Studying the Sterile Baryonic Neutrino Using Direct Detection and Spallation Source Experiments

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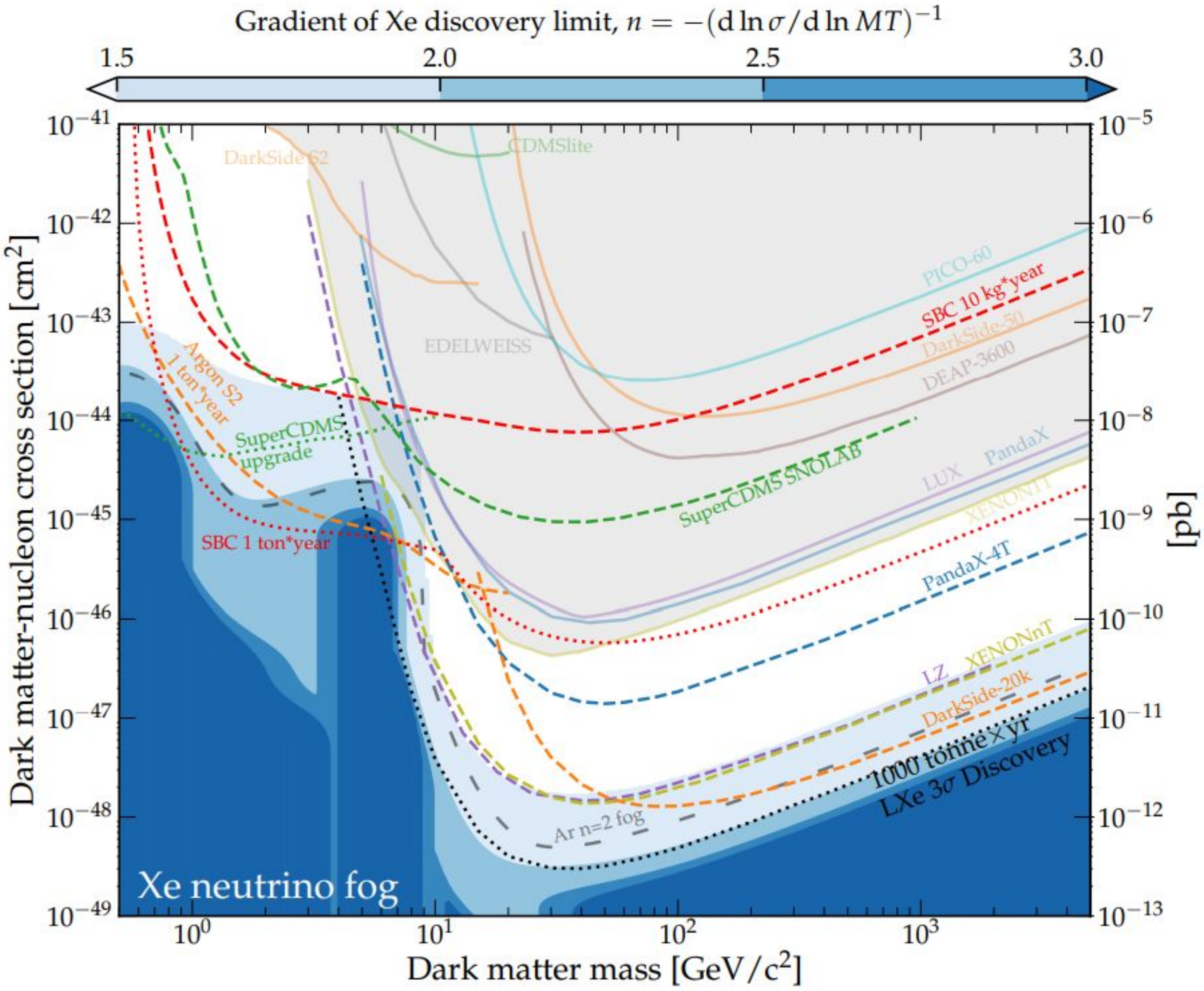
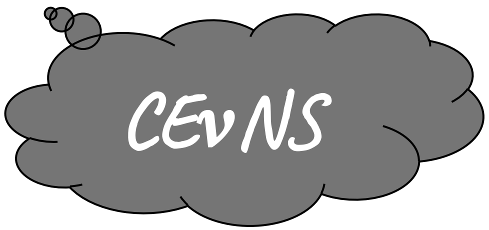
Introduction

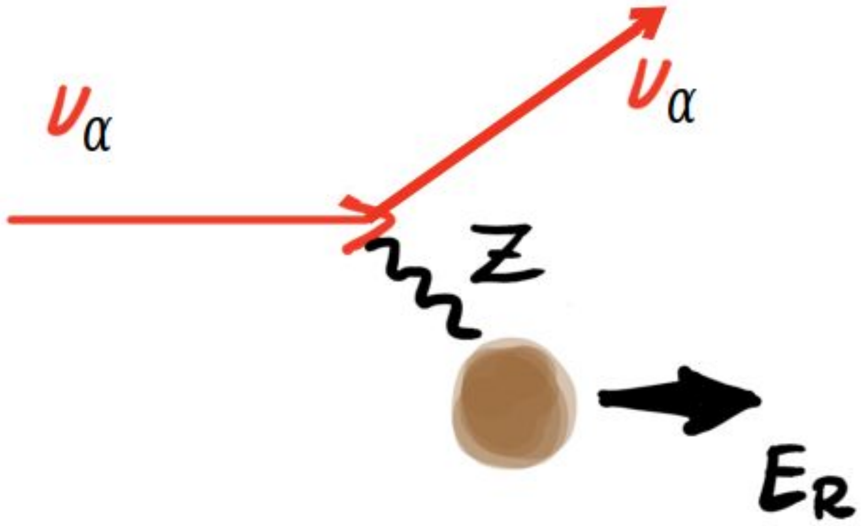
- Introduction
  - Coherent elastic neutrino-nucleus scattering
  - Spallation-Source experiments
  - Dark Matter Direct Detection Experiments



Gradient of Xe discovery limit, $n = -(\mathrm{d}\ln\sigma/\mathrm{d}\ln MT)^{-1}$
1.5
2.0
2.5
3.0
Dark matter-nucleon cross section [cm^2]
[pb]
Dark matter mass [GeV/c^2]
DarkSide-50
CDMSlite
PICO-60
SBC 10 kg*year
DarkSide-50
DEAP-3600
EDELWEISS
Argon S2
1 ton*year
SuperCDMS
upgrade
SuperCDMS SNOLAB
LUX
PandaX
XENON1T
SBC 1 ton*year
PandaX-4T
LZ
XENONnT
DarkSide-20k
1000 tonne×yr
LXe 3σ Discovery
Ar n=2 fog
Xe neutrino fog

Coherent elastic Neutrino-Nucleus scattering





Predicted by the SM: [Freedman (1974)]

$$\frac{d\sigma_{\nu N}}{dE_R} = \frac{G_F^2}{4\pi} Q_v^2 m_N \left(1 - \frac{m_N E_R}{2E_\nu^2}\right) F^2(E_R)$$

