Search for sterile neutrino with light gauge interactions: recasting collider, beam-dump, and neutrino telescope searches

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Based on **arXiv:2008.12598 [hep-ph]**
and **arXiv:2011.xxxxx (to be appear soon)**

Collaboration with
Jongkuk Kim (KIAS), Pyungwon Ko (KIAS),
and Seong Chan Park (IPAP, Seoul and Yonsei U.)

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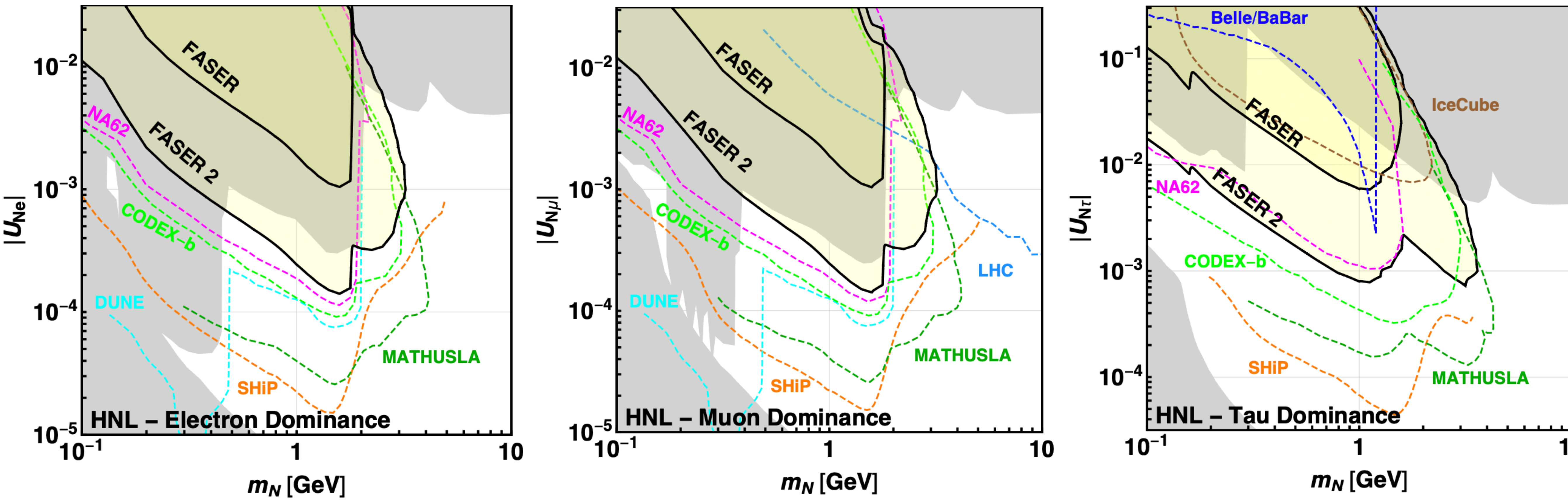
Forward Physics Facility
Kickoff Meeting

MeV-GeV scale Heavy Neutral Lepton (HNL) Searches (without new interaction)

A. Ariga et al. (FASER collaboration) [1811.12522]



- Decay channels are induced by CC/NC
- Width ~ suppressed by G_F^2 and $|U_{\ell 4}|^2$
- Can be probed by FPF, beam-dump exp, IceCube, rare meson decays

MeV-GeV HNL with light gauge interaction(s)

- Model

gauged $U(1)_{B-L}$

$m_4, m_X \sim$ MeV-GeV

$g_X \sim 10^{-4} - 10^{-6}$

which provide an intriguing scenario for FIDM

	$SU(3)_c$	$SU(2)_L$	Y	$B-L$
$\hat{Q}_i = (\hat{u}_i\ \hat{d}_i)^T$	$\mathbf{3}$	$\mathbf{2}$	$+\frac{1}{6}$	$+\frac{1}{3}$
$\hat{u}_i^c$	$\bar{\mathbf{3}}$	$\mathbf{1}$	$-\frac{2}{3}$	$-\frac{1}{3}$
$\hat{d}_i^c$	$\bar{\mathbf{3}}$	$\mathbf{1}$	$+\frac{1}{3}$	$-\frac{1}{3}$
$\hat{L}_i = (\hat{\nu}_i\ \hat{e}_i)^T$	$\mathbf{1}$	$\mathbf{2}$	$-\frac{1}{2}$	-1
$\hat{e}_i^c$	$\mathbf{1}$	$\mathbf{1}$	$+1$	$+1$
3 RH neutrinos $\hat{N}^c_{4,5,6}$	$\mathbf{1}$	$\mathbf{1}$	0	$+1$
H	$\mathbf{1}$	$\mathbf{2}$	$+\frac{1}{2}$	0
breaking gauged B-L Φ	$\mathbf{1}$	$\mathbf{1}$	0	$+2$

R. Marshak, R. Mohapatra [PLB 91 (1980) 222-224]

R. Mohapatra, N. Okada [1908.11325, 2005.00365]

$$\begin{aligned}\mathcal{L} = \mathcal{L}_{\rm SM} - \frac{1}{4}X_{\mu\nu}X^{\mu\nu} + \frac{1}{2}|(\partial_\mu + 2ig_X X_\mu)\Phi|^2 - \frac{\lambda_\Phi}{4}\left(|\Phi|^2 - v_\Phi^2\right)^2 \\ -\frac{g_X}{3}\left(\overline{\hat{Q}_{iL}}\gamma^\mu \hat{Q}_{iL} + \overline{\hat{u}_{iR}}\gamma^\mu \hat{u}_{iR} + \overline{\hat{d}_{iR}}\gamma^\mu \hat{d}_{iR}\right)X_\mu \\ +g_X\left(\overline{\hat{L}_{iL}}\gamma^\mu \hat{L}_{iL} + \overline{\hat{e}_{iR}}\gamma^\mu \hat{e}_{iR} + \overline{\hat{N}_{j'R}}\gamma^\mu \hat{N}_{j'R}\right)X_\mu \\ -\left(\hat{y}_\nu^{ii'}\overline{\hat{L}_{iL}}\tilde{H}\hat{N}_{i'R} + \frac{\hat{\lambda}_R^{i'j'}}{2}\Phi\overline{\hat{N}^c_{i'R}}\hat{N}_{j'R} + \text{h.c.}\right),\end{aligned}$$

$$\nu_{\ell L} = \sum_{i=1,2,3} U^{\rm PMNS}_{\ell i}\nu_{iL} + \sum_{j'=4,5,6} U_{\ell j'} N^c_{j'L} \quad (\ell = e, \mu, \tau)$$

