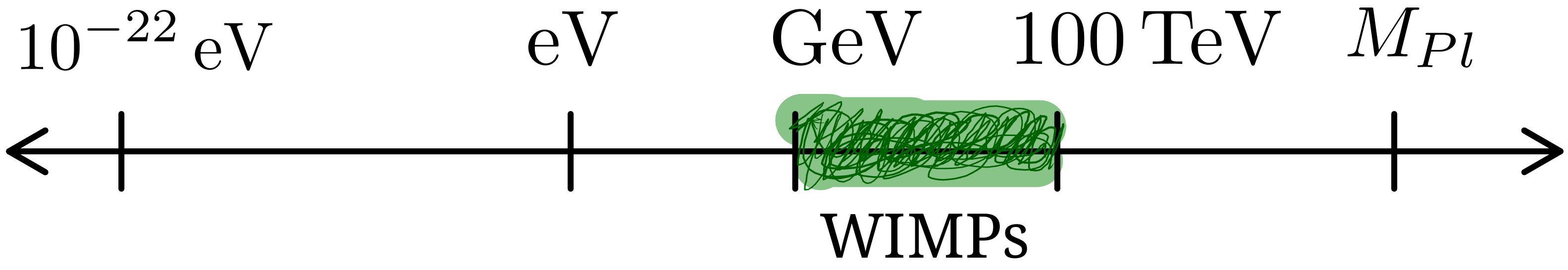
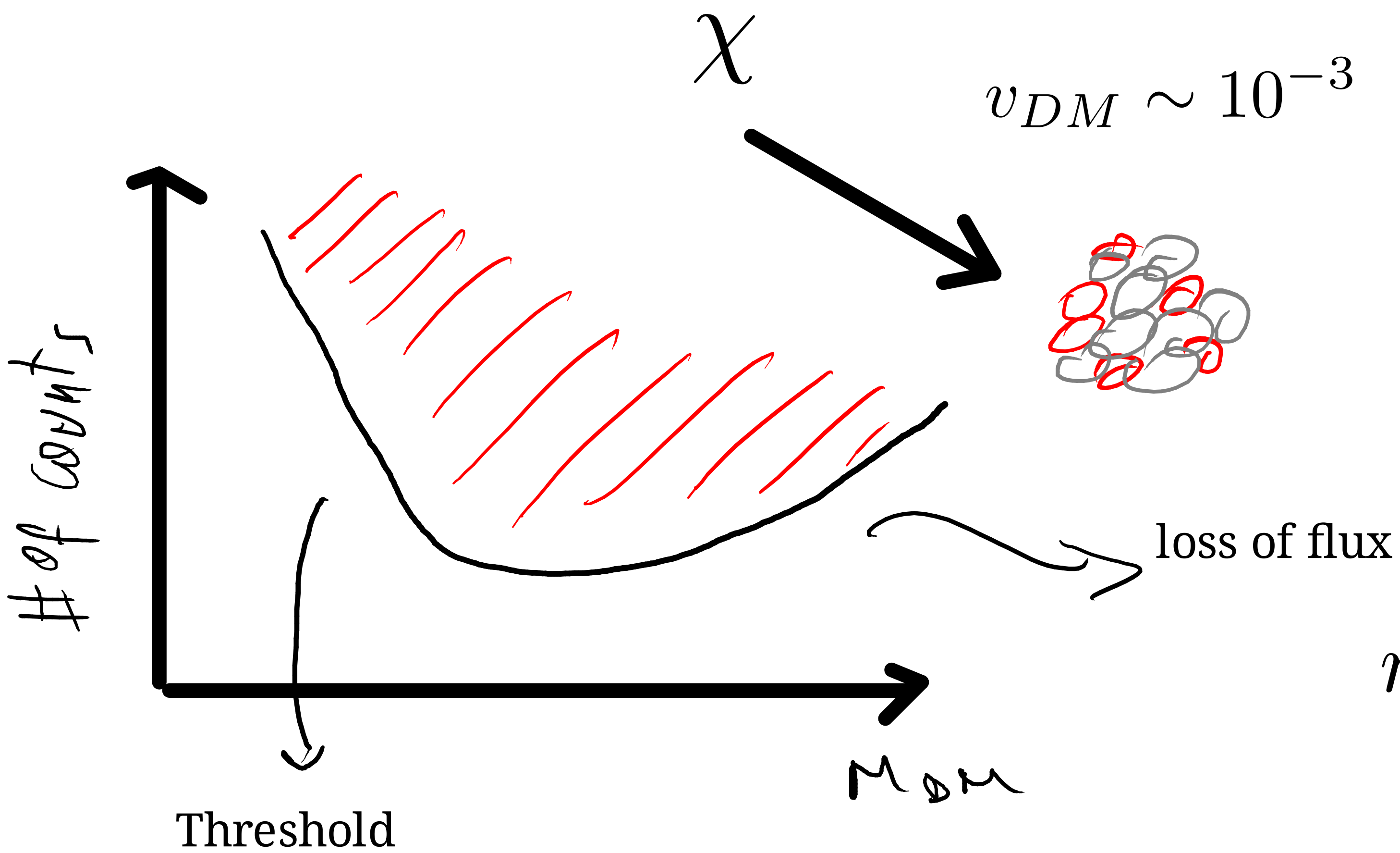
Neutrino backgrounds in matter-wave interferometry

