Based on [2307.05176]

Testing Sterile Neutrinos with Direct Detection and Spallation Source Experiments

DAVID ALONSO-GONZÁLEZ*

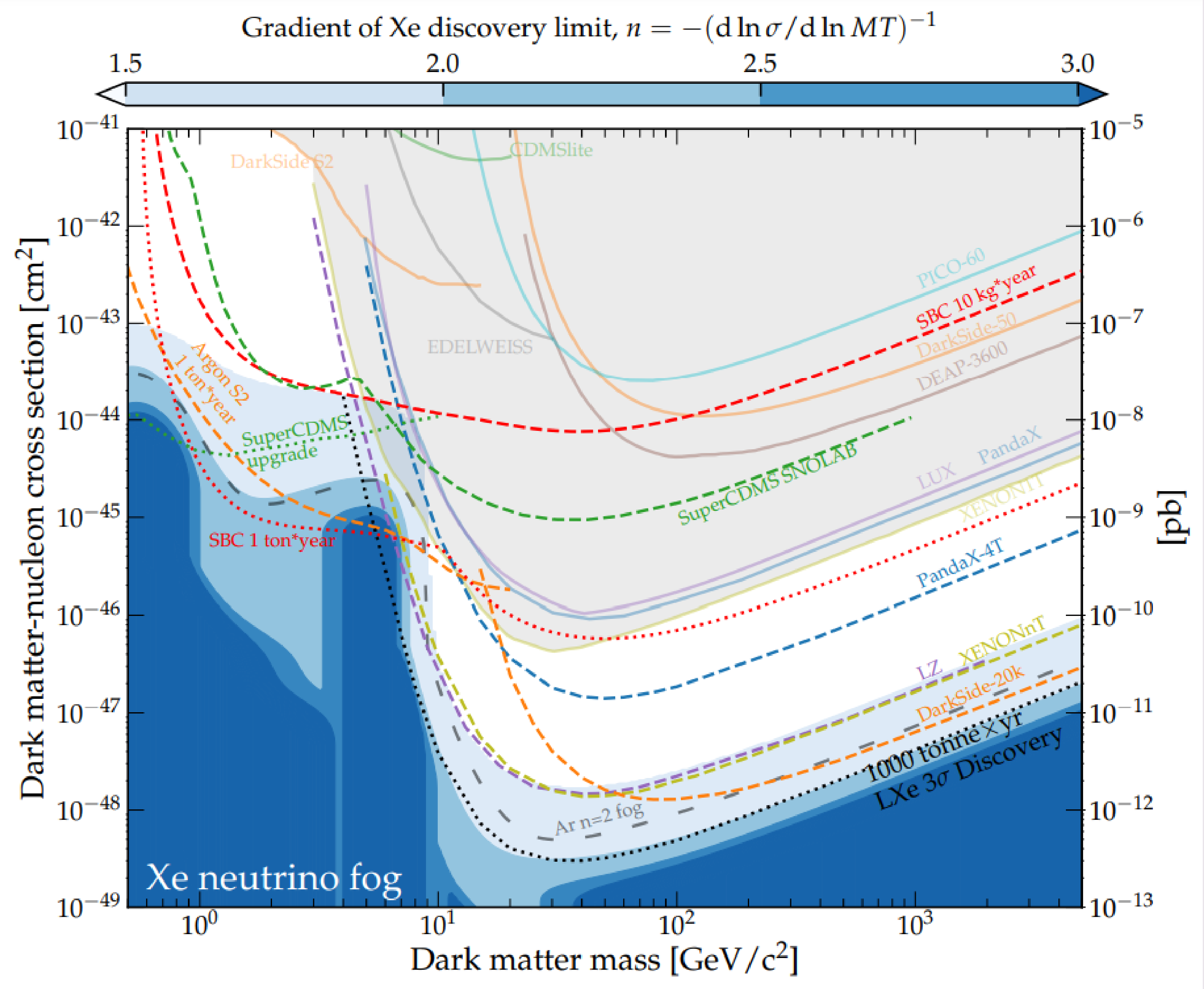
with D.W.P. Amaral, A. Bariego-Quintana, D. Cerdeño & M. de los Ríos

TeVPA 2023 (September 13th, Napoli)

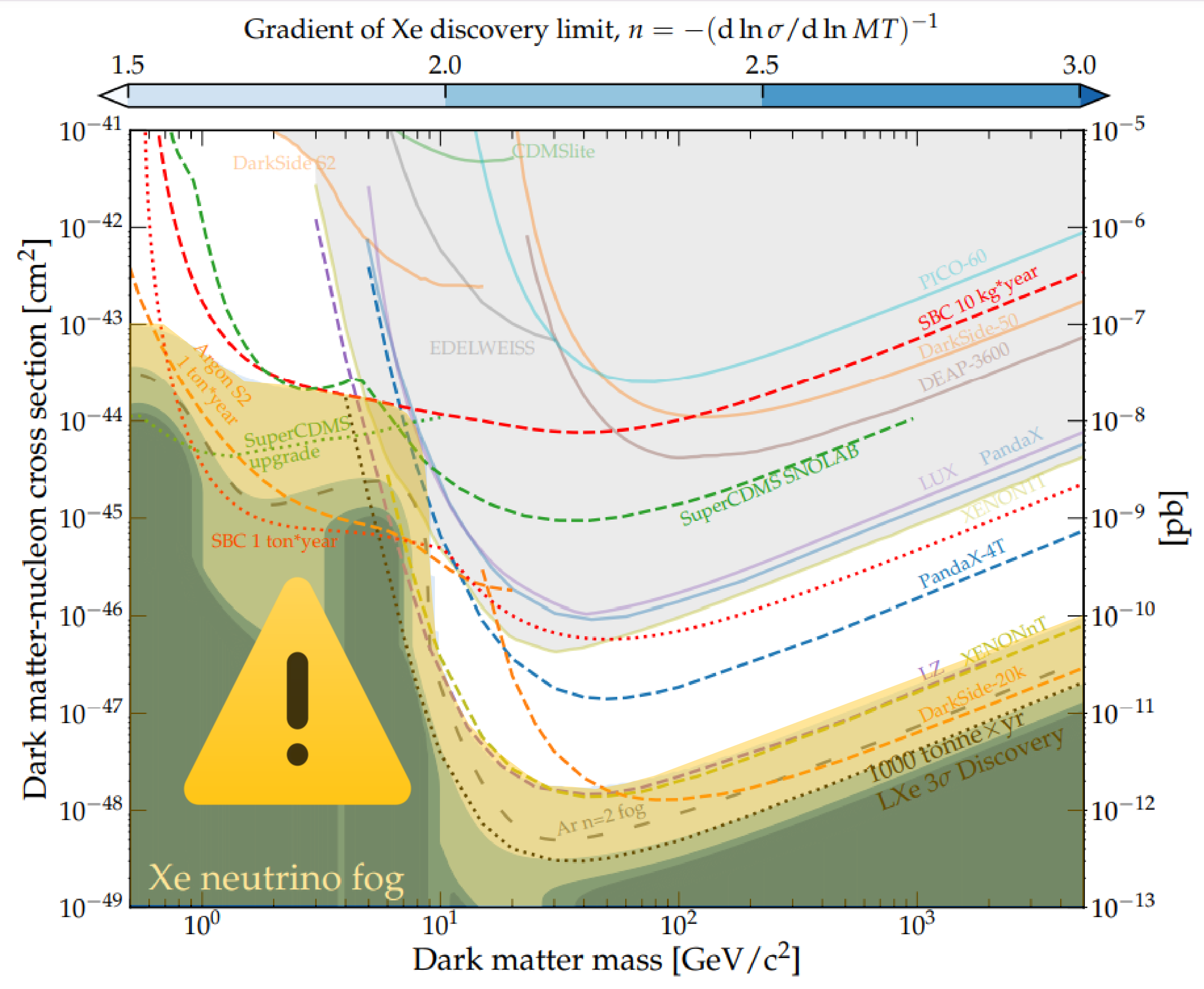
ift Instituto de Física Teórica UAM-CSIC

UAM Universidad Autónoma de Madrid

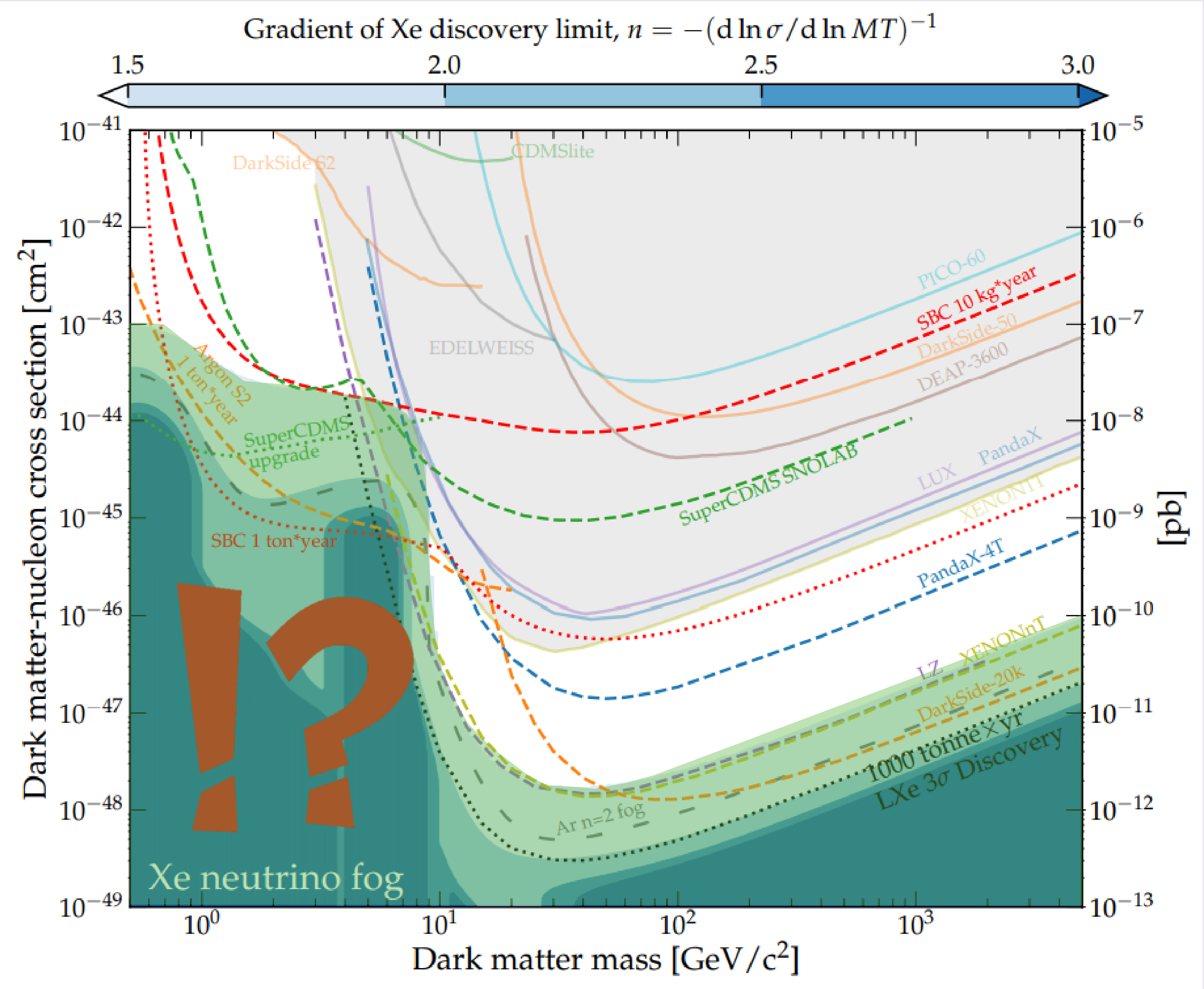
*david.alonsogonzalez@uam.es



[Akerib et al. 2203.08084 (2022)]



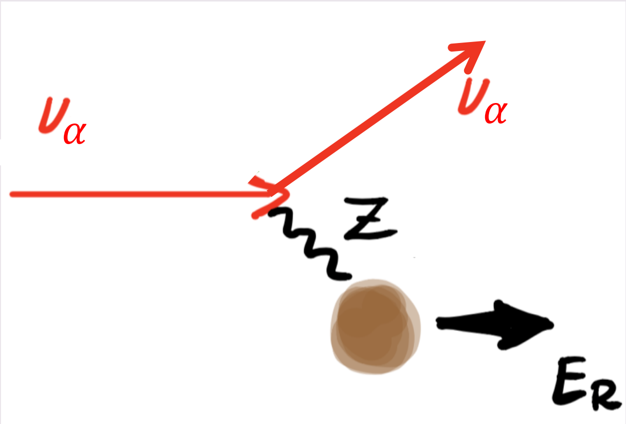
[Akerib et al. 2203.08084 (2022)]



[Akerib et al. 2203.08084 (2022)]

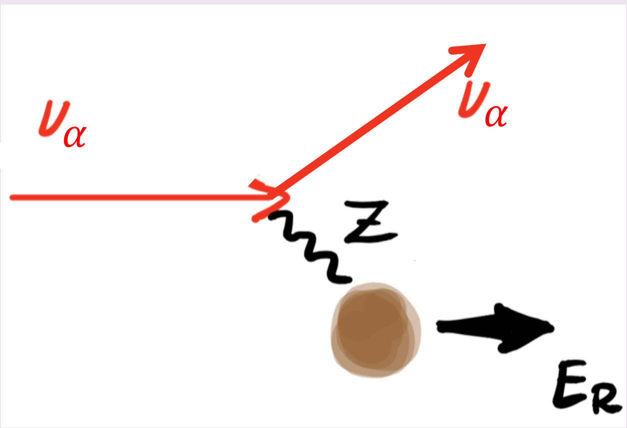
Coherent Elastic Neutrino – Nucleus Scattering

…or **CEνNS** for friends



Coherent Elastic Neutrino – Nucleus Scattering

...or **CEνNS** for friends



Predicted by the SM...

