Observing the string axiverse

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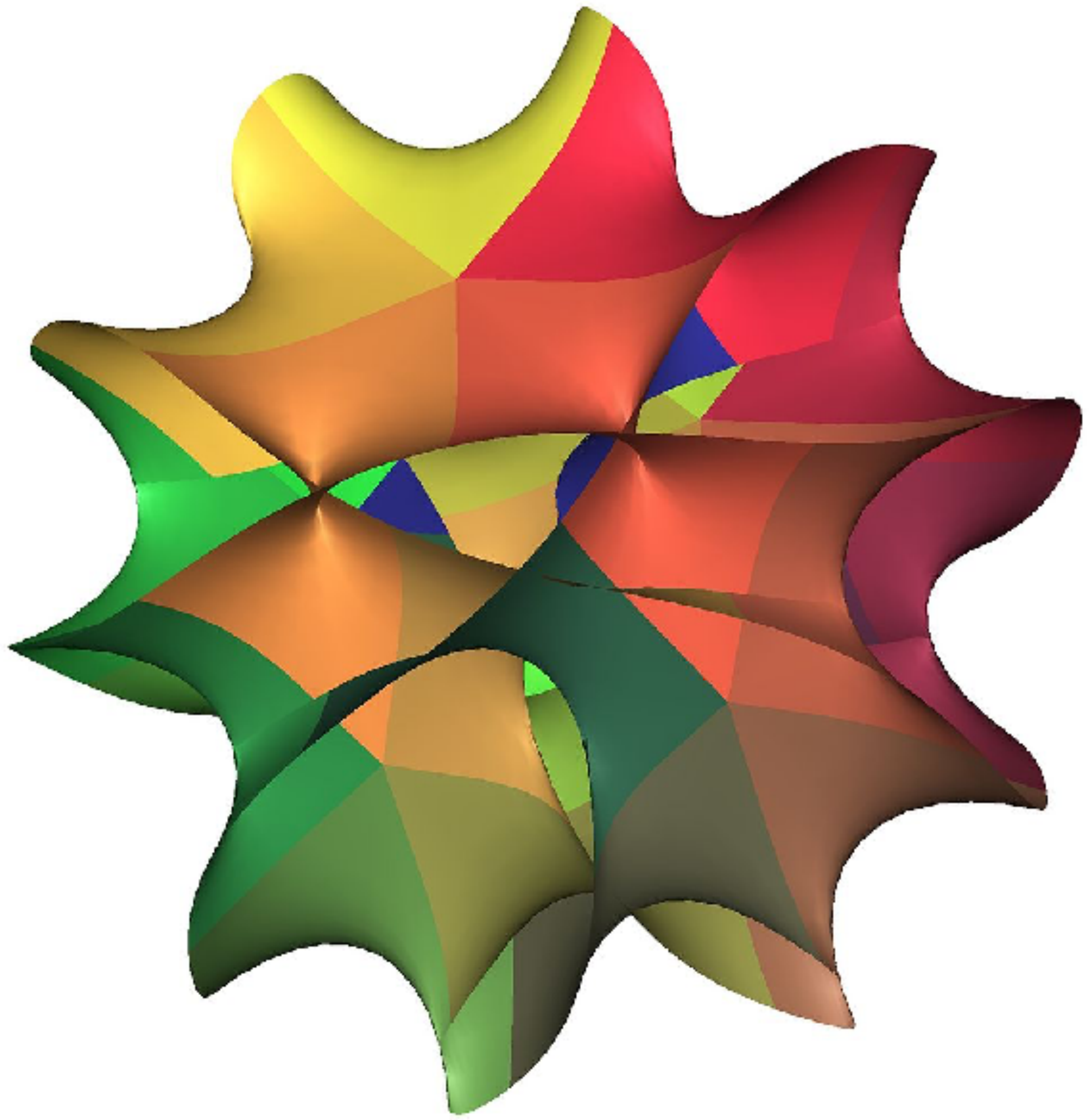
Patras Workshop on Axions, WIMPs and WISPs
Santa Cruz de Tenerife

Based on 2311.13658, 2107.12813 and ongoing work

Durham University

The String Axiverse

See David Marsh's Talk



Hanson, Notices of the Amer. Math. Soc. 41 (9): 1156-1163, (November/December 1994)

