

Supernova Neutrinos at DUNE

obtaining precision & probing ultralight dark matter

Ting Cheng

@ CETUP (July 15, 2026)

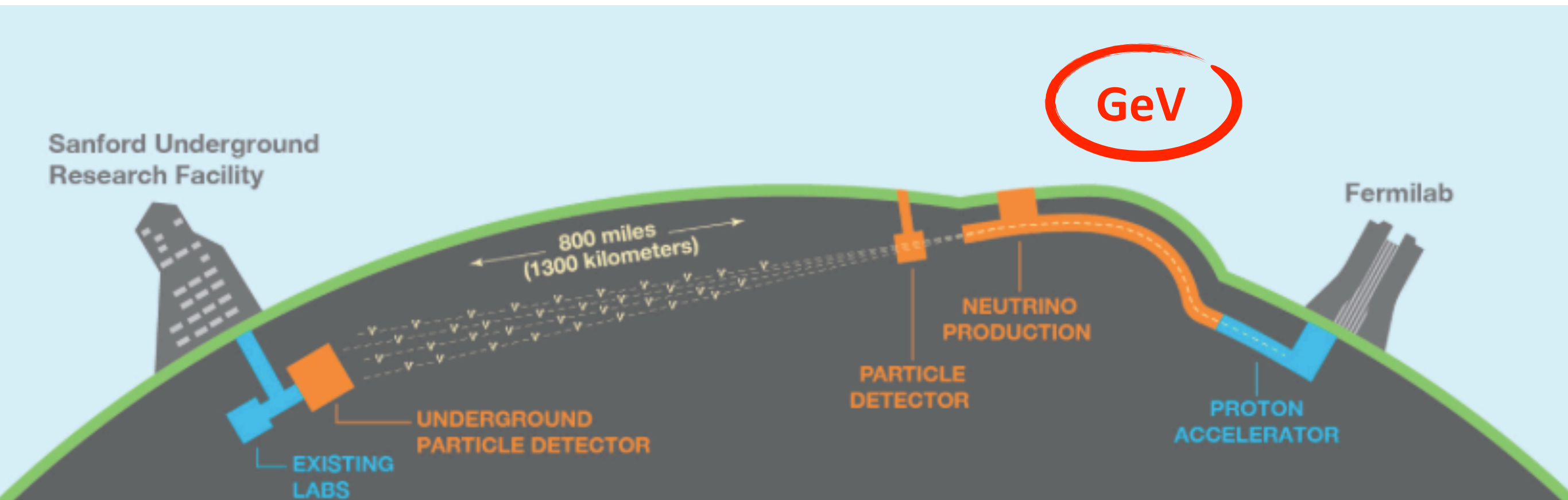
precision: 2606.18337, with Hostert, Machado, Mishra, Thompson

dark matter: 2605.06777, with Berlin, Capdevilla, Hostert, Machado

DUNE

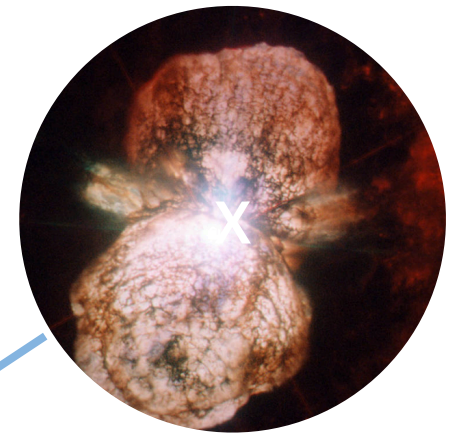


[SURF webpage, photo by Matthew Kapust]

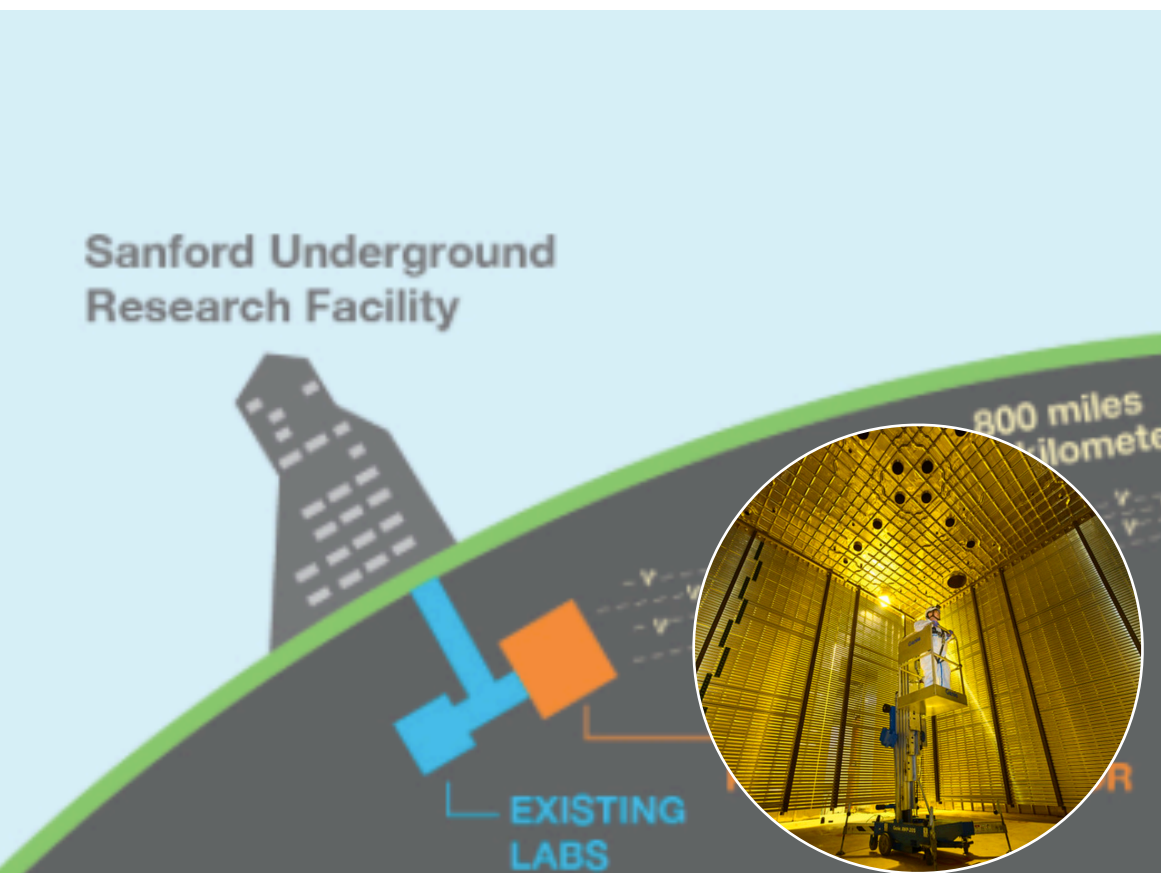


DUNE — just the far detector

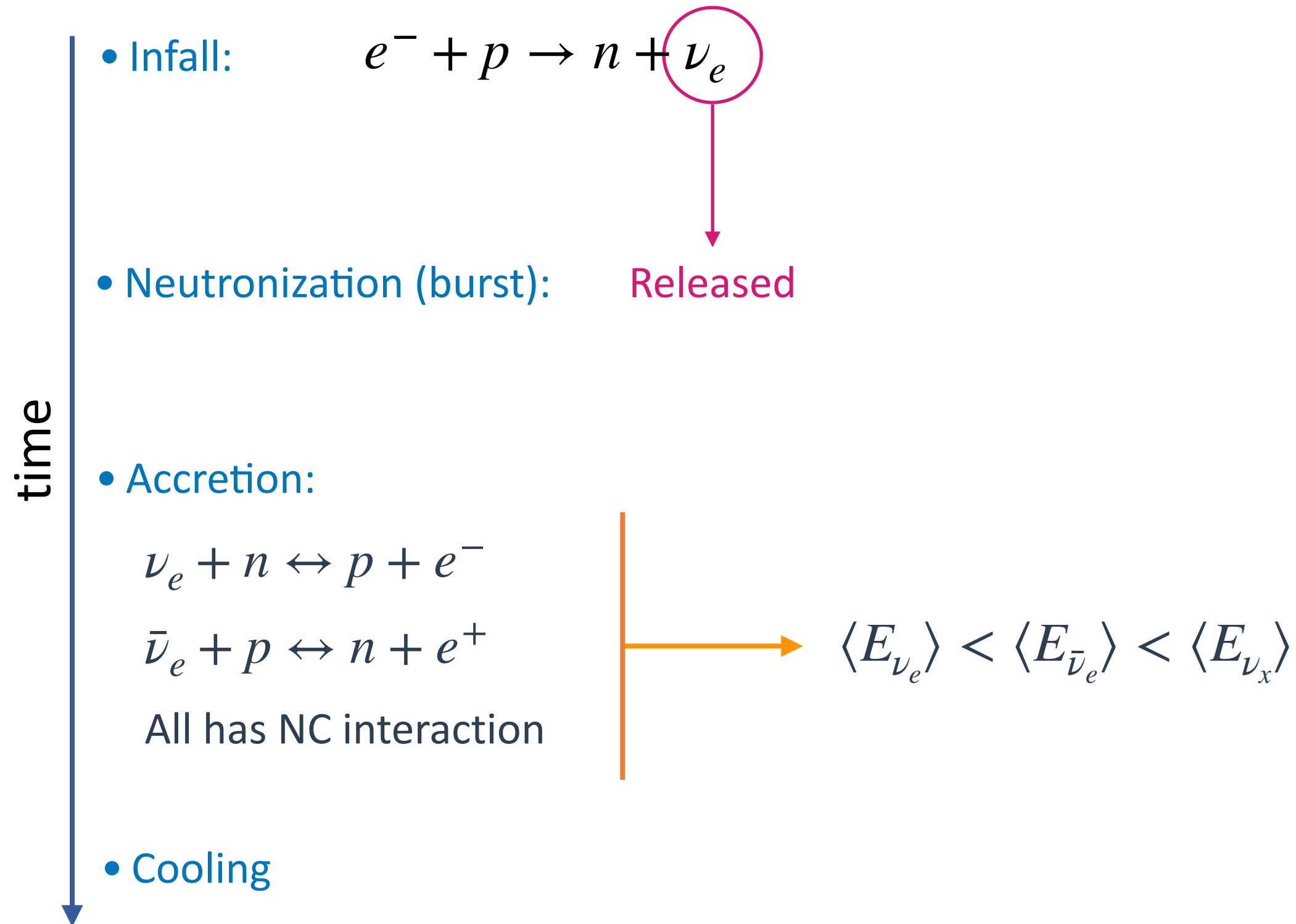
Type II - Supernova



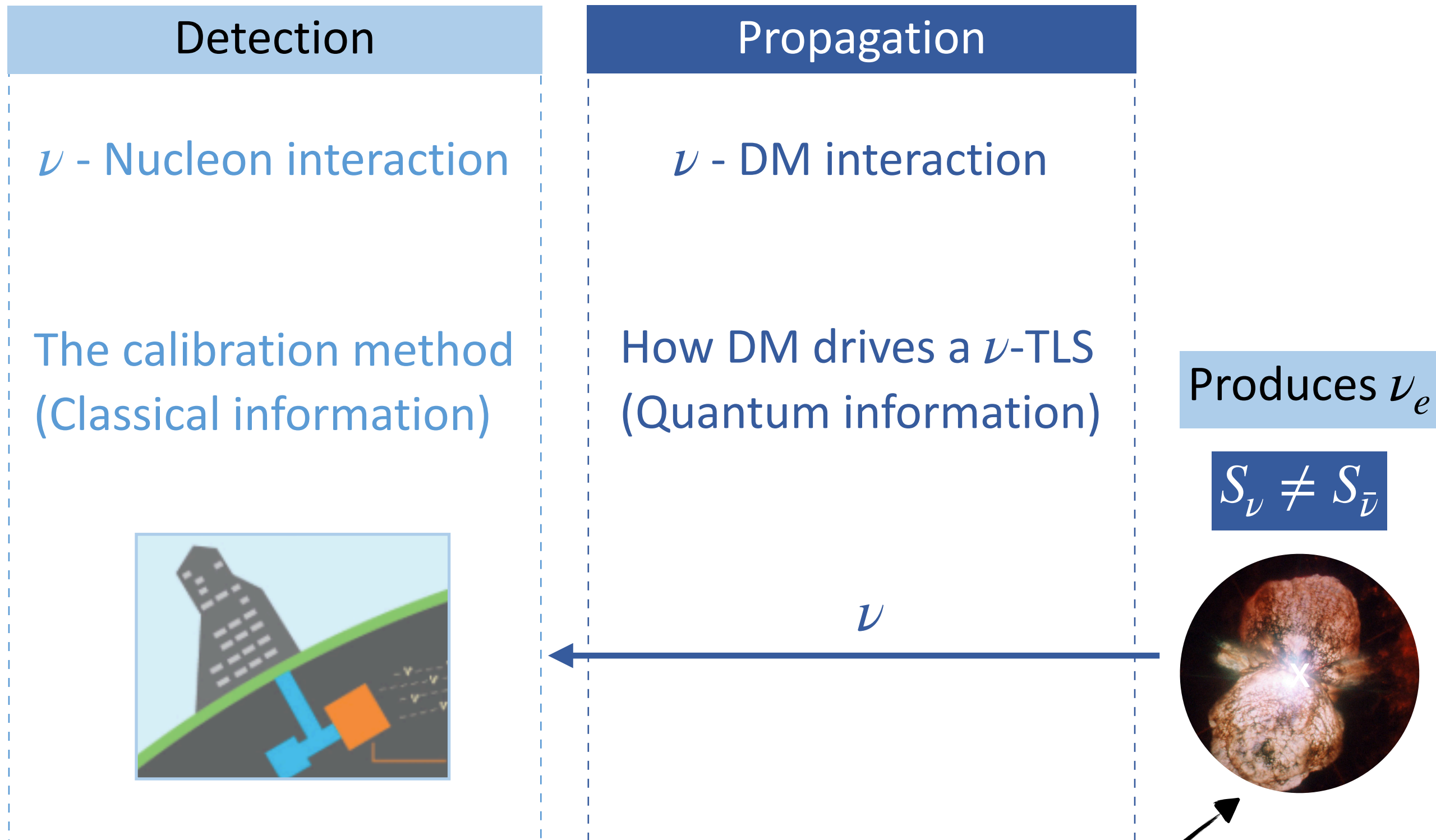
MeV



Core-collapse Supernova



This talk is *not* about supernova neutrino physics but about its:



For supernova neutrino physics see talks by:
Anna Suliga, Garv Chauhan, Christopher Cappiello, Yanou Cui

Detection

How we can see Supernova neutrinos

IBD: $\bar{\nu}_e + p \rightarrow n + e^+$ Target: H

Charge Current (CC): $\nu_e + n \rightarrow p + e^-$ Target: $^{40}\text{Ar}, ^{16}\text{O}, \dots$

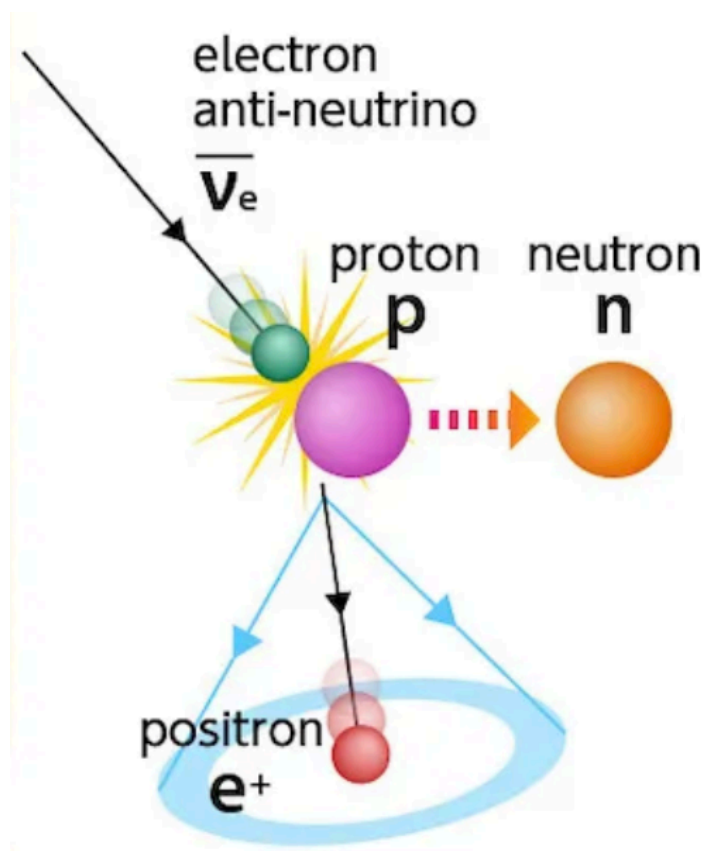
Neutral current (NC: pES, coherent):
 $\nu + p \rightarrow \nu + p$
 $\nu + N \rightarrow \nu + N$ All

Electron scattering (eES): $\nu_e + e \rightarrow \nu_e + e$ & $\nu + e \rightarrow \nu + e$

Linear combination

Big enough Detectors

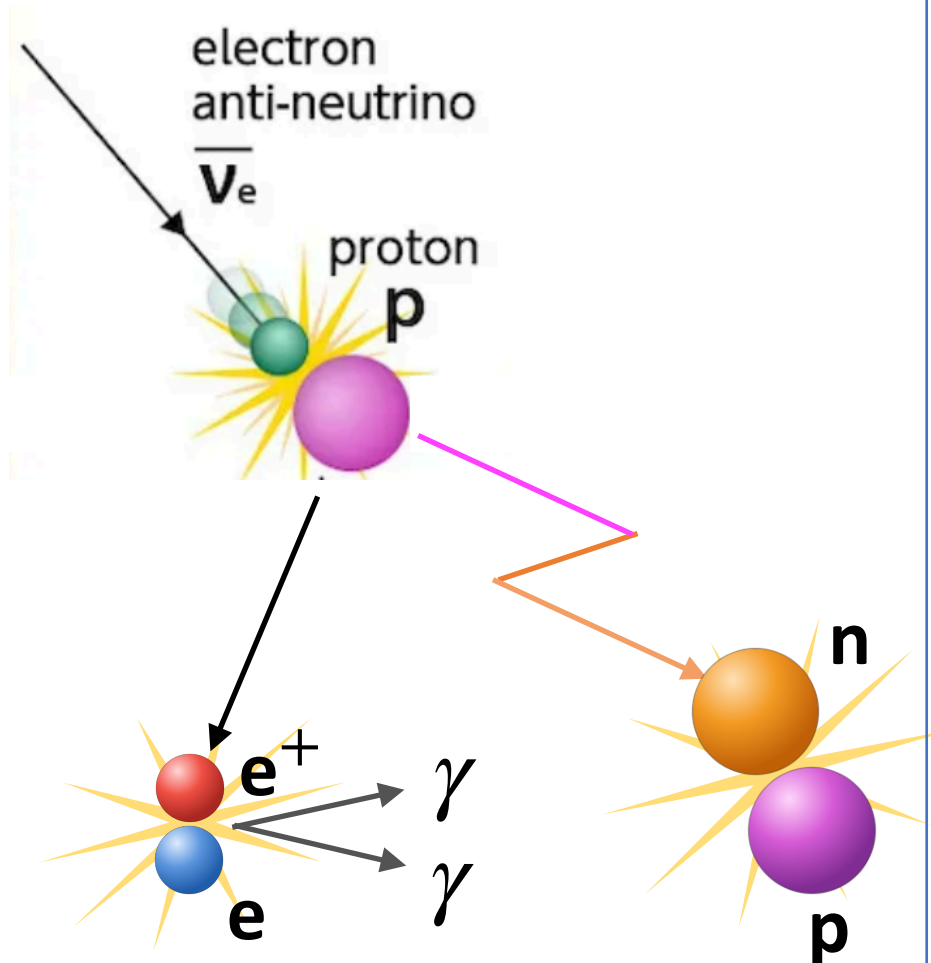
Water Cherenkov (HK)



