Sub-GeV Dark Matter Searches at Spallation Neutron Sources

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Based on: Aristizabal, De Romeri, DKP, Sanchez: arXiv: 2603.02132, JHEP accepted

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neutrinoSPHERE

Funded by the European Union

- **Motivation**
  - Traditional direct-detection experiments lose sensitivity for DM $\lesssim$ few GeV because nuclear recoil energies become extremely small.
  - Need alternative DM sources, how about producing DM in the lab?

- **Production chain & Requirements**
  - High intensity proton beam hits a target
  - Neutral pions, π^0, are produced
  - DM is produced from π^0 decays via a vector mediator (dark photon portal)
  - Clean signals and low thresholds
  - Background rejection

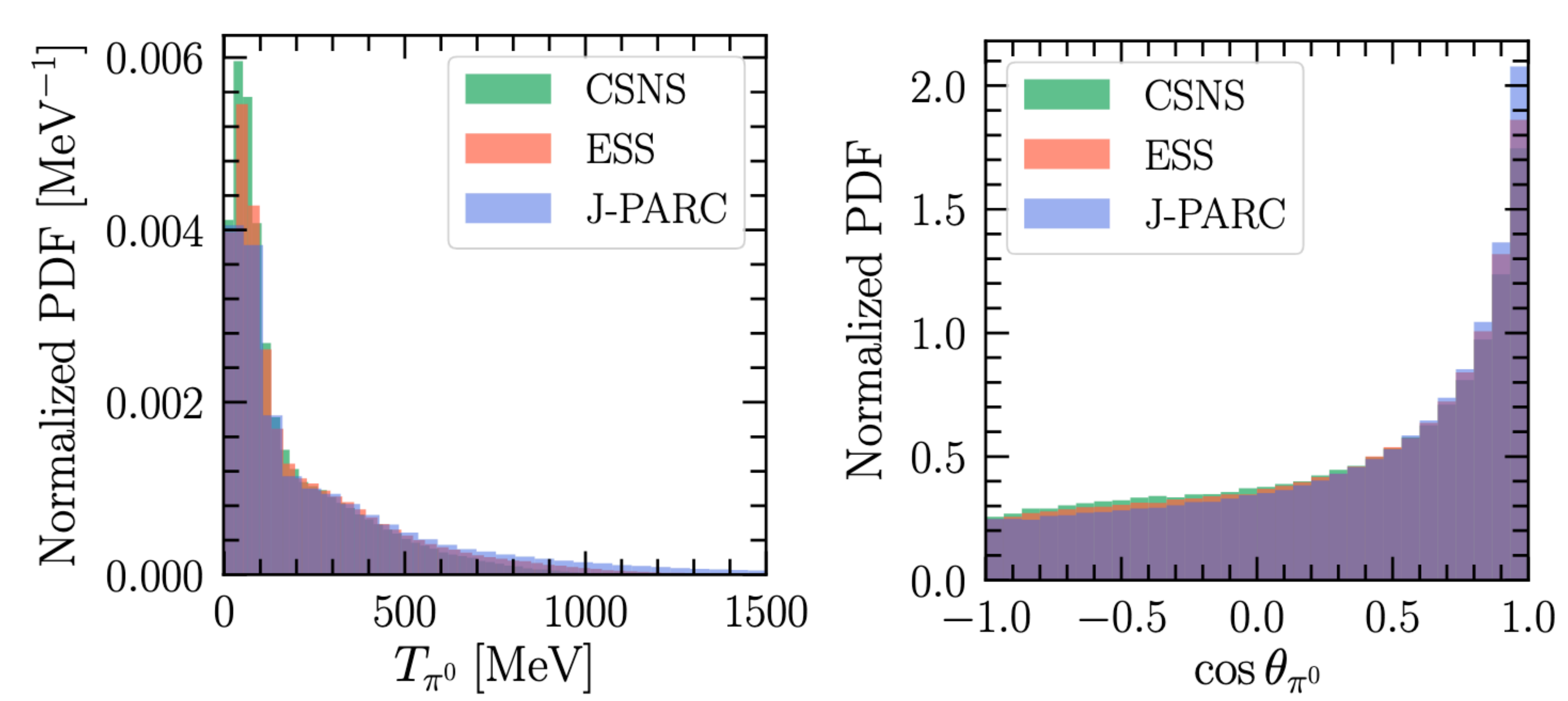
- **Available Facilities**
  - European Spallation Source (ESS) Baxter et al., JHEP 02 (2020)
  - Japan Proton Accelerator Research Complex (JPARC) Collar et al., JHEP 05 (2025)
  - China Spallation Neutron Source (CSNS) Wei et al., Chinese Physics C 33 (2009). Wei et al., Nuclear Engineering and Technology 54 (2022)
  - Spallation Neutron Source, Oak Ridge (COHERENT collaboration) COHERENT Collab, PRL 130 (2023) COHERENT Collab, PRD 106 (2022), 052004
  - LANSCE Lujan Center (Coherent CAPTAIN-Mills) CCM Collab, PRL 129 (2022) CCM Collab, PRD 106 (2022), 012001

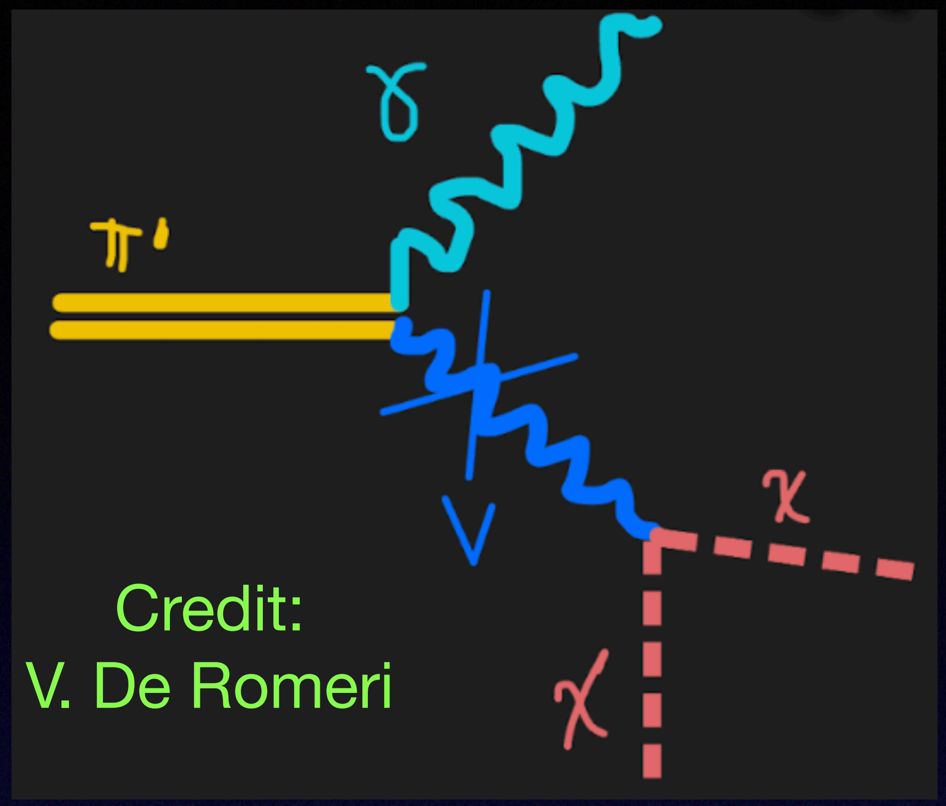
Artificially produced sub-GeV dark matter @ Spallation Sources

Schematic illustration of the sub-GeV DM production (through a vector portal) pipeline.

Aristizabal, De Romeri, DKP, Sanchez: arXiv: 2603.02132, *JHEP accepted*

GEANT4 simulations for π^0 spectra simulation





The generated pions are
- Forward peaked
- Symmetric over azimuthal angle ϕ

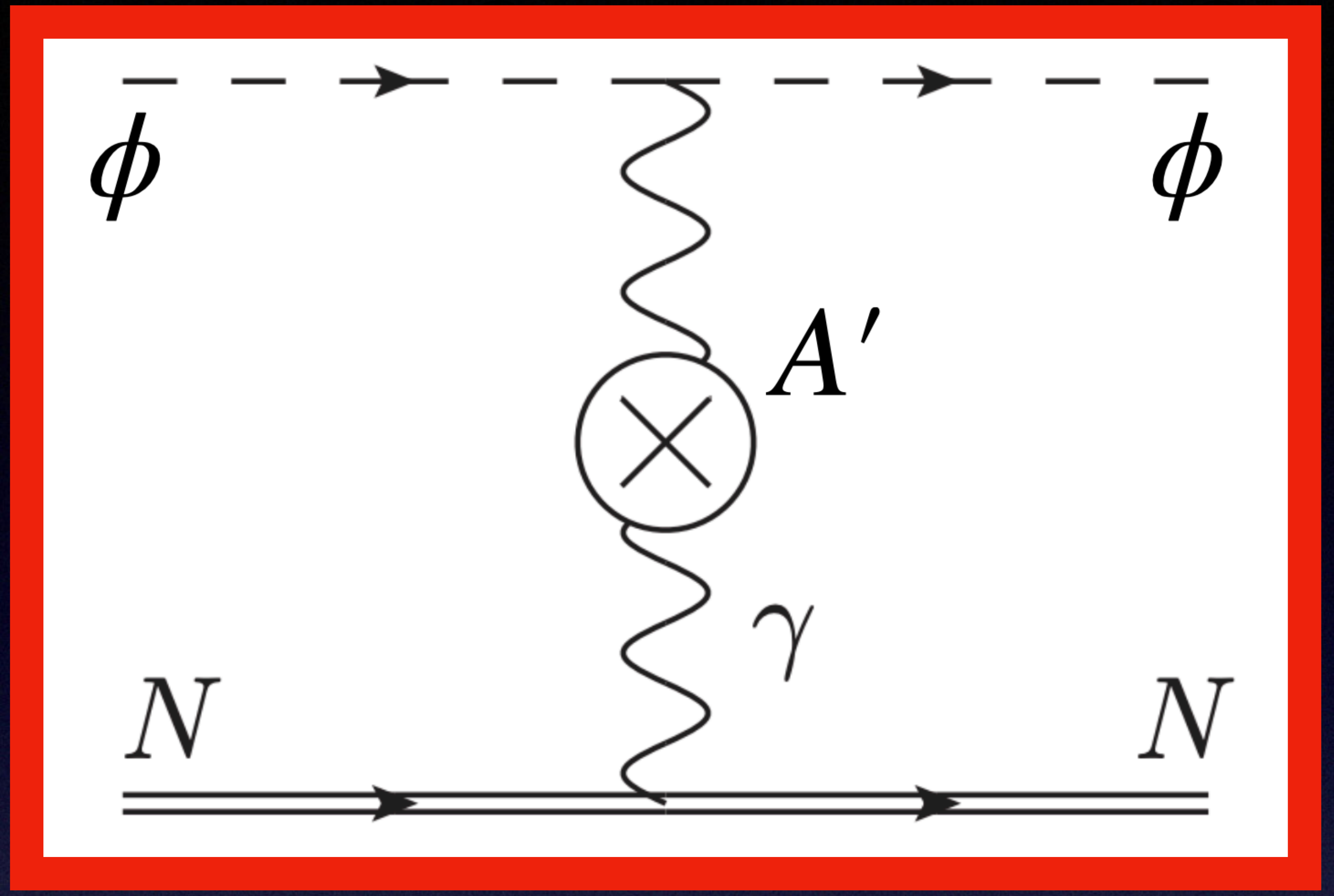
Setup of Spallation Sources

Facility	**Target**	T_p [GeV]	**P [MW]**	**B [m]**	**Detector**	a **[cm]**	**Pulse Timing**
ESS [38]	W	2	5	20	Xe (20 kg), Ge (7 kg) CsI (22.5 kg)	50, 11 17	14 Hz of 2.8-ms pulses
J-PARC [39]	Hg	3	$1 \to 1.3$	20	Xe (20 kg), Ge (7 kg) CsI (44 kg)	50, 11 21.4	25 Hz of 0.1-μs double pulses
CSNS [79]	W	1.6	$0.14 \to 0.5$	10.5	CsI (300 kg)	40.5	25 Hz of 0.5-μs pulses