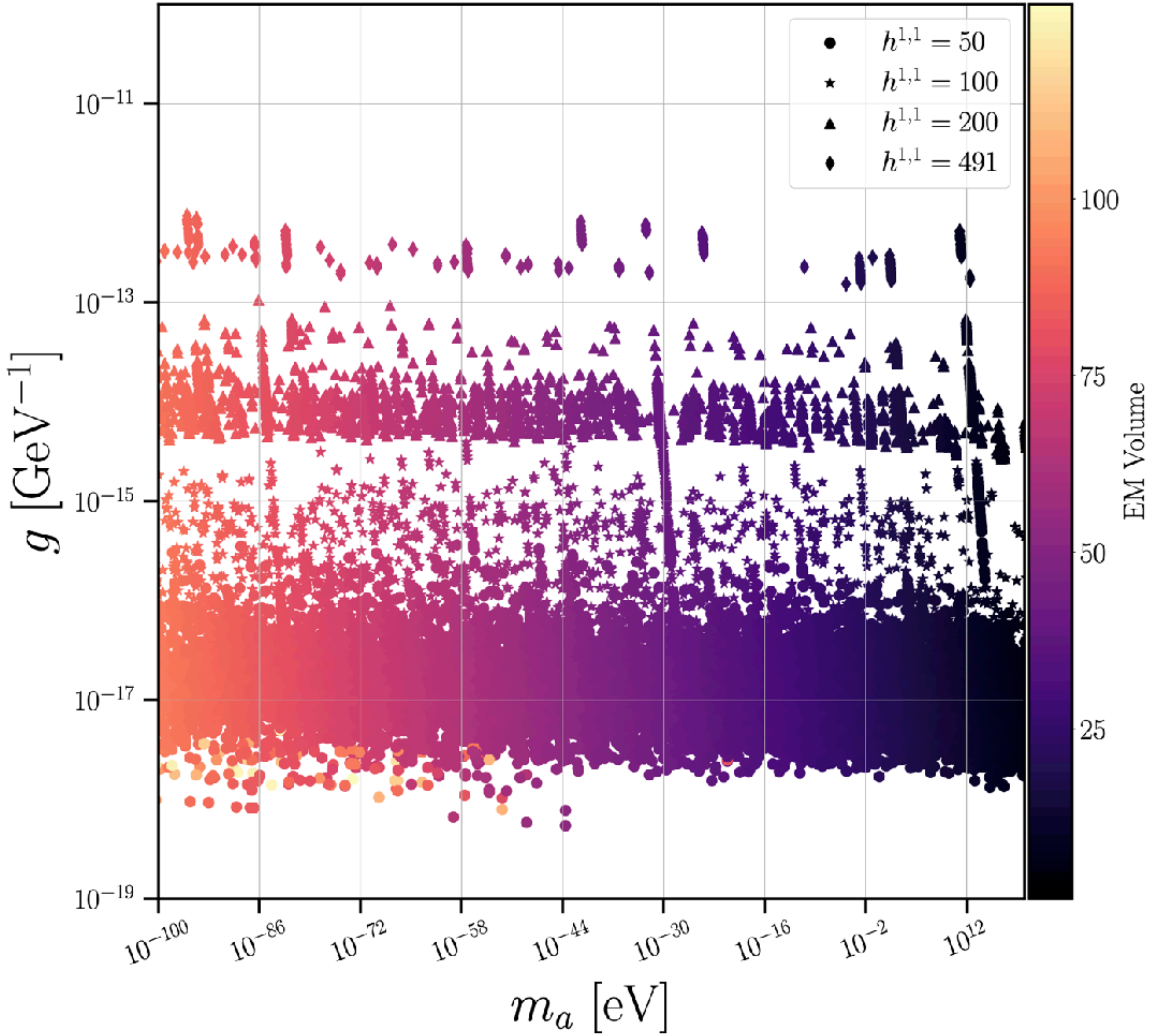


Figure from Gendler, Marsh, McAllister & Moritz, 2309.13145

The String Axiverse

Type IIb String Theory

Kreuzer-Skarke database

hep-th/0002240

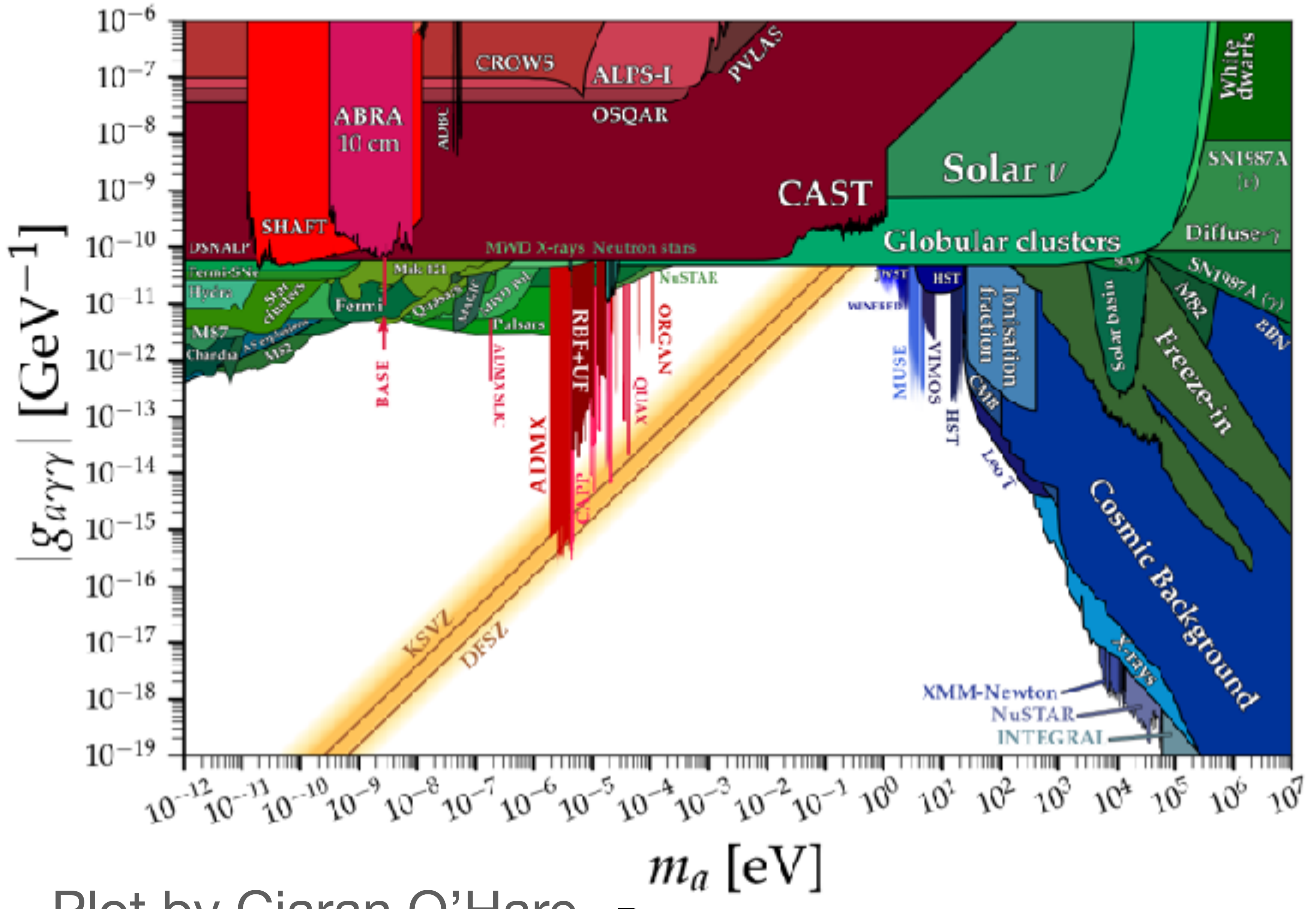
Compactification manifold

Demirtas, Rios-Tascon & McAllister
2211.03823

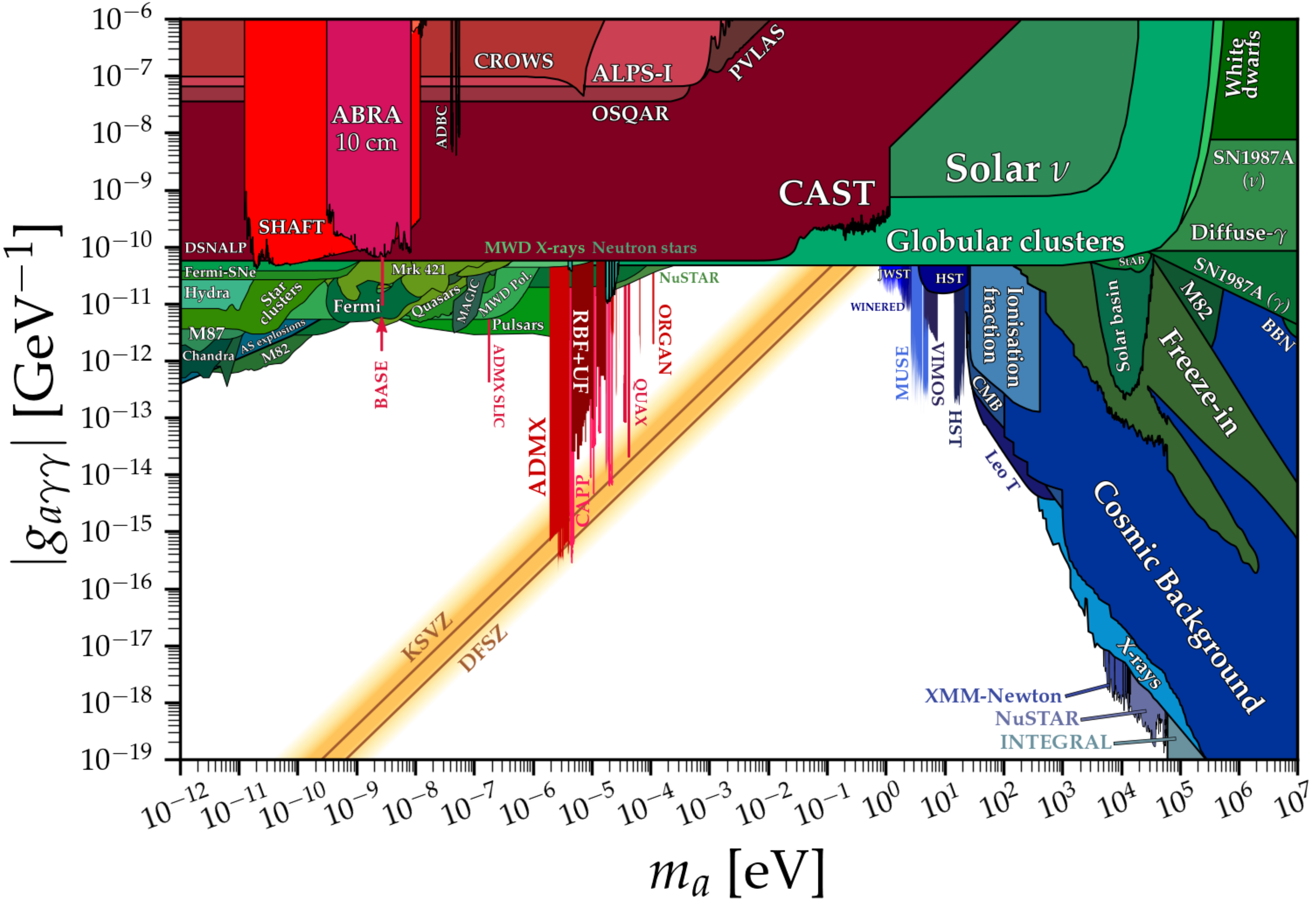
???