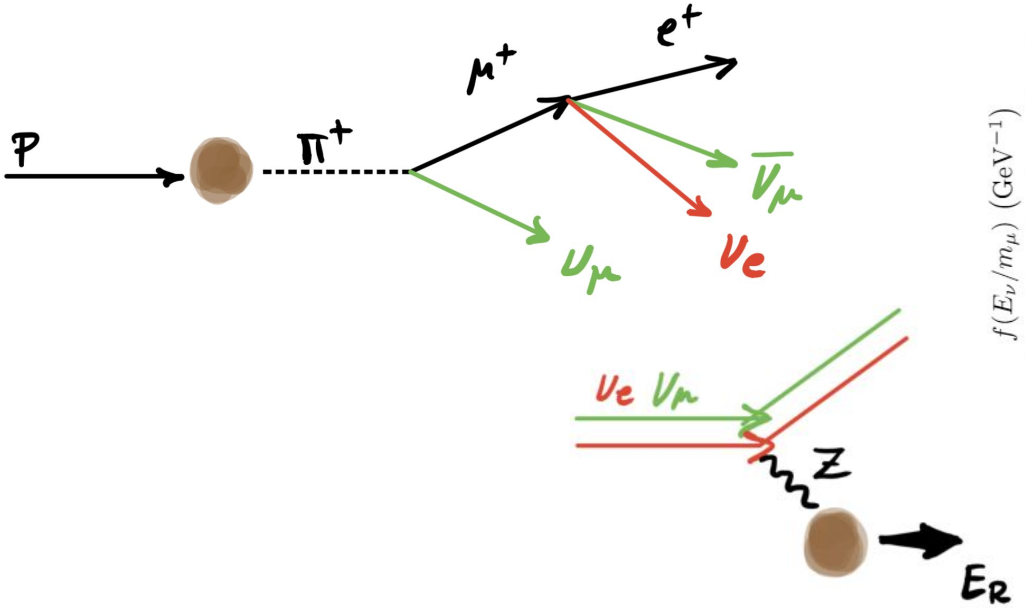
$$Q_v = N - (1 - 4\sin^2\theta_W)Z$$

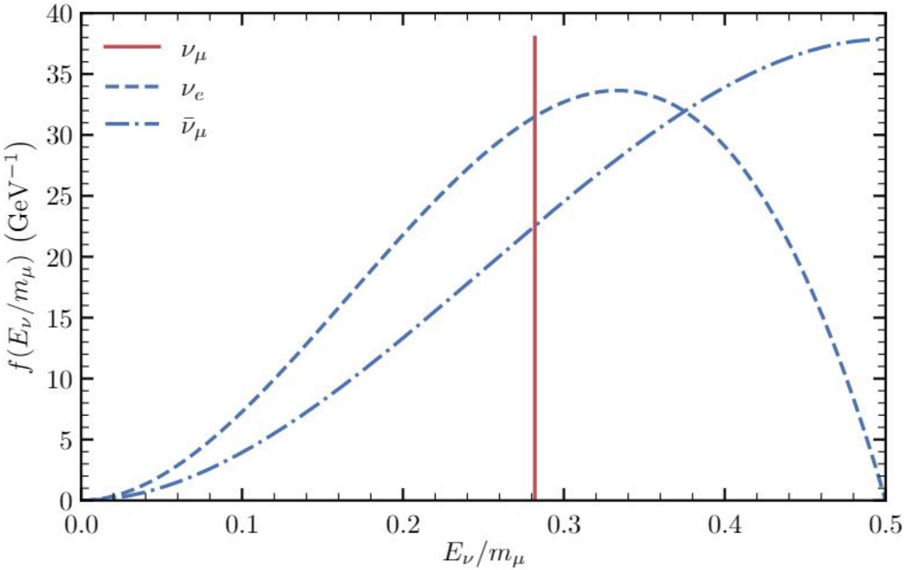
… And detected by the COHERENT collaboration!!

[Akimov et al. 1708.01294 (2017)]

CEνNS @ Spallation Source Experiments

$$N_{\mathrm{CE}\nu\mathrm{NS}} = \sum_{\nu_\alpha} N_{\mathrm{targ}} \int_{E_{\mathrm{th}}}^{E_R^{\max}} \int_{E_\nu^{\min}}^{E_\nu^{\max}} \frac{\mathrm{d}N_{\nu_\alpha}}{\mathrm{d}E_\nu}\, \epsilon(E_R)\, \frac{\mathrm{d}\sigma_{\nu_\alpha N}}{\mathrm{d}E_R}\, \mathrm{d}E_\nu\, \mathrm{d}E_R$$

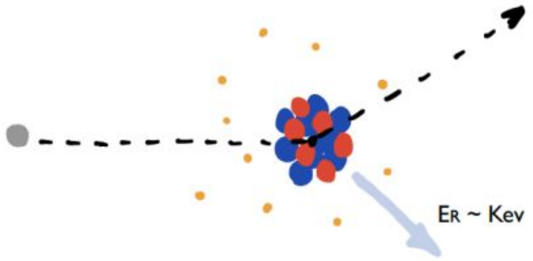


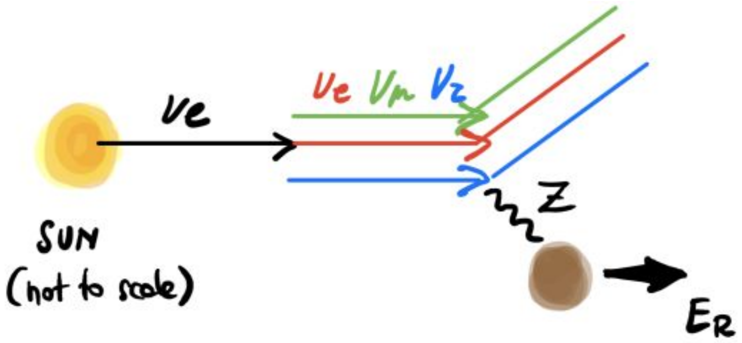


CEνNS @ DM Direct Detection Experiments

$$\frac{\mathrm{d}R}{\mathrm{d}E_R} = n_T \sum_{\nu_\alpha} \int_{E_\nu^{\mathrm{min}}} \frac{\mathrm{d}\phi_{\nu_e}}{\mathrm{d}E_\nu} P(\nu_e \to \nu_\alpha) \frac{\mathrm{d}\sigma_{\nu_\alpha T}}{\mathrm{d}E_R} \mathrm{d}E_\nu$$

Xenon, LZ,
SuperCDM, etc..





Different experimental setups

Spallation Source Experiments	DM Direct Detection Experiments
$\nu_e \quad \nu_\mu \quad \overline{\nu}_\mu$	$\nu_e \quad \overline{\nu}_e \quad \nu_\mu \quad \overline{\nu}_\mu \quad \nu_\tau \quad \overline{\nu}_\tau$

Different experimental setups

Spallation Source Experiments	DM Direct Detection Experiments
ν_e ν_μ $\overline{\nu_\mu}$	ν_e ν_e ν_μ ν_μ ν_τ ν_τ
Neutrinos up to ~50 MeV	Neutrinos up to ~20 MeV

Different experimental setups

Spallation Source Experiments	DM Direct Detection Experiments
$\nu_e \quad \nu_\mu \quad \overline{\nu_\mu}$	$\nu_e \quad \nu_e \quad \nu_\mu \quad \nu_\mu \quad \nu_\tau \quad \nu_\tau$
Neutrinos up to ~50 MeV	Neutrinos up to ~20 MeV
Not very small energy thresholds	Very small recoil energy thresholds

Different experimental setups

Spallation Source Experiments	DM Direct Detection Experiments
$\nu_e \quad \nu_\mu \quad \overline{\nu}_\mu$	$\nu_e \quad \nu_e \quad \nu_\mu \quad \nu_\mu \quad \nu_\tau \quad \nu_\tau$
Neutrinos up to ~50 MeV	Neutrinos up to ~20 MeV
Not very small energy thresholds	Very small recoil energy thresholds

So, why not to combine them??

Sterile Baryonic Neutrino Model

- Introduction
  - Coherent elastic neutrino-nucleus scattering
  - Spallation-Source experiments
  - Dark Matter Direct Detection Experiments
- Sterile Baryonic Neutrino Model

Sterile Baryonic Neutrino (SBN)

Pospelov 1103.3261 (2011)]

$$\mathcal{L} \supset \frac{m_{Z'}^2}{2} Z'^{\mu} Z'_{\mu} + g_b Z'^{\mu} \overline{\nu}_b \gamma_\mu \nu_b + \frac{1}{3} g_q Z'^{\mu} \sum_q \overline{q} \gamma_\mu q \,.$$