Aristizabal, De Romeri, DKP, Sanchez: arXiv: 2603.02132, *JHEP accepted*

DM scenarios

de Niverville, M. Pospelov, A. Ritz, PRD 84 (2011)



Generic dark photon scenario

$$\mathcal{L}^{\epsilon}_{A'} \supset -\frac{1}{4}F'_{\mu\nu}F'^{\mu\nu} - \frac{\epsilon}{2}F'_{\mu\nu}F^{\mu\nu} + |D_\mu\phi|^2 - m_\phi^2|\phi|^2 + \frac{1}{2}m_{A'}^2 A'_\mu A'^\mu$$

$$D_\mu = \partial_\mu - i g_D A'_\mu$$

DM-nucleus cross section

$$\frac{\mathrm{d}\sigma_{\phi\mathcal{N}}}{\mathrm{d}E_r} = \frac{g_D^2}{2\pi}\frac{m_{\mathcal{N}}E_\phi^2}{\left(E_\phi^2 - m_\phi^2\right)\left(2m_{\mathcal{N}}E_r + m_{A'}^2\right)^2}\left(1 - \frac{m_\phi^2 E_r}{2m_{\mathcal{N}}E_\phi^2} - \frac{E_r}{E_\phi}\right)\epsilon^2\, Z^2\, e^2 \mathcal{F}_Z^2(E_r)$$

See also:
Dutta et al., PRL 124 (2020)
Dutta et al., JHEP 01 (2022)

Baryophilic scenario

$$\mathcal{L}^{B}_{A'} \supset \frac{g_B}{3}\sum_q \bar{q}\gamma_\mu q\; A'^\mu + g_B Q_B j^B_\mu\; A'^\mu$$

DM-nucleus cross section

$$\left.\frac{\mathrm{d}\sigma_{\phi\mathcal{N}}}{\mathrm{d}E_r}\right|^{\text{baryophilic}} = \frac{g_B^4 Q_B^2}{2\pi}\frac{m_{\mathcal{N}}E_\phi^2}{\left(E_\phi^2 - m_\phi^2\right)\left(2m_{\mathcal{N}}E_r + m_{A'}^2\right)^2}\left(1 - \frac{m_\phi^2 E_r}{2m_{\mathcal{N}}E_\phi^2} - \frac{E_r}{E_\phi}\right)A^2\, \mathcal{F}_A^2(E_r)$$

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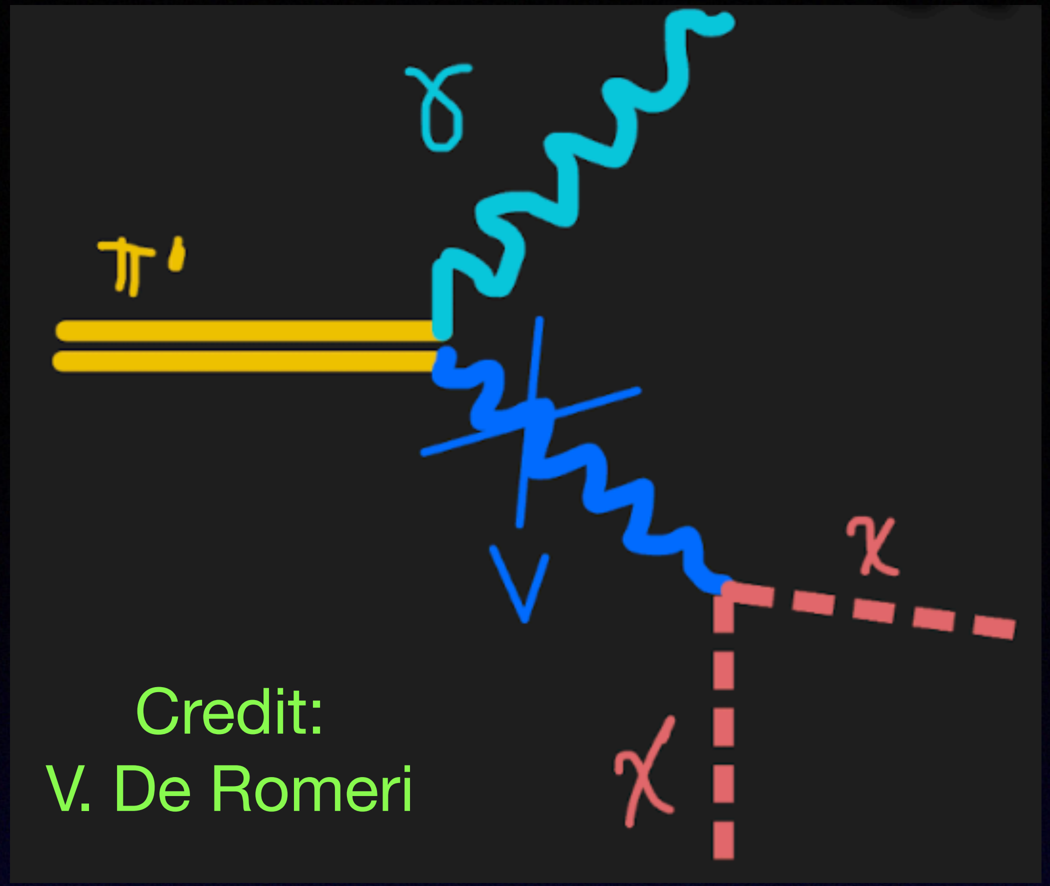
DM production (dark photon)



Branching ratio

Kinetic mixing

$$\mathcal{B}(\pi^0 \to \gamma + \phi + \phi^*) = \mathcal{B}(\pi^0 \to \gamma + \gamma) \times 2\varepsilon^2 \left(1 - \frac{m_{A'}^2}{m_{\pi^0}^2}\right)^3 \times \mathcal{B}(A' \to \phi + \phi^*)$$

≈ 0.99

We take it equal to 1
(Loop effects can lead to e^+e^-)

B. Batell, M. Pospelov, A. Ritz, PRD 80 (2009)
De Romeri, Kelly, Machado PRD 100 no 9, (2019)

- In the narrow-width approximation, the two-body decay $\pi^0 \to \gamma + A'$ is followed by the subsequent two-body decay $A' \to \phi + \phi$
- Loop-induced decays into e^+e^- are present, implying that a fraction of A' bosons will decay visibly.
- The fraction of generated DM particles (ϕ) is small even for a large mixing parameter (ε)
- High-intensity facilities such as spallation neutron sources are well suited for these searches, as their large statistics can compensate

DM fluxes (MC simulation)

DM flux @ production point

$$\left.\frac{\mathrm{d}N^\phi}{\mathrm{d}X}\right|^{\text{prod}} = N^{\text{POT}} \times c_{\pi^0} \times 2\,\mathcal{B}(\pi^0 \to \gamma + \phi + \phi^*) \times \left.\frac{\mathrm{d}N^\phi}{\mathrm{d}X}\right|^{\text{norm}=1}$$

Protons on target — π^0/POT — Two DM particles/π^0 — Branching ratio — DM PDF

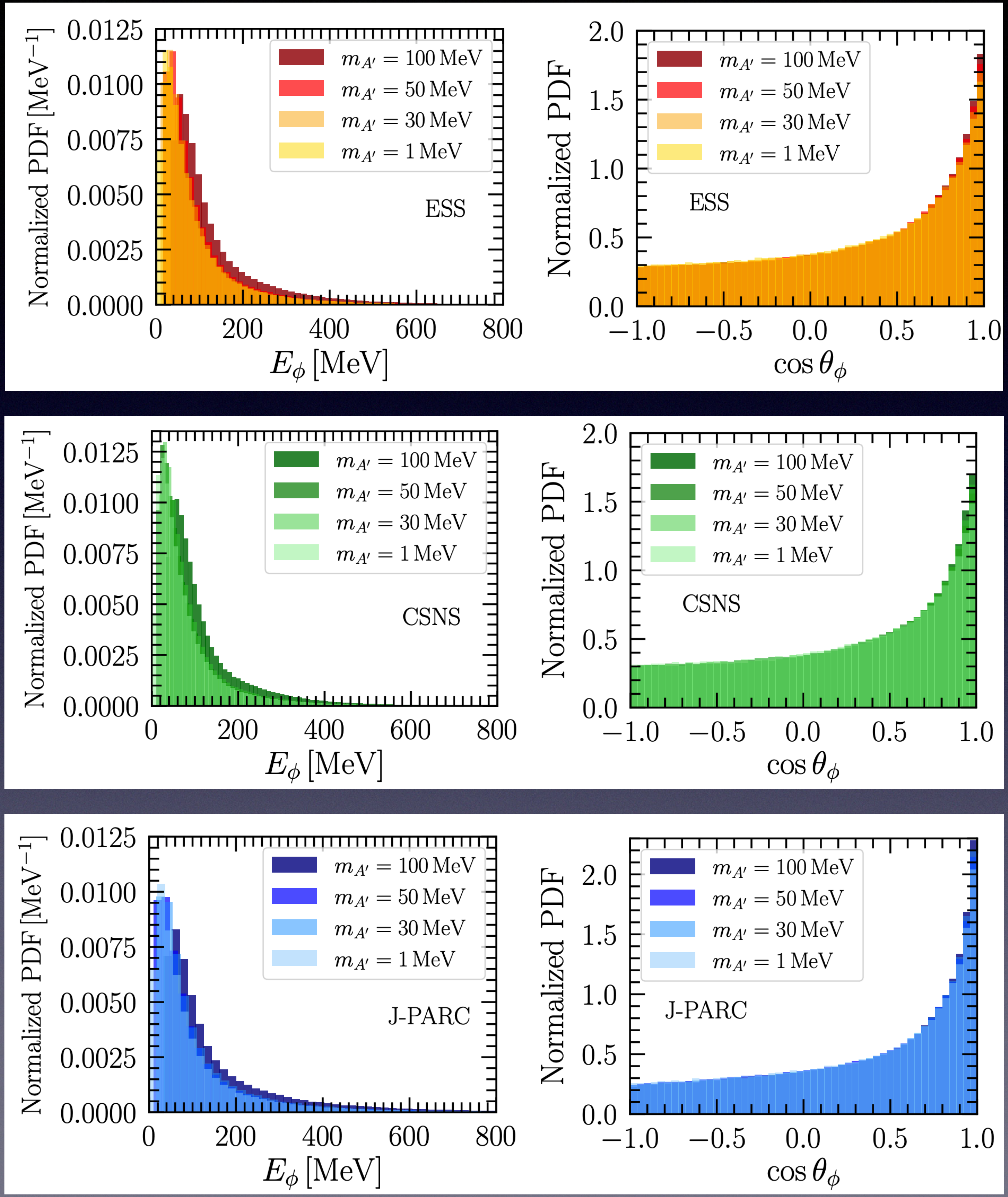
DM flux @ detector (detector geometry/baseline)

$$\left.\frac{\mathrm{d}N^\phi}{\mathrm{d}E_\phi}\right|^{\text{det}} = \left(\frac{N^\phi_{\text{cut}}}{N^\phi_{\text{prod}}}\right)\left(\frac{\Delta\varphi}{2\pi}\right)\left.\frac{\mathrm{d}N^\phi}{\mathrm{d}E_\phi}\right|^{\text{prod}} .$$

Protons On Target and π^0 yield

Facility	N^{POT}	c_{π^0}	c_{ν_μ}	$c_{\bar{\nu}_\mu}$	c_{ν_e}
ESS	2.8×10^{23}	0.31	0.15	0.15	0.15
J-PARC	3.5×10^{22}	0.54	0.24	0.24	0.24
CSNS	9.8×10^{21}	0.22	0.12	0.12	0.12

DM particle production has azimuthal symmetry but inherits the shape of the parent π^0 distribution



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DM fluxes (on/off axis)