ALP masses
and photon couplings

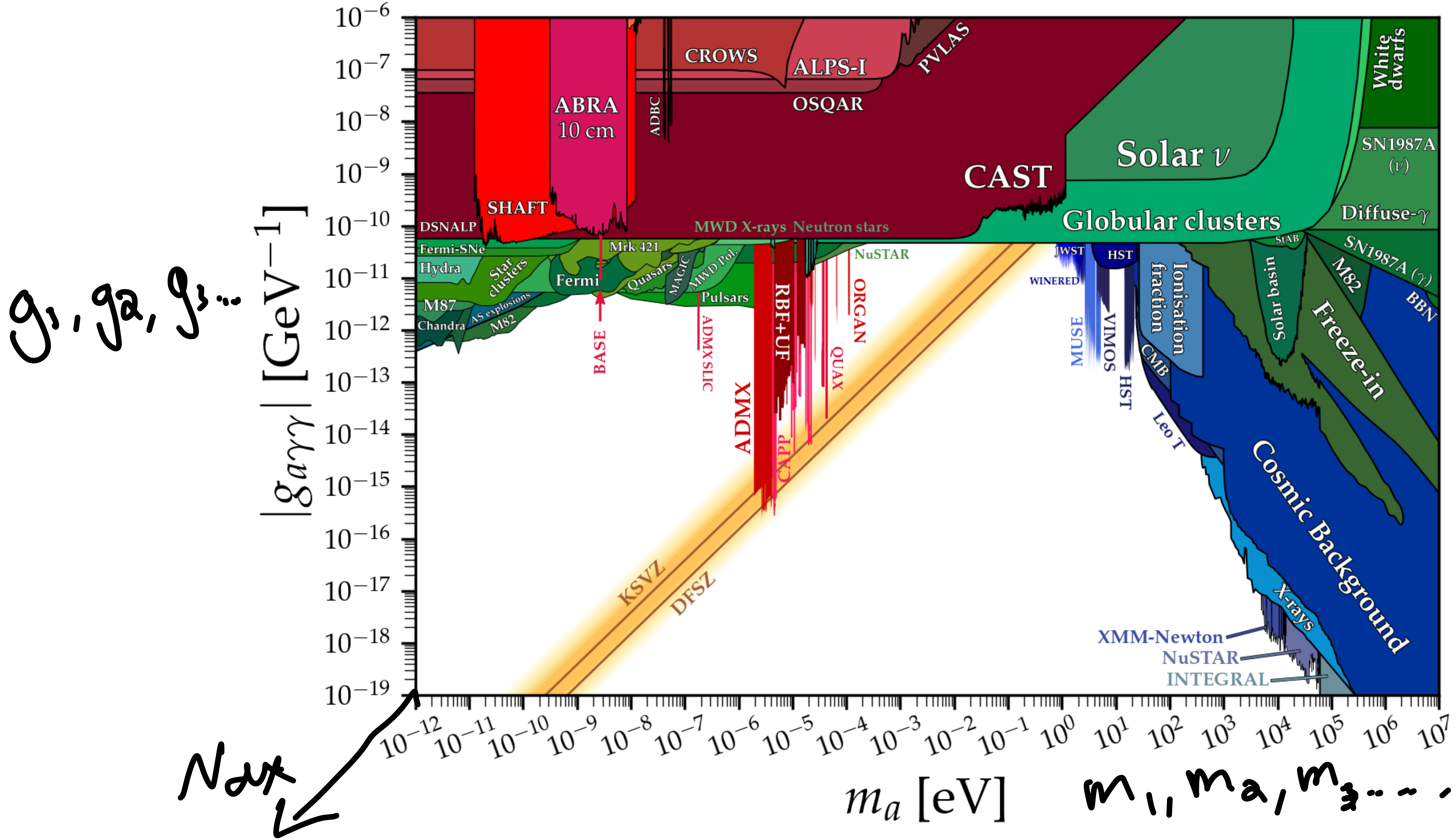
Other ALP couplings to SM



Plot by Ciaran O'Hare



$|g_{a\gamma\gamma}|$ [GeV^{-1}]
m_a [eV]
DSNALP
SHAFT
ABRA 10 cm
ADBC
CROWS
ALPS-I
OSQAR
PVLAS
CAST
Solar ν
White dwarfs
SN1987A (ν)
Diffuse-γ
Globular clusters
MWD X-rays
Neutron stars
Fermi-SNe
Hydra
Star clusters
Fermi
Mrk 421
Quasars
MAGIC
MWD Pol.
Pulsars
M87
AS explosions
Chandra
M82
NuSTAR
BASE
ADMX SLIC
ADMX
RBF+UF
CAPP
QUAX
ORGAN
KSVZ
DFSZ
JWST
WINERED
HST
MUSE
VIMOS
Ionisation fraction
CMB
Leo T
StAB
Solar basin
SN1987A (γ)
M82
BBN
Freeze-in
Cosmic Background
X-rays
XMM-Newton
NuSTAR
INTEGRAL



$|g_{a\gamma\gamma}|$ [GeV^{-1}]
m_a [eV]
g1, g2, g3...
m1, m2, m3....
Nax
CROWS
ALPS-I
PVLAS
OSQAR
ABRA
10 cm
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The String Axiverse

$$\mathcal{L} \supset \sum_i \left(-\frac{1}{2}\partial^\mu \phi_i \partial_\mu \phi_i - \frac{1}{2} m_i^2 \phi_i^2 - g_i^\gamma \phi_i \tilde{F}^{\mu\nu} F_{\mu\nu} + g_i^e \bar{\psi} \gamma^\mu \gamma_5 \psi \partial_\mu \phi_i \right)$$

Wish to work in a convenient basis:

- **Mass basis**: mass matrix is diagonal, no oscillations between propagating ALP states.
- **Electromagnetic basis**: only one ALP couples to the photon with coupling $g^\gamma = \sqrt{\sum g_i^{\gamma 2}}$.
- **Electronic basis**: only one ALP couples to the electron with coupling $g^e = \sqrt{\sum g_i^{e2}}$.
- The electromagnetic and electronic ALPs are in general neither orthogonal nor colinear.
- For the QCD basis see Gavela, Quilez & Ramos, 2305.15465.

Basis Choice

$$\mathcal{L} \supset \sum_i \left(-\frac{1}{2}\partial^\mu \phi_i \partial_\mu \phi_i - \frac{1}{2} m_i^2 \phi_i^2 - g_i^\gamma \phi_i \tilde{F}^{\mu\nu} F_{\mu\nu} + g_i^e \bar{\psi} \gamma^\mu \gamma_5 \psi \partial_\mu \phi_i \right)$$

- In the full theory, all basis choices give the same results.
- QFT with “flavour eigenstates” is non-trivial.
- Different bases may give different results when combined with other approximations.
- Oscillations between states when not in the mass basis, akin to neutrino oscillations (see FCD, Maxwell & Turner, 2311.13658).
- Misalignment between electromagnetic and electronic bases.
- Conserved charge in the massless limit must be considered for thermal production (see Gendler, Marsh, McAllister & Moritz, 2309.13145).

Mass eigenstates

$$\mathcal{L} \supset \sum_i \Big(-\frac{1}{2}\partial^\mu \phi_i \partial_\mu \phi_i - \frac{1}{2} m_i^2 \phi_i^2 - g_i^\gamma \phi_i \tilde{F}^{\mu\nu} F_{\mu\nu} + g_i^e \bar{\psi} \gamma^\mu \gamma_5 \psi \partial_\mu \phi_i \Big)$$

- Some experiments search for each mass eigenstate individually.
- Example: axion haloscopes, radio line searches

Searches for the Electromagnetic ALP

$$\phi_\gamma = \frac{1}{g_\gamma}\sum_i g_i^\gamma \phi_i$$

$$g^\gamma = \sqrt{\sum_i {g_i^\gamma}^2}$$

$$|\phi_i^{\mathrm{mass}}\rangle = U^\gamma_{\alpha i}|\phi_\alpha^{\mathrm{EM}}\rangle$$

- When no masses or other couplings are relevant, we can search for a single light ALP with coupling g_γ to photons.
- Example: stellar cooling bounds.

The Electromagnetic ALP

$$\phi_\gamma = \frac{1}{g_\gamma} \sum_i g_i^\gamma \phi_i$$

$$g^\gamma = \sqrt{\sum_i g_i^{\gamma 2}}$$

$$|\phi_i^{\text{mass}}\rangle = U_{\alpha i}^\gamma |\phi_\alpha^{\text{EM}}\rangle$$

- In the electromagnetic basis, other fields orthogonal to the EM ALP do not couple directly to electromagnetism.
- When the ALP mass is not relevant, the EM ALP is produced and detected by electromagnetic processes.
- The EM ALP is in general not a mass eigenstate, so will oscillate into the orthogonal “hidden” ALP states.
- Misalignment between electromagnetic and electronic bases.

The Electromagnetic ALP

$$\phi_\gamma = \frac{1}{g_\gamma} \sum_i g_i^\gamma \phi_i$$

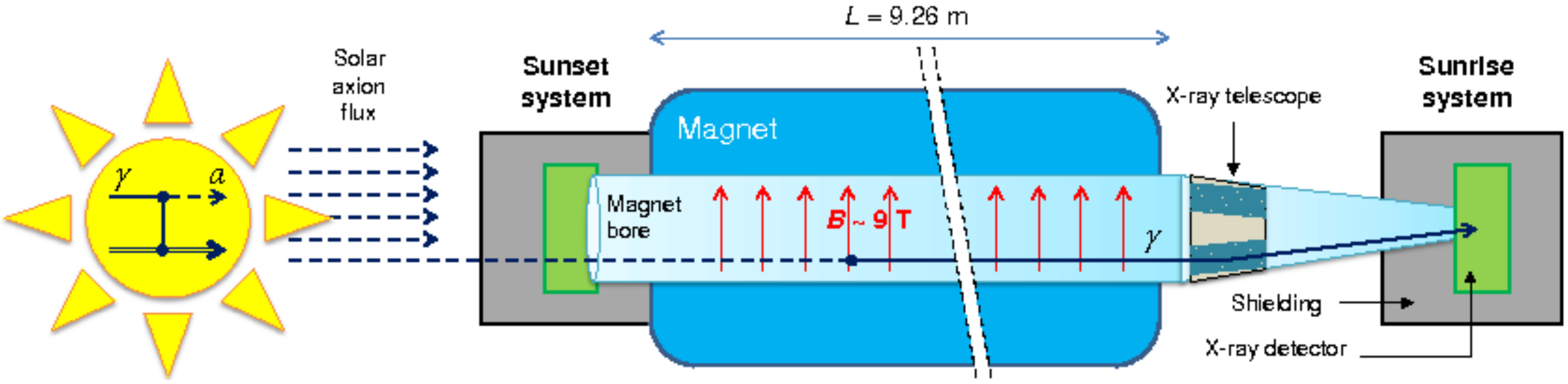
$$g^\gamma = \sqrt{\sum_i g_i^{\gamma 2}}$$

$$|\phi_i^{\text{mass}}\rangle = U_{\alpha i}^\gamma |\phi_\alpha^{\text{EM}}\rangle$$

