Search for BSM particles from high-energy supernova neutrinos

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with
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arXiv: 2206.06852 [JHEP **12** (2022) 050], 2312.13627 [JHEP **07** (2024) 057]

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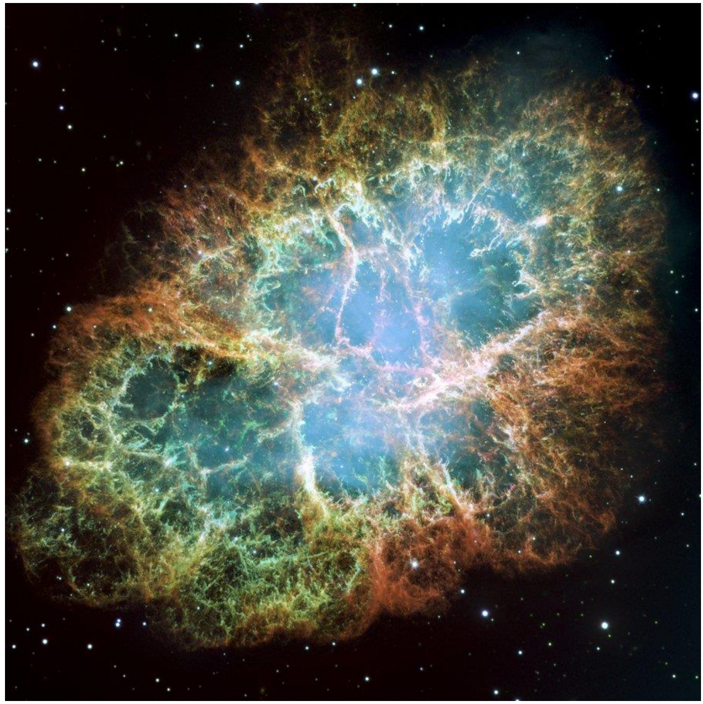
Supernovae (SNe)

- Core-collapse SN is one of the last-stage of the heavy star.

- Collapsing star becomes
  Hot and dense proto-neutron star.

  $T \sim 30\ \mathrm{MeV}$ $\rho \sim 3 \times 10^{14}\ \mathrm{g/cm^3}$ ~ nuclear density



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- Light particles with $m \sim \mathcal{O}(100)\ \mathrm{MeV}$ and small coupling
  can be produced in SNe.

SNe provide a unique environment to test feebly interacting light particles!

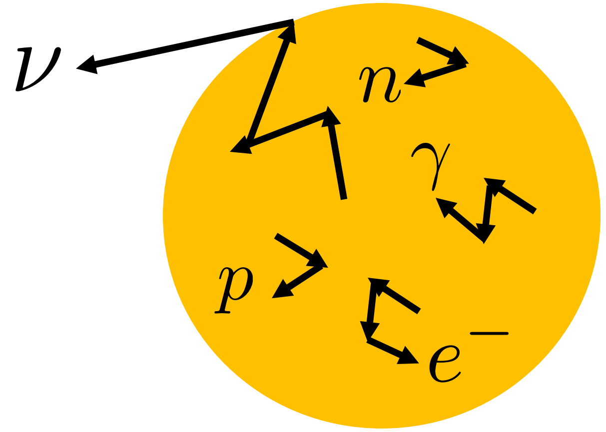
Supernovae (SNe)

- In the dense SN core,
  the Standard Model (SM) particles are trapped.

- The weakest interacting SM particles, i.e., neutrinos
  carry the huge energy outward and cool the core.

- SN neutrinos were indeed observed from SN 1987A!

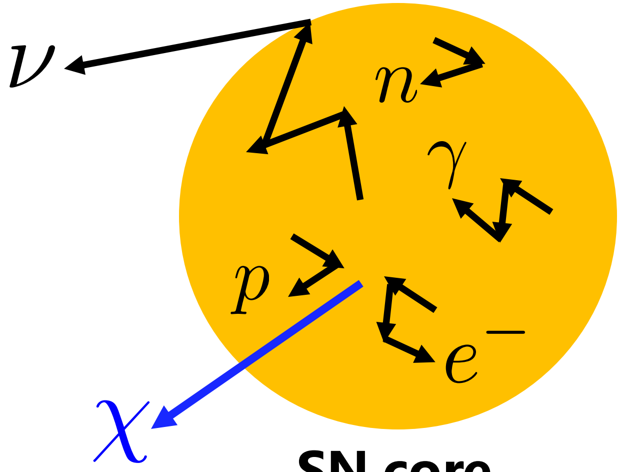
- The data is roughly consistent with the SM.



SN core

SN 1987A

SNe and light particles



- New particles, χ , with weaker interactions than neutrinos
  →an additional cooling channel

- Total $E_\chi \gtrsim$ Total E_ν :
  →The data for SN1987A neutrinos would be inconsistent.
  (SN energy loss argument)
  [G.G. Raffelt. (1994)]

- This argument uniquely constrain light particles such as axions.

- Recently, this arguments is improved.
  E.g, γ-ray observations can probe light particles decaying to EM particles with $E_\chi \ll E_\nu$.

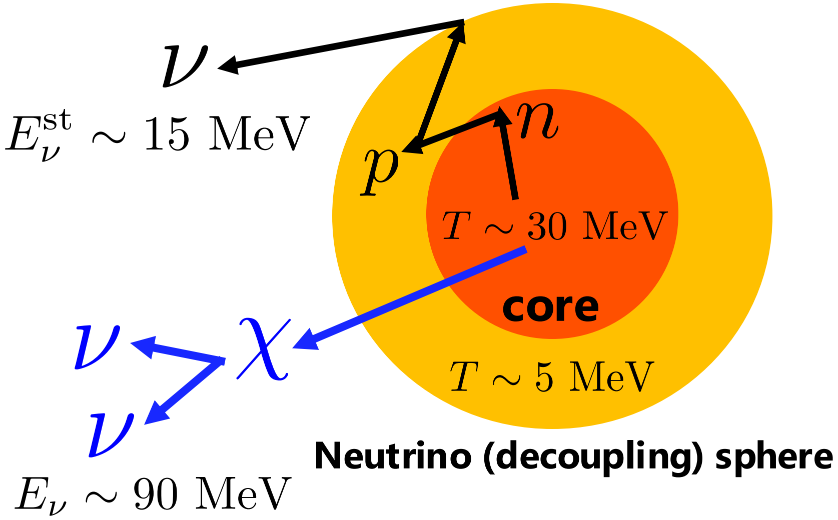
Light particles decaying to neutrinos

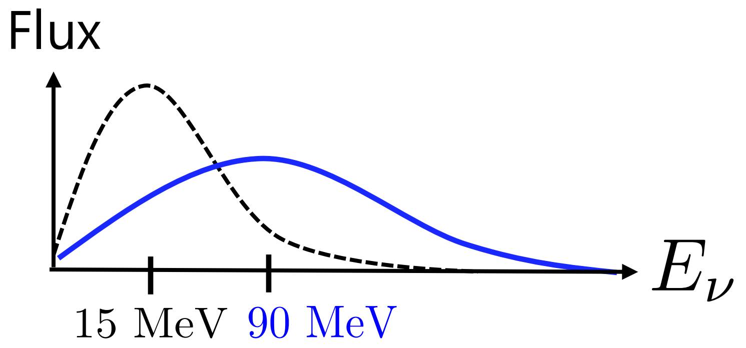
- Some light particles, χ,
  can decay to neutrinos outside the SN core.

(or $E_\chi \sim m_\chi/2$ etc.)

- Energy from the χ decay is $E_\nu \sim 3T \sim 90\ \mathrm{MeV}$
  higher than the standard one $E_\nu^{\mathrm{st}} \sim 15\ \mathrm{MeV}$.

- Detection rate in the Water-Cherenkov detector
  is roughly $\sigma_\nu \propto E_\nu^2$.



