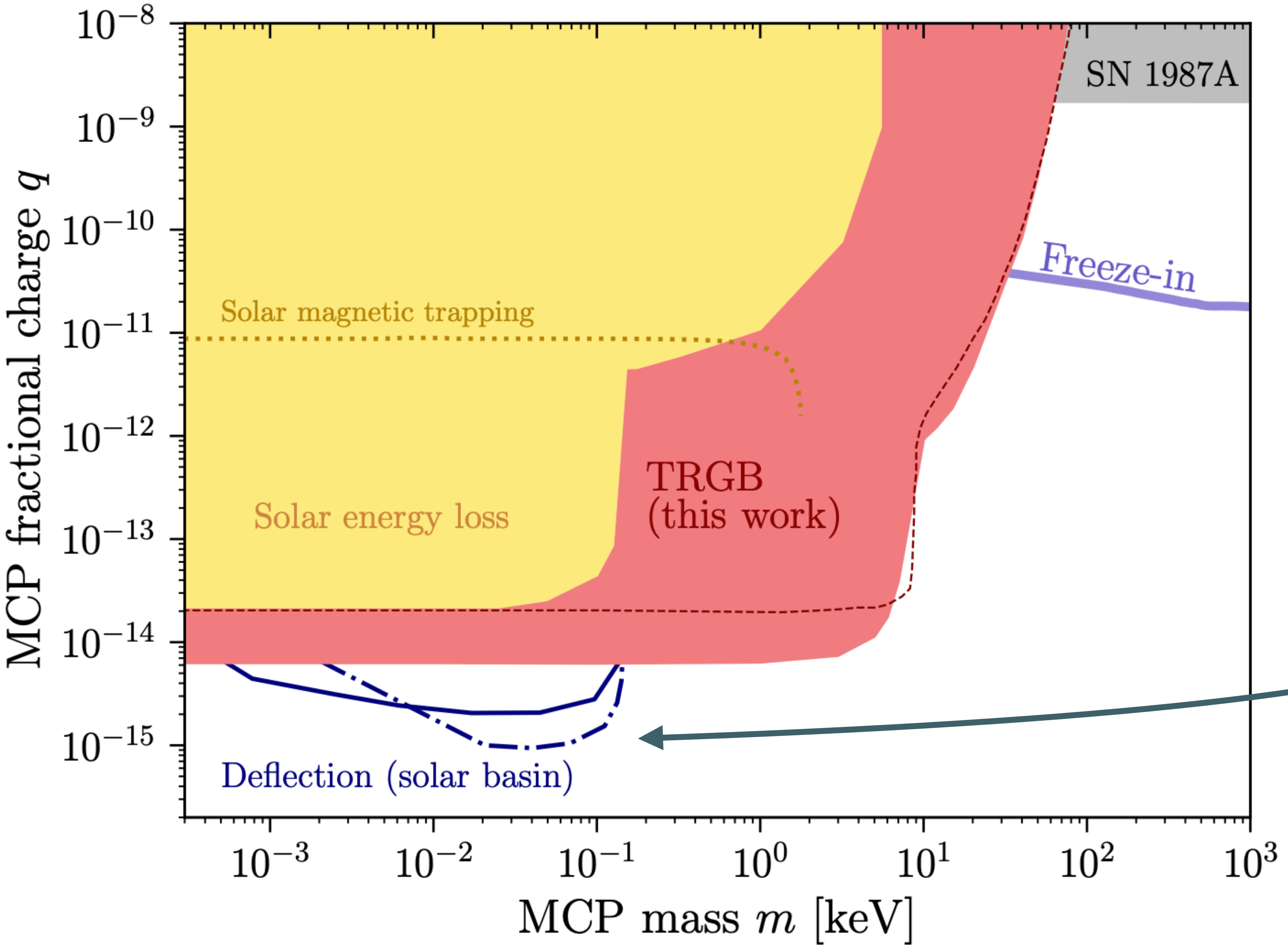
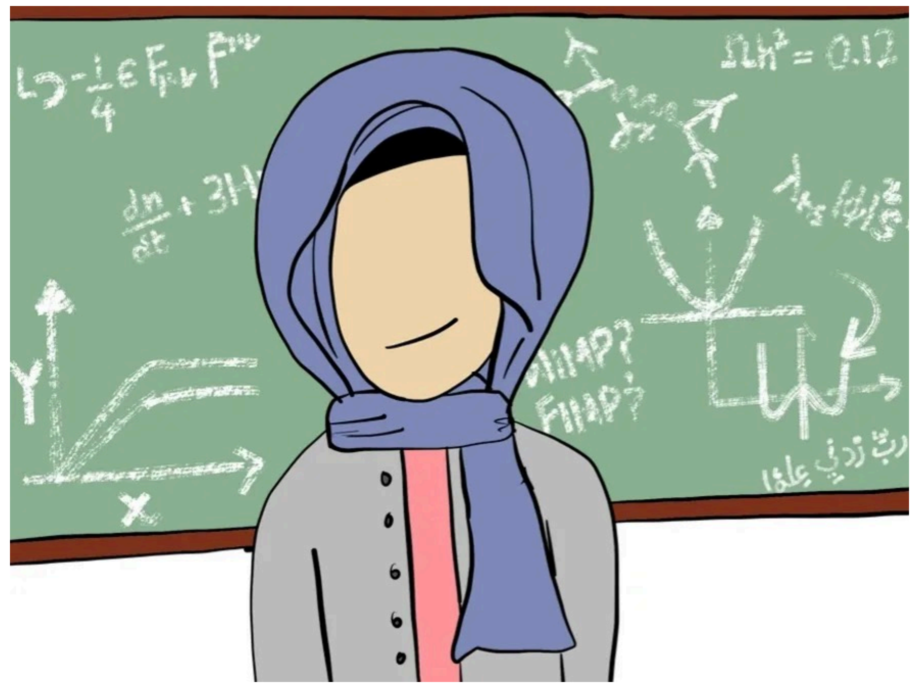
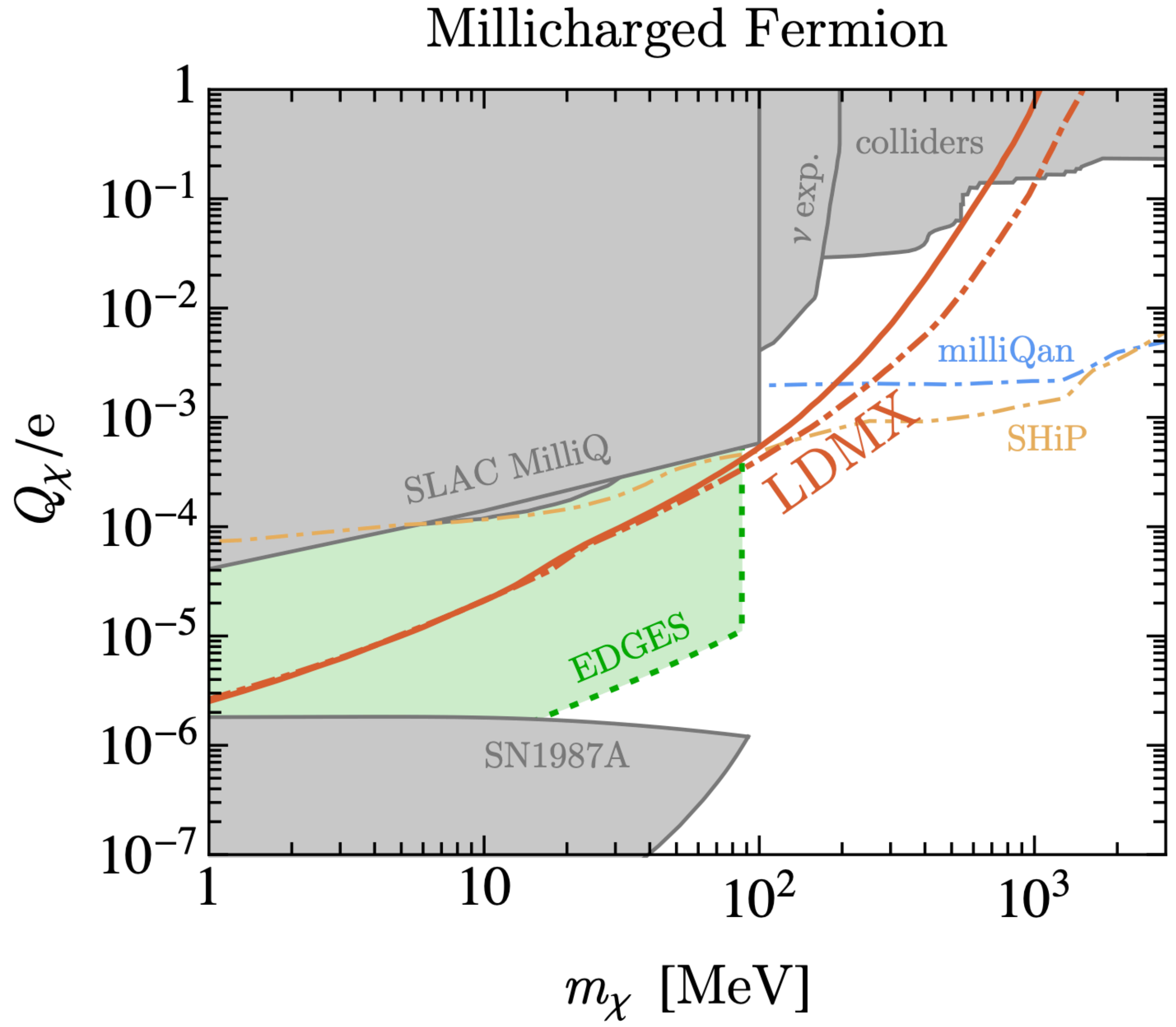


High degree of complementarity with “regular” intensity frontier!

Ask me about this later if you’re curious
Berlin & **KS** PRD (2022)



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



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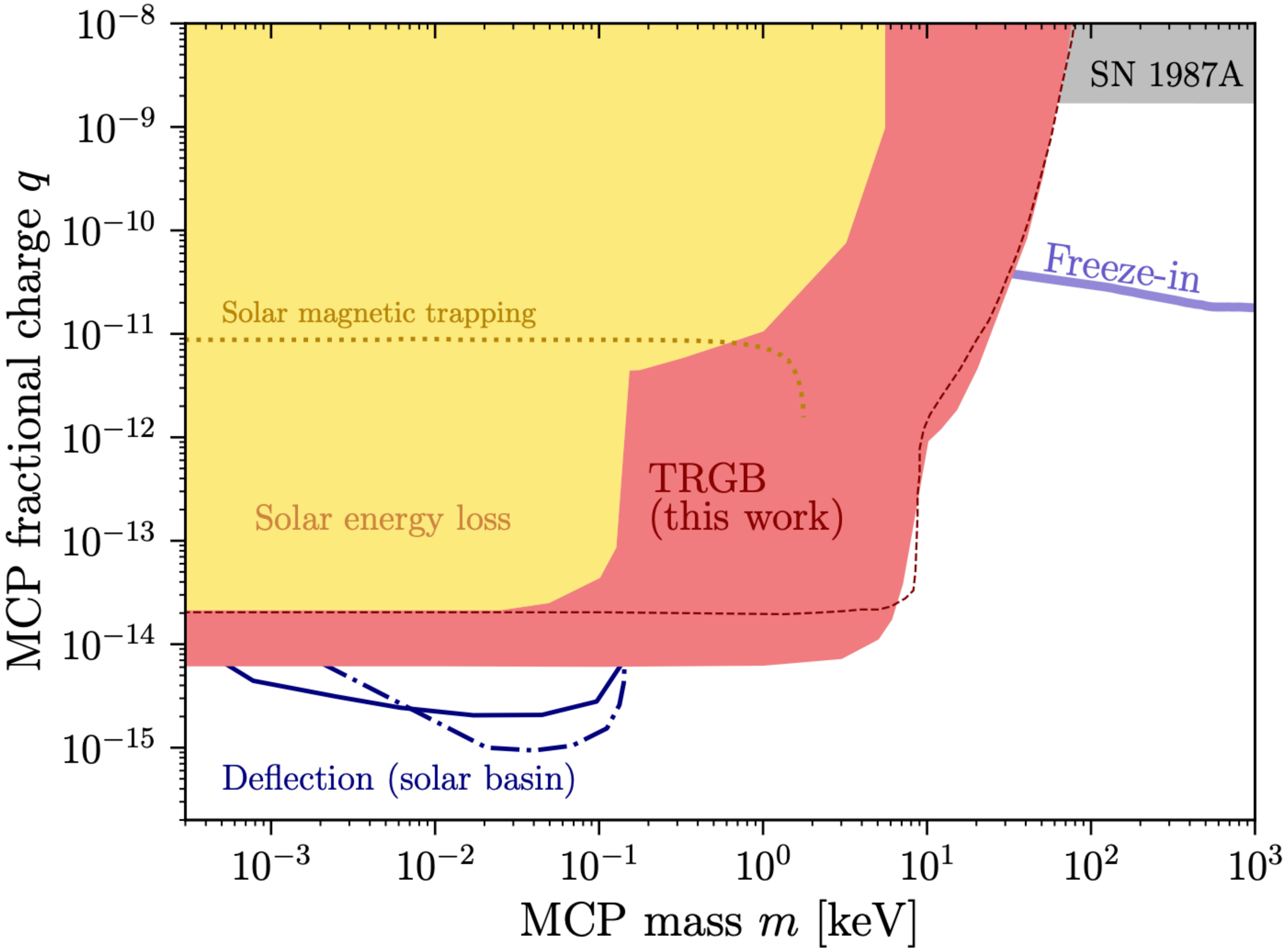
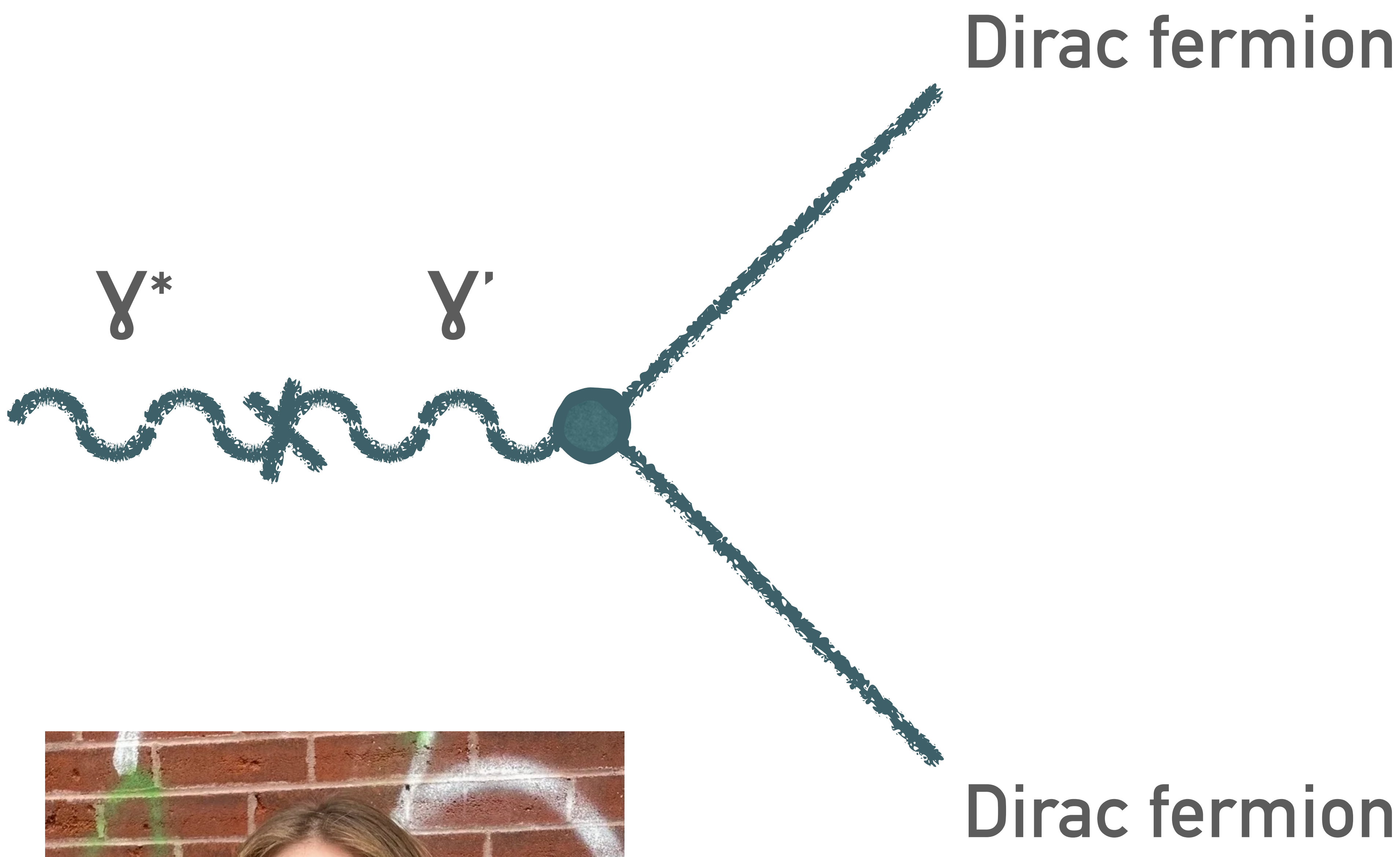


Can we fill in some of this intermediate parameter space? Yes! Using plasma during Big Bang Nucleosynthesis as source instead of star

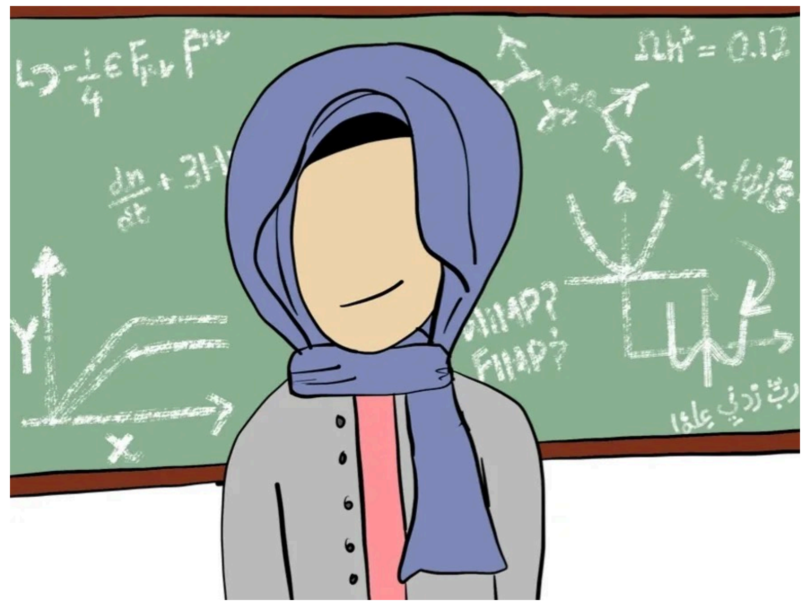
~10–100 KEV SCALE RELICS



Dirac fermion

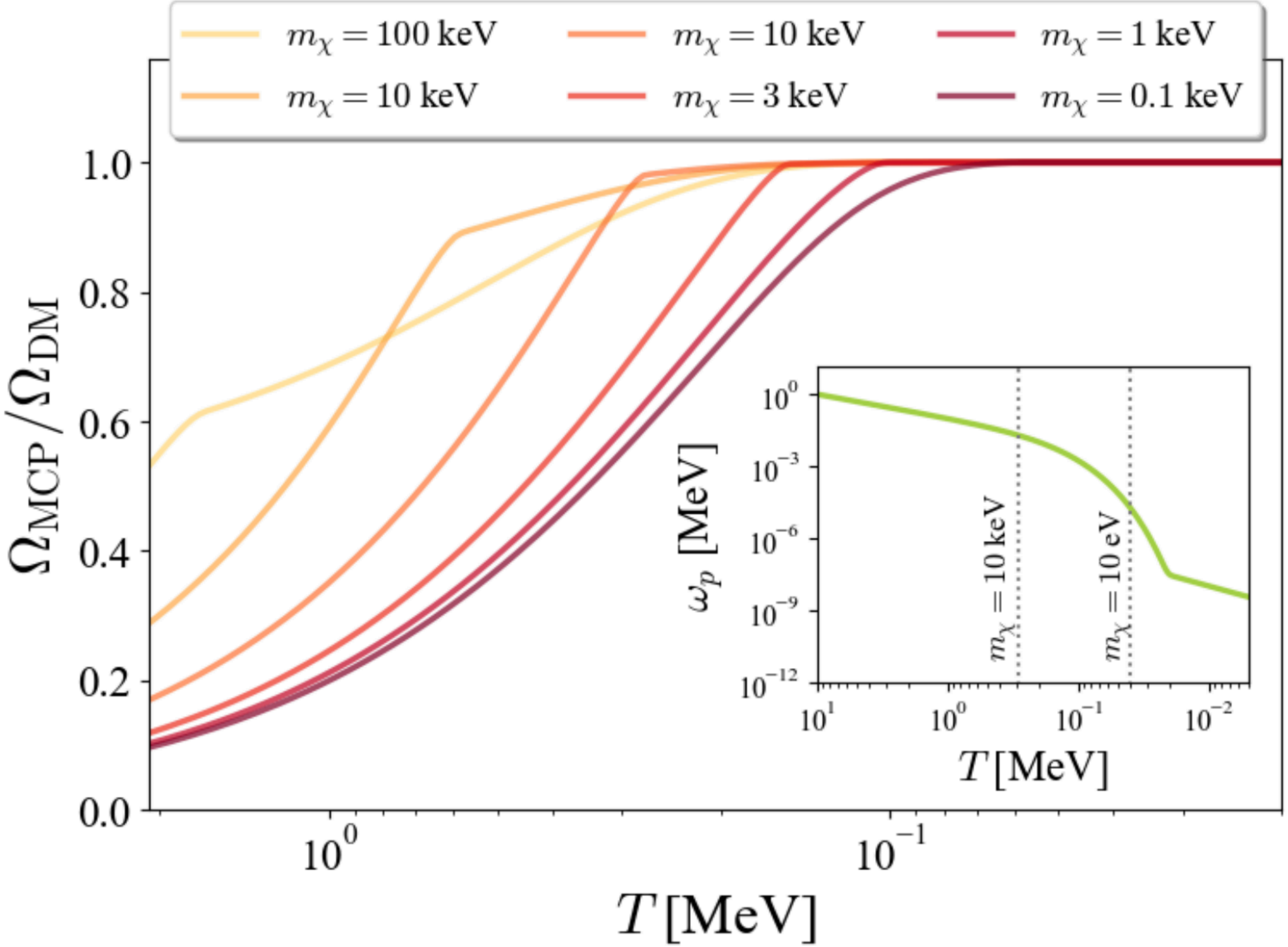
Dirac fermion

Ella Iles

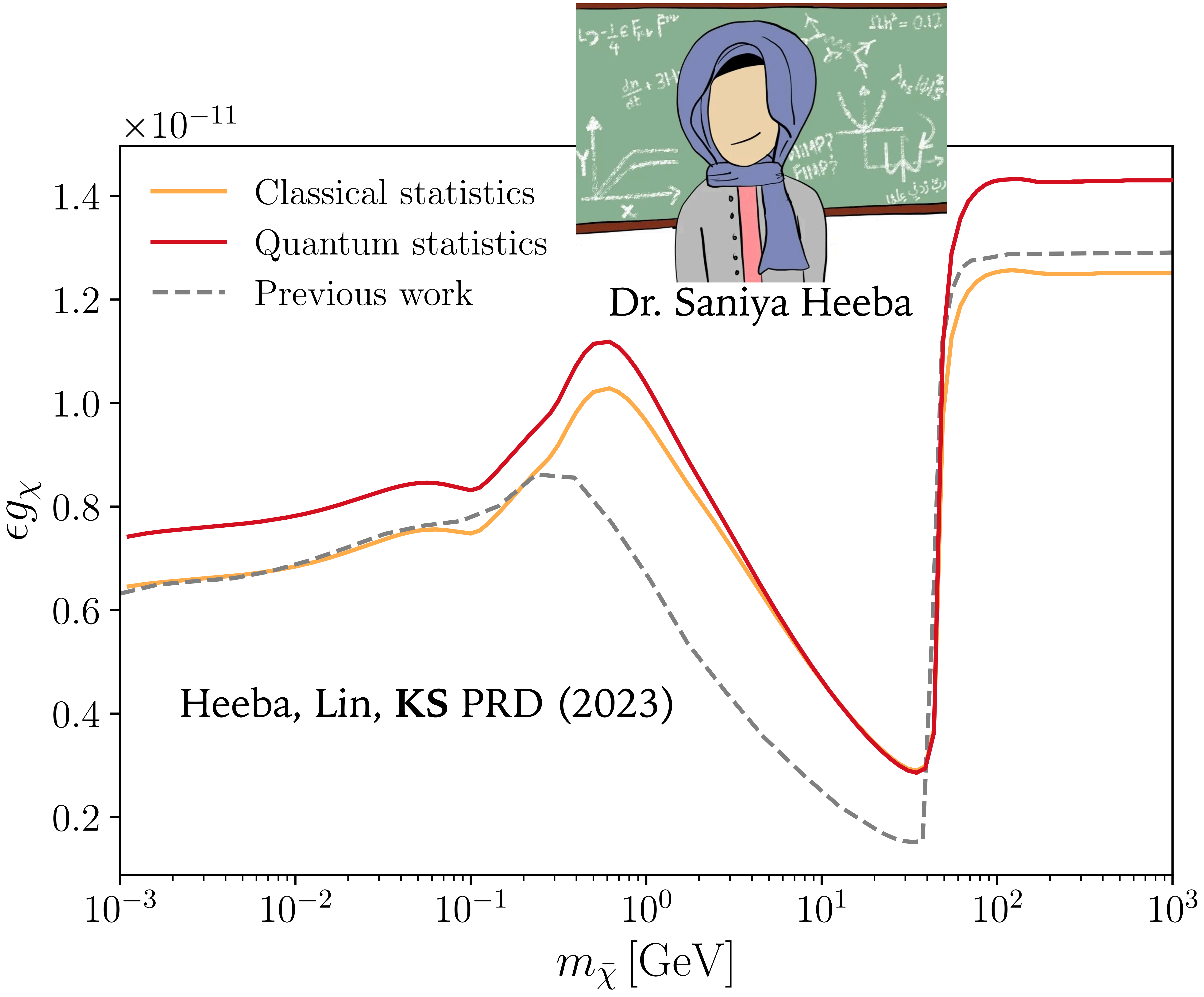


Dr. Saniya Heeba

Iles, Heeba, **KS** 2407.21096



MAKING HEAVIER RELICS (“FREEZE-IN” CURVE)