[SK webpage]

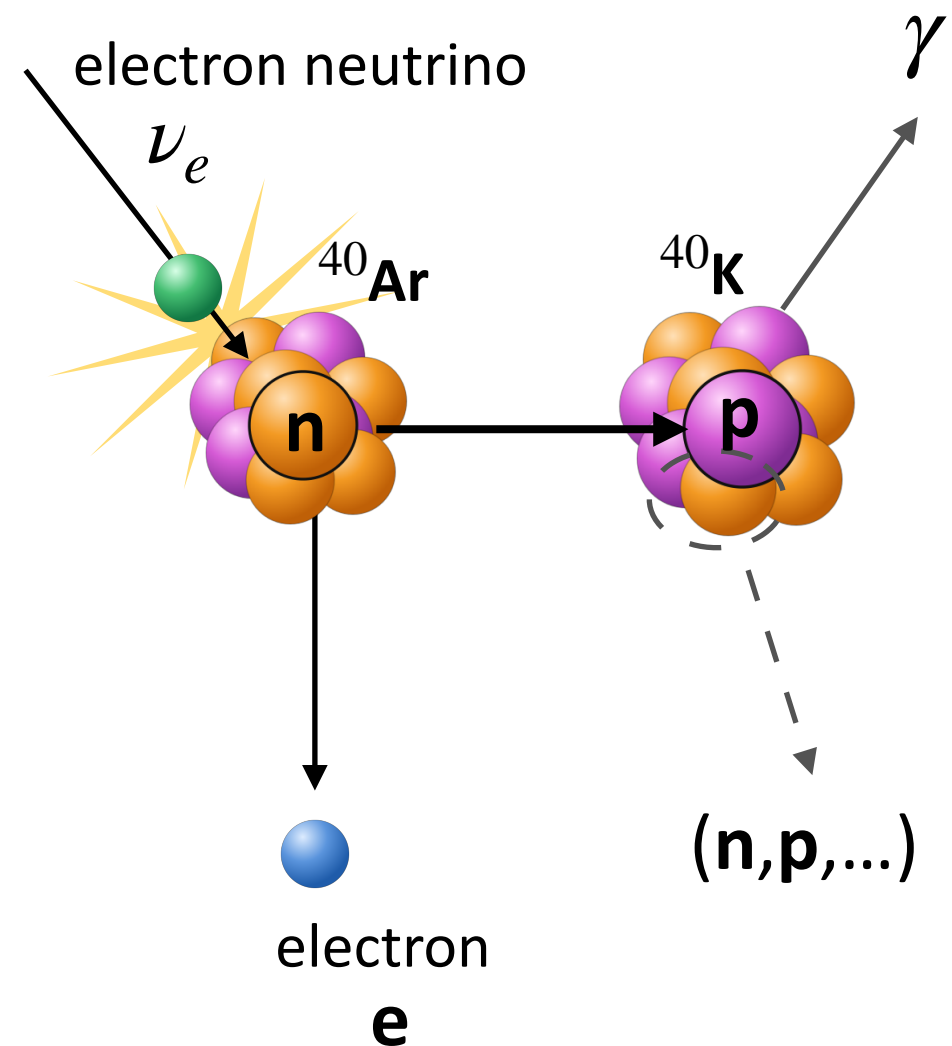
Cherenkov light

Liquid scintillator (JUNO)



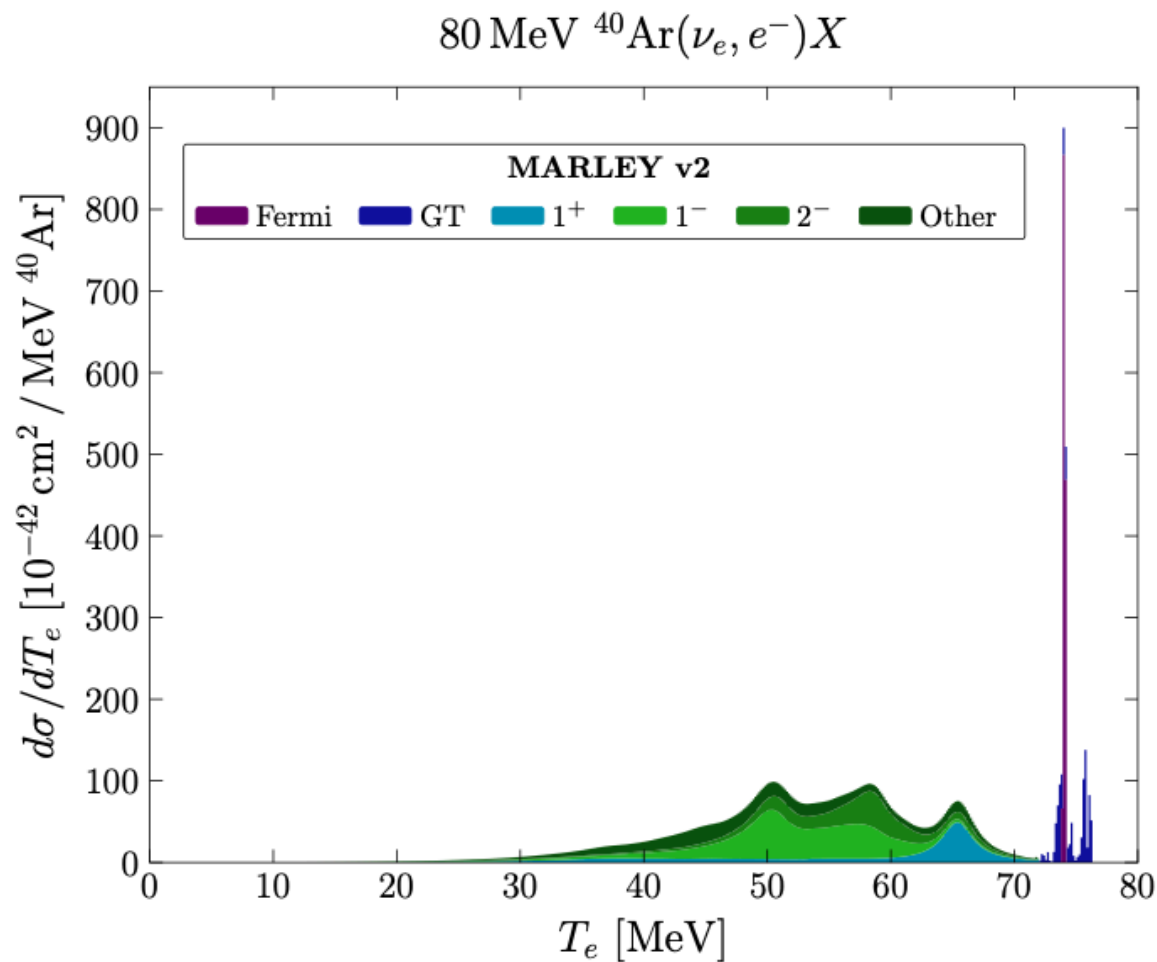
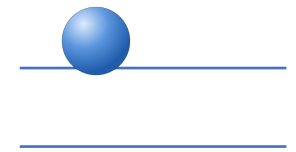
Scintillation light

LArTPC (DUNE)



blips

$\nu_e - {}^{40}\text{Ar}$ Cross section



[S. Gardiner, P. Barham Alz'as, A. Nikolakopoulos, L. Abu El-Haj, N. Jachowicz, V. Pandey, MARLEY V2]

$$\Delta E_k = E_\nu - T_e$$

Energy loss to the transition energy

Small $\Delta E_k \rightarrow$ Only (e, γ) final state $\rightarrow$ discrete

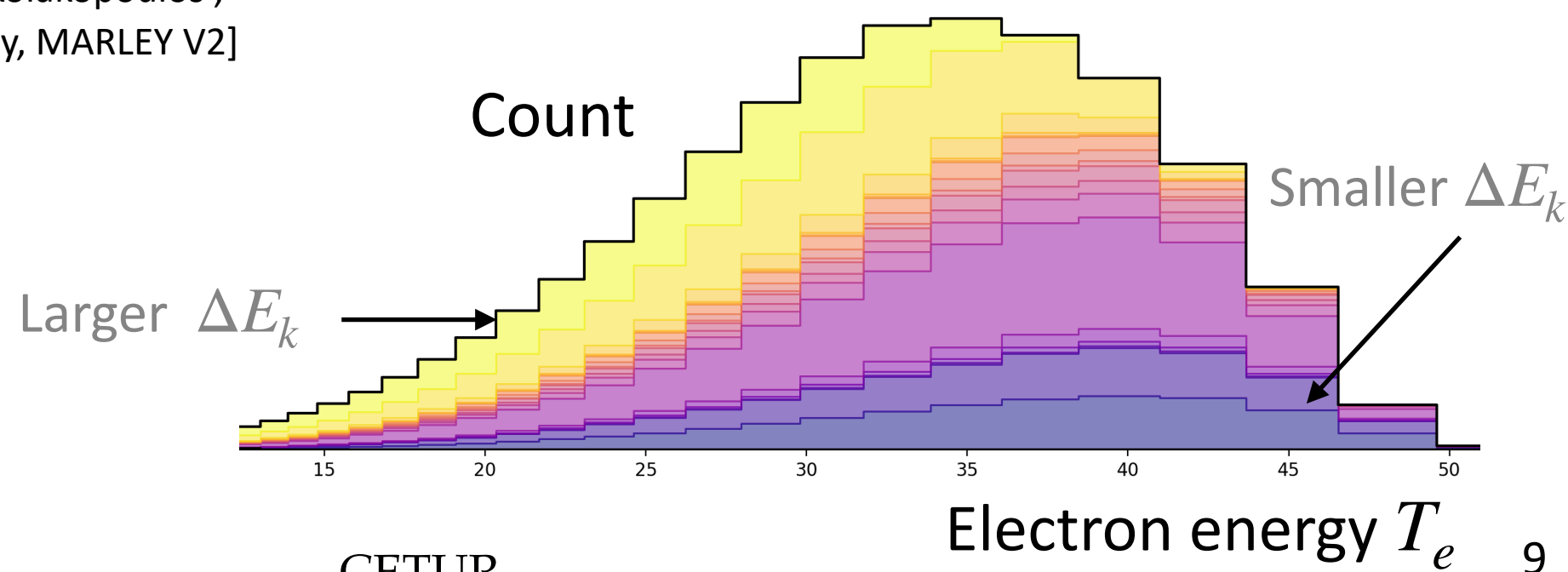


de-excitation γ

large $\Delta E_k \rightarrow$ + hadronic final states $\rightarrow$ continuous

More energy loss

Event spectrum (from discrete only)

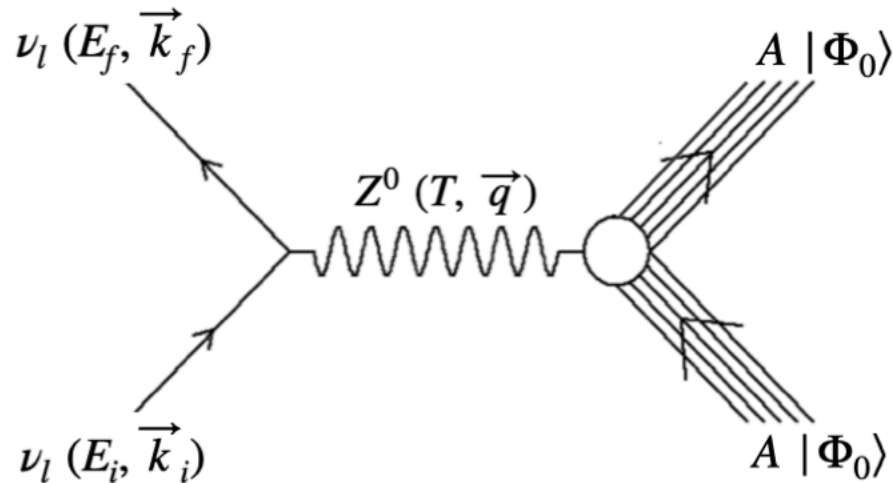


$T_e \rightarrow$ many possible E_ν

Vishvas Pandey's slides from last week:

10s of MeV Neutrinos-Nucleus Scattering

Coherent elastic [CEvNS]



$$\sum_{fi} |\mathcal{M}|^2 \propto \frac{G_F^2}{2} L_{\mu\nu} W^{\mu\nu}$$

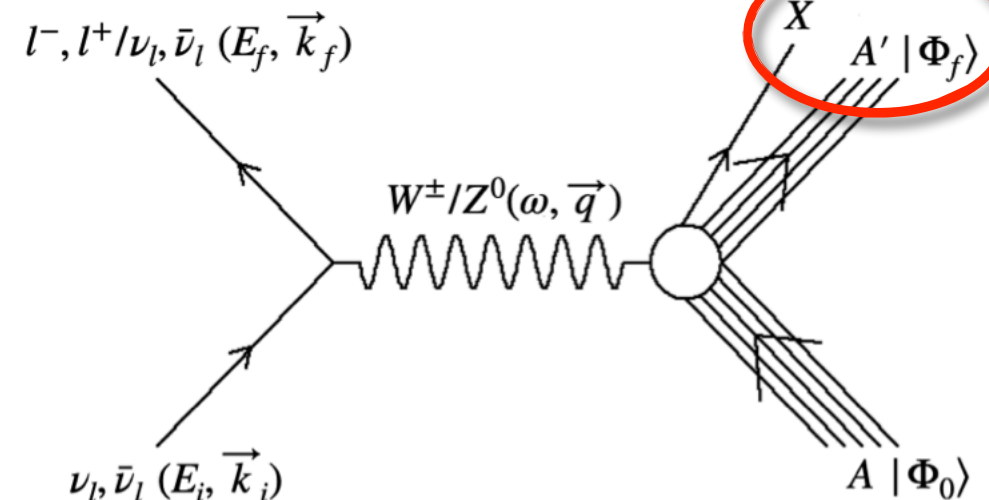
Leptonic Tensor: $L_{\mu\nu} = \sum_{fi} (\mathcal{J}_{l,\mu})^\dagger \mathcal{J}_{l,\nu}$

Transition Amplitude: $\mathcal{J}_n^\mu = \langle \Phi_0 | \hat{J}_n^\mu(q) | \Phi_0 \rangle$

Cross Section:

$$d\sigma \propto \frac{G_F^2}{4\pi} Q_W^2 F_W^2(q)$$

Inelastic CC/NC



Hadronic Tensor: $W^{\mu\nu} = \sum_{fi} (\mathcal{J}_n^\mu)^\dagger \mathcal{J}_n^\nu$

Transition Amplitude: $\mathcal{J}_n^\mu = \langle \Phi_f | \hat{J}_n^\mu(q) | \Phi_0 \rangle$

Cross Section:

$$d\sigma \propto \frac{G_F^2}{4\pi} \sum_{J^\pi} [\nu_{CC} W_{CC} + \nu_{CL} W_{CL} + \nu_{LL} W_{LL} + \nu_T W_T \pm \nu_{T'} W_{T'}]$$

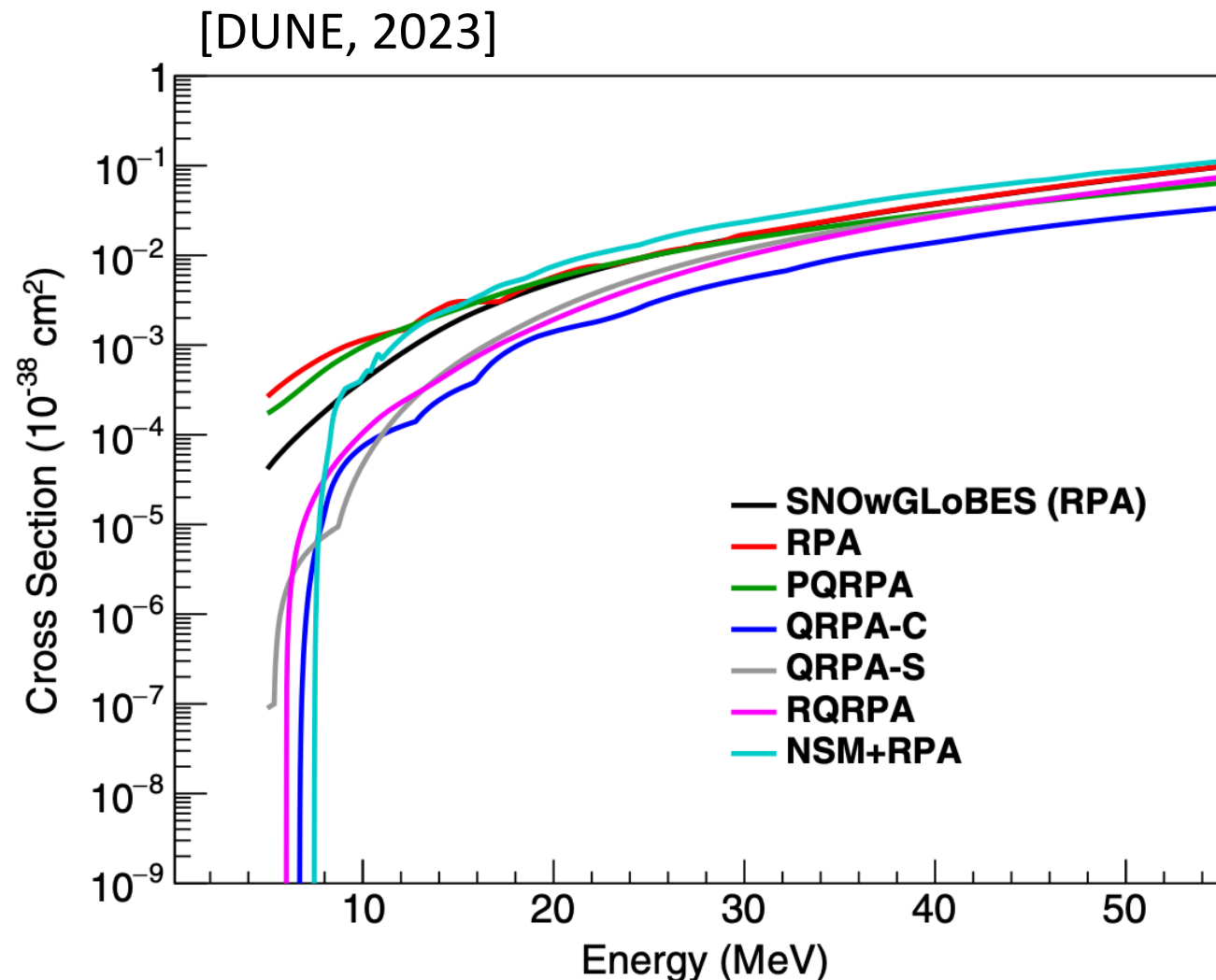
Distribution?

