# Probing non-standard neutrino interactions from future supernova neutrino observations

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# Introduction

# Introduction

- Neutrino oscillation experiments revealed

$$\Delta m_{21}^2 \simeq (8.6\ \mathrm{meV})^2 \qquad |\Delta m_{31}^2| \simeq |\Delta m_{32}^2| \simeq (50\ \mathrm{meV})^2$$

But, the neutrino-mass-generation mechanism remains mystery...

➡ This implies neutrinos have non-standard interactions.

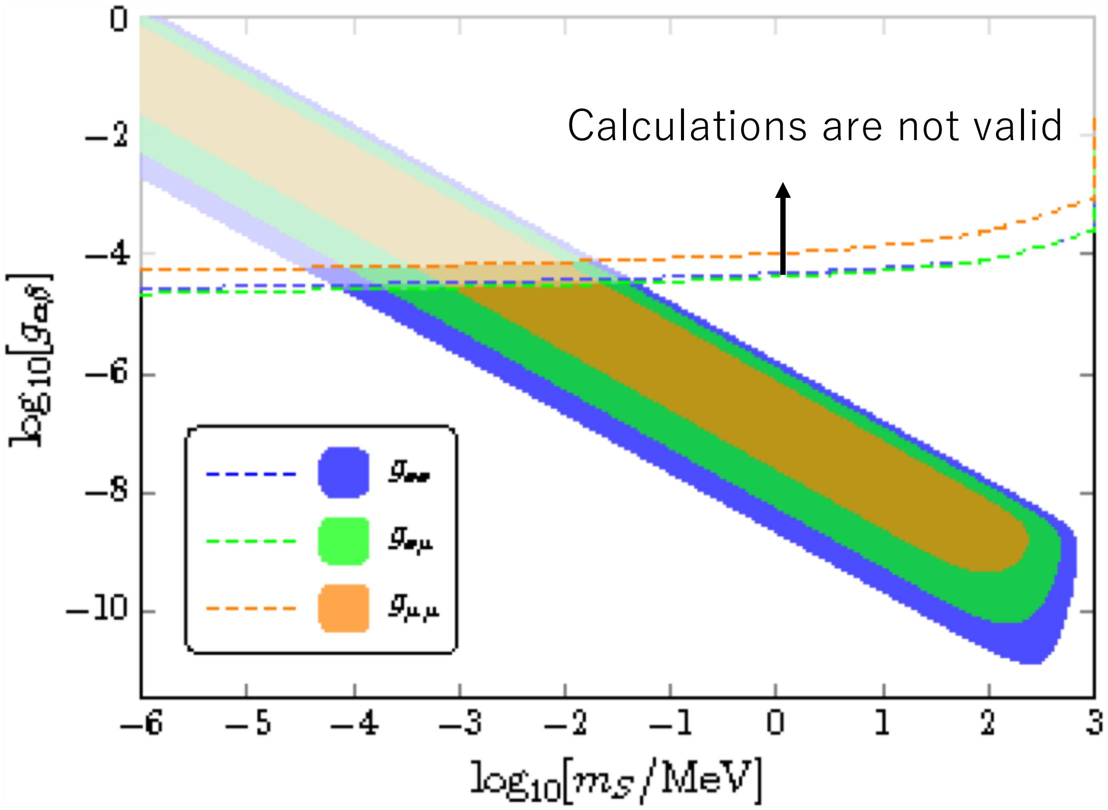
- We focus on neutrino interactions with a new boson $\phi$ :

$$\mathcal{L}_{\rm int} = g_{\alpha\beta}\phi\bar{\nu}_\alpha\nu_\beta$$

  - may be realized in the Majoron model: $\mathcal{L}_{\rm int} = y_1 \Phi \bar{N^C} N + y_2 \bar{L}\tilde{H}N + \mathrm{h.c.}$ $\quad \Phi = \frac{v_\chi + \chi + i\phi}{\sqrt{2}}$ Majoron
  - could also help some anomalies such as the muon g-2 anomaly, the Hubble tension, etc.