DM flux @ production point

$$\left.\frac{\mathrm{d}N^\phi}{\mathrm{d}X}\right|^{\text{prod}} = N^{\text{POT}} \times c_{\pi^0} \times 2\,\mathcal{B}(\pi^0 \to \gamma + \phi + \phi^*) \times \left.\frac{\mathrm{d}N^\phi}{\mathrm{d}X}\right|^{\text{norm}=1}$$

DM flux @ detector (detector geometry/baseline)

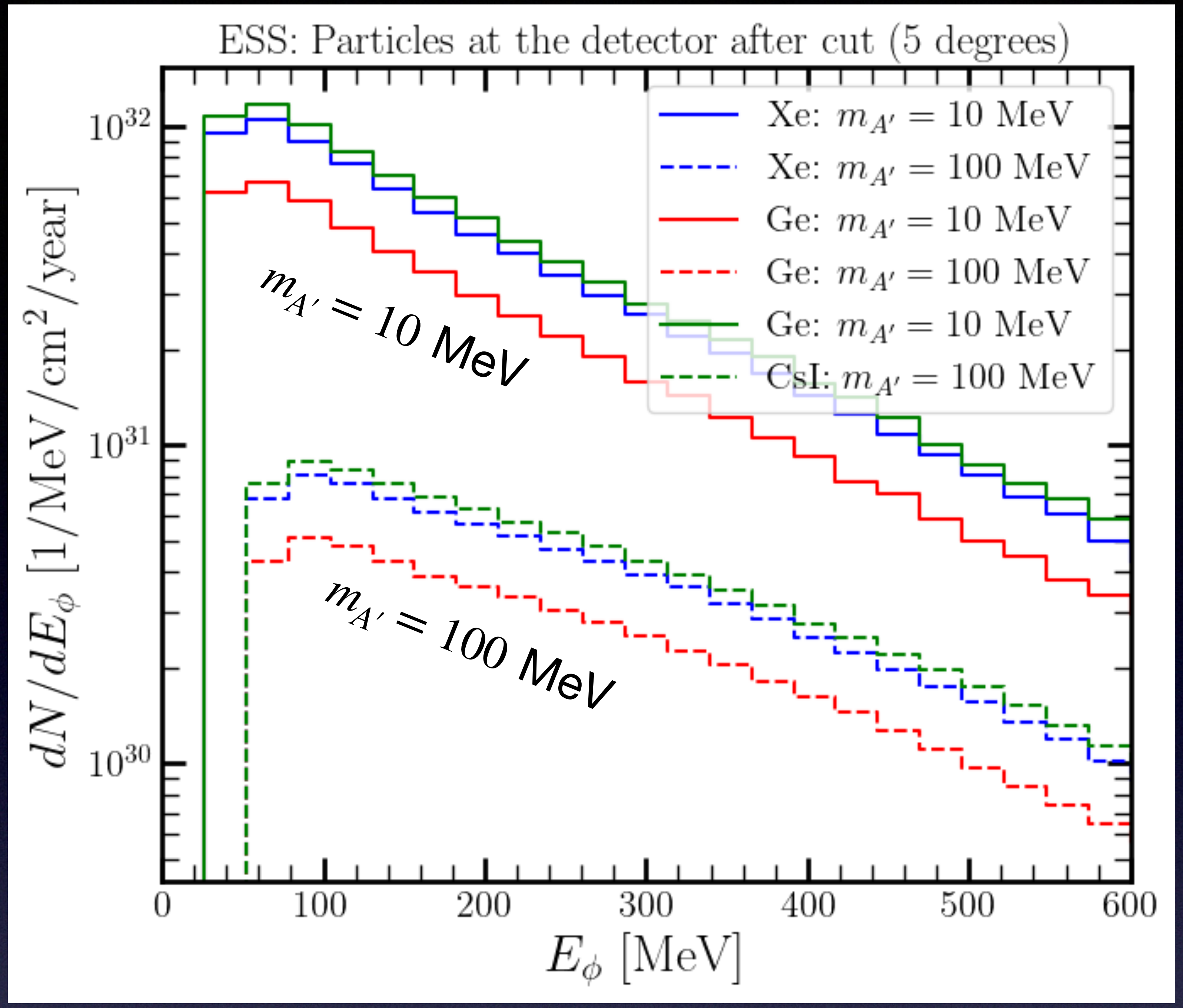
Polar angle cut

$$\left.\frac{\mathrm{d}N^\phi}{\mathrm{d}E_\phi}\right|^{\text{det}} = \left(\frac{N^\phi_{\text{cut}}}{N^\phi_{\text{prod}}}\right)\left(\frac{\Delta\varphi}{2\pi}\right)\left.\frac{\mathrm{d}N^\phi}{\mathrm{d}E_\phi}\right|^{\text{prod}} .$$

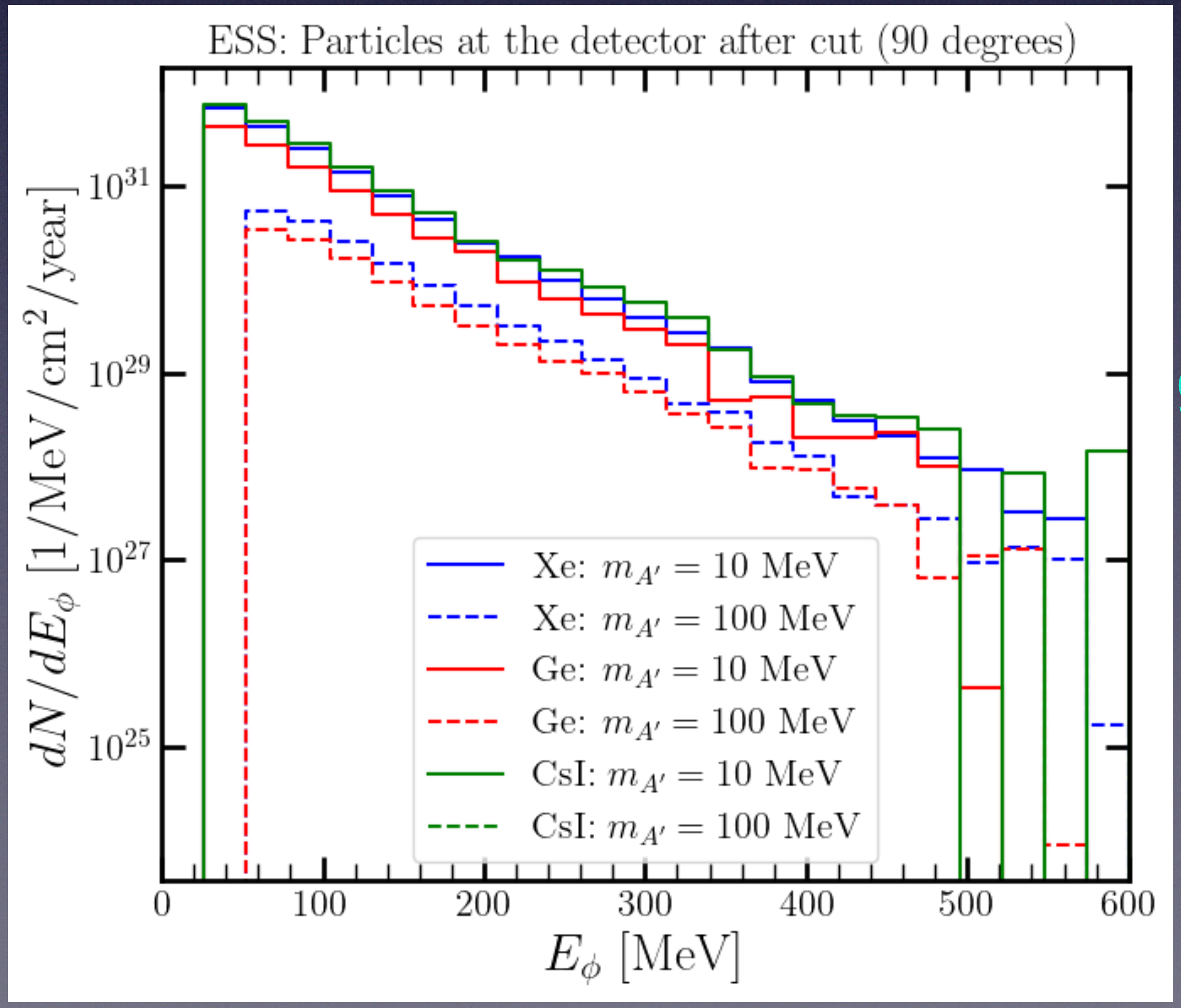
Azimuthal acceptance

Azimuthal acceptance

$$\Delta\varphi = \begin{cases} \dfrac{a}{L\sin\theta_{\text{det}}}\,, & \text{off-axis}\,, \\ 2\pi\,, & \text{on-axis}\,, \end{cases}$$



On-axis



90 degrees Off-axis

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DM-nucleus event rates

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$$\frac{\mathrm{d}N}{\mathrm{d}E_r} = t_{\rm run} n_A \langle \ell \rangle \int_{E_\phi^{\rm min}}^{E_\phi^{\rm max}} \mathrm{d}E_\phi \, \frac{\mathrm{d}N^\phi}{\mathrm{d}E_\phi}\bigg|^{\rm det} \frac{\mathrm{d}\sigma_{\phi\mathcal{N}}}{\mathrm{d}E_r}$$

Minimum DM energy to induce a nuclear recoil

$$E_\phi^{\rm min} = \frac{E_r}{2} + \frac{\sqrt{m_\mathcal{N}(E_r + 2m_\mathcal{N})\left(m_\mathcal{N}E_r + 2m_\phi^2\right)}}{2m_\mathcal{N}}$$