Joao Paulo Pinheiro
TDLI

Based on 2510.00142

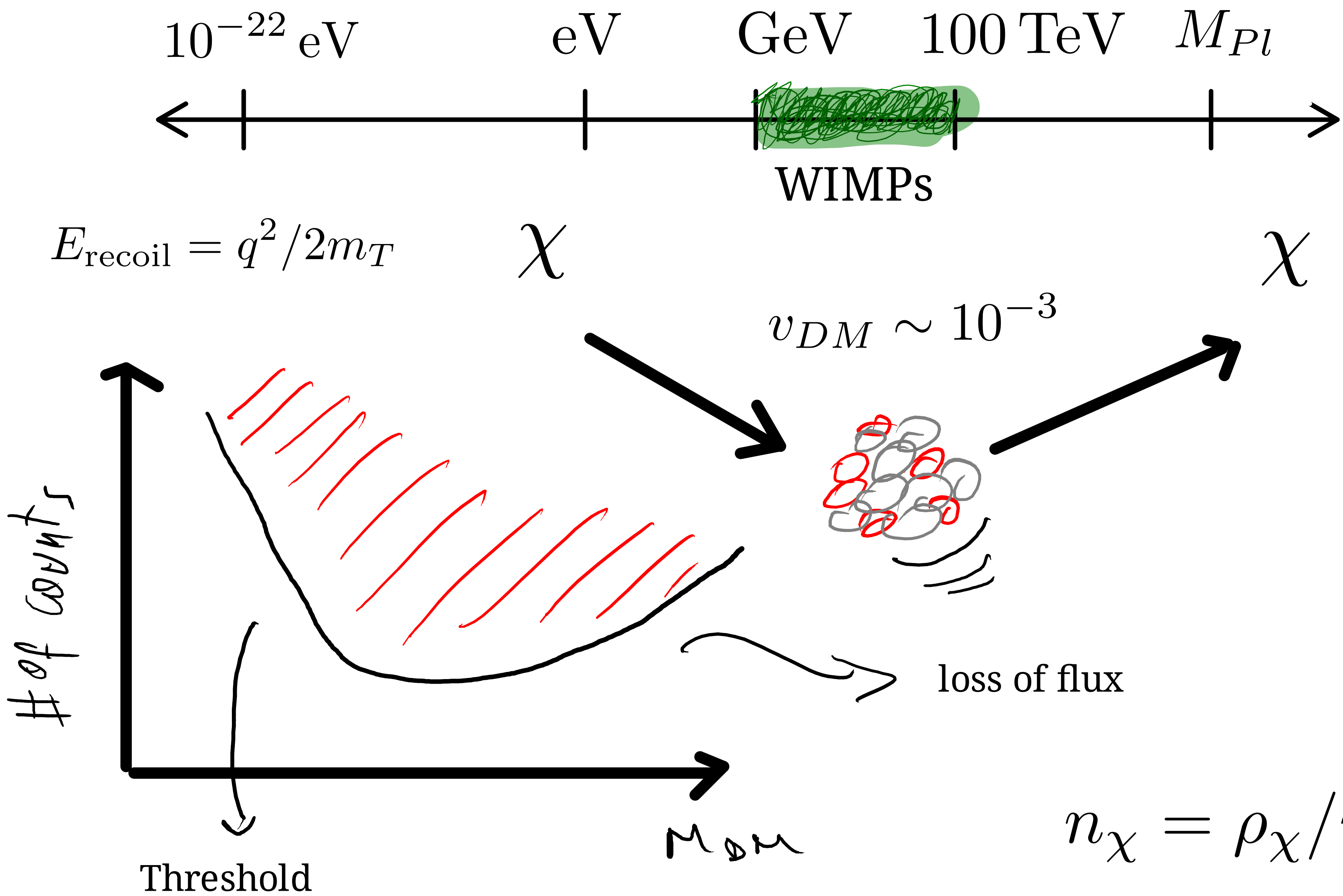
WIMP Miracle(?)





$$n_\chi = \rho_\chi / m_\chi$$

WIMP Miracle(?)



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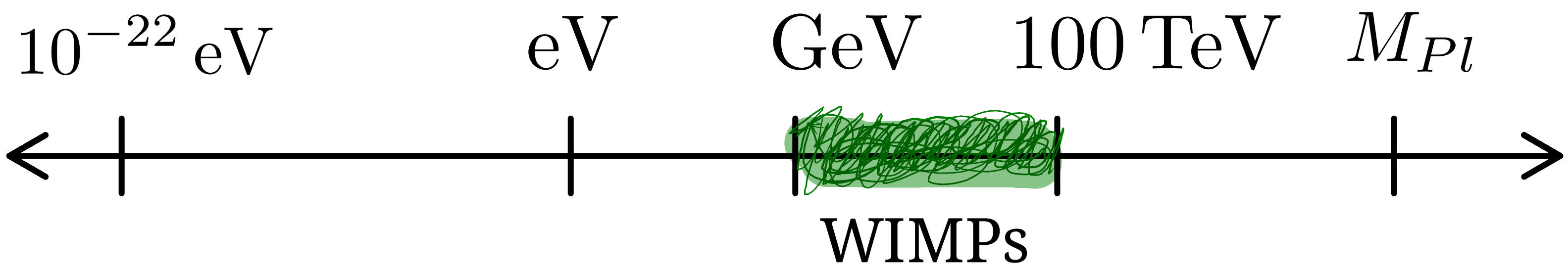
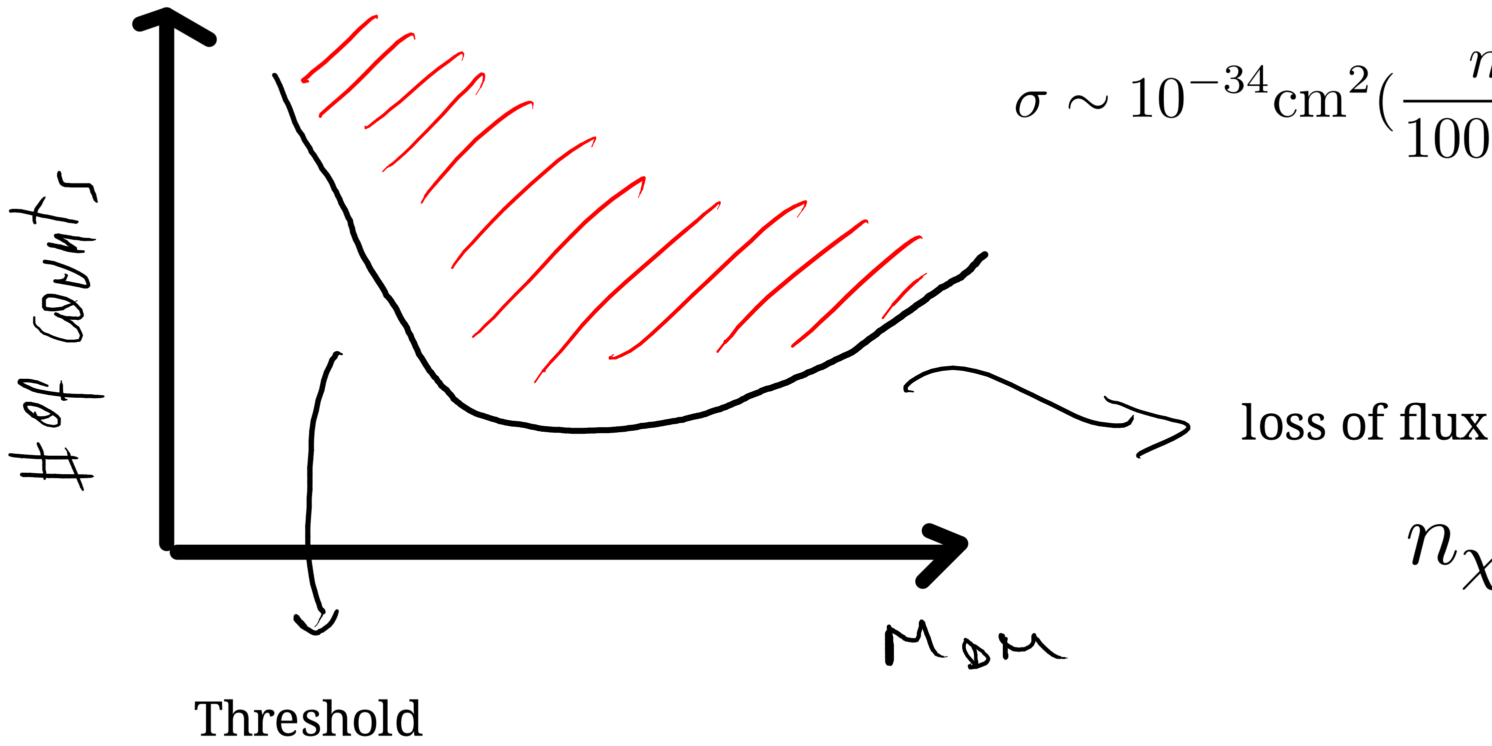
WIMP Miracle(?)