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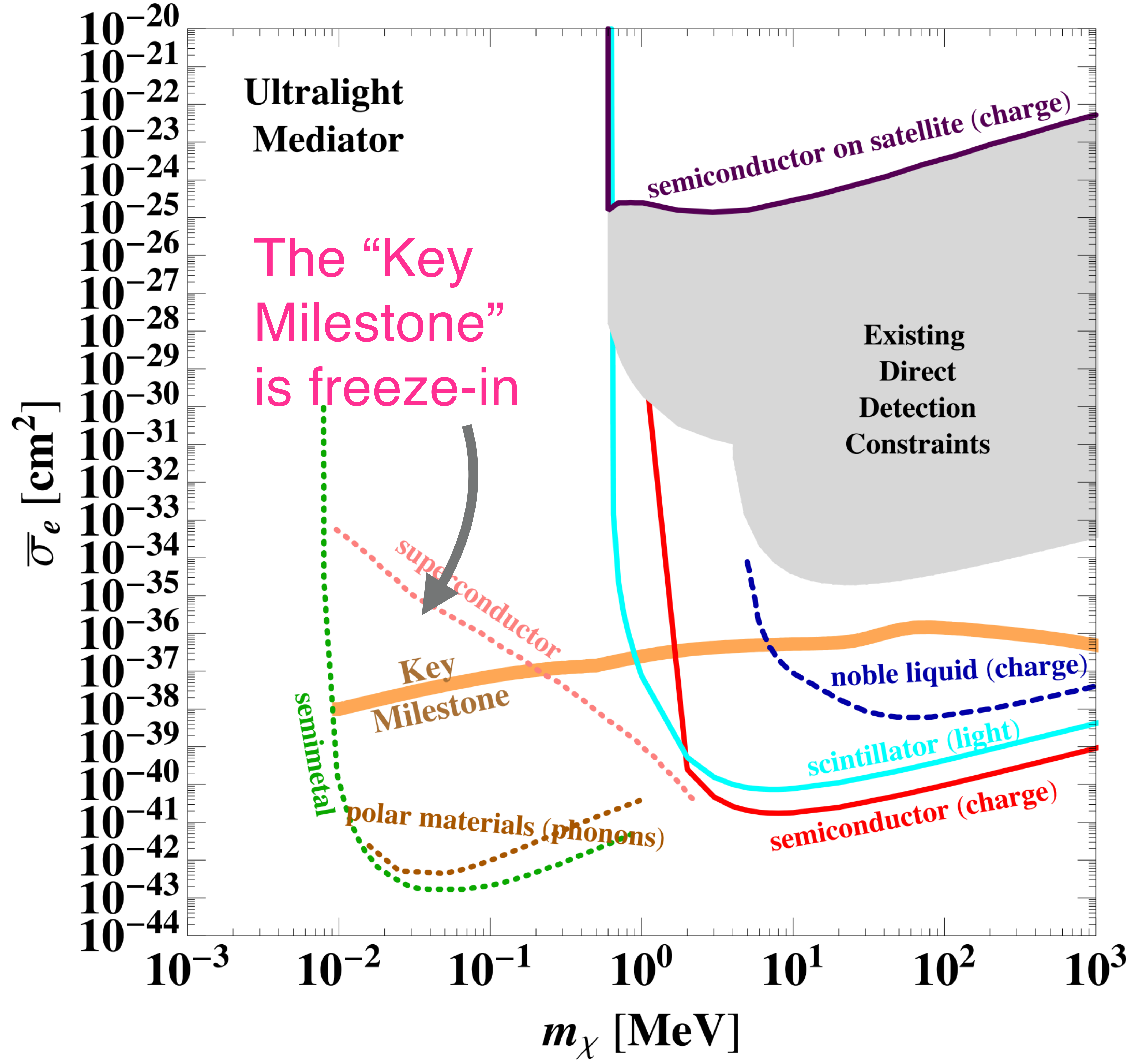
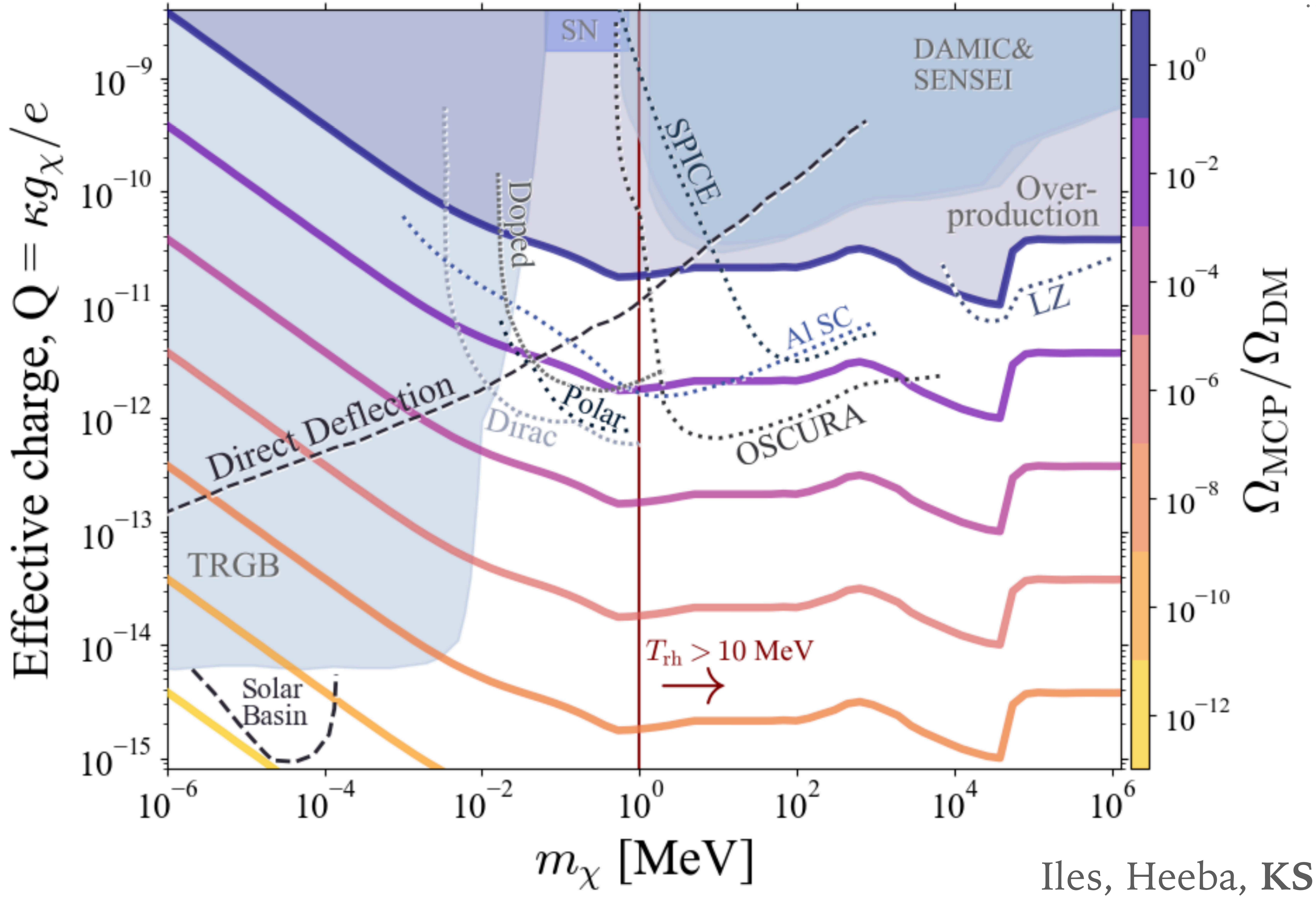
Heeba, Lin, **KS** PRD (2023)



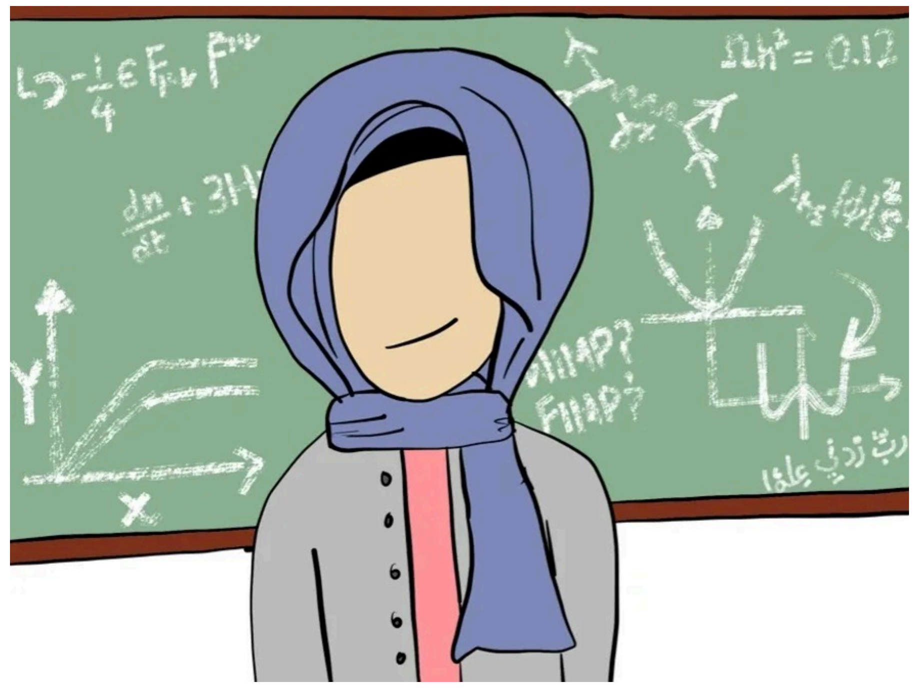
The “Key Milestone” is freeze-in

From Snowmass Cosmic Frontiers topical report

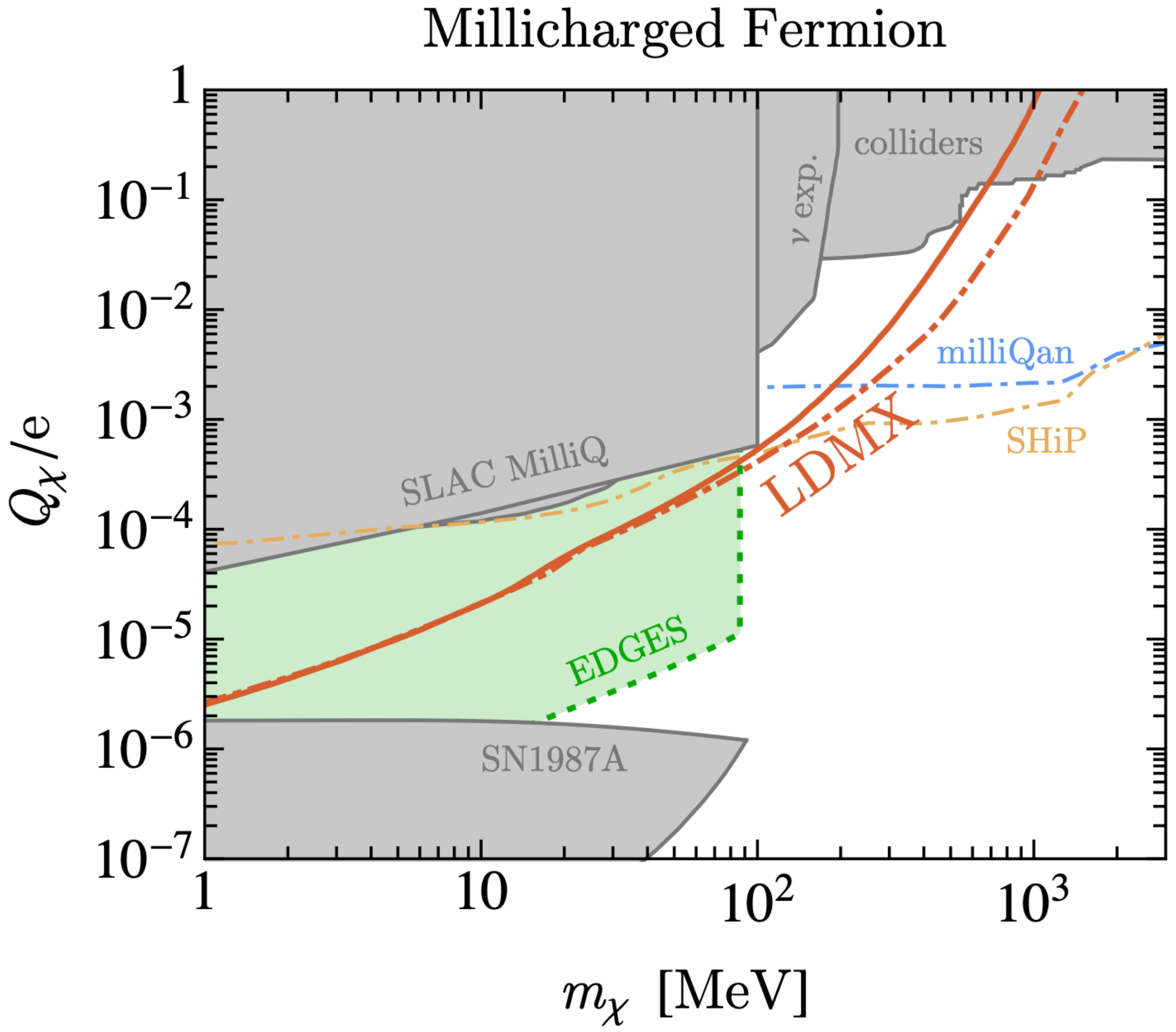
DIRECT DETECTION EXPERIMENTS ARE SENSITIVE BELOW FREEZE-IN!!



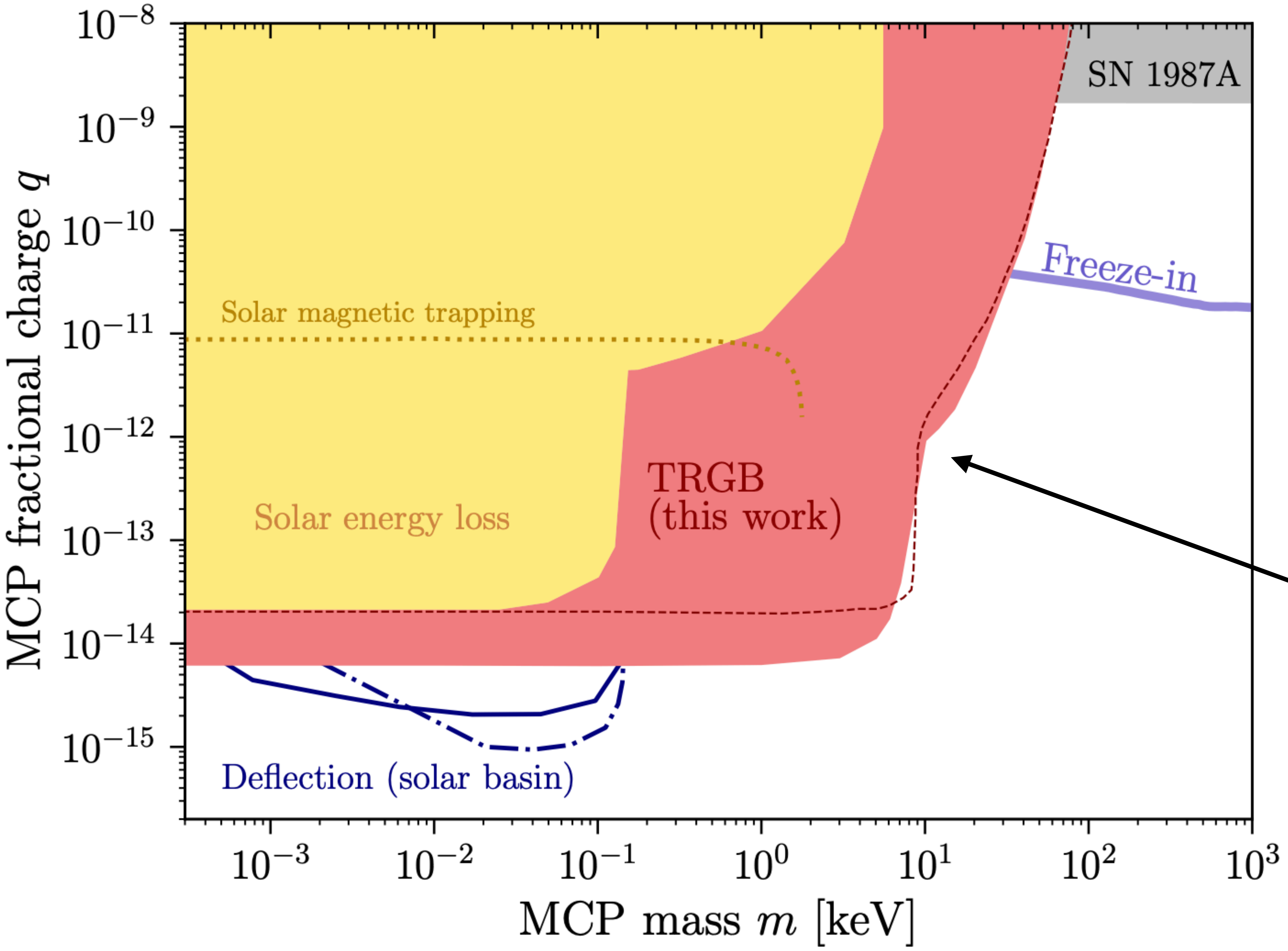
Iles, Heeba, **KS** 2407.21096



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



contrast with terrestrial searches e.g. Berlin et al. (2019)

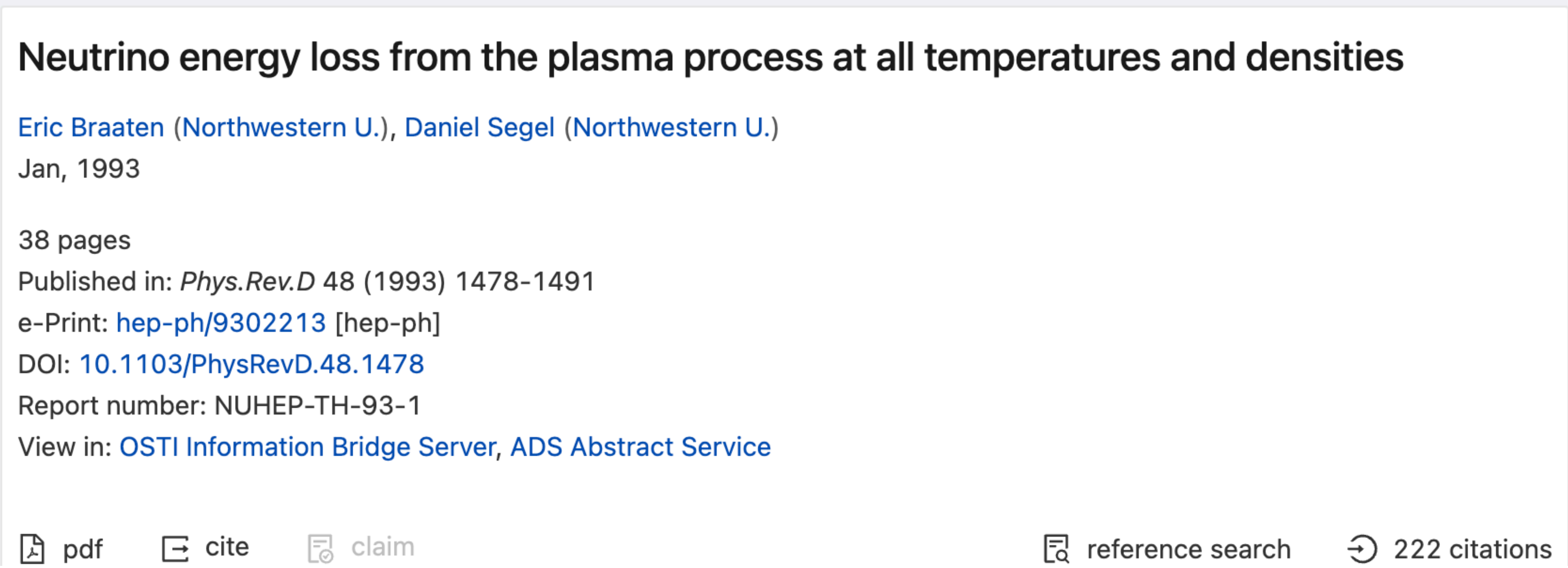


High degree of complementarity with “regular” intensity frontier!

What’s going on here? Plasma density isn’t high enough in order to decay to particles of these mass “on shell”