Electromagnetic ALP to hidden ALP oscillation probability for two mass eigenstates:

$$P_{\phi_\gamma \to \phi_h} = \sin^2 2\theta \sin^2\left(\frac{\Delta m^2 L}{4E}\right)$$

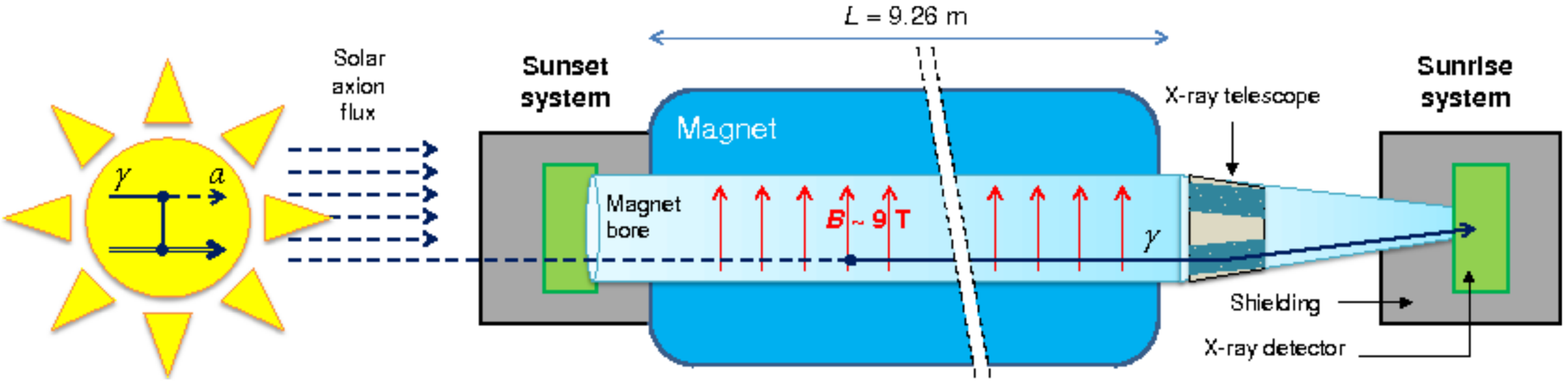
Example: The CERN Axion Solar Telescope



Reproduced from 1705.02290

- ALP states ϕ_γ and ϕ_e are produced in the sun.
- CAST with evacuated magnet bores detects the state ϕ_γ.
- ALPs produced in the Sun may oscillate into hidden ALPs as they travel to Earth, and therefore be unobservable to CAST.

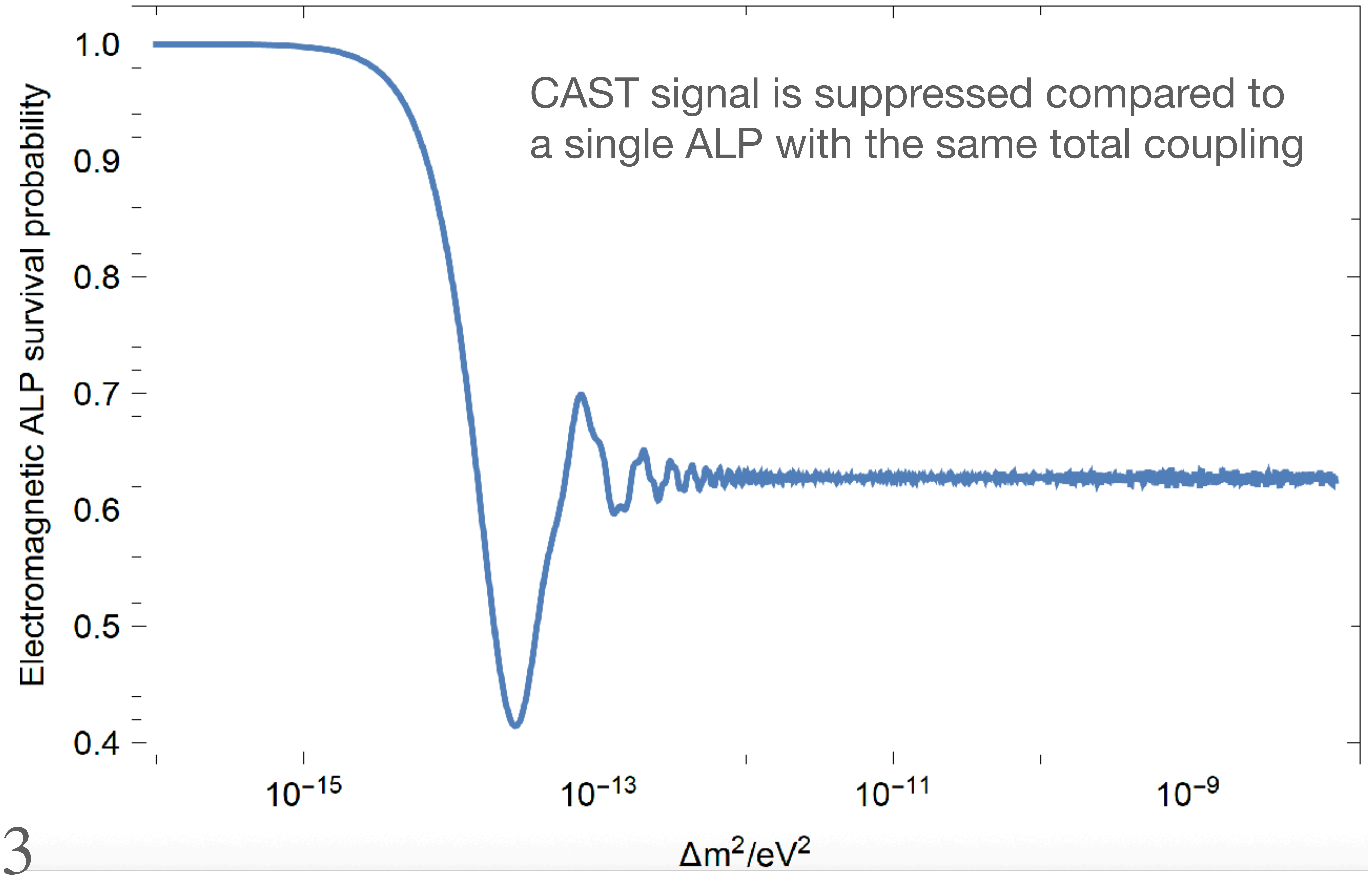
Example: The CERN Axion Solar Telescope



For 2 mass eigenstates:

$$P_{\phi_\gamma \to \phi_\gamma} = 1 - \sin^2 2\theta \frac{\int_{2\mathrm{keV}}^{7\mathrm{keV}} \sin^2\left(\frac{\Delta m^2 L}{4E}\right) \frac{d\Phi_a}{dE} dE}{\int_{2\mathrm{keV}}^{7\mathrm{keV}} \frac{d\Phi_a}{dE} dE}$$

Example: The CERN Axion Solar Telescope



$\theta = \pi/3$

The Matter Potential

- Propagation of ALP states is affected by the interactions of each mass eigenstate with their environment.
- This can be compared to the MSW effect for neutrino oscillations.
- In many environments (e.g. the sun) the matter potential is negligible, as ALPs interact even more feebly than neutrinos.

