

SN1987A constraints on the neutrino-dark-fermion interaction from resonant scattering with $C\nu B$

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OUTLINE

1. **Motivation** (why & how)
2. **Methods** (scattering rate & flux)
3. **Results** (current data & projections)
4. **Summary**

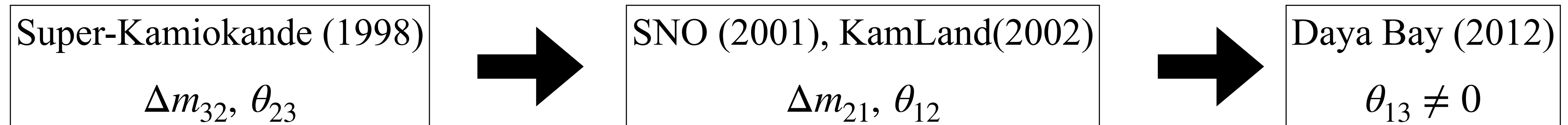
Where neutrino self-interaction comes from

Neutrino Oscillation: evidence for non-zero neutrino mass

Minimal Standard Model

Prediction: $m_\nu = 0$

Oscillation Observations



$$\nu_{\alpha L} = \sum_{i=1}^3 U_{\alpha i} \nu_{iL} \quad \Delta m_{ij}^2 \neq 0$$

How to explain neutrino masses?

From neutrino mass model to new interactions

The seesaw mechanism

$$\nu_L \xleftrightarrow{m_D} N_R$$
$$M_N \gg m_D \quad \longrightarrow \quad m_i \simeq \frac{m_{D_i}^2}{M_{N_i}}$$

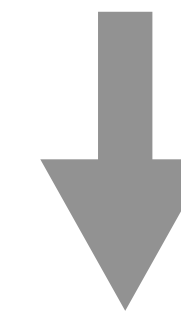


extension



New interaction

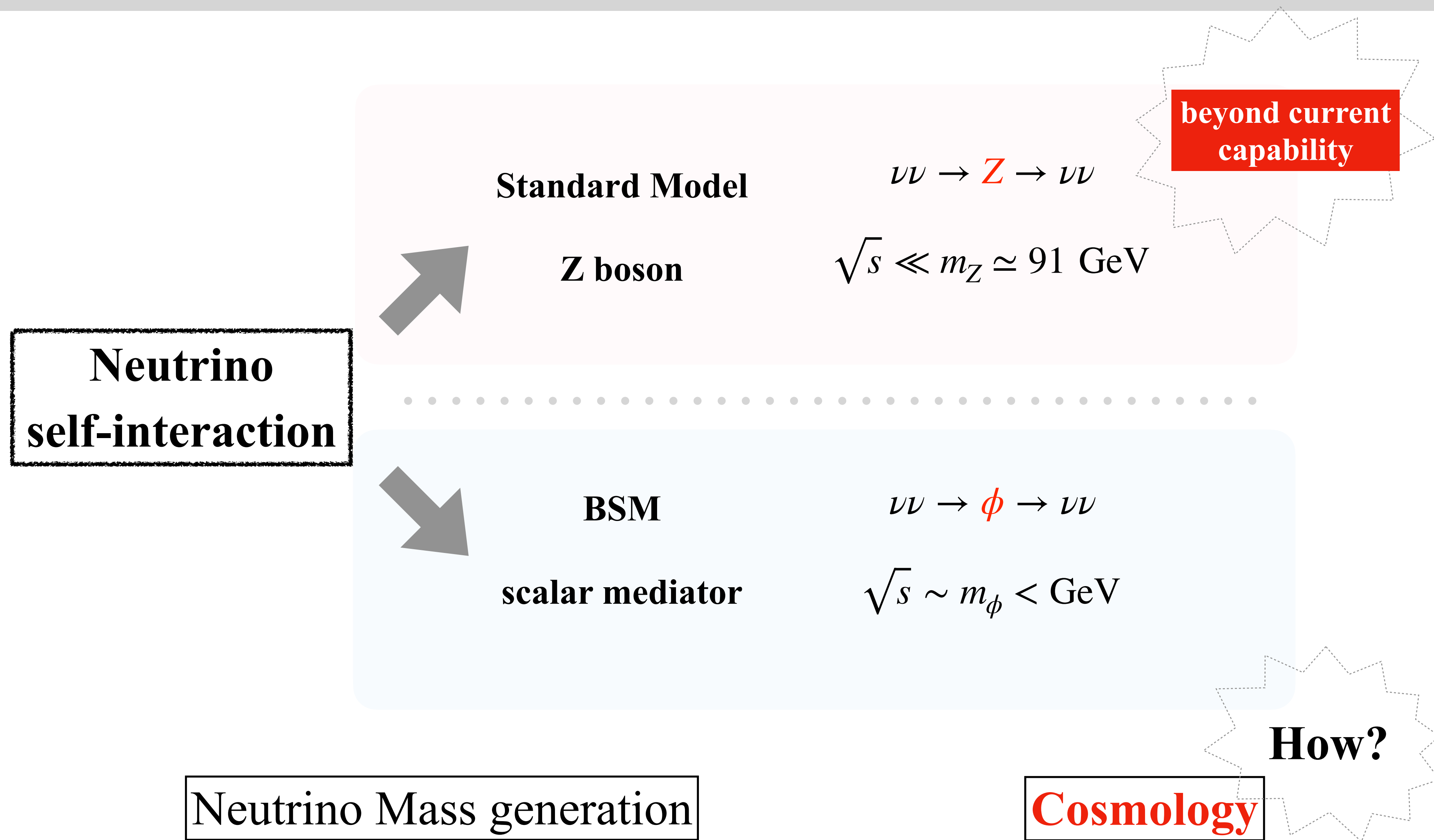
$$\phi \longleftrightarrow N_R N_R \xleftrightarrow{\text{mixing}} \nu_L \nu_L$$



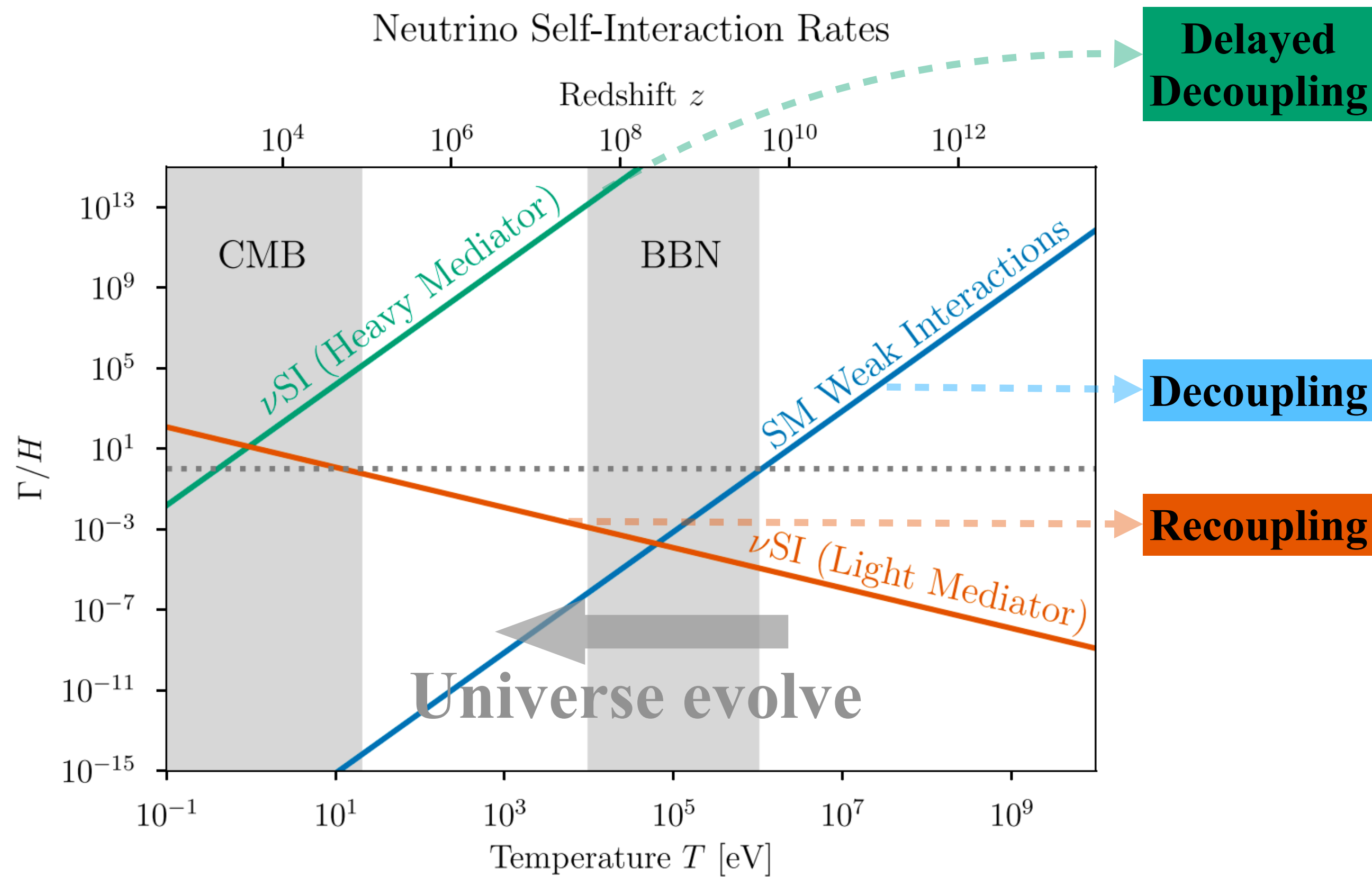
Neutrino self-interactions (νSI)
can arise naturally in extended
neutrino mass models.