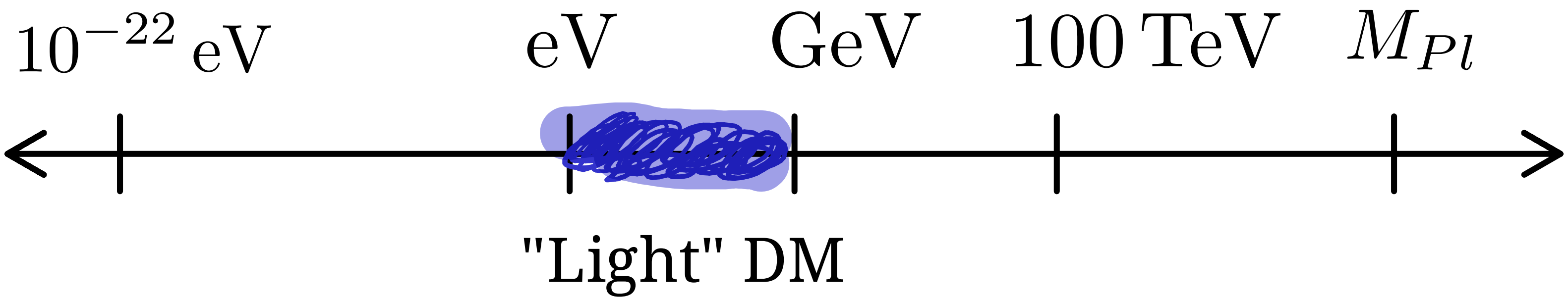
$E_{\rm recoil}^{\rm max} \sim (\frac{m_\chi}{\rm GeV})\rm keV$ → few keV

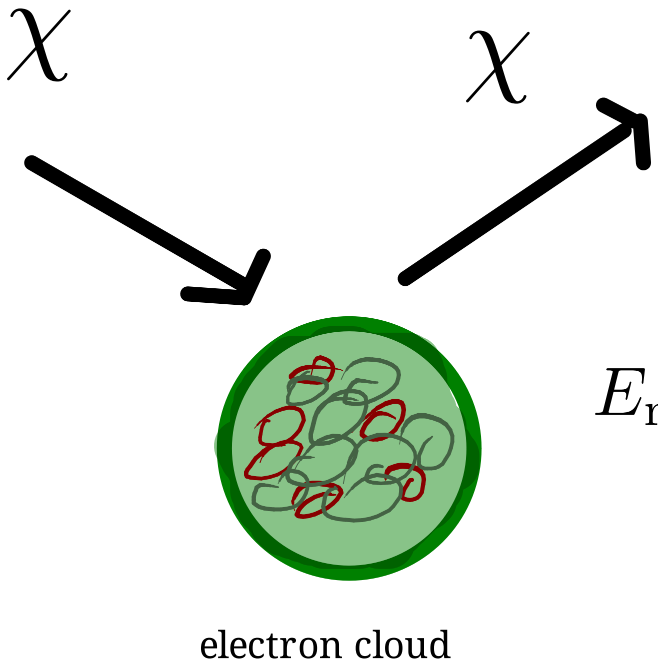
$\sigma \sim 10^{-34}{\rm cm}^2(\frac{m_\chi}{100\,{\rm GeV}})^2$



$$n_\chi = \rho_\chi / m_\chi$$

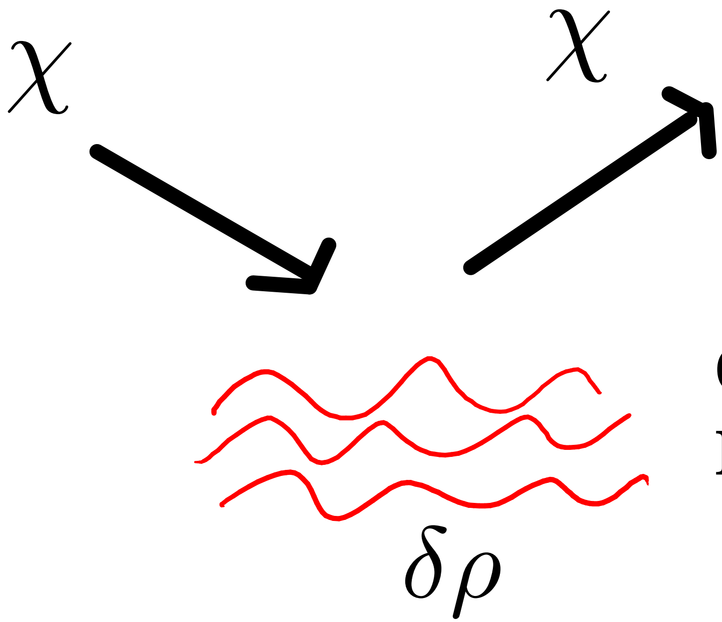
Hunting light DM





$$E_{\text{recoil}} = \frac{q^2}{2m_e}$$

Ionization

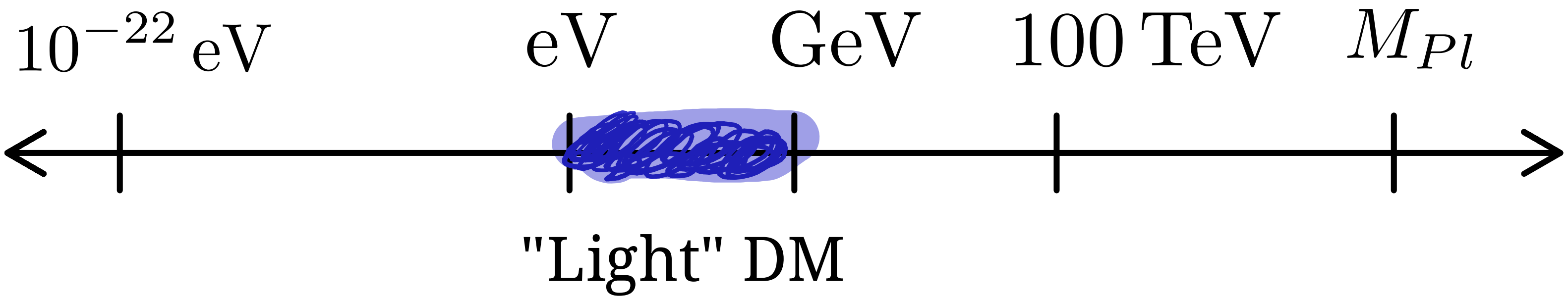


Colective Excitations

$\text{MeV} - \text{GeV}$

$\text{eV} - \text{MeV}$

Hunting light DM



ATOM INTERFEROMETERS

NO minimum energy deposition

Direct detection of classically undetectable dark matter through quantum decoherence
C Jess Riedel, 1212.3061

Decoherence as a way to measure extremely soft collisions with dark matter
Riedel and Yavin, 1609.04145