MeV-GeV HNL with light gauge interaction(s)

- Model

Sterile ν-specific $U(1)_s$
with a kinetic mixing $\epsilon_{\gamma X}$

$g_X \sim \mathcal{O}(1)$

$\epsilon_{\gamma X} \sim 10^{-4}$

$m_4, m_X \sim$ MeV-GeV

	$SU(3)_c$	$SU(2)_L$	Y	s
$\hat{Q}_i = (\hat{u}_i \ \hat{d}_i)^T$	$\mathbf{3}$	$\mathbf{2}$	$+\frac{1}{6}$	0
$\hat{u}_i^c$	$\bar{\mathbf{3}}$	$\mathbf{1}$	$-\frac{2}{3}$	0
$\hat{d}_i^c$	$\bar{\mathbf{3}}$	$\mathbf{1}$	$+\frac{1}{3}$	0
$\hat{L}_i = (\hat{\nu}_i \ \hat{e}_i)^T$	$\mathbf{1}$	$\mathbf{2}$	$-\frac{1}{2}$	0
$\hat{e}_i^c$	$\mathbf{1}$	$\mathbf{1}$	$+1$	0
RH neutrino(s) $\hat{N}_R$	$\mathbf{1}$	$\mathbf{1}$	0	0
a Dark sector Dirac neutrino $\hat{\nu}_s$	$\mathbf{1}$	$\mathbf{1}$	0	$+1$
H	$\mathbf{1}$	$\mathbf{2}$	$+\frac{1}{2}$	0
breaking gauged U(1)s ϕ	$\mathbf{1}$	$\mathbf{1}$	0	$+1$

$$\mathcal{L} = \mathcal{L}_{\rm SM} - \frac{1}{4} X_{\mu\nu} X^{\mu\nu} + \frac{m_X^2}{2} X_\mu X^\mu - \frac{\epsilon_{\gamma X}}{2} X_{\mu\nu} B^{\mu\nu}$$
$$- g_X \bar{\nu}_s \gamma^\mu \nu_s X_\mu - m_s \overline{\hat{\nu}_s} \hat{\nu}_s$$
$$- \left(\hat{y}_{\nu_s}^j \hat{N}_{Rj} \hat{\nu}_s \phi^\dagger + \hat{y}_\nu^{ij} \hat{L}_i \tilde{H} \hat{N}_{Rj} + {\rm h.c.} \right)$$

$U_{\ell 4} \sim \hat{y}_{\nu_s} v_\phi / m_s$

P. Ko, Y. Tang
[PLB 739 (2014) 62-67] [1404.0236]

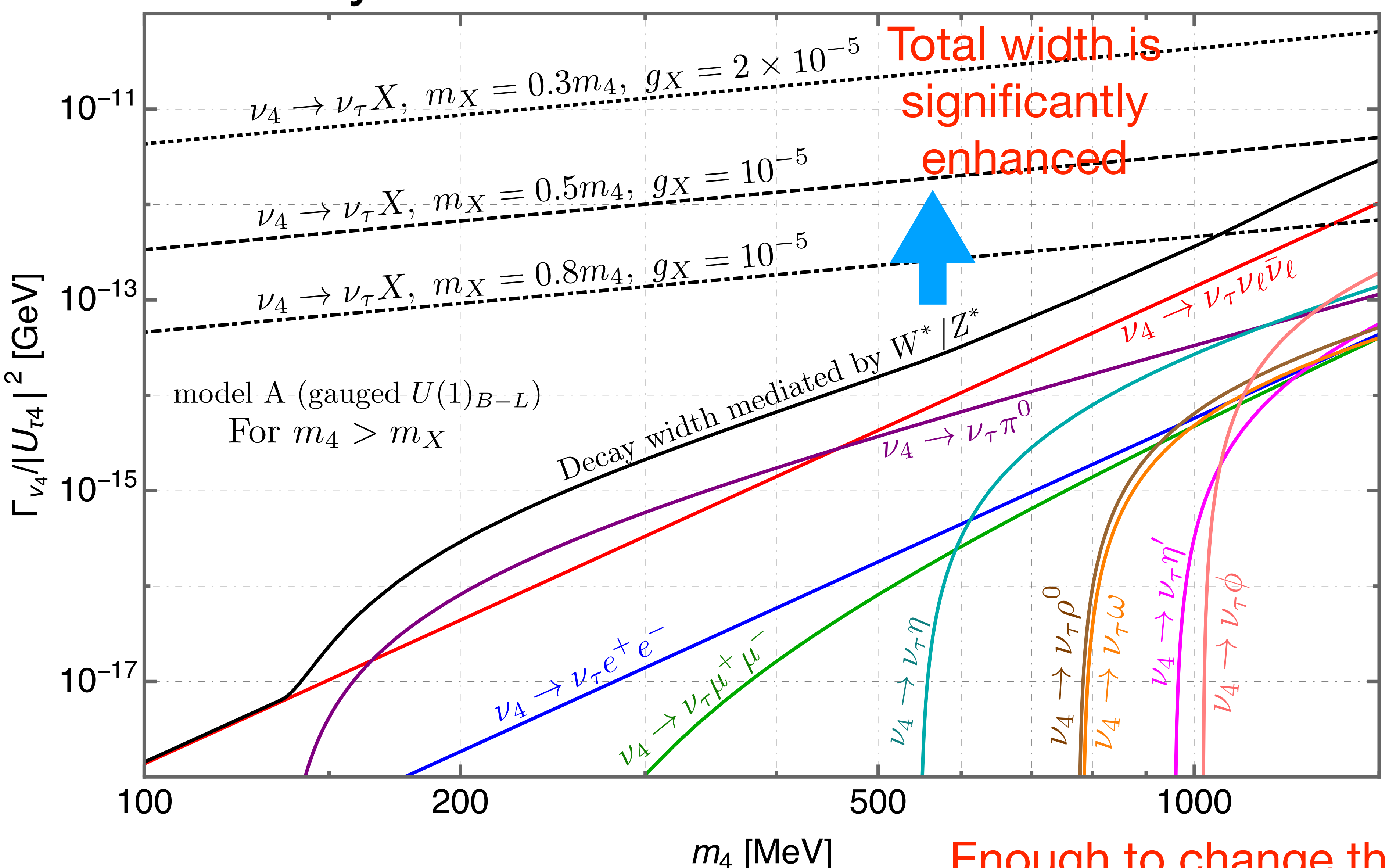
E. Bertuzzo, S. Jana, P.A.Machado, R.Z.Funchal
[PRL (2018) 241801] [1807.09877]

