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HIDDeν
Hunting Invisibles: Dark sectors, Dark matter and Neutrinos

Probing feebly interacting particles from solar nuclear reactions with JUNO

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Based on
G.L., N. Nath, F. Capozzi, M. Giannotti, A. Mirizzi, PRD 106 (2022) 12, 123007, arXiv: 2209.11780
F. D'eramo, G.L., N. Nath, S. Yun, arXiv: 2305.14420

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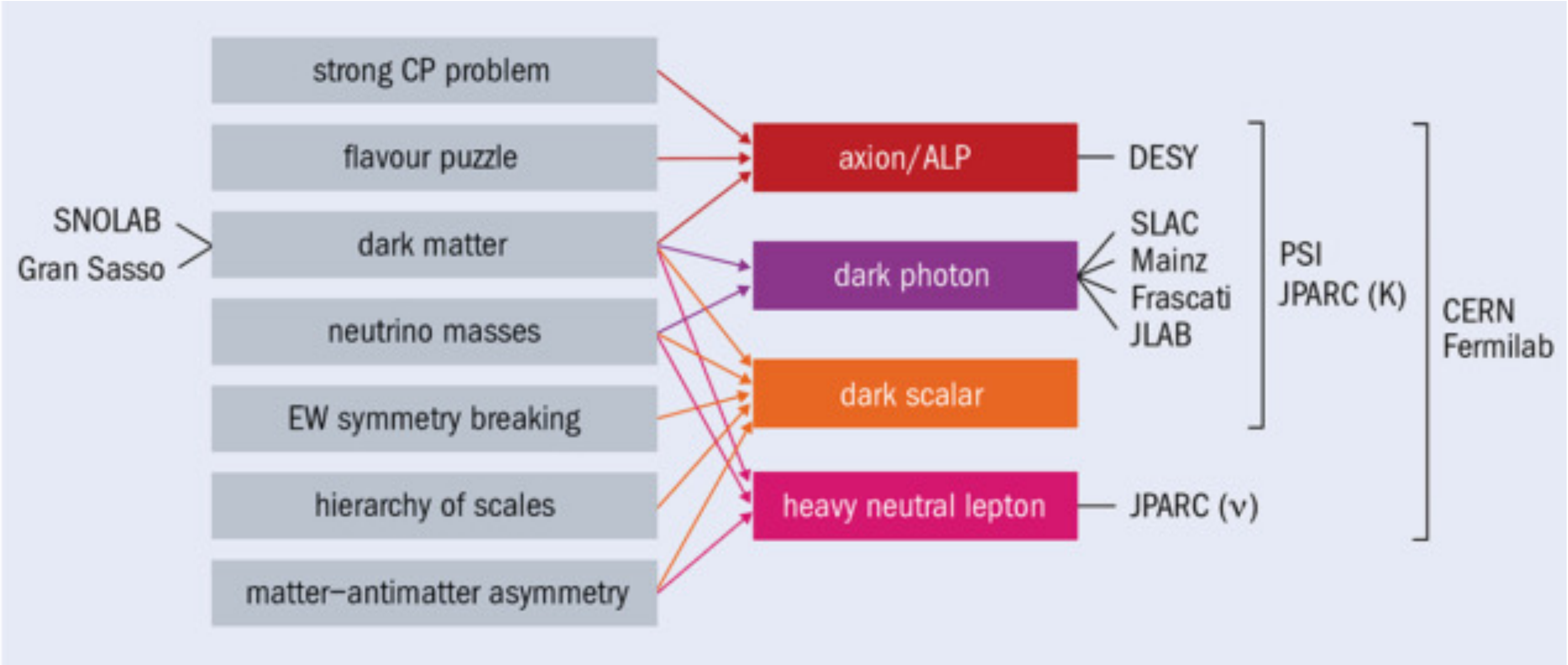
FEEBLY INTERACTING PARTICLES

[Agrawal et al., *Eur. Phys. J.C. 81* (2021)]

Feebly Interacting Particles (FIPs): light particles with suppressed interaction with SM particles, proposed to solve some SM open questions.

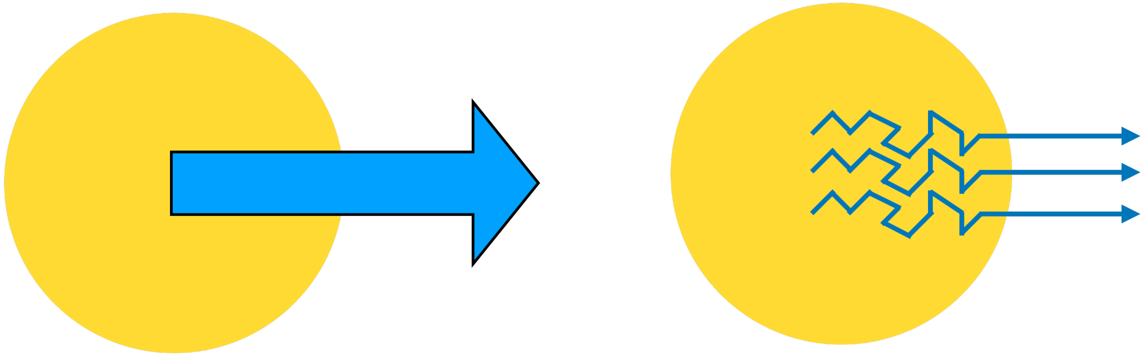


[Beacham et al., https://cerncourier.com/a/strong-interest-in-feeble-interactions/]

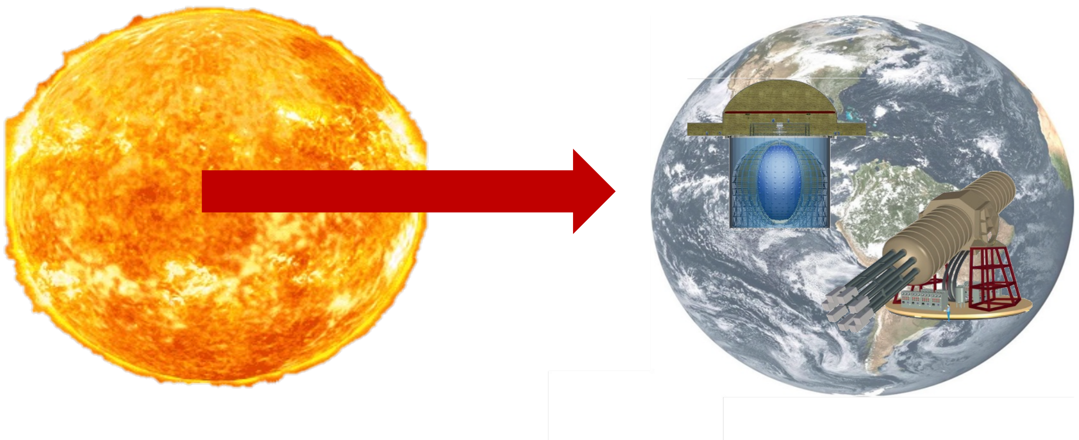
FIPs FROM THE SUN

The sun is an efficient laboratory to study FIPs. Two strategies:

- Indirect signatures: impact on the standard stellar evolution. [Gondolo & Raffelt (2009), Vinyoles et al. (2015), Li & Xu (2023)]



