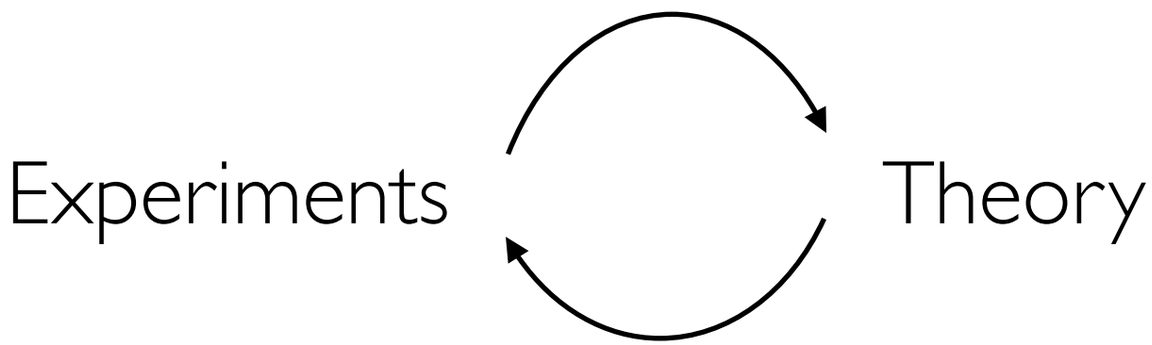
Searching for hidden sectors: new experiments and theory

Robert Lasenby

March 11, 2021

Searching for new physics

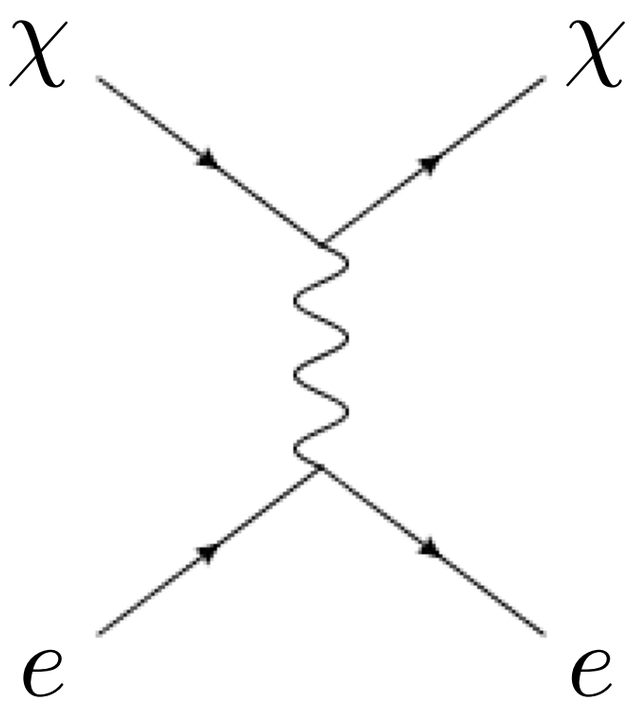
- There is physics beyond the Standard Model
  - Dark matter, early universe, gravity, …
- Very large space of possibilities — need to search as widely as possible

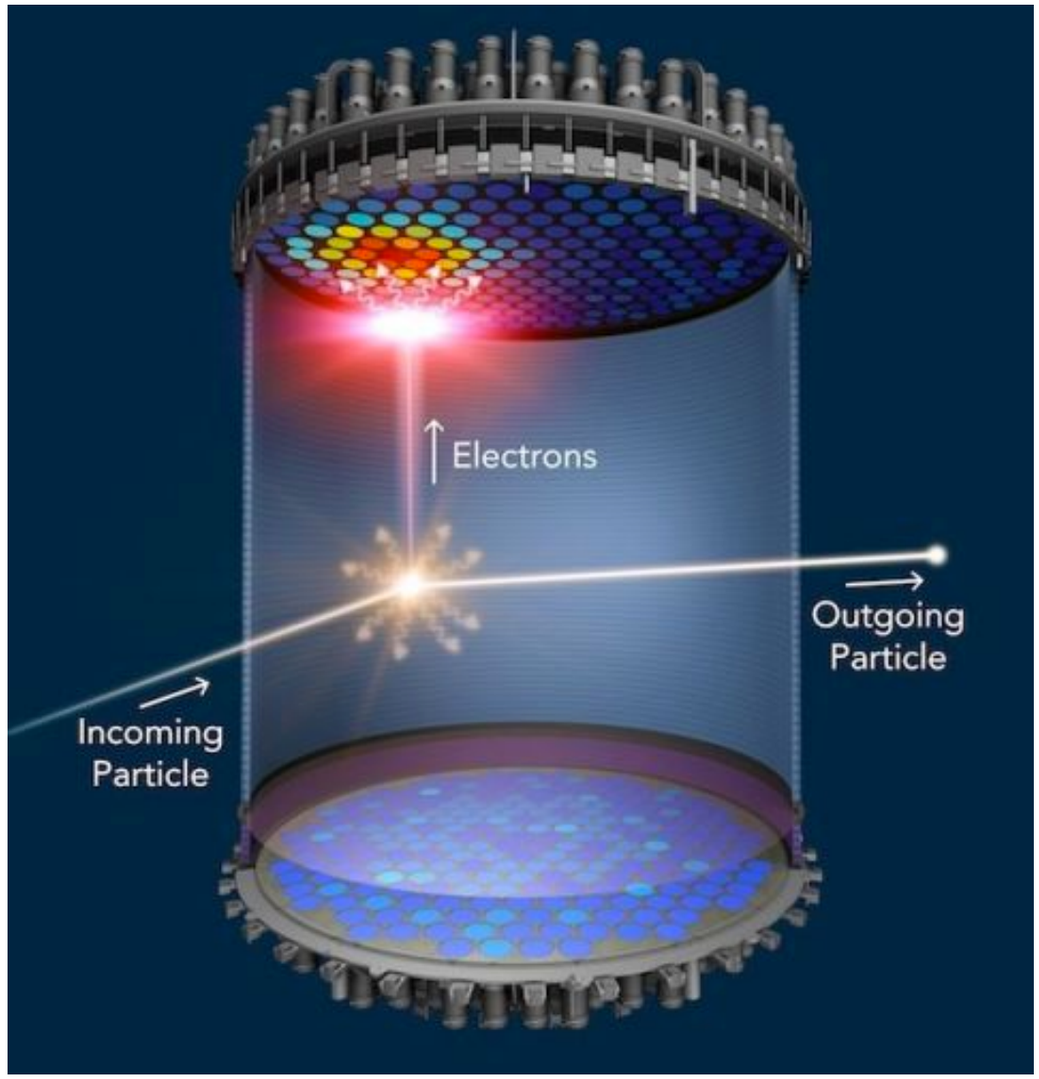


- Pushing the precision frontier: doing as well as QM allows

Dark matter detection

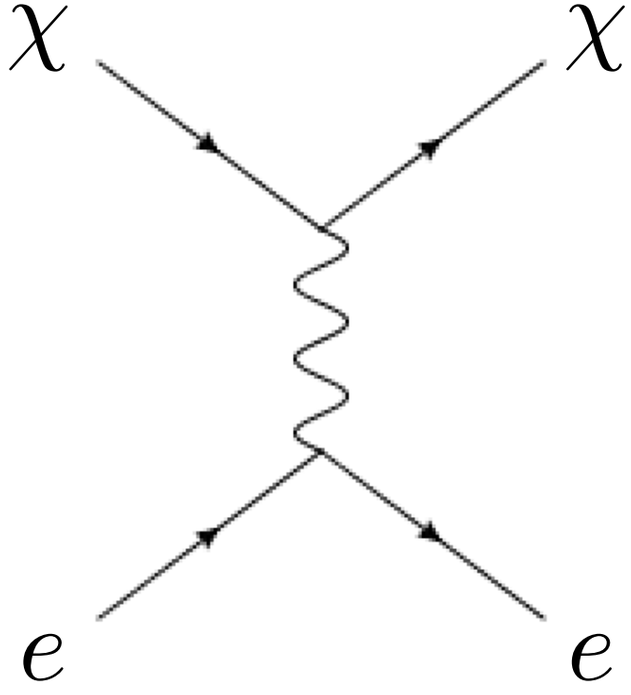
Scattering



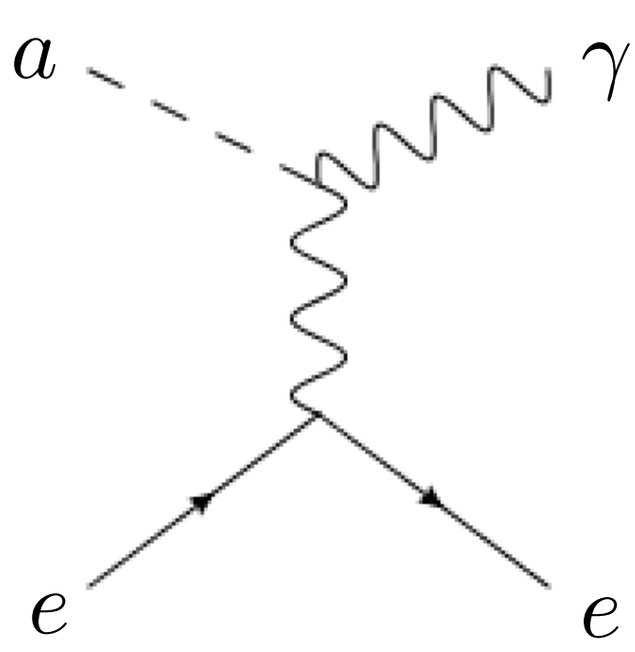


(bosonic) Dark matter detection

Scattering

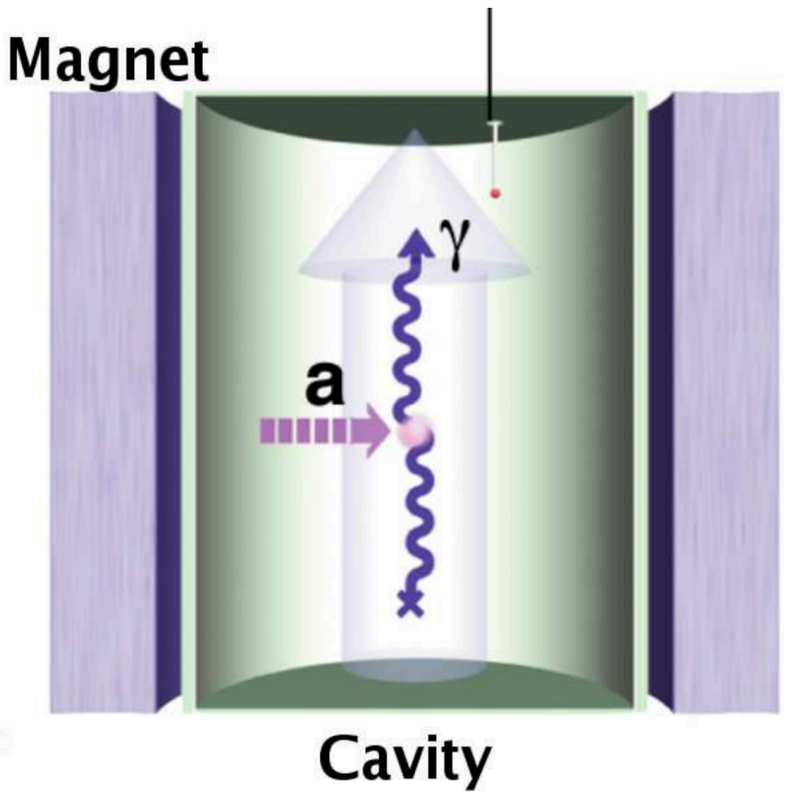


Absorption

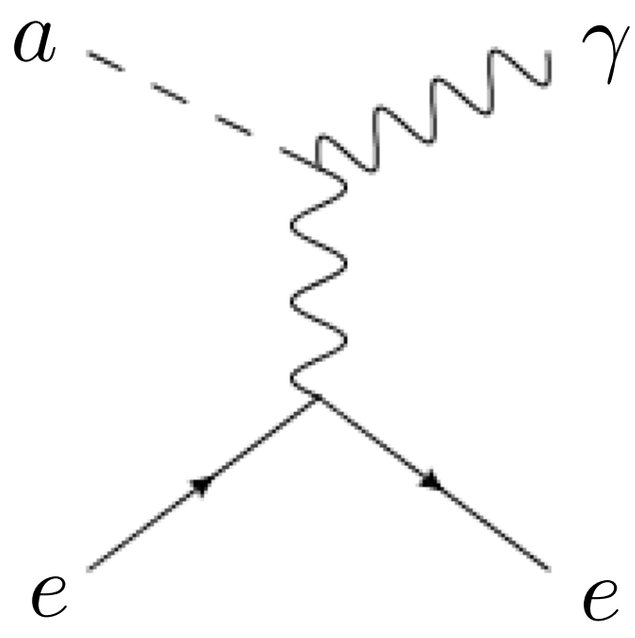


(bosonic) Dark matter detection

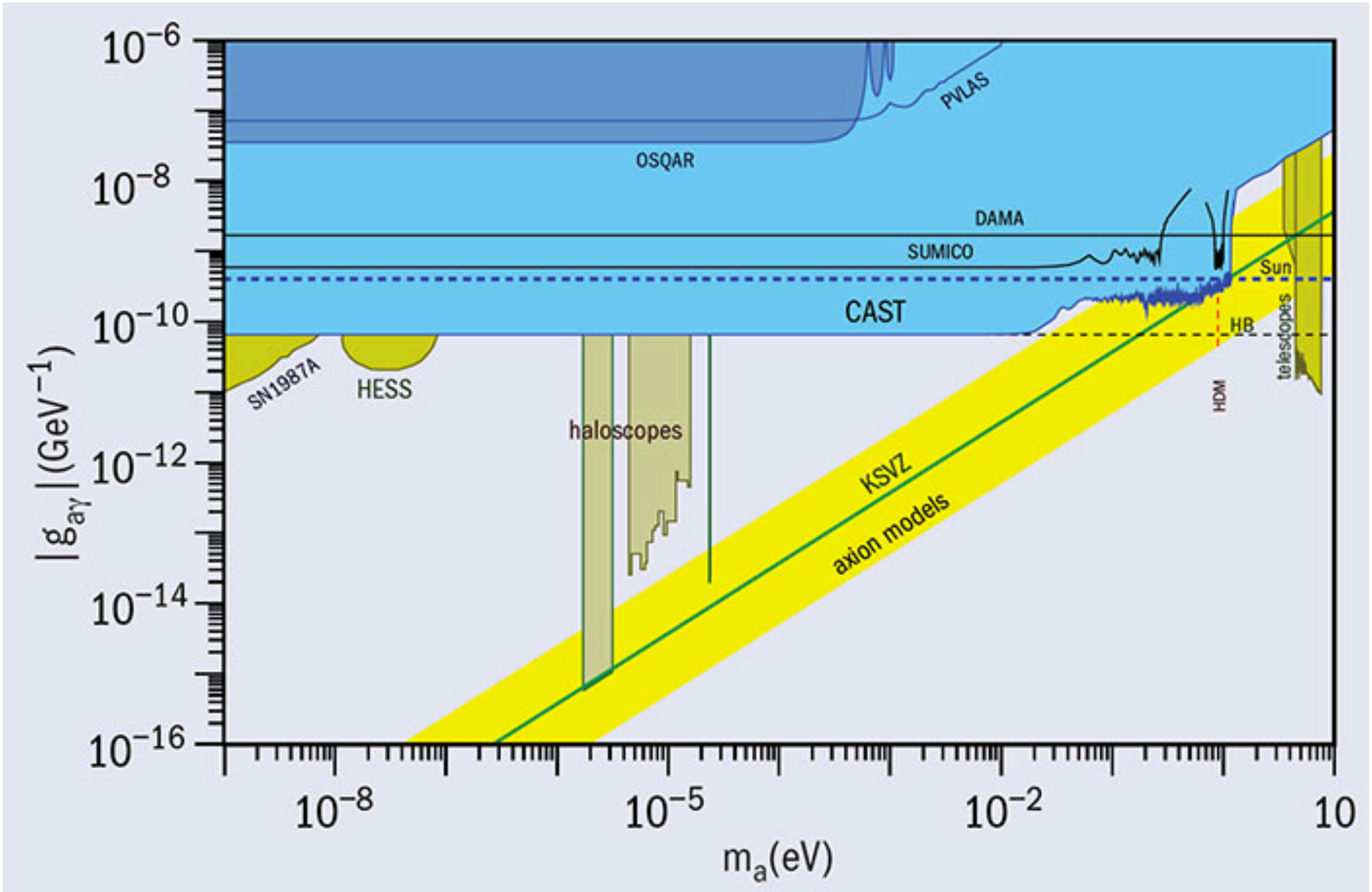
e.g. ADMX, …



Absorption

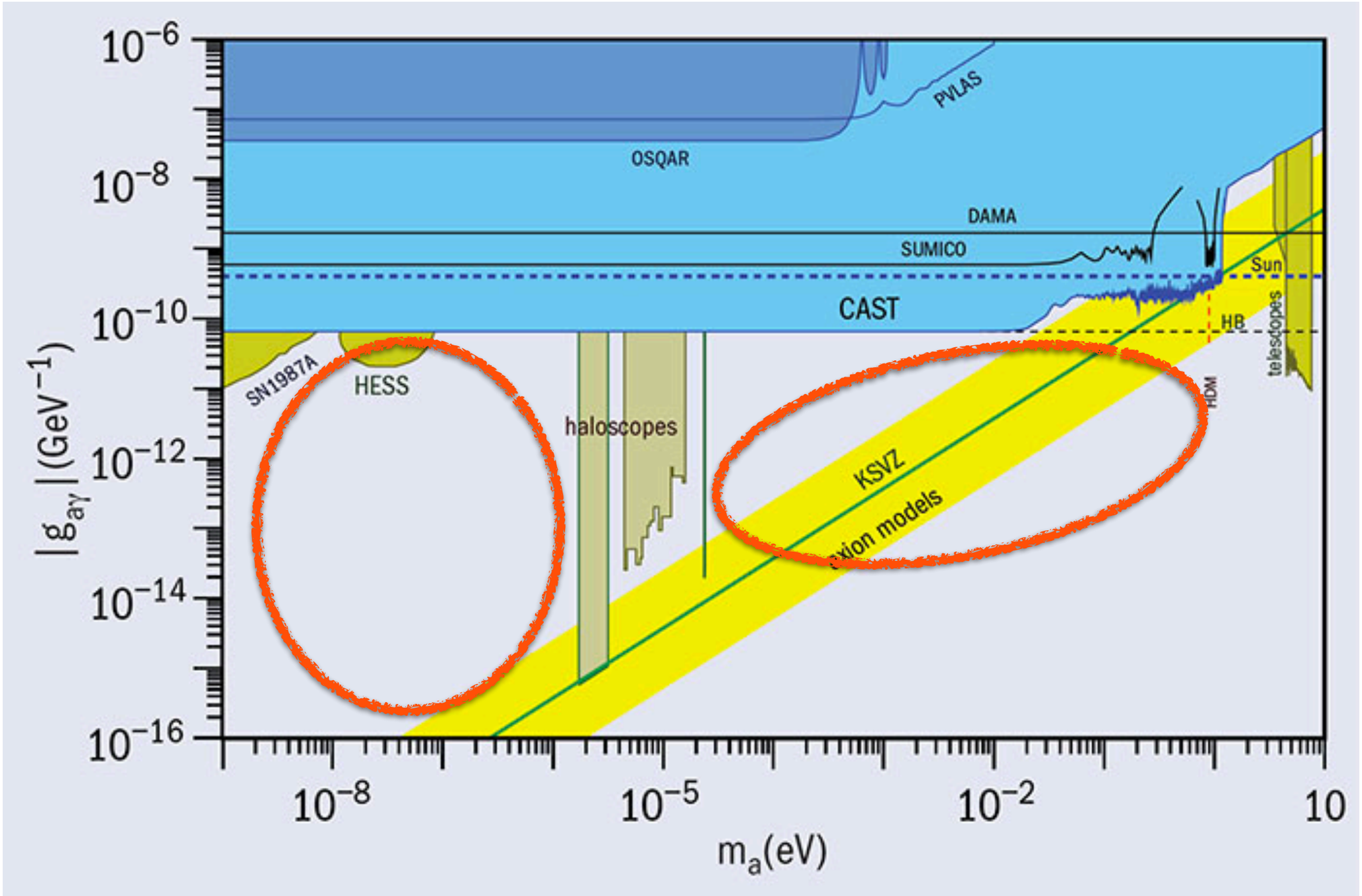


Axion DM



[CAST experiment]

Axion DM

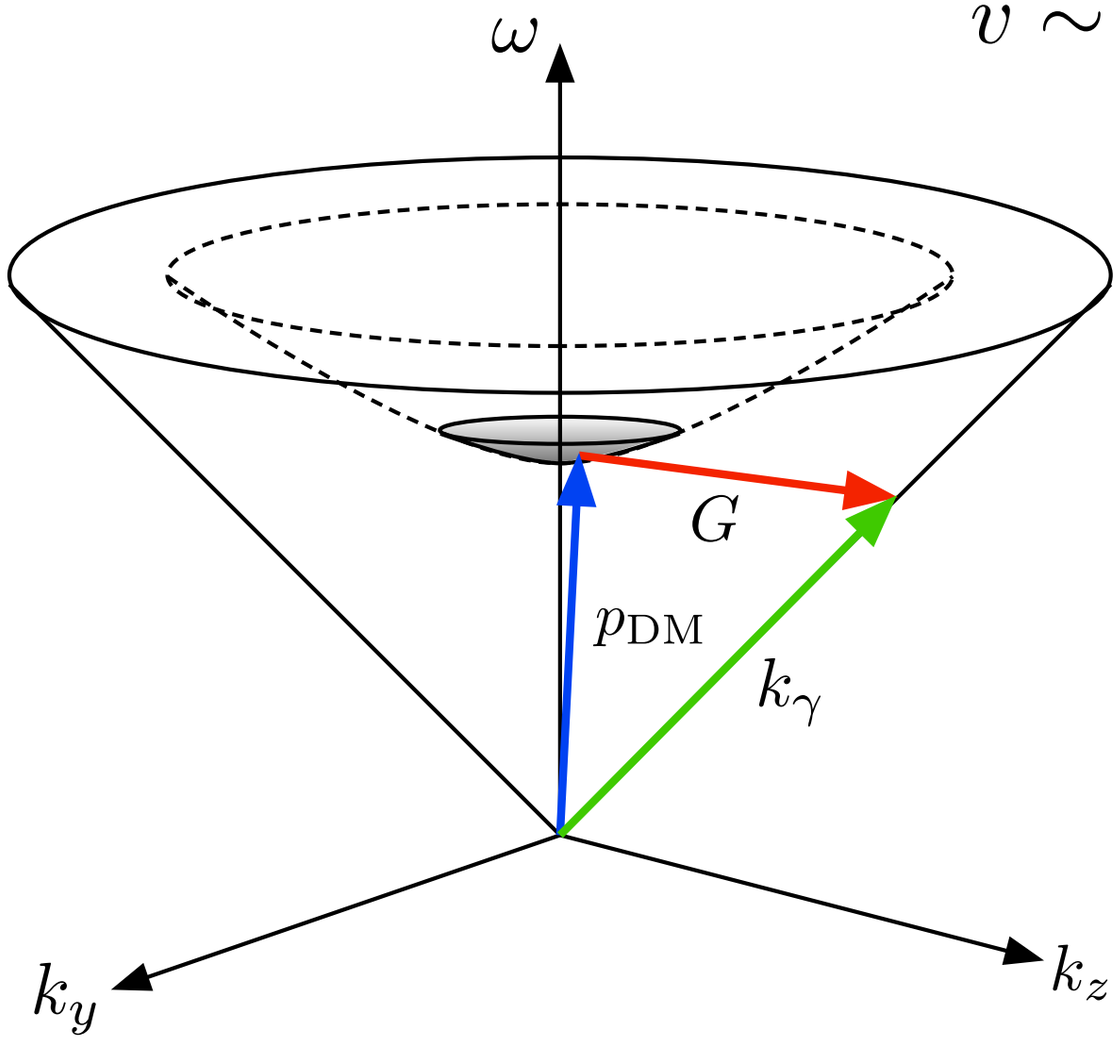


[CAST experiment]

Dark matter absorption

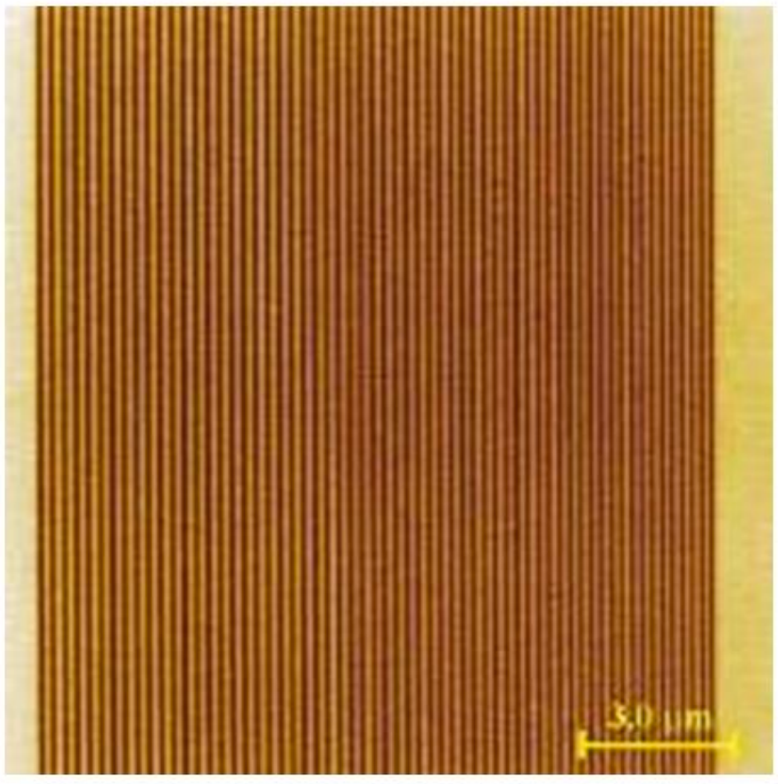
Absorption to photons: momentum mismatch

