ANOMALIES 2020, Hyderabad, Sept.11-13

Feeble Neutrino-portal Dark Matter at Neutrino Detectors

In collaboration with P. Bandyopadhyay (IITH)
and R. Mandal (Siegen U.), arXiv:2005.13933

Eung Jin Chun

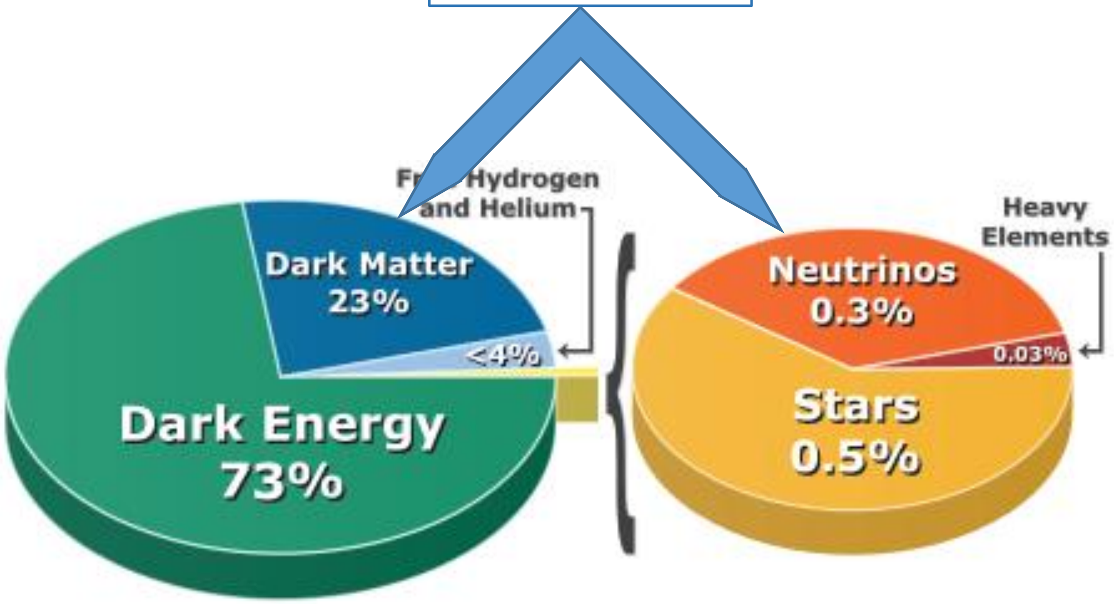
KIAS KOREA INSTITUTE FOR ADVANCED STUDY

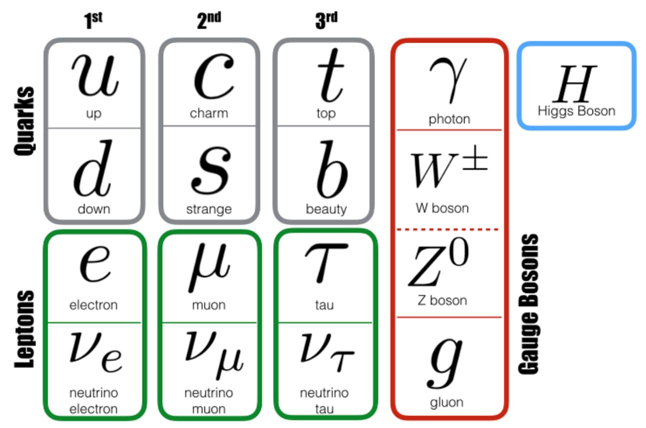
Outline

- Introduction: dark matter and neutrino mass
- Freeze-in scenarios of neutrino-portal DM
- Dark radiation and energetic neutrinos at SK/ICECUBE
- Conclusion

Dark matter and neutrinos

CONNECTED?





Neutrino mass from Seesaw

- Introduce a SM-singlet fermion N:

$$\mathcal{L}_{seesaw} = y_\nu\, LHN + \frac{1}{2} MNN + h.c.$$

$$\mathcal{L}_{mass} = y_\nu v_H\, \nu N + \frac{1}{2} MNN \rightarrow \frac{1}{2} m_\nu \nu\nu + \frac{1}{2} MNN \qquad m_\nu \approx \frac{y_\nu^2 v_H^2}{M^2}$$

- Small $\nu - N$ mixing: $\theta \approx y_\nu \frac{v_H}{M} \sim \sqrt{\frac{m_\nu}{M}} \lesssim 10^{-6} \sqrt{\frac{v_H}{M}}$

- Feeble coupling not to thermalize N:

$$\Gamma < H(T = M) \Rightarrow \frac{y_\nu^2 M}{8\pi} < \frac{M^2}{M_{pl}} \quad \Rightarrow \quad y_\nu \lesssim 10^{-7} \sqrt{\frac{M}{v_H}}$$

*) negligible contribution to neutrino mass.