PARAMETER SPACE

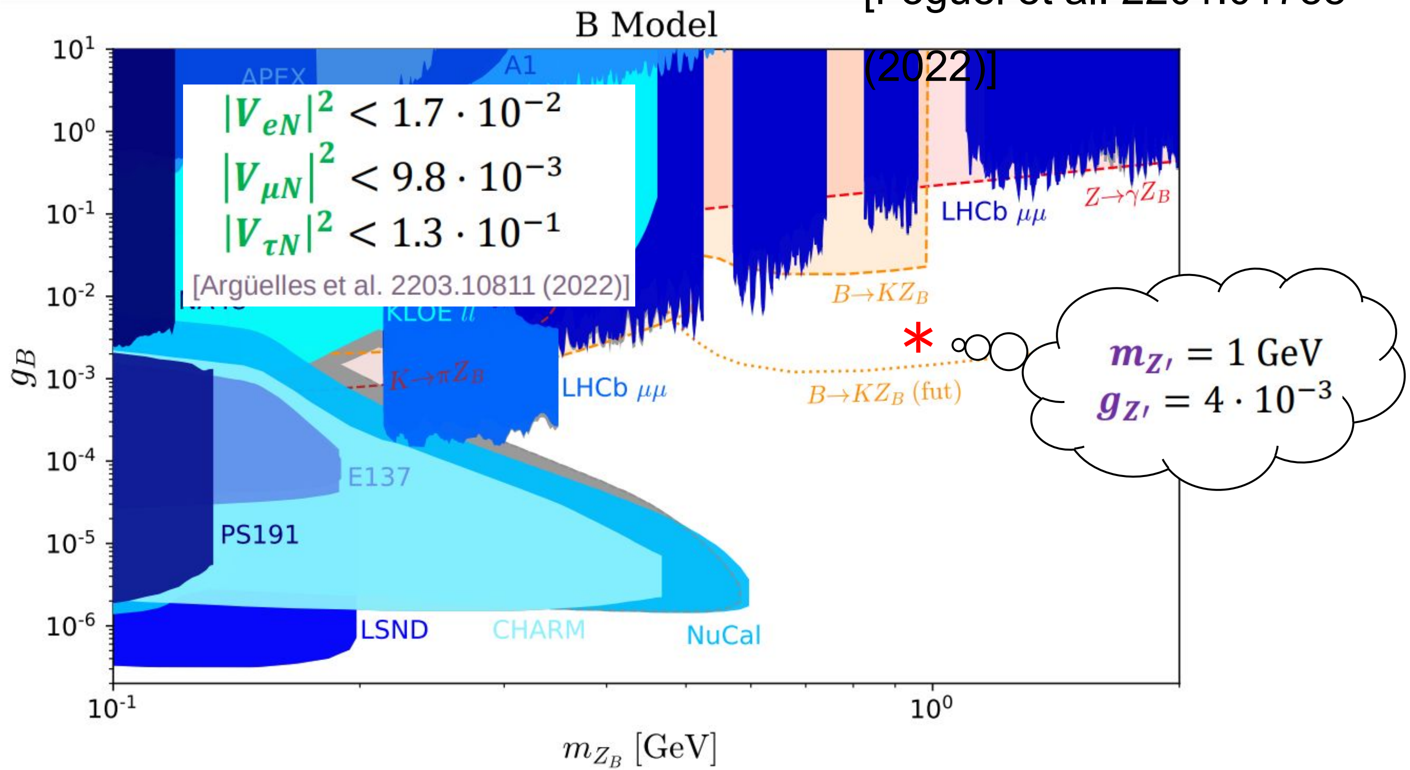
$g_{Z'}$, $m_{Z'}$

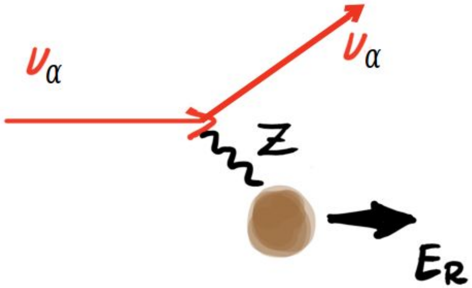
m_N, $|V_{eN}|$, $|V_{\mu N}|$, $|V_{\tau N}|$

Sterile Baryonic Neutrino (SBN)

$$\mathcal{L} \supset \frac{m_{Z'}^2}{2} Z'^{\mu} Z'_{\mu} + g_b Z'^{\mu} \overline{\nu}_b \gamma_\mu \nu_b + \frac{1}{3} g_q Z'^{\mu} \sum_q \overline{q} \gamma_\mu q \,.$$

[Foguel et al. 2201.01788 (2022)]





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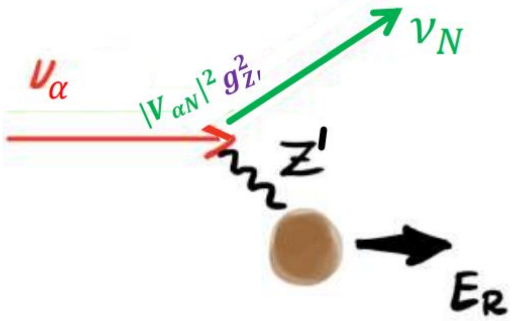
Predicted by the SM: [Freedman (1974)]

$$\frac{d\sigma_{\nu N}}{dE_R} = \frac{G_F^2}{4\pi} Q_v^2 m_N \left(1 - \frac{m_N E_R}{2E_\nu^2}\right) F^2(E_R)$$

$$Q_v = N - (1 - 4\sin^2\theta_W)Z$$



$$\frac{d\sigma_{\alpha 4}}{dE_R} = \frac{g_{Z'}^4 A^2 \left|U_{\alpha 4}\right|^2 M_N}{2\pi E_\nu^2 \left(2M_N E_R + m_{Z'}^2\right)^2} \left[4E_\nu^2 - 2E_R\left(M_N - E_R + 2E_\nu\right) - \frac{m_4^2}{M_N}\left(M_N - E_R - E_\nu\right)\right] F^2(E_R)$$

