Searching for new fundamental physics in astrophysical objects

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DESY.

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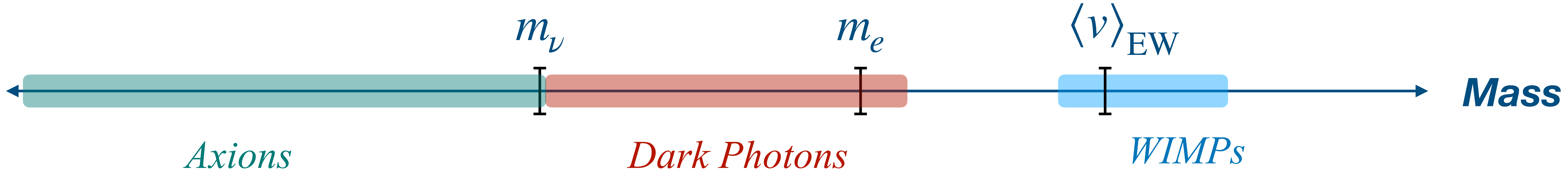
Overview of lecture 1

- What sort of fundamental physics will we discuss? How do we traditionally attempt to search for these particles (needed to contextualize complementarity of astro searches)?



Mass small relative to fundamental scales (Temp, plasma frequency, etc)

Wave-like limit (Coherence)

Mass/Energy greatest scale in problem (Dark matter limited)

Particle-like limit

- What do compact astrophysical objects offer in the search for these particles? Which objects are we interested in?

- The Sun as a first example

- *Lectures 2-4: will focus on selected topics related to neutron stars, black holes, etc*

General properties of axions

Motivation: *Strong CP problem, simple dark matter production mechanism, string axiverse, etc*

$$\mathscr{L} \supset \quad \text{(Dim-5)} \quad \frac{a}{f_a} G_{\mu\nu} \tilde{G}^{\mu\nu} \, , \quad \frac{a}{f_a} \underbrace{F_{\mu\nu} \tilde{F}^{\mu\nu}}_{\vec{E} \cdot \vec{B}} \, , \quad \frac{1}{f_a} \partial_\mu a \bar{\psi} \gamma^\mu \gamma^5 \psi \, , \quad \frac{m_\psi}{f_a^2} a^2 \bar{\psi} \psi + \cdots$$

$$\propto m_\psi \, a \bar{\psi} \gamma^5 \psi$$

*(*QCD axion only*)* *(spin density coupling)* *Mass Shifts*

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$\propto m_\psi \, a \bar{\psi} \gamma^5 \psi$

*(*QCD axion only*)*

(spin density coupling)

Mass Shifts

(Dim-6)

$$\frac{a^2}{f_a^2} F_{\mu\nu} F^{\mu\nu} \;, \quad \frac{a}{f_a m_\psi} F_{\mu\nu} i \bar{\psi} \sigma^{\mu\nu} \gamma^5 \psi \; + \cdots$$

*(*CP violating*)* $m_\psi \dfrac{a}{f_a} \bar{\psi} \psi$

Effective axion mass / shift in fine structure

Neutron EDM

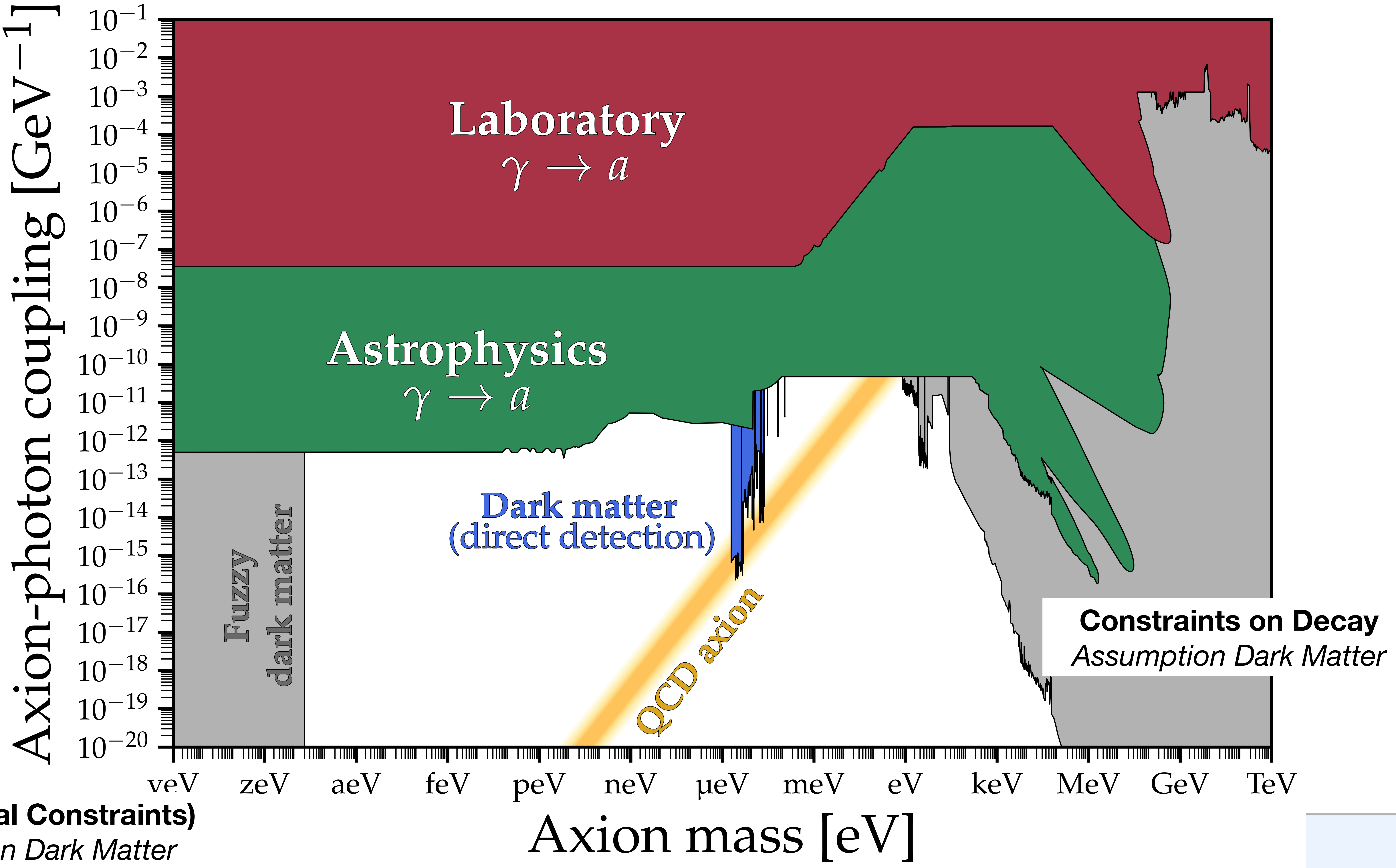
5th forces

Aspects of axion detection

To the blackboard

Intro to axion electrodynamics

Status of axion searches



O'hare Github

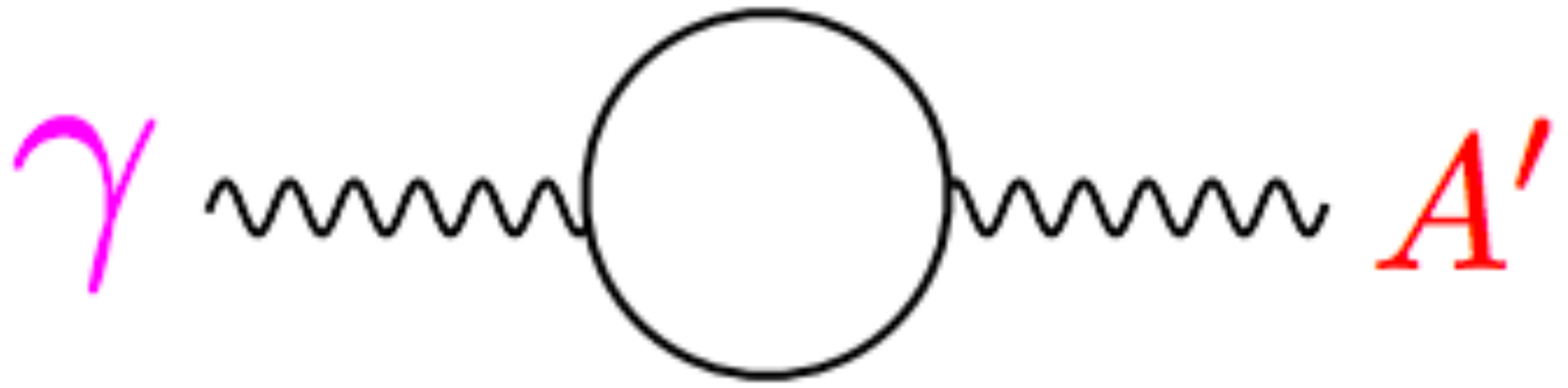
(Gravitaional Constraints)
Assumption Dark Matter

General properties of dark photons

Motivation: *General & minimal extension of SM*

New U(1) with gauge field A'_μ and mass $m_{\gamma'}$ (either Higgsed or Stuckelberg)

$$\mathscr{L} = \underbrace{-\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + J^{\mu}A_{\mu}}_{\text{E\&M}} \underbrace{- \frac{1}{4}F'_{\mu\nu}F'^{\mu\nu} + \frac{m_{\gamma'}^2}{2}A'_{\mu}A'^{\mu}}_{\text{Dark (Massive) E\&M}} \underset{\text{Mixing term}}{\underline{- \frac{\chi}{2}F_{\mu\nu}F'^{\mu\nu}}}$$



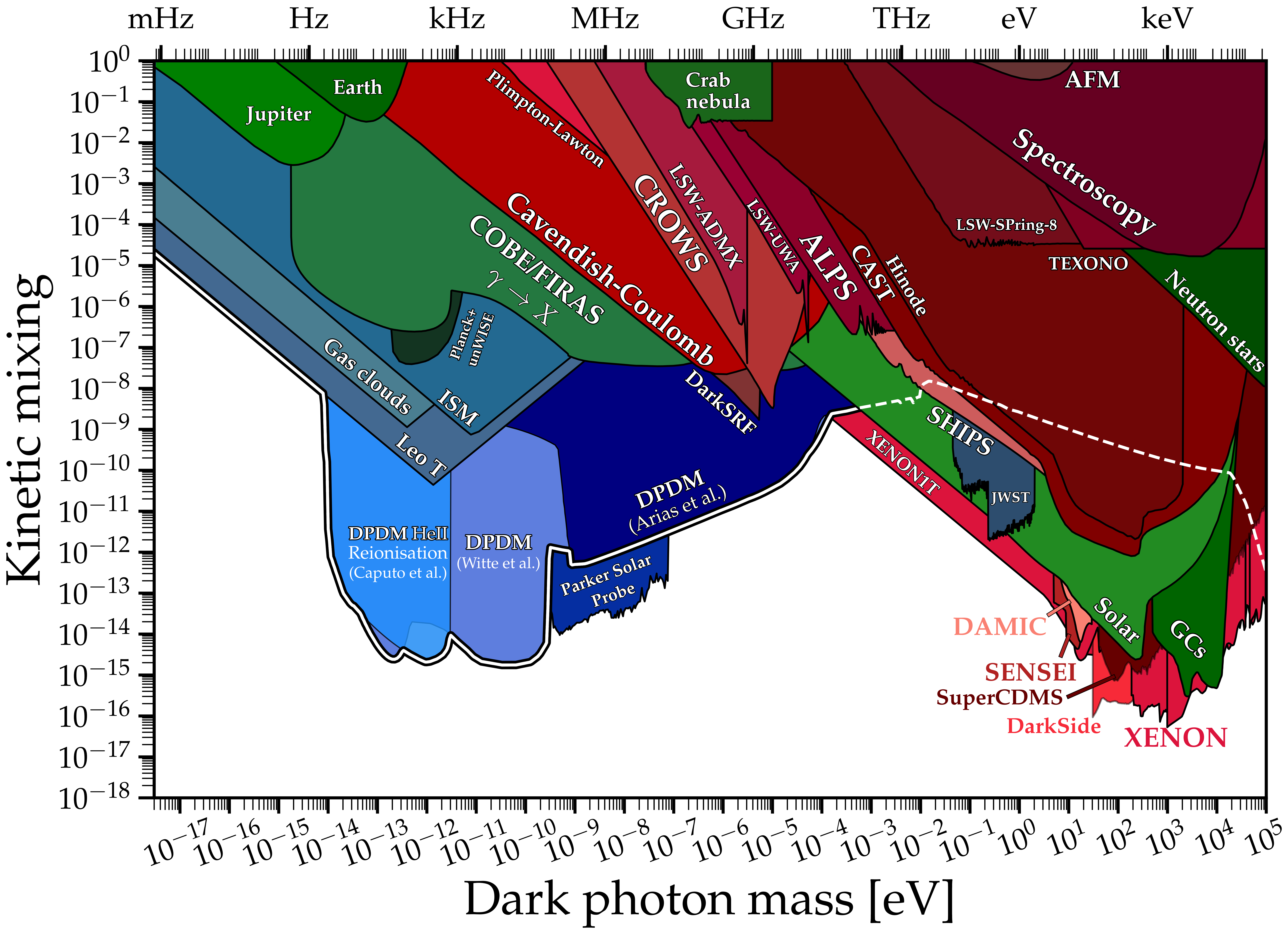
$$\chi \sim \frac{e g_D}{16\pi^2} \sim \mathcal{O}(10^{-3}) g_D$$

Aspects of dark photon detection

To the blackboard

Quick intro to dark photon electrodynamics

Status of dark photon searches



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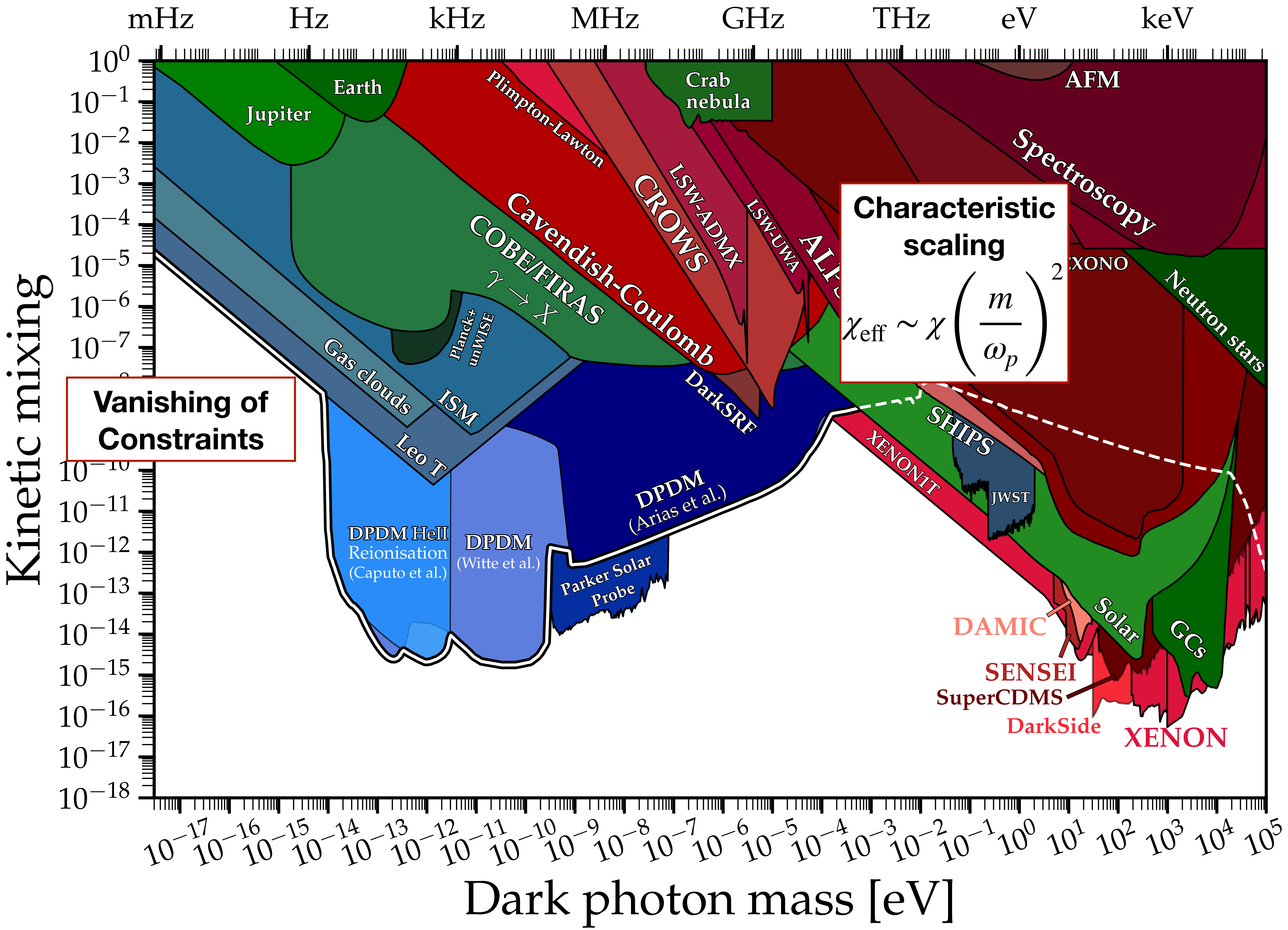

Vanishing of Constraints

Characteristic scaling

$$\chi_{\rm eff} \sim \chi \left(\frac{m}{\omega_p} \right)^2$$

WIMPs

Motivation: *New physics @ EW scale (heirarchy problem), simple thermal dark matter*

<u>*Traditional definition:*</u>

- Interactions mediated by Z/H
- Produced via thermal freeze-out

$m_\chi \lesssim \mathcal{O}(100\,\mathrm{TeV})$ (Unitarity $\langle \sigma v \rangle \sim g^2/m_{\mathrm{DM}}^2$)

$m_\chi \gtrsim \mathcal{O}(\mathrm{GeV})$ (Lee-Weinberg bound $\sigma \sim m^2/M^4$)

(ways to evade...)