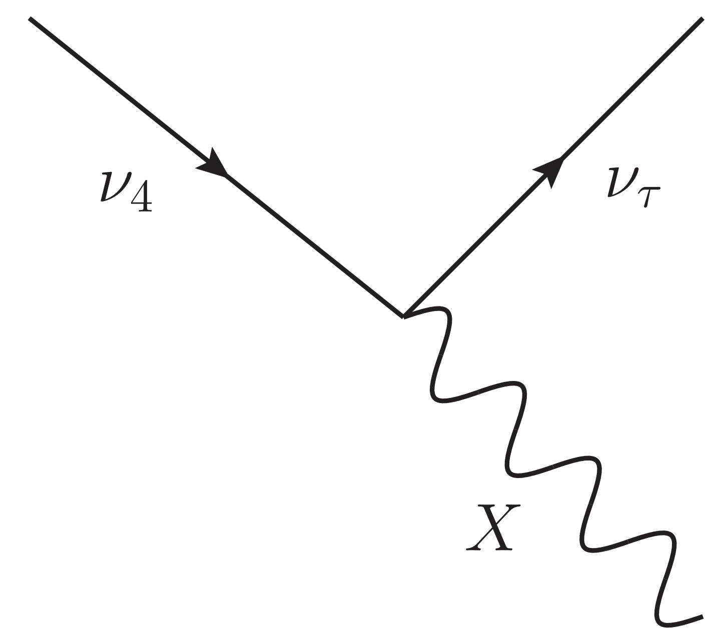
P. Ballett, S. Pascoli, M. Ross-Lonergan
[PRD (2019) 071701] [1808.02915]

MeV-GeV HNL with light gauge interaction(s)