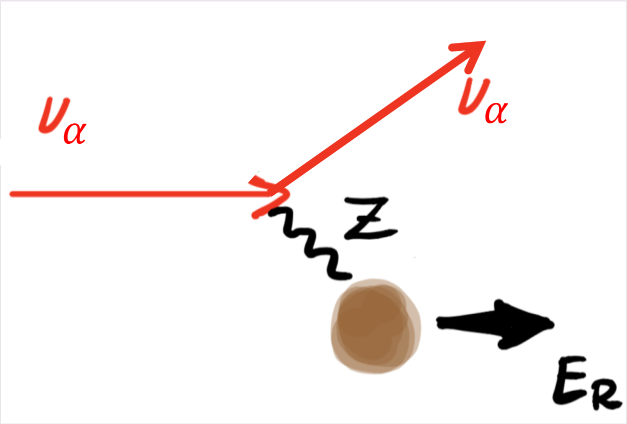
[Freedman (1974)]

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

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

Coherent Elastic Neutrino – Nucleus Scattering

...or **CEνNS** for friends



Predicted by the SM...

[Freedman (1974)]

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

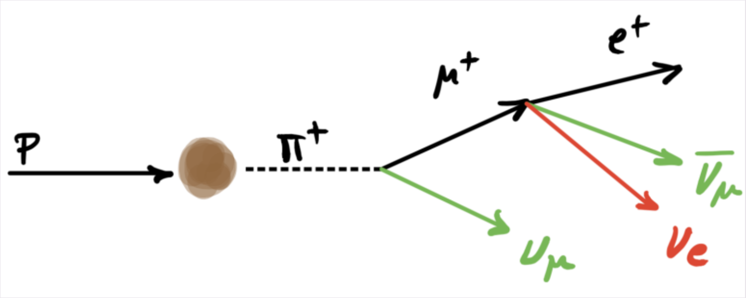
$$Q_v = N - (1 - 4\sin^2\theta_W)Z$$

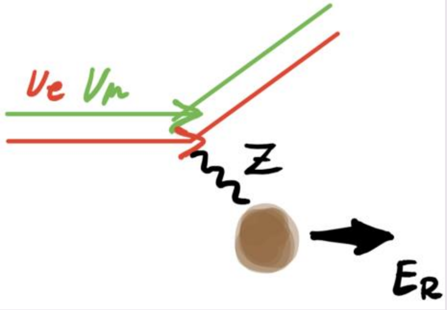
...and **experimentally detected** by COHERENT collaboration!

[Akimov et al. 1708.01294 (2017)]

CEνNS at Spallation Sources

like **COHERENT**

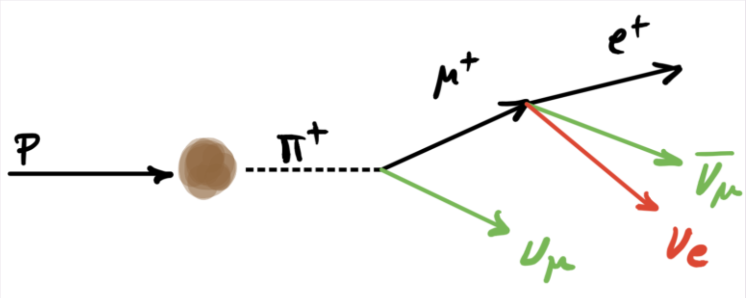


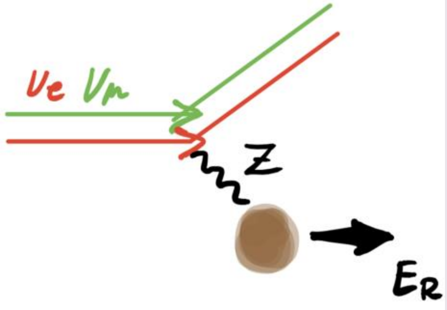


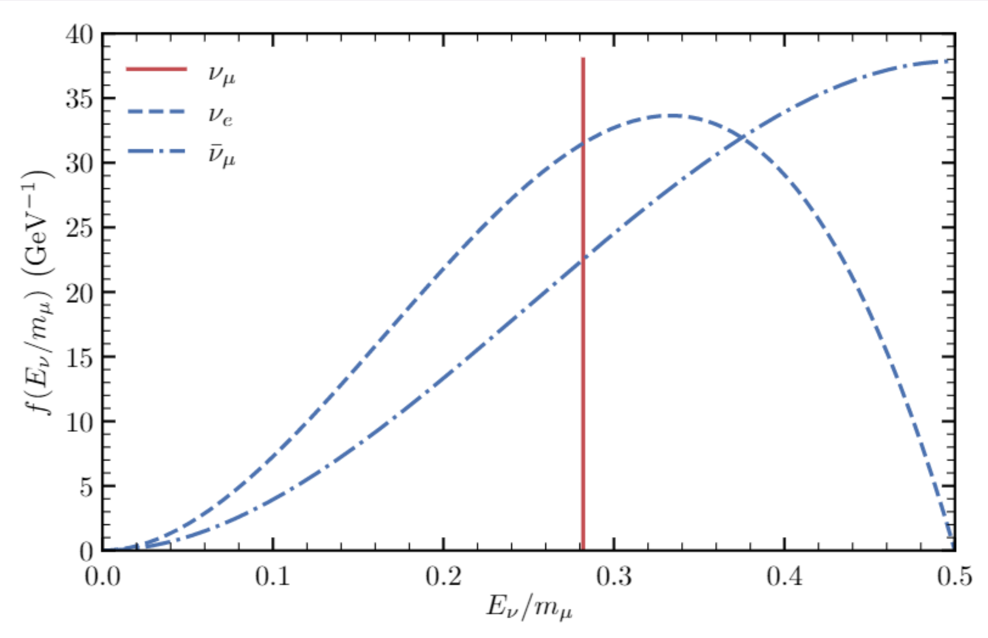
$$N_{\mathrm{CE}\nu\mathrm{NS}} = \sum_{\nu_\alpha} N_{\mathrm{targ}} \int_{E_{\mathrm{th}}}^{E_R^{\mathrm{max}}} \int_{E_\nu^{\mathrm{min}}}^{E_\nu^{\mathrm{max}}} \frac{\mathrm{d}N_{\nu_\alpha}}{\mathrm{d}E_\nu} \, \epsilon(E_R) \, \frac{\mathrm{d}\sigma_{\nu_\alpha N}}{\mathrm{d}E_R} \, \mathrm{d}E_\nu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

CEνNS at Spallation Sources

like **COHERENT**



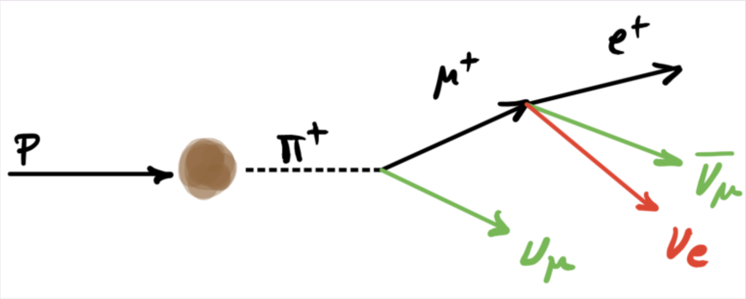


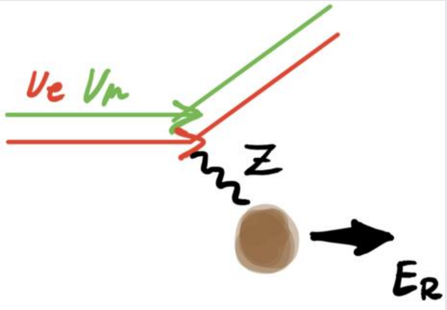


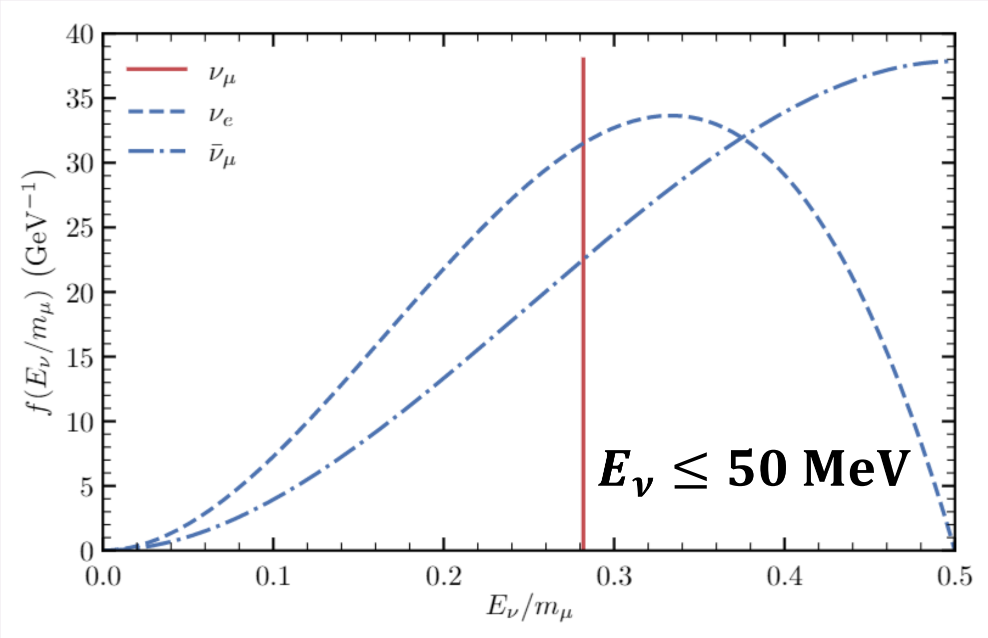
$$N_{\text{CE}\nu\text{NS}} = \sum_{\nu_\alpha} N_{\text{targ}} \int_{E_{\text{th}}}^{E_R^{\text{max}}} \int_{E_\nu^{\text{min}}}^{E_\nu^{\text{max}}} \frac{\mathrm{d}N_{\nu_\alpha}}{\mathrm{d}E_\nu}\, \epsilon(E_R)\, \frac{\mathrm{d}\sigma_{\nu_\alpha N}}{\mathrm{d}E_R}\, \mathrm{d}E_\nu\, \mathrm{d}E_R$$