Baek et al. hep-ph/0104141 Escudero et al. 1901.02010

# Current constraints on $g_{\alpha\beta}\phi\bar{\nu}_\alpha\nu_\beta$




SN 1987A energy loss constraints
Lucien et al. 1609.05882

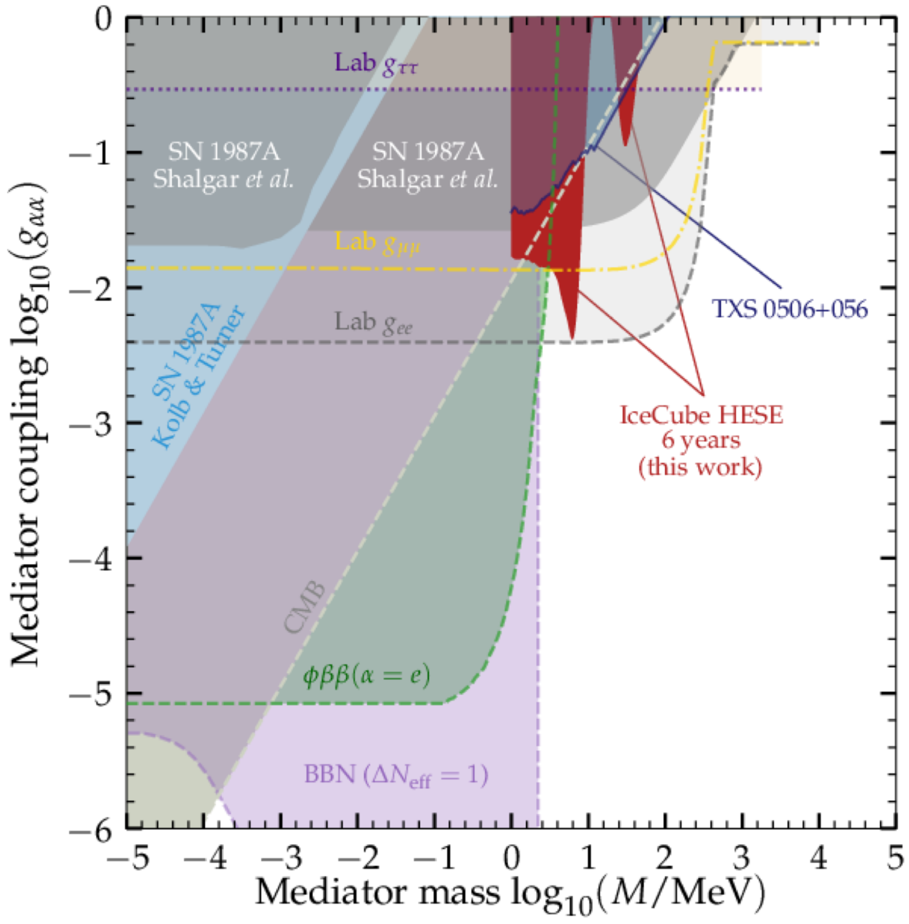



Figure from Mauricio et al. 2001.04994

- Many observations constrains such interactions but we observe no signal...
- Can we improve the sensitivity of $g_{\alpha\beta}\phi\bar{\nu}_\alpha\nu_\beta$ from future supernova observations?

# Supernovae (SNe)


before after

SN 1987A

- Core-collapse SN is a last-stage of the star, emitting $\mathcal{O}(10^{58})$ neutrinos and anti-neutrinos.

- Next galactic SNe
  A few SNe per galaxy*century might be observed.
  Typical distance for supernovae in our Galaxy is 10 kpc.

- Diffuse Supernova Neutrino Background(DSNB):
  is stationary neutrino flux from all past SNe.
  might be observed in the next generation neutrino detectors.

$$\frac{d\Phi_\nu}{dE_\nu} = c\int R_{\rm SN}(z)\frac{dN_\nu}{dE'_\nu}(E'_\nu)(1+z)\left|\frac{dt}{dz}\right|dz \qquad E'_\nu = E_\nu(1+z)$$

SN rate — $R_{\rm SN}(z)$; Mean neutrino flux per one SN — $\frac{dN_\nu}{dE'_\nu}$; redshift — $z$

Can we improve the sensitivity of $g_{\alpha\beta}\phi\bar{\nu}_\alpha\nu_\beta$ from the future SN neutrino observations?

# Outline

- Introduction
- Modifications of supernova neutrino flux by $\phi \to \nu\nu$
- Discovery potential of neutrino experiments
- Conclusion

# Modifications of SN neutrino flux by $\phi \to \nu\nu$

- A light boson can be produced in the SN core through the new interactions $g_{\alpha\beta}\phi\bar{\nu}_\alpha\nu_\beta$