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<u>Modern (2000s) definition often slightly looser:</u>

- Interactions mediated by new particle

$m_\chi \gtrsim \mathcal{O}(\mathrm{MeV})$ (BBN)

Free parameters: dark matter mass m_χ, mediator mass $m_{Z'}$, dark matter coupling g_χ, SM coupling g_{SM}

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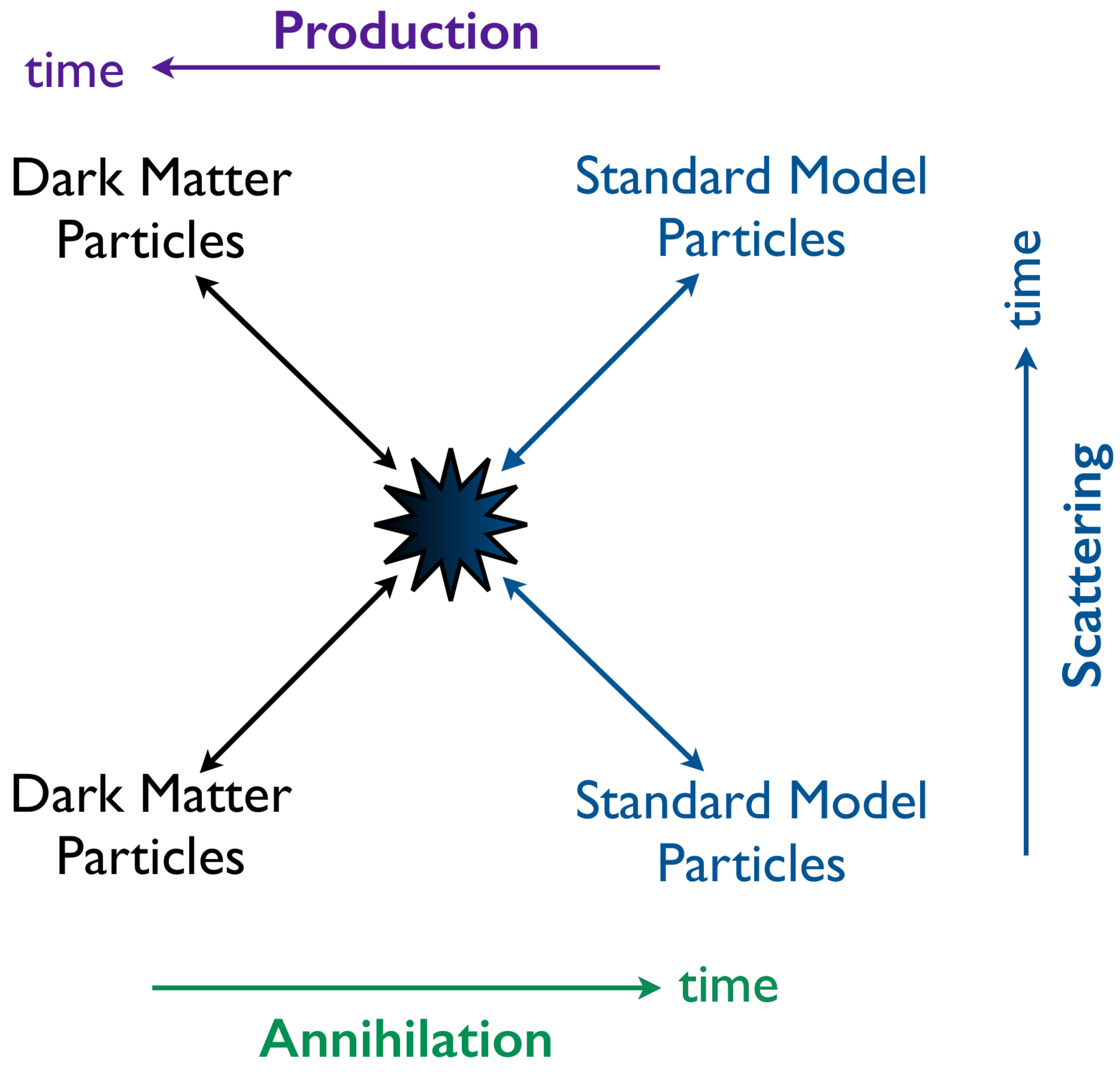


Free parameters: dark matter mass m_χ, mediator mass $m_{Z'}$, dark matter coupling g_χ, SM coupling g_{SM}

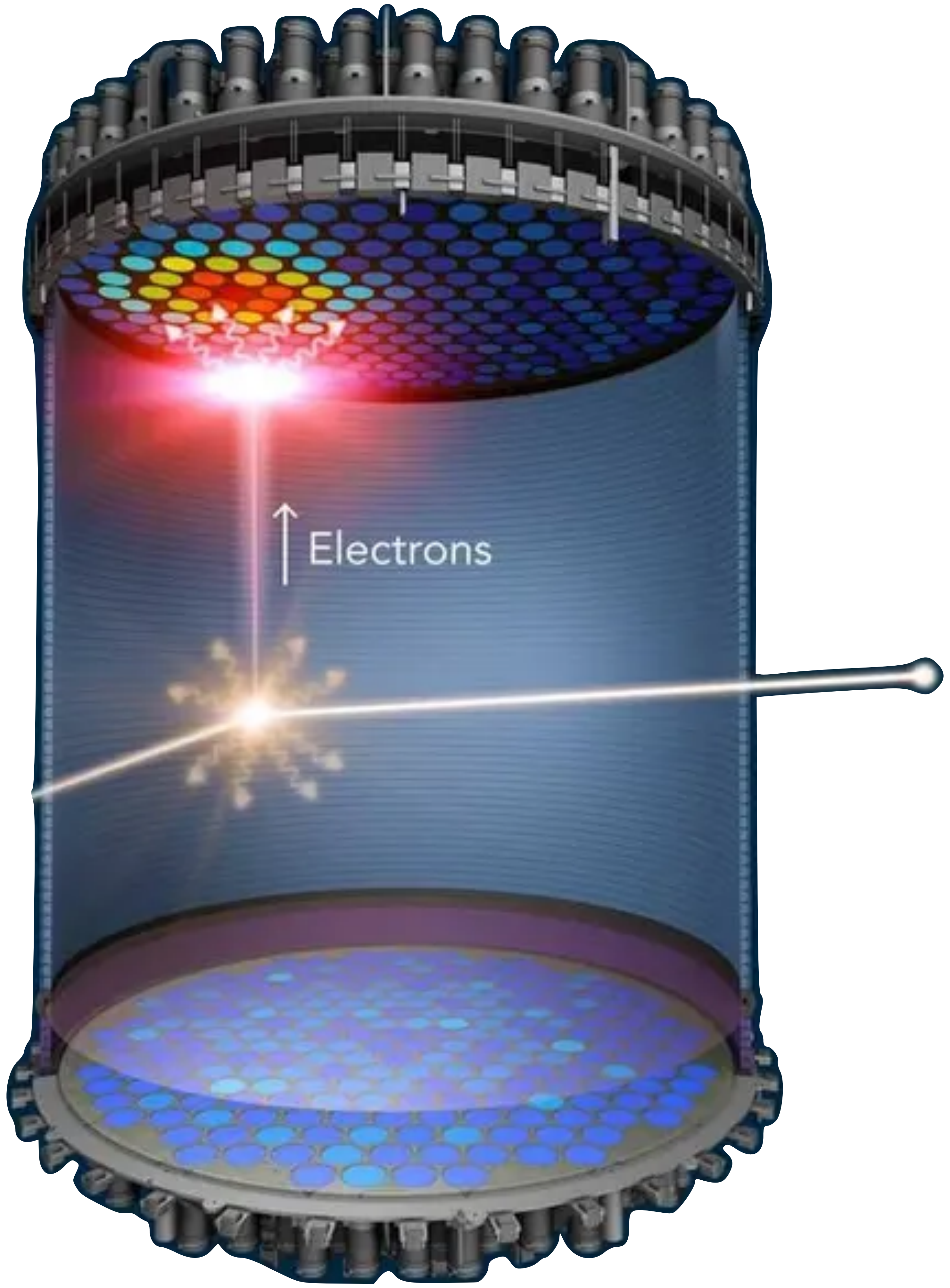
Thermal production mechanism fixes $g_\chi \times g_{\mathrm{SM}}$ for any set of masses

WIMP direct detection

- Direct detection probes product of coupling $(g_\chi g_q)^2$

Can couple to nucleon ***number*** $\sigma \propto A^2$ *or* ***spin*** $\sigma \propto \langle S_N \rangle^2$

$$\sigma_N \propto \left(\frac{q}{\mu_r}\right)^{2n} v_\perp^{2m} \qquad n, m \in \text{Integers}$$



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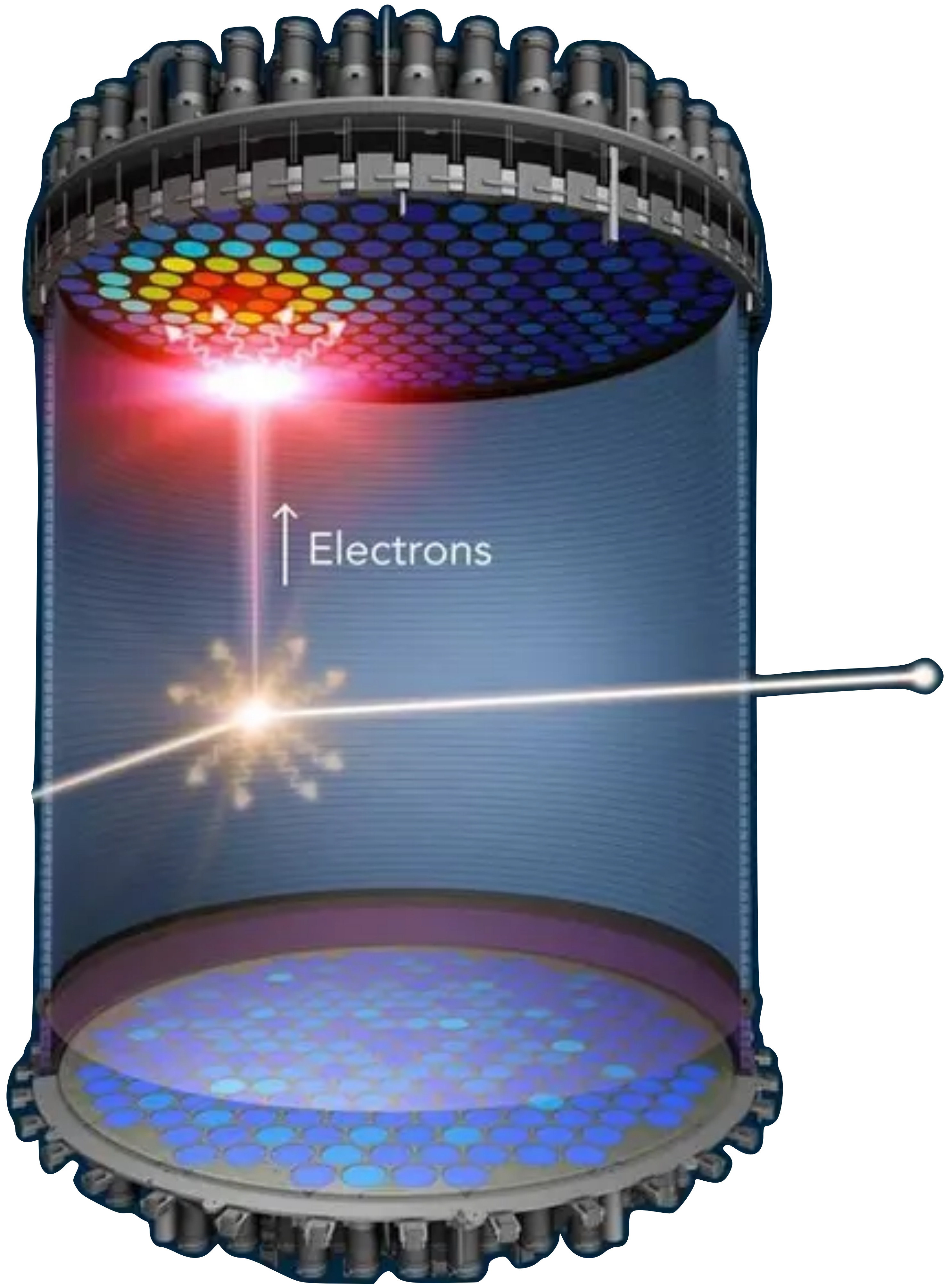
$$\sigma_N \propto \left(\frac{q}{\mu_r}\right)^{2n} v_\perp^{2m} \qquad n, m \in \text{Integers}$$

$$L_{\text{eff}} \sim \bar{\chi}\chi\, \bar{q}q \qquad\qquad L_{\text{eff}} \sim \bar{\chi}\gamma^\mu\gamma^5\chi\, \bar{q}\gamma_\mu\gamma^5 q$$

$$\sigma_{N,SI} \propto A^2 \qquad\qquad \sigma_{N,SI} \propto A^2 q^2 v_\perp^2$$

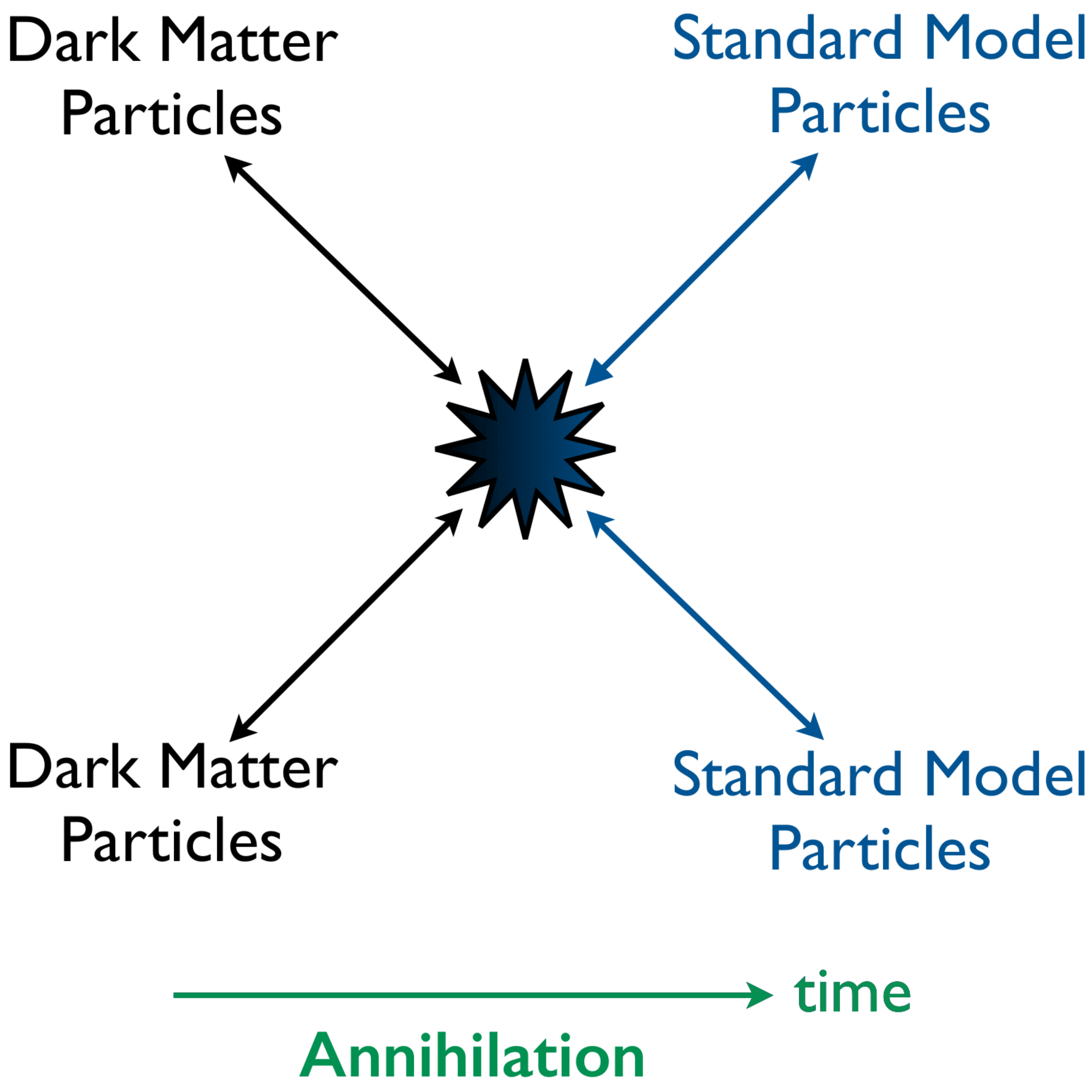
12 orders of magnitude difference in scattering cross section



WIMP indirect detection

- Annihilation cross section $\langle \sigma v \rangle_{fo} \sim 2 \times 10^{-26} \mathrm{cm}^3/\mathrm{s}$

Constraints on $\langle \sigma v \rangle_{\text{today}} \lesssim 2 \times 10^{-26}\, \mathrm{cm}^3/\mathrm{s}$ @ $m_\chi \lesssim \mathcal{O}(100\, \mathrm{GeV})$



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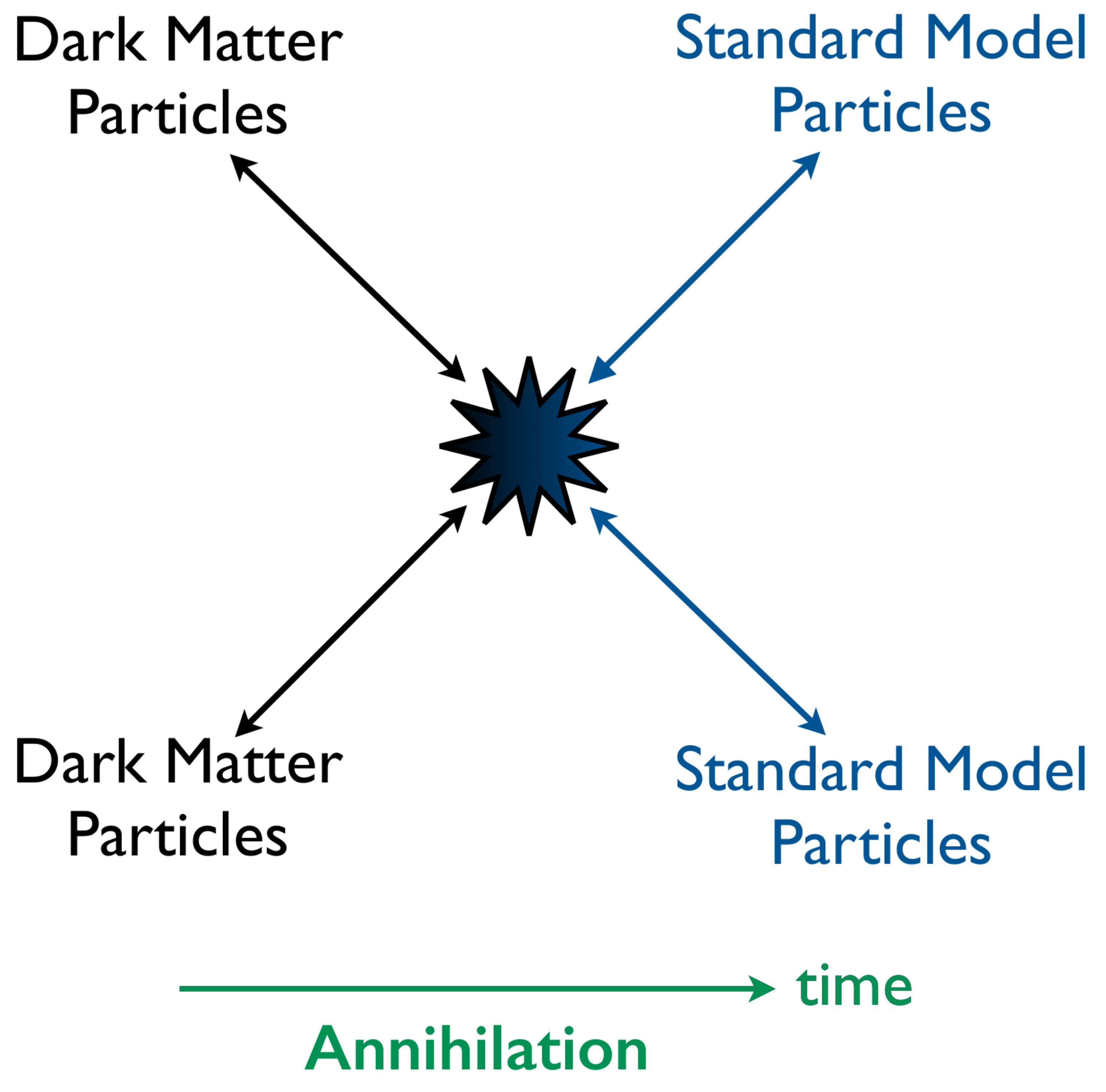
$$\langle \sigma v \rangle_{fo} \neq \langle \sigma v \rangle_{\mathrm{today}}$$

$$\langle \sigma v \rangle \sim \sum_L \sigma_i \, v^{2L}$$

Partial wave expansion with inital orbital ang. mom L

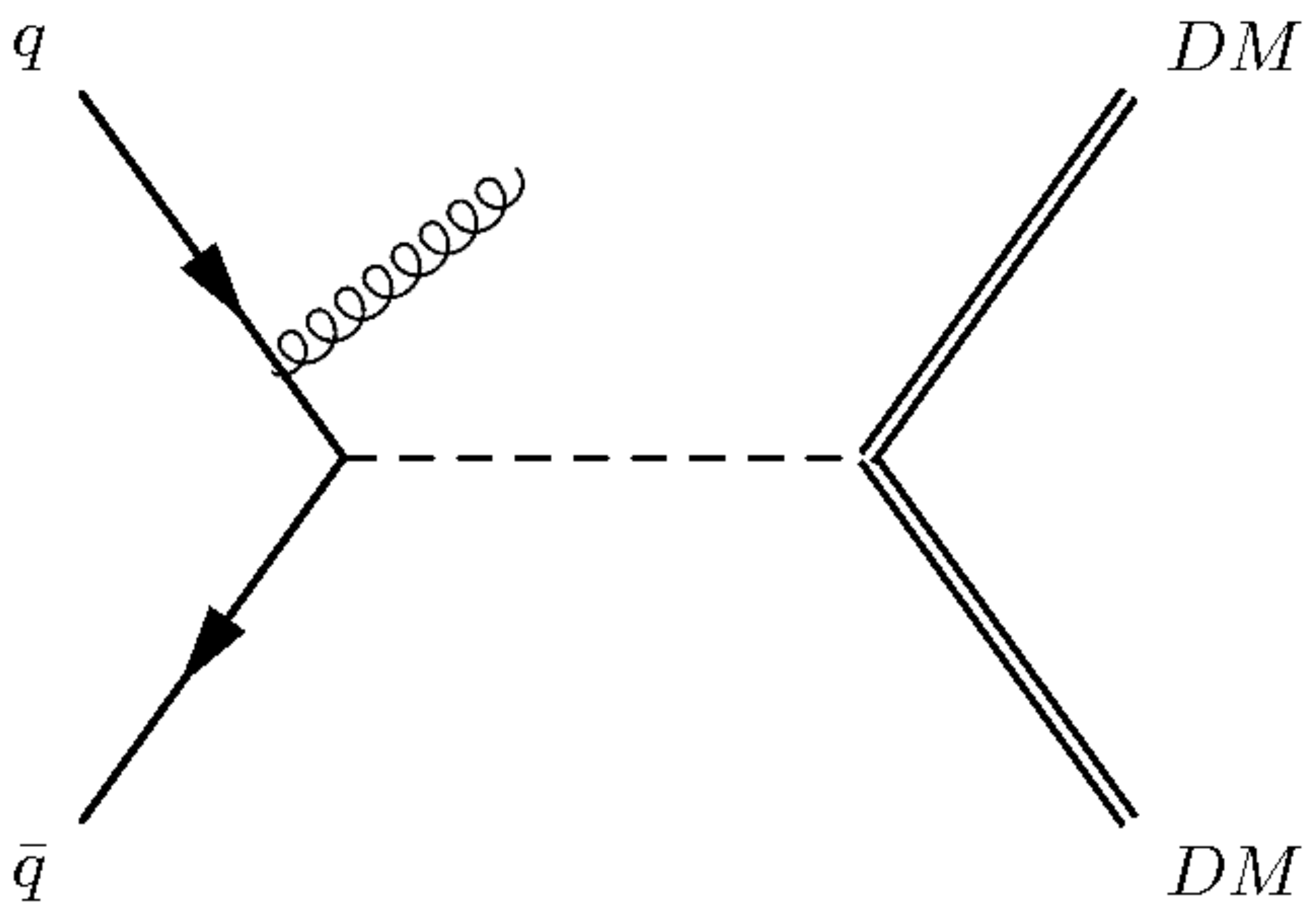
Vanishing s-wave contribution has large implications