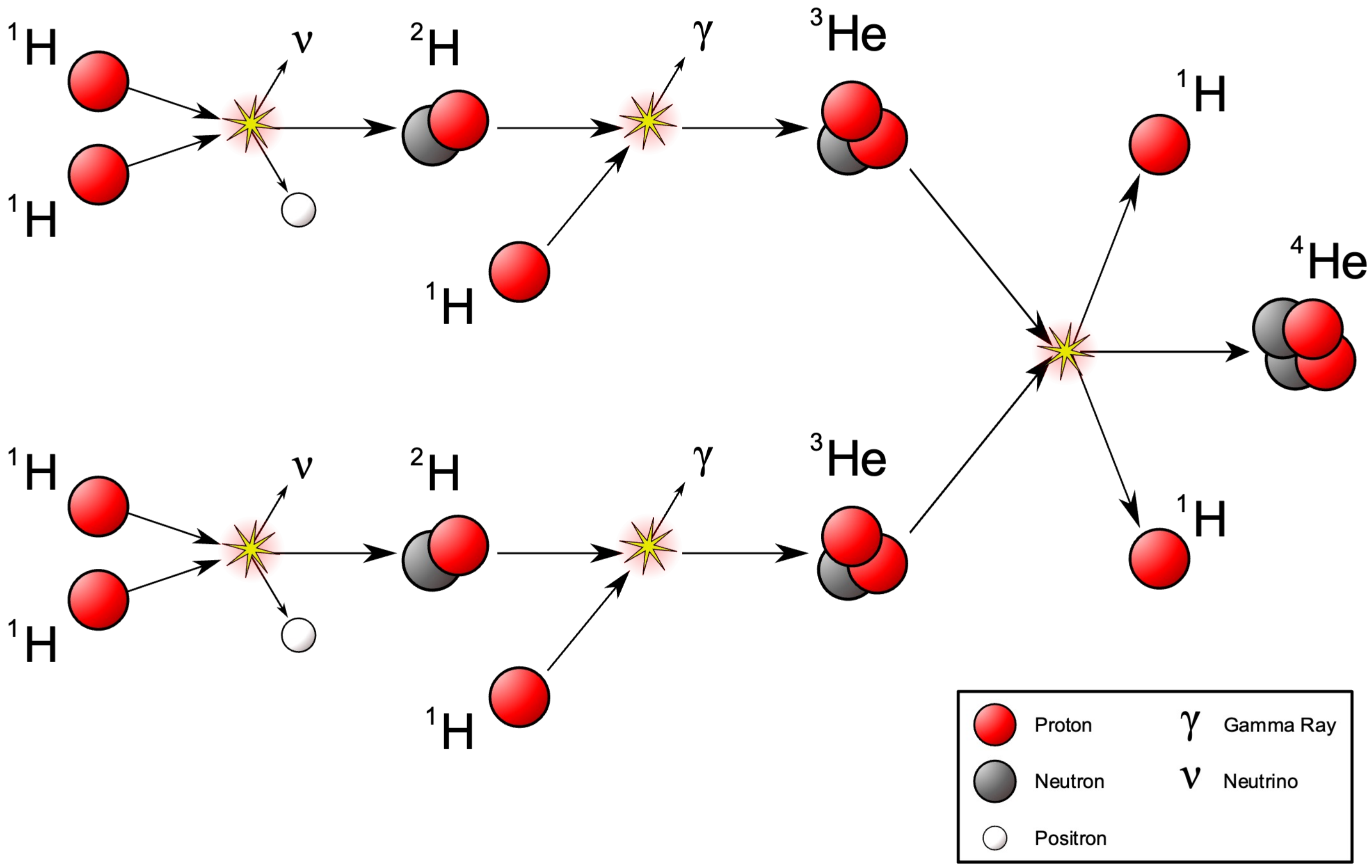
- Direct signature: observable signal on Earth. [Anastassopoulos et al. (2017), Fu et al. (2017), Aralis et al. (2020)]



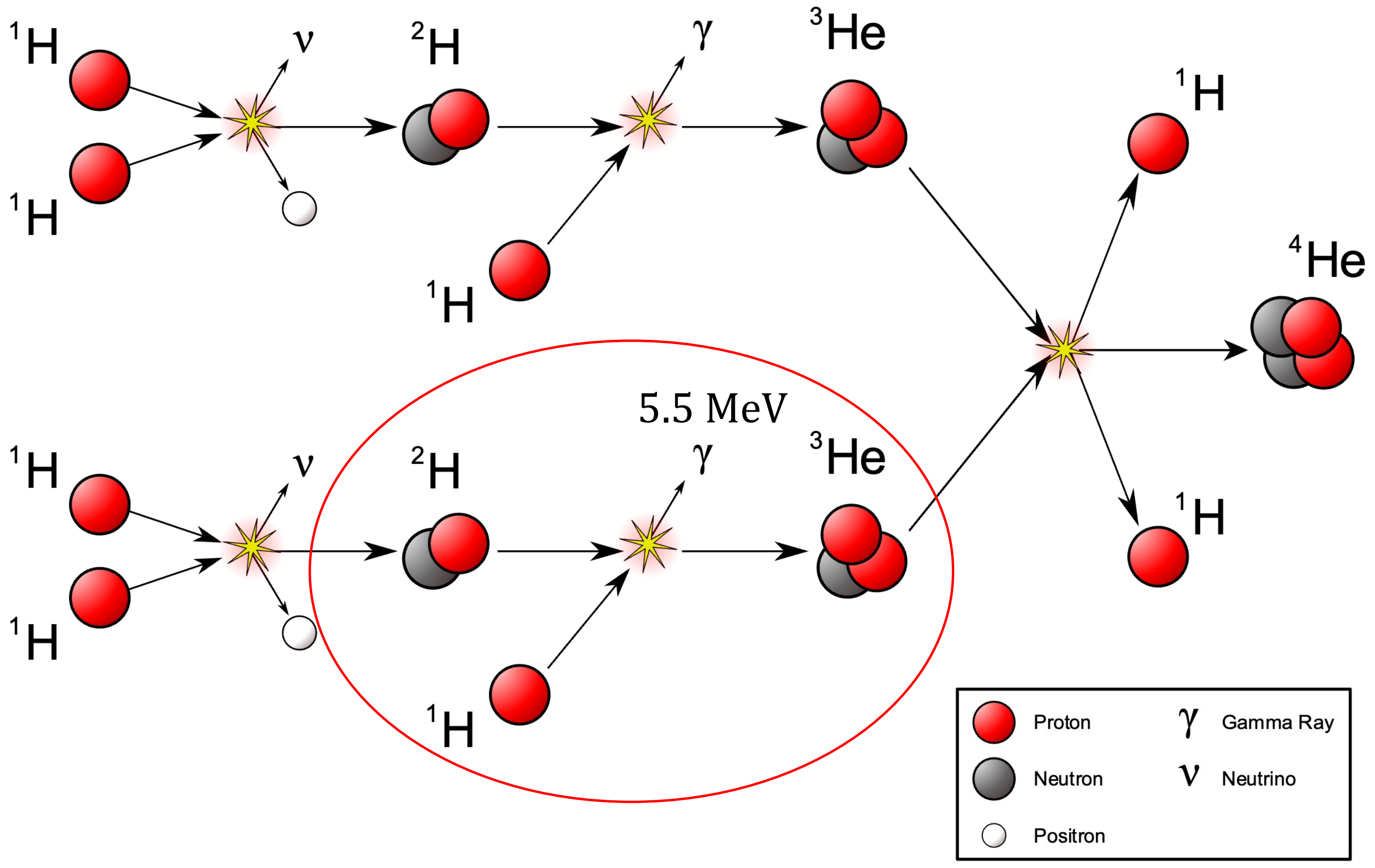
THE PROTON-PROTON CHAIN

FIPs can be produced in nuclear reactions in the Sun, just like neutrinos.

About 99% of the energy in the Sun is produced via the proton-proton chain.