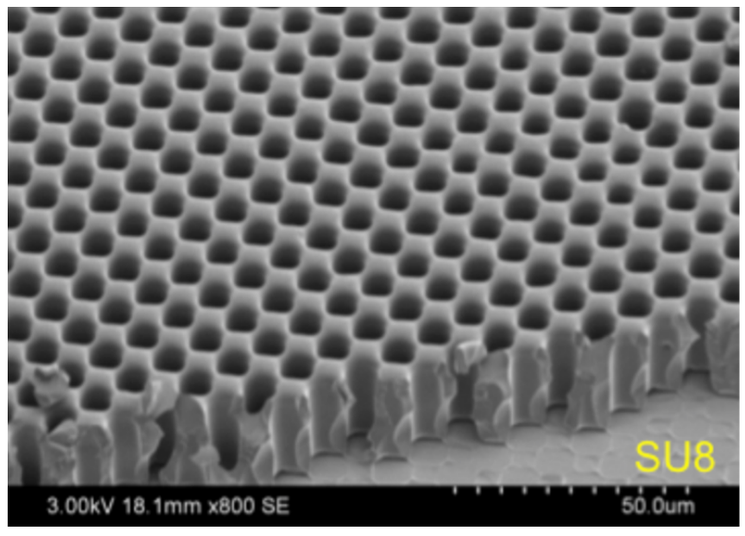
$v \sim 10^{-3}$

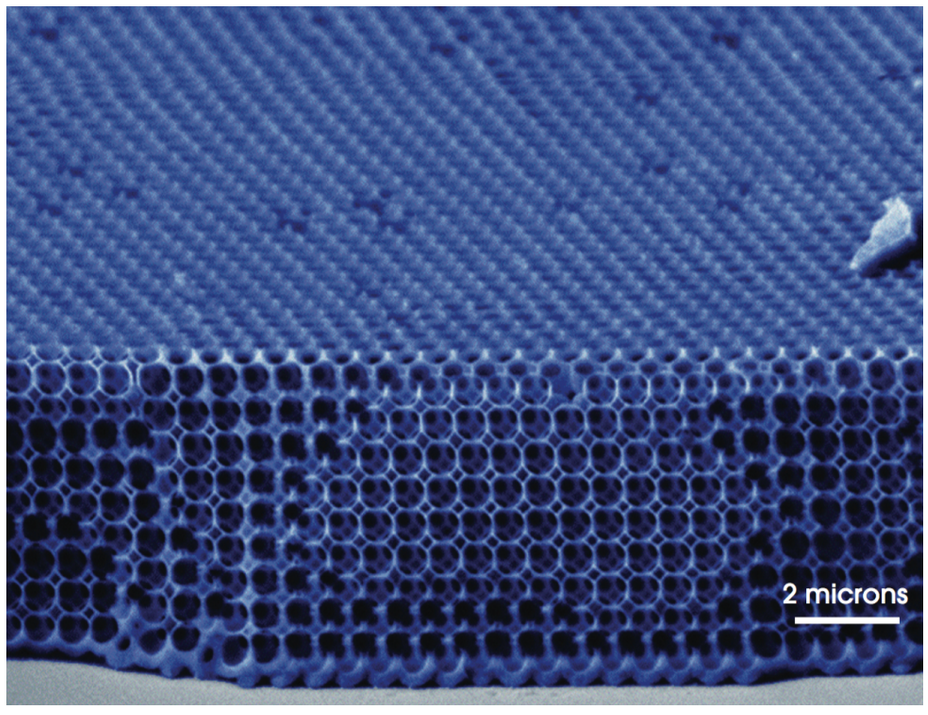


Photonic materials

- Materials with periodic optical properties



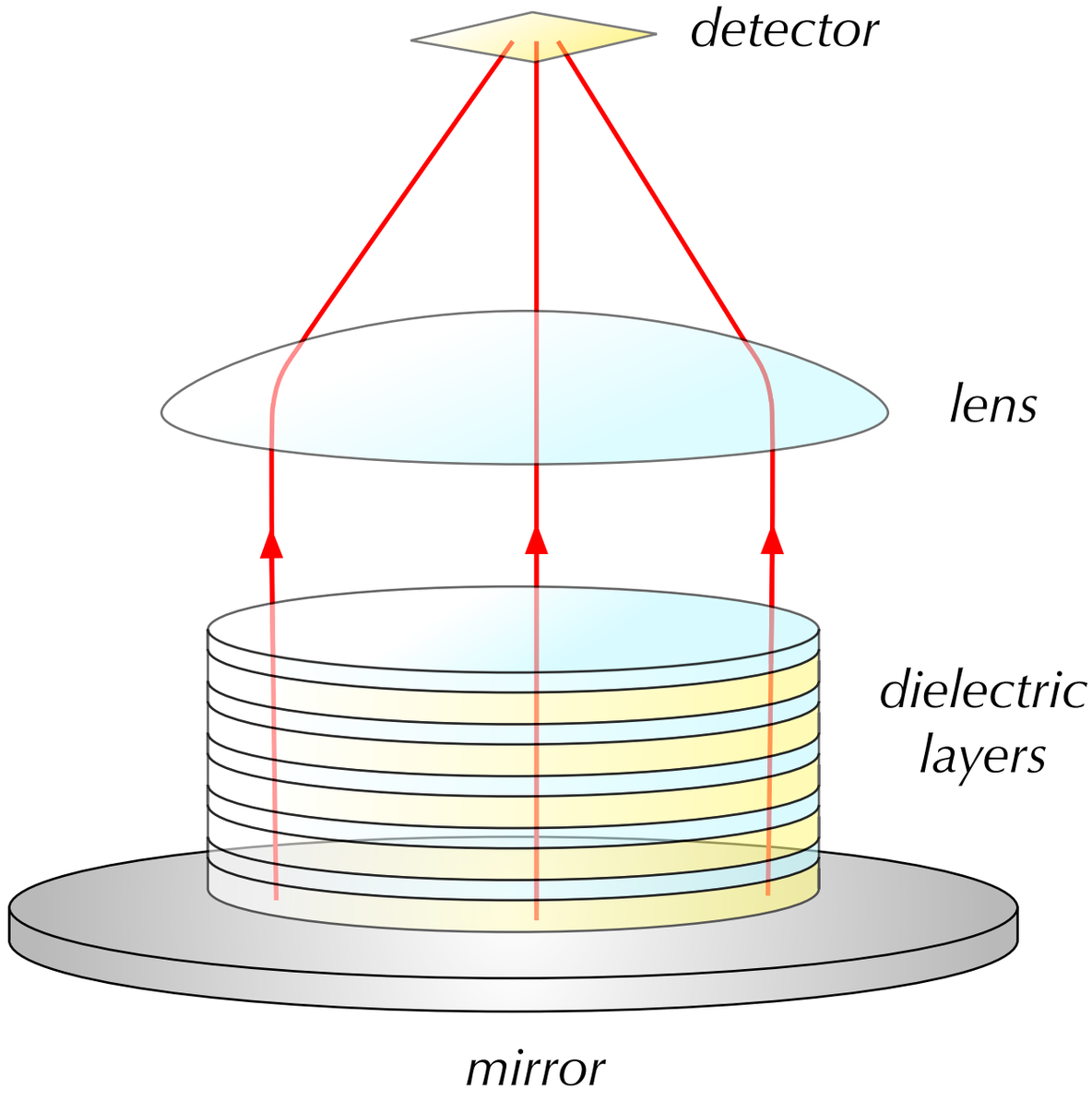




1D *2D* *3D*

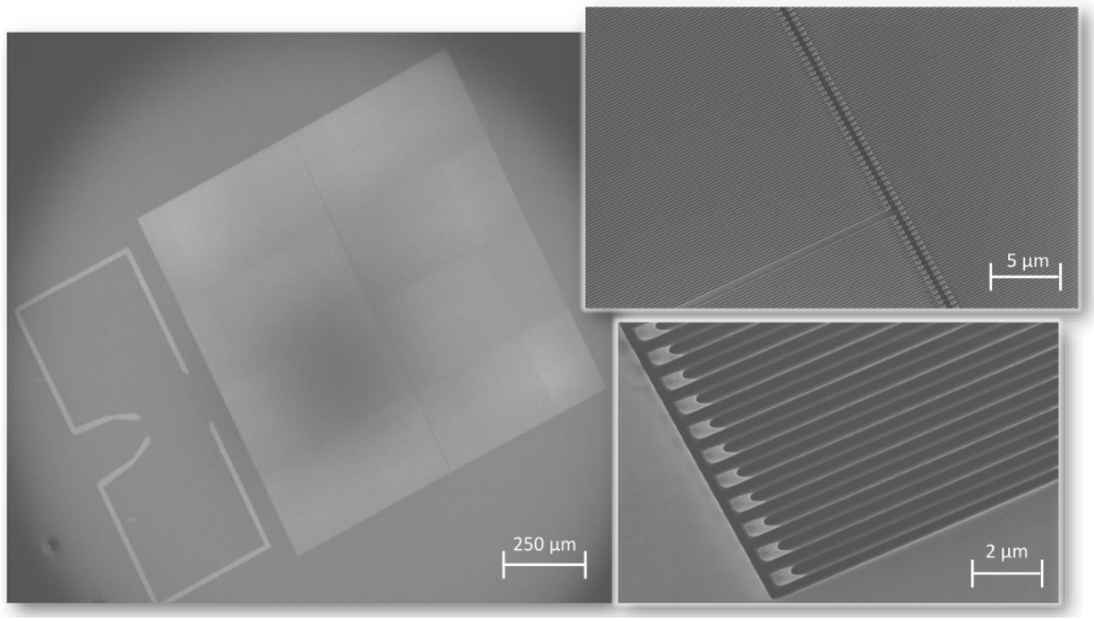
Dielectric haloscope

- DM can Bragg-convert in medium, producing photons:

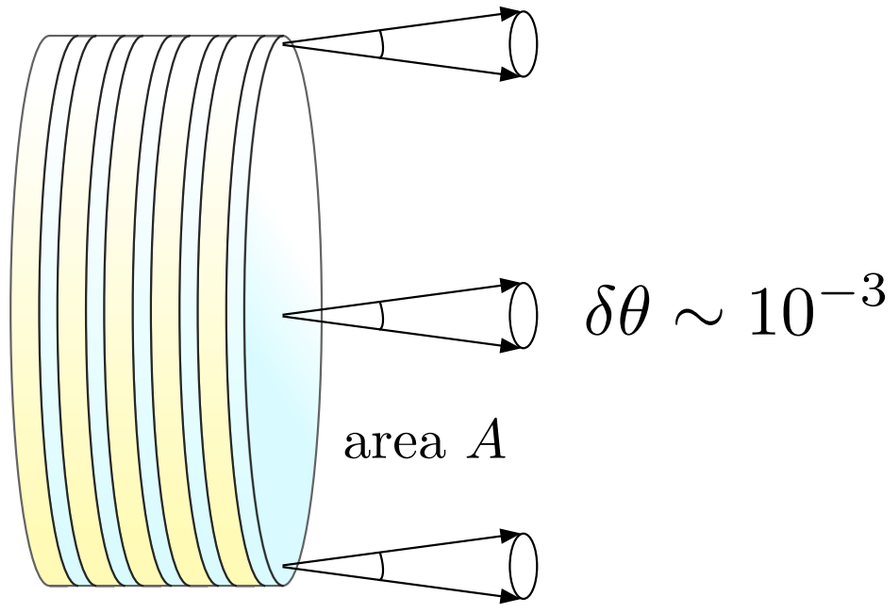


Photon detection

- Efficient, low-noise photon detection using quantum sensors - TES, MKID, SNSPD



- Coherent conversion enables focussing



Light A' Multilayer Periodic Optical SNSPD Target

LAMPOST: First Constraints on Dark Photon Dark Matter with Superconducting Nanowire Detectors in an Optical Haloscope

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[3] *Perimeter Institute for Theoretical Physics, Waterloo, Ontario, N2L 2Y5, Canada*
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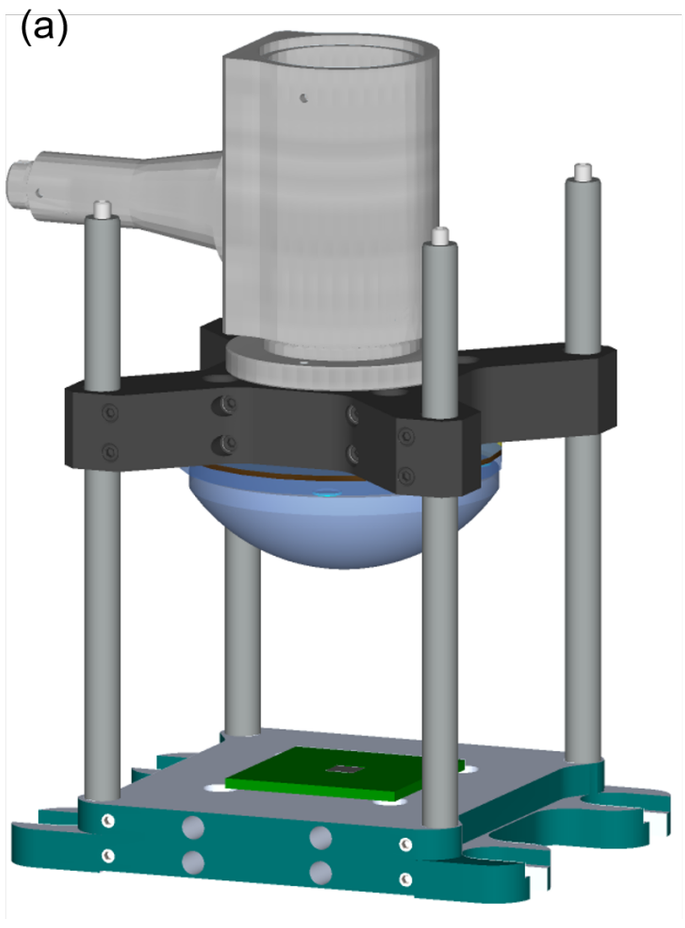
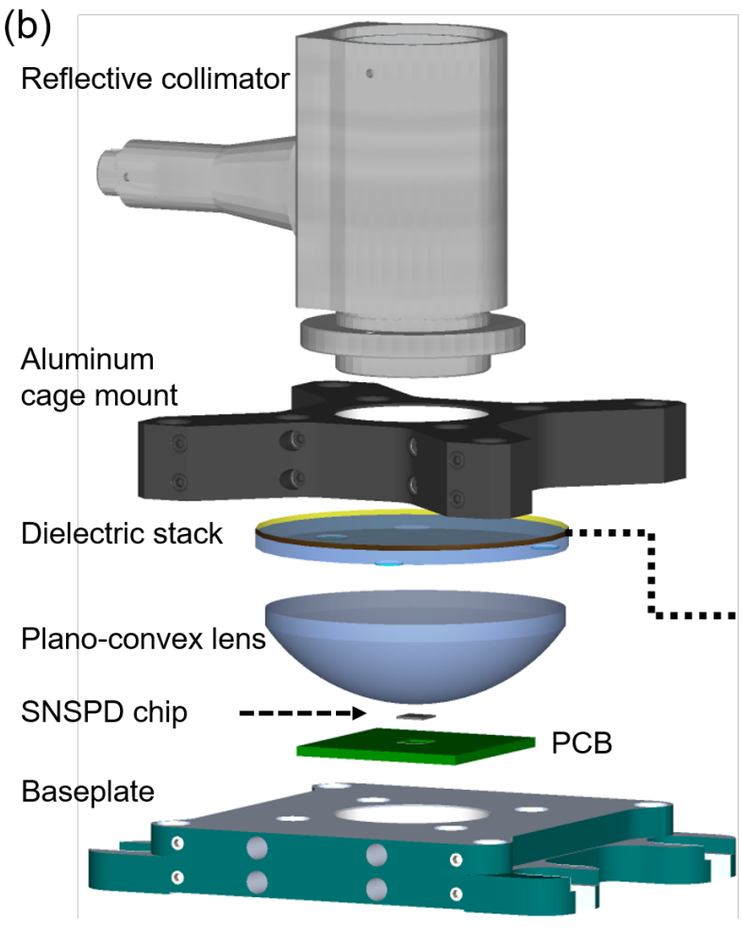
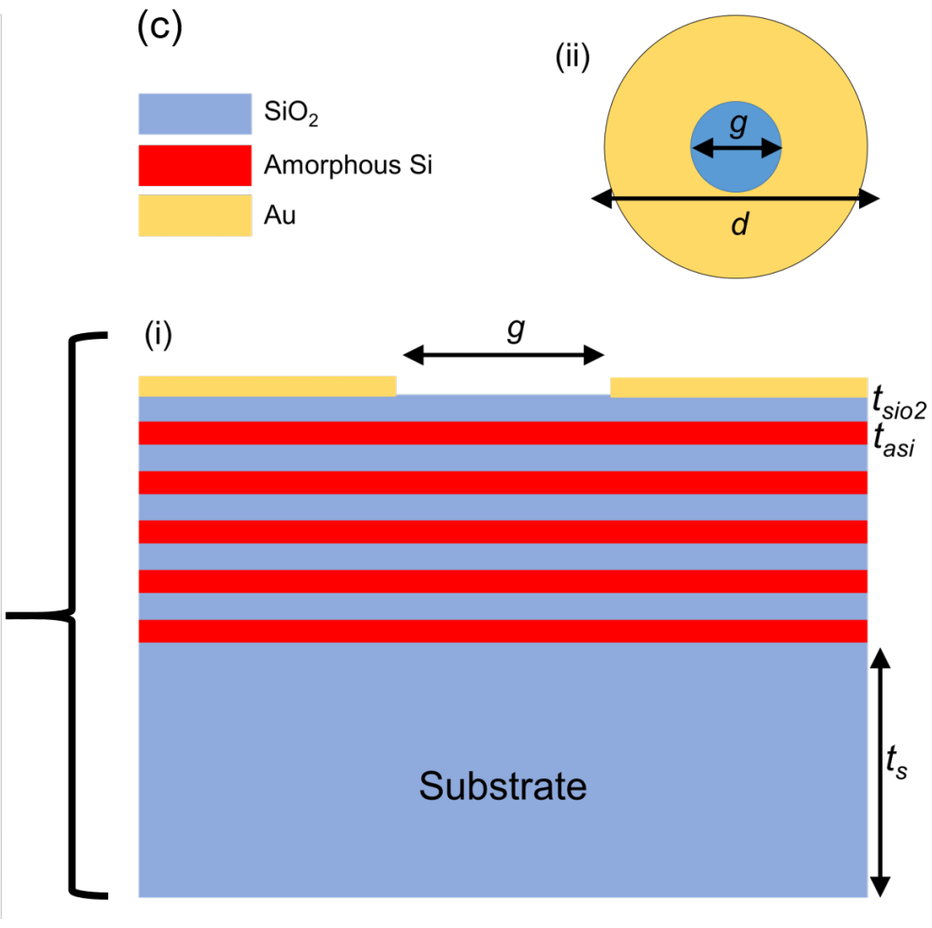
[5] *Stanford Institute for Theoretical Physics, Stanford University, Stanford, CA 94305, USA*
[6] *Center for Computational Astrophysics, Flatiron Institute, New York, NY 10010, USA*

Funded by DOE QuantISED program

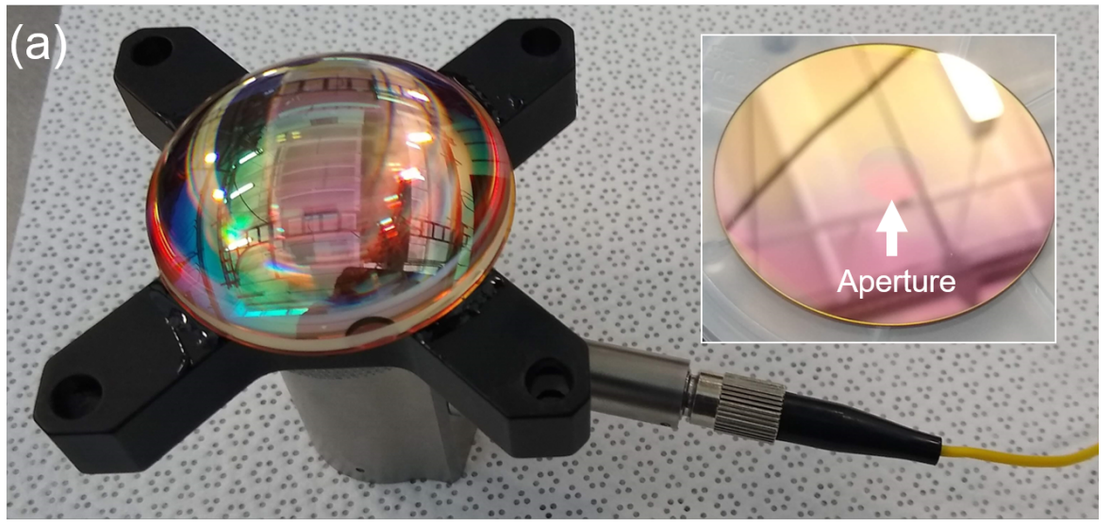
LAMPOST

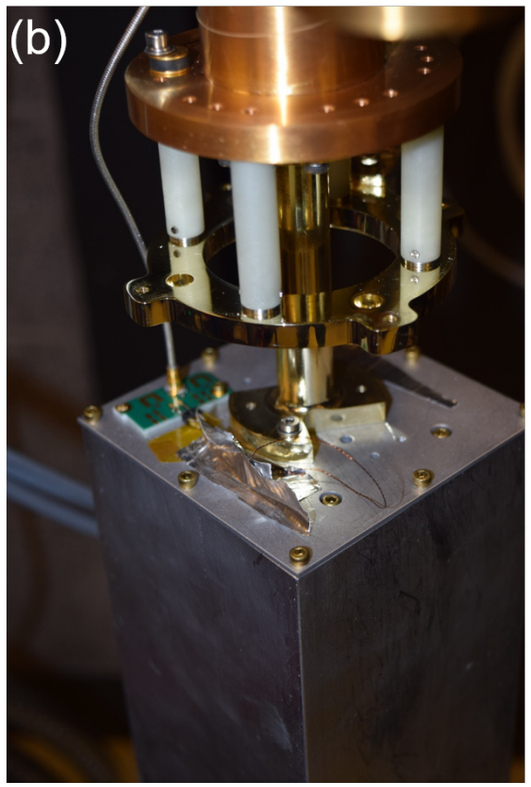

(a)


(b)
Reflective collimator
Aluminum cage mount
Dielectric stack
Plano-convex lens
SNSPD chip
PCB
Baseplate

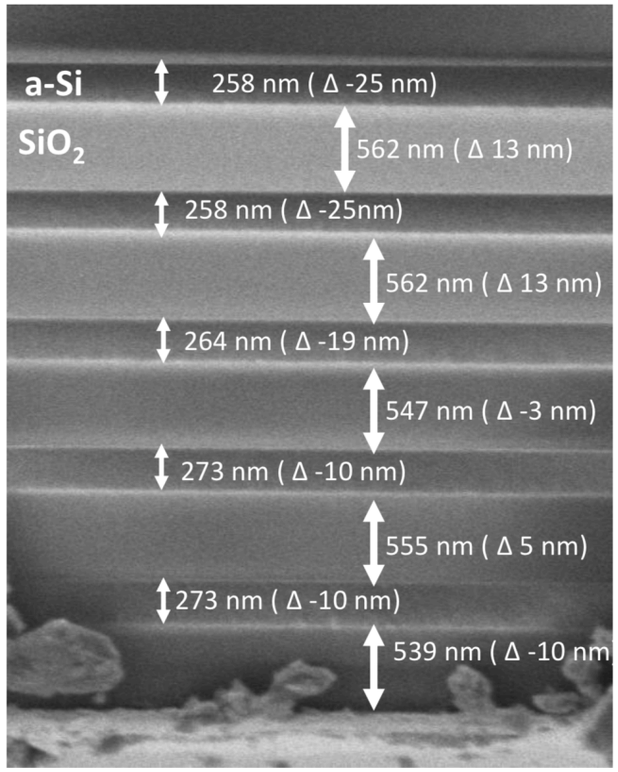

(c)
SiO_2
Amorphous Si
Au
(ii)
g
d
(i)
g
t_{sio2}
t_{asi}
t_s
Substrate

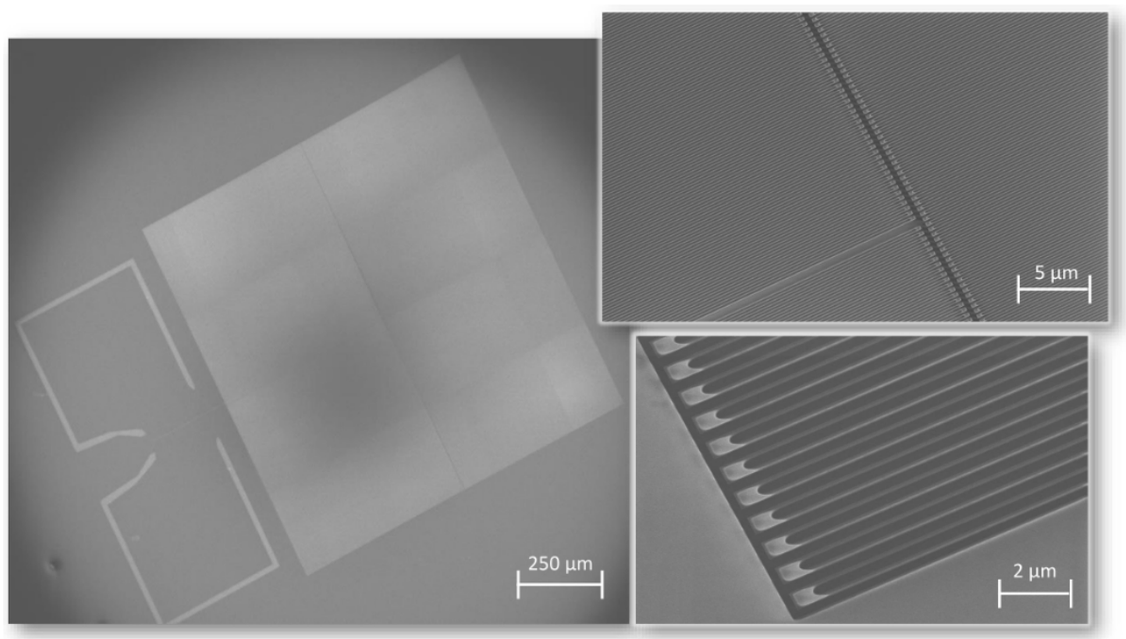
LAMPOST


(a)
Aperture

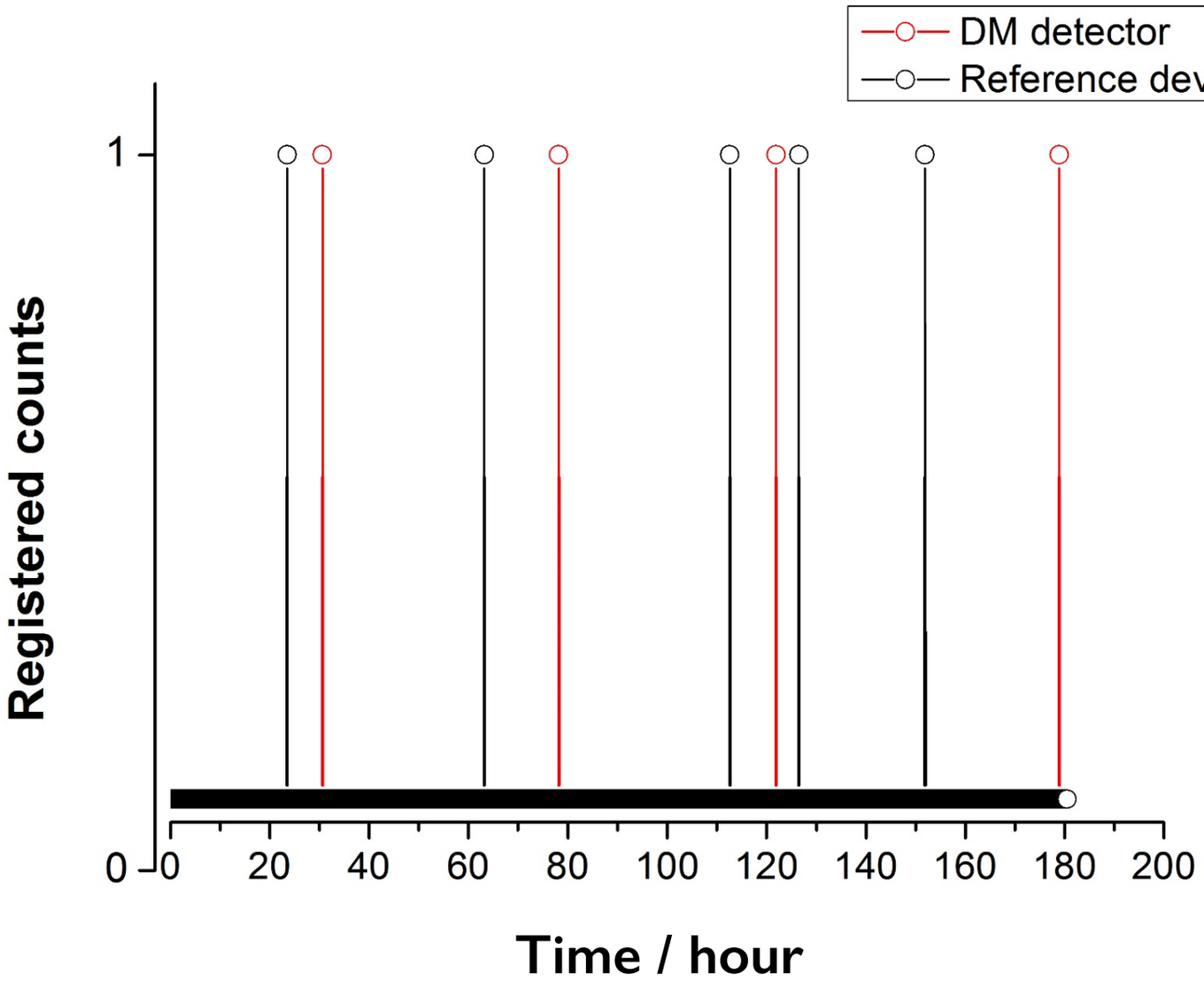

(b)