CEνNS at Spallation Sources

like **COHERENT**



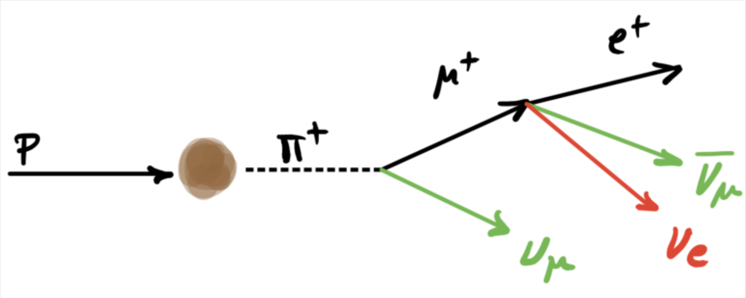


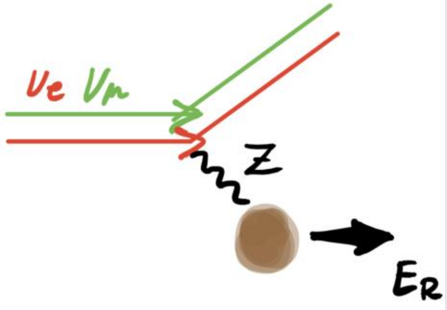


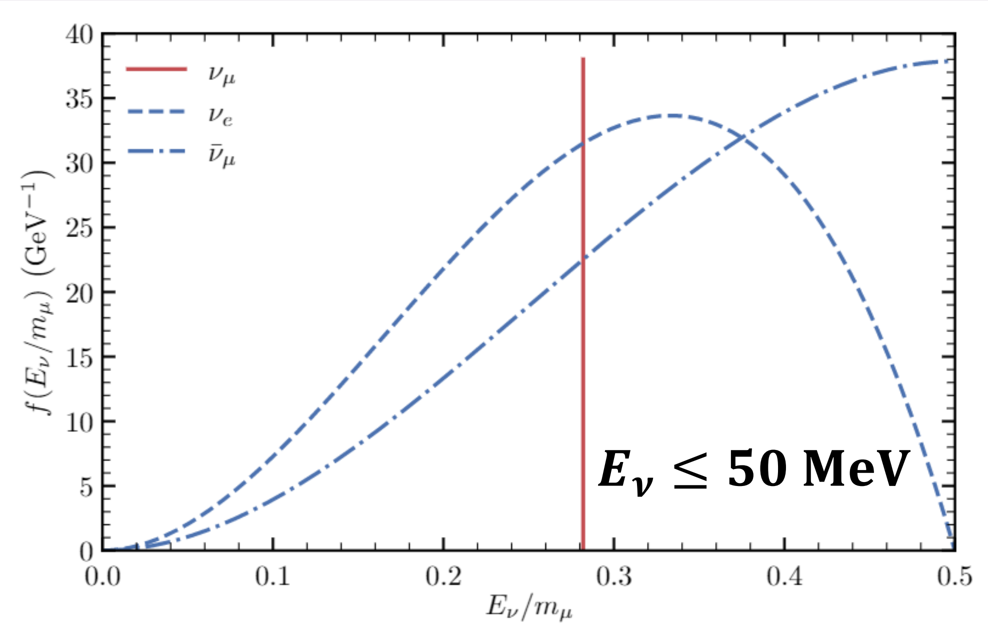
$$N_{\mathrm{CE}\nu\mathrm{NS}} = \sum_{\nu_\alpha} N_{\mathrm{targ}} \int_{E_{\mathrm{th}}}^{E_R^{\mathrm{max}}} \int_{E_\nu^{\mathrm{min}}}^{E_\nu^{\mathrm{max}}} \frac{\mathrm{d}N_{\nu_\alpha}}{\mathrm{d}E_\nu} \epsilon(E_R) \frac{\mathrm{d}\sigma_{\nu_\alpha N}}{\mathrm{d}E_R} \mathrm{d}E_\nu \,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

CEνNS at Spallation Sources

like **COHERENT**







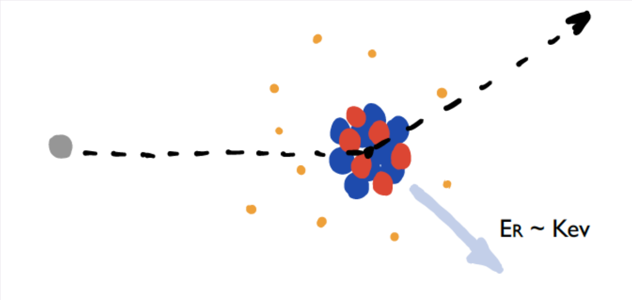
[Miranda et al. 2008.02759 (2020)]

Experiment	Mass [ton]	E_{th} [keV$_{nr}$]	NPOT [10^{23}/yr]	r	L [m]	σ_{sys}
CENNS610	0.61	~ 20	1.5	0.08	28.4	8.5%
ESS10	0.01	0.1	2.8	0.3	20	5%
CCM	7	10	0.177	0.0425	20	5%
ESS	1	20	2.8	0.3	20	5%

not low energy thresholds

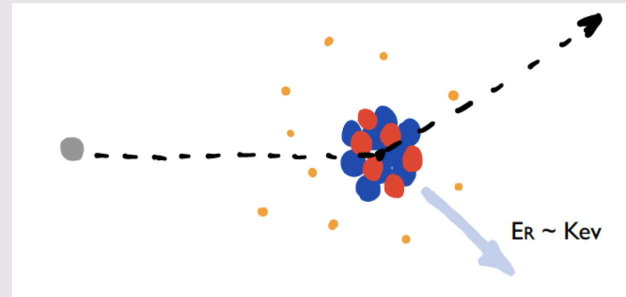
CEνNS at Direct Detection

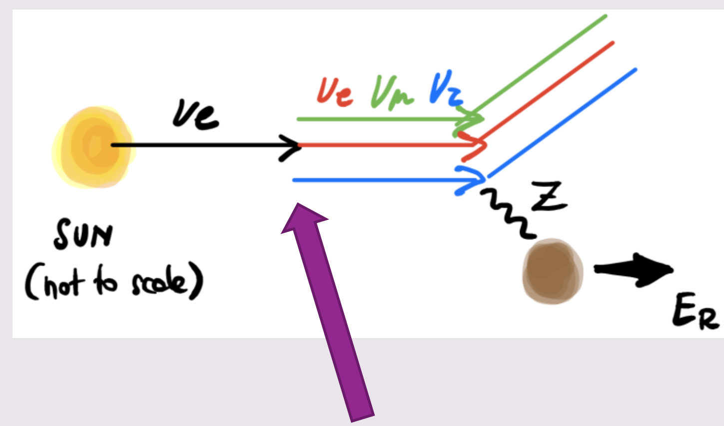
$$\frac{\mathrm{d}R}{\mathrm{d}E_R} = n_T \sum_{\nu_\alpha} \int_{E_\nu^{\min}} \frac{\mathrm{d}\phi_{\nu_e}}{\mathrm{d}E_\nu} P(\nu_e \to \nu_\alpha) \frac{\mathrm{d}\sigma_{\nu_\alpha T}}{\mathrm{d}E_R} \mathrm{d}E_\nu$$



CEνNS at Direct Detection

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

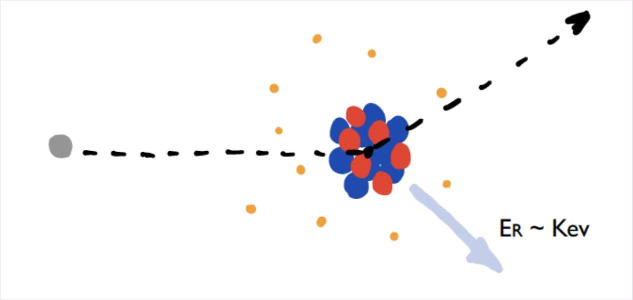




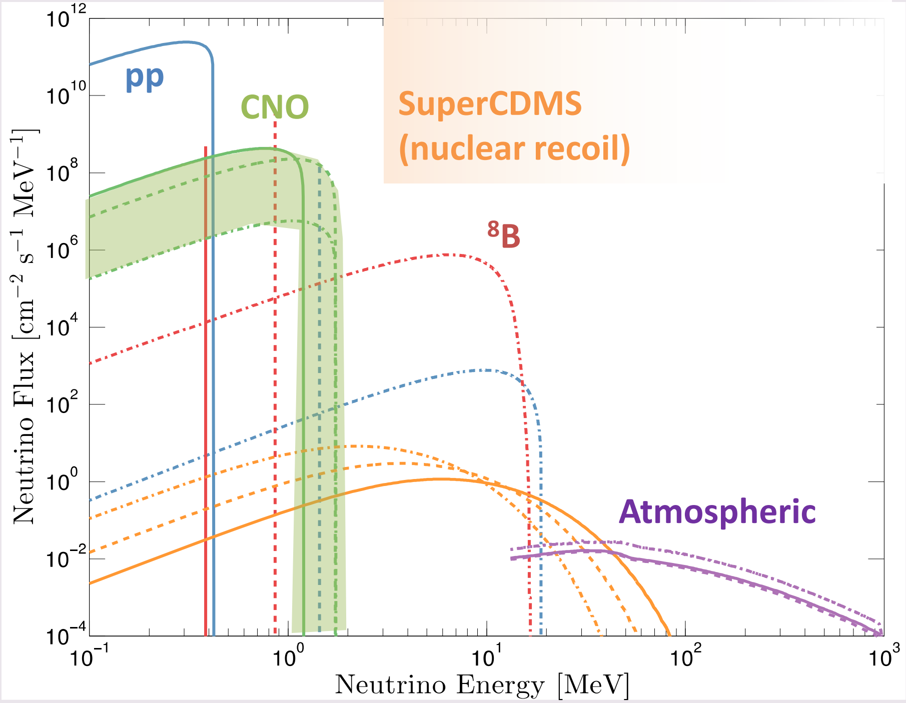
Neutrino oscillations

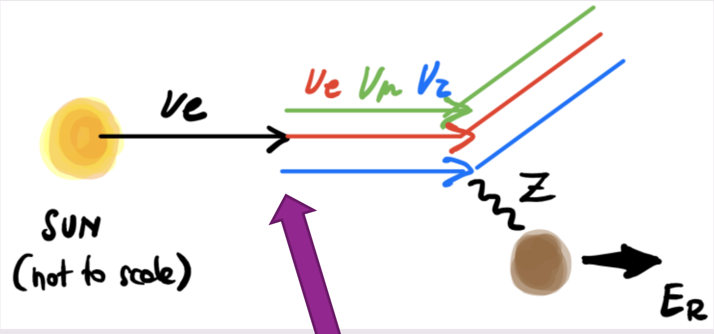
CEνNS at Direct Detection

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



Electron recoil

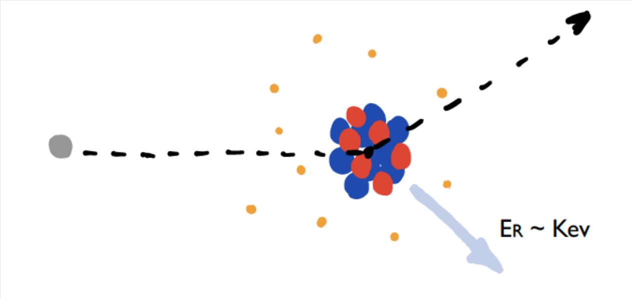




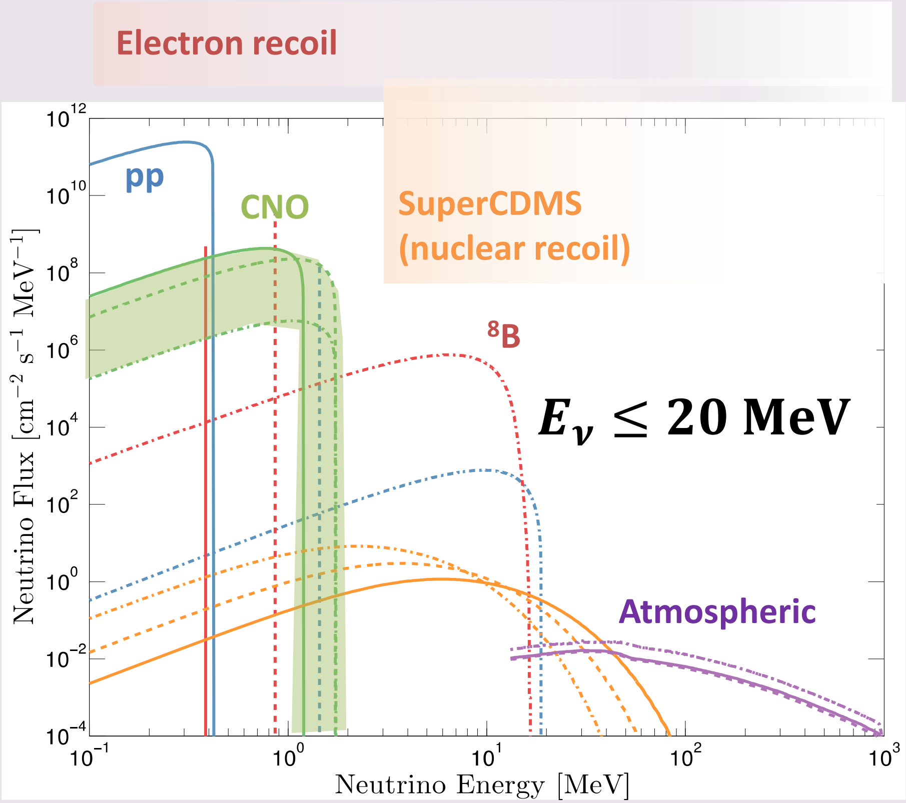
Neutrino oscillations

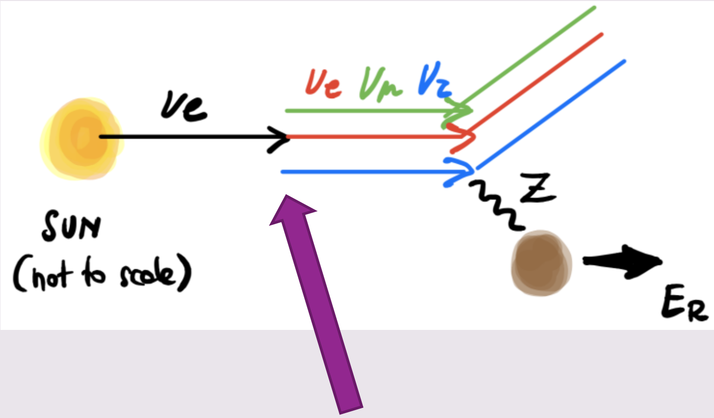
CEνNS at Direct Detection

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



Electron recoil





Neutrino oscillations

Different experimental setups…

Spallation Sources	Direct Detection

Different experimental setups…

Spallation Sources	Direct Detection
Source: Spallation	Source: Sun

Different experimental setups…

Spallation Sources	Direct Detection
Source: Spallation	Source: Sun
$\nu_e, \nu_\mu, \overline{\nu_\mu}$	$\nu_e, \overline{\nu_e}, \nu_\mu, \overline{\nu_\mu}, \nu_\tau, \overline{\nu_\tau}$