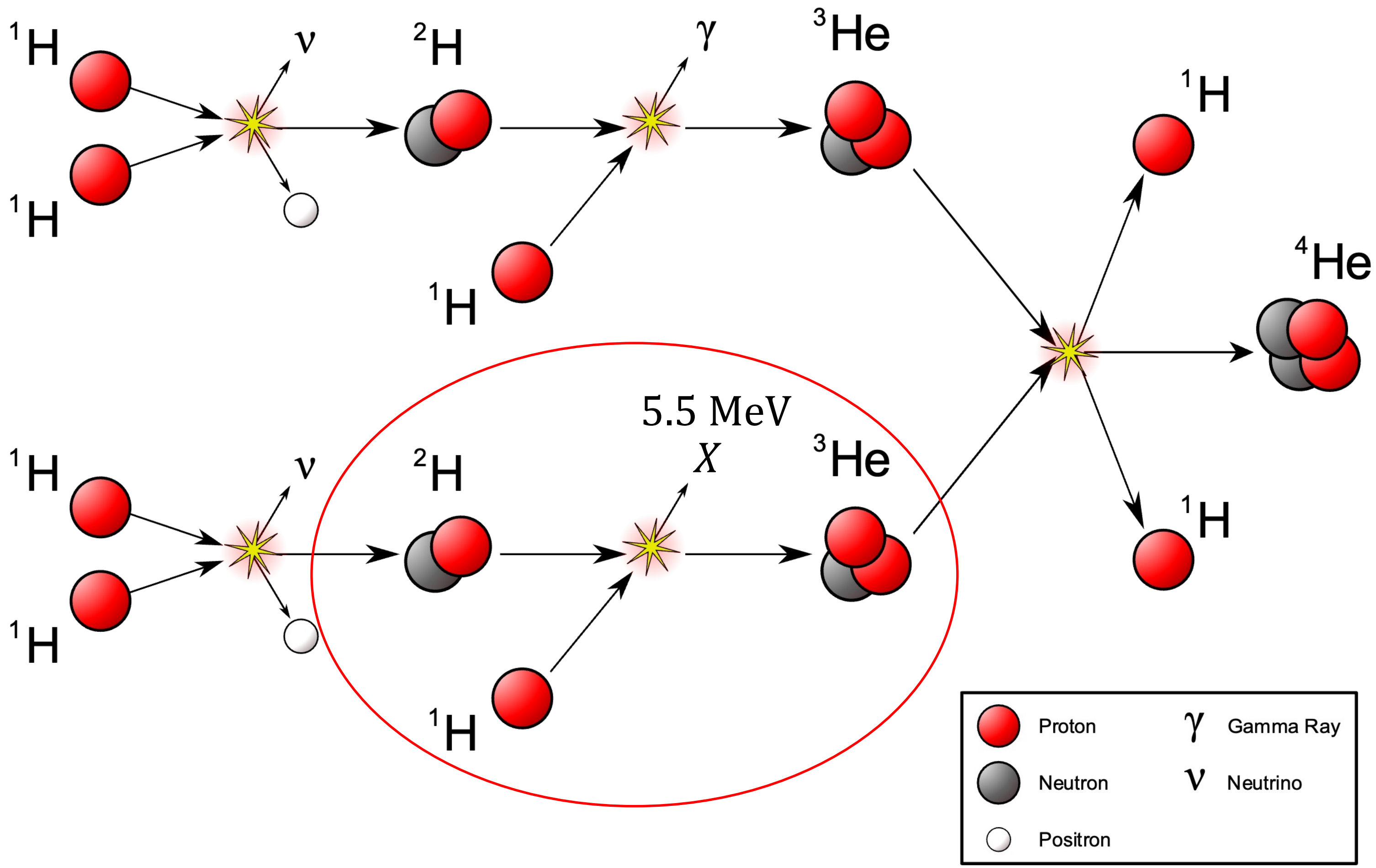


THE DEUTERIUM FUSION



FIP EMISSION VIA DEUTERIUM FUSION

The produced photon can be replaced by a FIP with energy 5.5 MeV.



JUNO EXPERIMENTAL SETUP

[JUNO coll., J.Phys. G 43 (2016)]

The 5.5 MeV solar FIP flux can be detected by neutrino detectors, e.g. JUNO.

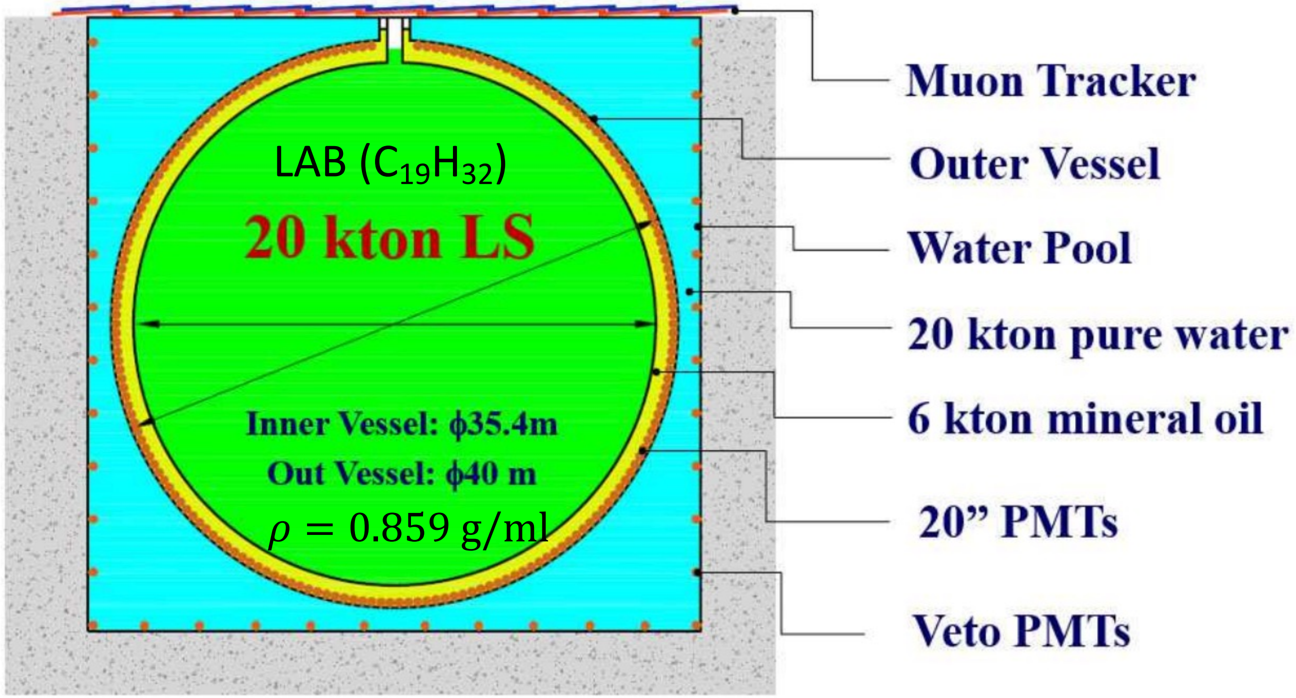
First analysis performed by Borexino for axions. [Borexino coll., PRD 85 (2012)]

Fiducial mass:

20 kton

Energy resolution:

$$\frac{\sigma}{\text{MeV}} = 3\% \sqrt{\frac{E}{\text{MeV}}}$$

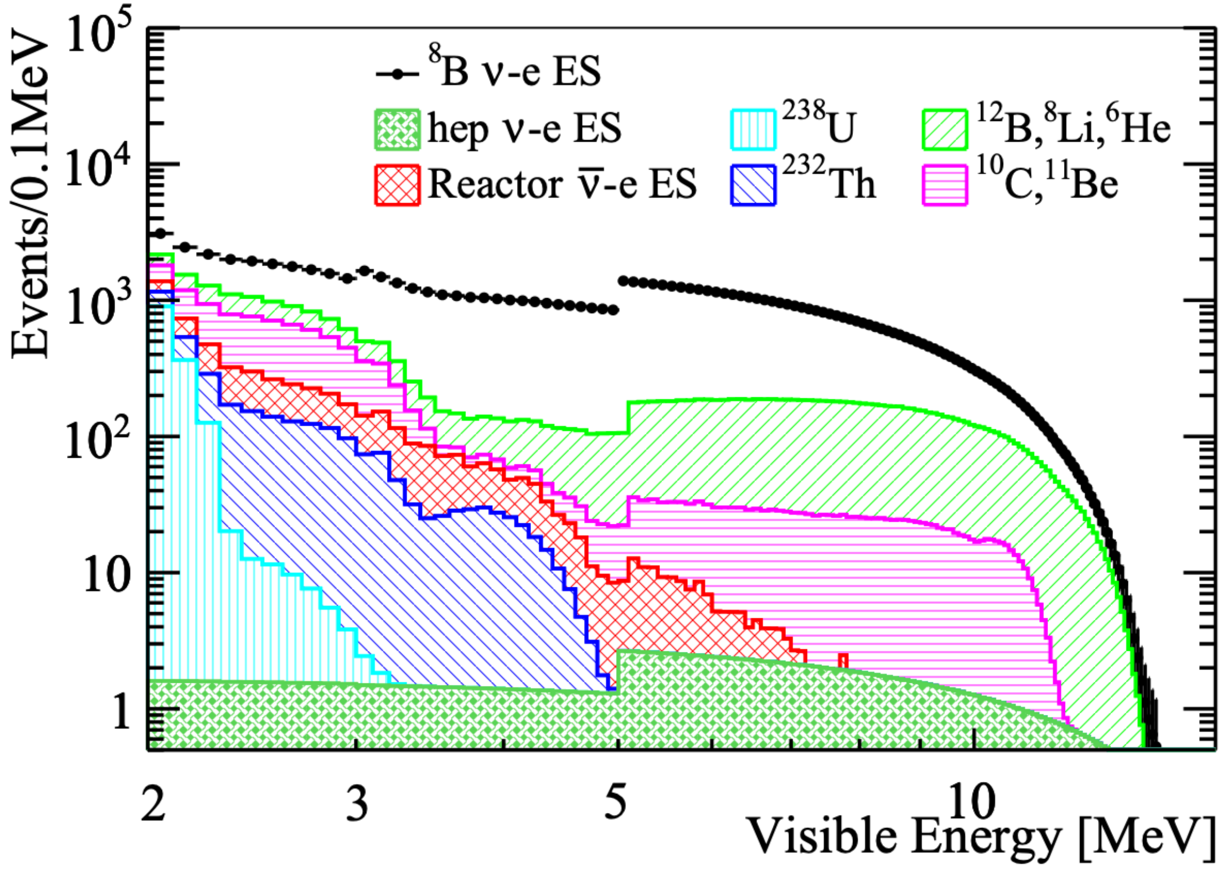


Large fiducial volume and **excellent energy resolution**: JUNO is the best neutrino detector for 5.5 MeV solar FIPs.