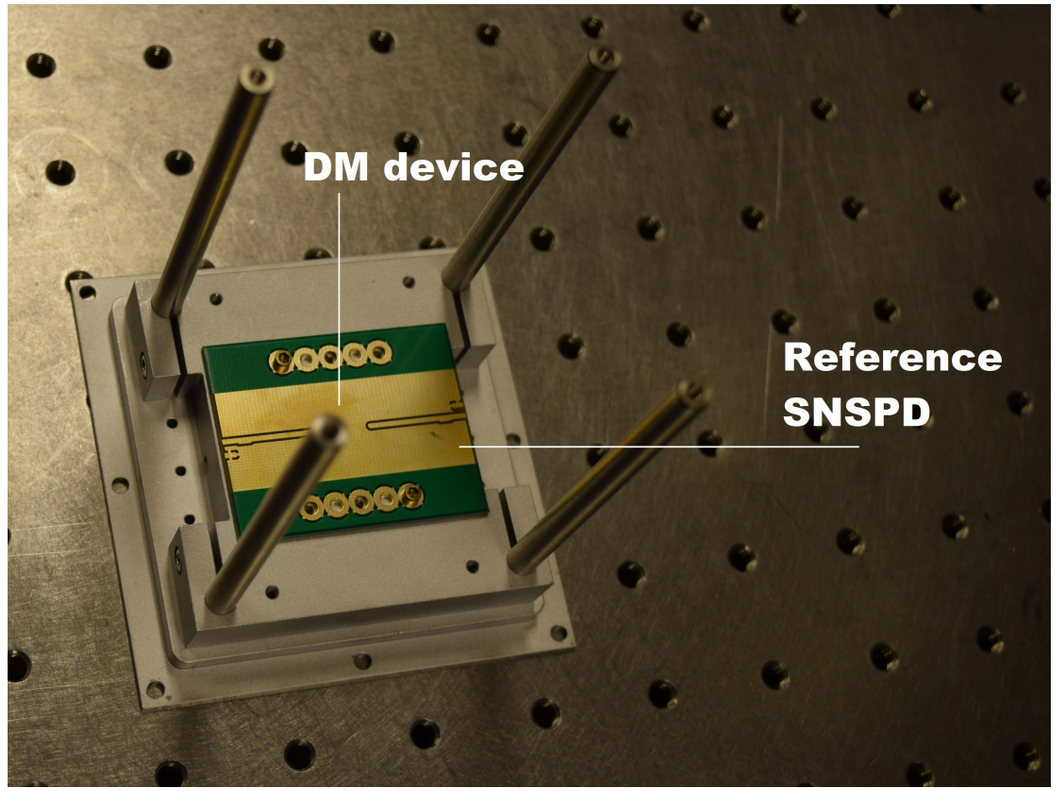

(c)


a-Si
SiO2
258 nm (Δ -25 nm)
562 nm (Δ 13 nm)
258 nm (Δ -25nm)
562 nm (Δ 13 nm)
264 nm (Δ -19 nm)
547 nm (Δ -3 nm)
273 nm (Δ -10 nm)
555 nm (Δ 5 nm)
273 nm (Δ -10 nm)
539 nm (Δ -10 nm


250 µm
5 µm
2 µm

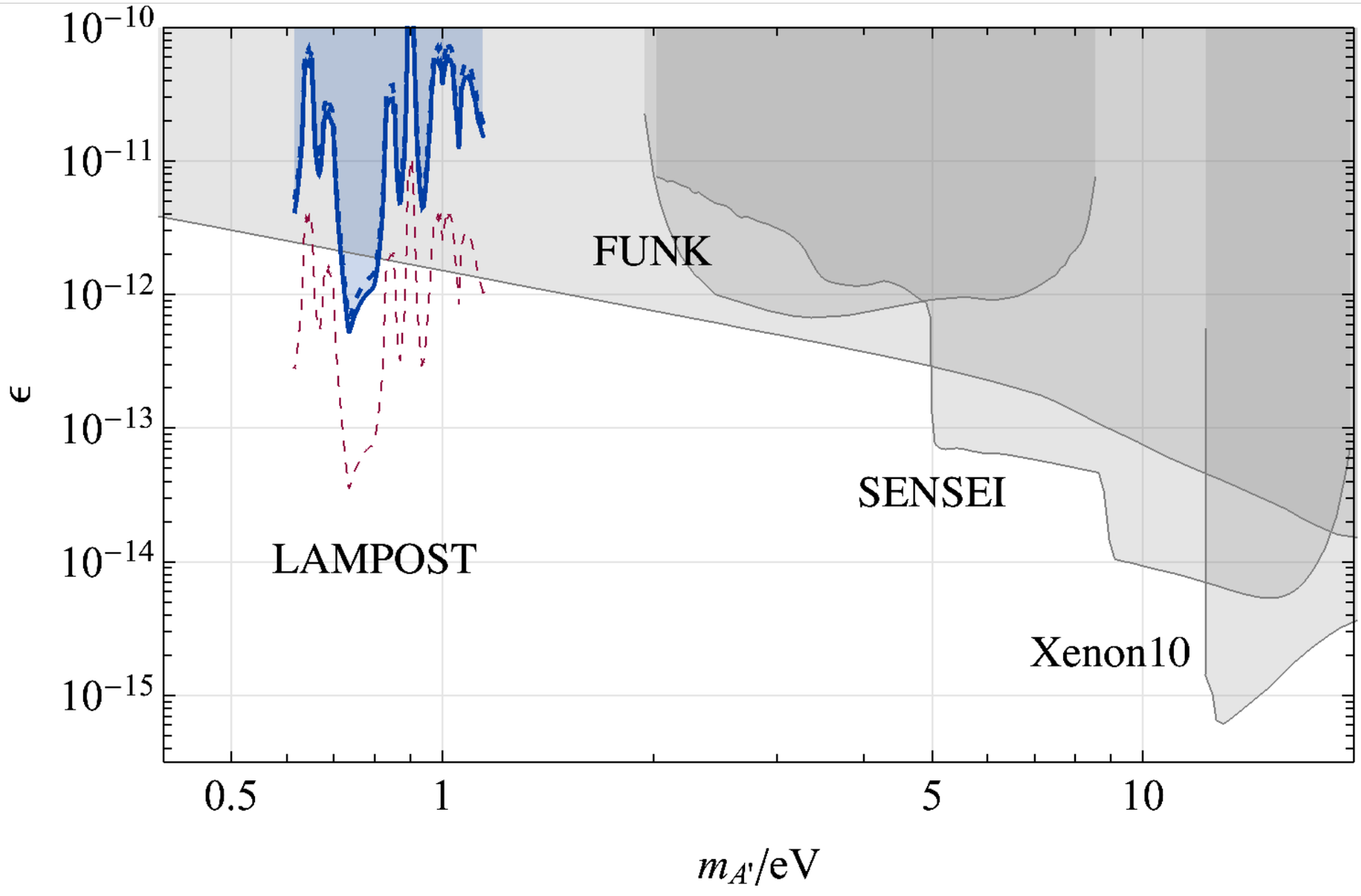
Results


DM detector
Reference device
Registered counts
0
1
0
20
40
60
80
100
120
140
160
180
200
Time / hour


DM device
Reference
SNSPD

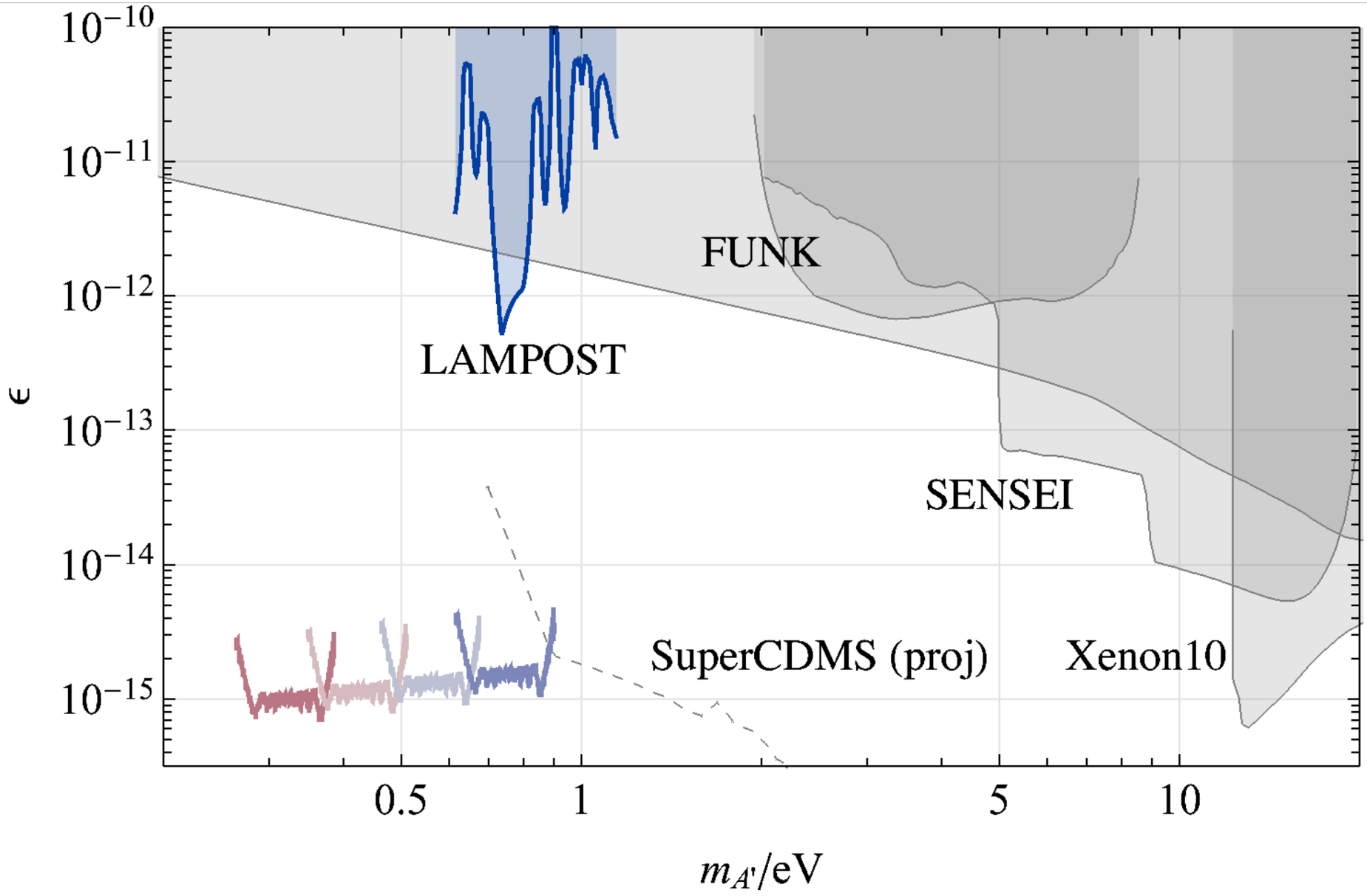
Dark photon dark matter

$$\mathcal{L} \supset -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} - \frac{1}{4}F'_{\mu\nu}F'^{\mu\nu} - \frac{1}{2}\epsilon F_{\mu\nu}F'^{\mu\nu} + \frac{1}{2}m^2_{A'}A'^2$$



Upgrade prospects

Dark photon DM



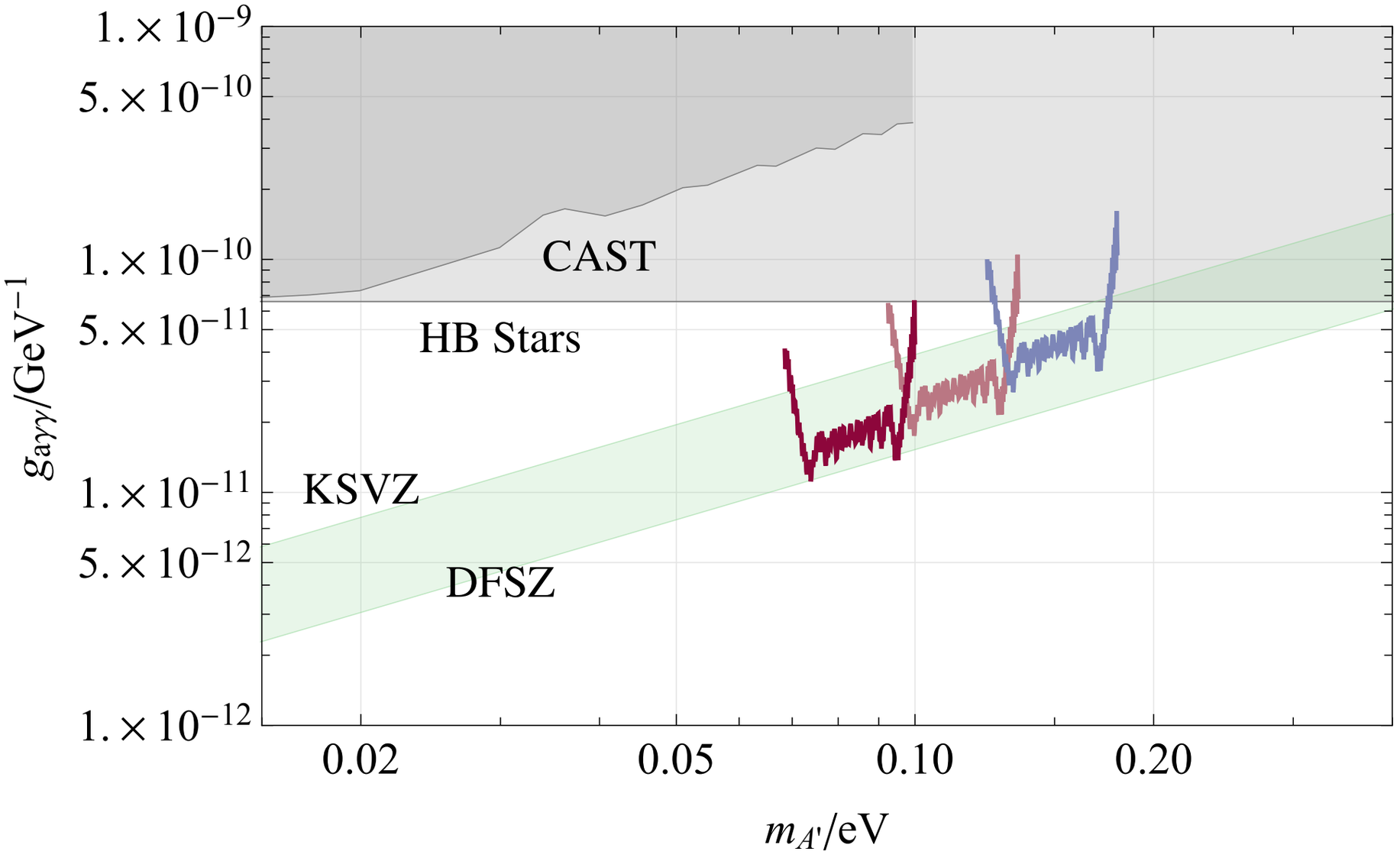
$N_{\rm periods} = 100$

$t_{\rm int} = 100\,{\rm day}$

$R_{\rm disk} = 5\,{\rm cm}$

Upgrade prospects

Axion DM



$N_{\mathrm{periods}} = 100$

$t_{\mathrm{int}} = 100\,\mathrm{day}$

$R_{\mathrm{disk}} = 5\,\mathrm{cm}$

$B = 10\,\mathrm{T}$

DM detection theory

Are there better ways of absorbing DM?

DM detection theory

$$|\psi_I(t)\rangle = \mathcal{T}\left\{e^{-i\int_0^t dt' H_I(t')}\right\}|\psi\rangle \simeq \left(1 - i\int_0^t dt' H_I(t')\right)|\psi\rangle$$
$$\equiv \left(1 - i\hat{V}\right)|\psi\rangle$$

DM detection theory

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$$\equiv \left(1 - i\hat{V}\right)|\psi\rangle$$

$$\Rightarrow \qquad |\langle\psi_I(t)|\psi\rangle| \simeq 1 - \frac{1}{2}\langle\psi|\left(\hat{V} - \langle\psi|\hat{V}|\psi\rangle\right)^2|\psi\rangle$$

Detectability of forcing ⇔ Fluctuations of interaction operator

$aF_{\mu\nu}\tilde{F}^{\mu\nu}$: axion

$F_{\mu\nu}F'^{\mu\nu}$: dark photon

: fluctuations of EM field

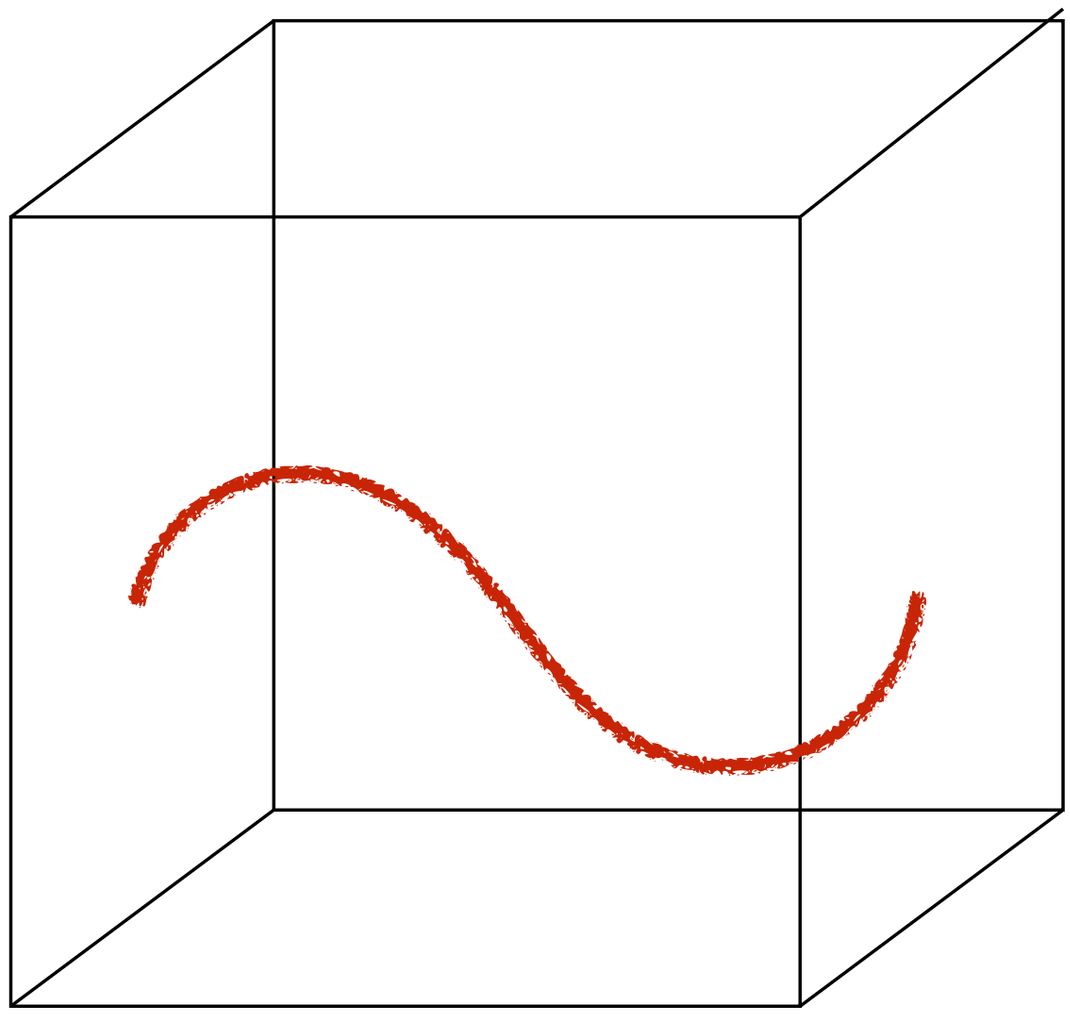
EM field fluctuations

"one photon per mode":

$$(\delta E)^2 V \sim \omega$$

$$\Rightarrow$$

$$(\delta A)^2 \sim \frac{1}{V\omega}$$



EM sum rules

$$\int_{-\infty}^{\infty} d\omega\, \omega\, \mathcal{F}_\omega \langle \hat{A}(t)\hat{A}(0)\rangle = \frac{\pi}{V}$$

c.f. permittivity sum rule:

$$\int_{-\infty}^{\infty} \frac{d\omega}{\omega} \mathrm{Im}\left(\frac{-1}{\epsilon(\omega)}\right) = \pi$$

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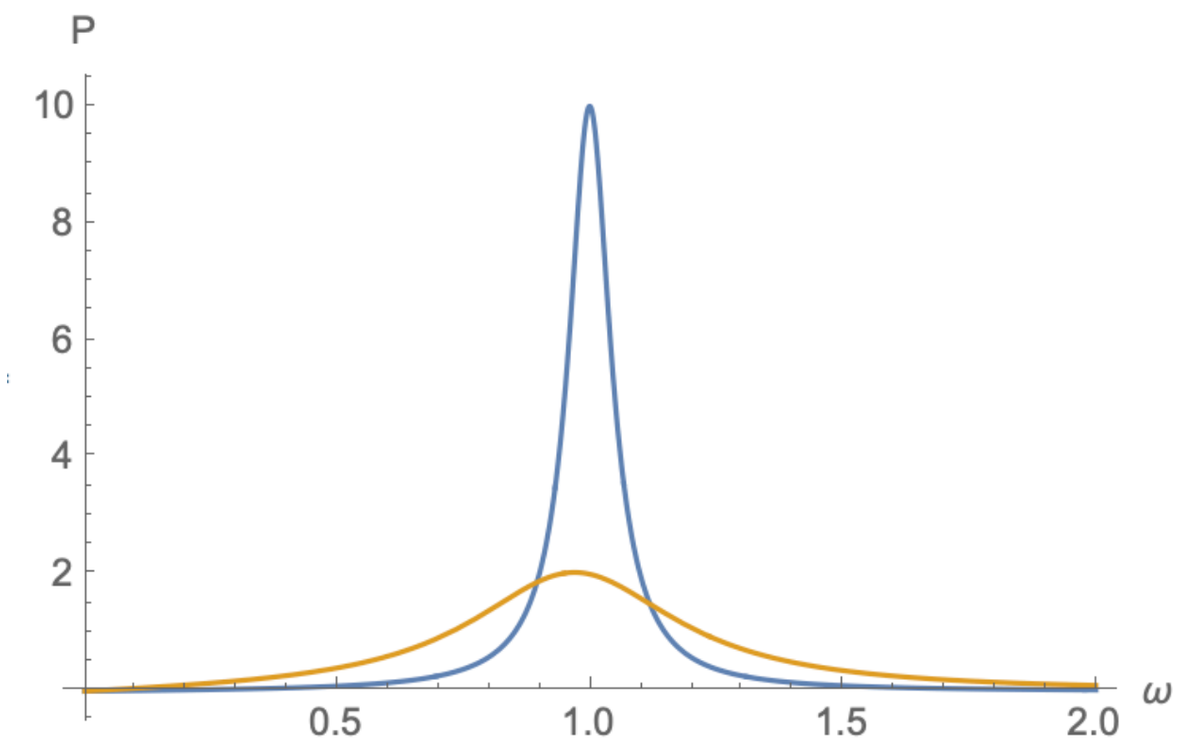