Different experimental setups…

Spallation Sources	Direct Detection
Source: Spallation	Source: Sun
$\nu_e, \nu_\mu, \overline{\nu_\mu}$	$\nu_e, \overline{\nu_e}, \nu_\mu, \overline{\nu_\mu}, \nu_\tau, \overline{\nu_\tau}$
Neutrinos up to 50 MeV	Neutrinos up to 20 MeV

Different experimental setups…

Spallation Sources

Source: Spallation

$\nu_e, \nu_\mu, \overline{\nu_\mu}$

Neutrinos up to 50 MeV

Not small energy thresholds

Direct Detection

Source: Sun

$\nu_e, \overline{\nu_e}, \nu_\mu, \overline{\nu_\mu}, \nu_\tau, \overline{\nu_\tau}$

Neutrinos up to 20 MeV

Very small thresholds

Different experimental setups...

Spallation Sources	**Direct Detection**
Source: Spallation	Source: Sun
$\nu_e, \nu_\mu, \overline{\nu_\mu}$	$\nu_e, \overline{\nu_e}, \nu_\mu, \overline{\nu_\mu}, \nu_\tau, \overline{\nu_\tau}$
Neutrinos up to 50 MeV	Neutrinos up to 20 MeV
Not small energy thresholds	Very small thresholds

...so why not **combine** them?

Sterile Baryonic Neutrino (SBN)

[Pospelov 1103.3261 (2011)]

$$L_{SBN} \supset g_{Z'} \frac{1}{3} \sum_q \bar{q}\, \gamma_\mu Z'^\mu q + g_{Z'} \overline{\nu_b} \gamma_\mu Z'^\mu \nu_b$$

Sterile Baryonic Neutrino (SBN)

[Pospelov 1103.3261 (2011)]

$$L_{SBN} \supset g_{Z'} \frac{1}{3} \sum_q \bar{q}\, \gamma_\mu Z'^\mu q + g_{Z'} \overline{\nu_b} \gamma_\mu Z'^\mu \nu_b$$

Z'^μ: baryonic vector boson $U(1)_B$ ($m_{Z'}$)

Sterile Baryonic Neutrino (SBN)

[Pospelov 1103.3261 (2011)]

$$L_{SBN} \supset g_{Z'} \frac{1}{3} \sum_{q} \bar{q}\, \gamma_{\mu} Z'^{\mu} q + g_{Z'} \overline{\nu_b} \gamma_{\mu} Z'^{\mu} \nu_b$$

Z'^{μ}: baryonic vector boson $U(1)_B$ ($m_{Z'}$)

$g_{Z'}$: $U(1)_B$ gauge coupling

Sterile Baryonic Neutrino (SBN)

[Pospelov 1103.3261 (2011)]

$$L_{SBN} \supset g_{Z'} \frac{1}{3} \sum_q \bar{q}\, \gamma_\mu Z'^\mu q + g_{Z'} \overline{\nu_b} \gamma_\mu Z'^\mu \nu_b$$

Z'^μ: baryonic vector boson $U(1)_B$ ($m_{Z'}$)

$g_{Z'}$: $U(1)_B$ gauge coupling

ν_b: sterile baryonic neutrino (m_4)

Sterile Baryonic Neutrino (SBN)

[Pospelov 1103.3261 (2011)]

$$L_{SBN} \supset g_{Z'} \frac{1}{3} \sum_q \bar{q}\, \gamma_\mu Z'^{\mu} q + g_{Z'} \overline{\nu_b} \gamma_\mu Z'^{\mu} \nu_b$$

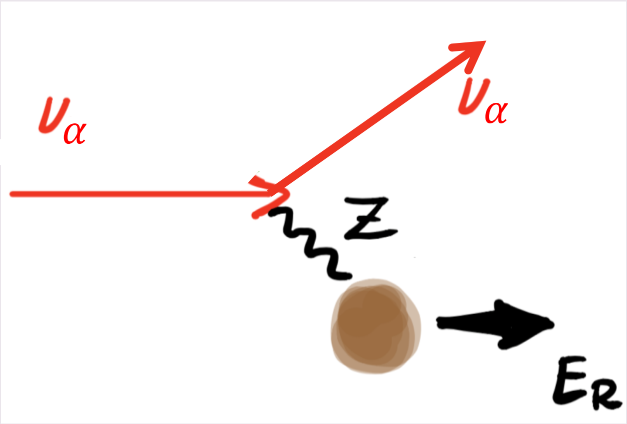
PARAMETER SPACE

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

m_4, $|U_{e4}|$, $|U_{\mu 4}|$, $|U_{\tau 4}|$

Coherent Elastic Neutrino – Nucleus Scattering

...or **CEνNS** for friends



Predicted by the SM...

[Freedman (1974)]

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

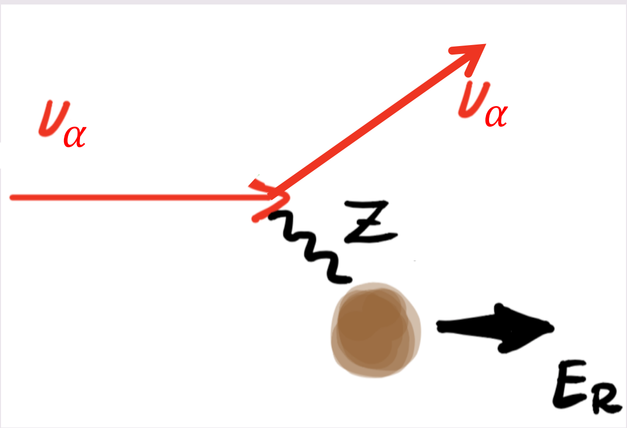
$$Q_v = N - (1 - 4\sin^2\theta_W) Z$$

...and **experimentally detected** by COHERENT collaboration!

[Akimov et al. 1708.01294 (2017)]

Coherent Elastic Neutrino – Nucleus Scattering

...or **CEνNS** for friends



Predicted by the SM...

[Freedman (1974)]

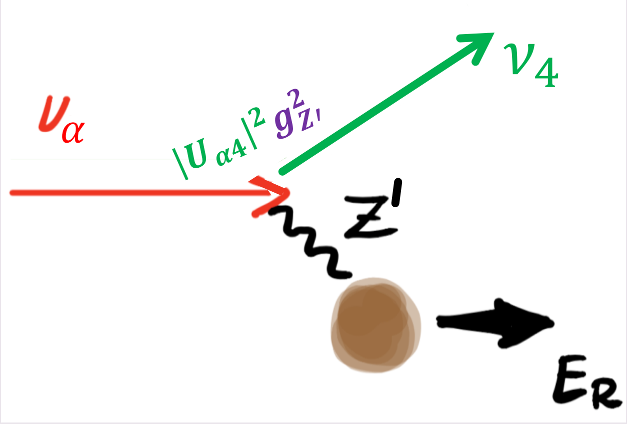
$$\frac{d\sigma_{\nu N}}{dE_R} = \frac{G_F^2}{4\pi} Q_v^2 m_N \left(1 - \frac{m_N E_R}{2E_\nu^2}\right) F^2(E_R)$$

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

...and **experimentally detected** by COHERENT collaboration!

[Akimov et al. 1708.01294 (2017)]

+

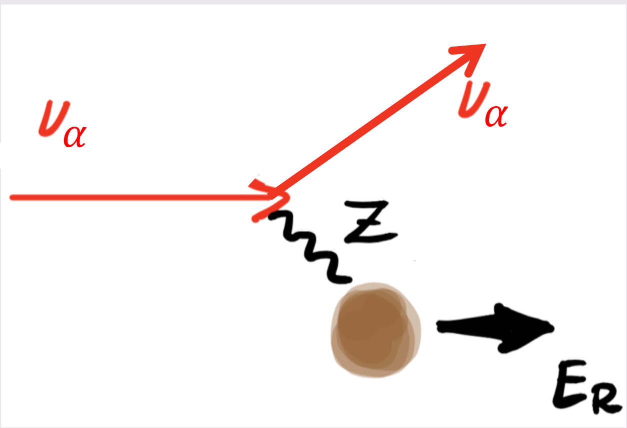


SBN predicts **upscattering** process:

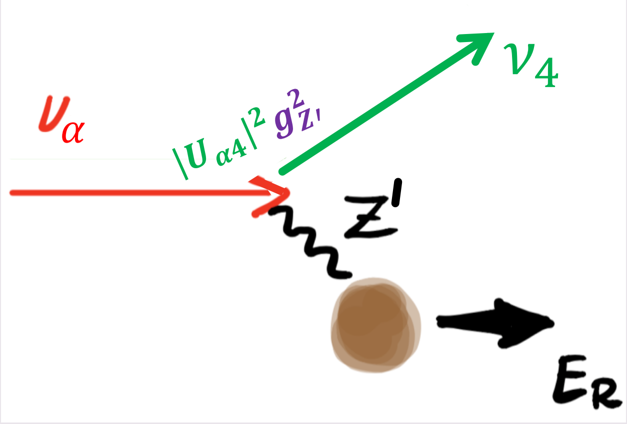
$$\frac{\mathrm{d}\sigma_{\alpha 4}}{\mathrm{d}E_R} = \frac{g_{Z'}^4 A^2 |U_{\alpha 4}|^2 m_A}{2\pi E_\nu^2 (2m_A E_R + m_{Z'}^2)^2} \left[4E_\nu^2 - 2E_R(m_A - E_R + 2E_\nu) - \frac{m_4^2}{m_A}(m_A - E_R - E_\nu)\right] F^2(E_R).$$

Coherent Elastic Neutrino – Nucleus Scattering

...or **CEνNS** for friends



+



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 **experimentally detected** by COHERENT collaboration!