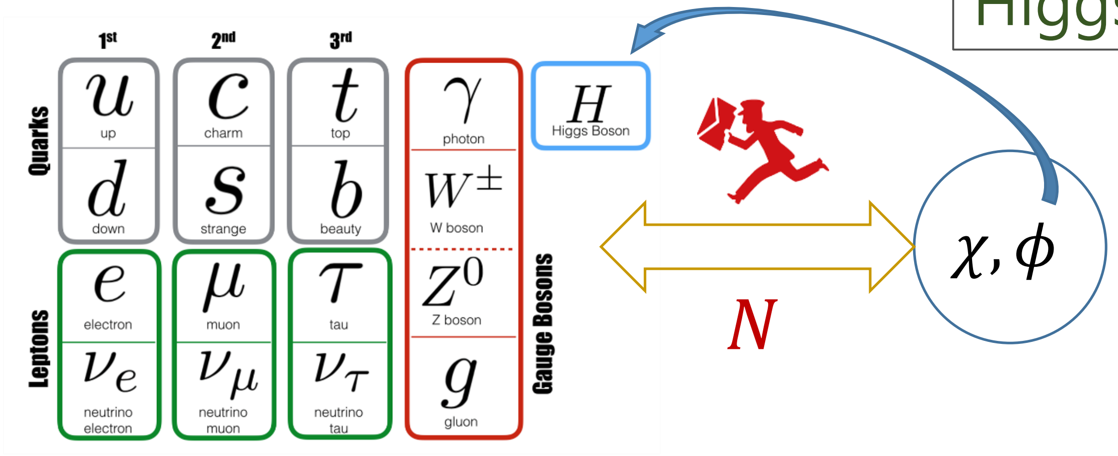
Neutrino-portal DM

- Dark sector with a fermion and a scalar:

$$y_\nu LHN + \lambda N\chi\phi$$

Higgs-portal: $\kappa\,|\phi|^2|H|^2$

Feeble coupling: $\kappa < 10^{-7}$



Conditions for freezed-in N, ϕ, χ

$$\mathcal{L} = y_\nu LHN + \lambda N\chi\phi + \kappa|\phi|^2|H|^2$$

$$\Gamma_{N\to\nu h} \approx \frac{y_\nu^2}{8\pi} m_N < H(T)\big|_{T=m_N} \Longrightarrow y_\nu \lesssim 10^{-7}\,,$$

$$\Gamma_{\phi\phi\to hh} \approx \frac{\kappa^4}{4\pi} T < H(T)\big|_{T=m_\phi} \Longrightarrow \kappa \lesssim 10^{-7}\,,$$

$$\Gamma_{\phi\chi\to\ell h} \approx \frac{y_\nu^2\lambda^2}{4\pi} T < H(T)\big|_{T=m_{\phi,\chi}} \Longrightarrow y_\nu\lambda \lesssim 10^{-7}\,,$$

Freeze-in production

- DM not in thermal equilibrium but producible from thermal particle scatterings (ex: gravitino, axino, RHsN)

$$\frac{dn_{DM}}{dt} + 3Hn_{DM} = \langle \sigma v \rangle [n_{eq}^2 - n_{DM}^2]$$