Atom interferometer tests of DM
Du, Murgui, Pardo, Wang and Zurek
2205.13546

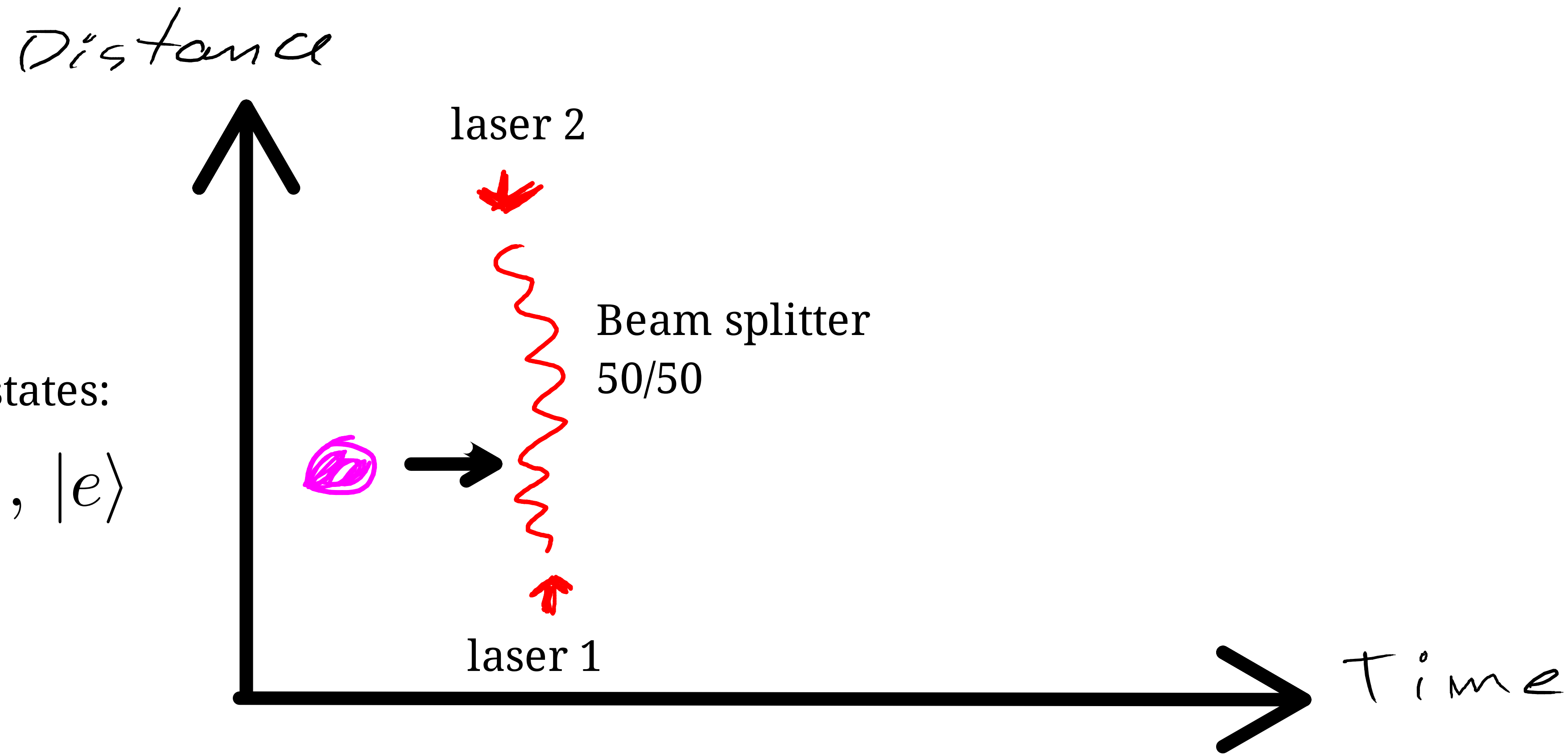
AI: Principle

2 states:

$|g\rangle, \; |e\rangle$

$|\Psi\rangle_0 = |g\rangle$

AI: Principle

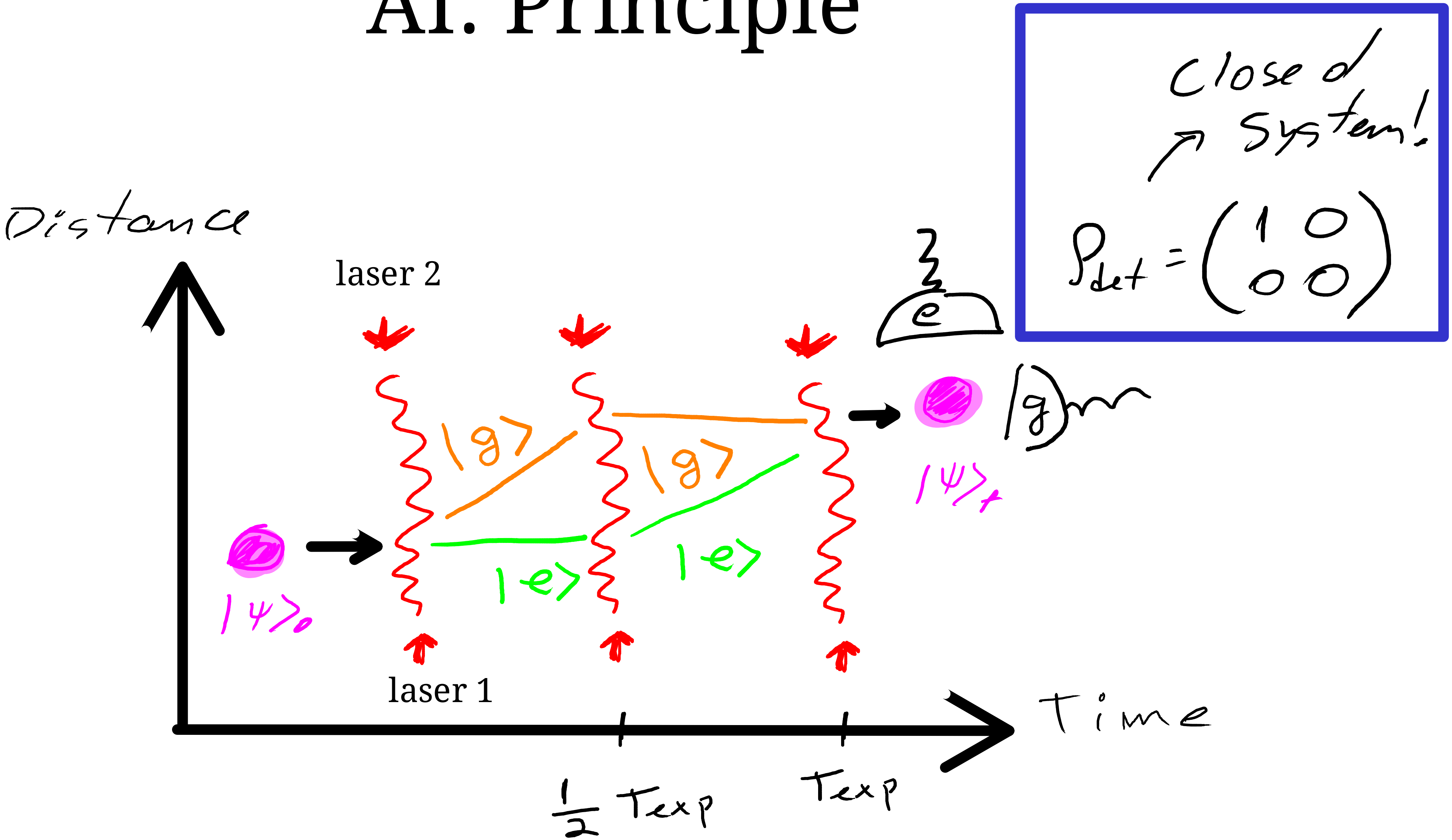


2 states:

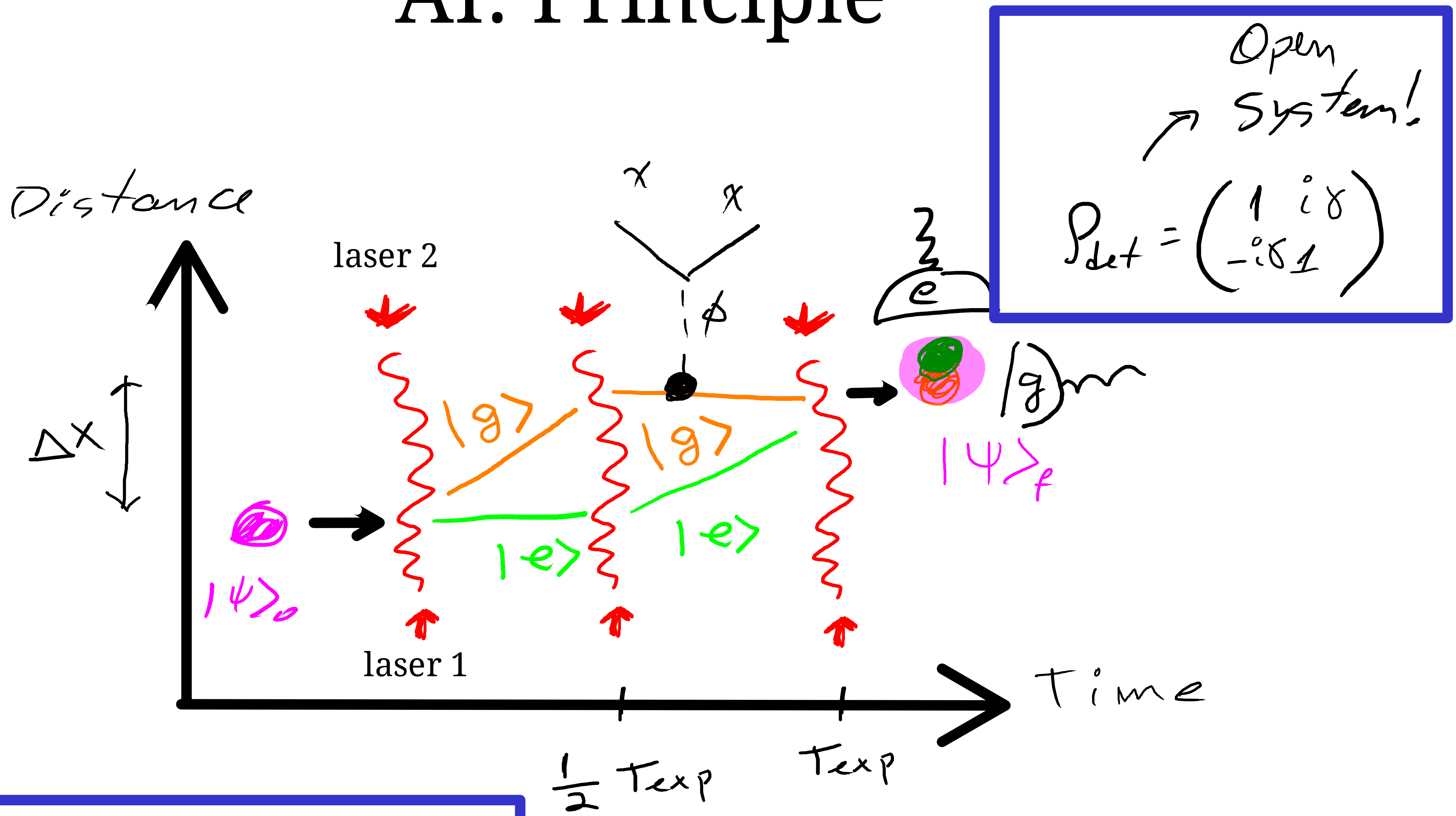
$$|g\rangle,\ |e\rangle$$

$$|\Psi\rangle_0 = |g\rangle \rightarrow |\Psi\rangle_{t_1} = \cos(\pi/4)|g\rangle + i\sin(\pi/4)|e\rangle$$