Why neutrino self-Interaction is important

νSI opens a new window for physics beyond the standard model



νSI can affect energy density and free-streaming history



Neutrino self-interactions: A white paper (2023)

$$\Gamma_{\nu\nu}/H \begin{cases} > 1 & \text{Collisional} \\ < 1 & \text{Free-streaming} \end{cases}$$

Standard Model

Collisional $\xrightarrow{T \sim 1 \text{ MeV}}$ Free-streaming

Heavy Mediator

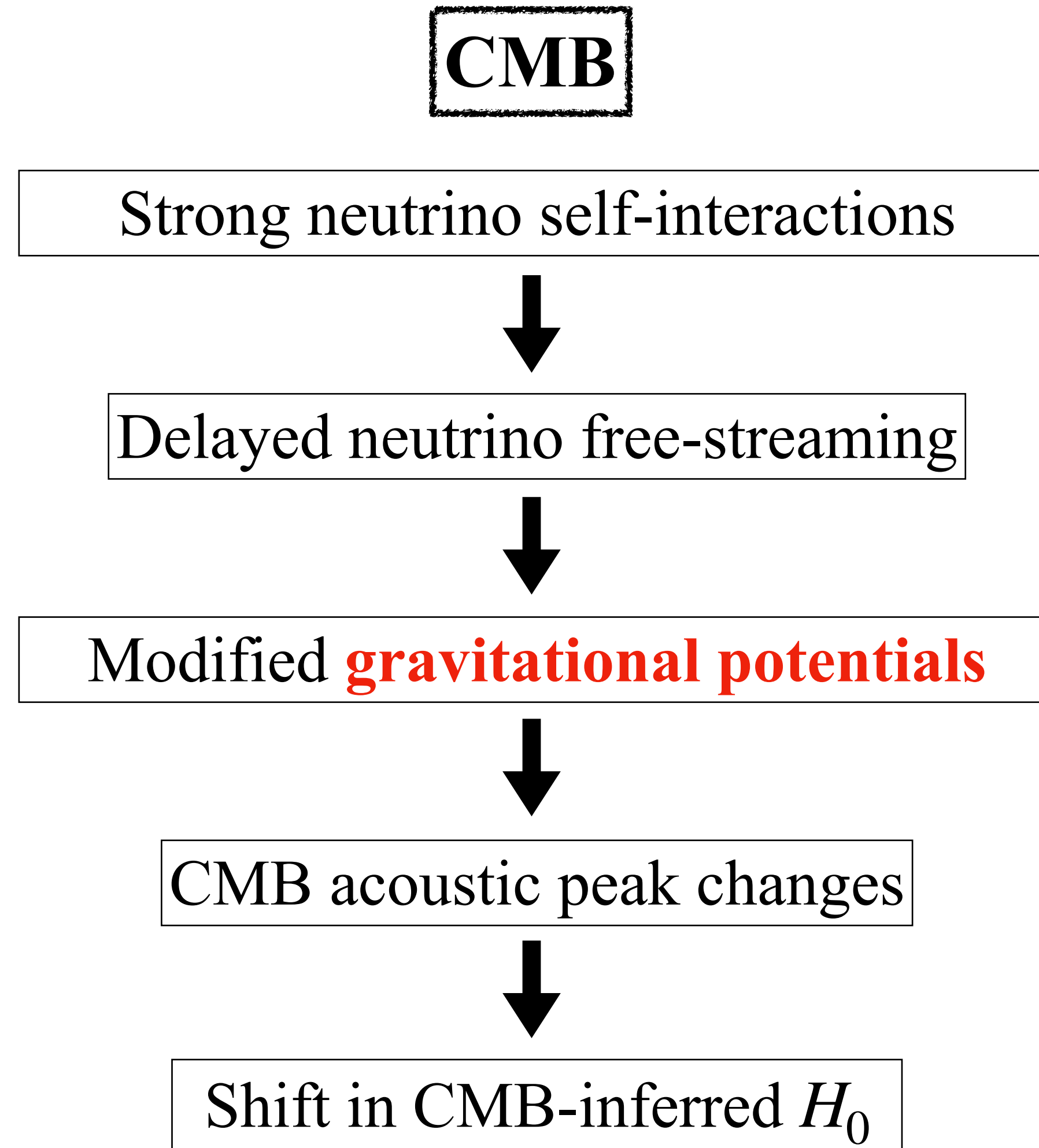
Collisional $\xrightarrow{\text{much later}}$ Free-streaming

Light Mediator

Free-streaming $\xrightarrow{\text{much later}}$ Recoupling

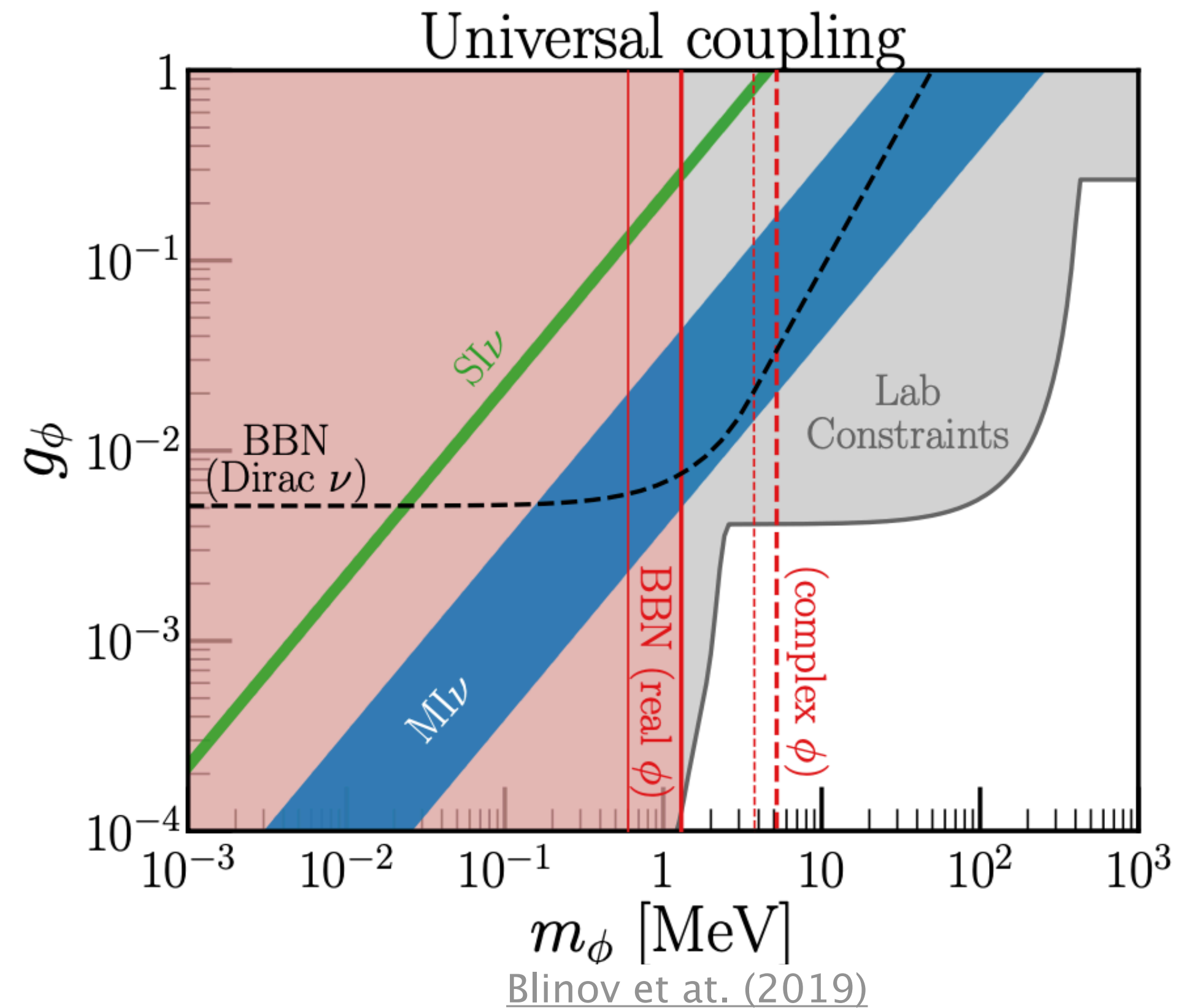
Change of Free-streaming history can leave observable signatures on BBN, CMB and LSS