High density region

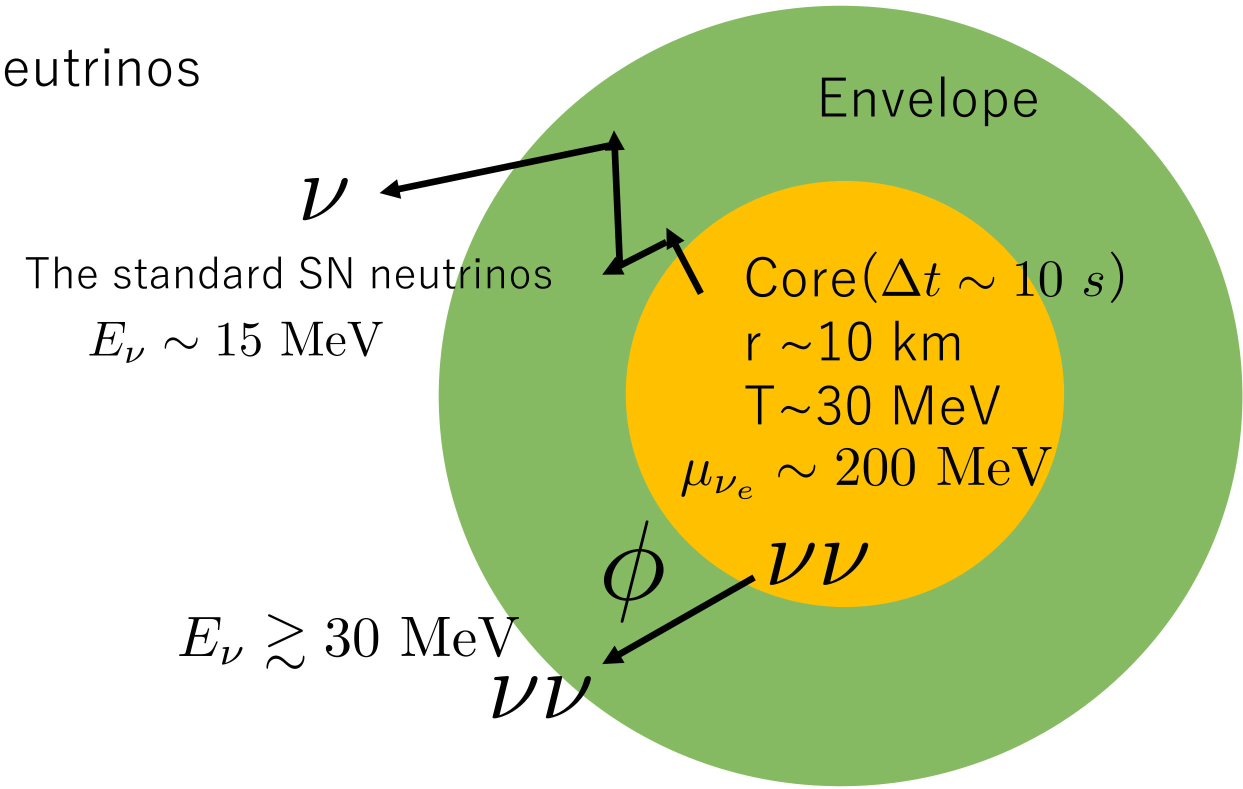
$$\nu\nu \to \phi$$

- After the emission, $\phi$ can decay back into neutrinos

$$\phi \to \nu\nu$$

More energetic neutrinos are produced!

➡ SN neutrino flux can be modified!



# Production of $\nu\nu \to \phi$ and Subsequent decay $\phi \to \nu\nu$

- Total emission number of $\nu\nu \to \phi$ per energy in the core (The Boltzmann eq.):

$$\frac{dN_\phi}{dE_\phi} = V\Delta t \sum_\nu \frac{g^2 m_\phi^2}{64\pi^3} e^{-\Gamma_\phi r_\nu/\gamma} \int_{p_1^{\rm min}}^{p_1^{\rm max}} dp_1 \; f_\nu(p_1) f_\nu(E_\phi - p_1),$$