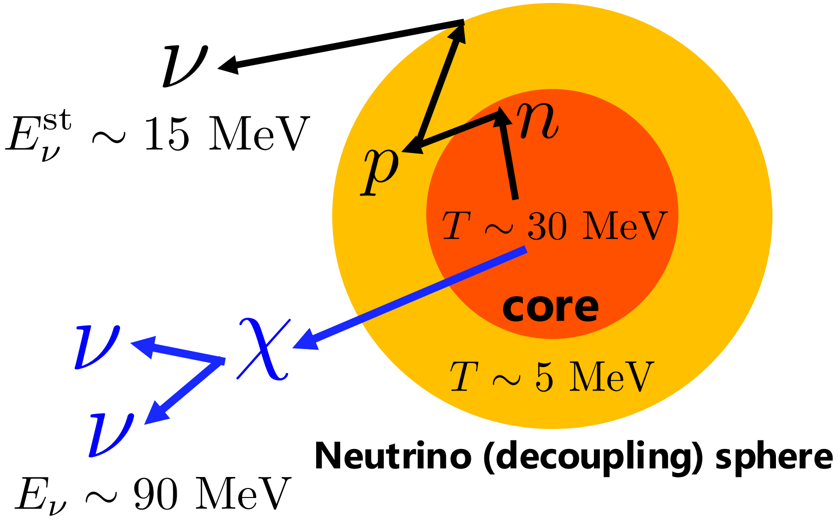


Even if total $E_\chi \sim \left(\frac{15\ \mathrm{MeV}}{90\ \mathrm{MeV}}\right)^2$ total E_ν^{st}, we may constrain χ decaying to neutrinos!

[KA, S. Im and M. Masud. (2022)] [D. Fiorillo, G. Raffelt and E. Vitagliano. (2023)] [KA, S. Im, M. Masud, S. Yun (2024)],...

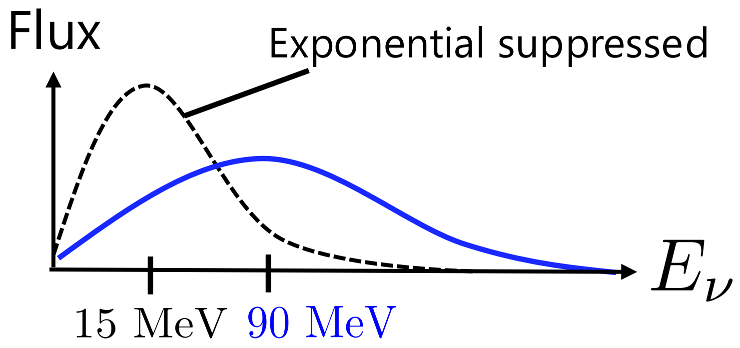
High energy neutrinos from decays

- More energetic
- High sensitivity, $\sigma_\nu \propto E_\nu^2$
- Less background



A few time per century may occur.

<u>Future galactic SN neutrinos in Hyper-K</u>



- Better sensitivity by larger detector
- Still less background
- Galactic SNe will be closer than SN 1987A.

An SN outside the MW galaxy

We will improve **the energy loss argument**
by **high energy SN 1987A and future galactic neutrinos**.

Strong Supernova 1987A Constraints on Bosons Decaying to Neutrinos

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Majoron-like bosons would emerge from a supernova (SN) core by neutrino coalescence of the form $\nu\nu \to \phi$ and $\bar{\nu}\bar{\nu} \to \phi$ with 100-MeV-range energies. Subsequent decays to (anti)neutrinos of all flavors provide a flux component with energies much larger than the usual flux from the "neutrino sphere." The absence of 100-MeV-range events in the Kamiokande-II and Irvine-Michigan-Brookhaven signal of SN 1987A implies that less than 1% of the total energy was thus emitted and provides the strongest constraint on the Majoron-neutrino coupling of $g \lesssim 10^{-9}\ \mathrm{MeV}/m_\phi$ for 100 eV $\lesssim m_\phi \lesssim$ 100 MeV. It is straightforward to extend our new argument to other hypothetical feebly interacting particles.

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In other cases, FIP decays include active neutrinos. In the free-streaming limit, FIPs escape from the inner SN core and so their decays provide 100-MeV-range events, much larger than the usual neutrino burst of few 10 MeV that emerges from the neutrino sphere at the edge of the SN core. The background of atmospheric muons has yet larger energies and so the new signal would stick out in a future SN neutrino observation. This argument was first advanced in Ref. [7] and offers an intriguing future detection opportunity.

[7] K. Akita, S. H. Im, and M. Masud, Probing non-standard neutrino interactions with a light boson from next Galactic and diffuse supernova neutrinos, J. High Energy Phys. 12 (2022) 050.

Light particles decaying to neutrinos

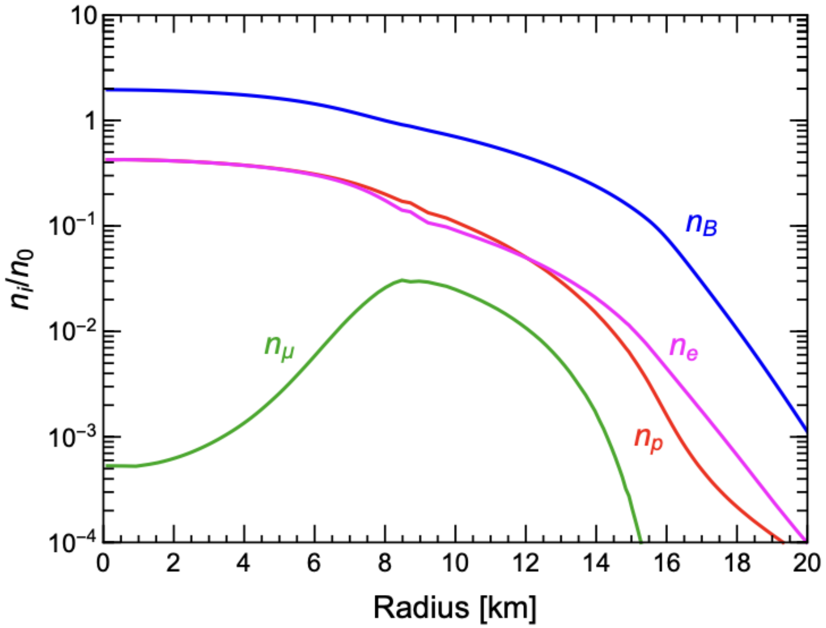
- Light particles interacting neutrinos (lepton sector) are well motivated.
  - Heavy neutral leptons (right-handed neutrinos)
    →Neutrino mass, baryon/lepton asymmetry etc.
  - $\mathrm{U}(1)_{L_\mu - L_\tau}$ gauge bosons
    →Muon g-2 anomaly, Hubble tension
  - $\mathrm{U}(1)_{B-L}$ gauge bosons
    →Neutrino mass, Hubble tension
  - Majorons (Pseudo-Nambu-Goldstone boson related with Majorana mass)
    →Neutrino mass

*Gauge bosons cannot decay to photons at tree level.
→Neutrino signal would be important for light gauge bosons.

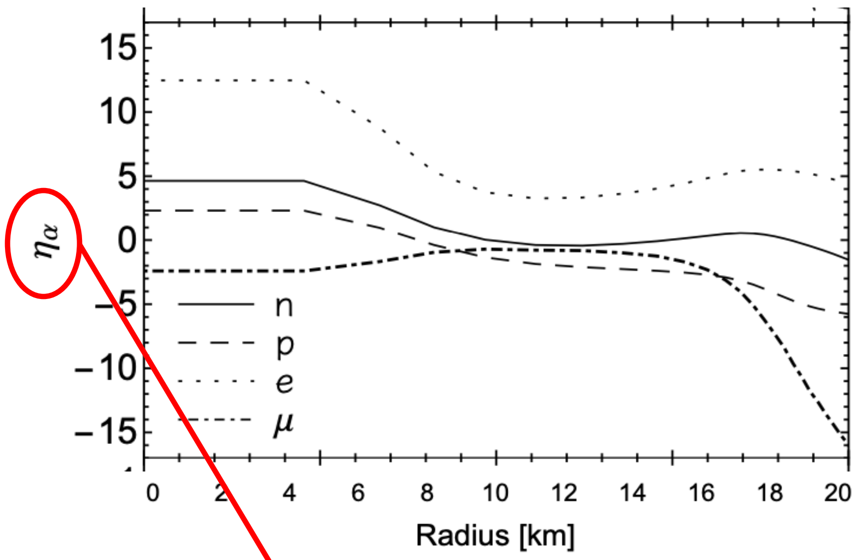
Outline

- Introduction
- Core profile in supernovae
- Neutrino oscillations for neutrinos decayed by light particles
- Event rates and statistical analysis
- Each results