νSI as a Possible Solution to the Hubble Tension



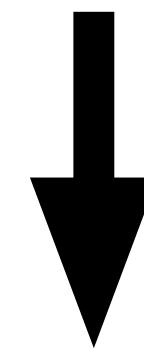
Preferred couplings for alleviating the Hubble tension

Scenario: $\nu\nu \leftrightarrow \phi$



CMB preferred regimes

SI_ν : strong/ MI_ν : moderate

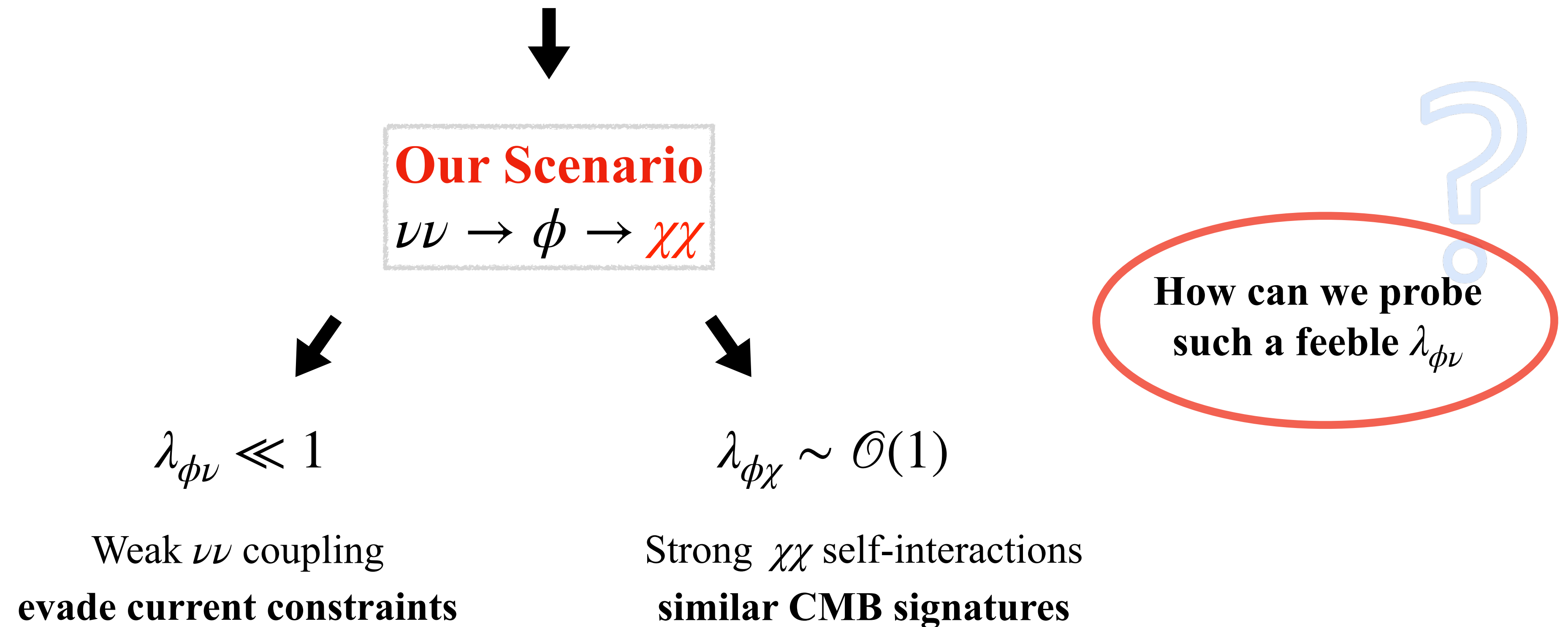


Problem

νSI preferred by CMB are excluded by BBN and laboratory constraints.

A New Possibility: neutrinos converting into dark radiation

Can we retain the CMB effects while evading current constraints?



How neutrino self-interaction is studied

Methods of constraining νSI

ASTROPHYSICAL

SN1987A · Stellar cooling · IceCube

Extreme environments and long baselines

Statistical errors

LABORATORY

$0\nu\beta\beta\phi$ · Meson decays · τ decays

Controlled and precise measurements

Flavor dependent

COSMOLOGICAL

BBN · CMB · LSS

Thermal history and structure growth

Model dependent

Combining different observations is essential

Example — Astrophysical constraint: Fiorillo (2023)

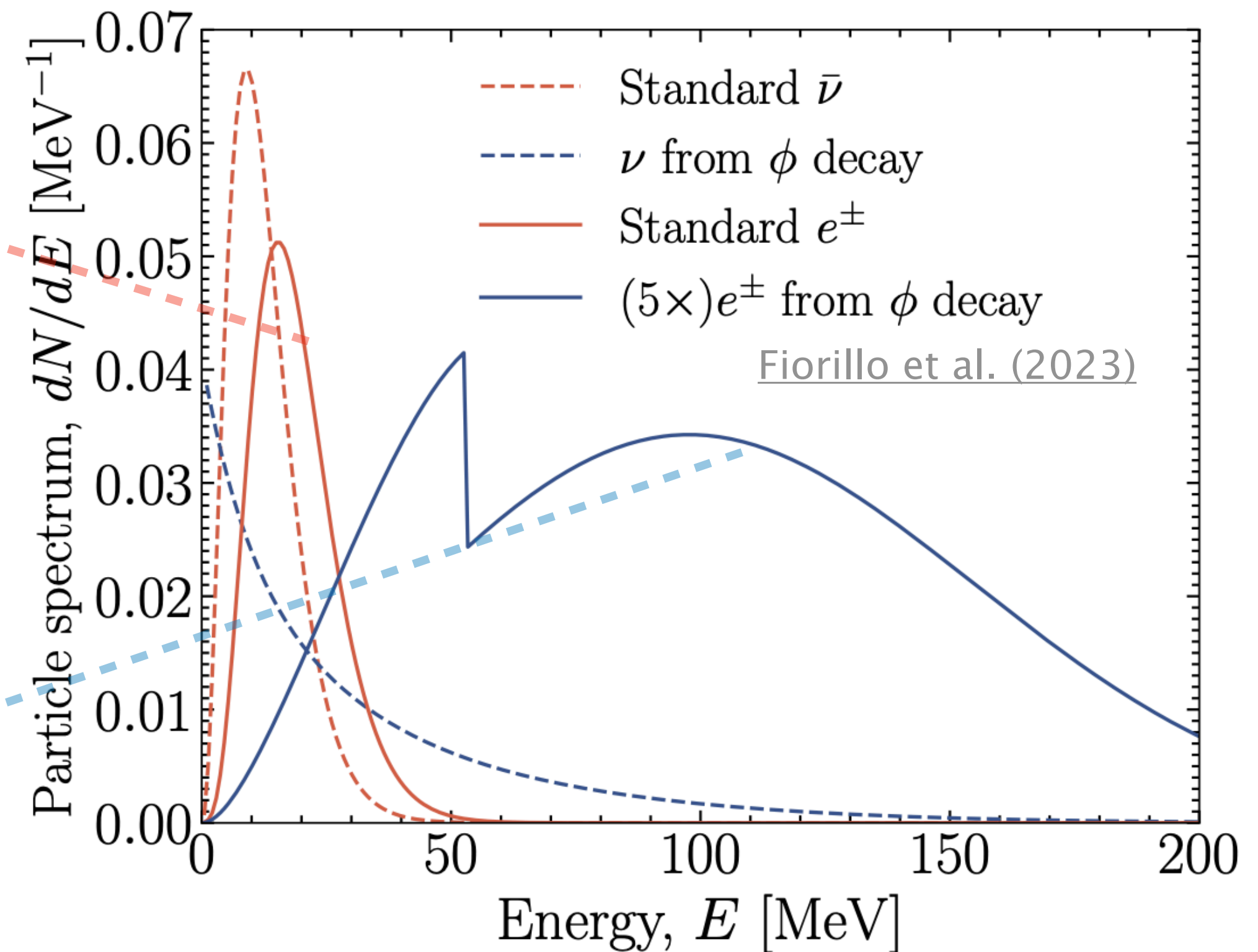
Scalar production and decay in SN1987A core