$$V = \frac{4}{3}\pi r_c^3$$

Survival probability outside $r_\nu \sim 50$ km

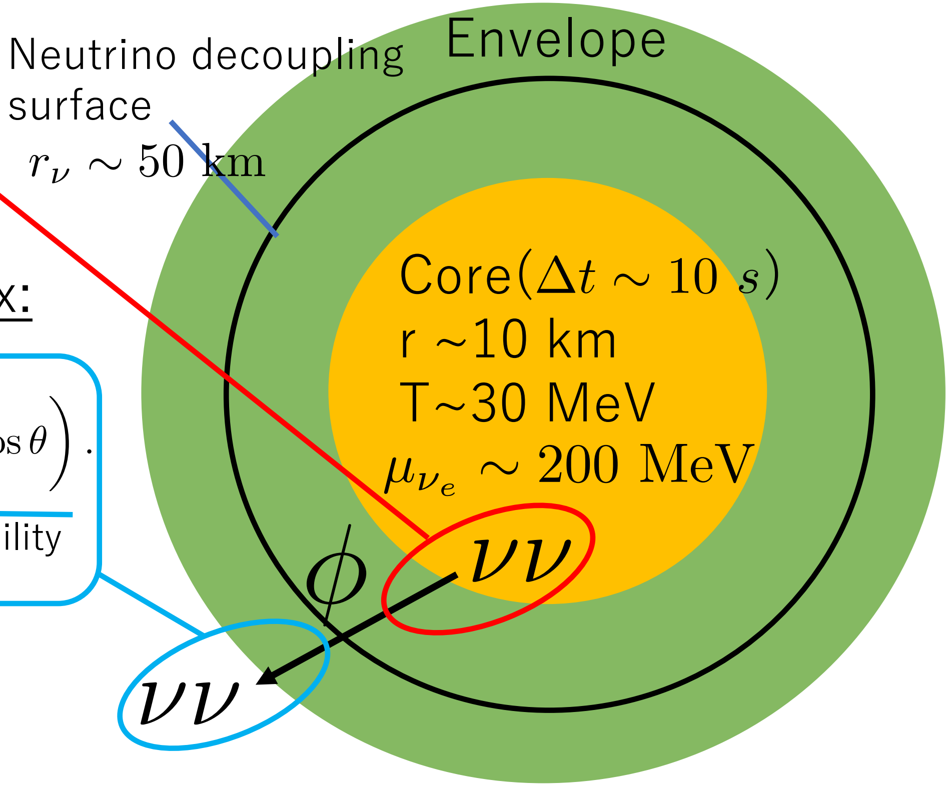
- After the emission of $\phi$ , their decays produce <u>a neutrino flux:</u>

$$\frac{dN_{\nu_\alpha}}{dtdE_\nu} = \int d\cos\theta \int dE_\phi \frac{1}{3\tau} \exp\left[-\frac{\gamma(1+\beta\cos\theta)t}{\tau}\right] \frac{dN_\phi(0,E_\phi)}{dE_\phi} f_{\nu_\alpha}\left(\frac{E_\nu}{\gamma(1+\beta\cos\theta)}, \cos\theta\right).$$

Production rate per time — $\phi$ spectrum — Distribution probability of $\theta$ and $E_\nu$

Neutrino energy and angle at the rest $\phi$

$$f_{\nu_\alpha}(\omega_\nu, \cos\theta) = \frac{1}{2}\delta\left(\omega_\nu - \frac{m_\phi}{2}\right). \qquad E_\nu = \gamma(1+\beta\cos\theta)\omega_\nu$$