SM+SM→DM+DM DM+DM→SM+SM

$$\Rightarrow \frac{dY_{DM}}{dT} = -\frac{C}{sHT}$$

$$*)\ Y = \frac{n}{s},\ dT/dt = -HT$$

$$
\begin{aligned}
\frac{dY_\chi}{dx} =& +\frac{1}{x^2}\frac{s(m_\chi)}{H(m_\chi)}\langle\sigma v\rangle_{NN\to\chi\chi}\left(Y_N^2-\left(\frac{Y_N^{\rm eq}}{Y_\chi^{\rm eq}}\right)^2 Y_\chi^2\right)+\frac{1}{x^2}\frac{s(m_\chi)}{H(m_\chi)}\langle\sigma v\rangle_{\phi\phi\to\chi\chi}\left(Y_\phi^2-\left(\frac{Y_\phi^{\rm eq}}{Y_\chi^{\rm eq}}\right)^2 Y_\chi^2\right)\\
&-\frac{1}{x^2}\frac{s(m_\chi)}{H(m_\chi)}\langle\sigma v\rangle_{\chi\phi\to h\nu}\left(Y_\chi Y_\phi-Y_\chi^{\rm eq}Y_\phi^{\rm eq}\right)+\frac{\tilde\Gamma_{\phi\to\chi N}}{H(m_\chi)}\,x\left(Y_\phi-\frac{Y_\phi^{\rm eq}}{Y_\chi^{\rm eq}Y_N^{\rm eq}}Y_\chi Y_N\right)\\
&+\frac{\tilde\Gamma_{\phi\to\chi\nu}}{H(m_\chi)}\,x\left(Y_\phi-\frac{Y_\phi^{\rm eq}}{Y_\chi^{\rm eq}}Y_\chi\right)+\frac{\tilde\Gamma_{N\to\chi\phi}}{H(m_\chi)}\,x\left(Y_N-\frac{Y_N^{\rm eq}}{Y_\chi^{\rm eq}Y_\phi^{\rm eq}}Y_\chi Y_\phi\right),\\
\frac{dY_\phi}{dx} =& -\frac{1}{x^2}\frac{s(m_\chi)}{H(m_\chi)}\langle\sigma v\rangle_{\phi\phi\to\chi\chi}\left(Y_\phi^2-\left(\frac{Y_\phi^{\rm eq}}{Y_\chi^{\rm eq}}\right)^2 Y_\chi^2\right)-\frac{1}{x^2}\frac{s(m_\chi)}{H(m_\chi)}\langle\sigma v\rangle_{\phi\phi\to NN}\left(Y_\phi^2-\left(\frac{Y_\phi^{\rm eq}}{Y_N^{\rm eq}}\right)^2 Y_N^2\right)\\
&-\frac{1}{x^2}\frac{s(m_\chi)}{H(m_\chi)}\langle\sigma v\rangle_{\phi\phi\to\rm SM}\left(Y_\phi^2-Y_\phi^{\rm eq2}\right)-\frac{1}{x^2}\frac{s(m_\chi)}{H(m_\chi)}\langle\sigma v\rangle_{\chi\phi\to h\nu}\left(Y_\chi Y_\phi-Y_\chi^{\rm eq}Y_\phi^{\rm eq}\right)\\
&-\frac{\tilde\Gamma_{\phi\to\chi N}}{H(m_\chi)}\,x\left(Y_\phi-\frac{Y_\phi^{\rm eq}}{Y_\chi^{\rm eq}Y_N^{\rm eq}}Y_\chi Y_N\right)-\frac{\tilde\Gamma_{\phi\to\chi\nu}}{H(m_\chi)}\,x\left(Y_\phi-\frac{Y_\phi^{\rm eq}}{Y_\chi^{\rm eq}}Y_\chi\right)\\
&+\frac{\tilde\Gamma_{N\to\chi\phi}}{H(m_\chi)}\,x\left(Y_N-\frac{Y_N^{\rm eq}}{Y_\chi^{\rm eq}Y_\phi^{\rm eq}}Y_\chi Y_\phi\right),\\
\frac{dY_N}{dx} =& -\frac{1}{x^2}\frac{s(m_\chi)}{H(m_\chi)}\langle\sigma v\rangle_{NN\to\chi\chi}\left(Y_N^2-\left(\frac{Y_N^{\rm eq}}{Y_\chi^{\rm eq}}\right)^2 Y_\chi^2\right)+\frac{1}{x^2}\frac{s(m_\chi)}{H(m_\chi)}\langle\sigma v\rangle_{\phi\phi\to NN}\left(Y_\phi^2-\left(\frac{Y_\phi^{\rm eq}}{Y_N^{\rm eq}}\right)^2 Y_N^2\right)\\
&-\frac{\tilde\Gamma_{N\to\rm SM}}{H(m_\chi)}\,x\left(Y_N-Y_N^{\rm eq}\right)+\frac{\tilde\Gamma_{\phi\to\chi N}}{H(m_\chi)}\,x\left(Y_\phi-\frac{Y_\phi^{\rm eq}}{Y_\chi^{\rm eq}Y_N^{\rm eq}}Y_\chi Y_N\right)\\
&-\frac{\tilde\Gamma_{N\to\chi\phi}}{H(m_\chi)}\,x\left(Y_N-\frac{Y_N^{\rm eq}}{Y_\chi^{\rm eq}Y_\phi^{\rm eq}}Y_\chi Y_\phi\right).
\end{aligned}
$$