Detector effects

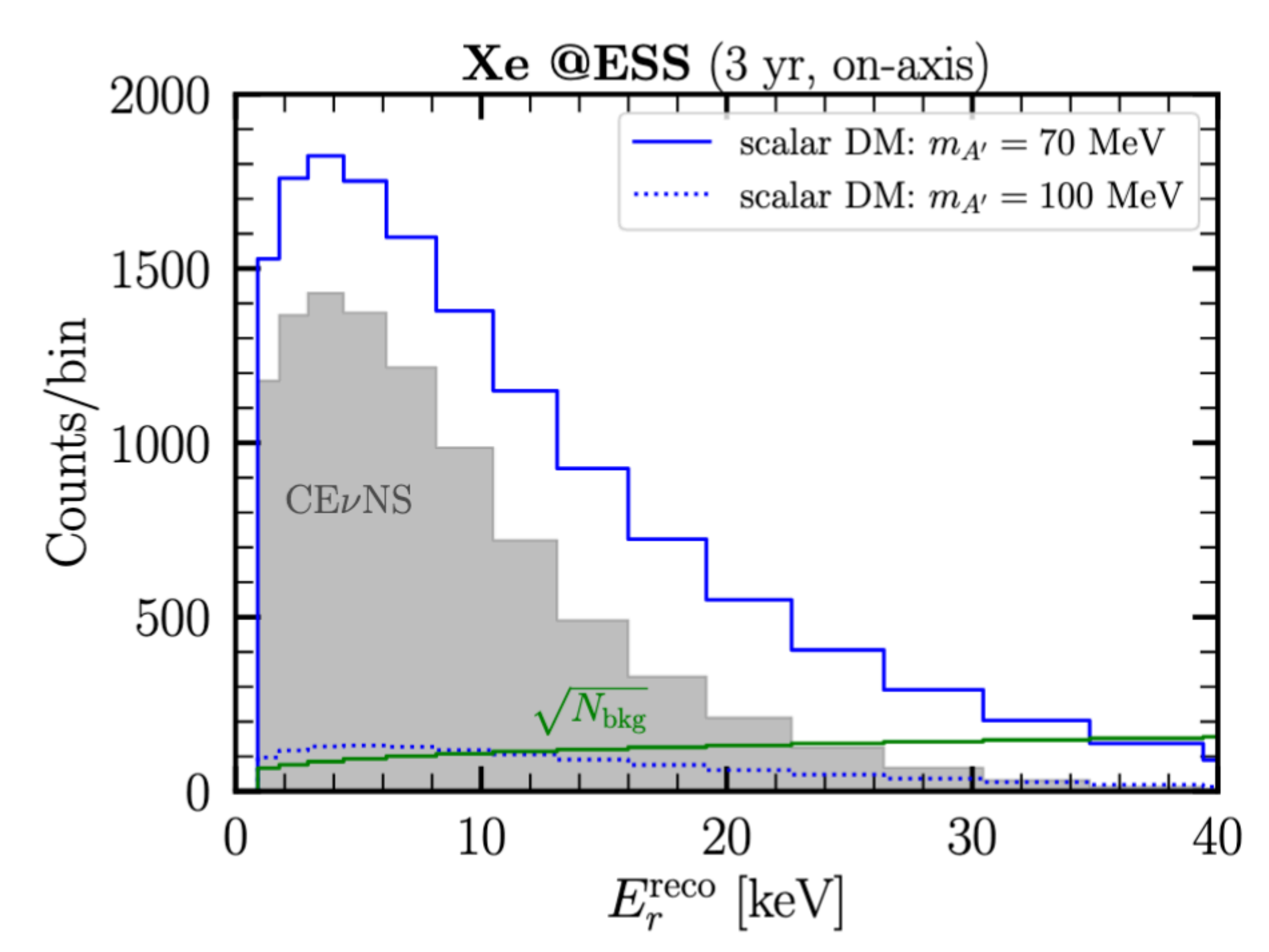
Energy reconstruction

$$\frac{\mathrm{d}N}{\mathrm{d}E_r^{\rm reco}} = \int_{E_r^{\rm min}}^{E_r^{\rm max}} \frac{\mathrm{d}N}{\mathrm{d}E_r} \mathcal{G}(E_r^{\rm reco}, E_r)\, \mathrm{d}E_r \,,$$

resolution power

$$\mathcal{G}(E_r^{\rm reco}, E_r) = \frac{1}{\sqrt{2\pi}\sigma} \exp\left[-\frac{(E_r^{\rm reco} - E_r)^2}{2\sigma^2}\right]$$

DM and CEvNS induce similar recoil spectra



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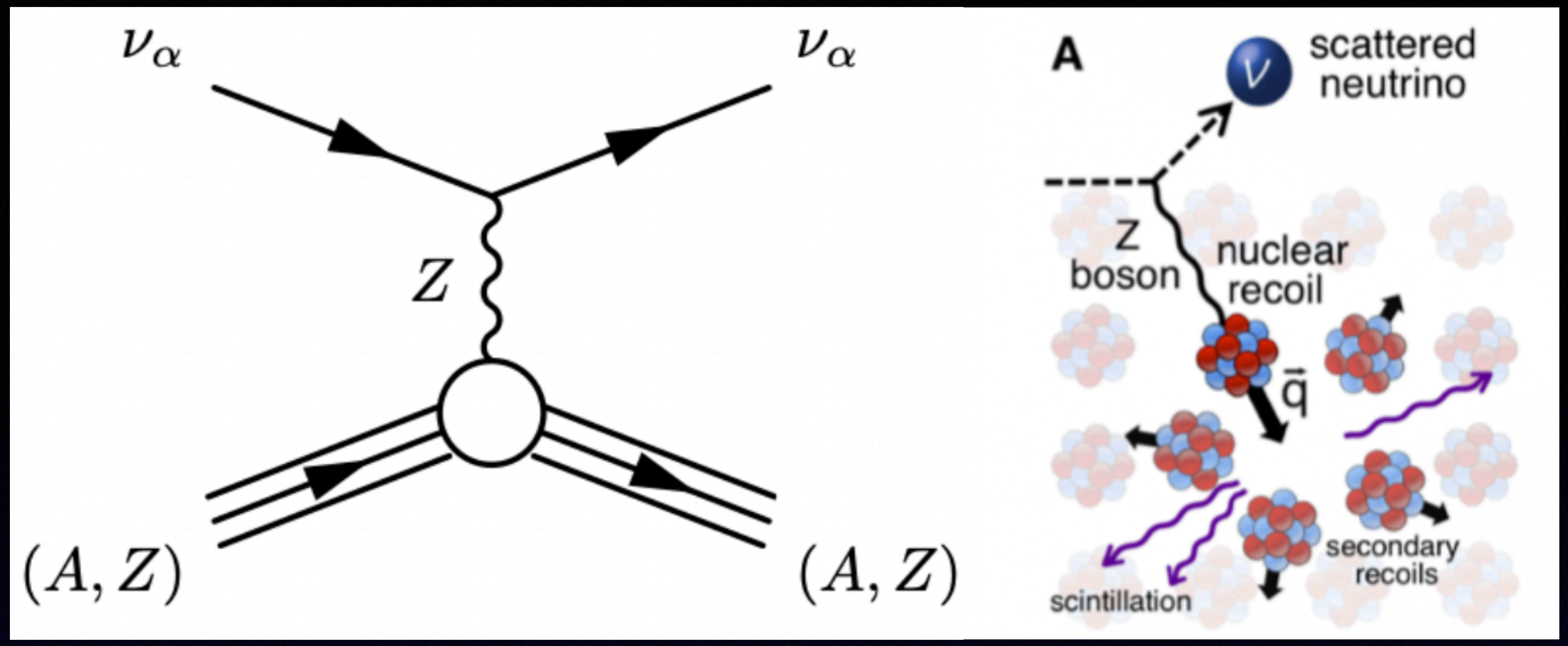
Coherent elastic neutrino nucleus scattering (CEvNS) as a background



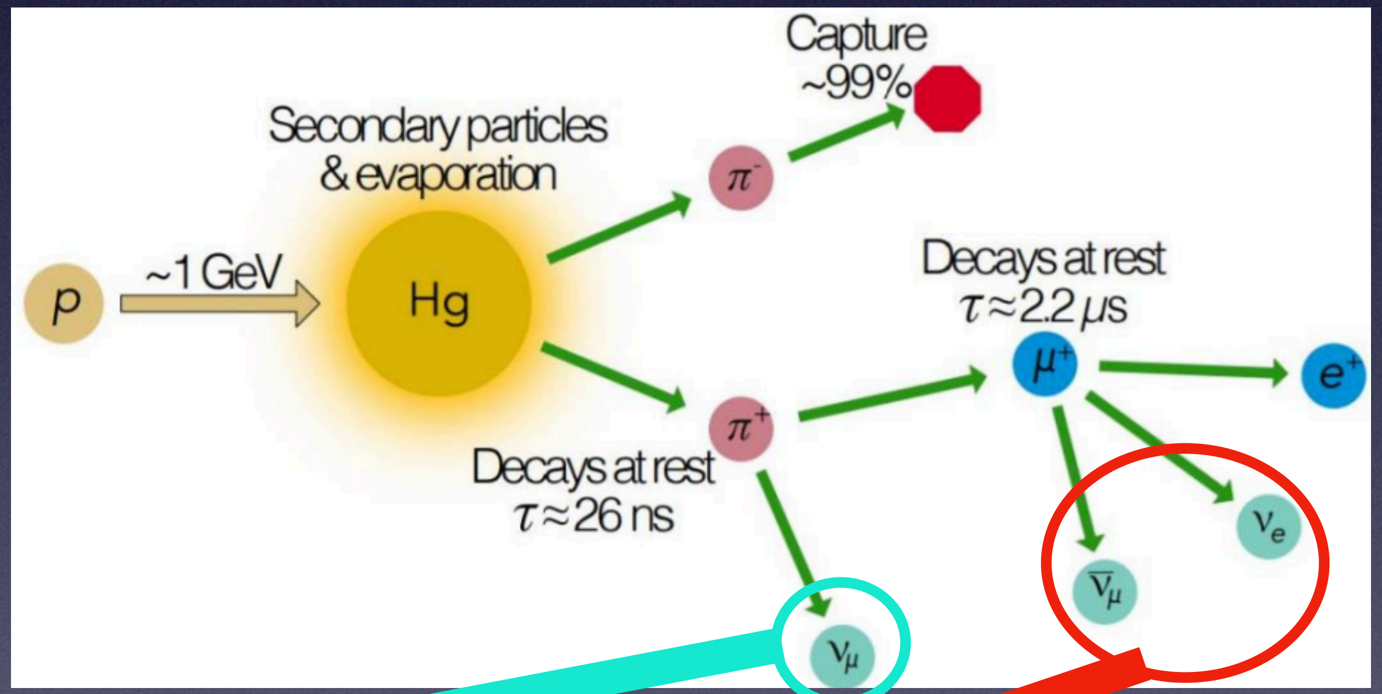
CEvNS cross section

$$\frac{d\sigma_{\nu\mathcal{N}}}{dE_r} = \frac{G_F^2 m_\mathcal{N}}{\pi}\left[Z F_Z(q^2) g_V^p + N F_N(q^2) g_V^n\right]^2 \left(1 - \frac{m_\mathcal{N} E_r}{2E_\nu^2}\right)$$

Proton pulse (J-PARC)

$$\frac{dp}{dt}(t) = \begin{cases} 0, & t < 0\,, \\ 5\ \mu s^{-1}, & 0 < t < 0.1\ \mu s\,, \\ 0, & 0.1 < t < 0.54\ \mu s\,, \\ 5\ \mu s^{-1}, & 0.54 < t < 0.64\ \mu s\,, \\ 0, & \text{otherwise}\,. \end{cases}$$

π-DAR neutrinos



Timing is important

$$\frac{d^2 N_i}{dt_{\rm reco}\, dE_r^{\rm reco}} = \sum_{x=\nu_e,\nu_\mu,\bar{\nu}_\mu} \int \frac{dN}{dE_r^{\rm reco}} \frac{d\mathcal{P}_x(t)}{dt} \mathcal{K}(t_{\rm reco}, t)\, dt\,,$$

Time profile of neutrinos from π^+ decay at rest

$$\frac{d\mathcal{P}_{\nu_\mu}(t)}{dt} = \int_0^t \frac{dp}{dt_p} \frac{e^{-(t-t_p)/\tau_\pi}}{\tau_\pi}\, dt_p\,,$$

$$\frac{d\mathcal{P}_{\nu_e,\bar{\nu}_\mu}(t)}{dt} = \int_0^t \frac{dp}{dt_p} \frac{e^{-(t-t_p)/\tau_\mu} - e^{-(t-t_p)/\tau_\pi}}{\tau_\mu - \tau_\pi}\, dt_p\,,$$

- CEvNS: Prompt (ν_μ) and delayed ($\nu_e, \bar{\nu}_\mu$) signal
- Timing can help to mitigate CEvNS background
- DM signal is prompt with π^0