ordinary SN neutrino: $E_\nu \sim 10$ MeV



- Scalar production in the **SN core**
- escapes and decays into energetic neutrinos

~ 100 MeV neutrinos from ϕ decay

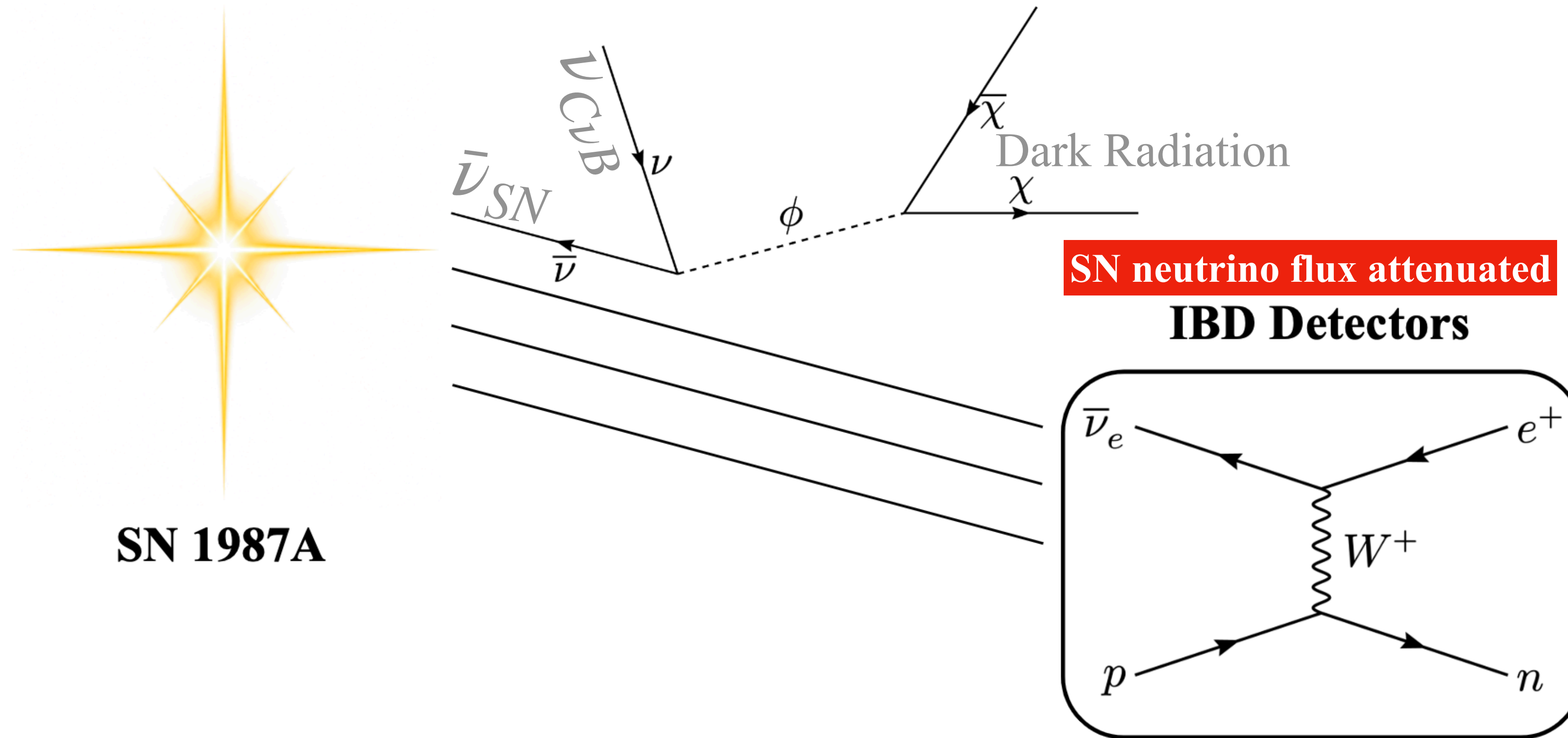


No detection of 100MeV neutrino

$$\longrightarrow g \lesssim 10^{-9} \frac{\text{MeV}}{m_\phi}$$

Our work: SN neutrinos scattering on the $C\nu B$

$$\bar{\nu}_{\text{SN}} + \nu_{C\nu B} \rightarrow \phi \rightarrow \chi + \bar{\chi}$$

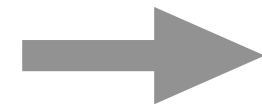


SN neutrinos scattering on the $C\nu B$

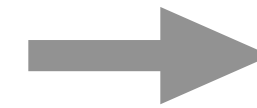
$$\mathcal{L} \supset -\frac{1}{2}\lambda_{\phi\nu}^{ij}\phi\nu_i\nu_j - \frac{1}{2}\lambda_{\phi\chi}\phi\chi\chi + h.c.$$