[Akimov et al. 1708.01294 (2017)]

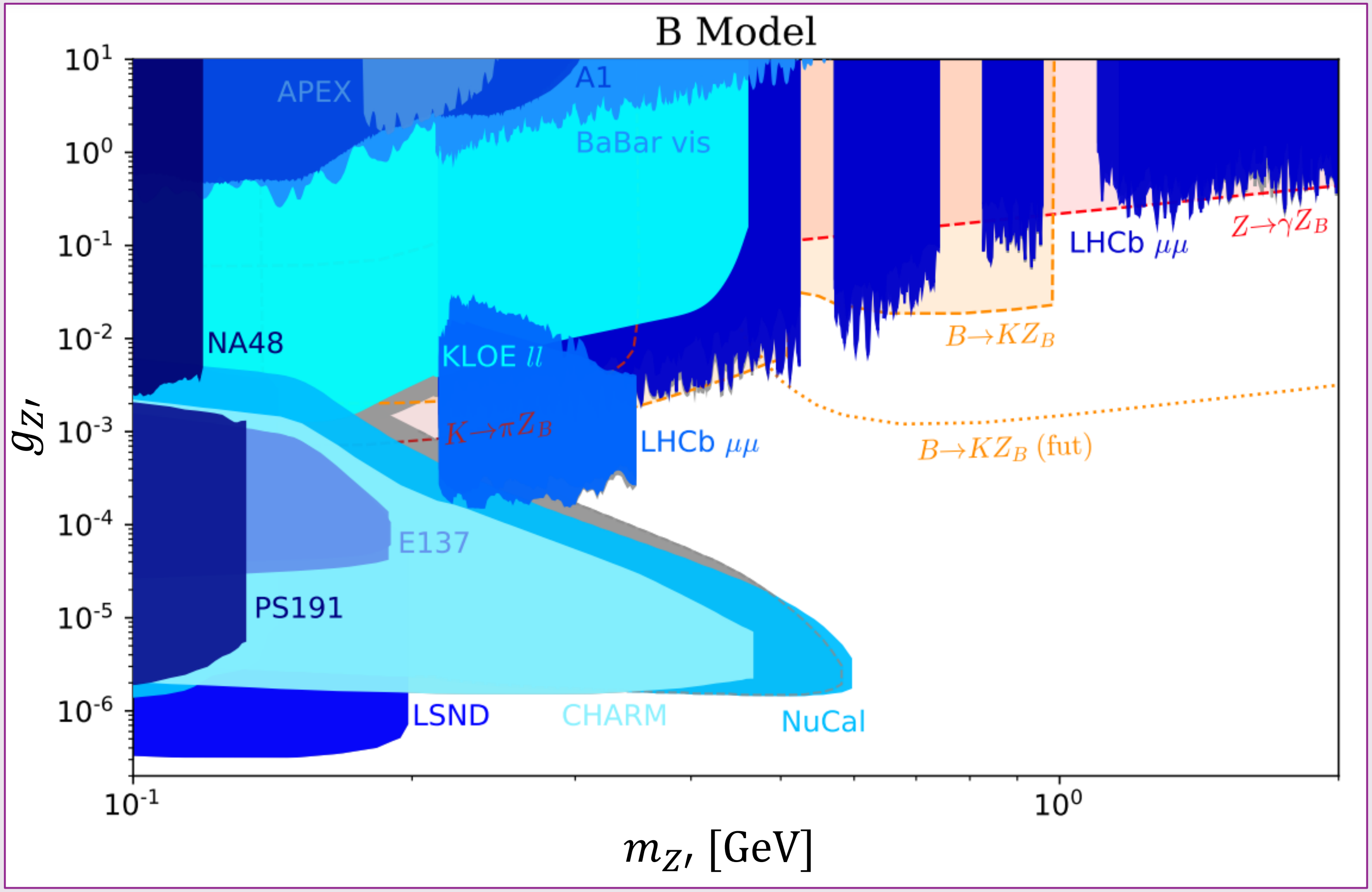
SBN predicts **upscattering** process:

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

that may **modify** the expected **recoil spectrum!**

Let's fix **our scenario…**

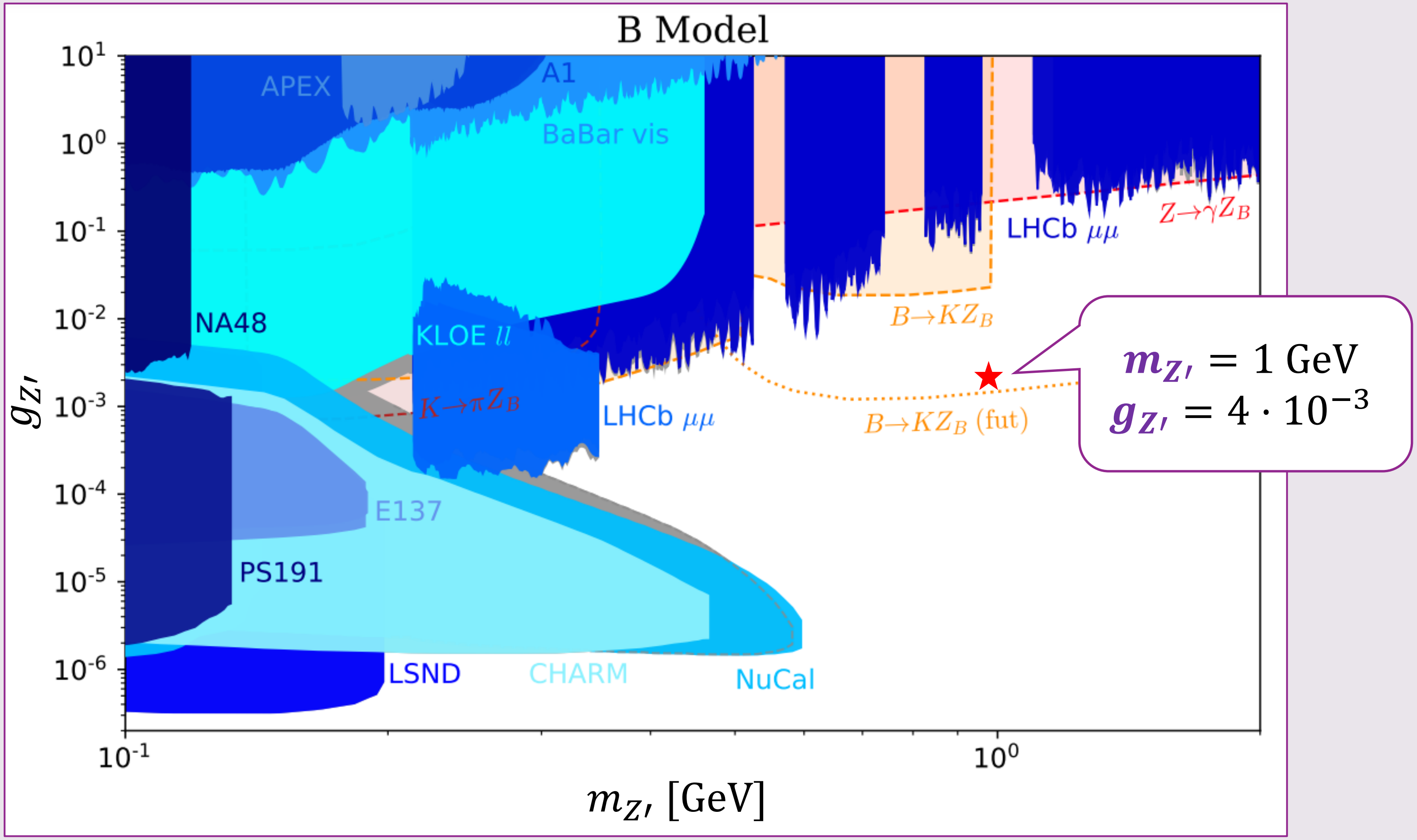
$$L_{SBN} \supset \frac{1}{3} g_{Z'} \sum_q \bar{q}\,\gamma_\mu Z'^{\mu} q + g_{Z'} \overline{\nu_b} \gamma_\mu Z'^{\mu} \nu_b$$



[Foguel et al. 2201.01788 (2022)]

Let's fix **our scenario...**

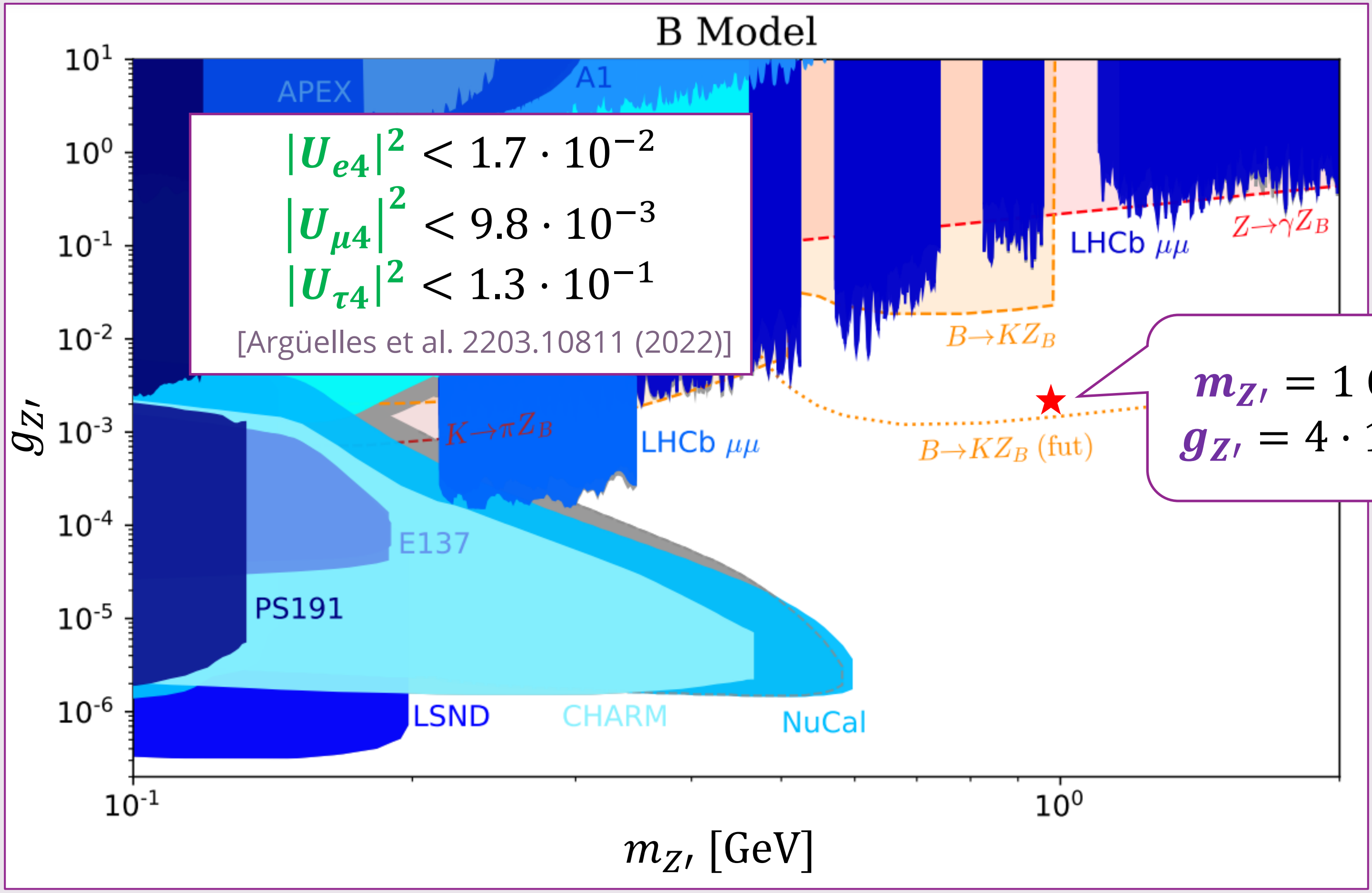
$$L_{SBN} \supset \frac{1}{3} g_{Z'} \sum_q \bar{q}\, \gamma_\mu Z'^{\mu} q + g_{Z'} \overline{\nu_b} \gamma_\mu Z'^{\mu} \nu_b$$



[Foguel et al. 2201.01788 (2022)]

Let's fix **our scenario...**

$$L_{SBN} \supset \frac{1}{3} g_{Z'} \sum_q \bar{q}\,\gamma_\mu Z'^\mu q + g_{Z'} \overline{\nu_b} \gamma_\mu Z'^\mu \nu_b$$



$|U_{e4}|^2 < 1.7 \cdot 10^{-2}$
$|U_{\mu4}|^2 < 9.8 \cdot 10^{-3}$
$|U_{\tau4}|^2 < 1.3 \cdot 10^{-1}$
[Argüelles et al. 2203.10811 (2022)]

$m_{Z'} = 1$ GeV
$g_{Z'} = 4 \cdot 10^{-3}$

[Foguel et al. 2201.01788 (2022)]

