
Vector Dark Matter Signals from Neutrino - antineutrino Conversion

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Based on: 2605.06777

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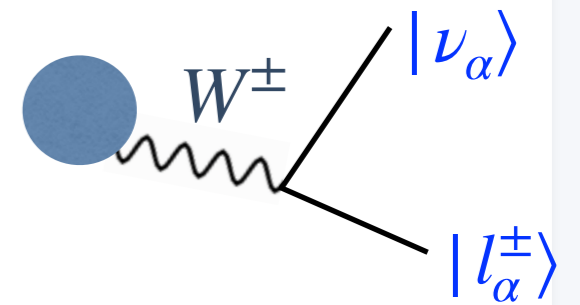
Neutrinos are a strange
but natural quantum system

Properties that make neutrinos unique

1

Weak \neq mass basis: $|\nu_\alpha\rangle = U_{\alpha 1} |\nu_1\rangle + U_{\alpha 2} |\nu_2\rangle + U_{\alpha 3} |\nu_3\rangle$

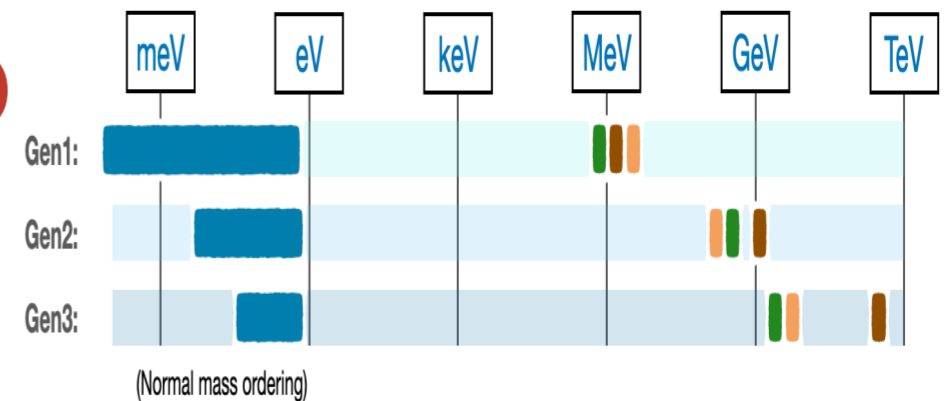
If lepton number is conserved
→ no mixing between $\nu, \bar{\nu}$



2

Masses are tiny (10^{-6} small)

Why? Lepton number violation
can explain a lot



3

Weak interactions are weak

Long coherence length:

it stays in a closed quantum system across a long distance



Neutrino - antineutrino transition?

Dirac Fermion (LNV = 0)

4 d.o.f:

2 charges × 2 spin

Spin flip:

$\nu_L \rightleftharpoons \nu_R$ (invisible/sterile)

$\bar{\nu}_L \rightleftharpoons \bar{\nu}_R$ (invisible/sterile)

No transition

Majorana Fermion (LNV = 2)

If neutrino is its own antiparticle
($\psi = \psi^c$)

2 d.o.f:

2 helicity

Spin flip:

$\nu_L \rightleftharpoons \bar{\nu}_L$ (always visible)

transition is possible

What can drive the ν - $\bar{\nu}$ transition?

If this new gauge boson is light Dark matter \rightarrow dense \rightarrow classical background

Textbook two-level system

- States: $|\uparrow\rangle$ and $|\downarrow\rangle$
- Intrinsic energy levels:
Energy splitting, degenerate
- External EM field in \hat{z} :
Zeemann/Stark Splitting
- External EM field in \hat{x}, \hat{y} :
Rabi Oscillation

$$|S\rangle \otimes |B\rangle$$

Fermion (1/2 spin)
Non-relativistic

Boson (EM field)
relativistic (massless)

Neutrino two-level system

- States: $|\nu\rangle$ and $|\bar{\nu}\rangle$
- Intrinsic energy levels:
degenerate
- External field in \hat{z} :
Splitting from \pm MSW-like potential
- External field in \hat{x}, \hat{y} :
LNV ($\nu \leftrightarrow \bar{\nu}$)

$$|S\rangle \otimes |B\rangle$$

Fermion (ν)
relativistic

Boson (DM field)
Non-relativistic
(cold, massive)

As quantum sensors...

Table top:

Challenge: states are very sensitive to the environment! :-)

Flip side: states are very sensitive to the environment!!! :-)

(From Roni Harnik's slides on: Dark Matter Searches with Quantum Computing Systems)

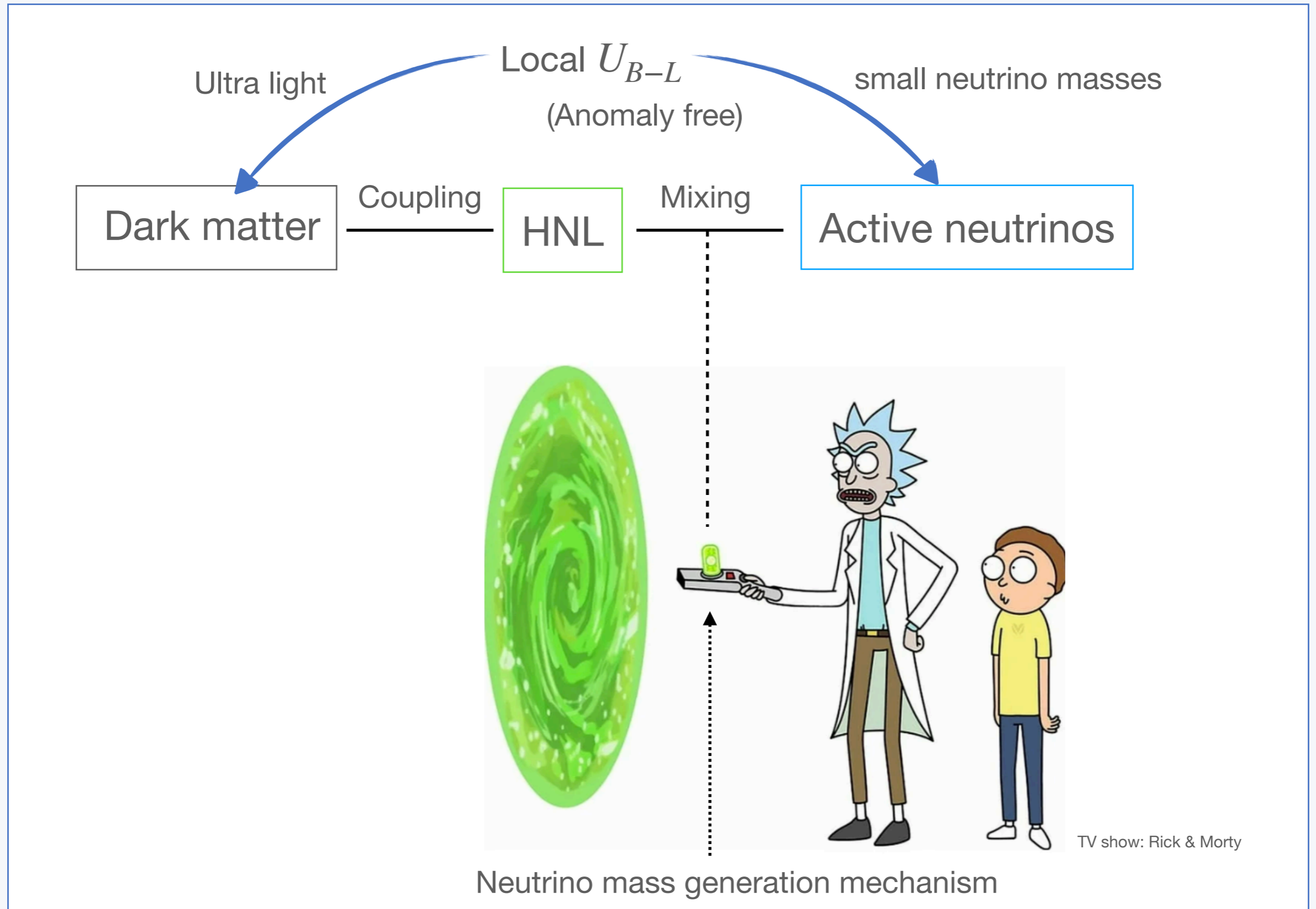
Neutrinos:

Challenge: states are very **in**sensitive to the environment! :-)

Flip side: states are very **insensitive to the environment!!! :-)**

How ultralight vector DM drives neutrino helicity conversion

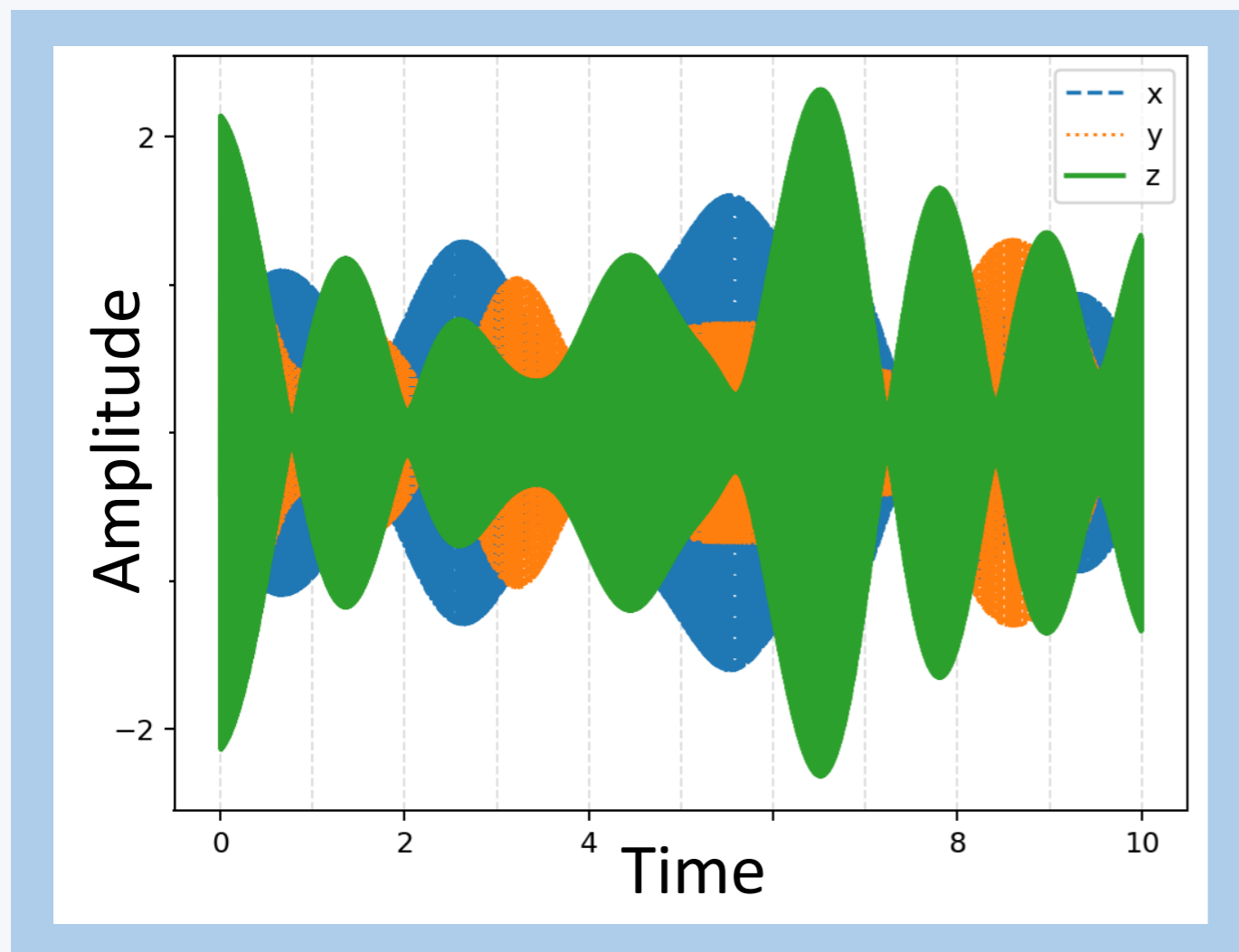
Neutrino Portal to Dark Matter



The vector DM field as a classical background

$$A'_i(t) \approx \frac{\sqrt{2\rho_{\text{DM}}/3}}{m_{A'}} \text{Re} \left[e^{im_{A'}t} \sum_i \alpha_i e^{i\varphi_i} \hat{n}_i \right] \quad \rho_{\text{DM}} \approx 0.4 \text{ GeV/cm}^3$$

- Large occupation number \rightarrow classical coherent field



$\sim 10^3$ periods
with frequency $m_{A'}$
in a wavepacket

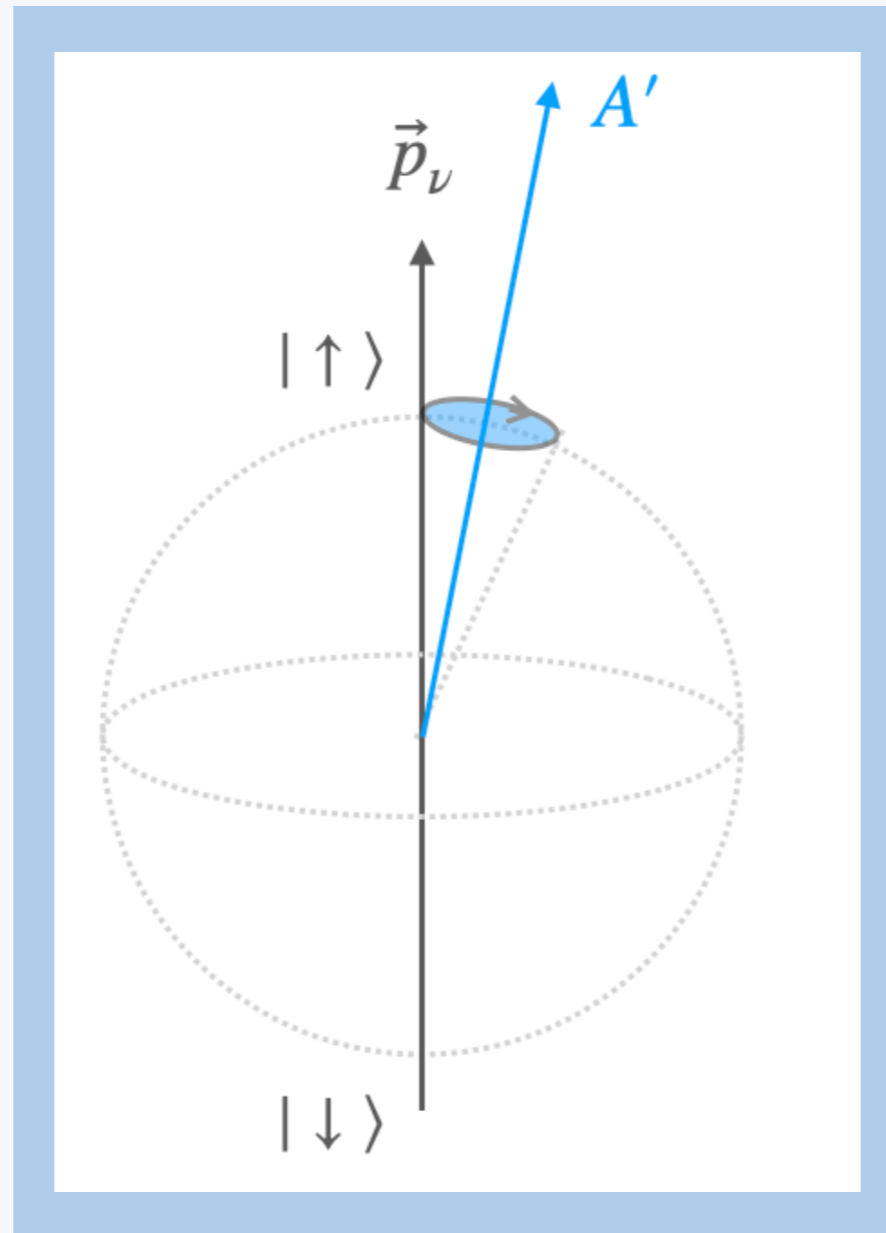
Elliptically polarized & random orientation