BACKGROUND SPECTRUM

JUNO will be able to detect ^{8}B solar neutrinos.

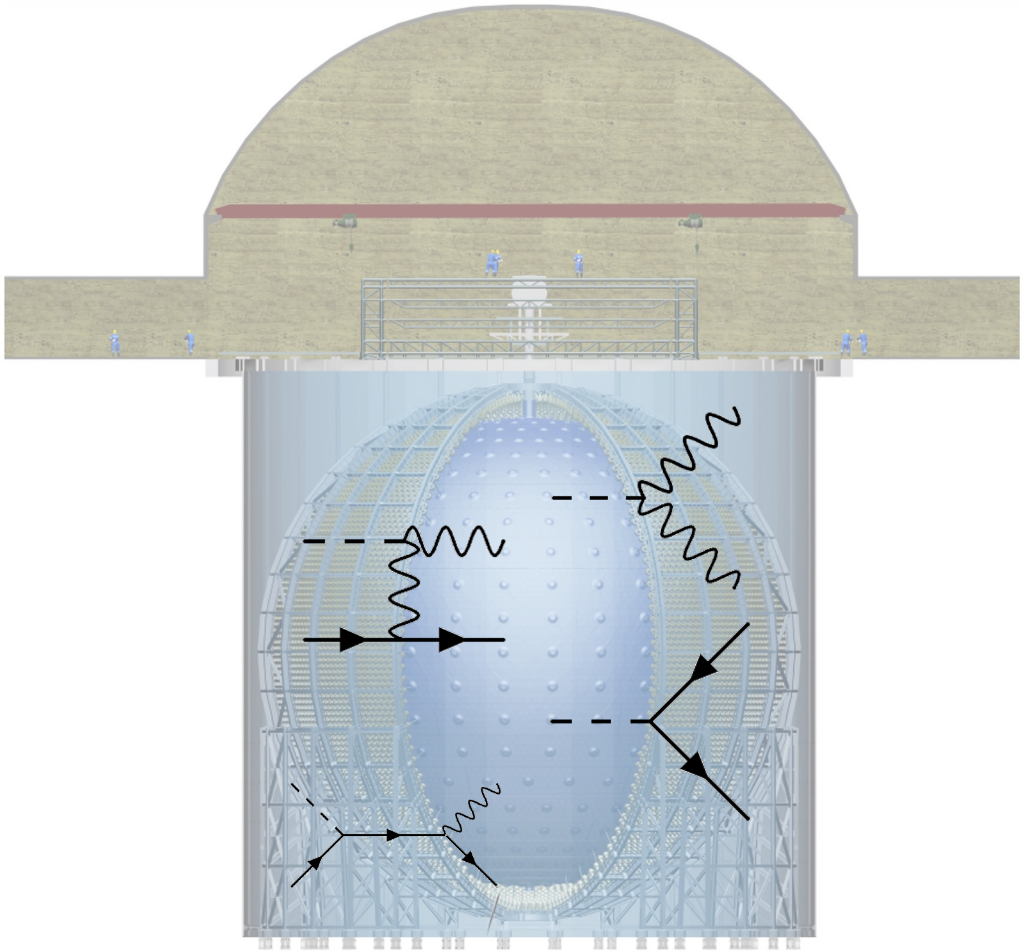
No available data: expected spectrum taken from JUNO coll., Chin.Phys. C 45 (2021).



In 10 yrs of data taking: 60,000 solar neutrino events
30,000 radioactive background events → Background for FIP-induced events

FIP SIGNAL

Detection channels:
1. Interaction with the detector material
2. Visible decays in the detector.



FIP-induced signal modelled with a Gaussian

$$N_X = \frac{S}{\sqrt{2\pi}\bar{\sigma}} e^{-\frac{(E-\bar{E})^2}{2\,\bar{\sigma}^2}}$$

S FIP peak intensity

$\bar{E} = 5.5$ MeV

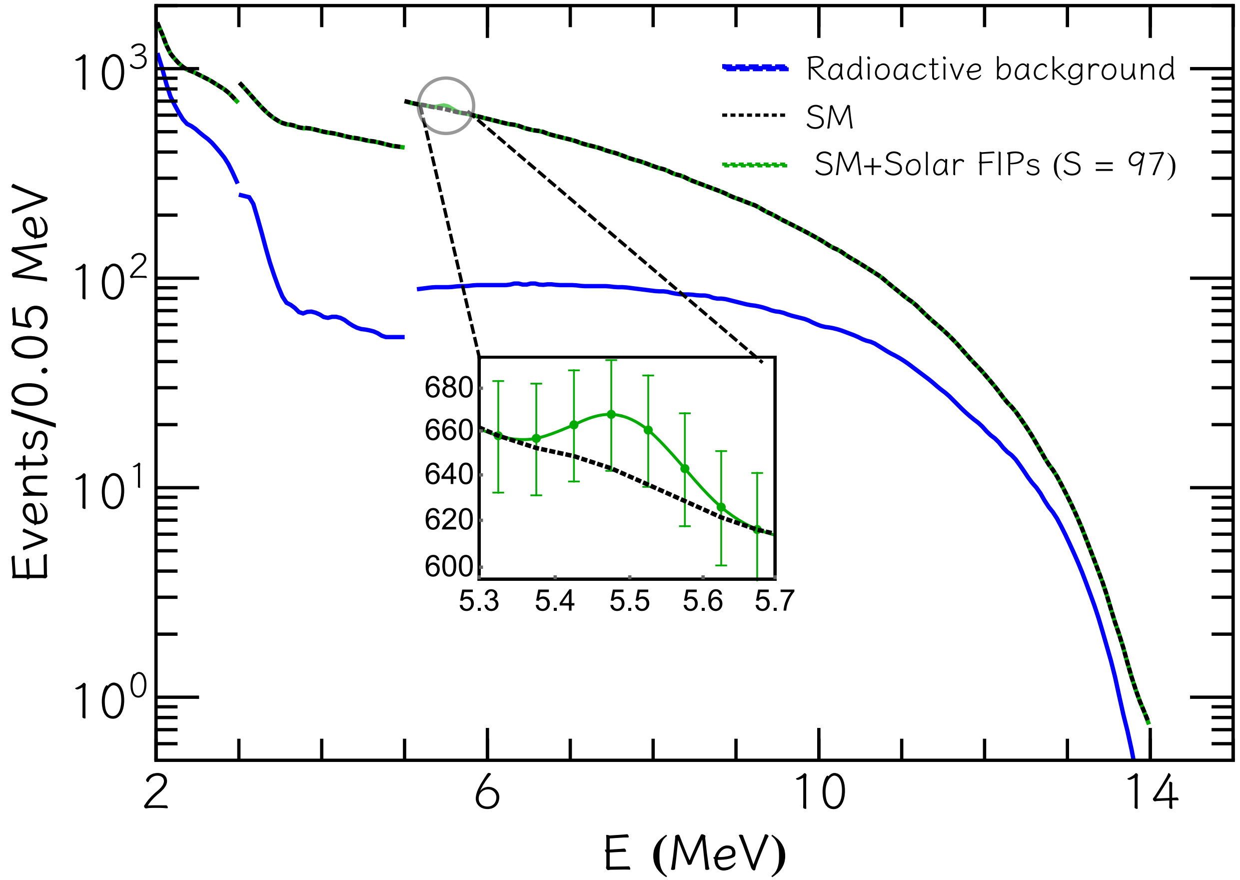
$\bar{\sigma} = 0.07$ MeV

PREDICTED EVENTS

$$N_{\mathrm{pre}} = B_{\mathrm{sb}} + B_{\mathrm{rb}} + \frac{S}{\sqrt{2\pi}\bar{\sigma}} e^{-\frac{(E-\bar{E})^2}{2\bar{\sigma}^2}}$$