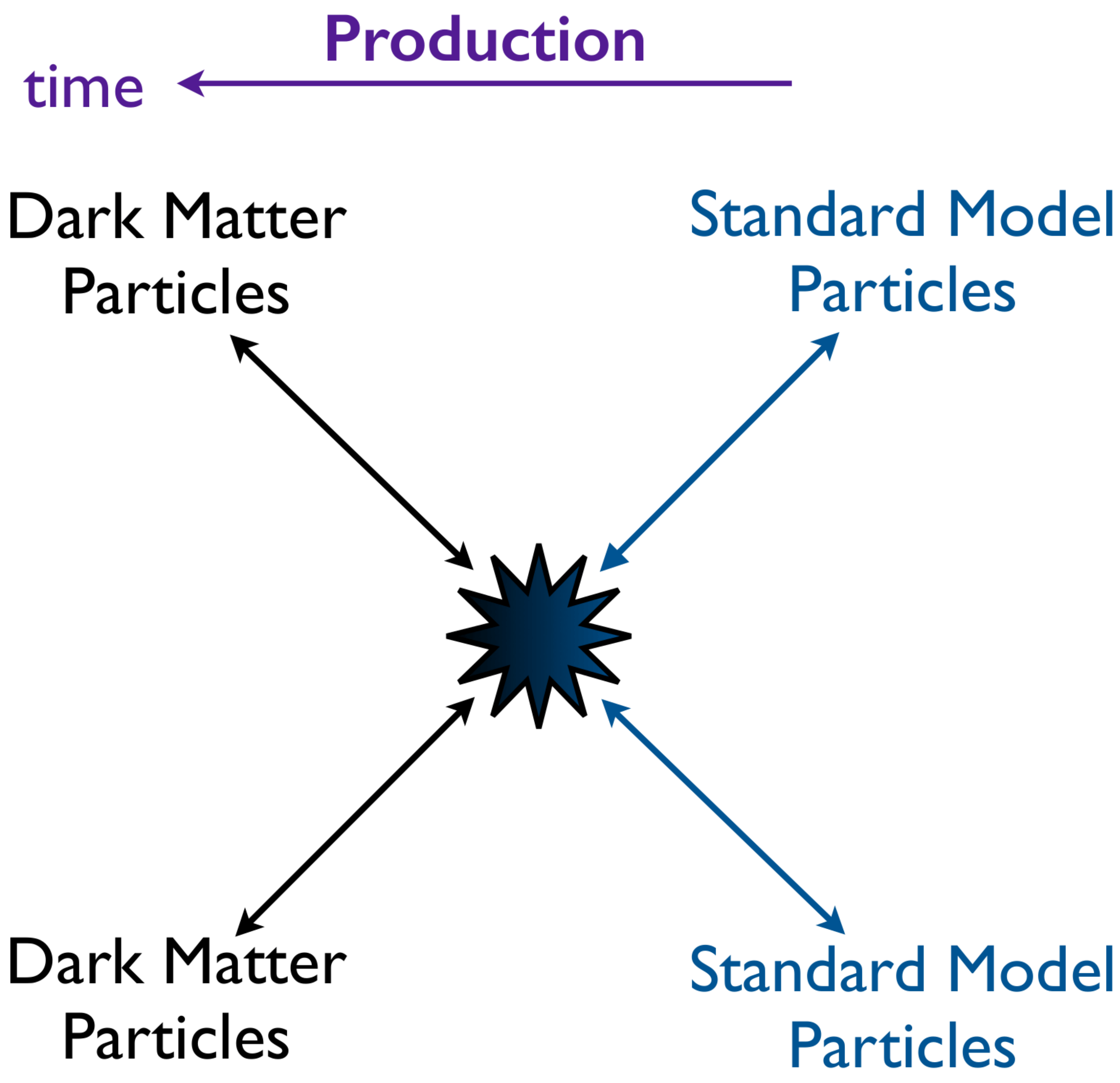
(Can also play with asymmetry in the dark sector…)



WIMP production at colliders

- Colliders typically *most* sensitive to the mediator-SM coupling





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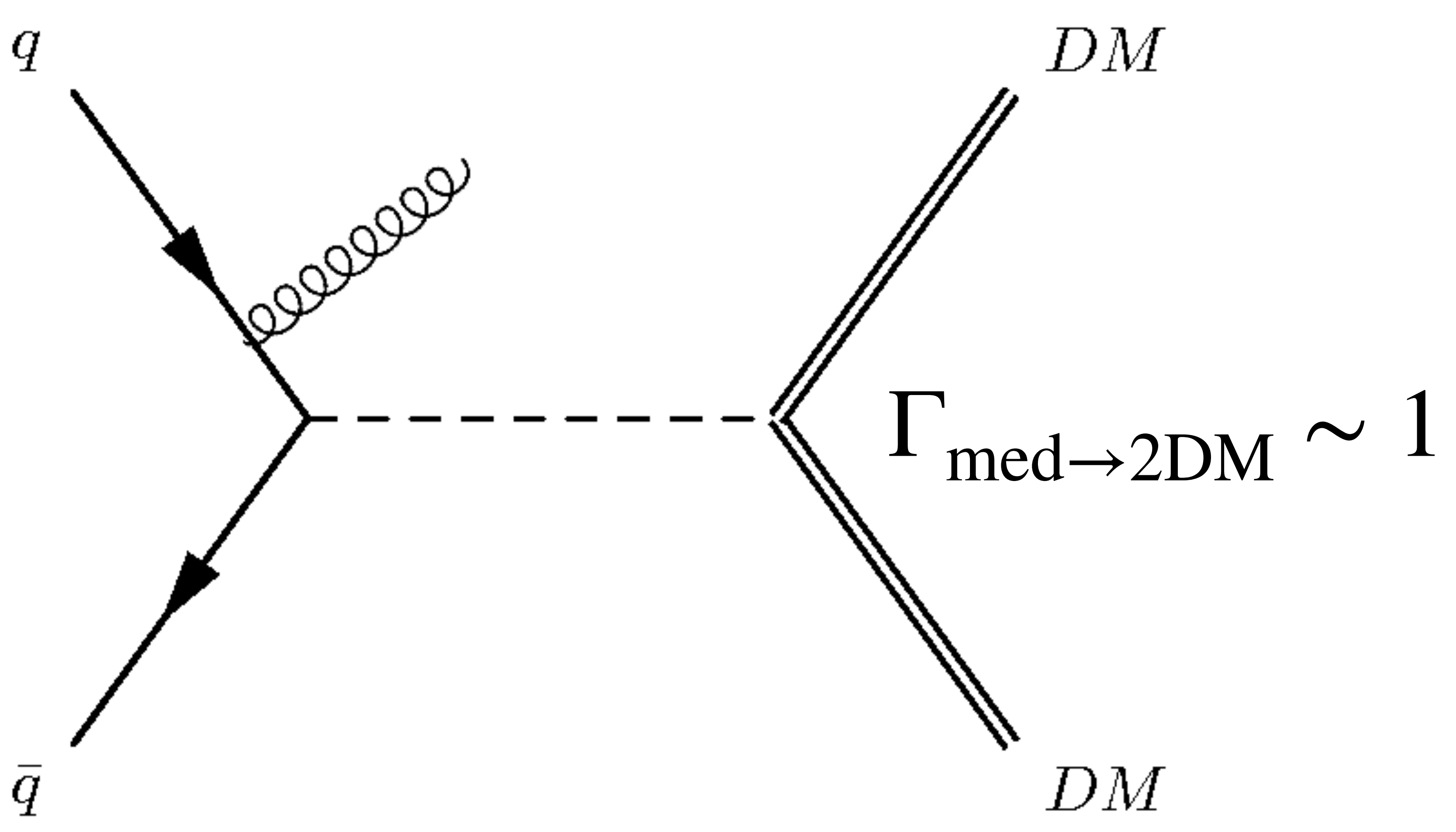
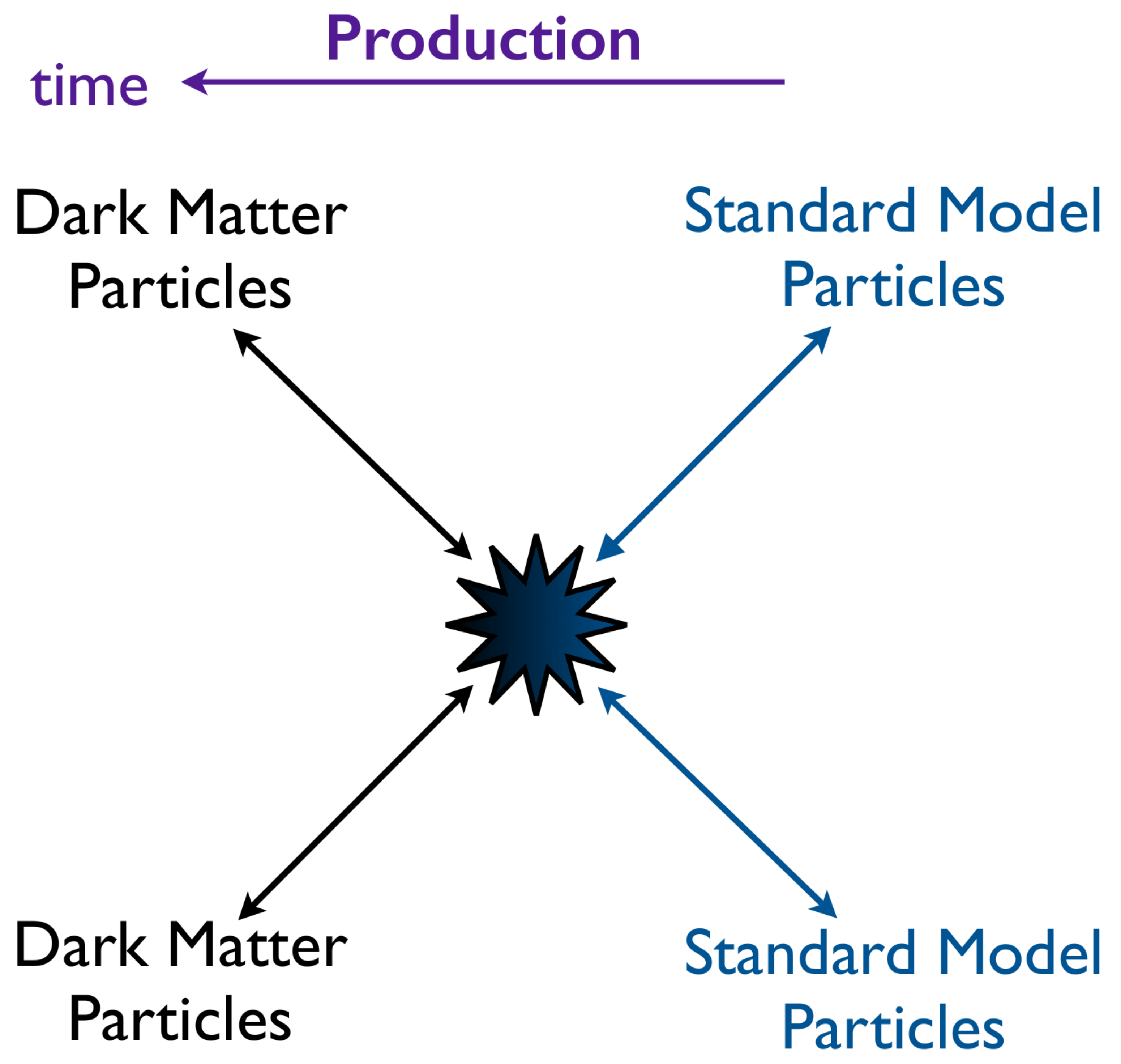


$m_{\mathrm{med}} \gg 2m_{\mathrm{DM}}$ $\quad$ $g_{\mathrm{DM}}/g_{\mathrm{SM}} \gg 1$

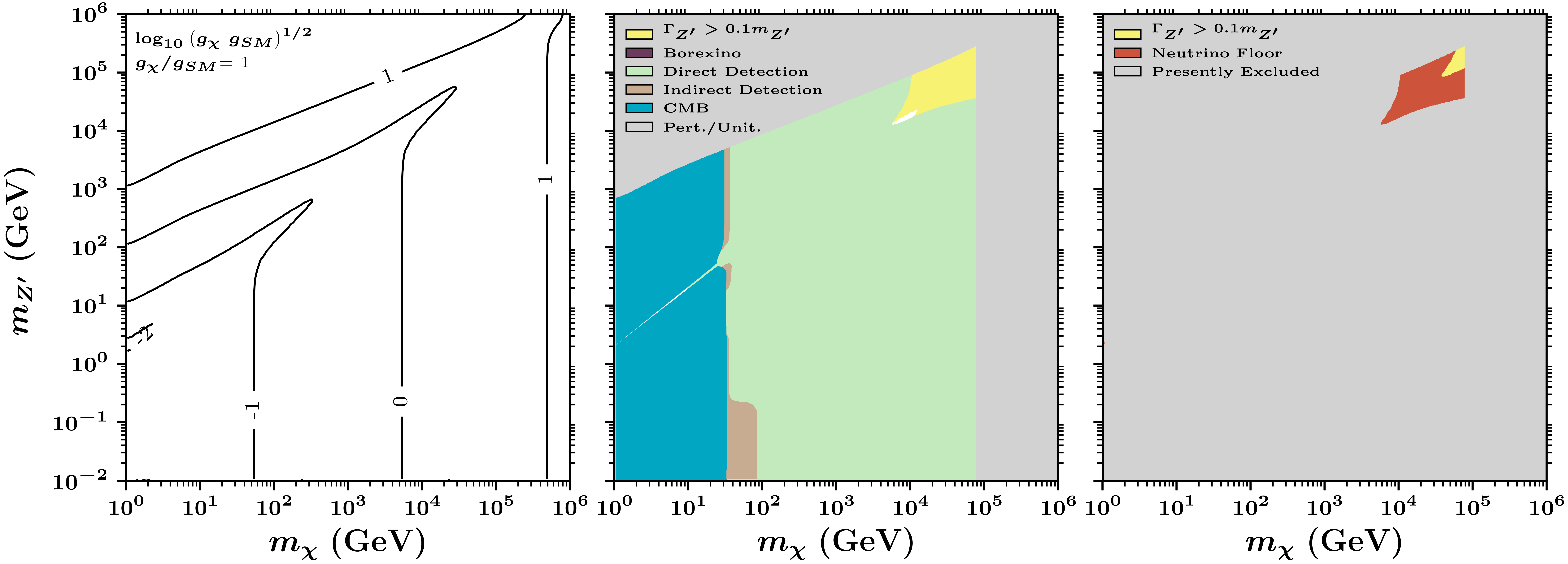


Small SM couplings means mediator never produced

Status of WIMP searches (as of 2018)

Dirac fermion coupled to universally to SM

Free parameters: dark matter mass m_χ, mediator mass $m_{Z'}$, dark matter coupling g_χ, SM coupling g_{SM}



Blanco, Escudero, Hooper, SJW (2018)

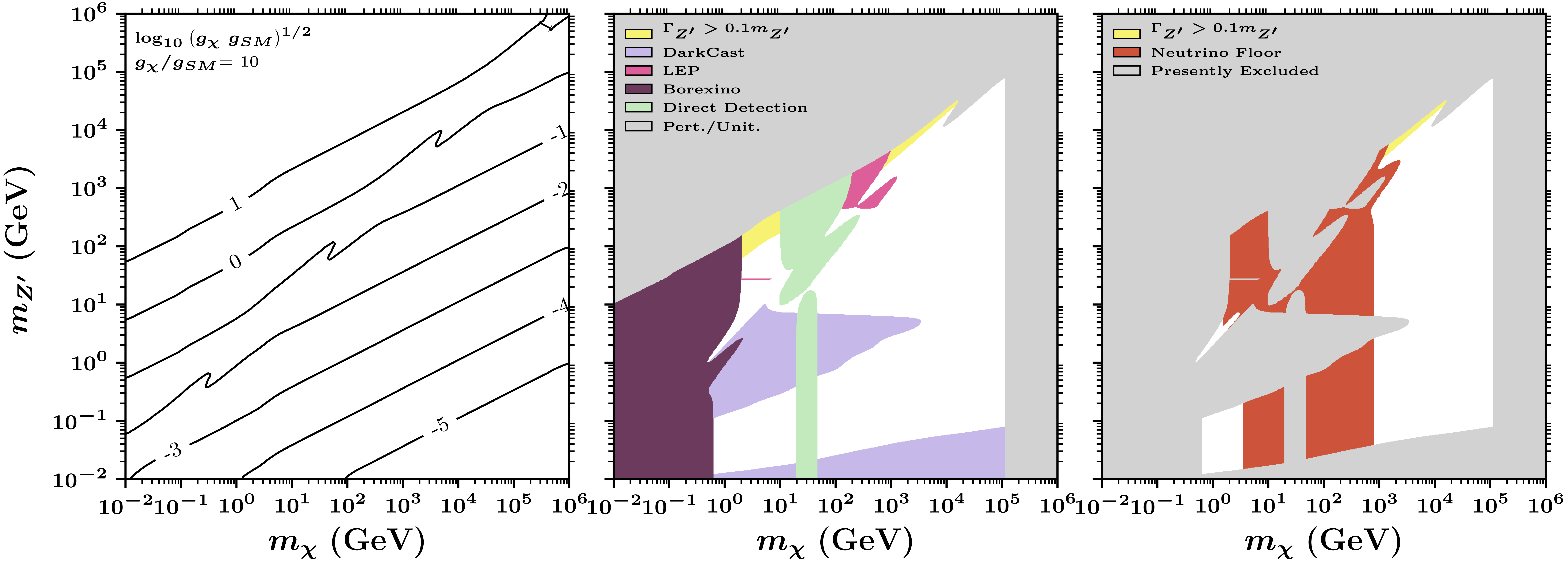
See also e.g. Escudero et al (2016), Arcadi et al (2024)

Status of WIMP searches (as of 2018)

Majorana fermion coupled to all SM leptons

$\mathscr{L} \supset g' q_\chi Z'_\mu \bar{\chi}\gamma^\mu\gamma_5\chi$

[p-wave, q^2 supressed]

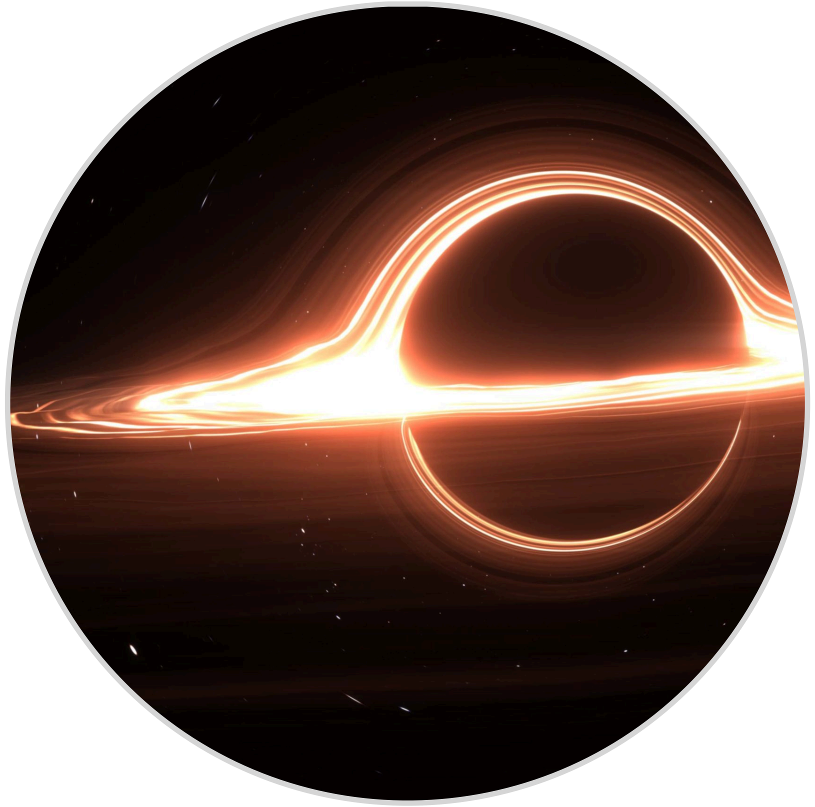


Why astrophysical objects?