Neutrino spin in a DM bath

Interaction: $\mathcal{L} \supset e' A'_\mu \nu^\dagger \bar{\sigma}^\mu \nu - \left(\frac{1}{2} m_\nu \nu \nu + \text{h.c.} \right)$

$$H = V_{\parallel} \sigma_z + V_{\perp} \sigma_{\perp}, \quad \frac{V_{\perp}}{V_{\parallel}} \sim \frac{m_\nu}{E_\nu}$$

helicity suppression

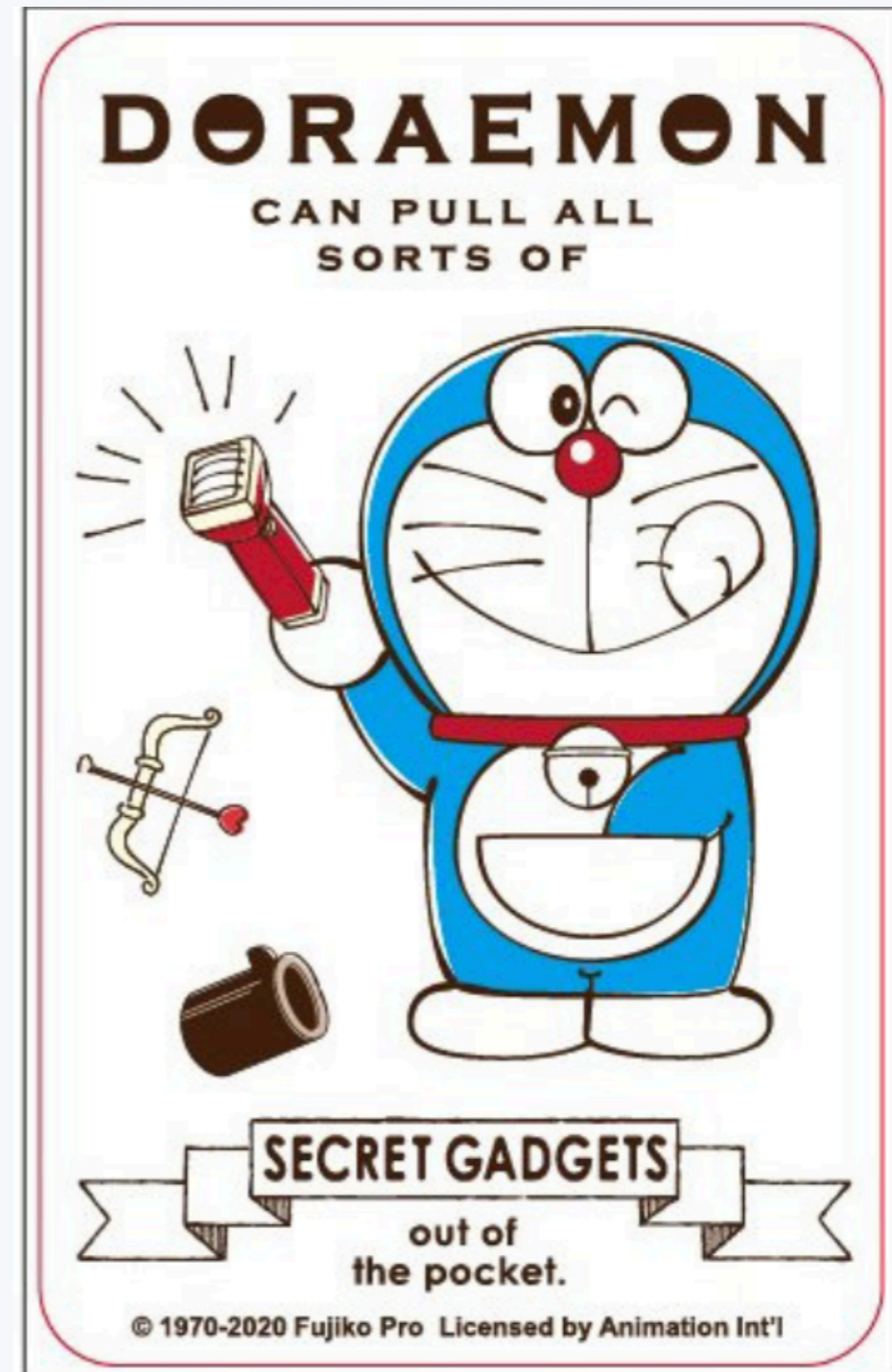


Two level system driven by a Bosonic bath