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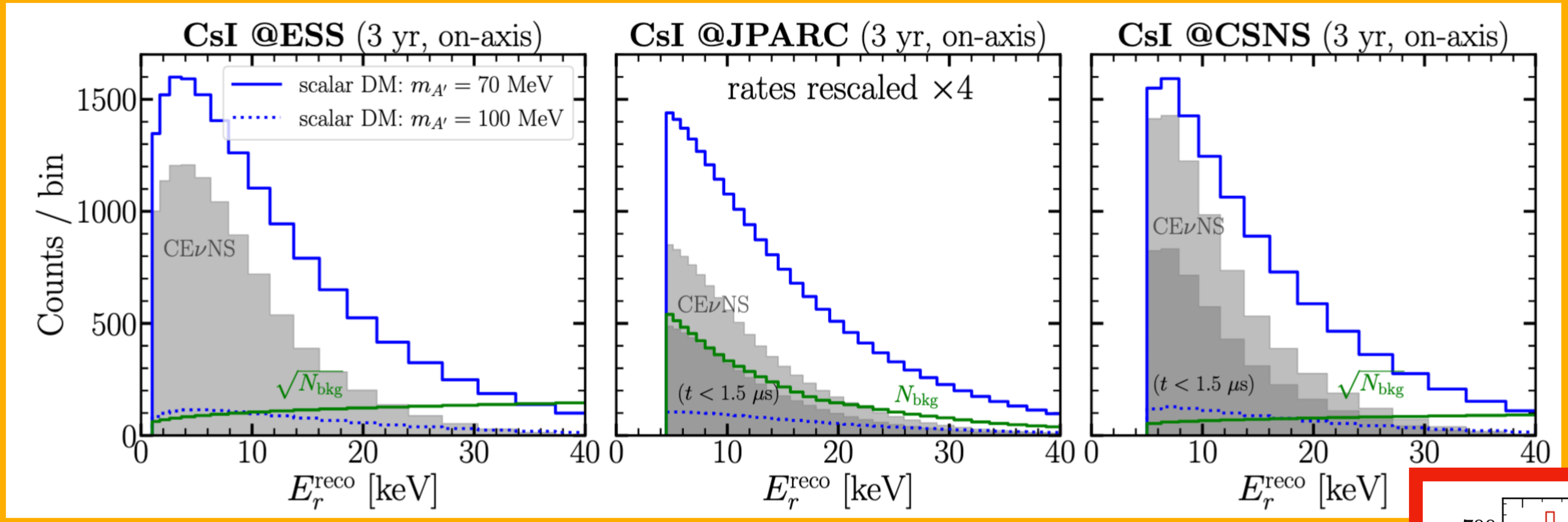
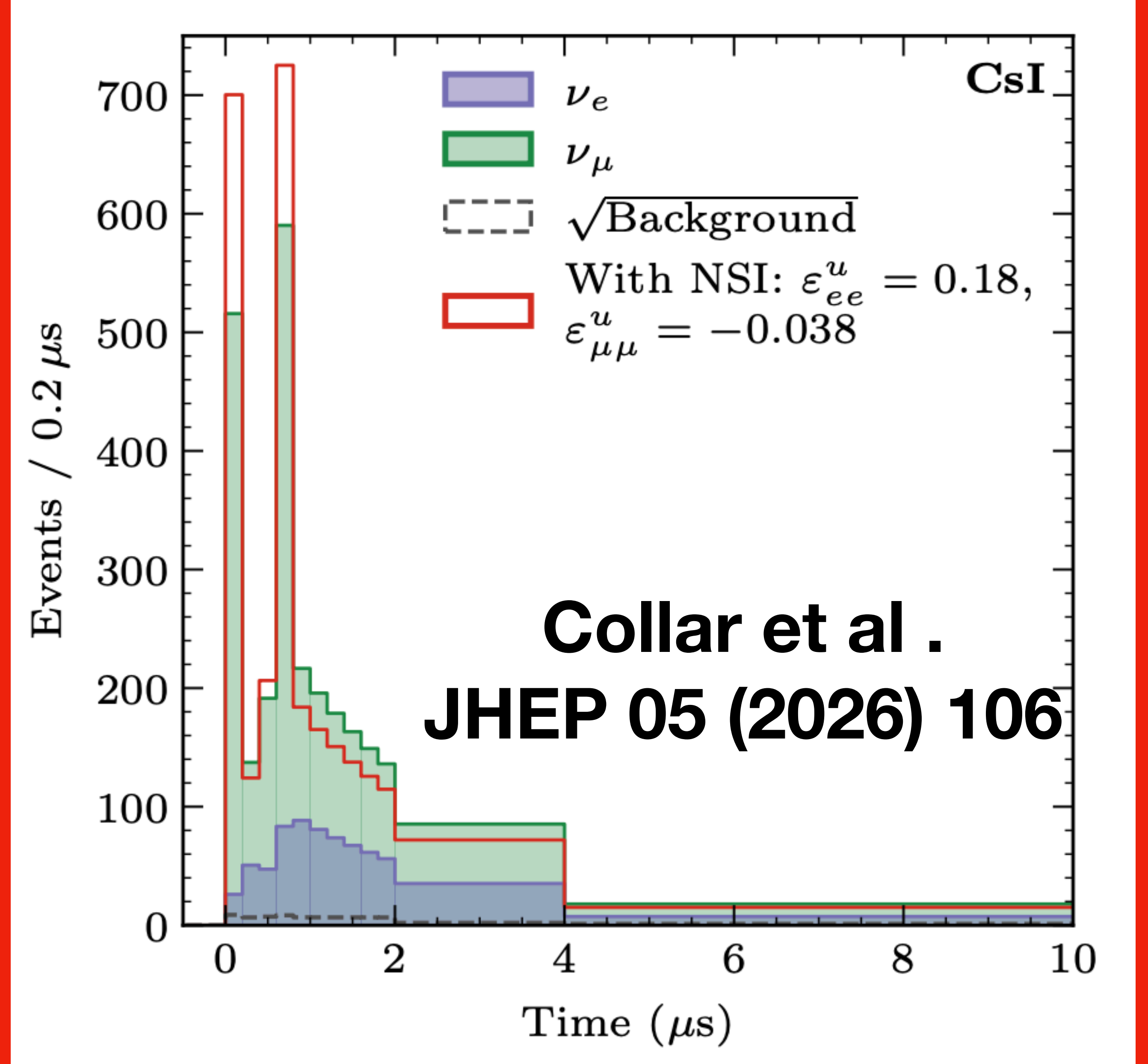
Mitigating CEvNS backgrounds via timing cuts



CsI target

Time profile of CEvNS-CsI spectra At JPARC



- Timing irrelevant at ESS (too wide proton pulses)
- Timing important at JPARC and CSNS

- Apply a conservative time-cut of 1.5μs which contains all the DM signal and rejects a large amount of CEvNS and steady-state-background

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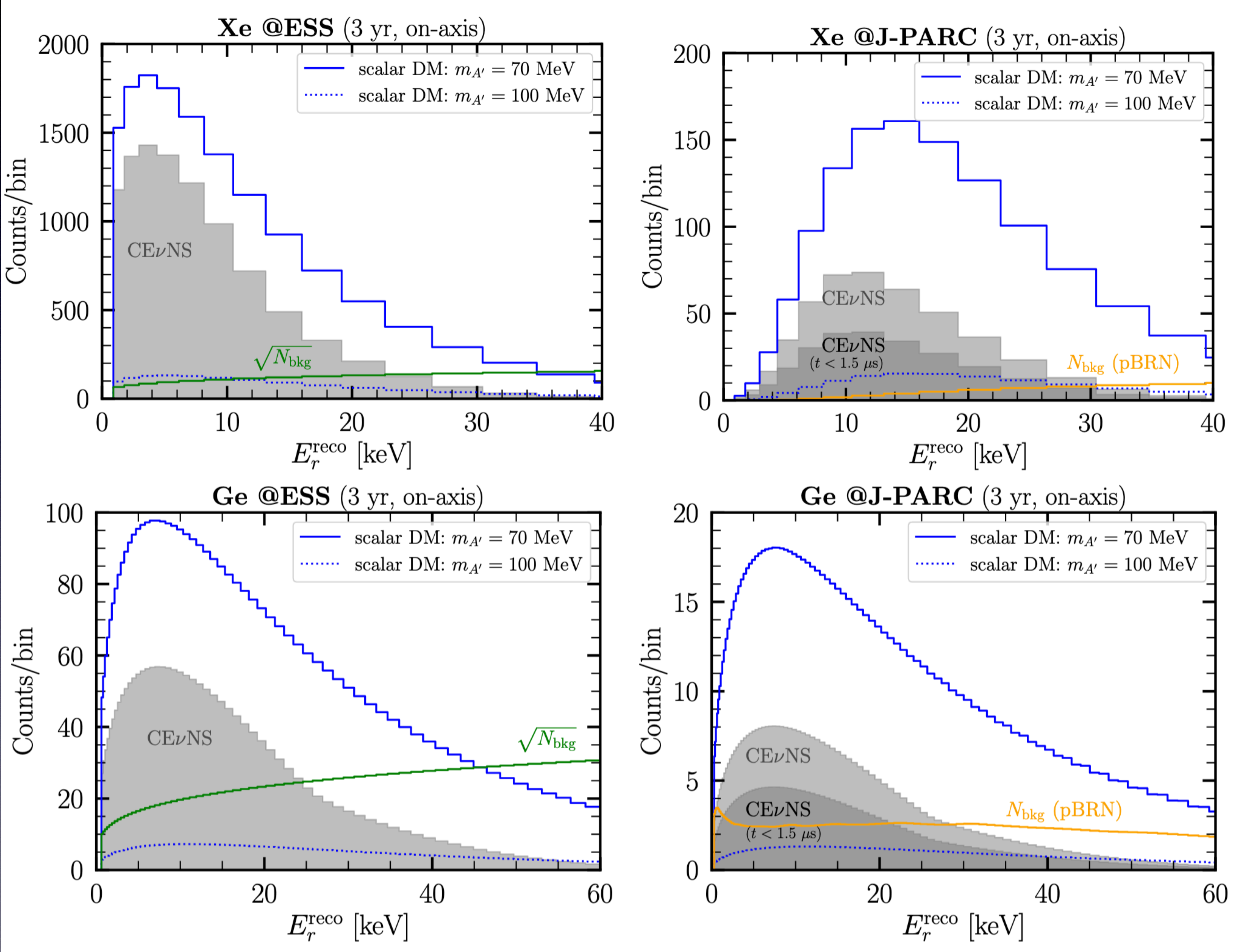
Predicted event rates@ ESS, JPARC



Xe target

Ge target

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Sensitivities (on-axis location)

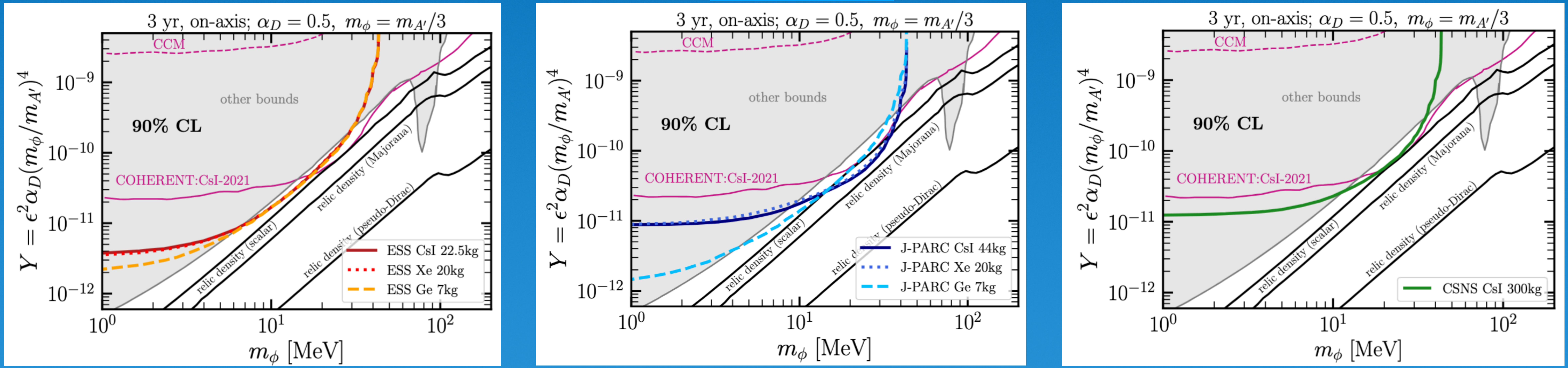
CEvNS-detectors

- can improve the constraints in $6 \lesssim m_\phi \lesssim 40$ MeV
- ESS and CSNS can probe new regions of the parameter space up to the relic density target
- Ge detectors at ESS and JPARC provide the strongest constraints for low $Y \sim 2 \times 10^{-12}$

Existing bounds from

- MiniBooNE (quasi-elastic scattering)
- LSND (β decay)
- NA64, E137 (bremsstrahlung, e^+e^-scattering)
- BaBar (e^+e^- scattering)

On-axis



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Sensitivities (off-axis location)