ν_i : mass eigenstate

Production
 $\bar{\nu}_\alpha$



Scattering
 $\bar{\nu}_i$

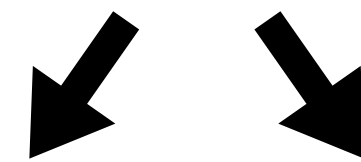


Detection (IBD)
 $\bar{\nu}_e$



Scattering rate between $\bar{\nu}_{SN}$ & $\nu_{C\nu B}$

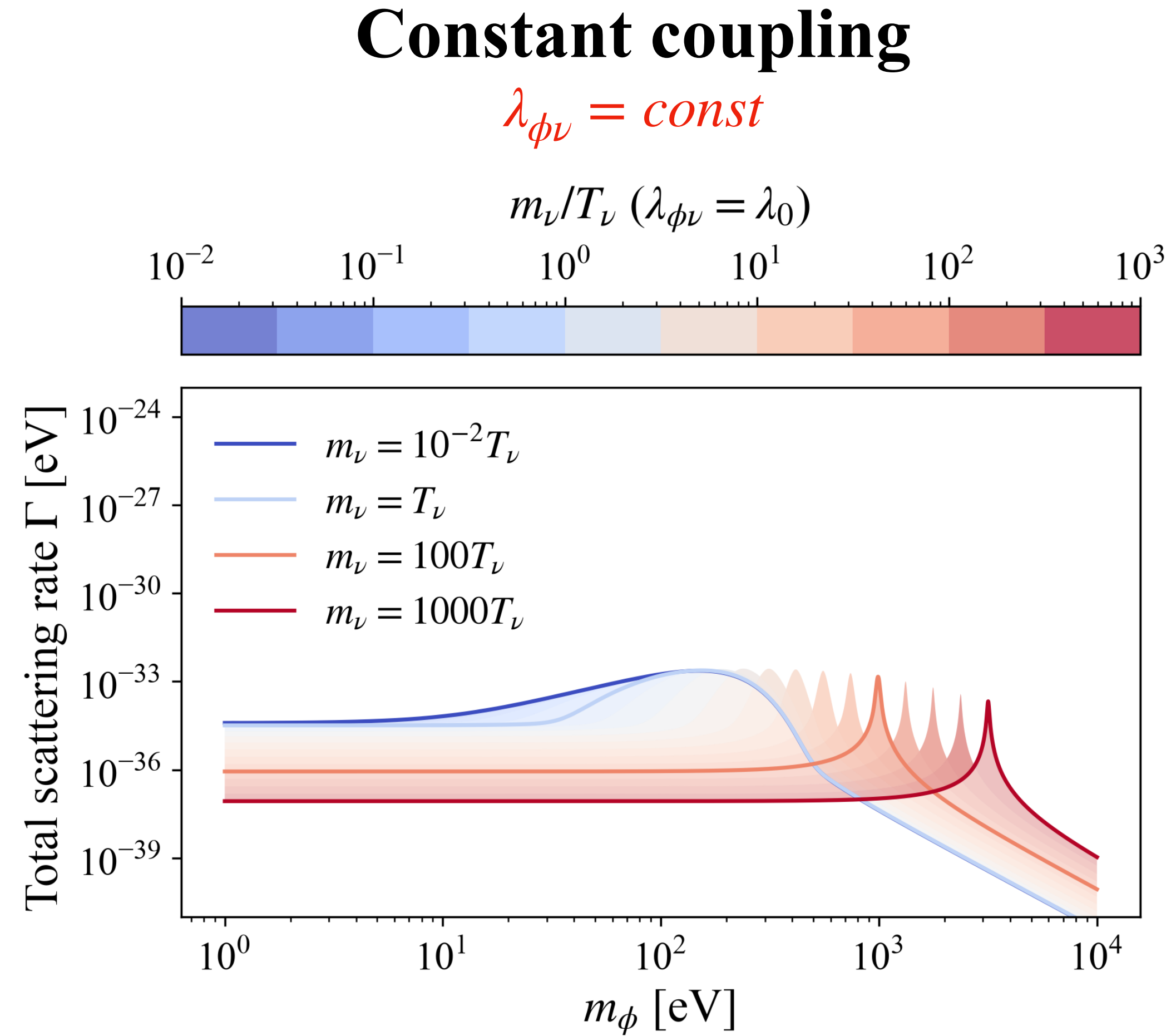
$$\Gamma \propto \lambda_{\phi\nu}^2 \mathcal{F}(m_\phi, m_\nu, E_\nu)$$



Constant coupling
 $\lambda_{\phi\nu} = \text{const}$

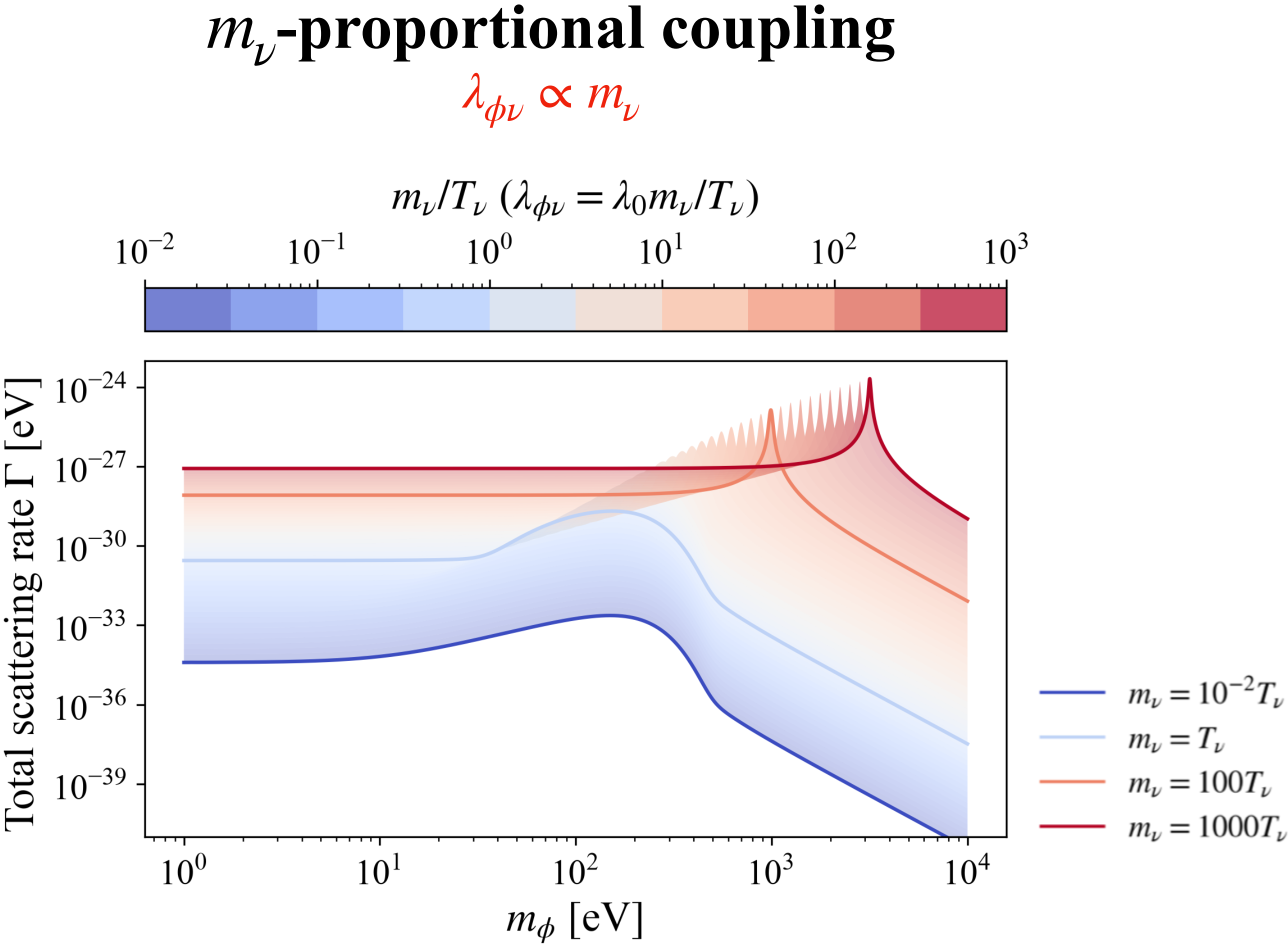
m_ν -proportional coupling
 $\lambda_{\phi\nu} \propto m_\nu$

Scattering Rate—two coupling structures



Light neutrinos dominate sub-KeV
Heavy neutrinos dominate > KeV

Scattering Rate—two coupling structures



Heavy neutrinos dominate

Attenuated flux (mass basis)

Optical depth

$$\tau_i(E_\nu) \simeq \Gamma_i(E_\nu, m_\nu) d_{\text{SN}}$$

SN1987A: $d_{\text{SN}} \simeq 50 \text{ kpc}$

Attenuated flux

$$\Phi_i = \Phi_i^0 e^{-\tau_i}$$

Electron flavor

$$\bar{\nu}_e \xrightarrow{1} \bar{\nu}_{1m} \xrightarrow{1} \bar{\nu}_1 \xrightarrow{|U_{e1}|^2} \bar{\nu}_e$$

adiabatic

Normal mass ordering

$$m_1 \ll m_2 < m_3$$

Heavy flavors

$$\bar{\nu}_x \xrightarrow{1} \bar{\nu}_{2m,3m} \xrightarrow{1} \bar{\nu}_{2,3} \xrightarrow{|U_{e2,e3}|^2} \bar{\nu}_e$$