$$H = V_{\parallel}\sigma_z + V_{\perp}\sigma_{\perp}$$

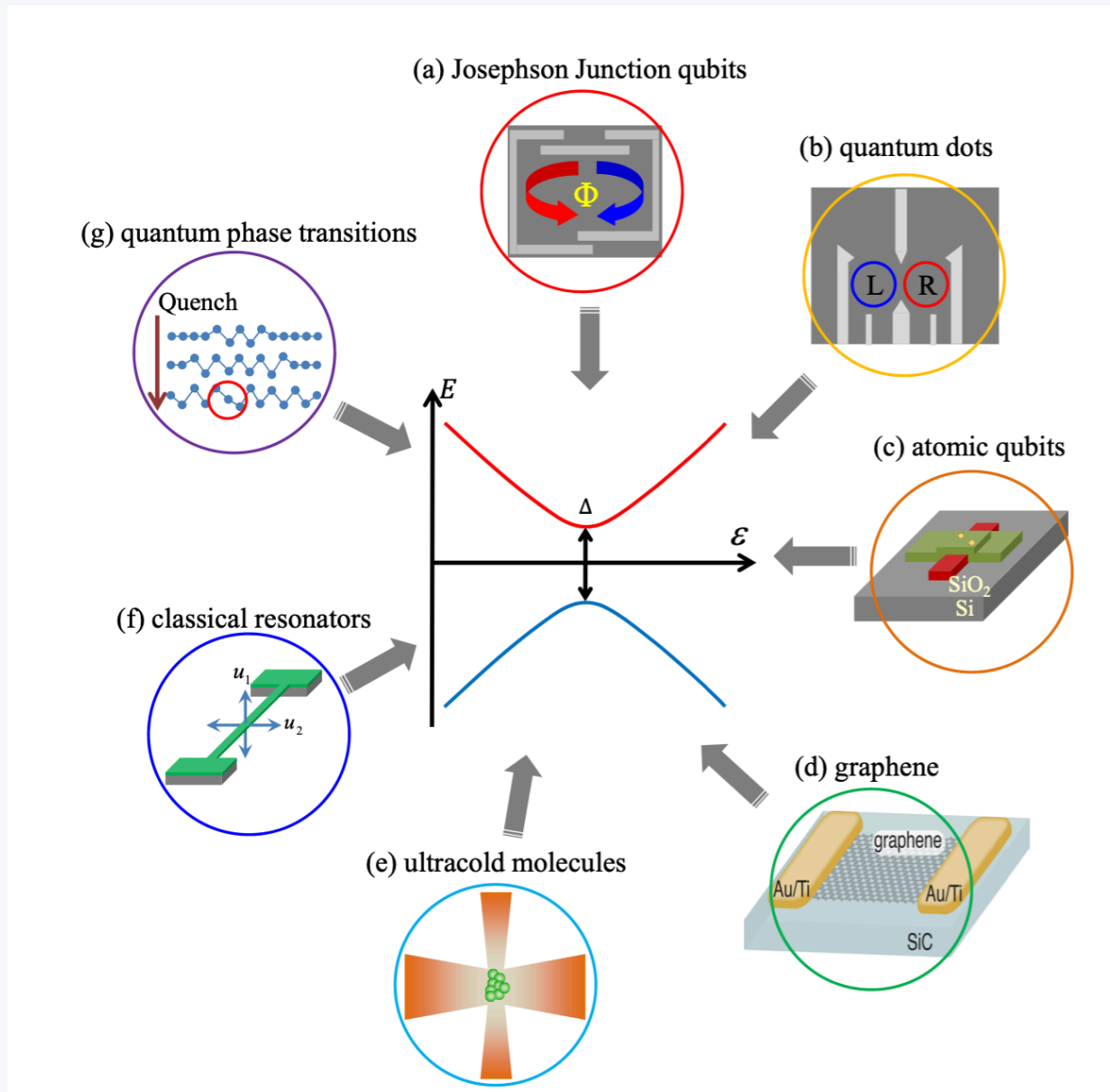
V_{\parallel} & V_{\perp} : periodic & out of phase

$$\frac{V_{\parallel}}{V_{\perp}} \approx 10^{-7} : \text{non-adiabatic @ } V_{\parallel} \rightarrow 0$$



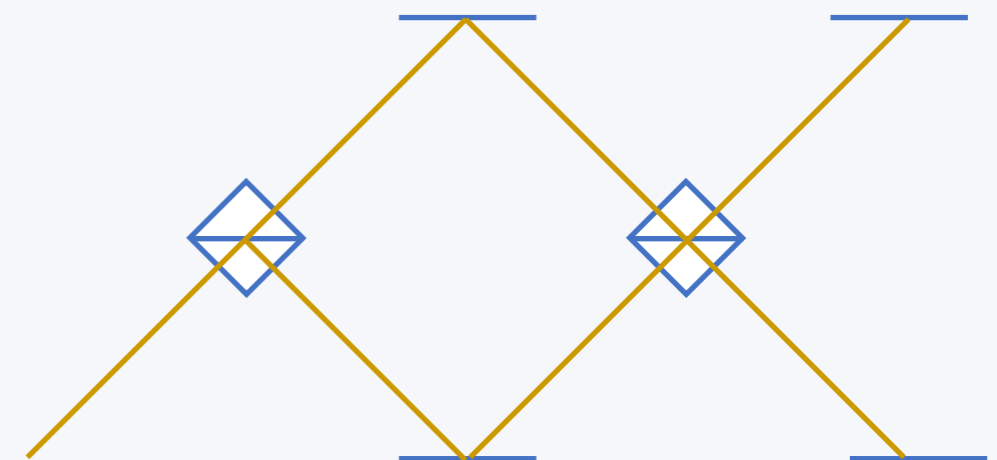
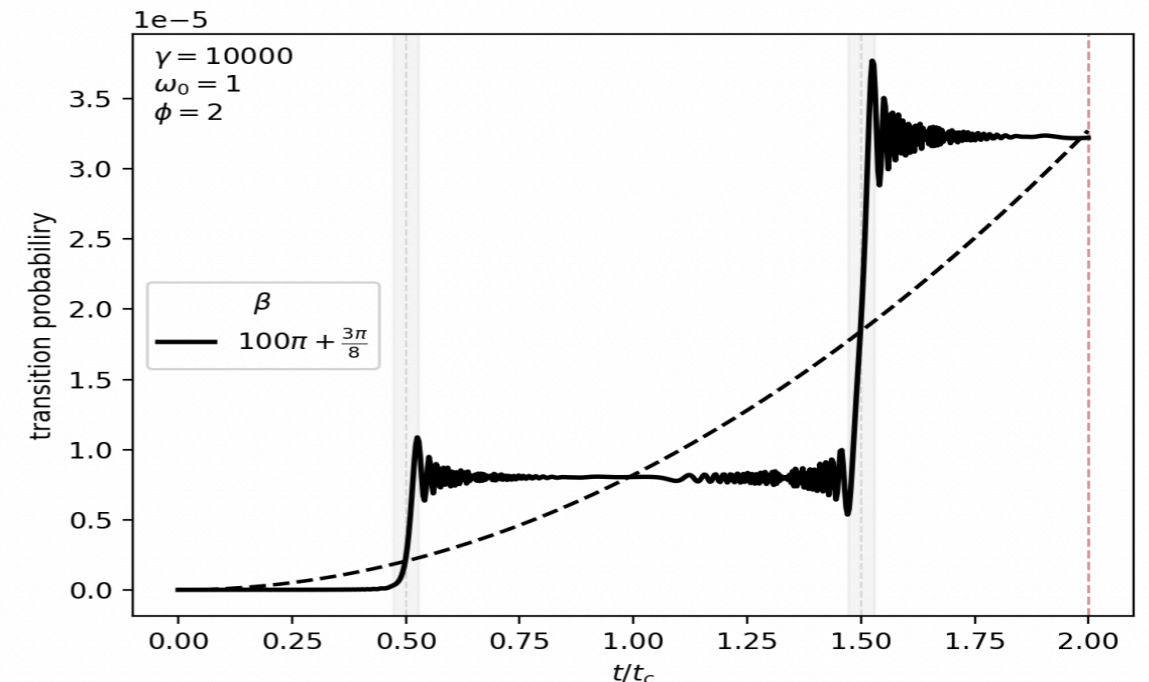
Landau-Zener-Stückelberg-Majorana transitions

(Periodic) avoided level crossings in TLS:



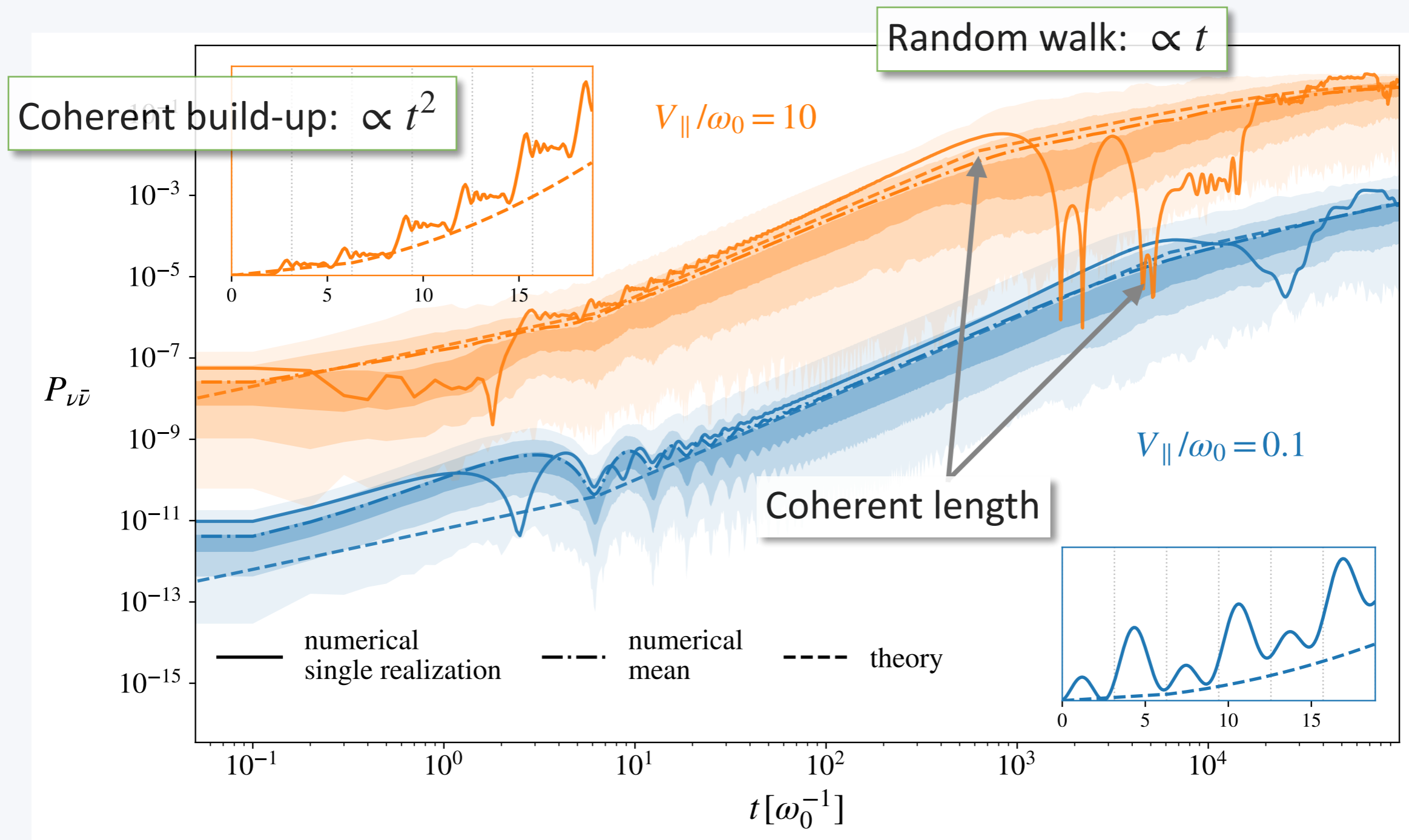
[O. Ivakhnenko, S.Shevchenko, F.Nori, 2022 Review]

Stückelberg inference
 ↗ ↘
 LZ transition LZ transition



Neutrino - antineutrino transition probability

Elliptically polarized DM $\rightarrow V_{\parallel}$ and V_{\perp} out of phase \rightarrow periodic avoided level crossings



Tiny rate per unit time, but accumulates over astrophysical baselines!

What can we observe?

Astrophysical baselines for $\nu/\bar{\nu}$ asymmetry

Source (SN, sun)

Detection

Asymmetrical $\nu/\bar{\nu}$

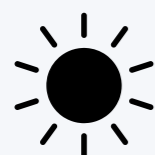
Asymmetrical $\nu/\bar{\nu}$

SN: $\langle E_{\nu_e} \rangle < \langle E_{\bar{\nu}_e} \rangle$

$\langle E_{\nu_e} \rangle < \langle E_{\bar{\nu}_e} \rangle$

Sun: Only ν flux

Only ν flux



Carries uncontaminated message from the source

Astrophysical baselines for $\nu/\bar{\nu}$ asymmetry

Source (SN, sun)

