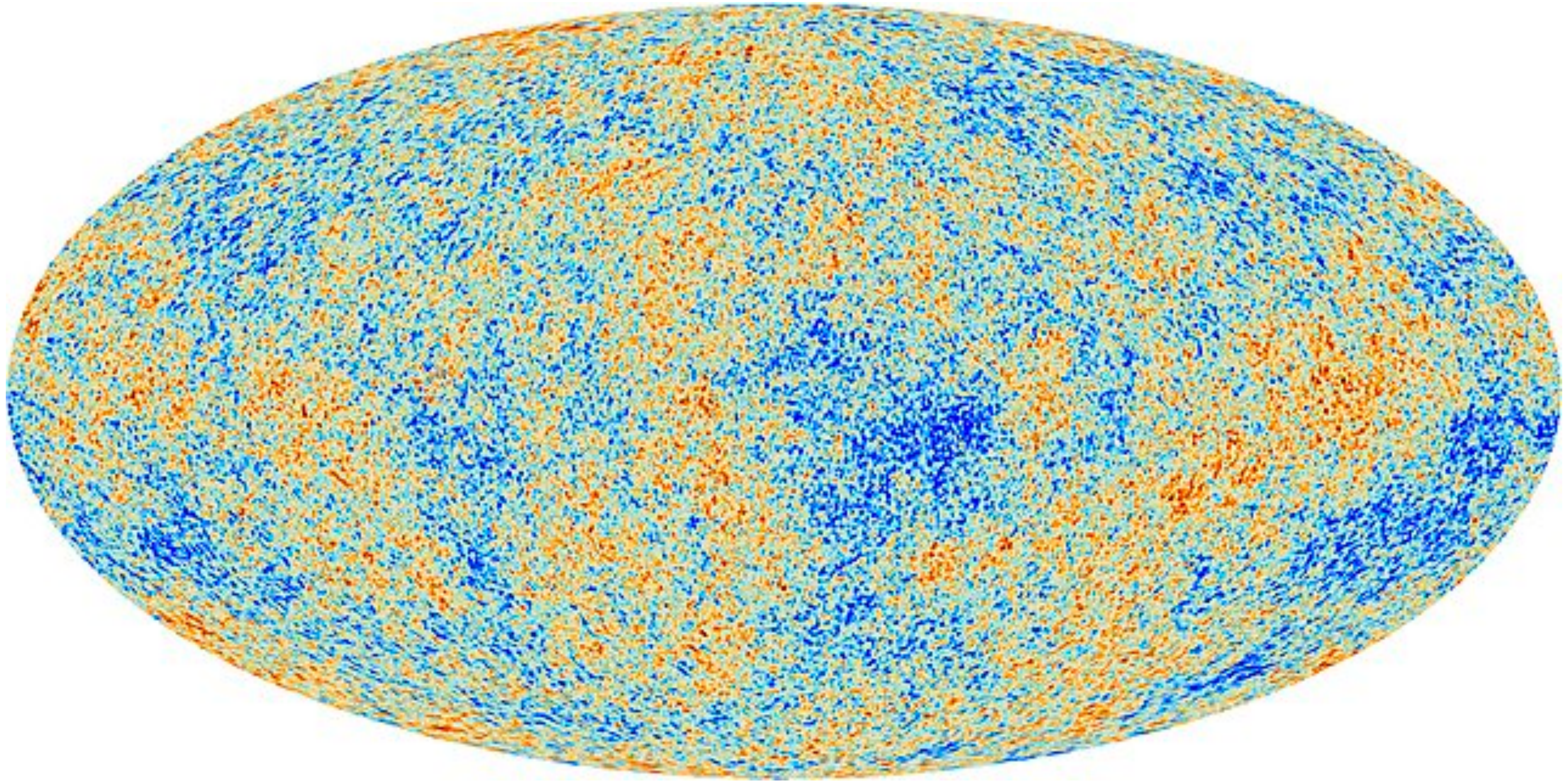
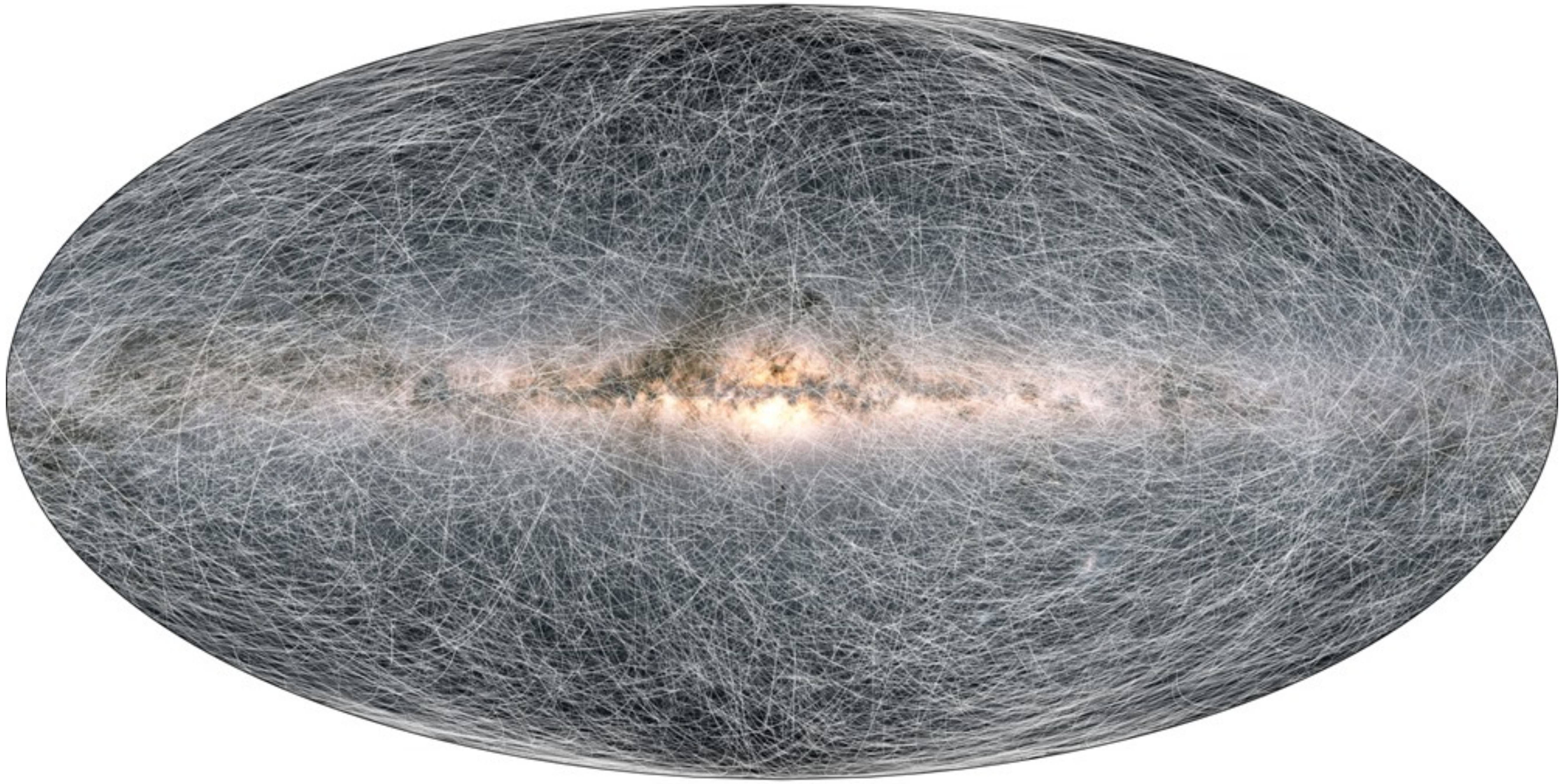
A NEW CHAPTER IN THE QUEST FOR DARK MATTER: THE ULTRALIGHT REGIME

Raffaele Tito D'Agnolo - IPhT Saclay



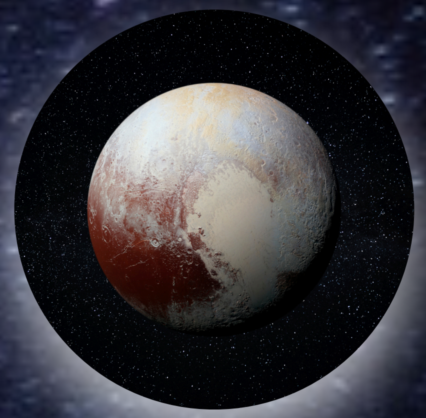


DARK MATTER MASS

one order of magnitude

DARK MATTER MASS

Person



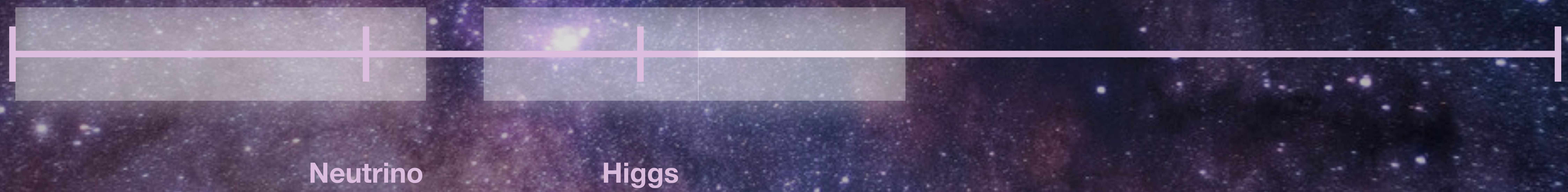
Neutrino

Higgs

Pluto


Self-coupling
100 O.M.
Mass
50 O.M.
80 O.M.
Couplings to ordinary matter

DARK MATTER MASS



Theory Spotlight

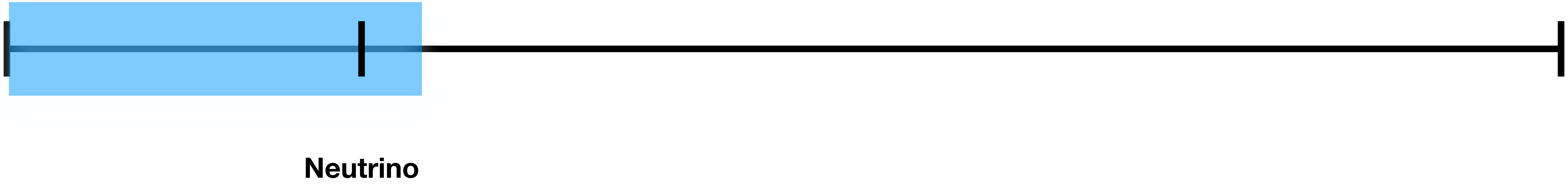
Natural Units

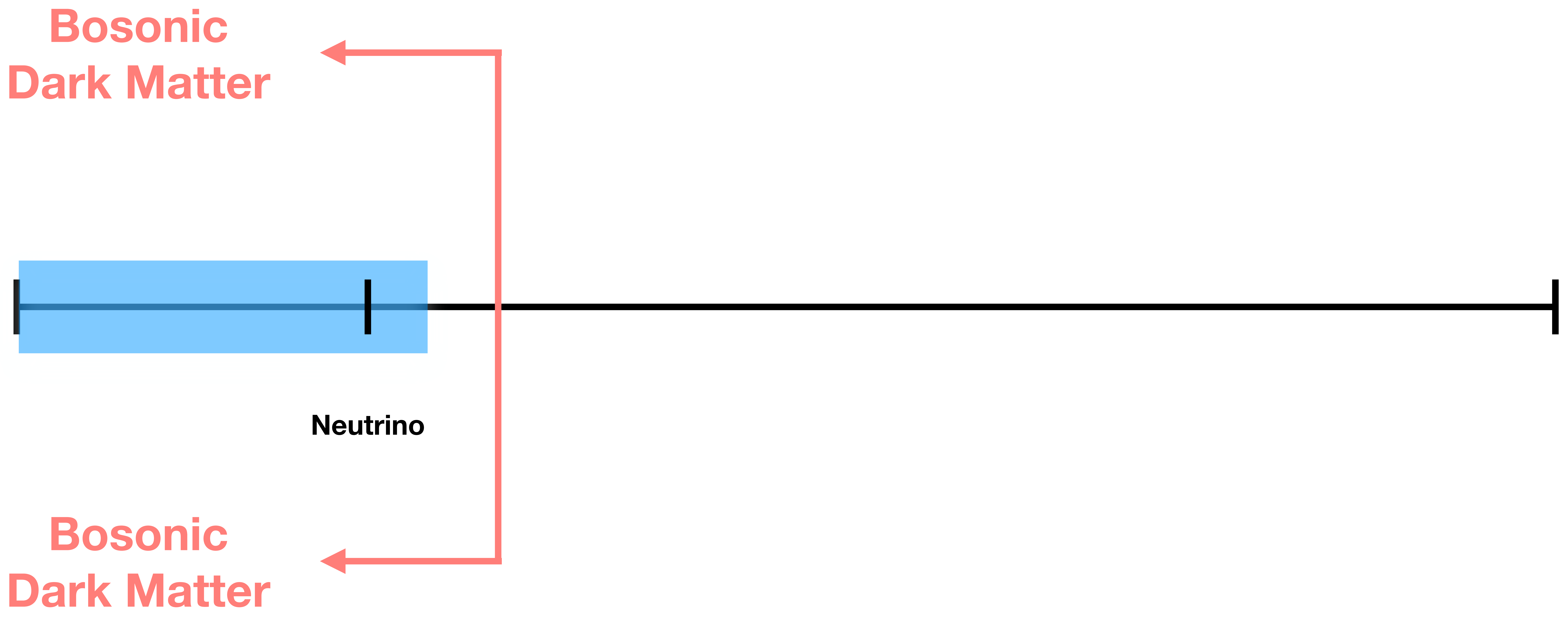
$$\hbar = c = 1$$

$$[m] = \mathrm{eV}$$

$$\mathrm{eV} \simeq 10^{-36}\mathrm{kg} \simeq 10^{-66} M_\odot$$

ULTRALIGHT DARK MATTER


Neutrino


Bosonic
Dark Matter
Neutrino
Bosonic
Dark Matter

Quantum Mechanics

$$v_F(r) = \left(\frac{3\pi^2\rho(r)}{m^4}\right)^{1/3}$$

Quantum Mechanics

Newtonian Gravity

$$v_F(r) = \left(\frac{3\pi^2 \rho(r)}{m^4} \right)^{1/3}$$

$$v_{\text{esc}}$$

Quantum Mechanics

Newtonian Gravity

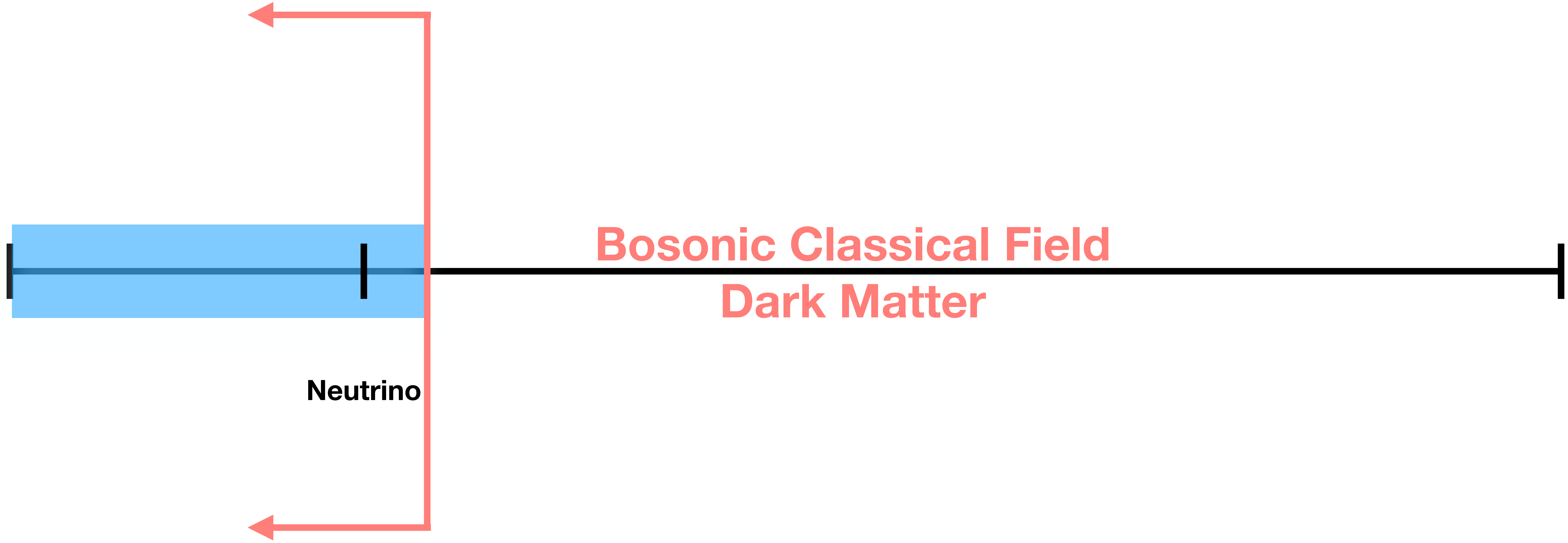
$$v_F(r) = \left(\frac{3\pi^2 \rho(r)}{m^4} \right)^{1/3} < v_{\rm esc}$$


Bosonic
Dark Matter
Neutrino
Bosonic
Dark Matter

Dark Matter Particles in a de Broglie Volume **Today**

Galaxy: $$N_{\rm DM} \simeq 10^{3} \left(\frac{\rm eV}{m_{\rm DM}} \right)$$

Universe: $$N_{\rm DM} \simeq 10^{-3} \left(\frac{\rm eV}{m_{\rm DM}} \right)$$


Bosonic Classical Field
Dark Matter
Neutrino

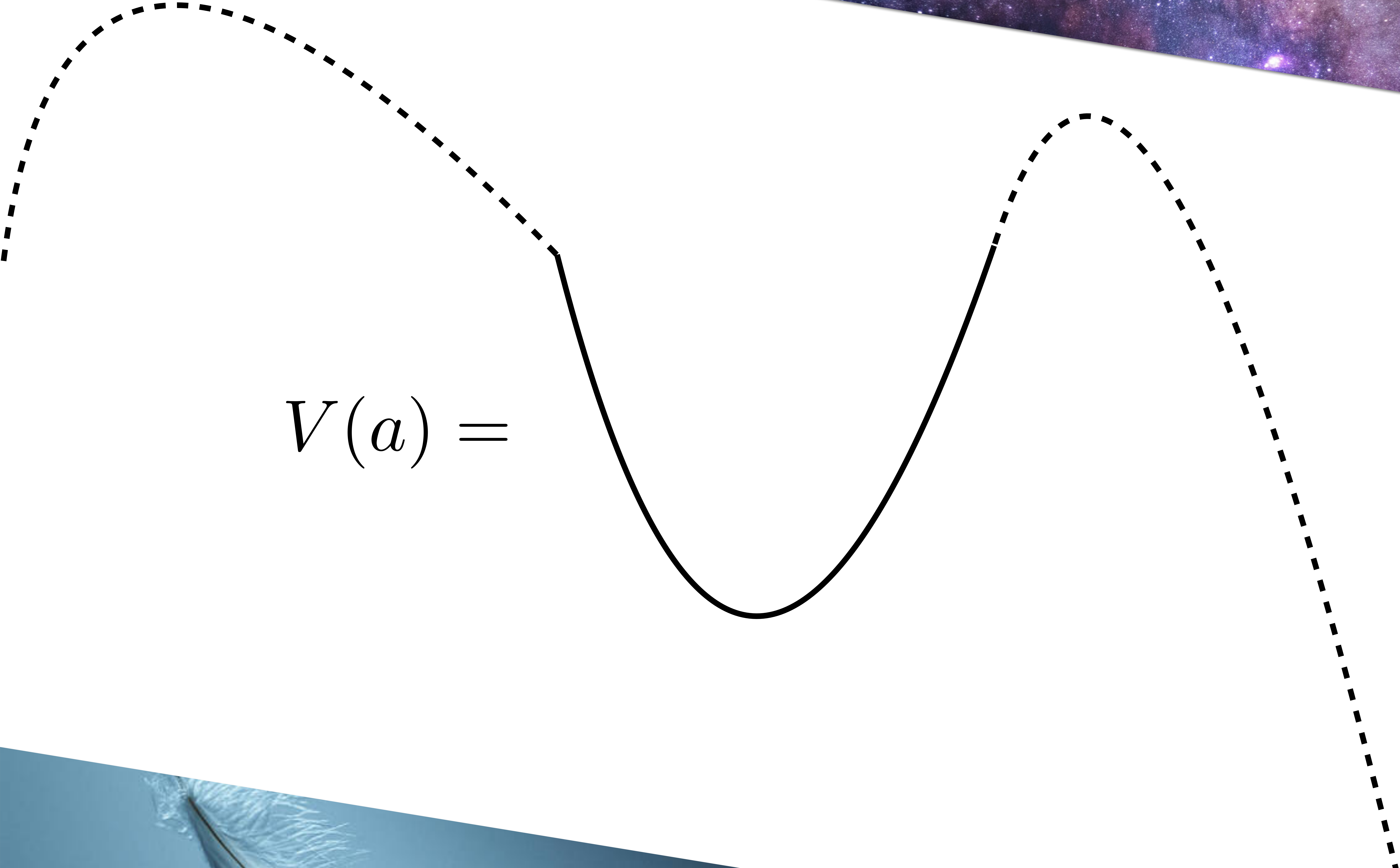
ULTRALIGHT DARK MATTER

- Minimal Extension of what we know to exist
- Simple and predictive cosmology

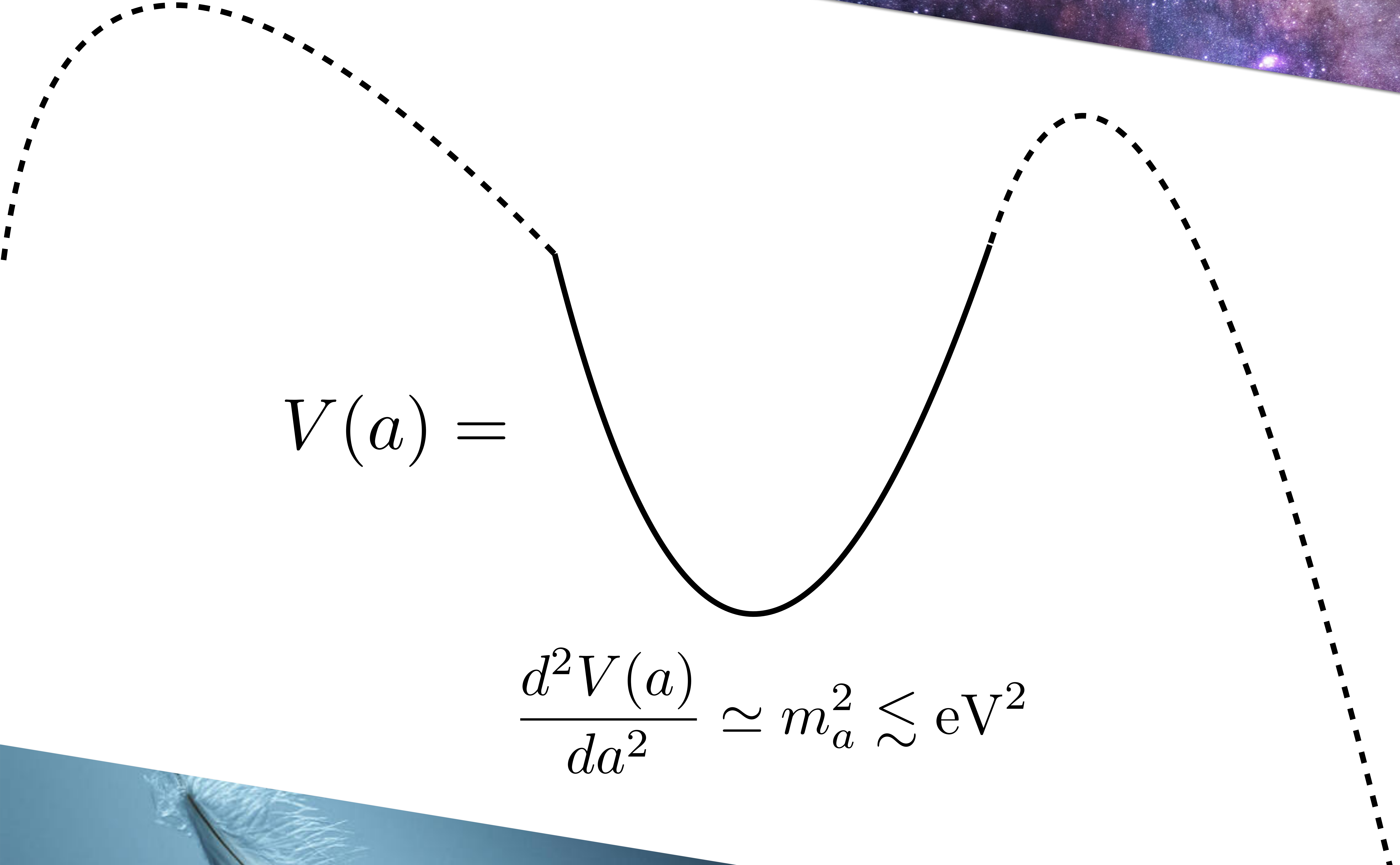
ULTRALIGHT DARK MATTER

- Minimal Extension of what we know to exist
- Simple and predictive cosmology
- Solve another big problem in particle physics

$$V(a) =$$

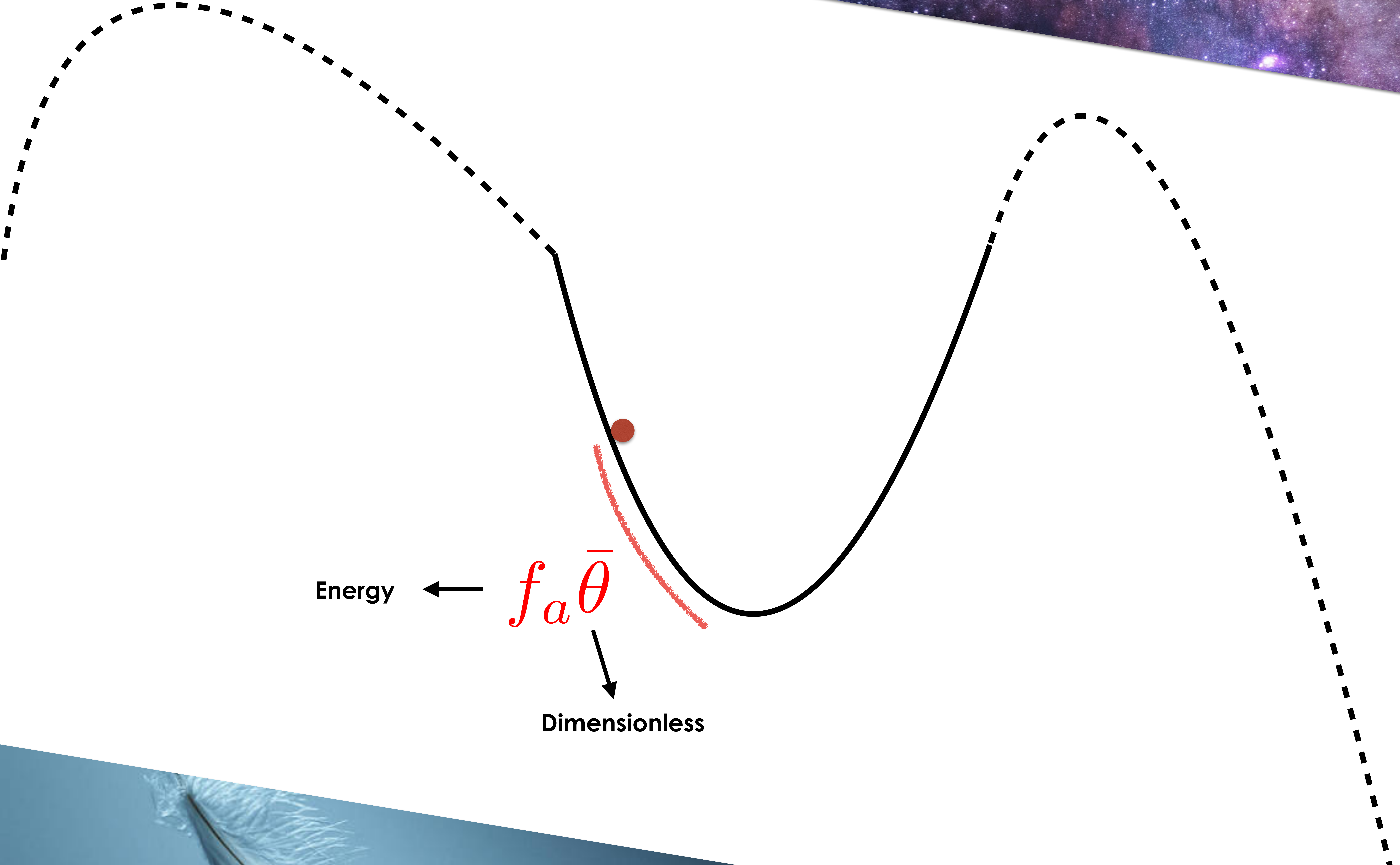


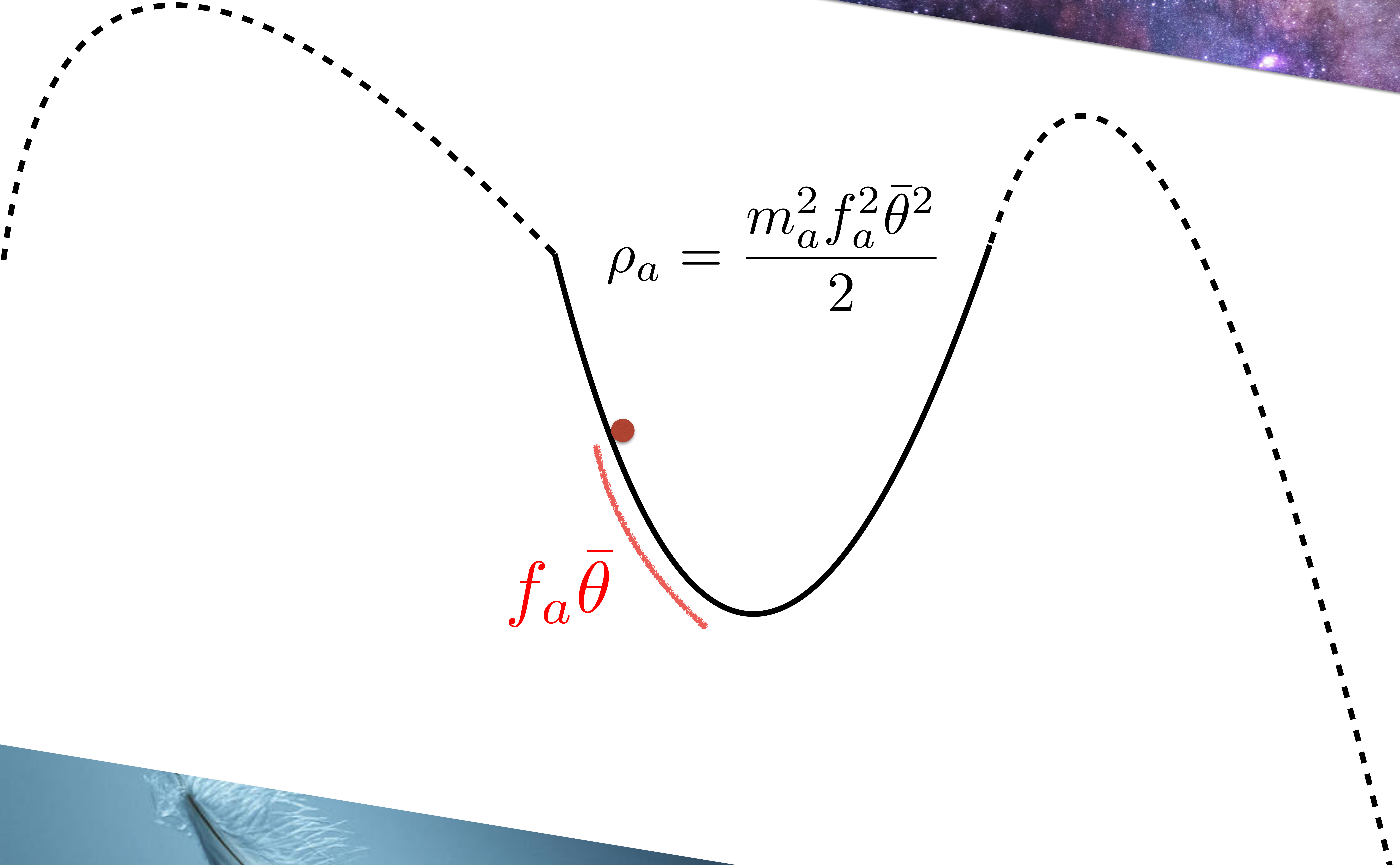
$$V(a) =$$



$$\frac{d^2V(a)}{da^2} \simeq m_a^2 \lesssim \mathrm{eV}^2$$

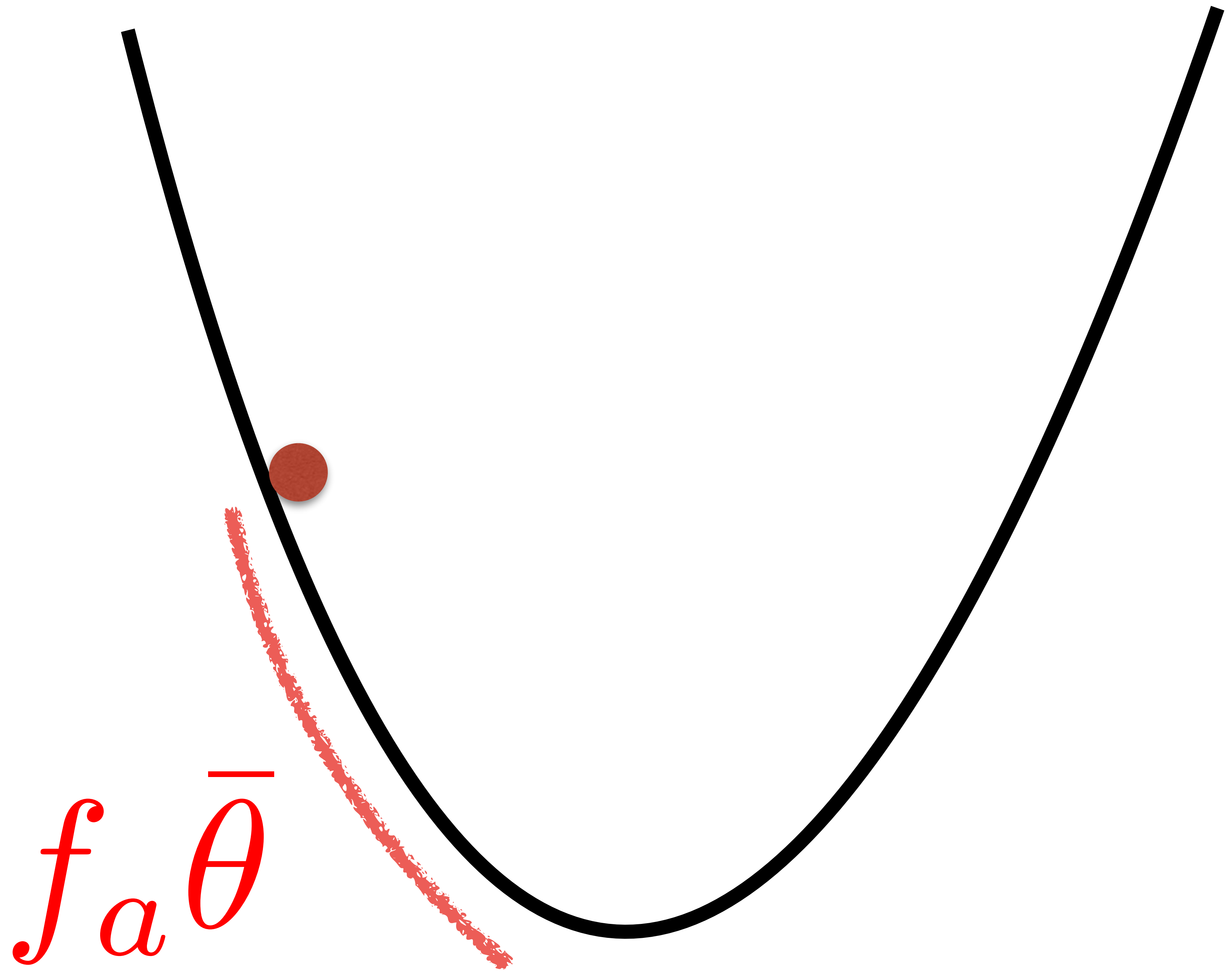

$f_a\bar{\theta}$


Energy
$f_a\bar{\theta}$
Dimensionless



$$\rho_a = \frac{m_a^2 f_a^2 \bar{\theta}^2}{2}$$

Classical Equation of Motion



$$\ddot{\theta} + 3H\dot{\theta} + m_a^2(T)\theta = 0$$

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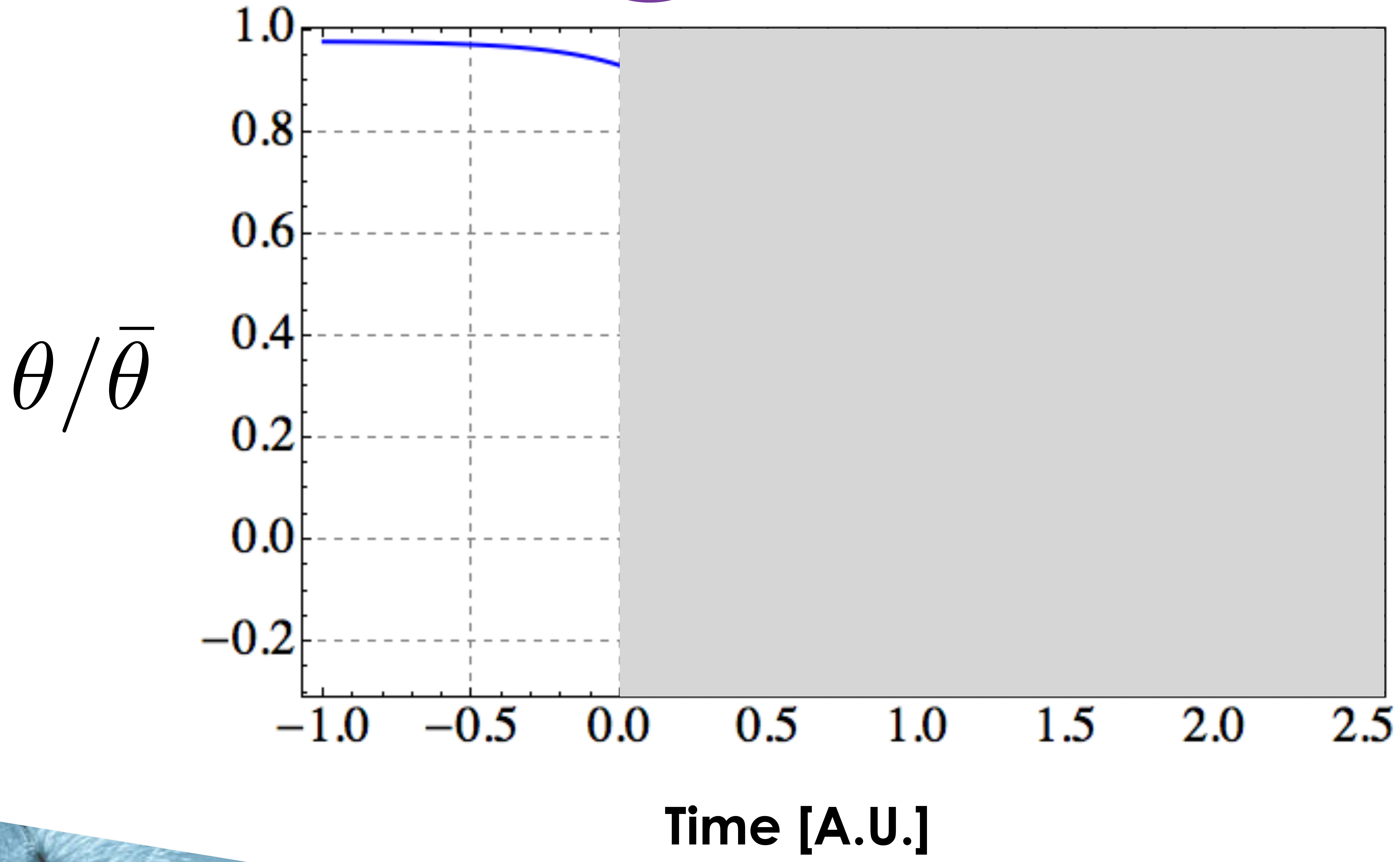