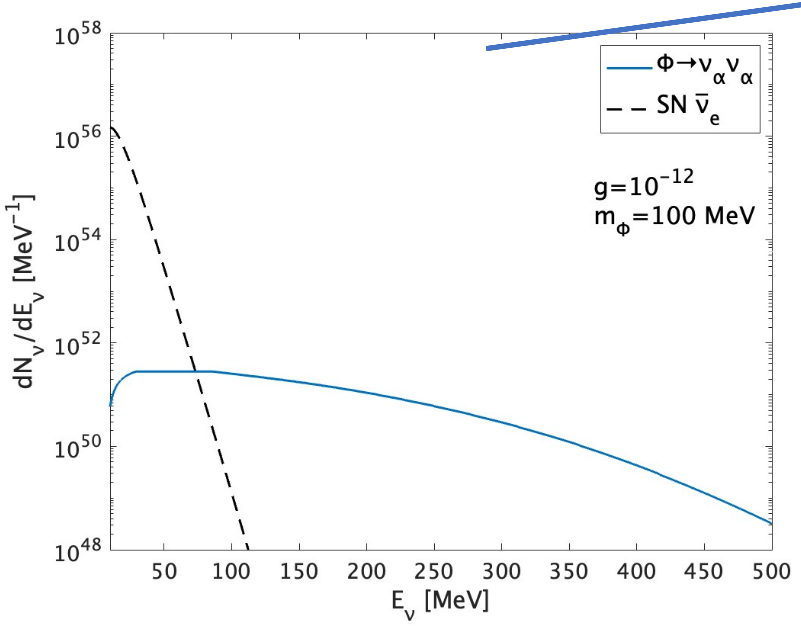
# Neutrino flux from $\phi \to \nu\nu$

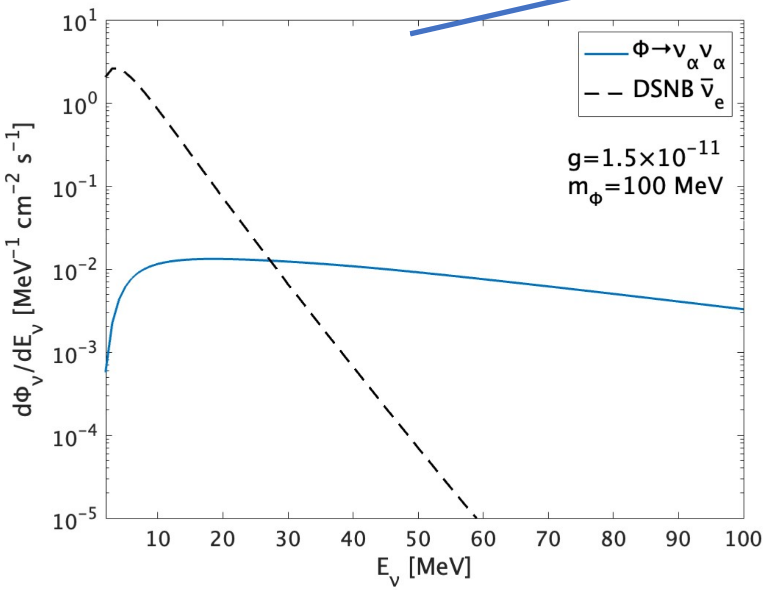
- For simplicity, we consider flavor-universal and diagonal neutrino interaction with $\phi$

$$\mathcal{L}_{\rm int} = g_{\alpha\beta}\phi\bar{\nu}_\alpha\nu_\beta$$

$$g_{ee} = g_{\mu\mu} = g_{\tau\tau} = g \text{ and the others are zeros}$$

- Neutrino fluxes by $\phi \to \nu\nu$ from a next galactic SN and all the past SNe




Neutrino fluxes are modified!

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# Next galactic supernova neutrinos with $d_{\mathrm{SN}} = 10\ \mathbf{kpc}$

The distance between the Earth and a supernova

# Event rate for Super-Kamiokande (SK)

- The main detection processes of neutrinos in SK are

$$\bar{\nu}_e + p \to n + e^+$$

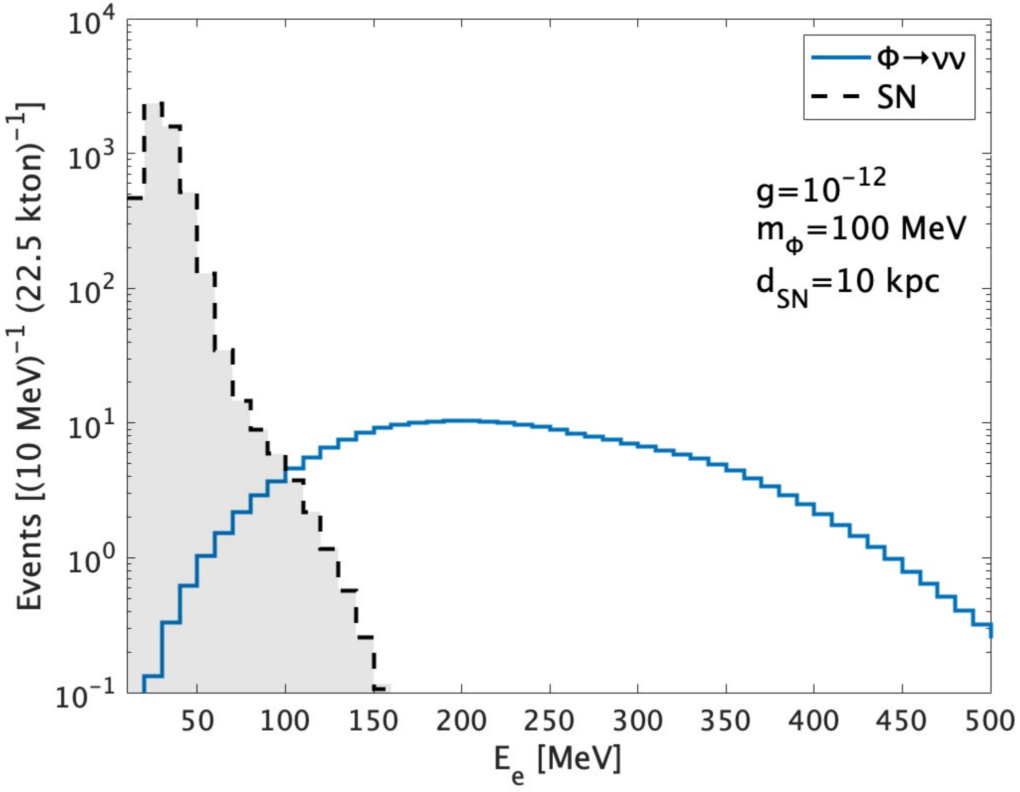
$$\bar{\nu}_e + ^{16}\mathrm{O} \to X + e^+$$

$$\nu_e + ^{16}\mathrm{O} \to X + e^-$$

We neglect $\nu_\mu$ events etc. for a conservative estimate.