Sterile-Tau mixing Dominant case

- Decay width & channels



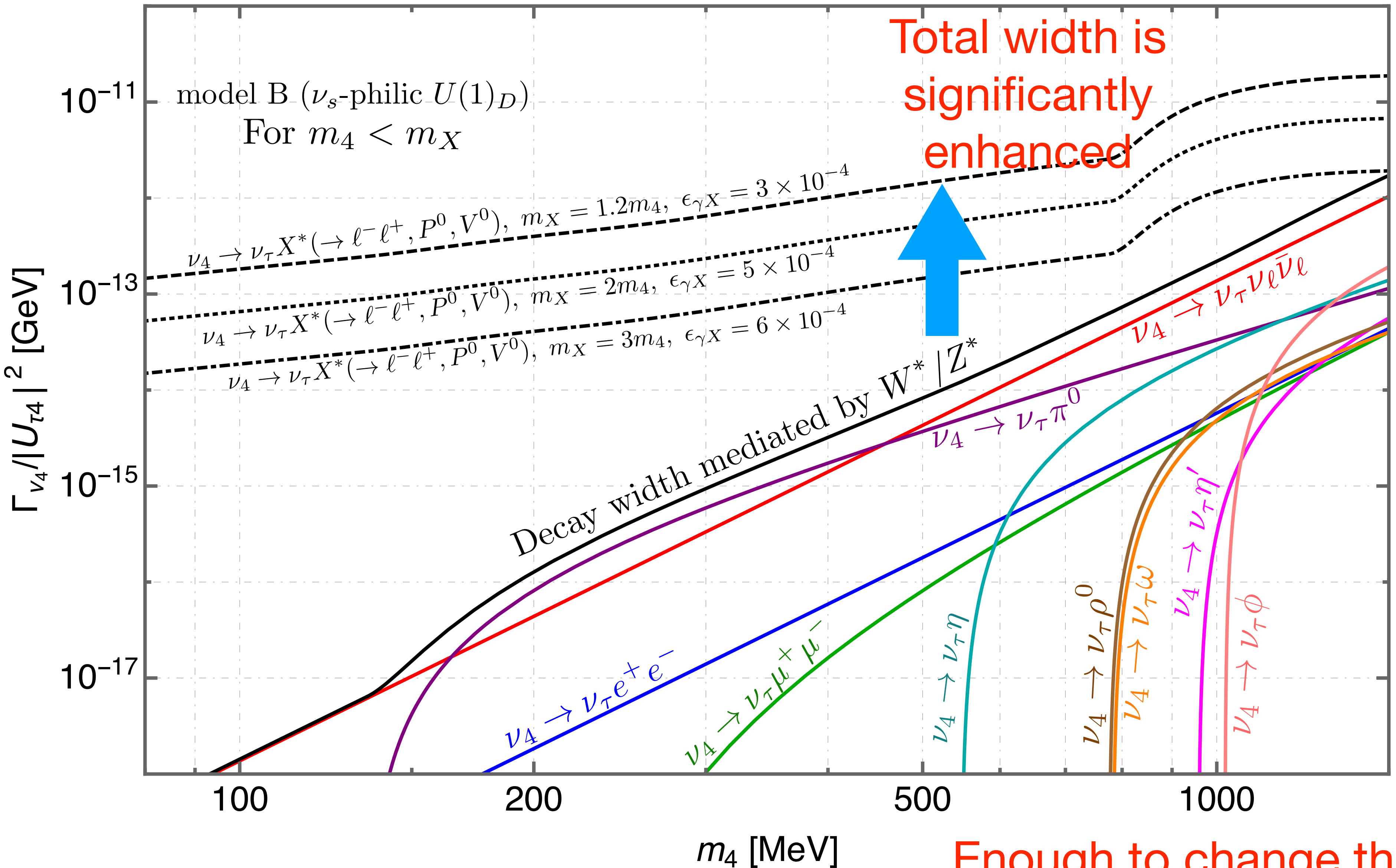


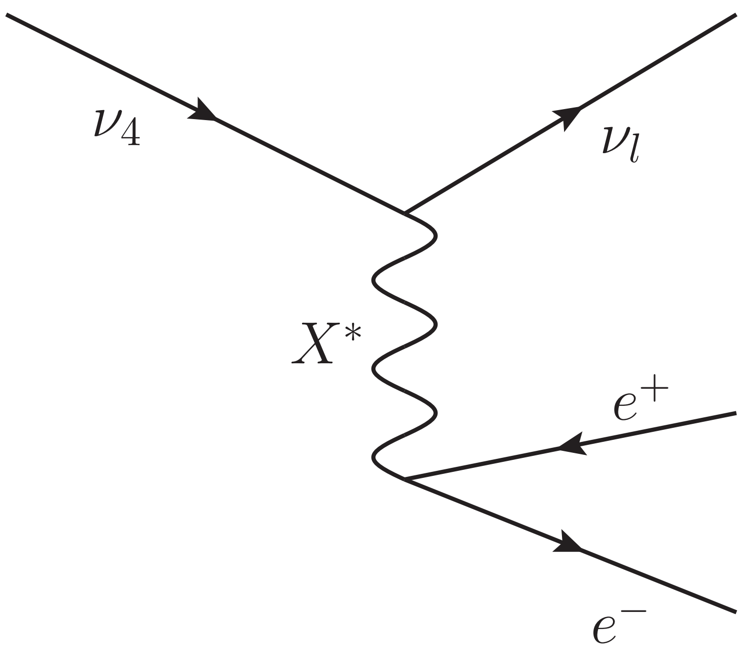
Enough to change the features in LLP searches

MeV-GeV HNL with light gauge interaction(s)

Sterile-Tau mixing Dominant case

- Decay width & channels





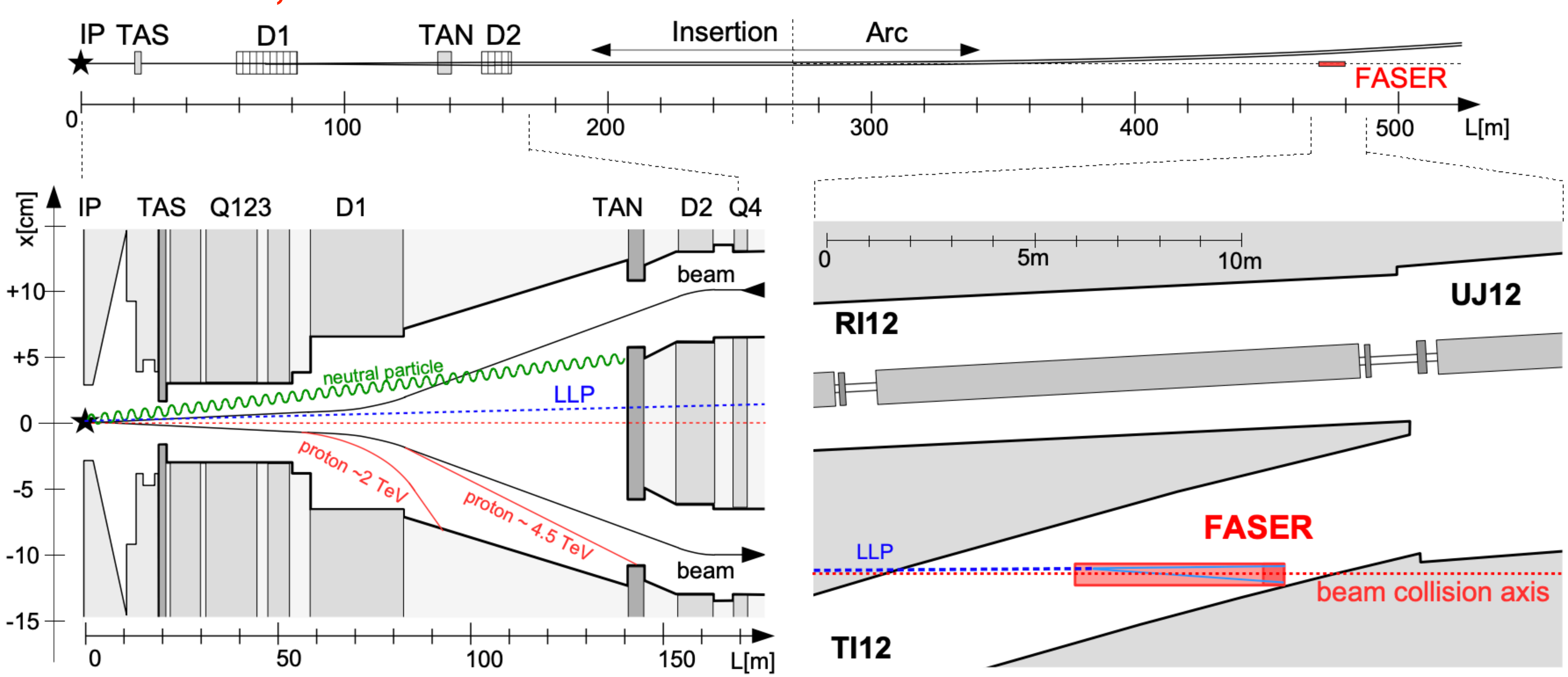
Enough to change the features in LLP searches