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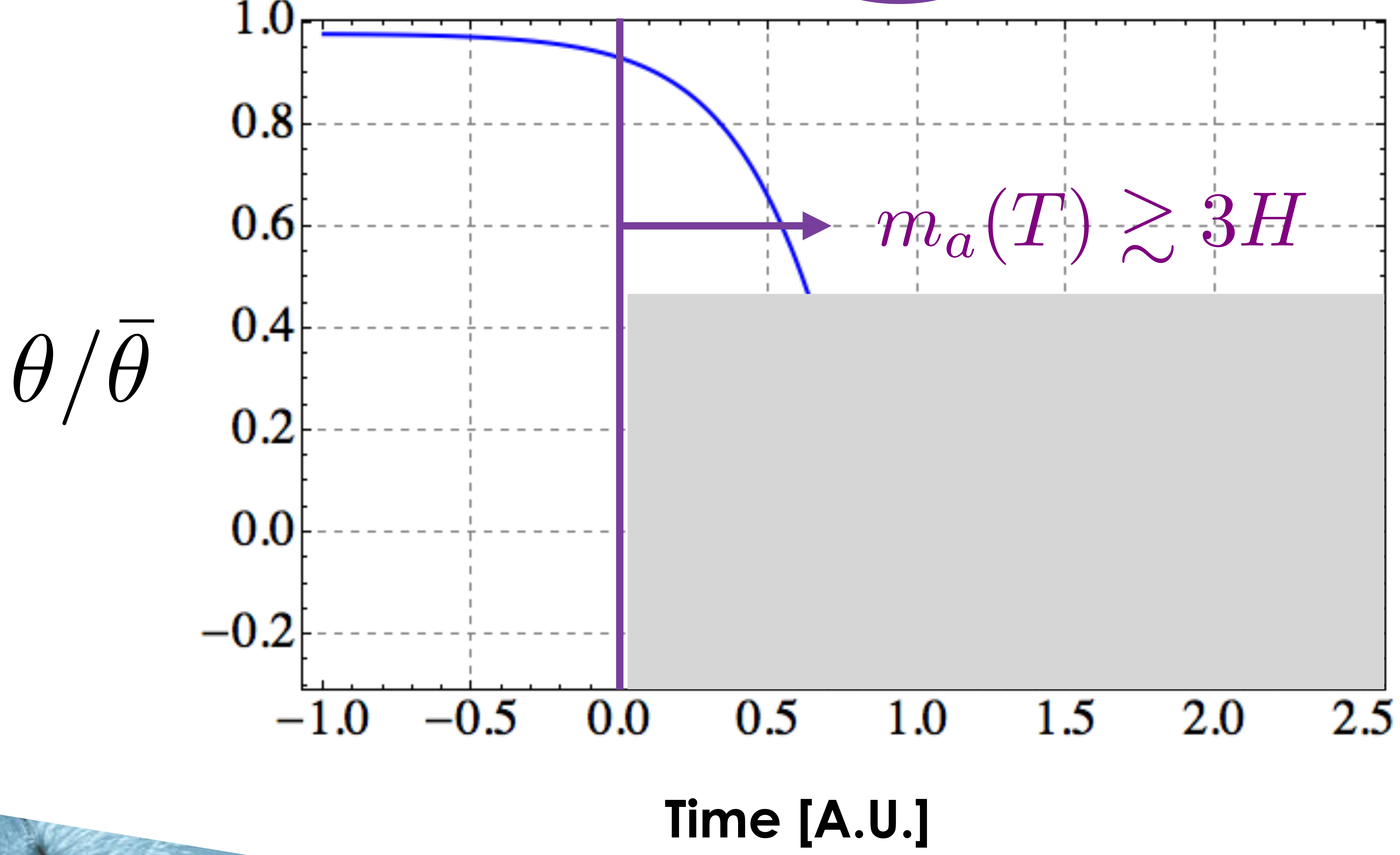

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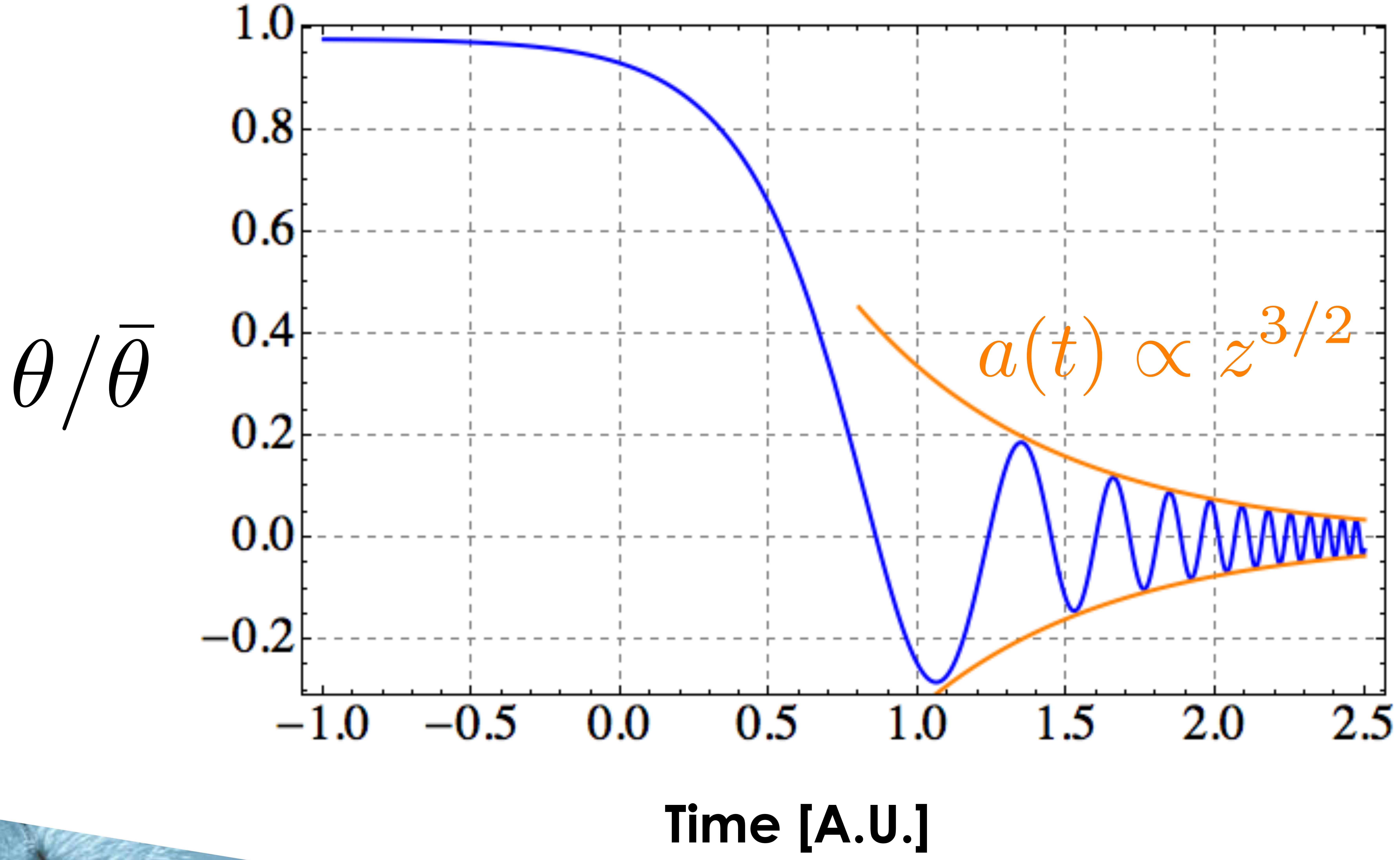


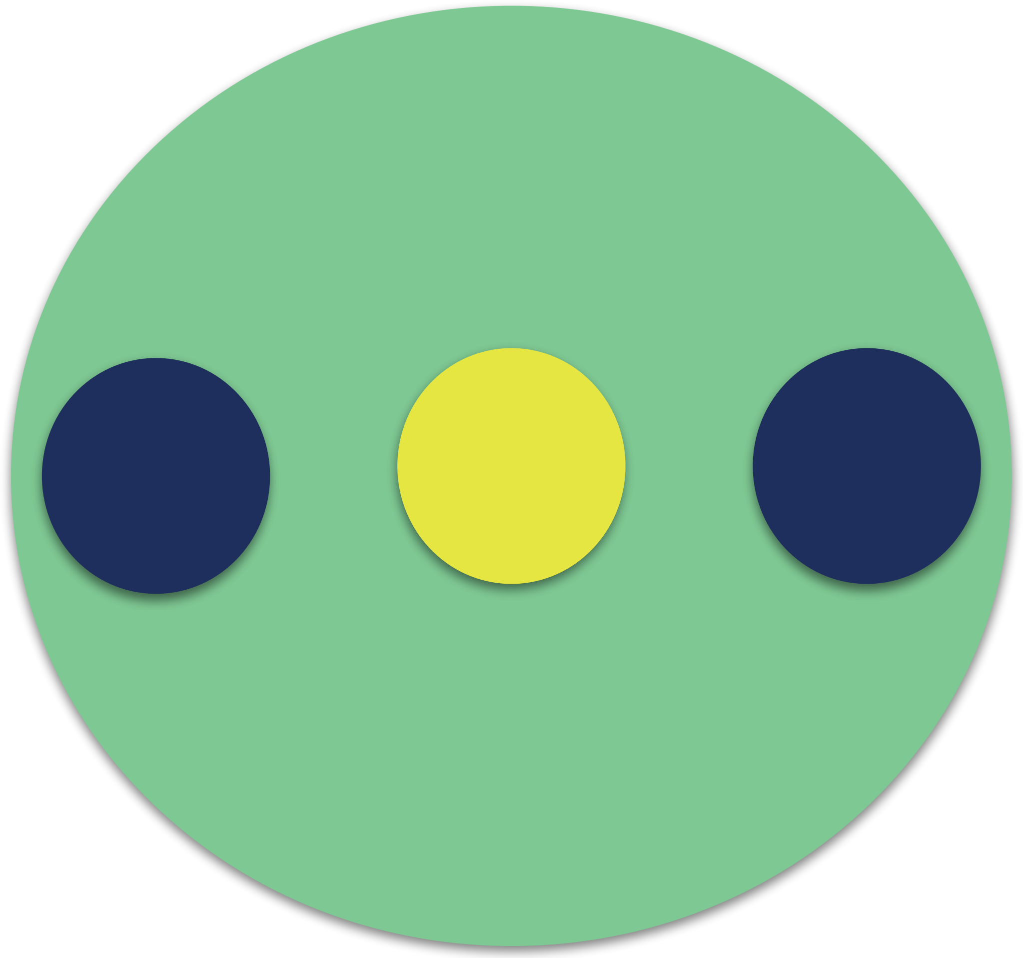
Redshifts as cold dark matter

ULTRALIGHT DARK MATTER

- Minimal Extension of what we know to exist
- Simple and predictive cosmology

$$\theta G\tilde{G}$$

Neutron $\theta = 0$



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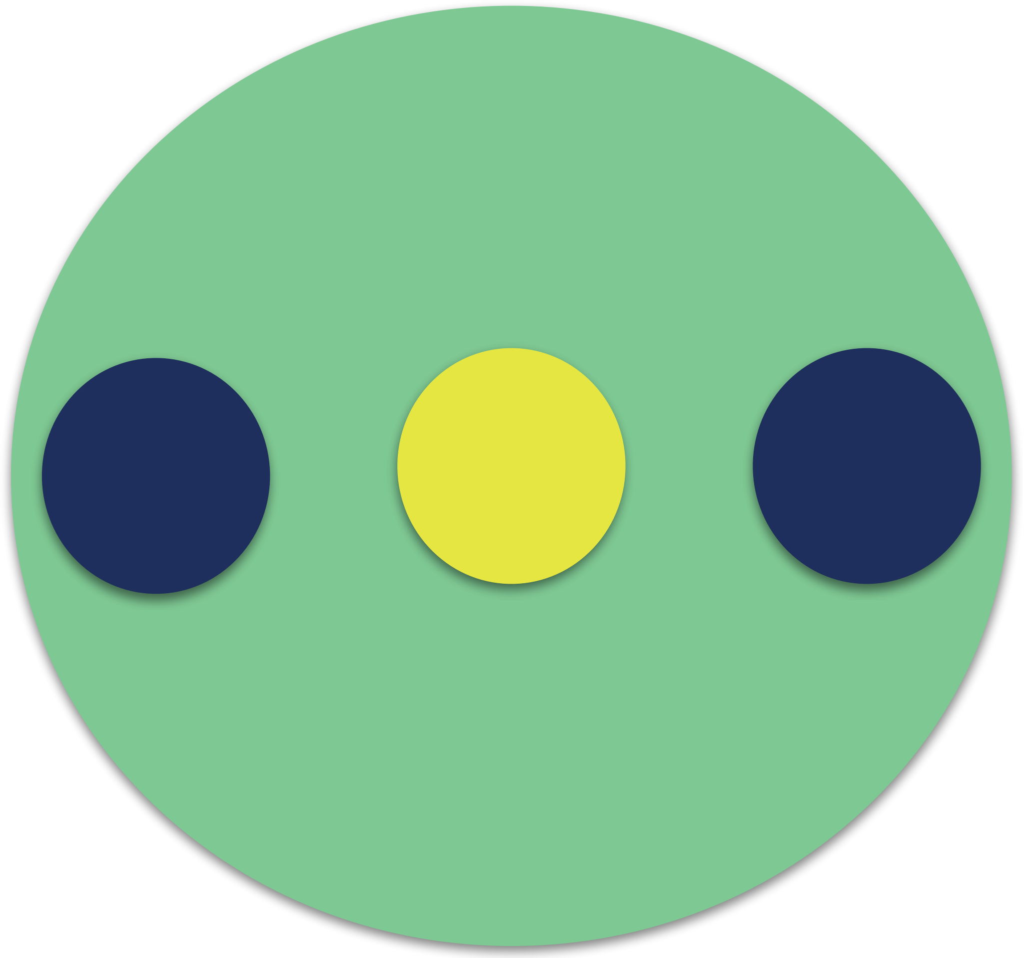
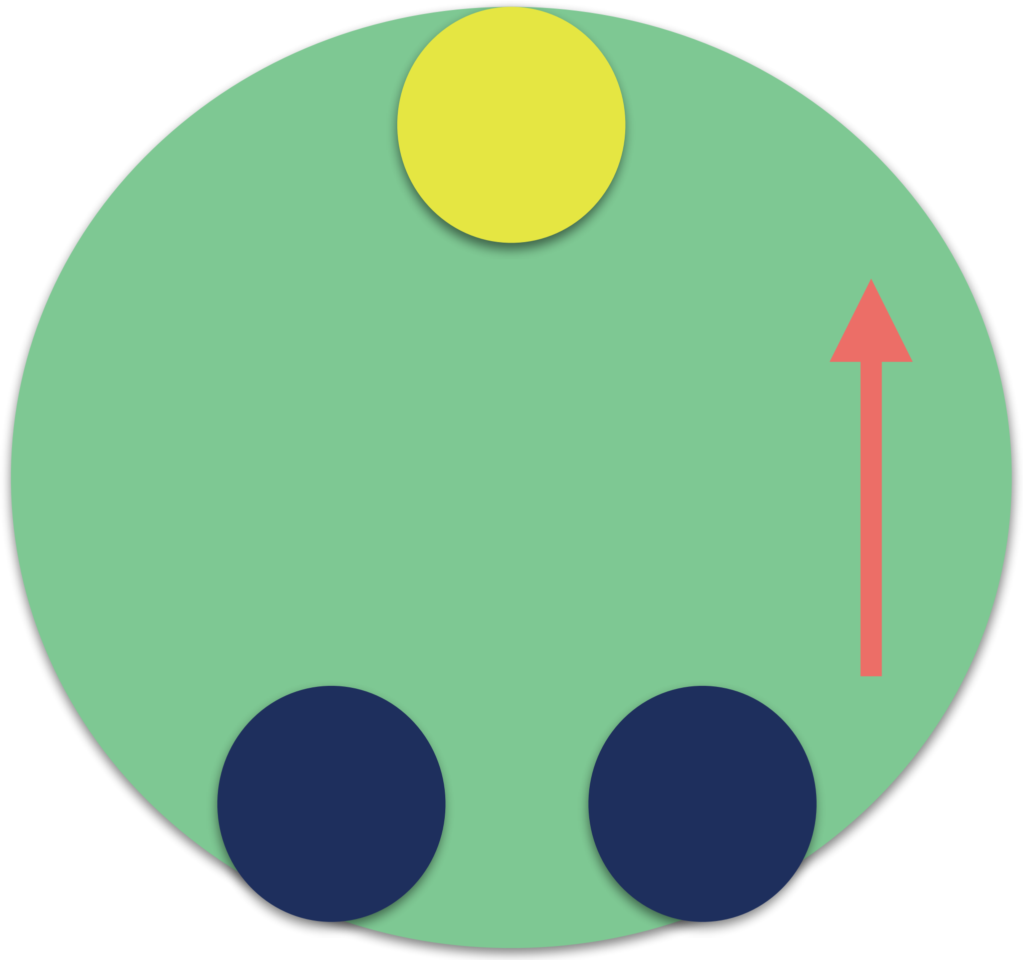


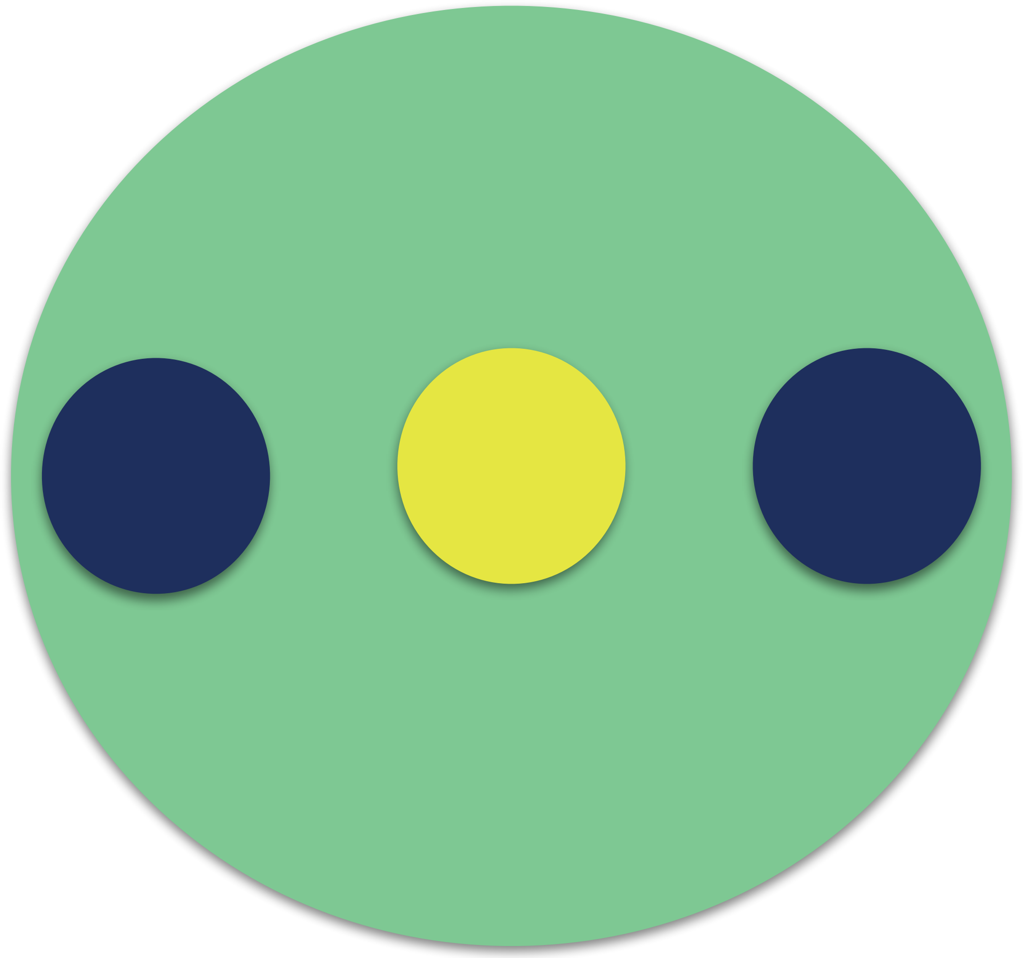
Neutron $\theta \neq 0$



Electric
Dipole

$\theta G\tilde{G}$

Neutron $\theta = 0$



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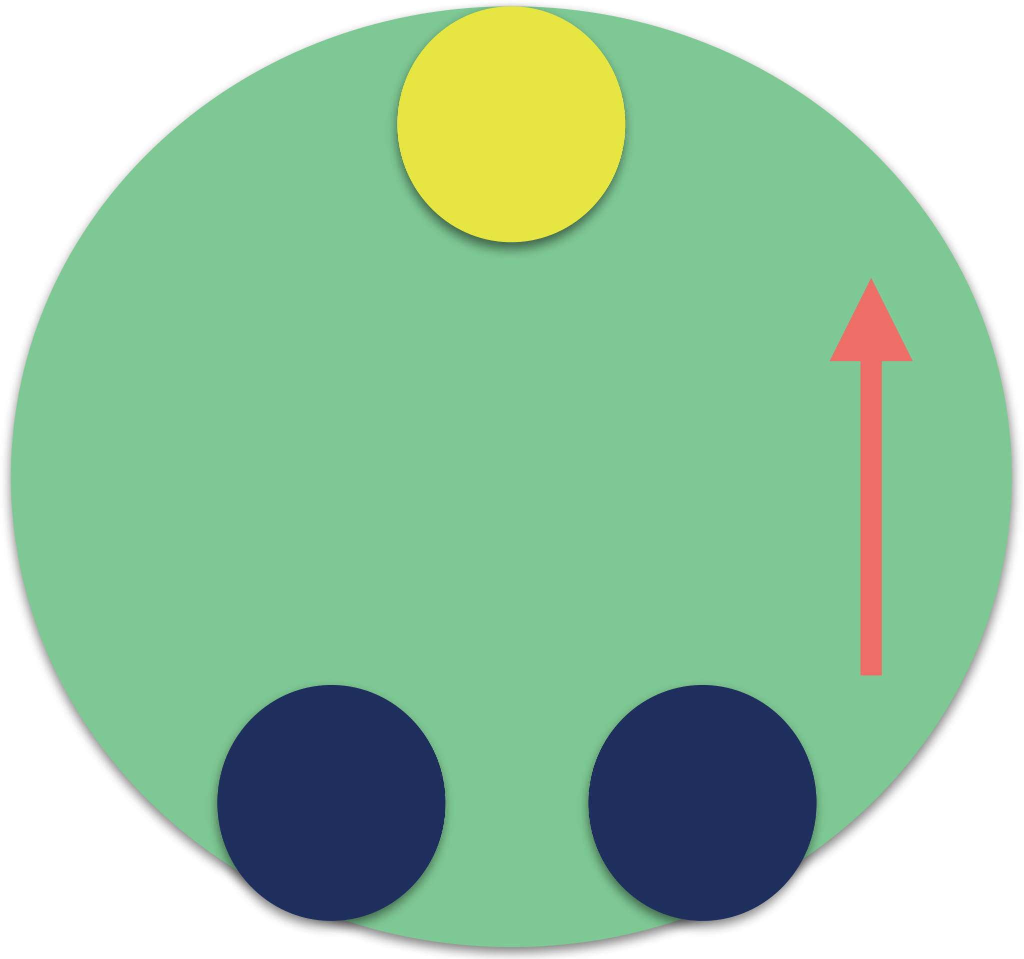


Electric Dipole

$|\theta| \lesssim 10^{-10}$ **Experimentally**

Introduce a new **global symmetry at fa**

$$\theta G\tilde{G} \longrightarrow \left(\theta + \frac{a}{f_a}\right) G\tilde{G}$$

At the minimum

$$\langle a \rangle = -\theta f_a$$

AXION-LIKE DARK MATTER

- Minimal Extension of what we know to exist
- Simple and predictive cosmology
- Solve another big problem in particle physics

Does anything change
as we vary the Higgs mass?

LOCAL

$$\mathrm{Tr}[G \wedge G] \equiv G\widetilde{G}$$

NON-LOCAL

On-shell N-point functions of massive SM particles

Does anything change as we vary the Higgs mass?

$$\mathrm{Tr}[G \wedge G] \equiv G\widetilde{G}$$

Present in many explanations of the small value of the Higgs mass

[Dvali, Vilenkin ’03], [Dvali ’04], [Geller, Hochberg, Kuflik,’18], [RTD, Teresi, ’21], [Arkani-Hamed, RTD, Kim, ‘20], ...

AXION-LIKE DARK MATTER

- Minimal Extension of what we know to exist
- Simple and predictive cosmology
- Potentially solves **two big problems** in particle physics

AXION

QCD Phase Transition

$$\frac{a}{f_a} G\tilde{G} \longrightarrow \frac{a}{f_a}\frac{\pi}{f_\pi} + \ldots$$

AXION

QCD Phase Transition

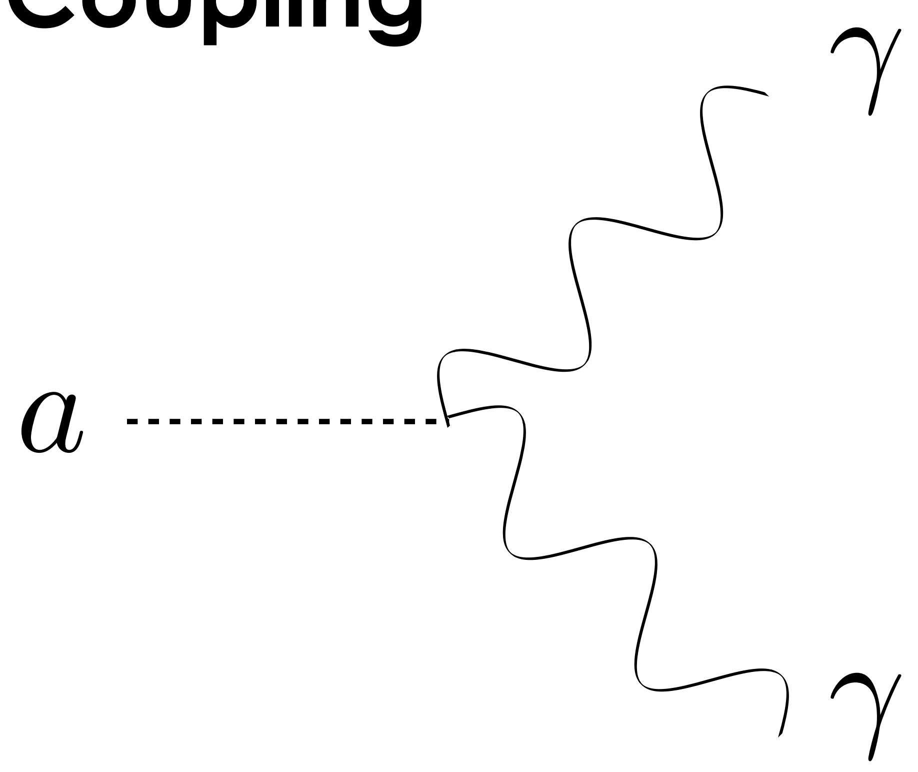
$$\frac{a}{f_a} G\tilde{G} \longrightarrow \frac{a}{f_a}\frac{\pi}{f_\pi} + \ldots$$

Mass

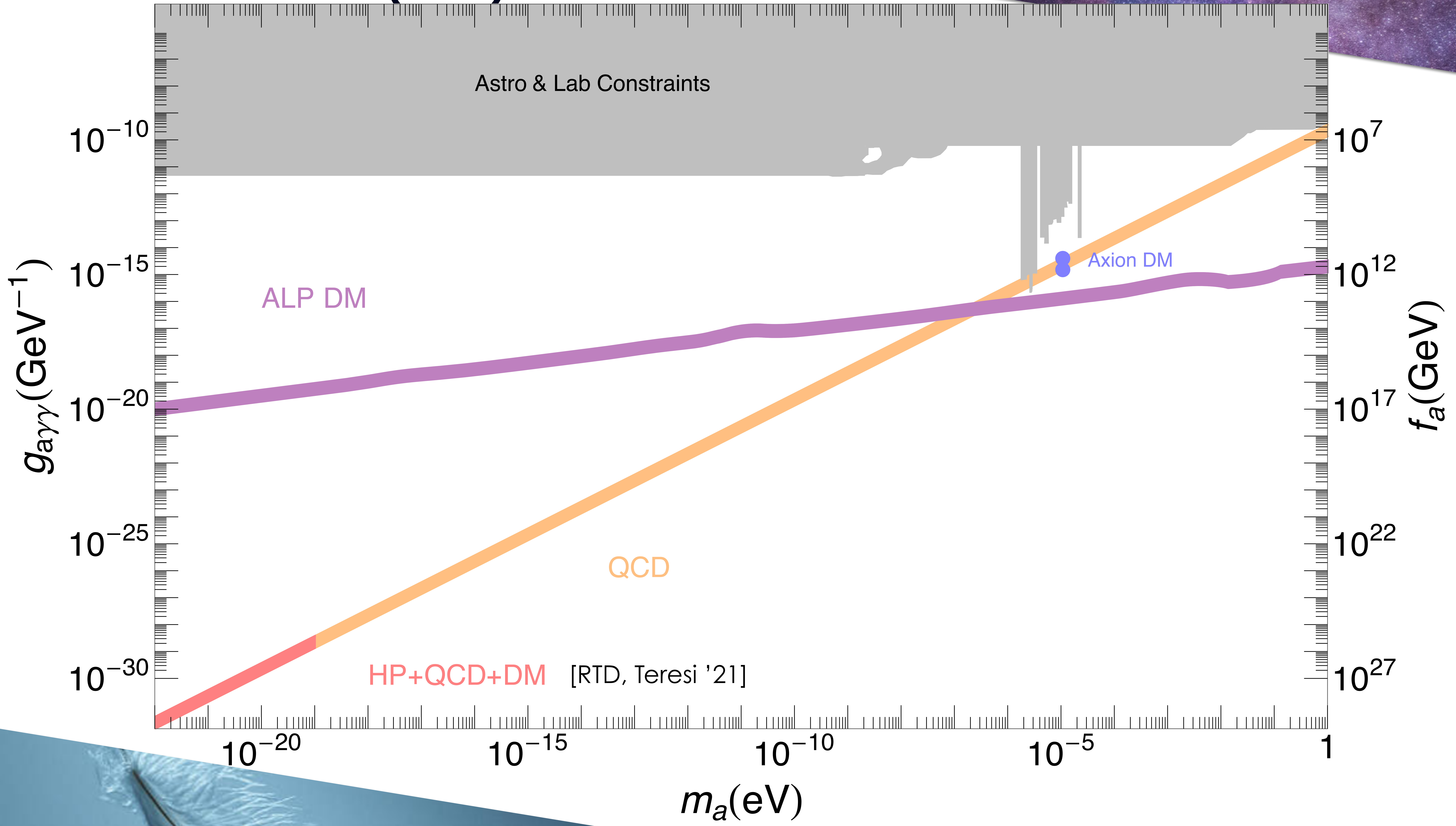
$$m_a \sim \frac{m_\pi^2}{f_a} \sim 10^{-2}\ \mathrm{eV}\ \frac{10^9\ \mathrm{GeV}}{f_a}$$

Relevant Coupling

$$\frac{a}{f_a}\mathbf{E}\cdot\mathbf{B}$$



AXION LIKE PARTICLES (ALPs)



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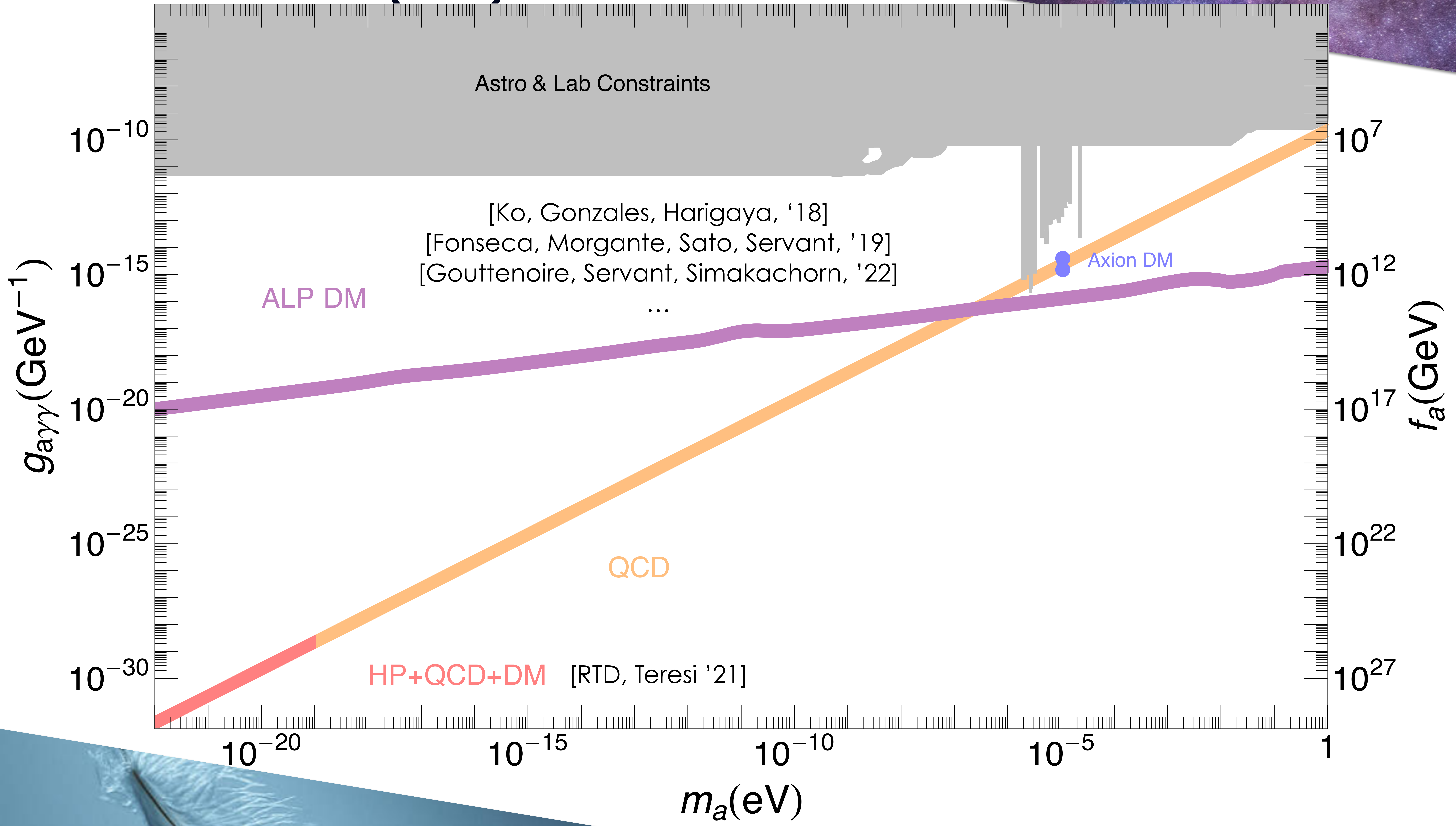

AXION LIKE PARTICLES (ALPs)

DESY and Hamburg University are at the forefront of this effort:
ALPS II, BabyIAXO, ...