SM background

FIP signal



χ^2 ANALYSIS

$$\chi^2 = 2\times\sum_i\left(N_{i,\text{pred}} - N_{i,\text{exp}} + N_{i,\text{exp}}\times\log\frac{N_{i,\text{exp}}}{N_{i,\text{pre}}}\right) + \left(\frac{\varepsilon_{\text{sb}}}{\sigma_{\text{sb}}}\right)^2 + \left(\frac{\varepsilon_{\text{rb}}}{\sigma_{\text{rb}}}\right)^2$$

$$N_{i,\text{pre}} = (1+\varepsilon_{\text{sb}})\times B_{i,\text{sb}} + (1+\varepsilon_{\text{rb}})\times B_{i,\text{rb}} + \frac{S}{\sqrt{2\pi}\bar{\sigma}}e^{-\frac{(E_i-\bar{E})^2}{2\,\bar{\sigma}^2}}$$

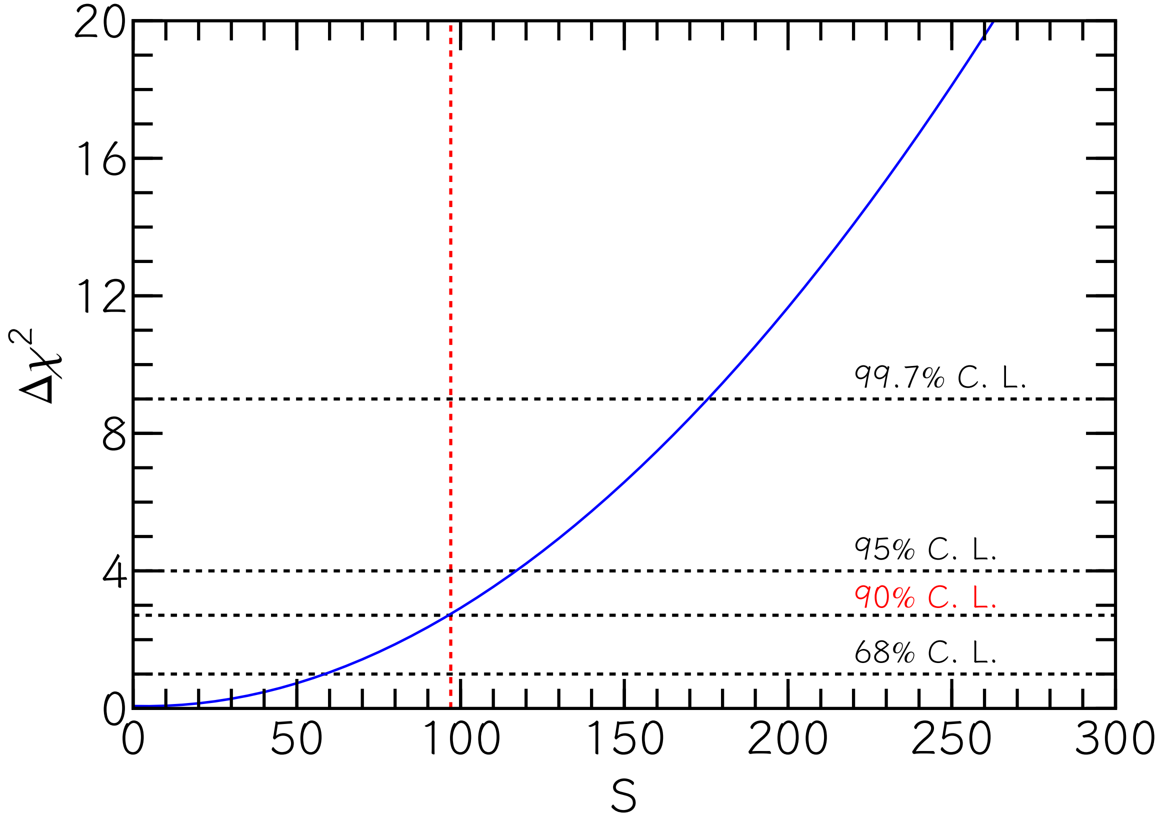
$$N_{i,\text{exp}} = B_{i,\text{sb}} + B_{i,\text{rb}}$$