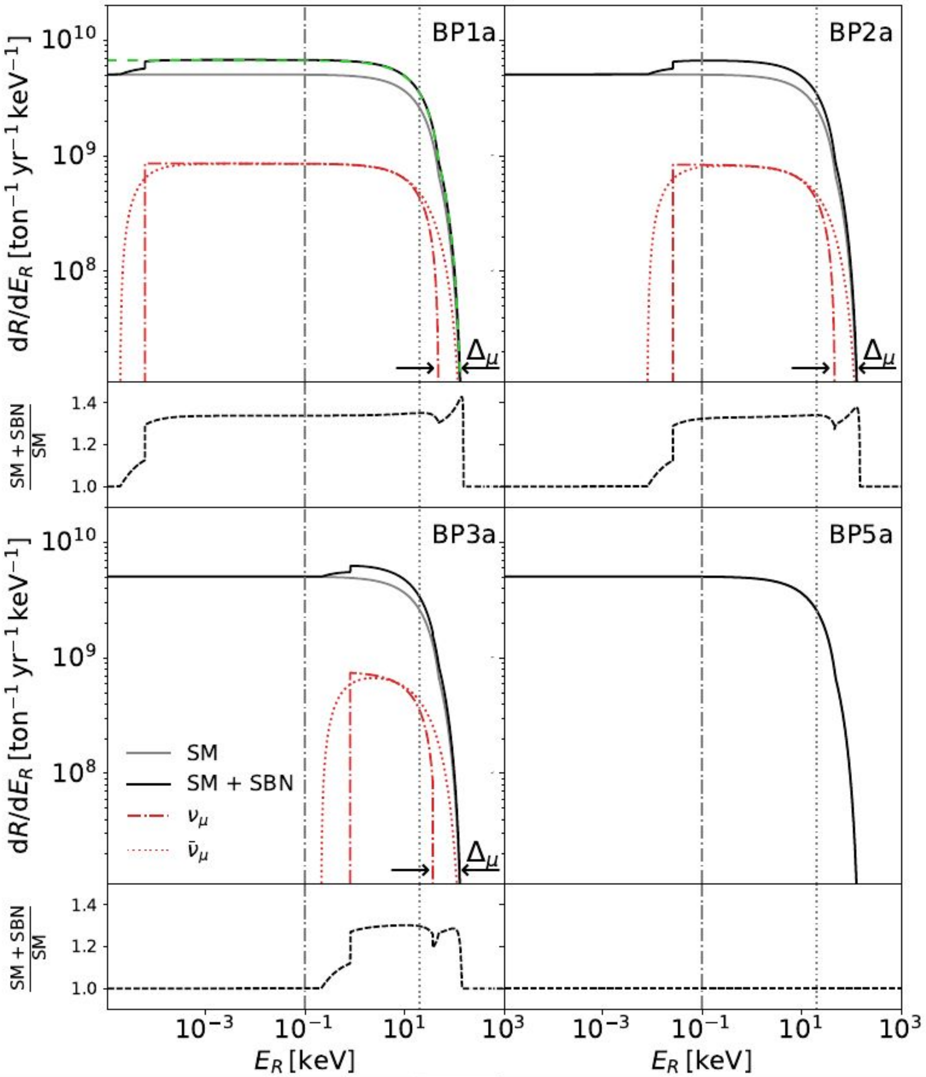
Results

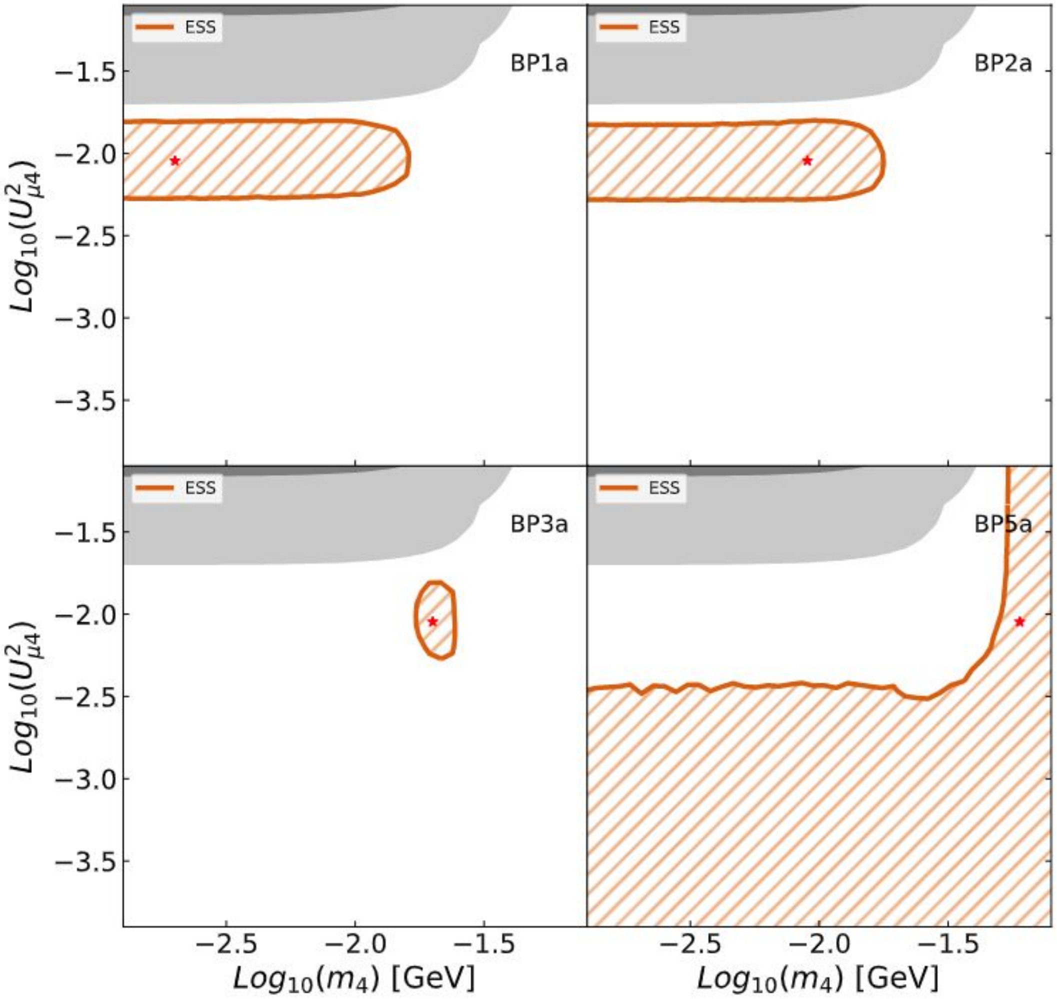
- Introduction
  - Coherent elastic neutrino-nucleus scattering
  - Spallation-Source experiments
  - Dark Matter Direct Detection Experiments
- Sterile Baryonic Neutrino Model
- Results

Let's study some benchmark points

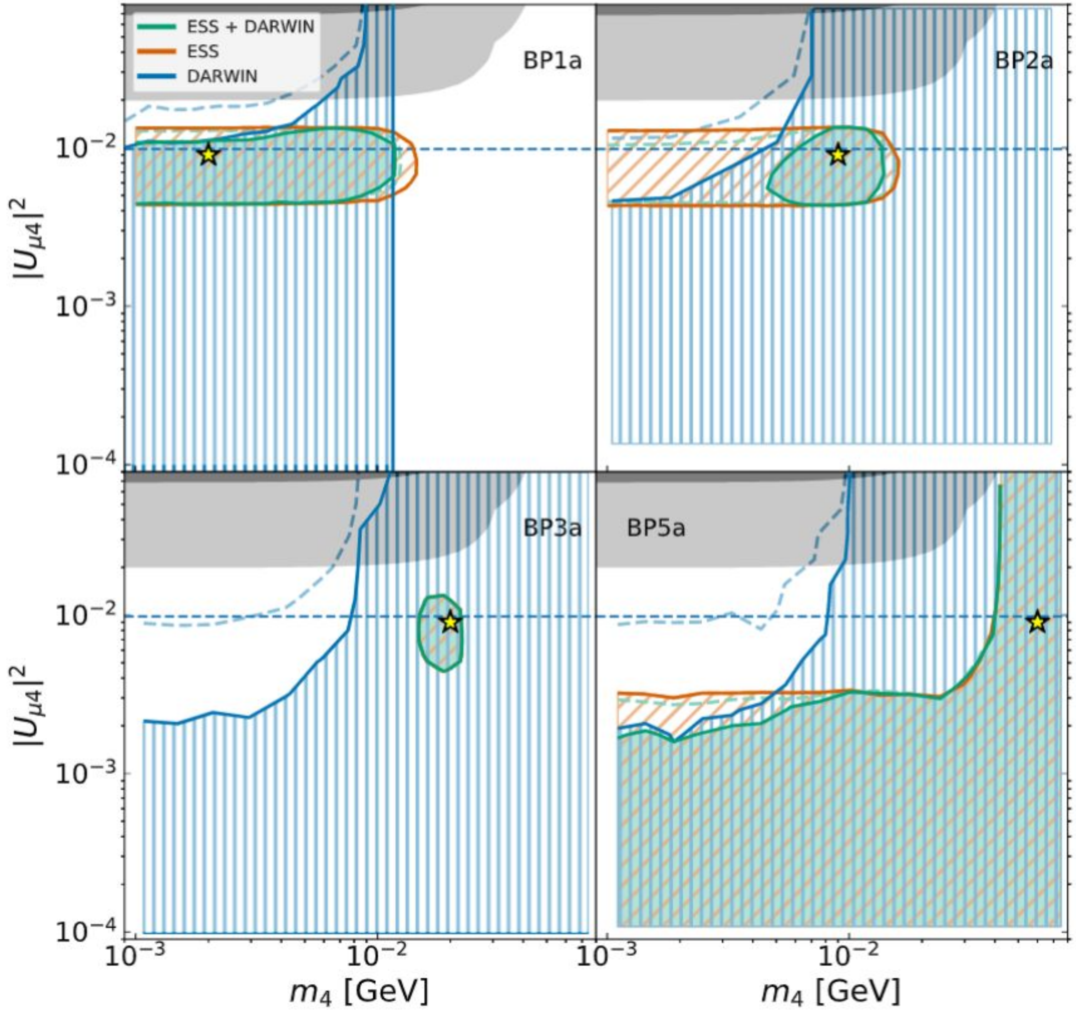
	m_4 [GeV]	$\|U_{e4}\|^2$	$\|U_{\mu4}\|^2$	$\|U_{\tau4}\|^2$
BP1a	2×10^{-3}	0	9×10^{-3}	0
BP1b	2×10^{-3}	0	9×10^{-3}	9×10^{-4}
BP1c	2×10^{-3}	0	9×10^{-3}	4×10^{-3}
BP1d	2×10^{-3}	0	9×10^{-3}	9×10^{-3}
BP1e	2×10^{-3}	9×10^{-3}	0	0
BP2a	9×10^{-3}	0	9×10^{-3}	0
BP2b	9×10^{-3}	0	9×10^{-3}	9×10^{-4}
BP2c	9×10^{-3}	0	9×10^{-3}	4×10^{-3}
BP2d	9×10^{-3}	0	9×10^{-3}	9×10^{-3}
BP3a	20×10^{-3}	0	9×10^{-3}	0
BP4a	40×10^{-3}	0	9×10^{-3}	0
BP4f	40×10^{-3}	9×10^{-3}	9×10^{-3}	0
BP5a	60×10^{-3}	0	9×10^{-3}	0

	m_4 [GeV]	$\|U_{e4}\|^2$	$\|U_{\mu4}\|^2$	$\|U_{\tau4}\|^2$
BP1a	2×10^{-3}	0	9×10^{-3}	0
BP1b	2×10^{-3}	0	9×10^{-3}	9×10^{-4}
BP1c	2×10^{-3}	0	9×10^{-3}	4×10^{-3}
BP1d	2×10^{-3}	0	9×10^{-3}	9×10^{-3}
BP1e	2×10^{-3}	9×10^{-3}	0	0
BP2a	9×10^{-3}	0	9×10^{-3}	0
BP2b	9×10^{-3}	0	9×10^{-3}	9×10^{-4}
BP2c	9×10^{-3}	0	9×10^{-3}	4×10^{-3}
BP2d	9×10^{-3}	0	9×10^{-3}	9×10^{-3}
BP3a	20×10^{-3}	0	9×10^{-3}	0
BP4a	40×10^{-3}	0	9×10^{-3}	0
BP4f	40×10^{-3}	9×10^{-3}	9×10^{-3}	0
BP5a	60×10^{-3}	0	9×10^{-3}	0