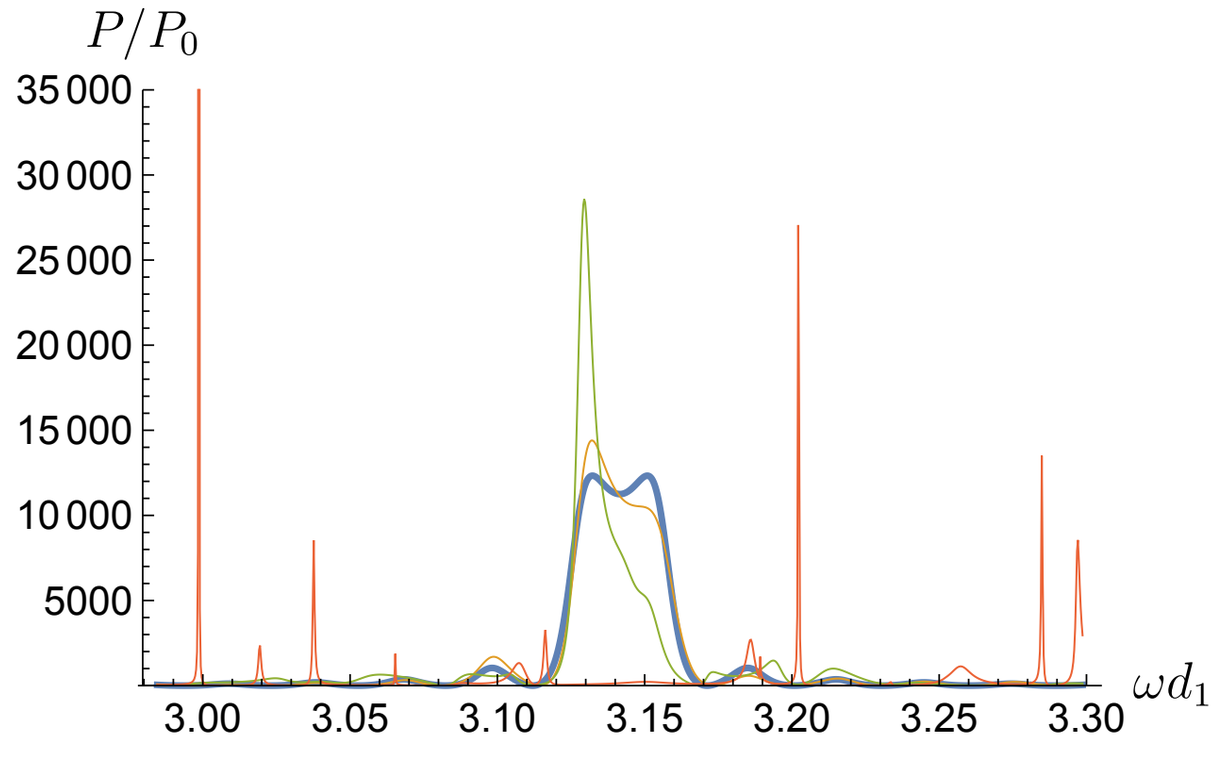

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Consequences for axion DM detection:

$$\mathcal{L} \supset \frac{1}{2}(\partial_\mu a)^2 - V(a) - \frac{1}{4} g a F_{\mu\nu}\tilde{F}^{\mu\nu}$$

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Consequences for axion DM detection:

$$\mathcal{L}_{\mathrm{int}} = \frac{1}{2} g \dot{a} B \cdot A$$

$$\mathcal{L} \supset \frac{1}{2}(\partial_\mu a)^2 - V(a) - \frac{1}{4} g a F_{\mu\nu} \tilde{F}^{\mu\nu}$$

EM sum rules

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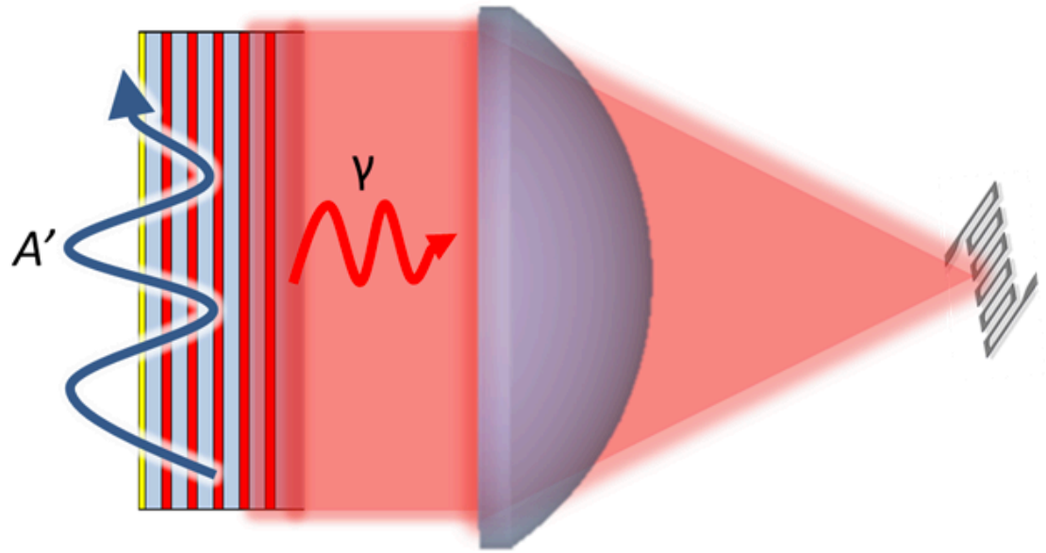
Searching for axion over mass range Δm: excitation probability

$$\bar{\mathbb{P}}_{\mathrm{ex}} \leq \frac{\pi}{2} \frac{g^2 \rho_a V B^2 t_{\mathrm{exp}}}{m \Delta m}$$

DM sensitivity

- Dielectric haloscope

$$\bar{P} = \frac{4}{\pi} \frac{g^2 B^2 V \rho_a}{\Delta m} \left(\frac{1}{n_2} - \frac{1}{n_1} \right)^2$$



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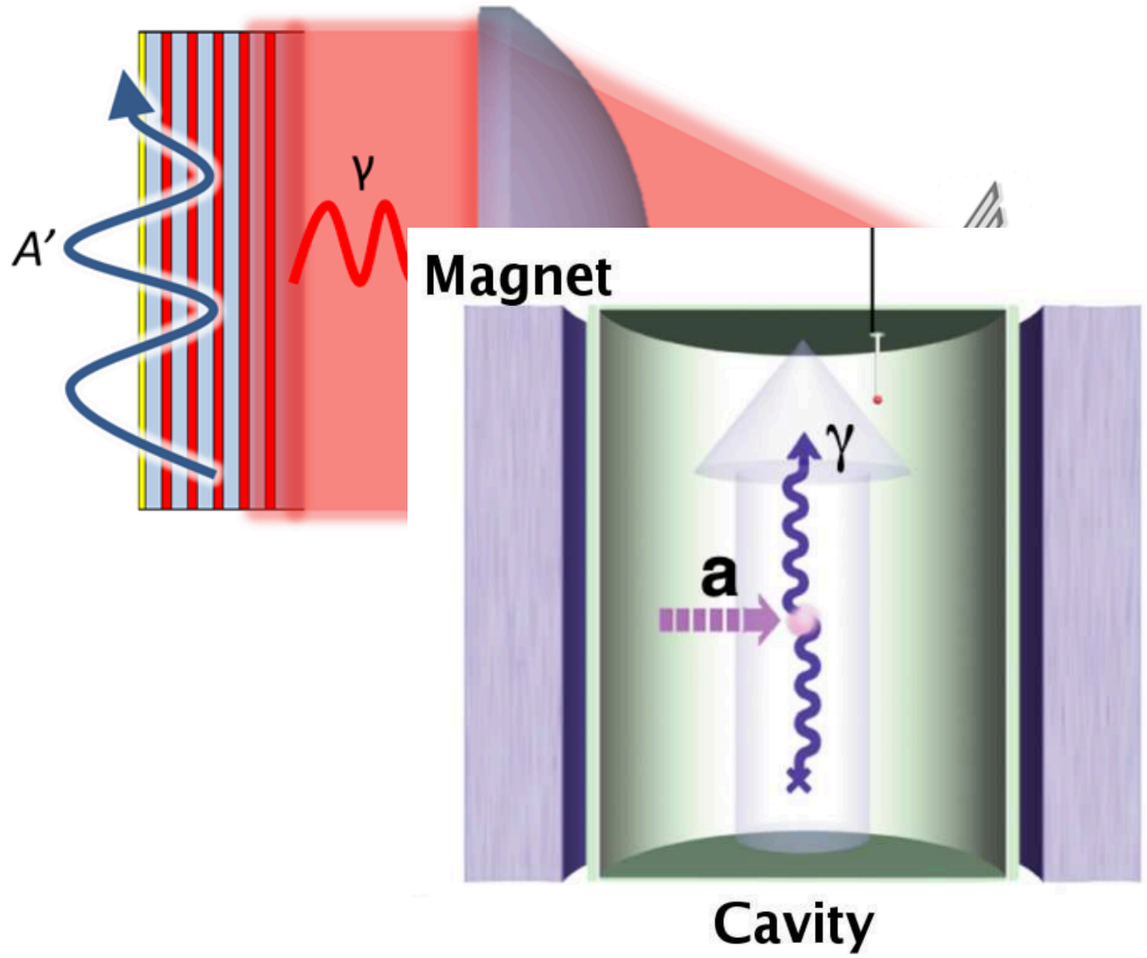
- Resonant cavity (e.g. ADMX)

$$\bar{P} = \frac{g^2 B^2 V \rho_a}{\Delta m} \frac{\pi}{2} C_{\text{mode}}$$



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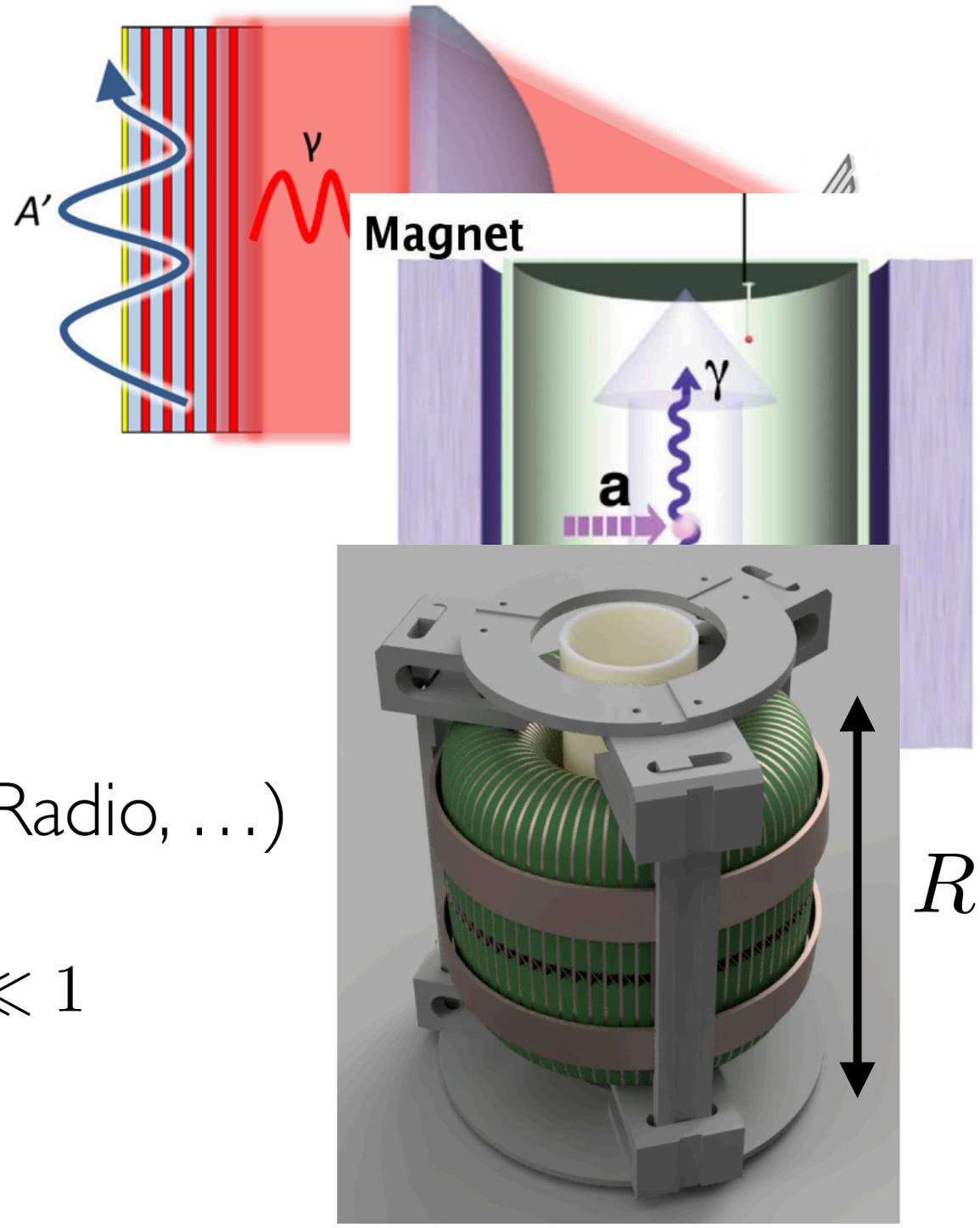
- Resonant cavity (e.g. ADMX)

$$\bar{P} = \frac{g^2 B^2 V \rho_a}{\Delta m}\frac{\pi}{2} C_{\rm mode}$$

- LC circuits (ABRACADABRA, DMRadio, …)

$$\bar{P} \sim \frac{g^2 B^2 V \rho_a}{\Delta m}(mR)^2 \quad , \qquad mR \ll 1$$

Quasi-static suppression



Axion up-conversion

$$\mathcal{L} \supset \frac{1}{2}(\partial_\mu a)^2 - V(a) + gaE \cdot B$$

$$J_a = g\dot{a}(t)B(t)$$

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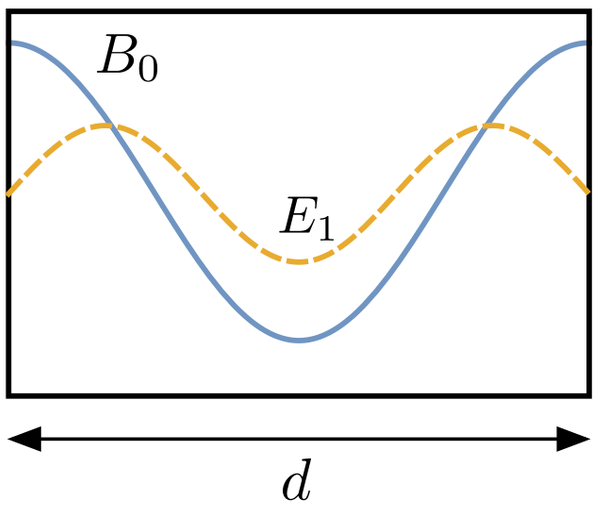
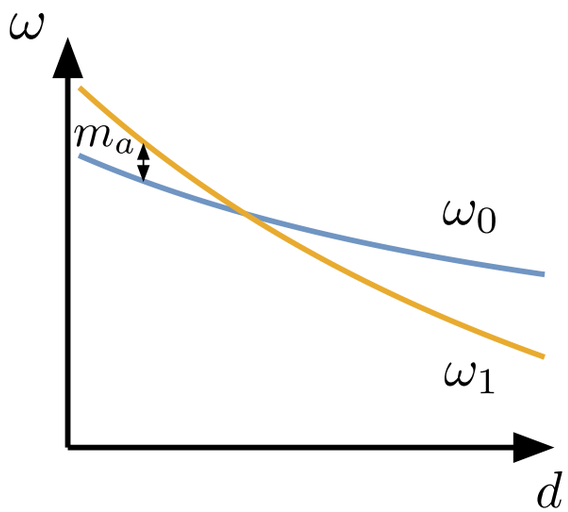
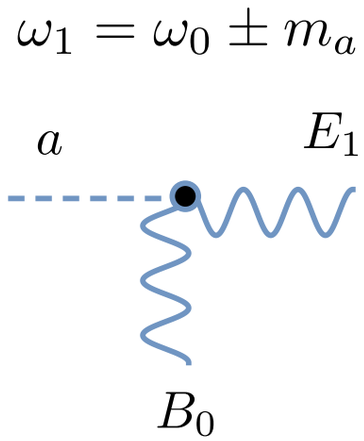


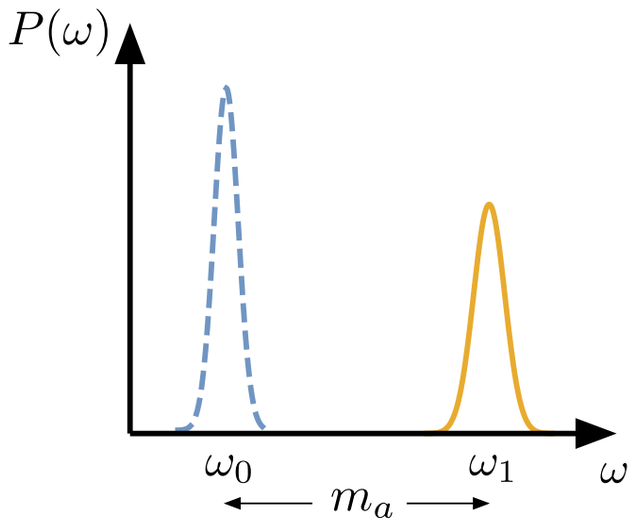
Cavity modes



Mode frequencies



Interaction



Signal

Axion up-conversion

SRF cavities:

$$f \sim \mathrm{GHz}$$

$$B_{\mathrm{wall}} \lesssim 0.2\,\mathrm{T}$$

$$Q \gtrsim 10^{11}$$

$$\bar{P} \sim \frac{g^2 \bar{B}^2 V \rho_a}{\Delta m} C_{01}$$

Axion up-conversion

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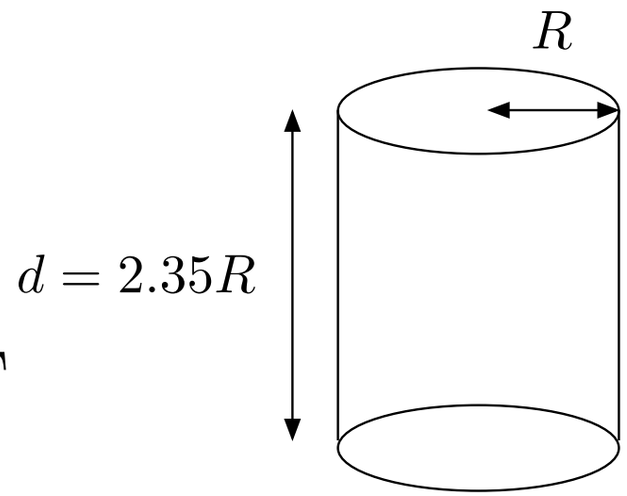
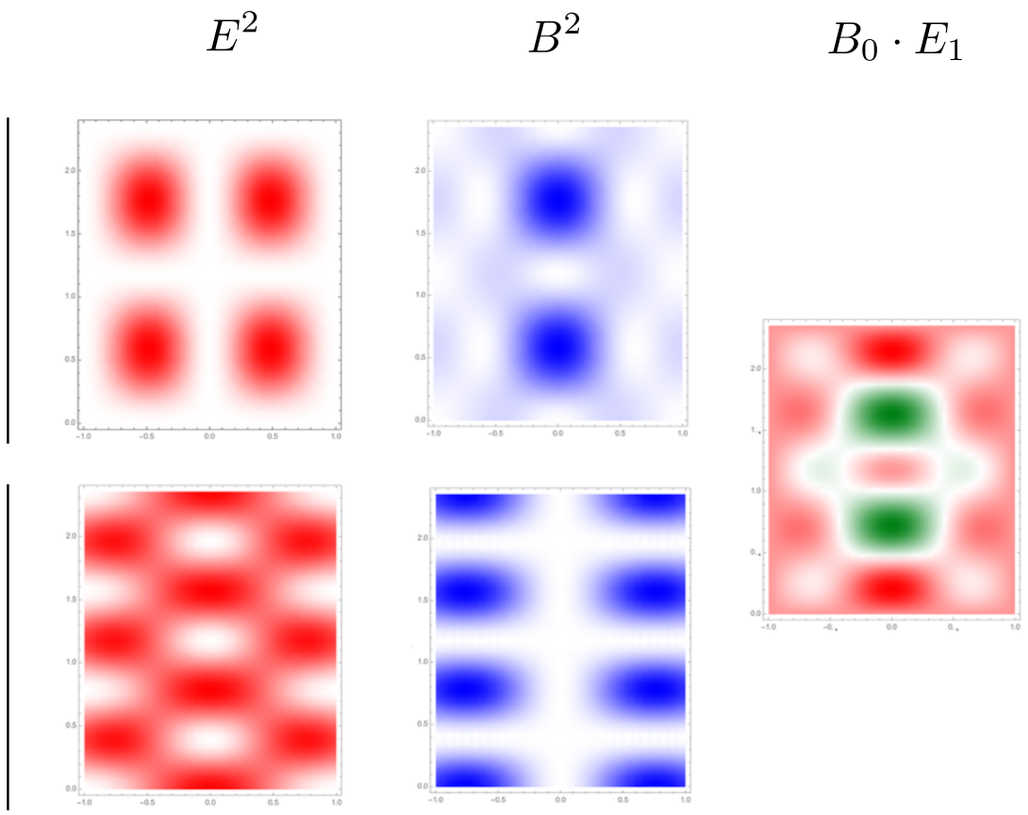


TE_{012} (drive)

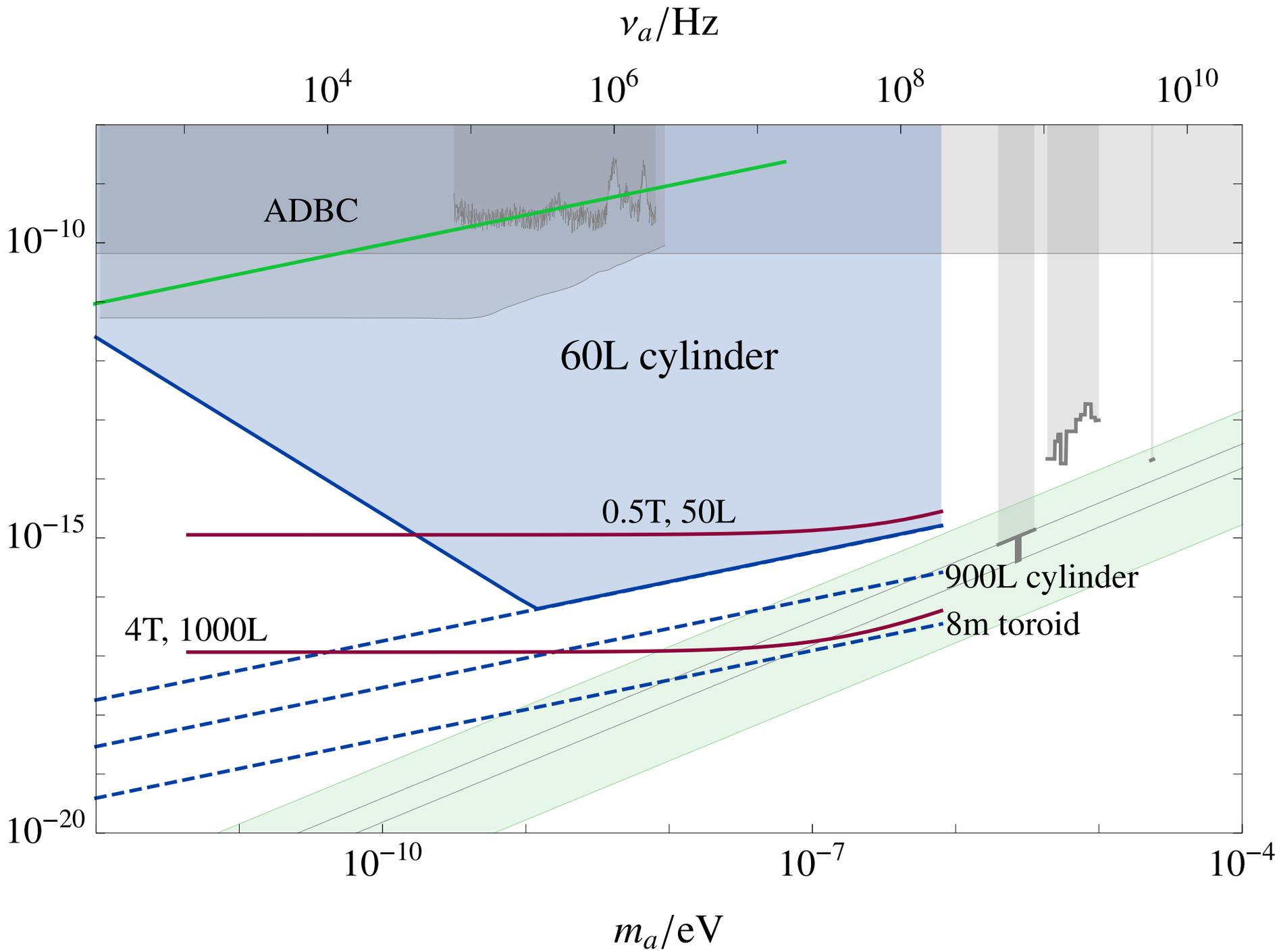
TM_{013} (signal)



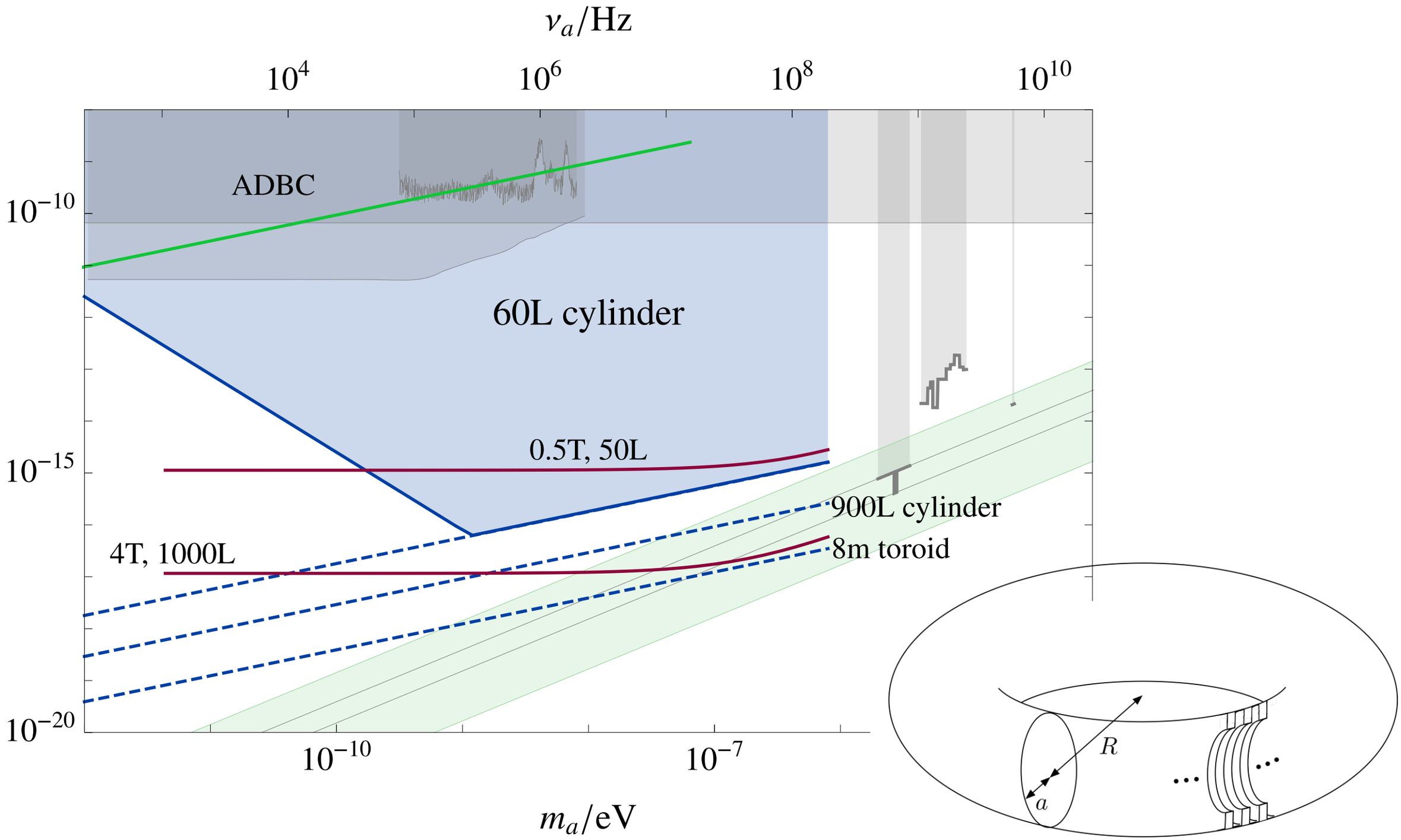
$$\bar{P} \sim \frac{g^2 \bar{B}^2 V \rho_a}{\Delta m} C_{01}$$