Production channels of N, ϕ, χ

$$\mathcal{L} = y_\nu LHN + \lambda N\chi\phi + \kappa|\phi|^2|H|^2$$

$$\nu h \xrightarrow{y_\nu} N \qquad N \xrightarrow{\lambda} \phi\chi$$

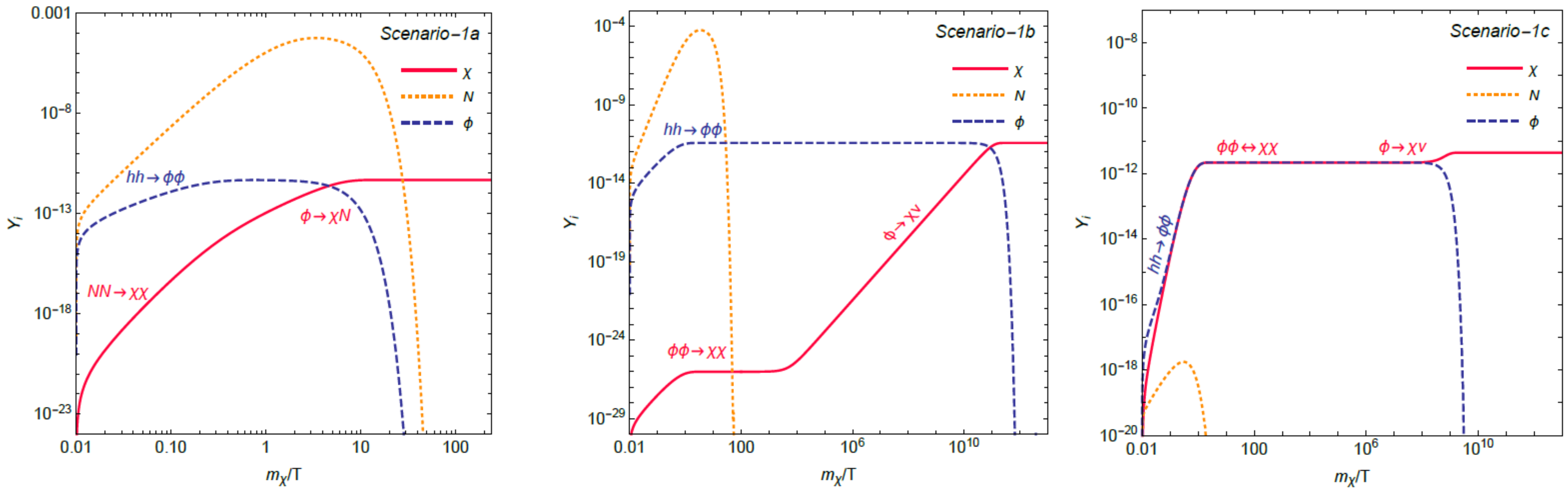
$$NN \xrightarrow{\lambda^2} \phi\phi/\chi\chi$$

$$\nu h \xrightarrow{y_\nu\lambda} \chi\phi \qquad \phi \xrightarrow{\lambda y_\nu} \nu\chi$$

$$hh \xrightarrow{\kappa} \phi\phi \qquad \phi\phi \xrightarrow{\lambda^2} \chi\chi \qquad \phi \xrightarrow{\lambda y_\nu} \chi\nu/N$$