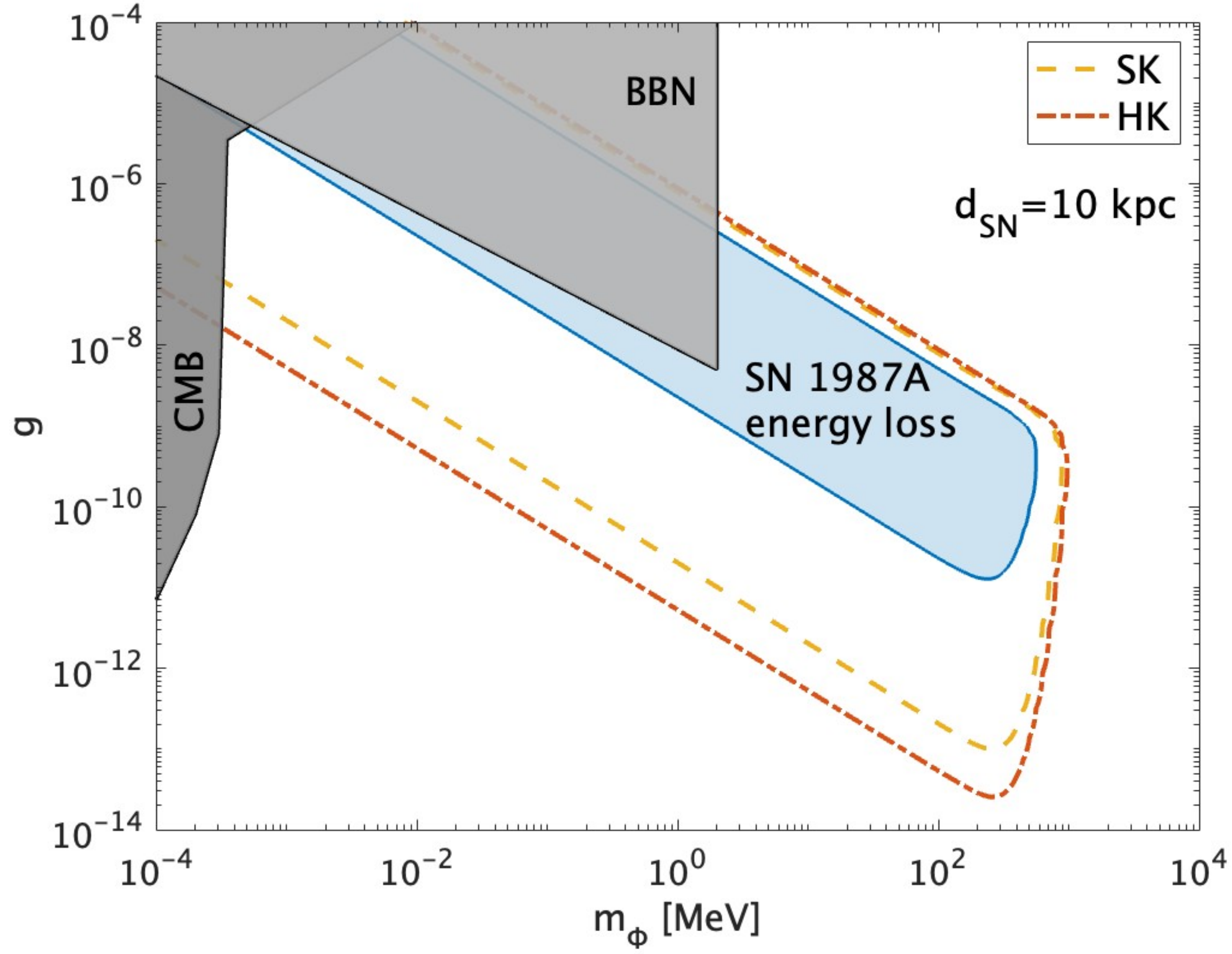
More than 100 events can be observed in SK for $m_\phi = 100\ \mathrm{MeV},\ g = 10^{-12}$ .

This coupling is much smaller than the current constraints!