ALPS DETECTION

ALP DARK MATTER IN THE LAB

Produced Colder than the SM (even if not via misalignment)

$$E_a \approx m_a$$

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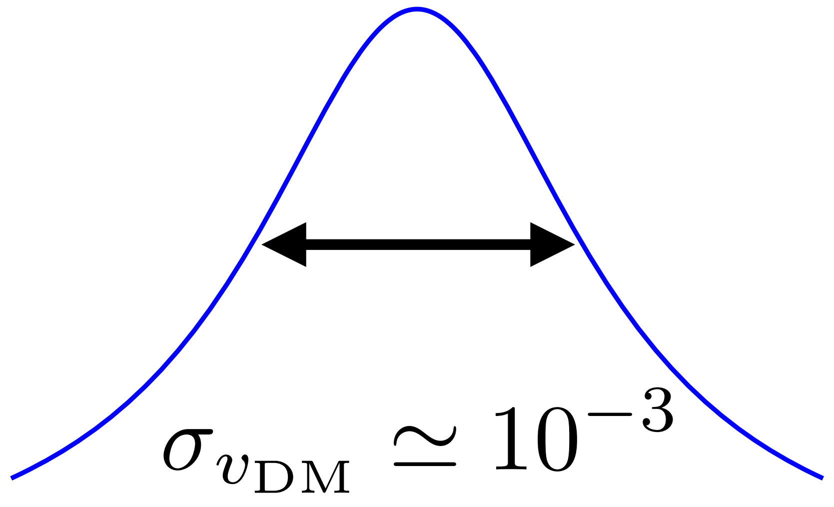
$$E_a \approx m_a$$

It acquires a **small velocity dispersion** from virialization **in the Milky Way**

$$E_a \simeq m_a \left(1 + \frac{v_{\rm DM}^2}{2}\right)$$



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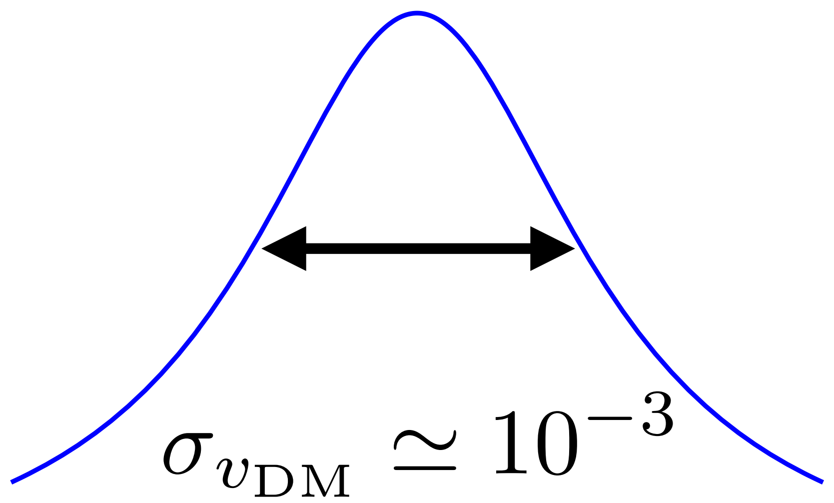
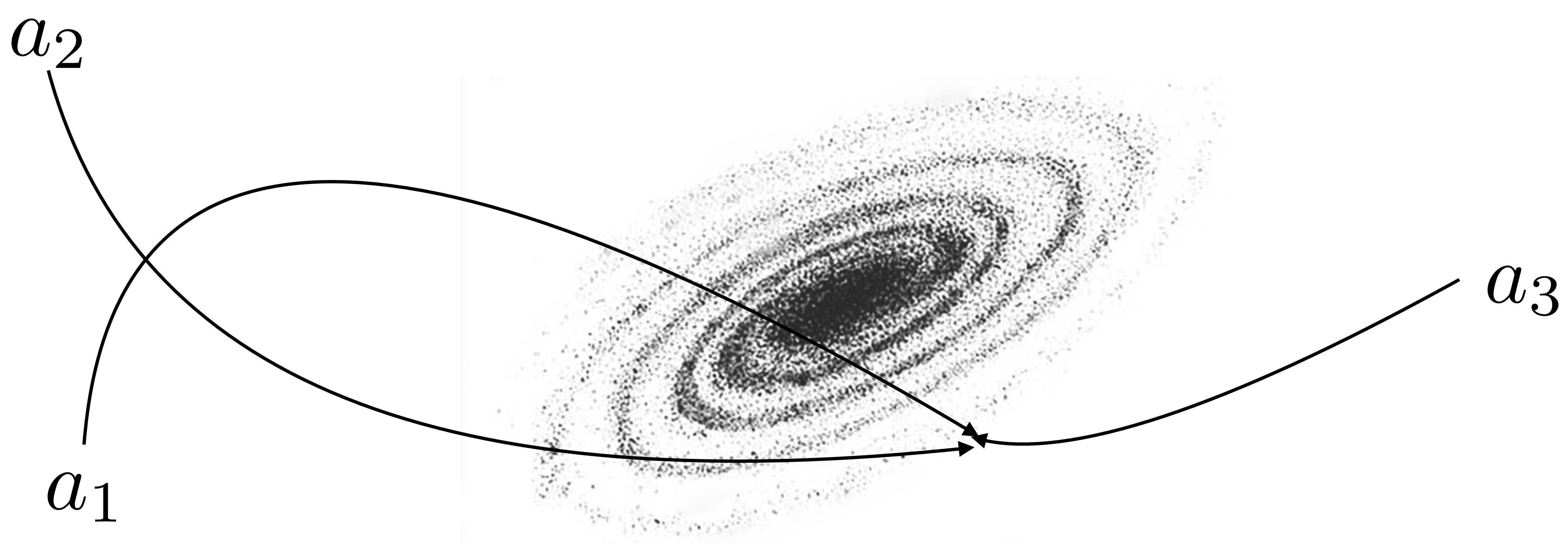


Lots of axions in each frequency bin that we can resolve
(even more in a De Broglie volume):

$$\Delta N_a \simeq \frac{\rho_{\rm DM} V}{m_a^2 t_{\rm int} v_{\rm DM}^2} \simeq 10^{24} \left(\frac{10^{-14}\ {\rm eV}}{m_a}\right)^2 \left(\frac{\rm year}{t_{\rm int}}\right) \left(\frac{V}{\rm m^3}\right)$$

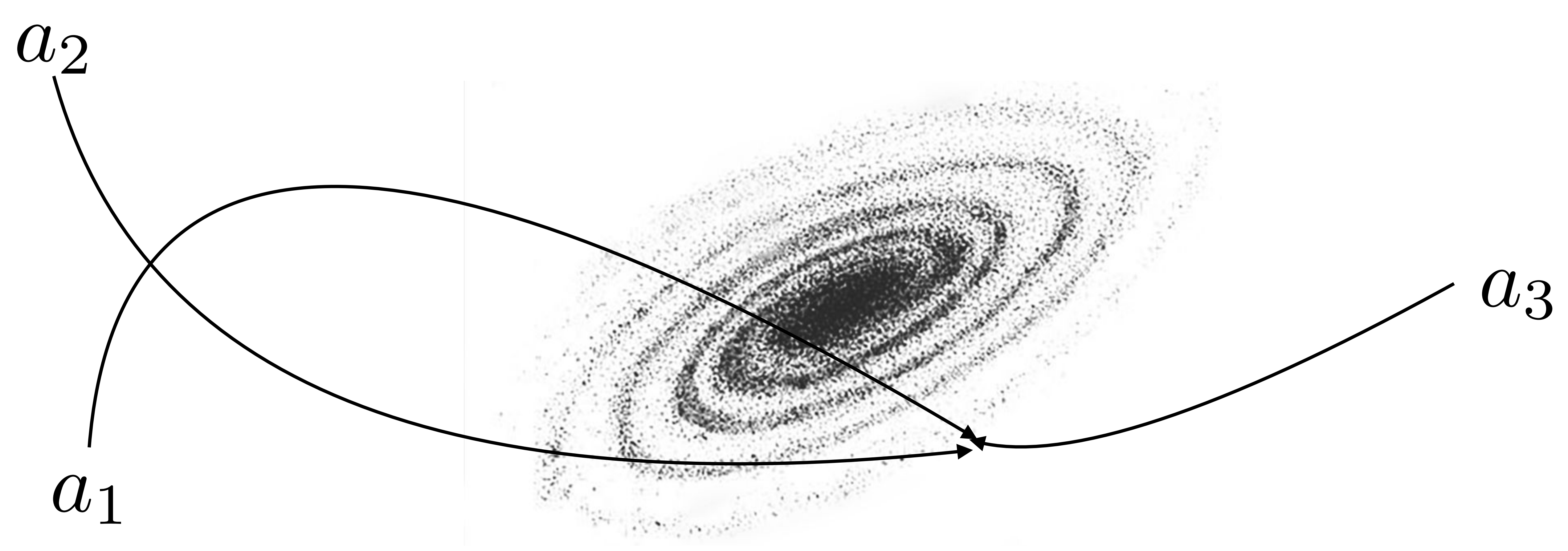
ALP DARK MATTER IN THE LAB

In each experimental bin we are summing over a multitude of plane waves with different phases



ALP DARK MATTER IN THE LAB

In each experimental bin we are summing over a multitude of plane waves with different phases



$$a(t) = a_0 \left[\cos\left(m_a \left(1 + \frac{v_1^2}{2}\right) t + \phi_1 \right) + \cos\left(m_a \left(1 + \frac{v_2^2}{2}\right) t + \phi_2 \right) + \ldots \right]$$

$$\simeq a_0 \cos(m_a t + \phi) \left[\cos(\delta\omega_a t + \phi') + \ldots \right]$$

$$\delta\omega_a \simeq \frac{1}{m_a \langle v_{\mathrm{DM}}^2 \rangle} \simeq \frac{10^6}{m_a}$$

Effectively: very **slow modulation of** an approximately **monochromatic field**

ALP DARK MATTER IN THE LAB

$$a(t) \simeq \frac{\sqrt{2\rho_{\mathrm{DM}}}}{m_a} \cos(\omega_a t + \phi)$$

ALP DARK MATTER IN THE LAB

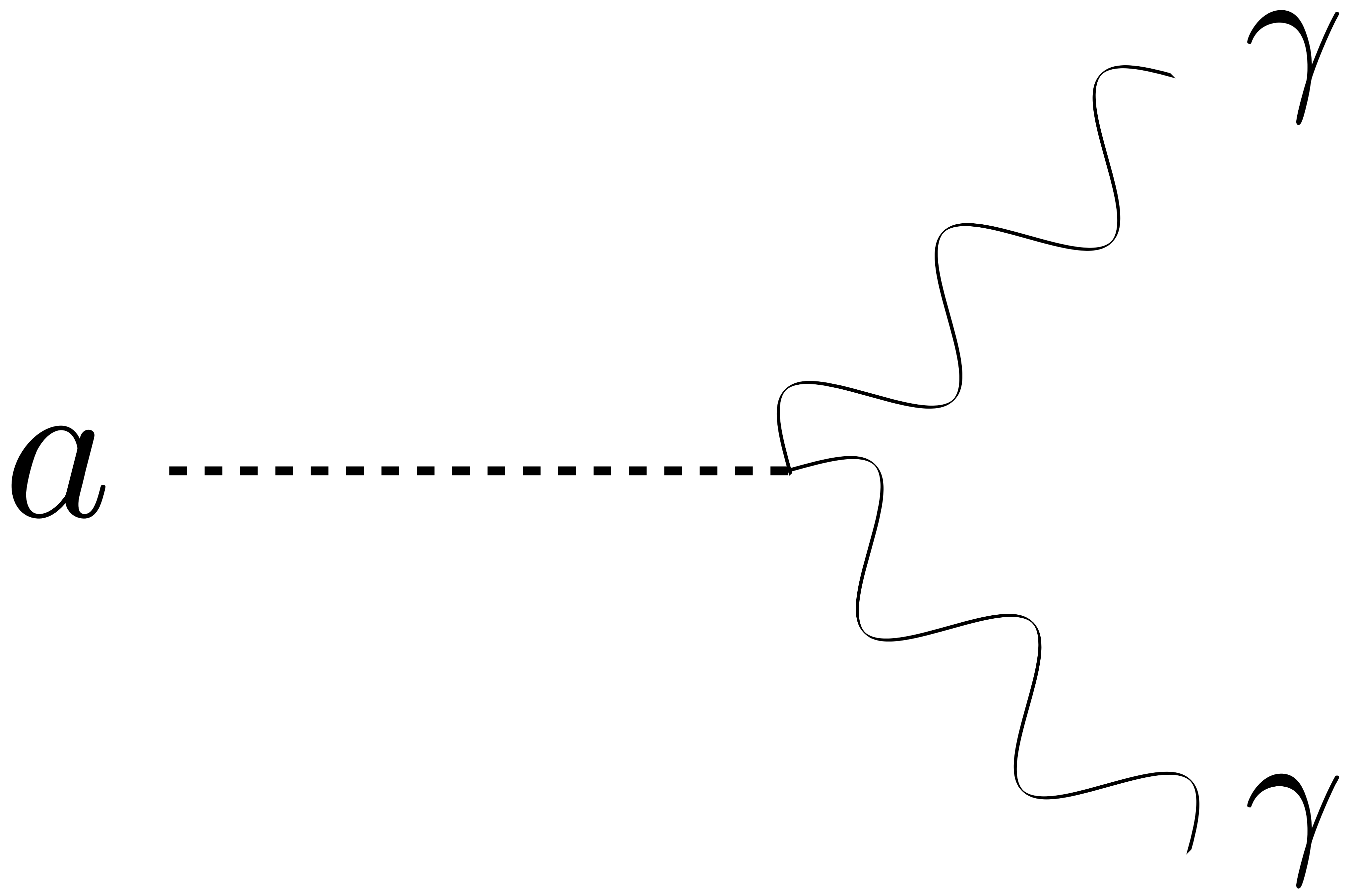
$$a(t) \simeq \frac{\sqrt{2\rho_{\rm DM}}}{m_a}\cos(\omega_a t + \phi)$$

Frequency: $\omega_a \simeq \mathrm{GHz}\ \frac{m_a}{10^{-6}\ \mathrm{eV}}$

Coherence: $\tau_a \simeq \mathrm{ms}\ \frac{10^{-6}\ \mathrm{eV}}{m_a}$

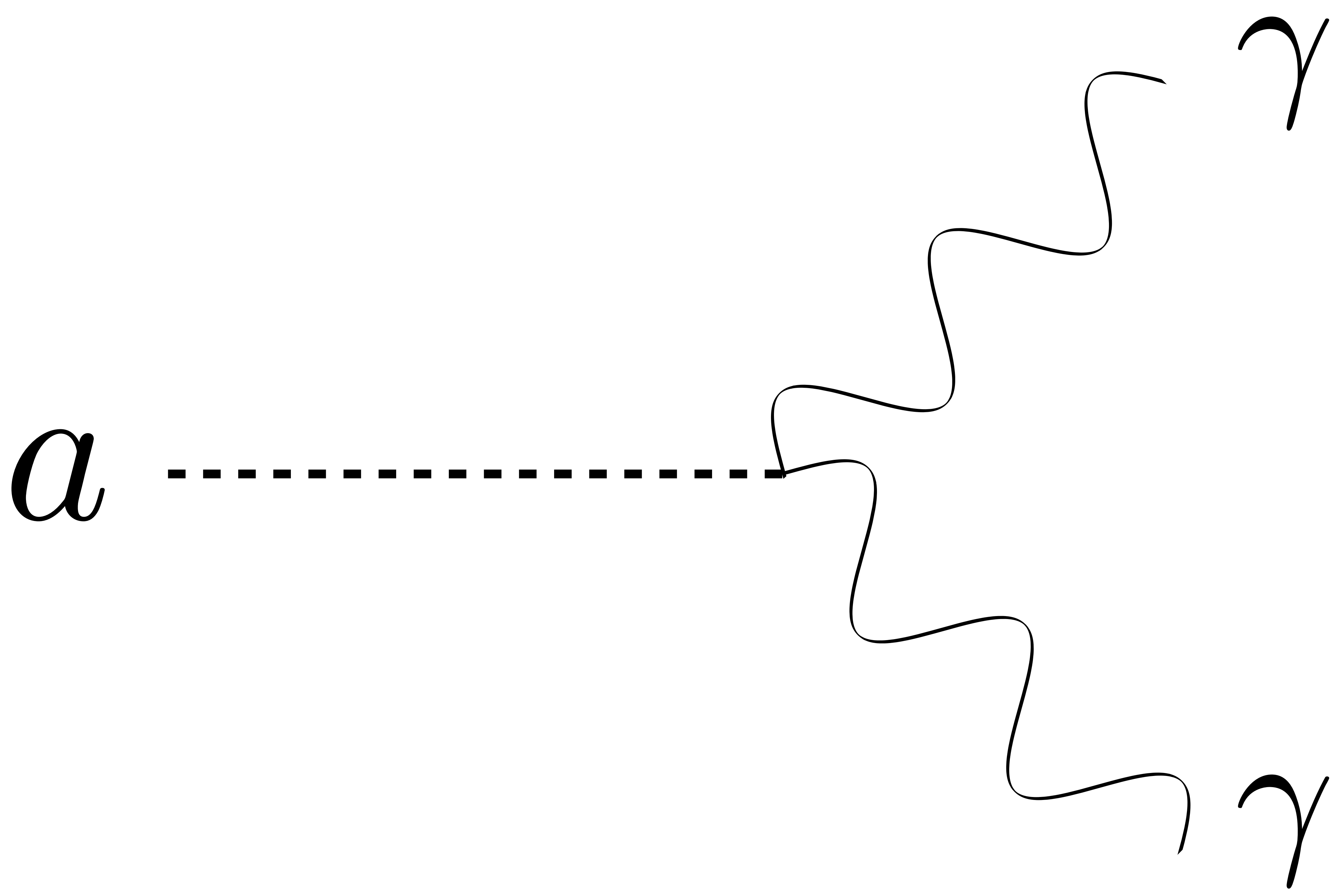
Max Exp. Size: $\lambda_a \simeq 200\ \mathrm{m}\ \frac{10^{-6}\ \mathrm{eV}}{m_a}$

ALP DARK MATTER DETECTION



$$\nabla \times \mathbf{B} \simeq \partial_t \mathbf{E} + \mathbf{J} + \underline{g_{a\gamma\gamma} \mathbf{B}\, \partial_t a}$$

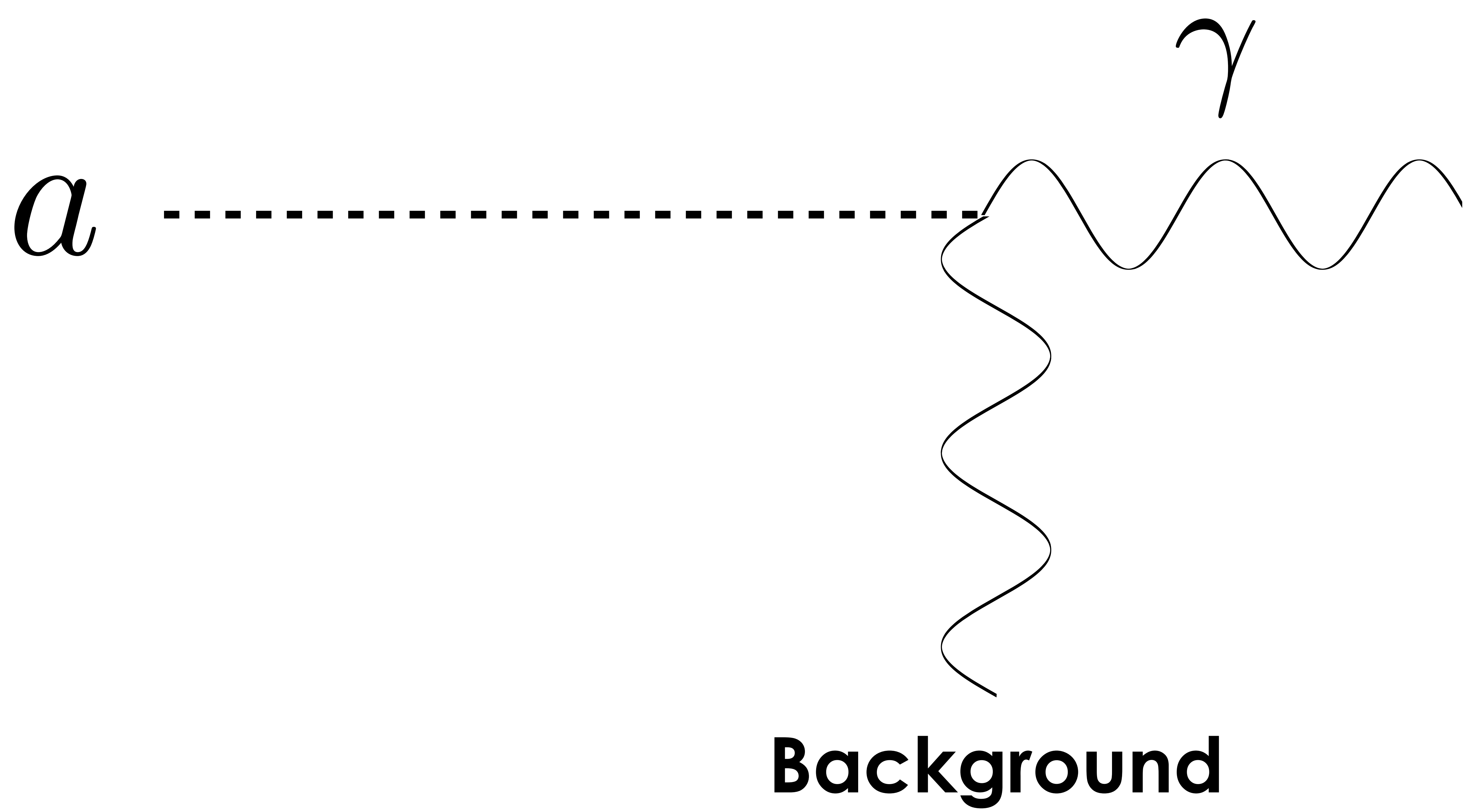
ALP DARK MATTER DETECTION



$$\nabla \times \mathbf{B} \simeq \partial_t \mathbf{E} + \mathbf{J} + \underline{g_{a\gamma\gamma} \mathbf{B}\, \partial_t a}$$

$$J_{\mathrm{eff}}(t) \sim g_{a\gamma\gamma} B_0(t) \sqrt{\rho_{\mathrm{DM}}} \cos m_a t$$

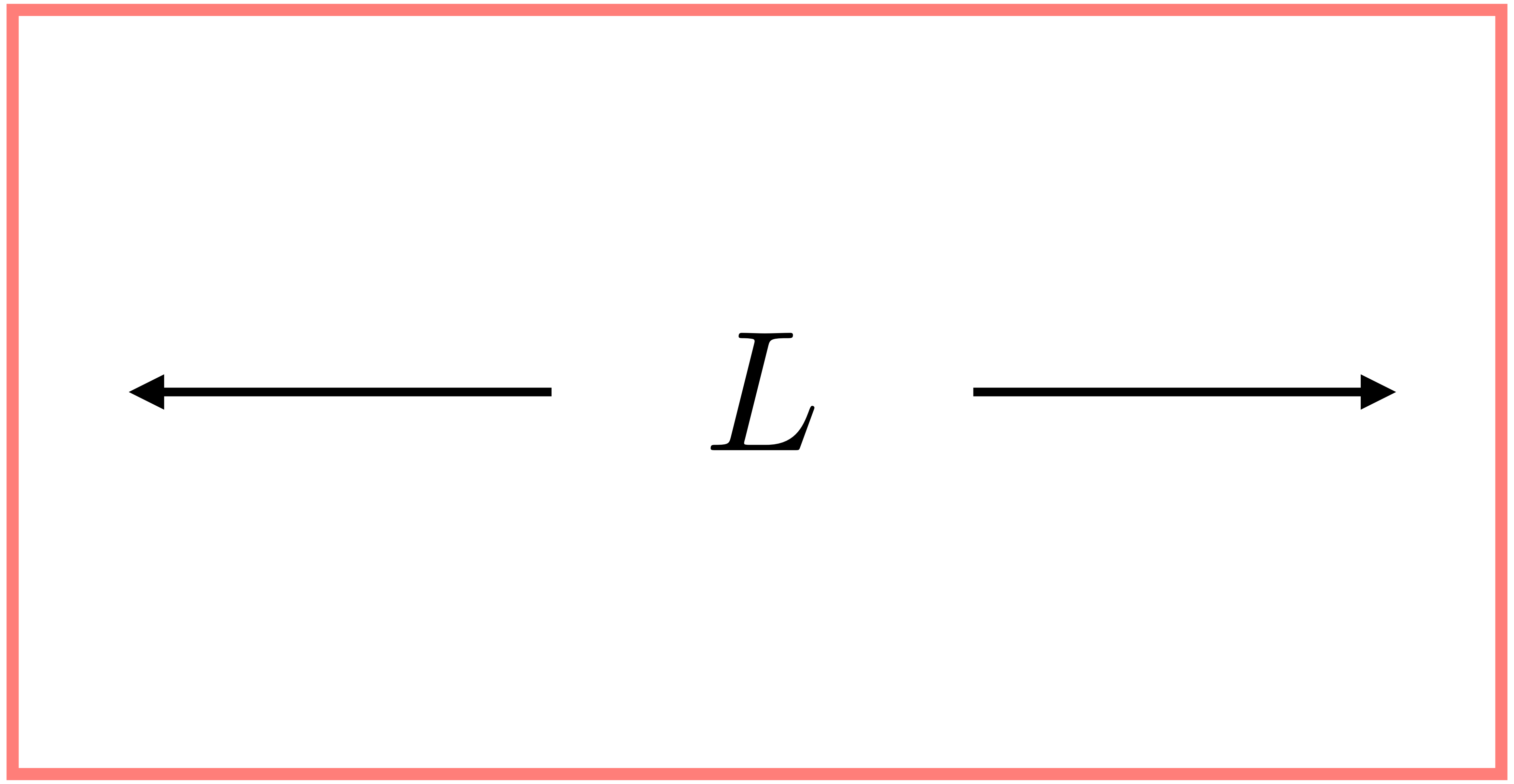
ALP DARK MATTER DETECTION



$$\sim \frac{a}{f_a} E_{\rm bkg} \simeq 10^{-21} E_{\rm bkg}$$

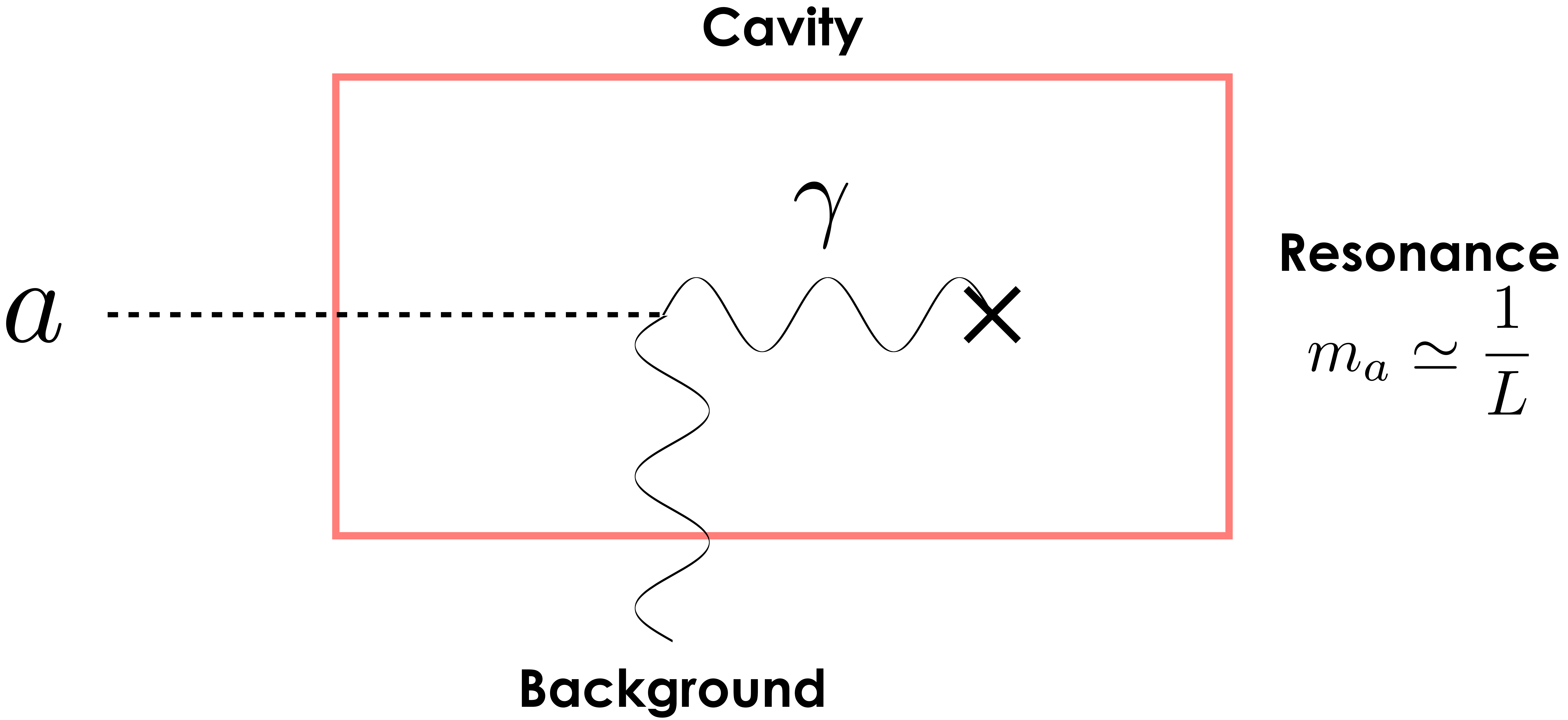
AXION DARK MATTER DETECTION

Cavity



$$m_\gamma \simeq \frac{1}{L}$$

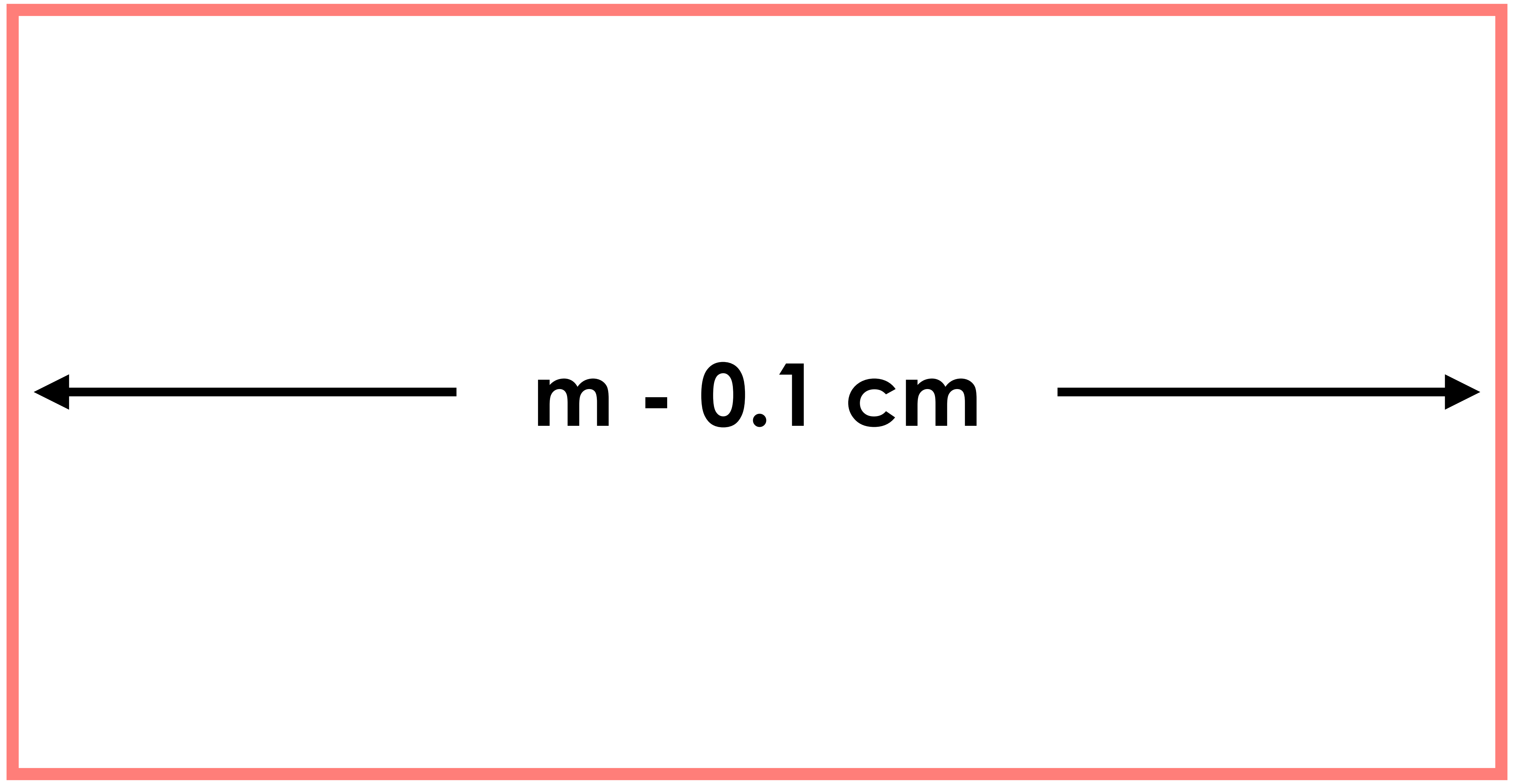
AXION DARK MATTER DETECTION



Astro & Lab Constraints
Axion DM
ALP DM
QCD
HP+QCD+DM
10^{-10}
10^{-15}
10^{-20}
10^{-25}
10^{-30}
$g_{a\gamma\gamma}(\mathrm{GeV}^{-1})$
10^{7}
10^{12}
10^{17}
10^{22}
10^{27}
$f_a(\mathrm{GeV})$
10^{-20}
10^{-15}
10^{-10}
10^{-5}
1
$m_a(\mathrm{eV})$

AXION DETECTION

Cavity



Low noise electronics

High quality factors

Astro & Lab Constraints
Impractical
(fine control of
huge cavities)
Axion DM
QCD
HP+QCD+DM
$g_{a\gamma\gamma}(\mathrm{GeV}^{-1})$
10^{-10}
10^{-15}
10^{-20}
10^{-25}
10^{-30}
$f_a(\mathrm{GeV})$
10^{7}
10^{12}
10^{17}
10^{22}
10^{27}
10^{-20}
10^{-15}
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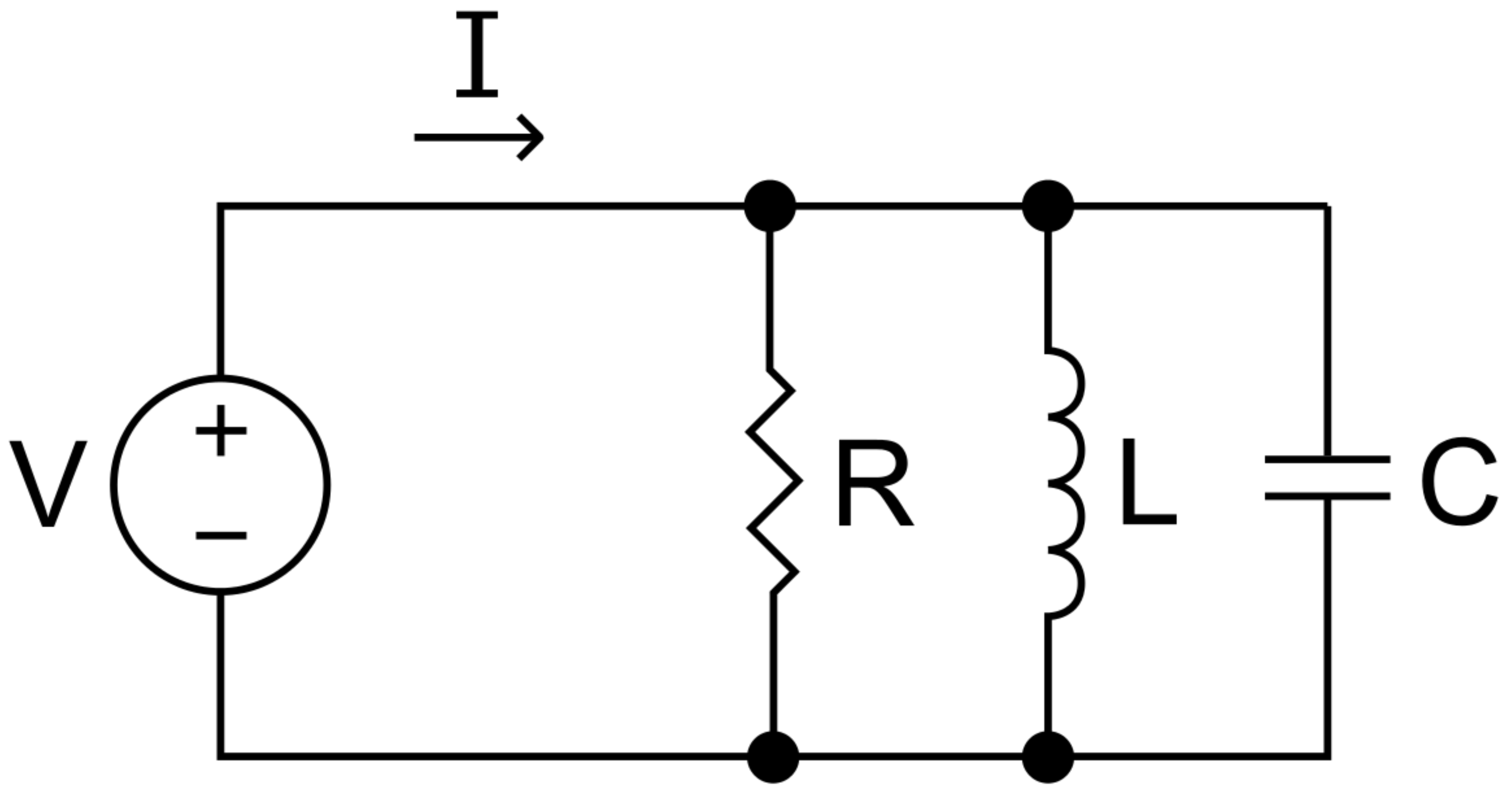
10^{-5}
1
$m_a(\mathrm{eV})$