MeV-GeV HNL w light gauge int. at LLP searches

LLP searches at ground experiments

Experiment	$N_{\rm POT}$ or $\int \mathcal{L}\, dt$	$\sqrt{s}$	E_p beam	L	Δ	$\langle E_{\nu_4} \rangle$	95% C.L. limit
FASER (LHC Run 3)	$\int \mathcal{L}\, dt = 150$ fb^{-1}	14 TeV	7 TeV	480m	1.5m	~ 1 TeV	$N_{\rm sig} \geq 3$
FASER2 (HL-LHC)	$\int \mathcal{L}\, dt = 3$ ab^{-1}						
SHiP	$N_{\rm POT} = 2 \times 10^{20}$	27.4 GeV	400 GeV	110m	50m	~ 50 GeV	
CHARM	$N_{\rm POT} = 2.4 \times 10^{18}$			515m	35m		
NOMAD	$N_{\rm POT} = 4.1 \times 10^{19}$	29 GeV	450 GeV	835m	290m		

For FASER,



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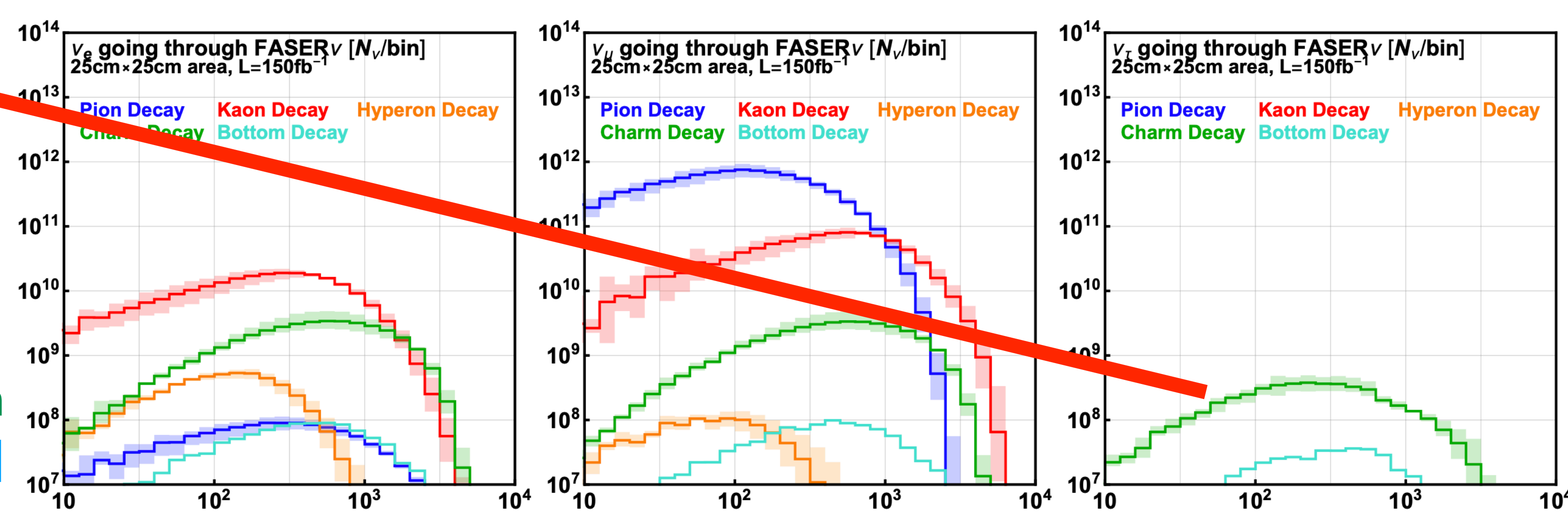
$$N_{\rm sig.} = \int_{E_{\rm min}}^{E_{\rm max}} dE_{\nu_4} \left[\frac{dN_{\nu_4}(E_{\nu_4})}{dE_{\nu_4}} \times \left(e^{-\frac{L-\Delta}{d}} - e^{-\frac{L}{d}} \right) \times {\rm Br}(X/\nu_4 \to {\rm visible}) \times A_{\rm eff}(E_{\nu_4}) \right]$$

$$\frac{dN_{\nu_4}}{dE_{\nu_4}} \approx \frac{dN_{\nu_\tau}}{dE_{\nu_\tau}} \times |U_{\tau 4}|^2 \times ({\rm phase/helicity\ space\ suppresion\ factor})$$



FASER collaboration

[EPJC 80 (2020) no.1, 61] [1908.02310]

MeV-GeV HNL w light gauge int. at IceCube, by atm/astro neutrinos

- GeV-energy tau-sterile probe
  by (Earth-penetrating) atmospheric neutrinos

provide an significant constraints on Sub-GeV region

$$P(\nu_\mu \to \nu_\tau) = \sum_{j,k} U_{\mu j} U^*_{\tau j} U^*_{\mu k} U_{\tau k} \exp\left(i \frac{\Delta m^2_{jk} L}{2E_\nu}\right) \approx \cos^4\theta_{13} \sin^2\theta_{23} \sin^2\left(\frac{\Delta m^2_{jk} L}{4E_\nu}\right)$$

- TeV(~PeV)-energy tau-sterile probe
  by (almost) isotropic (and ~1:1:1 flavor) astrophysical neutrinos

$$\frac{d\Phi_{\nu+\bar{\nu}}}{dE_\nu} = \Phi_0 \times 10^{-18} \left(\frac{E_\nu}{100\ \mathrm{TeV}}\right)^{-\gamma} [\mathrm{GeV}^{-1}\mathrm{cm}^{-2}\mathrm{s}^{-1}\mathrm{sr}^{-1}]$$