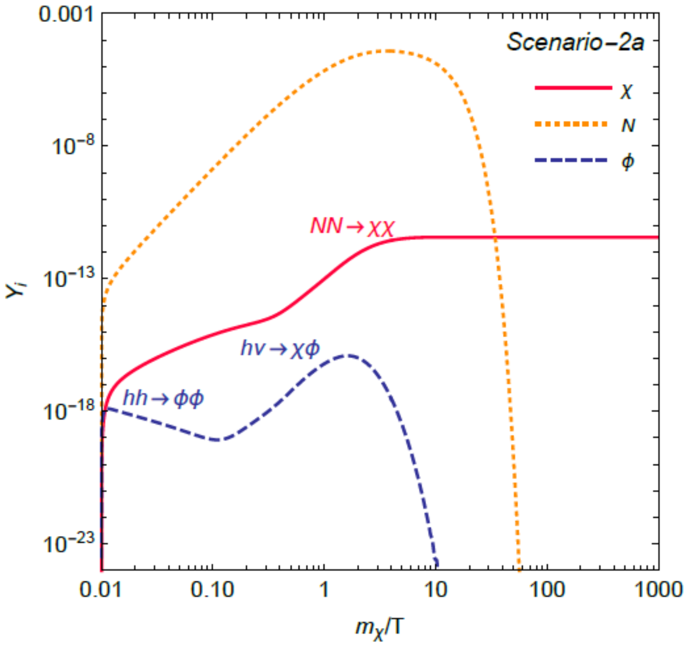
Freeze-in scenario I: $hh \to \phi\phi \to \nu\nu\chi\chi$

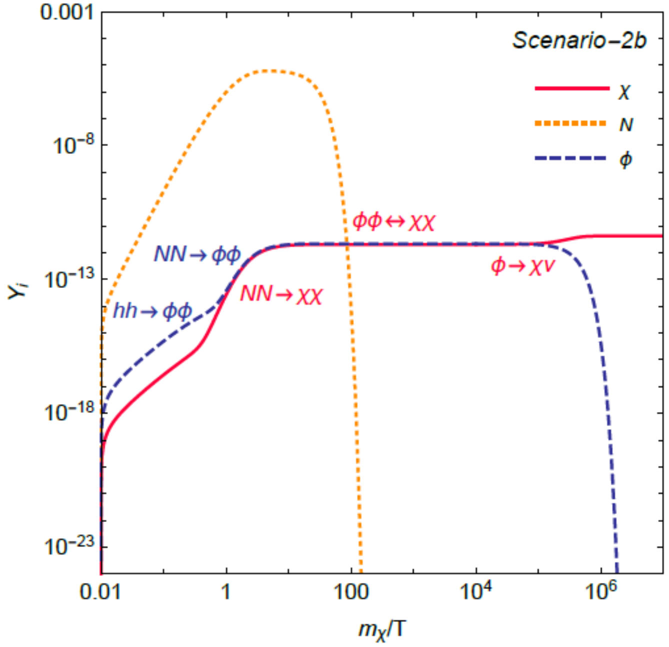
Scenario	Masses in GeV			Couplings		
	m_χ	m_N	m_ϕ	y_ν	κ	λ
1a	100	200	500	10^{-8}	4×10^{-11}	10^{-8}
1b	100	200	180	10^{-8}	2×10^{-11}	10^{-10}
1c	100	500	250	2.5×10^{-12}	10^{-12}	10^{-4}



Freeze-in scenario II: $NN \to \chi\chi/\phi\phi \to \chi\chi/\nu\nu\chi\chi$

Scenario	Masses in GeV			Couplings		
	m_χ	m_N	m_ϕ	y_ν	κ	λ
2a	100	200	500	8.0×10^{-9}	10^{-12}	10^{-4}
2b	100	200	180	3.0×10^{-9}	10^{-12}	10^{-4}