Where?

How strong?

→ a really complicated many-body nuclear problem

Cross section models

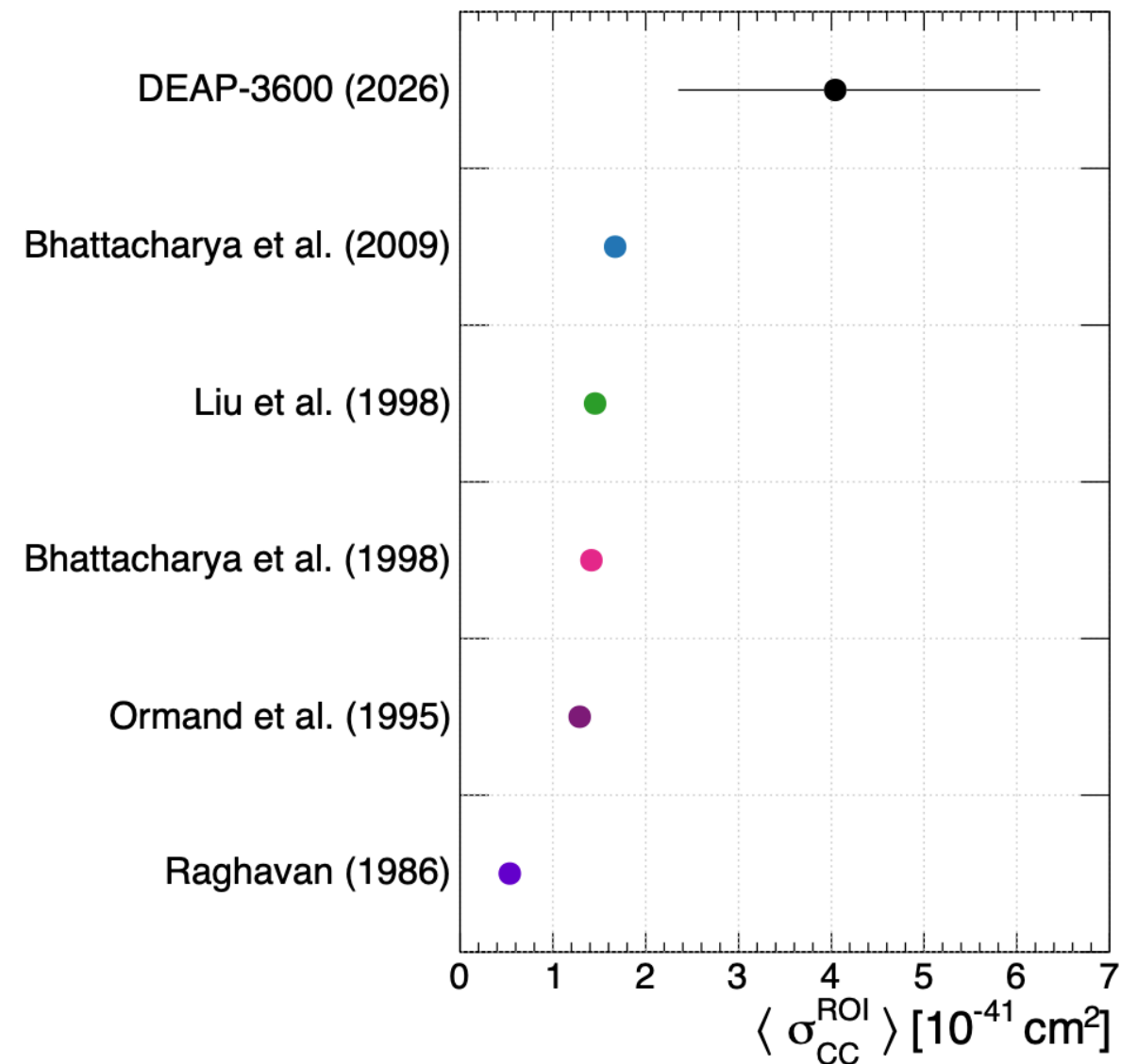


Different “models”:

Transition strengths inferred by measurements of
e.g. ^{40}Ti mirror β -decay, (p,n) charge-exchange reactions

first solar neutrino measurement with Ar

[DEAP, 2605.12769]

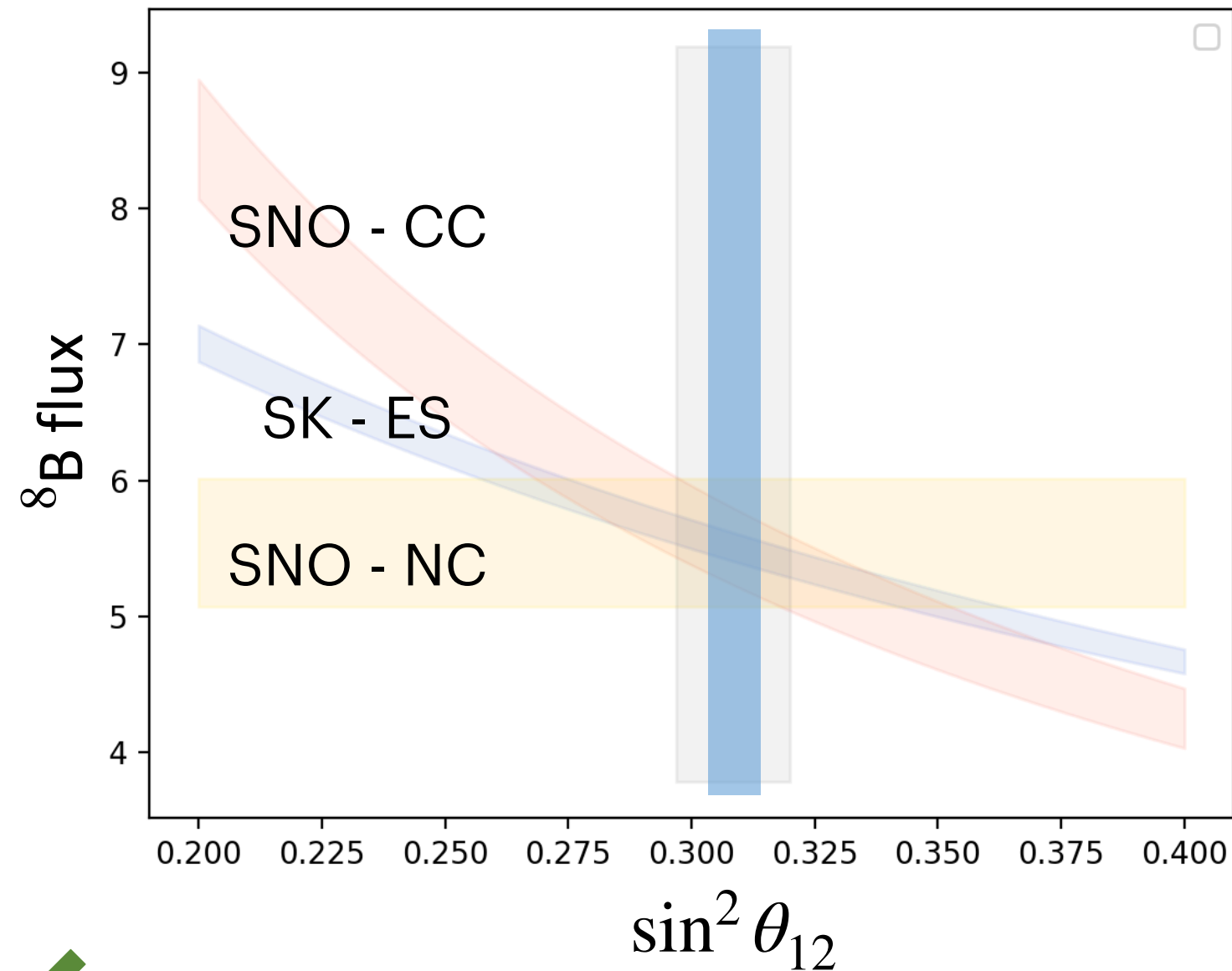
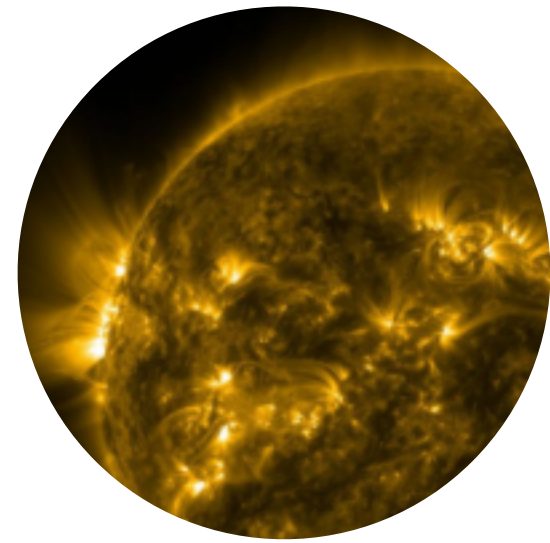


The cross section has
 $\mathcal{O}(100)\%$ uncertainty

The Standard Candles

Solar neutrinos

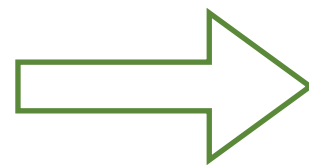
JUNO



DAR: shape ✓

ES + CC + NC detection:

Total flux + oscillation ✓

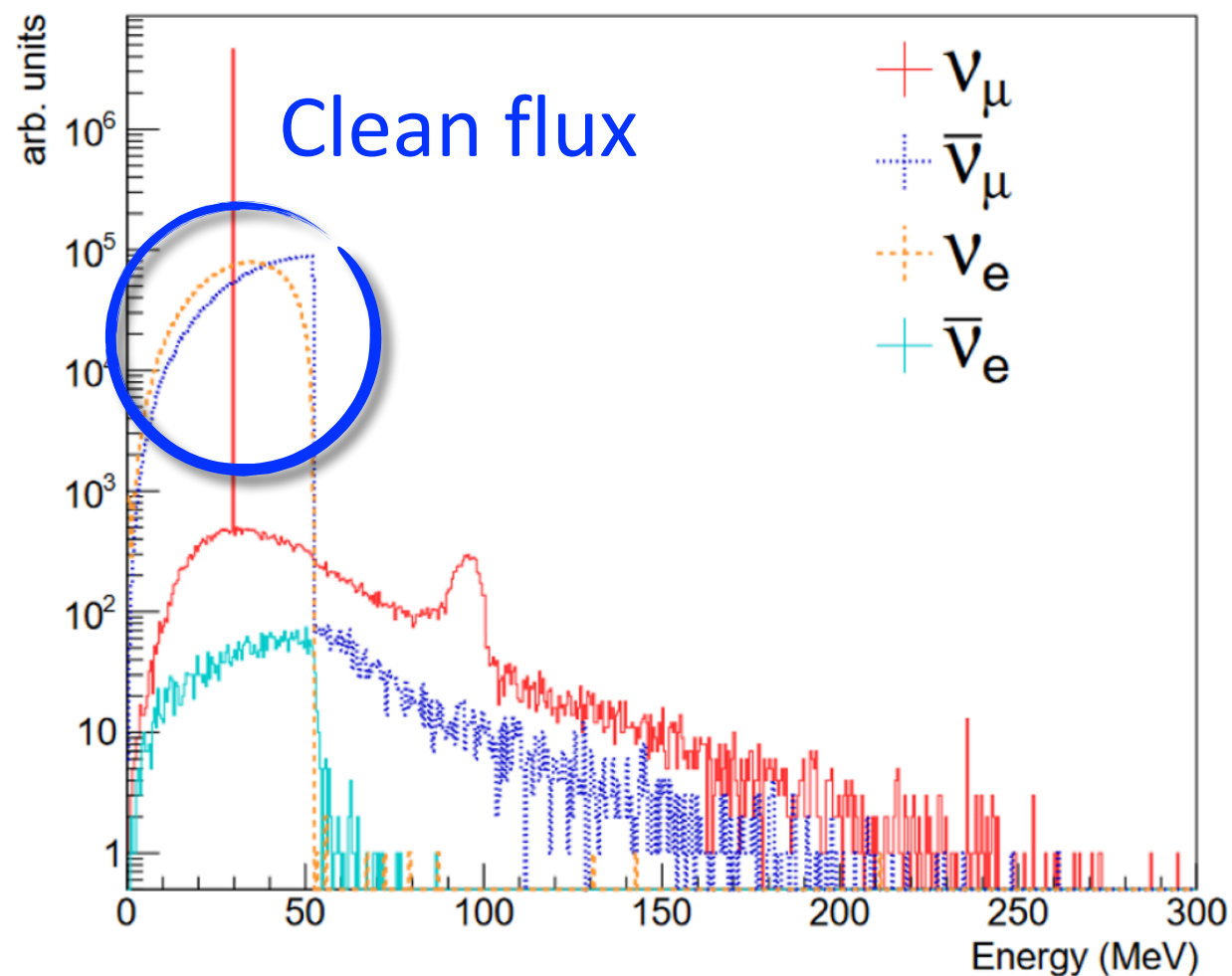


Know flux (few % level)

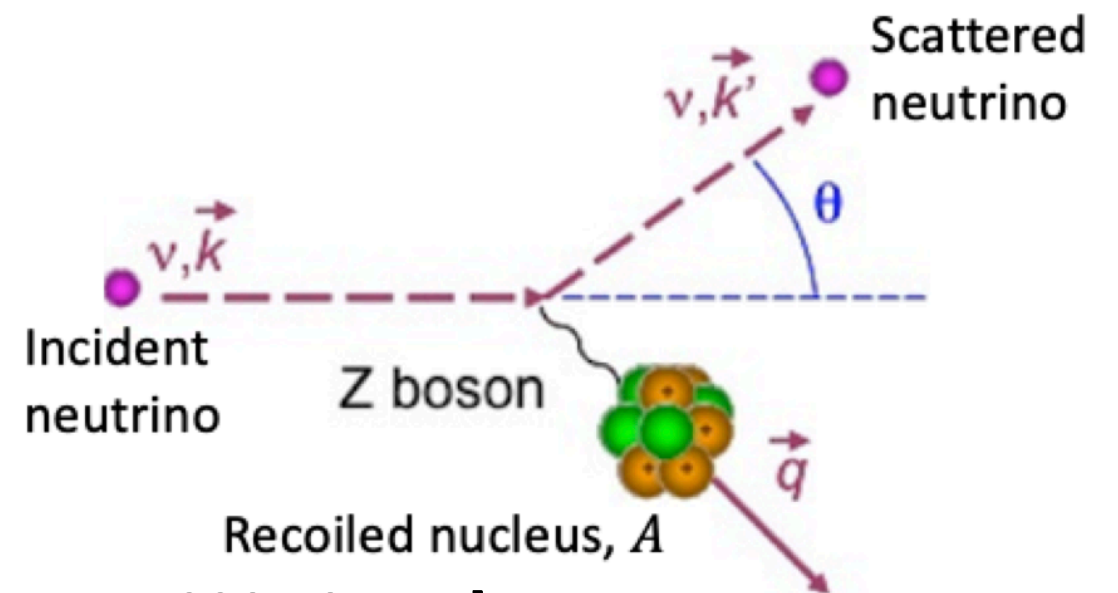
μ DAR neutrinos



Spallation Neutron Source @Oak Ridge National Laboratory



CEvNS: large cross section

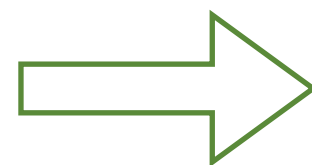


[COHERENT, 2204.04575]

DAR: shape ✓

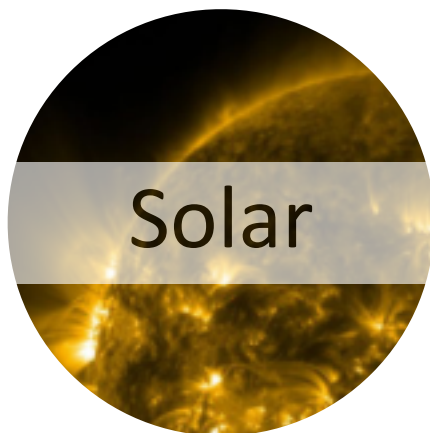
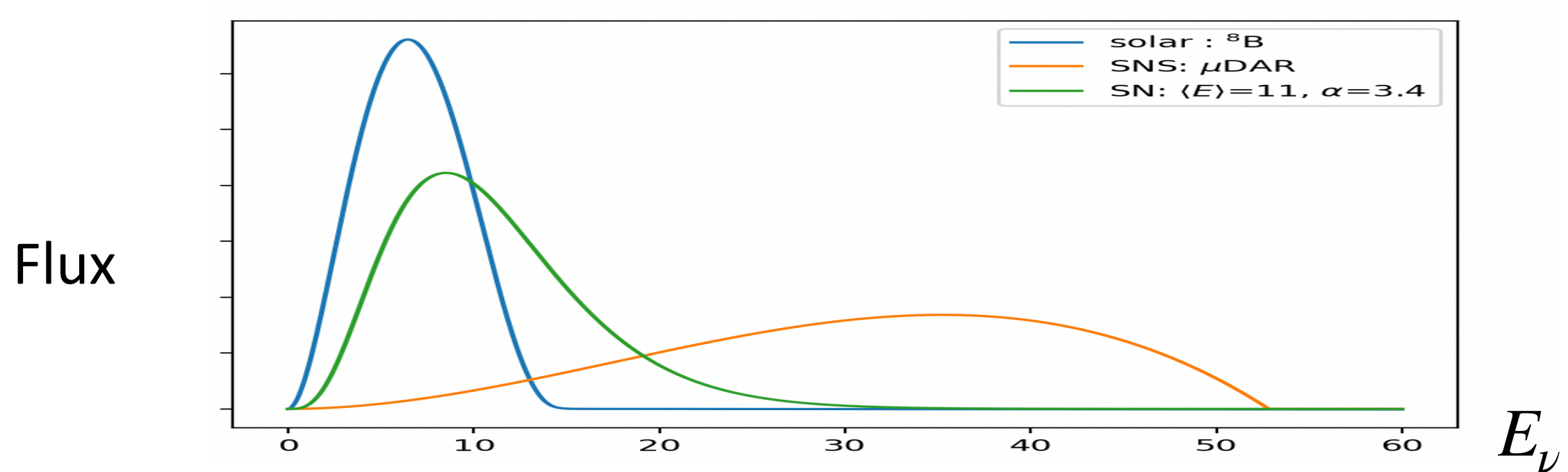
NC detection: total flux ✓