Nature has already given us the most extrodinary laboratories…

Strong electromagnetic fields

High densities



Strong gravity

High temperatures /
Low temperatures

Different baselines

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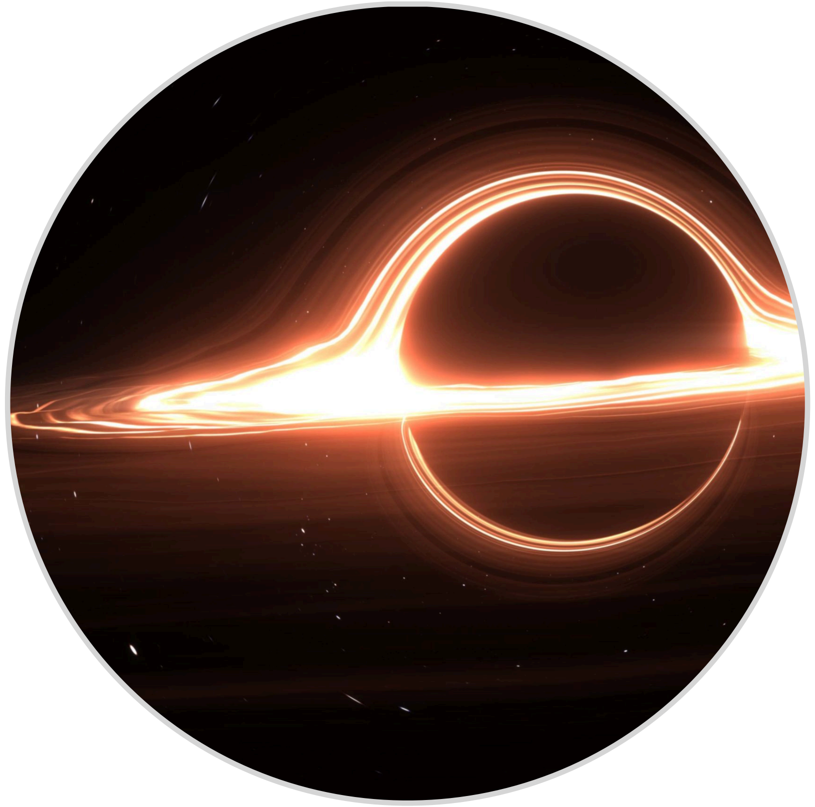

Strong gravity

High temperatures /
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Different baselines

E.g. Axion @ Earth ≠ Axions @ compact object

Relevant questions to be asking…

- **For a given object, what makes it particularly special?**

  Informs what physics you search for and what physics must be included…

- **How do we identify meaningful observables?**

  Intrinsic trade-off between robustness and precision

- **How are these probes complementary to other searches?**

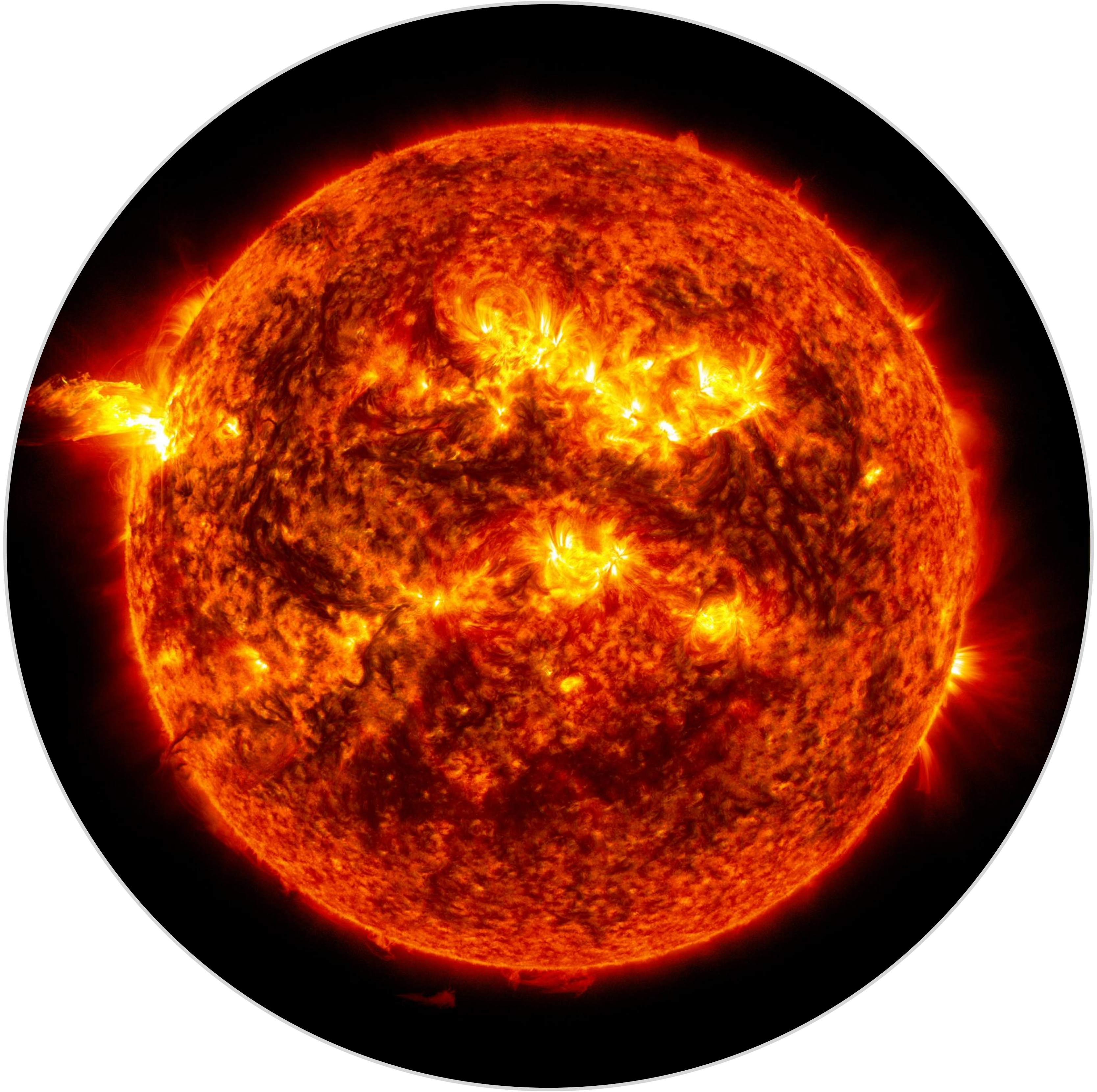
  Different underlying assumptions, expediate laboratory searches, extract secondary information, …

The Sun as an example

Why?

It's close to Earth

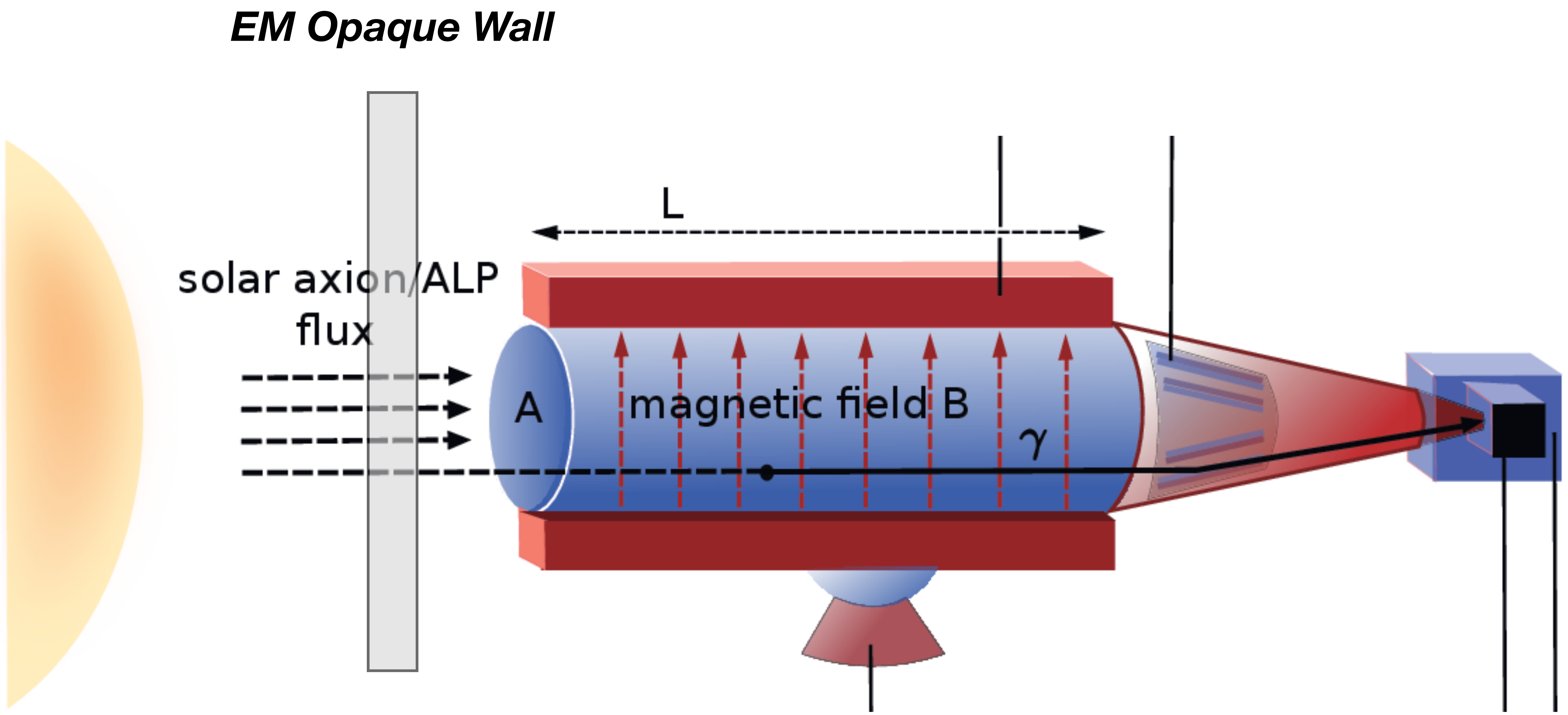
It's relatively mundane
(low systematics)



The Sun as an example: Axions

What makes the Sun special?

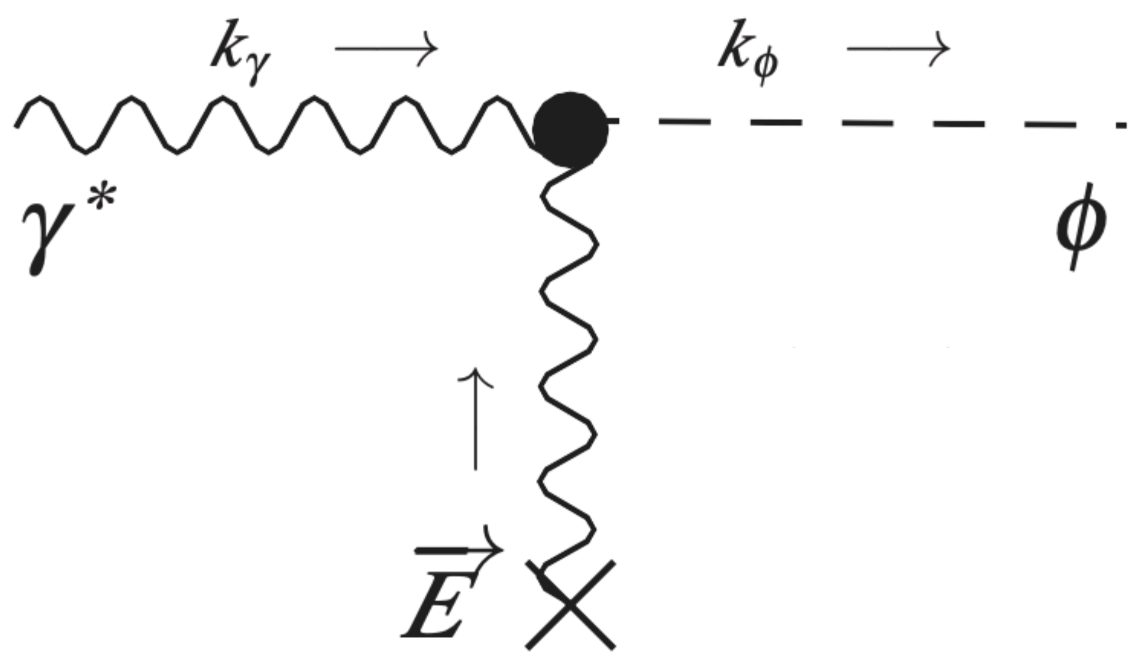
Large, hot-ish nearby thermal bath



The Sun as an example: Axions

How are axions produced in the Sun?

Primakoff



$$\boxed{\gamma + (Ze) \to (Ze) + a}$$

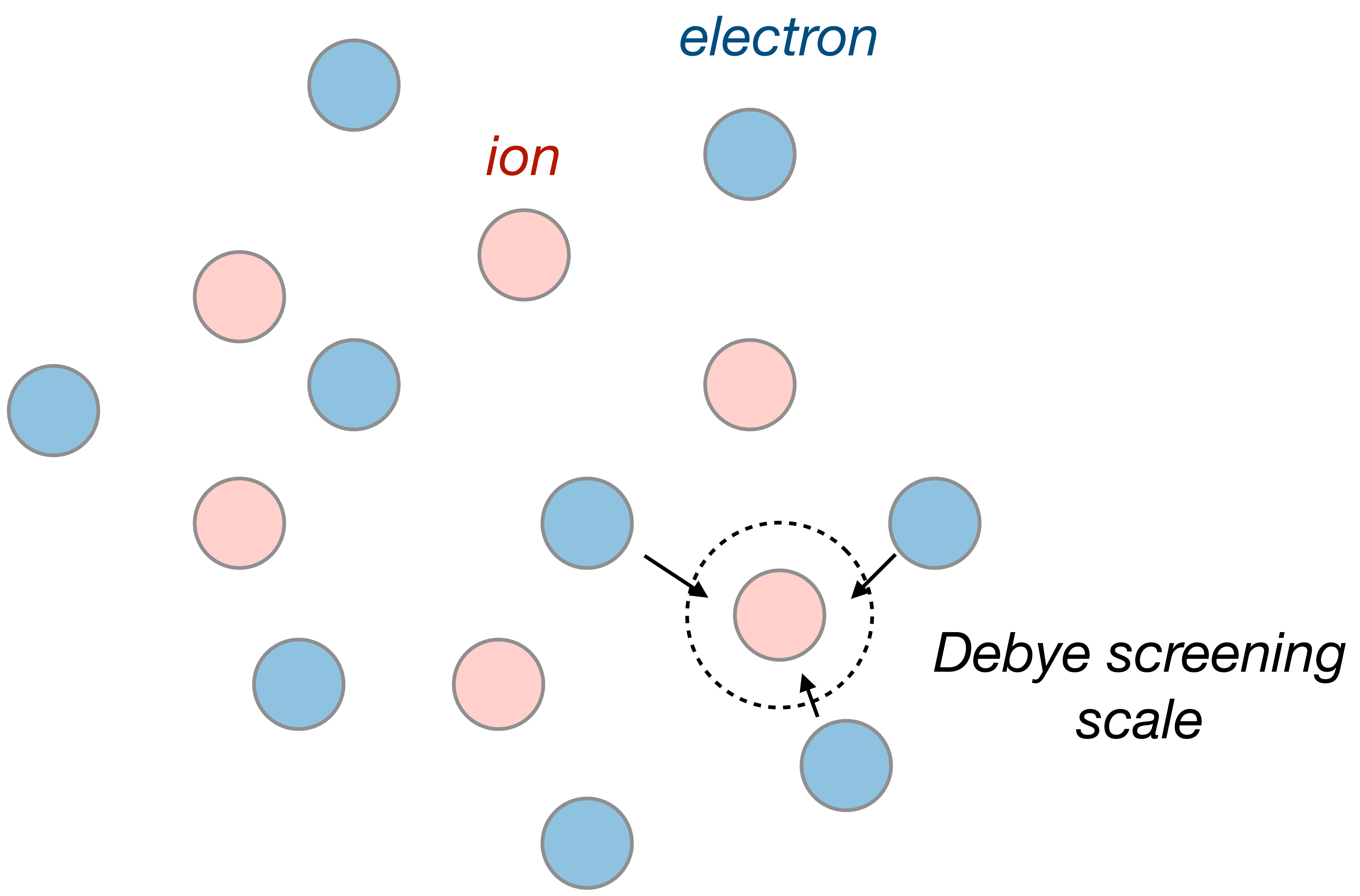
$$L_a \sim \int dV \int d^3k\, \omega_\gamma\, f_\gamma(\omega_\gamma) \sum_{i \in \text{species}} (g_{a\gamma} Z_i e)^2\, n_i\, K(k)\, D(k)$$

Bose-Einstein Distribution

Coupling

Kinematic factors (T)

Screening



See e.g. Raffelt (1988), Review 2401.13728

The Sun as an example: Axions

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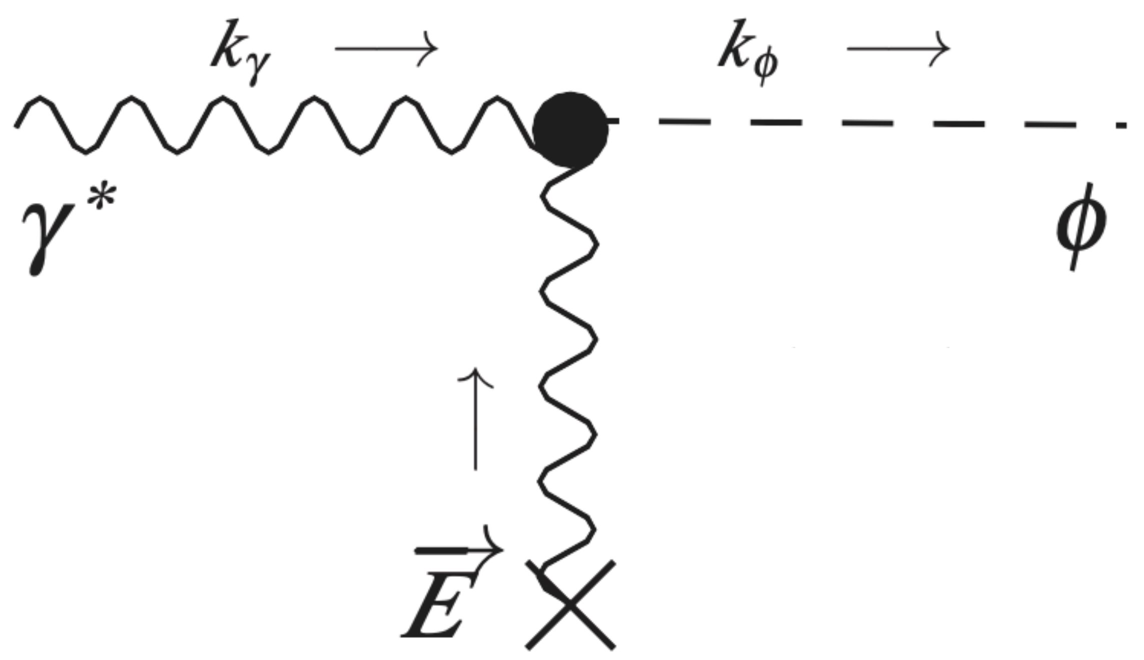