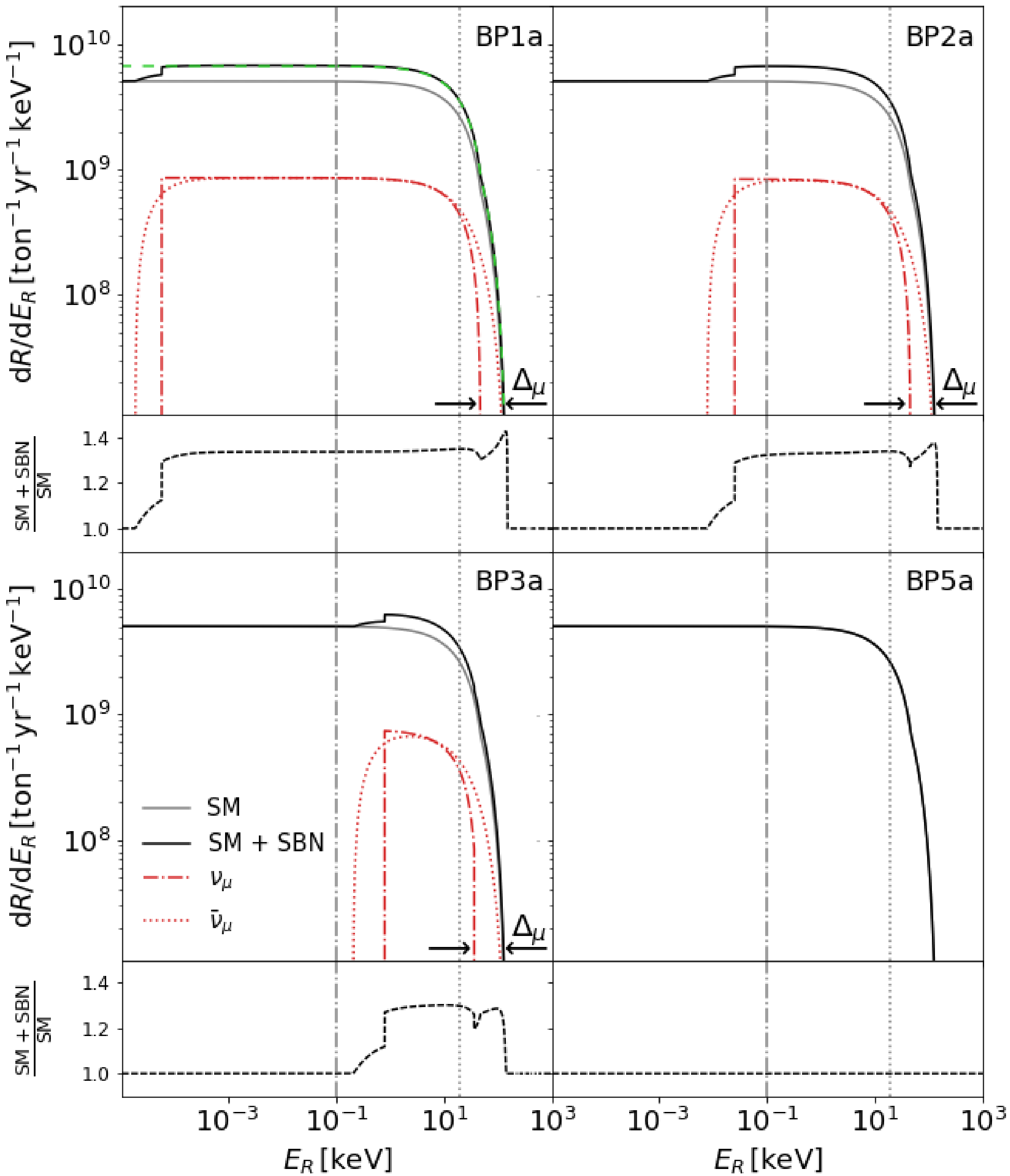
Let's fix some **benchmark points...**

	m_4 [GeV]	$\|U_{e4}\|^2$	$\|U_{\mu 4}\|^2$	$\|U_{\tau 4}\|^2$
BP1a	2×10^{-3}	0	9×10^{-3}	0
BP1d	2×10^{-3}	0	9×10^{-3}	9×10^{-3}
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
BP5a	60×10^{-3}	0	9×10^{-3}	0

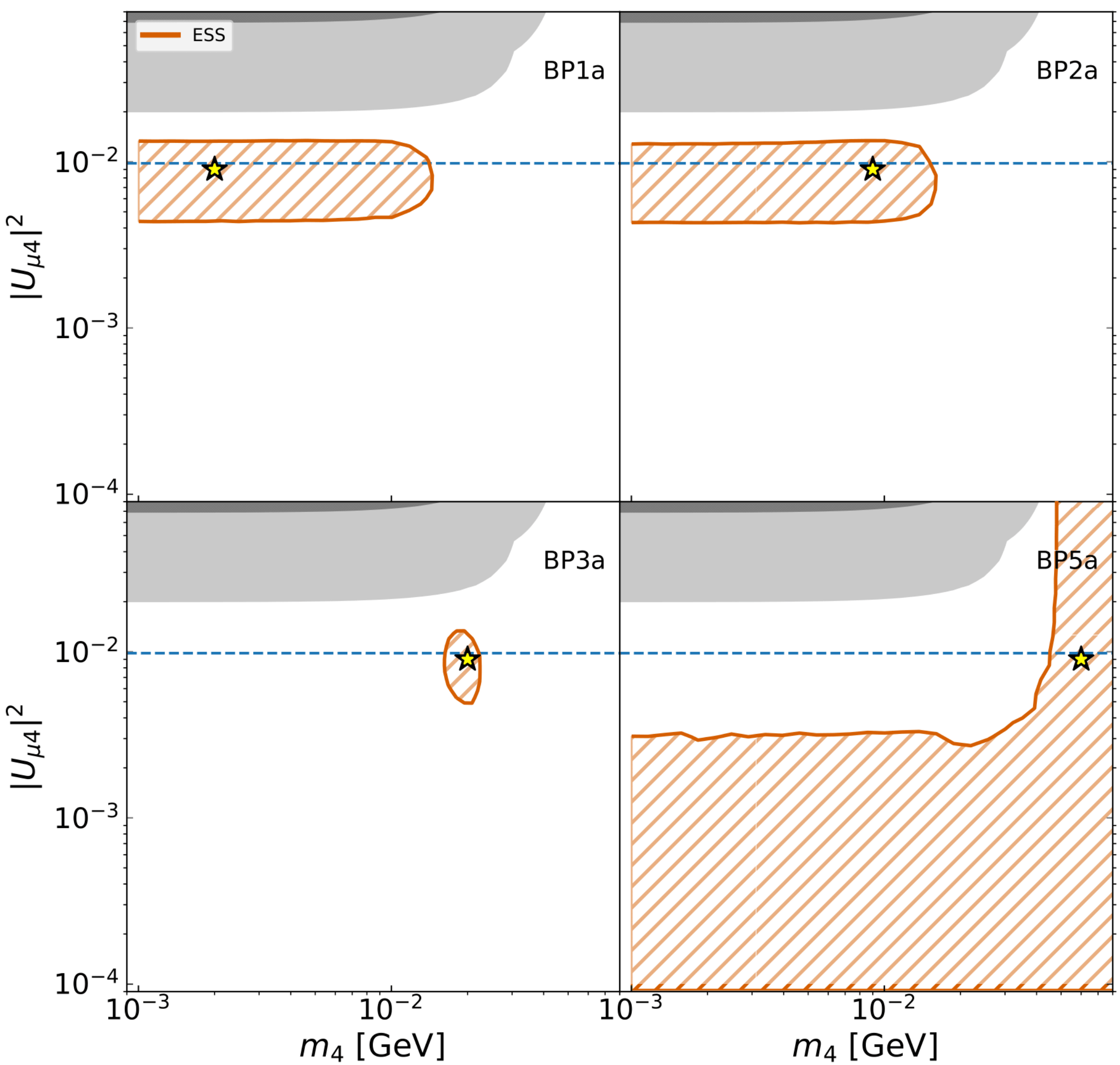
Let’s fix some **benchmark points...**

	m_4 [GeV]	$\|U_{e4}\|^2$	$\|U_{\mu 4}\|^2$	$\|U_{\tau 4}\|^2$
BP1a	2×10^{-3}	0	9×10^{-3}	0
BP1d	2×10^{-3}	0	9×10^{-3}	9×10^{-3}
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
BP5a	60×10^{-3}	0	9×10^{-3}	0