Core profile in supernovae (at $t_{\text{post-bounce}} = 1\ \text{s}$)



[A. Caputo, et al. (2022)]



[P. Carenza, et al. (2023)]

Degeneracy parameter:

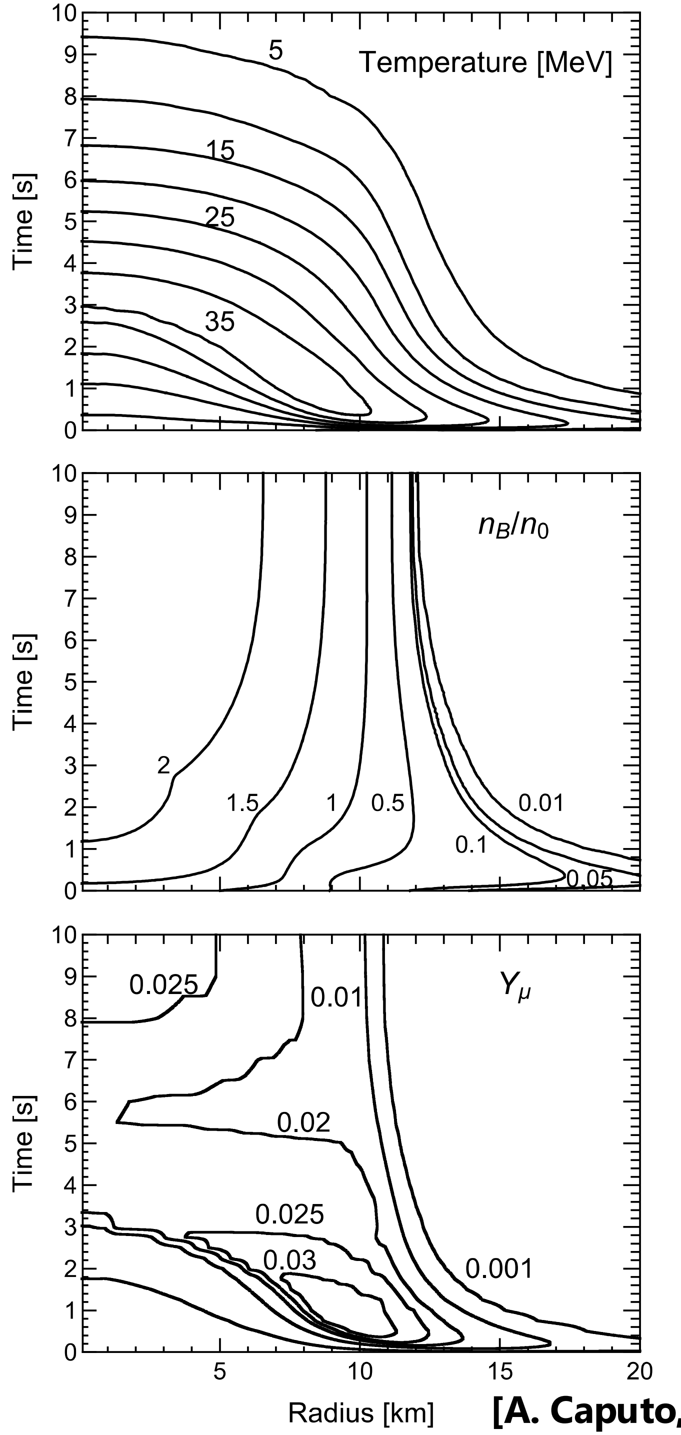
$$\eta = \frac{\mu - m}{T}$$

- Electrons are highly degenerate.
  →The phase space of electrons is filled and some reactions are Pauli-blocked.
- n, p, μ are mildly degenerate → Some reactions are NOT highly suppressed.

Core profile (up to $t_{\text{post-bounce}} = 10 \text{ s}$)

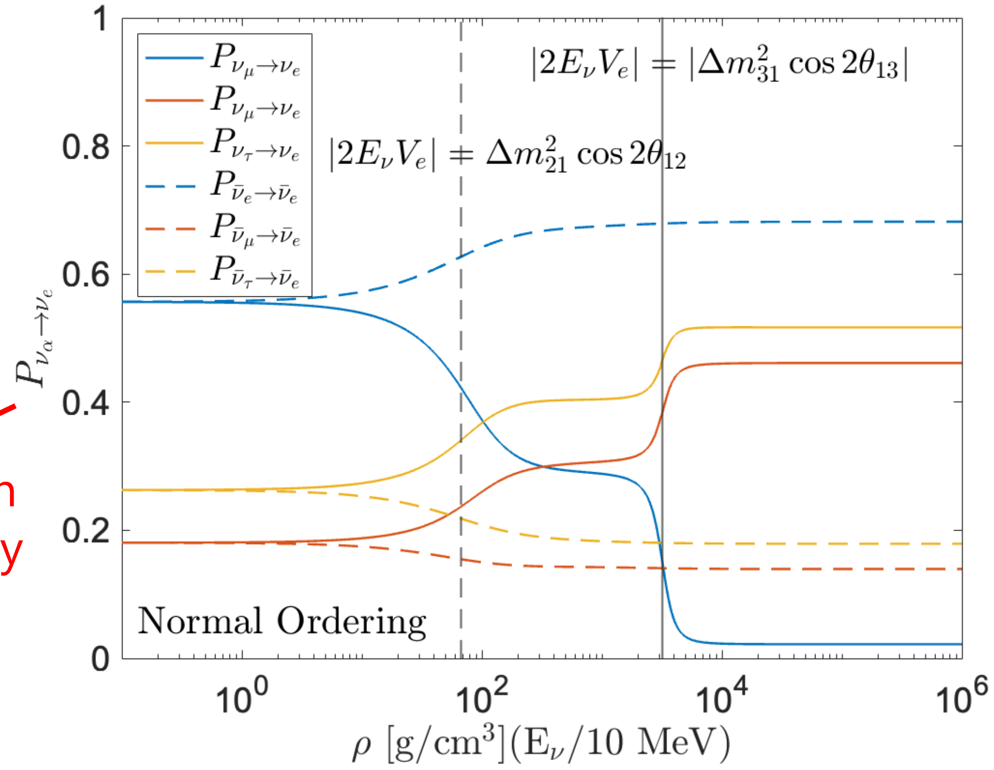
- We use the publicly available data of SFHo-18.8 [A. Caputo, et al. (2022)]. because this is a conservative model in public models.