$C_{01} \to 0.19$

Sensitivity projections



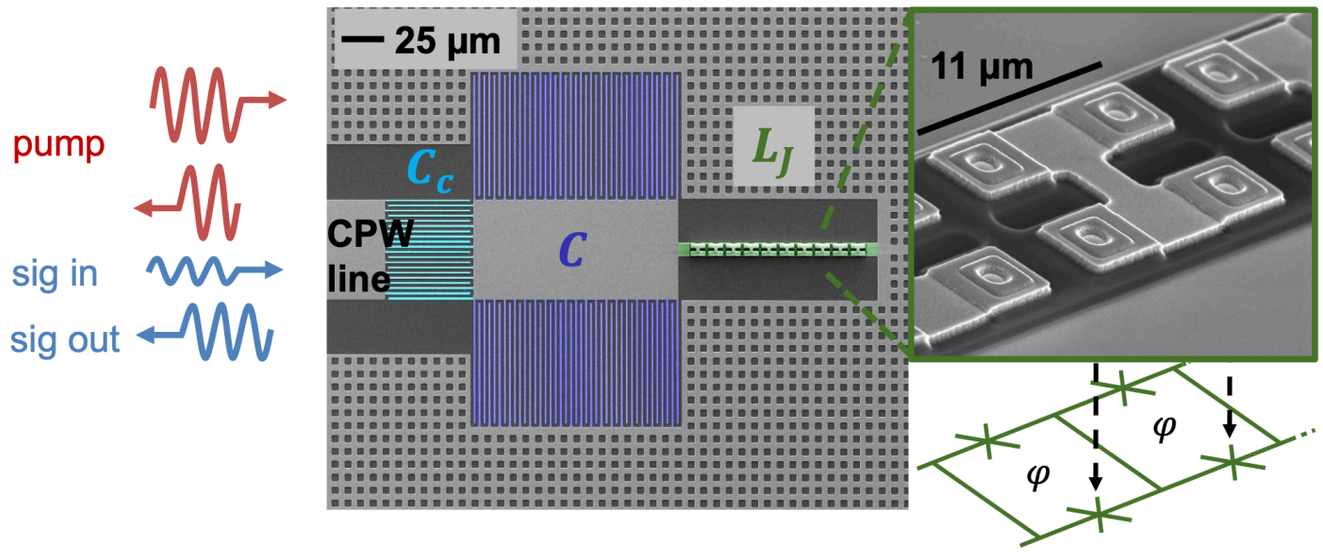
Sensitivity projections



Quantum-limited sensitivity

Quantum-limited amplifiers:

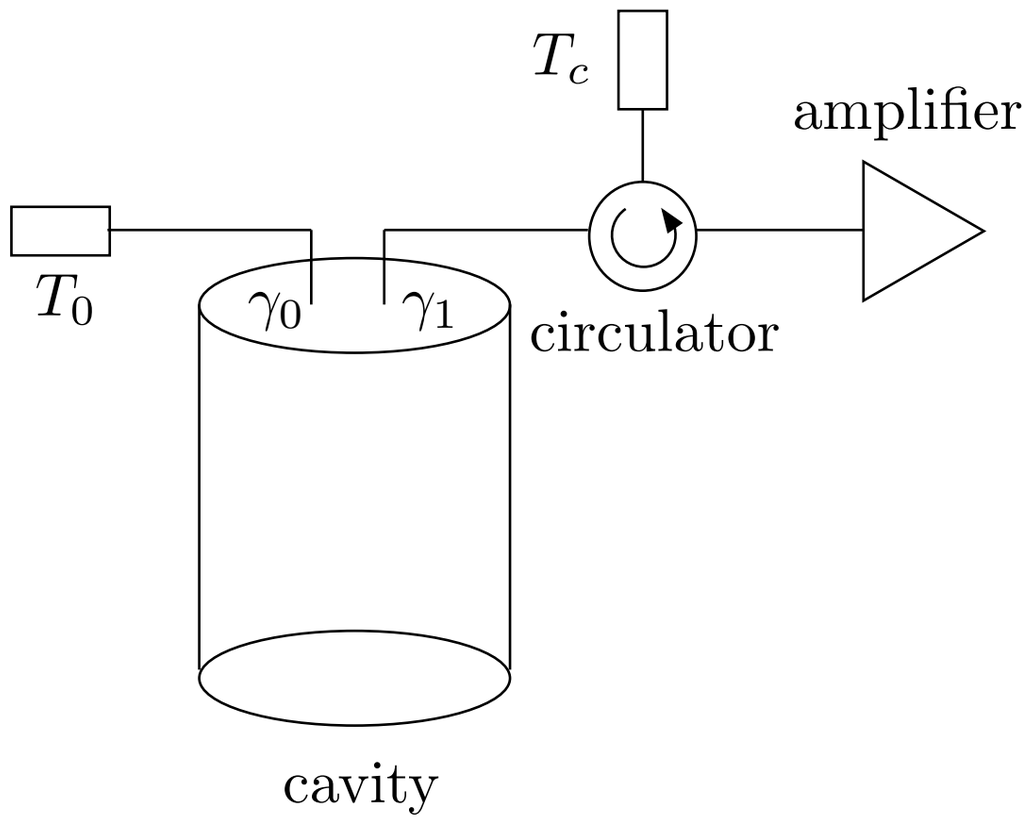
(JPA)



$$T_{\text{cavity}} \sim \text{few K} \gg 2\pi\,\text{GHz}$$

Mitigation: over-couple to cold load

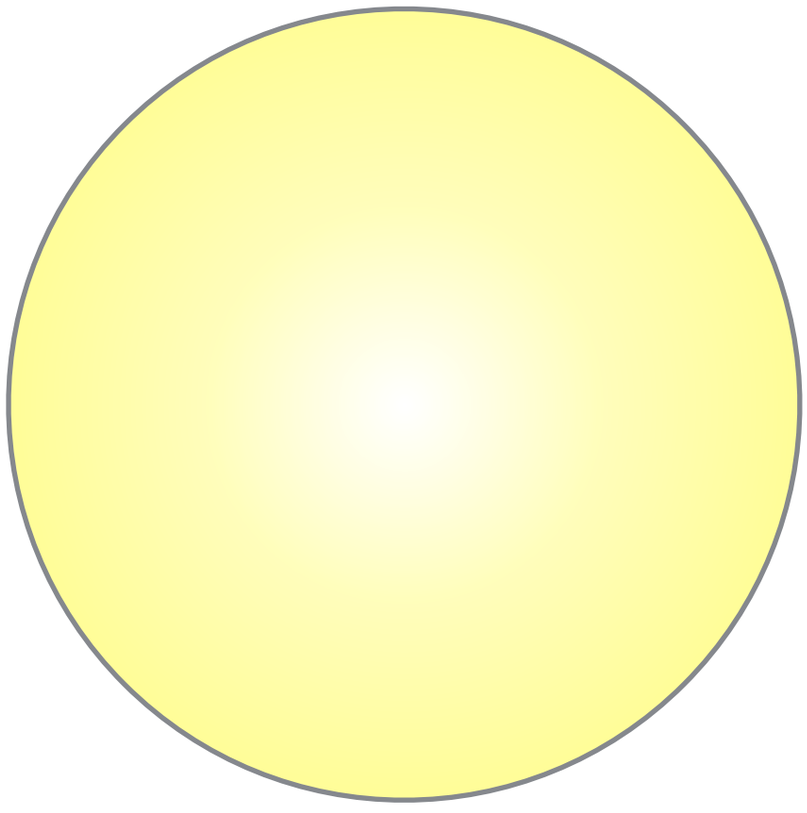
$$T_{\text{eff}} = \frac{\gamma_0 T_0 + \gamma_1 T_c}{\gamma_0 + \gamma_1}$$



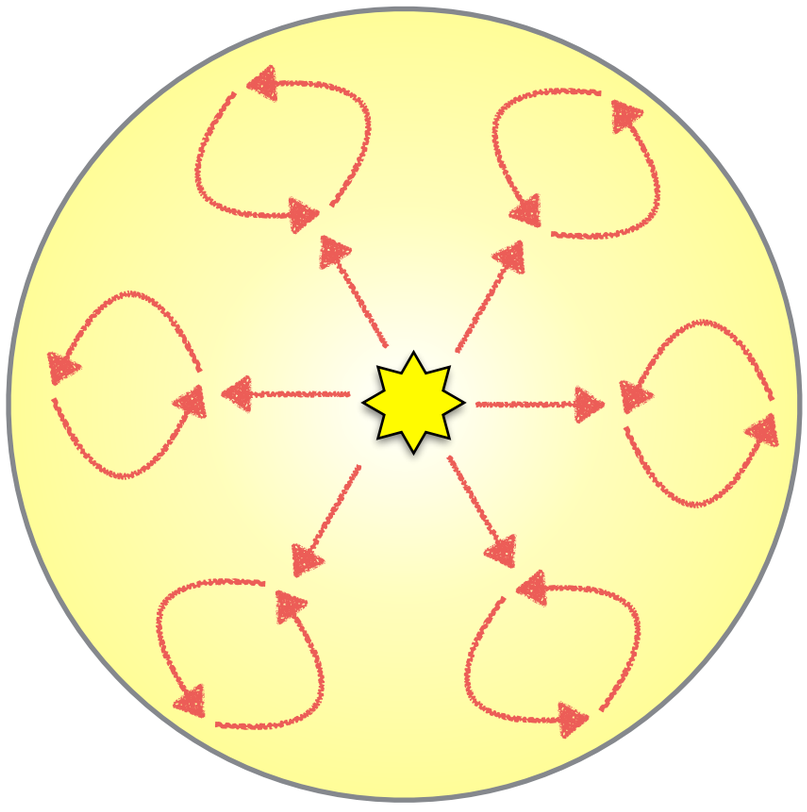
Intermission

- Thinking systematically about detection of new physics → new experimental concepts
- Other detection problems
    - Different couplings, DM scattering, Gravitational Waves …
- As well as thinking about how to look for things, need to think about what to look for!

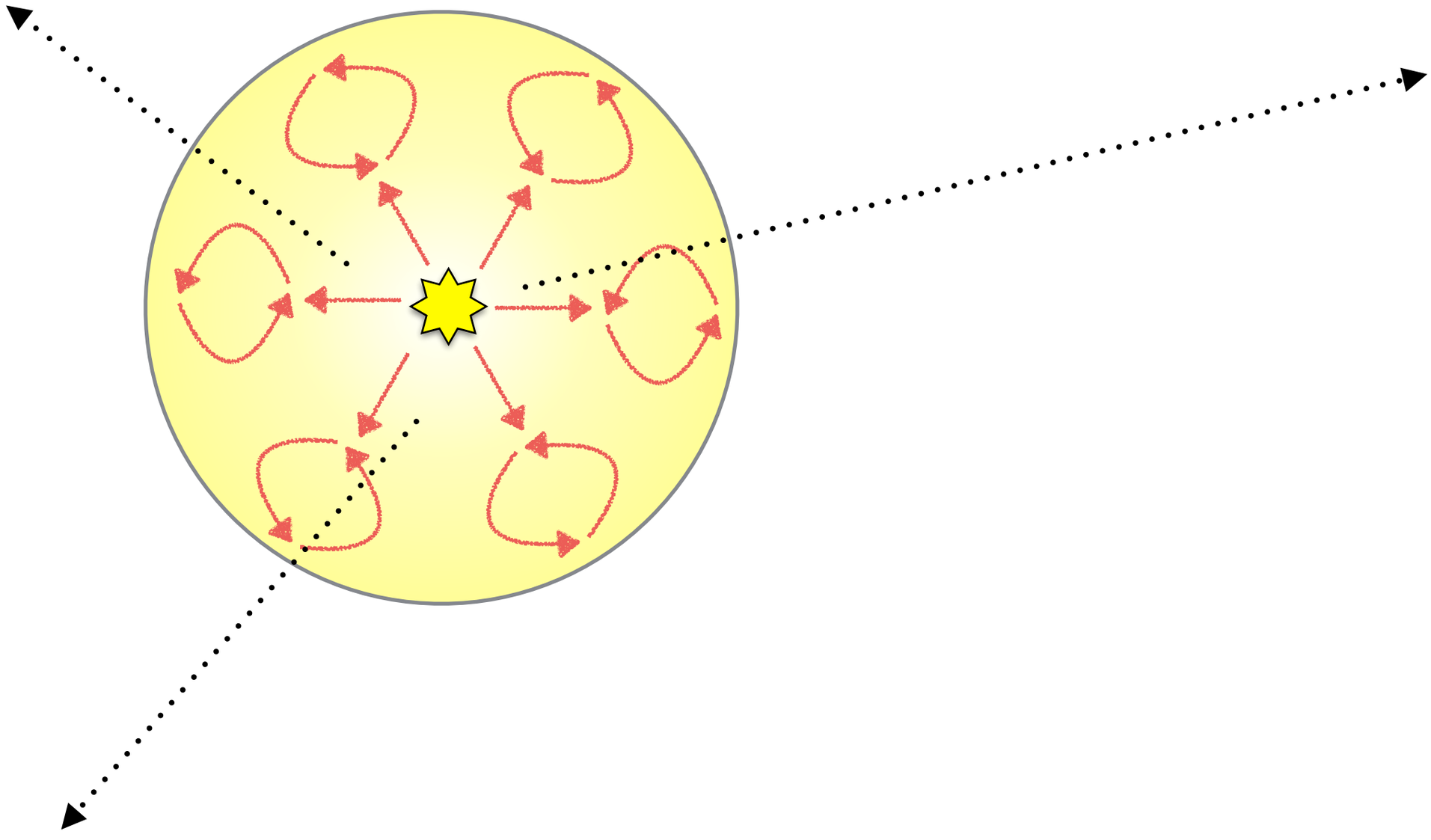
Solar particle production



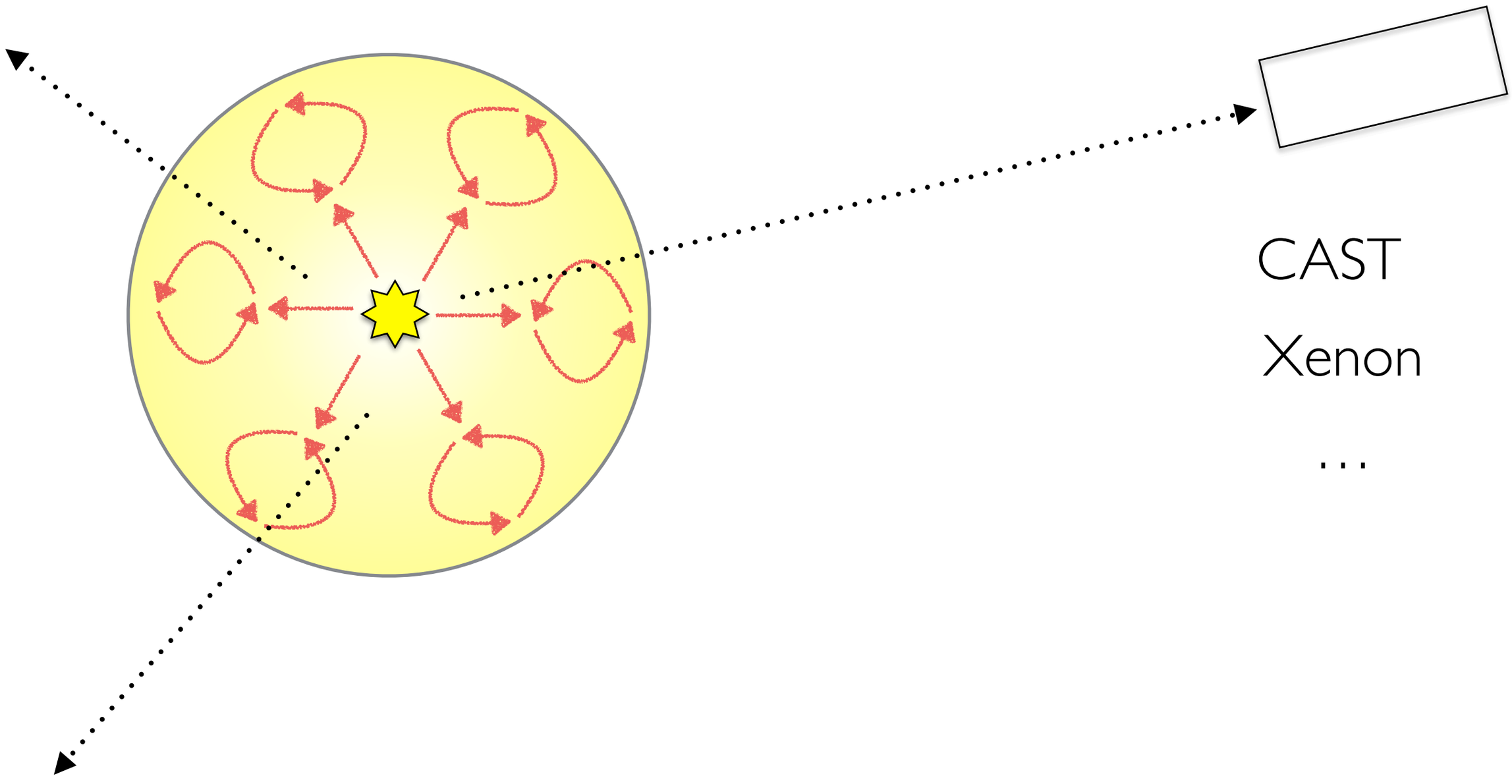
Solar particle production



Solar particle production



Solar particle production

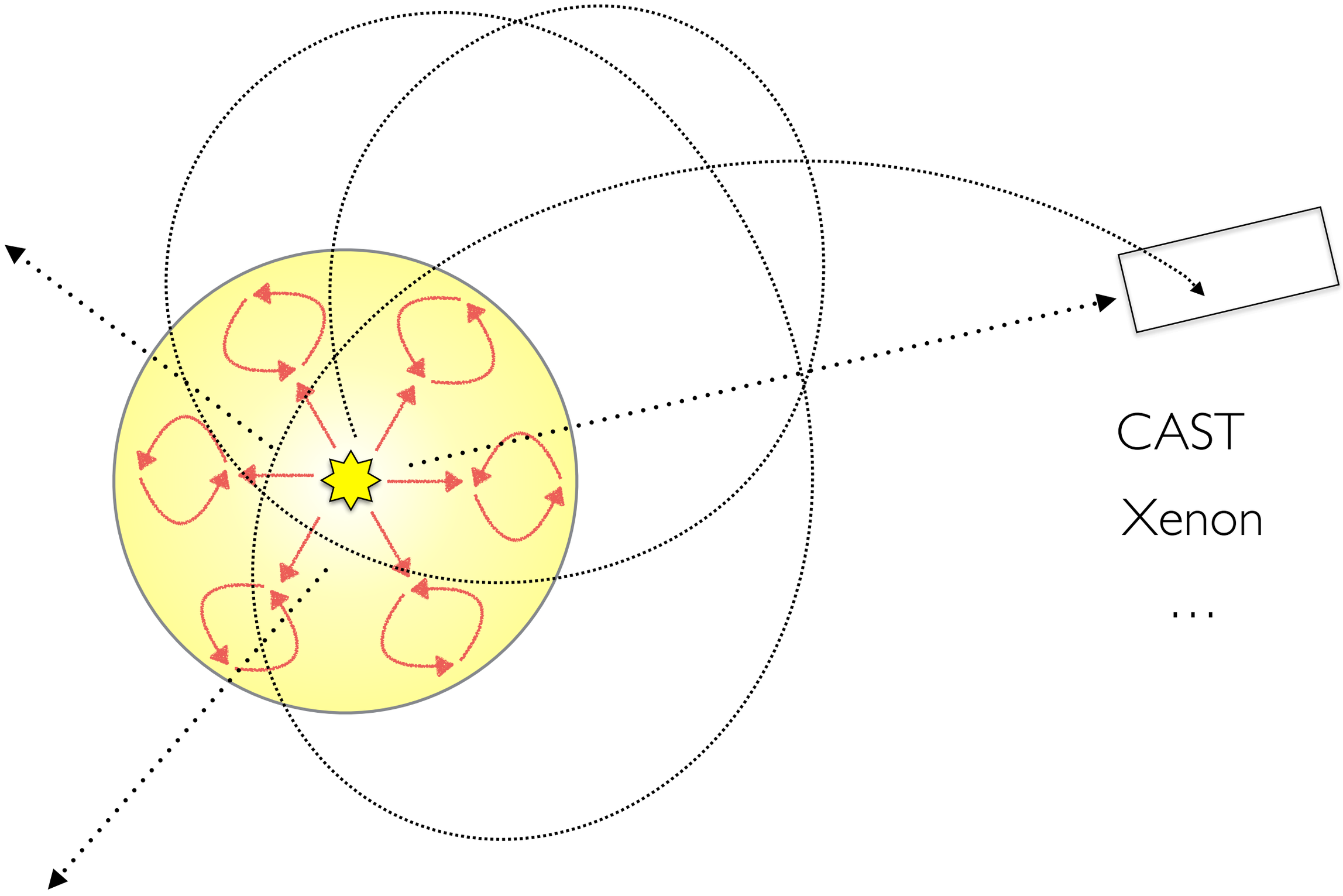


CAST

Xenon

…

Solar particle production



CAST

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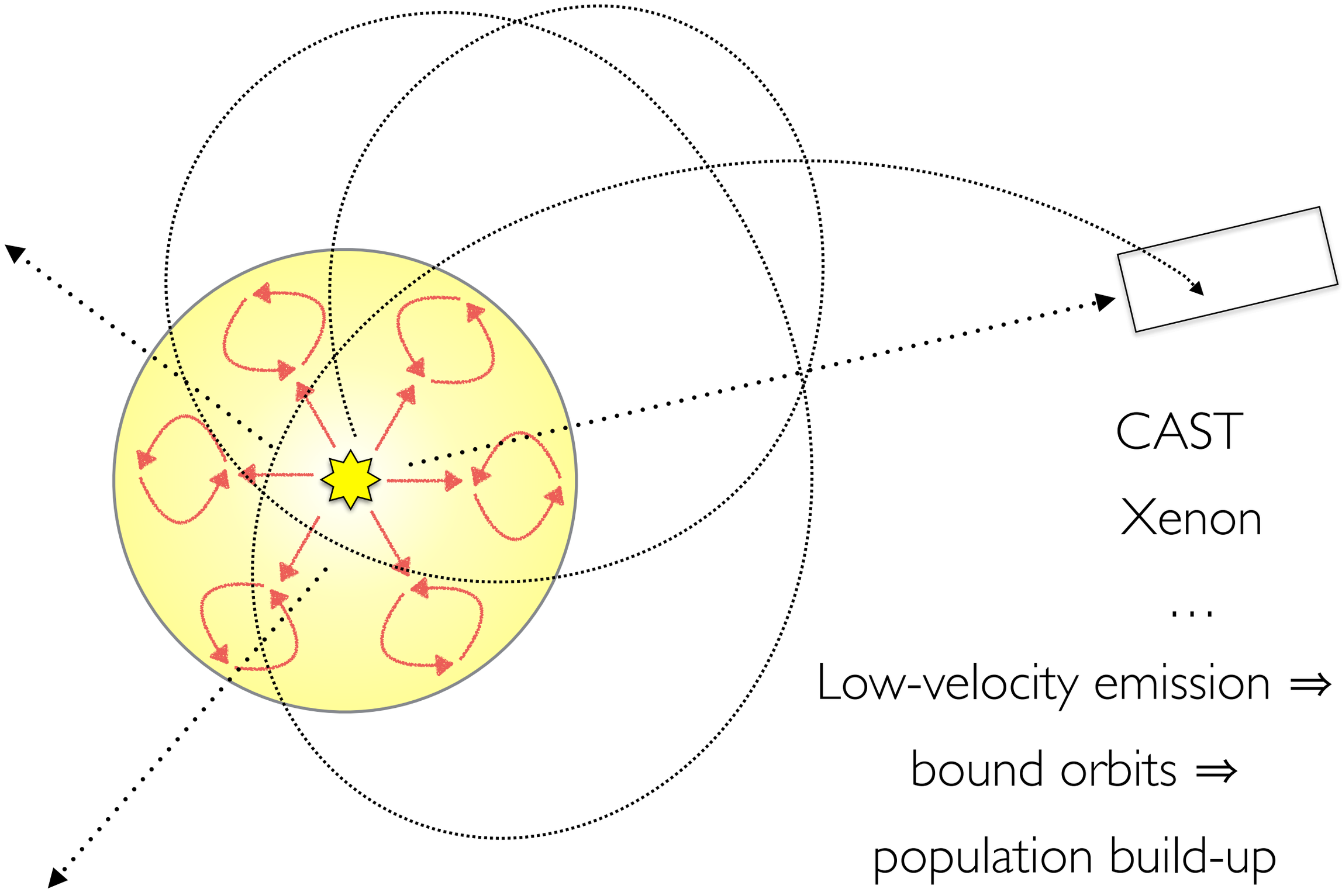
Solar particle production



CAST

Xenon

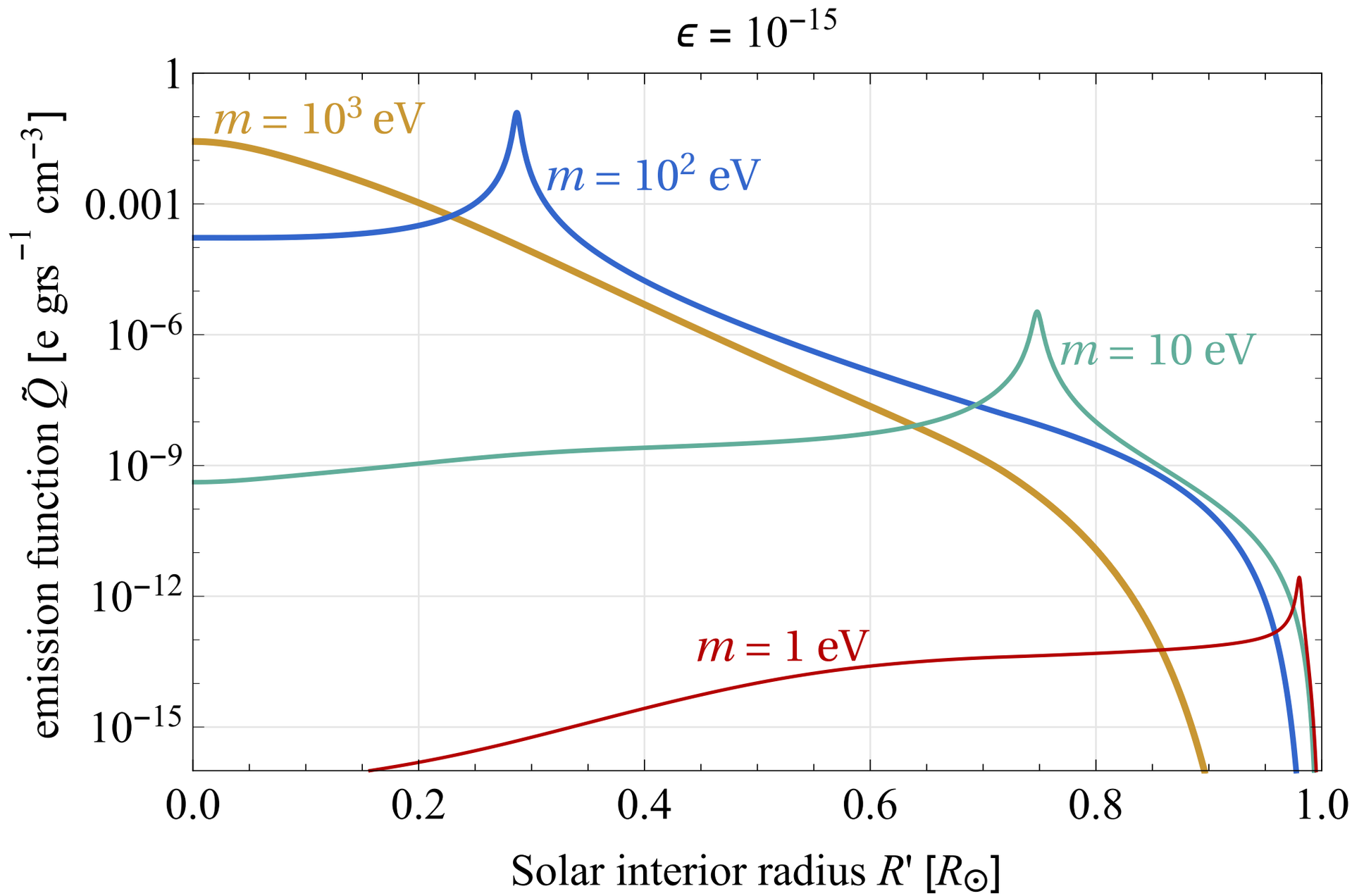
...