BP1a
BP2a
BP3a
BP5a
dR/dE_R [ton^{-1} yr^{-1} keV^{-1}]
$\frac{SM+SBN}{SM}$
Δ_μ
SM
SM + SBN
ν_μ
$\bar{\nu}_\mu$
E_R [keV]

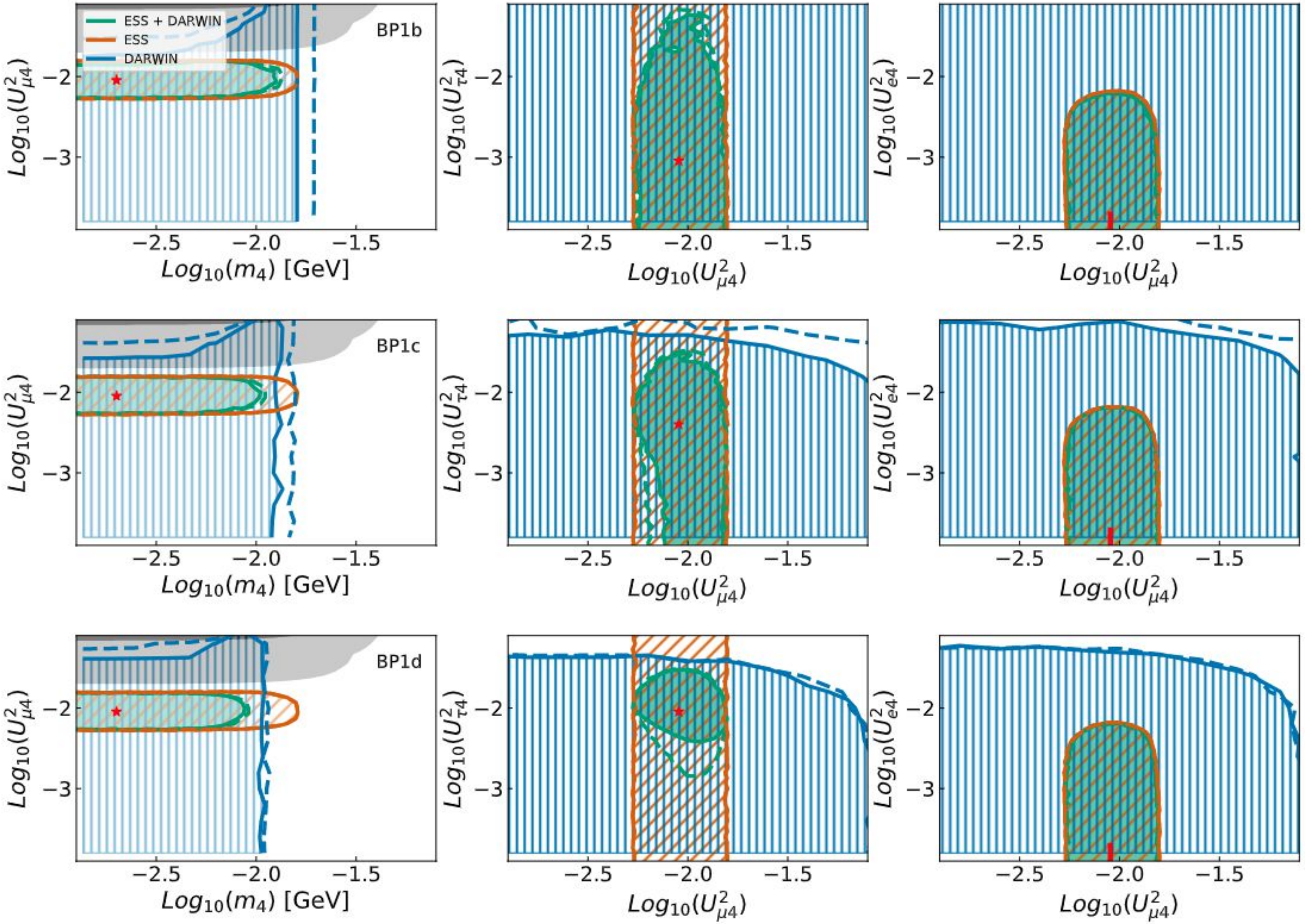


ESS
BP1a
BP2a
BP3a
BP5a
−1.5
−2.0
−2.5
−3.0
−3.5
$Log_{10}(U^2_{\mu 4})$
−2.5
−2.0
−1.5
$Log_{10}(m_4)$ [GeV]



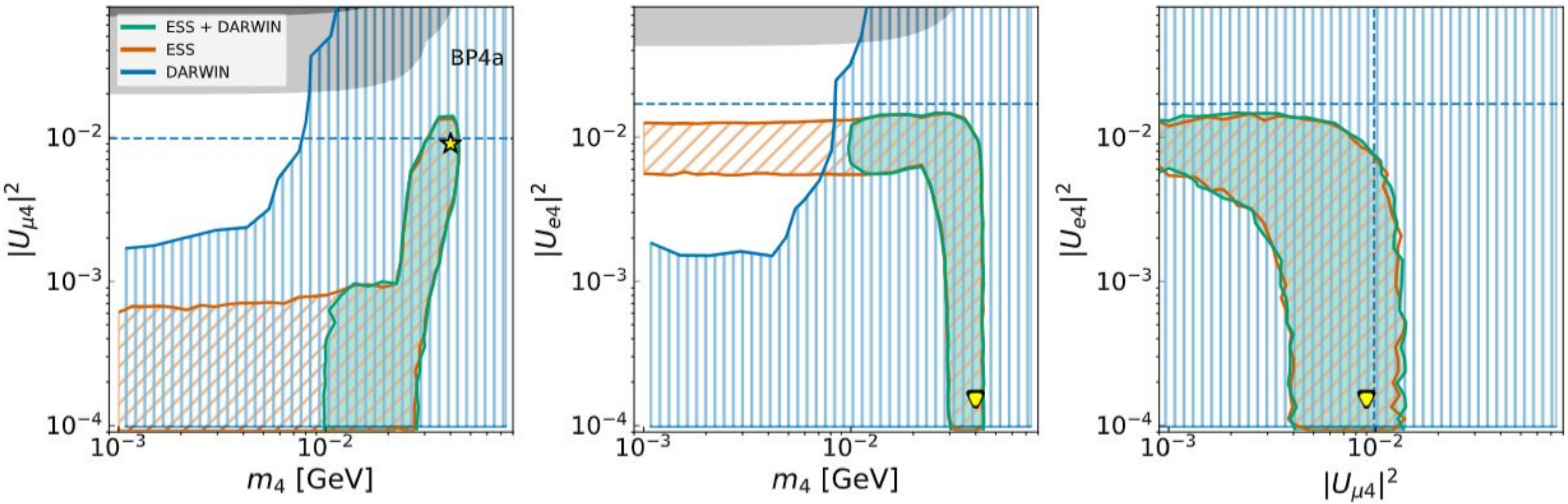
ESS + DARWIN
ESS
DARWIN
BP1a
BP2a
BP3a
BP5a
$|U_{\mu4}|^2$
10^{-2}
10^{-3}
10^{-4}
10^{-3}
10^{-2}
m_4 [GeV]

	m_4 [GeV]	$\lvert U_{e4}\rvert^2$	$\lvert U_{\mu4}\rvert^2$	$\lvert U_{\tau4}\rvert^2$
BP1a	2×10^{-3}	0	9×10^{-3}	0
BP1b	2×10^{-3}	0	9×10^{-3}	9×10^{-4}
BP1c	2×10^{-3}	0	9×10^{-3}	4×10^{-3}
BP1d	2×10^{-3}	0	9×10^{-3}	9×10^{-3}
BP1e	2×10^{-3}	9×10^{-3}	0	0
BP2a	9×10^{-3}	0	9×10^{-3}	0
BP2b	9×10^{-3}	0	9×10^{-3}	9×10^{-4}
BP2c	9×10^{-3}	0	9×10^{-3}	4×10^{-3}
BP2d	9×10^{-3}	0	9×10^{-3}	9×10^{-3}
BP3a	20×10^{-3}	0	9×10^{-3}	0
BP4a	40×10^{-3}	0	9×10^{-3}	0
BP4f	40×10^{-3}	9×10^{-3}	9×10^{-3}	0
BP5a	60×10^{-3}	0	9×10^{-3}	0