$\sigma_{\text{sb}} = 5\%$

$\sigma_{rb} = 15\%$

Background uncertainties

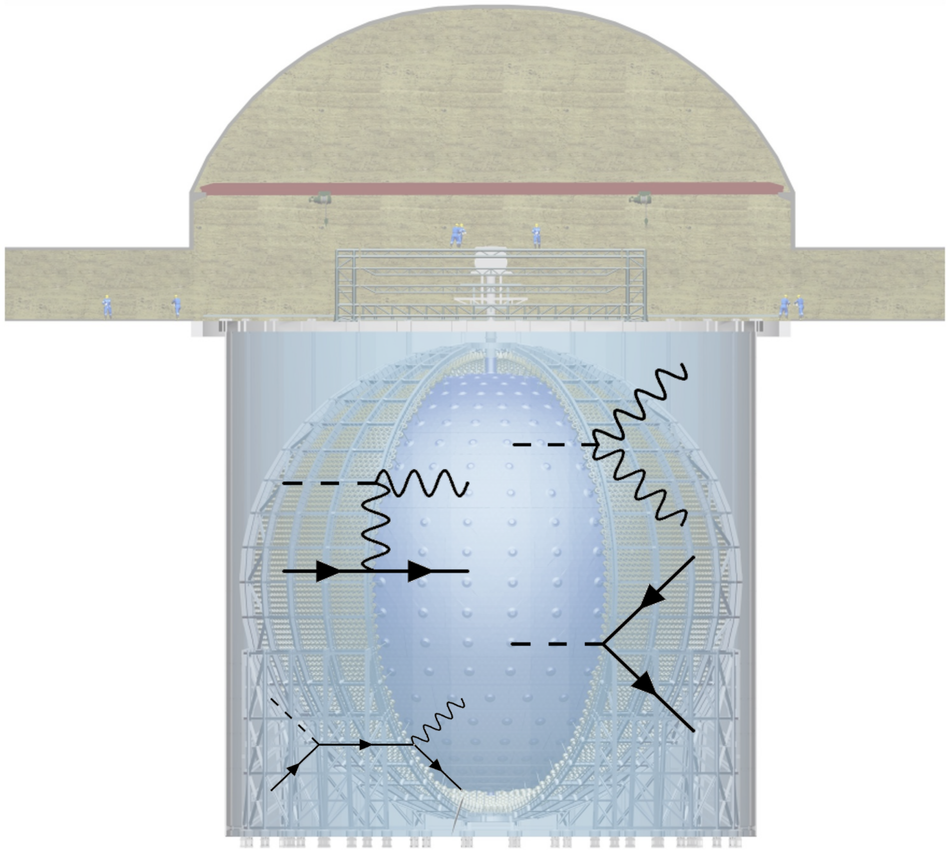
$S_{\text{lim}} = 97$ counts in 10 yrs



JUNO SENSITIVITY

The JUNO sensitivity at 90 % Confidence Level is found requiring

$$S_{\text{events}} \leq S_{\text{lim}}$$



JUNO SENSITIVITY

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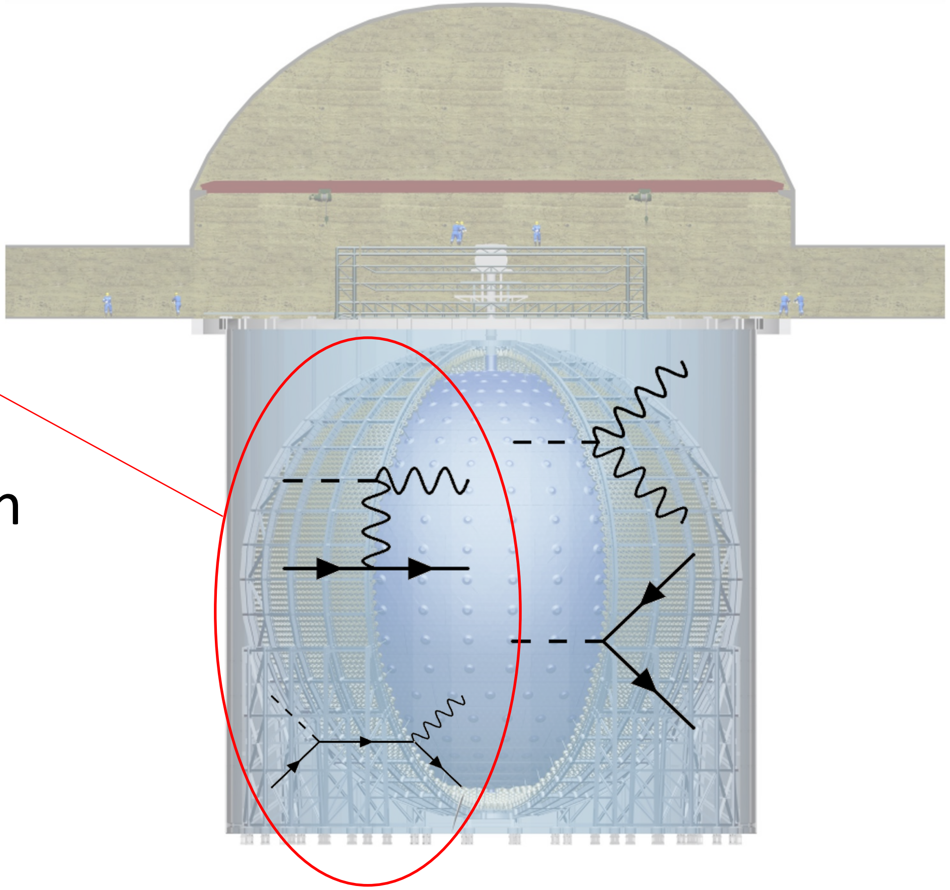
INTERACTION WITH MATTER

$$S_{\text{scatt}} = \Phi_X \, \sigma_X \, N_T \, T \, \varepsilon$$



σ_X interaction cross section
N_T number of targets
$T = 10$ yrs
$\varepsilon = 1$

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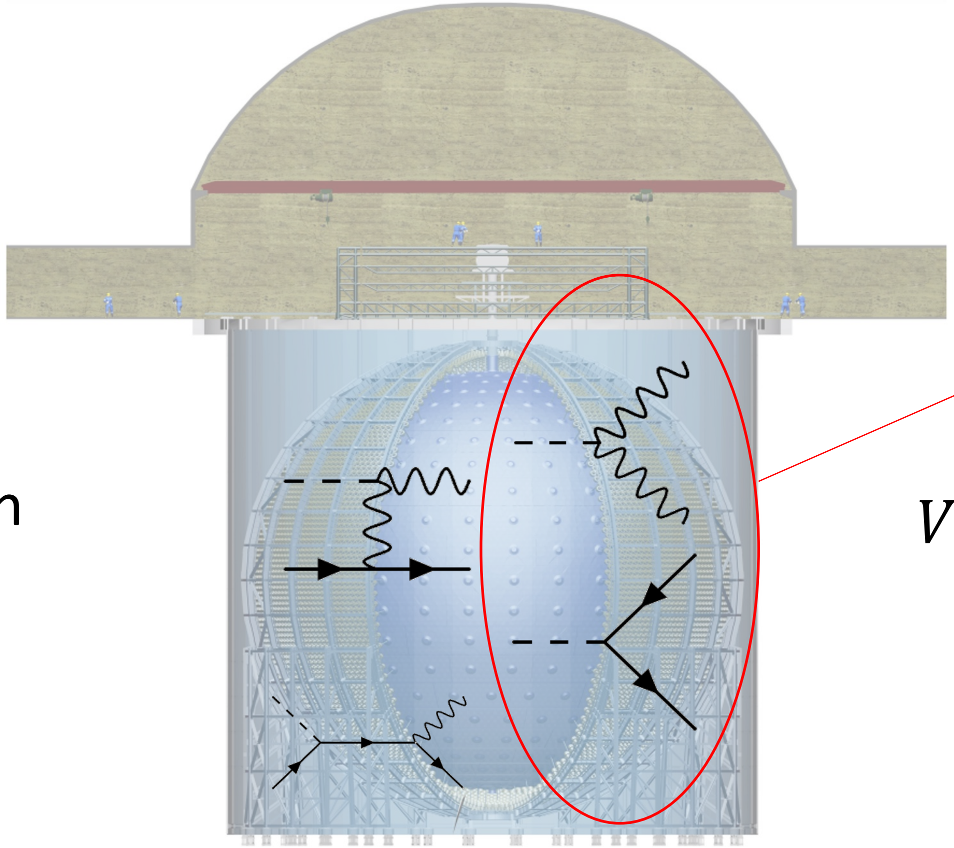


VISIBLE DECAYS

$$S_{\text{dec}} = \Phi_X \frac{V}{l_i} T \, \varepsilon$$

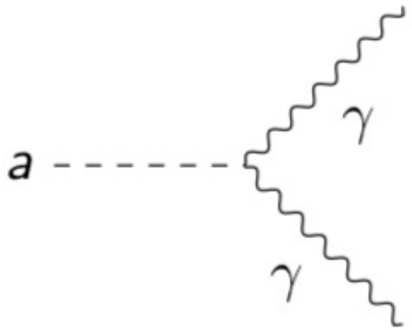
V sphere of radius 16.5 m

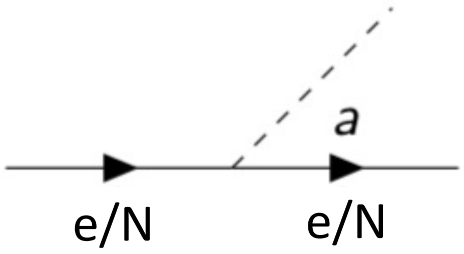
AXIONS

Axion-like particles, or simply axions, are pseudoscalar particles introduced in UV completions of the Standard Model (SM). [Di Luzio et al., Phys. Rept. 870 (2020)]

We consider axions simultaneously interacting with nucleons and photons or electrons

$$\mathcal{L}_a = \frac{1}{2}(\partial_\mu a)^2 - m_a^2 a^2 - \frac{1}{4} g_{a\gamma}\, a\, \tilde{F}^{\mu\nu} F_{\mu\nu} - i\, g_{ae} a \bar{e}\gamma_5 e - i a \bar{N}\, \gamma_5 (g_{0aN} + \tau_3 g_{3aN}) N$$





$$g_{ap} = g_{0aN} + g_{3aN}$$

$$g_{an} = g_{0aN} - g_{3aN}$$

AXION FLUX FROM DEUTERIUM FUSION

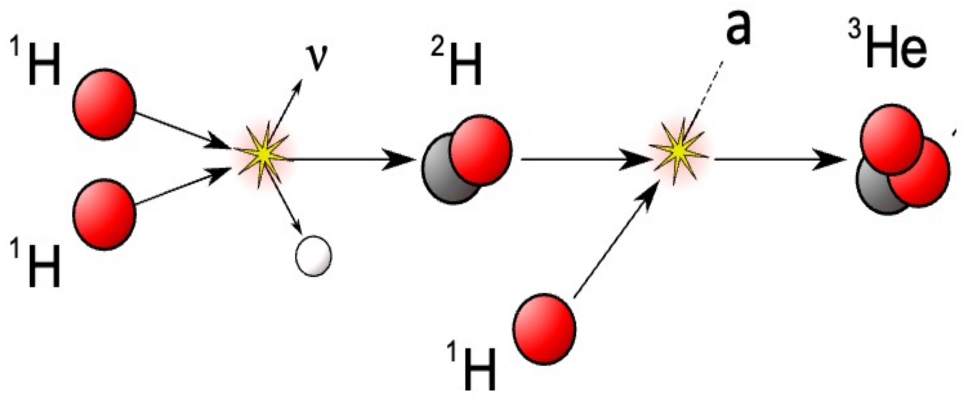
The 5.5 MeV axion flux on Earth is

$$\Phi_a = \Phi_{\nu pp} \frac{\Gamma_a}{\Gamma_\gamma}\, e^{-d_\odot/l} = 3.23\times 10^{10} g_{3aN}^2 \left(\frac{k_a}{k_\gamma}\right)^3 e^{-d_\odot/l}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$$

$$\Phi_{\nu pp} = 6.0\times 10^{10}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$$ [Borexino coll., PRD 100 (2019)]

$$\frac{\Gamma_a}{\Gamma_\gamma} = 0.54\, g_{3aN}^2 \left(\frac{k_a}{k_\gamma}\right)^3$$ [Donnelly et al., PRD 18 (1978), Schmid et al., PRC 56 (1997)]