DM RADIO AND ABRACADABRA

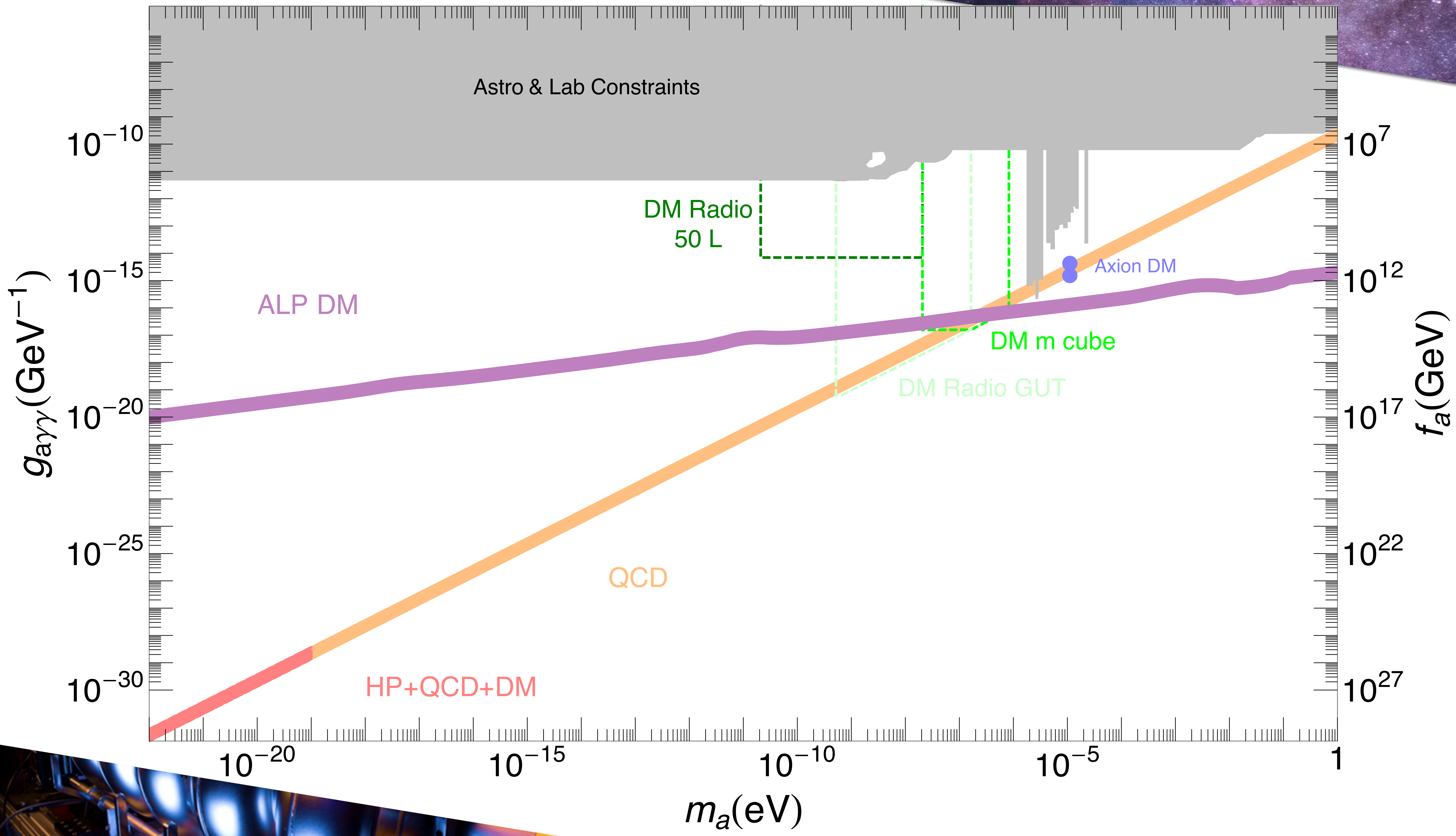
[Kahn, Safdi, Tahler '16][Chauduri, Irwin, Graham, Mardon '18-'19]

Cavity

RLC Circuit



$$\omega = \frac{1}{\sqrt{LC}}$$



Astro & Lab Constraints
DM Radio
50 L
Axion DM
ALP DM
DM m cube
DM Radio GUT
QCD
HP+QCD+DM
$g_{a\gamma\gamma}(\mathrm{GeV}^{-1})$
$f_a(\mathrm{GeV})$
$m_a(\mathrm{eV})$
10^{-10}
10^{-15}
10^{-20}
10^{-25}
10^{-30}
10^{7}
10^{12}
10^{17}
10^{22}
10^{27}
10^{-20}
10^{-15}
10^{-10}
10^{-5}
1

AXION DETECTION

Cavity:

$$\sum_n \left(\partial_t^2 + \frac{\omega_n}{Q_n} \partial_t + \omega_n^2 \right) \mathbf{E}_n = g_{a\gamma\gamma} \partial_t (\mathbf{B} \partial_t a)$$

AXION DETECTION

Cavity:

$$\sum_n \left(\partial_t^2 + \frac{\omega_n}{Q_n} \partial_t + \omega_n^2 \right) \mathbf{E}_n = g_{a\gamma\gamma} \partial_t (\mathbf{B} \partial_t a)$$

$$\omega_1 \simeq m_a \qquad \partial_t(\mathbf{B}) \simeq 0$$

AXION DETECTION

Cavity:

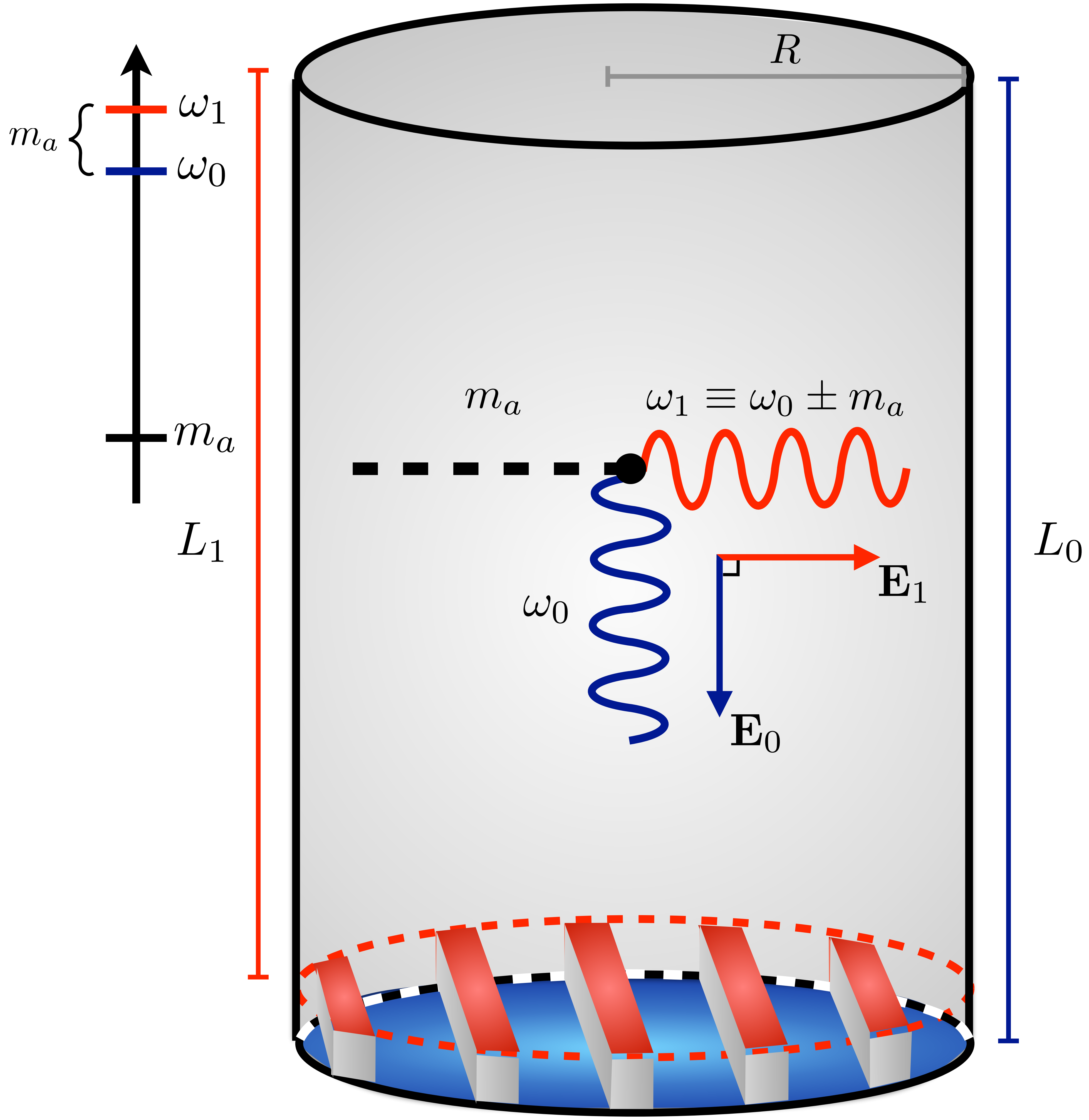
$$\sum_n \left(\partial_t^2 + \frac{\omega_n}{Q_n} \partial_t + \omega_n^2 \right) \mathbf{E}_n = g_{a\gamma\gamma} \partial_t (\mathbf{B} \partial_t a)$$

$$\omega_1 \simeq m_a \qquad \partial_t(\mathbf{B}) \simeq 0$$

$$\left(\partial_t^2 + \frac{m_a}{Q_1} \partial_t + m_a^2 \right) \mathbf{E}_1 = \boxed{g_{a\gamma\gamma} \mathbf{B} \sqrt{\rho_{\mathrm{DM}}} m_a \cos m_a t}$$

HETERODYNE DETECTION

[Berlin, RTD, S. Ellis, C. Nantista, J. Nielson, P. Schuster, S. Tantawi, N. Toro, K. Zhou‘19]



HETERODYNE DETECTION

[Berlin, RTD, S. Ellis, C. Nantista, J. Nielson, P. Schuster, S. Tantawi, N. Toro, K. Zhou‘19]

$$\sum_n \left(\partial_t^2 + \frac{\omega_n}{Q_n}\partial_t + \omega_n^2 \right) \mathbf{E}_n = \boxed{g_{a\gamma\gamma}\partial_t(\mathbf{B}\partial_t a)}$$

$$\boxed{\partial_t(\mathbf{B}) \simeq i\omega_0 \mathbf{B} \qquad \omega_1 \simeq \omega_0 + m_a}$$

$$\boxed{\partial_t J_{\text{eff}} = g_{a\gamma\gamma}\partial_t(\mathbf{B}\partial_t a) \propto \omega_0 m_a \gg m_a^2}$$

Astro & Lab Constraints
DM Radio
HETERODYNE
Axion DM
ALP DM
QCD
HP+QCD+DM
10^{-10}
10^{-15}
10^{-20}
10^{-25}
10^{-30}
10^{7}
10^{12}
10^{17}
10^{22}
10^{27}
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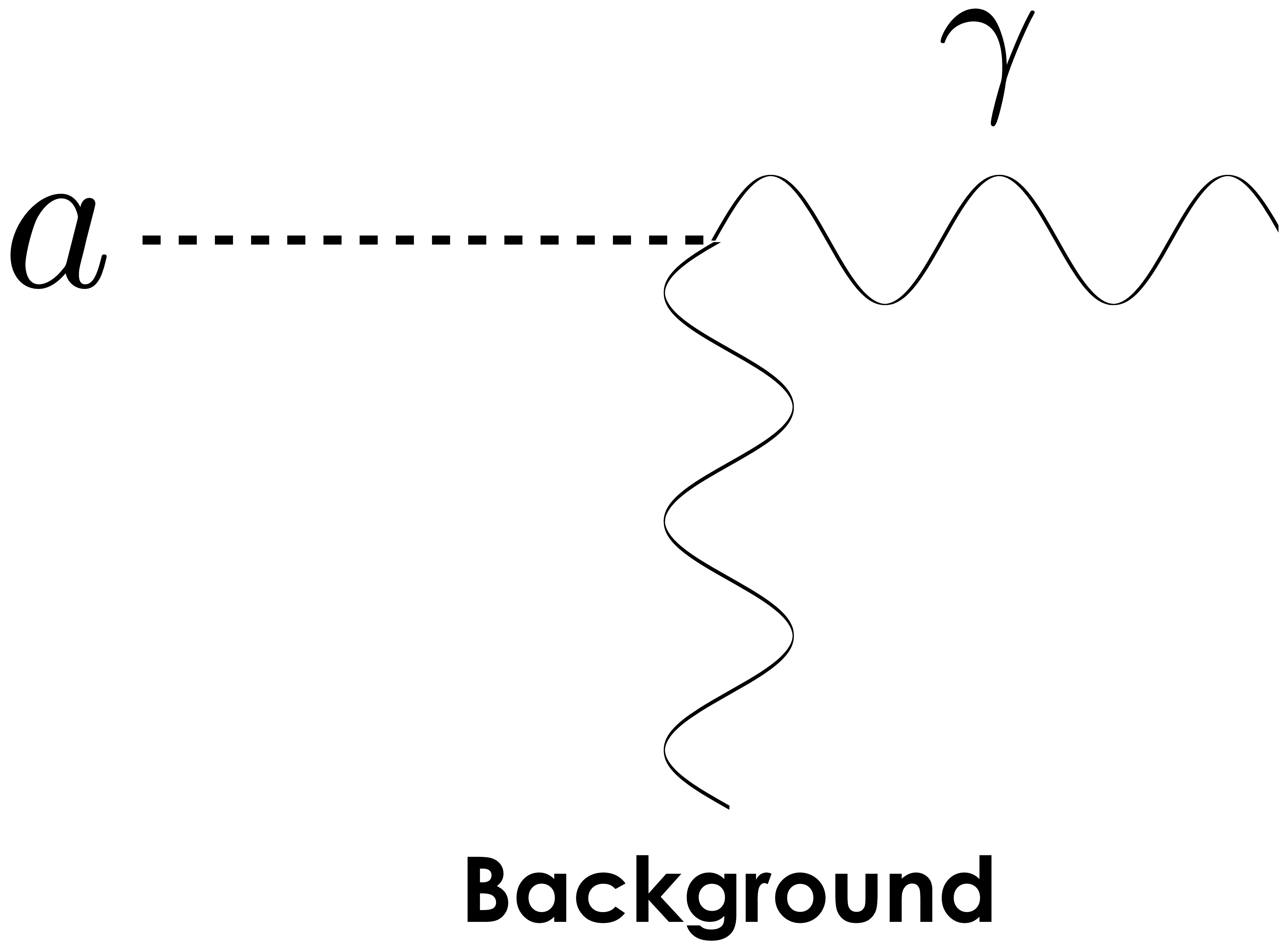
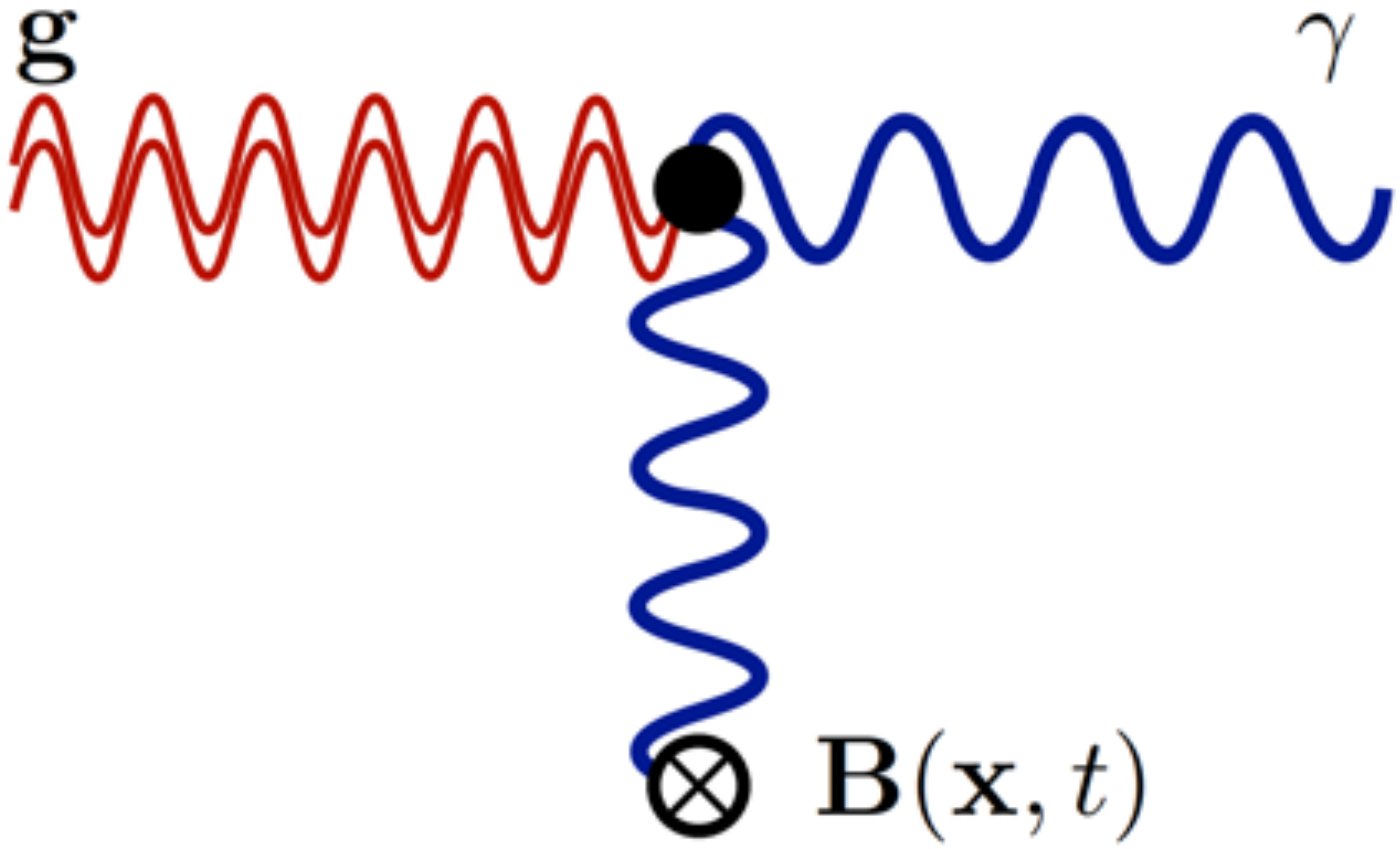
10^{-15}
10^{-10}
10^{-5}
1
$g_{a\gamma\gamma}(\mathrm{GeV}^{-1})$
$f_a(\mathrm{GeV})$
$m_a(\mathrm{eV})$

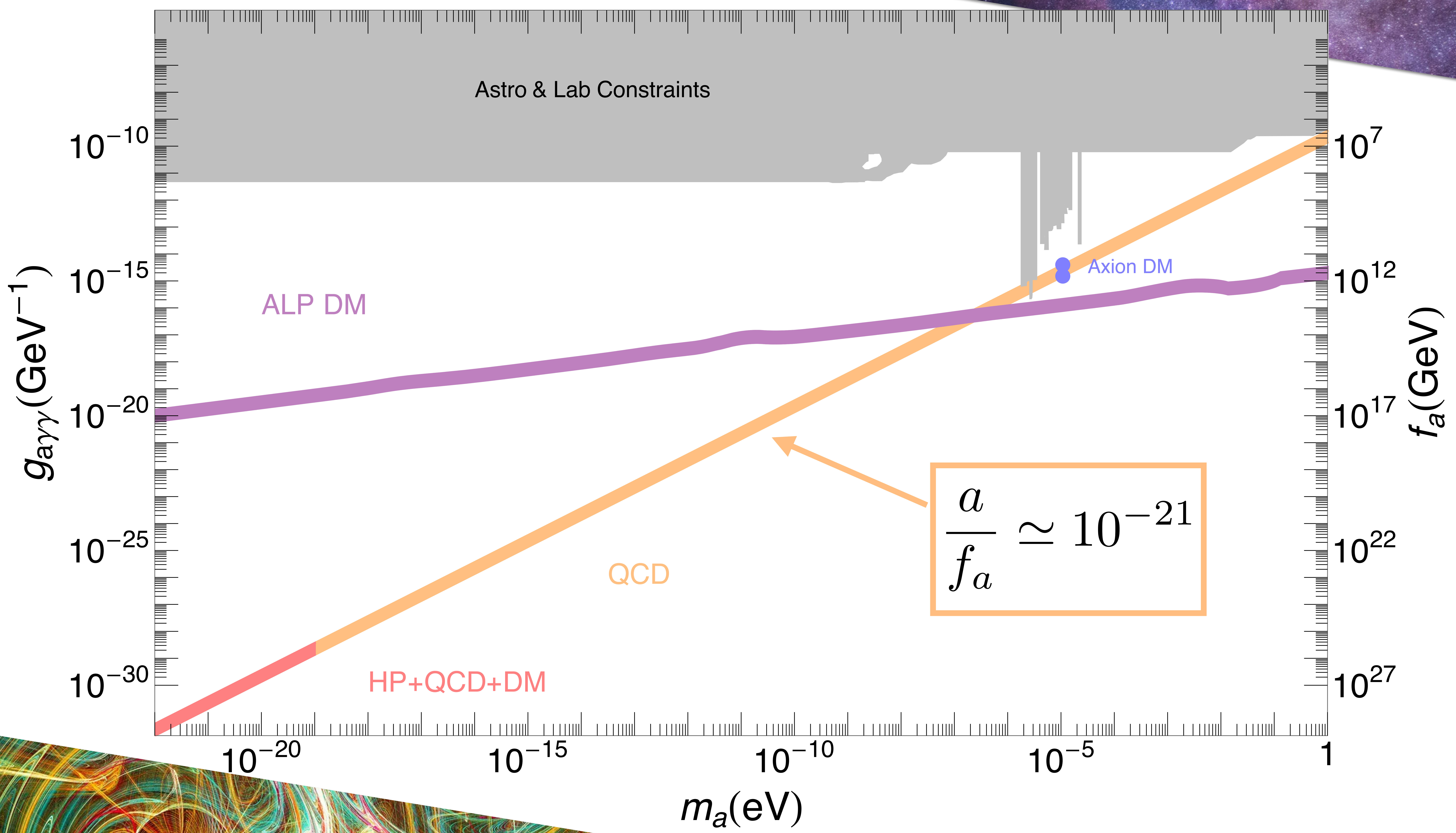
HIGH-FREQUENCY GRAVITATIONAL WAVES



γ
a
Background



g
γ
$\mathbf{B}(\mathbf{x}, t)$



Astro & Lab Constraints
ALP DM
Axion DM
QCD
HP+QCD+DM
$\frac{a}{f_a} \simeq 10^{-21}$
10^{-10}
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10^{27}
$f_a(\mathrm{GeV})$
10^{-20}
10^{-15}
10^{-10}
10^{-5}
1
$m_a(\mathrm{eV})$

$$\omega_g$$

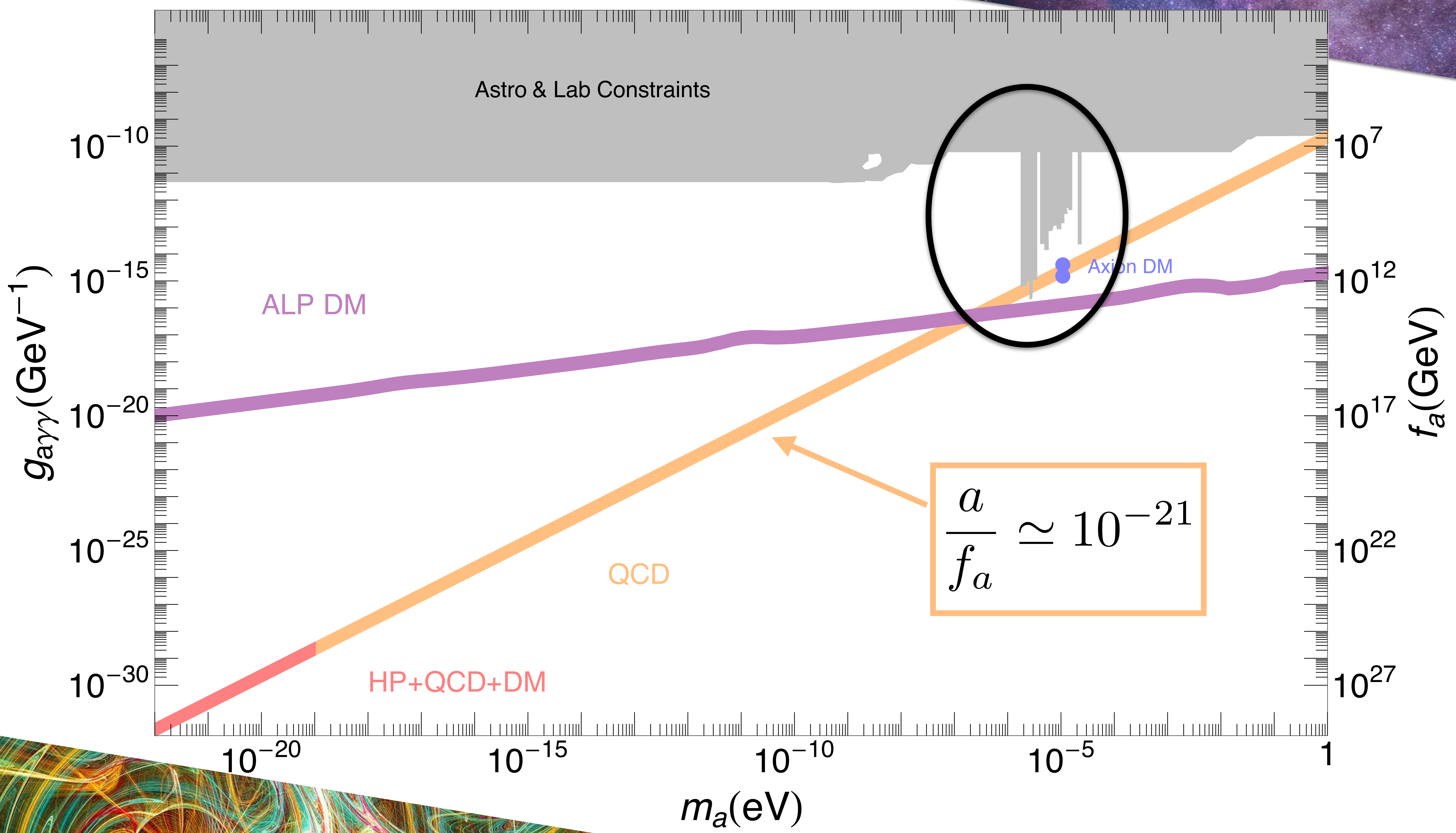
$$\lambda(T_*) < \frac{1}{H(T_*)}$$ Causality

$$\omega_g$$

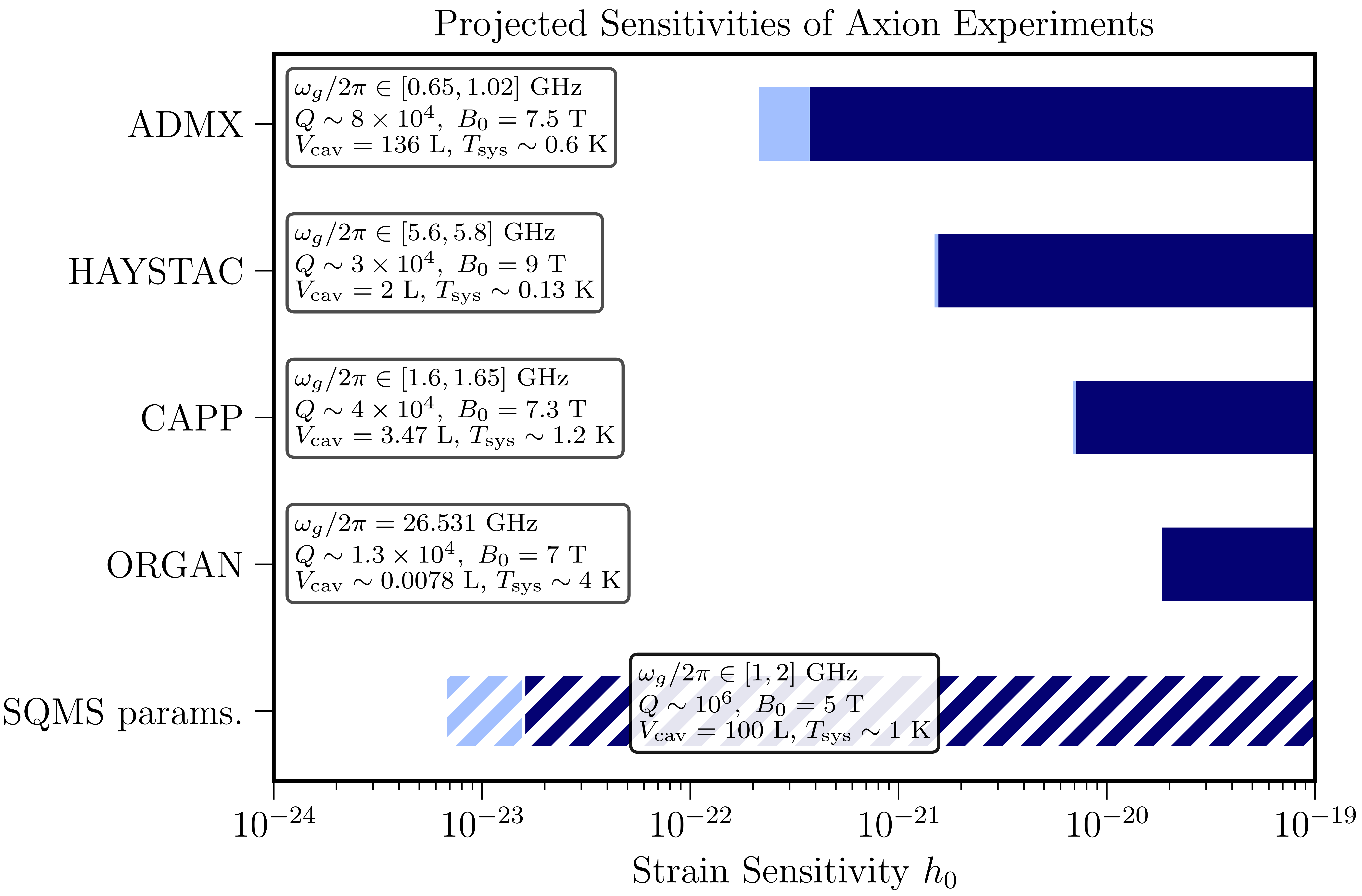
$$\lambda(T_*) < \frac{1}{H(T_*)}$$

Causality

$$\omega_0(T_*) = \omega(T_*)\frac{a(T_*)}{a_0} \gtrsim \boxed{100\ \mathrm{MHz}} \left(\frac{T_*}{10^{15}\mathrm{GeV}}\right)\left(\frac{g_*(T_*)}{100}\right)^{1/6}$$


Astro & Lab Constraints
Axion DM
ALP DM
QCD
HP+QCD+DM
$\frac{a}{f_a} \simeq 10^{-21}$
$g_{a\gamma\gamma}(\mathrm{GeV}^{-1})$
$f_a(\mathrm{GeV})$
$m_a(\mathrm{eV})$
10^{-10}
10^{-15}
10^{-20}
10^{-25}
10^{-30}
10^{7}
10^{12}
10^{17}
10^{22}
10^{27}
10^{-20}
10^{-15}
10^{-10}
10^{-5}
1

GRAVITATIONAL WAVE DETECTION



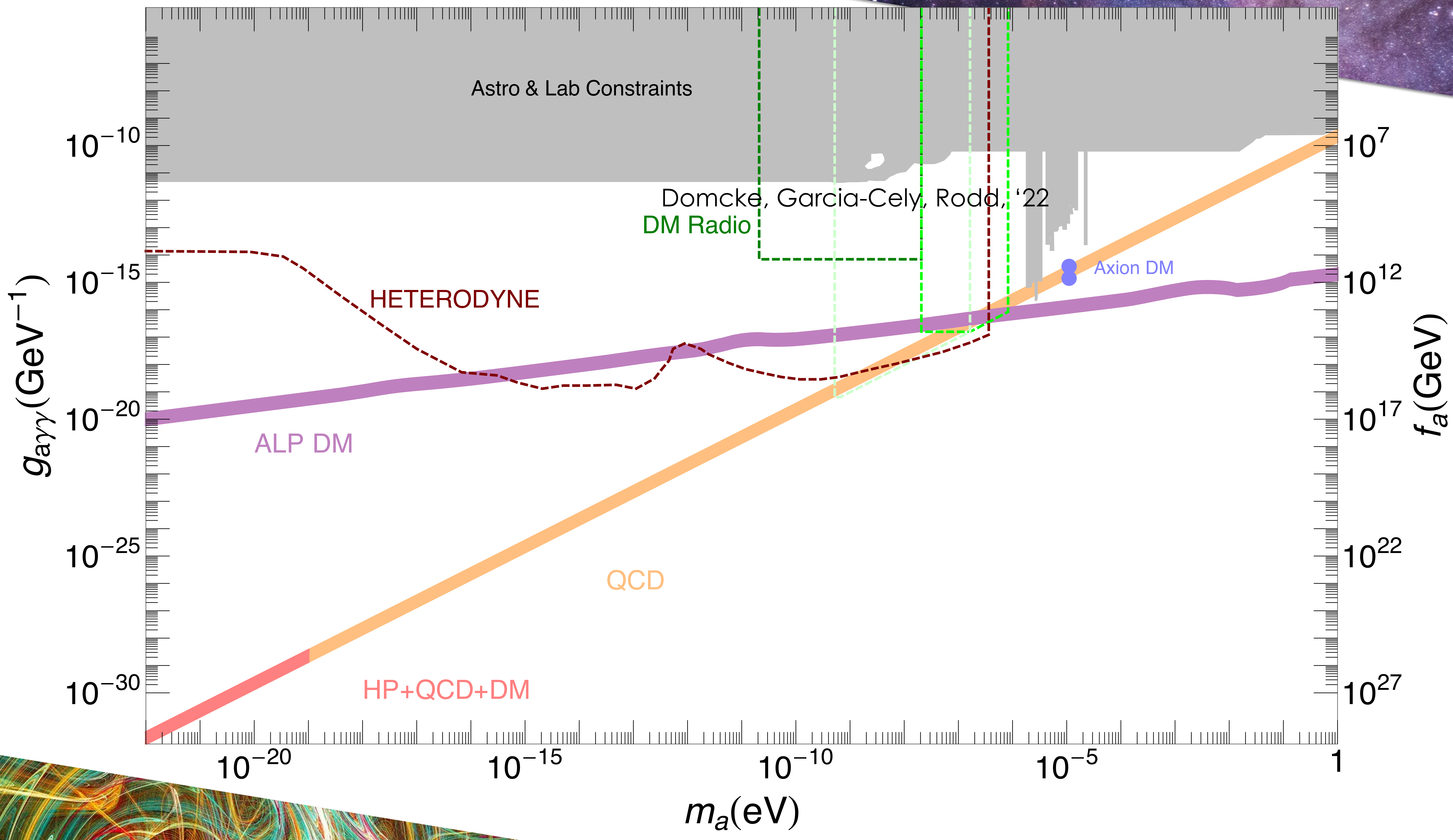
Berlin, Blas, RTD, Ellis, Harnik, Kahn, Schutte-Engel '21