Low-velocity emission ⇒

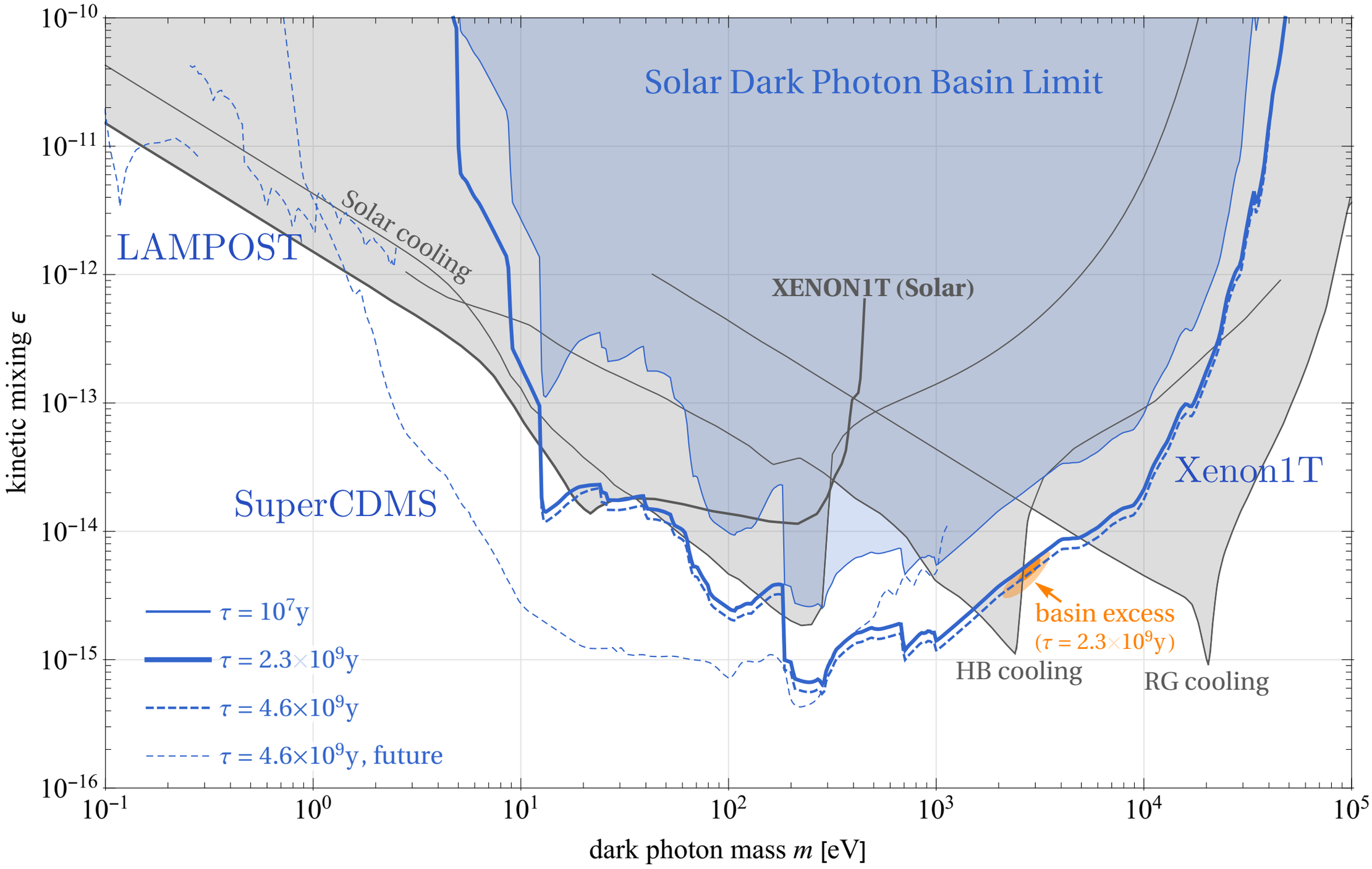
bound orbits ⇒

population build-up

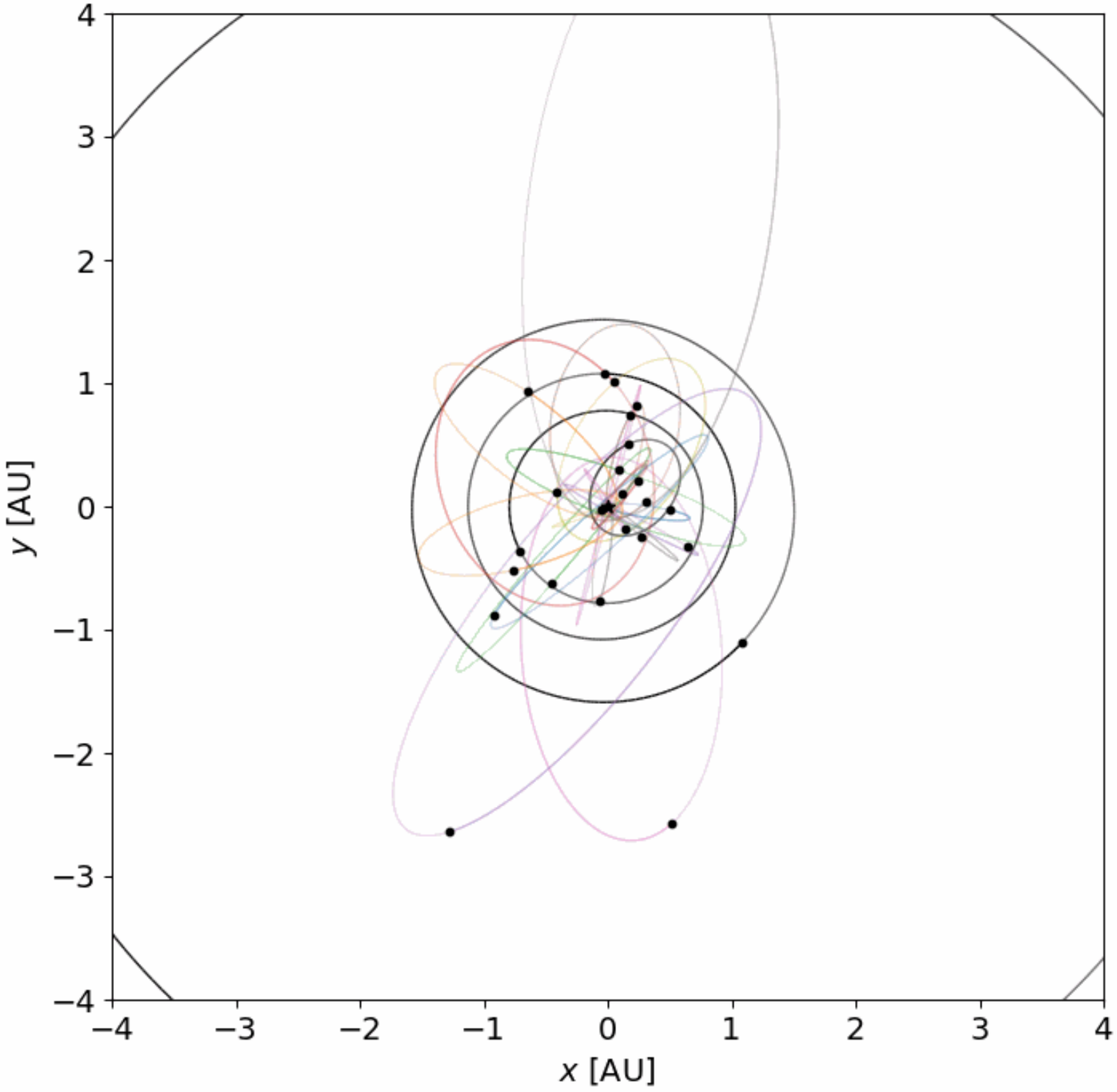
Dark photon production

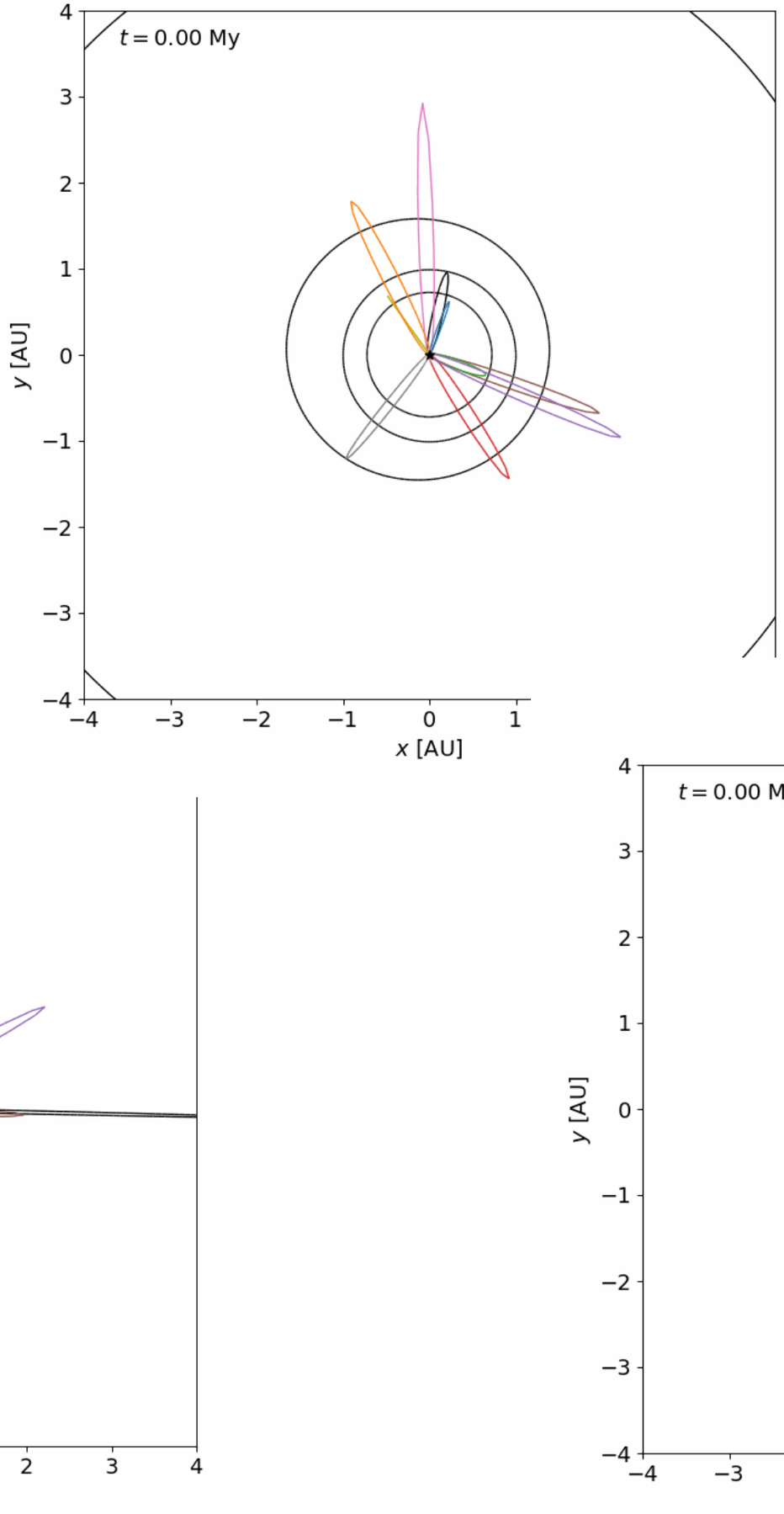


Dark photon sensitivity

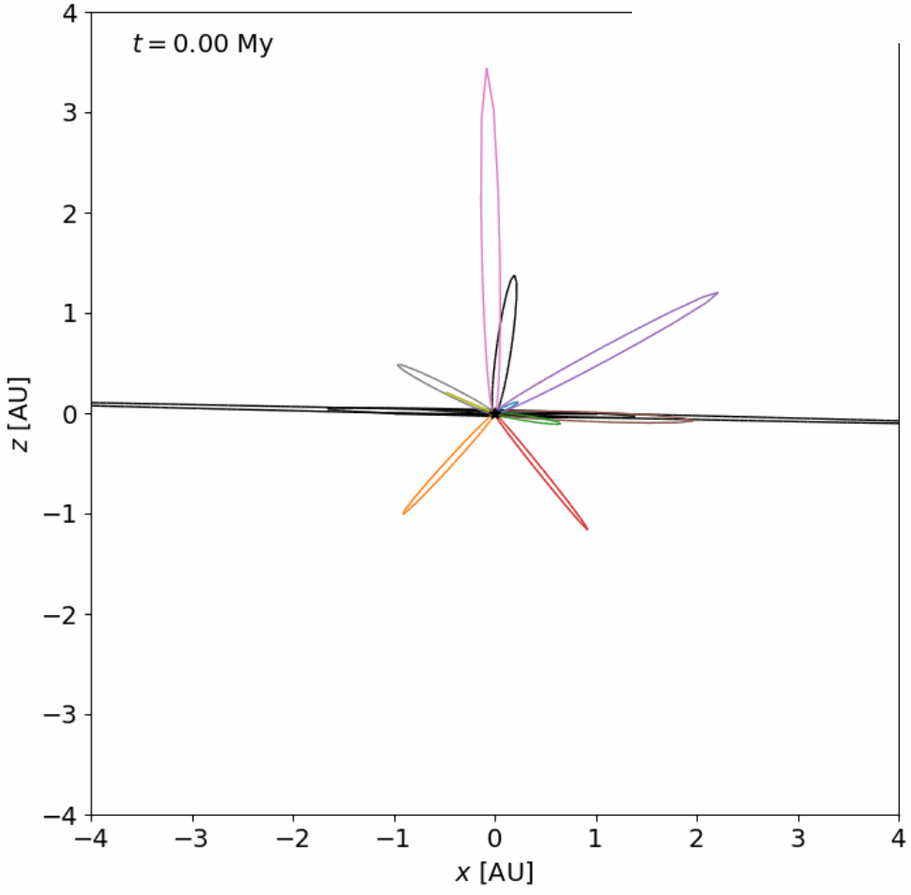


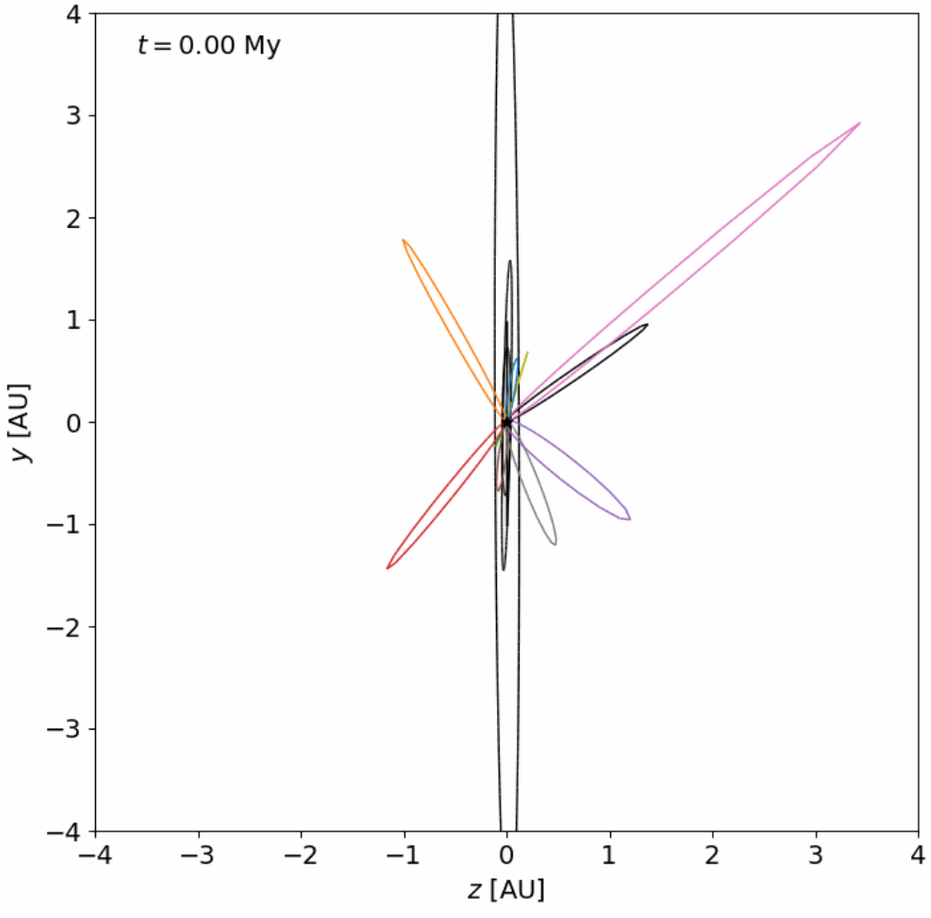
Orbital dynamics [PRELIMINARY]





[PRELIMINARY]





Orbital dynamics

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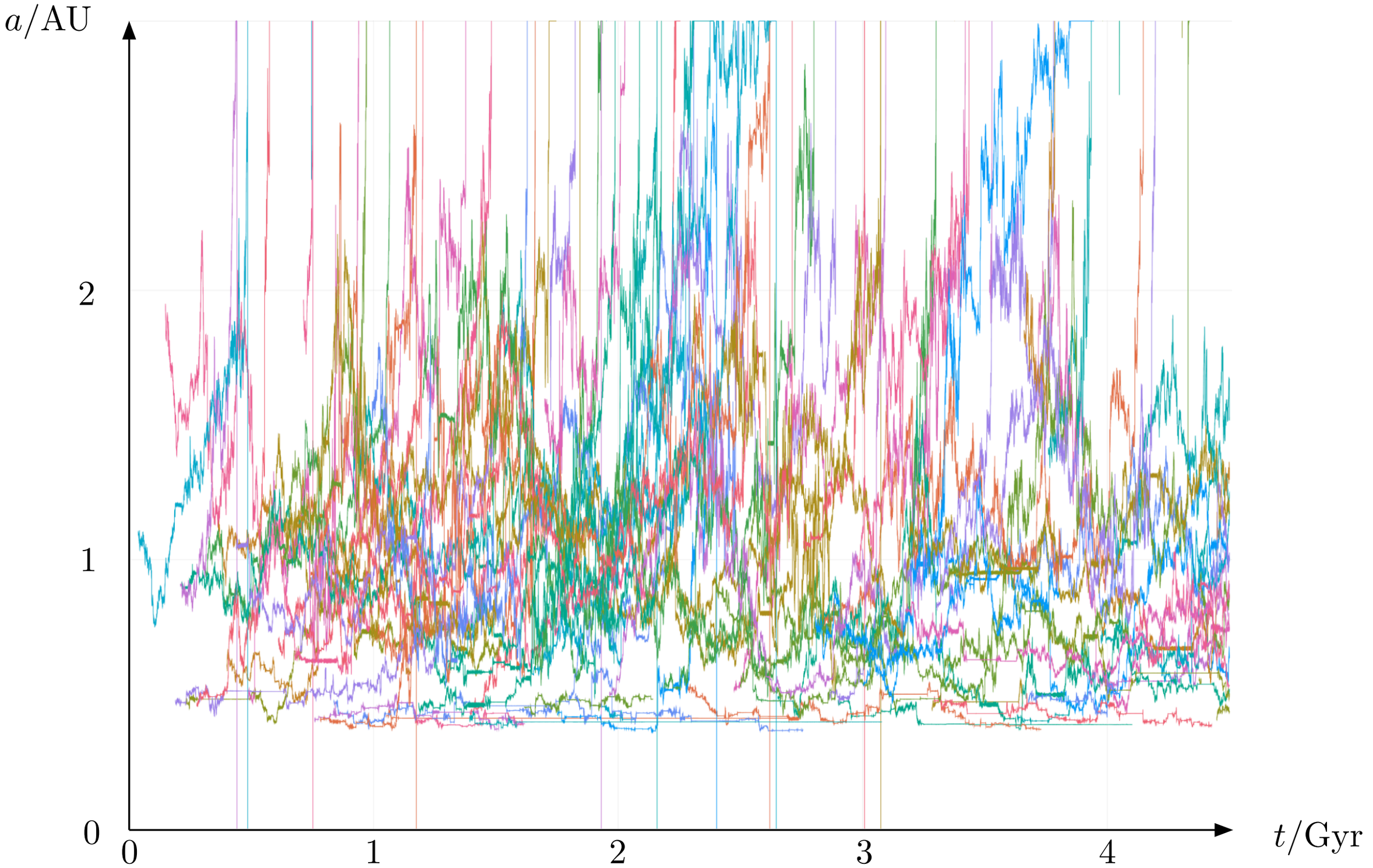

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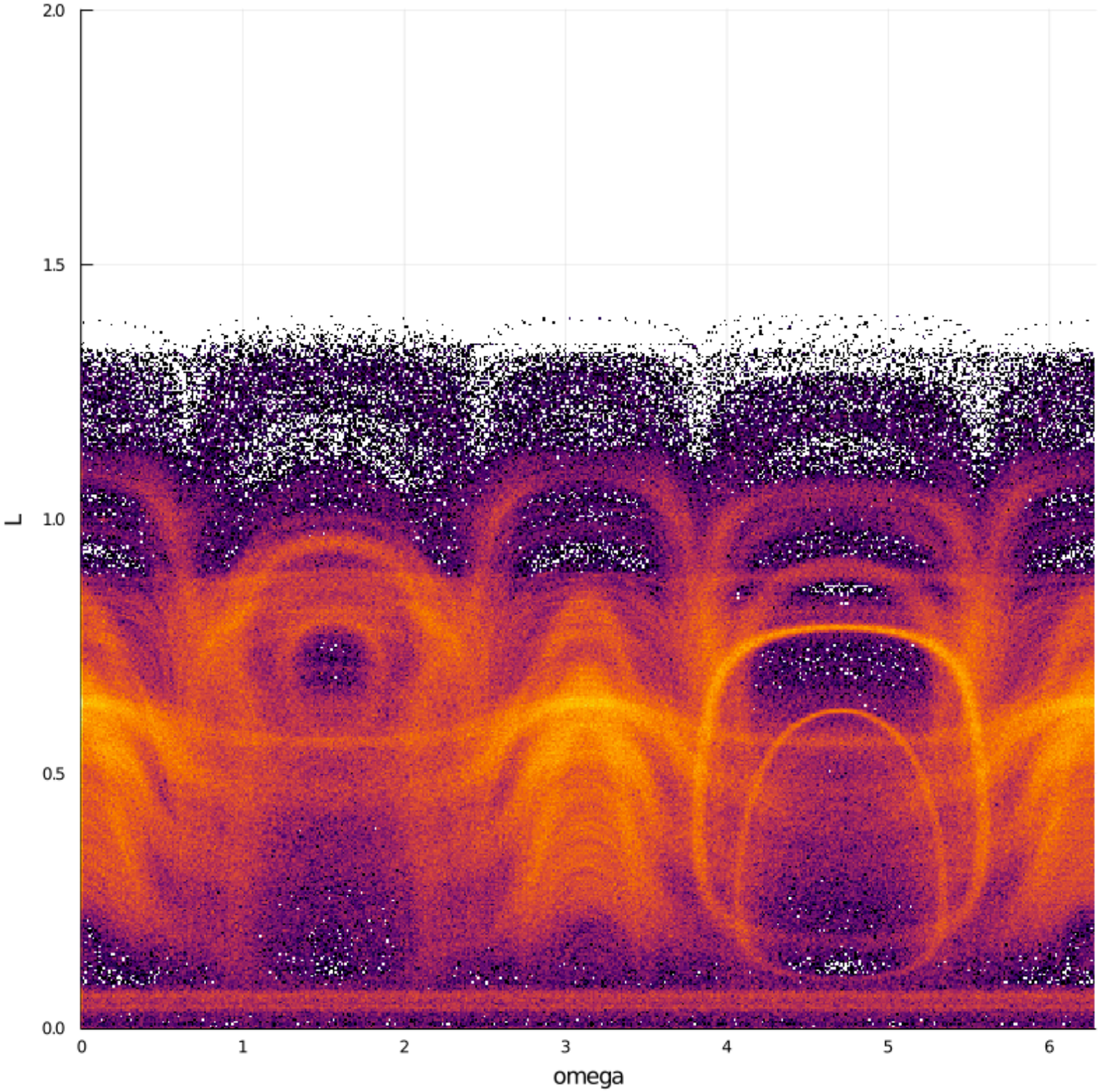