But too small flux to probe small $|U_{\tau 4}|^2$

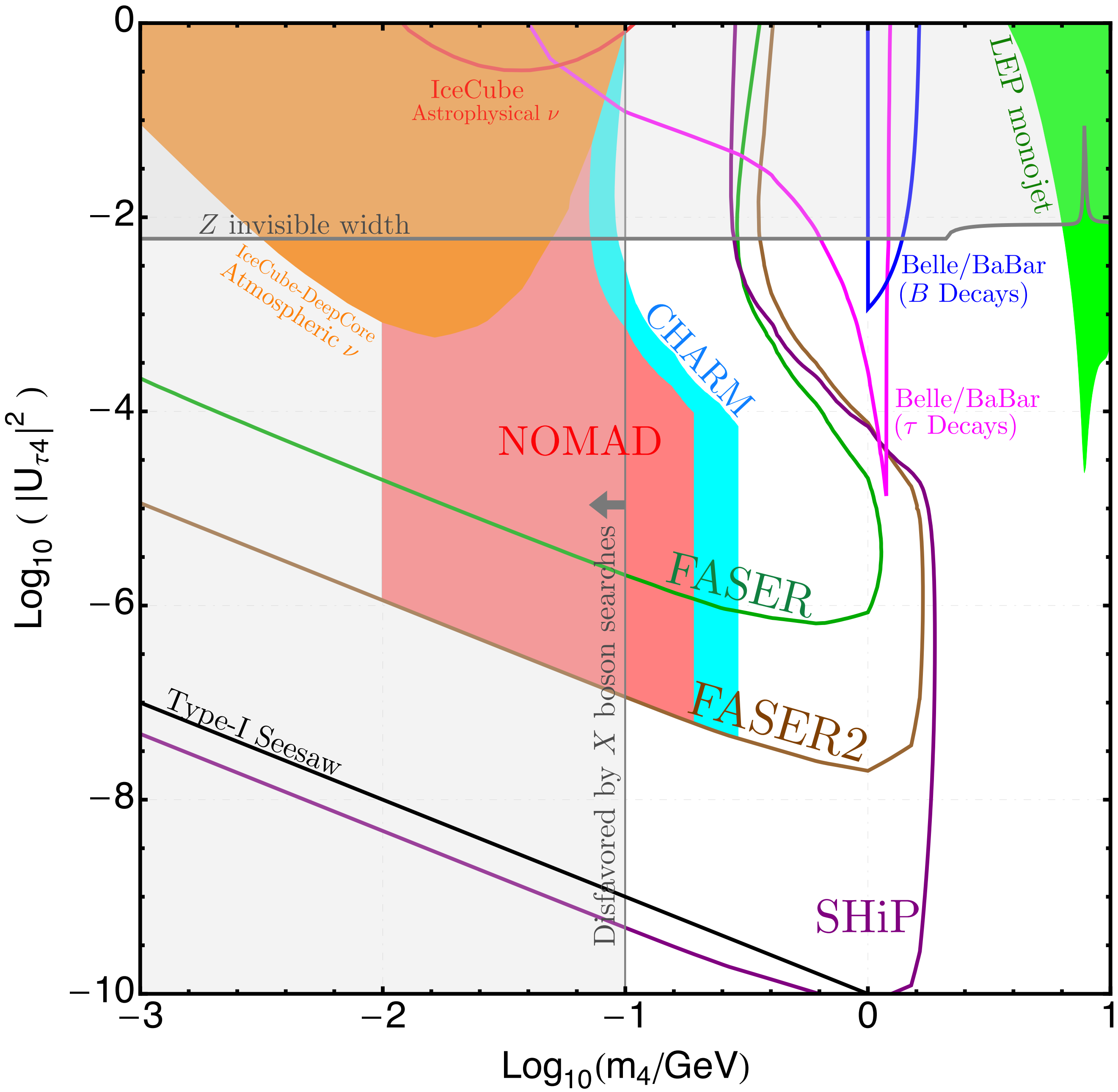
- Double-cascade ("double-bang") event rate at IC

$$N_{\mathrm{sig.}} \simeq \int dE_\nu \left[\frac{dN^{\nu_\tau}_{\mathrm{NC}}}{dE_\nu} \times \left(e^{-\frac{L-\Delta}{d}} - e^{-\frac{L}{d}}\right) \times \mathrm{Br}(X/\nu_4 \to \mathrm{visible})\right]$$