adiabatic

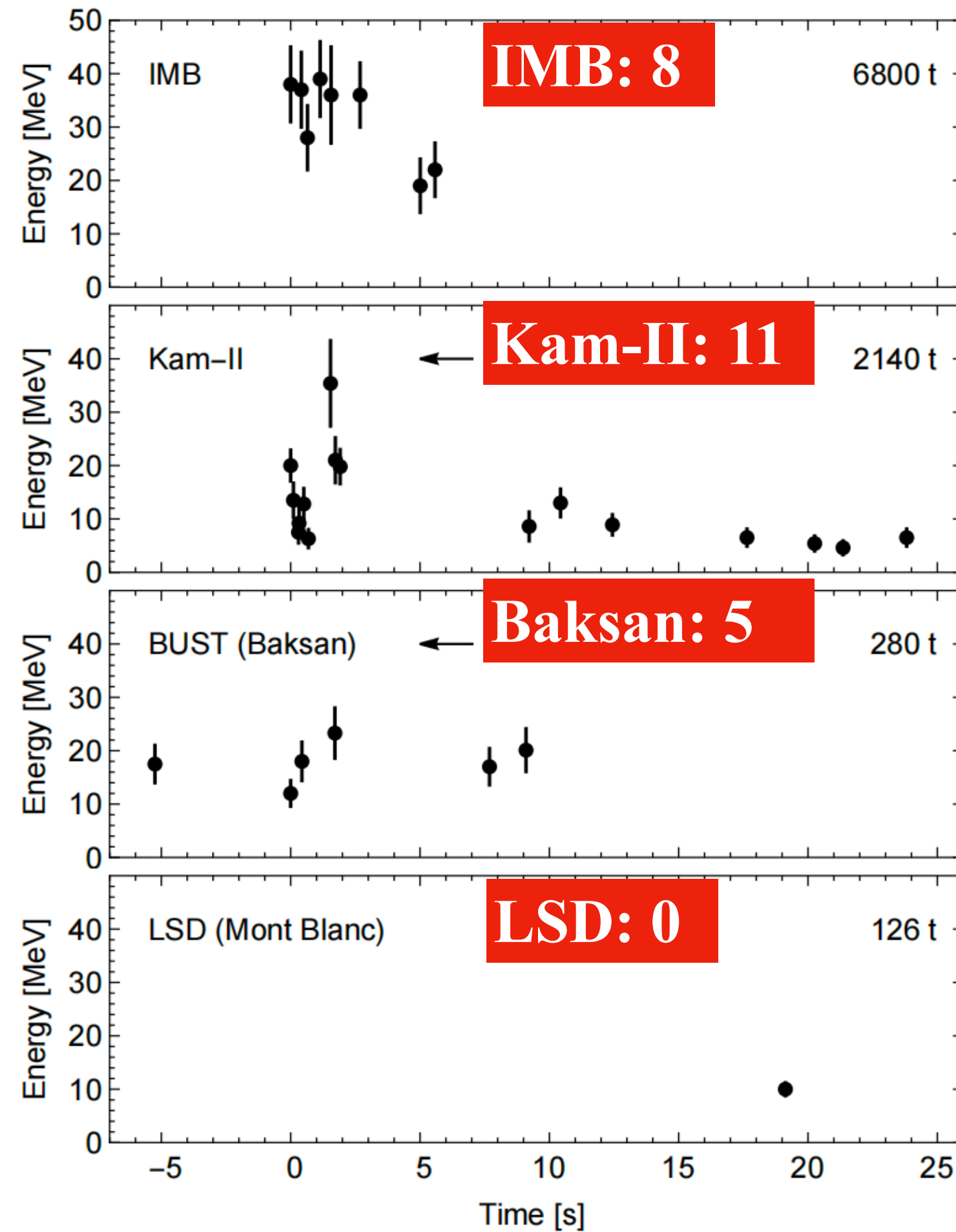
Detected $\bar{\nu}_e$ flux

$$\Phi_{\bar{\nu}_e}^{\text{osc}}(m_\phi, \lambda_{\phi\nu}) = |U_{e1}|^2 e^{-\tau_1} \Phi_{\bar{\nu}_e}^0 + \left(|U_{e2}|^2 e^{-\tau_2} + |U_{e3}|^2 e^{-\tau_3} \right) \Phi_{\bar{\nu}_x}^0$$

Analysis and Results

Bayesian framework

24 events for SN1987A



Poisson Likelihood

$$\mathcal{L}_d \propto e^{-N_{exp}} \prod_{i=1}^{N_d} \mathcal{R}(t_i, E_i, c_{\theta,i})$$

Two flux models

Parameterized (mainly $\bar{\nu}_e$)

Hydrodynamic ($\bar{\nu}_e$ & $\bar{\nu}_x$)

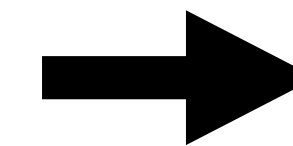
Two coupling structures

$$\lambda_{\phi\nu} = \text{const}$$

$$\lambda_{\phi\nu} \propto m_\nu$$

$$P(\Theta | \text{Events}) = \mathcal{L}_d(\text{Events} | \Theta) P_0(\Theta)$$

MCMC analysis

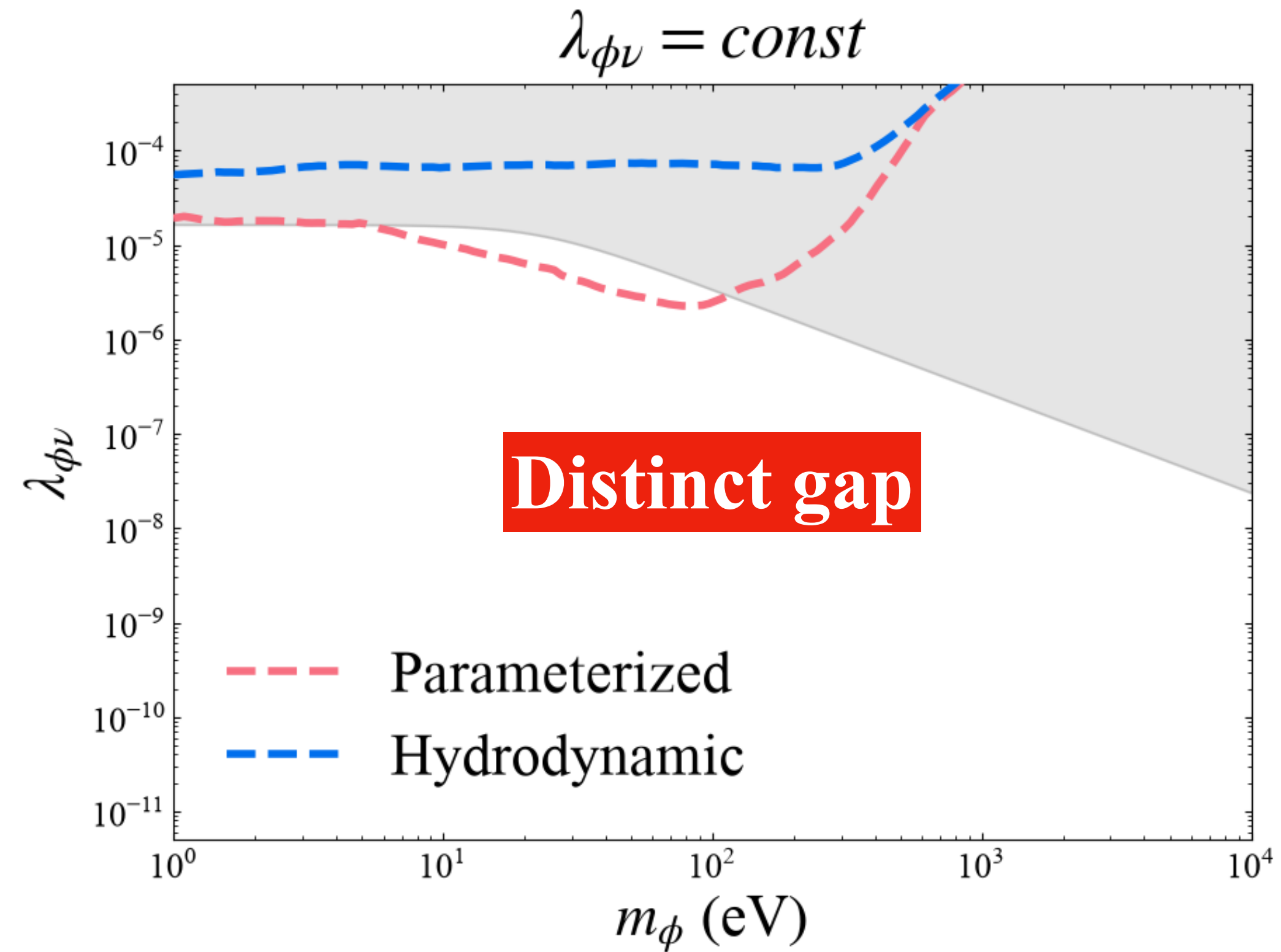


$\lambda_{\phi\nu}, m_\phi$ constraints

Results of constant coupling (small dataset)