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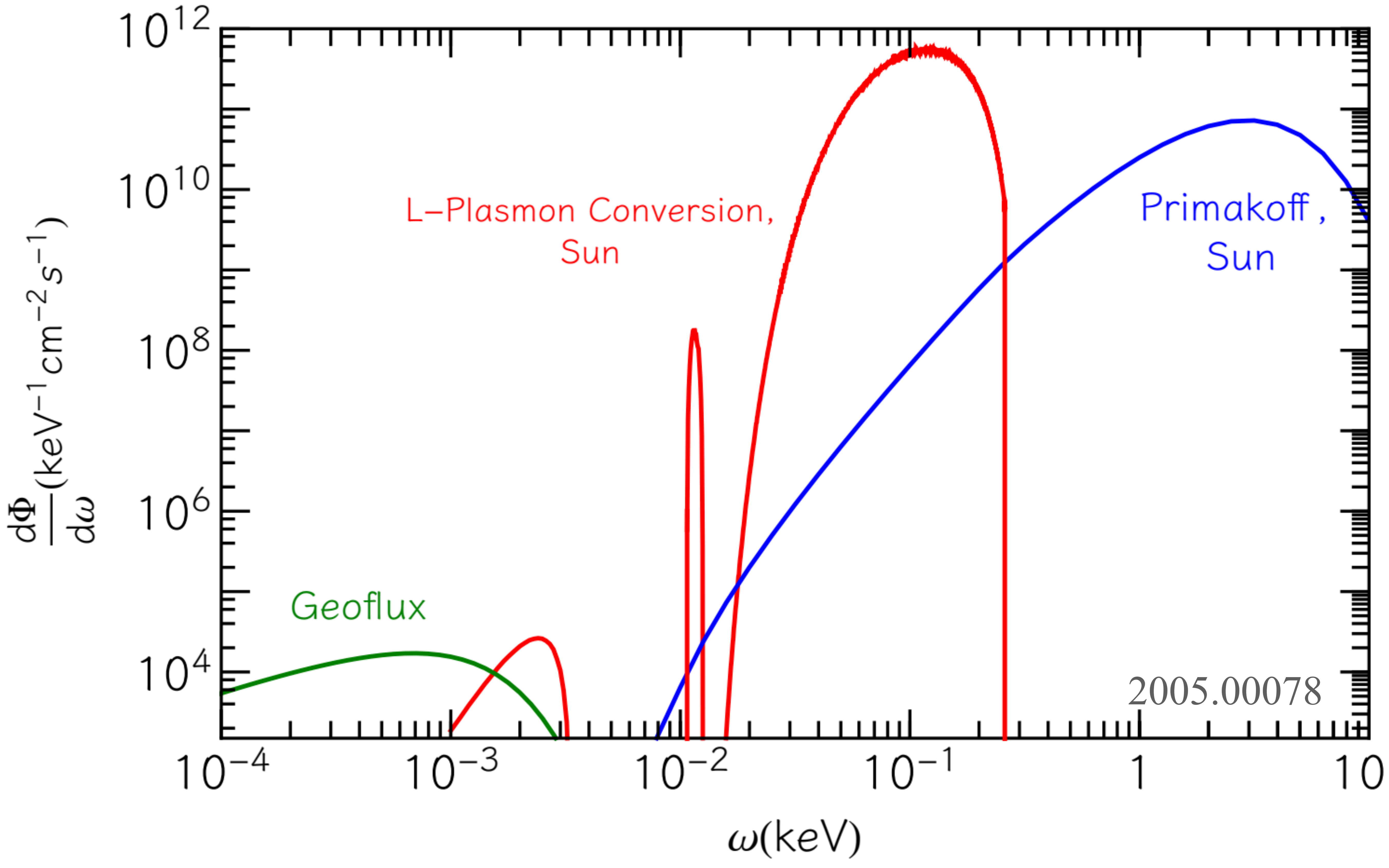

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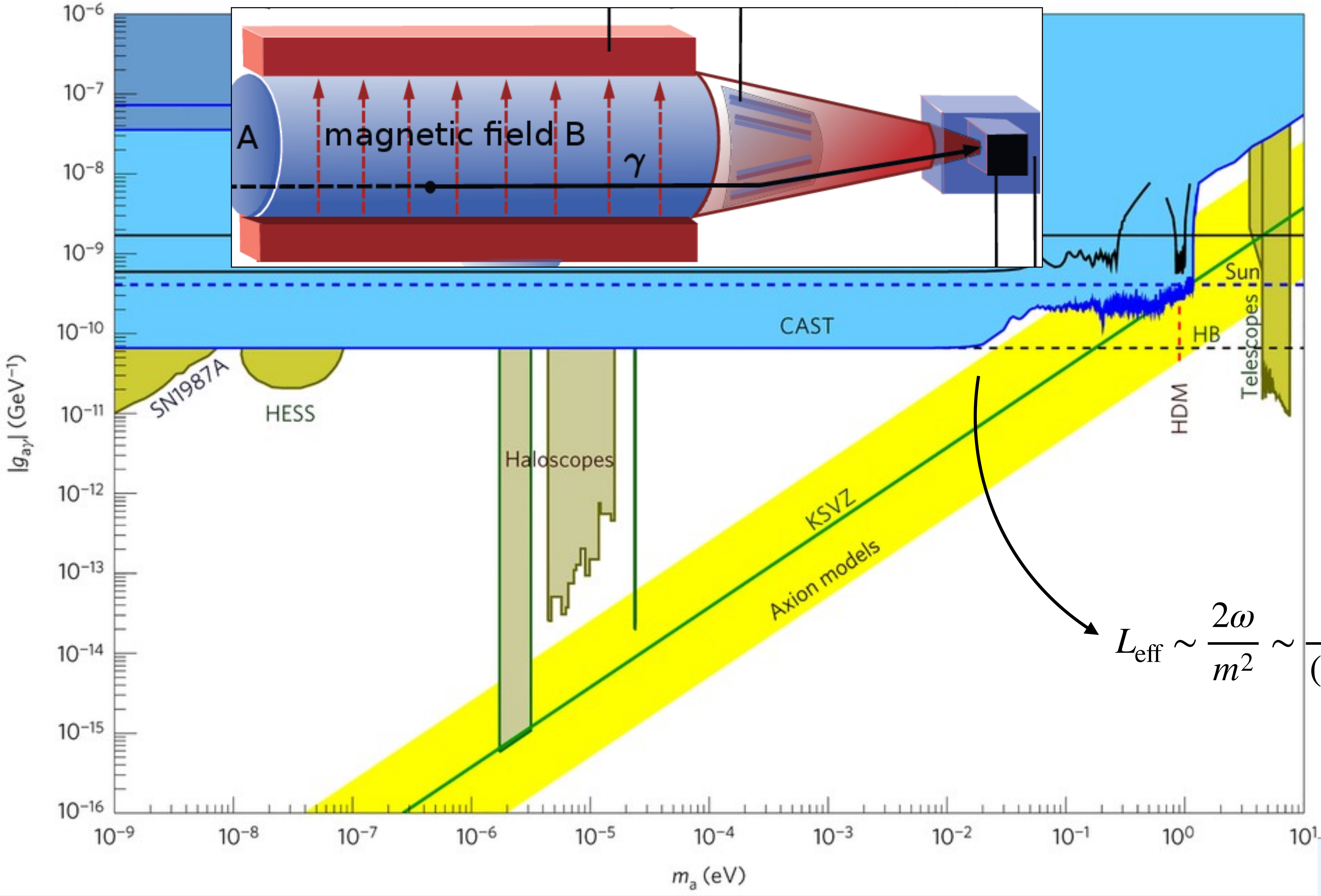
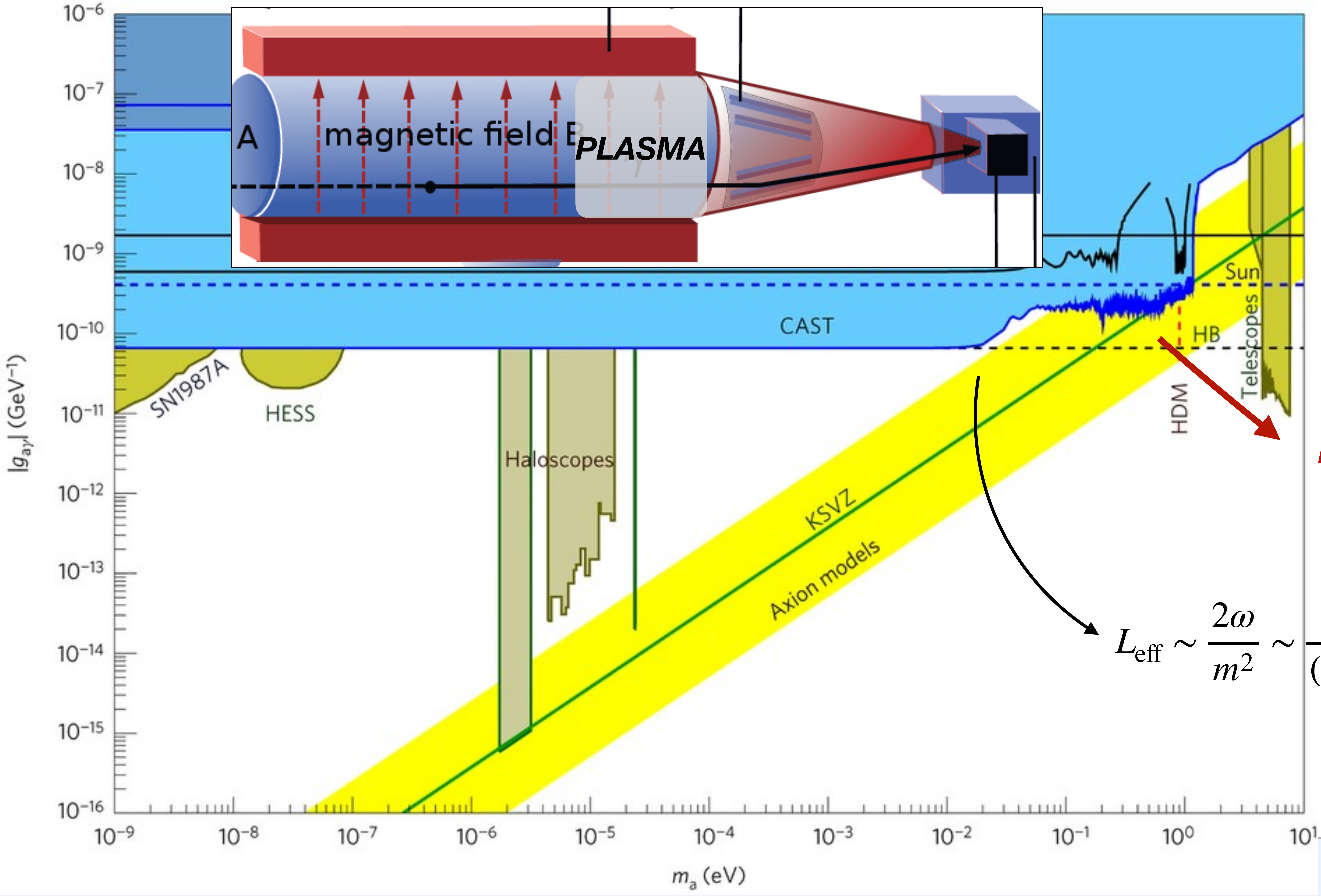
The Sun as an example: Axions



$$L_{\text{eff}} \sim \frac{2\omega}{m^2} \sim \frac{\text{keV}}{(10^{-2}\,\text{eV})^2} \sim \mathcal{O}(\text{m})$$

The Sun as an example: Axions



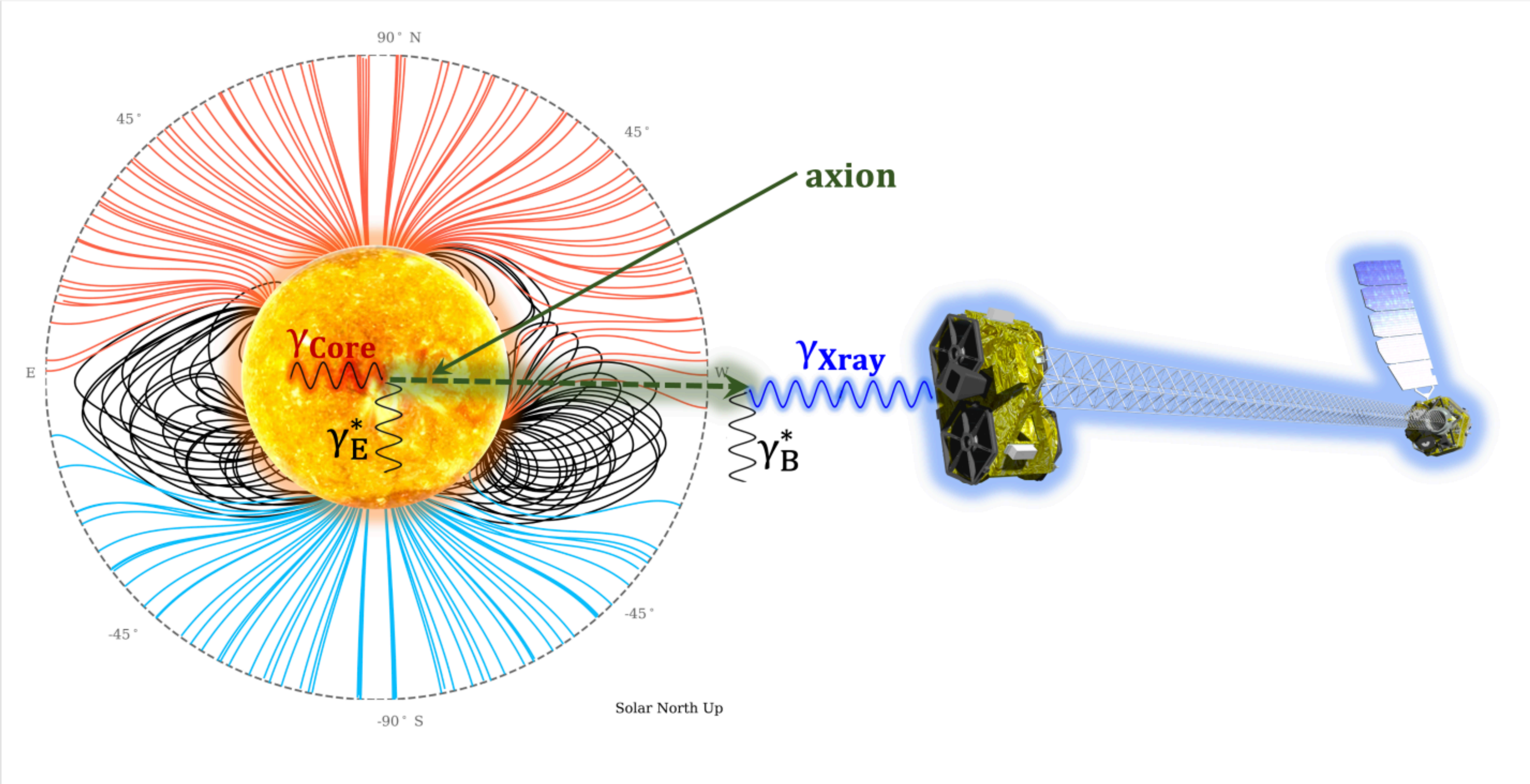
Modify photon dispersion relation in detector

$L_{\rm eff} \sim (k_\gamma - k_a)^{-1}$

$$L_{\rm eff} \sim \frac{2\omega}{m^2} \sim \frac{\rm keV}{(10^{-2}\,{\rm eV})^2} \sim \mathcal{O}({\rm m})$$

The Sun as an example: Axions

Can also try to re-convert using solar magentic fields



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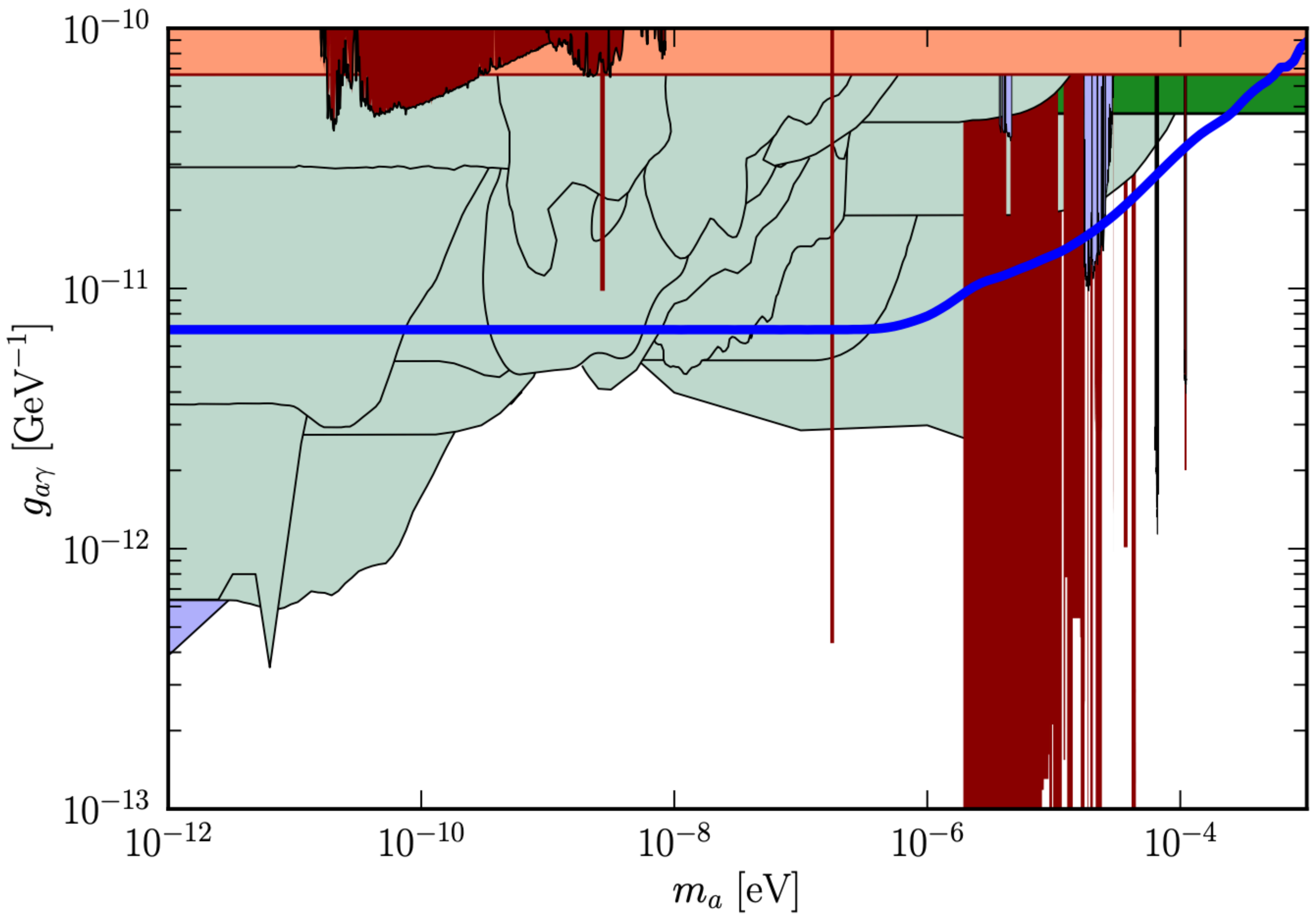
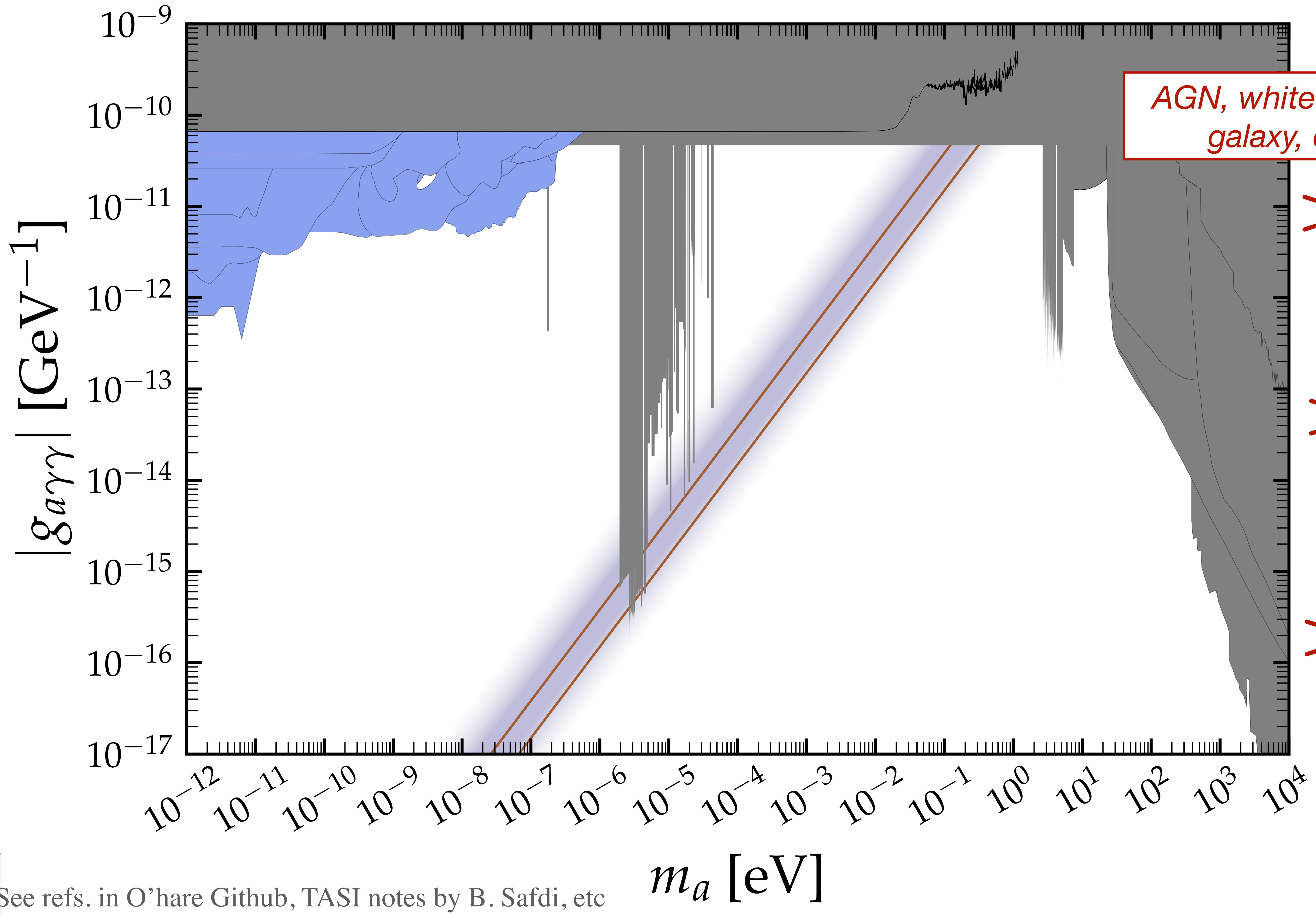
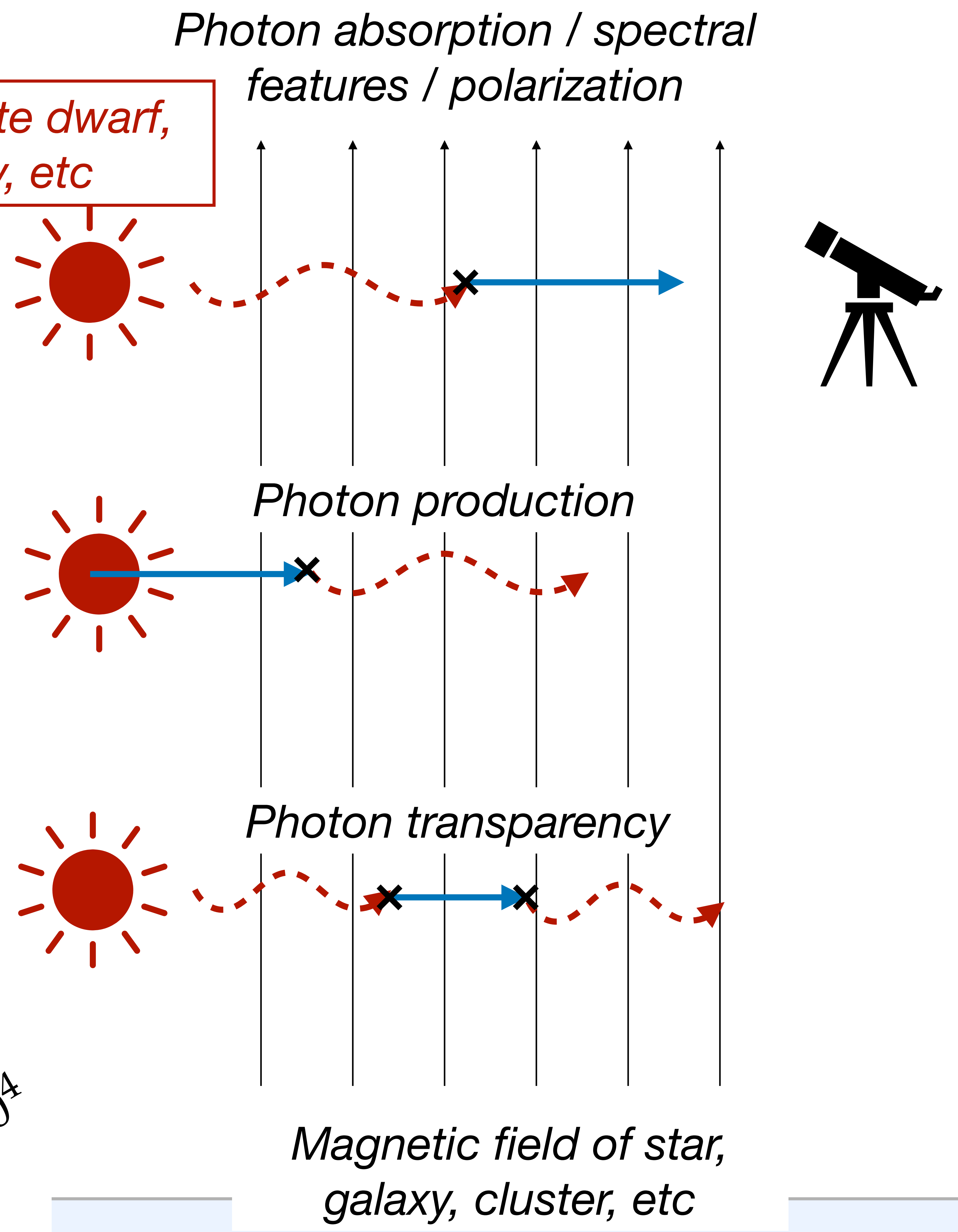