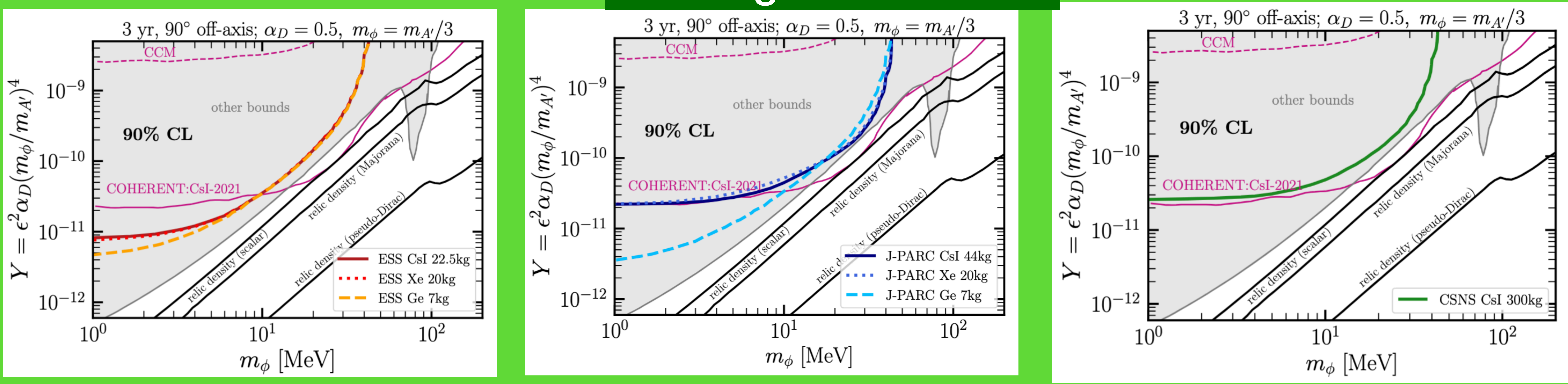
CEvNS-detectors

- Going off-axis the sensitivity reduces significantly
- Still they remain complementary to existing searches

Existing bounds from

- MiniBooNE (quasi-elastic scattering)
- LSND (β decay)
- NA64, E137 (bremsstrahlung, e^+e^-scattering)
- BaBar (e^+e^- scattering)

90 degrees off-axis



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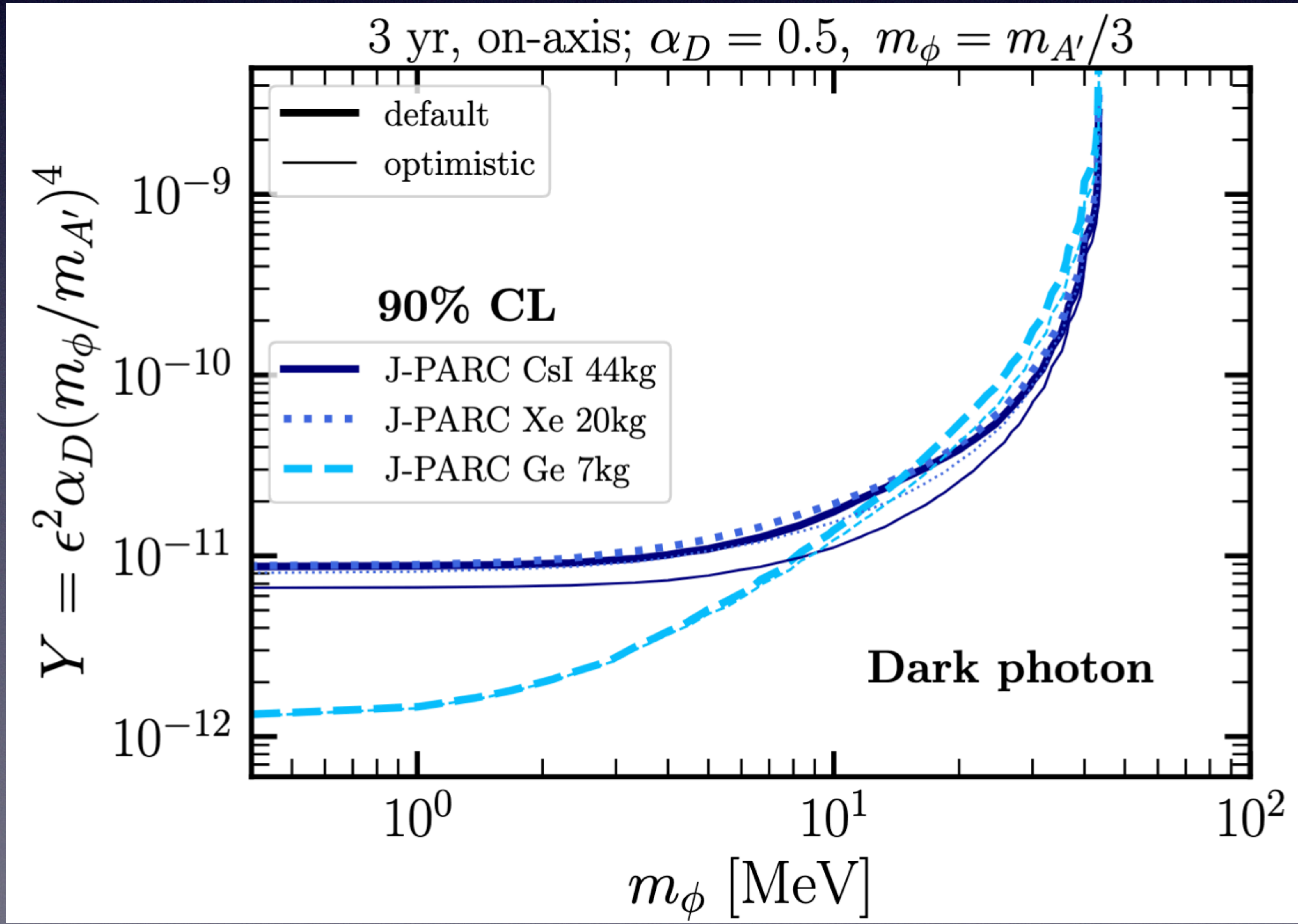
Future expectations

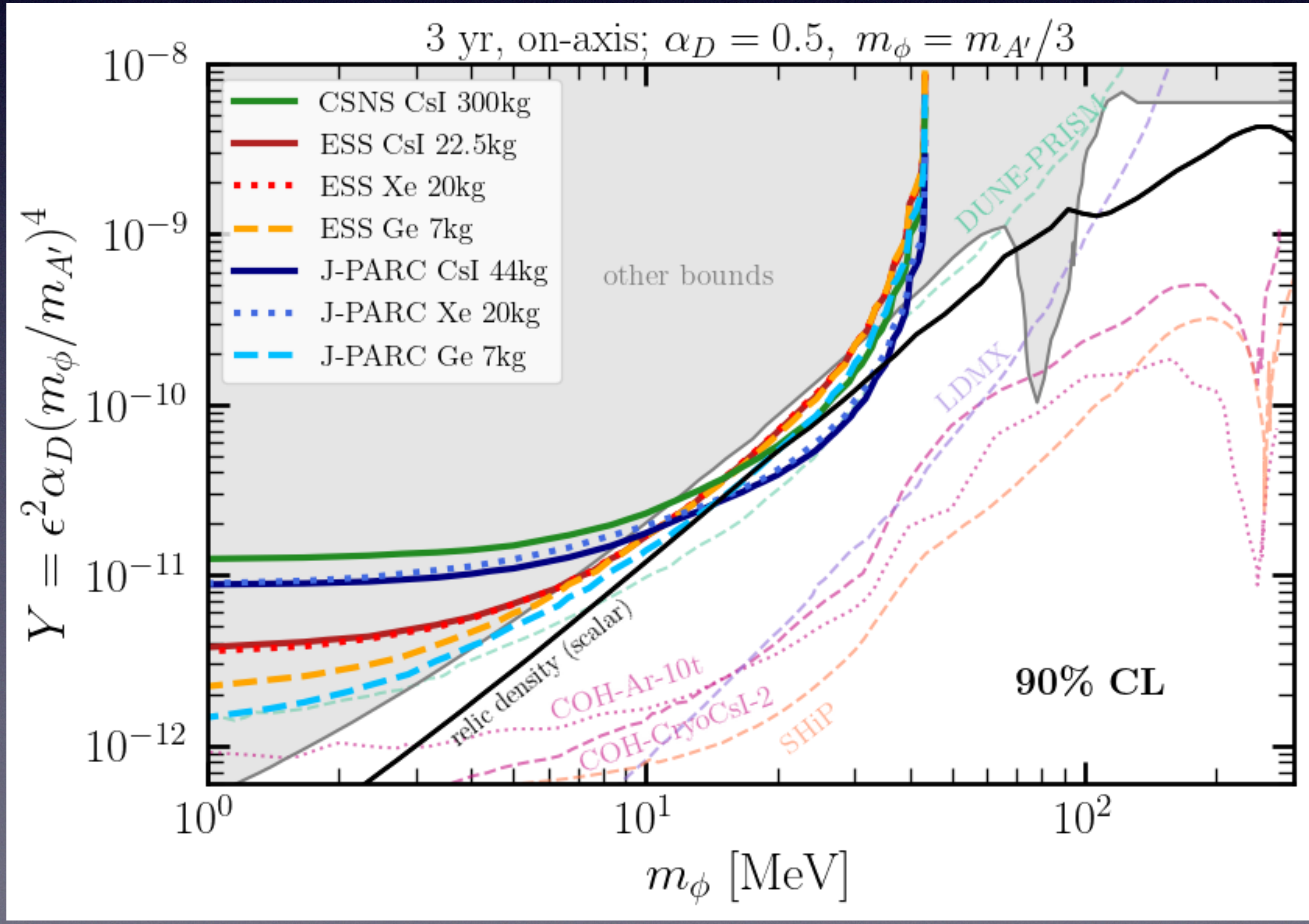
CEvNS-detectors

- Lowering the error budget does not improve significanlty the sensitivity
- Need larger masses, e.g., the upgrades of COHERENT experiment
- Need lower recoil energy threshold