Next galactic supernova neutrinos

# Discovery potential of SK (22.5 kton) and HK (374 kton)



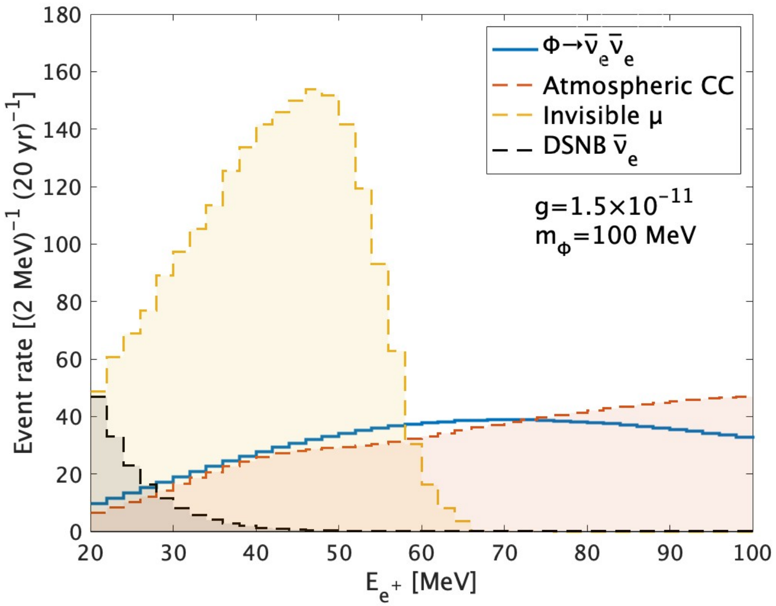

Discovery potential at 99.7 % C.L.

The sensitivity for $g_{\alpha\beta}\phi\bar{\nu}_\alpha\nu_\beta$ will be significantly improved by several orders of magnitude!

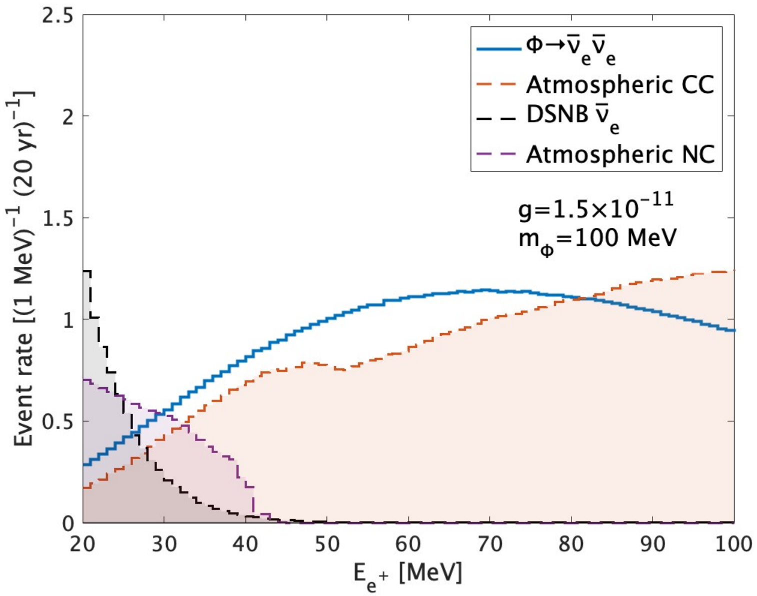
SK and HK might be still sensitive to $m_\phi \sim 1\ \mathrm{GeV}$.

# Neutrinos from all the past SNe

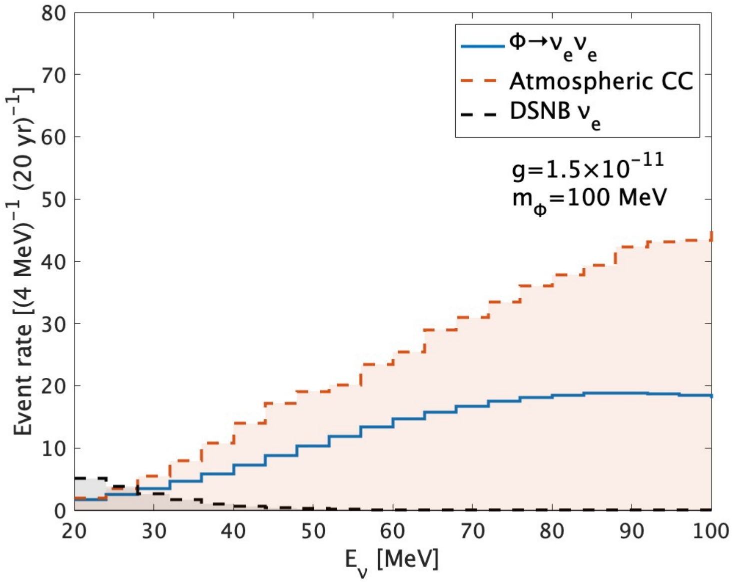
# Event rate for HK with Gd, JUNO and DUNE




HK with Gadolinium (Gd)