Similar searches using other objects…



AGN, white dwarf, galaxy, etc



See refs. in O'hare Github, TASI notes by B. Safdi, etc

The Sun as an example: Dark Photons

What makes the Sun special?

Large, hot-ish nearby thermal bath

$$\mathscr{L} \supset \frac{1}{2} m_{\gamma'}^2 S^\mu S_\mu - \chi m_{\gamma'}^2 S^\mu A_\mu + J^\mu A_\mu$$

Sterile state *EM Coupled state*

See e.g. 0801.1527 (Redondo), An et al (2013, 2020)

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Sterile state *EM Coupled state*

<u>Coupled Equations of motion</u>

$$(\omega^2 - k^2 - \pi^{\mu\nu})A_\nu + \chi m_{\gamma'}^2 S^\mu = 0$$

Polarization tensor (defines dispersion relation)

ω_p^2 *(Trans.)*

$\omega_p^2 - k^2$ *(Long.)*

$$(\omega^2 - k^2 - m_{\gamma'}^2)S^\mu + \chi m_{\gamma'}^2 A^\mu = 0$$

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The Sun as an example: Dark Photons

Going to mass basis:

$$A_i \to \quad \tilde{A}_i + \chi \frac{m_{\gamma'}^2}{\pi_i - m_{\gamma'}^2} \tilde{S}_i \qquad i = \mathrm{T/L}$$

EM Coupled *Photon* *Dark Photon*

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EM Coupled *Photon* *Dark Photon*

$$L_\chi \sim \int dV \int d^3k \, \omega_\gamma \, f_\gamma(\omega_\gamma) \, \Gamma_i \left(\frac{\chi m_{\gamma'}^2}{\pi_i - m_{\gamma'}^2} \right)^2$$

Bose-Einstein Distribution

Rate

Contribution of dark photon to A

See e.g. 0801.1527 (Redondo), An et al (2013, 2020)

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EM Coupled *Photon* *Dark Photon*

Start from Boltzmann Eqn

$$(\partial_t + v\partial_x)f = \Gamma_E(1+f) - \Gamma_A f = \Gamma_E - (\Gamma_A - \Gamma_E)f$$

$$\equiv \Gamma_A^*$$

$$L_\chi \sim \int dV \int d^3k\, \omega_\gamma\, f_\gamma(\omega_\gamma)\, \Gamma_i \left(\frac{\chi m_{\gamma'}^2}{\pi_i - m_{\gamma'}^2} \right)^2$$

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Start from Boltzmann Eqn

$$(\partial_t + v\partial_x) f = \Gamma_E (1 + f) - \Gamma_A f = \Gamma_E - \underbrace{(\Gamma_A - \Gamma_E)}_{\equiv \Gamma_A^*} f$$

Equilibrium implies RHS = 0

$$\Gamma_A = e^{\omega/T} \, \Gamma_E$$

$$\Gamma \equiv \Gamma_A^* = \Gamma_A (1 - e^{-\omega/T})$$

Consider deviations from Equil.

$$\Delta f = f - f_{\mathrm{eq}}$$

$$(\partial_t + v\partial_x) \Delta f = - \Gamma \Delta f$$

See e.g. 0801.1527 (Redondo), An et al (2013, 2020)

The Sun as an example: Dark Photons

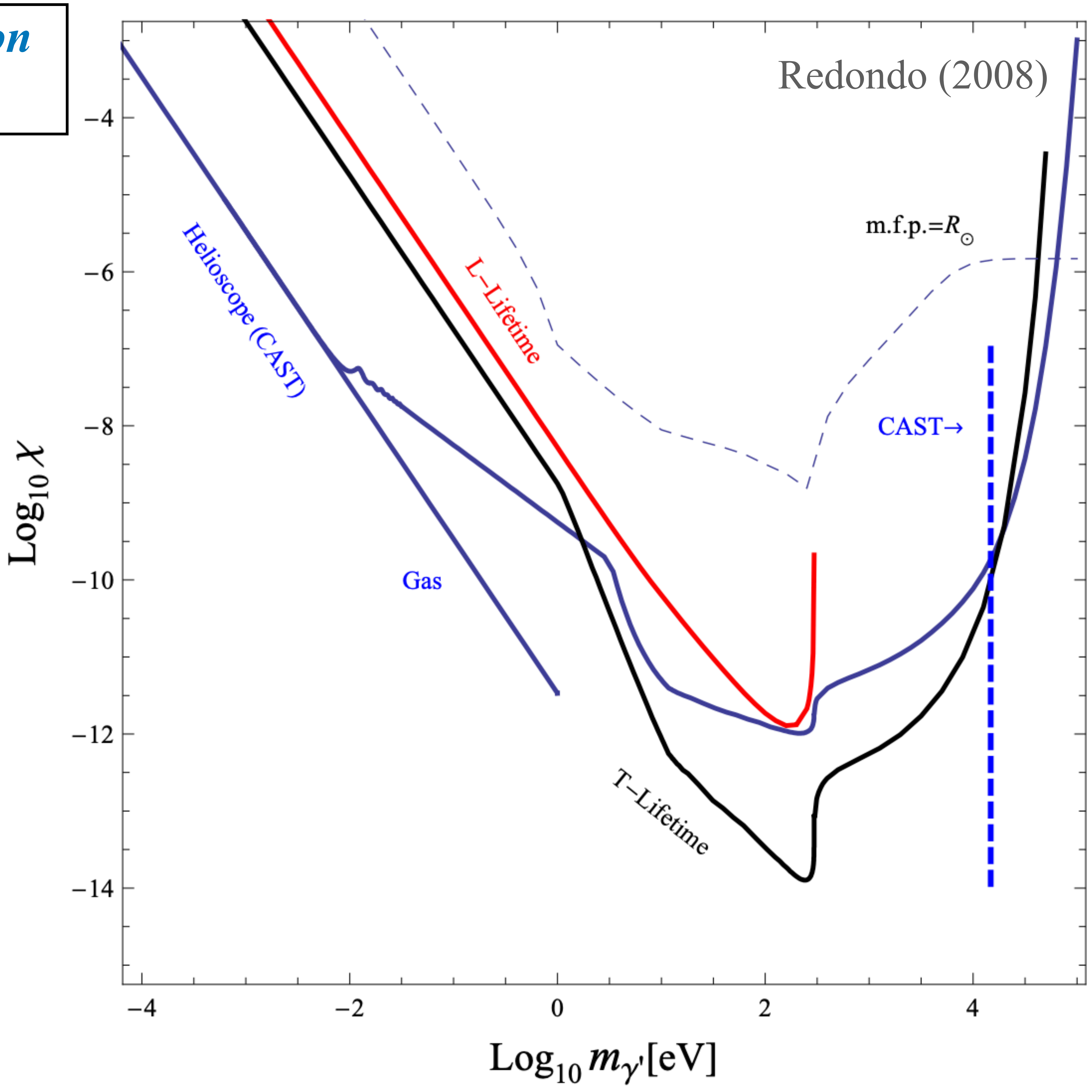
Redondo (2008)

Observables:

- Sun is roughly 4.57 Gyr, halfway through hydrogen burning
- Neutrino fluxes (depend on Tc)
    - Excess luminosity (via transverse / longitudinal conversion) shorten lifetime
- Dark photons re-converting to x-rays in CAST *(no magnetic field necessary)*

The Sun as an example: Dark Photons

In-medium suppression
$\chi_{\text{eff}} \sim \chi(m_{\gamma'}/\omega_p)^2$



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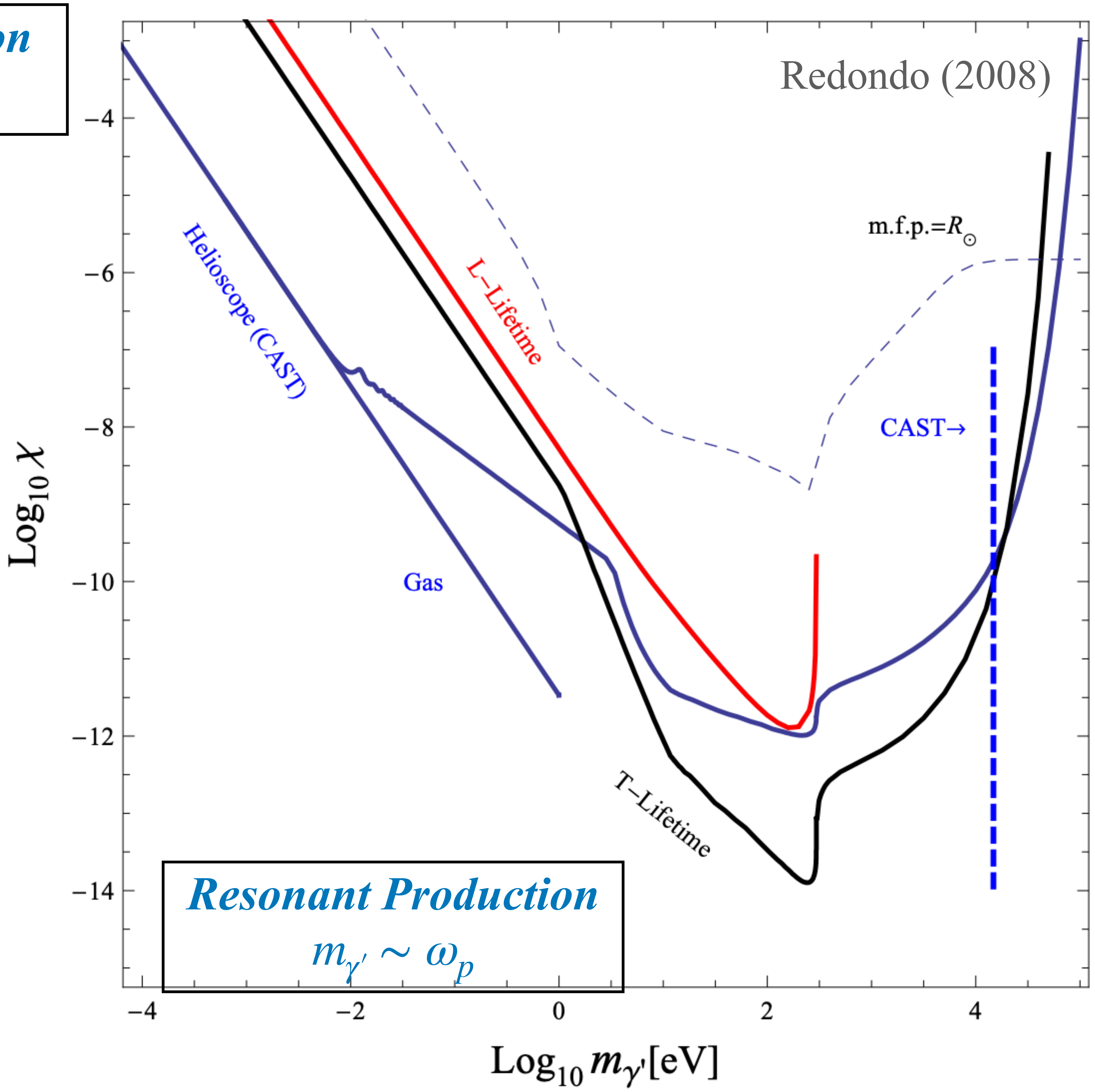
The Sun as an example: Dark Photons

In-medium suppression
$\chi_{\text{eff}} \sim \chi(m_{\gamma'}/\omega_p)^2$

Observables:

- Sun is roughly 4.57 Gyr, halfway through hydrogen burning
- Neutrino fluxes (depend on Tc)
  - Excess luminosity (via transverse / longitudinal conversion) shorten lifetime
- Dark photons re-converting to x-rays in CAST *(no magnetic field necessary)*



Resonant Production
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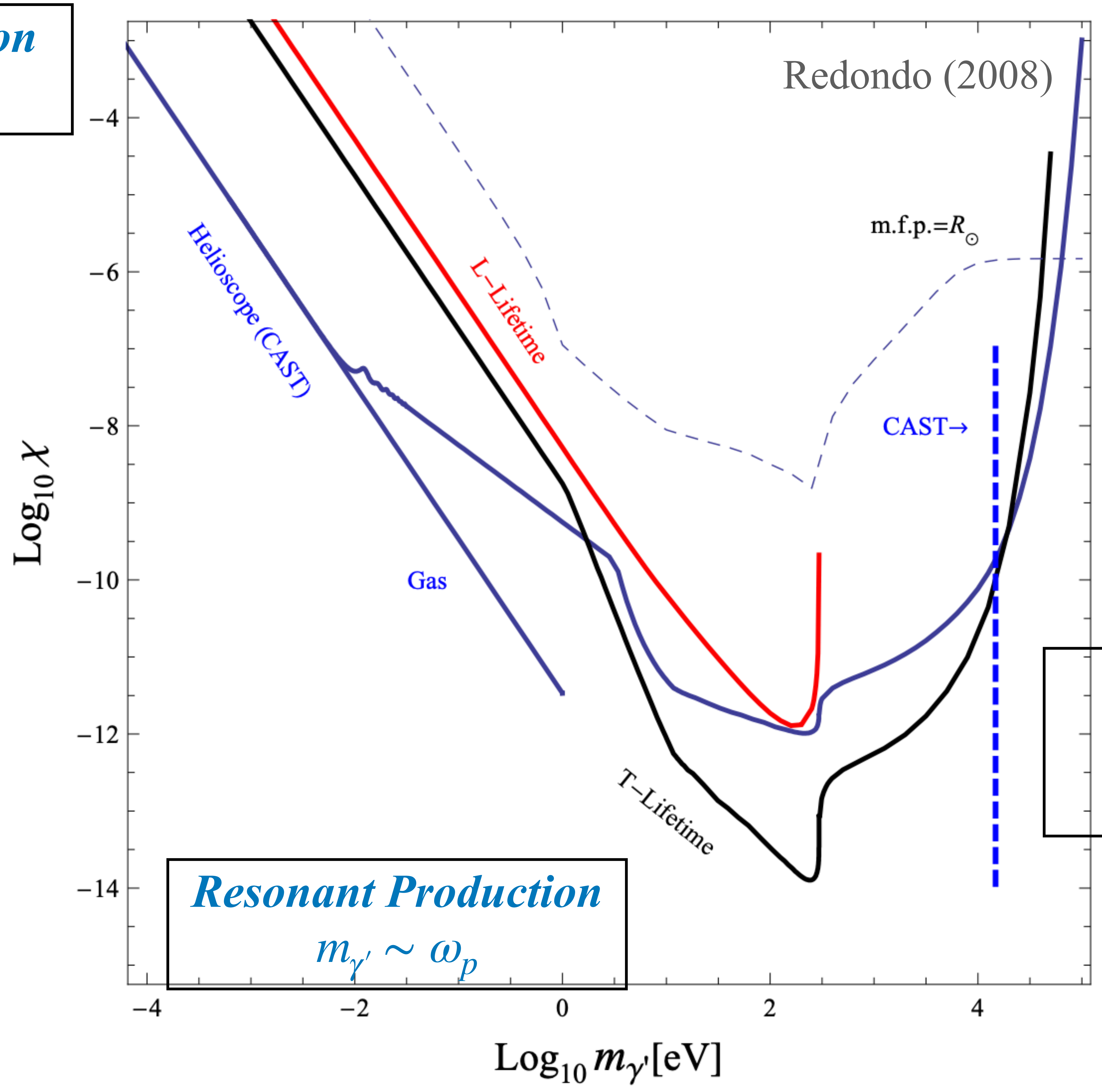