Detection

Asymmetrical $\nu/\bar{\nu}$

Asymmetrical

$\nu, \bar{\nu}$

Washed out

SN: $\langle E_{\nu_e} \rangle < \langle E_{\bar{\nu}_e} \rangle$

Vector DM Background

$\langle E_{\nu_e} \rangle \sim \langle E_{\bar{\nu}_e} \rangle$

Sun: Only ν flux

$\bar{\nu}$ flux excess

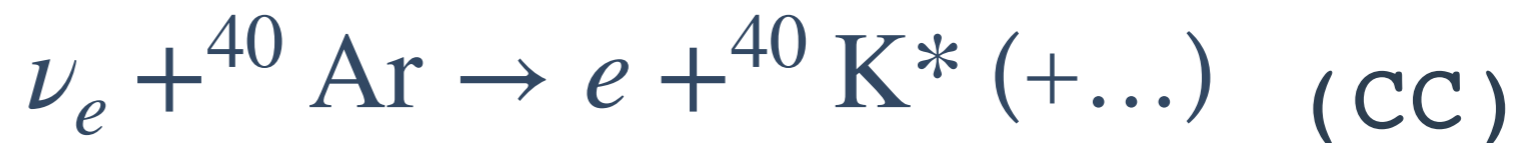


If DM induces $\nu \leftrightarrow \bar{\nu}$, the asymmetry is washed out

Detection: complementary experiments

DUNE

LArTPC



→ ν_e spectrum

Kamland, JUNO

Liquid scintillator



→ Clean $\bar{\nu}_e$ measurement

Super/Hyper-K

Water Cherenkov



→ Large statistics

SN: ν_e spectrum v.s. $\bar{\nu}_e$ spectrum

Solar: $\bar{\nu}_e$ excess @ Kamland/JUNO

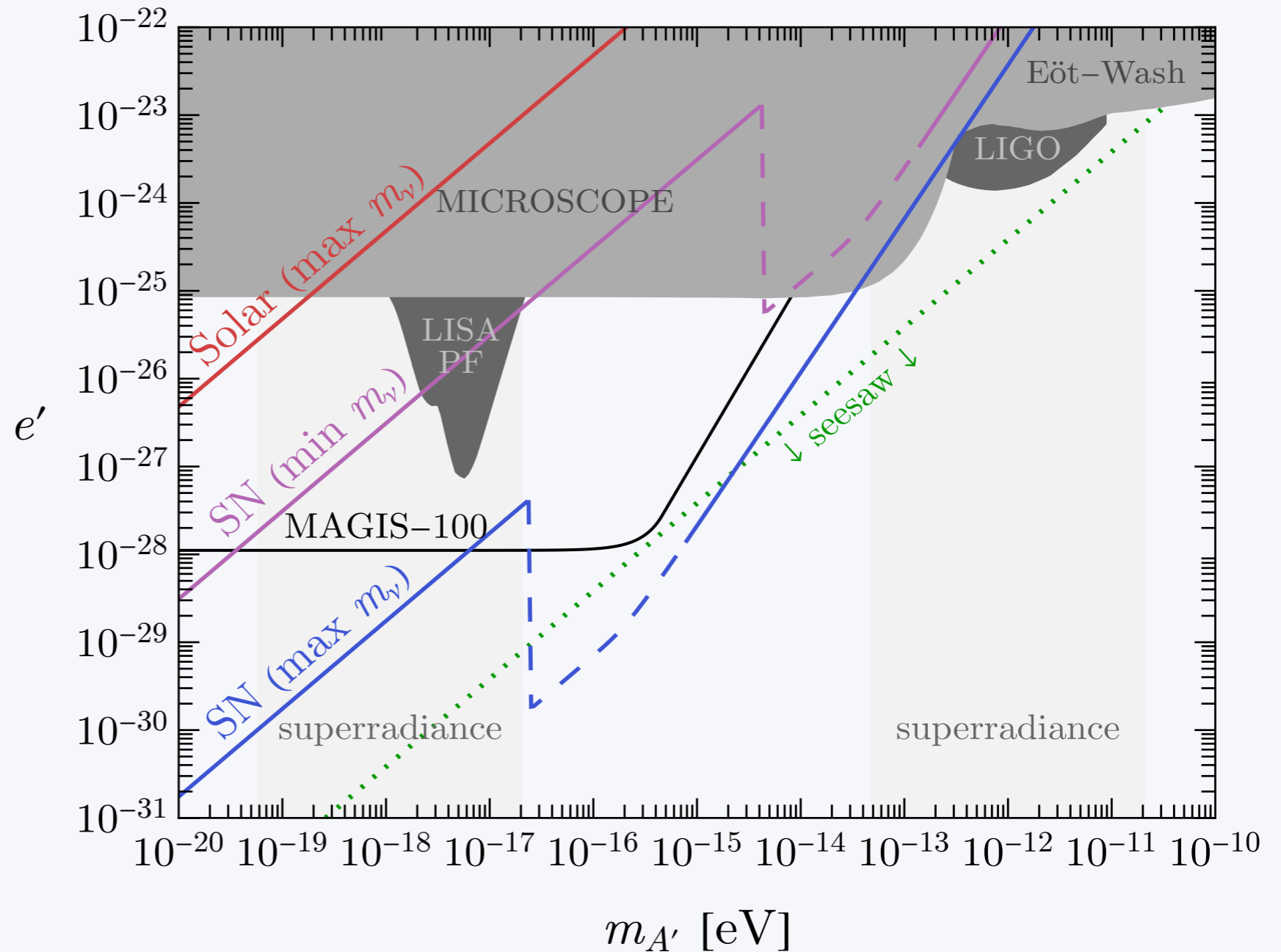
Experimental reach for U_{B-L} vector DM

- For SN neutrinos:

$$P_{\nu\bar{\nu}} \sim 0.5$$

- For Solar neutrinos:

$$P_{\nu\bar{\nu}} \sim 2 \times 10^{-6} \text{ (JUNO)}$$



Summary

- 1 Neutrinos are nature's quantum system
- 2 Majorana neutrinos are theoretically motivated and has a $(\nu, \bar{\nu})$ two level system
- 3 Ultralight vector dark matter drives neutrino helicity conversion $(\nu \leftrightarrow \bar{\nu})$ via spin precession — suppressed by m_ν/E but enhanced by long astrophysical baselines.
- 4 Taking advantage of the complementary features of DUNE / Hyper-K / JUNO, Supernova neutrinos can probe orders of magnitude of new parameter space for vector DM.

Thank you!

Neutrino spin in a DM bath

Interaction: $\mathcal{L} \supset e' A'_\mu \nu^\dagger \bar{\sigma}^\mu \nu - \left(\frac{1}{2} m_\nu \nu \nu + \text{h.c.} \right)$

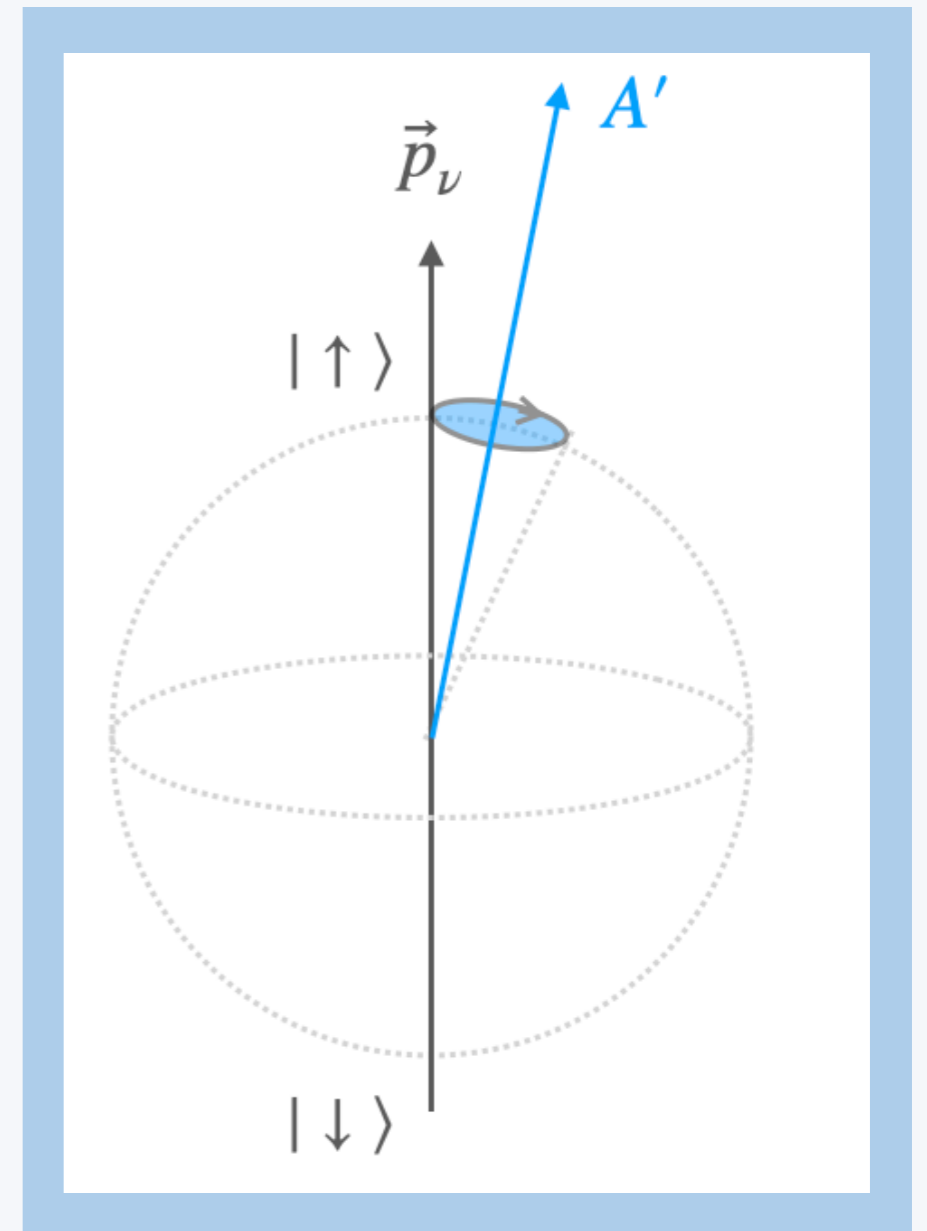
$$H = V_{\parallel} \sigma_z + V_{\perp} \sigma_{\perp}, \quad \frac{V_{\perp}}{V_{\parallel}} \sim \frac{m_\nu}{E_\nu}$$