Near: no oscillation ✓



Know flux (few % level)

< 60 MeV sources @ LArTPC



Flux known



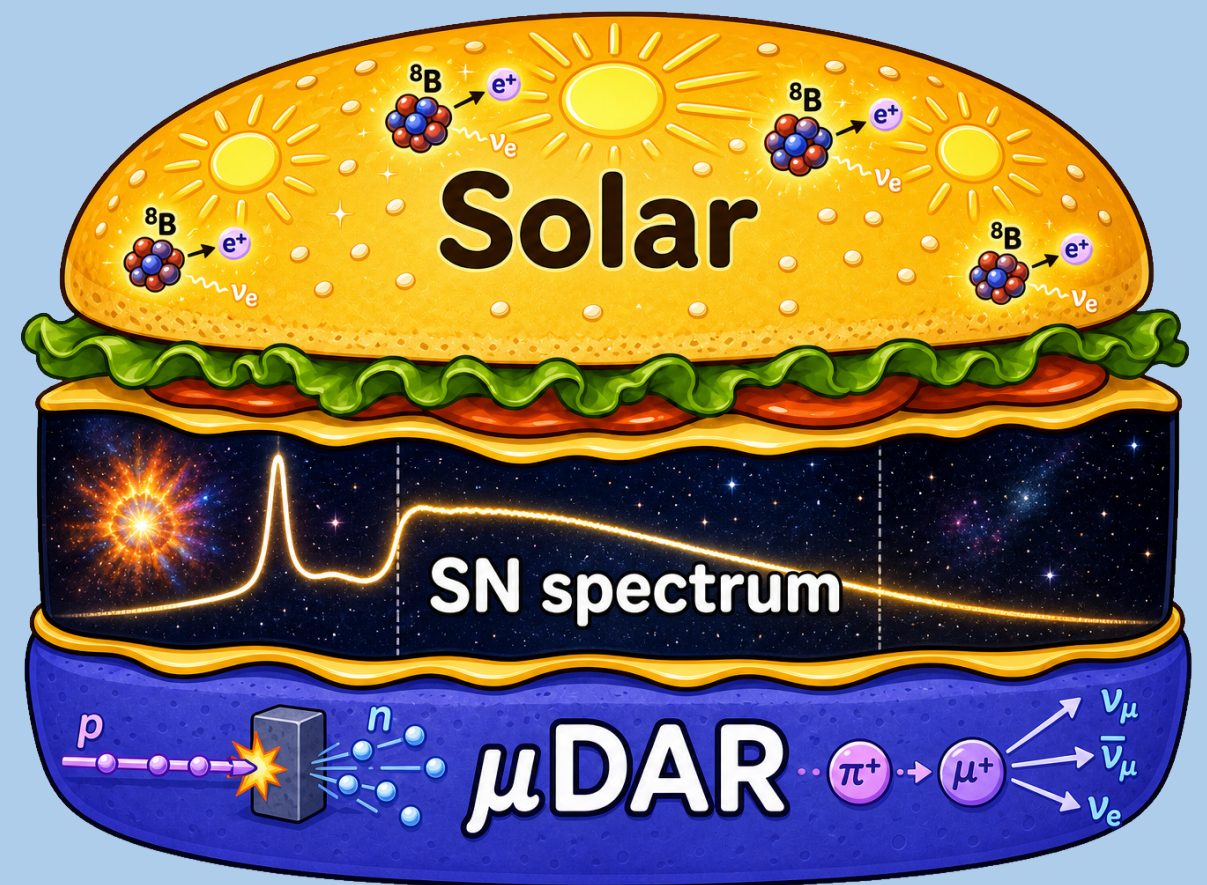
?



Flux known



The Sandwich Method



Step1: over-parametrize the cross section

$$\frac{d\sigma}{dT_e} = \sigma_0 \sum_k w_k \left(\frac{E_e p_e}{1 \text{ MeV}^2} \right) \delta(E_e - E_\nu + \Delta E_k)$$

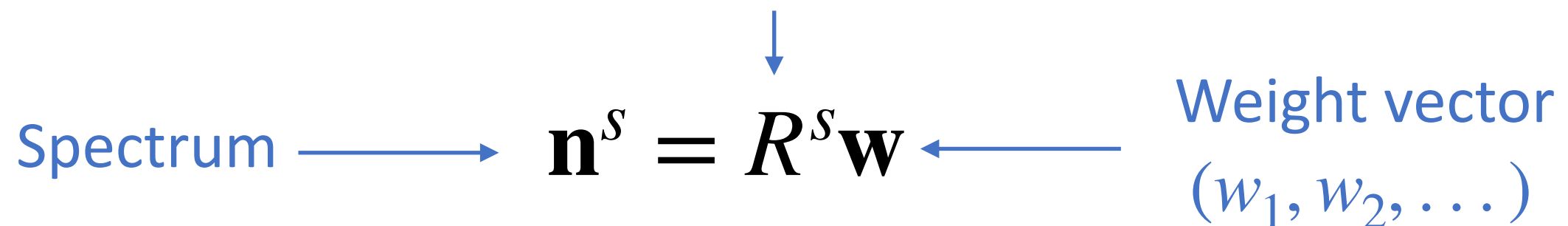

Many, many k s, as dense as we want. w_k is free.

Discrete: most w_k will be 0

Continuous: dense k with smoothish w_k s

Supports both cases

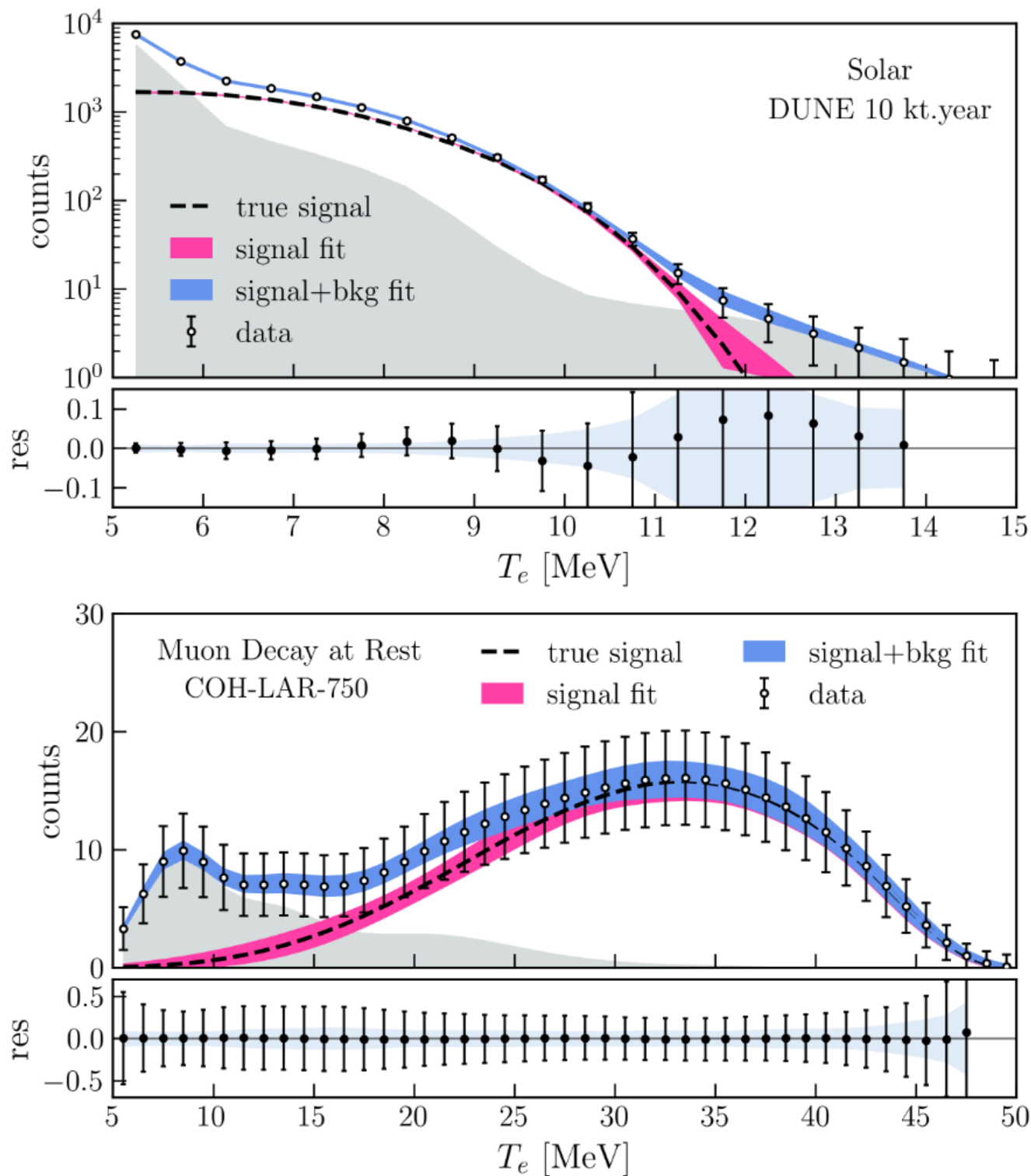
Response matrix (flux dependent)


$$\text{Spectrum} \longrightarrow \mathbf{n}^s = R^s \mathbf{w} \longleftarrow \text{Weight vector } (w_1, w_2, \dots)$$

All sources (s) share the same $\mathbf{w}$

Step2: spectral decomposition

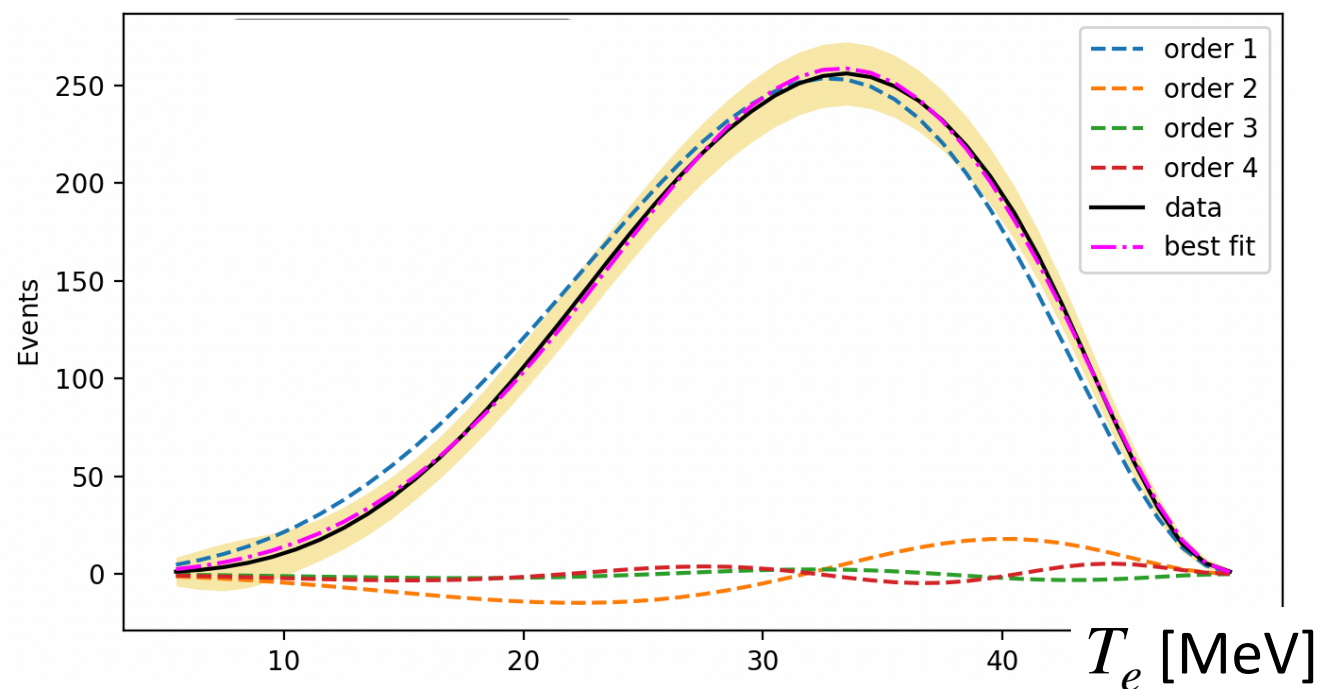
The candles (known R^s) $\rightarrow$ Flux-based basis



Rotate $\mathbf{w} \rightarrow \mathbf{w}^s$

such that $(R^s)^T R^s$ is diagonal

e.g. μ DAR spectrum $\mathbf{n}^\ominus$ in the $\mathbf{w}^\ominus$ basis:



$w_1^\ominus$ dominates $\rightarrow$ tightly constrained by data

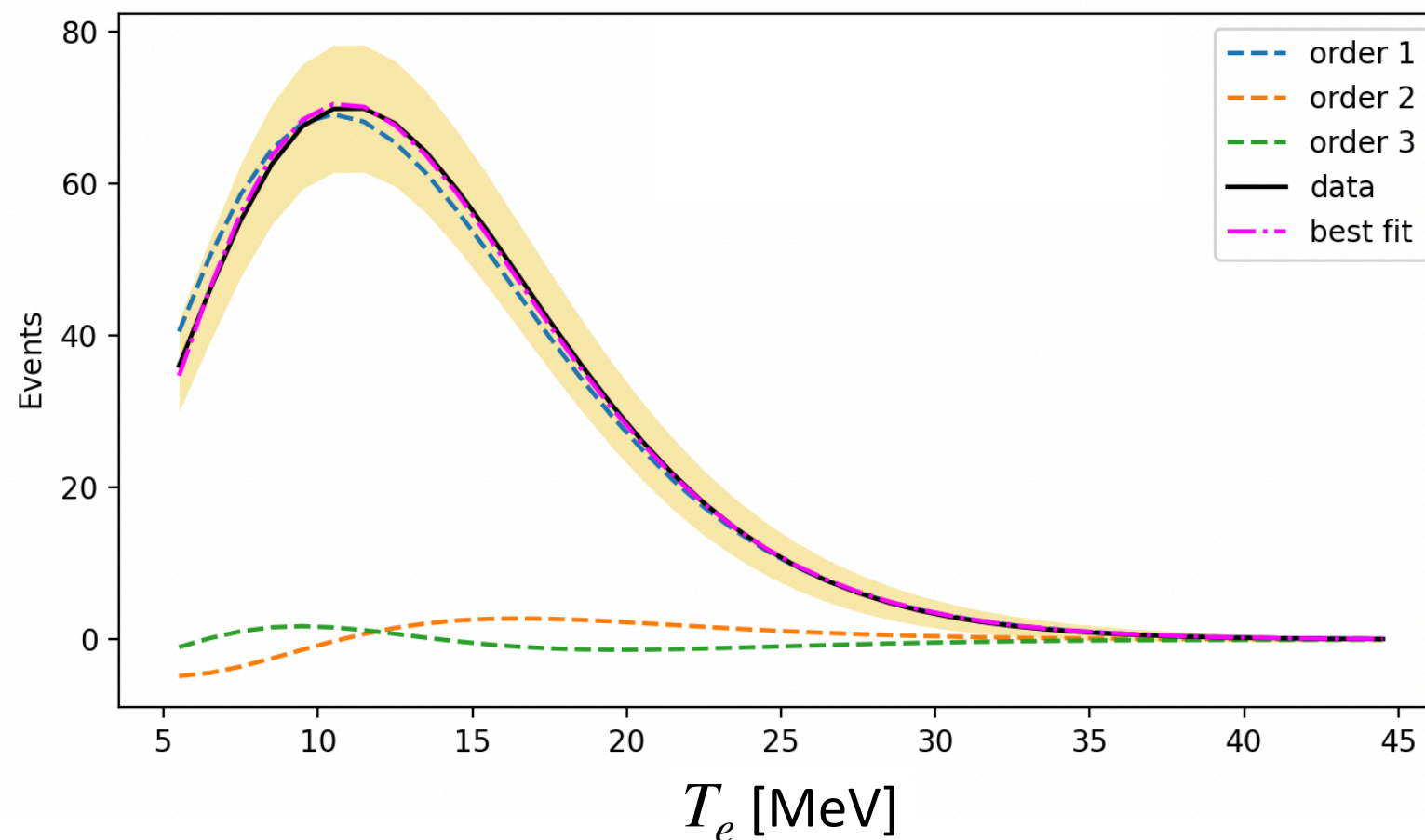
$w_{2-6}^\ominus \rightarrow$ somewhat constrained by data

$w_{7-X}^\ominus \rightarrow$ does not affect data (truncate)

Step2: spectral decomposition

Supernova $\rightarrow$ Data-based basis (Fisher information)

For every SN model, rotate $\mathbf{w} \rightarrow \mathbf{w}^\star$, such that $(R^\star)^T C^{-1} R^\star$ is diagonal



If the SN flux is smooth, it can also be described by only a few modes

But even for $n^\star = r^\star \times w_1^\star$, we need to know $w_1^\star$ to constrain $r^\star$

↑
Measure

CETUP

Step3: projection

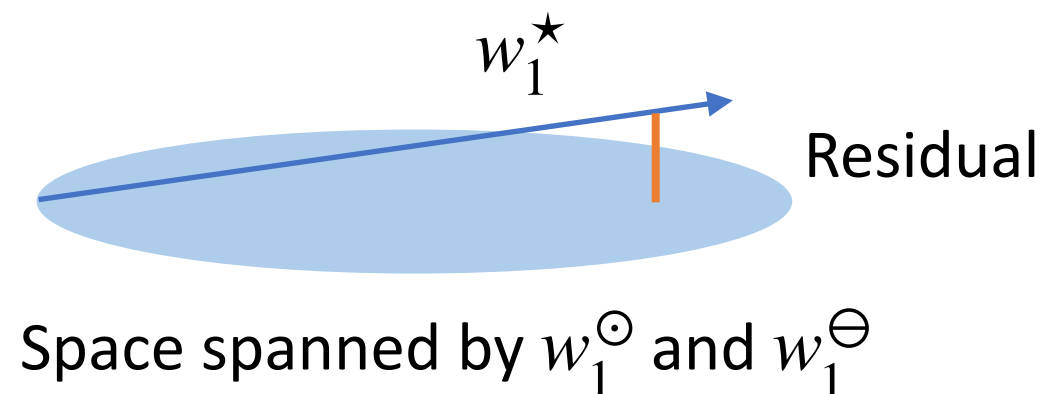
Exercise:

We only need to know $w_1^\star = \alpha_1 w_1 + \alpha_2 w_2 + \dots$ (SN)

Can we get that by knowing $w_1^\odot = \beta_1 w_1 + \beta_2 w_2 + \dots$ (solar)

and $w_1^\ominus = \gamma_1 w_1 + \gamma_2 w_2 + \dots$ (μ DAR) ?