SUPERRADIANCE

$$\omega_g \simeq 2m_a \simeq \mathrm{GHz}\left(\frac{10^{-4}M_\odot}{M_{\mathrm{BH}}}\right)$$

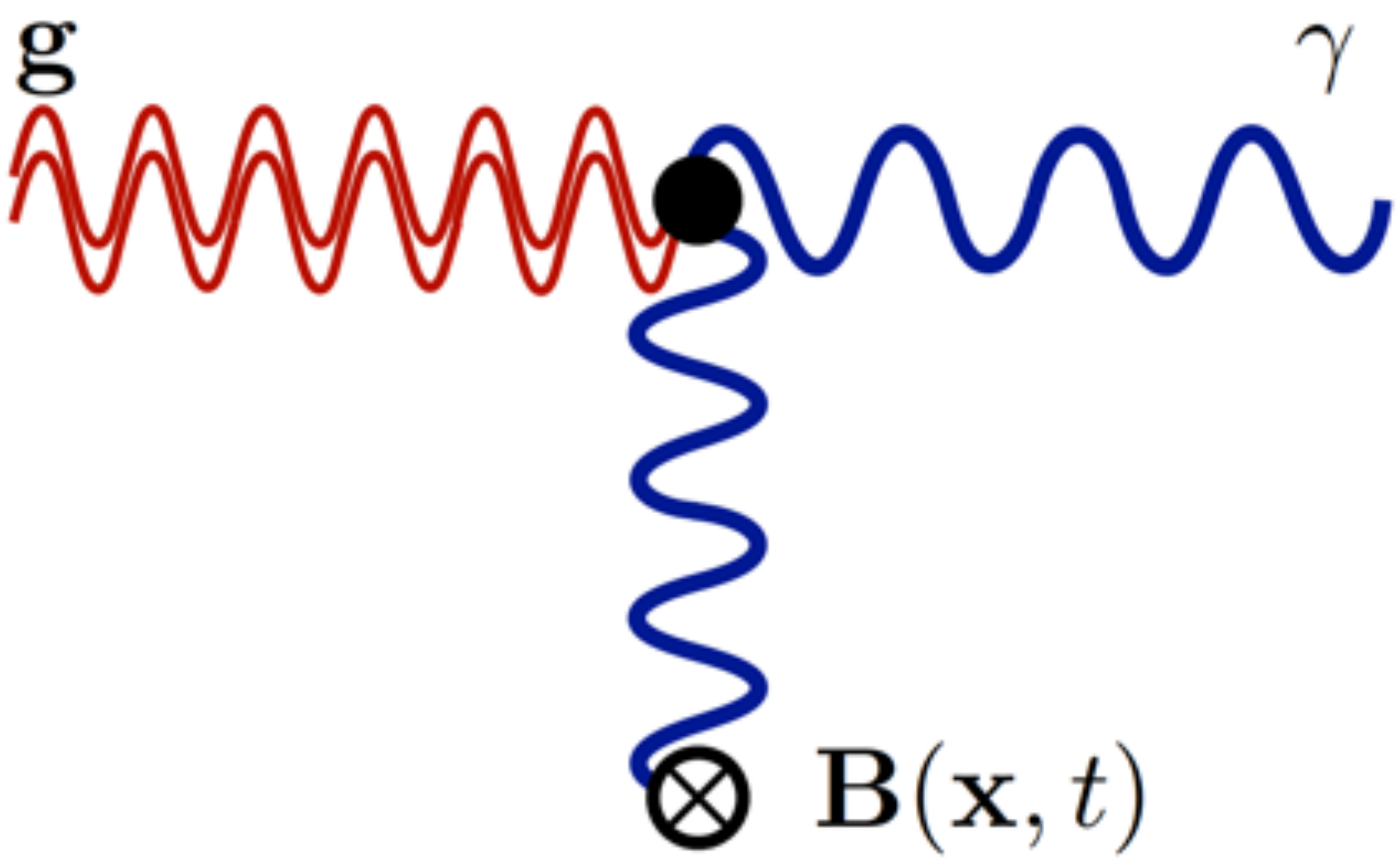
$$h \simeq 10^{-23}\left(\frac{1\,\mathrm{pc}}{D}\right)\frac{\mathrm{GHz}}{\omega_g}$$

Signal from:[Arvanitaki, Geraci '12]



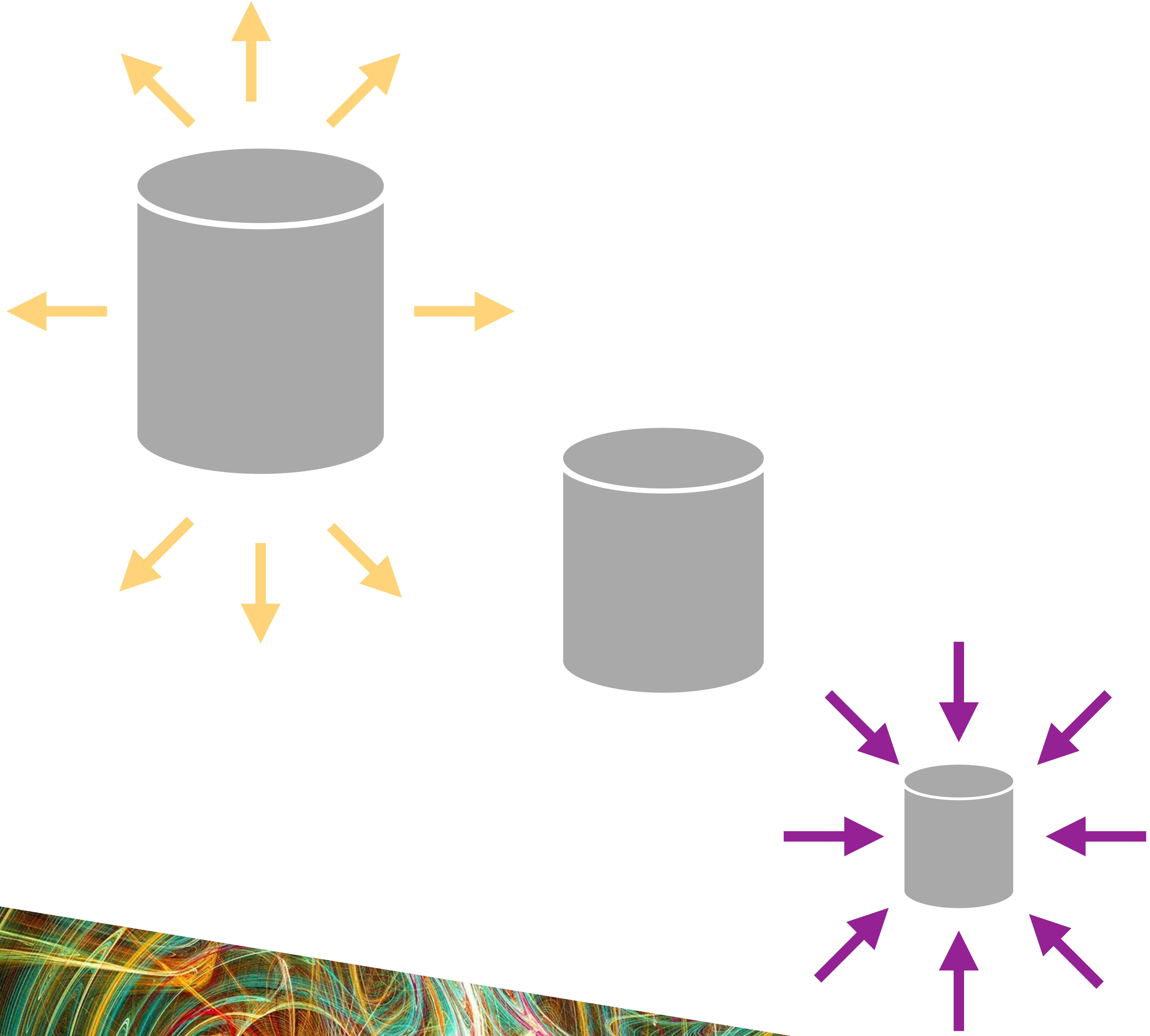
Astro & Lab Constraints
Domcke, Garcia-Cely, Rodd, '22
DM Radio
HETERODYNE
Axion DM
ALP DM
QCD
HP+QCD+DM
$g_{a\gamma\gamma}(\mathrm{GeV}^{-1})$
$f_a(\mathrm{GeV})$
$m_a(\mathrm{eV})$
10^{-10}
10^{-15}
10^{-20}
10^{-25}
10^{-30}
10^{7}
10^{12}
10^{17}
10^{22}
10^{27}
10^{-20}
10^{-15}
10^{-10}
10^{-5}
1

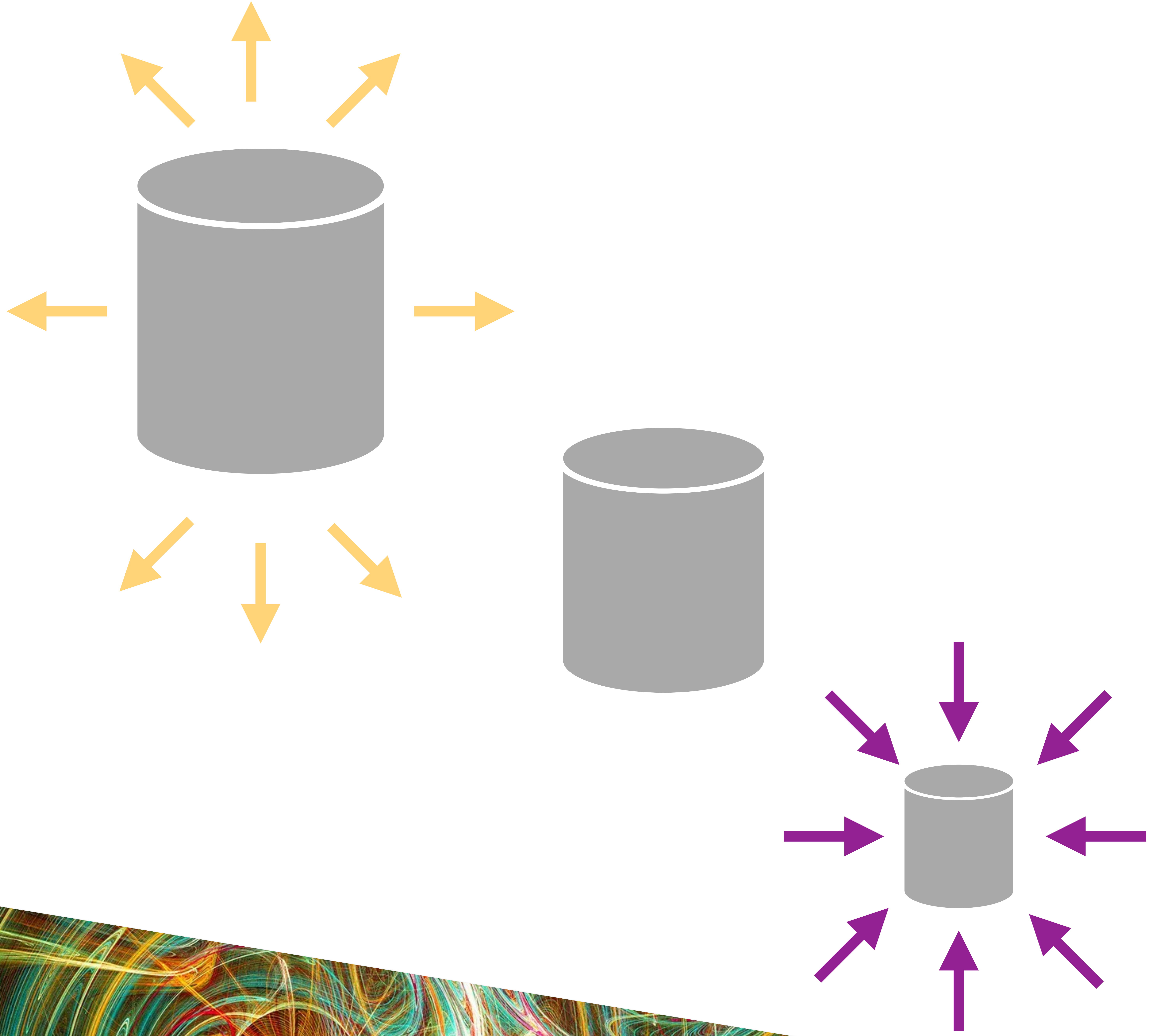
ELECTROMAGNETIC

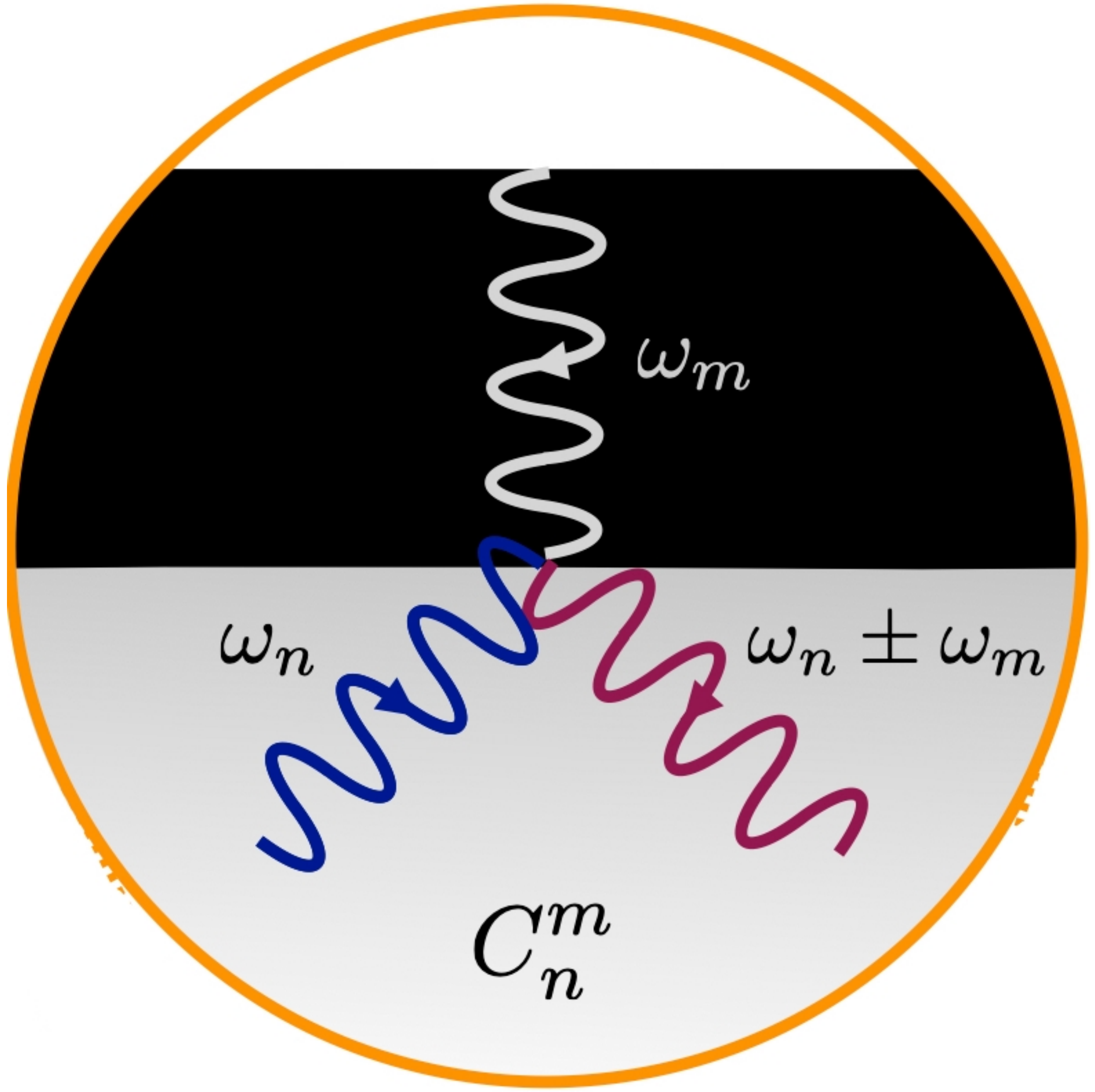


$$E_{\text{sig}} \sim Q\, h\, E_0\, (\omega_g L_{\text{cav}})^2$$

$$(\omega_g L_{\text{cav}}) \ll 1$$






ω_m
ω_n
$\omega_n \pm \omega_m$
C_n^m

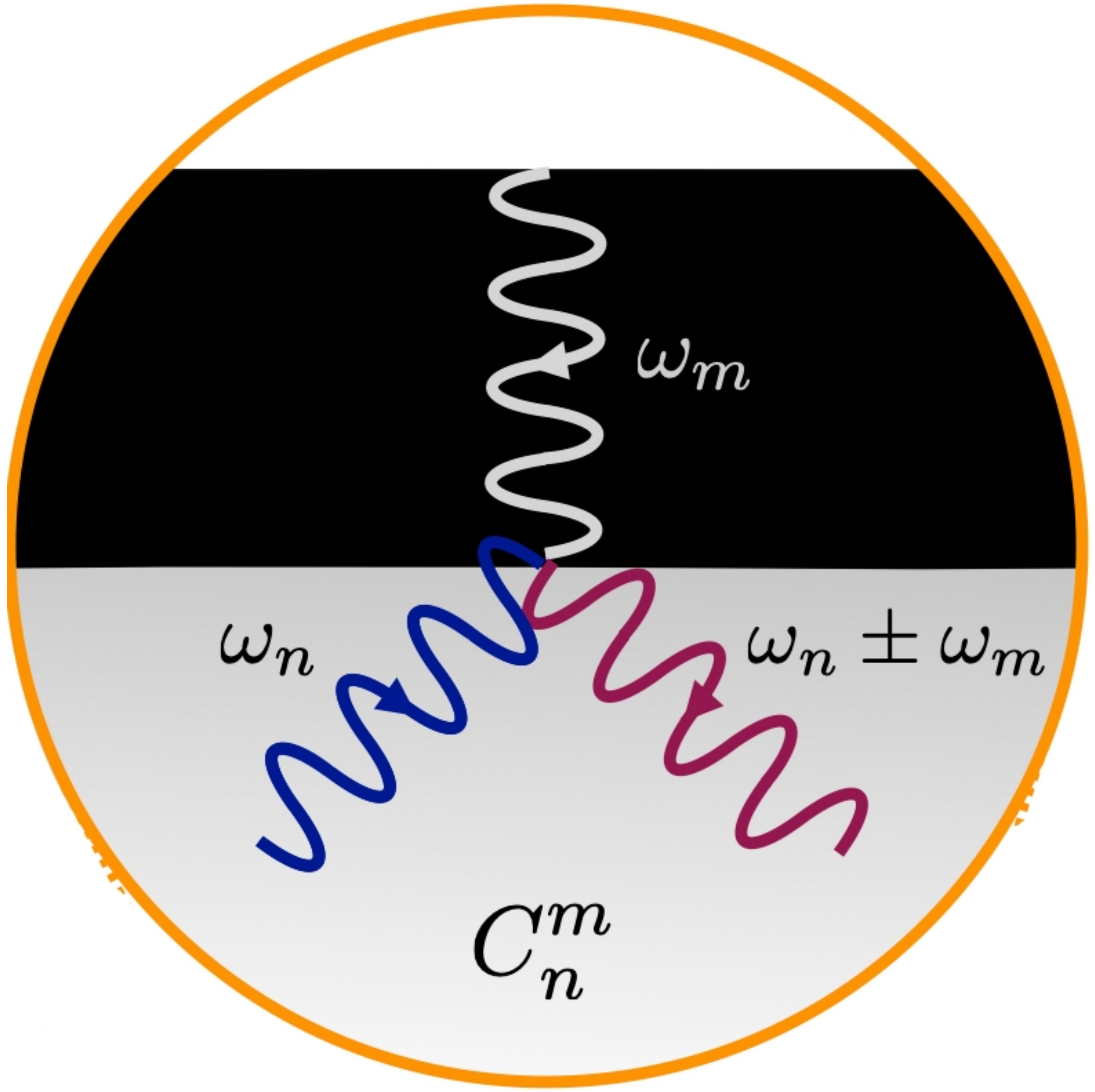
MECHANICAL

On resonance

$$E_{\text{sig}} \sim Q_m Q(hB_0)$$

Below resonance

$$E_{\text{sig}} \sim Q(hB_0)\frac{\omega_g^2}{(\omega_m^{\text{min}})^2}$$



[Caves '78], [Radicati, Pegoraro, Picasso '78]

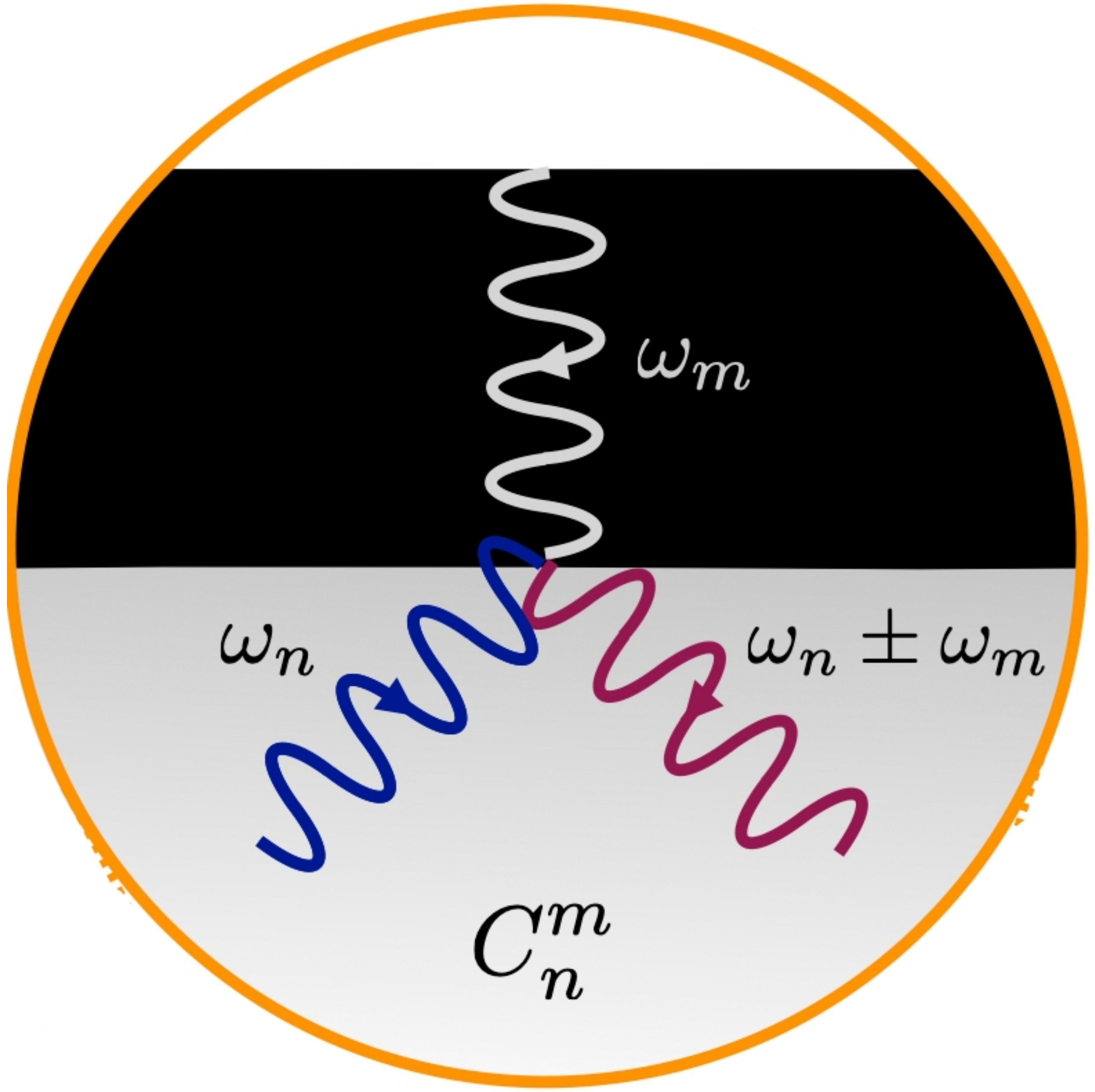
Mechanical Mode

$$\omega_m \sim \frac{c_s}{L_{\rm cav}} < 1/L$$

$$\omega_m^{\rm min} \simeq {\rm kHz}$$

Niobium ~0.5 m cavity

MECHANICAL



[Caves '78], [Radicati, Pegoraro, Picasso '78]

CONCLUSION

- We have motivated dark matter candidates in a large range of masses
- We have probed the heaviest particle candidates for decades
- Ultralight dark matter is just as motivated, but experimentally we have only just started to scratch the surface!
- There is a fascinating interplay between ultralight dark matter and gravitational waves searches

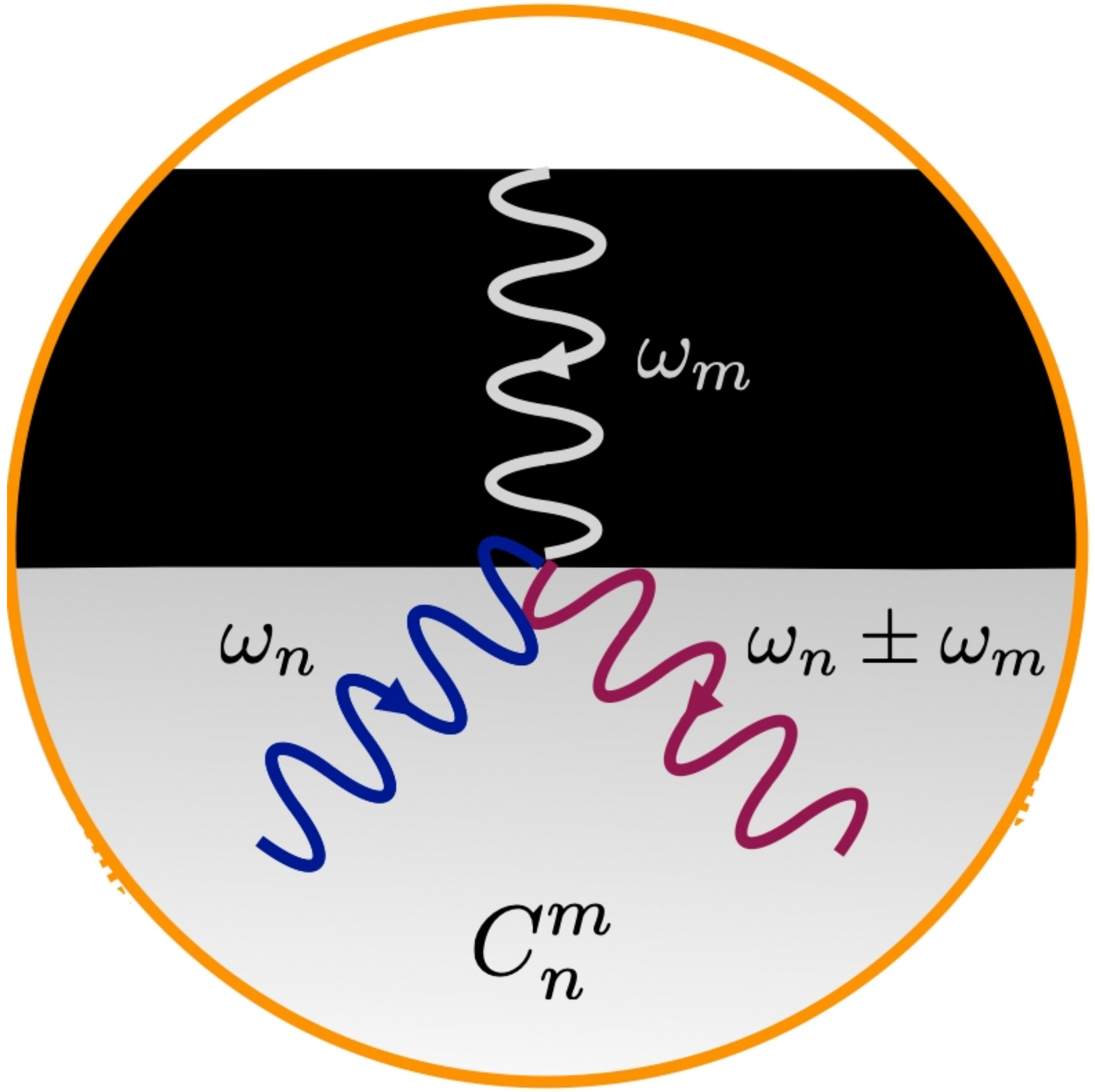
BACKUP

Mechanical Mode

$$\left(\partial_t^2 + \frac{\omega_m}{Q}\partial_t + \omega_m^2\right) \underline{u_m} = \frac{F_m}{M_{\rm cav}}$$

$$F_m \sim \text{Riemann}$$

MECHANICAL



[Caves ’78], [Radicati, Pegoraro, Picasso ’78]

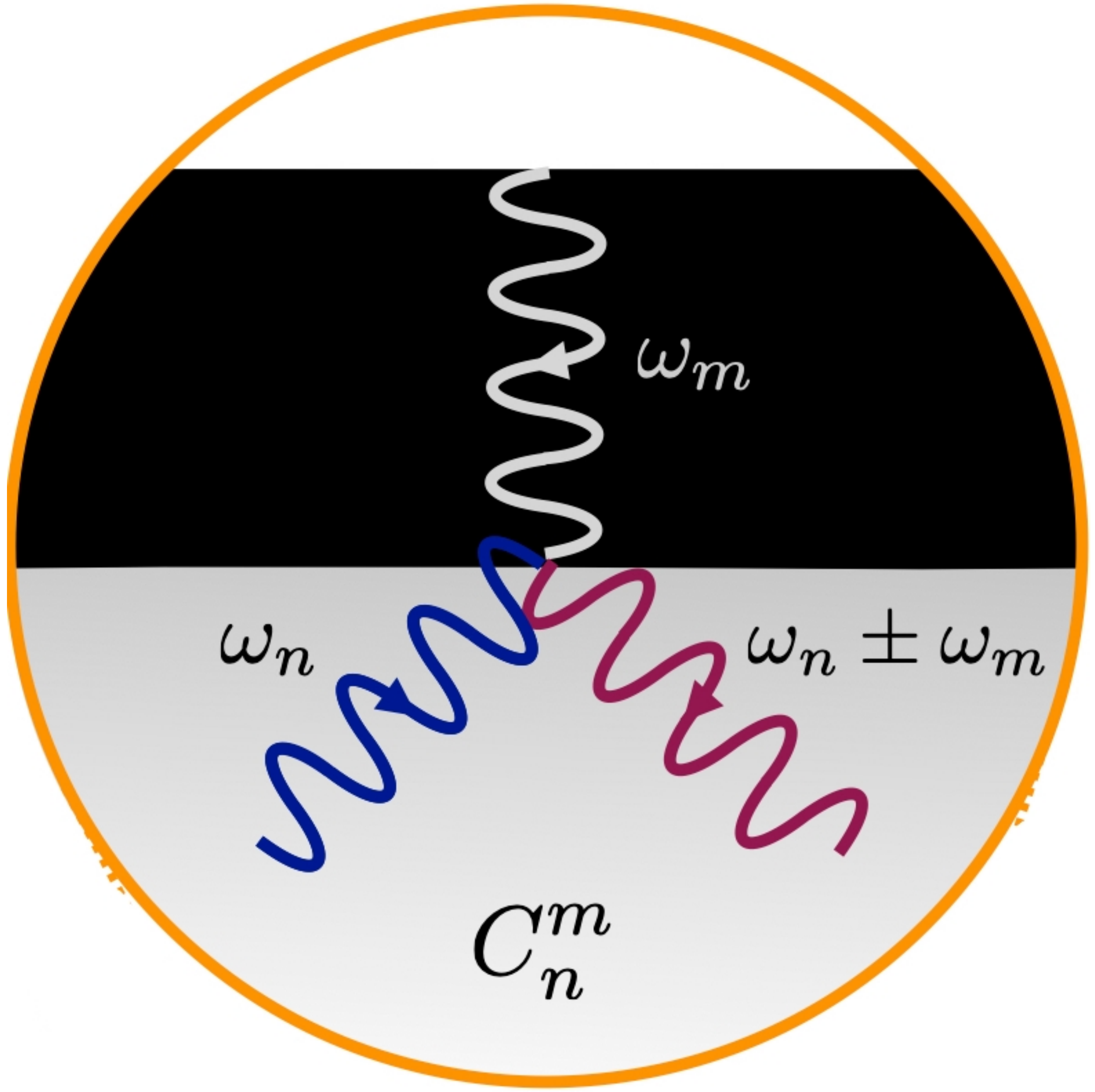
Mechanical Mode

$$\left(\partial_t^2 + \frac{\omega_m}{Q}\partial_t + \omega_m^2\right) \underline{u_m} = \frac{F_m}{M_{\rm cav}}$$

$$F_m \sim \text{Riemann}$$

$$u_m \sim Q \frac{\omega_g^2}{\omega_m^2}(h L_{\rm cav})$$

MECHANICAL



[Caves '78], [Radicati, Pegoraro, Picasso '78]

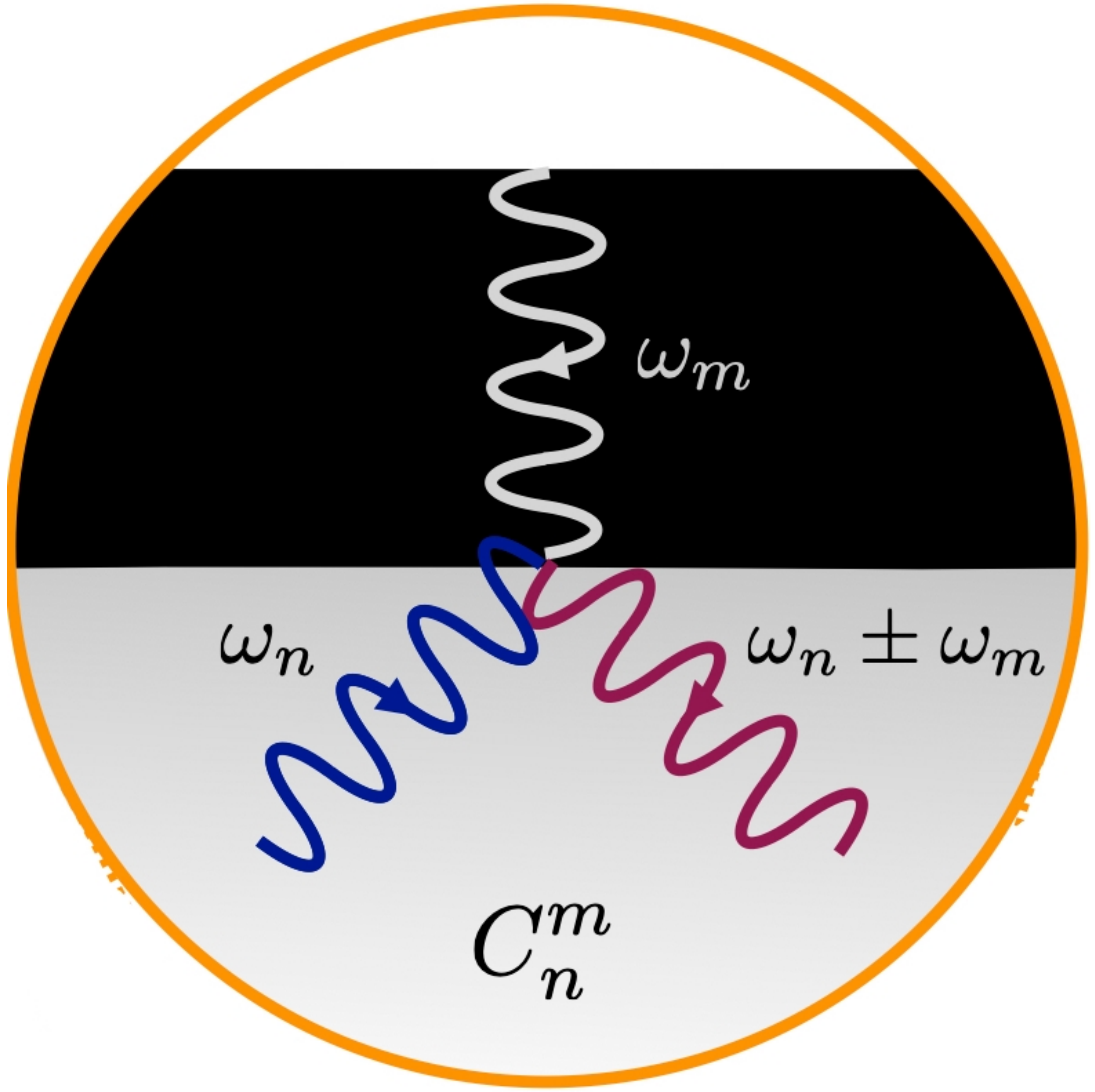
MECHANICAL

On resonance

$$E_{\rm sig} \sim Q_m Q_1 (h B_0)$$

Below resonance

$$E_{\rm sig} \sim Q_1 (h B_0) \frac{\omega_g^2}{(\omega_m^{\rm min})^2}$$



[Caves '78], [Radicati, Pegoraro, Picasso '78]