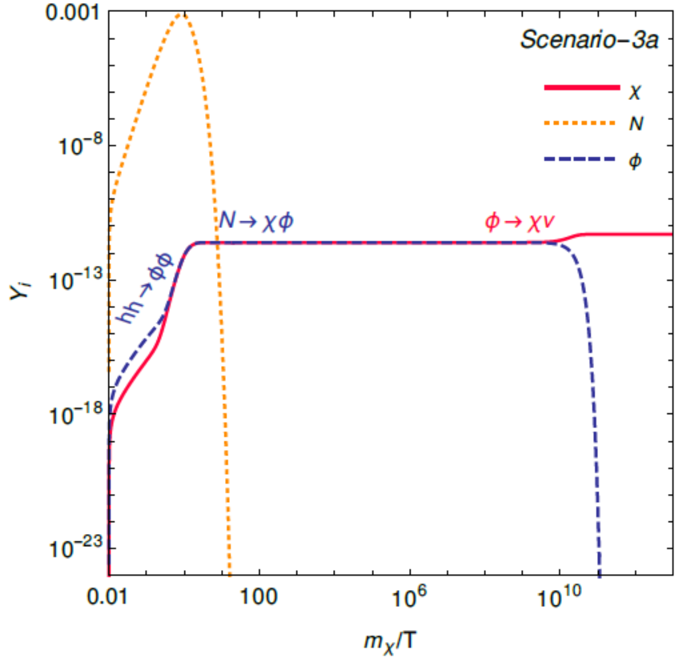


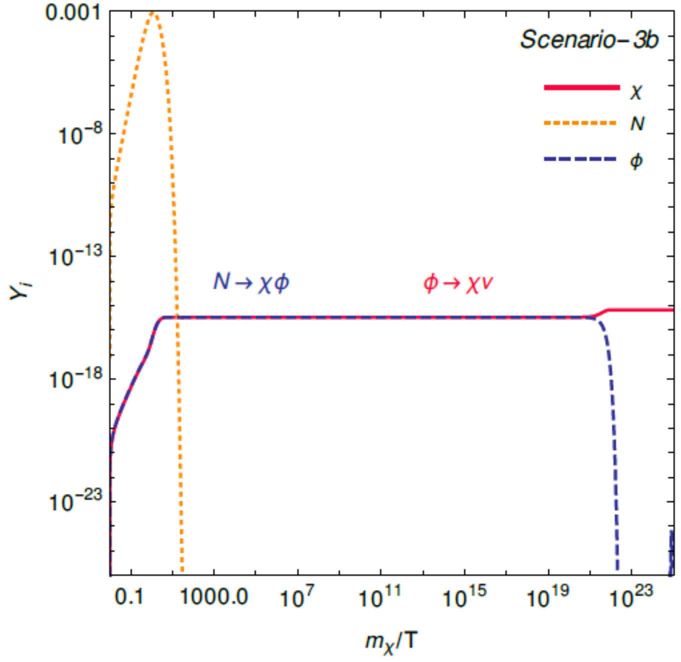
Freeze-in scenario III: $N \to \phi\chi \to \nu\chi\chi$

Scenario	Masses in GeV			Couplings		
	m_χ	m_N	m_ϕ	y_ν	κ	λ
3a	100	341	241	10^{-7}	10^{-12}	6.1×10^{-11}
3b	1.0×10^6	2.05×10^6	1.05×10^6	10^{-5}	10^{-12}	2.4×10^{-11}

$\tau_\phi = 10^{10}\ sec$

$4\ 10^{12} sec$





Energetic neutrinos from dark sector

- Energetic neutrinos produced from the ϕ decay:

$$\phi \xrightarrow{\lambda y_\nu} \nu\chi$$

- Feeble coupling $y_\nu \lambda$, determining the ϕ lifetime, can be made arbitrarily small.
- Relevant parameters: $\tau_\phi, m_\chi(m_\phi)$, and the neutrino energy

$$E_0 = (m_\phi^2 - m_\chi^2)/2m_\phi$$

Observational consequences

- $\tau_\phi \lesssim t_{eq} \sim 10^{12} sec$: χ is 100% (stable) DM, and the produced neutrinos are red-shifted away for $\tau_\phi \ll t_{eq}$.
- $t_{eq} \lesssim \tau_\phi \ll t_0$: ϕ behaves like a decaying DM. The produced neutrinos contribute to dark radiation constrained by the CMB measurement. Being red-shifted, they may be detectable.

$\rho_{DR} < 0.1\, \rho_{DM}$ at t_{eq} $\qquad \frac{E_0}{m_\chi}\left(\frac{\tau_\phi}{t_{eq}}\right)^{1/2} \lesssim 0.1$

- $\tau_\phi \gtrsim t_0 \sim 4\, 10^{17} sec$: The decaying ϕ can be 100% DM, and its lifetime is strongly constrained by neutrino observations.