USAGE OF BRAATEN & SEGEL APPROXIMATION

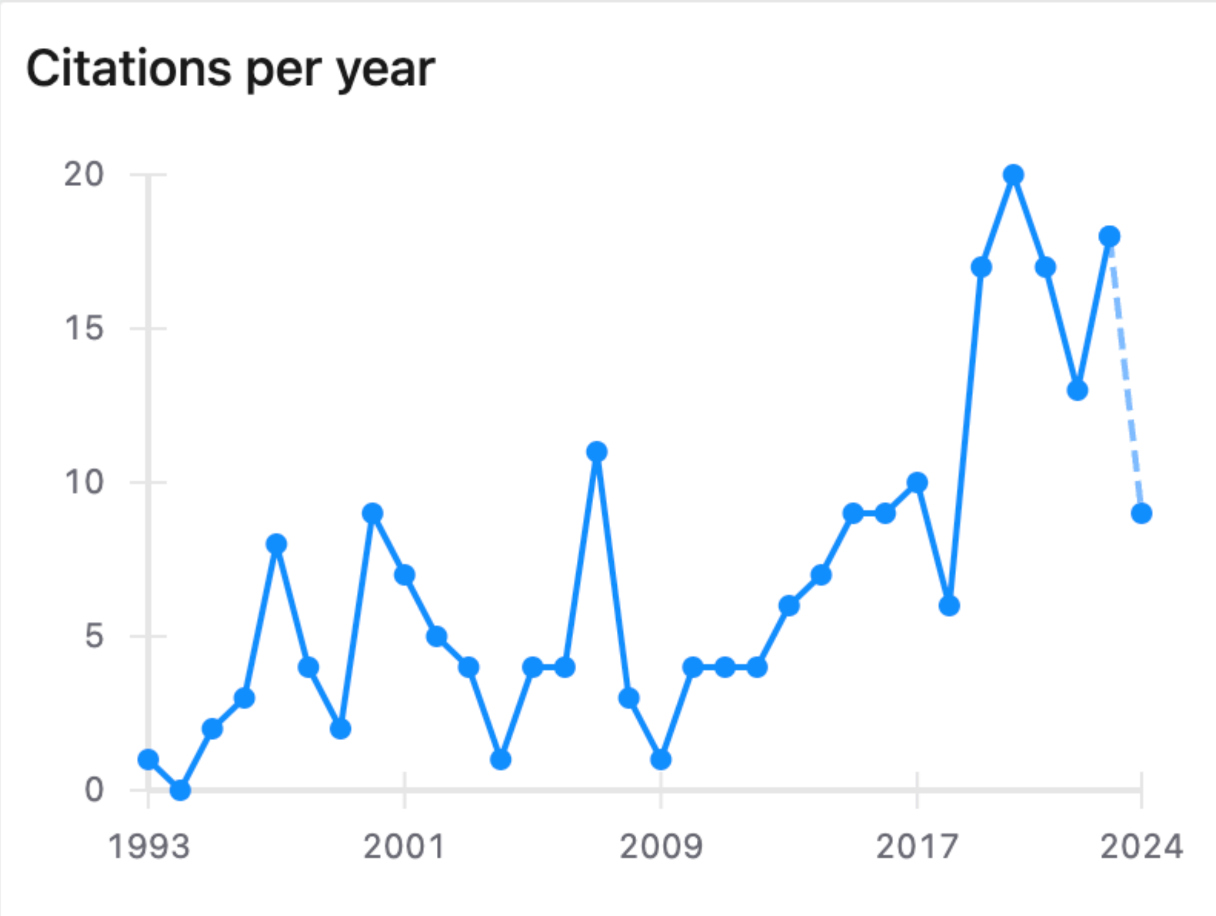
Hugo Schérer

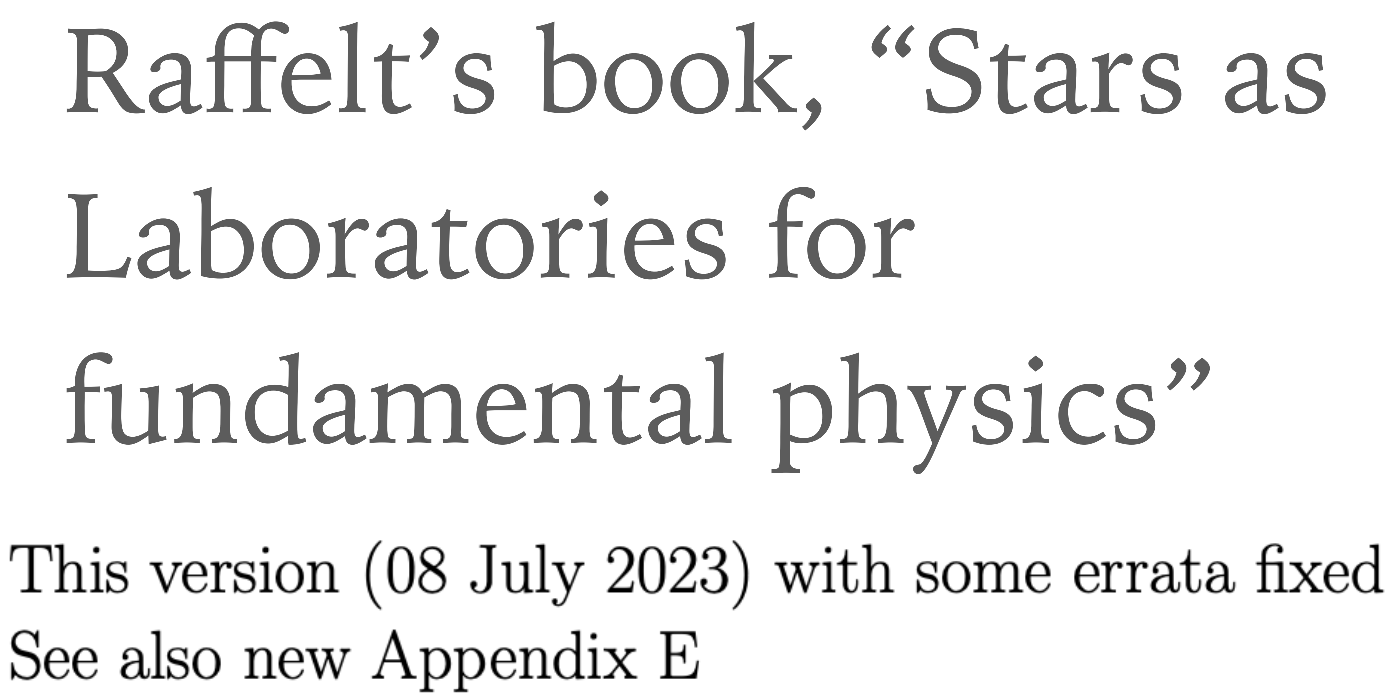


Neutrino energy loss from the plasma process at all temperatures and densities

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

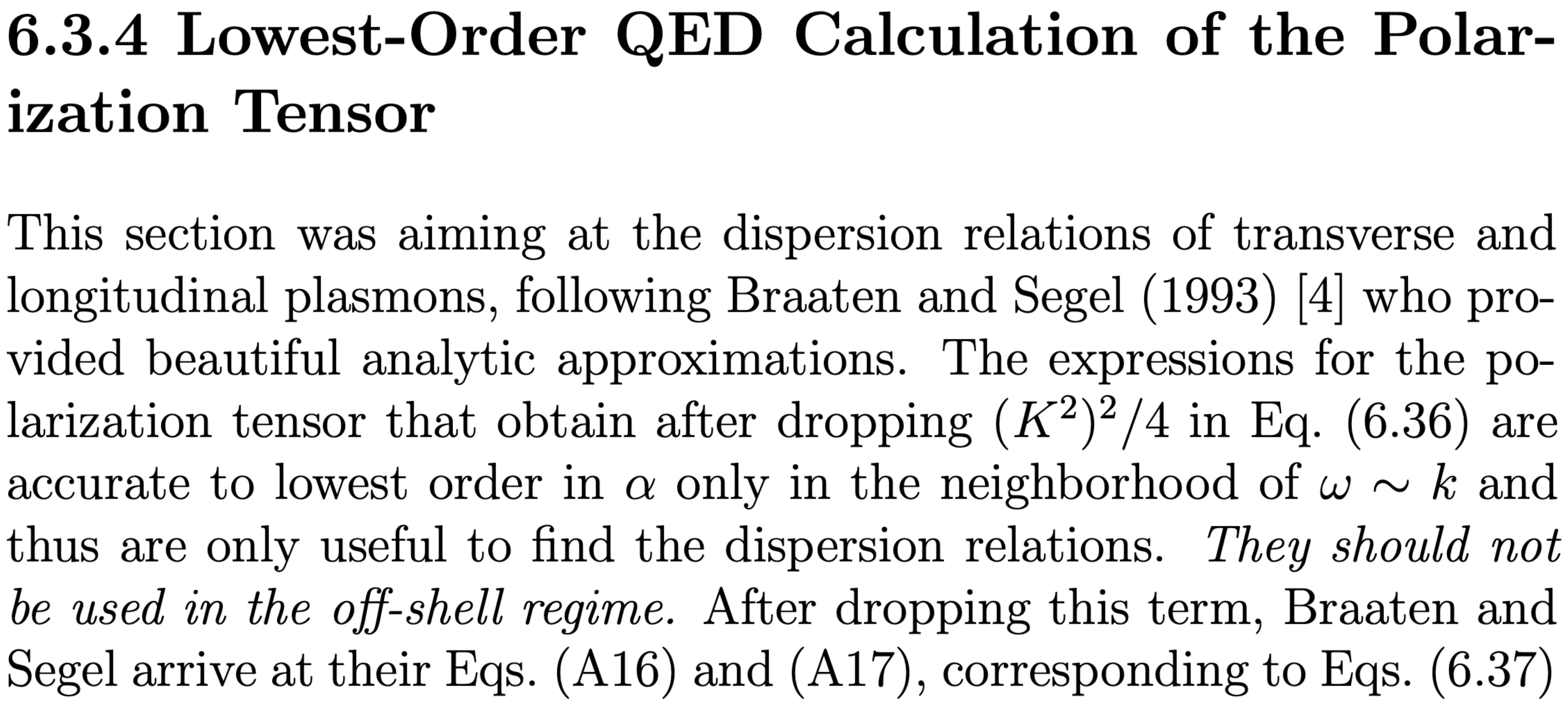
38 pages
Published in: *Phys.Rev.D* 48 (1993) 1478-1491
e-Print: hep-ph/9302213 [hep-ph]
DOI: 10.1103/PhysRevD.48.1478
Report number: NUHEP-TH-93-1
View in: OSTI Information Bridge Server, ADS Abstract Service





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

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

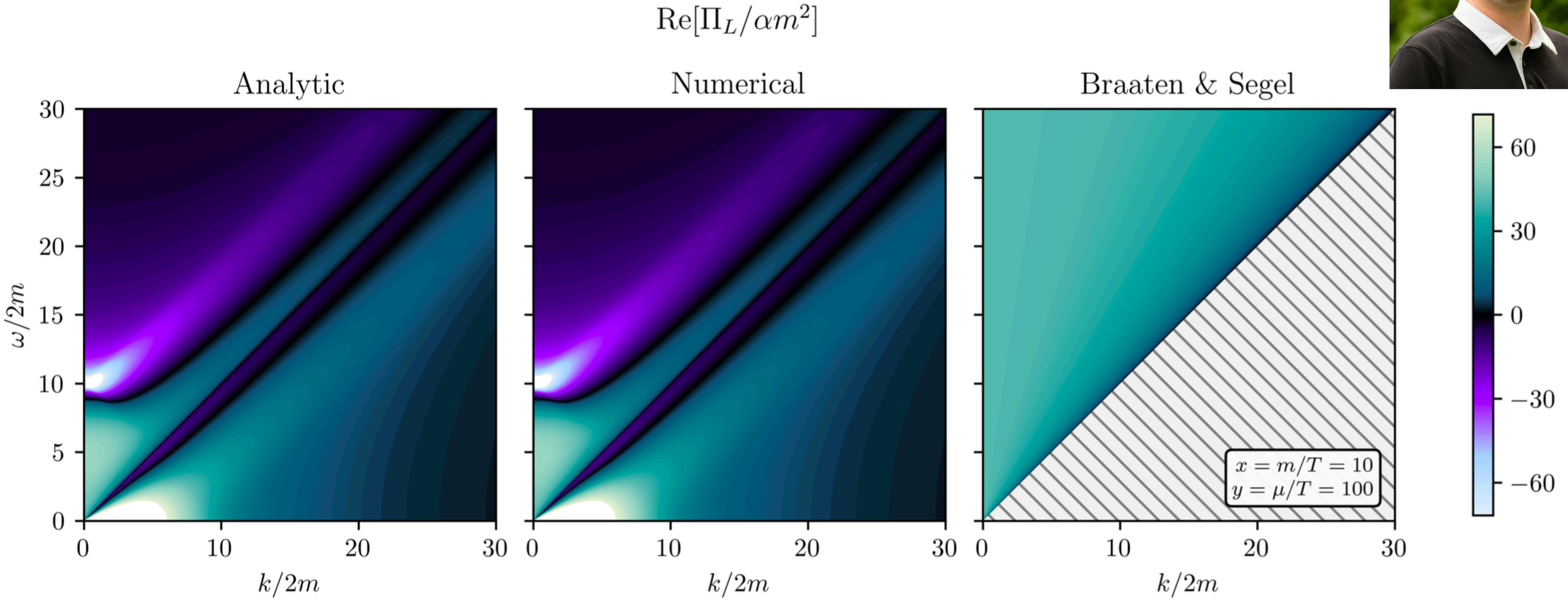
$$\Pi_T = \omega_p^2 \Bigg[\frac{k^2+2\omega^2}{2k^2 v_*^2} + \frac{K^2}{4E_*^2 v_*^3} \log\left(\frac{1+v_*}{1-v_*}\right) - \frac{\omega\big(3(\omega^2-k^2v_*^2)+(\omega^2+3k^2)K^2/4E_*^2\big)}{8k^3 v_*^3} \log\left|\frac{(\omega+kv_*)^2-(K^2)^2/4E_*^2}{(\omega-kv_*)^2-(K^2)^2/4E_*^2}\right|$$
$$+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

where

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

Schérer, **KS** 2405.18466

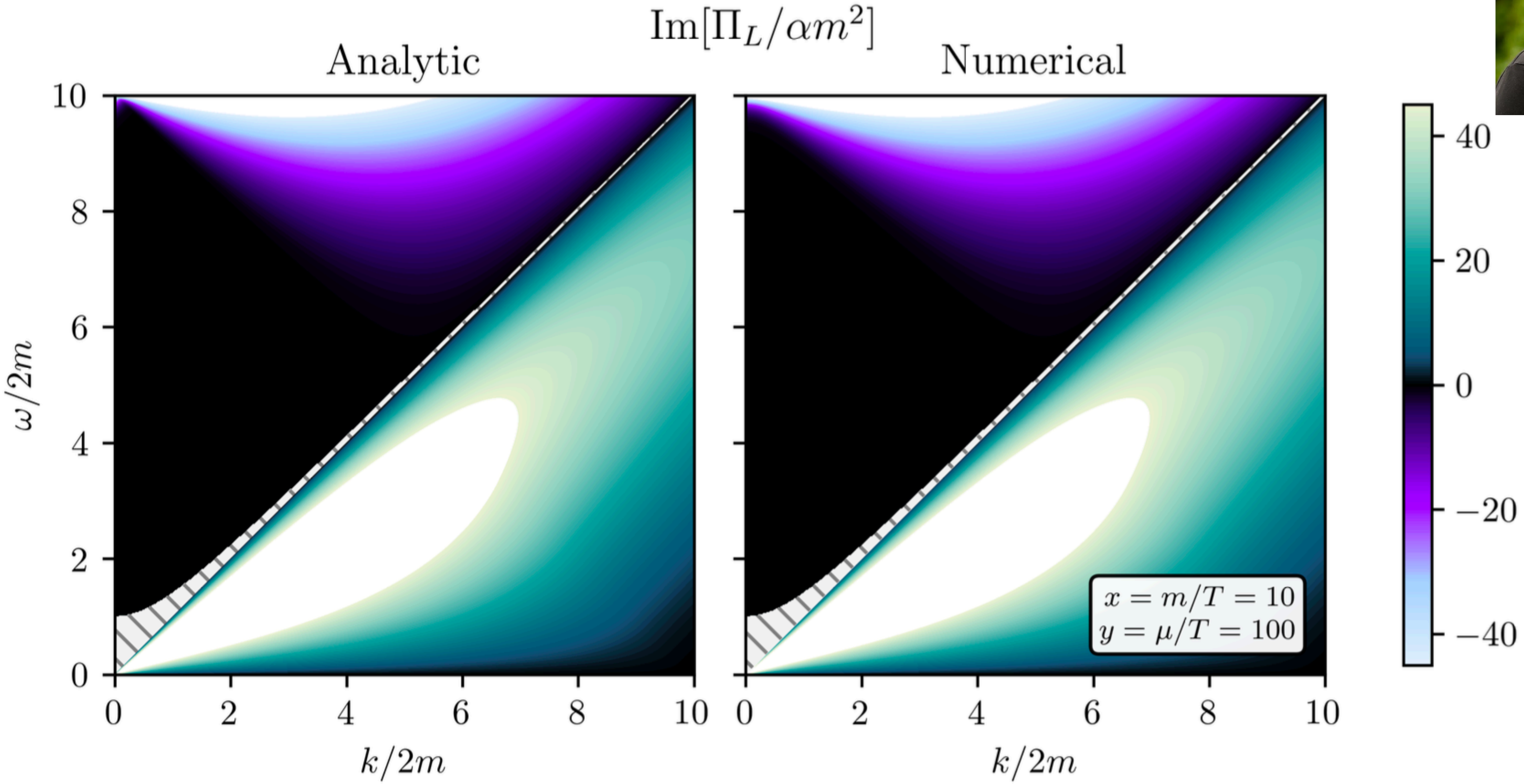
HOW WELL DOES THE APPROXIMATION DO?



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

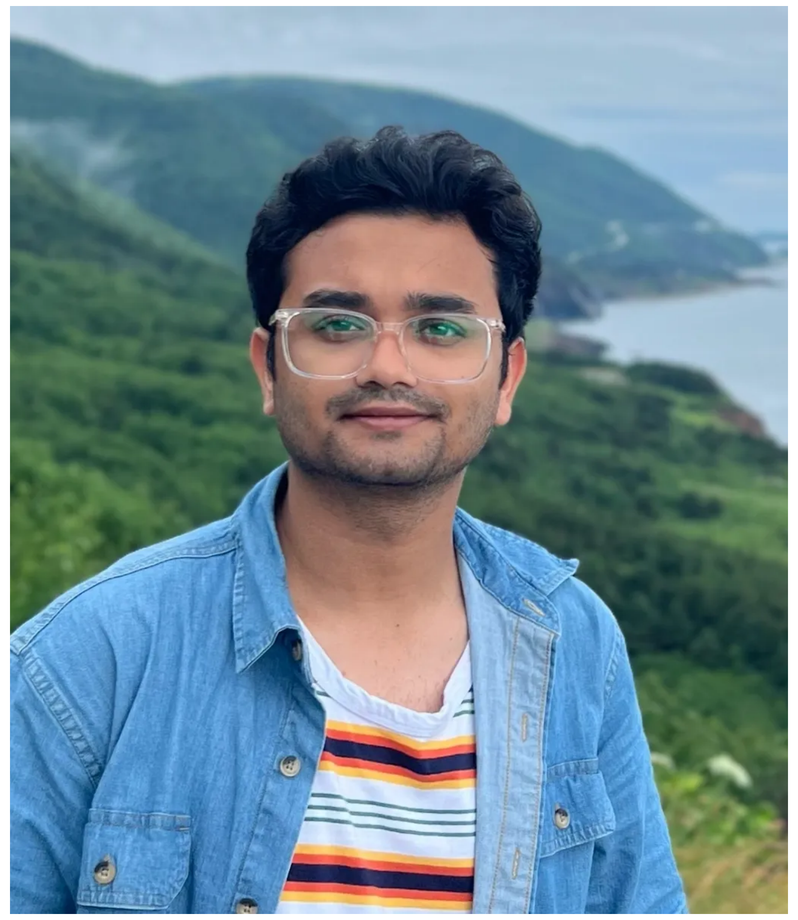
Schérer, **KS** 2405.18466

HOW WELL DOES THE APPROXIMATION DO?



Schérer, **KS** 2405.18466

CRUCIAL CAVEAT: ALL OF THIS ASSUMES AN ISOTROPIC PLASMA!

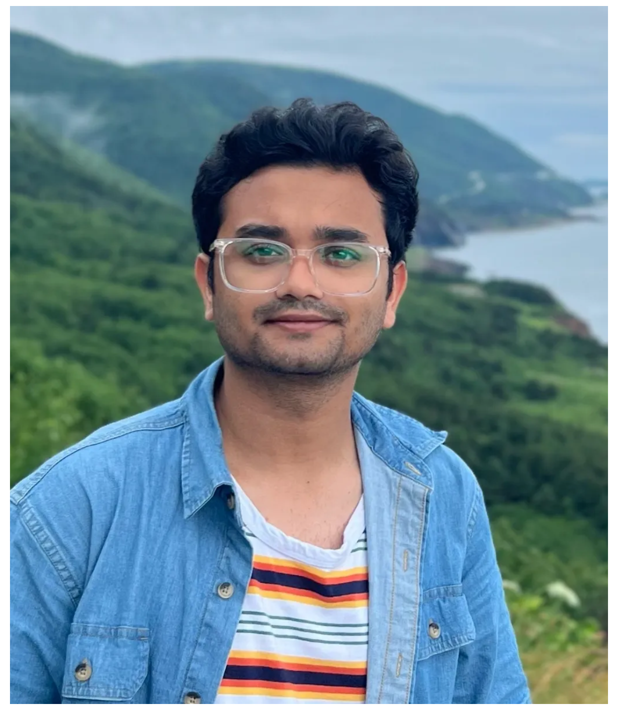


Nirmalya Brahma

MOST ASTROPHYSICAL SYSTEMS HAVE MAGNETIC FIELDS— NOT ISOTROPIC!

HOW DOES ANISOTROPY PLAY A ROLE?

Brahma, **KS** 2410.14771



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

Project onto e.g. transverse subspace

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

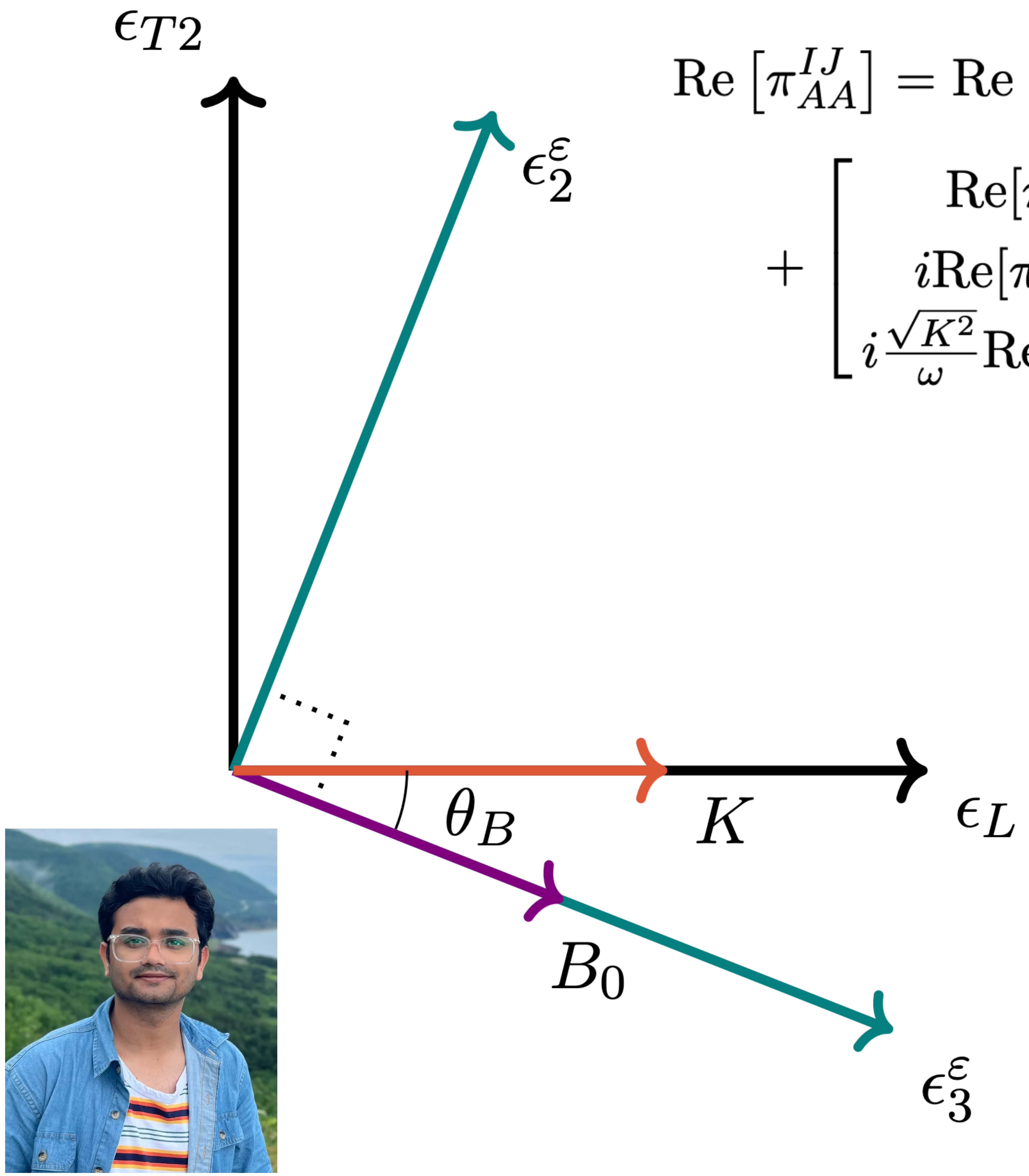
Π_T if plasma is isotropic

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

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

PLASMA NORMAL MODES

Brahma, **KS** 2410.14771



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

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

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

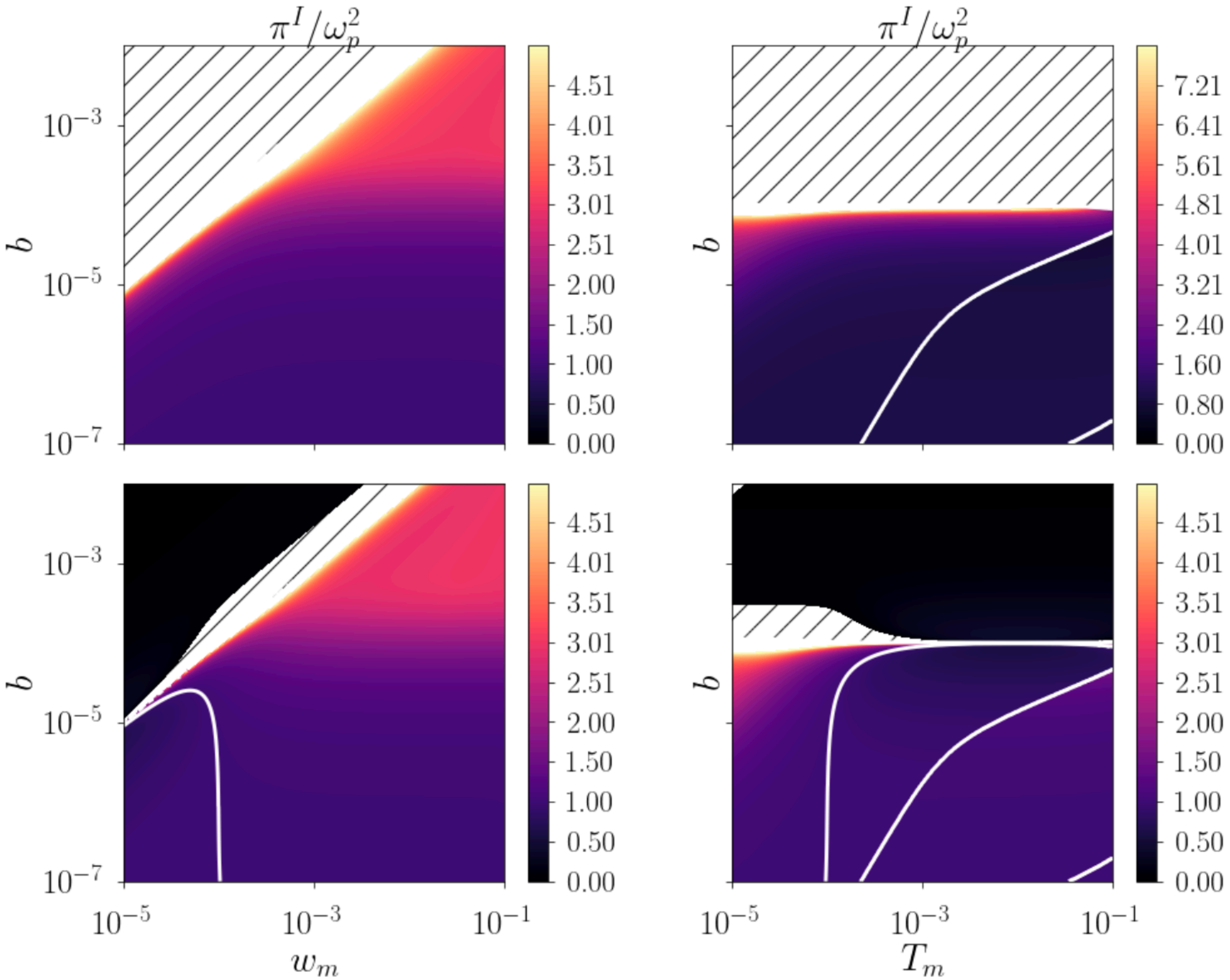
e.g. $\pi_\parallel^{(n)} = \int \frac{dq_{\parallel,b}}{2\pi}\frac{f_e\left(E_q^n\right) + f_{\bar{e}}\left(E_q^n\right)}{2E_q^n}\frac{\left(2-\delta_0^n\right)4m_e^2 + \left(1-\delta_0^n\right)16neB}{\left(E_q^n\right)^2 - \frac{\omega^2}{4}}$