MADMAX and LAMPOST

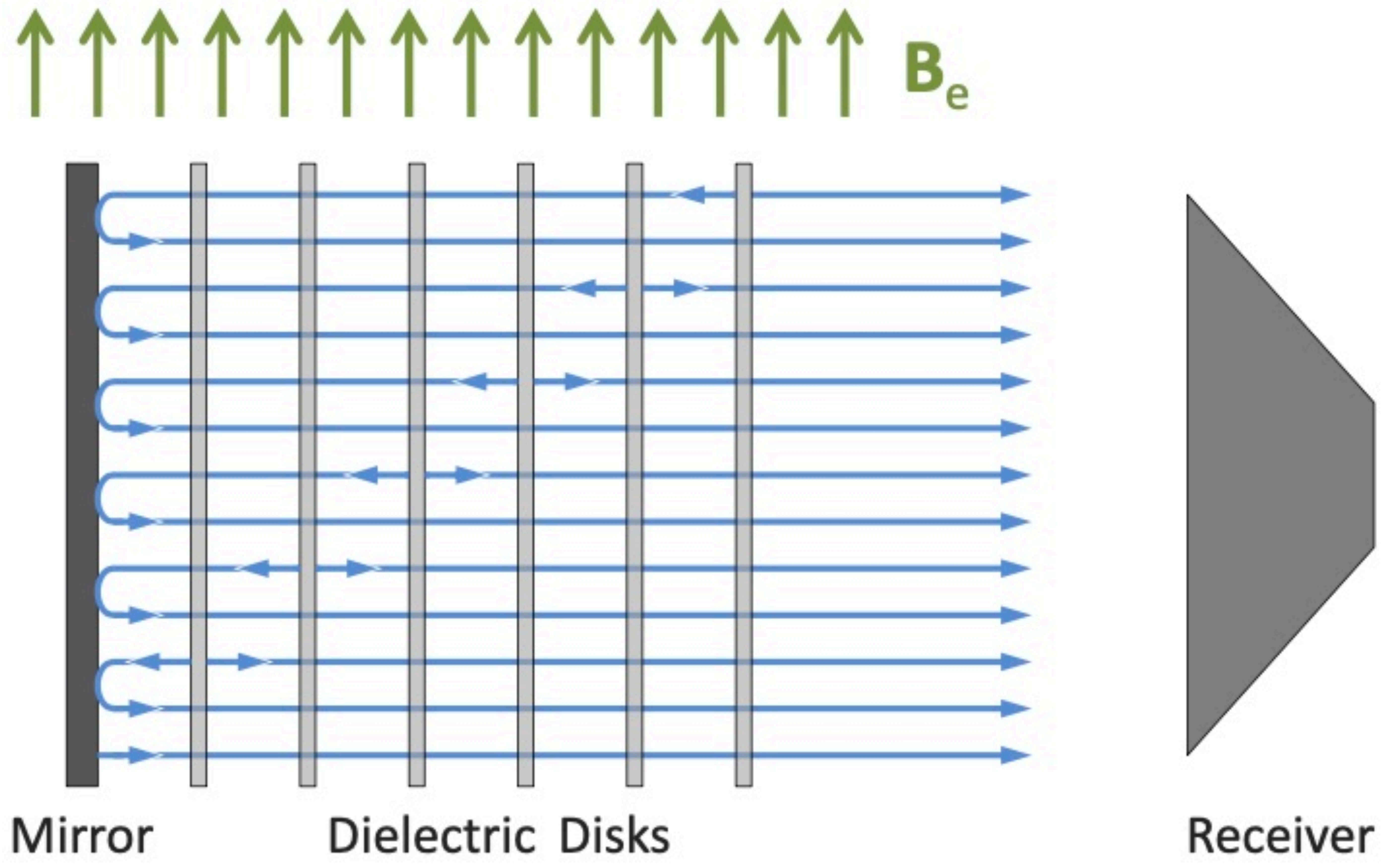
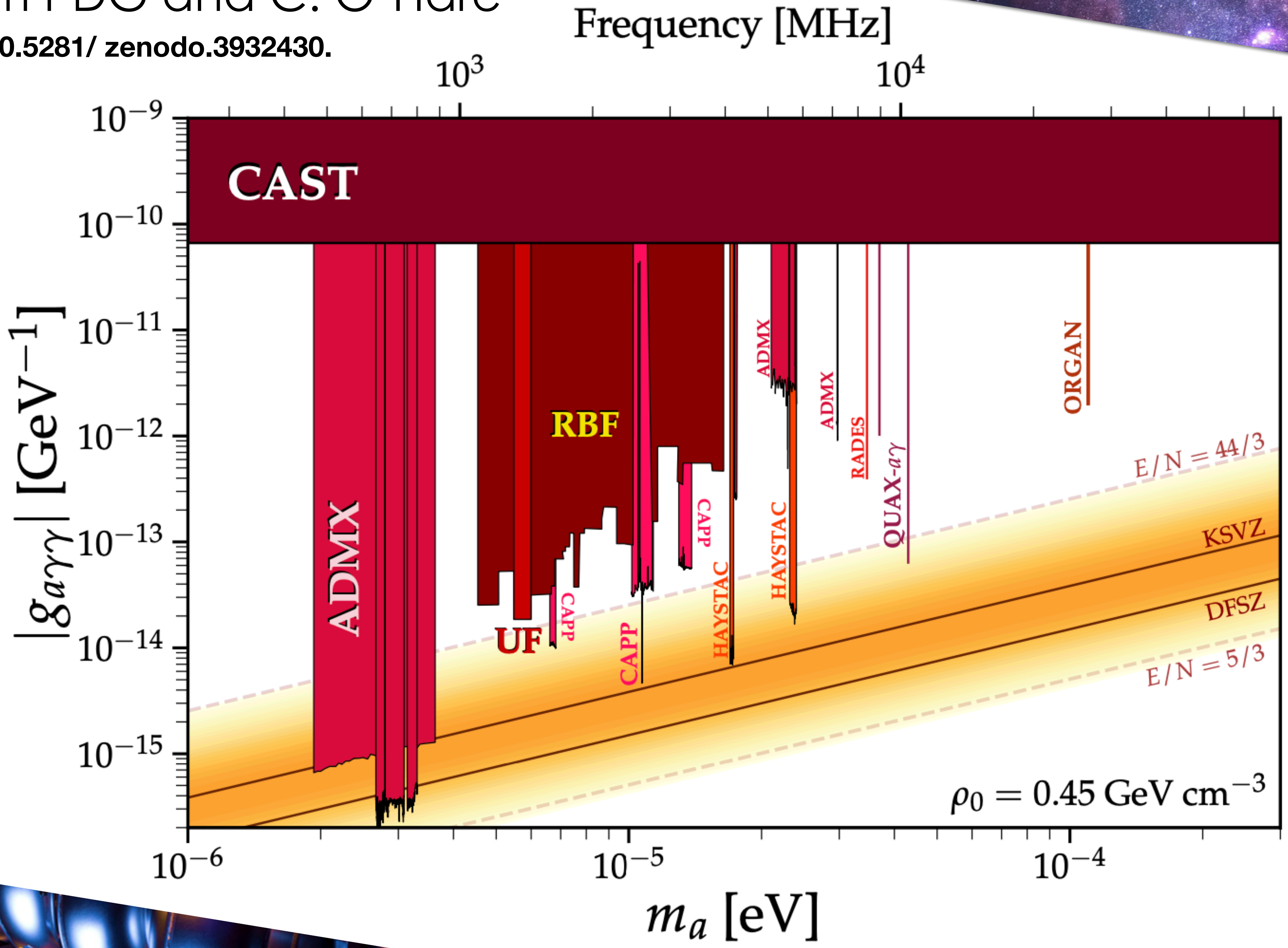
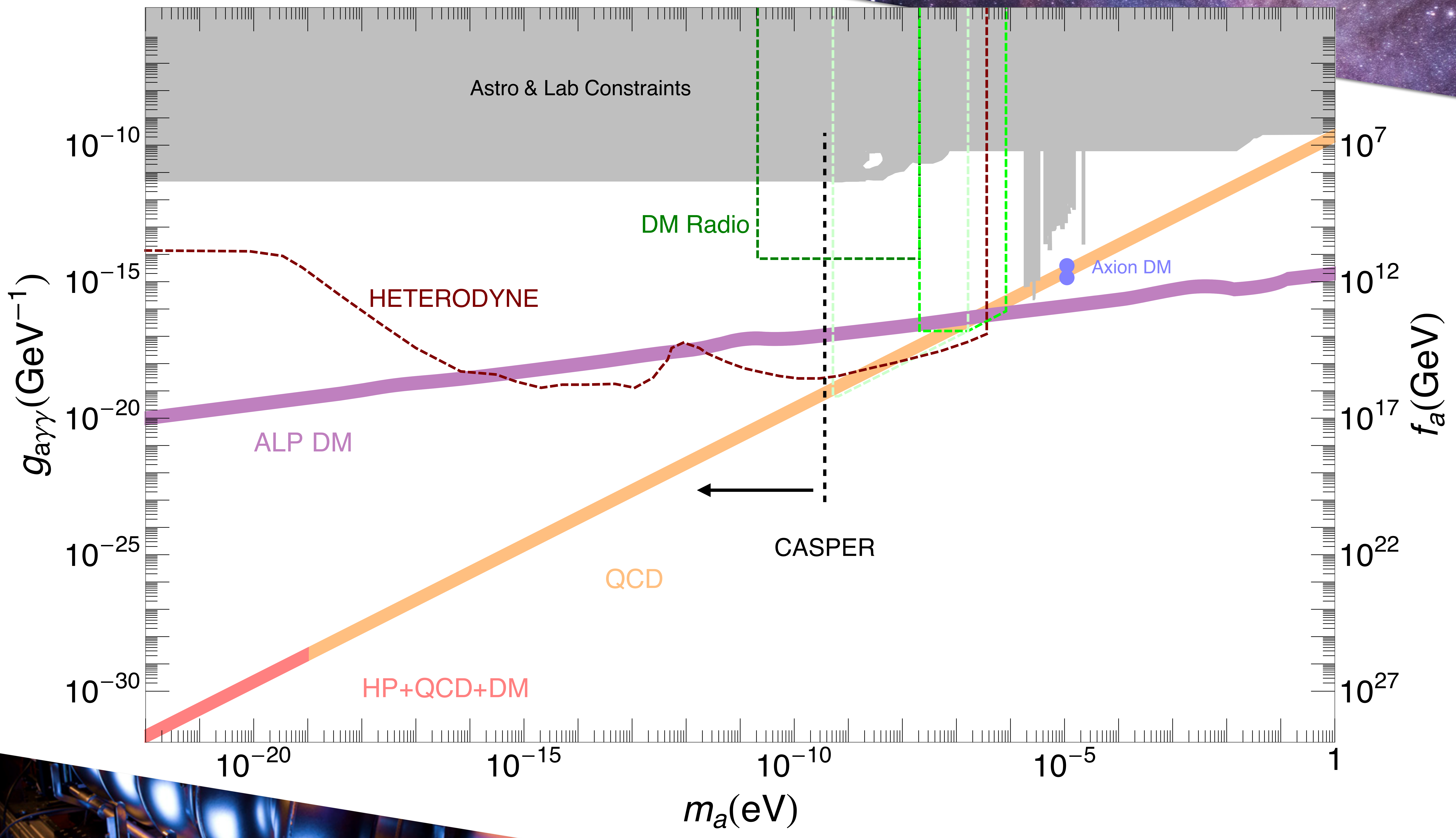


Figure from PDG and C. O'Hare

https://doi.org/10.5281/ zenodo.3932430.





Astro & Lab Constraints
DM Radio
HETERODYNE
Axion DM
ALP DM
CASPER
QCD
HP+QCD+DM
$g_{a\gamma\gamma}(\mathrm{GeV}^{-1})$
$f_a(\mathrm{GeV})$
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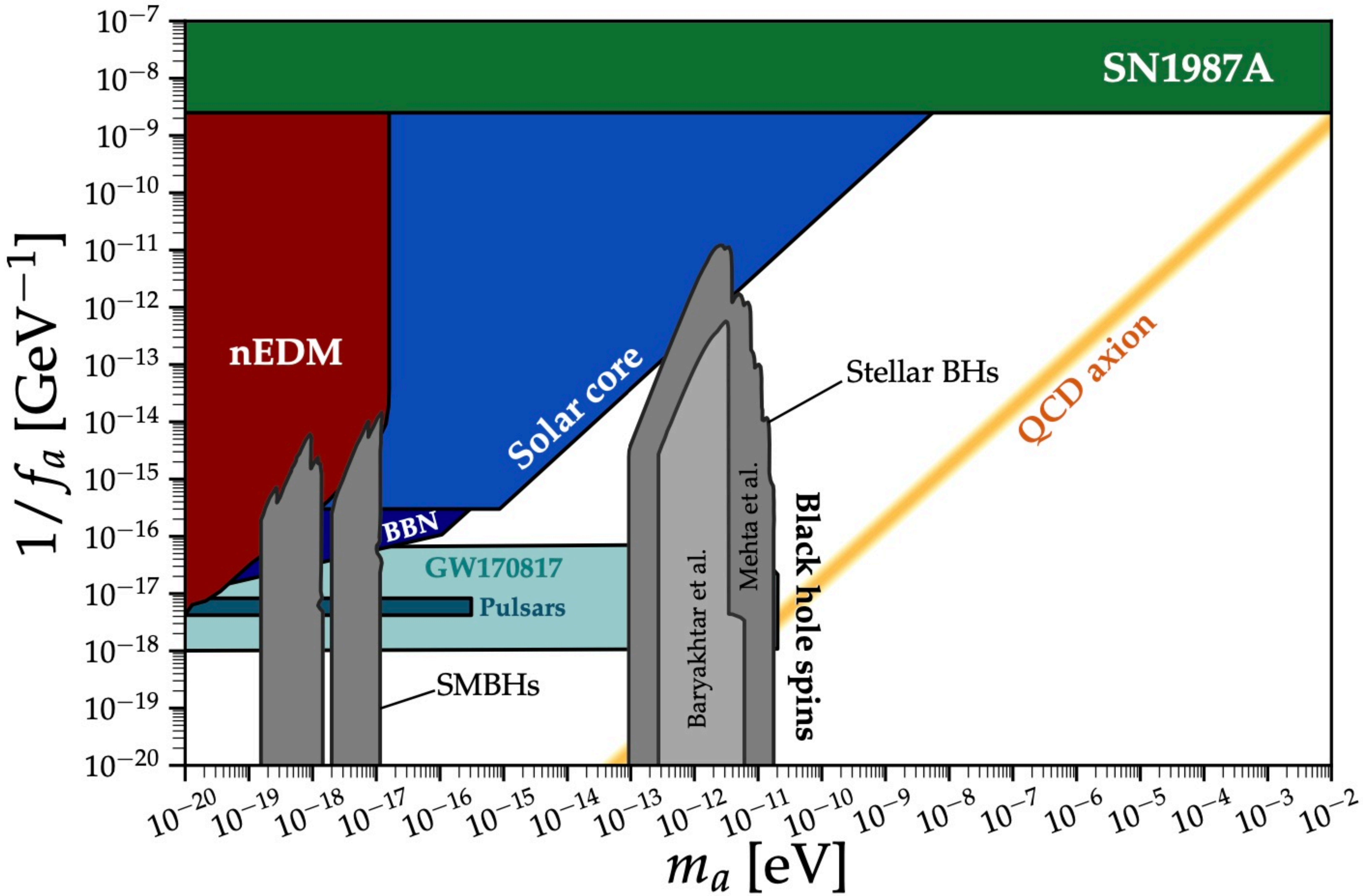
10^{-10}
10^{-5}
1

Figure from PDG and C. O'Hare

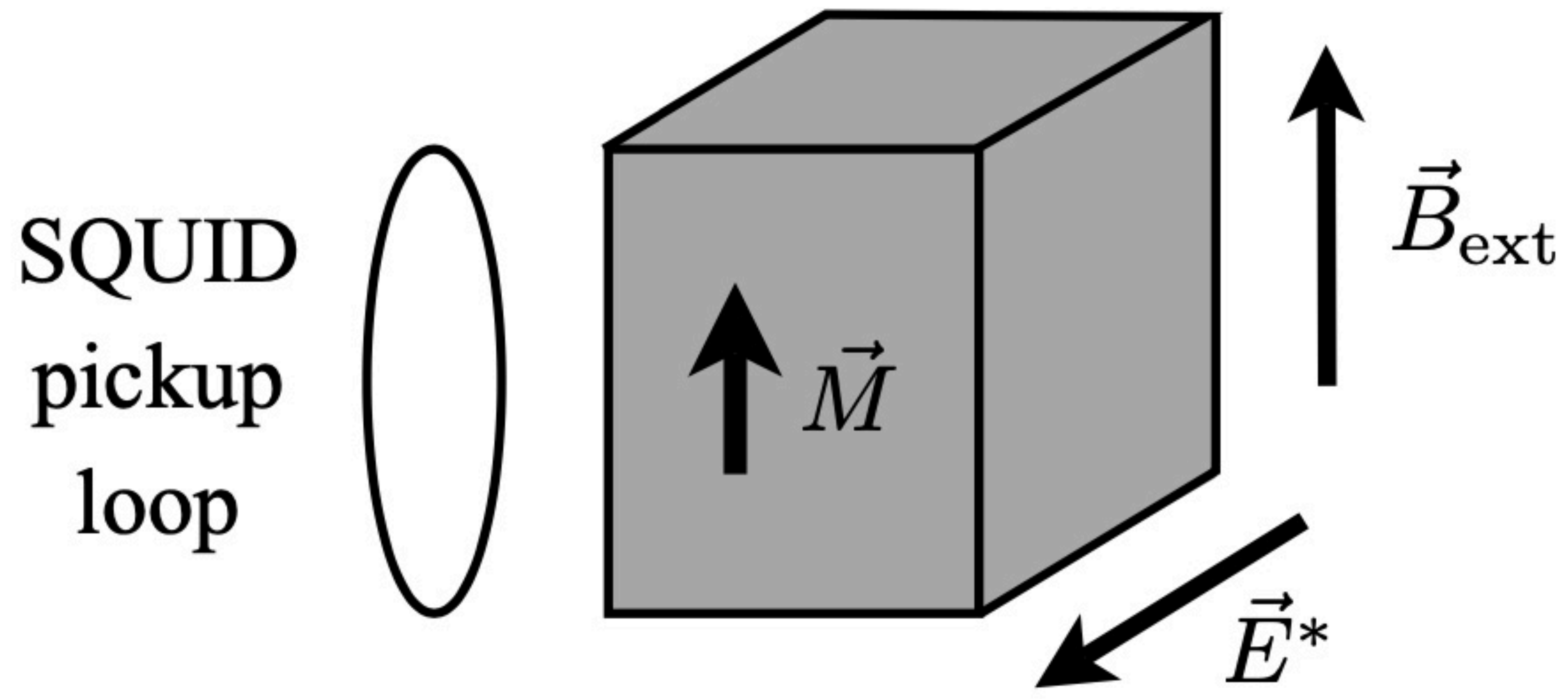
https://doi.org/10.5281/ zenodo.3932430.



Valid for QCD Axion!

CASPER

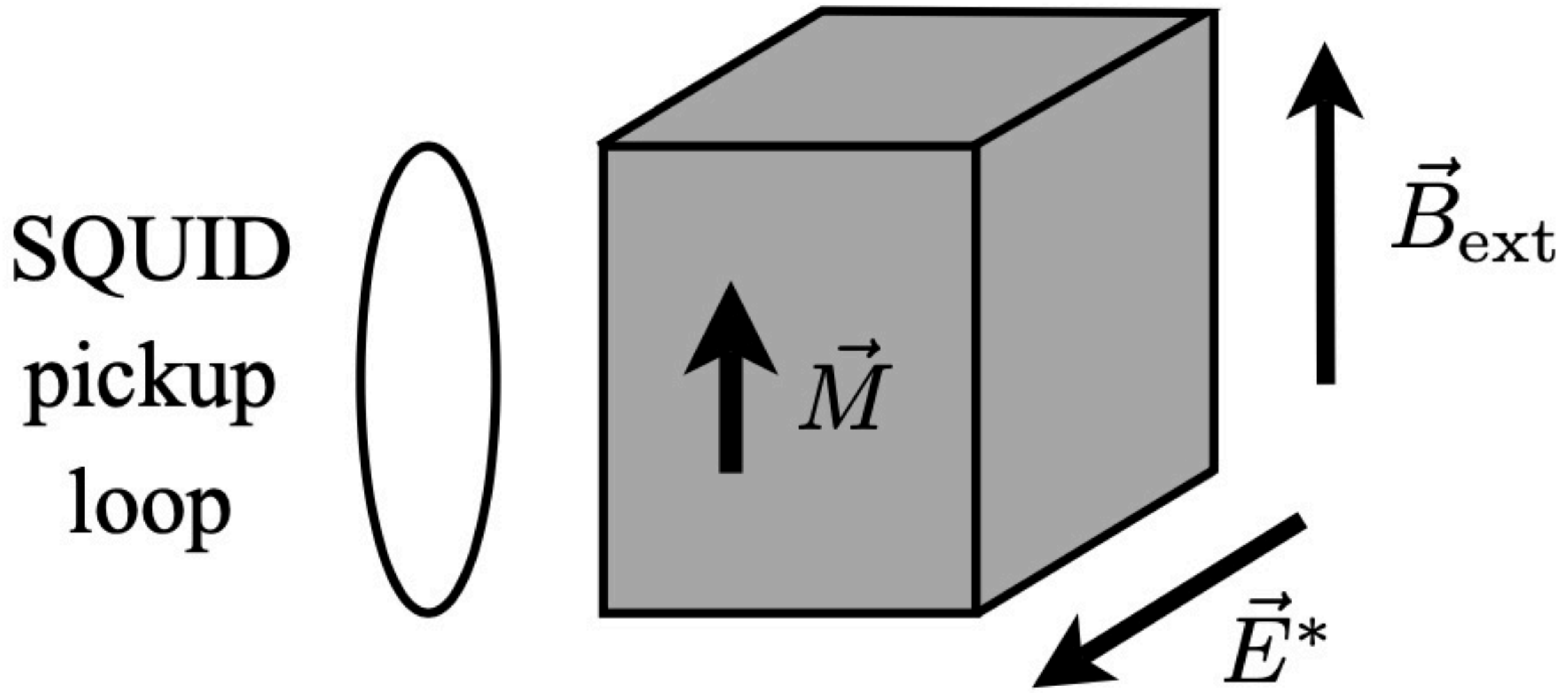
$$H \simeq \frac{a}{m_N f_a} \vec{\sigma} \cdot \vec{E}$$



Without the axion you have a magnetisation component precessing around B (Larmor frequency)

CASPER

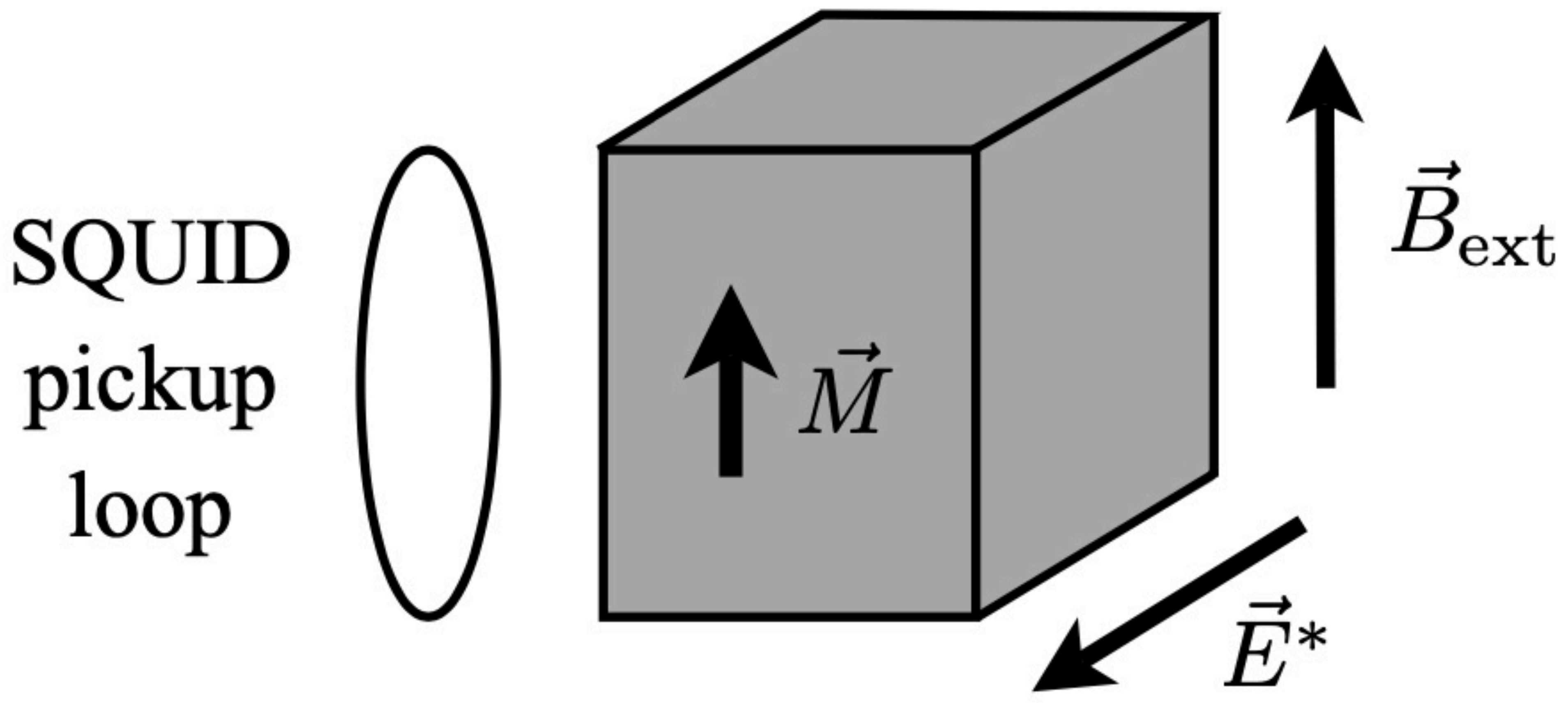
$$H \simeq \frac{a}{m_N f_a} \vec{\sigma} \cdot \vec{E}$$



$$M(t) \approx np\mu E^* \epsilon_S d_n \frac{\sin\left[\left(\frac{2\mu B_{\text{ext}} - m_a c^2}{\hbar}\right) t\right]}{\frac{2\mu B_{\text{ext}} - m_a c^2}{\hbar}} \sin\left(2\mu B_{\text{ext}} t\right)$$

CASPER

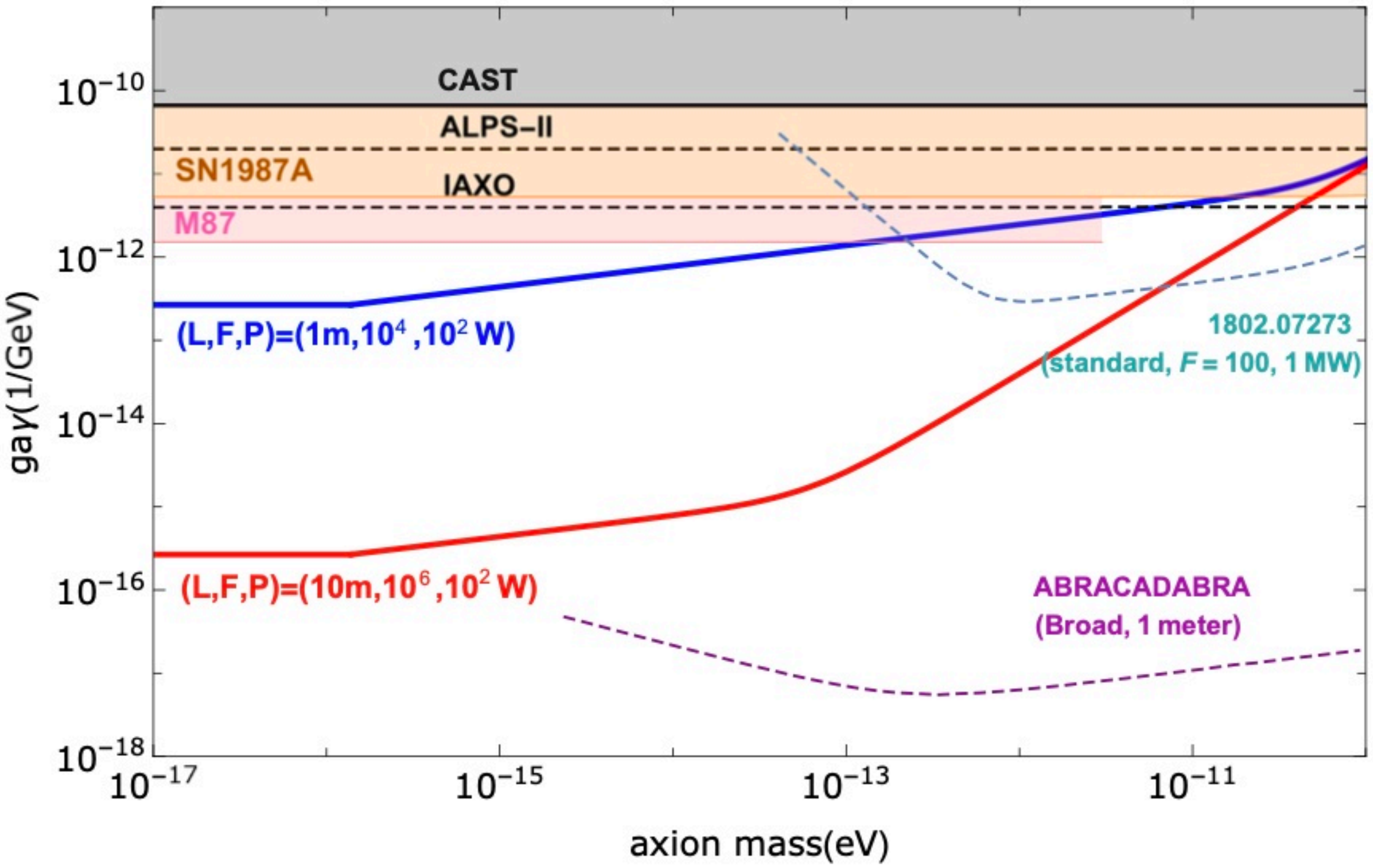
$$H \simeq \frac{a}{m_N f_a} \vec{\sigma} \cdot \vec{E}$$

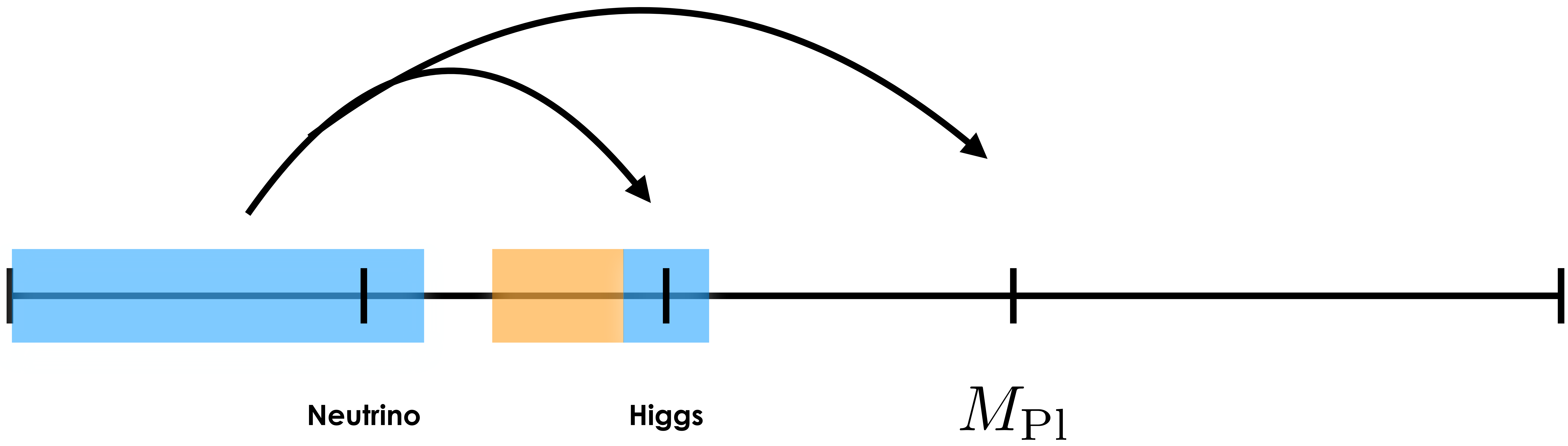


	n	E^*	p	T_2	Max. B_{ext}
Phase 1	$10^{22}\ \frac{1}{\text{cm}^3}$	$3 \times 10^8\ \frac{\text{V}}{\text{cm}}$	10^{-3}	1 ms	10 T
Phase 2	$10^{22}\ \frac{1}{\text{cm}^3}$	$3 \times 10^8\ \frac{\text{V}}{\text{cm}}$	1	1 s	20 T

DANCE

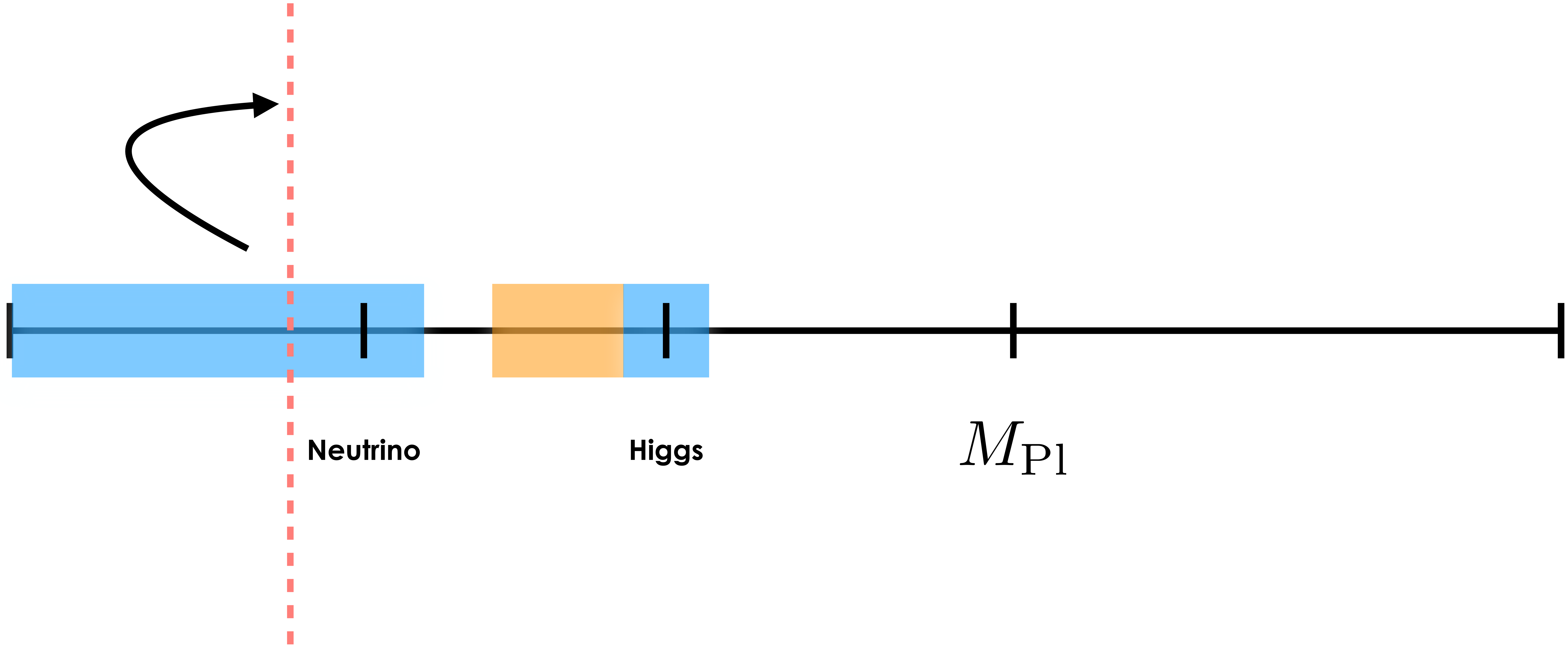
Obata, Fujita, Michimura, '18





Neutrino
Higgs
$M_{\rm Pl}$

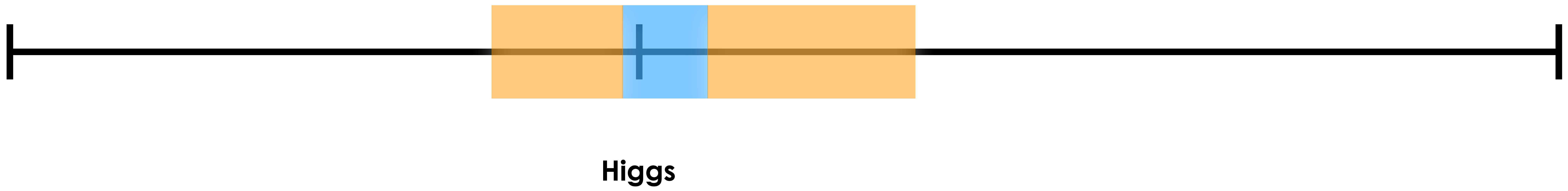
New Symmetry



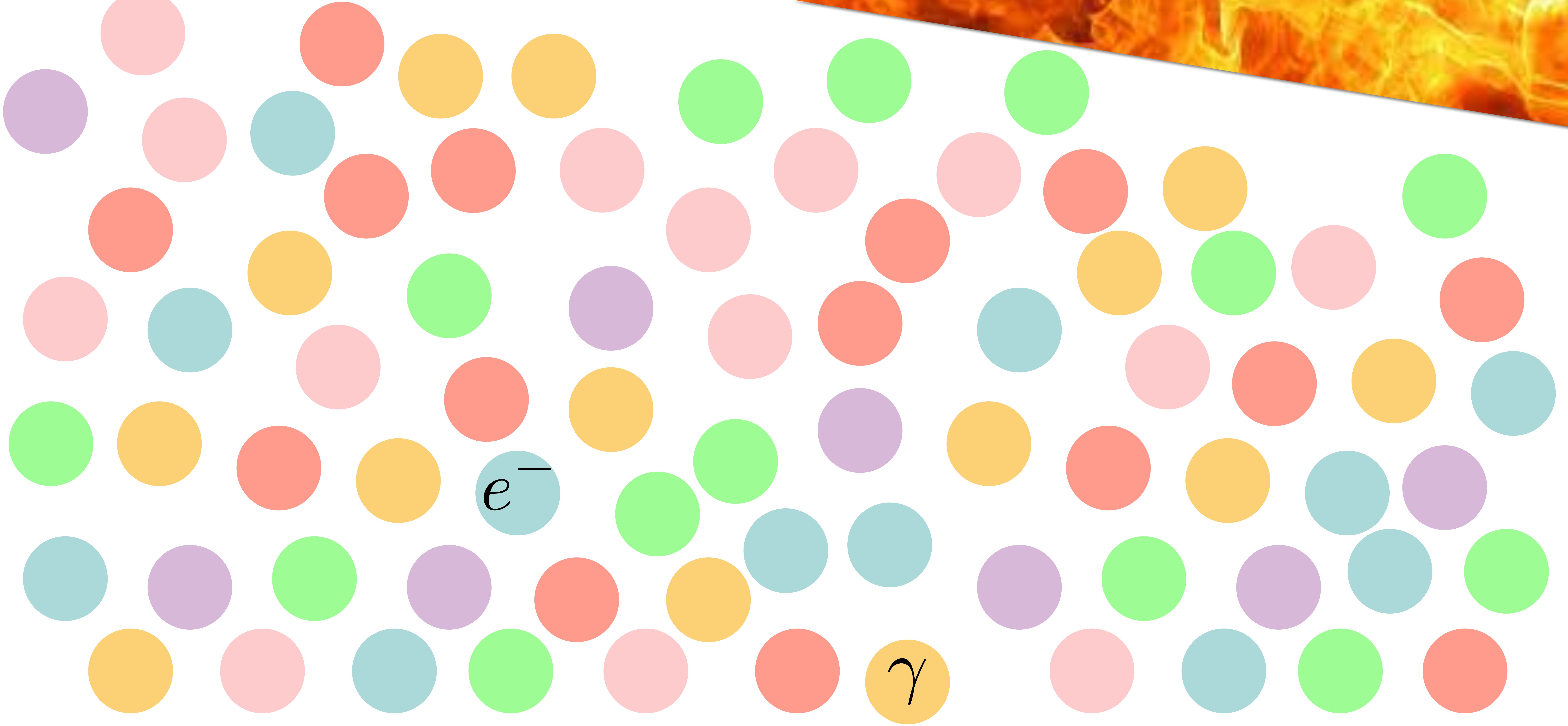
AXION

AXION

- **Minimal Extension of what we know to exist**
- **Naturally light**
- Simple and predictive cosmology
- Solve two other big problems in particle physics