No, but we can know how much is missing — projection and residual



$w_1^\star$ can be inferred by $w_1^\odot$ & $w_1^\ominus$ through projection with some error by the residual

Step4: data fit (SN), with priors (Candles)

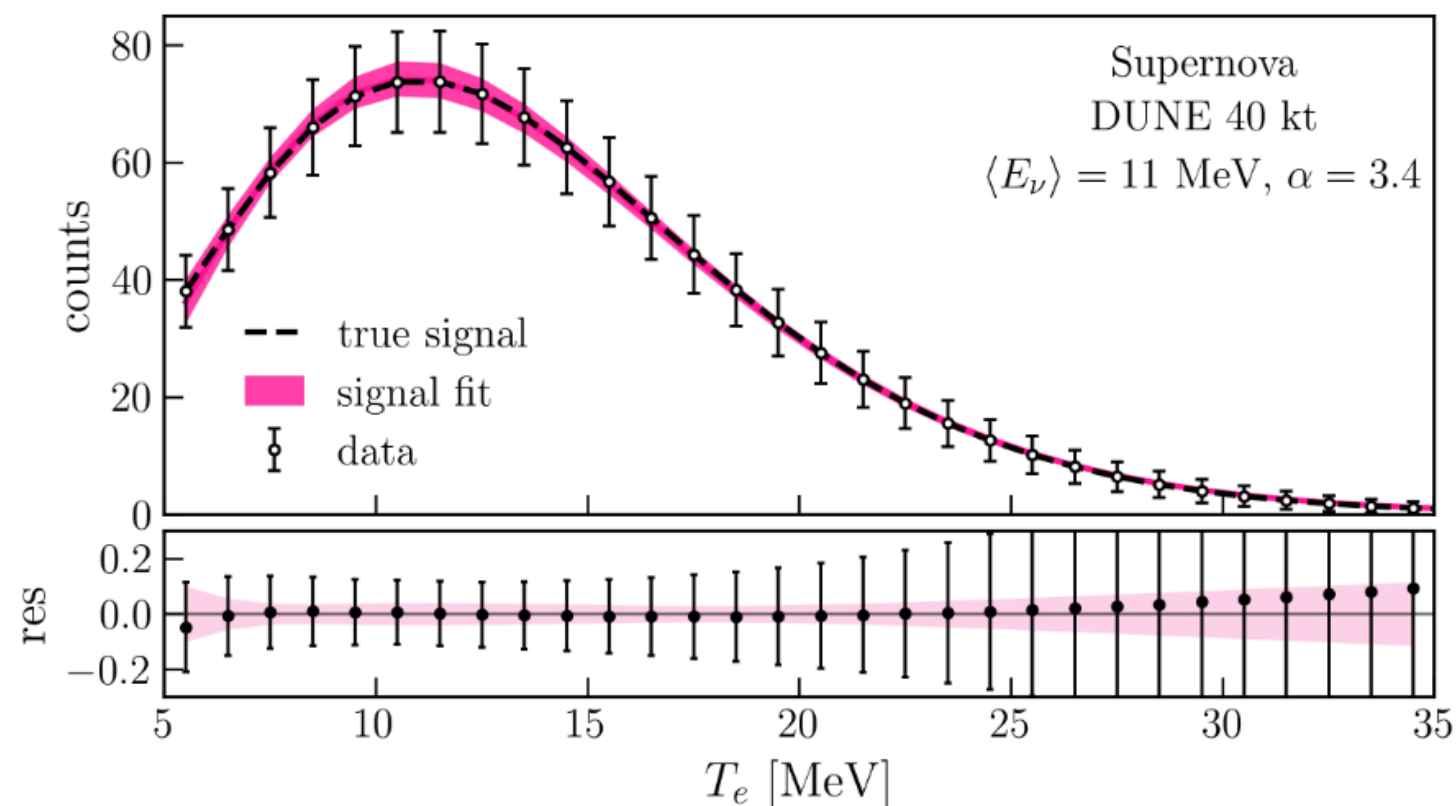
$$\chi^2 = (\mathbf{d}^* - R^* U_{m_*}^* \mathbf{w}^*)^T (C_{T_e}^*)^{-1} (\mathbf{d}^* - R^* U_{m_*}^* \mathbf{w}^*) + (\mathbf{w}^* - \mathbf{w}_{\text{cal}}^*)^T (C_{\text{cal}}^*)^{-1} (\mathbf{w}^* - \mathbf{w}_{\text{cal}}^*),$$

SN Data

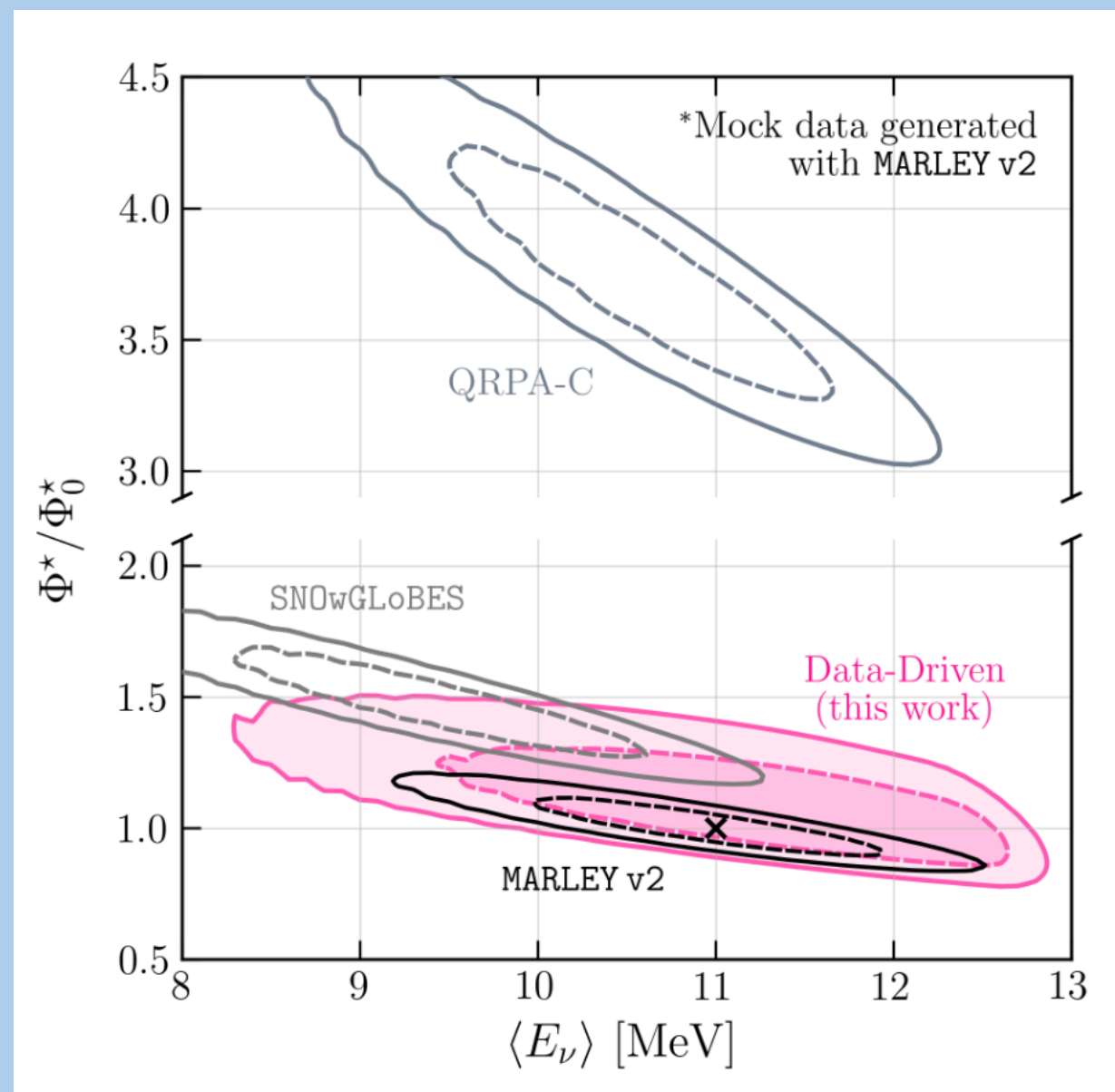
SN Fisher basis

Calibration basis projection to SN basis

Solar, μ DAR uncertainties + residual



Data-driven



Now, what can we do with this precision on ν_e ?

For example...

Neutrino-antineutrino Asymmetry

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

Source (SN, sun)

Detection

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

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

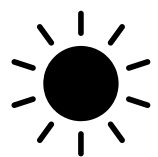
SN: $\langle E_{\nu_e} \rangle < \langle E_{\bar{\nu}_e} \rangle$

DUNE IBDs

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

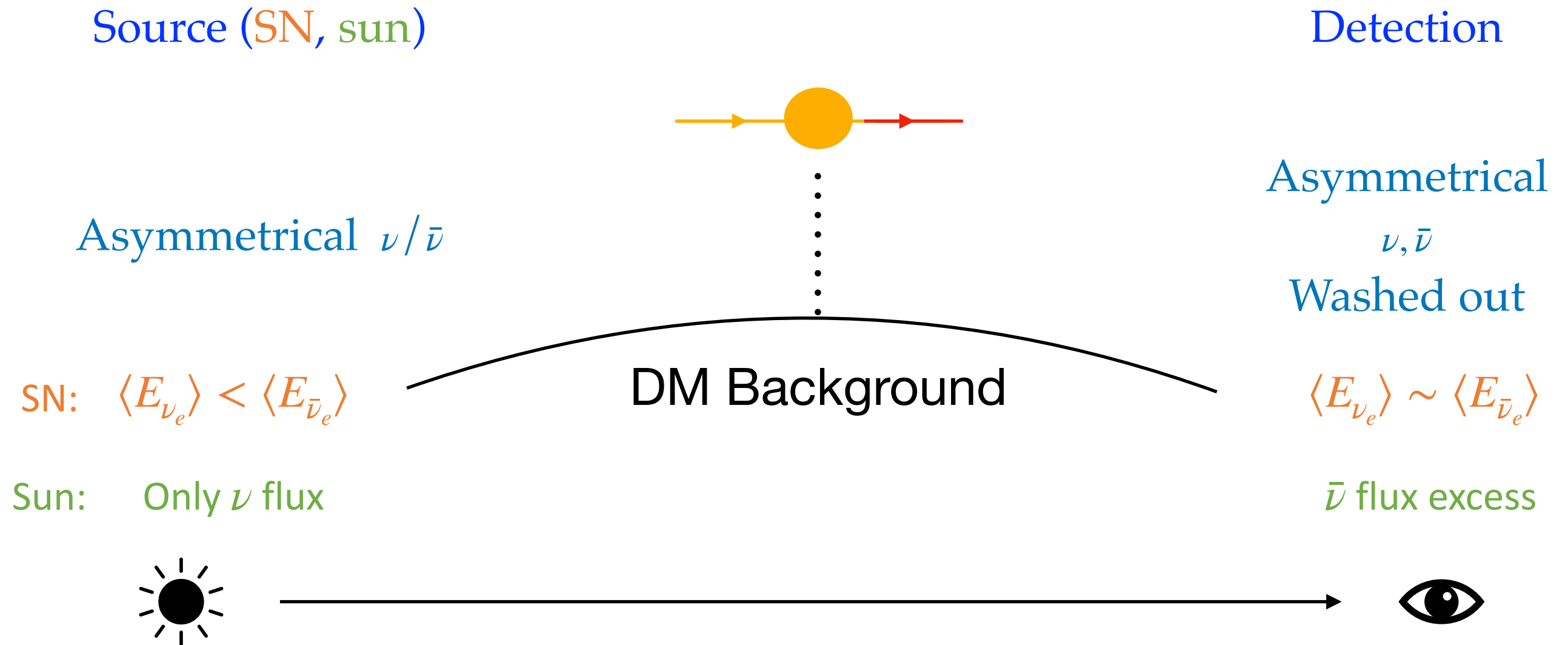
Sun: Only ν flux

Only ν flux



Carries uncontaminated message from the source

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



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

Why should dark matter interact
with neutrinos?

Majorana neutrinos

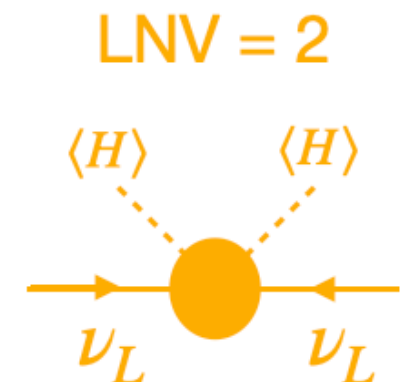
Why are neutrino masses so small, yet non-zero?

The unique dim-5 Weinberg operator (EFT)

$$\mathcal{L} = \mathcal{L}_{SM} + \frac{1}{\Lambda} \alpha_{LH}^{(5)} \mathcal{O}_{LH}^{(5)} + \frac{1}{\Lambda^2} \sum_i \alpha_i \mathcal{O}_i + \frac{1}{\Lambda^3} \sum_j \alpha_j \mathcal{O}_j + \dots$$

Majorana neutrino mass

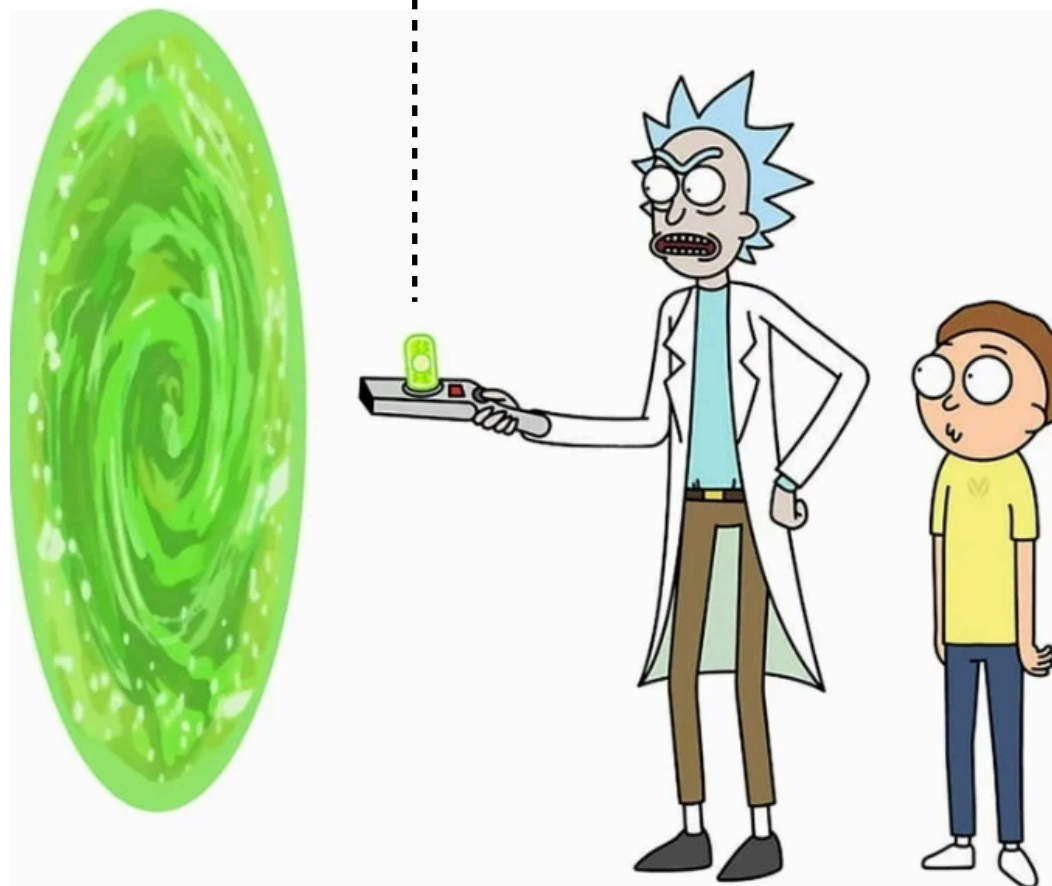
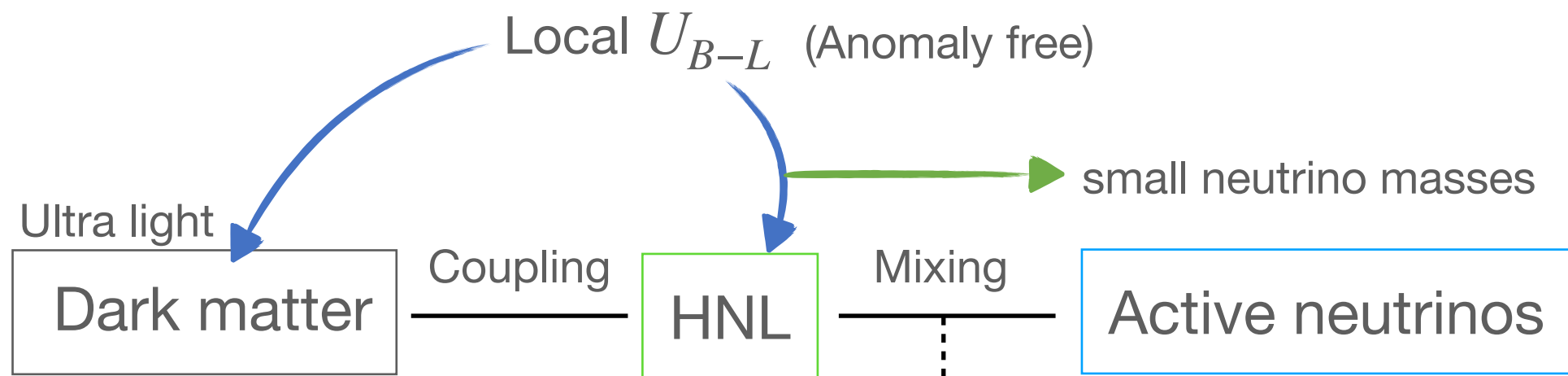
→ UV complete story: U_{B-L}



seesaw mechanisms,
Loop generated

If lepton number is part of a *local* symmetry, U_{B-L} , broken spontaneously
→ new boson coupled to ν