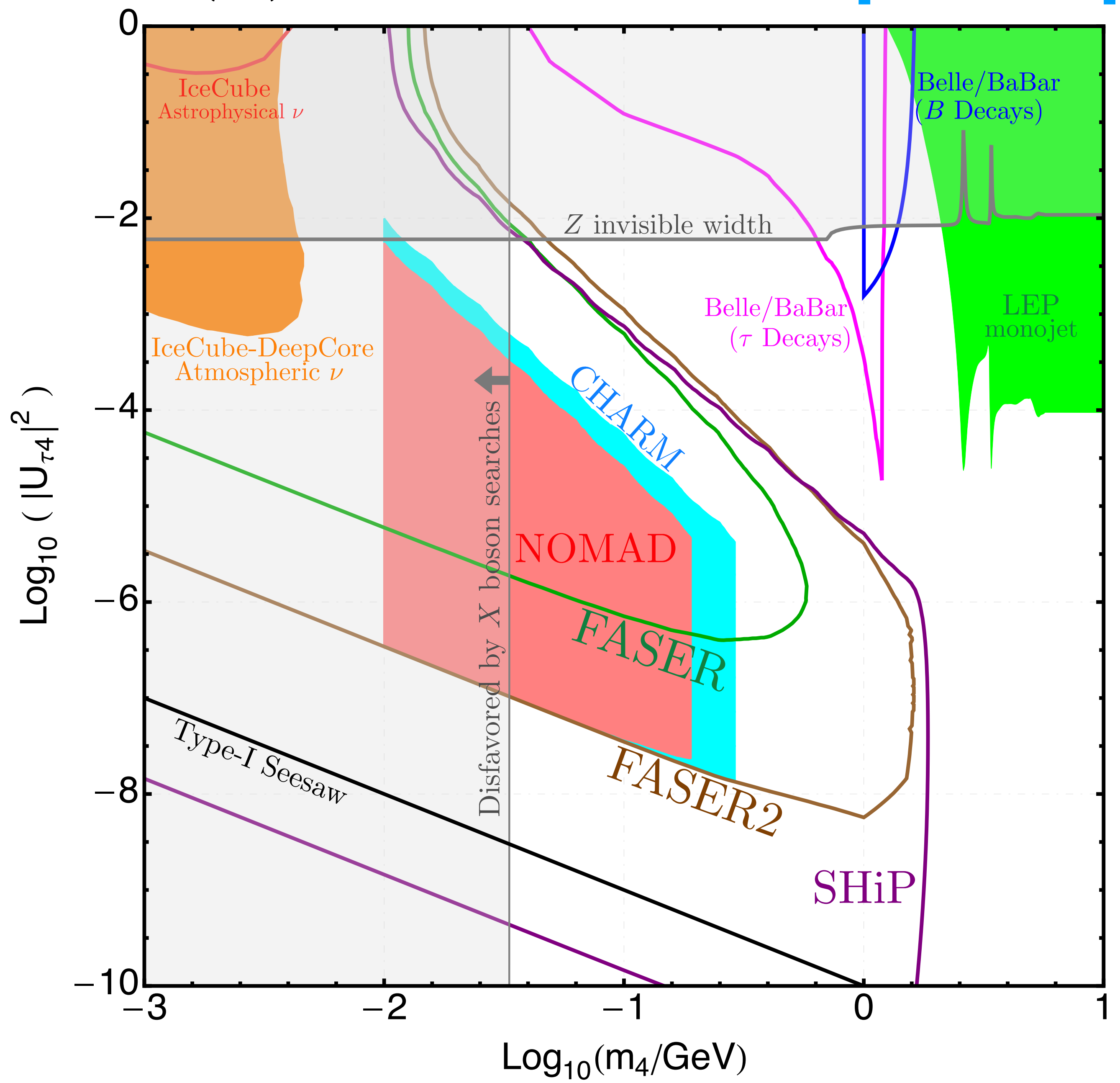
MeV-GeV HNL w light gauge int. : Sensitivity limits on tau-sterile mixing

- Current & Future limits: gauged $U(1)_{B-L}$

YSJ, J.Kim, P.Ko, S.C.Park
[2008.12598]