AI: Principle

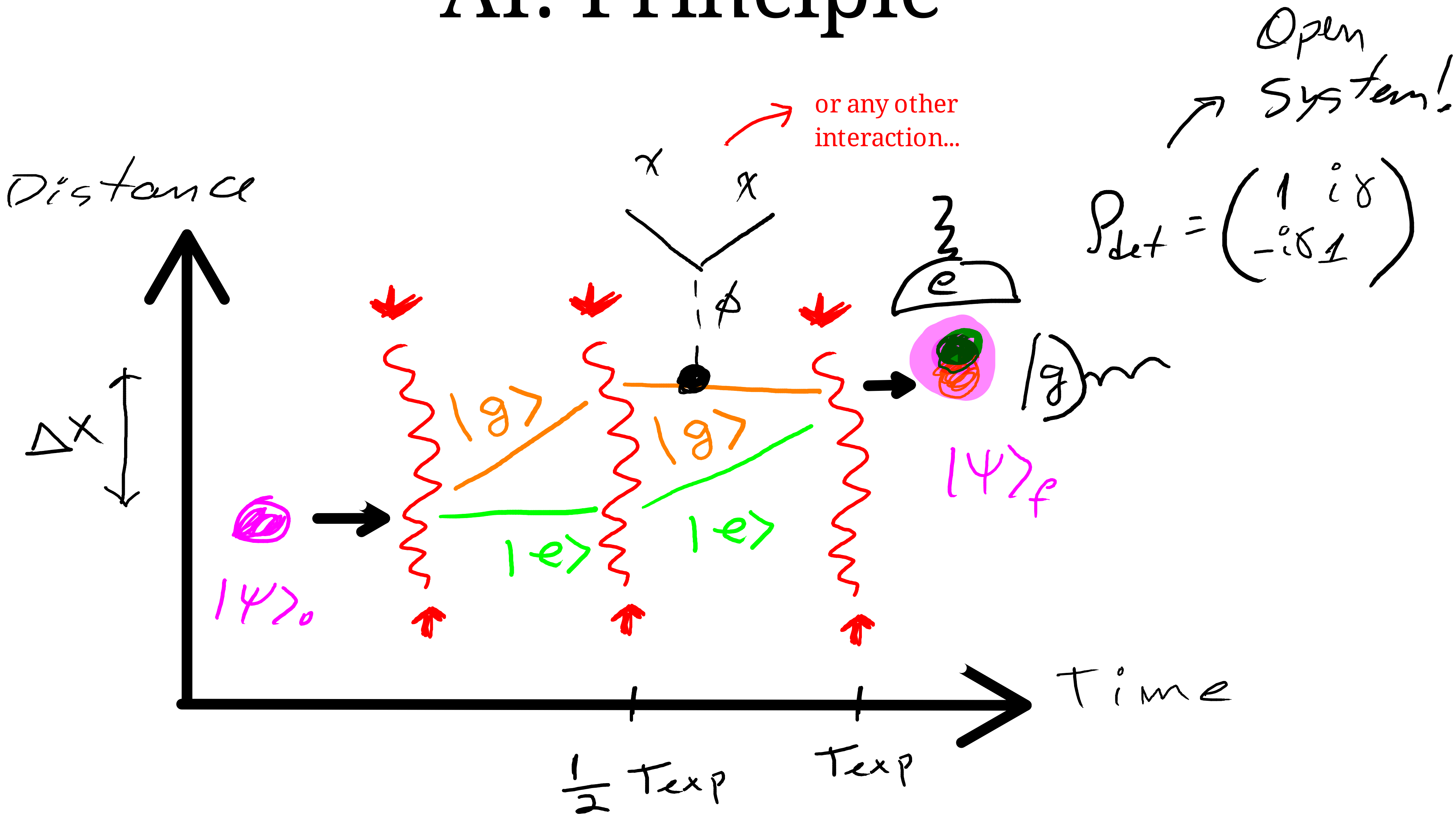


AI: Principle



$$\gamma = e^{-s+i\phi} = e^{-s} e^{i\phi}$$

AI: Principle



$$\gamma = e^{-s+i\phi} = e^{-s} e^{i\phi}$$

Phase shift

Overall decoherence

AI: Principle

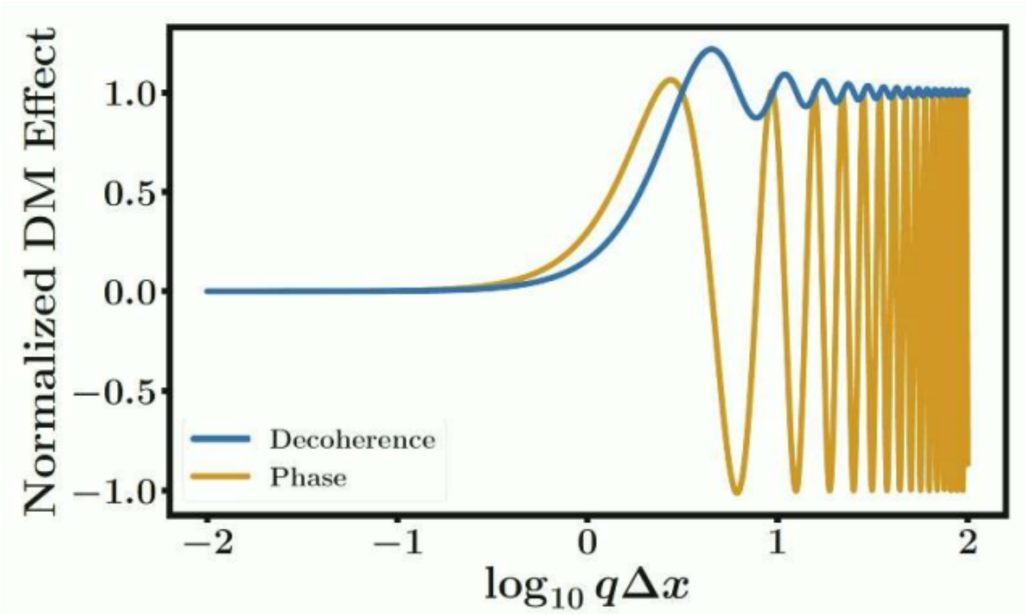
Overall decohence/ Visibility (V)

$$\frac{1}{2}\int_{-1}^{1} \mathrm{Re}[\mathcal{F}_{\mathrm{decoh}}(\mathbf{q})]\, d\cos\theta_{q\cdot\Delta x} = 1 - \sin(q\Delta x)/(q\Delta x)$$

Colisional overall decoherence
persists in isotropic enviroment

Form Factor

$$\mathcal{F}_{\mathrm{decoh}}(\mathbf{q}) = 1 - \exp(i\mathbf{q}\cdot\mathbf{\Delta x})$$



Phase shift

$$\frac{1}{2}\int_{-1}^{1} \mathrm{Im}[\mathcal{F}_{\mathrm{decoh}}(\mathbf{q})]\, d\cos\theta_{q\cdot\Delta x} = 0$$

Colisional phase shift decoherence
is null in isotropic enviroment

Any effect is proportional
to the anisotropies

AI: the Rate

For DM: $$R = \frac{n_\chi}{m_T} \int d^3\mathbf{v} f(\mathbf{v}) \Gamma(\mathbf{v}) \mathcal{F}_{\rm decoh}(\mathbf{q})$$

AI: the Rate

There is not a threshold

It only depends on the Rate

For DM: $$R = \frac{n_\chi}{m_T}\int d^3\mathbf{v}\, f(\mathbf{v})\Gamma(\mathbf{v})\mathcal{F}_{\rm decoh}(\mathbf{q})$$

Rate

Flux of DM

Interaction

Decoherence

Sources of Background:

Electromagnetic: 1109.5937,2102.00992 (Hornberger et al)

Gravitational waves: 1704.00120 Marletto and Vedral

Gaseous collision: 0402146, (Hornberger et al)
Phys.Rev.A 42 (1990) (Gallis and Fleming)

What about Neutrinos?

Main questions:

Cosmic flux of neutrinos could be a source of background for the detection of light DM?

What is the sensitivity of atom interferometers to new physics in the neutrino sector?