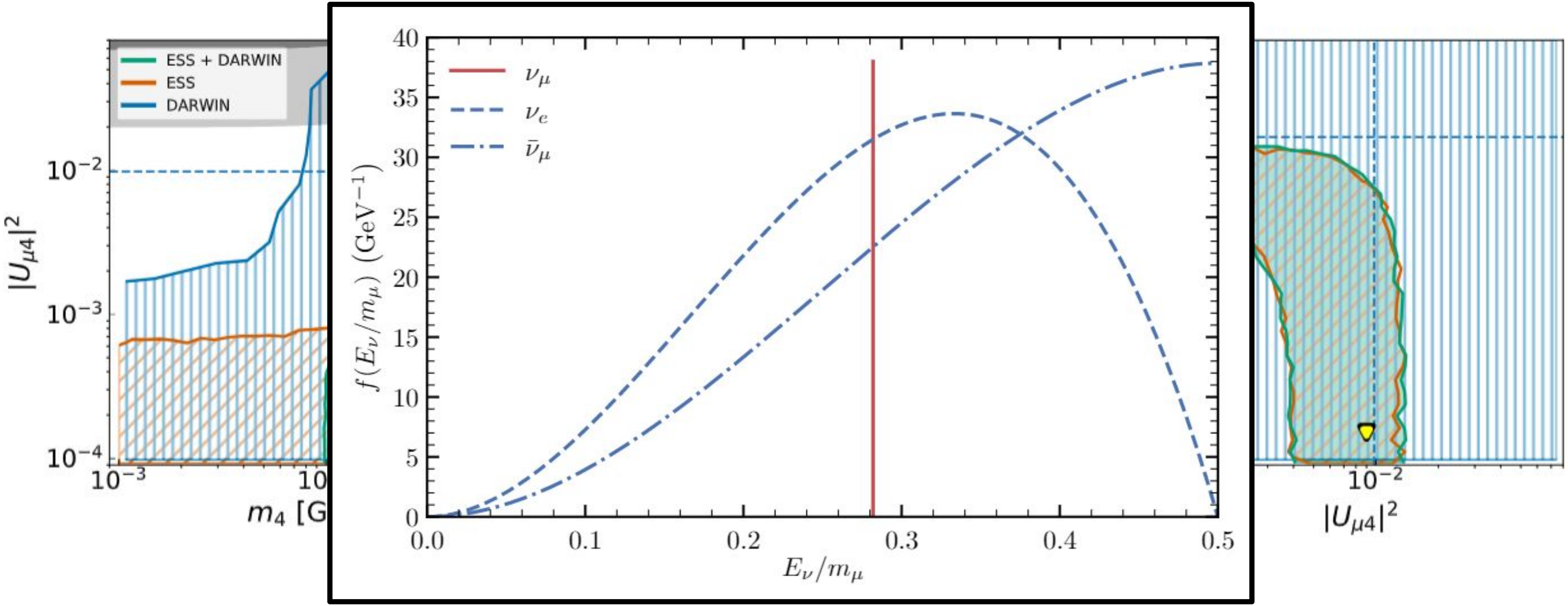


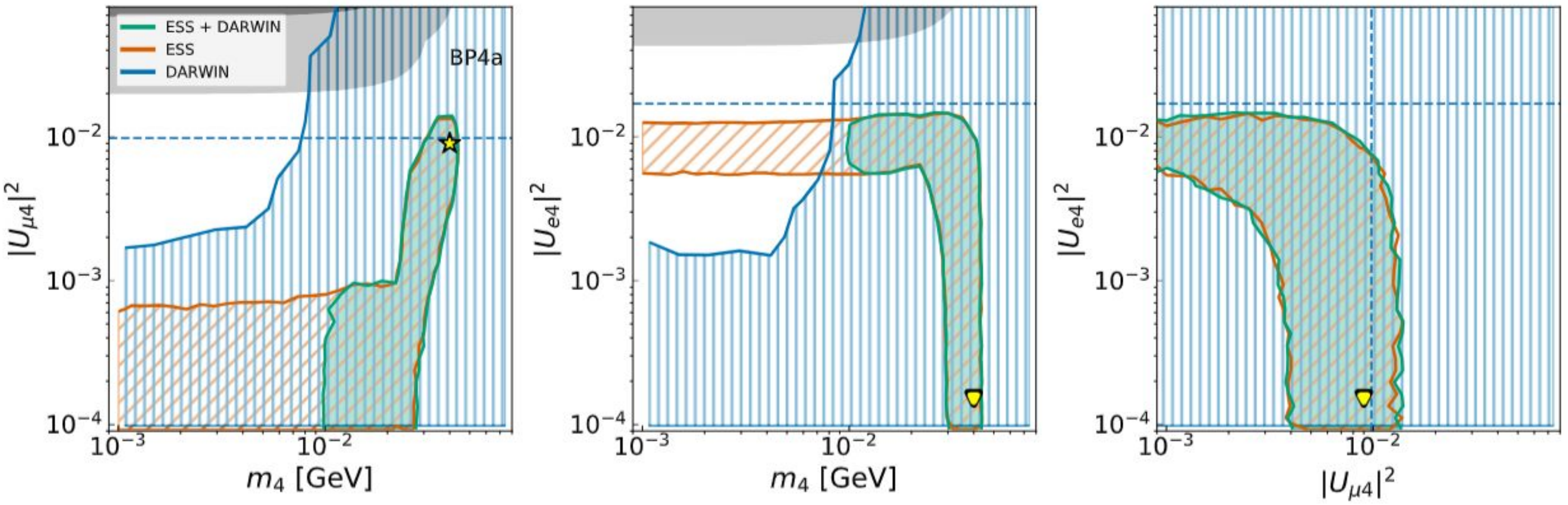
ESS + DARWIN
ESS
DARWIN
BP1b
BP1c
BP1d
$Log_{10}(U^2_{\mu 4})$
$Log_{10}(U^2_{\tau 4})$
$Log_{10}(U^2_{e4})$
$Log_{10}(m_4)$ [GeV]

	m_4 [GeV]	$\|U_{e4}\|^2$	$\|U_{\mu4}\|^2$	$\|U_{\tau4}\|^2$
BP1a	2×10^{-3}	0	9×10^{-3}	0
BP1b	2×10^{-3}	0	9×10^{-3}	9×10^{-4}
BP1c	2×10^{-3}	0	9×10^{-3}	4×10^{-3}
BP1d	2×10^{-3}	0	9×10^{-3}	9×10^{-3}
BP1e	2×10^{-3}	9×10^{-3}	0	0
BP2a	9×10^{-3}	0	9×10^{-3}	0
BP2b	9×10^{-3}	0	9×10^{-3}	9×10^{-4}
BP2c	9×10^{-3}	0	9×10^{-3}	4×10^{-3}
BP2d	9×10^{-3}	0	9×10^{-3}	9×10^{-3}
BP3a	20×10^{-3}	0	9×10^{-3}	0
BP4a	40×10^{-3}	0	9×10^{-3}	0
BP4f	40×10^{-3}	9×10^{-3}	9×10^{-3}	0
BP5a	60×10^{-3}	0	9×10^{-3}	0