Additional expectations from

- SHiP, LDMX (DM experiments)
- DUNE ND-LAr





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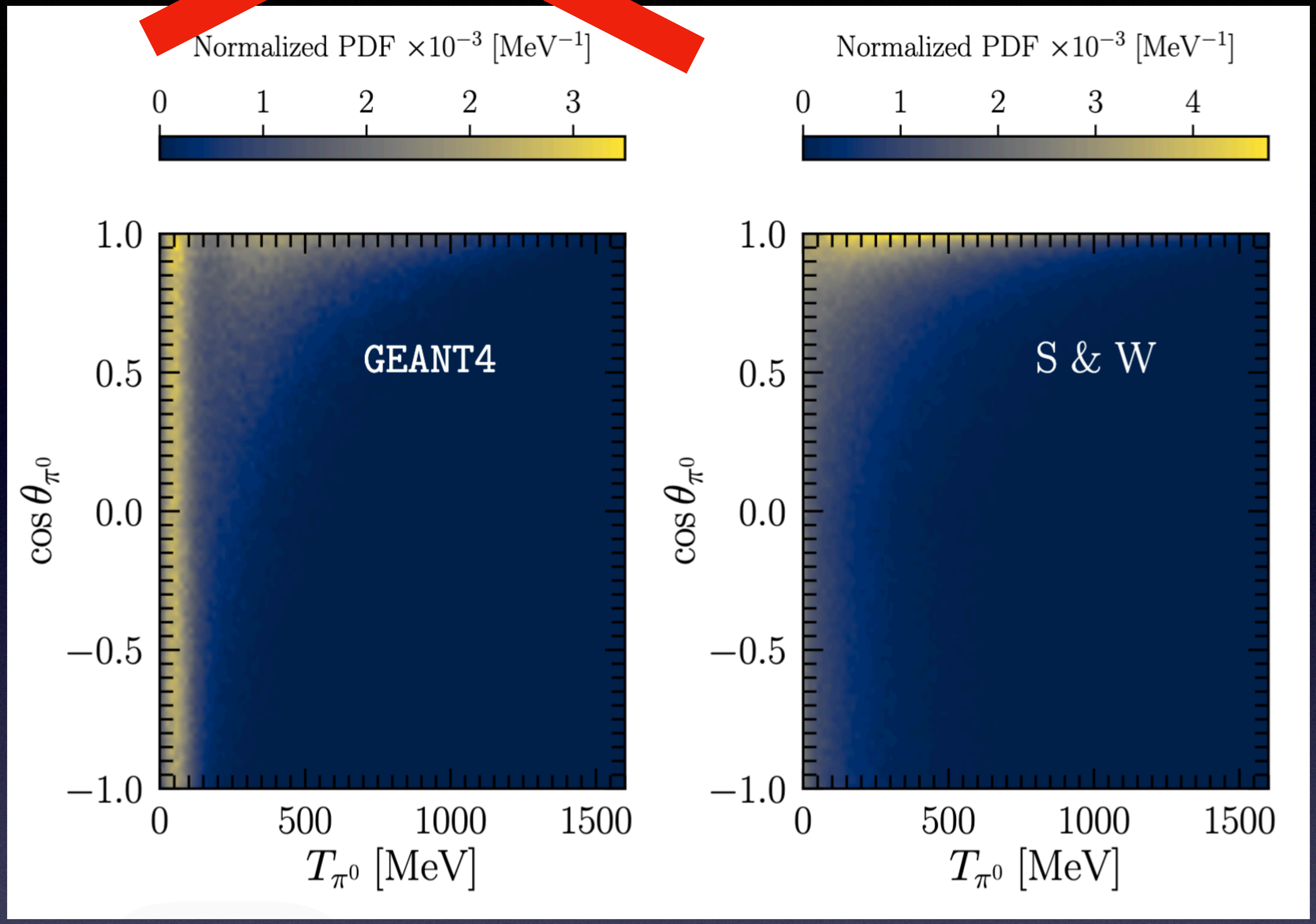
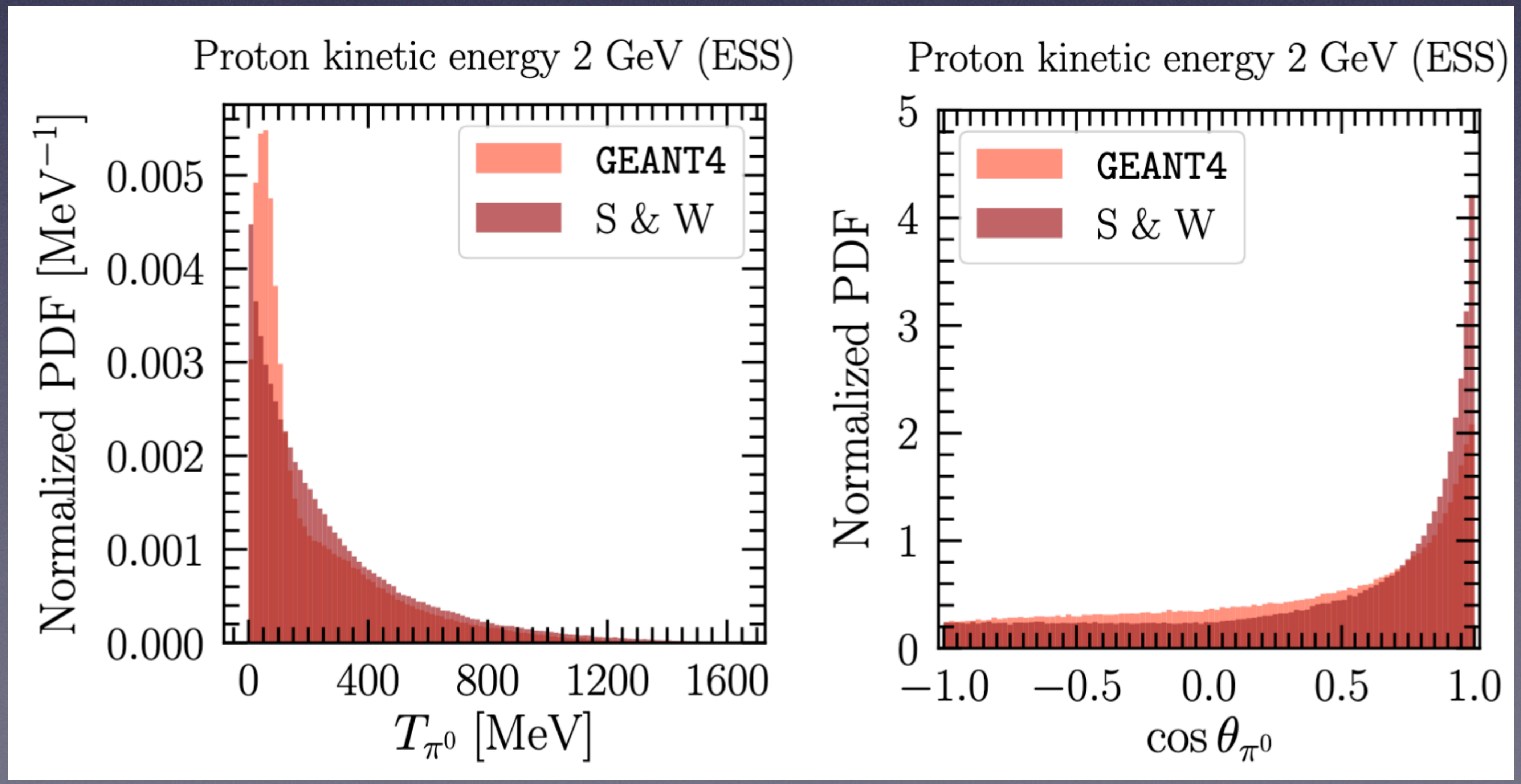
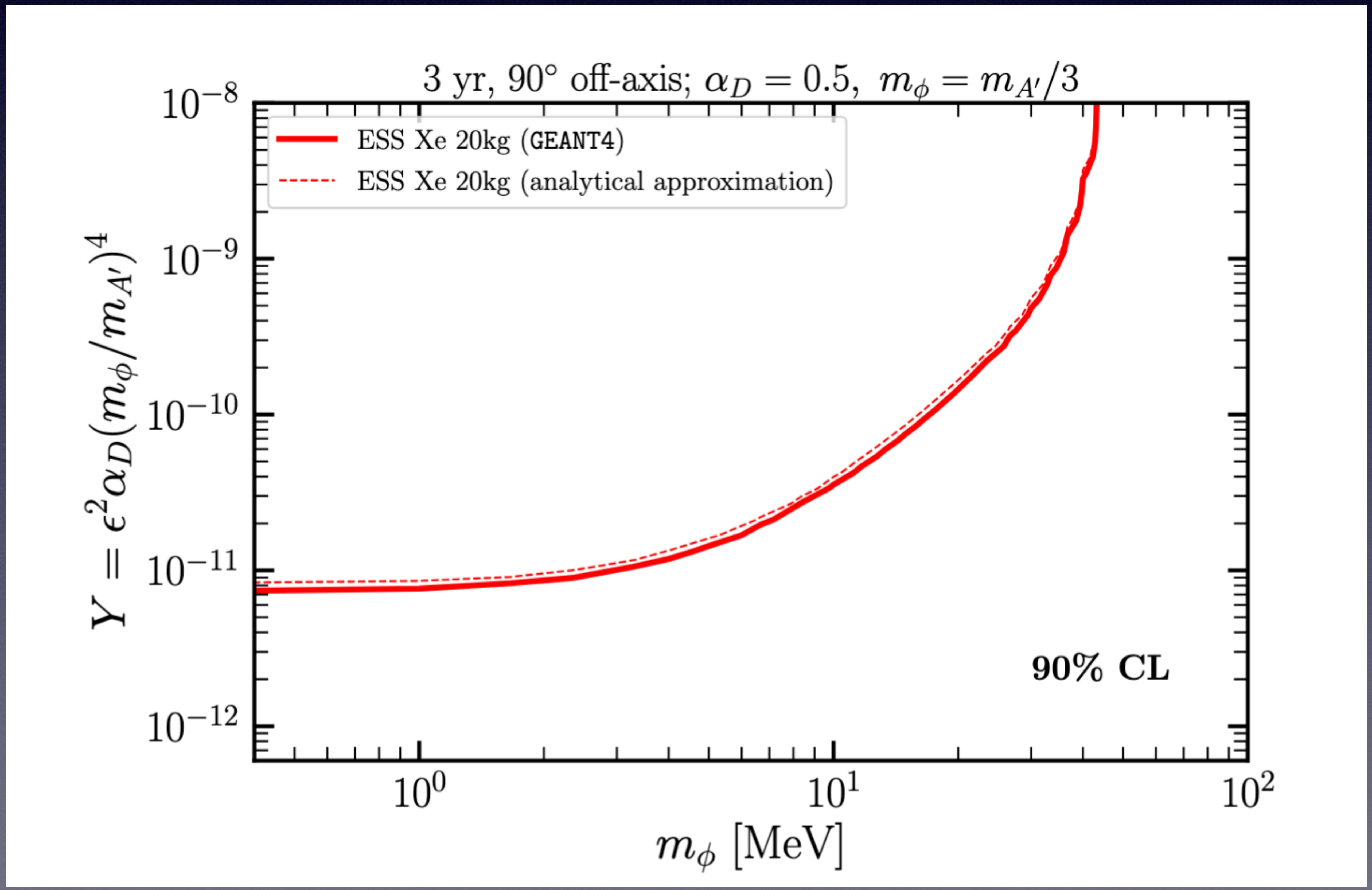
~~GEANT4~~ Analytical approximation





- The analytical method of Sanford & Wang provides results in reasonable agreement with GEANT4
- S&W params come from fitting the MiniBooNE data (9 GeV)
- S&W does not account for secondary π^0 production, or absorption of charged pions in the thick target



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Summary

- Spallation sources facilities can probe artificially generated sub-GeV dark mater
- It is feasible to explore the low DM mass region where direct detection searches lose sensitivity
- CEvNS detectors proposed to be built at the ESS, JPARC and CSNS can offer stringent constraints, complementary to direct detection, beam-dump and collider searches
- Excellent agreement between GEANT4 and analytical Sanford & Wang approaches

- High intensity proton beam to produce sizeable DM fluxes
- DM and CEvNS signals can mimic each other
- Timing information helps reducing the CEvNS “background” component
- Lowering the nuclear recoil threshold is essential

Thank you for your attention

Acknowledgement

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More on DM from π^0decay

decay channels

$$\Gamma(\pi^0 \to \gamma + \gamma) = \frac{\alpha^2}{2 \times 32\pi^3} \frac{m_{\pi^0}^3}{f_\pi^2}$$

$$\Gamma(\pi^0 \to \gamma + A') = 2\Gamma(\pi^0 \to \gamma + \gamma)\epsilon^2 \left(1 - \frac{m_{A'}^2}{m_{\pi^0}^2}\right)^3$$

$$\Gamma(A' \to \phi + \phi^*) = \frac{g_D^2}{48\pi} m_{A'} \left(1 - 4\frac{m_\phi^2}{m_{A'}^2}\right)^{3/2}$$