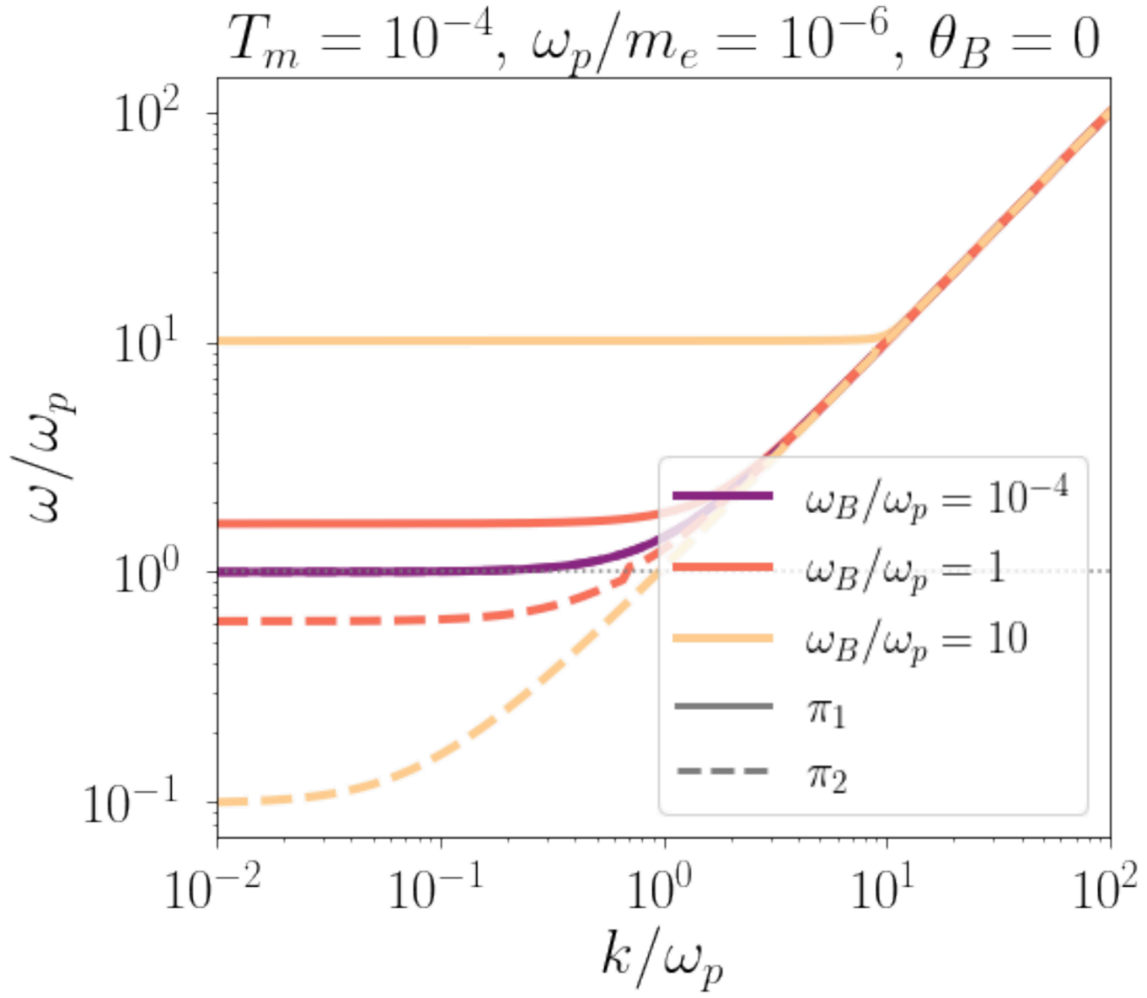
energy of nth Landau level $E_q^n \equiv \sqrt{q_{\parallel,b}^2 + m_e^2 + 2neB}$

PLASMA NORMAL MODES

- “mass” of normal modes is not just simply the plasma frequency!
- Transverse modes stop being degenerate!
- 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** 2410.14771



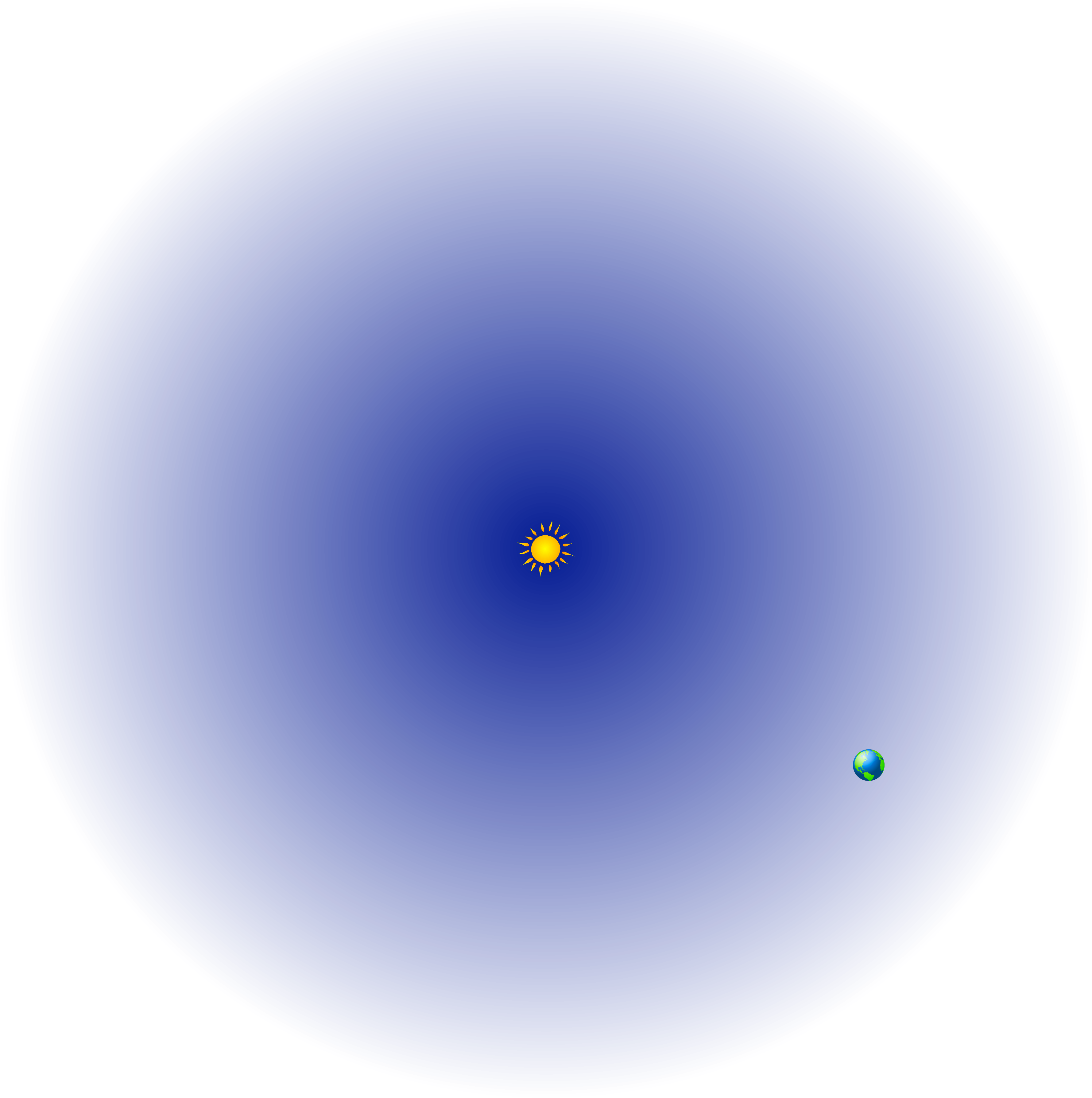


OUTLOOK

- Lots of rich physics at the “astrophysical intensity frontier” providing a testbed that is complementary to the terrestrial collider program
- New observables (e.g. asteroseismology) will provide additional handle
- Lots to still understand about how to do QFT in dense, anisotropic astrophysical media, but lots of opportunities for new phenomena
- It’s a big universe, lots of room for creativity!

BACKUP: DEFLECTION

A SOLAR BASIN OF MCP DUE TO GRAVITY



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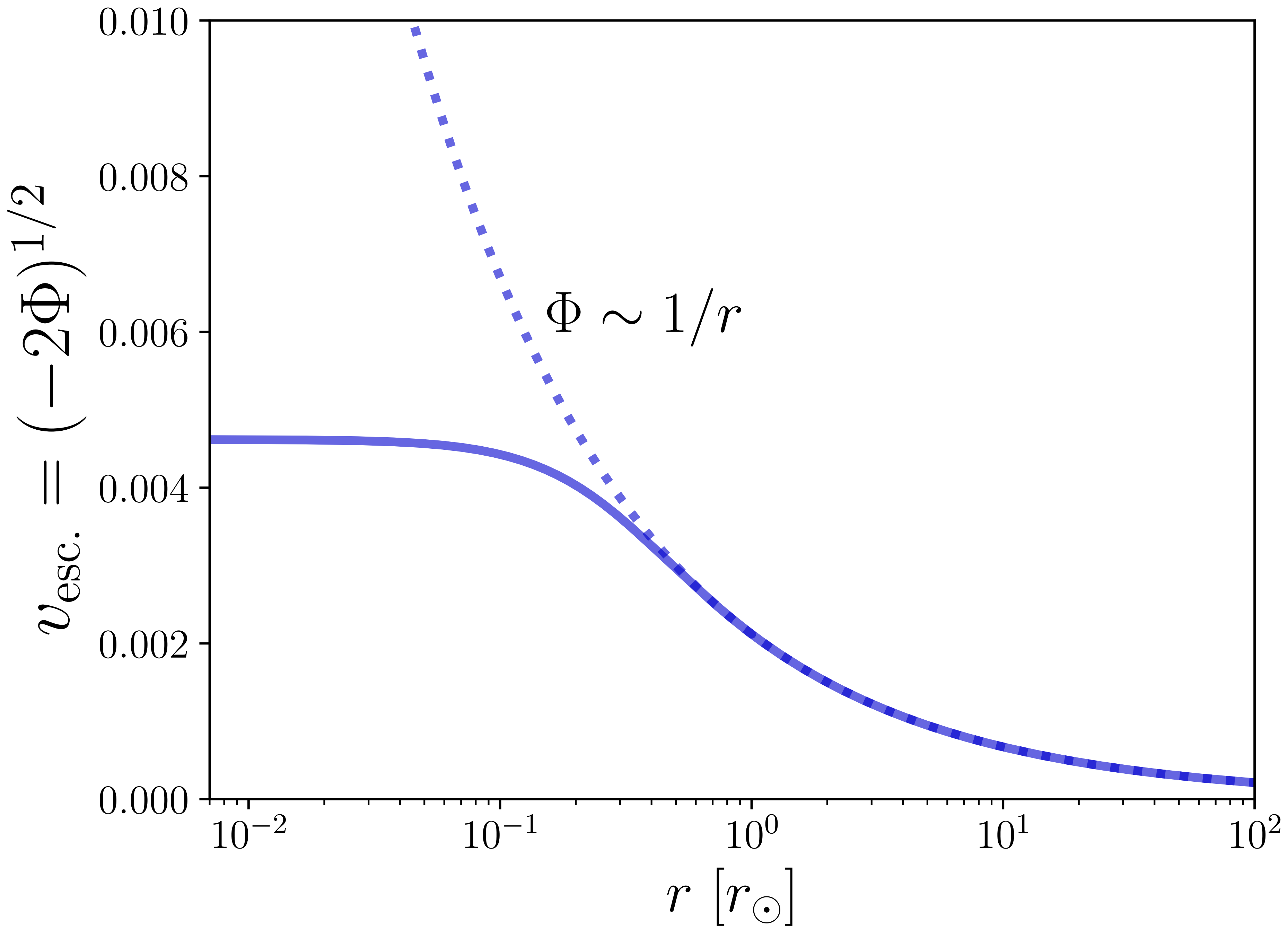
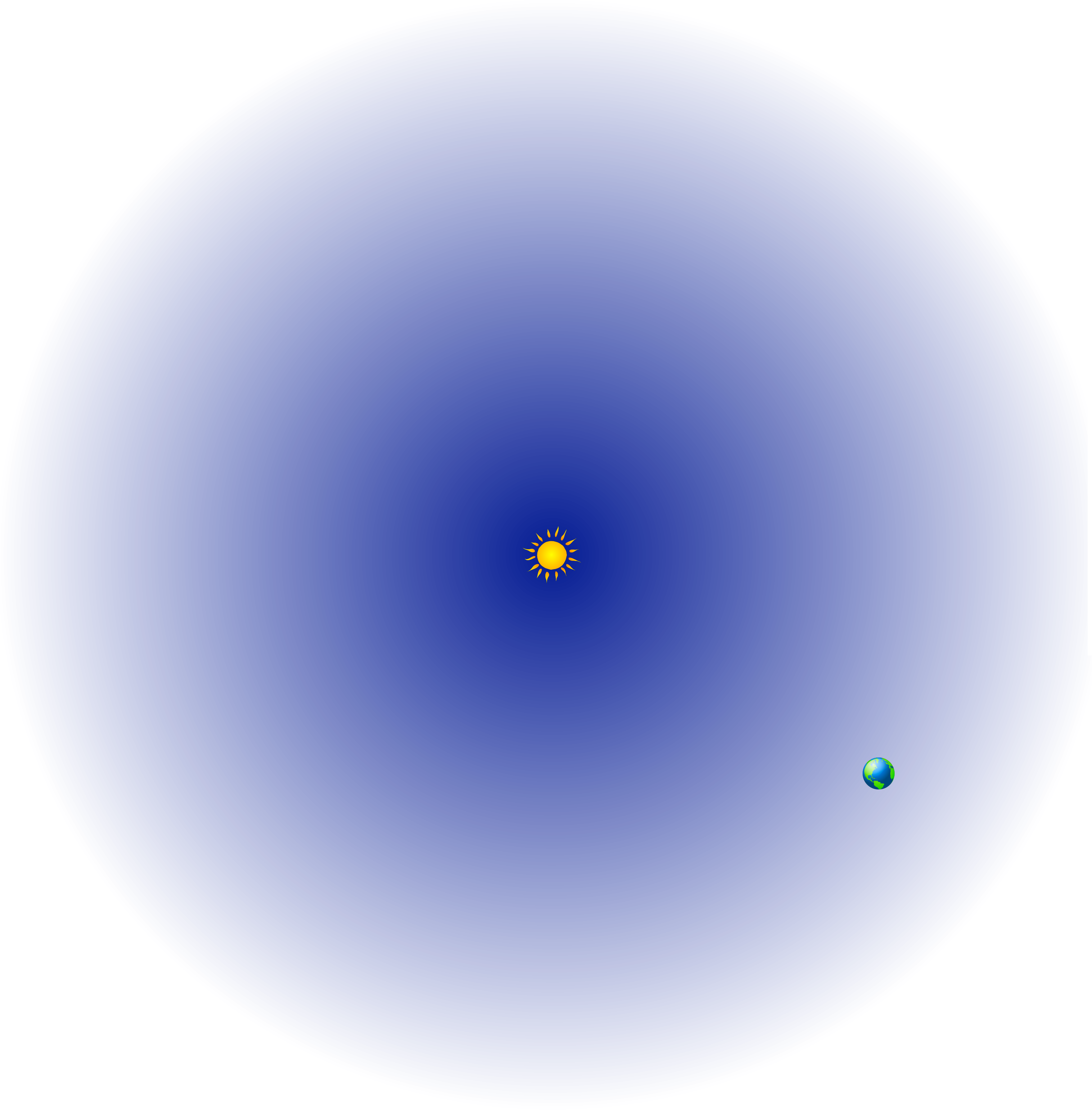


- MCP produced going slower than ~0.005c will be gravitationally bound, accumulate over time

Van Tilburg (2021)

A SOLAR BASIN OF MCP DUE TO GRAVITY



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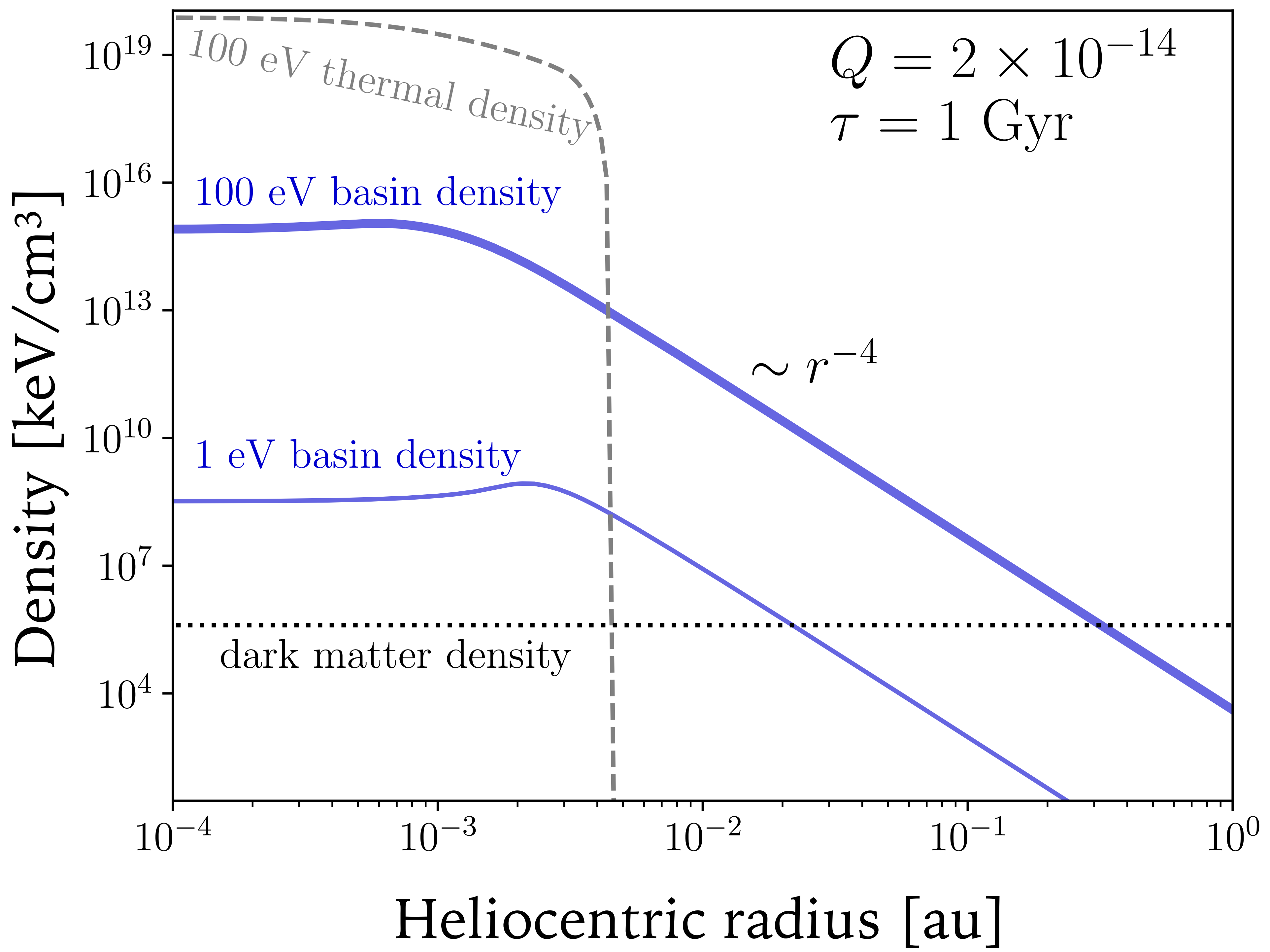


- Density falls precipitously but can be non-negligible at Earth

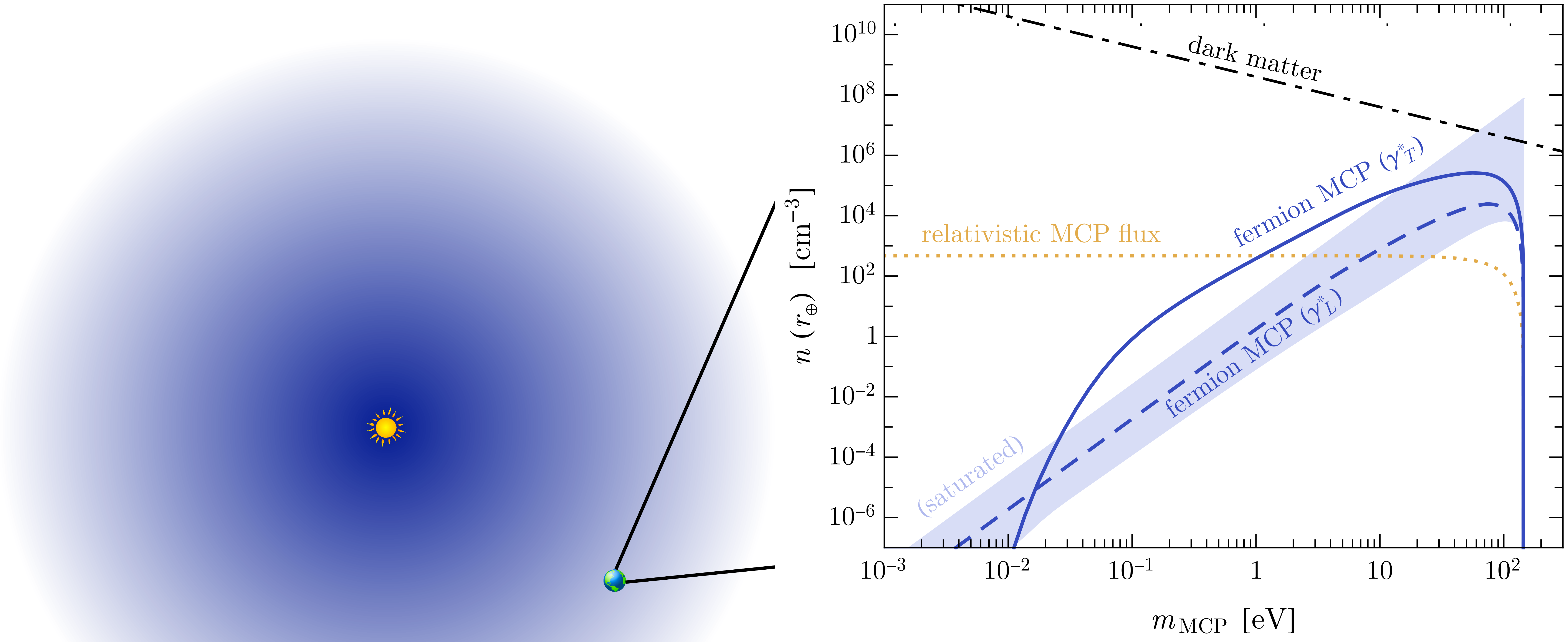
Berlin & **KS** PRD (2022)

LIST OF CAVEATS/REQUIREMENTS

- ☑ MCP can’t be trapped by scattering in the Sun or the Sun’s ~Gauss magnetic field
- ☑ Annihilation can’t efficiently deplete the abundance
- ☑ Scattering can’t efficiently transport orbital energy and distort the density profile and phase space
- ☑ MCP needs to be able to reach experiment at sea level in spite of Earth atmospheric voltage

Claim: these can be satisfied with massive dark photon and small charge in wide portions of parameter space

DENSITY AT EARTH



(not to scale)

- Density from the basin exceeds the unbound flux over a few orders of magnitude in mass

Berlin & **KS** PRD (2022)

WHAT ABOUT THE KINEMATICS?