If this new boson is Dark Matter



TV show: Rick & Morty

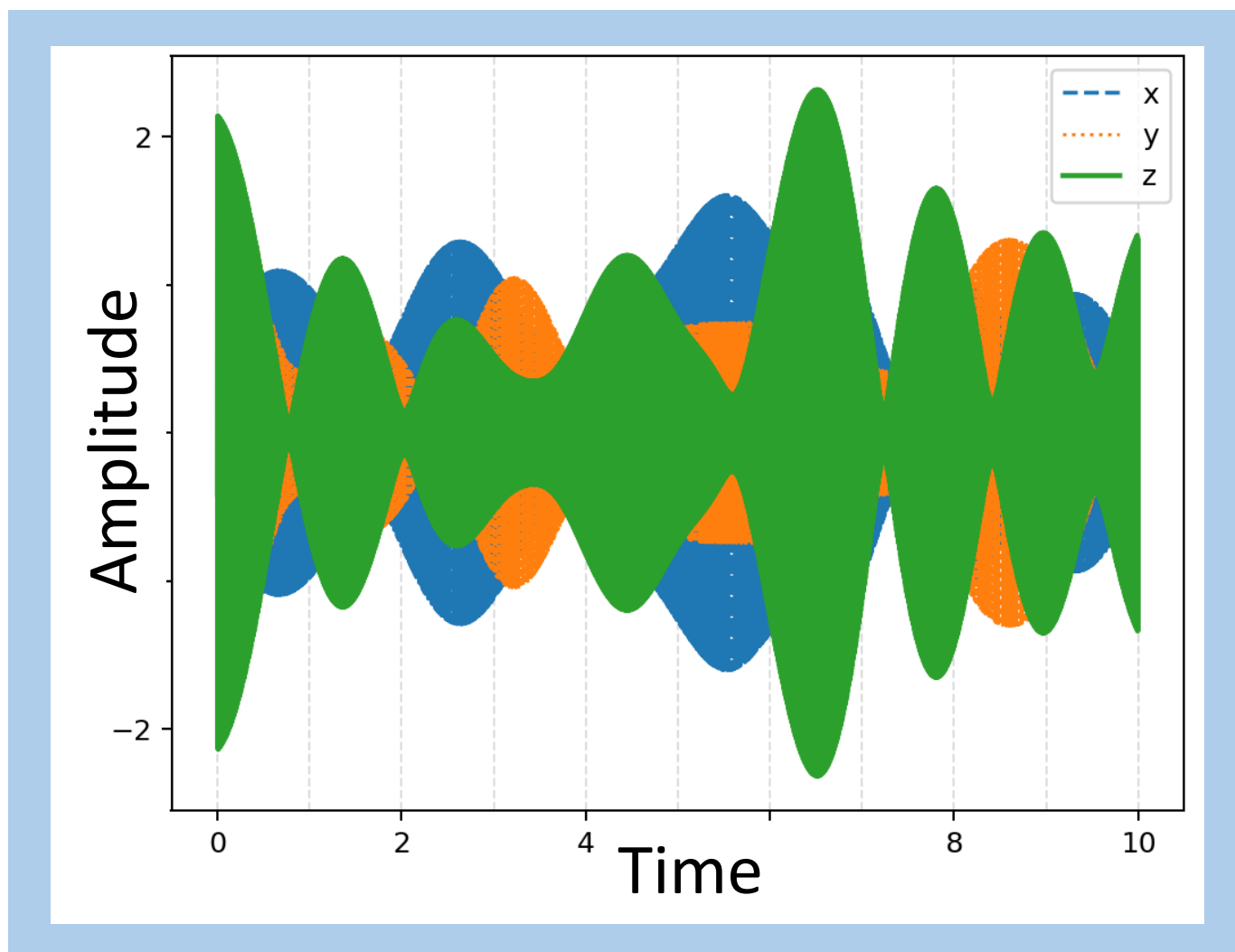
Neutrino portal to dark matter

How Vector Dark Matter drives
Neutrino - antineutrino transition

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



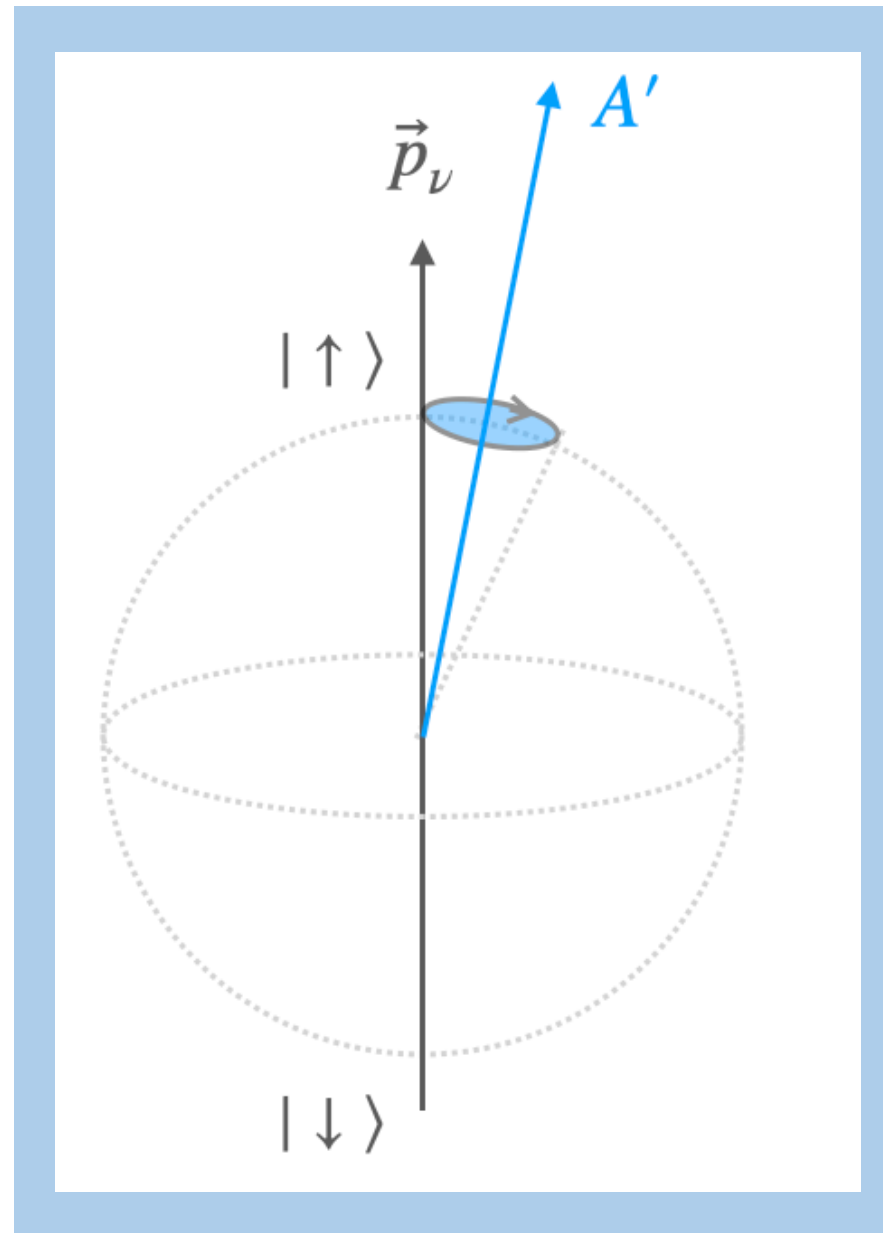
$$\text{Coherence time} \sim 10^3 \times \frac{2\pi}{m_{A'}}$$

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



driving ν - $\bar{\nu}$ transition

two-level system

Fermion
(quantum system)

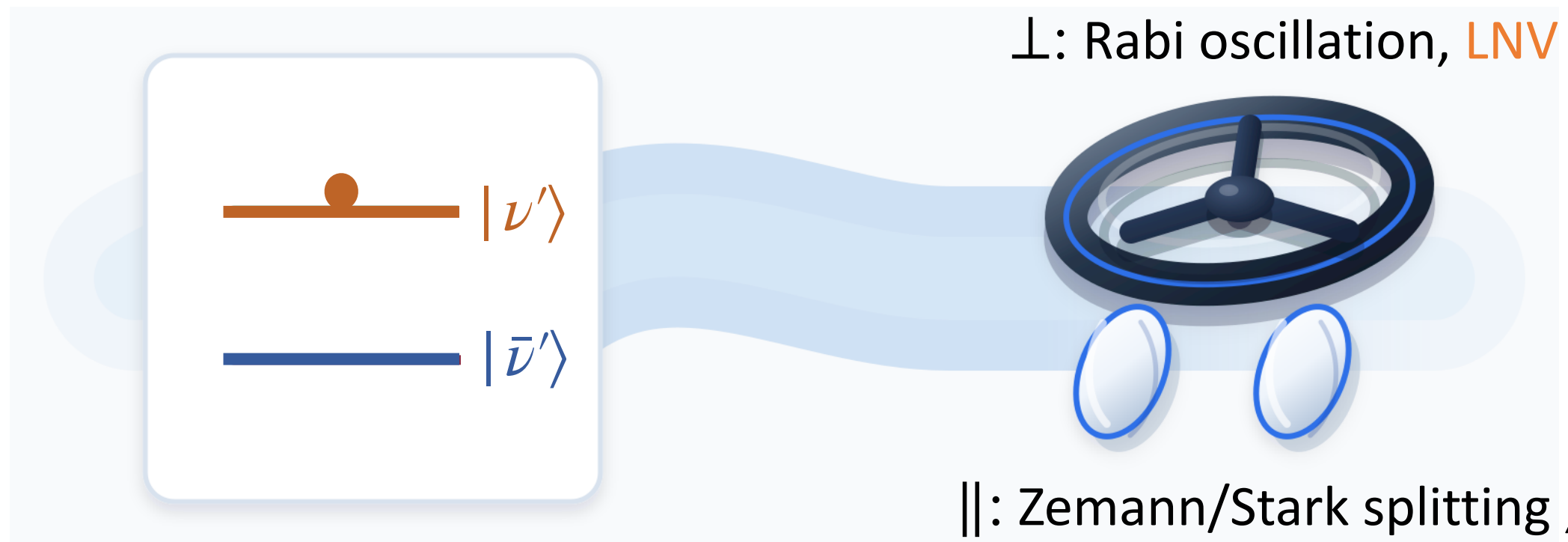


external field

Boson
($\sim$ classical system)



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

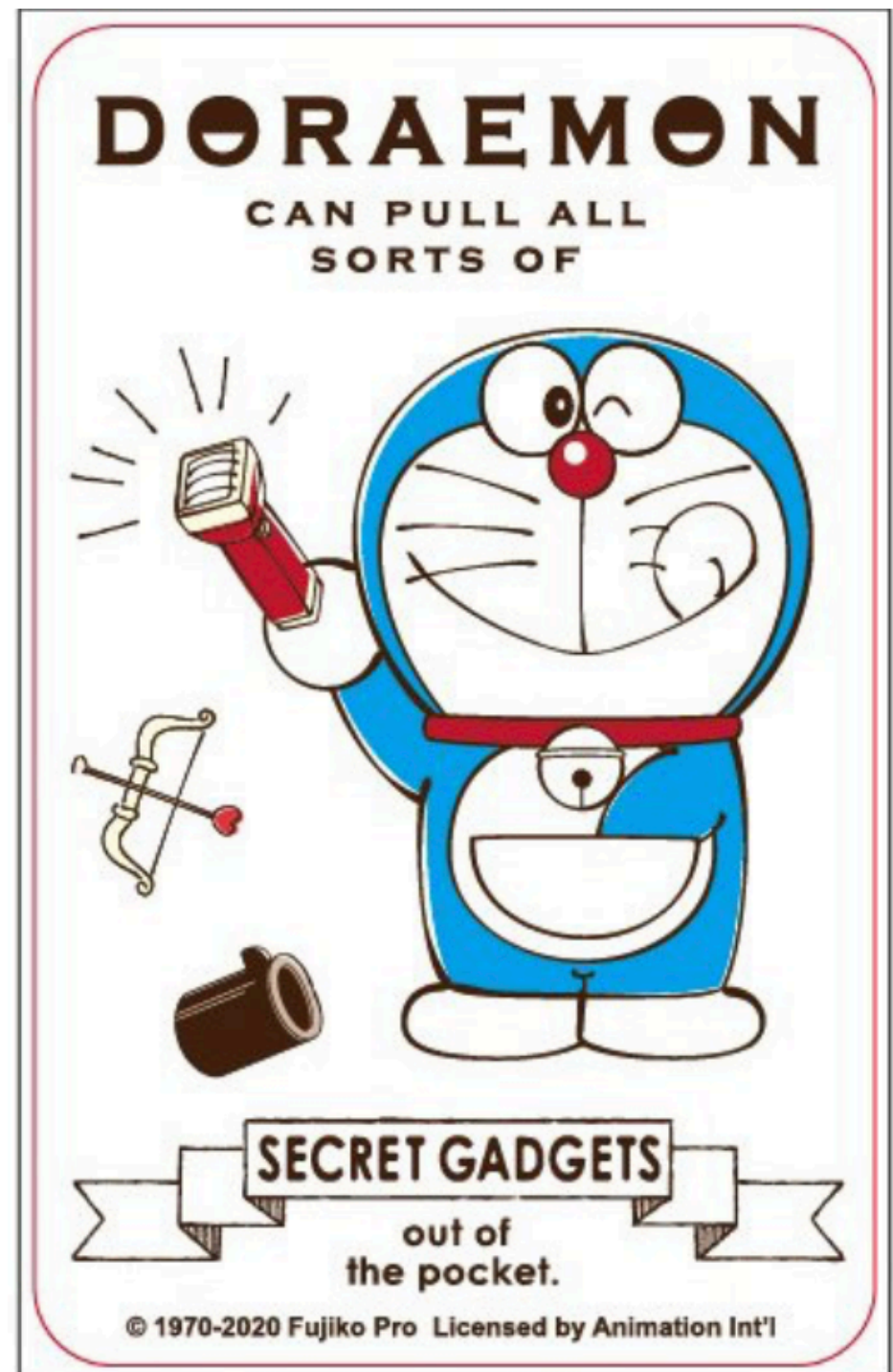


Two level system driven by a Bosonic bath

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

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

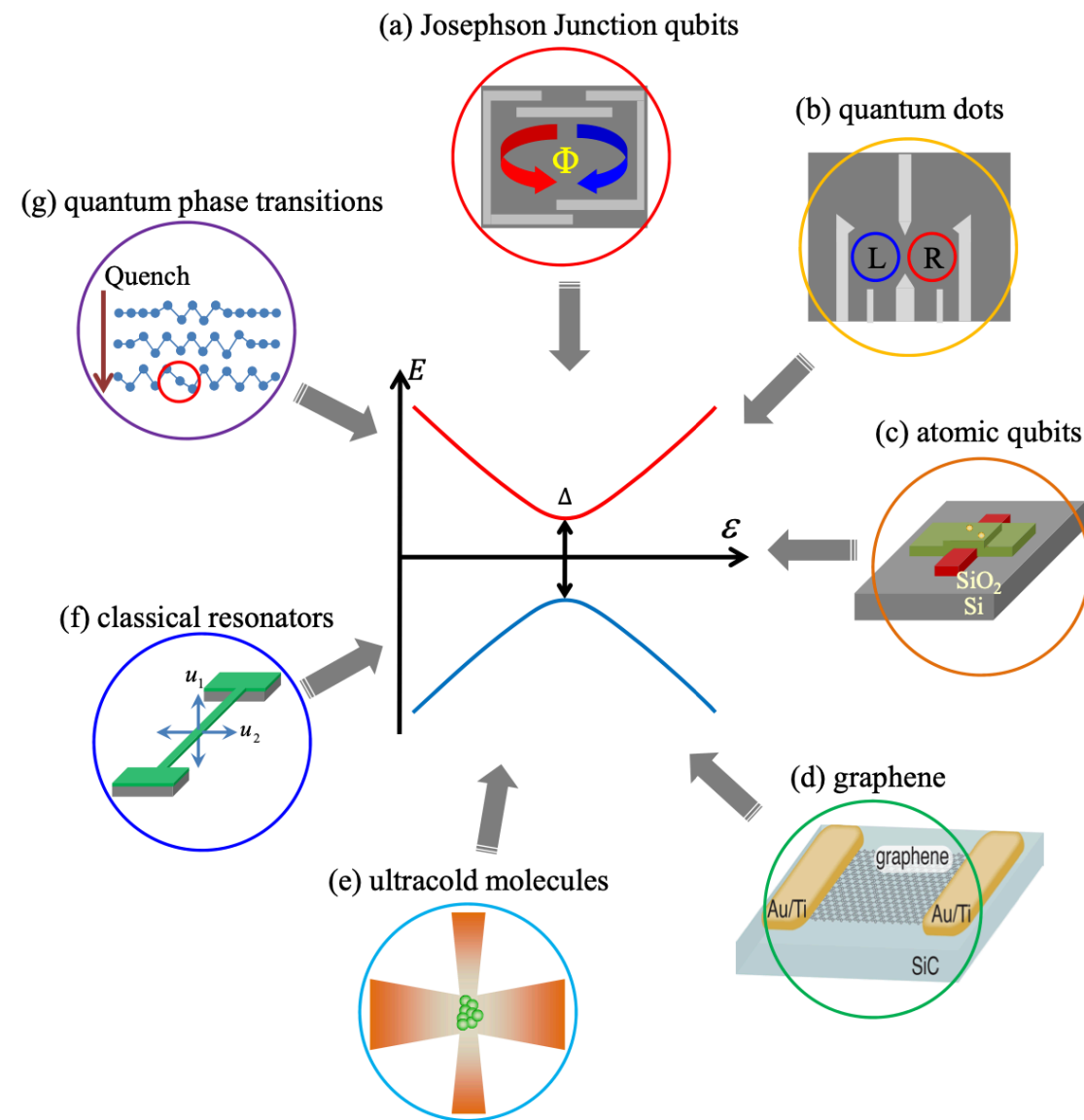
$$\frac{V_{\parallel}}{V_{\perp}} \lesssim 10^{-7} : \text{non-adiabatic @ } V_{\parallel} \rightarrow 0$$