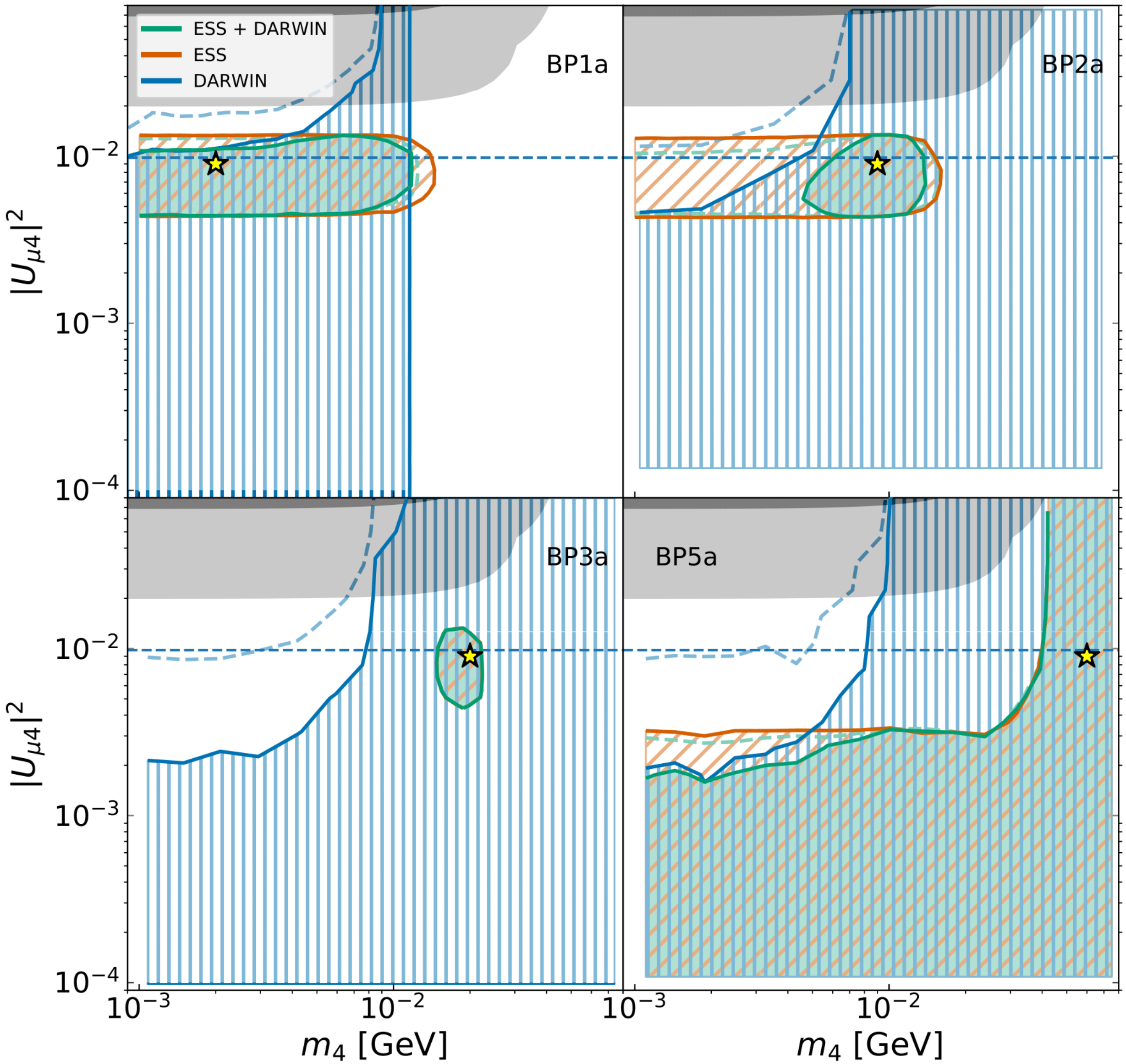
Predicted SS energy spectra

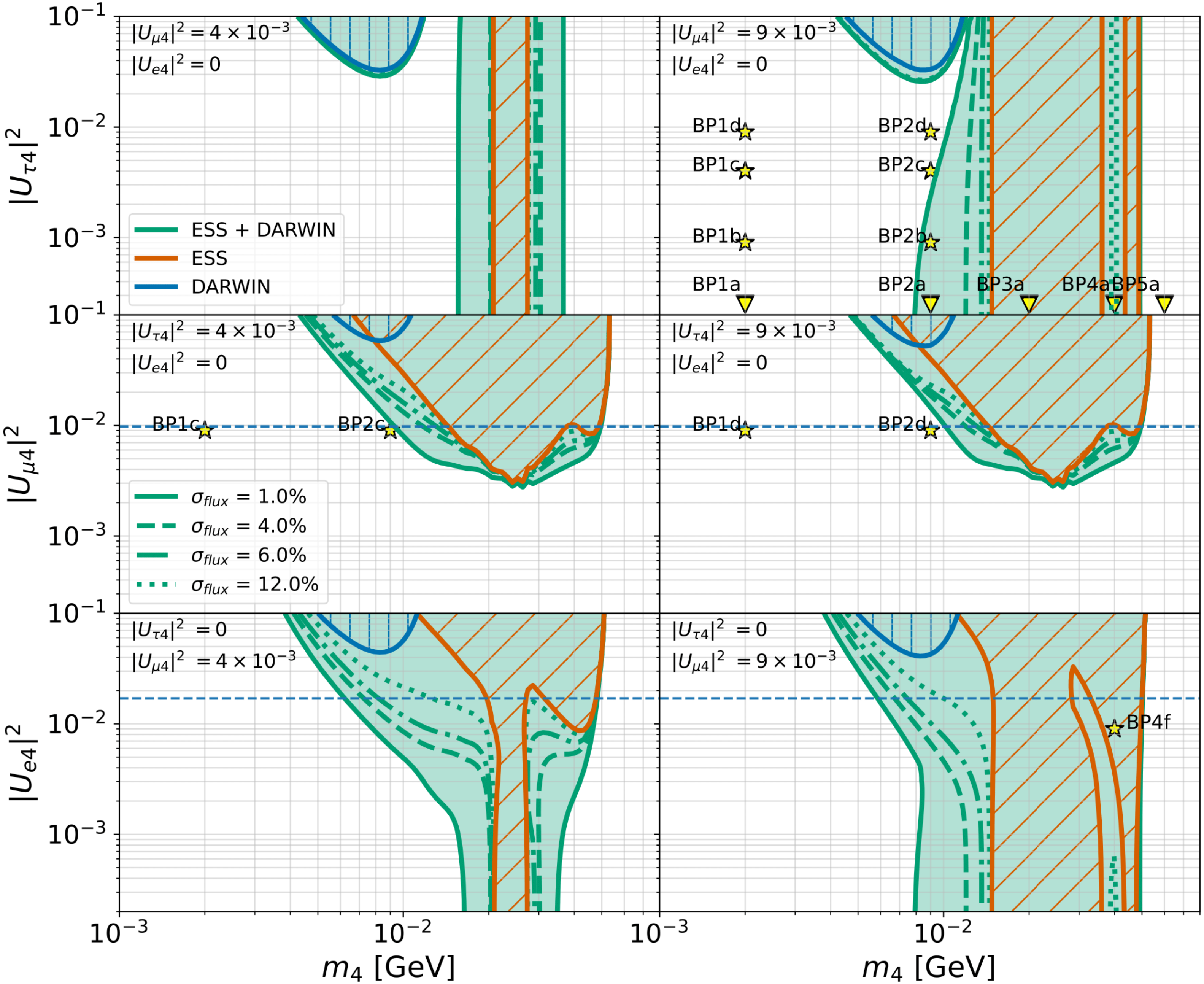


SS Profile likelihood results



SS+DD Profile likelihood results





$|U_{\mu4}|^2 = 4\times10^{-3}$
$|U_{e4}|^2 = 0$
$|U_{\mu4}|^2 = 9\times10^{-3}$
$|U_{e4}|^2 = 0$
ESS + DARWIN
ESS
DARWIN
BP1d
BP1c
BP1b
BP1a
BP2d
BP2c
BP2b
BP2a
BP3a
BP4a
BP5a
$|U_{\tau4}|^2 = 4\times10^{-3}$
$|U_{e4}|^2 = 0$
$|U_{\tau4}|^2 = 9\times10^{-3}$
$|U_{e4}|^2 = 0$
σ_{flux} = 1.0%
σ_{flux} = 4.0%
σ_{flux} = 6.0%
σ_{flux} = 12.0%
$|U_{\tau4}|^2 = 0$
$|U_{\mu4}|^2 = 4\times10^{-3}$
$|U_{\tau4}|^2 = 0$
$|U_{\mu4}|^2 = 9\times10^{-3}$
BP4f
$|U_{\tau4}|^2$
$|U_{\mu4}|^2$
$|U_{e4}|^2$
m_4 [GeV]
10^{-1}
10^{-2}
10^{-3}

Conclusions

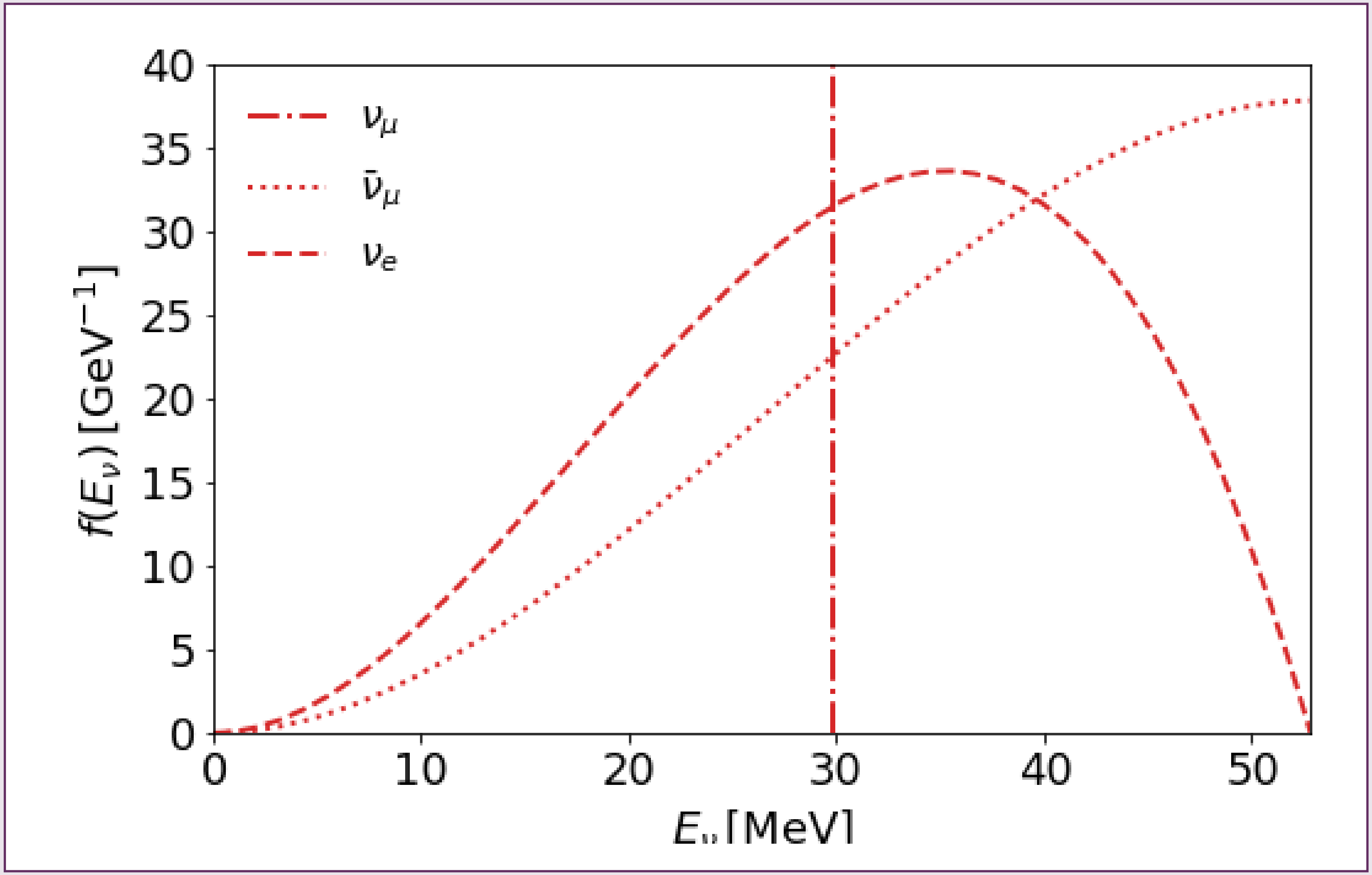
- Sterile neutrino models can be **probed** with Spallation Source (**SS**) and Direct Detection (**DD**) experiments.
- **DD** will be able to access to very **low recoil energies, all the neutrino flavours** but not big masses.
- **SS** will be able to access to **heavier sterile neutrinos** but not to all neutrino flavours.
- **Combining** DD and SS may help…
  - **improving the significance,**
  - constraining the parameter space and allowing **parameter reconstruction (specially in the neutrino mass m_4** and in τ mixing),
  - and allowing model discrimination (Sterile Baryonic Neutrino vs NSI).
- DD must reach smaller thresholds and the **uncertainty in solar neutrino fluxes need to be reduced** in order to be competitive.

Thanks for your attention!

Backup Slides

Direct Detection and
Spallation Experiments to test the
Baryonic Sterile Neutrino