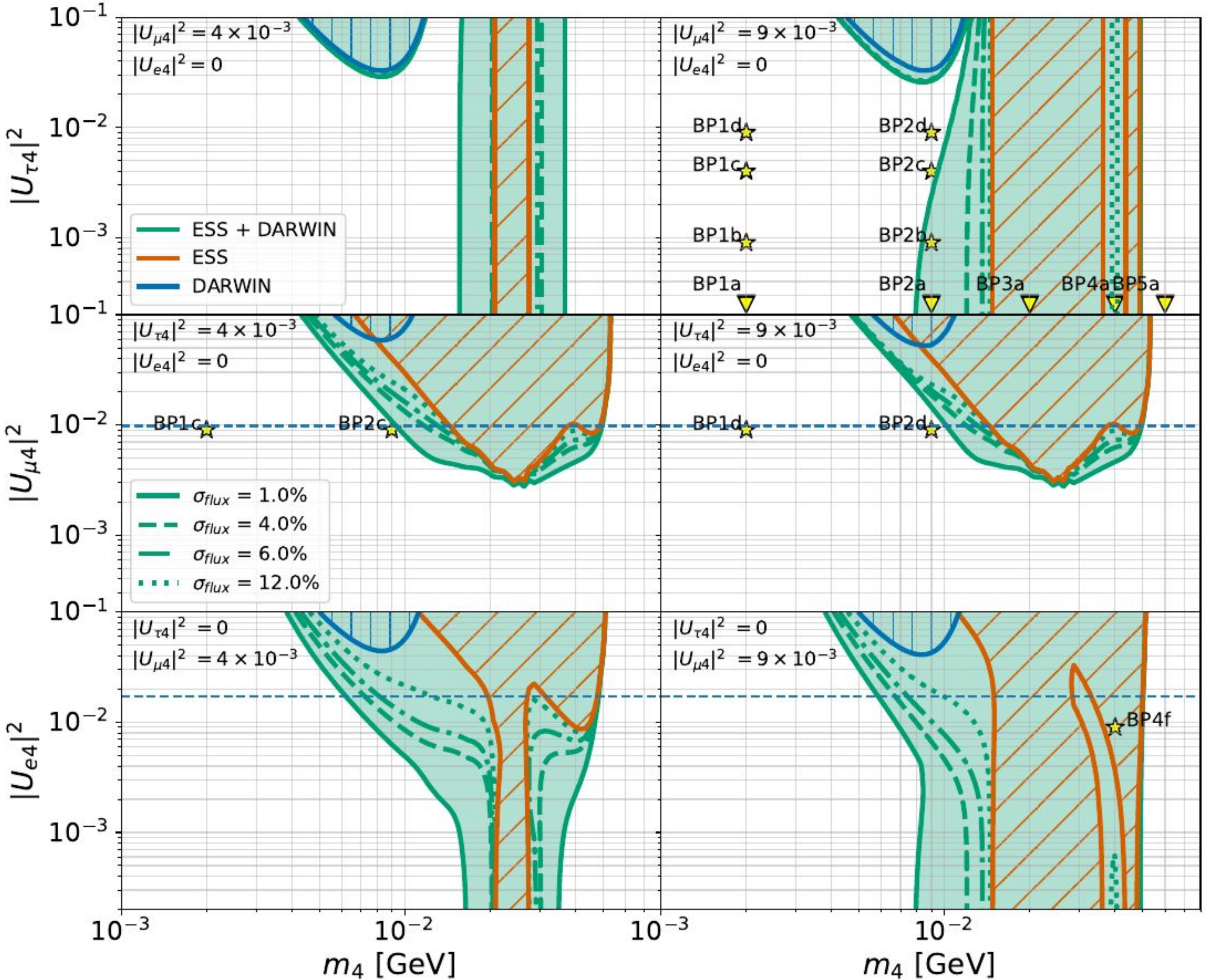


ESS + DARWIN
ESS
DARWIN
BP4a
$|U_{\mu 4}|^2$
m_4 [GeV]
$|U_{e4}|^2$
m_4 [GeV]
$|U_{e4}|^2$
$|U_{\mu 4}|^2$
10^{-2}
10^{-3}
10^{-4}


ESS + DARWIN
ESS
DARWIN
$|U_{\mu4}|^2$
m_4 [G
ν_μ
ν_e
$\bar{\nu}_\mu$
$f(E_\nu/m_\mu)$ (GeV^{-1})
E_ν/m_μ
$|U_{\mu4}|^2$



ESS + DARWIN
ESS
DARWIN
BP4a
$|U_{\mu 4}|^2$
$|U_{e4}|^2$
$|U_{e4}|^2$
m_4 [GeV]
m_4 [GeV]
$|U_{\mu 4}|^2$
10^{-2}
10^{-3}
10^{-4}



$|U_{\mu4}|^2 = 4\times10^{-3}$
$|U_{e4}|^2 = 0$
$|U_{\mu4}|^2 = 9\times10^{-3}$
$|U_{e4}|^2 = 0$
$|U_{\tau4}|^2$
ESS + DARWIN
ESS
DARWIN
BP1d
BP1c
BP1b
BP1a
BP2d
BP2c
BP2b
BP2a
BP3a
BP4a
BP5a
$|U_{\tau4}|^2 = 4\times10^{-3}$
$|U_{e4}|^2 = 0$
$|U_{\tau4}|^2 = 9\times10^{-3}$
$|U_{e4}|^2 = 0$
$|U_{\mu4}|^2$
$\sigma_{flux} = 1.0\%$
$\sigma_{flux} = 4.0\%$
$\sigma_{flux} = 6.0\%$
$\sigma_{flux} = 12.0\%$
$|U_{\tau4}|^2 = 0$
$|U_{\mu4}|^2 = 4\times10^{-3}$
$|U_{\tau4}|^2 = 0$
$|U_{\mu4}|^2 = 9\times10^{-3}$
BP4f
$|U_{e4}|^2$
m_4 [GeV]

Conclusions

- Sterile neutrino models can be probed with Spallation Source (SS) and Direct Detection (DD) experiments.
- DD will be able to access to very low recoil energies, all the neutrino flavours but not big masses.
- SS will be able to access to heavier sterile neutrinos but not to all neutrino flavours.
- Combining DD and SS may help…
  - improving the significance,
  - constraining the parameter space
  - allowing parameter reconstruction (especially in the couplings),
  - and allowing model discrimination (Sterile Baryonic Neutrino).

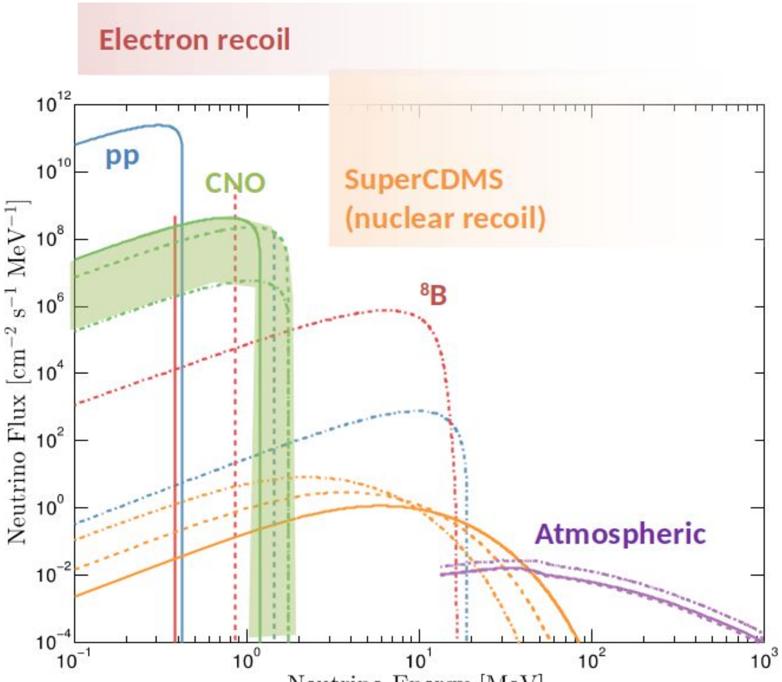
THANK YOU

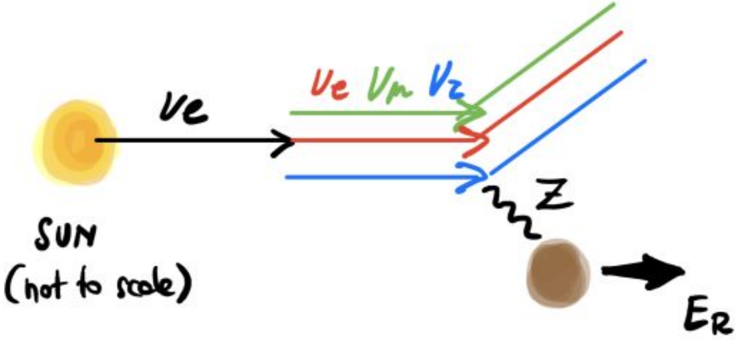
Back up

CEνNS @ DM Direct Detection Experiments

$$\frac{\mathrm{d}R}{\mathrm{d}E_R} = n_T \sum_{\nu_\alpha} \int_{E_\nu^{\min}} \frac{\mathrm{d}\phi_{\nu_e}}{\mathrm{d}E_\nu} P(\nu_e \to \nu_\alpha) \frac{\mathrm{d}\sigma_{\nu_\alpha T}}{\mathrm{d}E_R} \, \mathrm{d}E_\nu$$

Xenon, LZ,
SuperCDM, etc..