Extra neutrino fluxes

- Cosmic flux from early DM decay:

$$\frac{d\varphi_{\rm cos}}{dE_\nu} = \frac{n_\phi^0}{\tau_\phi}\int_0^\infty dz\, \frac{e^{-t(z)/\tau_\phi}}{H(z)}\frac{dN}{dE_\nu}$$

$$E_0 = \frac{m_\phi^2 - m_\chi^2}{2m_\phi} \text{ and } E_\nu = \frac{E_0}{1+z}$$

$$\Phi_{\rm cos} \equiv E_\nu^2 \frac{d\varphi_{\rm cos}}{dE_\nu} = E_\nu \frac{n_\phi^0}{\tau_\phi}\frac{e^{-t(z)/\tau_\phi}}{H(z)}\theta(z)$$

$$H(z) = H_0\sqrt{\Omega_\Lambda + (1+z)^3\Omega_{\rm m} + (1+z)^4\Omega_{\rm r}}$$

$$t(z) = \int_z^\infty dz'[(1+z')H(z')]^{-1}$$

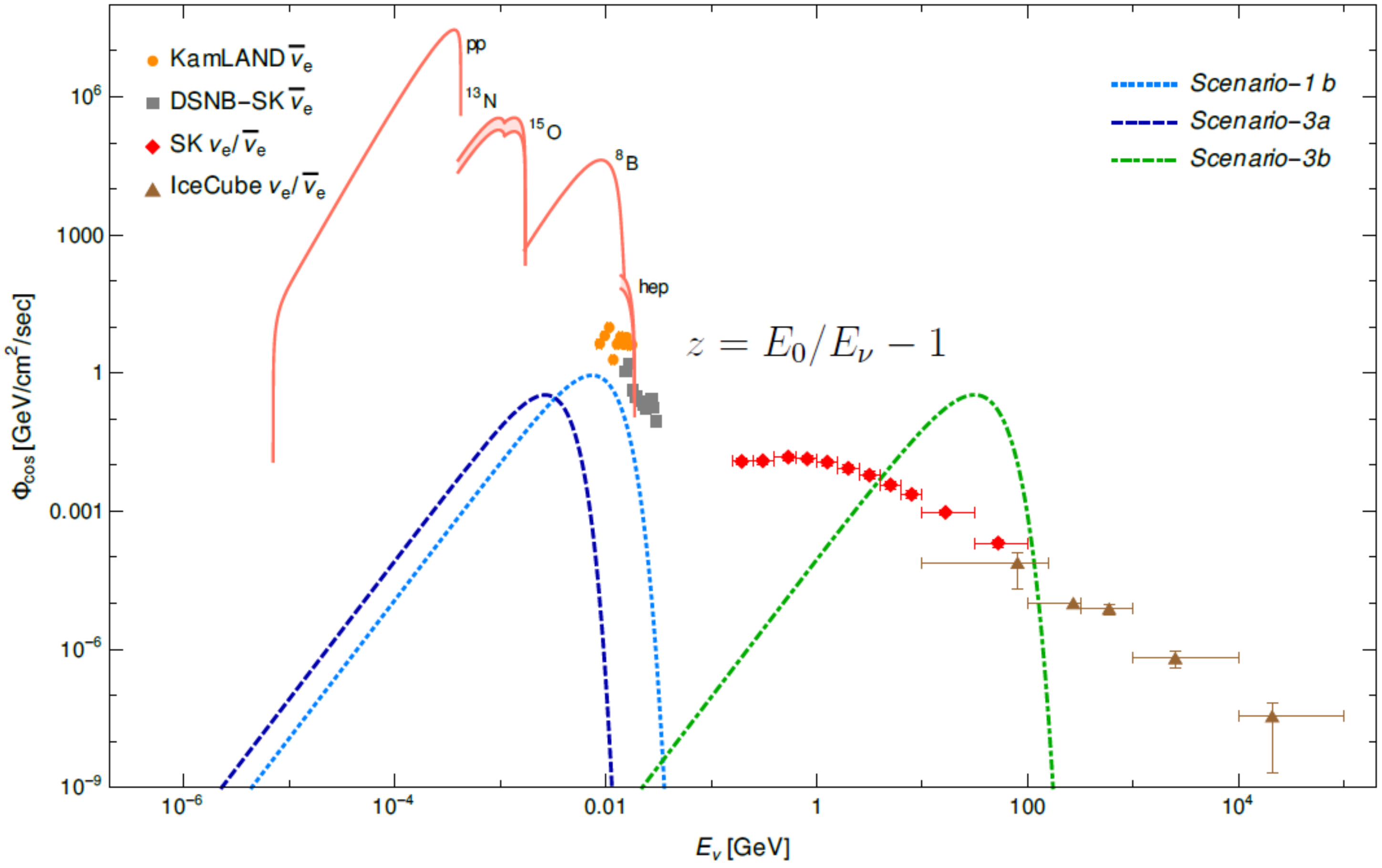
- Galactic neutrino flux:

$$\Phi_{\rm gal} = E_\nu^2 \frac{d\varphi_{\rm gal}}{dE_\nu} = E_\nu^2 \frac{e^{-t_0/\tau_\phi}}{\tau_\phi m_\phi}\frac{dN}{dE_\nu} \times R_{\rm sol}\,\rho_{\rm sol}\,\langle J\rangle$$