Flavour Oscillations in Quantum Field Theory

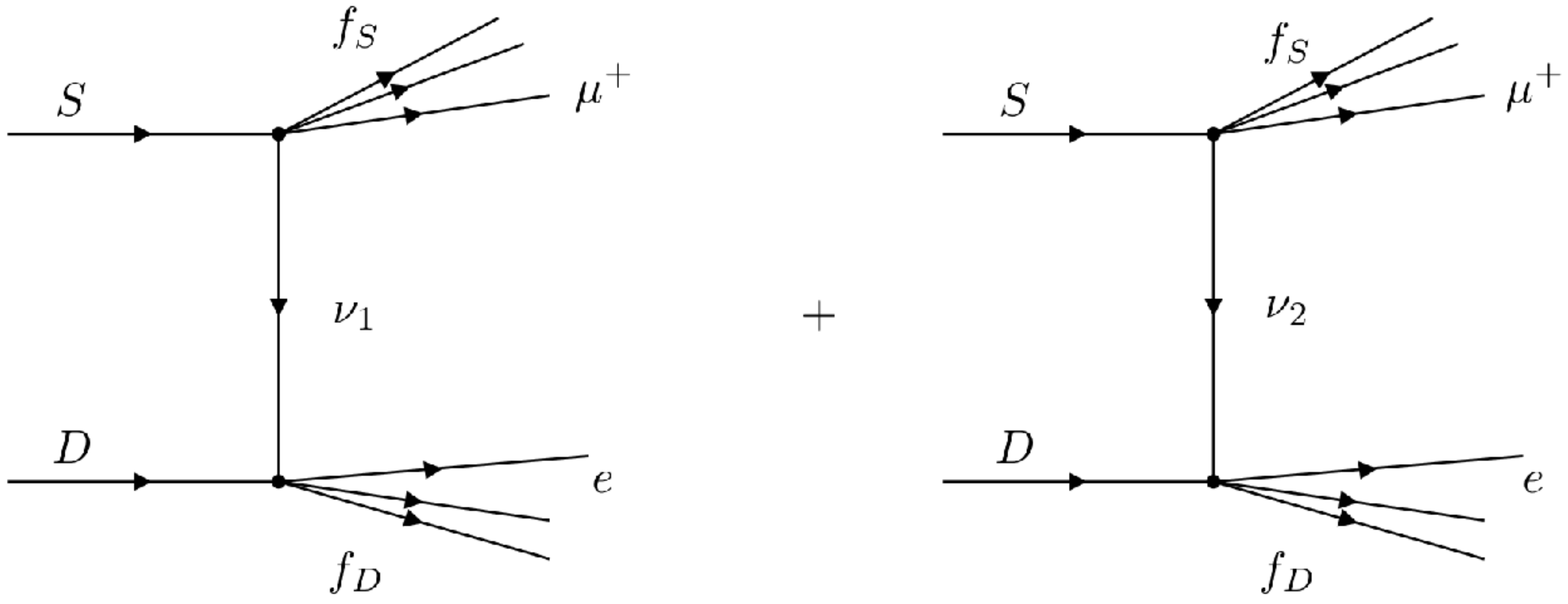


Figure from Dobrev, Melnikov & Schwetz, 2504.10600

Flavour Oscillations with Unruh-DeWitt Detectors

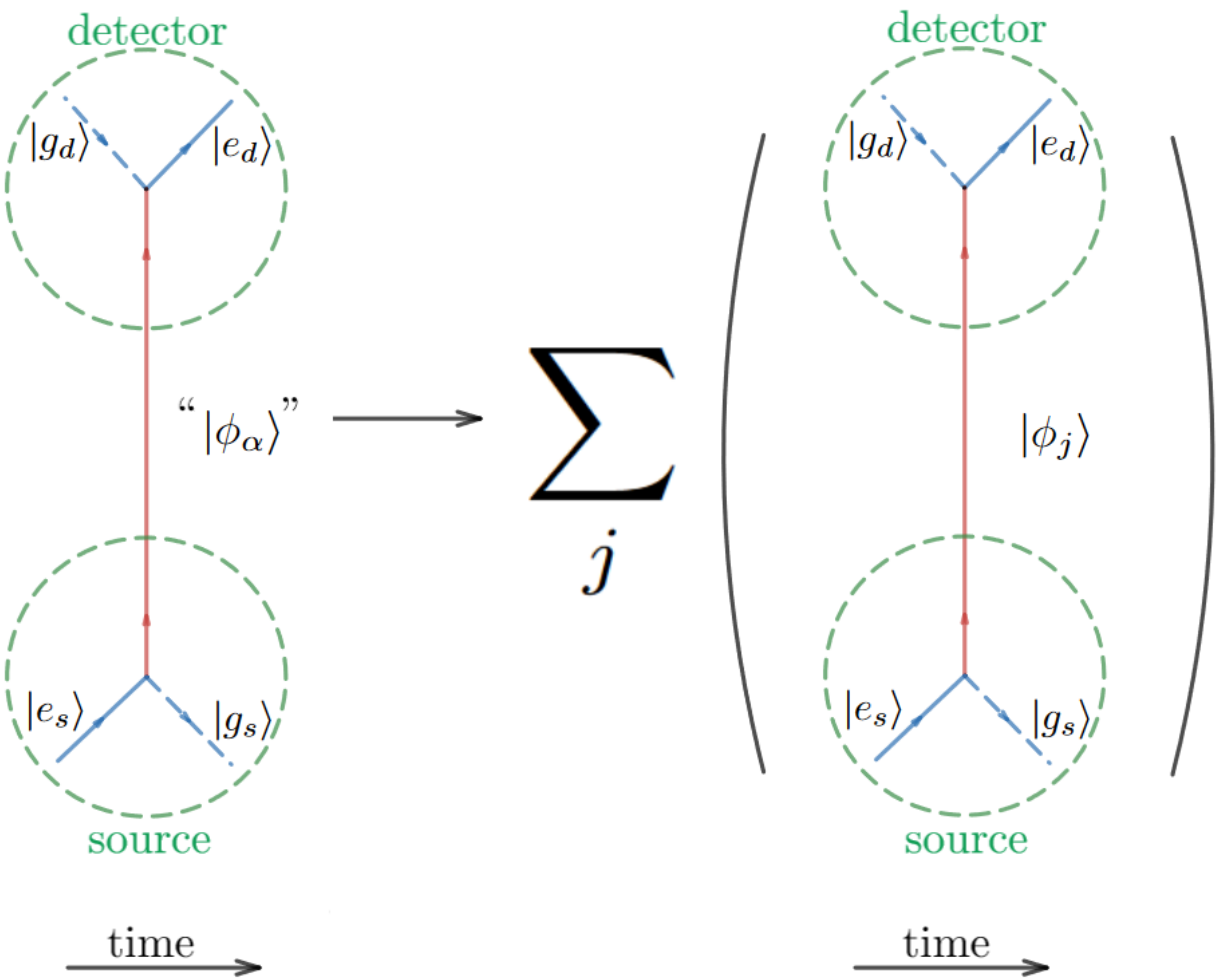
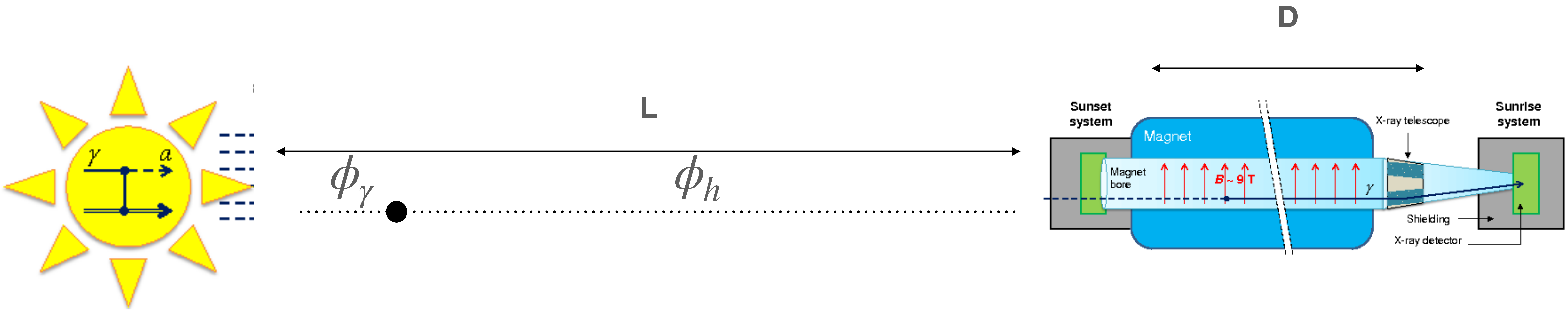


Figure from Torres, Perche, Landulfo & Matsas, 2009.10165

Oscillation and detection



Production of ALP state(s)

Propagation

Detection

$$P_{\rm 2ALPs}(\phi \to \gamma) = P_{\rm 1ALP}(\phi \to \gamma)\, .\, P_{\phi_\gamma \to \phi_h}(L)$$

Oscillation Probability

- Finite detector size becomes relevant when $D \gtrsim \frac{E}{m^2}$
- For $D < \frac{E}{m^2}$, the detector is effectively point-like and can use neutrino-like oscillation theory
- From considering “smeared” Unruh-DeWitt detectors
- Corresponds to $D \gtrsim$ ALP oscillation length
- In this case, we can still use the mass basis…

ALP to photon conversion in the mass basis

$$\left(\omega + \begin{pmatrix} \Delta_\gamma & 0 & \Delta_{\gamma a x} \\ 0 & \Delta_\gamma & \Delta_{\gamma a y} \\ \Delta_{\gamma a x} & \Delta_{\gamma a y} & \Delta_a \end{pmatrix} - i\partial_z\right)\begin{pmatrix} |\gamma_x\rangle \\ |\gamma_y\rangle \\ |\phi\rangle \end{pmatrix} = 0$$

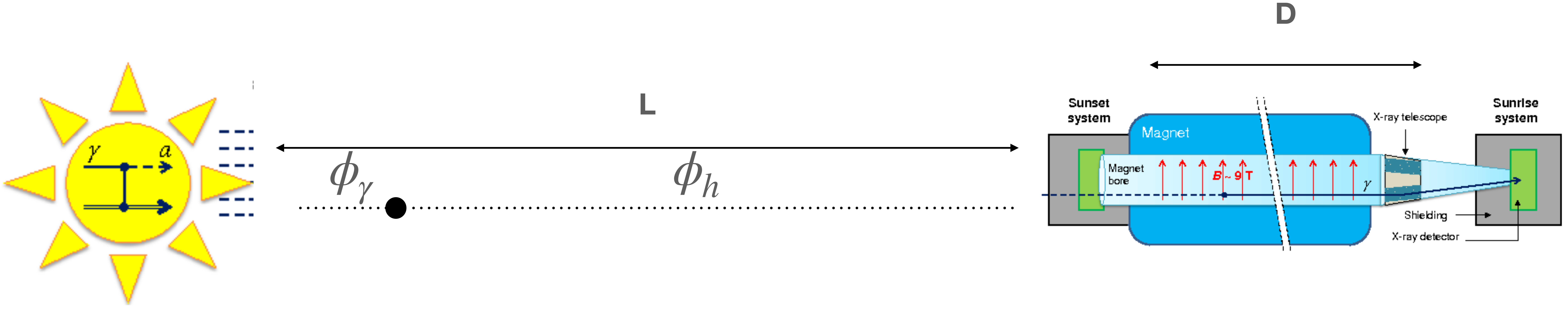
$$P_{a\to\gamma}(L) = |\langle 1,0,0|f(L)\rangle|^2 + |\langle 0,1,0|f(L)\rangle|^2$$