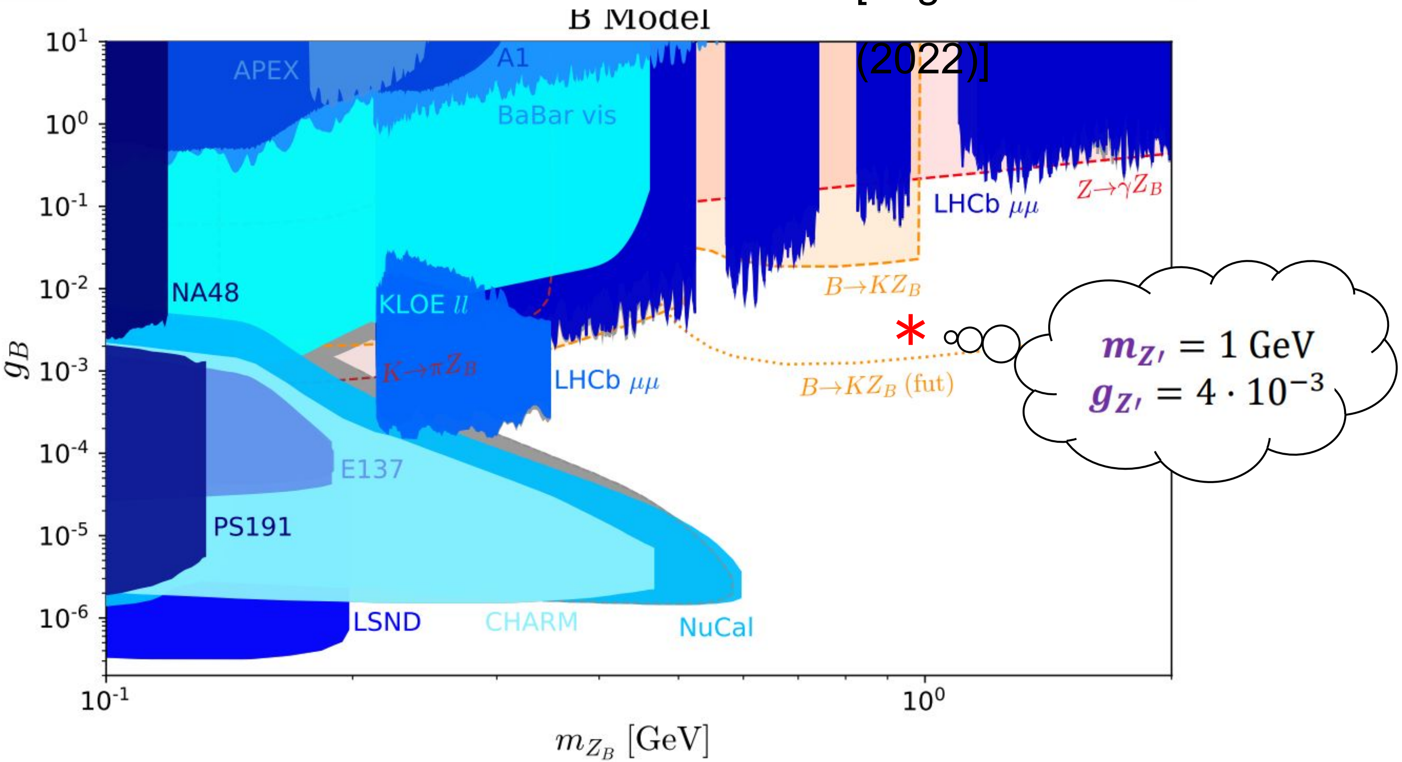


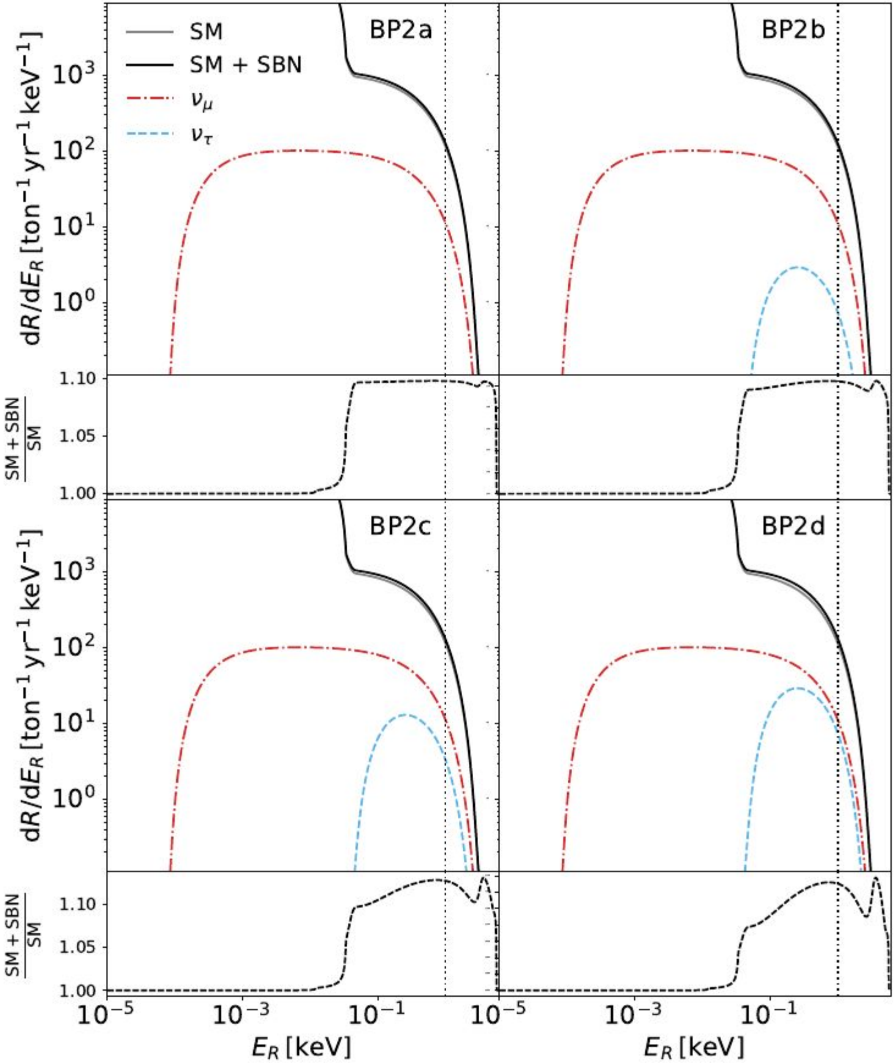


Sterile Baryonic Neutrino (SBN)

$$\mathcal{L} \supset \frac{m_{Z'}^2}{2} Z'^{\mu} Z'_{\mu} + g_b Z'^{\mu} \overline{\nu}_b \gamma_\mu \nu_b + \frac{1}{3} g_q Z'^{\mu} \sum_q \overline{q} \gamma_\mu q \,.$$

[Foguel et al. 2201.01788 (2022)]





SM
SM + SBN
ν_μ
ν_τ
BP2a
BP2b
BP2c
BP2d
dR/dE_R [ton^{-1} yr^{-1} keV^{-1}]
$\frac{SM+SBN}{SM}$
E_R [keV]

Let's study some benchmark points

	m_4 [GeV]	$\lvert U_{e4}\rvert^2$	$\lvert U_{\mu4}\rvert^2$	$\lvert U_{\tau4}\rvert^2$
BP1a	2×10^{-3}	0	9×10^{-3}	0
BP1b	2×10^{-3}	0	9×10^{-3}	9×10^{-4}

Experiment	M_{det} (ton)	E_{th} (keV_{nr})	N_{POT} ($\times 10^{23}$)	r	L (m)	σ_{sys}
ESS	1	20	2.8	0.3	20	5%

BP2b	9×10^{-3}	0	9×10^{-3}	9×10^{-4}
BP2c	9×10^{-3}	0	9×10^{-3}	4×10^{-3}

Experiment	M_{det} (ton)	E_{th} (keV_{nr})	$\sigma_{^8B}$
DARWIN	200	1	1(4)%

BP4f	40×10^{-3}	9×10^{-3}	9×10^{-3}	0
BP5a	60×10^{-3}	0	9×10^{-3}	0