Non-adiabatic transitions

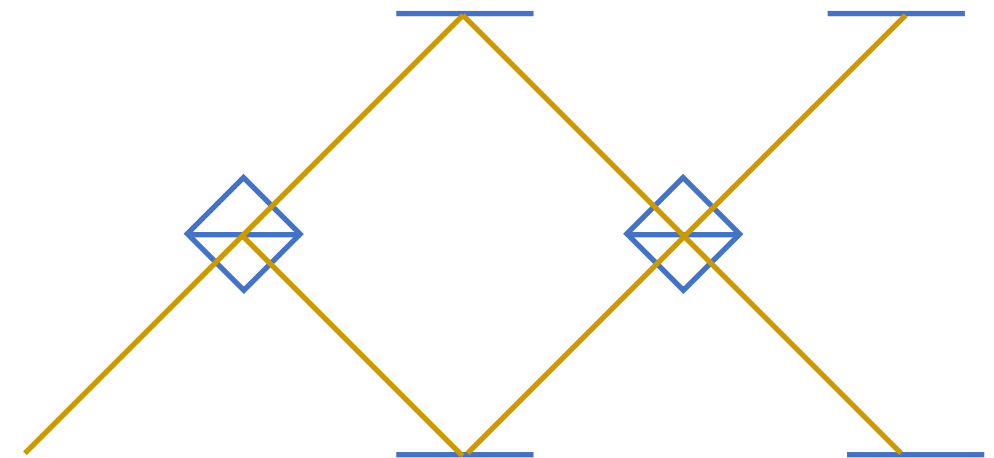
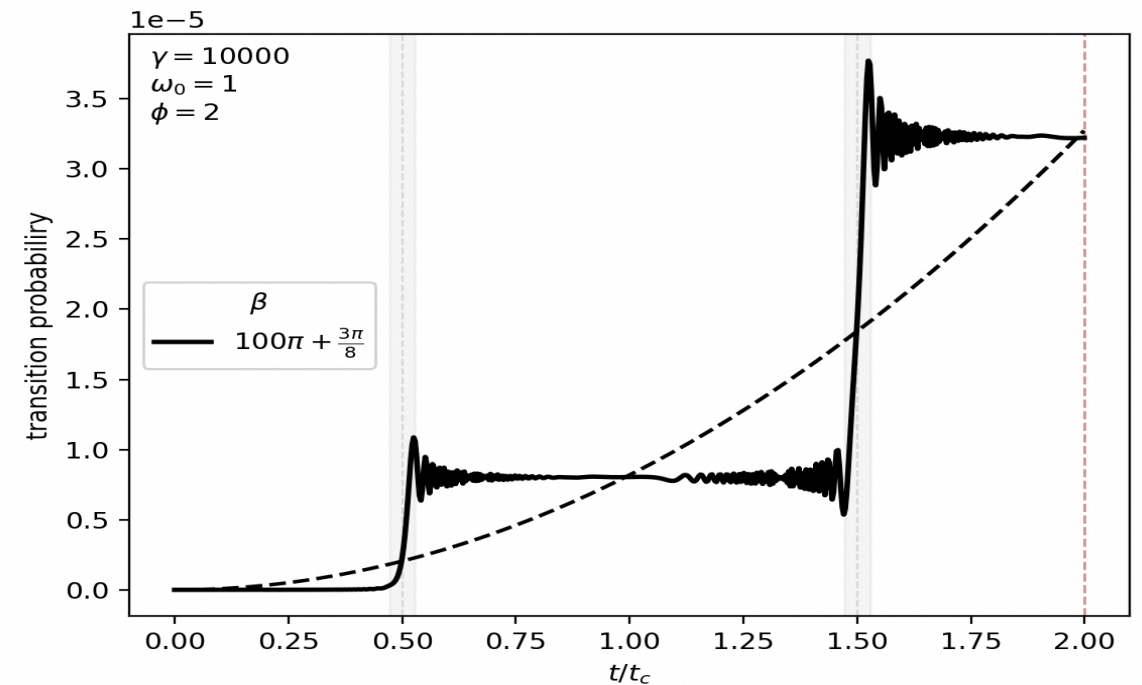
Landau-Zener-Stückelberg-Majorana transitions

(Periodic) avoided level crossings in TLS:



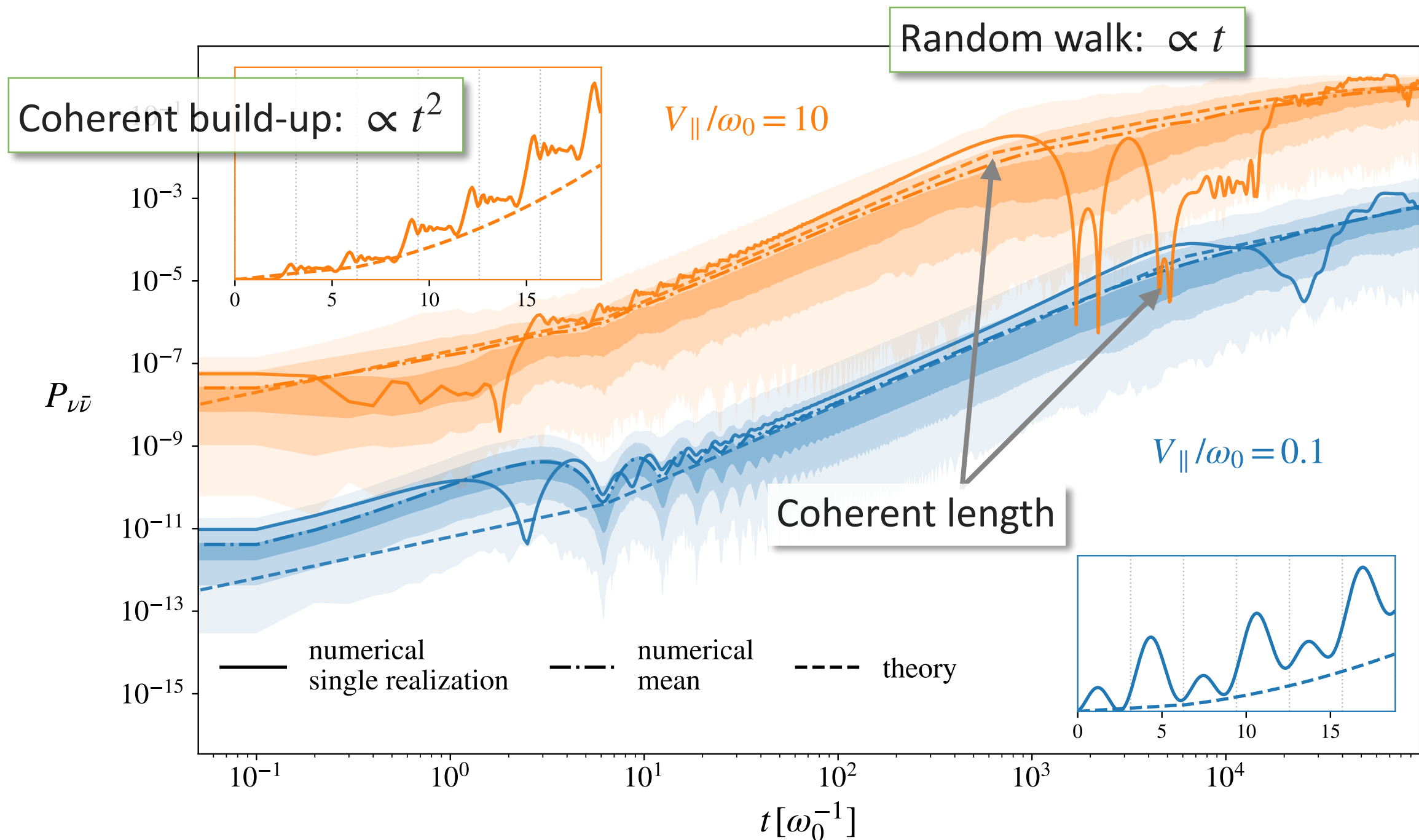
[O. Ivakhnenko, S.Shevchenko, F.Nori, 2022 Review]

Stückelberg inference
 LZ transition LZ transition



Neutrino - antineutrino transition probability

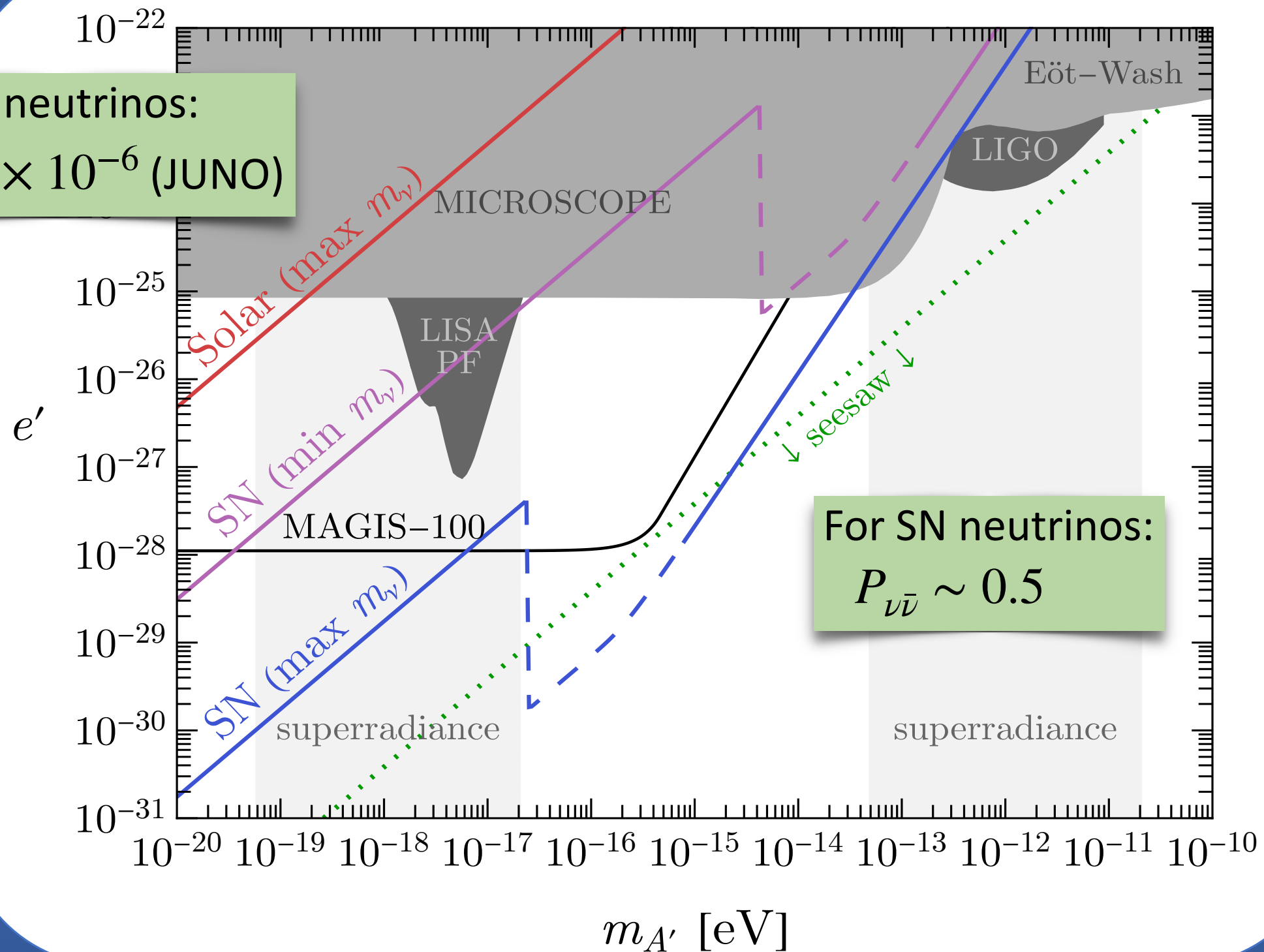
Elliptically polarized DM $\rightarrow V_{\parallel}$ and $V_{\perp}$ out of phase $\rightarrow$ periodic avoided level crossings



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

Experimental reach for U_{B-L} vector DM

For solar neutrinos:
 $P_{\nu\bar{\nu}} > 2 \times 10^{-6}$ (JUNO)

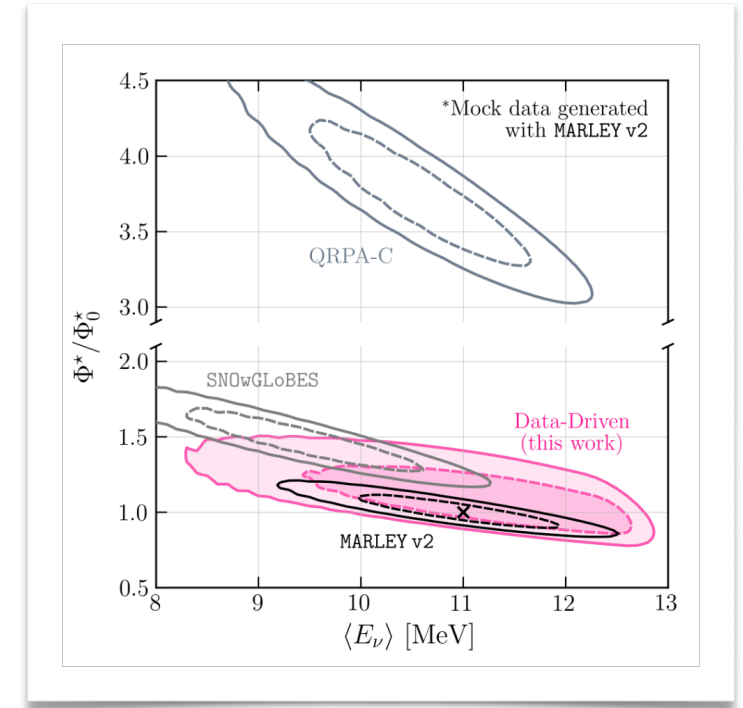
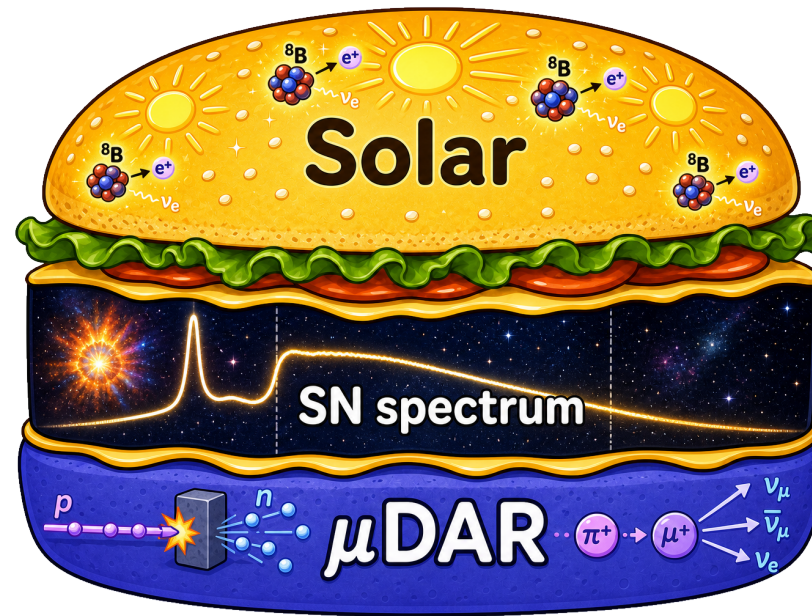


Summary

Known flux



Known flux



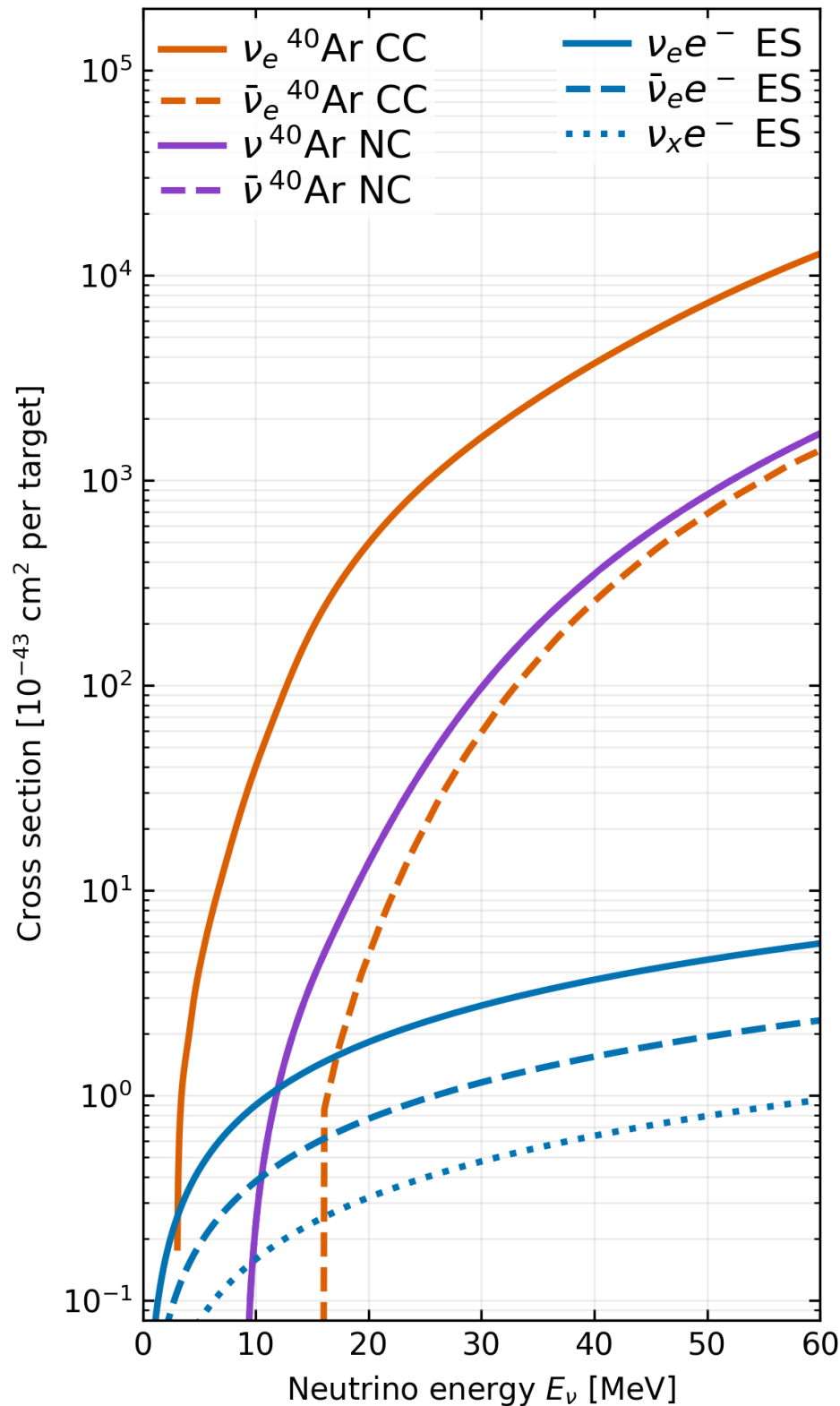
Missing piece of measuring neutrino - antineutrino asymmetry from SN