Parameterized (mainly $\bar{\nu}_e$)

Hydrodynamic ($\bar{\nu}_e$ & $\bar{\nu}_x$)

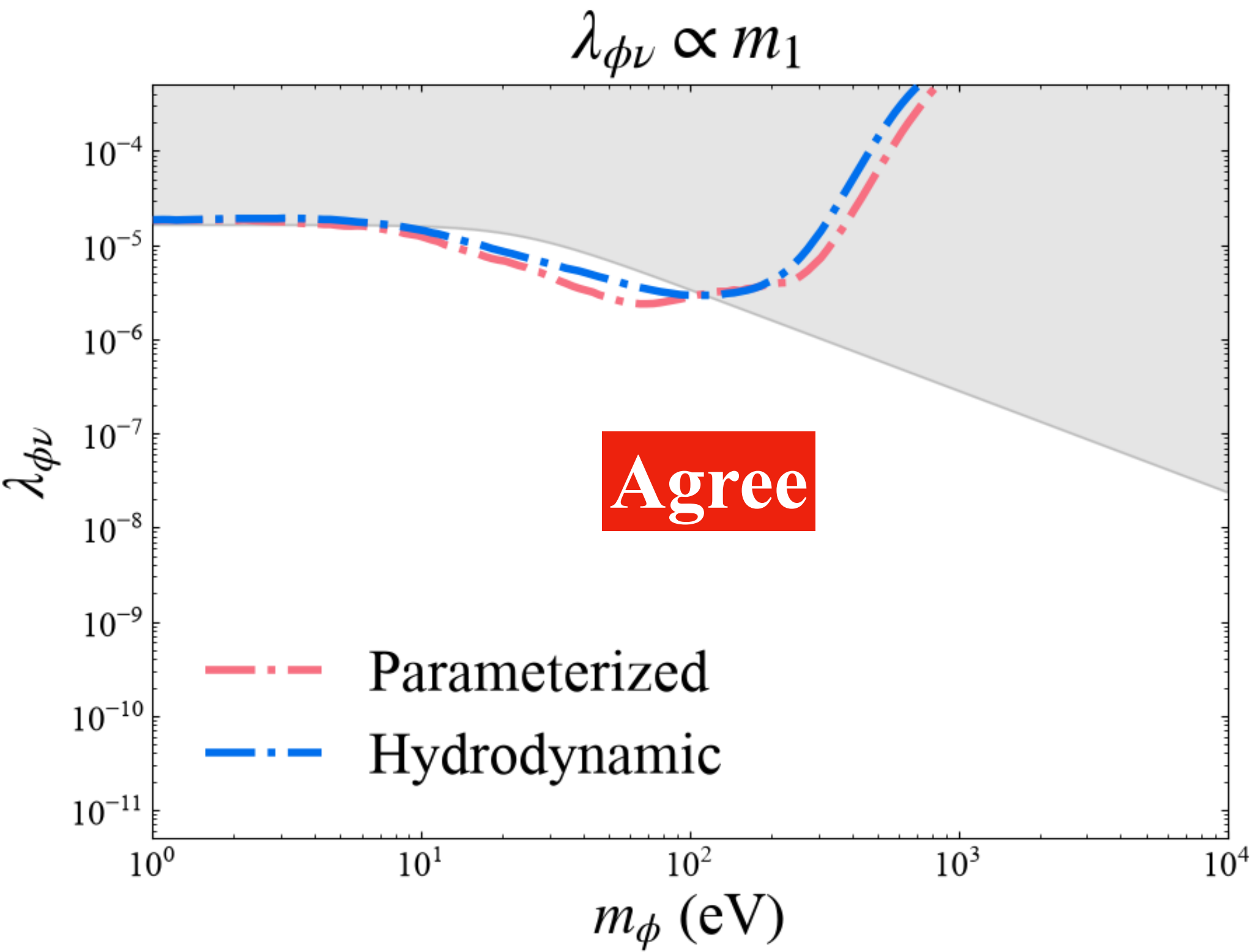


P model predicts very few $\bar{\nu}_x$ flux, but oscillation allows $\bar{\nu}_x$ to contribute to detected $\bar{\nu}_e$ flux, So **H model** needs stronger coupling to reduce the flux to the same level as **P model**.

Results of mass proportional coupling (small dataset)

Parameterized (mainly $\bar{\nu}_e$)

Hydrodynamic ($\bar{\nu}_e$ & $\bar{\nu}_x$)



Projected sensitivity (large dataset with Hyper-Kamiokande)

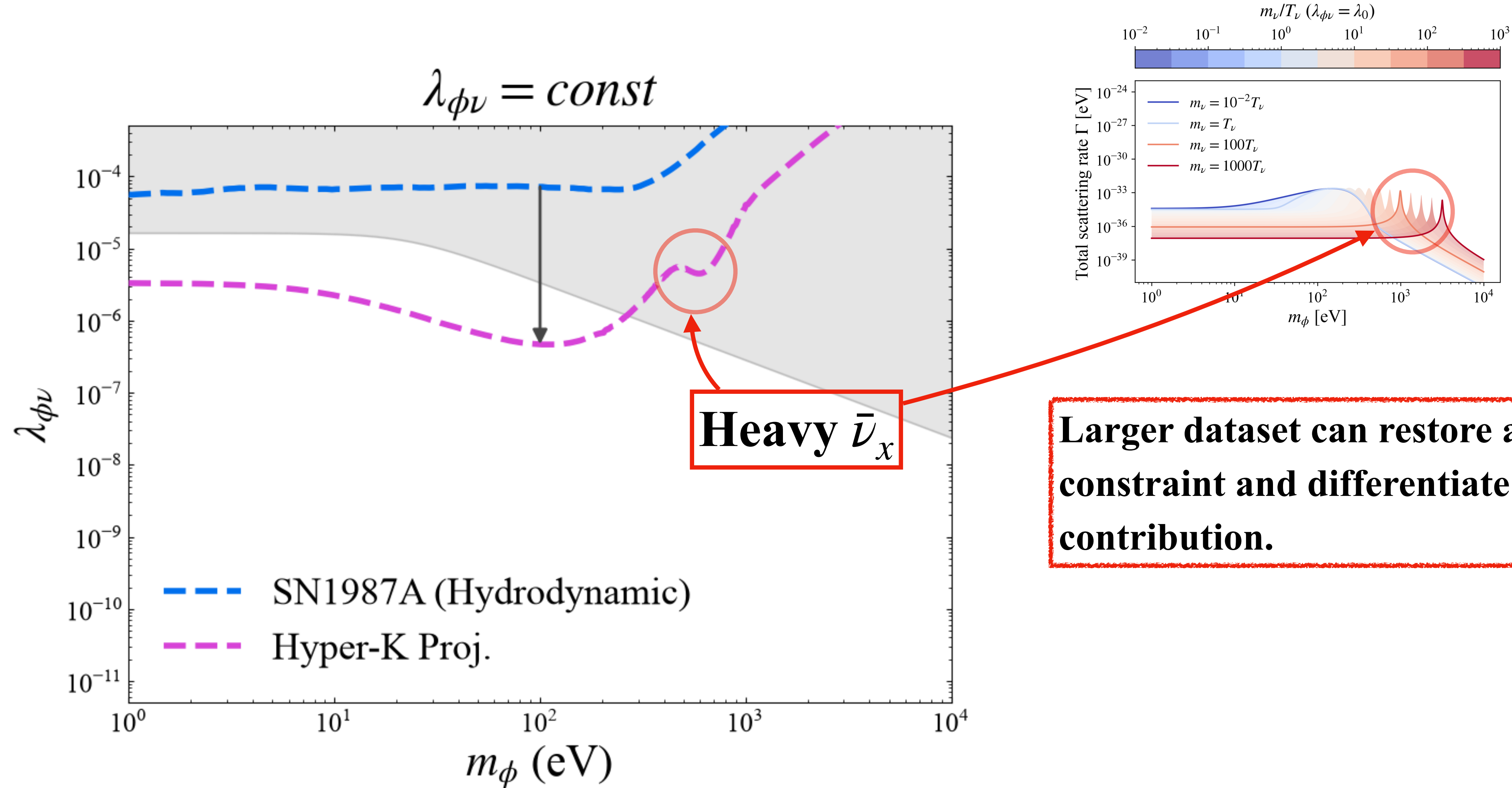
Dataset: ~ 2000 events

Null hypothesis: no new physics included

Method: likelihood ratio test

$$\chi^2 = -2 \log \frac{\mathcal{L}_d(m_\phi, \lambda_{\phi\nu})}{\mathcal{L}_d(m_\phi, \lambda_{\phi\nu} = 0)}$$