- $\Delta_\gamma = -\frac{\omega_{pl}^2}{2\omega}$
- $\Delta_a = \frac{-m^2}{\omega}$
- $\Delta_{\gamma a i} = g^\gamma B_i$

ALP to photon conversion in the mass basis

$$\left(\omega + \begin{pmatrix} \Delta_\gamma & 0 & \Delta_{\gamma a x 1} & \Delta_{\gamma a x 2} \\ 0 & \Delta_\gamma & \Delta_{\gamma a y 1} & \Delta_{\gamma a y 2} \\ \Delta_{\gamma a x 1} & \Delta_{\gamma a y 1} & \Delta_{a 1} & 0 \\ \Delta_{\gamma a x 2} & \Delta_{\gamma a y 2} & 0 & \Delta_{a 2} \end{pmatrix} - i\partial_z \right) \begin{pmatrix} \mid \gamma_x \rangle \\ \mid \gamma_y \rangle \\ \mid \phi_1 \rangle \\ \mid \phi_2 \rangle \end{pmatrix} = 0$$

Oscillation and detection



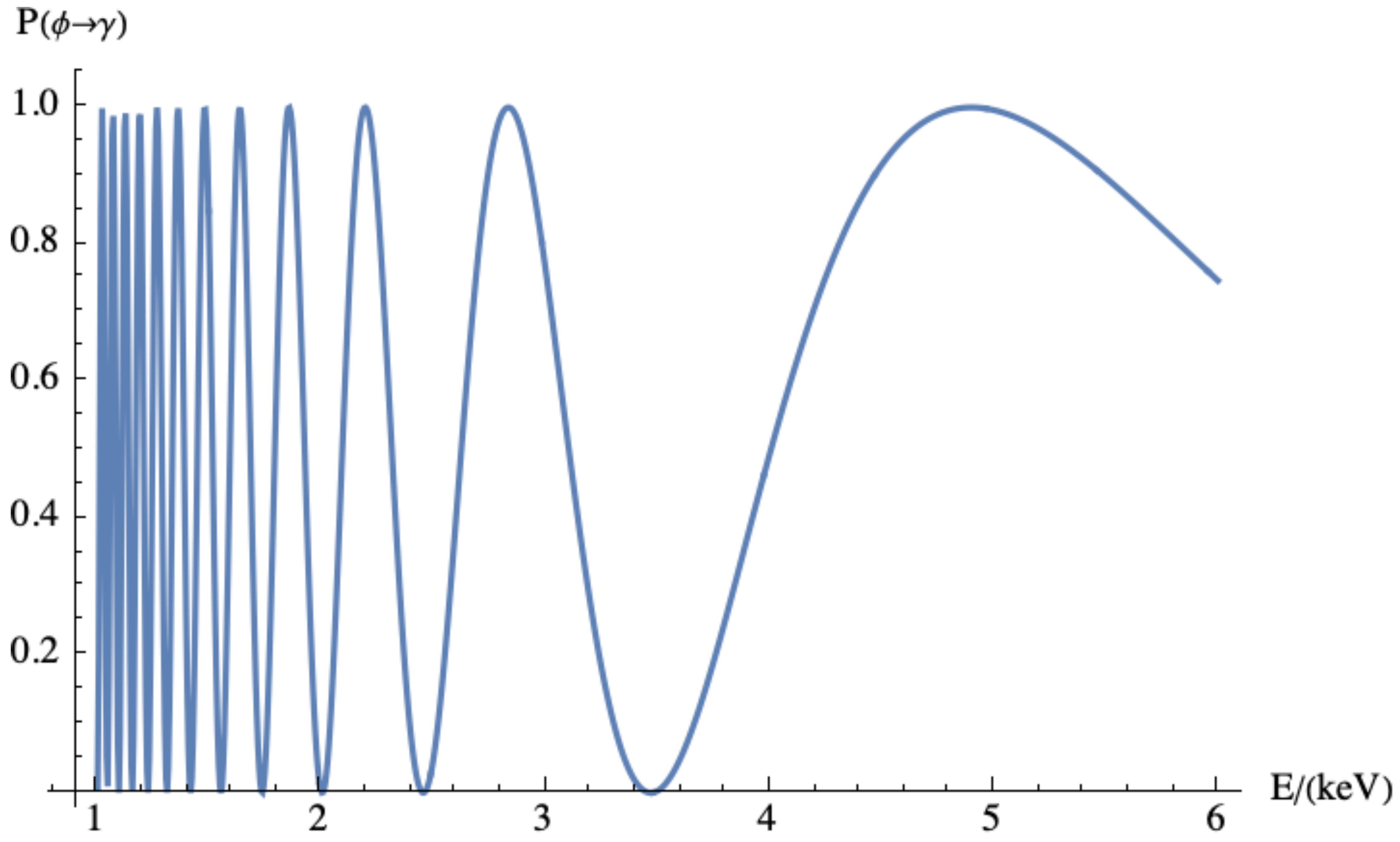
Production of ALP state(s)

Propagation

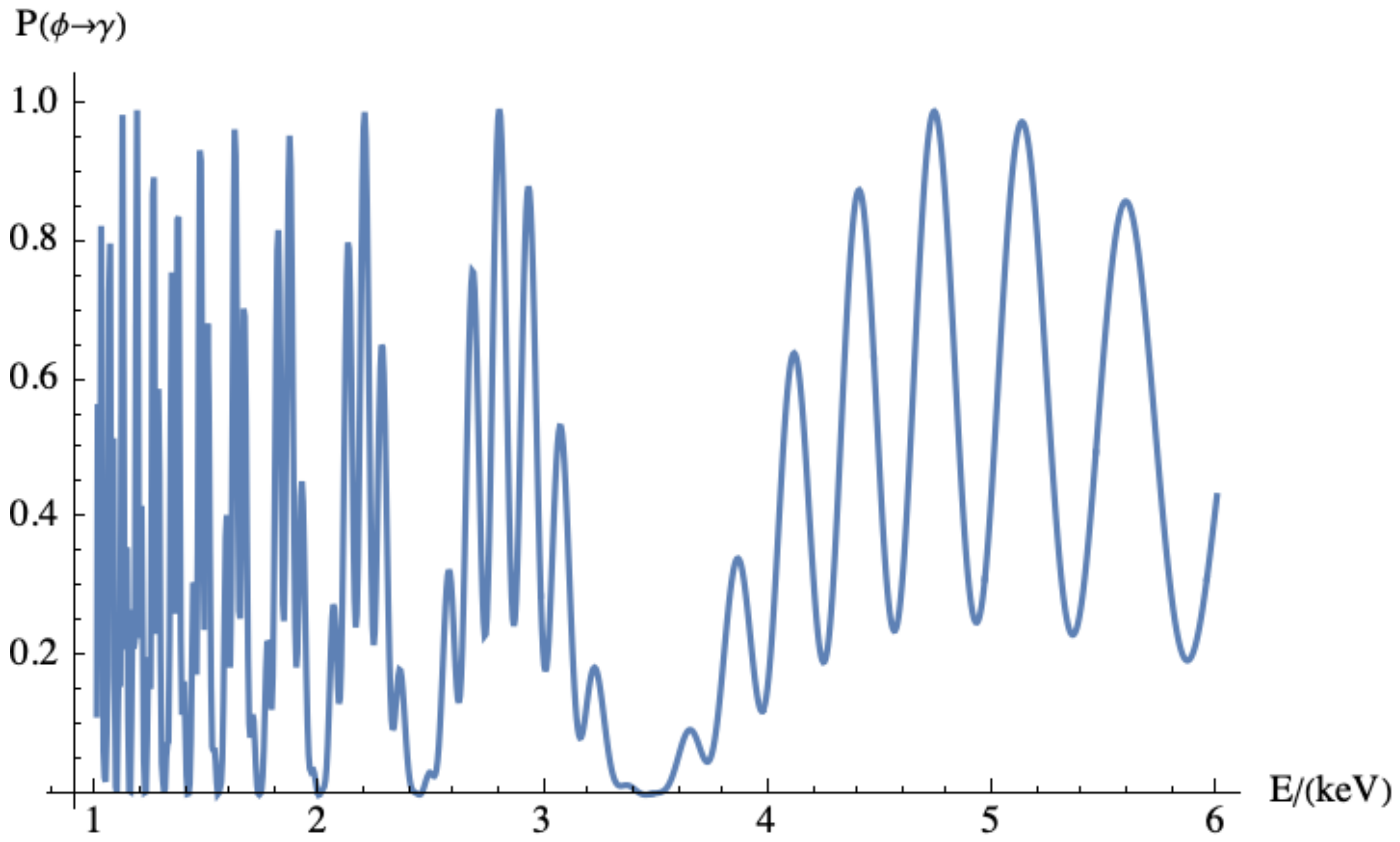
Detection

$$P_{2\mathrm{ALPs}}(\phi \to \gamma) = P_{1\mathrm{ALP}}(\phi \to \gamma) \, . \, P_{\phi_\gamma \to \phi_h}(L)$$