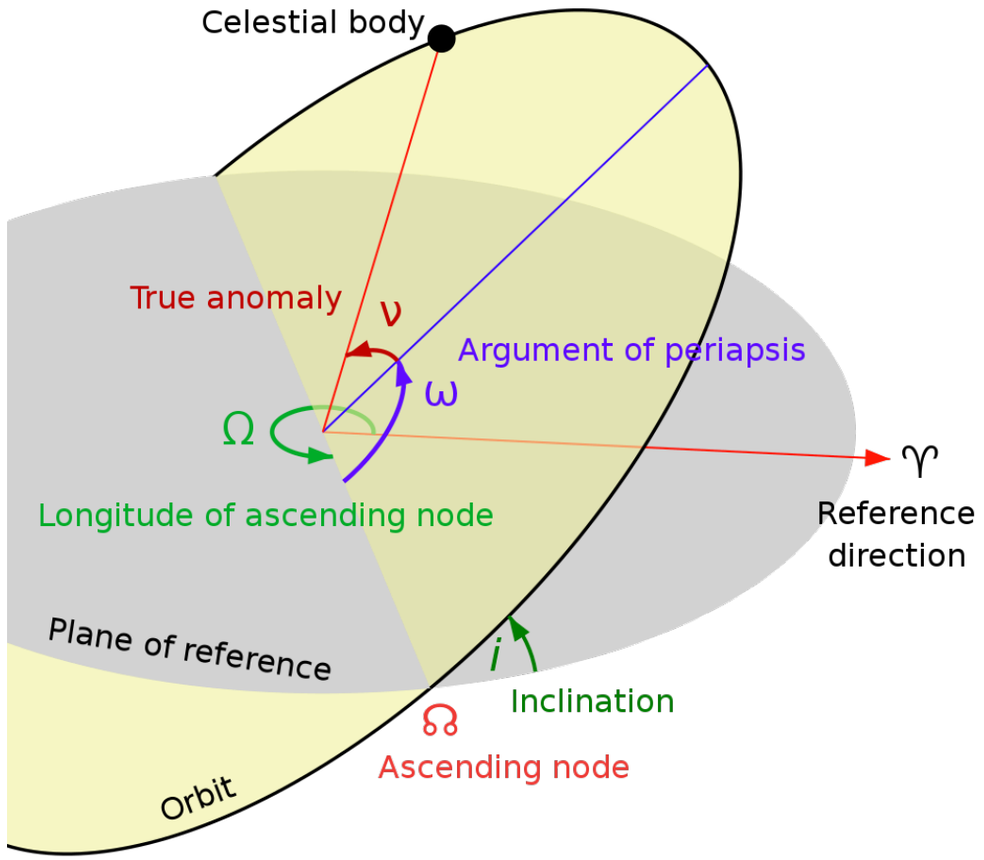

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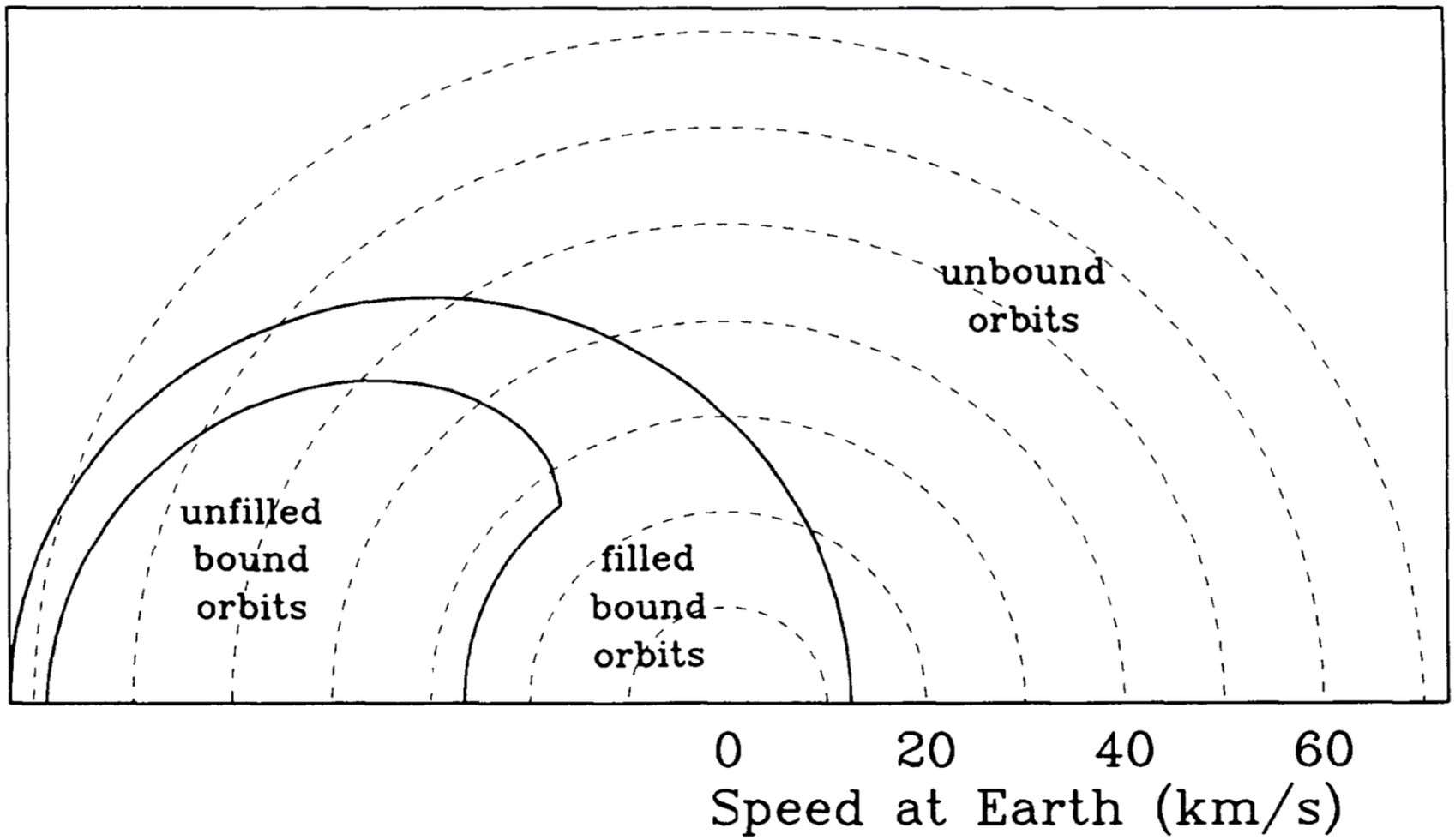
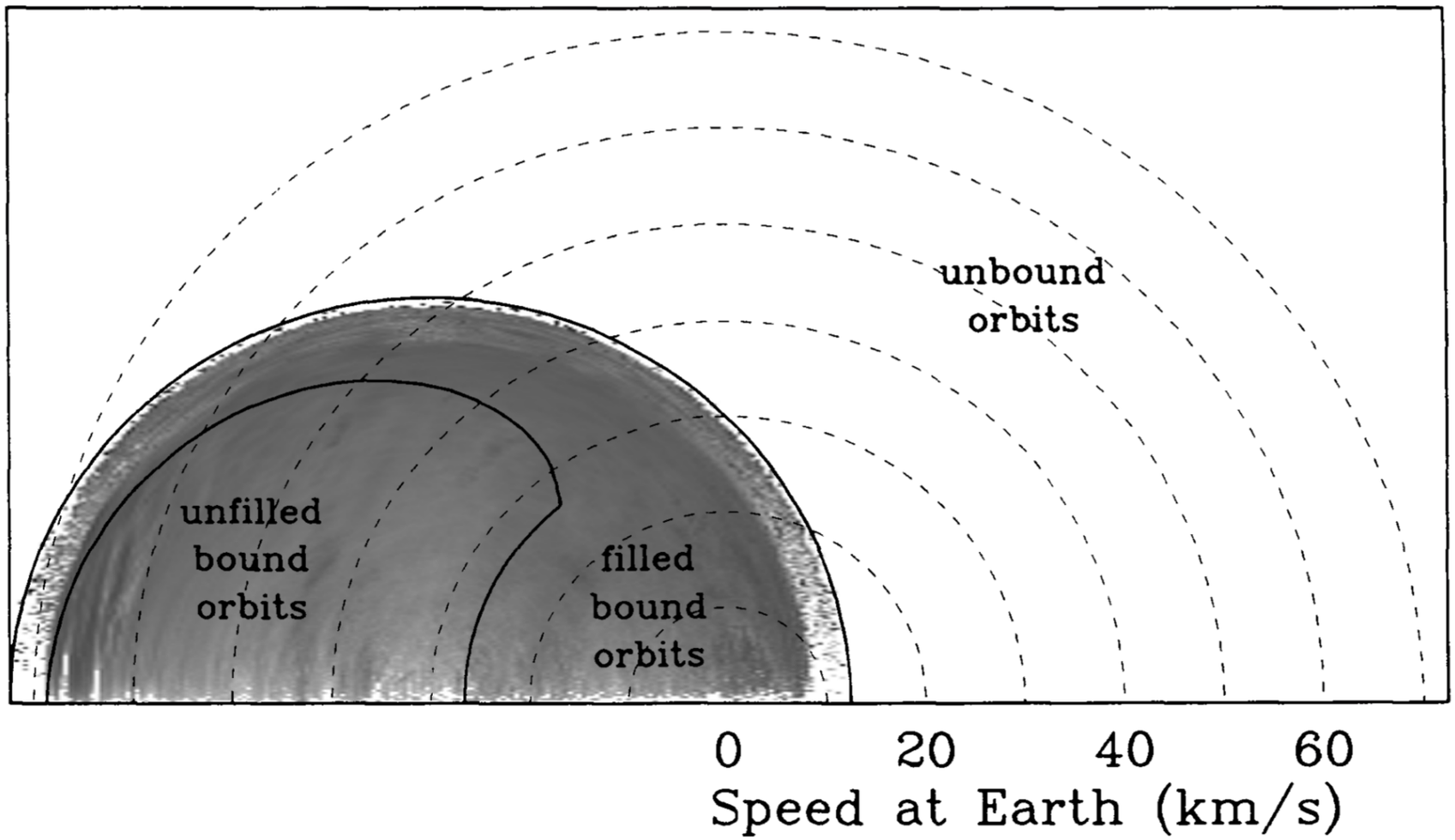


FIG. 3.—Bound and unbound low-velocity WIMPs. Dashed semicircles are curves of constant speed relative to the Earth. The solid semicircle delimits the bound from the unbound orbits, and the solid contour encloses the region of orbits which remain empty over an Earth lifetime. Note that for any given "cutoff velocity," the phase space inside the corresponding semicircle is mostly populated.

[Gould 1991]

Orbital dynamics [PRELIMINARY]



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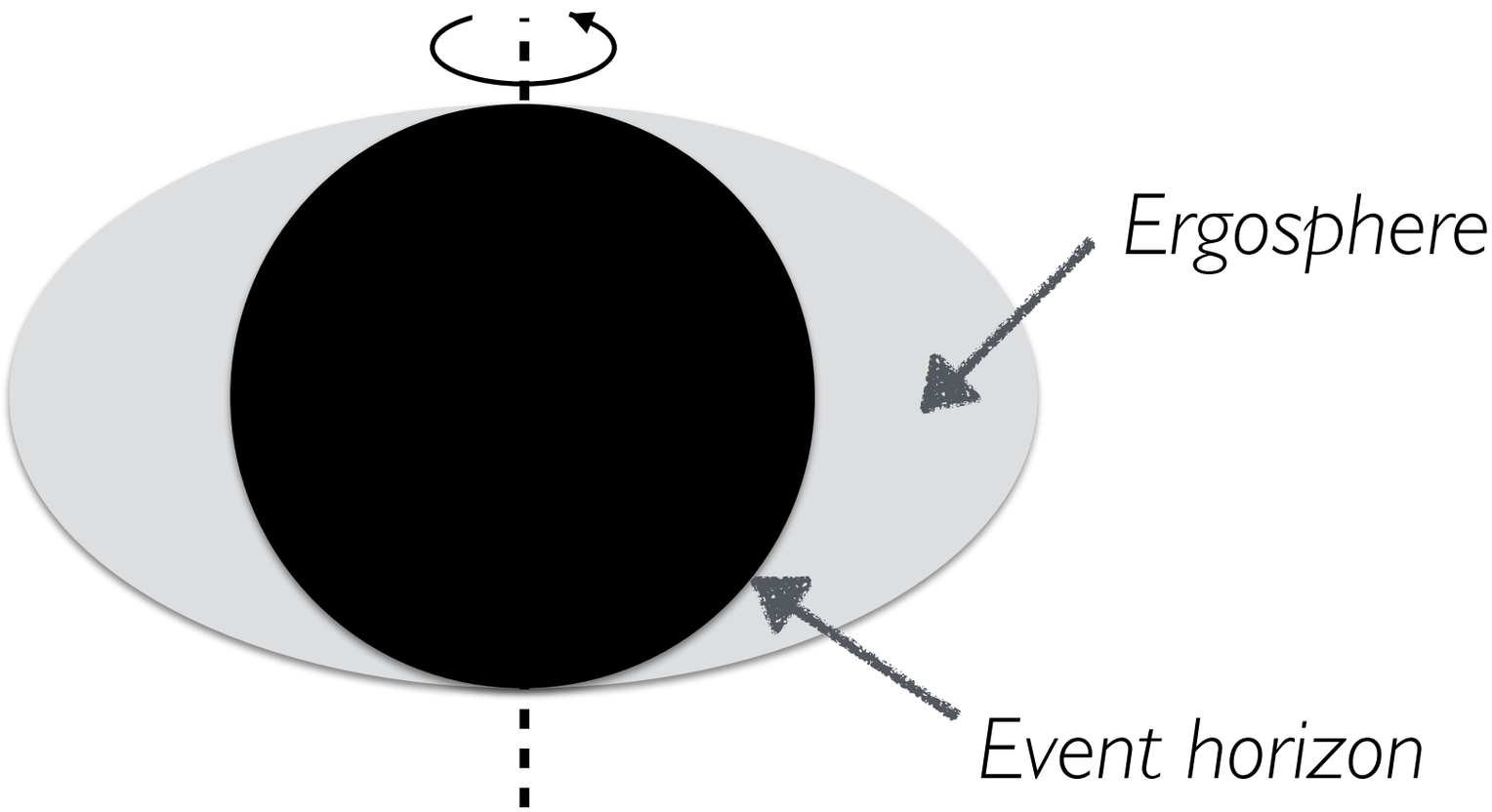
[Gould 1991]

Black hole superradiance

- New particles *must* couple to SM through gravity
- Problem: astrophysically, spacetime curvature scale $\gtrsim \mathrm{km}$
  $\Rightarrow$ effective source density very low
  - e.g. BH Hawking temperature, $T_H = 1/(8\pi GM) \sim 10^{-8}\,\mathrm{K}$ for $M \sim 10 M_\odot$
- Take advantage of coherence enhancement: classical energy extraction from spinning BHs

Extracting energy and angular momentum from black holes

- Spinning BHs have *ergosphere* - region where particles can have negative energy (as viewed from infinity)



- Mechanical Penrose process: throwing negative-energy particle into horizon

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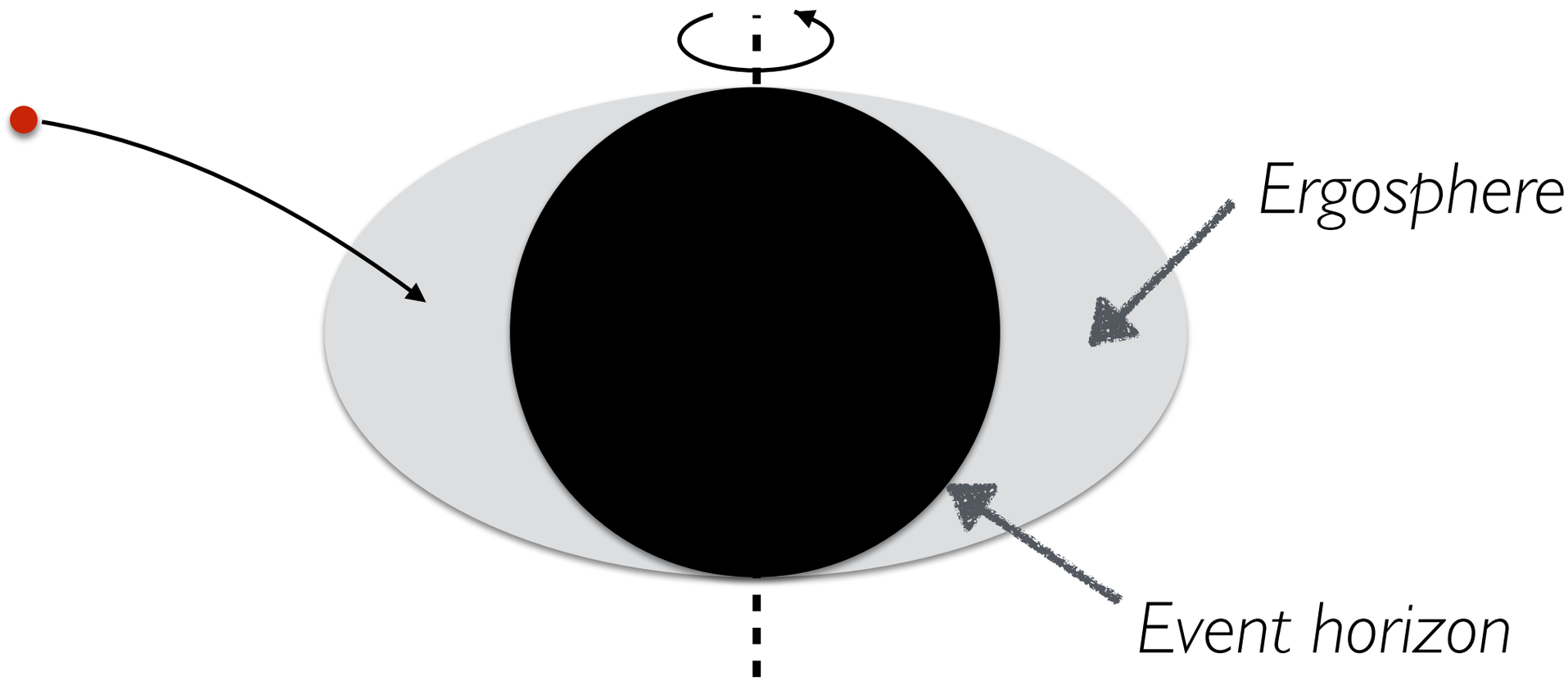

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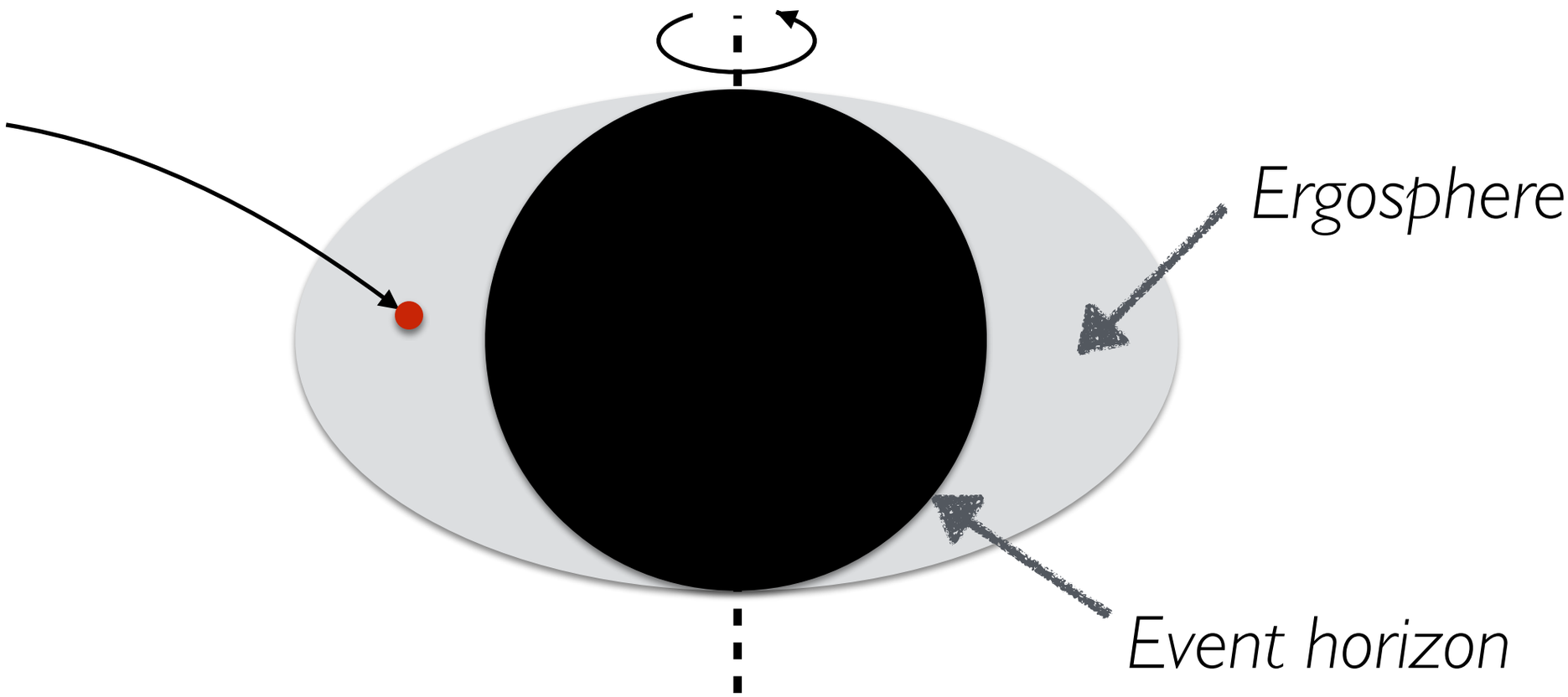

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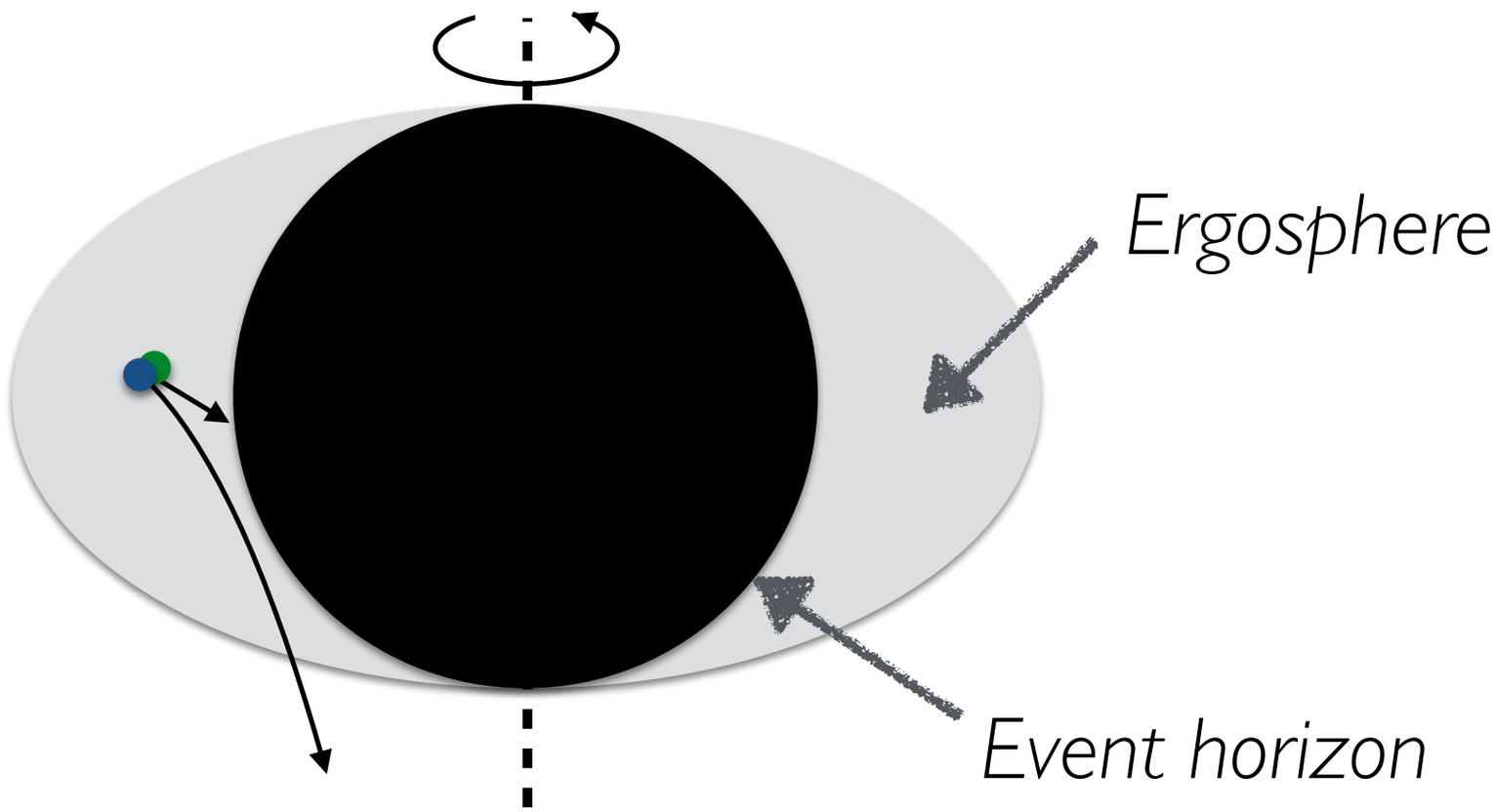