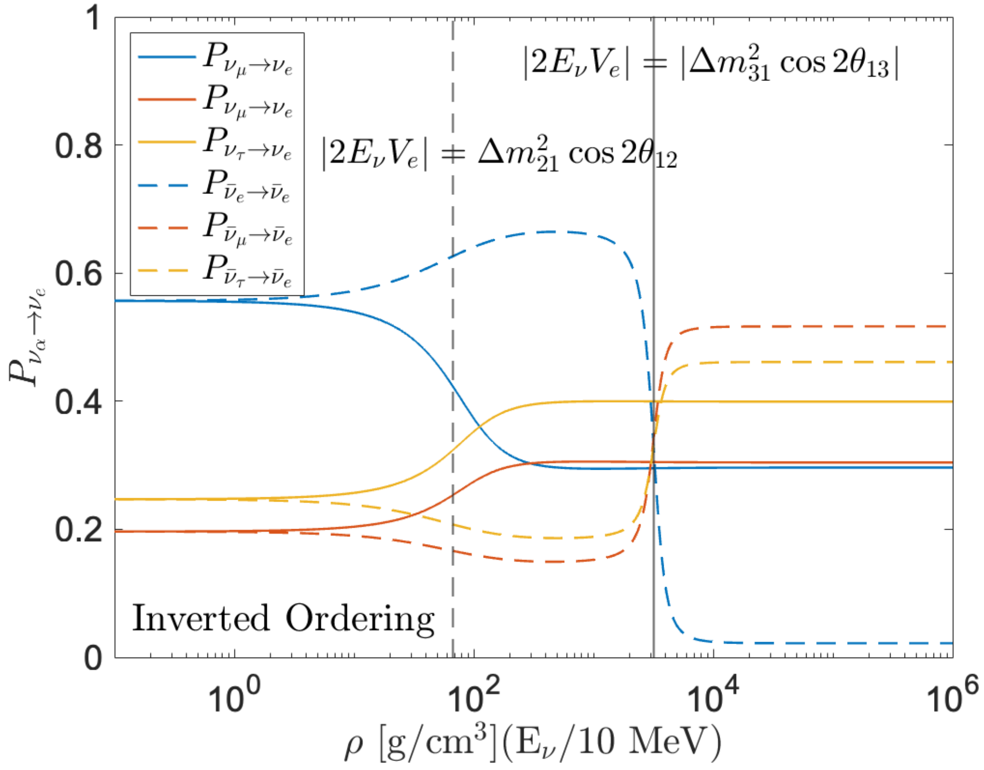
- A publicly available data is limited. We further assume
    1. $Y_p \simeq Y_e \equiv n_{p,e}/n_b \simeq 0.2$ **[T. Fischer, et al. (2021)]**
    2. $Y_{\pi^-} \equiv n_{\pi^-}/n_b \sim 0.01$ **[T. Fischer, et al. (2021)]**



[A. Caputo, et al. (2022)]

Effects of neutrino oscillations on the neutrino fluxes





Oscillation probability

Density, i.e., the decay point

- ν_e and $\bar\nu_e$ are mainly detected via $e^\pm$ in 100-MeV region → $P_{\nu_\alpha\to\nu_e}$ is important.
- No big differences between the normal and inverted mass orderings of neutrinos.
- No big differences between $\nu_\mu \to \nu_e$ and $\nu_\tau \to \nu_e$.

Event rates

- **Detector:**

  Kamiokande (0.78 kton) and IMB (6.8 kton) for SN 1987A

  Hyper-Kamiokande (220 kton) for a future galactic SN

- **Detector efficiency:** the right figure

  Kamiokande (0.78 kton) is important for the standard SN neutrinos.

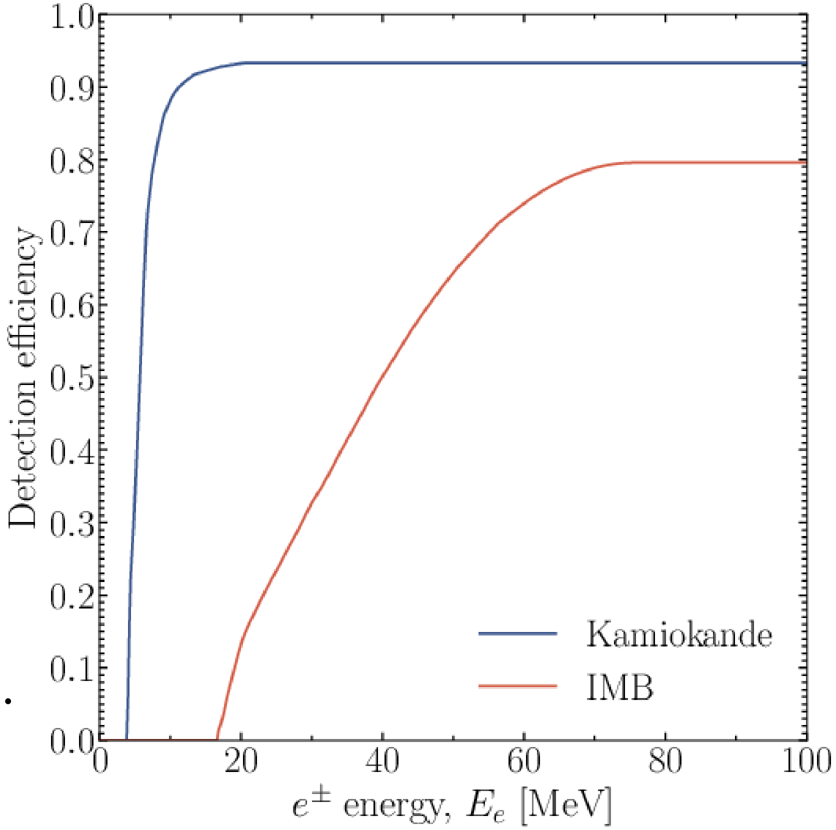
  IMB (6.8 kton) is important for high-energy SN neutrinos!

- **Energy range to be analyzed:**

  Kamiokande: 7.5 MeV-50 MeV

  IMB: 19 MeV-

  Hyper-K: 10 MeV-1 GeV



[D. F. G. Fiorillo, et al. (2023)]