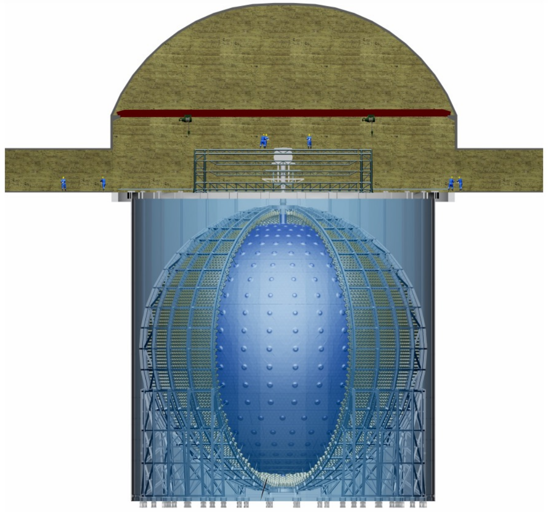
5.49 MeV



DETECTION PROCESSES

$$p + d \to 3\text{He} + a(5.5\ \text{MeV})$$

$$\Phi_X \propto g_{3aN}^2$$



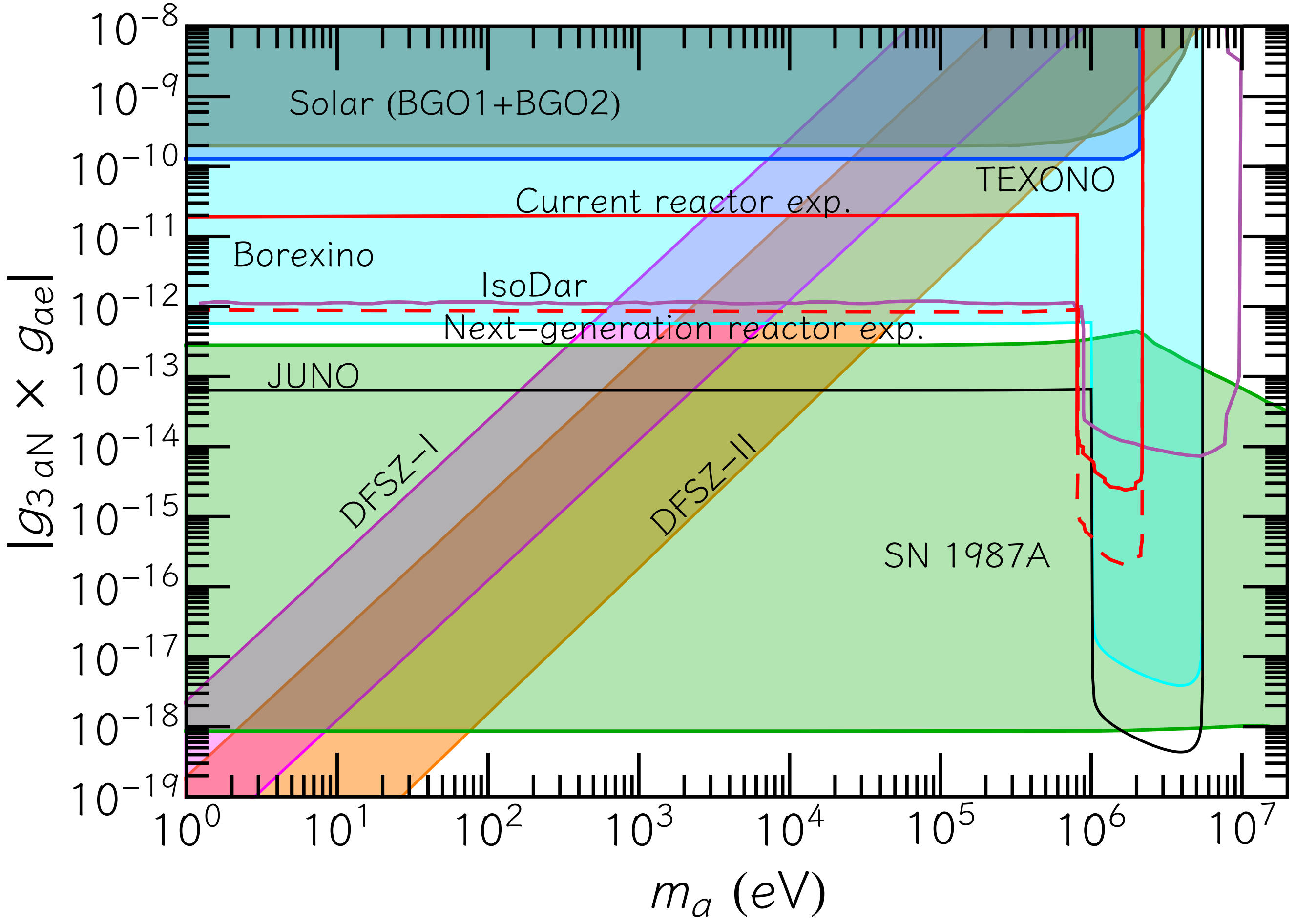
$$a \to e^+e^-$$
$$a + e \to \gamma + e$$
$$\sigma_{ae} \propto g_{ae}^2$$

$$a \to \gamma\gamma$$
$$a + Ze \to \gamma + e$$
$$\sigma_{a\gamma} \propto g_{a\gamma}^2$$

SENSITIVITY ON $g_{3aN} \times g_{ae}$

[G.L. et al., PRD 106 (2022) 12, 123007, arXiv:2209.11780]

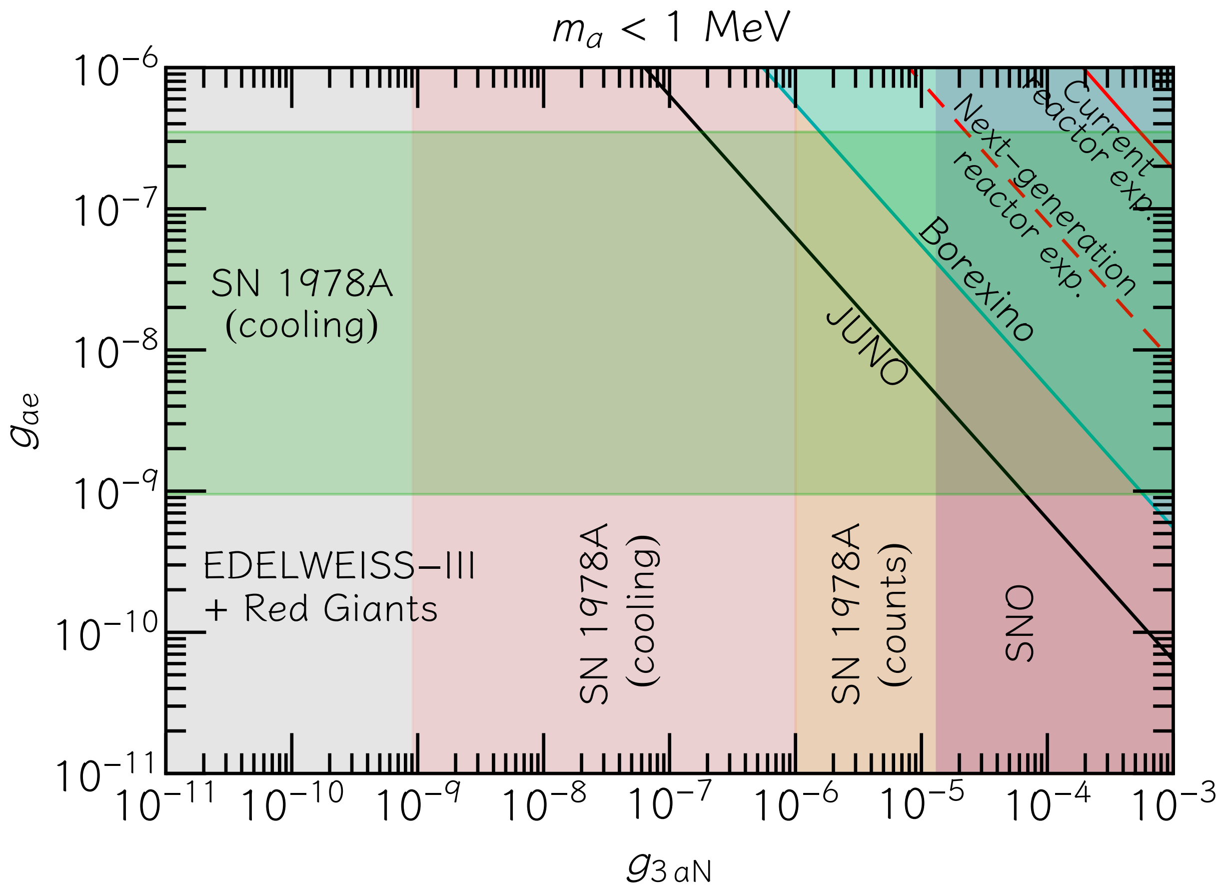
JUNO can set the strongest experimental limits on $|g_{a3N} \times g_{ae}|$ for $m_a \lesssim 5.5$ MeV.