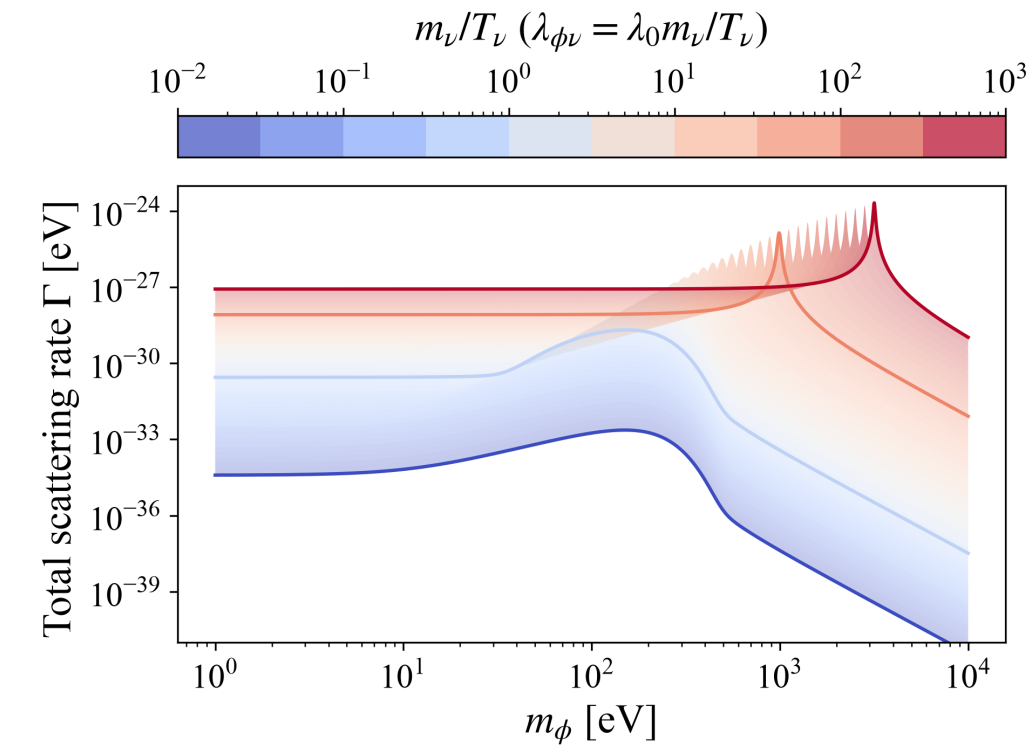
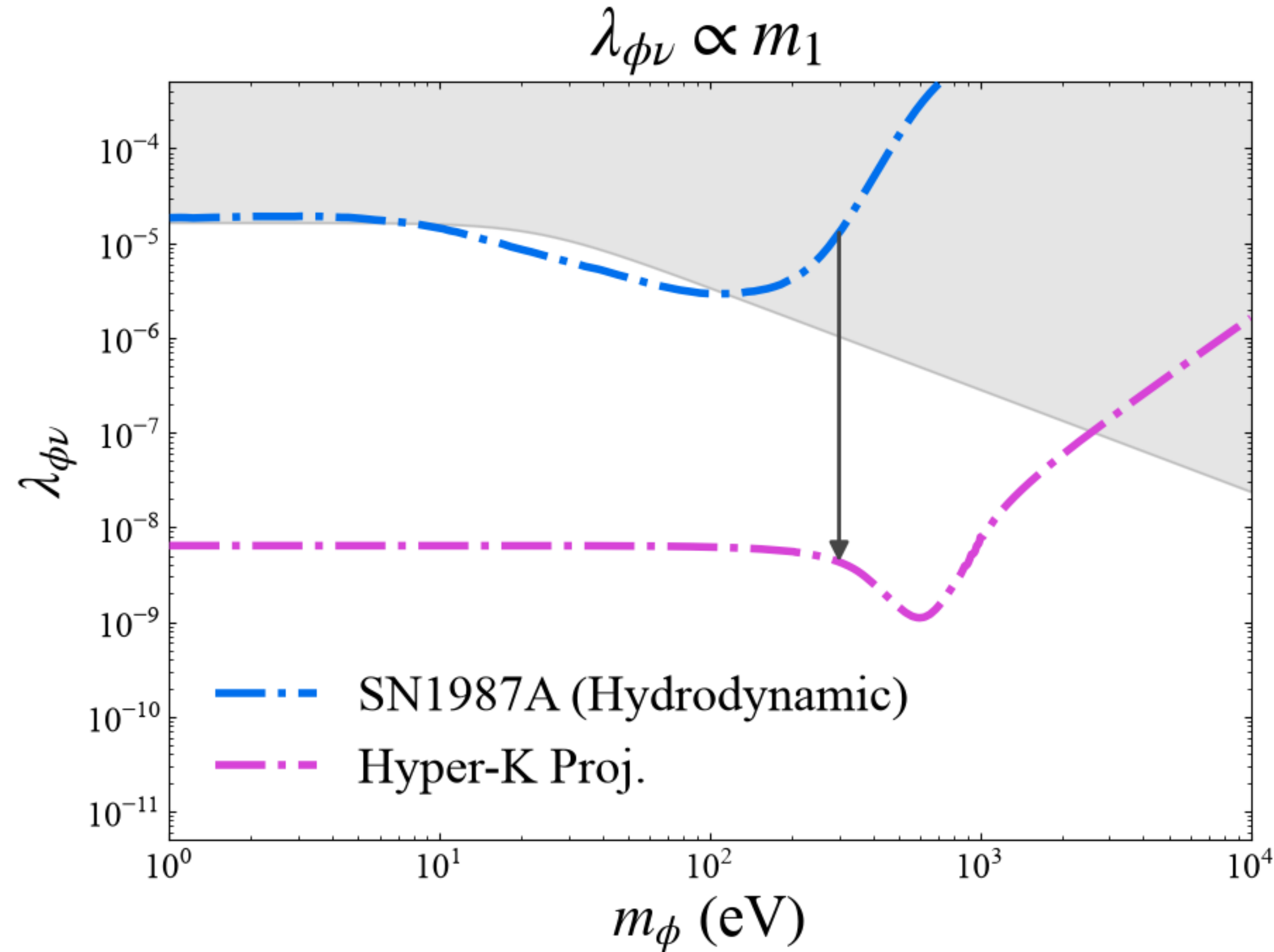
Projected sensitivity of constant coupling (large dataset)



Heavy $\bar{\nu}_x$

Larger dataset can restore an efficient constraint and differentiate each flavor's contribution.

Projected sensitivity of mass proportional coupling (large dataset)



Scattering is mostly driven by coupling of heavy neutrinos $\lambda_{\phi\nu} \propto m_{2,3}$, coupling of light neutrino $\lambda_{\phi\nu} \propto m_1$ can be very small

$$\bar{\nu}_{\text{SN}} + \nu_{\text{C}\nu\text{B}} \rightarrow \phi \rightarrow \chi + \bar{\chi}$$

- Investigated neutrino conversion into dark radiation
- Compared two SN flux models and coupling structures
- Constrained neutrino couplings using SN1987A data
- Forecasted the sensitivity of future observations

Key finding: Constraints depend on both the flavor treatment and the coupling structure

Thanks for your attention !!!