Event rates

- **Main detection processes:**

$$\bar{\nu}_e + p \to e^+ + n \qquad (E_\nu \lesssim 70\ \mathrm{MeV})$$

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

$$\nu_e + \mathrm{O} \to e^- + Y \qquad (E_\nu \gtrsim 70\ \mathrm{MeV})$$

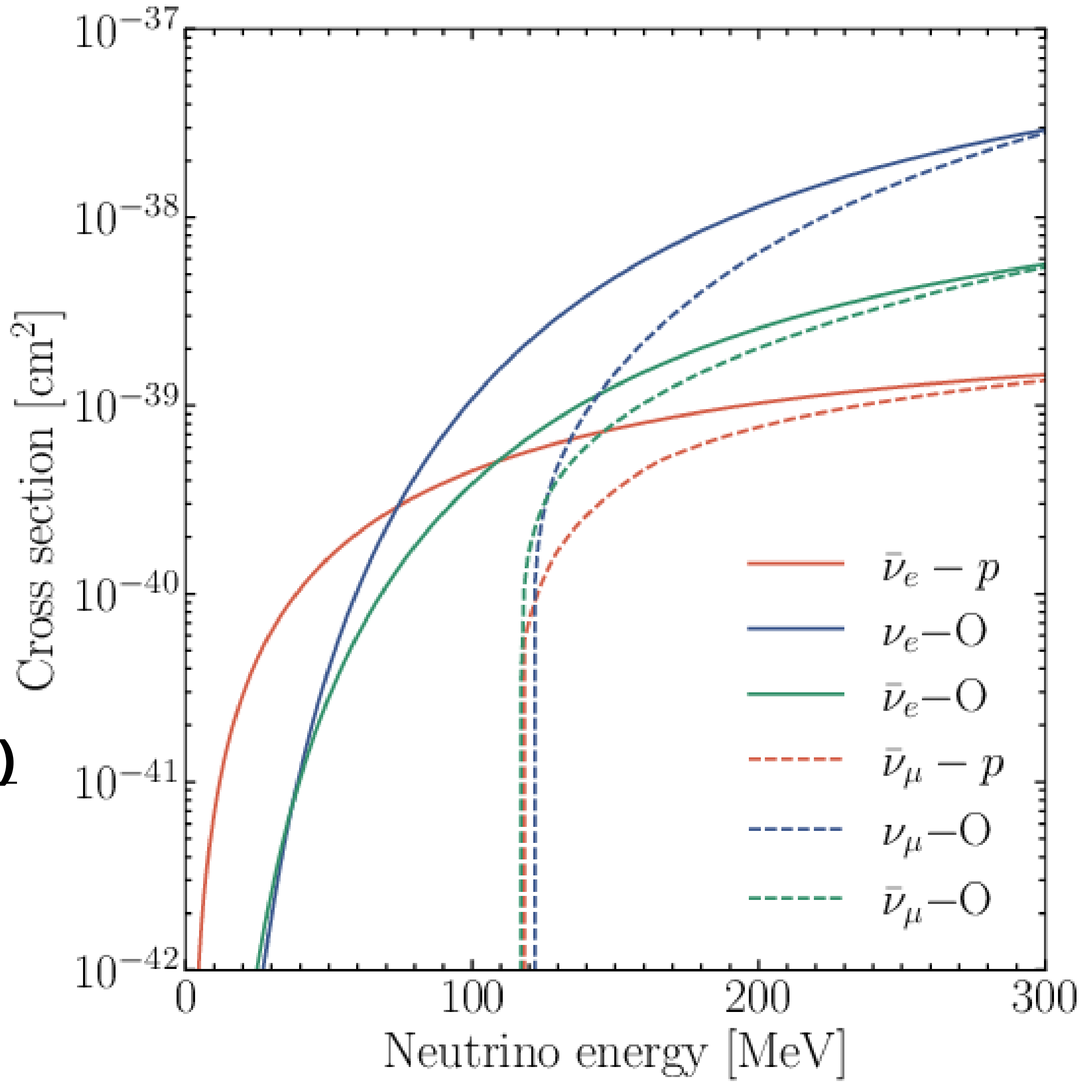
Oxygen Nucleus

- **Data-taking time (after the first neutrino event)**

$t_{\mathrm{data}} \sim 10\ \mathrm{s}$ for SN 1987A

$t_{\mathrm{data}} \sim 10^3\ \mathrm{s}$ for a future galactic SN

We expect atmospheric neutrino background is negligible until this time in HK.



[D. F. G. Fiorillo, et al. (2023)]

Statistical analysis

- **Standard SN neutrino flux:** A fitting formula

$$\frac{dN_\nu}{dE_\nu} = \frac{E_{\rm tot}}{6E_0^2}\frac{(1+\alpha)^{1+\alpha}}{\Gamma(1+\alpha)}\left(\frac{E_\nu}{E_0}\right)^\alpha e^{-(1+\alpha)E_\nu/E_0},$$

Total energy Average energy Shape parameter

- **Likelihood function:** Poisson likelihood

$$\mathcal{L} \propto \exp\left[-\int_{E_{\rm low}}^{E_{\rm high}} \frac{dN_e}{dE_e^{\rm det}} dE_e^{\rm det}\right] \prod_i^{N_{\rm bin}} N_e^{N_i}$$

$$\propto \exp\left[-\int_{E_{\rm low}}^{E_{\rm high}} \frac{dN_e}{dE_e^{\rm det}} dE_e^{\rm det}\right] \prod_i^{N_{\rm obs}} \frac{dN_e}{dE_e^{\rm det}}(E_i)$$

- **Maximum likelihood analysis:**

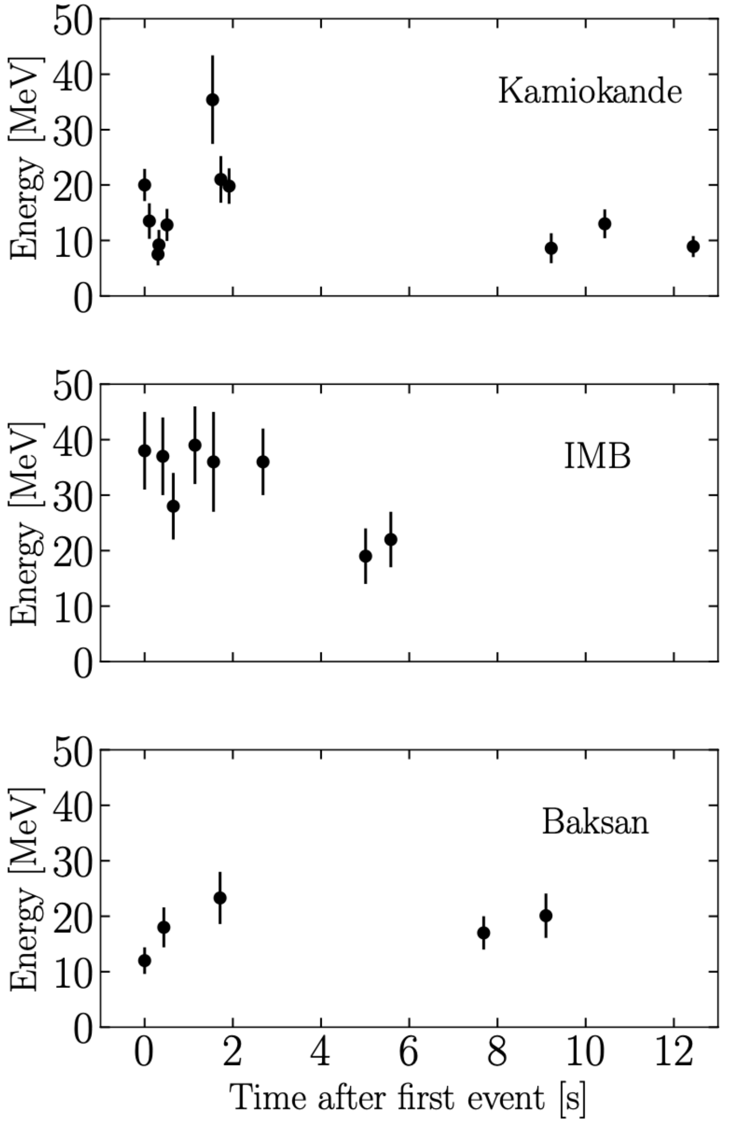
$$\tilde{\mathcal{L}}(g,m) = \max_{E_0, E_{\rm tot}} \mathcal{L}(g,m,E_0,E_{\rm tot}),$$

$$\chi^2 = 2\left[\log \tilde{L}(0,m) - \log \tilde{L}(g,m_\phi)\right].$$

We marginalize $E_{\rm tot}, E_0$ to minimize χ^2.

Fiducial values for averaged all $\bar{\nu}$

$E_0 = 1.98 \times 10^{53}$ erg,
$E_0 = 12.7$ MeV,
$\alpha = 2.39$



[D. F. G. Fiorillo, et al. (2023)]

Heavy neutral leptons (sterile neutrinos)

- We consider a single Majorana mass eigenstate N mixing only with ν_e or ν_μ or ν_τ .

- **Dominant production process**

$$\nu n \to N n$$

$$\nu p \to N p$$

+ their charge-conjugate processes

$$\ell^- p \to N n \quad (\ell^- = e^-, \mu^-)$$

⟵ the charged current processes only for mixing with ν_e and ν_μ

Their cross sections are enhanced by $m_{n,p} \simeq 1\ \mathrm{GeV}$, compared with, e.g., $\nu\nu \to \nu N$.
Their productions are only <u>mildly</u> Pauli-blocked.