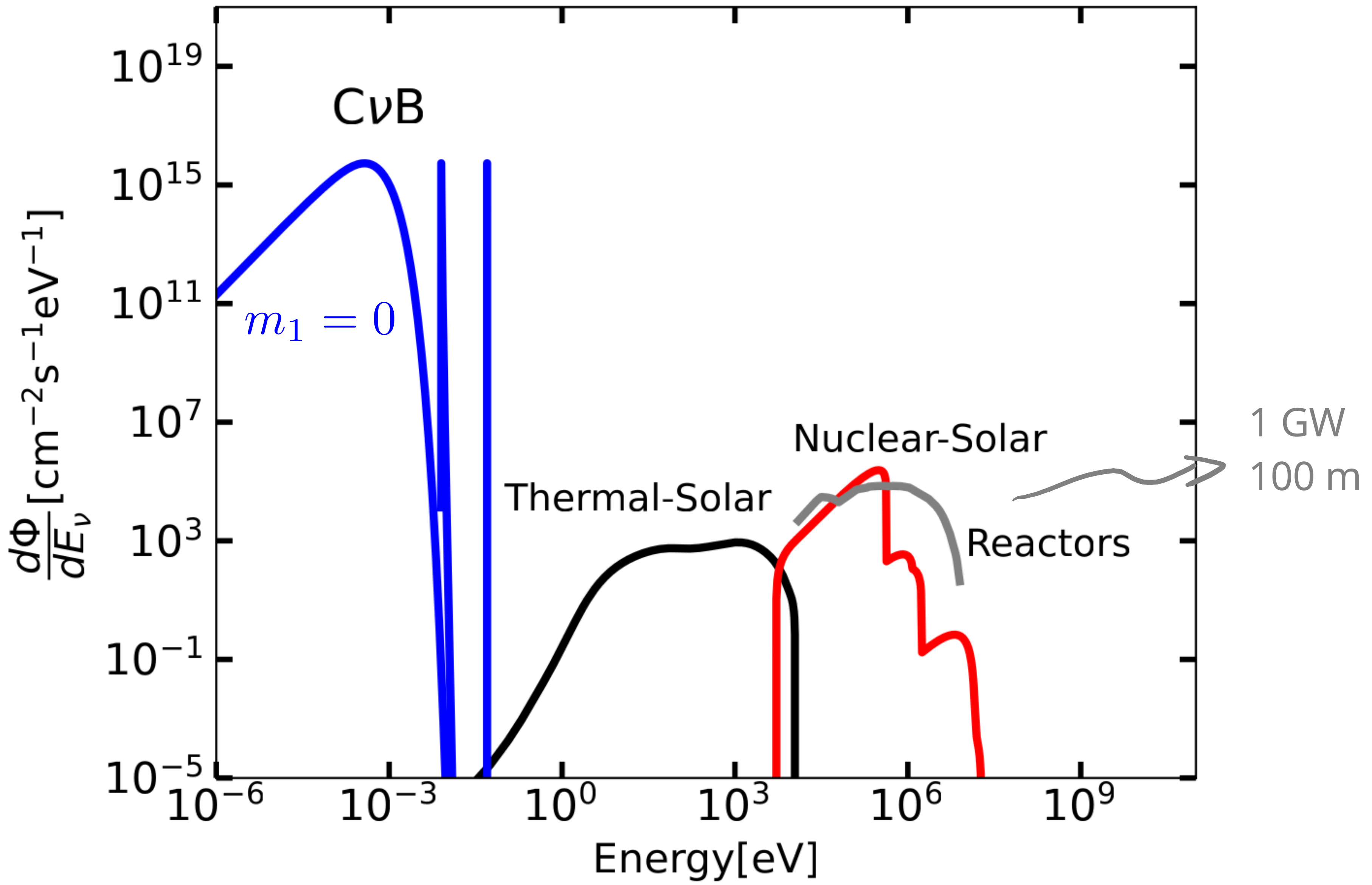
Neutrino backgrounds in matter-wave interferometry: implications for dark matter searches and beyond-Standard Model physics

João Paulo Pinheiro[1,*]

2510.00142

Already accepted in JHEP!

Low energy Neutrino flux



AI: the Rate

TOTAL RATE →

$$R = \sum_i \int \left(\frac{d\Phi_\nu}{dE_\nu}\right) \left(N_i \, d\sigma_{\nu,i}\right) \left(p_{\rm decoh}\right) dE_\nu$$

FLUX

SCATTERING TARGETS

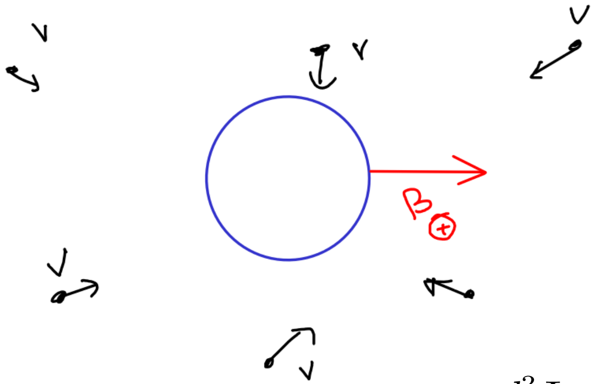
DECOHERENCE PROBABILITY

-Neutrinos are almost massless and have a broad flux with different sources, with different energy distribution and directionality;

-Neutrinos can hit incoherently the electrons (refining the analysis of 2205.13546);

FLUX

$C\nu B$



$$R = \sum_{i=1}^{3} \int \frac{d^3\Phi_\nu}{dE_\nu d\cos\theta_\nu d\phi_\nu} N_i \, d\sigma_{\nu,i}(M_i, p_\nu) \, p_{\rm decoh} \, dE_\nu d\cos\theta_\nu d\phi_\nu$$

CvB neutrinos in Earth ref.

$$\frac{d^3\Phi_\nu}{d\cos\theta_\nu d\phi_\nu dE_\nu} = \frac{1}{(2\pi)^3} \frac{|\mathbf{p}_\nu|^2 + \beta_\oplus E_\nu |\mathbf{p}_\nu| \cos\theta_\nu}{\exp(\sqrt{|\mathbf{p}_\nu|^2 + 2\beta_\oplus E_\nu |\mathbf{p}_\nu| \cos\theta_\nu}/T_{\nu,0}) + 1} \simeq$$

$$\frac{1}{(2\pi)^3} \frac{|\mathbf{p}_\nu|^2}{\exp(|\mathbf{p}_\nu|/T_{\nu,0}) + 1} \times \left[1 + \beta_\oplus \cos\theta_\nu E_\nu \frac{1 - \exp(-|\mathbf{p}_\nu|/T_{\nu,0})(|\mathbf{p}_\nu|/T_{\nu,0} - 1)}{|\mathbf{p}_\nu|(\exp(|\mathbf{p}_\nu|/T_{\nu,0}) + 1)}\right].$$

Dipole correction

-Very low energies;
-In principle, isotropic, reducing effects on phase shifts, corrected by the speed of the Earth relative to the CMB frame;
-Solar and Reactor are fixed in direction, depending in energy only;

SCATTERING TARGETS

a) Incoherent scattering of the neutrinos with neutrons,protons and electrons

$$d\sigma_{\nu,1} = N_A \left[g_p^2 \frac{Z}{A} d\sigma_{\nu,\text{fund}}(M_N, p_\nu) + g_n^2 \frac{A-Z}{A} d\sigma_{\nu,\text{fund}}(M_N, p_\nu) \quad + g_e^2 \frac{Z}{A} d\sigma_{\nu,\text{fund}} \right.$$
$$(1 - |F_{\text{min}}(|\mathbf{q}|r_{\text{min}})|^2)$$