- Populate one part of 6D phase space inside Sun at a given time when a particle is produced
- At some later time, solve for where in 6D phase space it has to be given conserved quantities (orbital energy, angular momentum vector)
- Integrate over all kinematically accessible Solar volume to get velocity phase space

$$f(r, v_r, v_\theta) = \frac{t}{t_{\mathrm{orb.}}} \int_{r'<r_\odot} dr' \left(\frac{v_{\mathrm{tot.}}(r')}{v_r(r')}\right)^2 \frac{Q_v}{m} \, \Theta(v_r(r')^2)$$

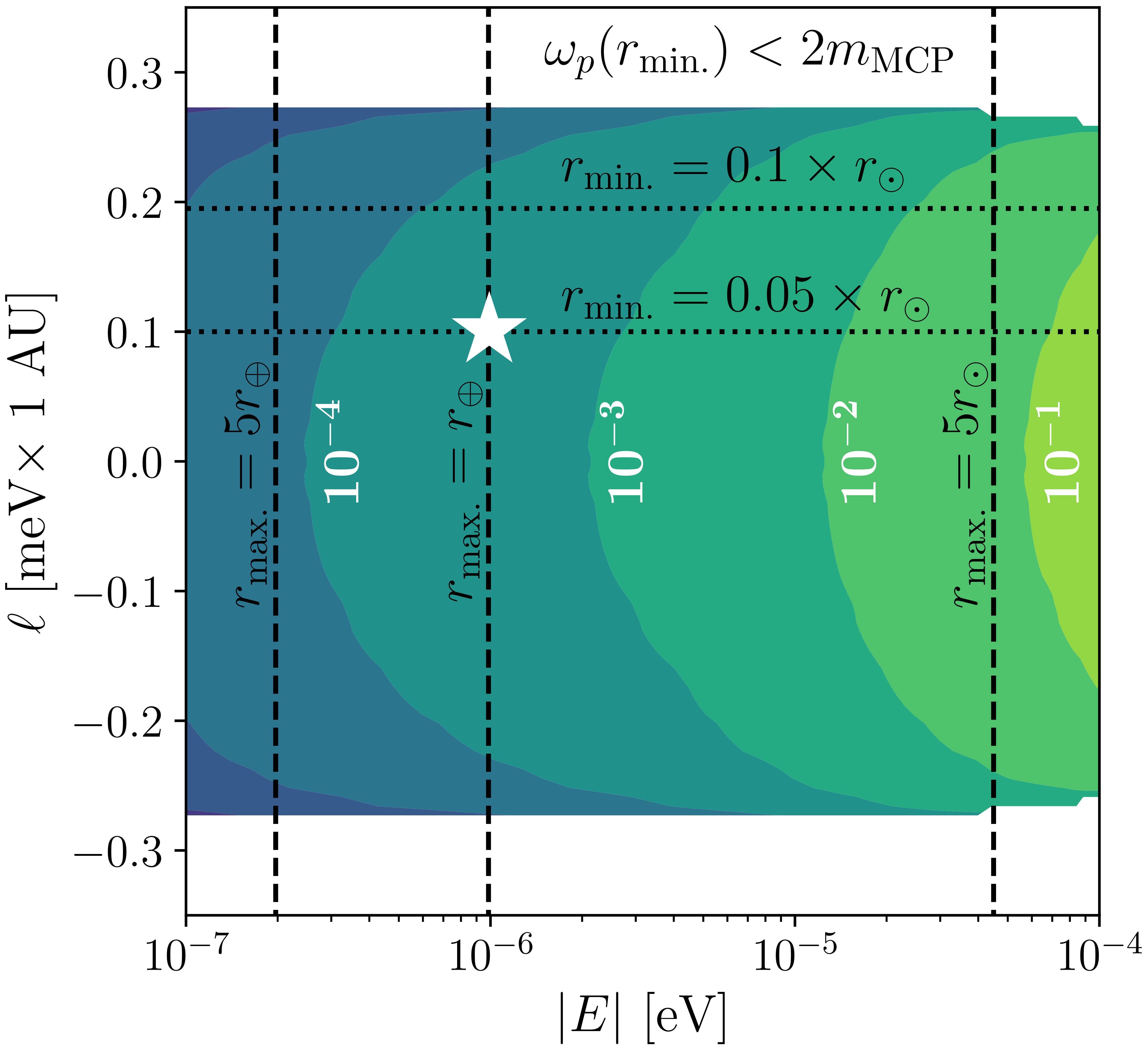
Total and radial velocities at production in the Sun

Production rate per phase space volume per mass

Ensures we don't go past centrifugal barrier in 1D effective potential

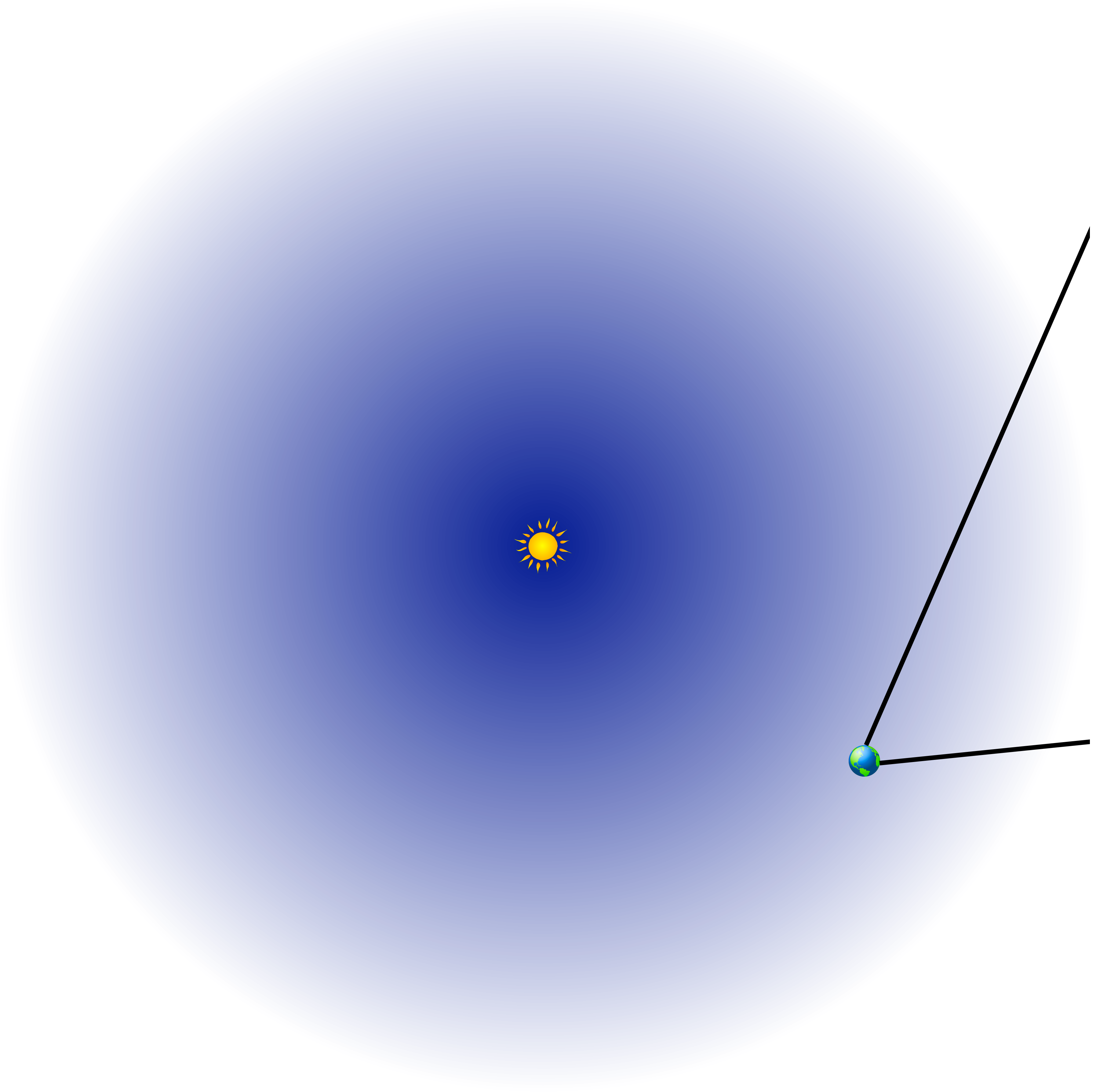
PHASE SPACE AT EARTH FROM PRODUCTION AND ORBITAL MOTION

- Motion of particles coming from Sun is radially collimated (low angular momentum/high orbital eccentricity ~0.9998 at starred point)
- Occupation numbers can be very high, even Pauli blocked in some parts of phase space that saturate
- Gravitational encounters with planets can scramble phase space, "isotropize" orbits on long timescales



Berlin & **KS** PRD (2022)

DENSITY AT EARTH



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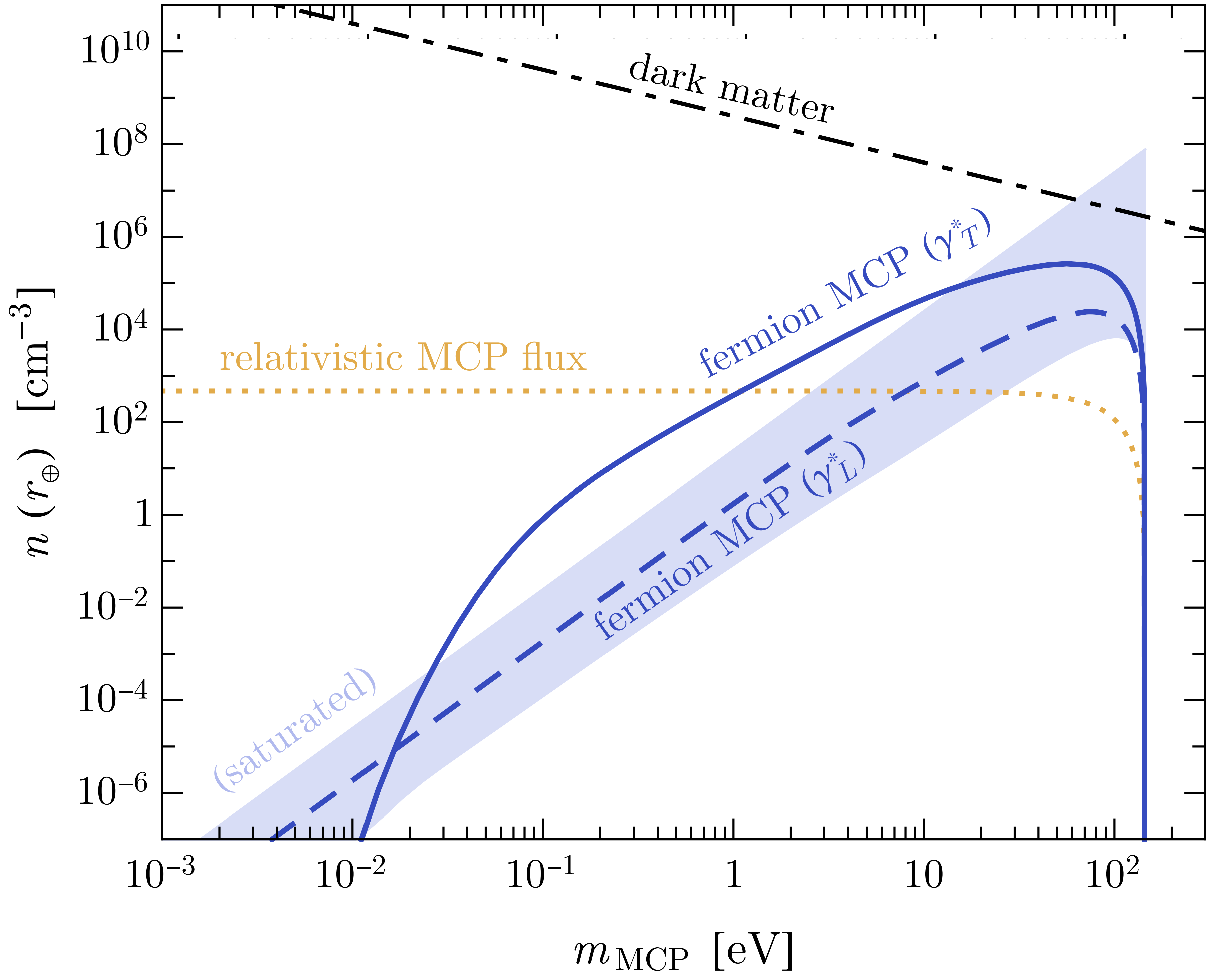


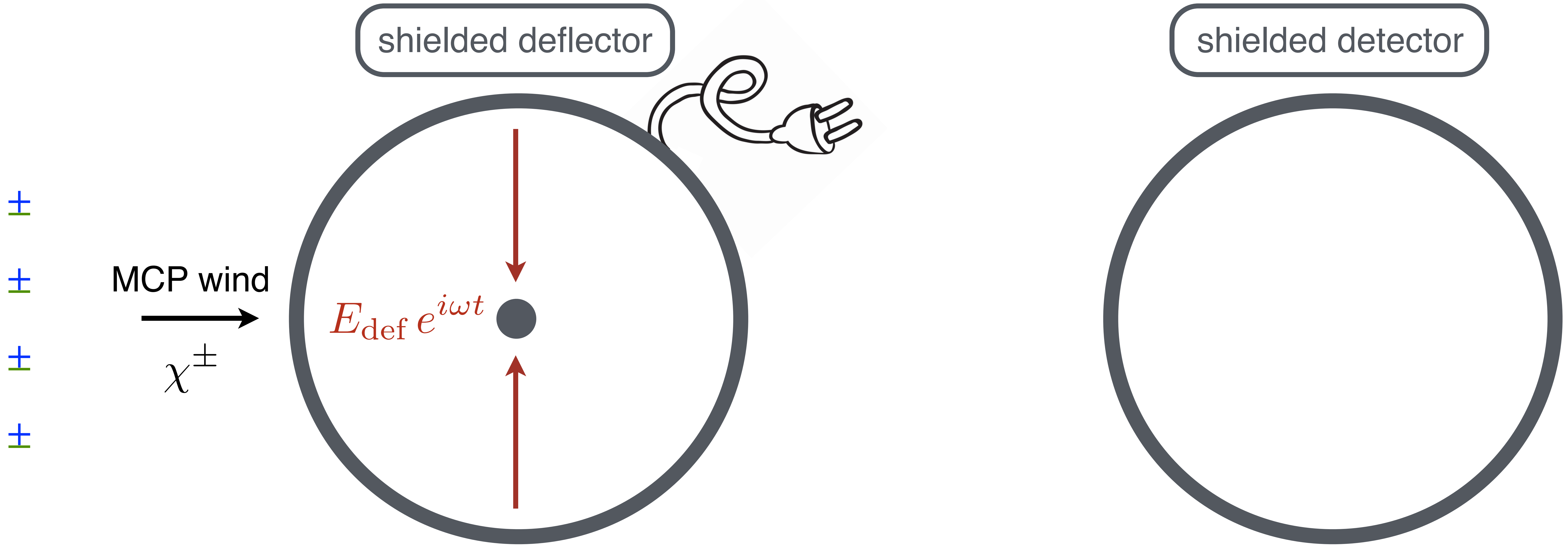
- Density from the basin exceeds the unbound flux over a few orders of magnitude in mass

Berlin & **KS** PRD (2022)

TRADITIONAL METHODS OF DETECTION WILL BE CHALLENGING

- Particles with conserved charge can only scatter elastically
- Unlike previous stellar basins (axions and dark photons considered by van Tilburg, Lasenby) particle absorption in terrestrial experiment is not a viable detection strategy
- Typical particle speed in basin is 10^{-4} c, so sub-keV particles will have at most μeV kinetic energy, not enough to be above experimental energy threshold
- Need to exploit collective effects that are not penalized for low particle speed in order to observe something

DEFLECTION OVERVIEW (BERLIN ET AL. 2020)



shielded deflector

shielded detector

MCP wind

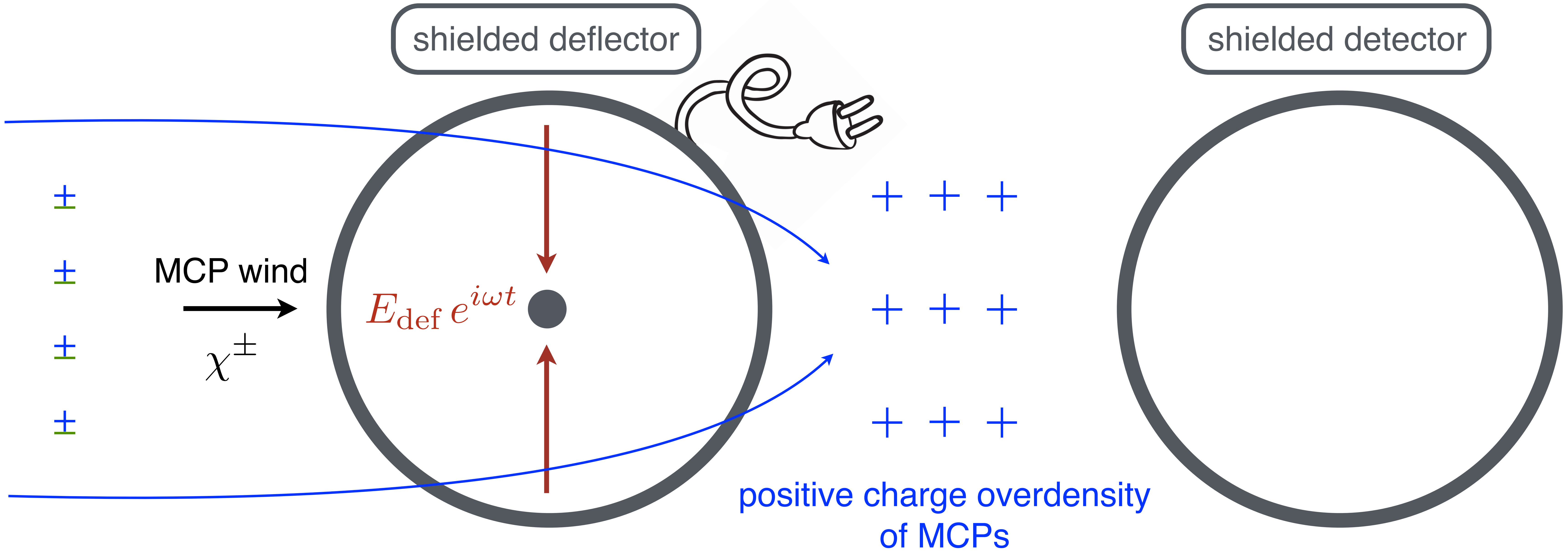
$\chi^{\pm}$

$E_{\rm def}\, e^{i\omega t}$

(similar to “~~light-shining~~ *wind-blowing*-through-wall” experiments)

Slide credit: Asher Berlin

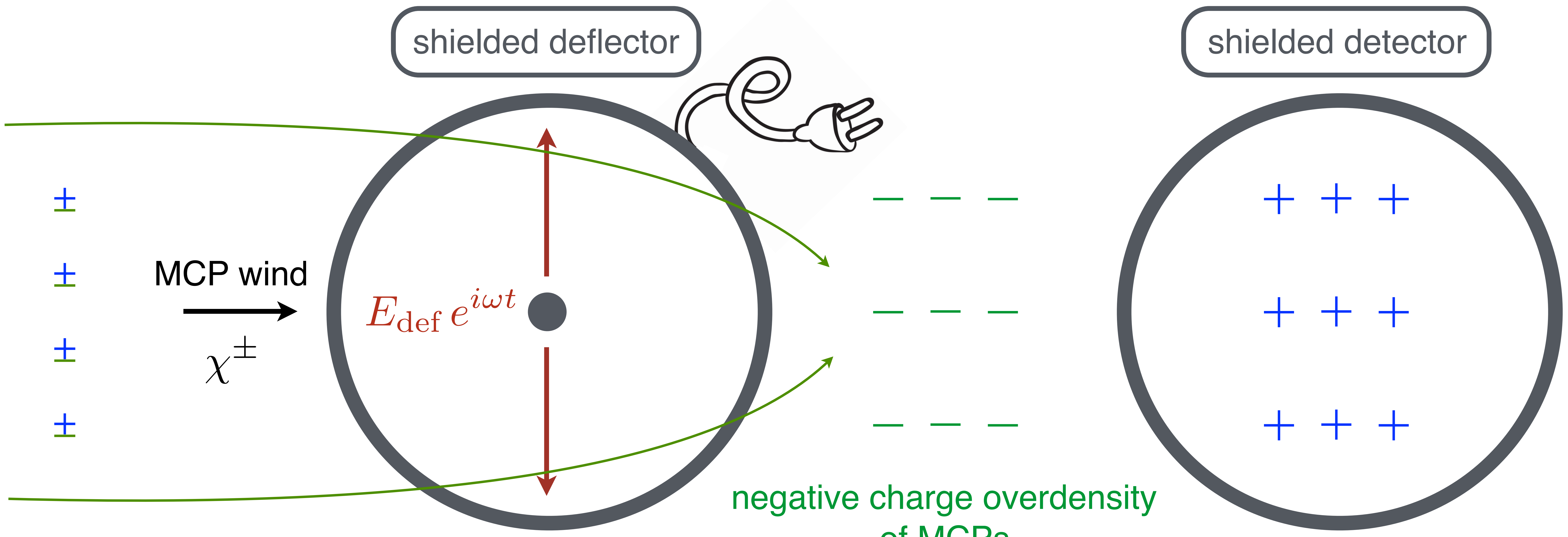
DEFLECTION OVERVIEW (BERLIN ET AL. 2020)



wind-blowing
(similar to “~~light-shining~~-through-wall” experiments)

Slide credit: Asher Berlin

DEFLECTION OVERVIEW (BERLIN ET AL. 2020)



shielded deflector

shielded detector

MCP wind

$\chi^{\pm}$

$E_{\rm def}\, e^{i\omega t}$

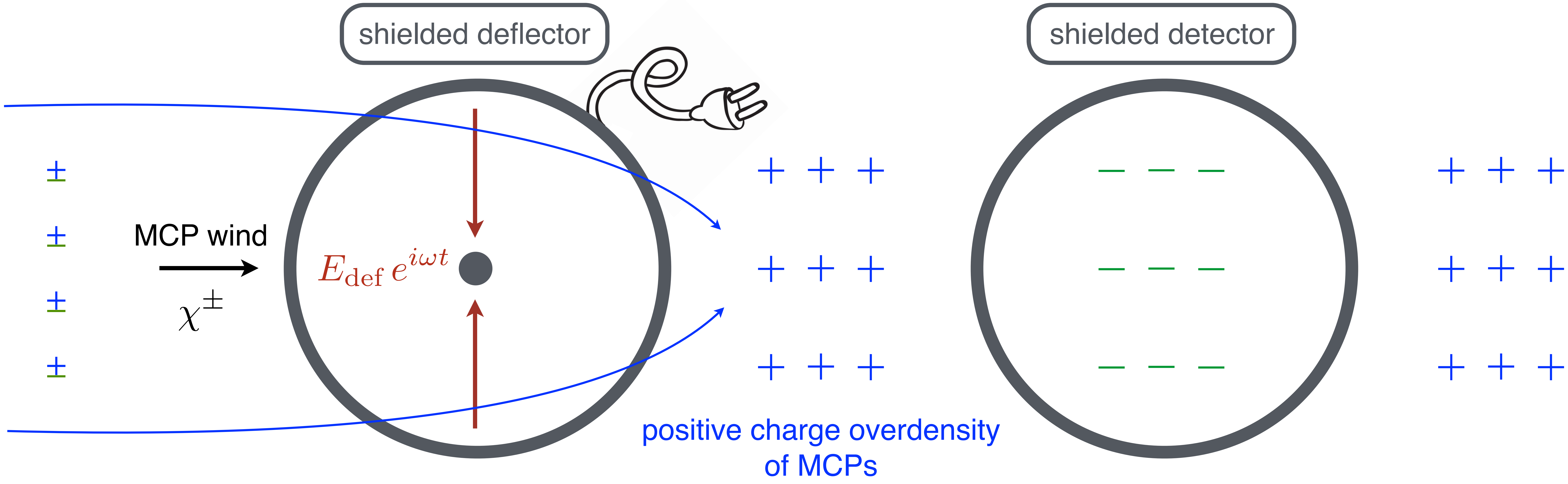
negative charge overdensity of MCPs

wind-blowing

(similar to “~~light-shining~~-through-wall” experiments)

Slide credit: Asher Berlin

DEFLECTION OVERVIEW (BERLIN ET AL. 2020)



shielded deflector

shielded detector

MCP wind

$\chi^{\pm}$

$E_{\rm def}\, e^{i\omega t}$

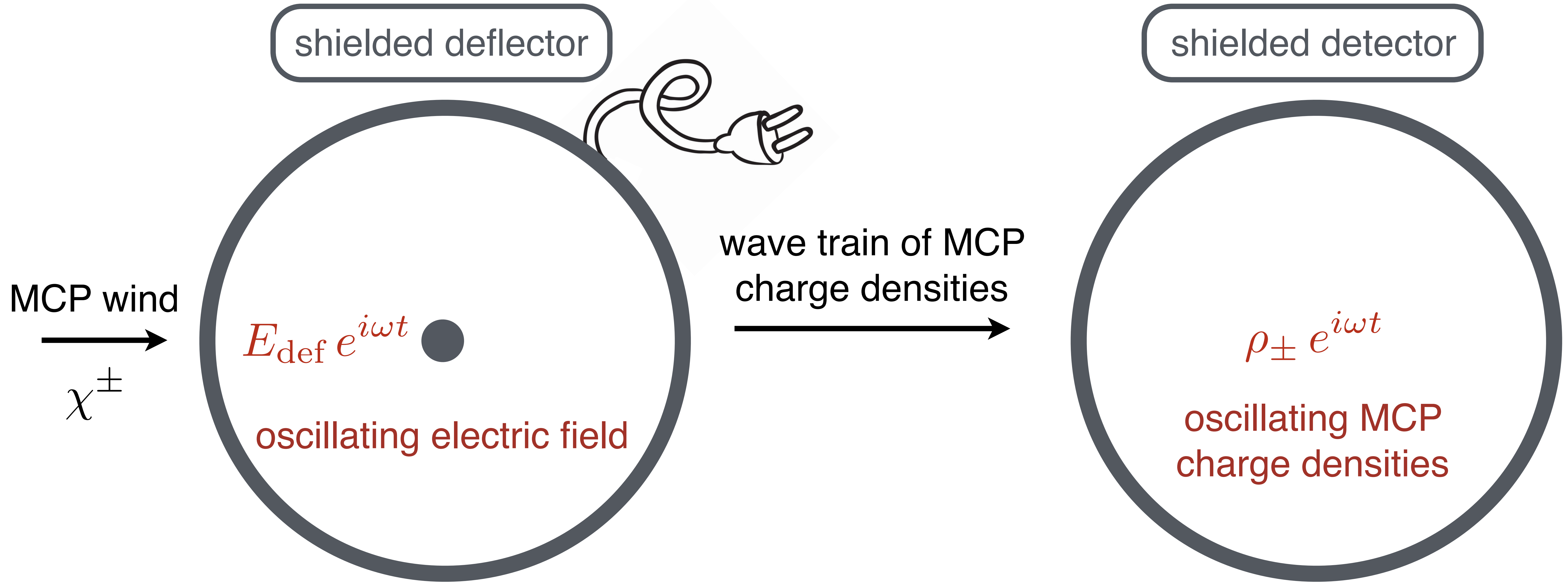
positive charge overdensity of MCPs

wind-blowing

(similar to “~~light-shining~~-through-wall” experiments)