- **Decay process:**

$$N \to \nu_\alpha \pi_0$$

$$N \to \nu_\alpha \nu_\beta \bar{\nu}_\beta$$

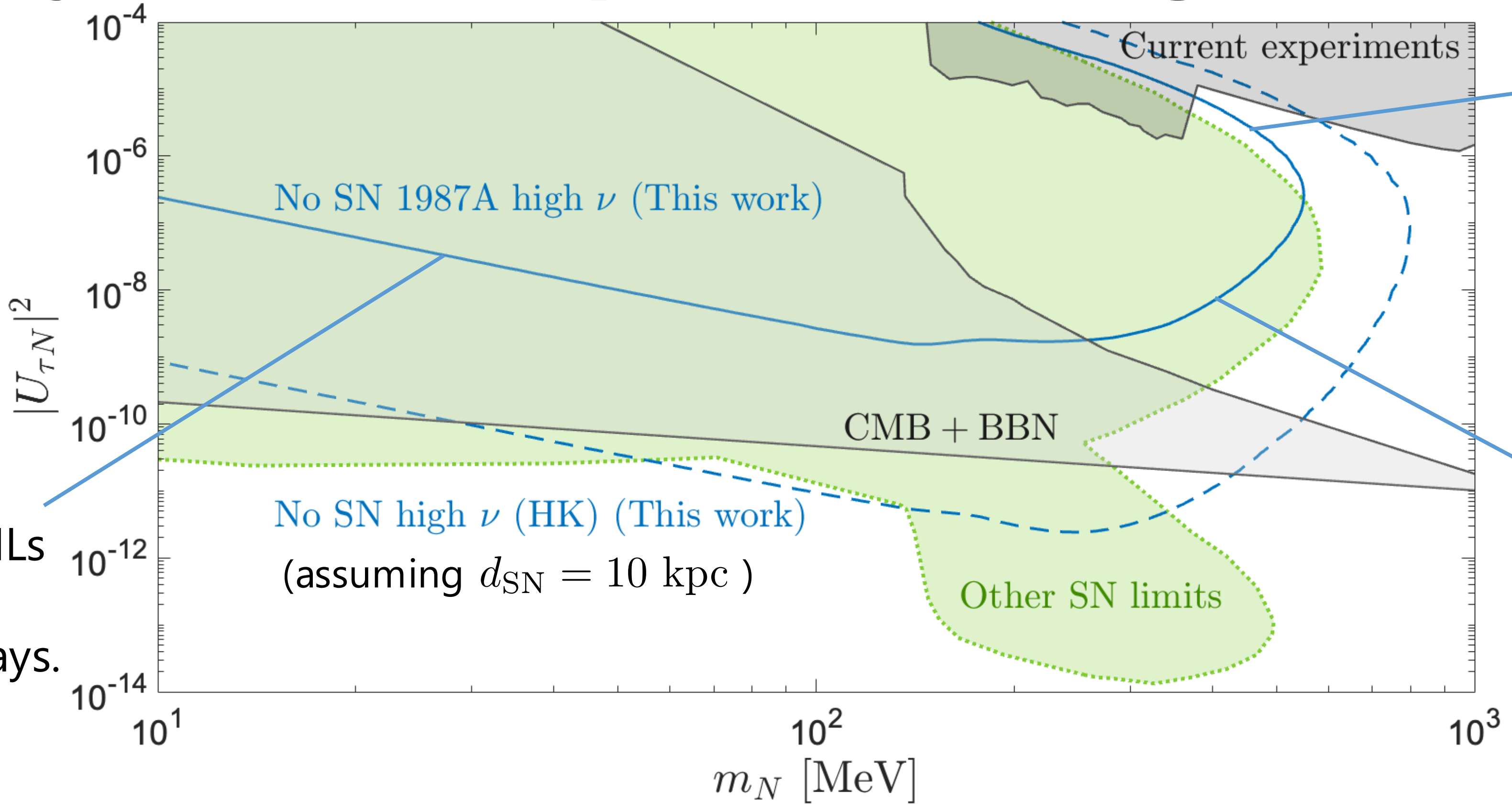
$$N \to \nu_\alpha \ell^+ \ell'^- \ (\ell, \ell' = e, \mu)$$

$$N \to \ell \pi^+$$

+ their charge-conjugate processes

etc.

Heavy neutral leptons mixing with ν_τ



Trapping in the core

The Boltzmann suppression

The lifetime of HNLs is too longer to observe their decays.

- Other SN limits come from no γ-ray observations from HNL decays etc.
- Galactic SN observations will improve by $(10\ \mathrm{kpc}/50\ \mathrm{kpc})^{-2} \times (220\ \mathrm{kton}/6.8\ \mathrm{kton}) \simeq 8 \times 10^2$.

$\mathrm{U}(1)_{L_\mu - L_\tau}$ gauge bosons

$$\mathcal{L}_{L_\mu - L_\tau} = \mathcal{L}_{SM} - \frac{1}{4} Z'_{\mu\nu} Z'^{\mu\nu} - \frac{\epsilon}{2} Z'_{\mu\nu} Z^{\mu\nu} + \frac{m_{Z'}^2}{2} Z'_\mu Z'^\mu$$
$$+ g_{\mu-\tau} Z'_\alpha (\bar{\mu}\gamma^\alpha \mu + \bar{\nu}_\mu \gamma^\alpha P_L \nu_\mu - \bar{\tau}\gamma^\alpha \tau - \bar{\nu}_\tau \gamma^\alpha P_L \nu_\tau)$$

New gauge bosons

- **Dominant production process**

neutrino-pair coalescence: $\nu\bar{\nu} \to Z'$

semi-Compton scattering: $\gamma\mu \to Z'\mu$

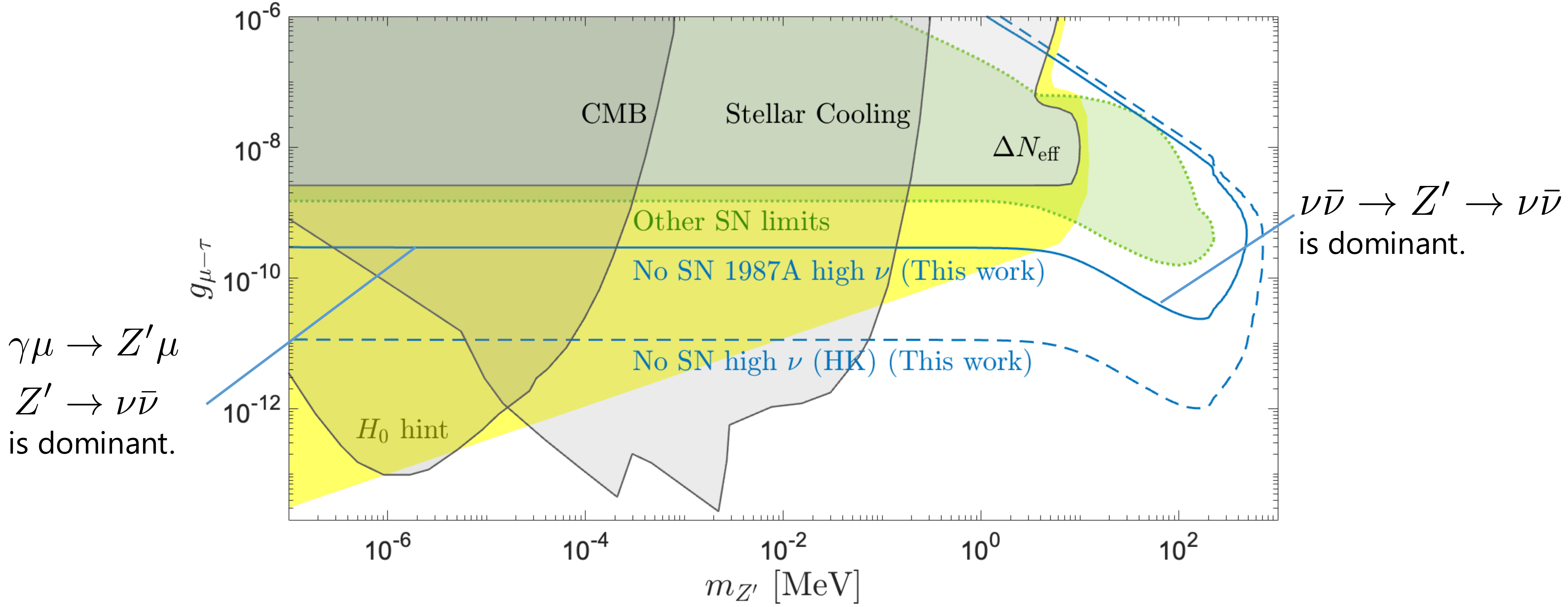
This process is dominant for $m_{Z'} \ll T$.
→We use the same formula with the Compton scattering.

- **Decay process**

$Z' \to \nu\bar{\nu}$

$Z' \to \mu^+\mu^-$

$\mathrm{U}(1)_{L_\mu - L_\tau}$ gauge bosons



- We have improved the previous SN 1987A limits by a factor of 3-10.
- Future galactic SN observations in HK will further improve by a factor of 26.
- Our limit is overlapped with the region to relax the Hubble tension.

Summary

- Hot and dense environment in SNe can produce feebly interacting light hypothetical particles.
- Their subsequent decays to neutrinos outside the SN core produce the secondary flux, modifying the high-energy tail of total SN neutrino flux.
- We obtain new strong limits and future sensitivities on heavy neutral lepton (sterile neutrino), $\mathrm{U}(1)_{L_\mu - L_\tau}$ and $\mathrm{U}(1)_{B-L}$ gauge bosons, and majoron from the absence of high energy SN 1987A and galactic neutrinos.

Thank you!