JUNO

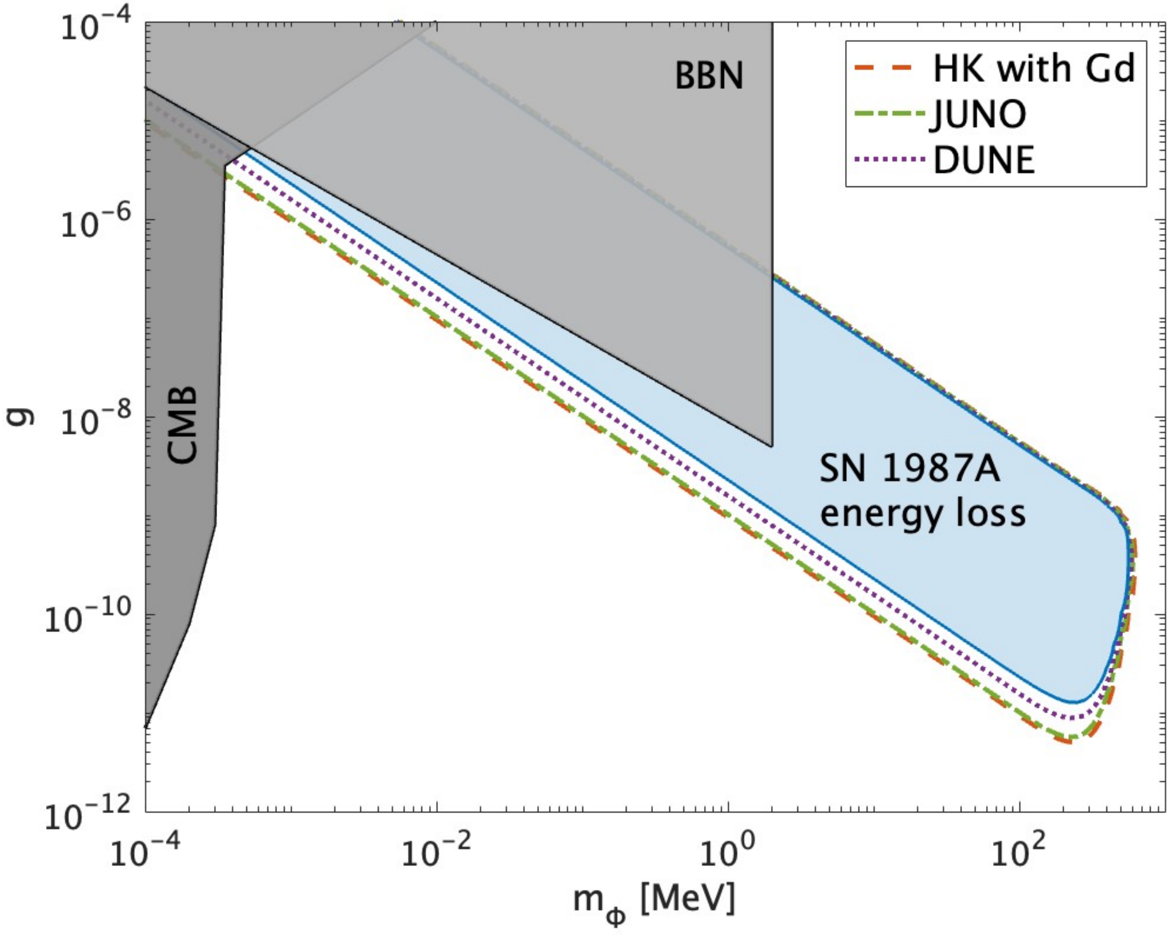



DUNE

We show event rates for 20 years data-taking.

$g = 1.5 \times 10^{-11}$ and $m_\phi = 100\ \mathrm{MeV}$ is not excluded by the current observations.

# Discovery potential of HK with Gd, JUNO and DUNE




Discovery potential at 90 % C.L.

The sensitivity for $g_{\alpha\beta}\phi\bar{\nu}_\alpha\nu_\beta$
will be improved
by a factor of 2.

However, our result might include
an uncertainty larger than a factor of 2
because our simulation is not precise.

# Conclusion

- A light boson can be produced in the SN core through $g_{\alpha\beta}\phi\bar{\nu}_\alpha\nu_\beta$ .
- The late time decay can modify SN neutrino flux.
- Future observations of next galactic SN neutrinos in SK and HK will be sensitive to $g_{\alpha\beta}\phi\bar{\nu}_\alpha\nu_\beta$ by several order of magnitude beyond the SN 1987A constraint.
  ( $g_{ee} = g_{\mu\mu} = g_{\tau\tau} = g$ )
- Future observations of neutrinos in all the past SNe in HK, JUNO and DUNE will be sensitive to $g_{\alpha\beta}\phi\bar{\nu}_\alpha\nu_\beta$ by a factor of 2 beyond the SN 1987A constraint.
  ( $g_{ee} = g_{\mu\mu} = g_{\tau\tau} = g$ )

Thank you!