Slide credit: Asher Berlin

DEFLECTION OVERVIEW (BERLIN ET AL. 2020)



shielded deflector

shielded detector

MCP wind

$\chi^{\pm}$

$E_{\text{def}}\, e^{i\omega t}$

oscillating electric field

wave train of MCP charge densities

$\rho_{\pm}\, e^{i\omega t}$

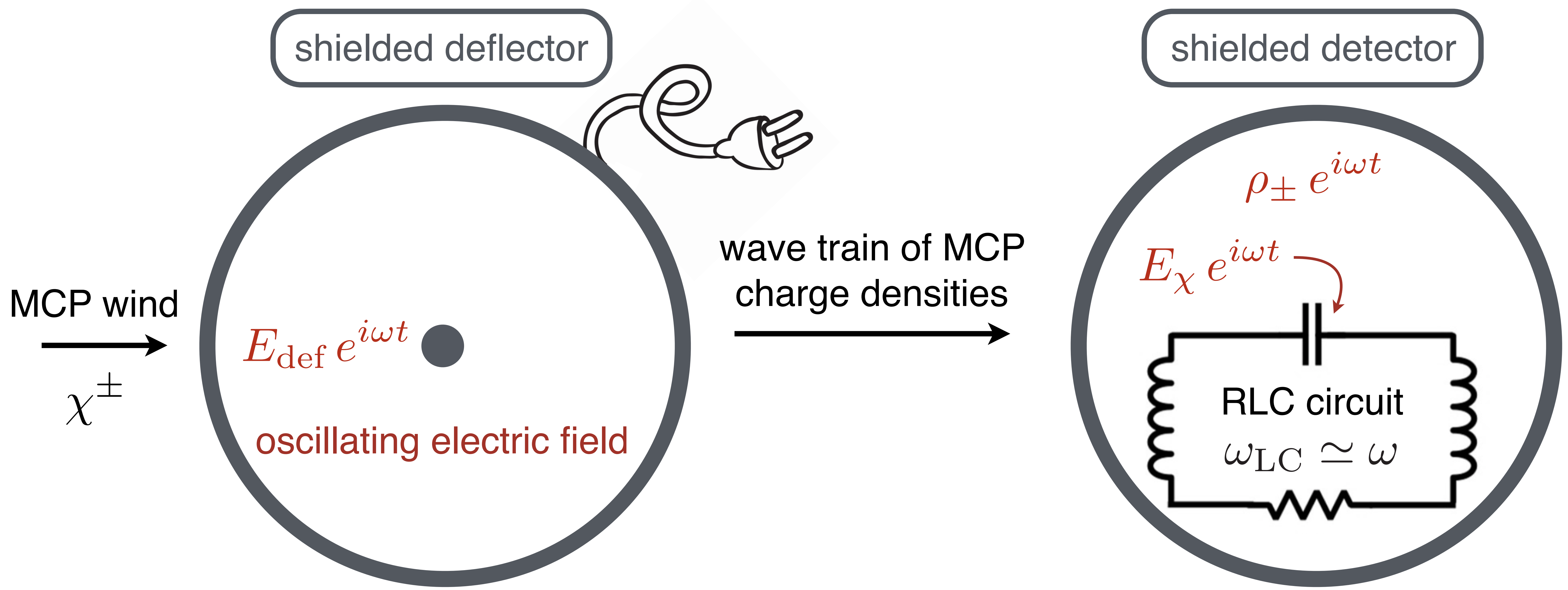
oscillating MCP charge densities

wind-blowing

(similar to ~~“light-shining~~-through-wall” experiments)

Slide credit: Asher Berlin

DEFLECTION OVERVIEW (BERLIN ET AL. 2020)



shielded deflector

MCP wind

$\chi^{\pm}$

$E_{\rm def}\, e^{i\omega t}$

oscillating electric field

wave train of MCP charge densities

shielded detector

$\rho_{\pm}\, e^{i\omega t}$

$E_{\chi}\, e^{i\omega t}$

RLC circuit

$\omega_{\rm LC} \simeq \omega$

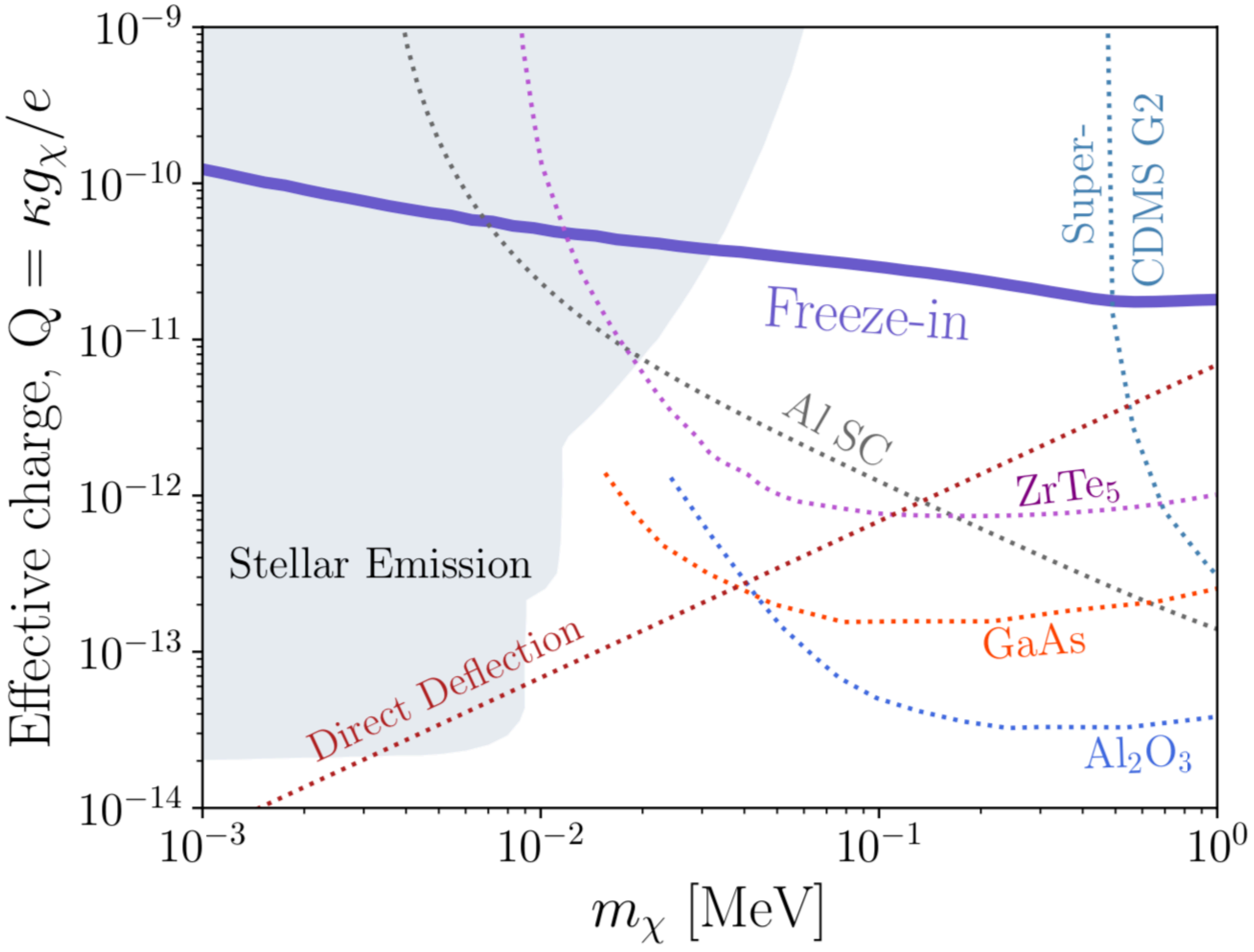
wind-blowing

(similar to "~~light-shining~~-through-wall" experiments)

inducing and detecting collective disturbances $\Longrightarrow$ no kinematic barrier

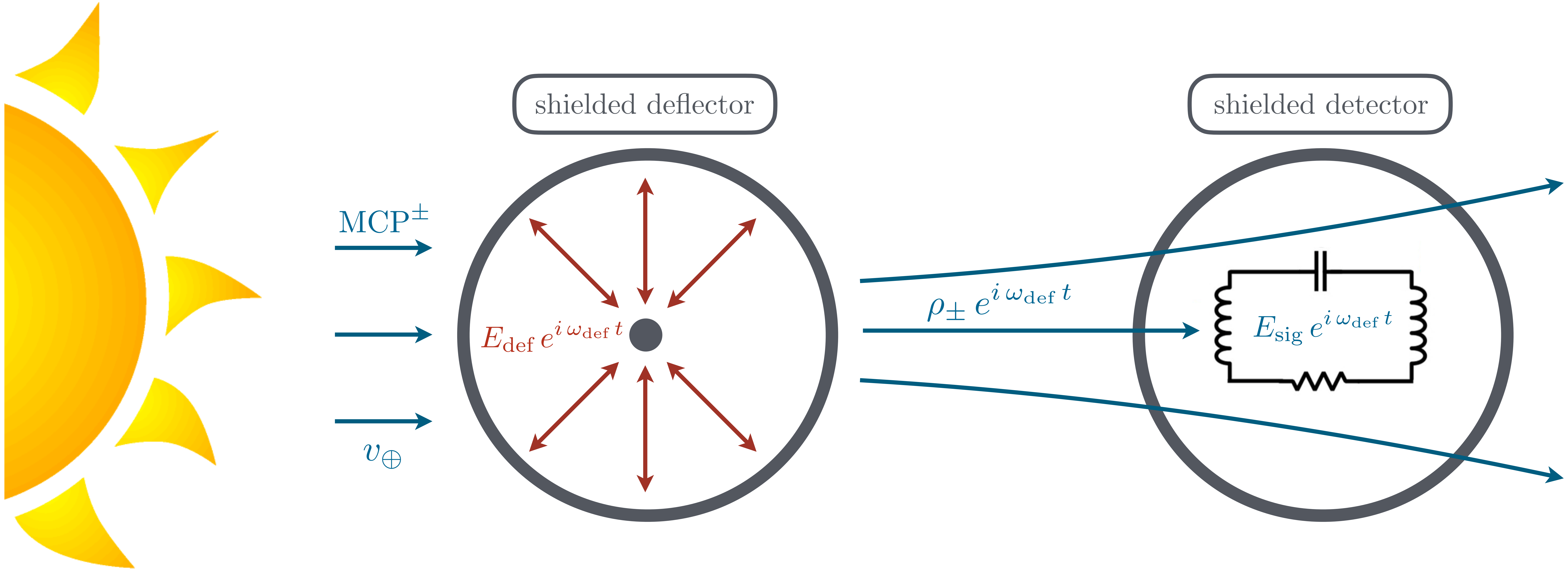
Slide credit: Asher Berlin

DIRECT DEFLECTION SENSITIVITY TO DARK MATTER



Dvorkin, Lin, **KS** (PRD 2019)

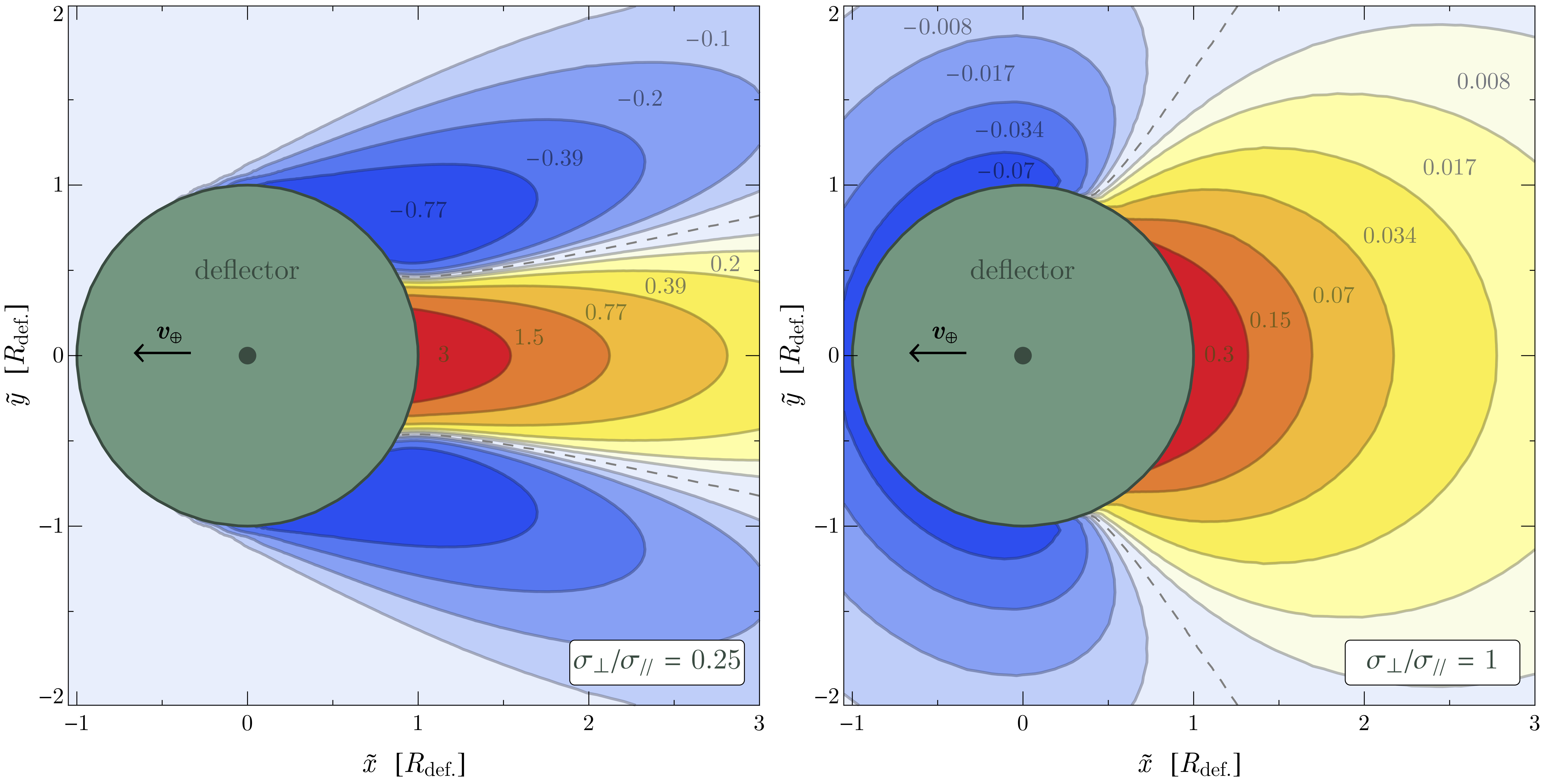
DEFLECTION OF MCPS FROM THE SUN



- MCP velocity distribution determines how easy particles are to deflect and size of resulting charge overdensity

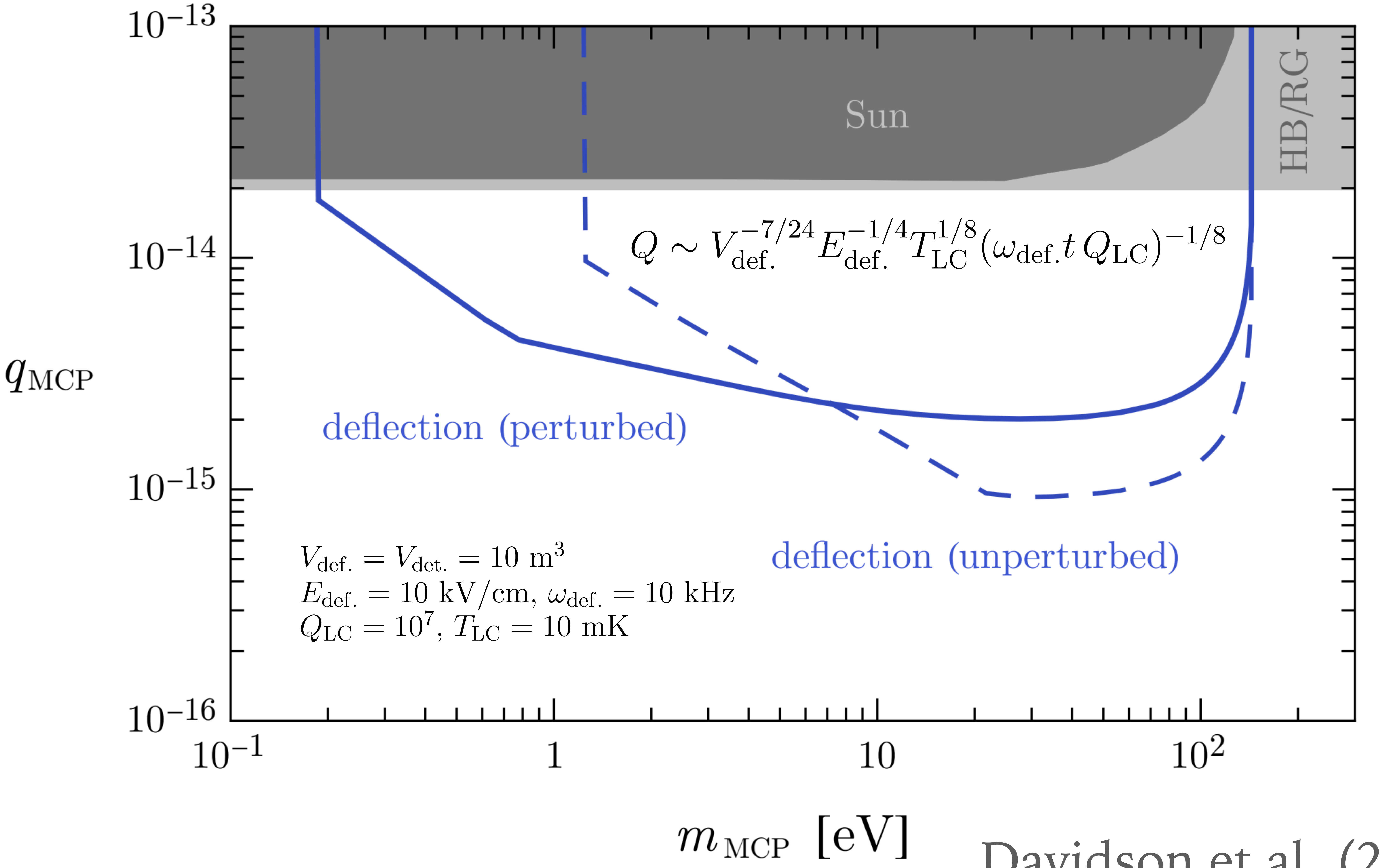
Berlin & **KS** PRD (2022)

DEFLECTION DEPENDENCE ON PHASE SPACE



- More coherent velocity phase space leads to an enhanced charge density in the wake Berlin & **KS** PRD (2022)

PREDICTED REACH

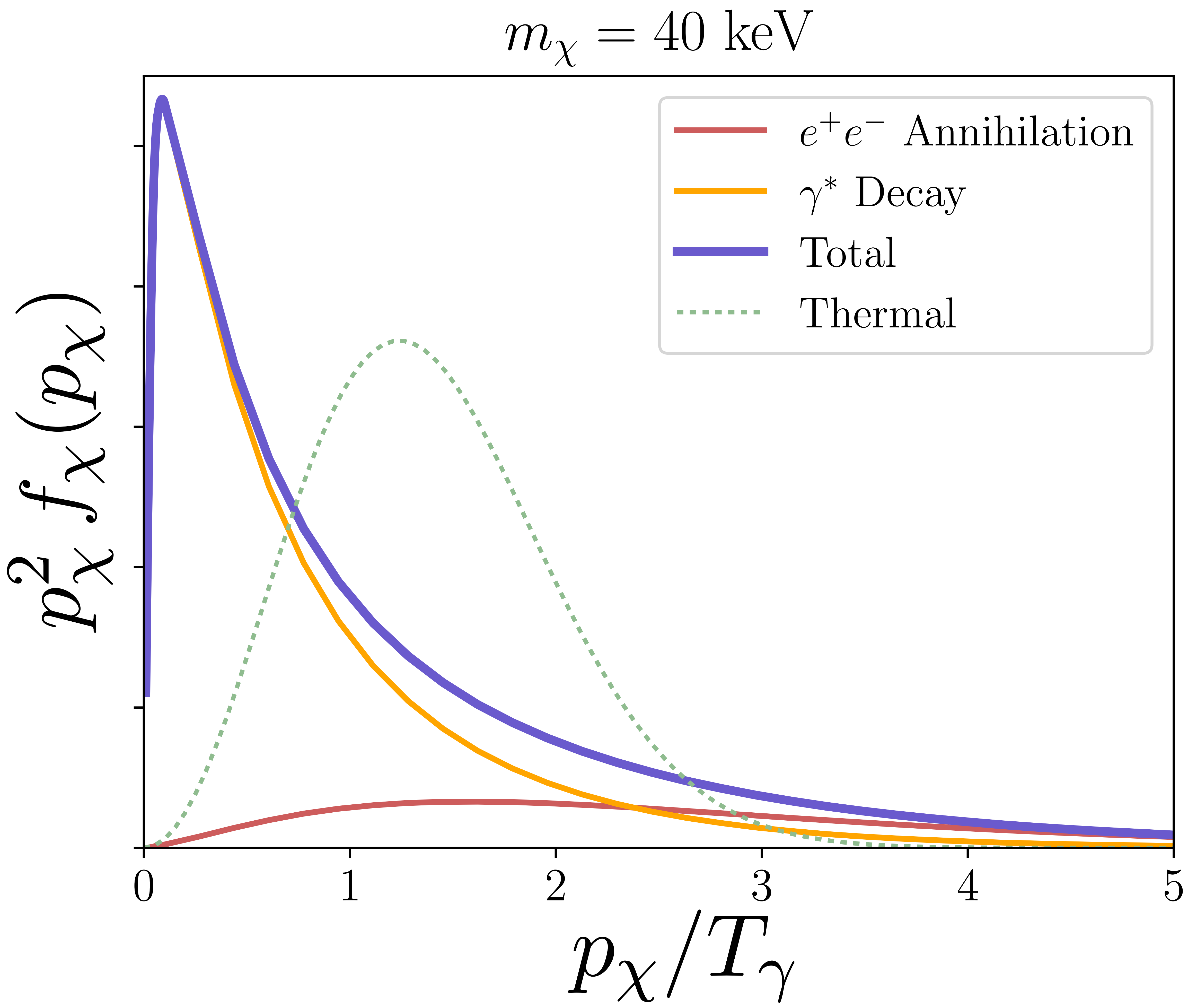


Davidson et al. (2000)

Berlin & **KS** PRD (2022)

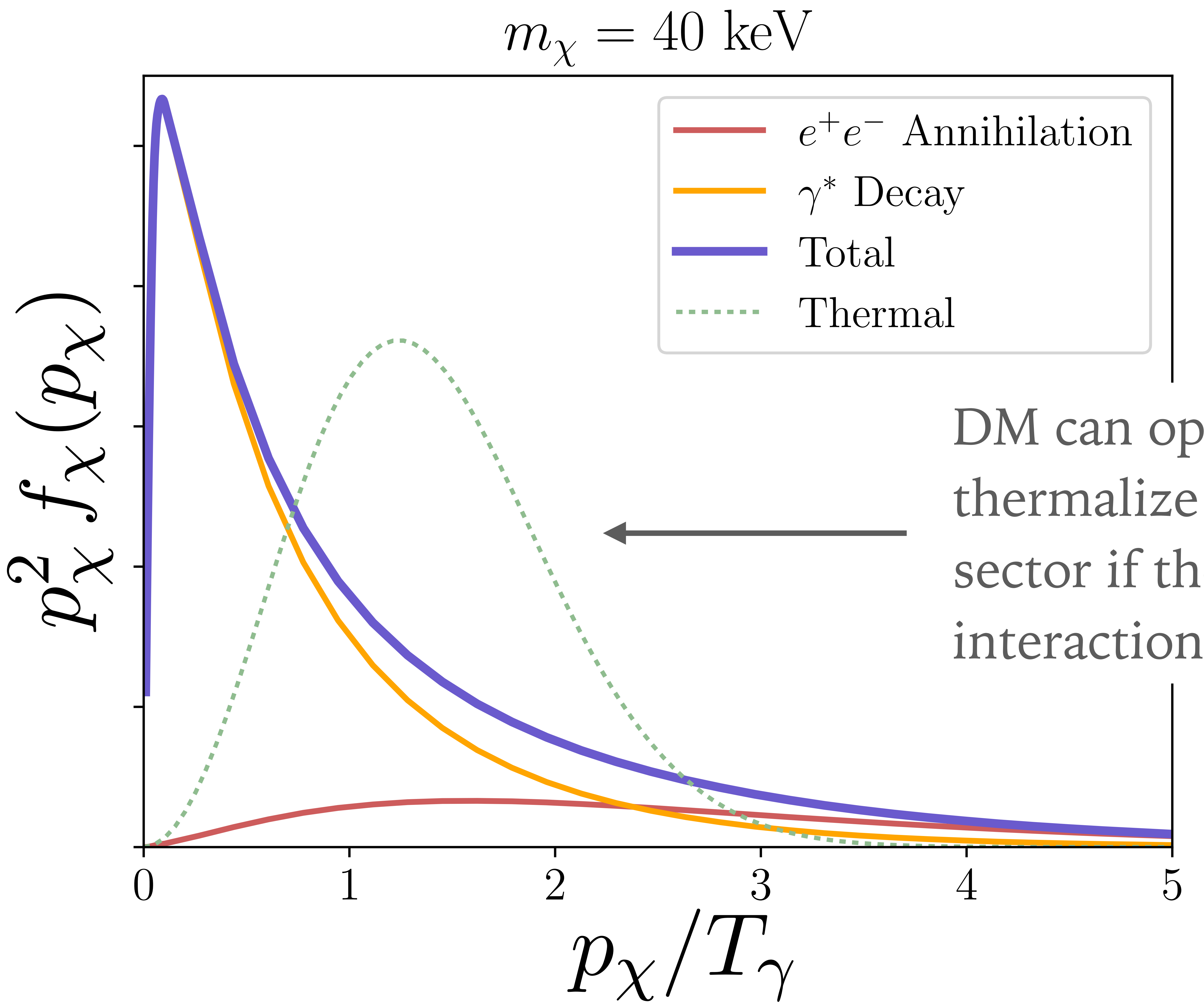
BACKUP: FREEZE-IN COSMOLOGY

DEALING WITH NON-THERMAL PHASE SPACE



Dvorkin, Lin, **KS** (PRD 2019)