Backup

Production of new particles and secondary ν fluxes

- We solve the Boltzmann equation for new particles, χ , to estimate their productions:

$$\frac{\partial f_\chi}{\partial t} = \mathcal{C}[f]$$

Collision term to describe scatterings and annihilations

- **<u>The emitted spectrum for χ from a SN:</u>**

Decay rate

$$\frac{dN_\chi}{dE_\chi} = \int dt \int dV \langle e^{-\tau_{\rm abs}(E_\chi, r)} \rangle e^{-\Gamma_\chi r_\nu/(\gamma\beta)} \int d\Omega \frac{E_\chi p_\chi}{(2\pi)^3} \frac{\partial f_\chi}{\partial t},$$

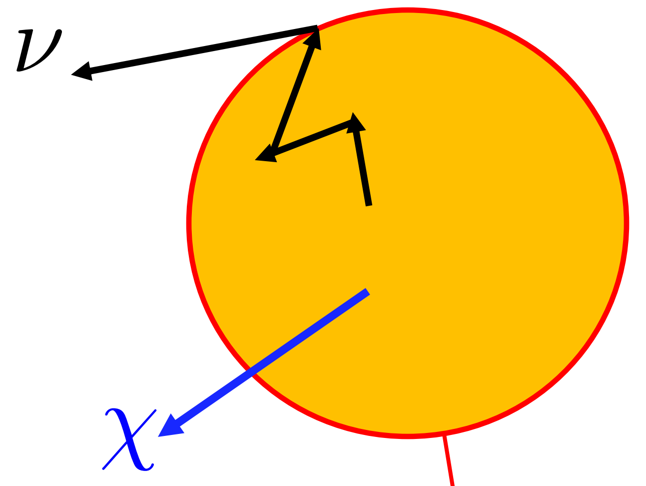
Momentum angles

Trapping by absorptions/rescatterings
(averaged by angles from the radial direction)

New particles should survive outside the neutrino sphere.

$$\tau_{\rm abs}(E, r) = \int_r^\infty dr' \Gamma_{\rm abs}(E, r')/\beta$$

Absorption rate



Neutrino (decoupling) sphere
$r_\nu \simeq 20$ km

Production of new particles and secondary ν fluxes

- **The secondary neutrino flux:**

The emitted angle in the rest frame of χ

$$\frac{d^2 N_{\nu_\alpha}}{dt_D d\omega_\nu} = \int \cos\theta \int dE_\chi \underbrace{\frac{\mathrm{Br}_{\nu_\alpha} \bar{N}_{\nu_\alpha}}{\tau\gamma}}_{\frac{1}{N_\chi}\frac{dN_\chi}{dt_D}} \underbrace{\exp\left(-\frac{t_D}{\tau\gamma}\right) \frac{dN_\chi}{dE_\chi}(t_D = 0)}_{\text{The remaining } \chi \text{ flux}} \underbrace{\frac{1}{\Gamma_\chi} \frac{d^2\Gamma_\chi}{d\omega_\nu d\cos\theta}}_{\text{Distribution of } \omega_\nu \text{ and } \theta \text{ from a decay}}$$

Time in the lab frame

Neutrino energy in the rest frame of χ

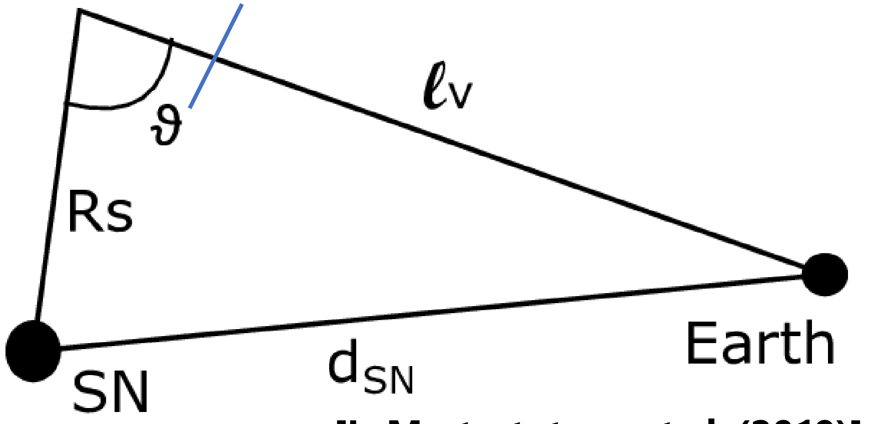
- **Time delay:**

$$t_{\mathrm{delay}} = \frac{t_D}{\gamma^2 (1 + \beta\cos\theta)} \qquad \gamma = E_\chi / m_\chi$$

Lorentz boost factor

Velocity

The emitted angle in the lab frame



[L. Mastrototaro, et al. (2019)]

- Time delay is suppressed by the Lorentz boosted factor.
- We consider a data-taking time as $\frac{d^2 N_{\nu_\alpha}}{dt_D d\omega_\nu} \to \frac{d^2 N_{\nu_\alpha}}{dt_D d\omega_\nu} \Theta(t_{\mathrm{data}} - t_{\mathrm{delay}})$.

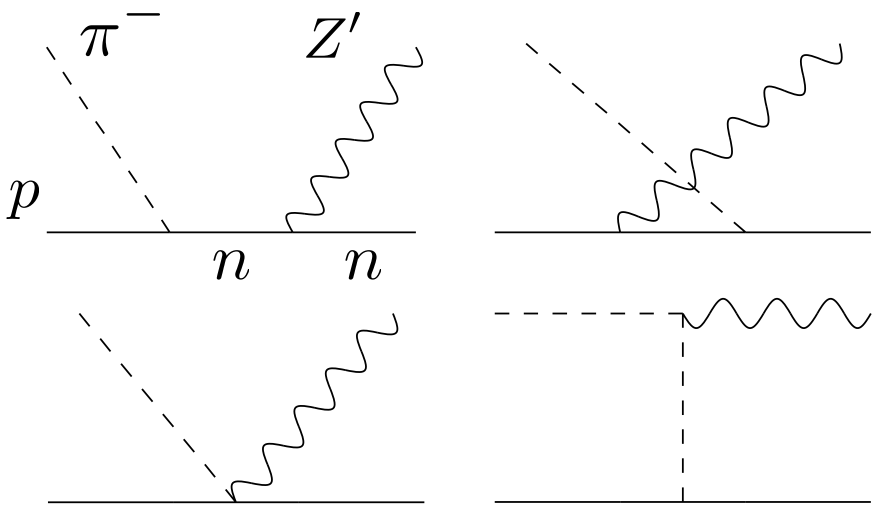
$\mathrm{U}(1)_{B-L}$ gauge bosons

$$\mathcal{L}_{B-L} = \mathcal{L}_{SM} - \frac{1}{4} Z'_{\mu\nu} Z'^{\mu\nu} - \frac{\varepsilon}{2} Z'_{\mu\nu} F^{\mu\nu} + \frac{m_{Z'}^2}{2} Z'_\mu Z'^\mu + g_{B-L} Z'_\mu \left(\frac{1}{3} \bar{q} \gamma^\mu q - \bar{\ell} \gamma^\mu \ell \right)$$

- **<u>Production process</u>**

$$\pi^- p \to Z' n$$

*Other processes might be important
but we neglect them for simplicity and conservatively.