Mass basis calculations



1 ALP

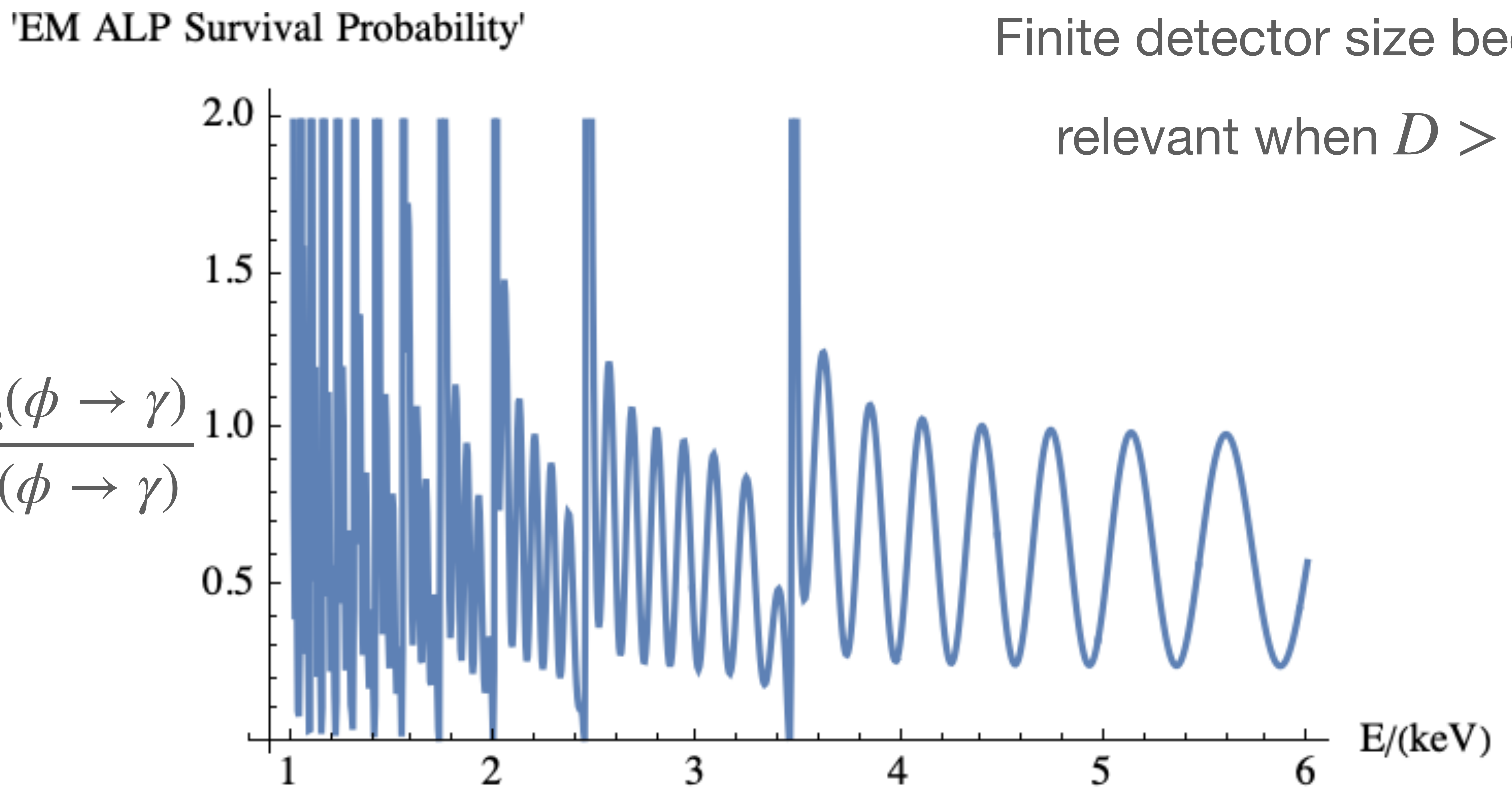


2 ALPs

Single domain with $m_i \ll \omega_{pl}$ and $D \sim \dfrac{E}{m^2}$

Mass basis calculations

$$P_{\phi_\gamma \to \phi_h}(L) = \frac{P_{2\mathrm{ALPs}}(\phi \to \gamma)}{P_{1\mathrm{ALP}}(\phi \to \gamma)}$$



Finite detector size becomes relevant when $D > \frac{E}{m^2}$

Cannot use flavour oscillations picture

Consistent with flavour oscillations picture

Oscillation Probability

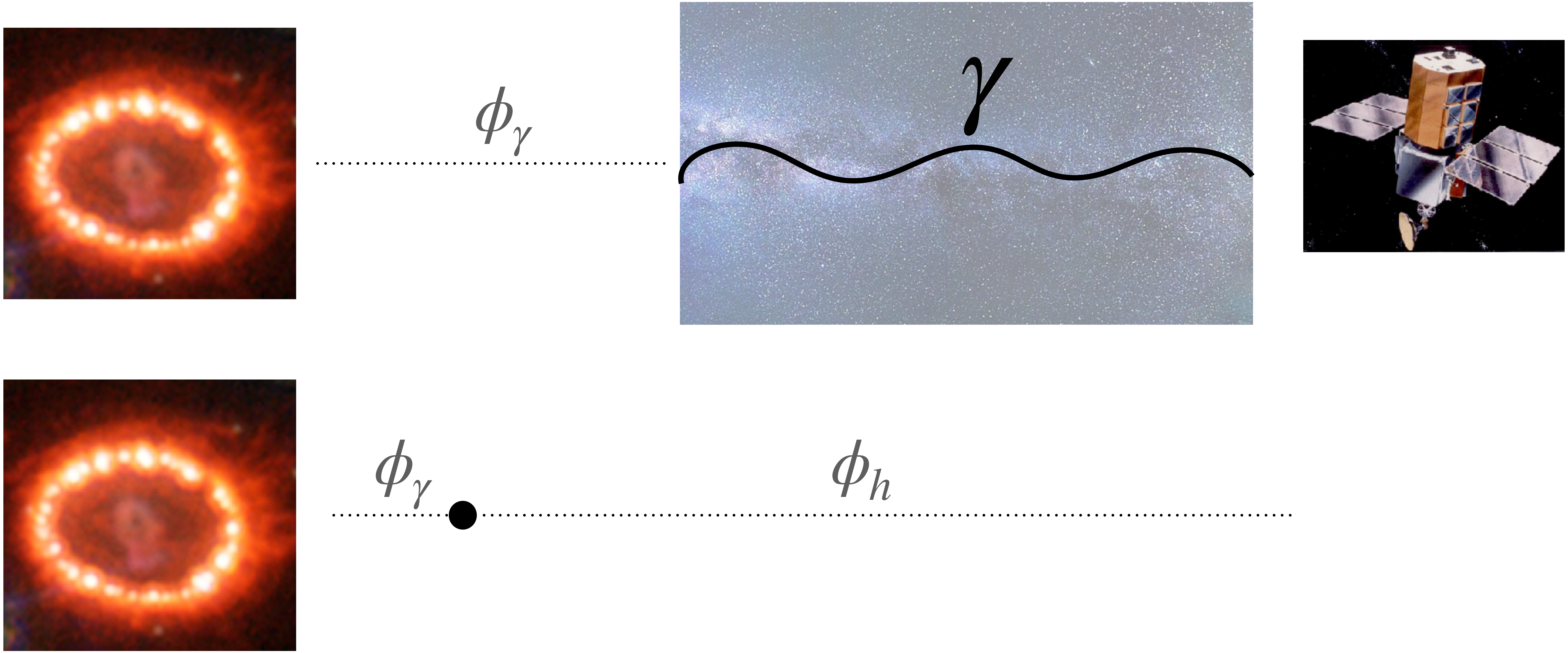
For $D < \dfrac{E}{m^2}$, the detector is effectively point-like and can use neutrino-like oscillation theory

Example: CAST evacuated bore operation

$$E \sim \mathrm{keV}$$
$$m < 10^{-2}\mathrm{eV}$$

$$\frac{E}{m_{\mathrm{max}}^2} \sim 1\,\mathrm{m}$$
$$D \sim 10\,\mathrm{m}$$

Example: SN 1987A



Oscillation Probability

For $D < \dfrac{E}{m^2}$, the detector is effectively point-like and can use neutrino-like oscillation theory