Vector DM background can washout Neutrino - antineutrino asymmetry

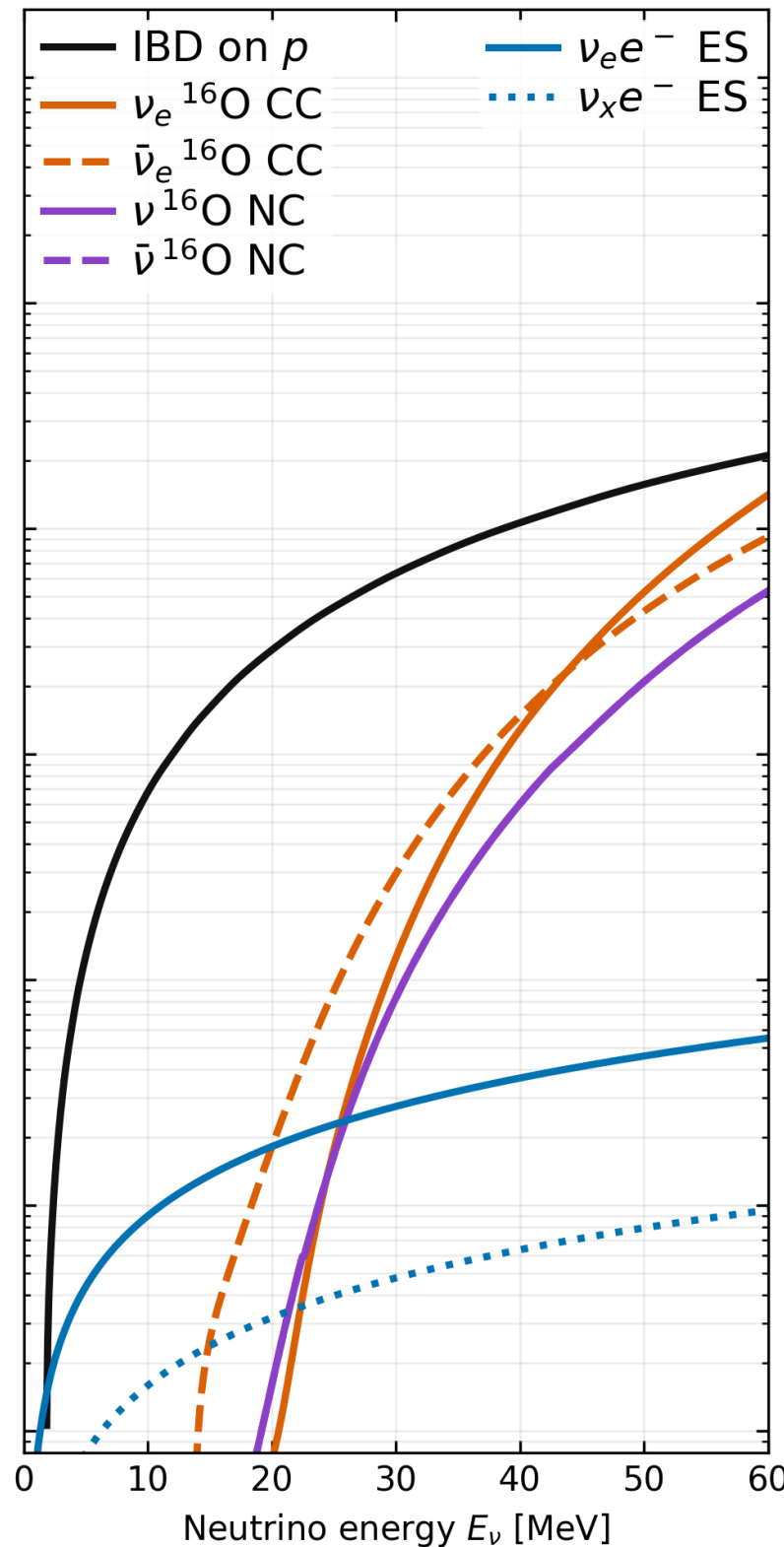
→ test U_{B-L} vector DM

Cross sections

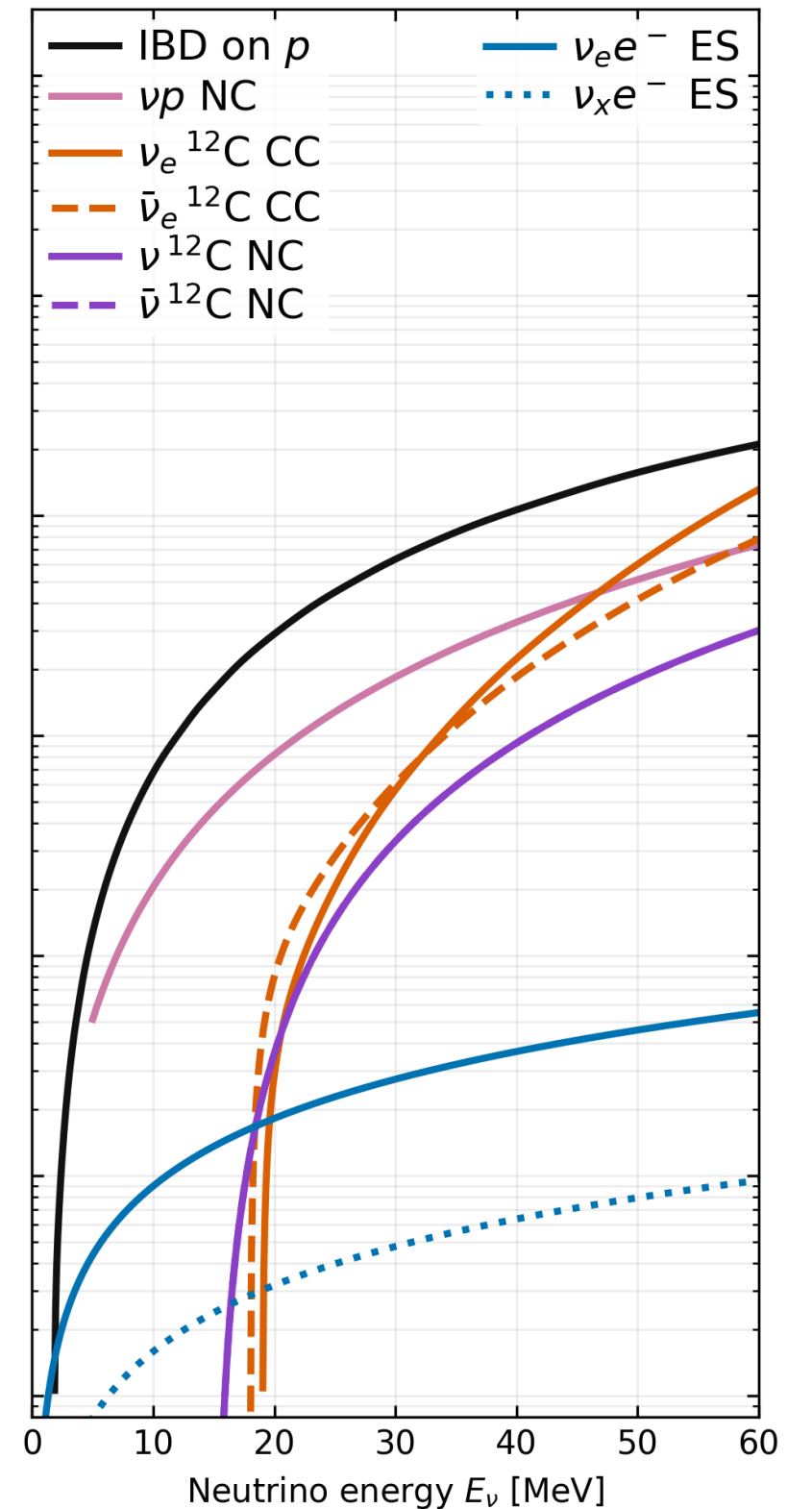
Argon / DUNE



Water or ice / HK, IceCube



Liquid scintillator / JUNO



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

Neutrino spin in a DM bath

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

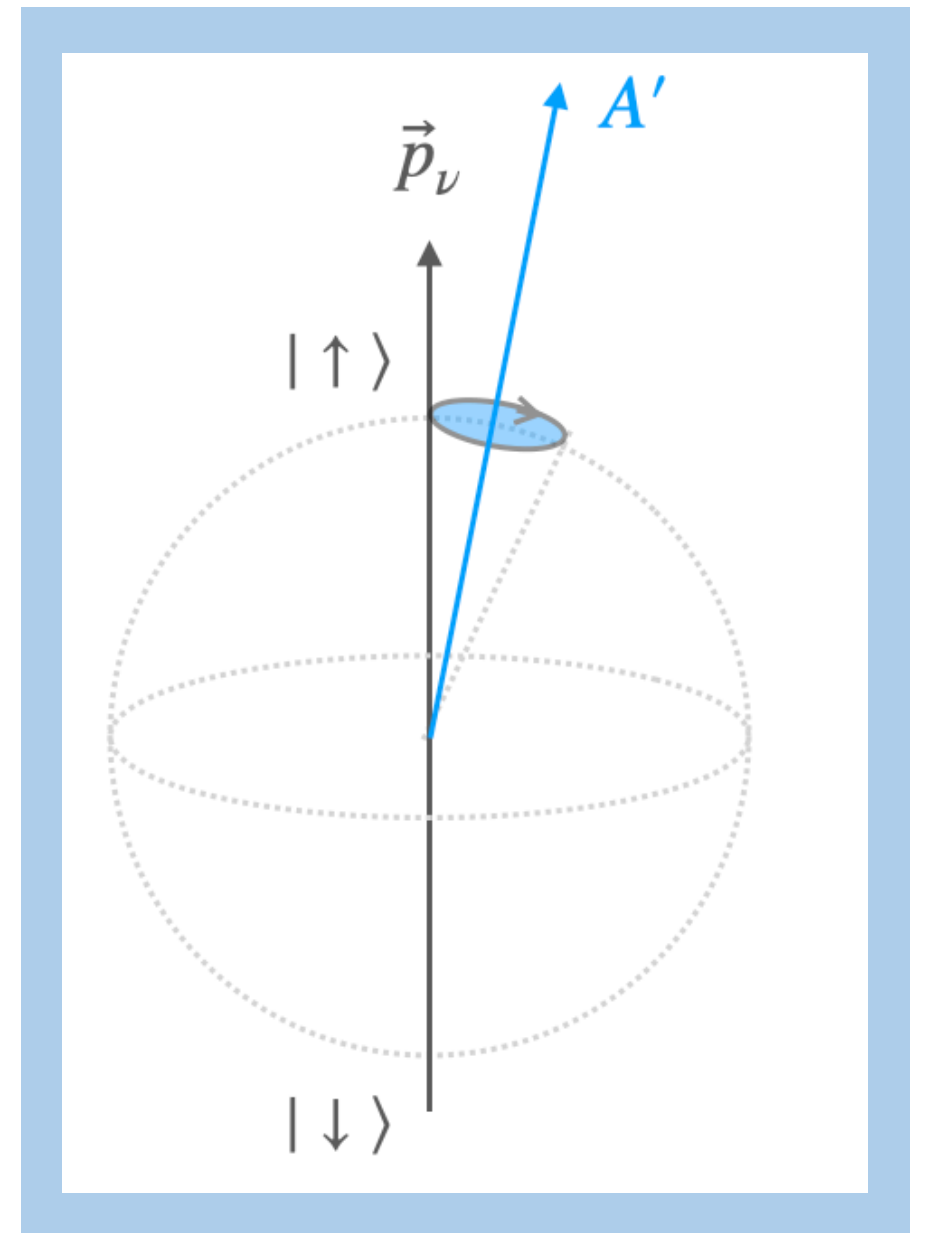
$$H = V_{\parallel} \sigma_z + V_{\perp} \sigma_{\perp}, \quad \frac{V_{\perp}}{V_{\parallel}} \sim \frac{m_\nu}{E_\nu}$$

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:**

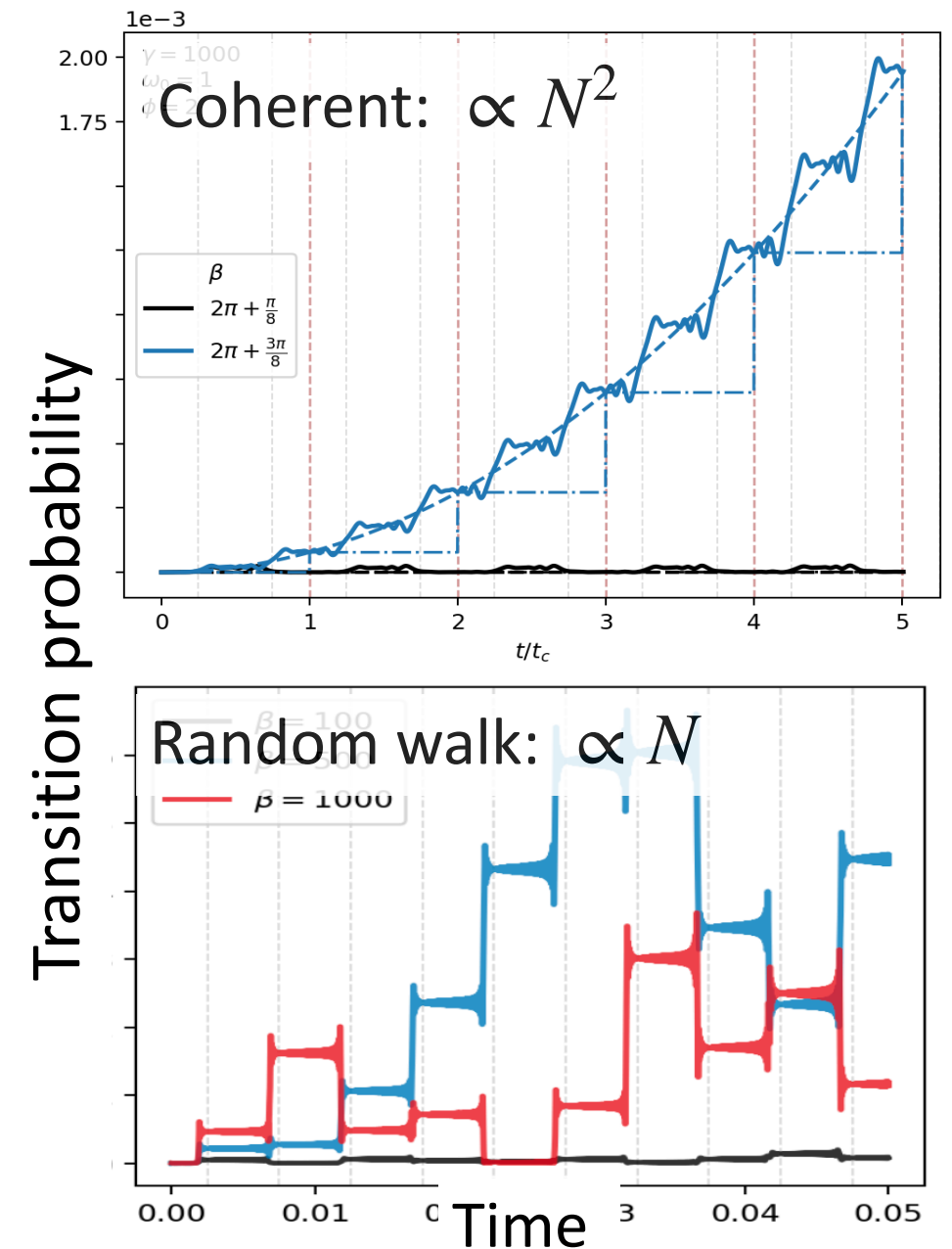
$$\delta = \frac{V_{\perp}^2 \varepsilon^2}{2 V_{\parallel} \omega} \propto \frac{1}{\gamma^2} \ll 1 \text{ (non adiabatic)}$$

- **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):**

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



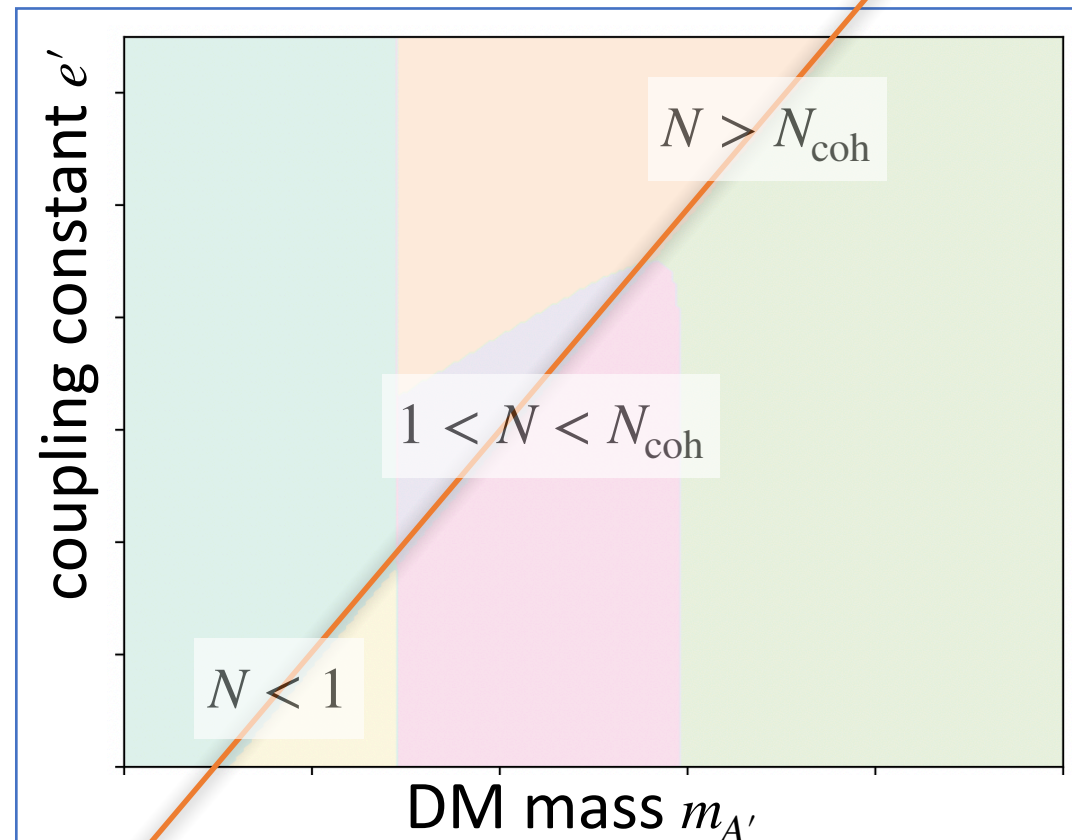
Tiny rate per unit time, but accumulates over astrophysical baselines!

Quantum regiem

N_{coh}

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

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



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

Coherent build-up
Effective Rabi Osc

Random walk
with small (t_{osc}) steps

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

N_{coh}

Parameters:

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