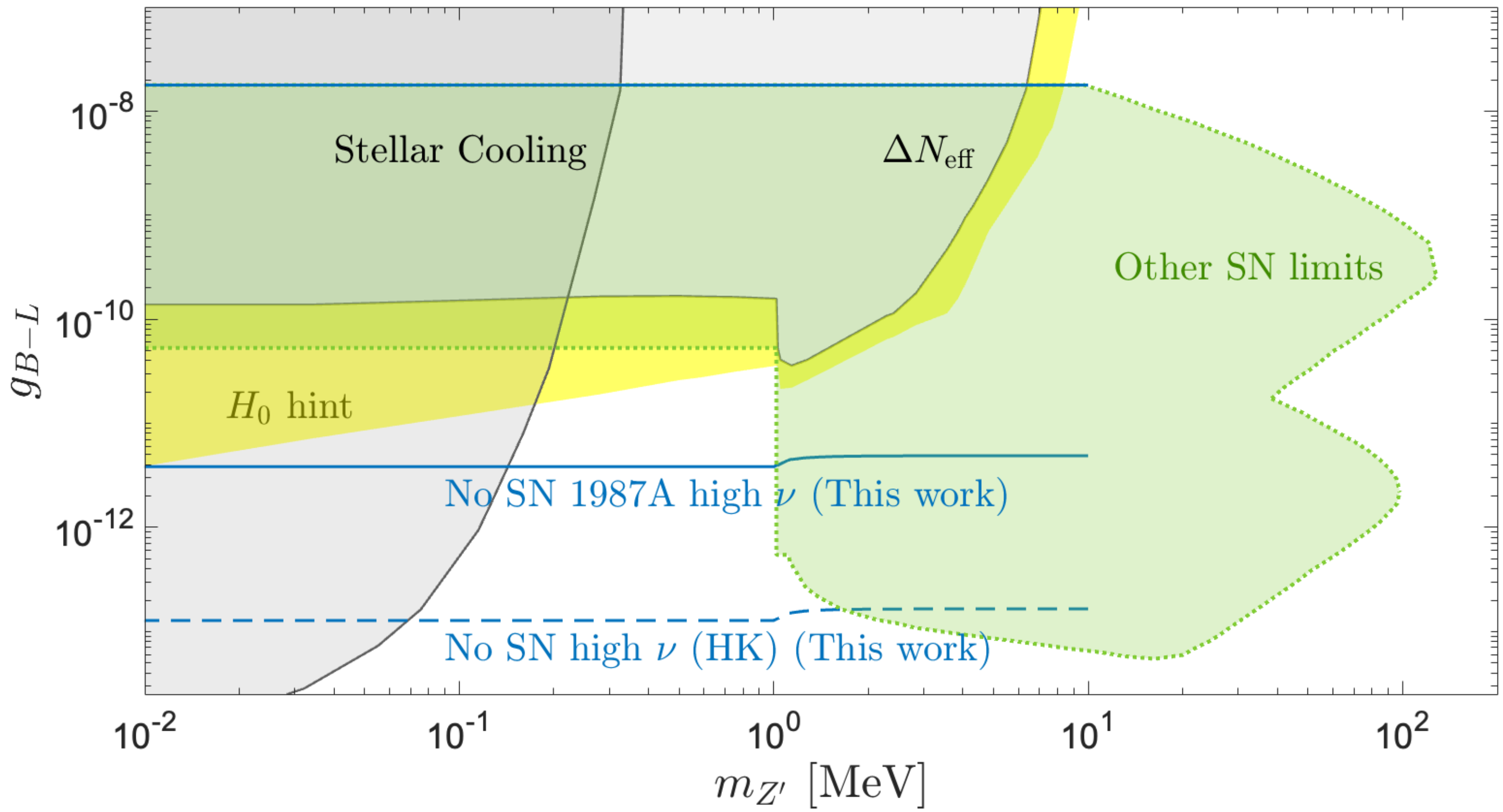


[C. S. Shin, et al. (2022)]

- **<u>Decay process</u>**

$$Z' \to \nu \bar{\nu}$$
$$Z' \to \ell^+ \ell^-$$

$\mathrm{U}(1)_{B-L}$ gauge bosons



- Z' cannot decay into $e^{\pm}$ below 1 MeV.
- We have improved the previous SN 1987A limits by a factor of 14.

Majoron

$$\mathcal{L}_{\rm int} = \frac{1}{2} g_{\alpha\beta} \bar{\nu}_\beta \nu_\alpha \phi,$$

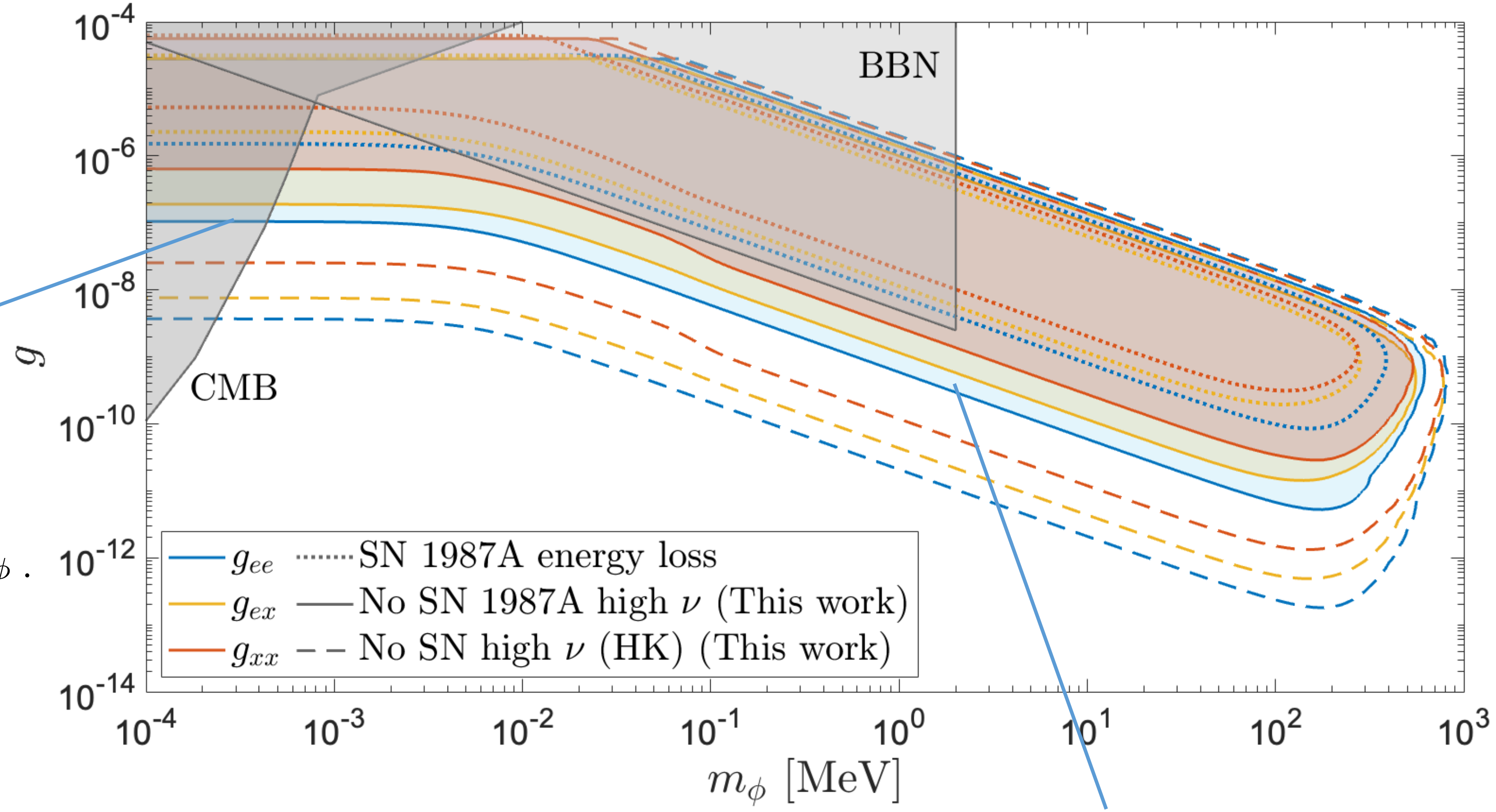
- **Production process**

$$\nu\nu, \bar{\nu}\bar{\nu} \to \phi$$

- **Decay process**

$$\phi \to \nu\nu, \bar{\nu}\bar{\nu}$$

Majoron



Matter potentials modify the dispersion relation for ν.

→The production rate for ϕ becomes independent of m_ϕ .

The production rate for $\nu\nu \to \phi \propto m_\phi^2$ due to $(p_1 + p_2)^2 = p_\phi^2 = m_\phi^2$.

- ν_e is most populated in the core due to $p + e^- \to n + \nu_e$.