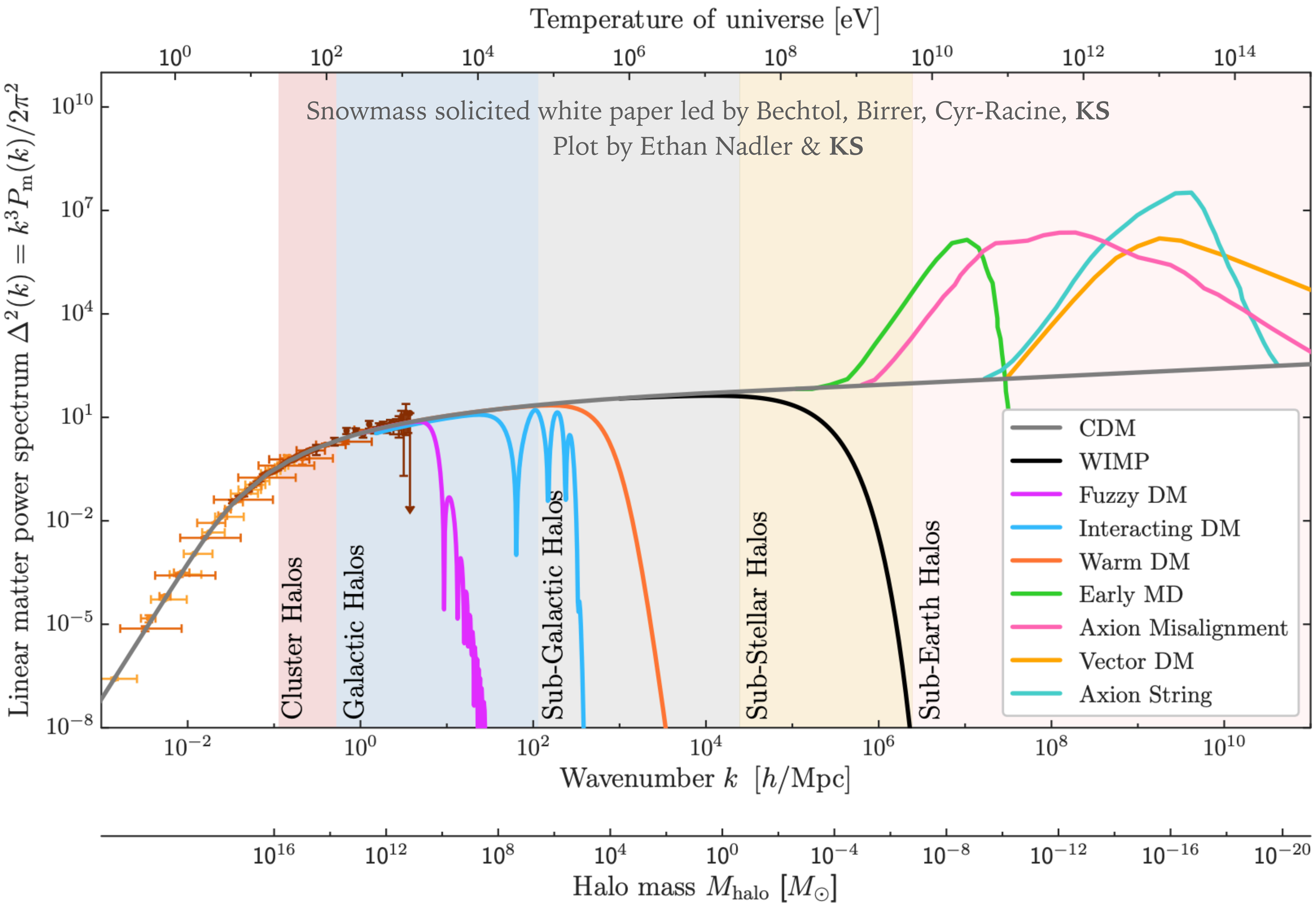
DEALING WITH NON-THERMAL PHASE SPACE



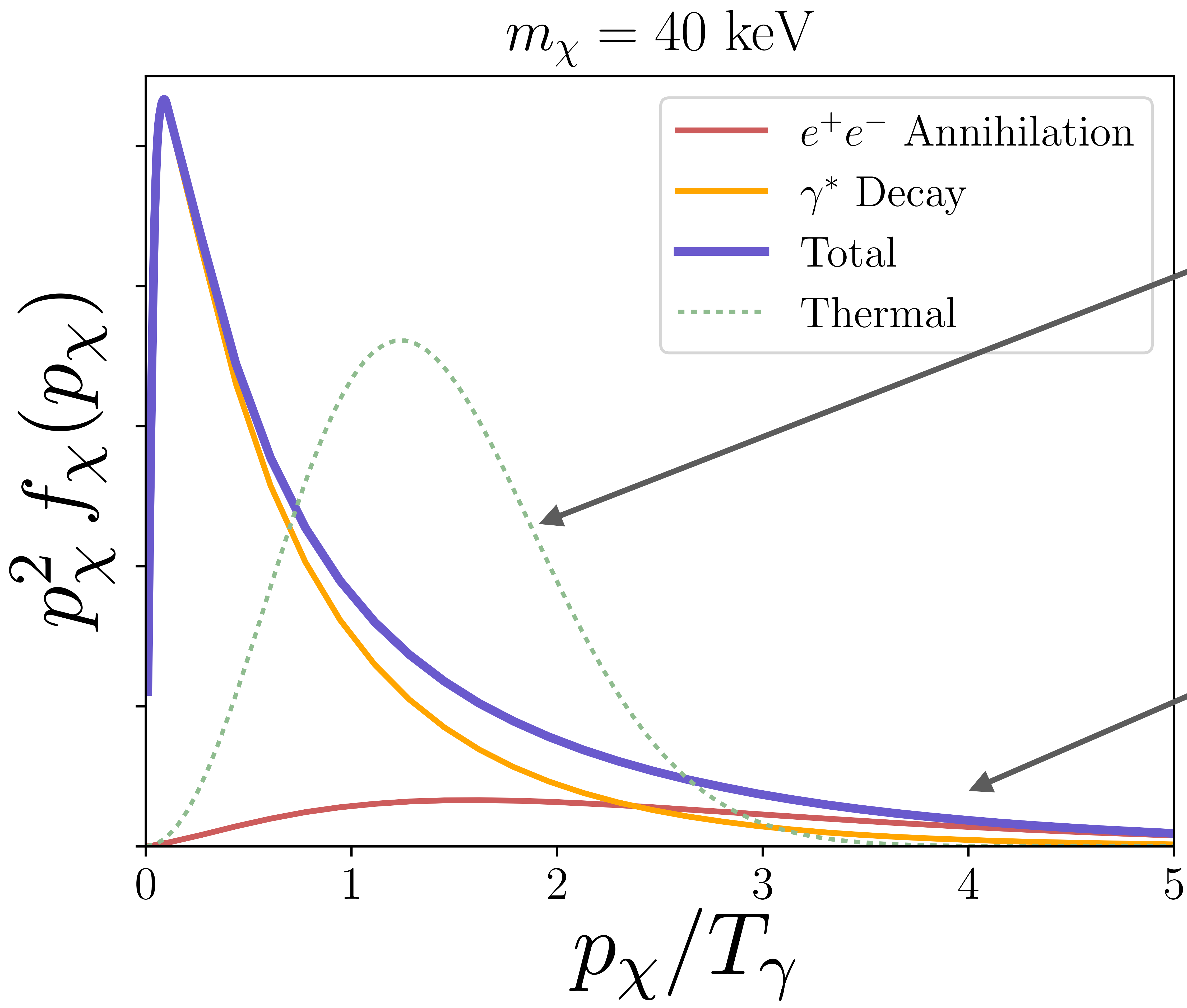
DM can optionally thermalize in its own sector if there are self-interactions

Dvorkin, Lin, **KS** (PRD 2019)

PROBES OF STRUCTURE FORMATION ON SMALL SCALES



GRAVITATIONAL CLUSTERING AND PHASE SPACE

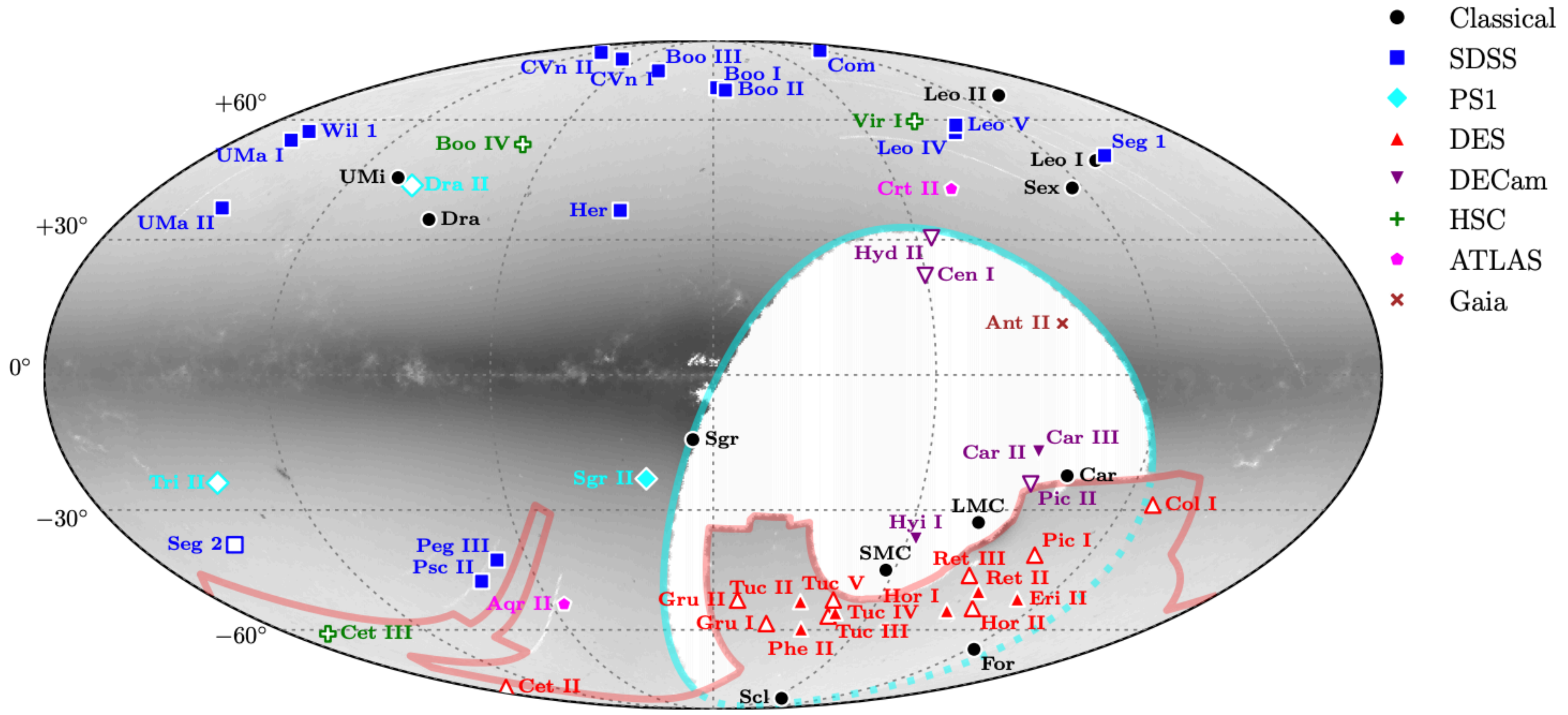


If DM can self-thermalize then it must have a nontrivial sound speed and can't stream freely

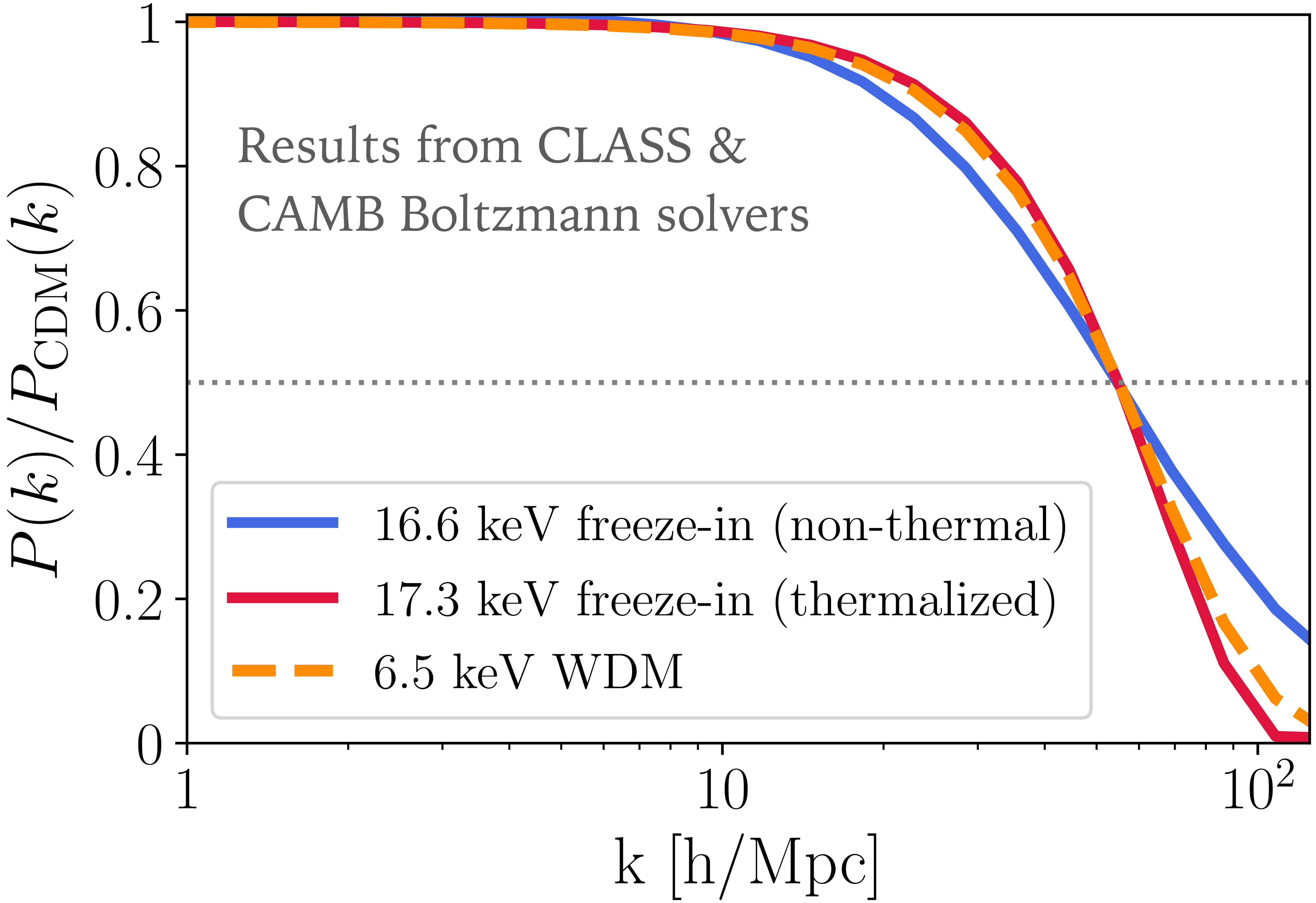
Non-thermal distribution has more low-low velocity particles but fatter high-velocity tail, can stream freely (like neutrinos)

Dvorkin, Lin, **KS** (PRL 2021)

MAPPING WDM CONSTRAINTS TO FREEZE-IN CONSTRAINTS

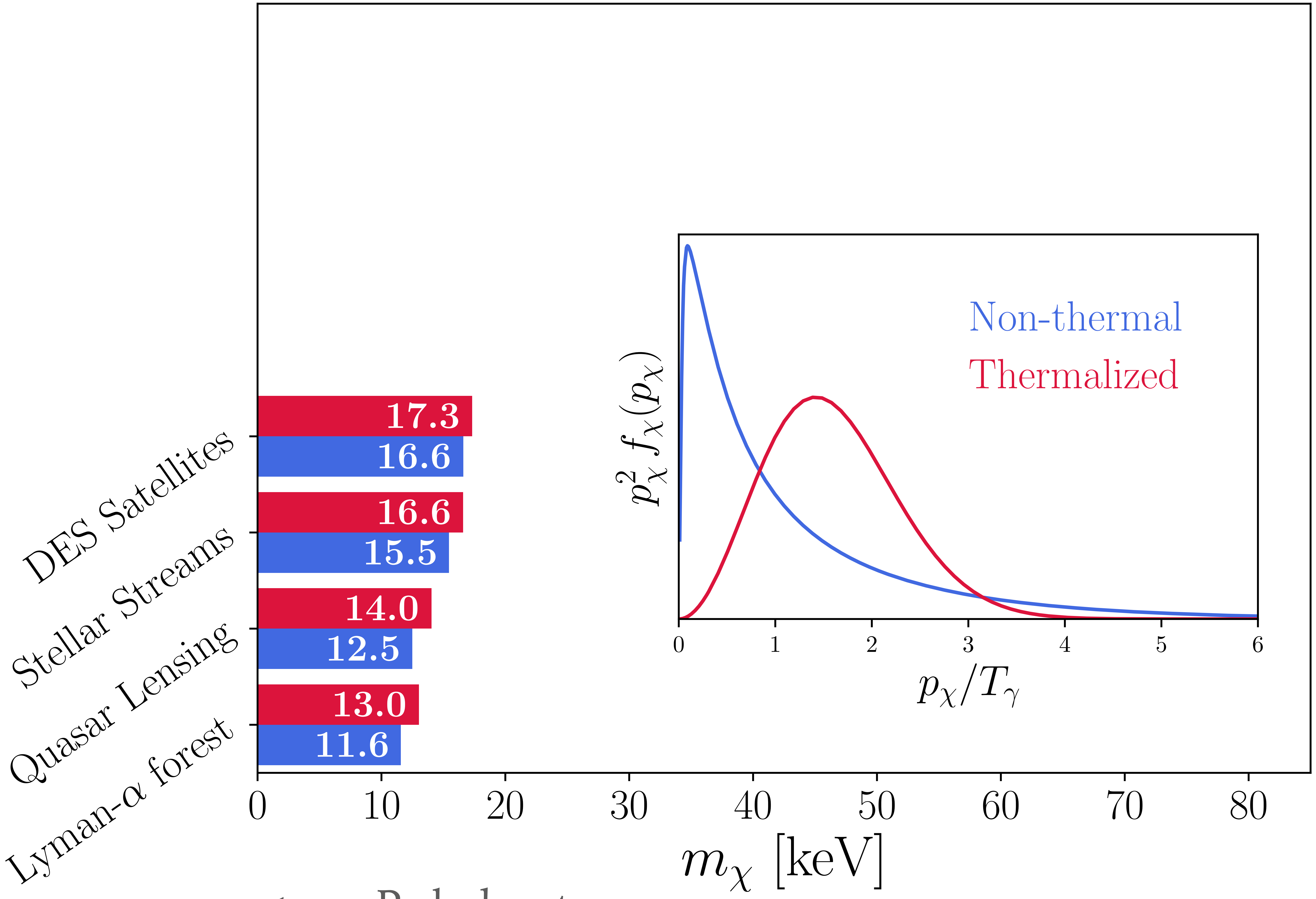


Some of the strongest WDM limits (6.5 keV) come from DES measurement of low-mass subhalos



Dvorkin, Lin, **KS** (PRL 2021)