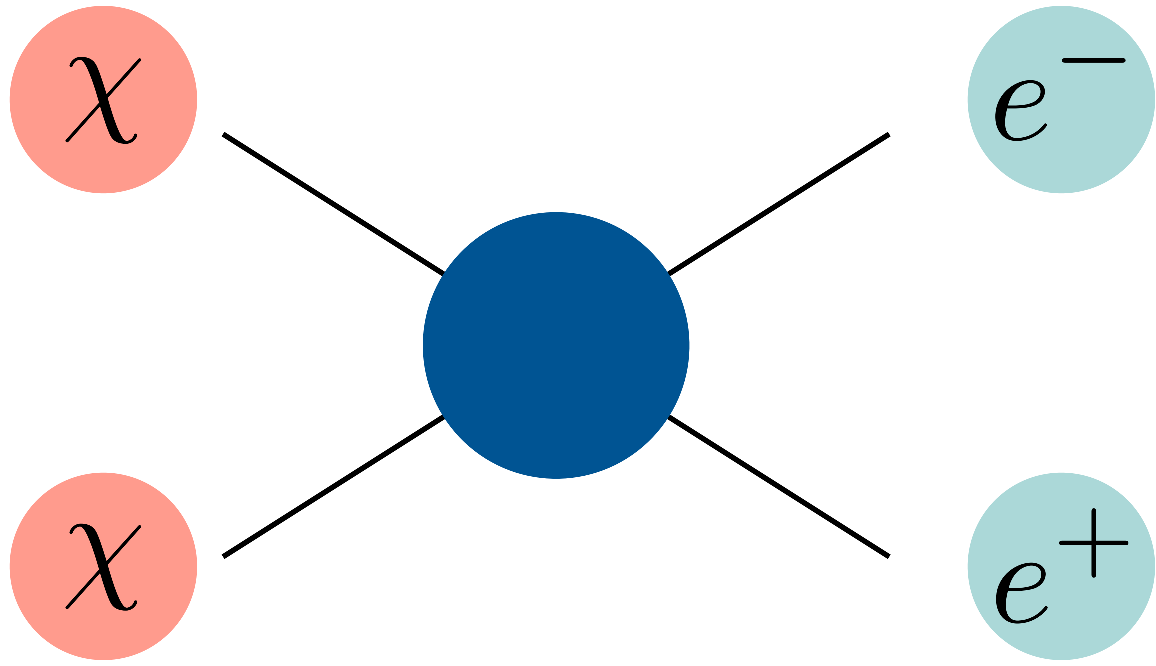

Higgs

THERMAL DARK MATTER

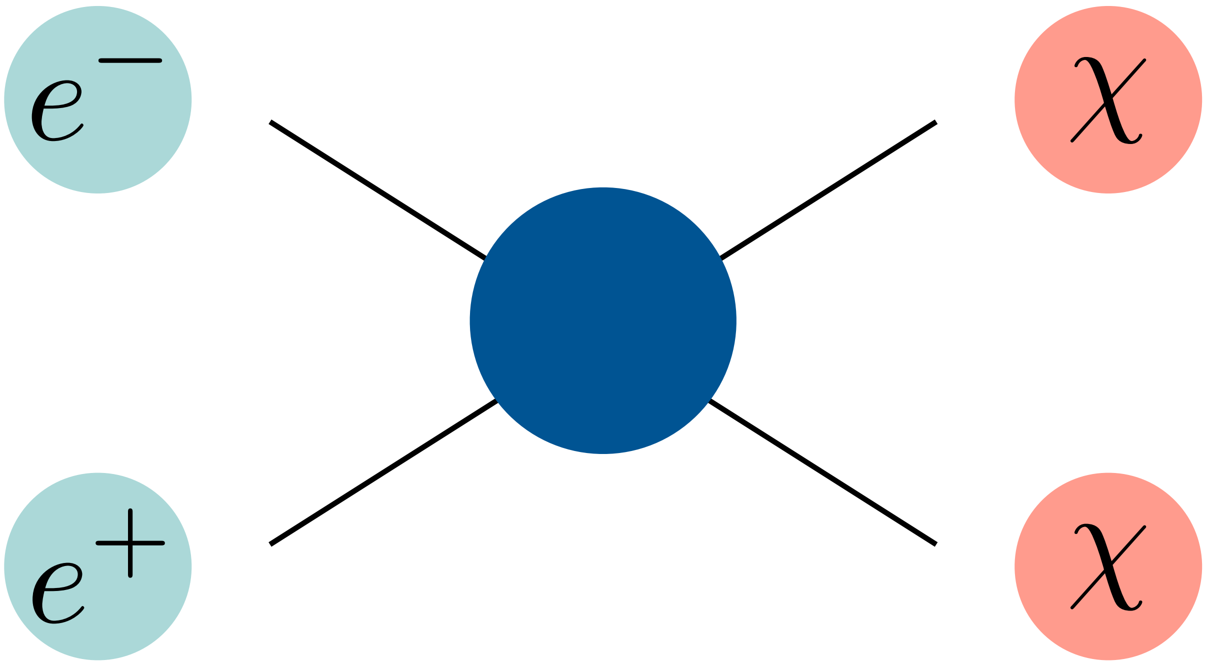


Standard Model Thermal Bath

$$T \gg m_\chi, m_e$$

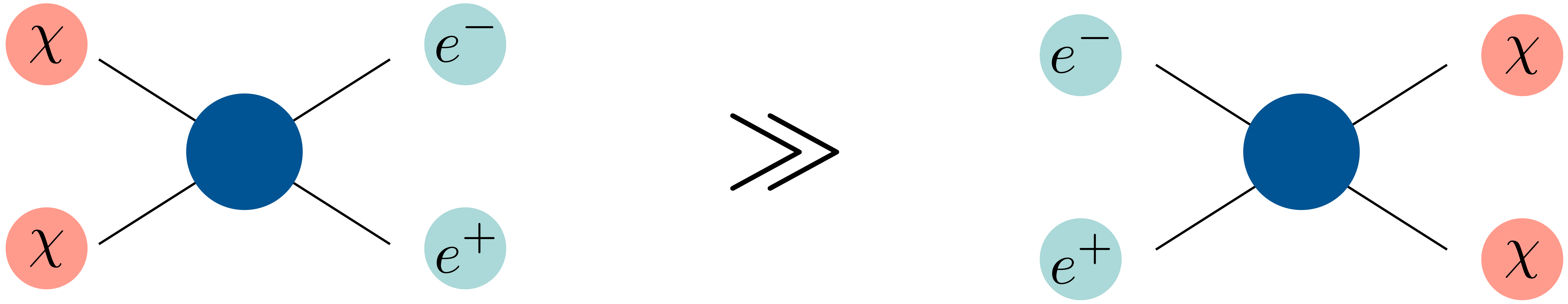


$$\simeq$$

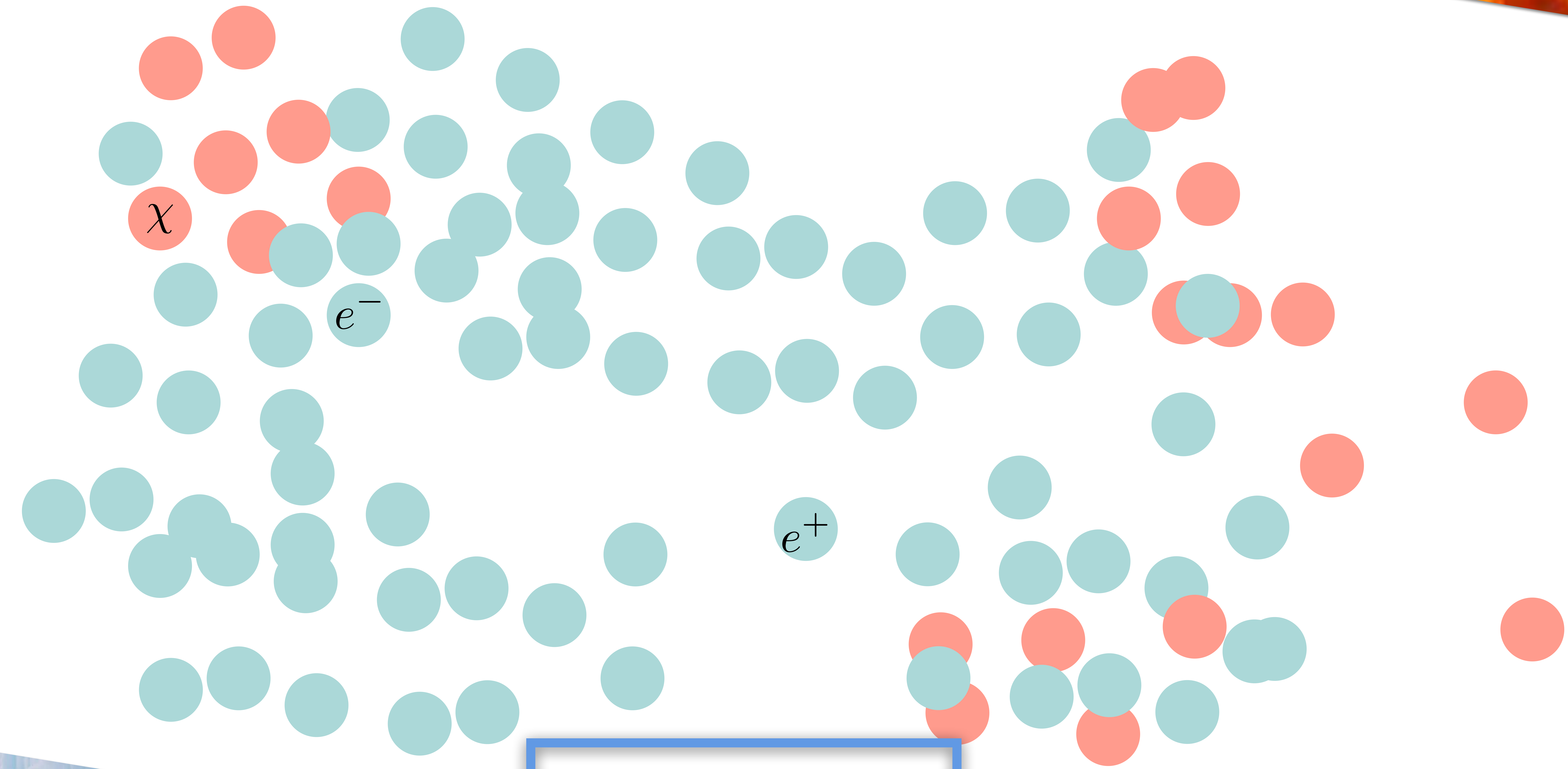


$$T \gg m_\chi, m_e$$

$$m_e \ll T \lesssim m_\chi$$

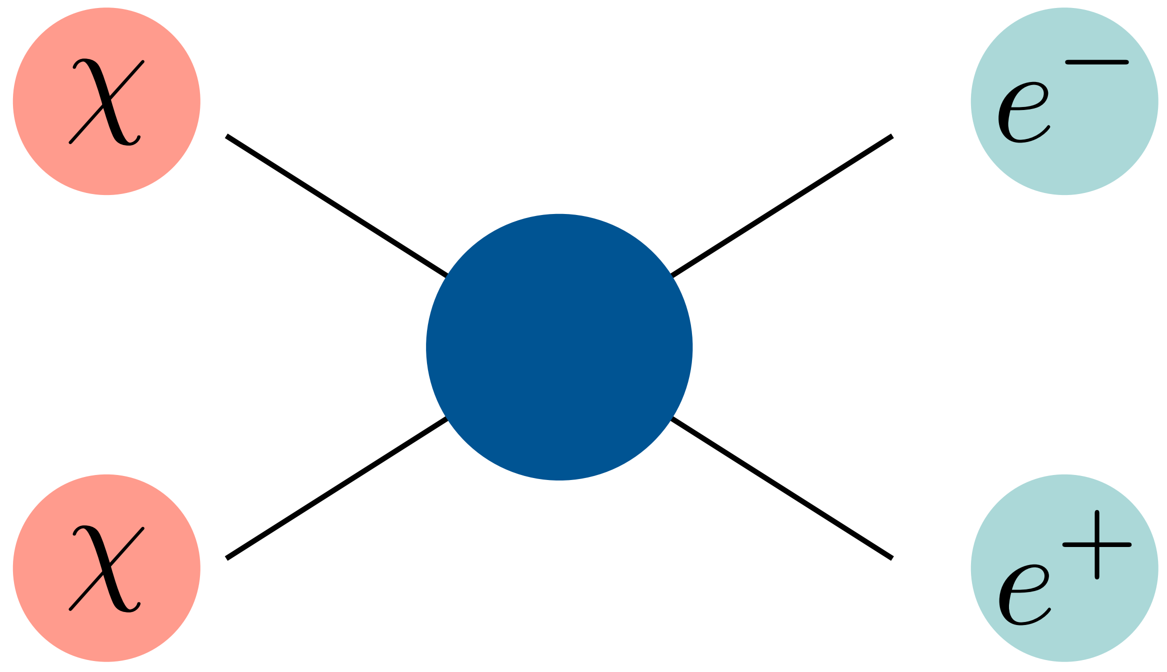


Not enough Kinetic Energy to Produce DM

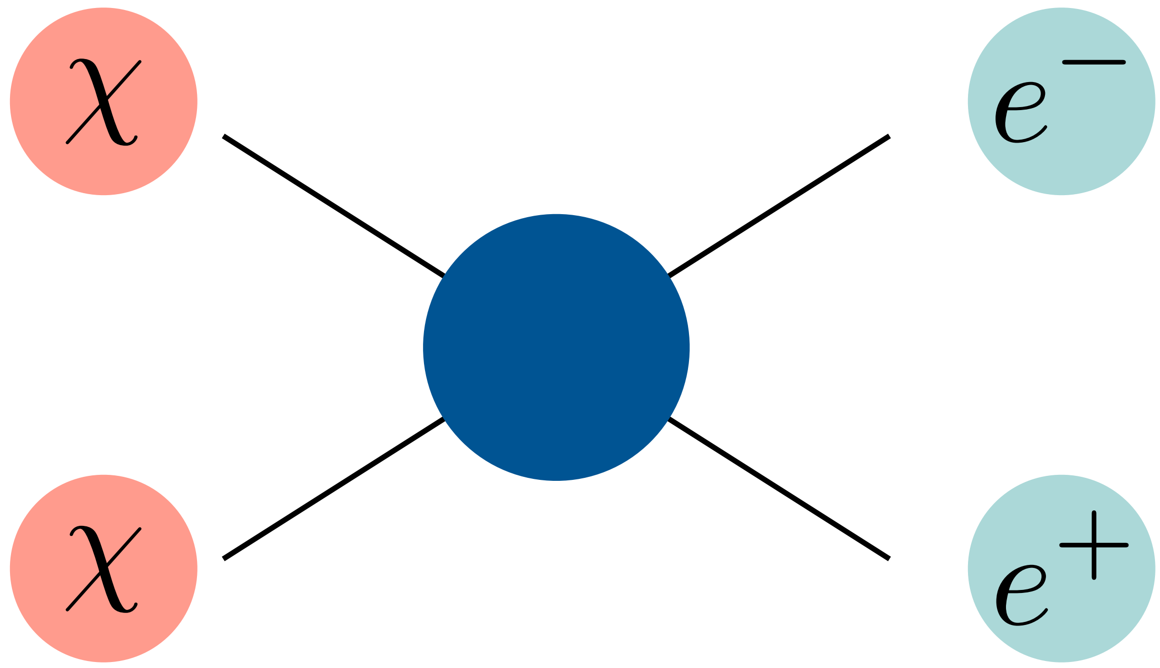


$$m_e \ll T \lesssim m_\chi$$

$$\Gamma_{\chi\to\mathrm{SM}} = n_\chi \langle \sigma v \rangle$$



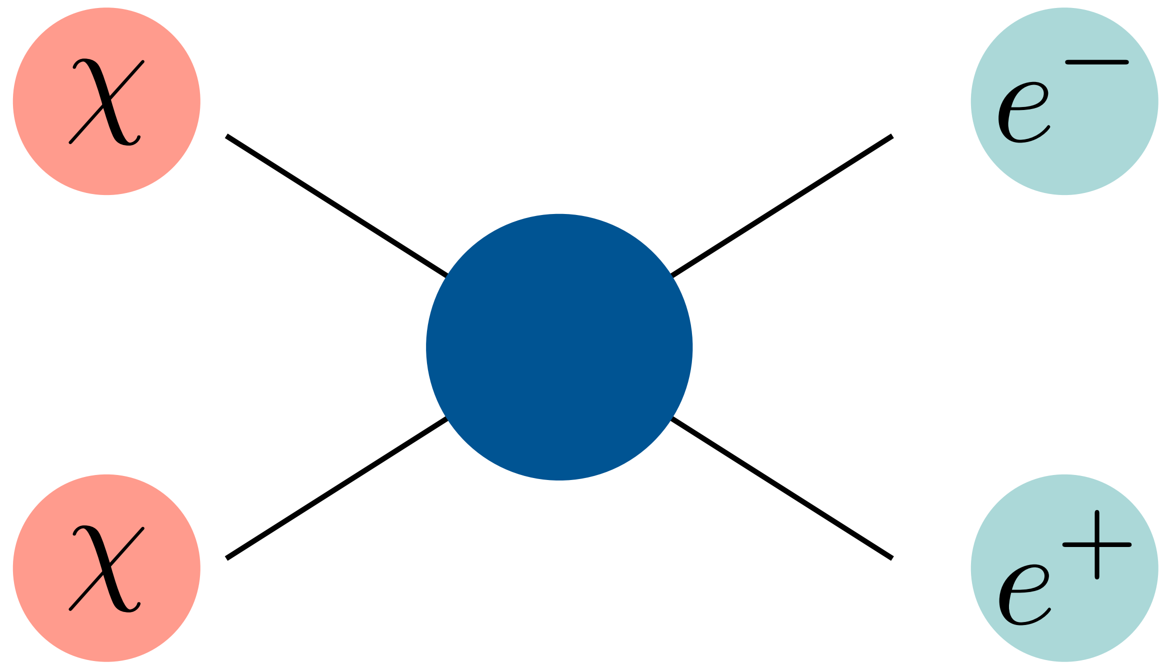
$$\Gamma_{\chi \to \mathrm{SM}} = n_\chi \langle \sigma v \rangle$$



$$\ll \qquad H$$

Expansion Rate
of the Universe

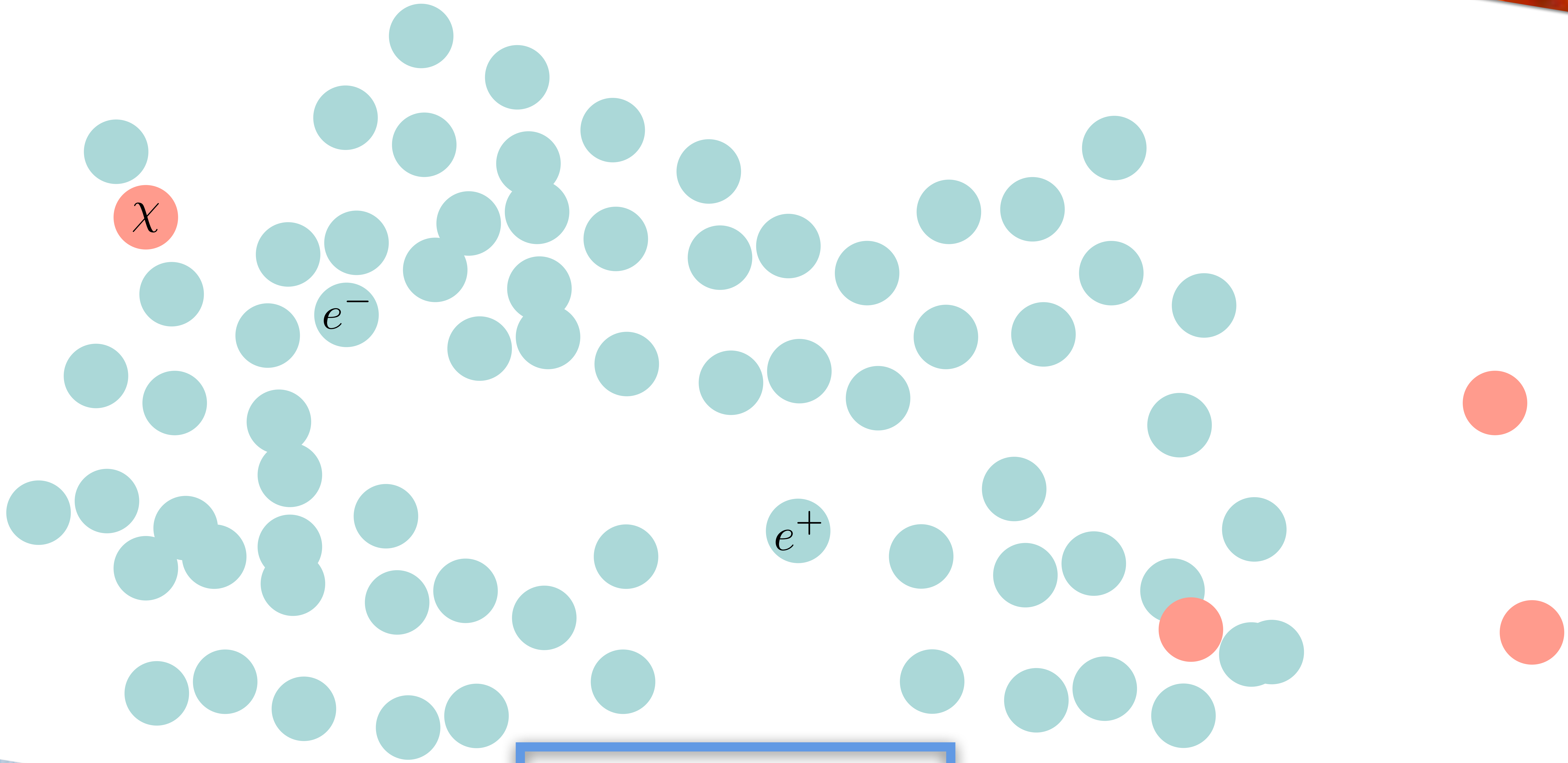
$$\Gamma_{\chi \to \mathrm{SM}} = n_\chi \langle \sigma v \rangle$$



$$\ll \qquad H$$

DM particles (almost) never meet: Number of DM particles is frozen

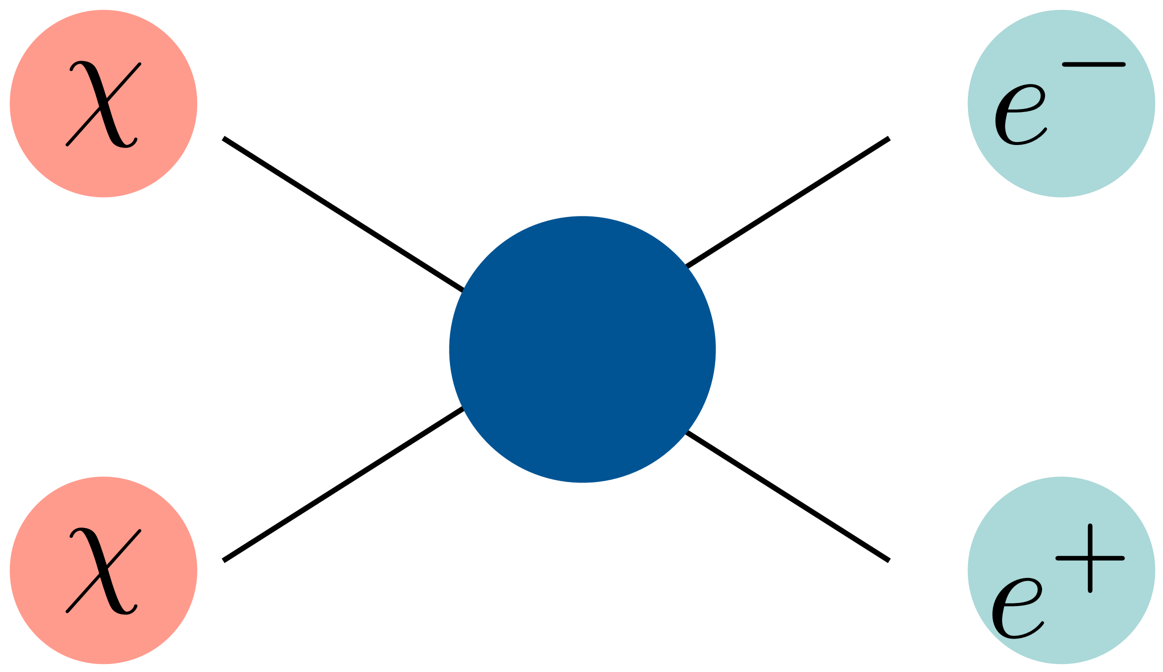
$$T \lesssim m_\chi / 20$$



$$T \lesssim m_\chi$$

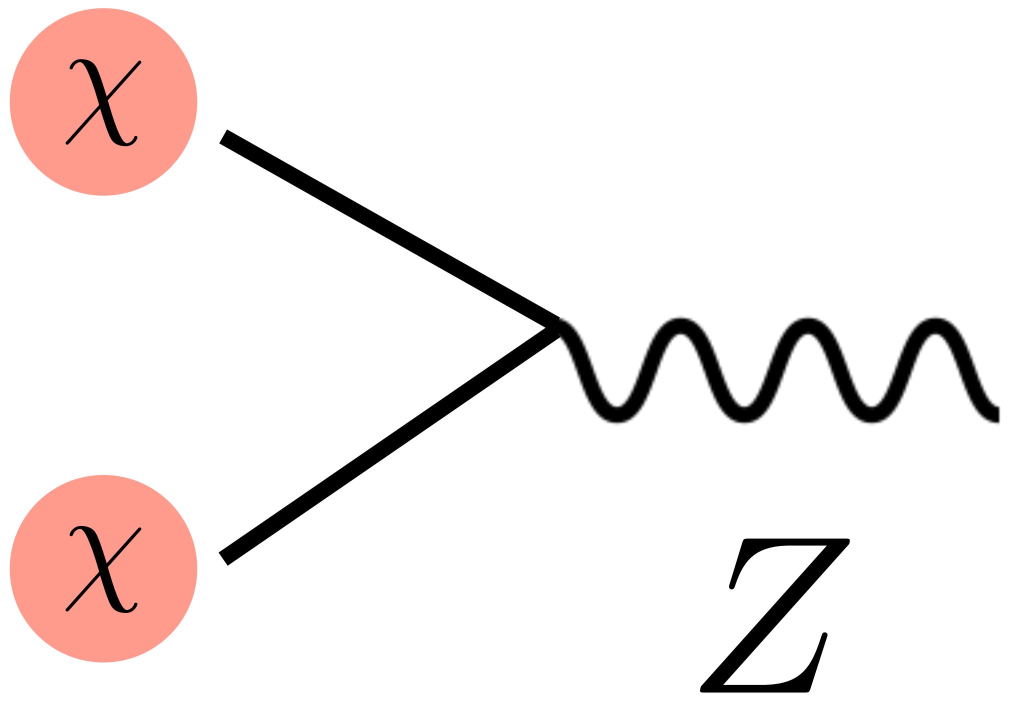
The amount of DM today depends on its interactions

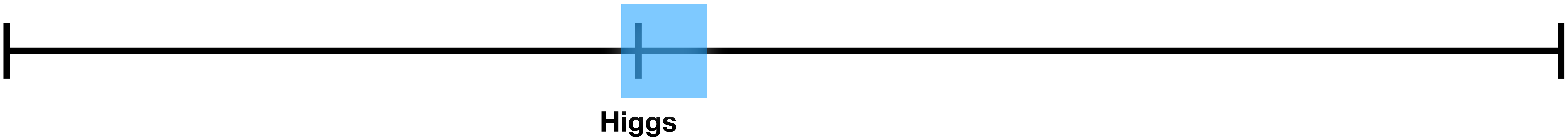
$$\Gamma_{\chi\to\mathrm{SM}} = n_\chi \langle \sigma v \rangle \simeq H$$

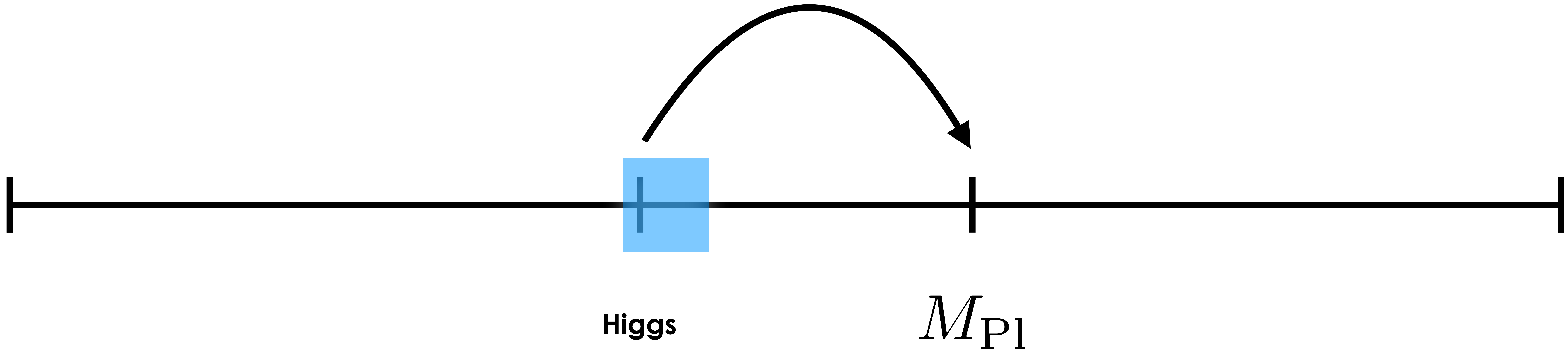


$$n_\chi^{\mathrm{today}} \sim \frac{1}{\langle \sigma v \rangle} \sim \frac{m_\chi^2}{\alpha_\chi^2}$$

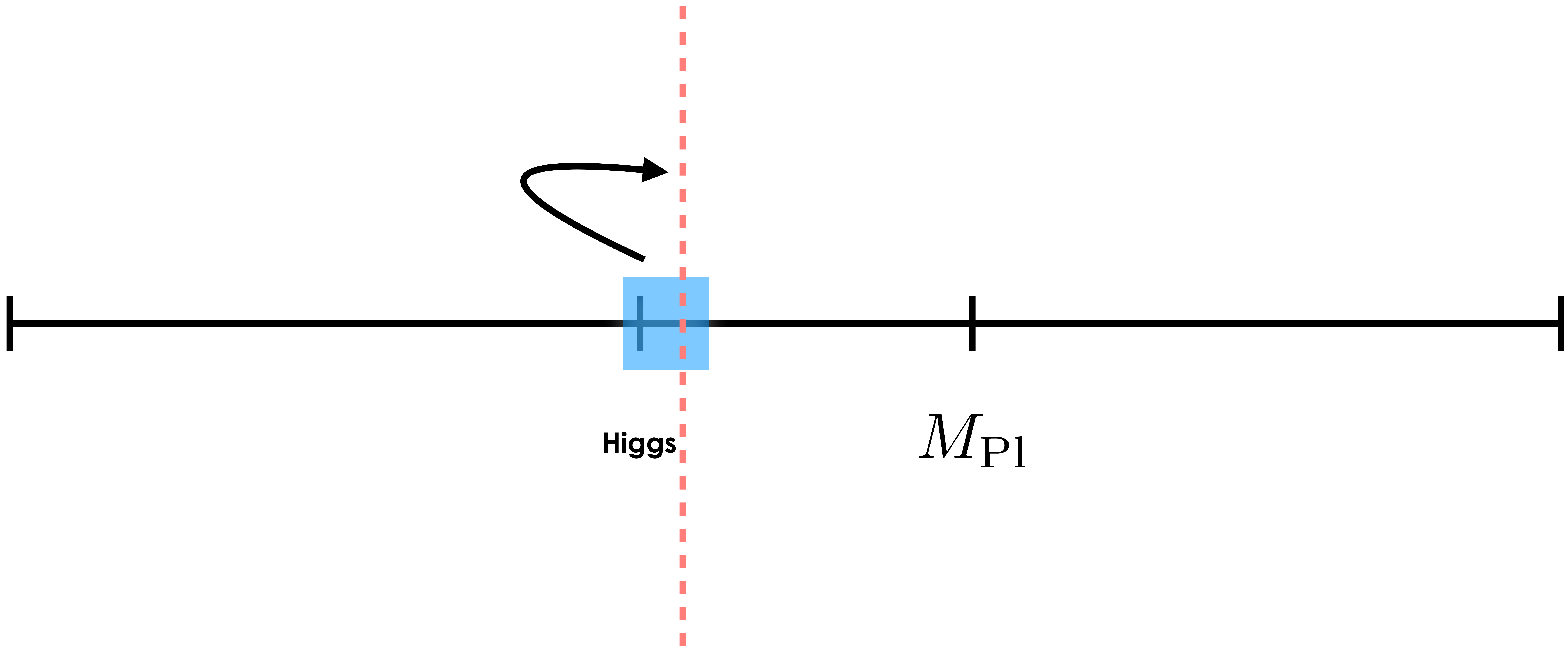
Perfect match!