$$(m_X, g_X) = (0.1 m_4, 10^{-5})$$

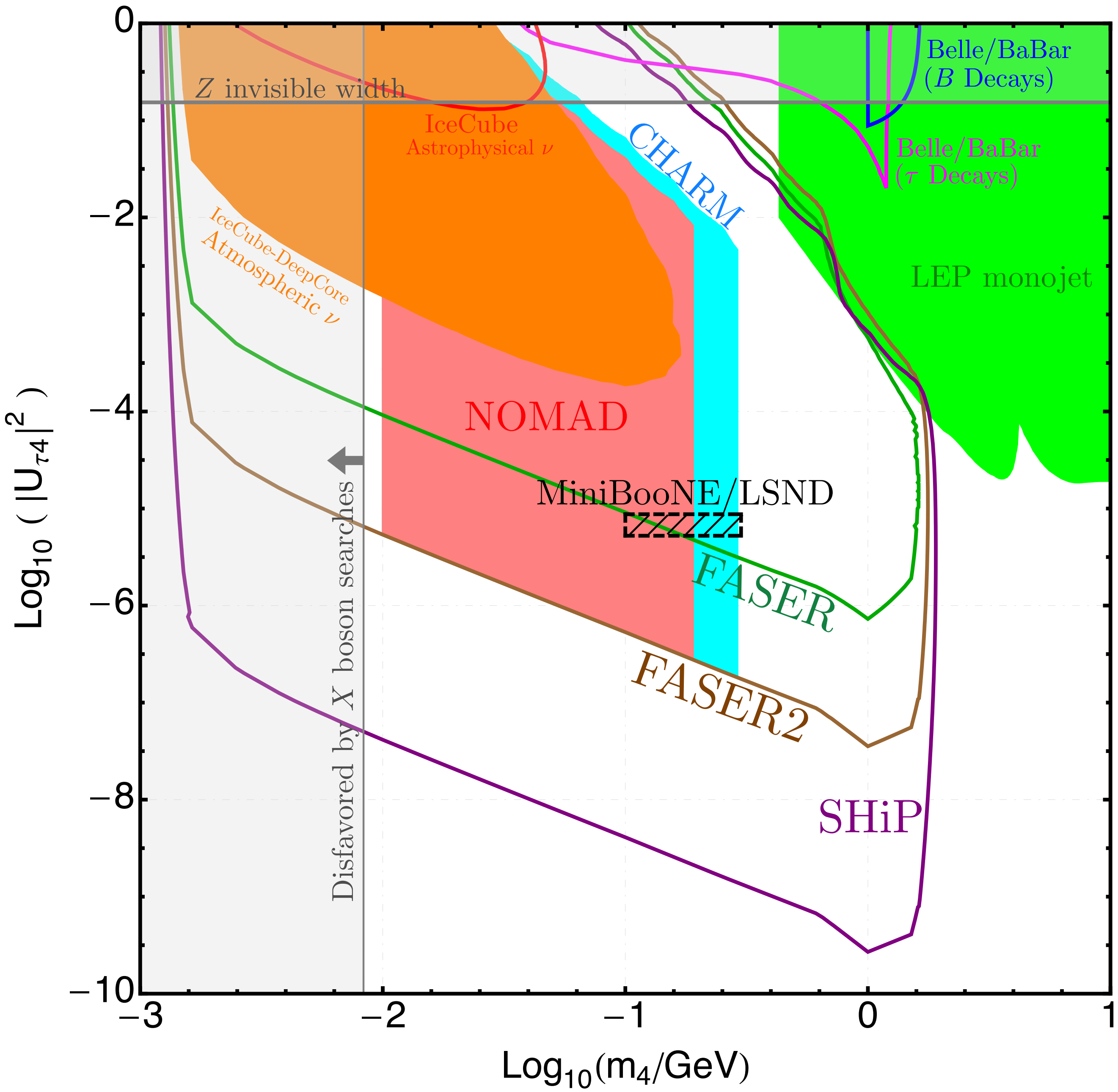


$$(m_X, g_X) = (0.3 m_4, 10^{-4})$$

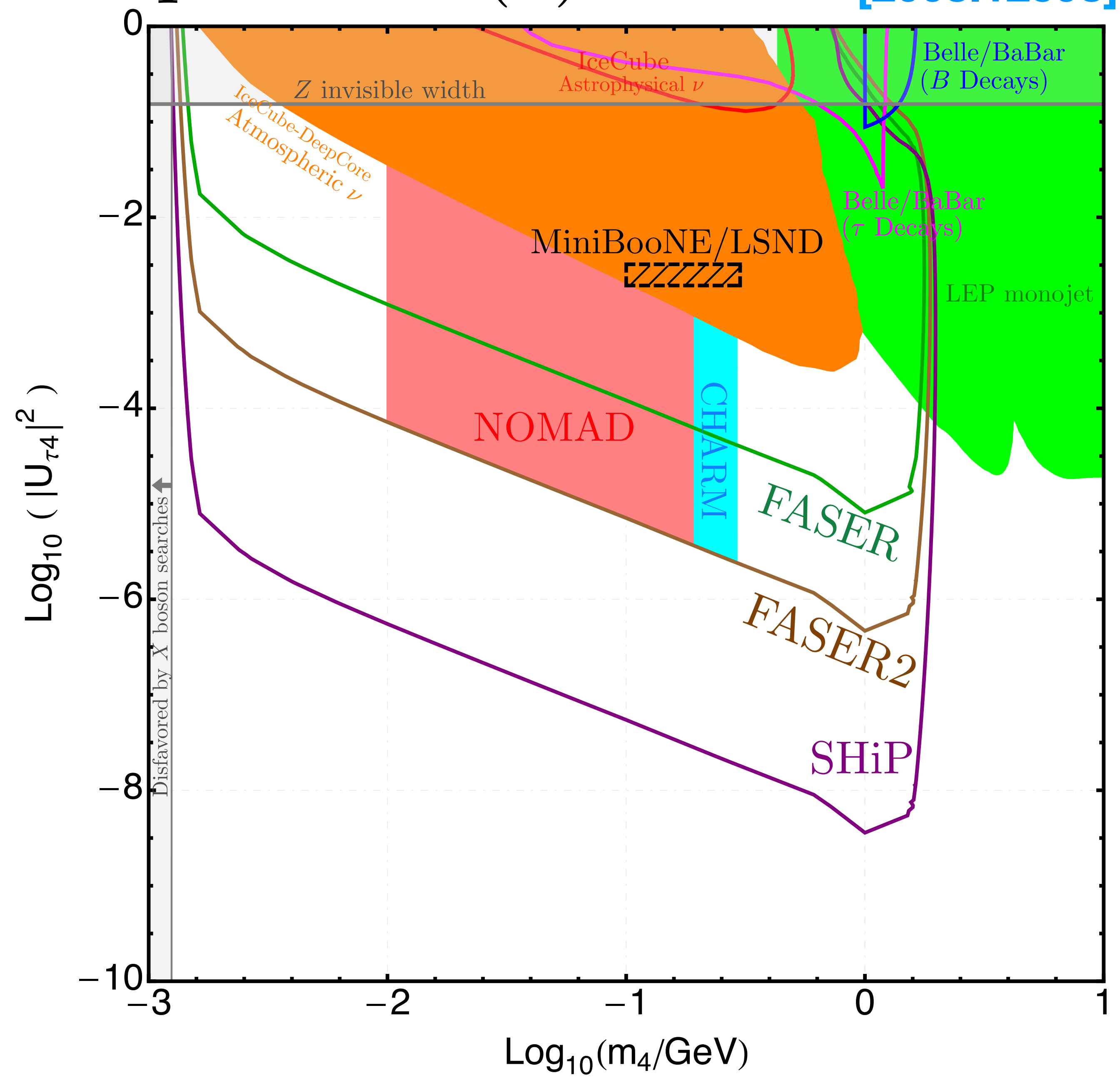
MeV-GeV HNL w light gauge int. : Sensitivity limits on tau-sterile mixing

- Current & Future limits: Sterile ν-specific $U(1)_s$

YSJ, J.Kim, P.Ko, S.C.Park
[2008.12598]



$(m_X, g_X) = (1.2 m_4, 3\times 10^{-4})$



$(m_X, g_X) = (8 m_4, 10^{-3})$

Conclusion

- We consider MeV-GeV Heavy Neutral Lepton in the presence of light gauge interactions in the neutrino sector. As benchmark model, we consider **Gauged B-L and Sterile neutrino-specific dark photon** in this study.

- Due to the different kinematics and decay channels of HNL, the signatures at LLP searches and neutrino telescopes can be significantly changed.

- FPF, future beam-dump experiments, IceCube telescope are expected to probe even very small tau-sterile mixing region in near future.

- In the presence both muon-sterile and tau-sterile mixings,
  By considering MiniBooNE/LSND signatures together,
  FPF and other future LLP searches can be expected to have the excellent sensitivity to reach the Low E excess favored parameters
  in this type of NP scenarios [**2011.xxxxx** (to be appear soon)**]**

Thank you for your attention

End of slides