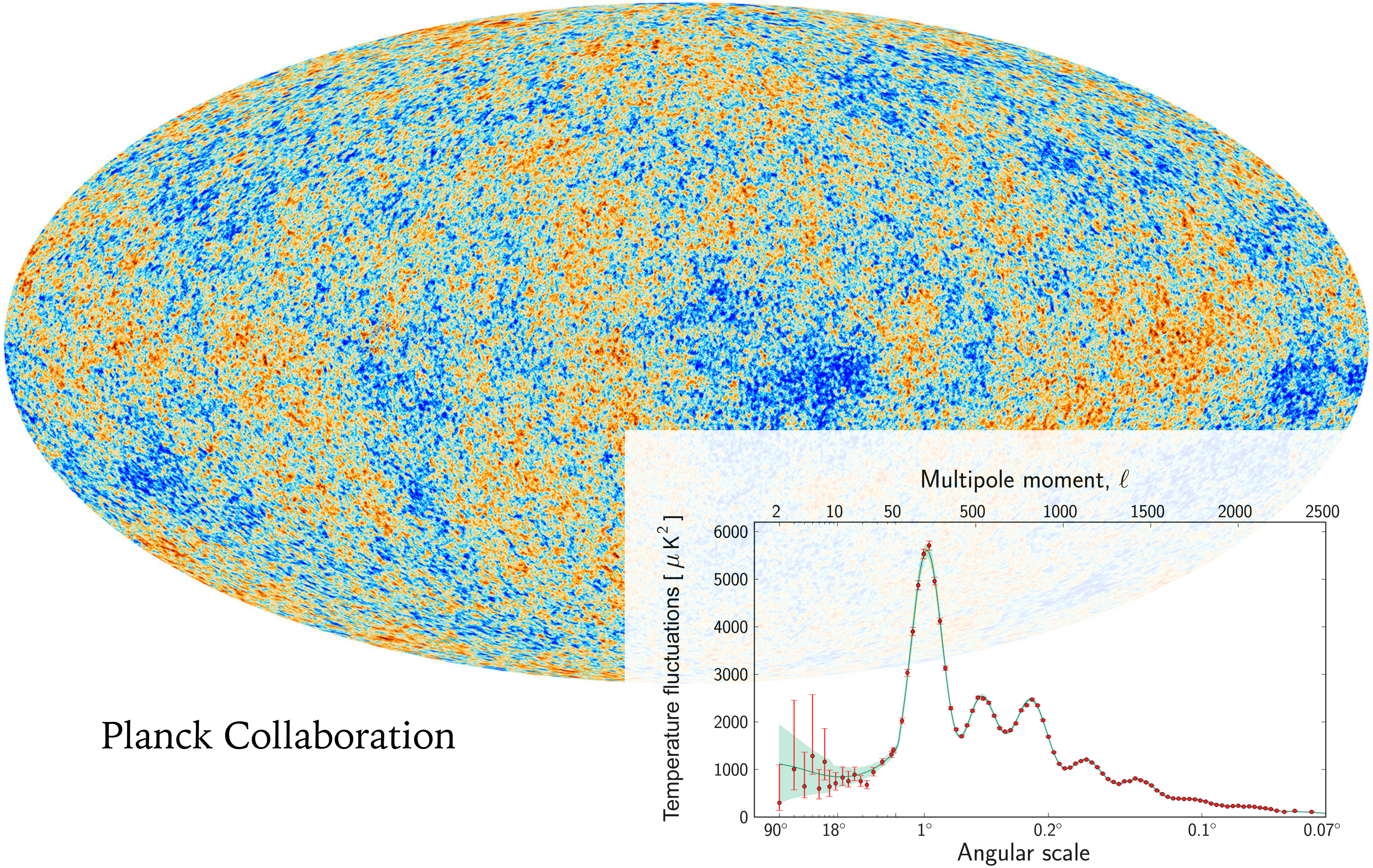
COSMOLOGICAL CONSTRAINTS ON FREEZE-IN



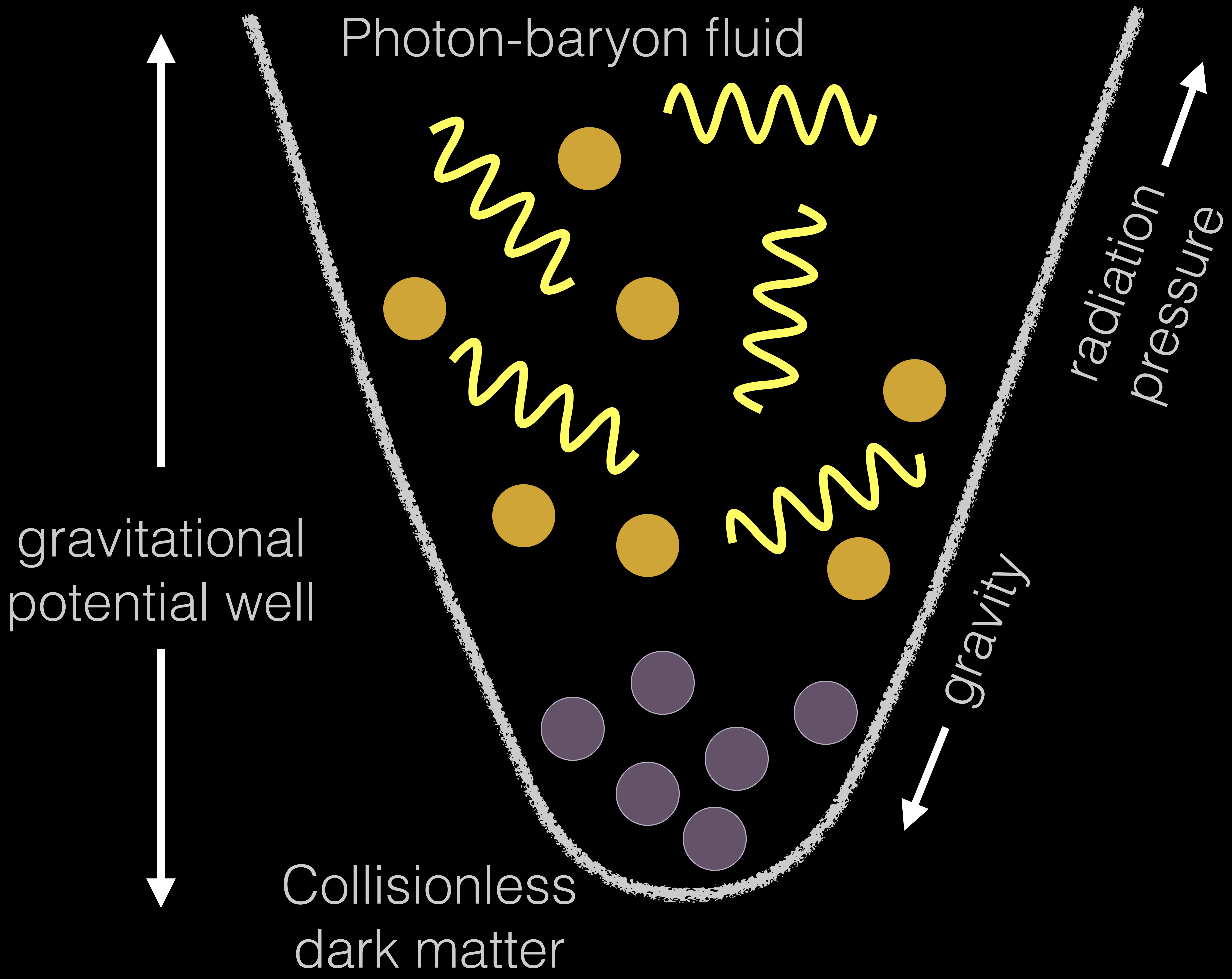
← Ruled out

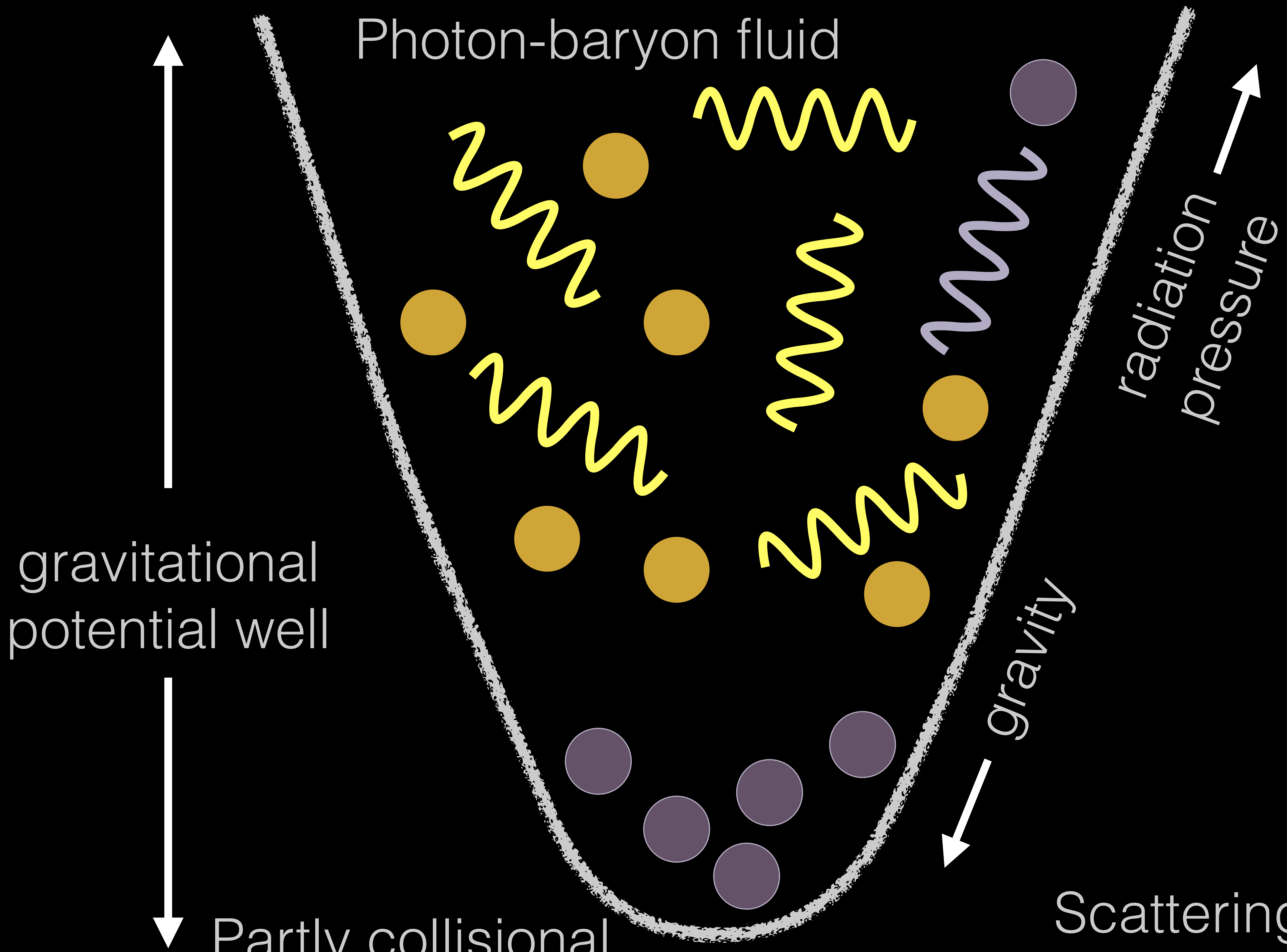
Dvorkin, Lin, **KS** (PRL 2021)

DARK MATTER–BARYON DRAG APPARENT IN THE CMB



Planck Collaboration


Photon-baryon fluid
gravitational
potential well
radiation
pressure
gravity
Collisionless
dark matter



Photon-baryon fluid

gravitational
potential well

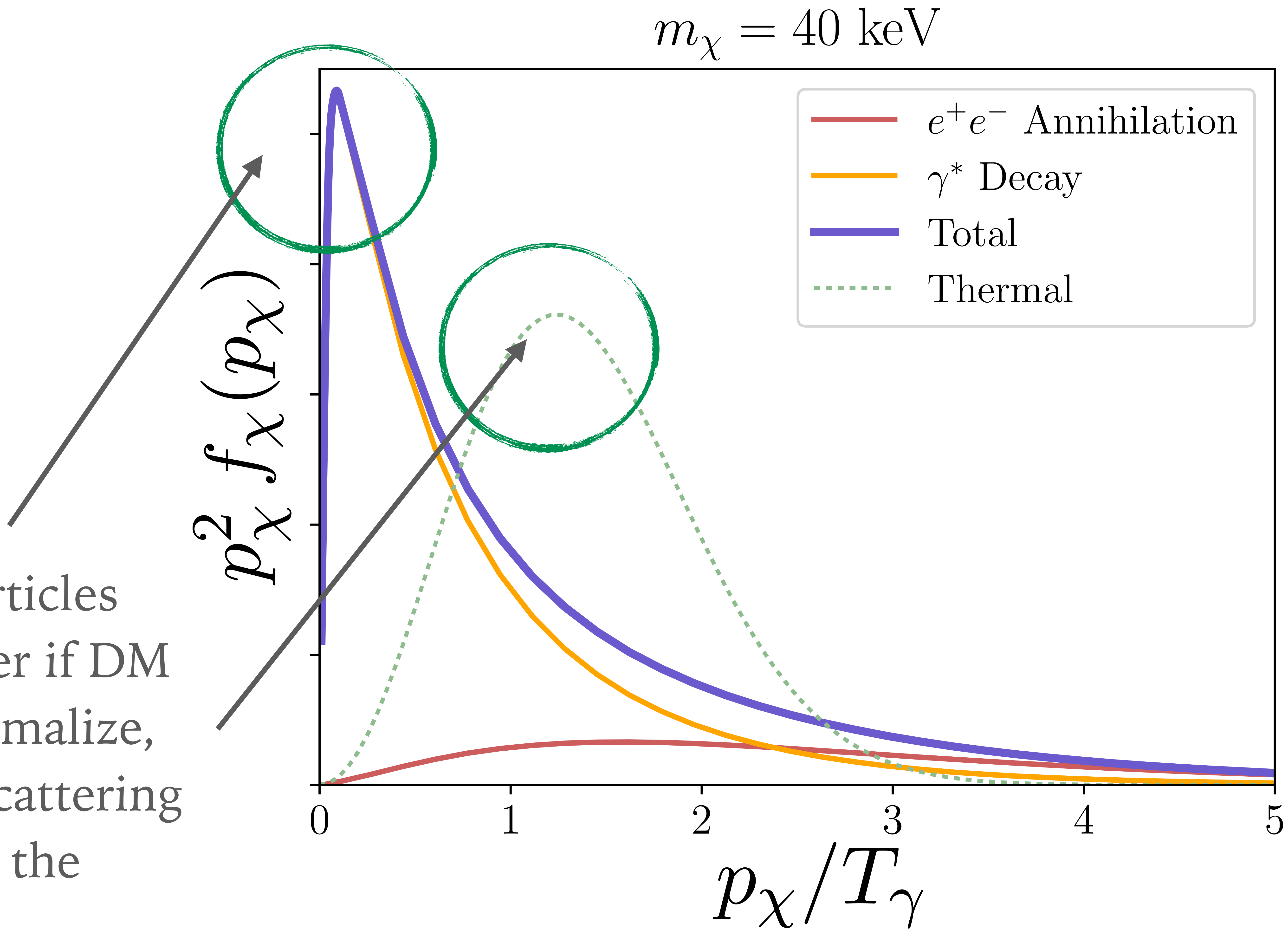
radiation
pressure

gravity

Partly collisional
dark matter

Scattering $\sim v^{-4}$
for freeze-in

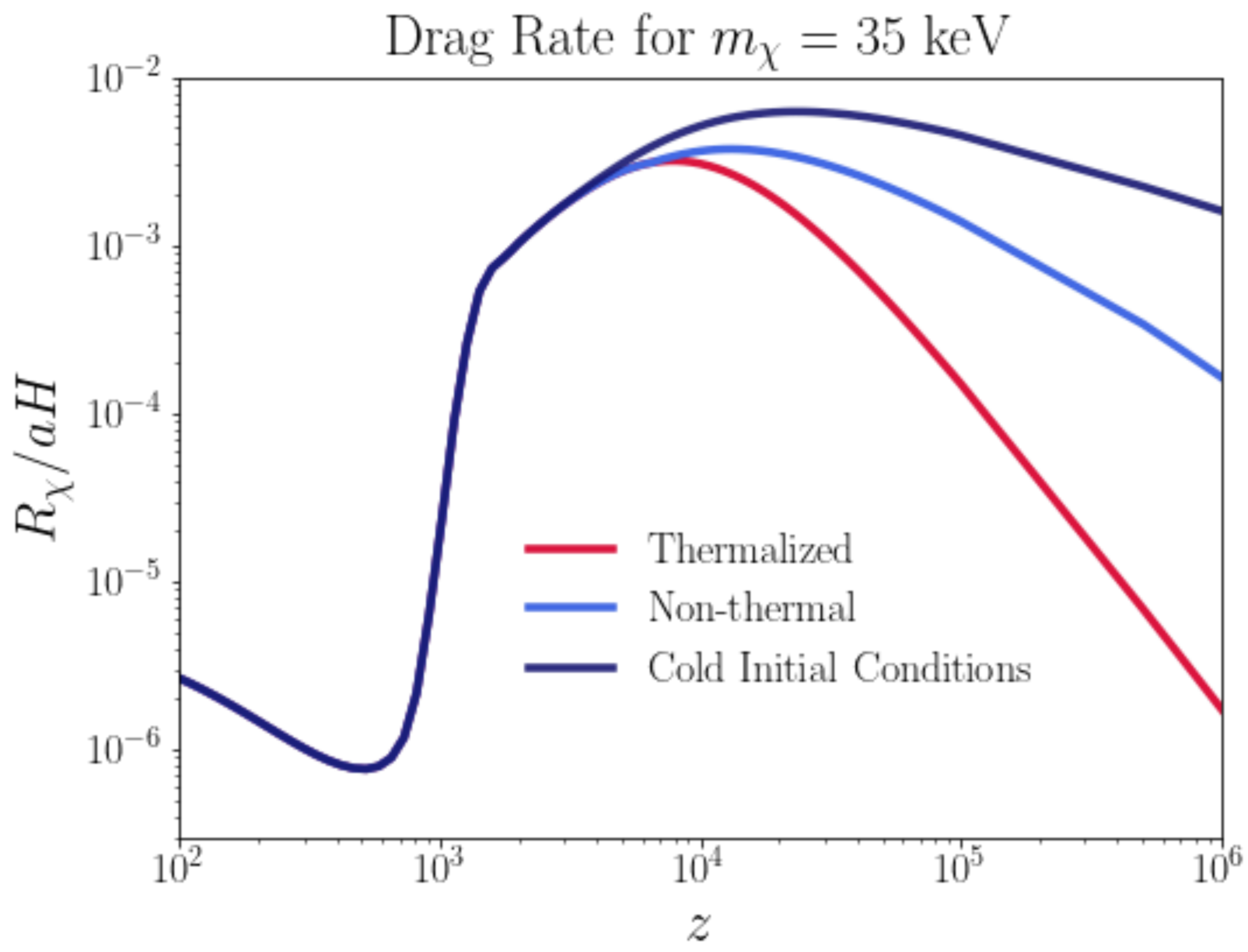
DM–BARYON SCATTERING AND PHASE SPACE

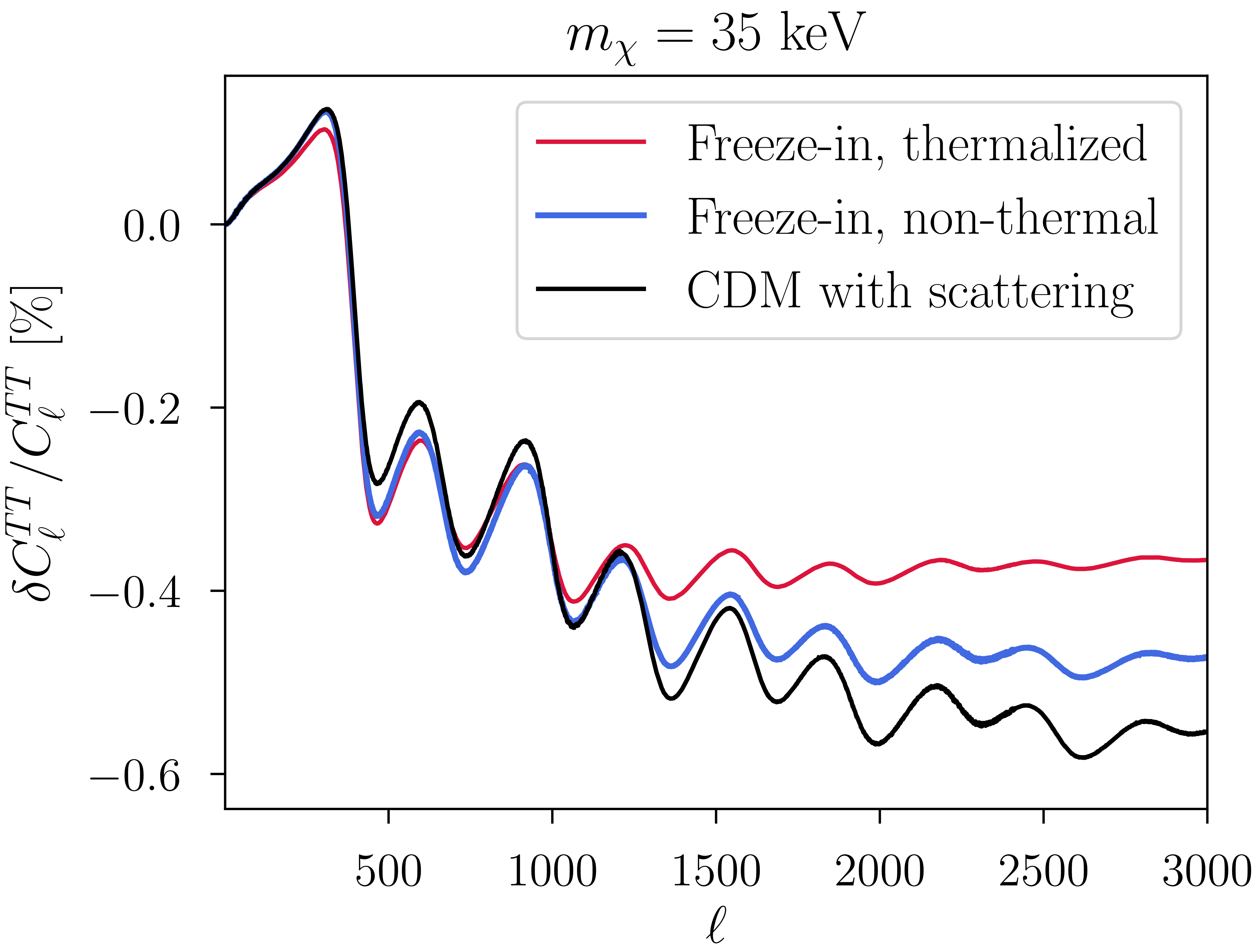


More DM particles moving slower if DM does not thermalize, stronger v^{-4} scattering effect seen in the CMB!

Dvorkin, Lin, **KS** (PRL 2021)

DM-BARYON DRAG RATE





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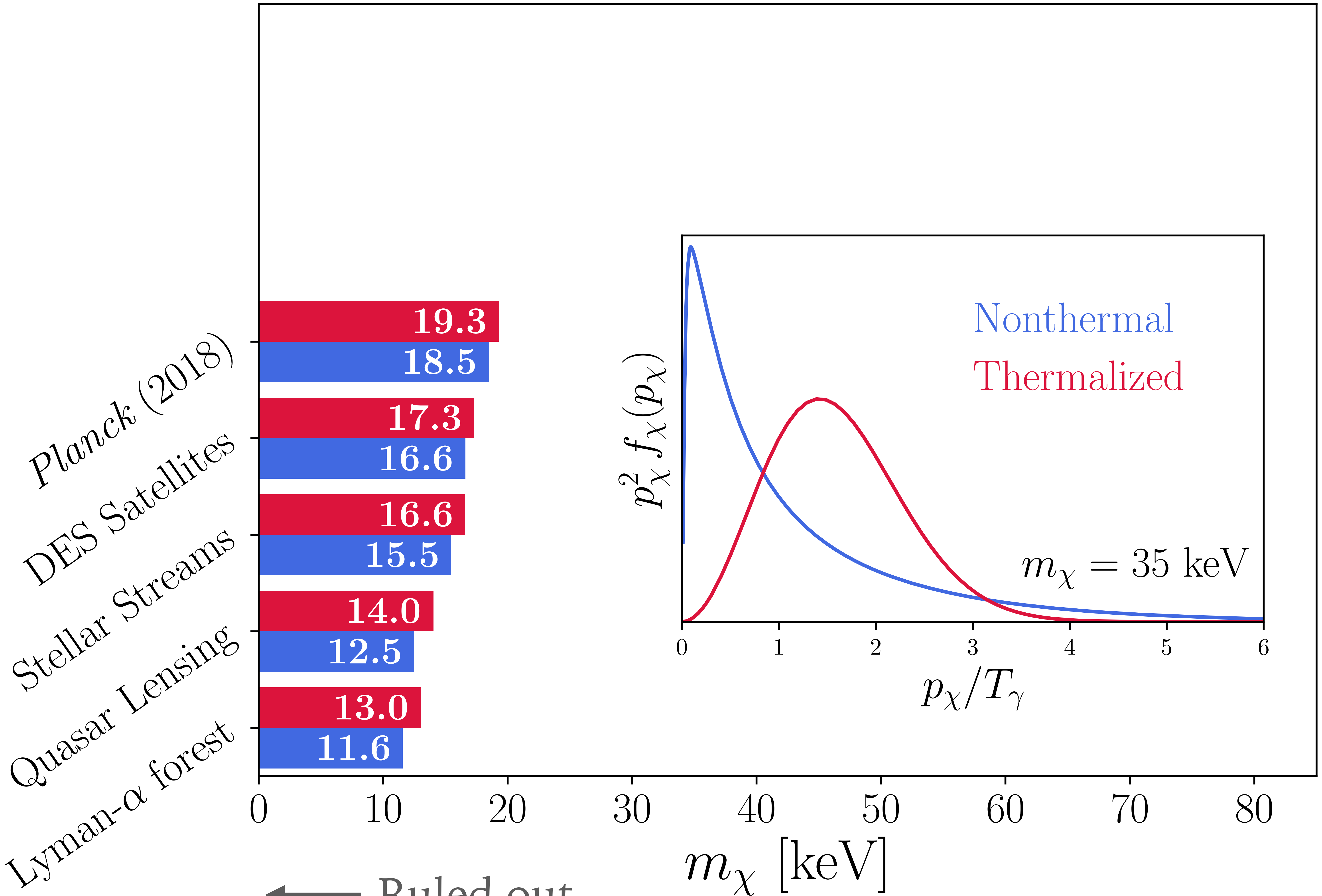
COSMOLOGICAL CONSTRAINTS ON FREEZE-IN



← Ruled out

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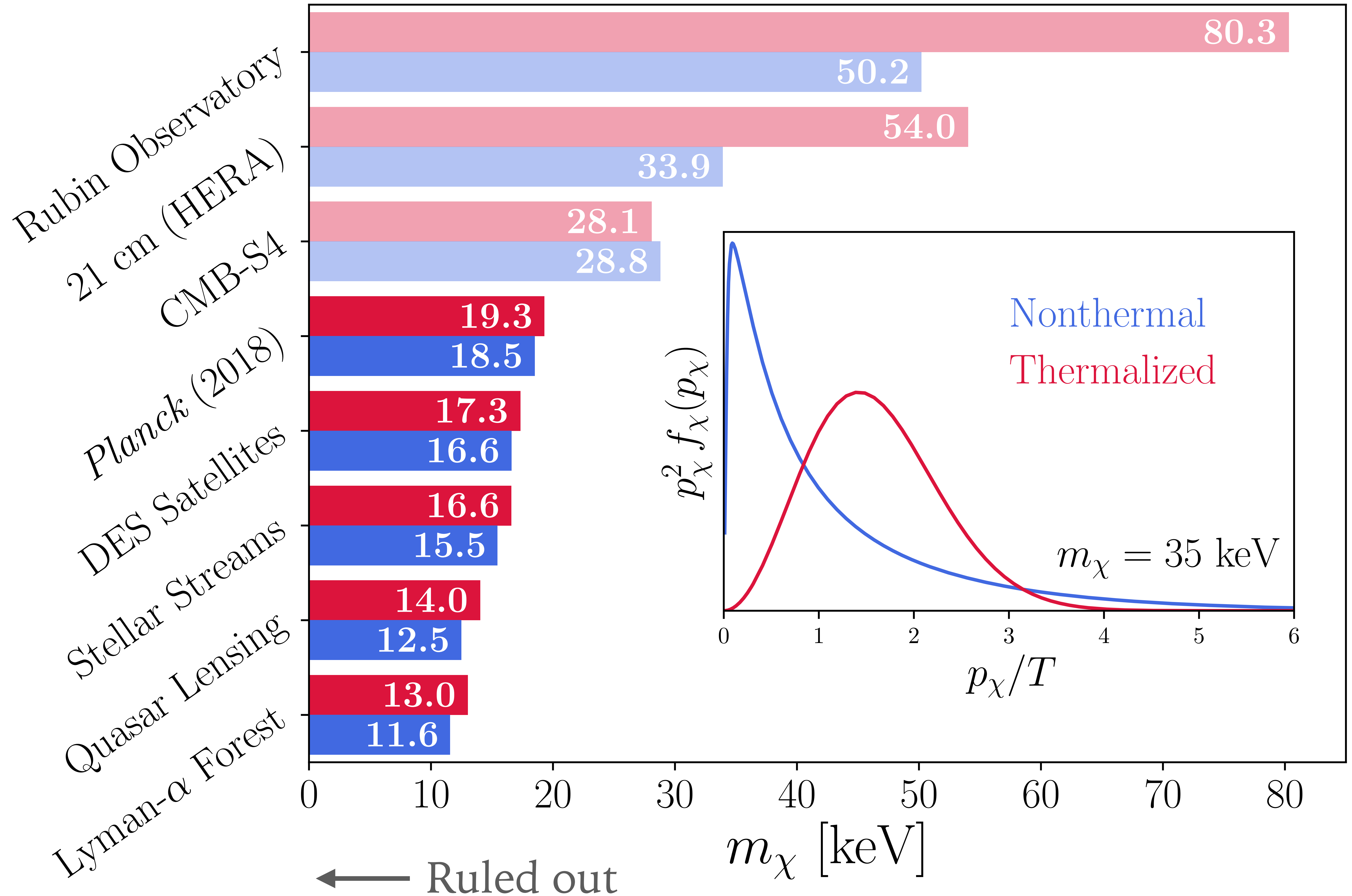
COSMOLOGICAL CONSTRAINTS ON FREEZE-IN



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