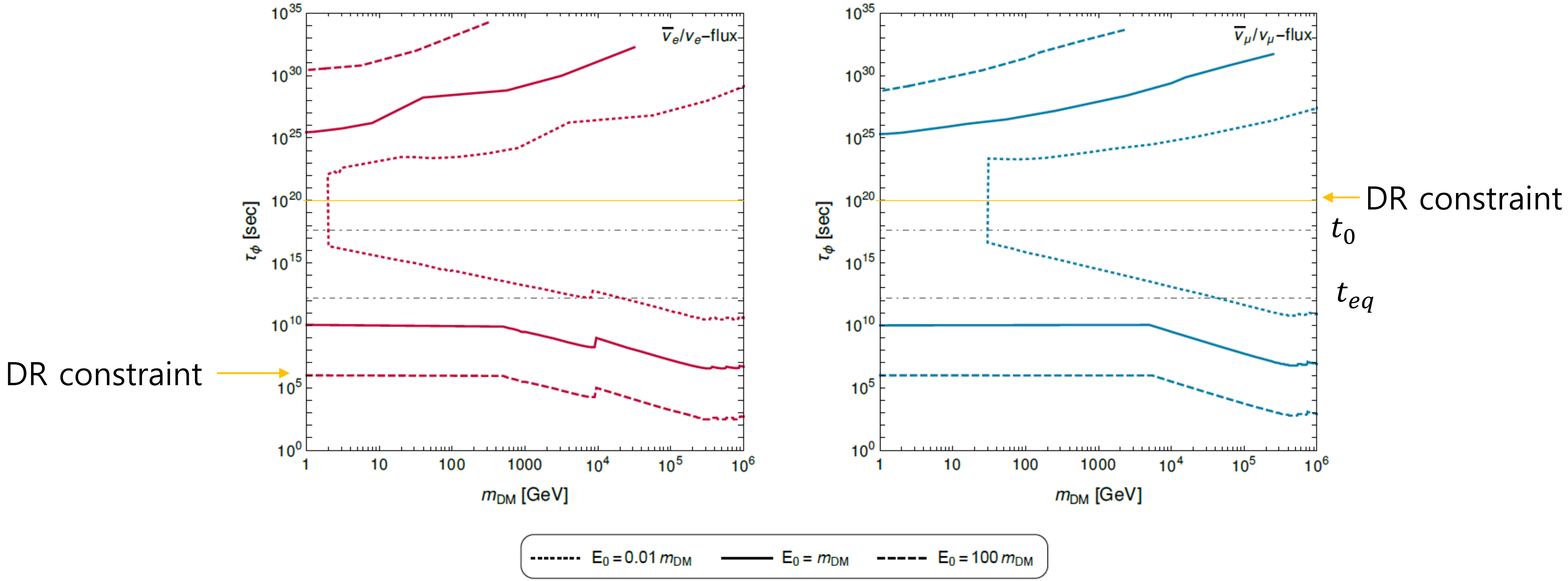
$$R_{\rm sol} = 8.33\,{\rm kpc} \qquad \rho_{\rm sol} = 0.3\ {\rm GeV/cm^3}$$

$$\langle J\rangle \simeq 2.1$$

Signals and observations



Constraints



Conclusion

- Neutrino-portal: $\lambda N \phi \chi$ with a decaying ϕ and a stable χ DM.
- Characteristic channels of freeze-in production:

i) $hh \to \phi\phi,\ \phi\phi \to \chi\chi,\ \phi \to \chi N/\nu,$
ii) $\nu h \to N^{(*)} \to \phi\chi,\ \phi \to \chi\nu$
iii) $\nu h \to N,\ NN \to \phi\phi/\chi\chi,\ \phi \to \chi\nu$

- The decay $\phi \to \chi\nu$, involving y_ν, λ, can be very late to provide an additional source of energetic neutrinos.
- They contribute to dark radiation or exotic signals at neutrino detectors.