B. Batell, M. Pospelov, A. Ritz, PRD 80 (2009)
De Romeri, Kelly, Machado PRD 100 no 9, (2019)

Branching ratio

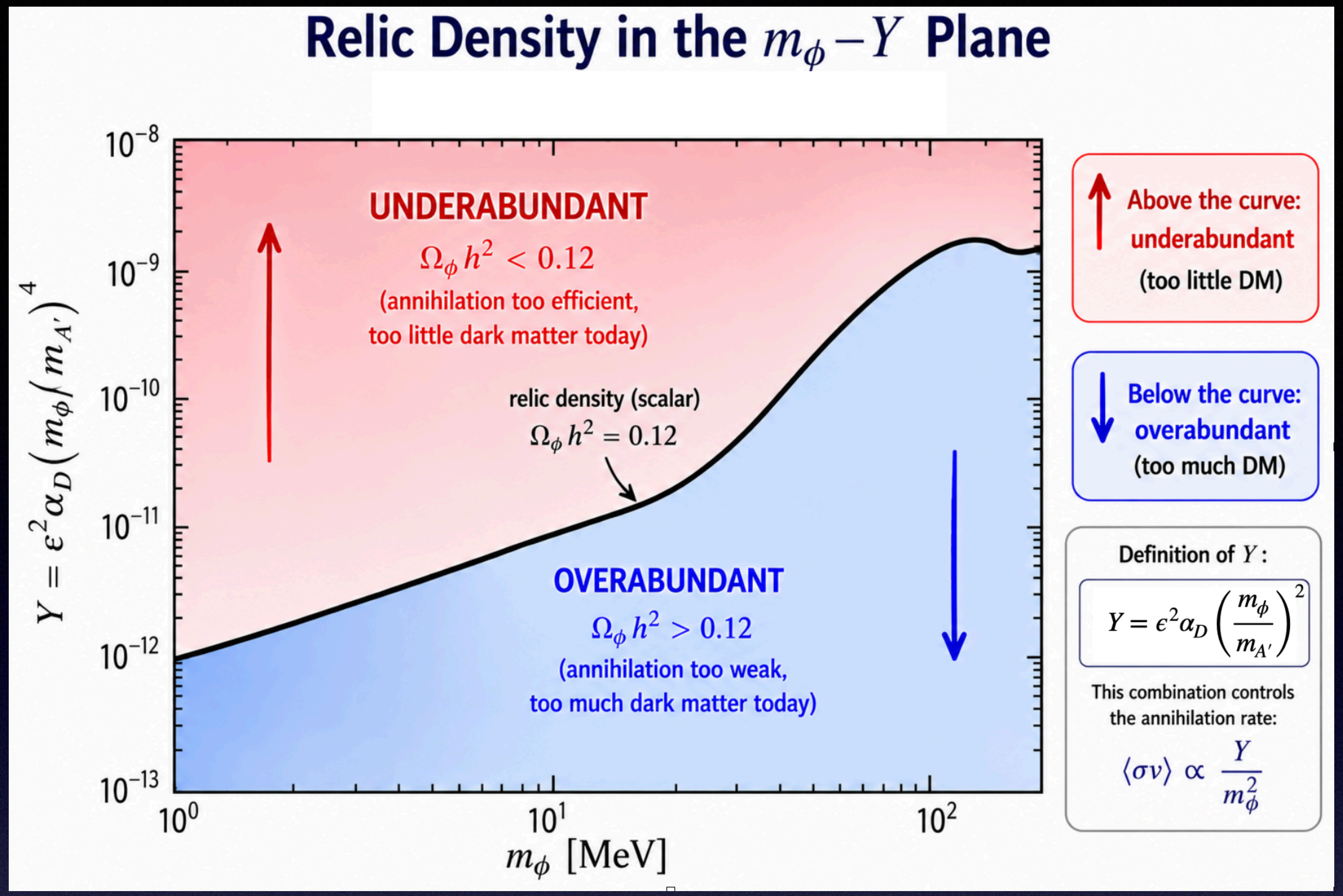
$$\mathcal{B}(\pi^0 \to \gamma + \phi + \phi^*) = \mathcal{B}(\pi^0 \to \gamma + \gamma) \times 2\varepsilon^2 \left(1 - \frac{m_{A'}^2}{m_{\pi^0}^2}\right)^3 \times \mathcal{B}(A' \to \phi + \phi^*)$$

$$\mathcal{B}(\pi^0 \to \gamma\gamma) = 0.99 \qquad \mathcal{B}(A' \to \phi\phi^*) = 1$$

Even when the kinetic mixing vanishes A' can decay visibly via quark loops

$$\epsilon_1 = \frac{e g_D}{16\pi^2}$$

DM relic abundance



- If $m_\phi > m_{A'}$

DM annihilates via the t channel $\phi + \phi^* \rightarrow A' + A'$ leading to under-abundant DM relic density

- If $m_\phi < m_{A'}$

DM annihilates via the s channel $\phi + \phi^* \rightarrow$ SM + SM mediated by an off-shell A'

the s channel annihilation cross section (scalar DM)

$\alpha_D = g_D / 4\pi$

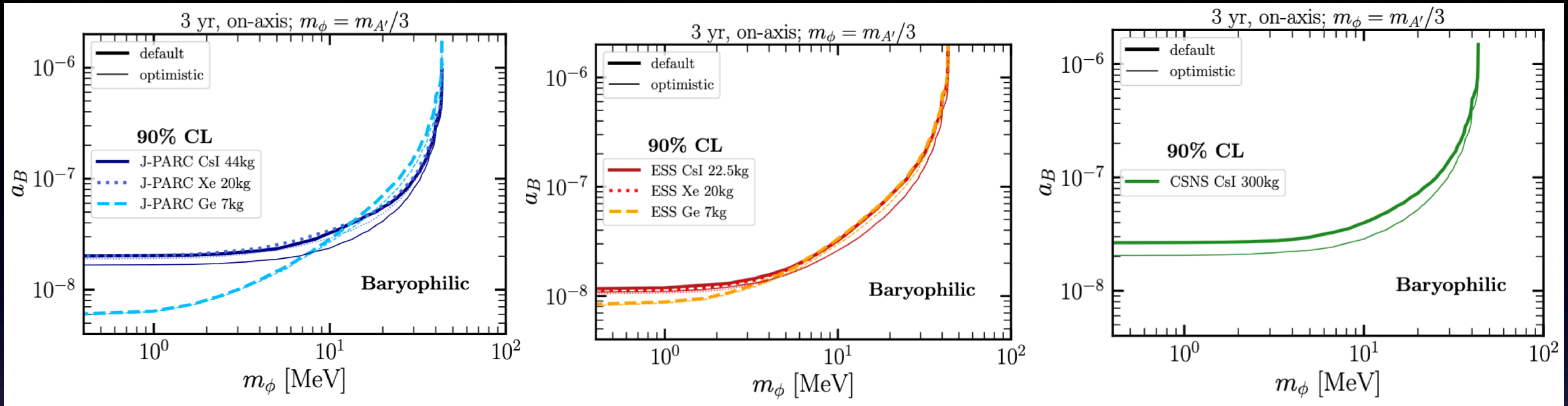
$$\sigma_{\text{s-channel}} \simeq \frac{16\pi^2 \alpha}{m_\phi^2} v^2 \epsilon^2 \alpha_D \left(\frac{m_\phi}{m_{A'}}\right)^4 = \frac{16\pi^2 \alpha}{m_\phi^2} v^2 Y$$

Dimensionless parameter

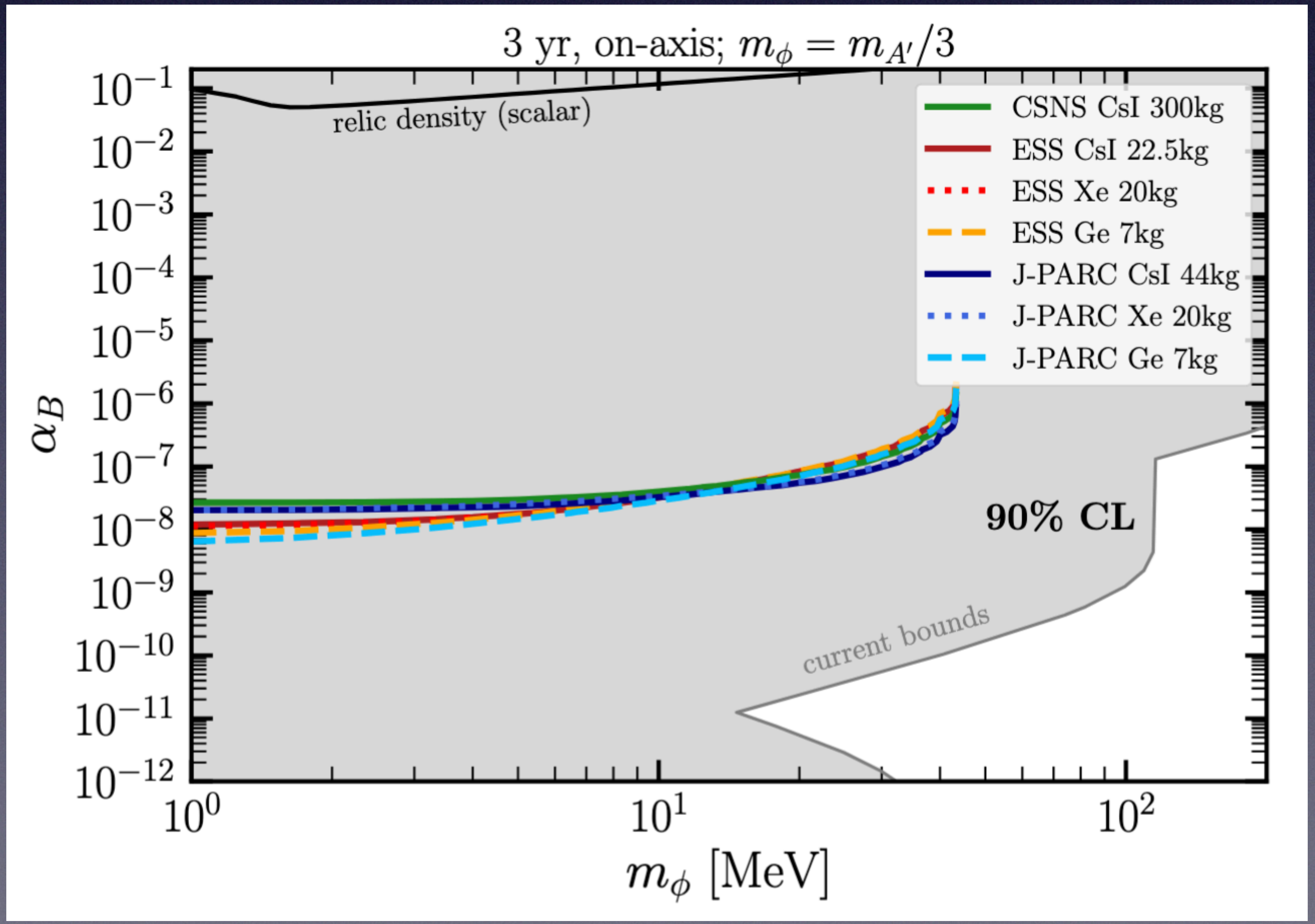
$$Y \equiv \epsilon^2 \alpha_D (m_\phi / m_{A'})^4$$

- conveniently captures the combination of couplings and mass ratios relevant for thermal freeze-out.
- requiring the relic abundance to match the observed DM density, fixes the annihilation cross section and therefore selects a target value of Y for each m_ϕ

Baryophilic model



Poor sensitivity
if the baryon DM charge
is fixed to $Q_B = 1$



For a different charge
assignment see

COHERENT Collab, PRL 130 (2023)
COHERENT Collab, PRD 106 (2022), 052004

CCM Collab, PRL 129 (2022)
CCM Collab, PRD 106 (2022), 012001

Aristizabal, De Romeri, DKP, Sanchez: arXiv: 2603.02132, *JHEP accepted*

Statistical analysis details

CEvNS and DM signals are reconstructed in both energy and time

Poisson χ^2

$$\chi^2 = 2\sum_i \left[N_i^{\text{th}} - N_i^{\text{exp}} + N_i^{\text{exp}} \ln\left(\frac{N_i^{\text{exp}}}{N_i^{\text{th}}}\right)\right] + \left(\frac{\alpha}{\sigma_\alpha}\right)^2 + \left(\frac{\beta_1}{\sigma_{\beta_1}}\right)^2 + \left(\frac{\beta_2}{\sigma_{\beta_2}}\right)^2$$

Include two nuisance parameters

$$N_i^{\text{th}} = N_i^{\text{DM}}(1+\alpha) + N_i^{\text{CEvNS}}(1+\beta_1) + N_i^{\text{SSB/pBRN}}(1+\beta_2).$$

Systematic uncertainties

$\sigma_\alpha = 10\,\%$ CEνNS

$\sigma_{\beta_1} = 10\,\%$ DM

$\sigma_{\beta_2} = 1\,\%$ (or 25%) SSB (or pBRN)

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