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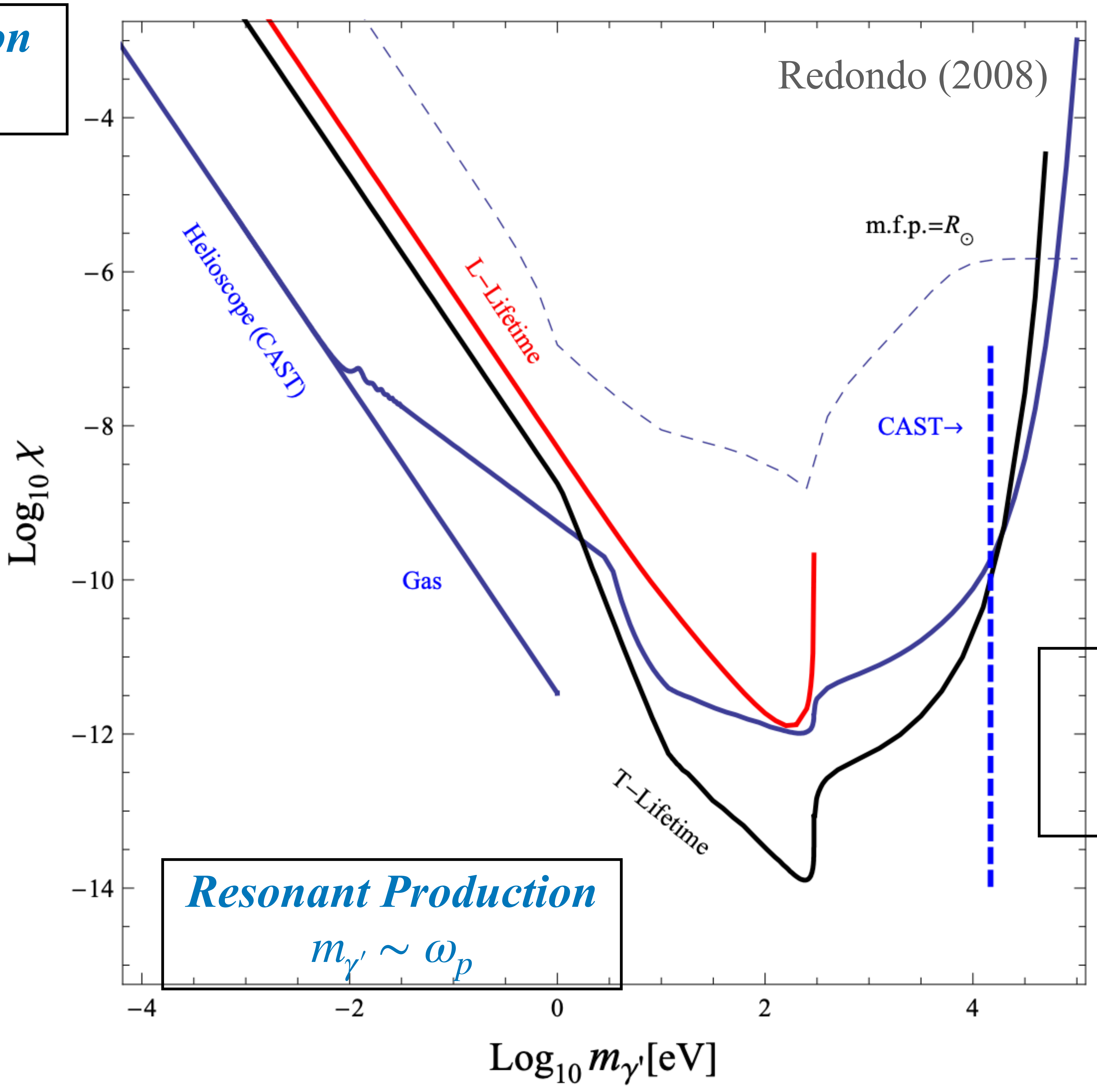

Distribution function suppressed @ $\omega/T \gg 1$

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$\omega > \omega_p$
$\chi_{\rm eff} \sim \chi$

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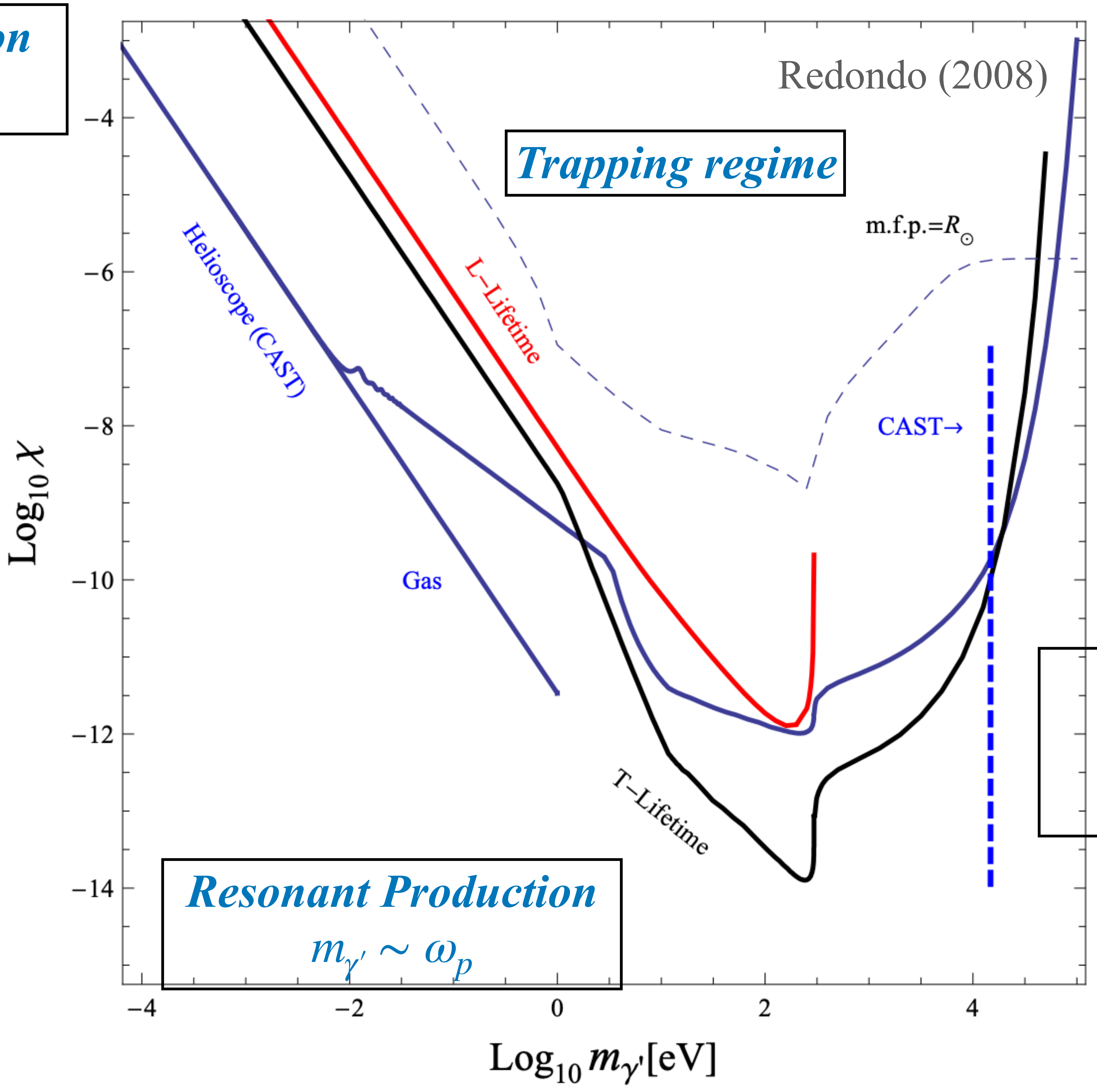


Trapping regime

Resonant Production
$m_{\gamma'} \sim \omega_p$

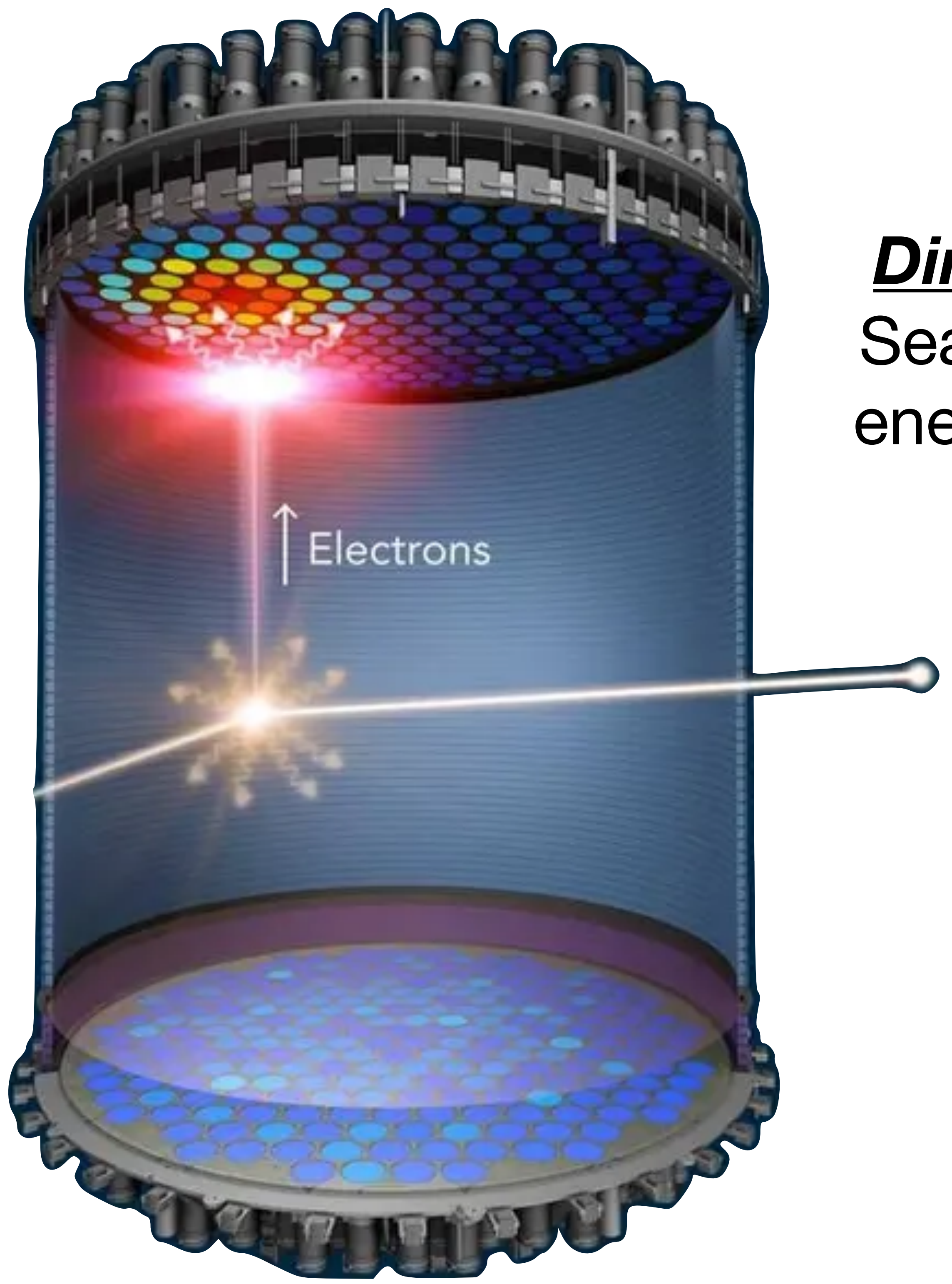
Distribution function suppressed @ $\omega/T \gg 1$

Unsuppressed production
$\omega > \omega_p$
$\chi_{\text{eff}} \sim \chi$

The Sun as an example: WIMPs

What makes the Sun special?

Giant ball of nucleons



Direct detction:
Search for kinetic energy deposition

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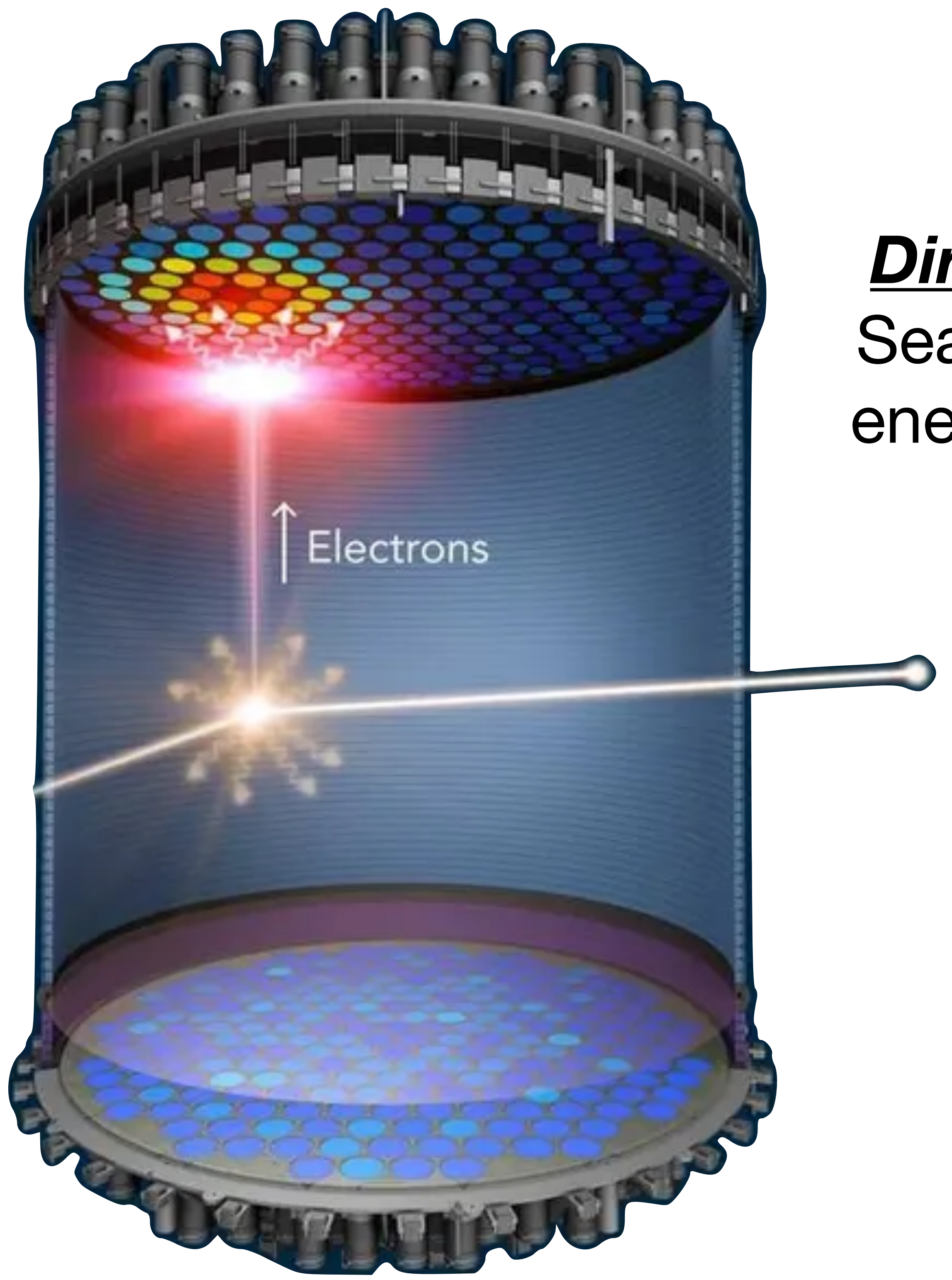

Direct detction:
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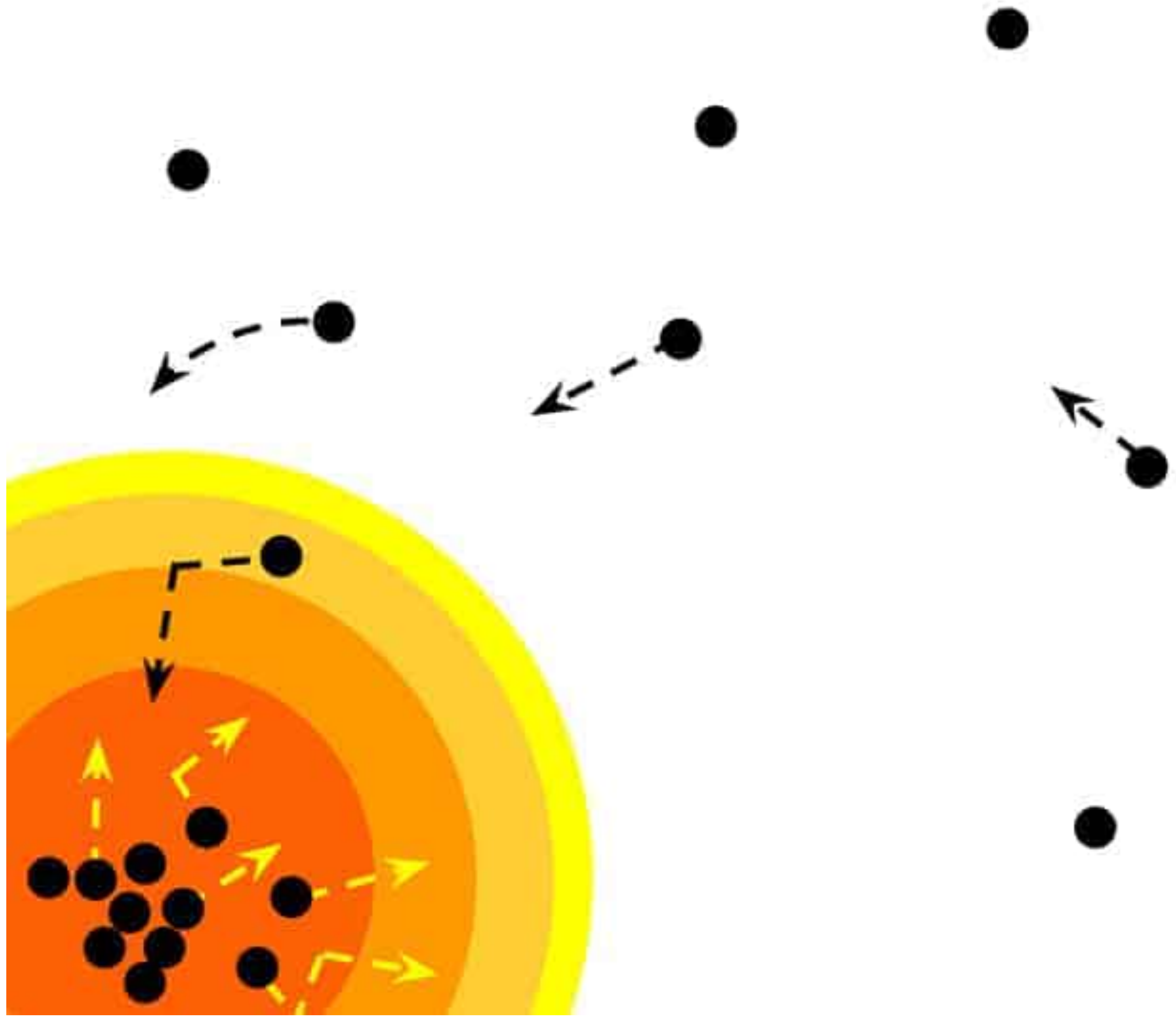
Here:
Kinetic energy negligible

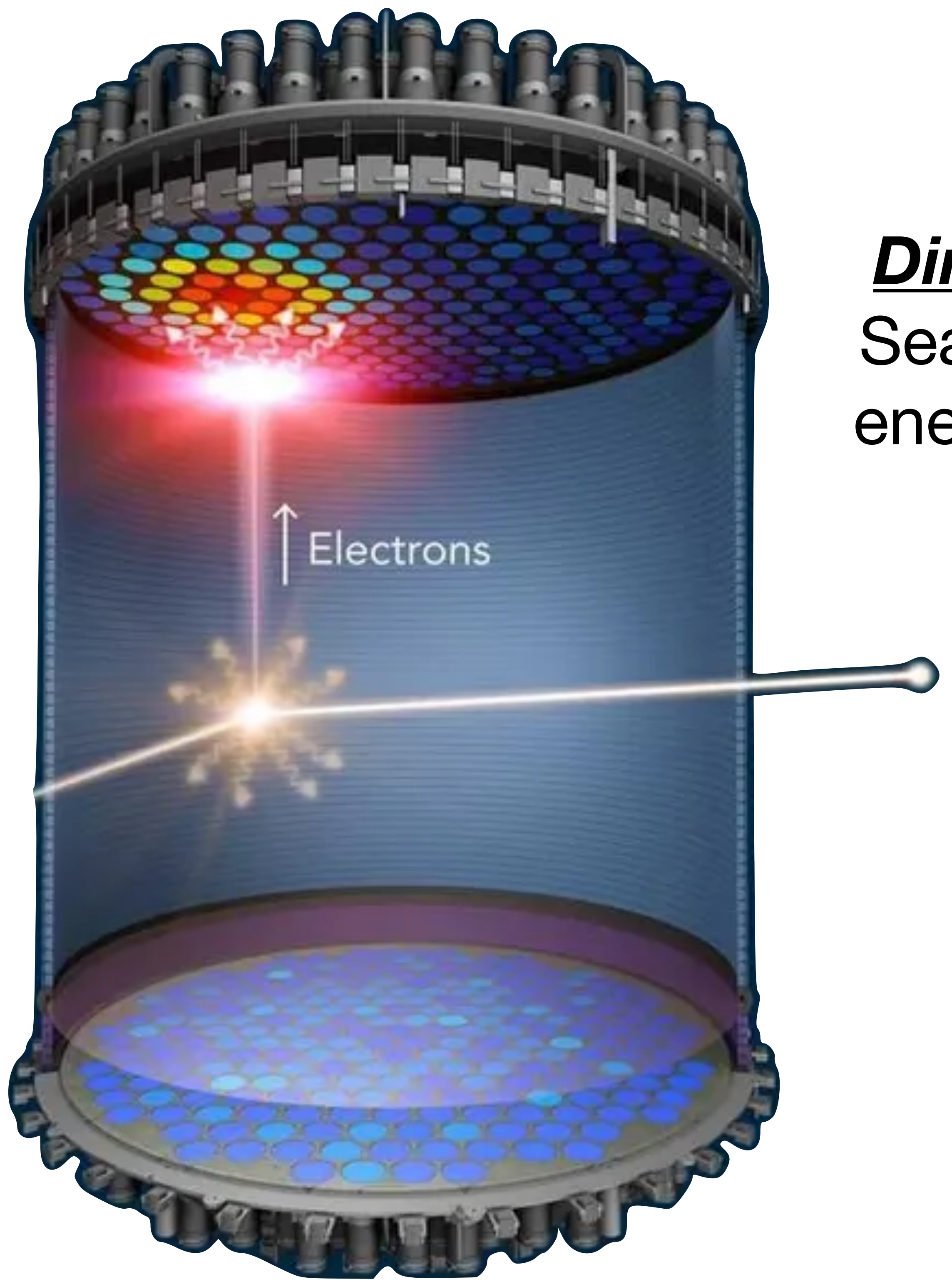
$$\frac{\text{(KE flux DM)}}{\text{(Sun's Luminosity)}} \ll 10^{-10}$$



The Sun as an example: WIMPs

What makes the Sun special?