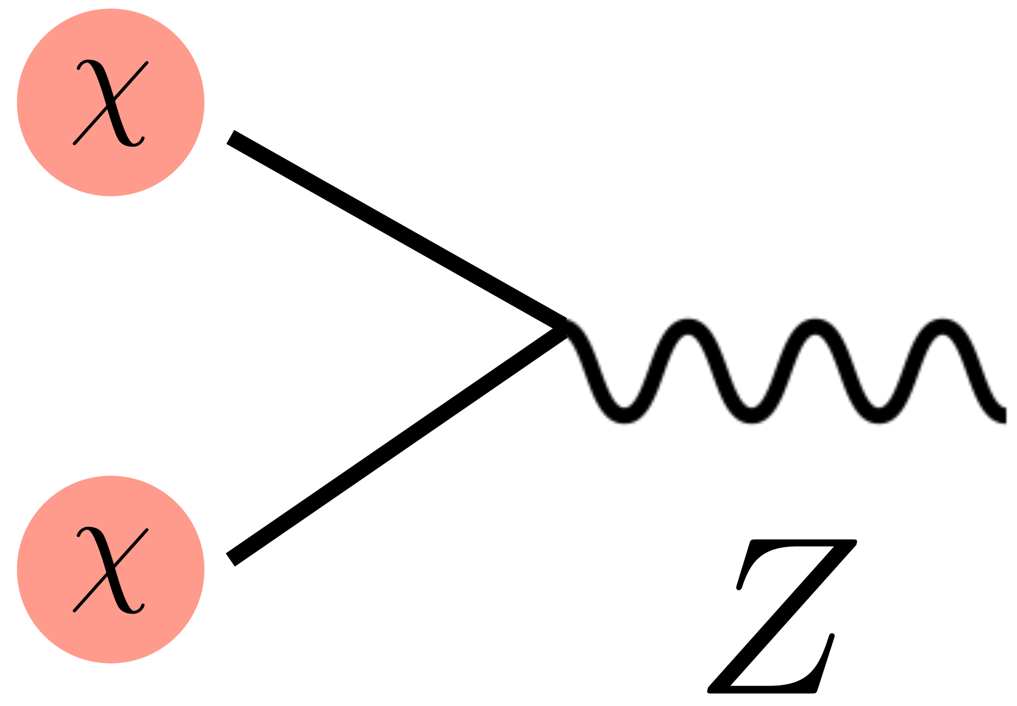





Higgs
M_{Pl}

New Symmetry

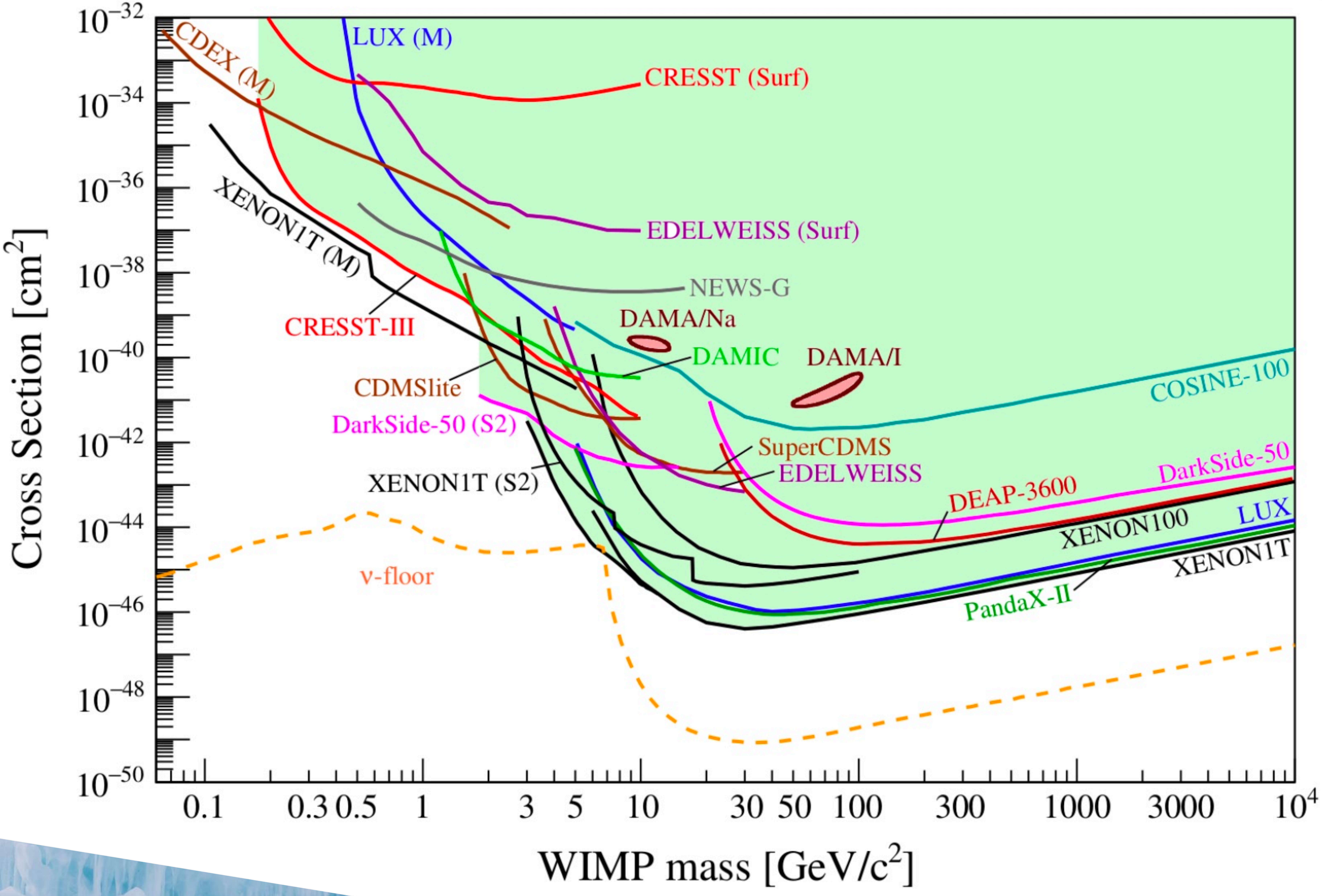




- Minimal Extension of what we know to exist
- Simple and predictive cosmology
- Solves another big problem in particle physics

DIRECT DETECTION OF THERMAL DM

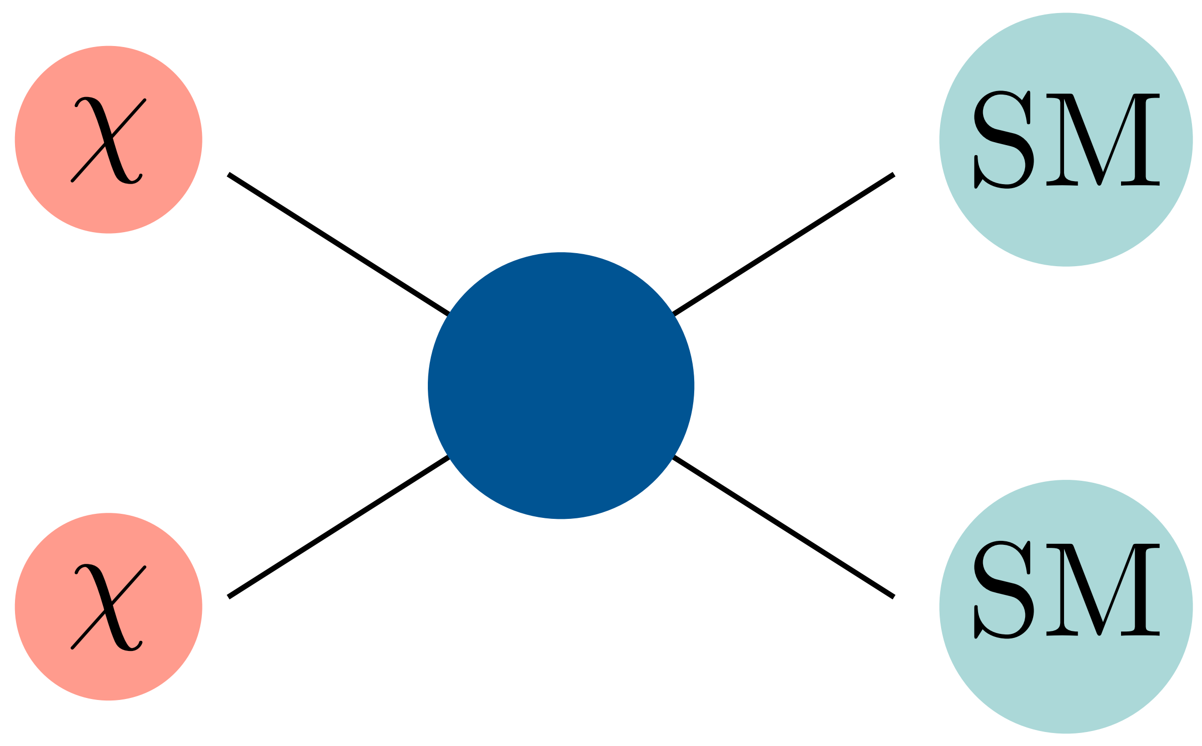
[APPEC '21, 2104.07634]




Higgs

[Griest, Seckel '89][RTD, Ruderman '15][RTD, Liu,Ruderman, Wang '15]

$$m_\chi < m_{\rm SM}$$



[Griest, Seckel '89][RTD, Ruderman '15][RTD, Liu,Ruderman, Wang '15]

$$m_\chi < m_{\rm SM}$$

$$n_\chi^{\rm today} \sim \frac{1}{\langle \sigma v \rangle} \sim \frac{m_\chi^2}{\alpha_\chi^2} e^{\Delta \frac{m_\chi}{T_f}}$$

The **same amount of DM** requires a **smaller mass**

$$S \supset -\frac{1}{2}\int d^4x \; j^{\mu}_{\text{eff}} \, A_{\mu}$$

GW

$$\underline{j^{\mu}_{\text{eff}}} = \partial_{\nu}\left(\frac{1}{2}\,h\,F^{\mu\nu} + h^{\nu}{}_{\alpha}\,F^{\alpha\mu} - h^{\mu}{}_{\alpha}\,F^{\alpha\nu}\right)$$

Axion

$$\underline{j^{\mu}_{\text{eff}}} = \epsilon^{\mu\nu\rho\sigma}\partial_{\nu}(aF_{\rho\sigma})$$

Not a covariant vector

Proper Detector Frame (PDF) Vs **Transverse Traceless (TT) Frame**

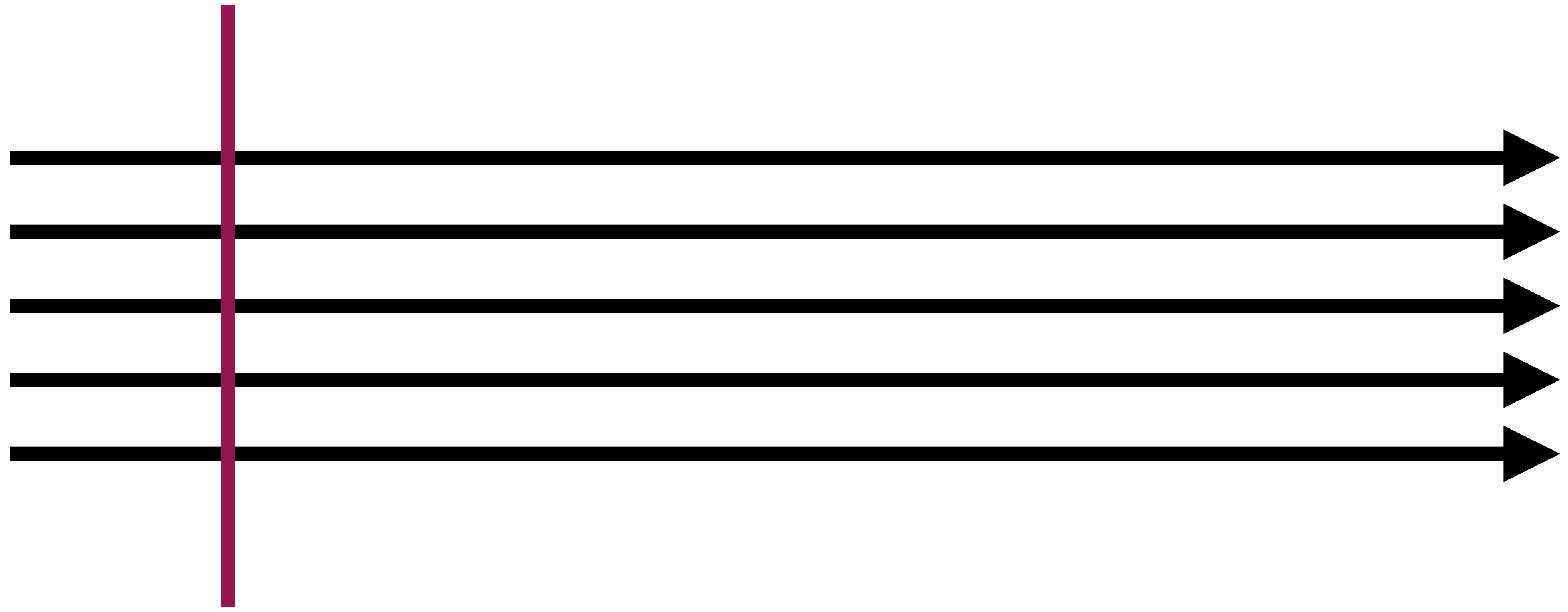
(Fermi Normal Coordinates)

proper detector frame = laboratory

$$(t, x, y, z)$$

probe wire

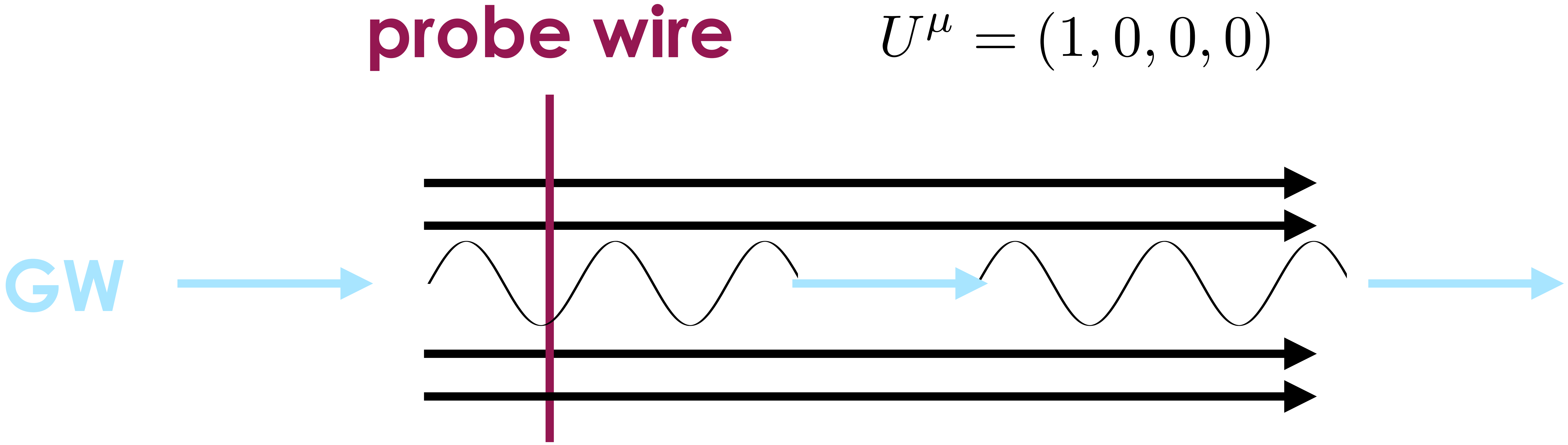
$$U^\mu = (1, 0, 0, 0)$$



$$\mathbf{B} = B_0 \hat{z}$$

proper detector frame = laboratory

$$(t, x, y, z)$$



TT gauge = comoving with the wave

$$(t_{\mathrm{TT}}, x_{\mathrm{TT}}, y_{\mathrm{TT}}, z_{\mathrm{TT}})$$

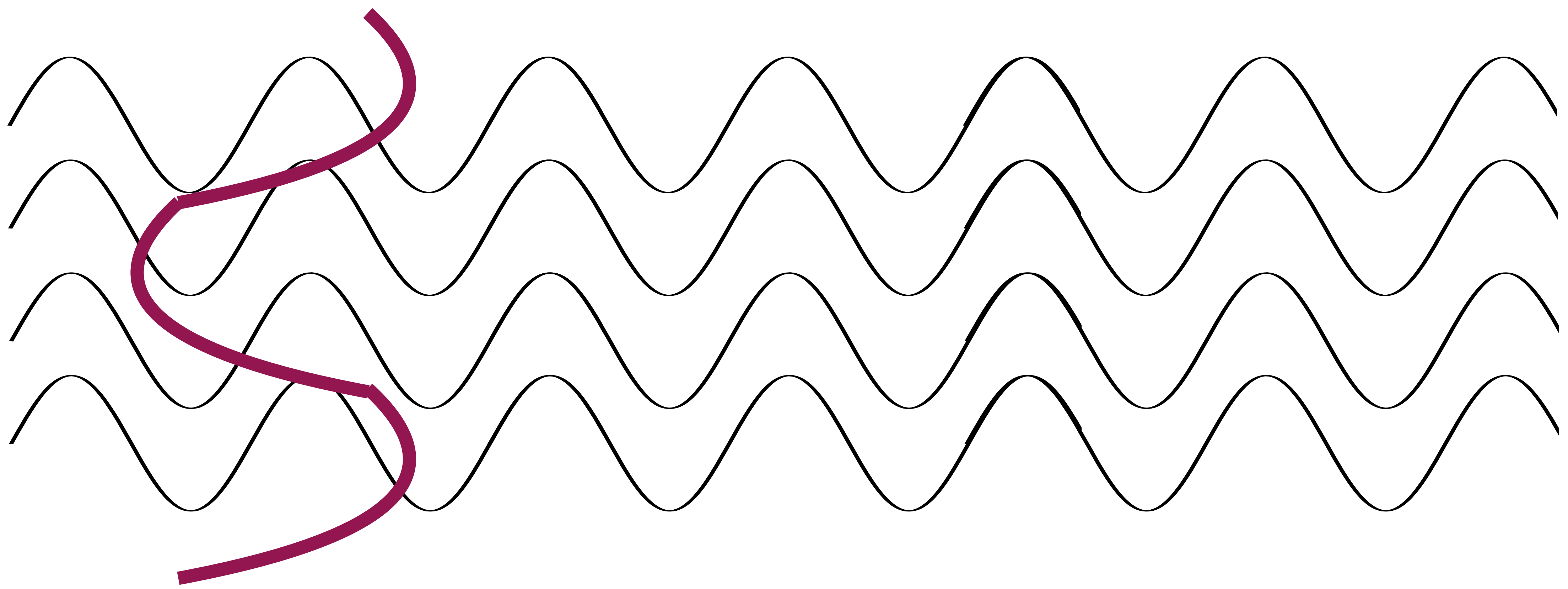
$$t_{\mathrm{TT}} \simeq t - \frac{i}{4}\,\omega_g\,(x^2 - y^2)\,h_+\,e^{i\omega_g t} \quad , \quad x_{\mathrm{TT}} \simeq x - \frac{1}{2}\,x\,(1 - i\omega_g z)\,h_+\,e^{i\omega_g t}$$

$$y_{\mathrm{TT}} \simeq y + \frac{1}{2}\,y\,(1 - i\omega_g z)\,h_+\,e^{i\omega_g t} \quad , \quad z_{\mathrm{TT}} \simeq z - \frac{i}{4}\,\omega_g\,(x^2 - y^2)\,h_+\,e^{i\omega_g t}$$

TT gauge = comoving with the wave

$$(t_{\mathrm{TT}}, x_{\mathrm{TT}}, y_{\mathrm{TT}}, z_{\mathrm{TT}})$$

probe wire



$$\mathbf{B} = B_0 \hat{z} + \frac{i}{2}(h_+ B_0) e^{i\omega_g t}(\omega_g x, -\omega_g y, 0) + \mathcal{O}(h^2)$$

TT gauge = comoving with the wave

$$(t_{\mathrm{TT}}, x_{\mathrm{TT}}, y_{\mathrm{TT}}, z_{\mathrm{TT}})$$

$$\mathbf{B} = B_0 \hat{z}$$

Theorem: $j^{\mu}_{\mathrm{eff,TT}} = 0$

TT gauge = comoving with the wave

$$(t_{\mathrm{TT}}, x_{\mathrm{TT}}, y_{\mathrm{TT}}, z_{\mathrm{TT}})$$

Wrong Conclusion

Theorem: $j^{\mu}_{\mathrm{eff,TT}} = 0$ → No signal

Surprisingly common mistake in the literature
(confusion between TT frame and laboratory frame)

TT gauge = comoving with the wave

$$(t_{\mathrm{TT}}, x_{\mathrm{TT}}, y_{\mathrm{TT}}, z_{\mathrm{TT}})$$

Wrong Conclusion

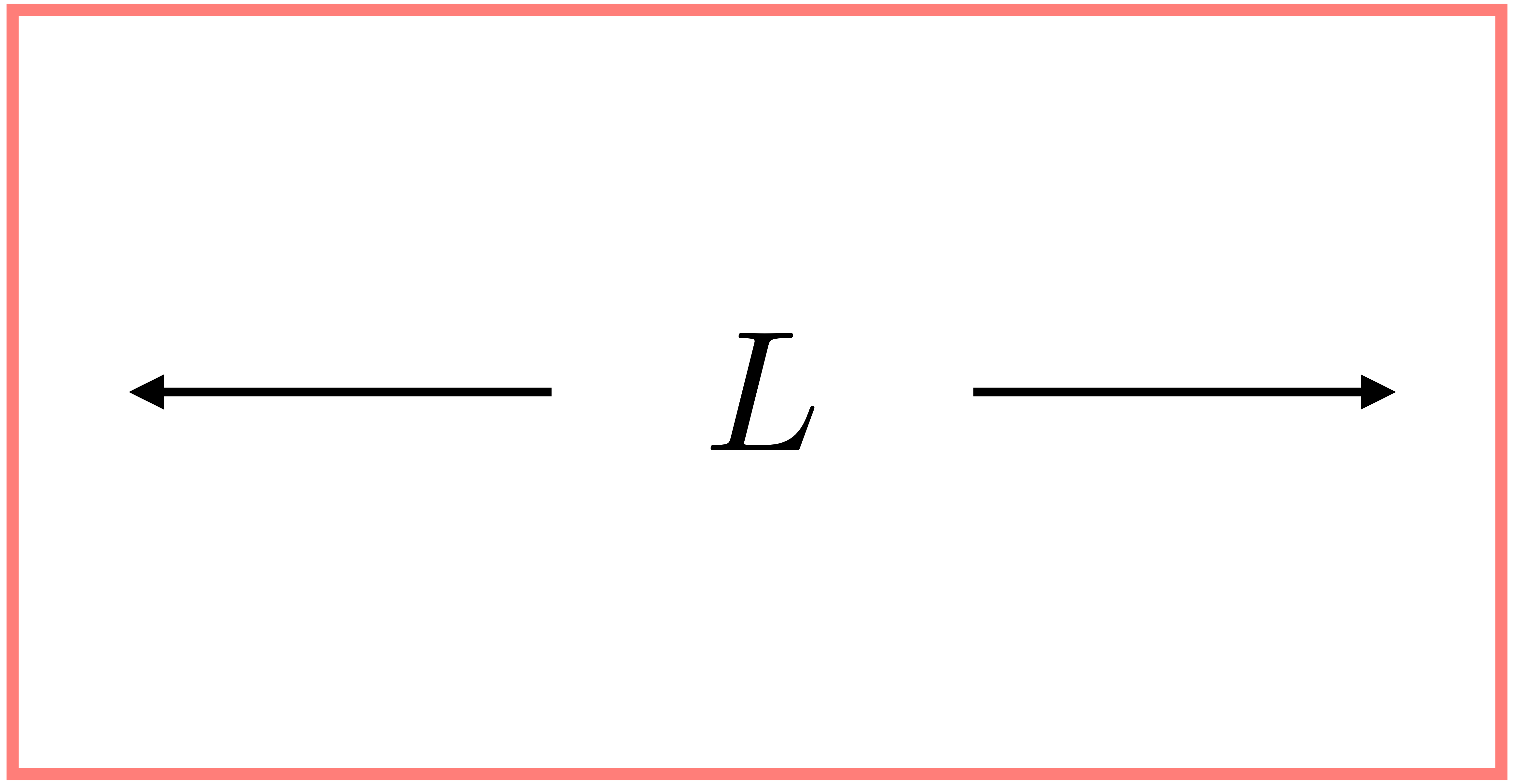
Theorem: $j^{\mu}_{\mathrm{eff,TT}} = 0$ → No signal

Doubly Wrong:

1. Impossible to prepare a uniform B-field in the TT frame
2. Even if you could do it, there would still be a signal (wire moving)

OUR CALCULATION

Cavity



$$\lambda_g \simeq L$$

OUR CALCULATION

ADMX, HAYSTAC, …

$$\mathbf{j}_\times \cdot \hat{z} \propto \sin\phi \, \sin\beta \left(-1 + \frac{2i}{3}\, \omega_g \, (z\cos\beta - r\sin\phi\sin\beta) + \mathcal{O}(\omega_g^2 \, L_{\rm det}^2) \right)$$

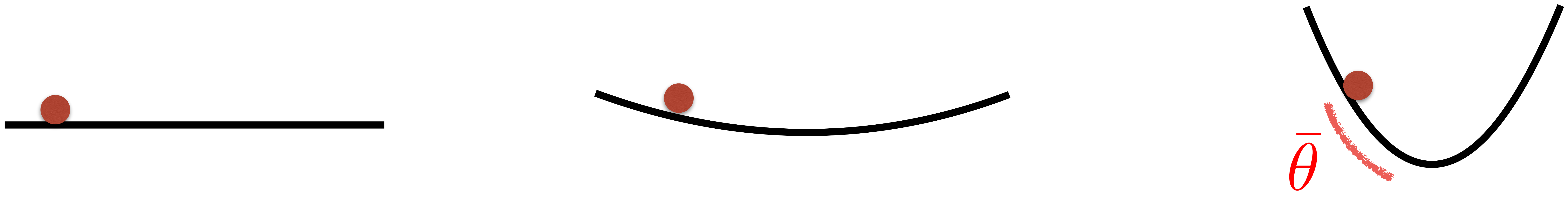
The volume integral of the leading order piece vanishes

AXION

The Universe cools below the QCD scale

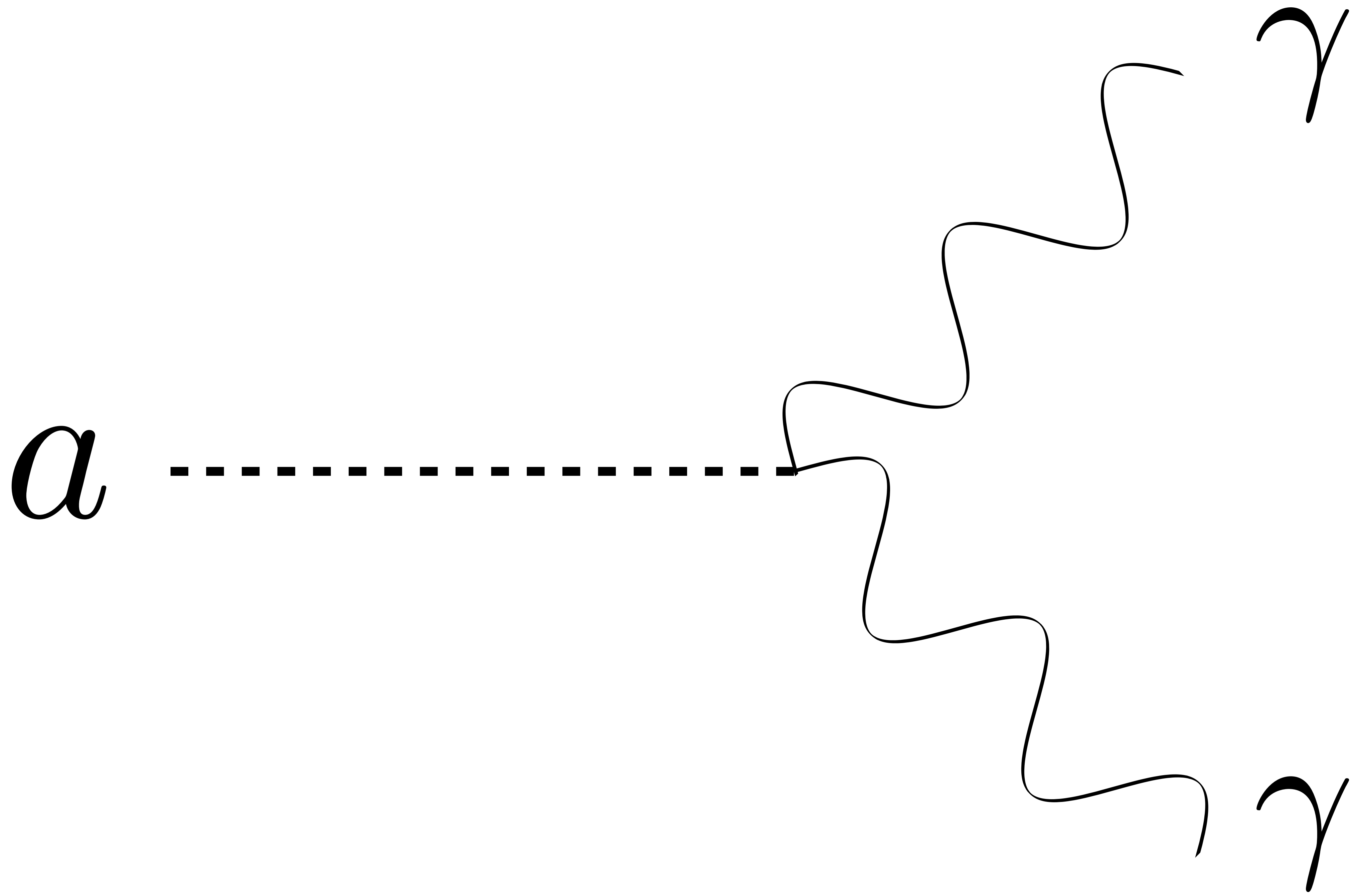
$$m_a(T) \approx 0.1 m_a \left(\frac{\Lambda_{\rm QCD}}{T} \right)^4$$

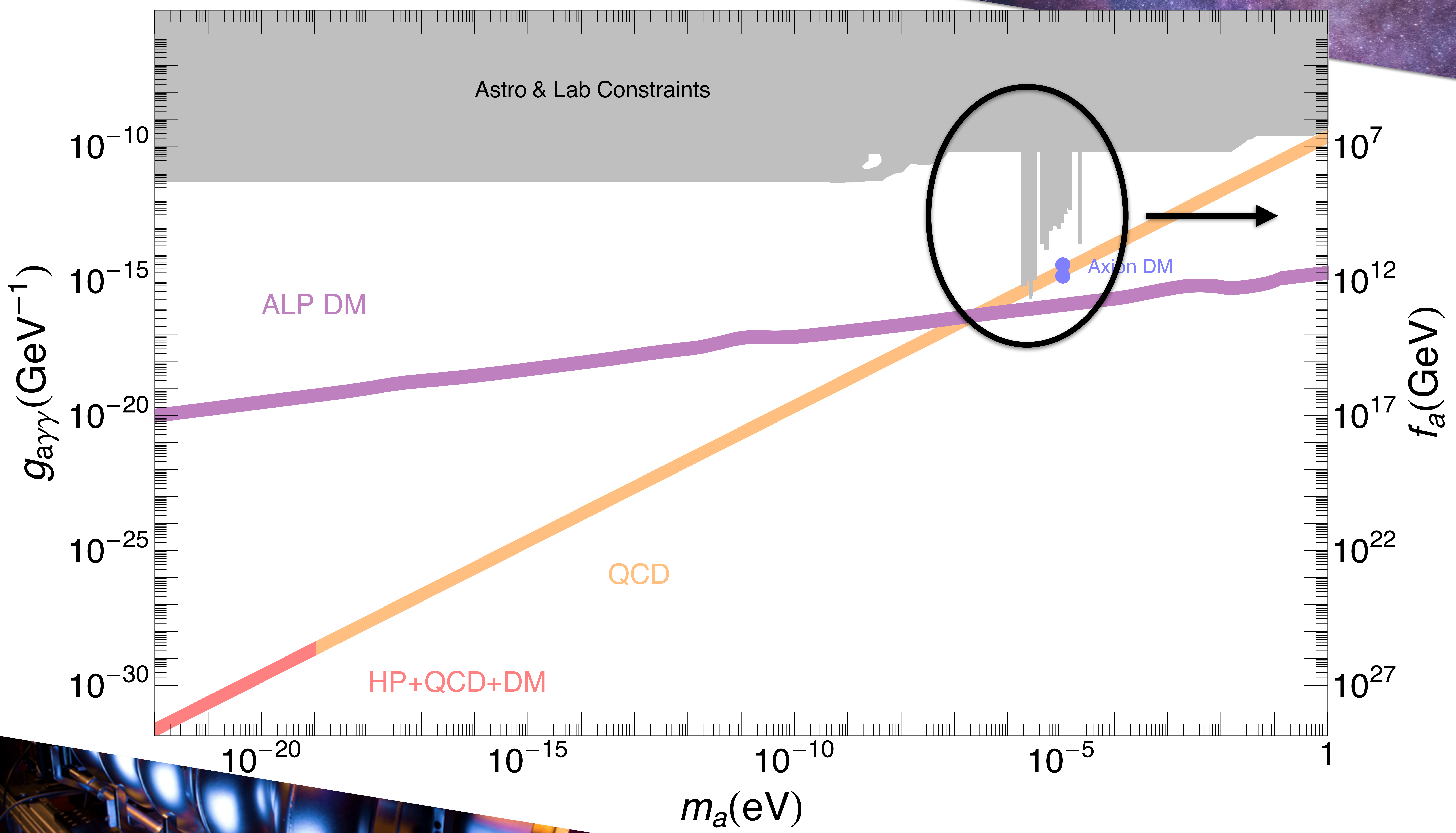
AXION



$$\rho_a = \frac{m_a^2 f_a^2 \bar{\theta}^2}{2}$$

ALP DARK MATTER DETECTION





Astro & Lab Constraints
Axion DM
ALP DM
QCD
HP+QCD+DM
$g_{a\gamma\gamma}(\mathrm{GeV}^{-1})$
$f_a(\mathrm{GeV})$
$m_a(\mathrm{eV})$
10^{-10}
10^{-15}
10^{-20}
10^{-25}
10^{-30}
10^{7}
10^{12}
10^{17}
10^{22}
10^{27}
10^{-20}
10^{-15}
10^{-10}
10^{-5}
1

THE TIP OF AN ICEBERG

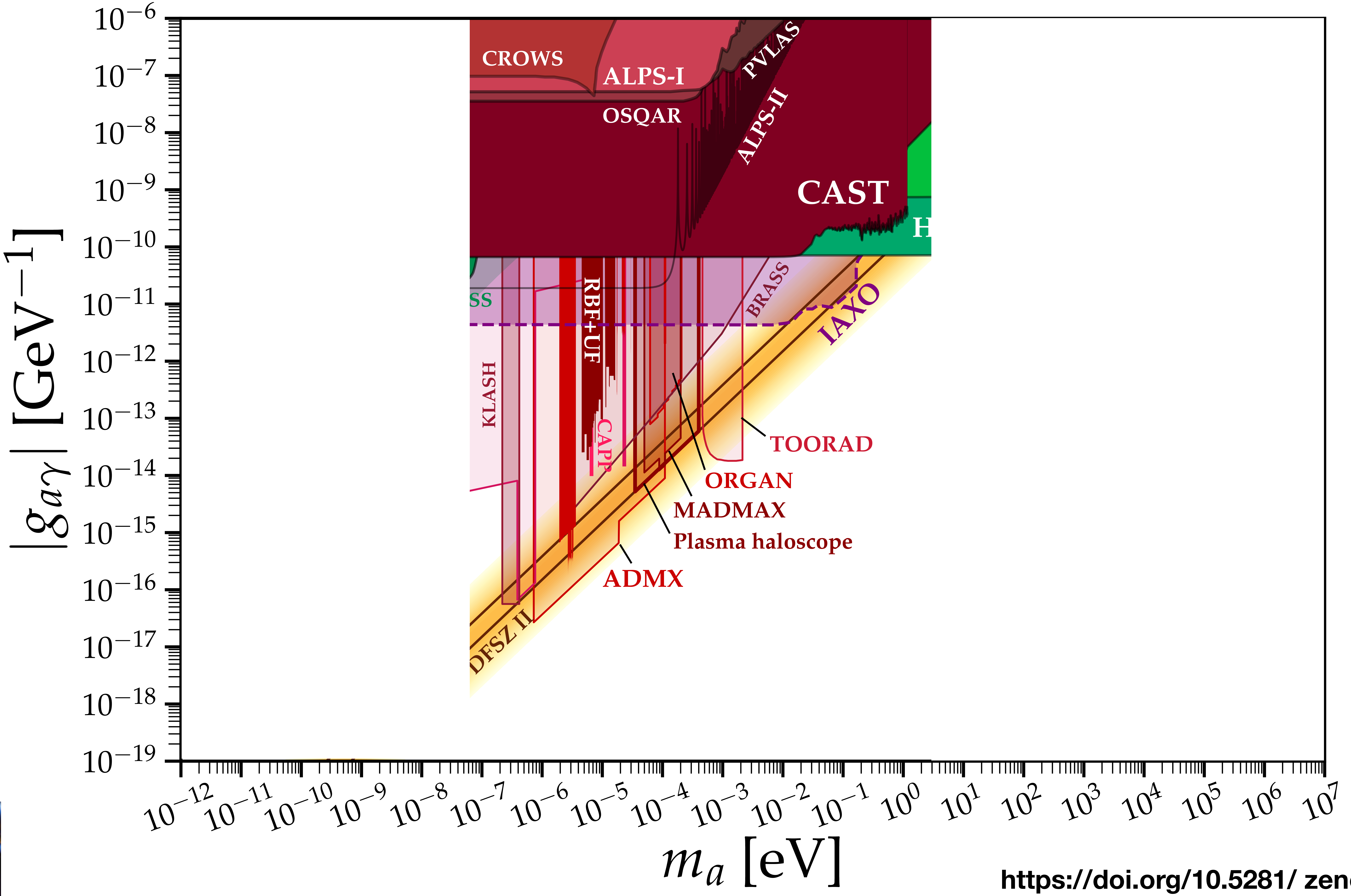


Figure from PDG and C. O'Hare

https://doi.org/10.5281/ zenodo.3932430.