Lab frame: helicity suppression

- $H = e' \langle A' \rangle (\sigma_z + m_\nu/E_\nu \sigma_{\perp})$, $\sigma_{\perp} = (e^{i\phi} \sigma_+ + e^{-i\phi} \sigma_-)$
- diagonal σ_z : energy splitting between helicity states
- off-diagonal $\sigma_{x,y}$: drives $\nu \leftrightarrow \bar{\nu}$ helicity suppressed

Neutrino rest frame: spin precession around A'

- $H_{\nu\text{RF}} = e' (A'_x, A'_y, \gamma A'_z) \cdot \vec{\sigma}$
- Longitudinal enhanced by boost $\gamma = E_\nu/m_\nu$
- Transverse component drives the spin flip



Landau-Zener-Stückelberg-Majorana transitions

Elliptically polarized DM $\rightarrow V_{\parallel}$ and V_{\perp} out of phase \rightarrow periodic avoided level crossings

- **Adiabaticity parameter:**

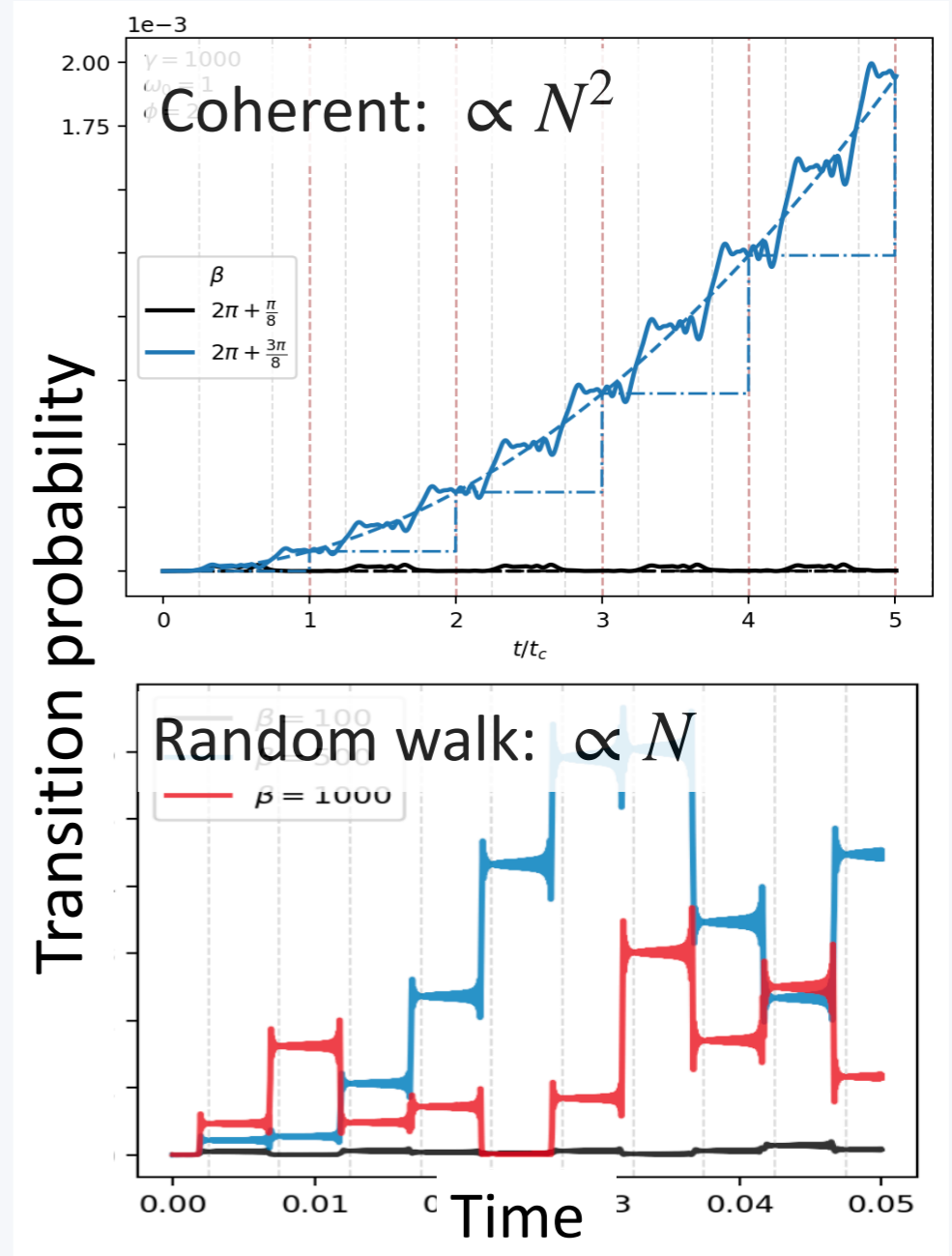
$$\delta = \frac{V_{\perp}^2 \varepsilon^2}{2 V_{\parallel} \omega} \propto \frac{1}{\gamma^2} \ll 1 \text{ (non adiabatic)}$$

- **Within coherence length:**

$$P_{\nu\bar{\nu}} = \sin^2(\Omega_{\text{eff}} \cdot t), \quad \Omega_{\text{eff}} \approx V_{\perp} J_1(2\beta) \varepsilon$$

- **Beyond coherence length (random walk):**

$$P_{\nu\bar{\nu}} = \frac{1}{2} \left(1 - e^{-t/T_2} \right) \longrightarrow \text{saturates to } \frac{1}{2}$$



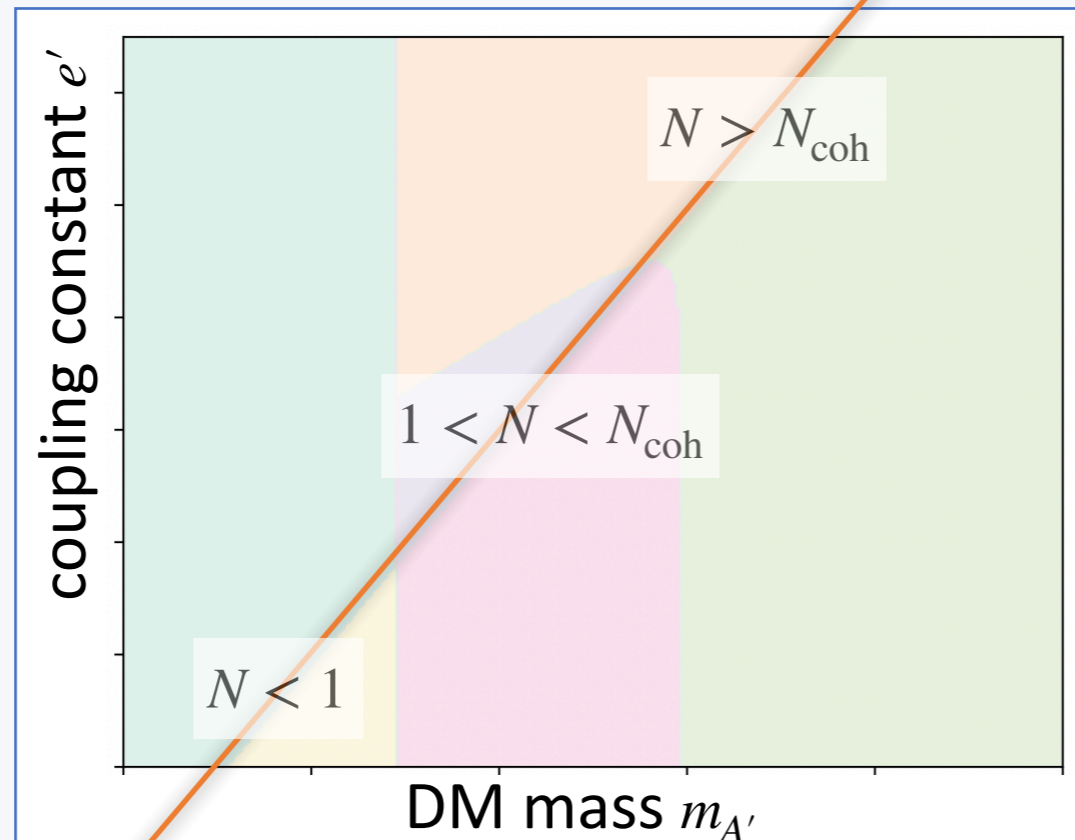
Tiny rate per unit time, but accumulates over astrophysical baselines!