Giant ball of nucleons



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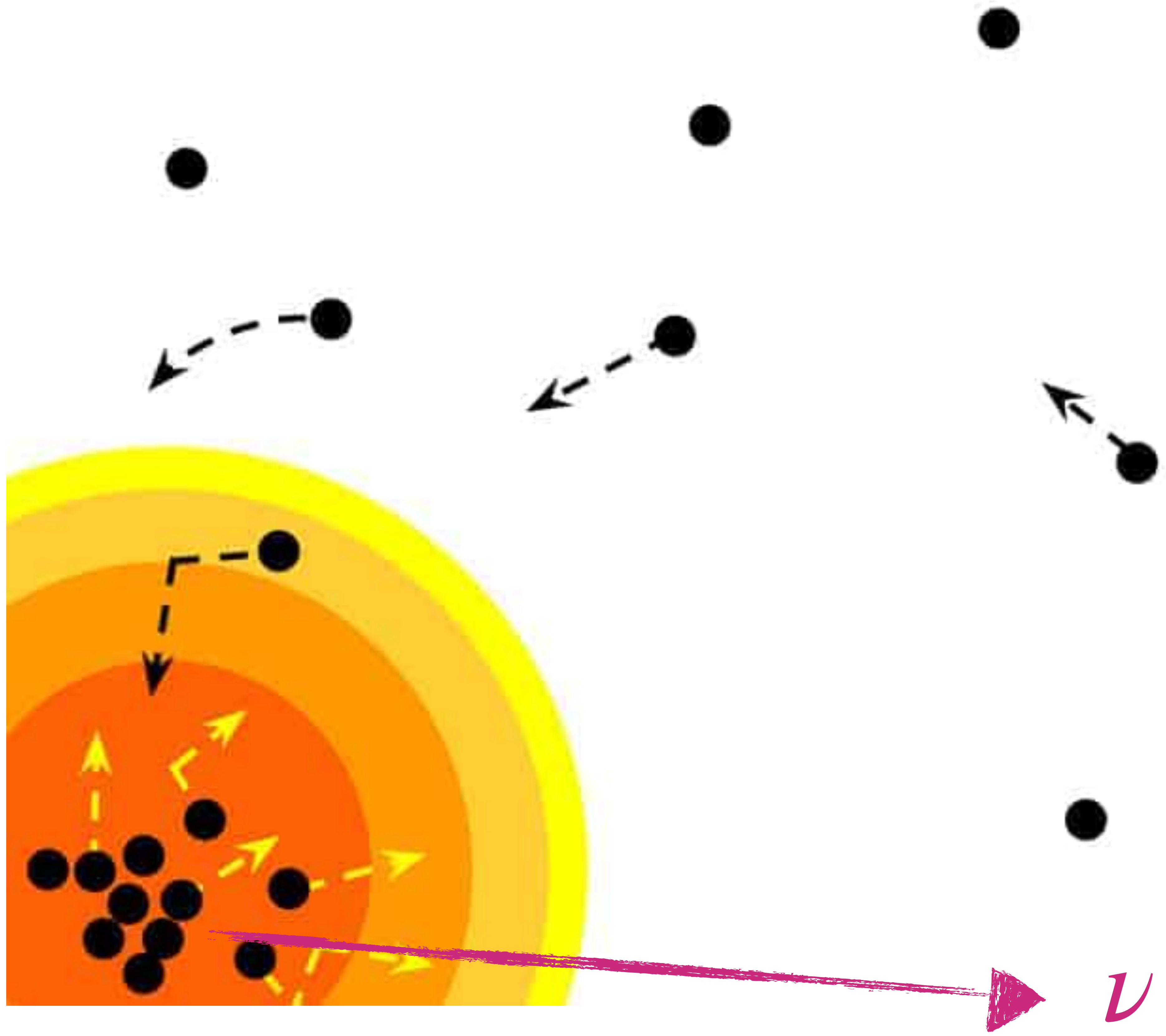


The Sun as an example: WIMPs

What makes the Sun special?

Giant ball of nucleons

$$\frac{dN}{dt} = \Gamma_{\rm capt} - \Gamma_{\rm evap} - 2\Gamma_{\rm ann}$$

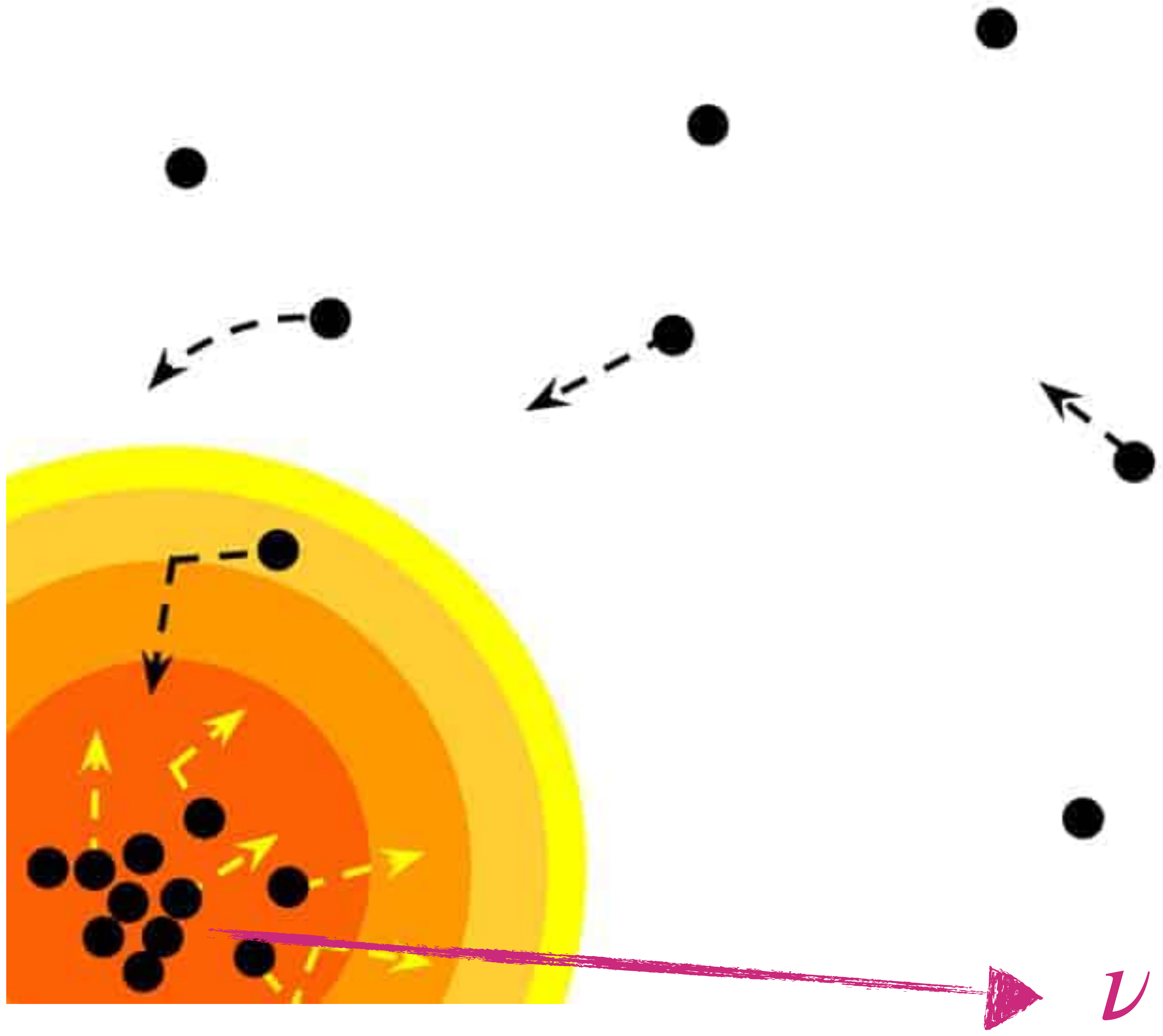
Capture Probability

Capture rate: $\Gamma_{\rm capt} \sim n_{\rm DM}\, N_N \left\langle v_{\rm rel} \right\rangle \sigma_N\, P_{\rm capture}$

Evaporation Probability

Evaporation rate: $\Gamma_{\rm eval} \sim n_{\rm capt}\, N_N\, \sigma_N \left\langle v_{\rm rel} \right\rangle\, P_{\rm evap}$

Anniliation rate of bound WIMPs: $2\Gamma_{\rm ann} = \int dV\, n^2 \left\langle \sigma v \right\rangle$



The Sun as an example: WIMPs

What makes the Sun special?

Giant ball of nucleons

Equilibrium Distribution: $n(r) \propto e^{-r^2/r_0^2}$

$$r_0 \sim 10^{-2} R_\odot \sqrt{\frac{100\,\mathrm{GeV}}{m_{\mathrm{DM}}}}$$

(From Virial Theorem $\langle K \rangle = -\frac{1}{2}\langle V \rangle$*)*

$$\frac{dN}{dt} = \Gamma_{\mathrm{capt}} - \Gamma_{\mathrm{evap}} - 2\Gamma_{\mathrm{ann}}$$

Capture Probability

Capture rate: $\Gamma_{\mathrm{capt}} \sim n_{\mathrm{DM}} N_N \left\langle v_{\mathrm{rel}} \right\rangle \sigma_N P_{\mathrm{capture}}$

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Evaporation rate: $\Gamma_{\mathrm{eval}} \sim n_{\mathrm{capt}} N_N \sigma_N \left\langle v_{\mathrm{rel}} \right\rangle P_{\mathrm{evap}}$

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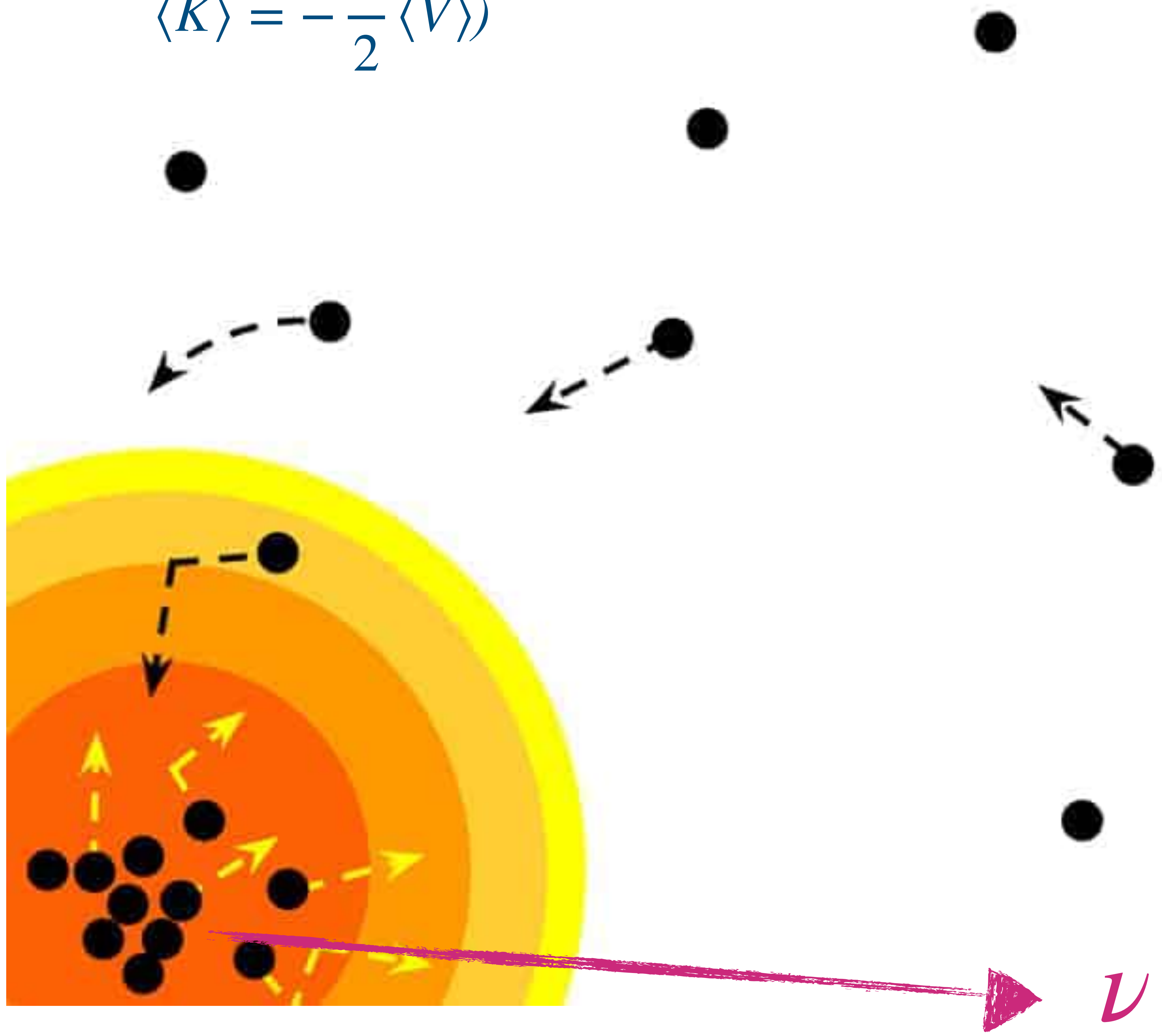
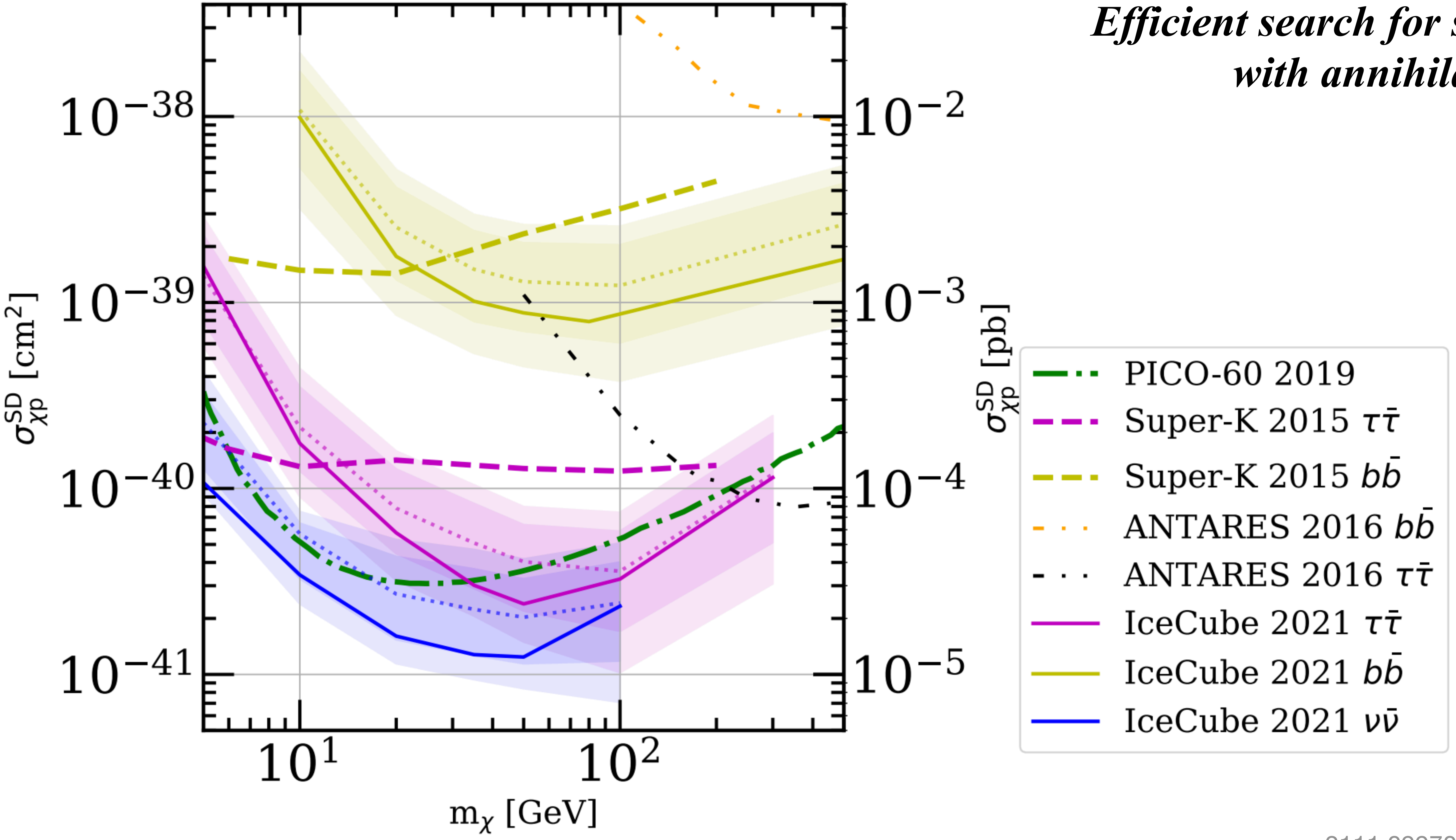


The Sun as an example: WIMPs

Efficient search for spin-dependent scattering with annihilation to neutrinos



2111.09970

The Sun as an example: WIMPs

2405.05312

	Celestial Body Properties				
	Escape velocity $[c]$	Mass $[\mathcal{M}_\odot]$	Radius $[R_\odot]$	$\mathrm{T_{core}}$ [K]	σ_{tr} $[\mathrm{cm}^2]$
Neutron Star	0.7	1.4	10^{-5}	10^5	10^{-45}
White Dwarf	10^{-2}	0.6	10^{-2}	10^5	10^{-41}
Average MS Star	10^{-3}	0.3	0.3	10^7	10^{-36}
Sun	10^{-3}	1	1	10^7	10^{-35}
Brown Dwarf	10^{-3}	10^{-2}	0.1	10^4–10^6	10^{-35}
Jupiter	10^{-4}	10^{-3}	0.1	10^4	10^{-34}
Earth	10^{-5}	10^{-6}	10^{-2}	10^4	10^{-33}

(Also relevant: DM density, DM velocity, Distance)

Can play similar game with any other astrophyscial object