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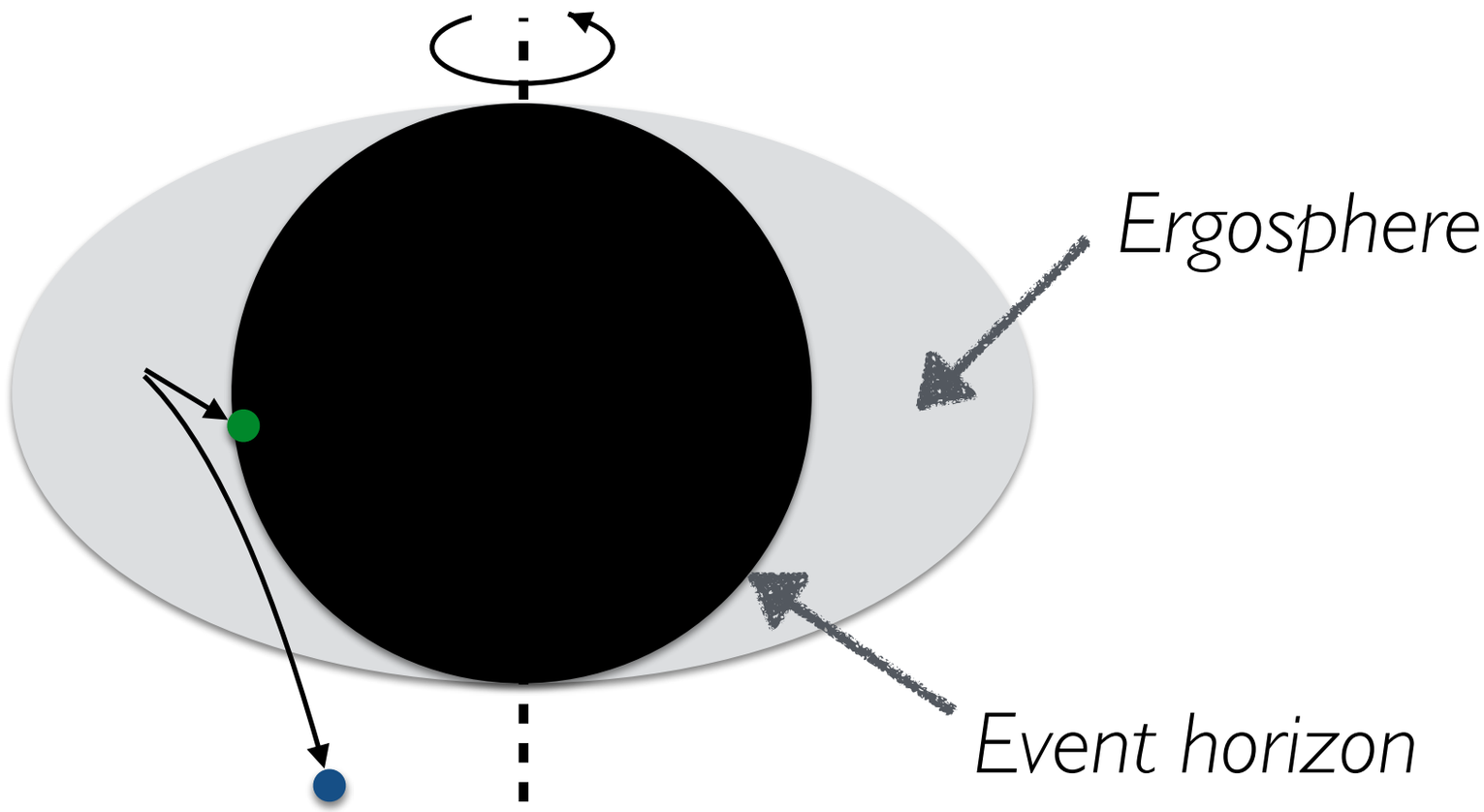

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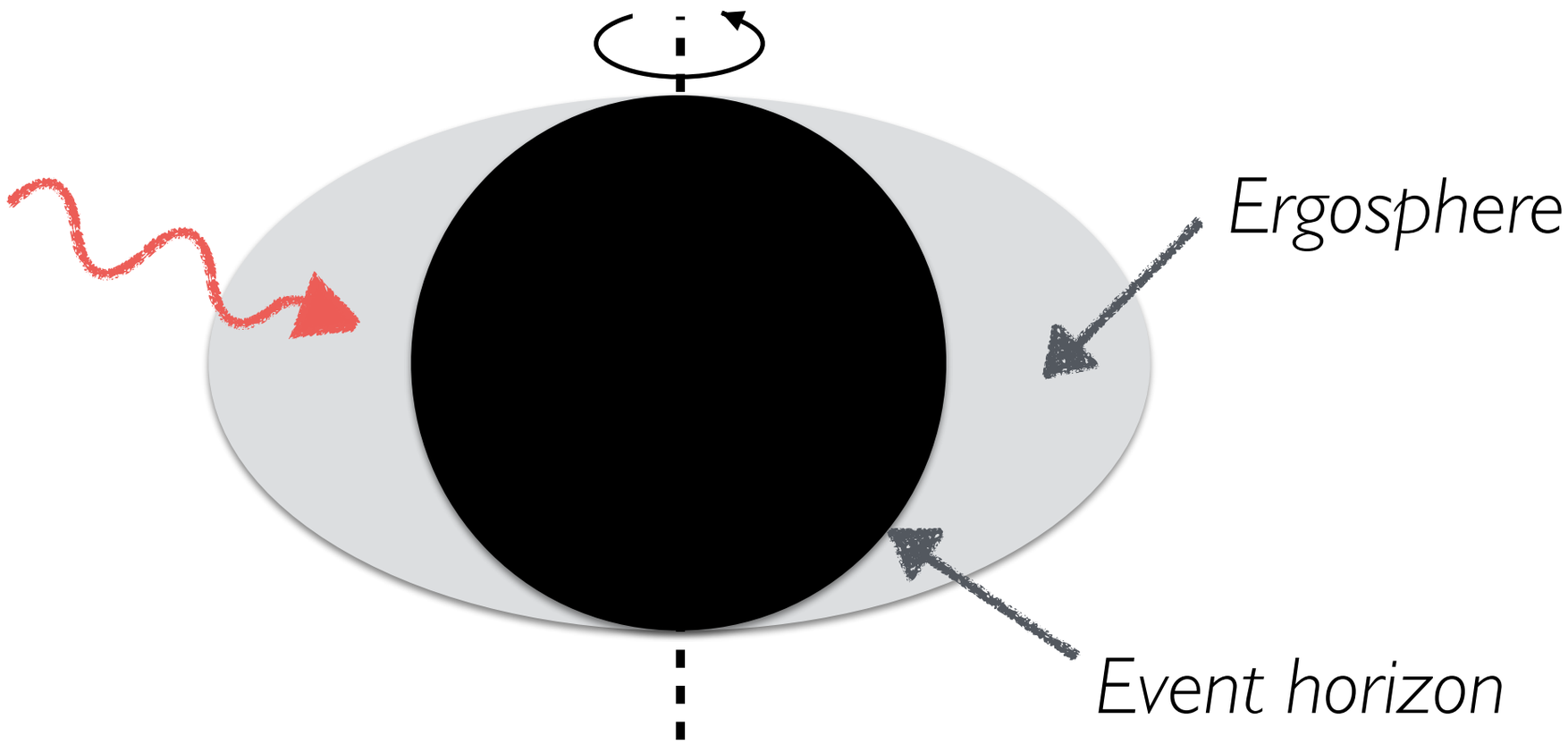

- *Wave* Penrose process: transmitted wave has negative energy, reflected wave carries extra energy away

Extracting energy and angular momentum from black holes

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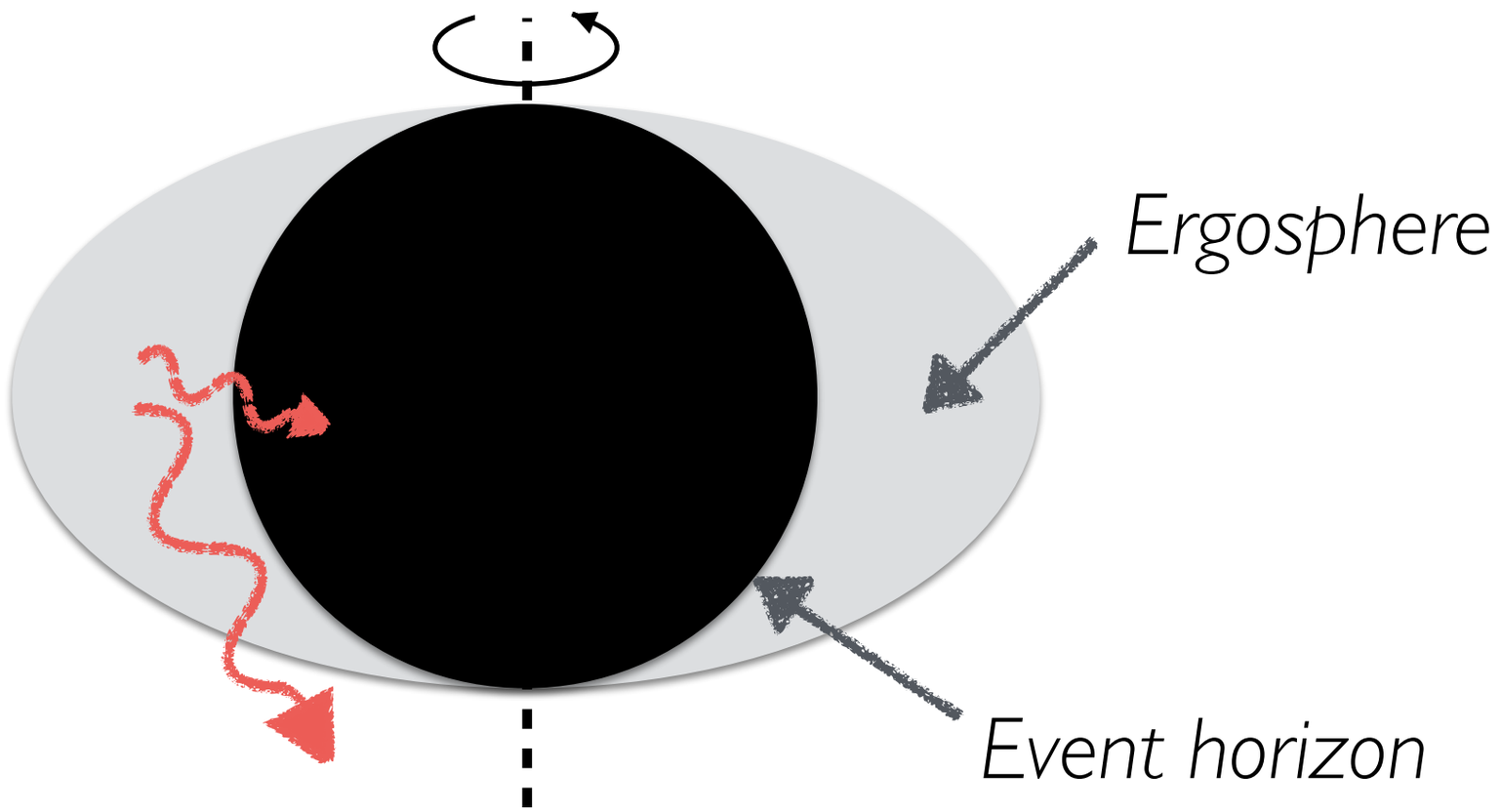

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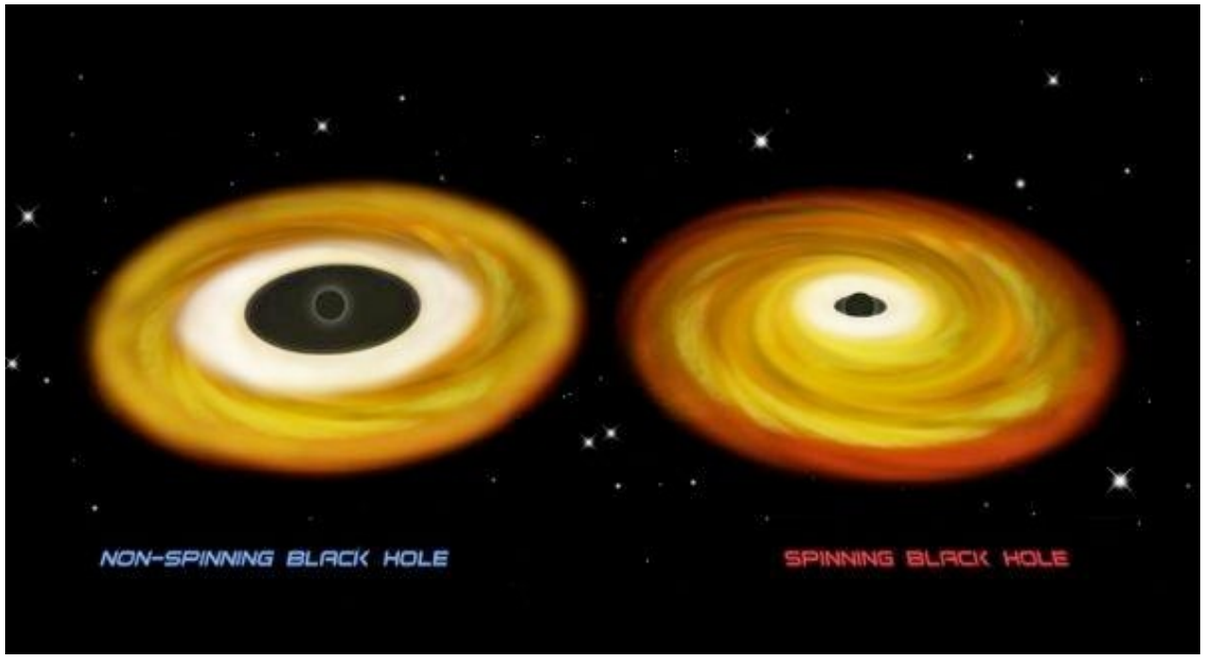
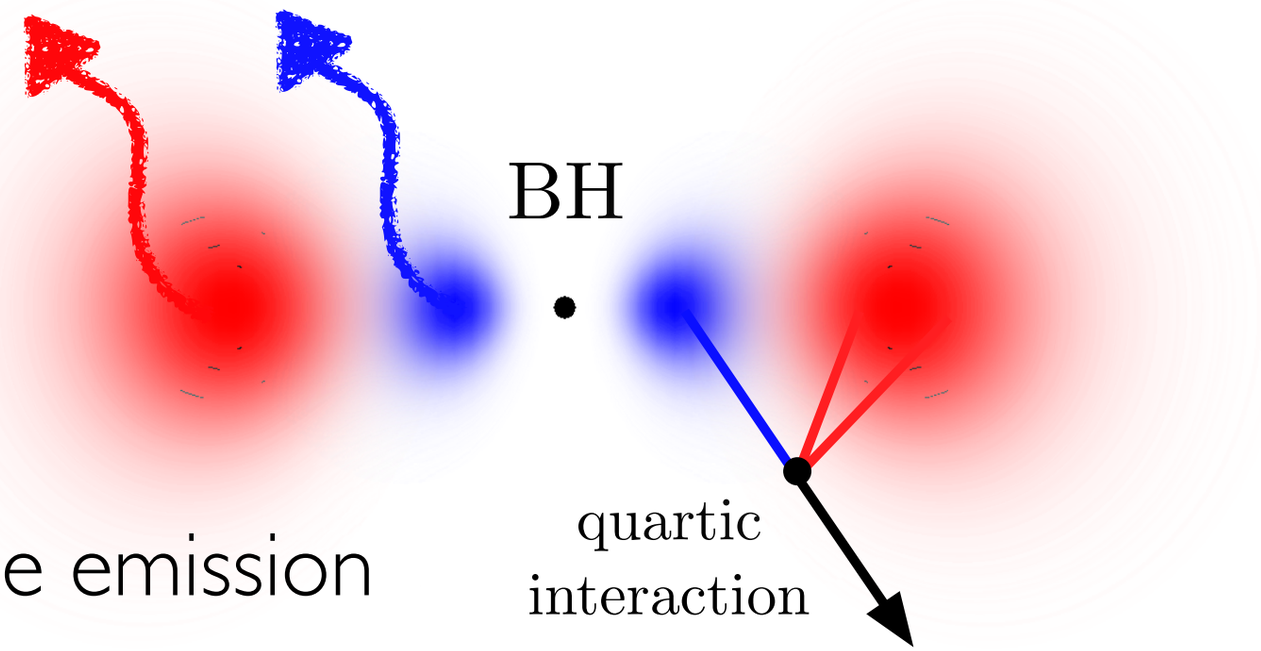
Observational signatures

Black hole spin-down



Gravitational radiation



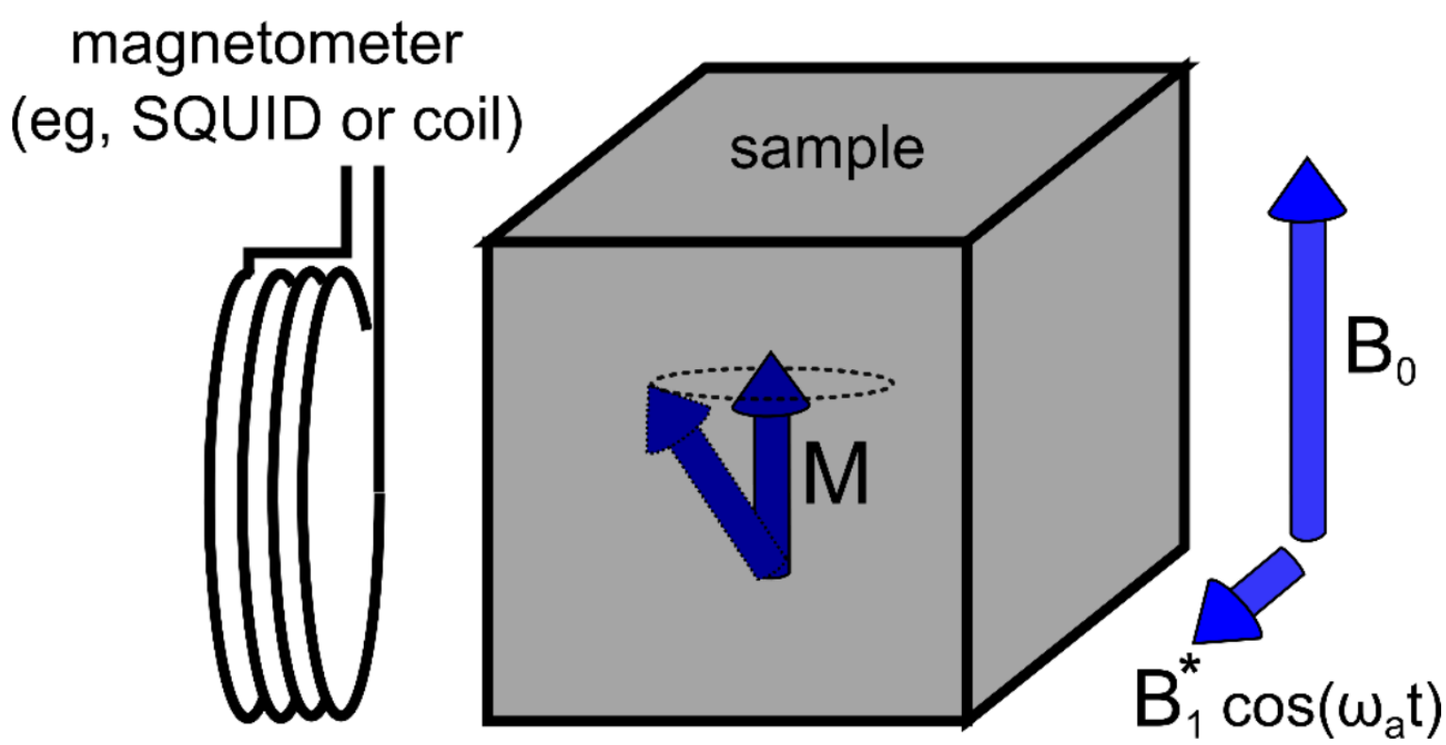
Coherent particle emission

Axion-nucleon coupling

"Axion wind" coupling: effective magnetic field

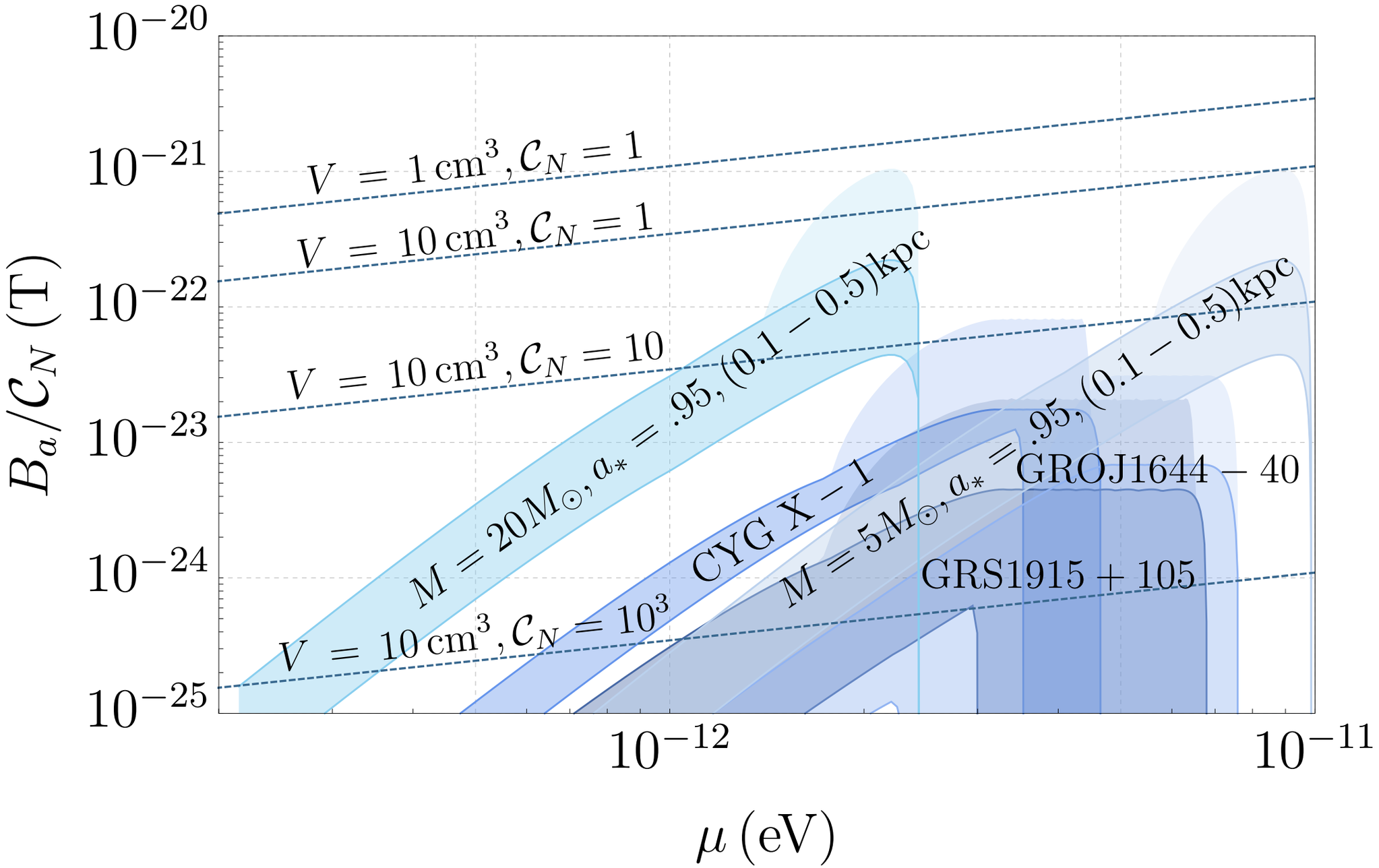
$$\mathcal{L} \supset g_n(\partial_\mu a)\bar{n}\gamma^\mu\gamma^5 n$$

$$H_n \supset g_n\sigma \cdot (\nabla a + \dot{a}v_n)$$
$$\simeq B_a \cdot \mu_n$$



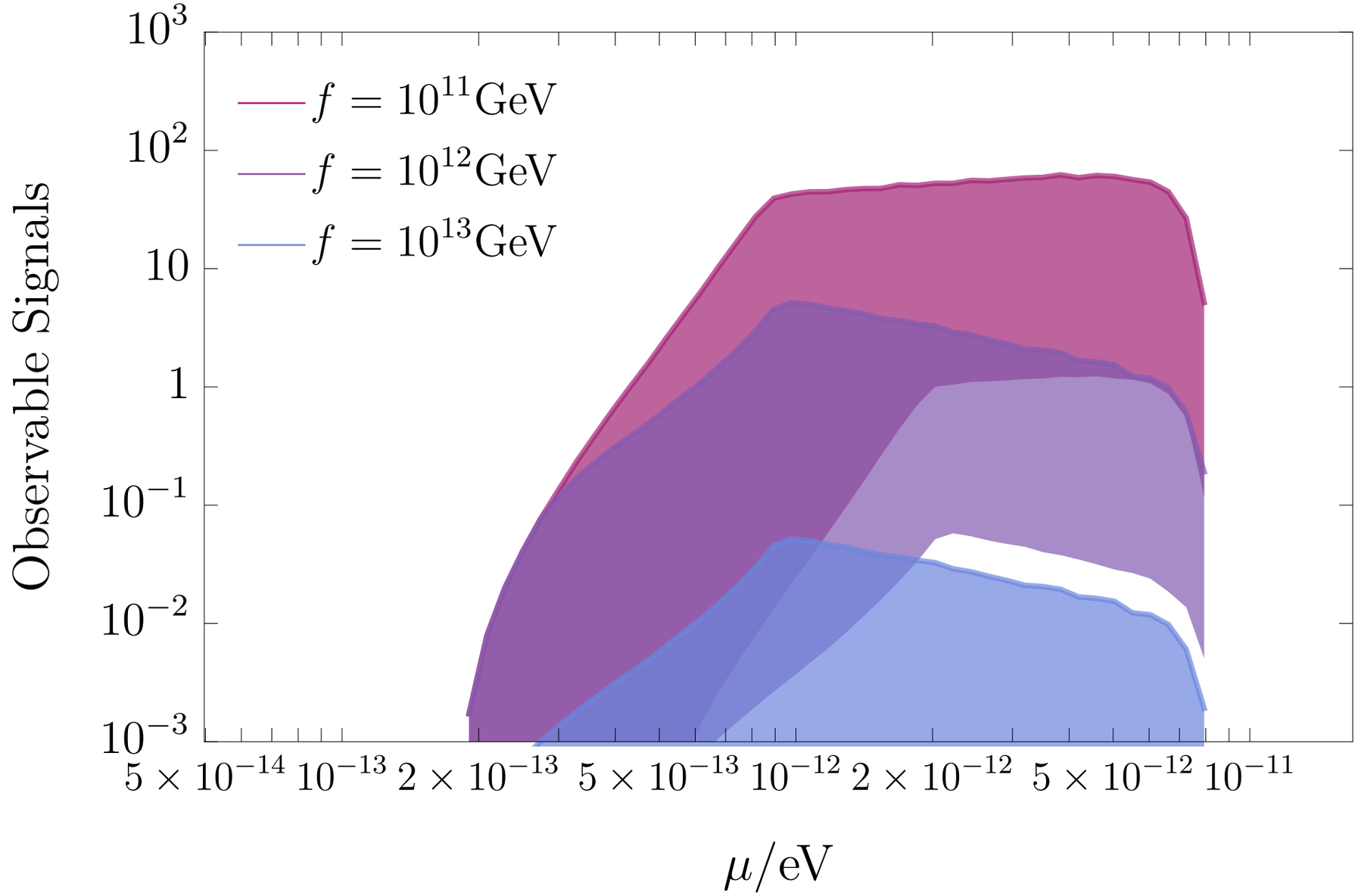
[CASPEr-Wind]

Axion-nucleon coupling



Axion-nucleon coupling

$$V = 10\,\mathrm{cm}^3$$
$$n_{\mathrm{spin}} = 10^{22}\,\mathrm{cm}^{-3}$$



Summary

- To learn about physics beyond the Standard Model, we need new data
- New experiments a key aspect of that
- Important to think systematically about
  - how best to look for motivated signals
  - what kinds of signals too look for