Quantum regimens

N_{coh}

$$\beta \equiv \frac{V_{\parallel}}{\omega} \sim e' \frac{\sqrt{\rho_{\text{DM}}}}{m_{A'}^2} = 1$$

$$1 \ll \beta \ll \gamma^2 : P_{\nu\bar{\nu}} \sim \frac{4\pi\beta}{\gamma^2} N \max\left(1, \min\left(N, \frac{1}{\beta v_{\text{DM}}}\right)\right)$$



Random walk
with large ($N_{\text{coh}} t_{\text{osc}}$) steps

Coherent build-up
Effective Rabi Osc

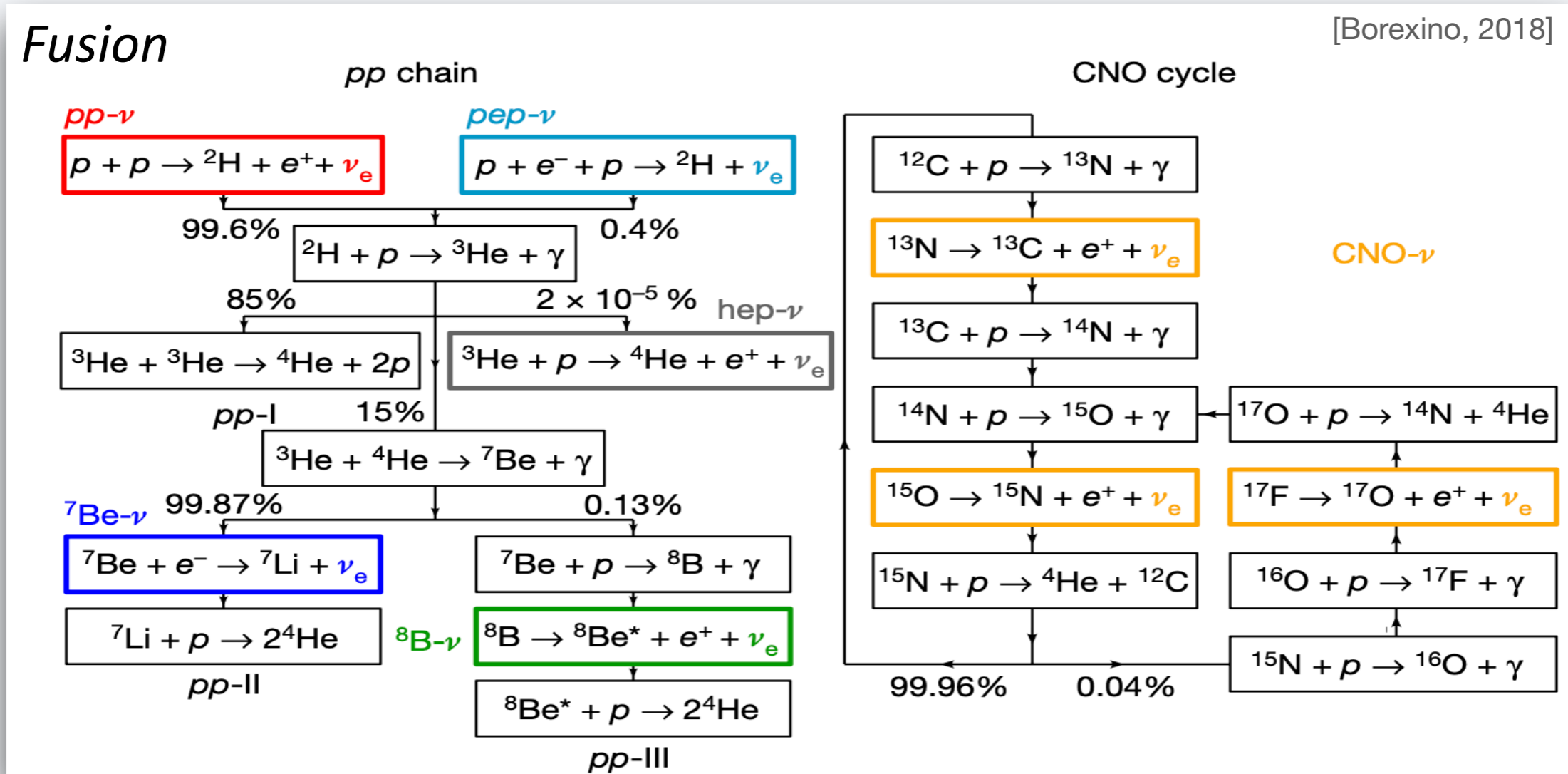
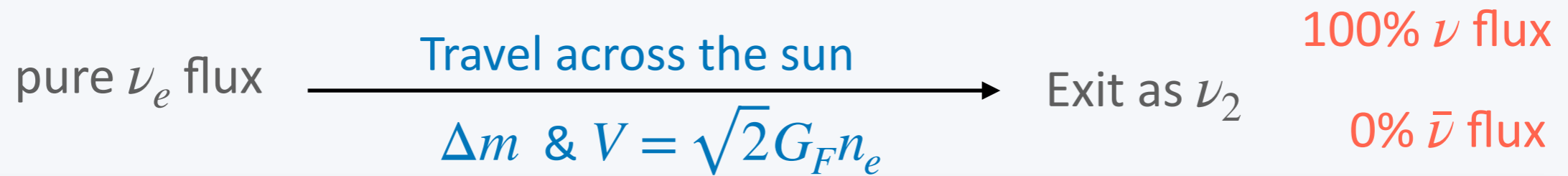
Random walk
with small (t_{osc}) steps

$$\beta \ll 1 : P_{\nu\bar{\nu}} \sim \frac{(2\pi)^2 \beta^4}{\gamma^2} N \max\left(1, \min\left(N, \frac{1}{v_{\text{DM}}}\right)\right)$$

Parameters:

DM osc. period: $t_{\text{osc}} = 2\pi/\omega$, **steps:** $N = T/t_{\text{osc}}$, **Coherent steps:** $N_{\text{coh}} \lesssim 10^3$

Solar neutrinos > 2 MeV



@ Reactor (*fission*) neutrino (pure $\bar{\nu}_e$) detectors

\longrightarrow Kamland: $P_{\nu\bar{\nu}} \lesssim 3 \times 10^{-5}$

PHENO26

Supernova neutrinos