SS experiment **fluxes**

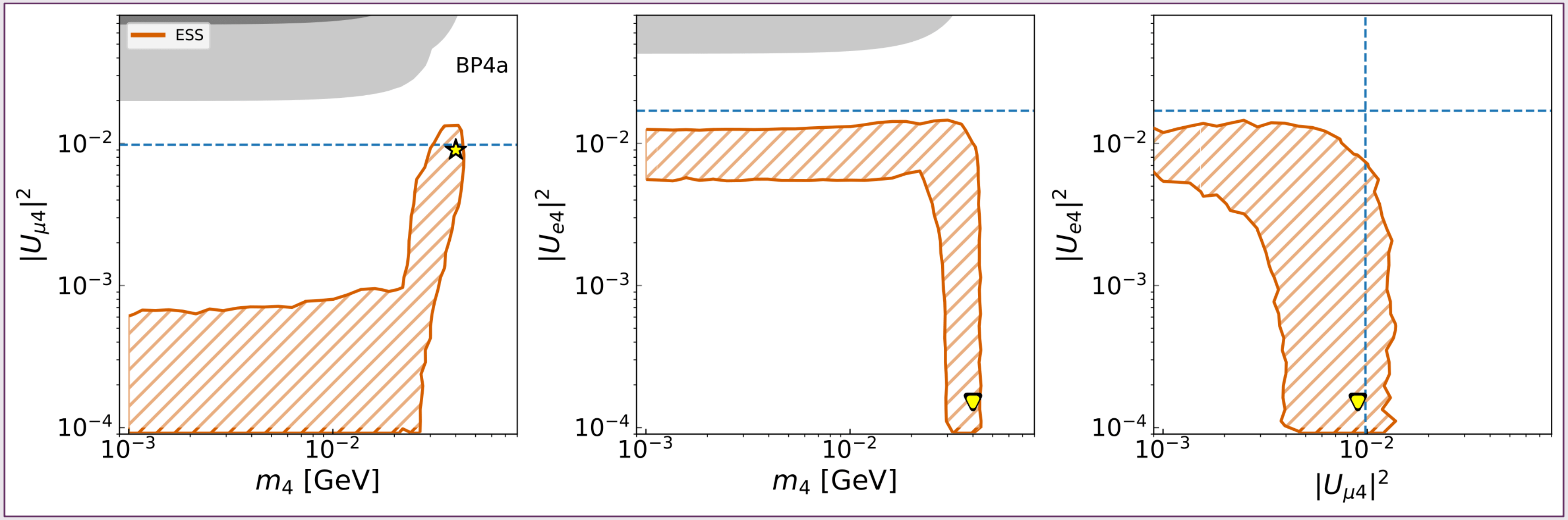


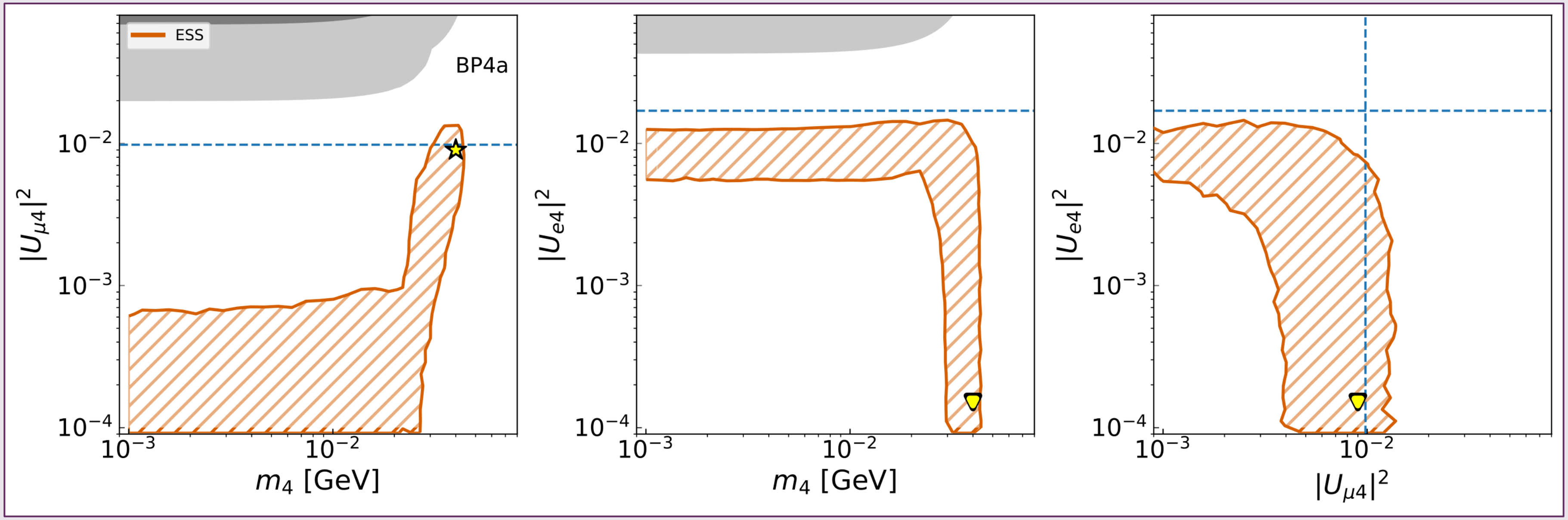
DD + SS: why it’s a good idea

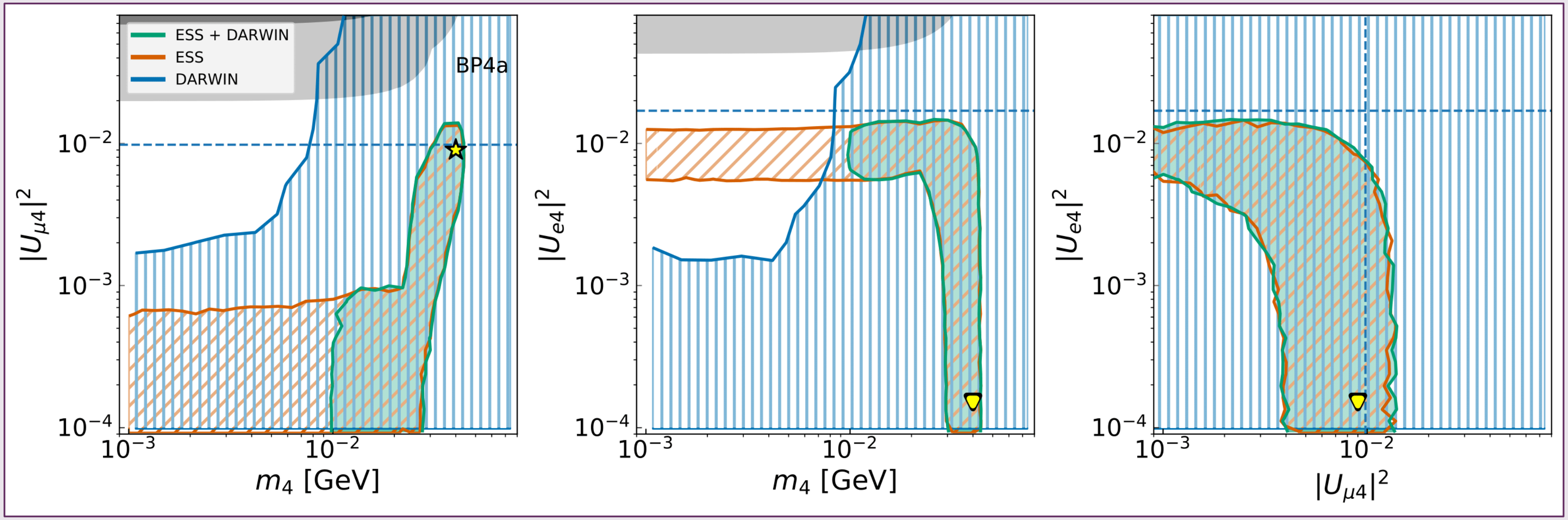
1. Increase the **statistical significance** of a prospective discovery.
2. Improve the **parameter reconstruction** of the model.
3. Allow to **discriminate** between our model and other **models** that can give similar experimental evidence.

Let's fix some **benchmark points...**

	m_4 [GeV]	$\|U_{e4}\|^2$	$\|U_{\mu 4}\|^2$	$\|U_{\tau 4}\|^2$
BP1a	2×10^{-3}	0	9×10^{-3}	0
BP1d	2×10^{-3}	0	9×10^{-3}	9×10^{-3}
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
BP5a	60×10^{-3}	0	9×10^{-3}	0


ESS
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}

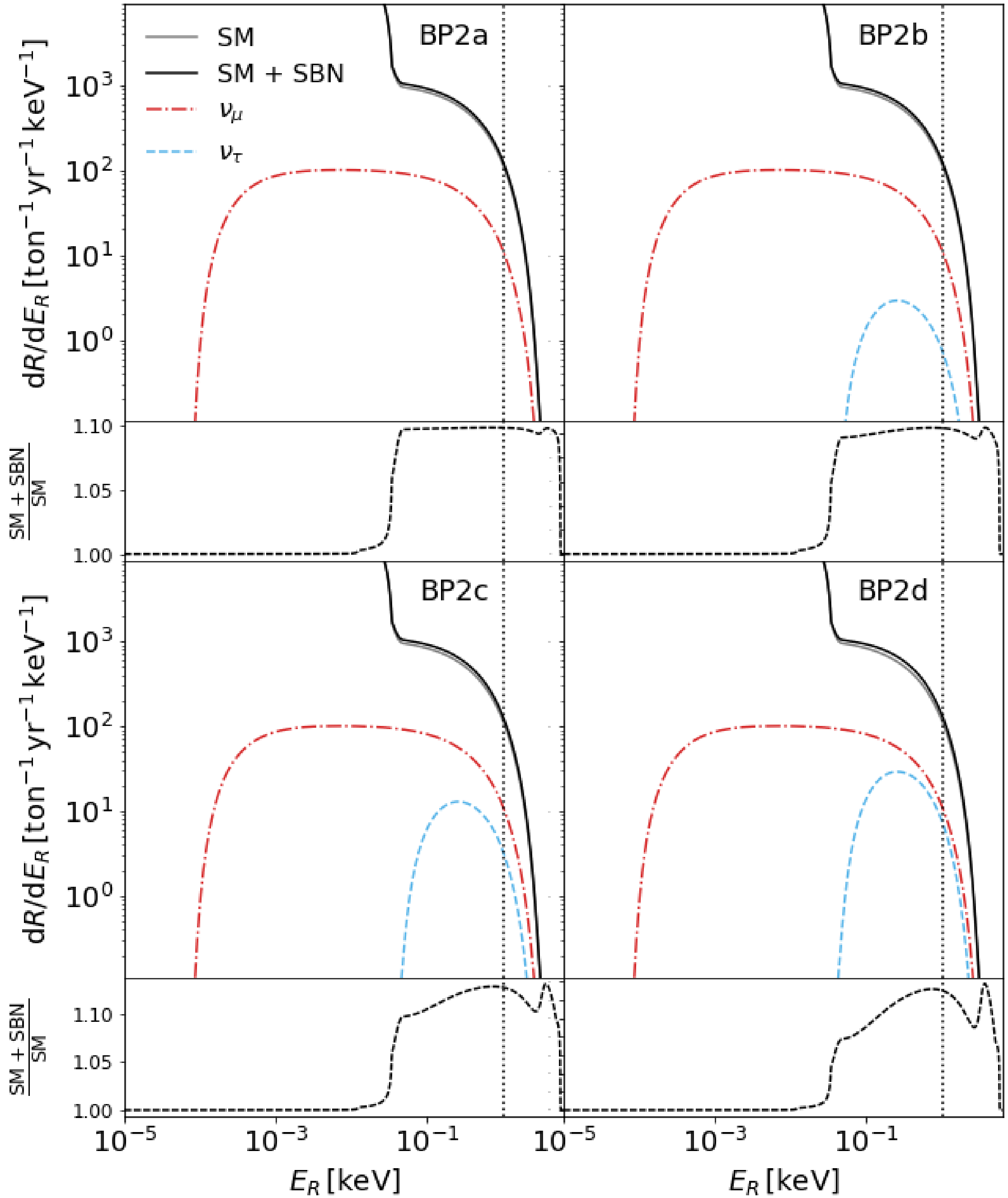

ESS
BP4a
$|U_{\mu4}|^2$
m_4 [GeV]
$|U_{e4}|^2$
m_4 [GeV]
$|U_{e4}|^2$
$|U_{\mu4}|^2$


ESS + DARWIN
ESS
DARWIN
BP4a
$|U_{\mu4}|^2$
m_4 [GeV]
$|U_{e4}|^2$
m_4 [GeV]
$|U_{e4}|^2$
$|U_{\mu4}|^2$

Let's fix some **benchmark points...**

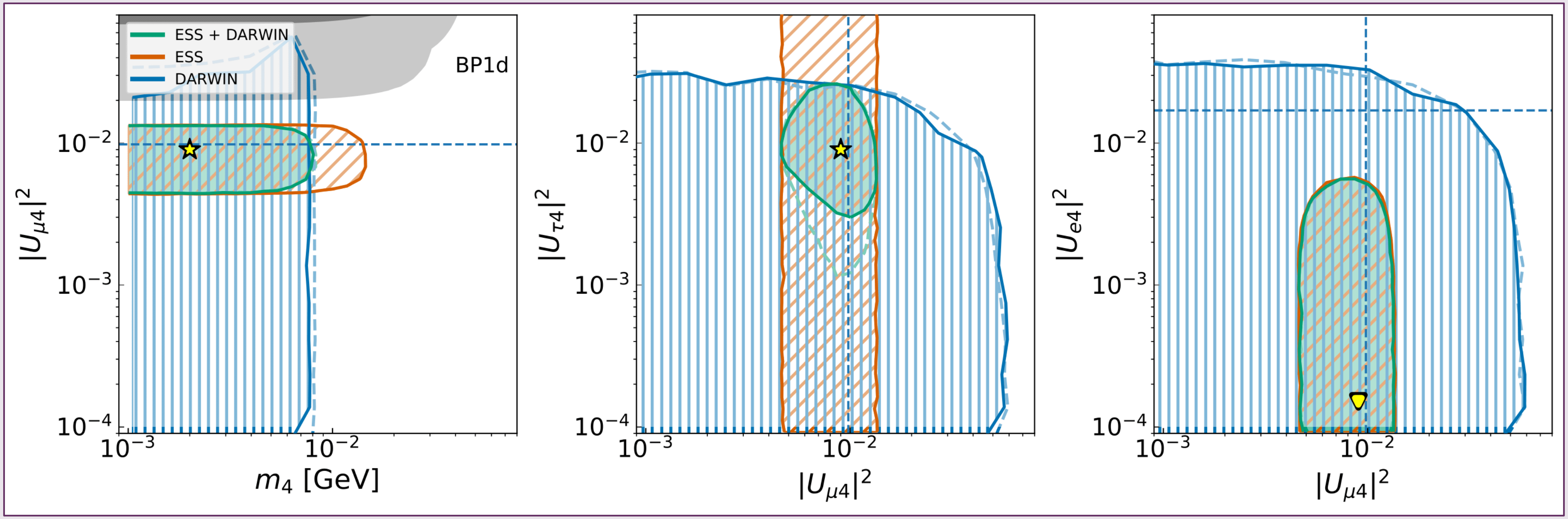
	m_4 [GeV]	$\|U_{e4}\|^2$	$\|U_{\mu 4}\|^2$	$\|U_{\tau 4}\|^2$
BP1a	2×10^{-3}	0	9×10^{-3}	0
BP1d	2×10^{-3}	0	9×10^{-3}	9×10^{-3}
BP2a	9×10^{-3}	0	9×10^{-3}	0
BP2b	9×10^{-3}	0	9×10^{-3}	9×10^{-4}
BP2c	9×10^{-3}	0	9×10^{-3}	4×10^{-3}
BP2d	9×10^{-3}	0	9×10^{-3}	9×10^{-3}
BP3a	20×10^{-3}	0	9×10^{-3}	0
BP4a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

Predicted DD energy spectra



Let's fix some **benchmark points…**

	m_4 [GeV]	$\lvert U_{e4}\rvert^2$	$\lvert U_{\mu 4}\rvert^2$	$\lvert U_{\tau 4}\rvert^2$
BP1a	2×10^{-3}	0	9×10^{-3}	0
BP1d	2×10^{-3}	0	9×10^{-3}	9×10^{-3}
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
BP5a	60×10^{-3}	0	9×10^{-3}	0



ESS + DARWIN
ESS
DARWIN
BP1d
$|U_{\mu 4}|^2$
m_4 [GeV]
$|U_{\tau 4}|^2$
$|U_{\mu 4}|^2$
$|U_{e4}|^2$
$|U_{\mu 4}|^2$
10^{-2}
10^{-3}
10^{-4}