Example: SN1987A

$$E \sim 100\,\mathrm{MeV}$$
$$m < 10^{-8}\mathrm{eV}$$

$$\frac{E}{m_{\mathrm{max}}^2} \sim 10^{18}\,\mathrm{m}$$

$$\text{Milky Way} \sim 10^{20}\,\mathrm{m}$$

Summary

- String theory suggests there are a handful of ALPs with significant couplings to the SM
- Several ALPs $\neq$ one ALP with equivalent total coupling
- ALPs are not neutrinos - we expect new kinds of oscillation physics

Unruh-DeWitt detectors

$$S = -\lambda \int \mathrm{d}\tau\, \chi(\tau) \left[\hat{\sigma}^{+}(\tau)\hat{\phi}(\mathrm{x}(\tau)) + \hat{\sigma}^{-}(\tau)\hat{\phi}(\mathrm{x}(\tau)) \right]$$

Smeared Detector:

$$S = -\lambda \int d^3\mathbf{x} \int \mathrm{d}\tau\, \chi(\tau) \left[F(\mathbf{x})\hat{\sigma}^{+}(\tau)\hat{\phi}(\mathrm{x}(\tau), \mathbf{x}) + F^{*}(\mathbf{x})\hat{\sigma}^{-}(\tau)\hat{\phi}(\mathrm{x}(\tau), \mathbf{x}) \right]$$

Unruh-DeWitt Detectors

Our UDW source and detector couple to the electromagnetic ALP state:

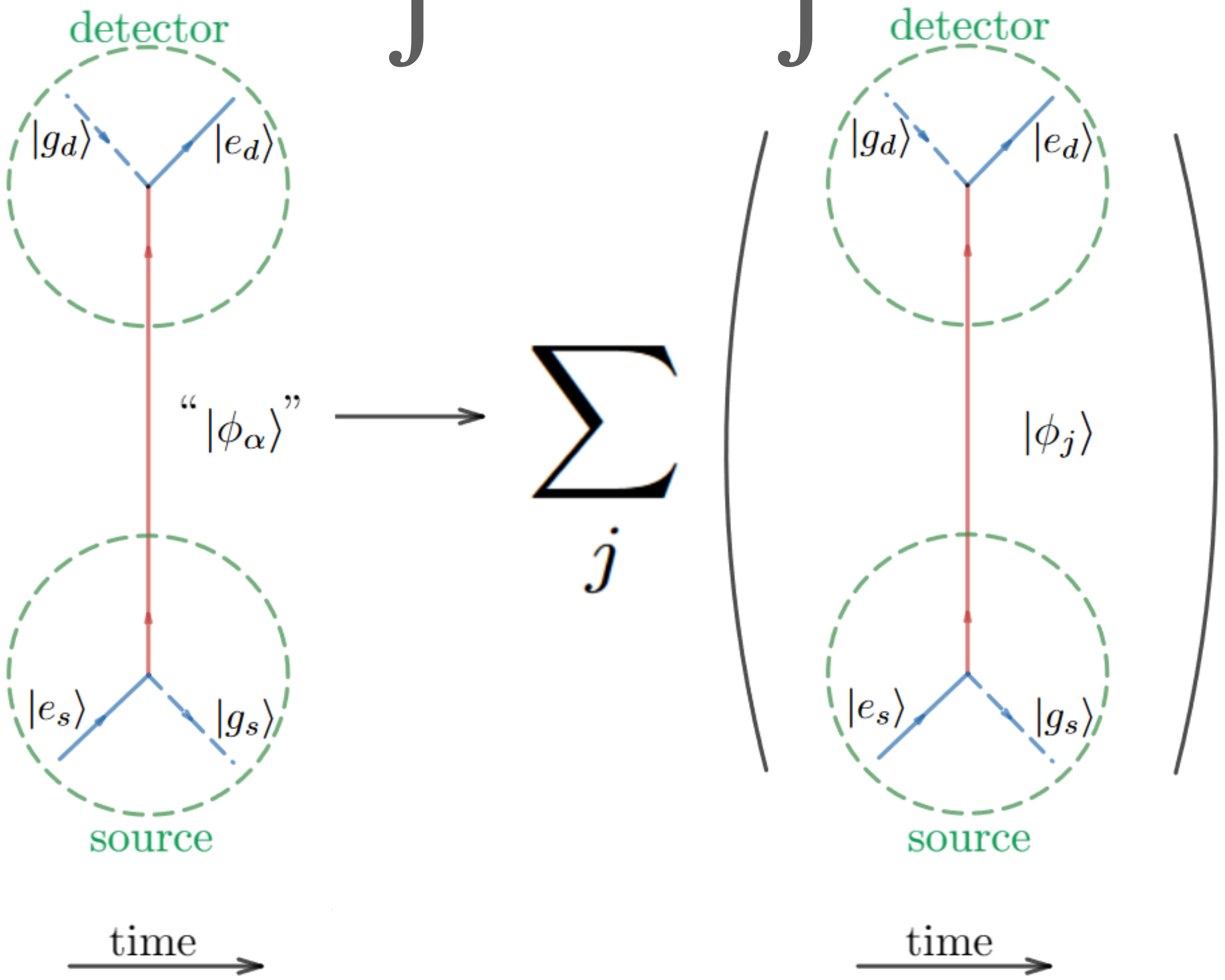
$$\hat{H}_I(t) = \underbrace{\lambda_s \chi_s(t) F_s(\mathbf{x}) \hat{\sigma}_s^-(t) \hat{\phi}_\gamma\left(\mathrm{x}_s\right) + \text{ h.c.}}_{=\hat{H}_s\left(\mathrm{x}_s\right)}$$

$$+\underbrace{\lambda_d \chi_d(t) F_d(\mathbf{x} - \mathbf{L}) \hat{\sigma}_d^-(t) \hat{\phi}_\gamma\left(\mathrm{x}_d\right) + \text{ h.c.}}_{=\hat{H}_d\left(\mathrm{x}_d\right)}$$

Oscillation Amplitude

$$\mathcal{A}_{\gamma\to\gamma} = \langle f | \mathcal{T} \exp\left(\mathrm{i}S\right) | i\rangle$$

$$= -\int \mathrm{d}t\, d^3\mathbf{x} \int \mathrm{d}t' d^3\mathbf{x}' \langle f | \hat{H}_s(t)\hat{H}_d(t') + \hat{H}_d(t)\hat{H}_s(t') | i\rangle + \mathcal{O}(\lambda^3)$$



$$|i\rangle = |0\rangle \left|e_s\right\rangle \left|g_d\right\rangle$$

$$|f\rangle = |0\rangle \left|g_s\right\rangle \left|e_d\right\rangle$$

Oscillation Amplitude

Evaluate using:

$$\langle 0 \,|\, \phi_j(x)\phi_k\,(x')\,|\,0\rangle = \delta_{jk}\int \frac{\mathrm{d}^3 p_j}{16\pi^3\omega_j(\boldsymbol{p})} e^{-\mathrm{i}p_j\cdot(x-x')}$$

$$|\,\phi_i^{\mathrm{mass}}\rangle = U^{\gamma}_{\alpha i}\,|\,\phi_\alpha^{\mathrm{EM}}\rangle$$

Oscillation probability

Assume detector switched in for some finite time interval:

$$\chi_s(t) = e^{-\epsilon|t|}, \quad \chi_d(t) = \Theta\left(t - t_0\right) - \Theta\left(t - t_1\right)$$

$$\Delta t \equiv t_1 - t_0 > 0$$

Detector excitation rate for arbitrarily long detector times:

$$\Gamma_{\gamma\to\gamma} \equiv \lim_{\Delta t\to+\infty} \frac{\left|\mathscr{A}_{\gamma\to\gamma}\right|^2}{\Delta t}$$

Oscillation Probability

$$P_{\gamma\to\gamma} = \frac{\Gamma_{\gamma\to\gamma}}{\sum_\alpha \Gamma_{\gamma\to\alpha}} = \frac{\left| \int d^3\mathbf{x} d^3\mathbf{x}' \sum_j U_{\gamma j} U_{\gamma j} e^{\mathrm{i}\frac{m_j^2 |\mathbf{x}-\mathbf{x}'|}{2E}} F_s(\mathbf{x}) F_d(\mathbf{x}'-\mathbf{L}) \right|^2}{N}$$

Oscillation Probability

For a point-like source and a step function detector of size D:

$$P_{\gamma\to\gamma} = \frac{\Gamma_{\gamma\to\gamma}}{\sum_\alpha \Gamma_{\gamma\to\alpha}} = \frac{\sum_{i,j} U_{\gamma i}^2 U_{\gamma j}^{*2} e^{\frac{iL}{2E}(m_i^2 - m_j^2)} \frac{4E}{m_i^2 D} \frac{4E}{m_j^2 D} \sin\frac{m_i^2 D}{4E} \sin\frac{m_j^2 D}{4E}}{\sum_i U_{\gamma i} U_{\gamma i}^* \left(\frac{4E}{m_i^2 D}\right)^2 \sin^2\frac{m_i^2 D}{4E}}$$