Preventing double couting with the coherent regime

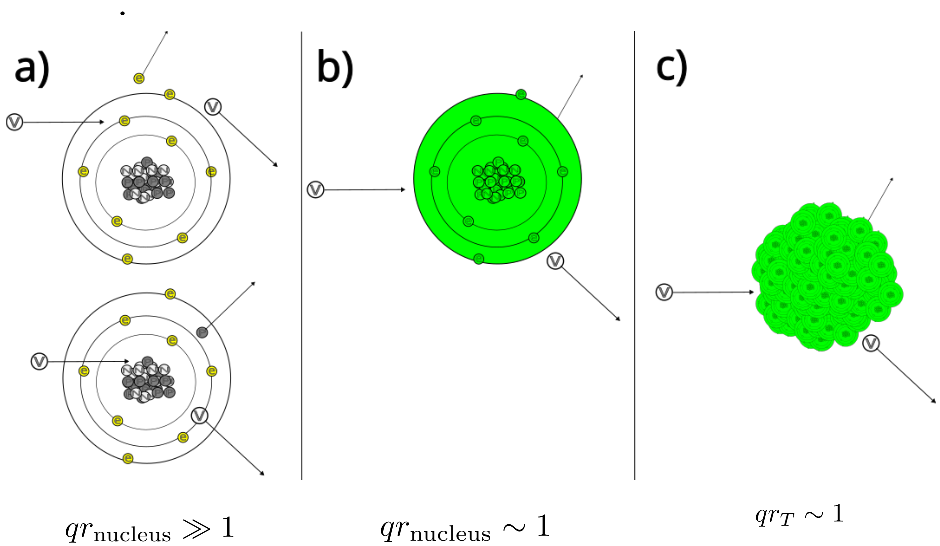
b) Coherent nucleus and atomic scattering

$$d\sigma_{\nu,2} = N_A(Zg_p + (A-Z)g_n)^2 |F_{\text{nuc}}(|\mathbf{q}|r_{\text{nuc}})|^2 \times \left[1 - |F_{\text{atom}}(|\mathbf{q}|r_{\text{atom}})|^2\right] d\sigma_{\nu,\text{fund}}(M_{\text{nuc}}, p_\nu) + N_A(Z(g_e + g_p) + (A-Z)g_n)^2 |F_{\text{atom}}(|\mathbf{q}|r_{\text{atom}})|^2 \times \left[1 - |F_T(|\mathbf{q}|r_T)|^2\right] d\sigma_{\nu,\text{fund}}(M_{\text{atom}}, p_\nu).$$

$$F_{\text{nuc}}(|\mathbf{q}|r) = \frac{3j_1(|\mathbf{q}|r)}{|\mathbf{q}|r} \exp\left(-\frac{|\mathbf{q}|^2 s_p^2}{2}\right) \qquad F_{\text{atom}}(|\mathbf{q}|r) = \exp(-r^2|\mathbf{q}|^2/2)$$

b) Macroscopic coherent scattering

$$d\sigma_{\nu,3} = N_A^2 [Z(g_e + g_p) + (A-Z)g_n]^2 |F_T(|\mathbf{q}|r_T)|^2 d\sigma_{\nu,\text{fund}}(M_T, p_\nu)$$



Z and Z' exchange

If the target size is huge, there is a possibility for coherent scattering with the full cloud of atoms at very low momentum transfer

$$F_T(|\mathbf{q}|r) = \frac{3j_1(|\mathbf{q}|r)}{|\mathbf{q}|r}$$

Sensitivity

Exp	Tgt	r_{tgt}[m]	N_{nuc}	Δx[m]	t_{exp}[s]	σ_ϕ[rad]
MAQRO	SiO_2	1.2×10^{-7}	10^{10}	10^{-7}	100	1.0
Pino	Nb	10^{-6}	2.2×10^{13}	2.9×10^{-7}	0.483	1.0

Not suitable for CvB

Coherent effect with the hole target would enhance the cross section by N_{nuc}^2

$$\frac{(X - X_{\mathrm{bkg}})^2}{(\sigma_X^T)^2} = 1$$

ϕ

An AI has sensitivity to a given neutrino interaction when the estimated signal is larger than the expected noise

$$\sigma_X^T = \frac{\sigma_X}{\sqrt{N_{\mathrm{meas}}}} = \sigma_X \sqrt{\frac{t_{\mathrm{exp}}}{t_{\mathrm{tot}}}} = 1.2 \times 10^{-3}\ (1.2 \times 10^{-4})\ \text{ per } \sqrt{\mathrm{yr}} \text{ at MAQRO (Pino)}$$

The noise for each observable over the full running time which we will assume to be one year

Results

SM predictions

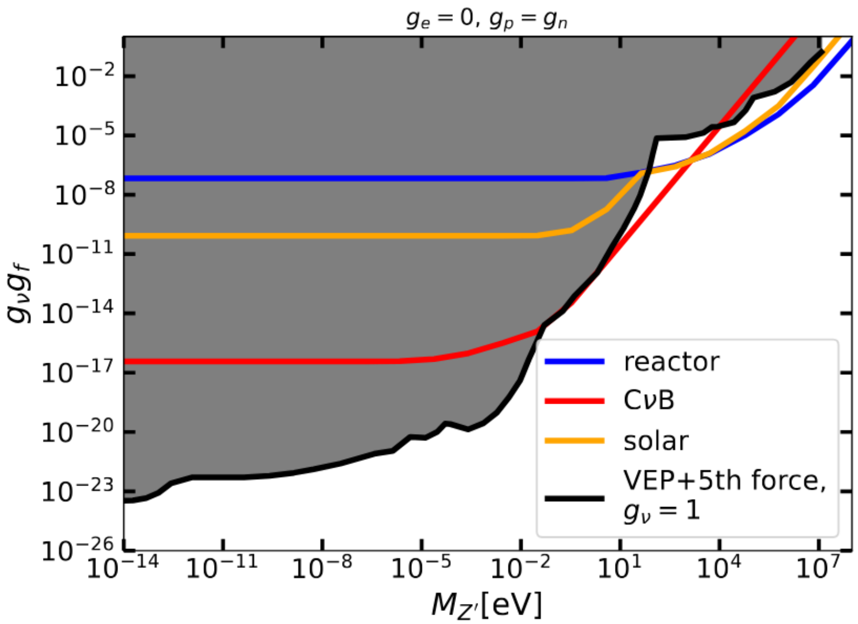
Neutrino Source	Pino	MAQRO
Cosmic neutrino background	1.3×10^{-22}	3.7×10^{-27}
Solar neutrinos	6.4×10^{-17}	2.2×10^{-19}
Reactor neutrinos (100 m)	5.0×10^{-15}	1.7×10^{-17}

BSM predictions

$$\mathcal{L}_V = -\sum_{i=\nu,n,p,e} g_i \overline{\psi}_i \gamma^\mu \psi_i Z'_\mu + \frac{1}{2} M_{Z'}^2 Z'^\mu Z'_\mu$$

neutrinophilic Z', for which the couplings to neutrinos are order 1, while the couplings to nucleons are suppressed

$$\frac{d\sigma_{\nu,\mathrm{tgt}}}{dT} = \frac{g_\nu^2}{2\pi} \frac{M}{(2MT + M_{Z'}^2)^2} \left[1 - \frac{MT}{2E_\nu^2}\left(1 + \frac{m_\nu^2}{M^2}\right) + \frac{T}{2E_\nu}\left(\frac{T}{E_\nu} - 2\right)\right]$$



Conclusion

- Matter interferometers can provide threshold-free bounds on light/ultralight DM observing the decoherence patterns;

- If standard neutrinos are considered, specifically for the proposed experimen-ts, MAQRO and Pino, their background for light-DM is marginal;

- It is possible to look for ultralight mediators for nu-N interactions by using matter interferometers;

Thanks!