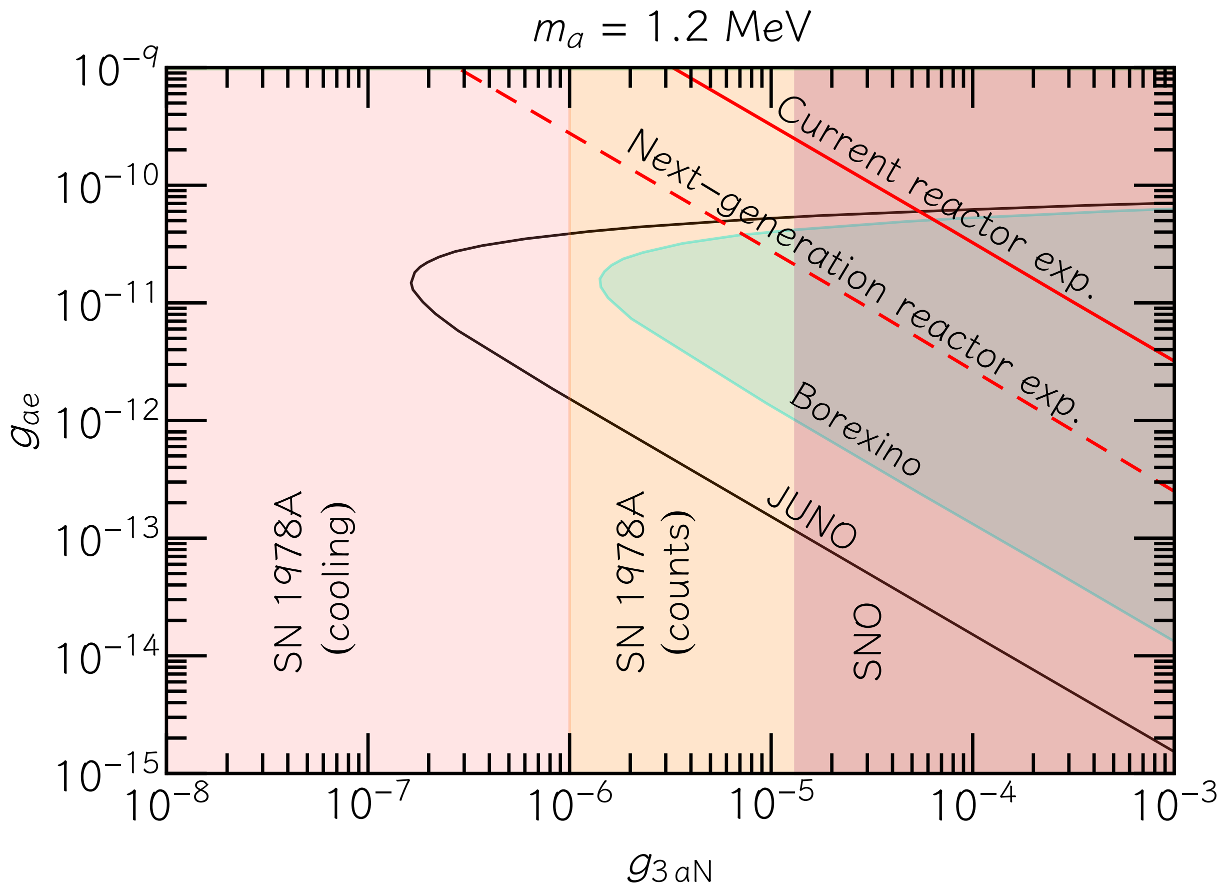


For $m_a > 2m_e$ it is assumed no reduction in the flux due to in-flight decay ($g_{ae} \lesssim 10^{-12}$).

SENSITIVITY ON (g_{3aN}, g_{ae})

[G.L. et al., PRD 106 (2022) 12, 123007, arXiv:2209.11780]





$$S_C = \Phi_a \, \sigma_C \, N_e \, T \approx g_{3aN}^2 \, g_{ae}^2 \, 2.42 \times 10^{28}$$

$$S_{e^+e^-} = \Phi_a \frac{V}{l_e} \, T$$

SENSITIVITY ON $g_{3aN} \times g_{a\gamma}$

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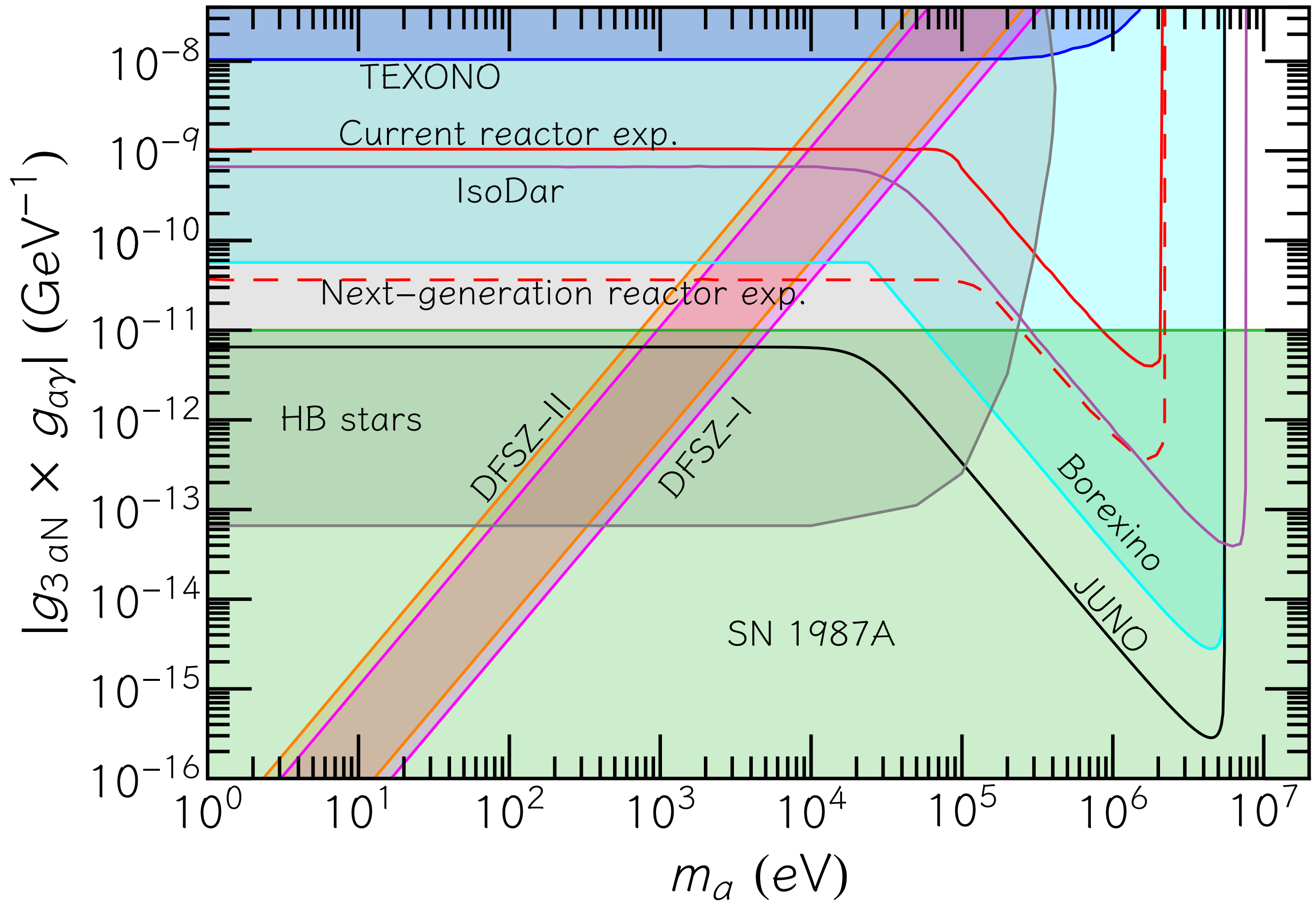
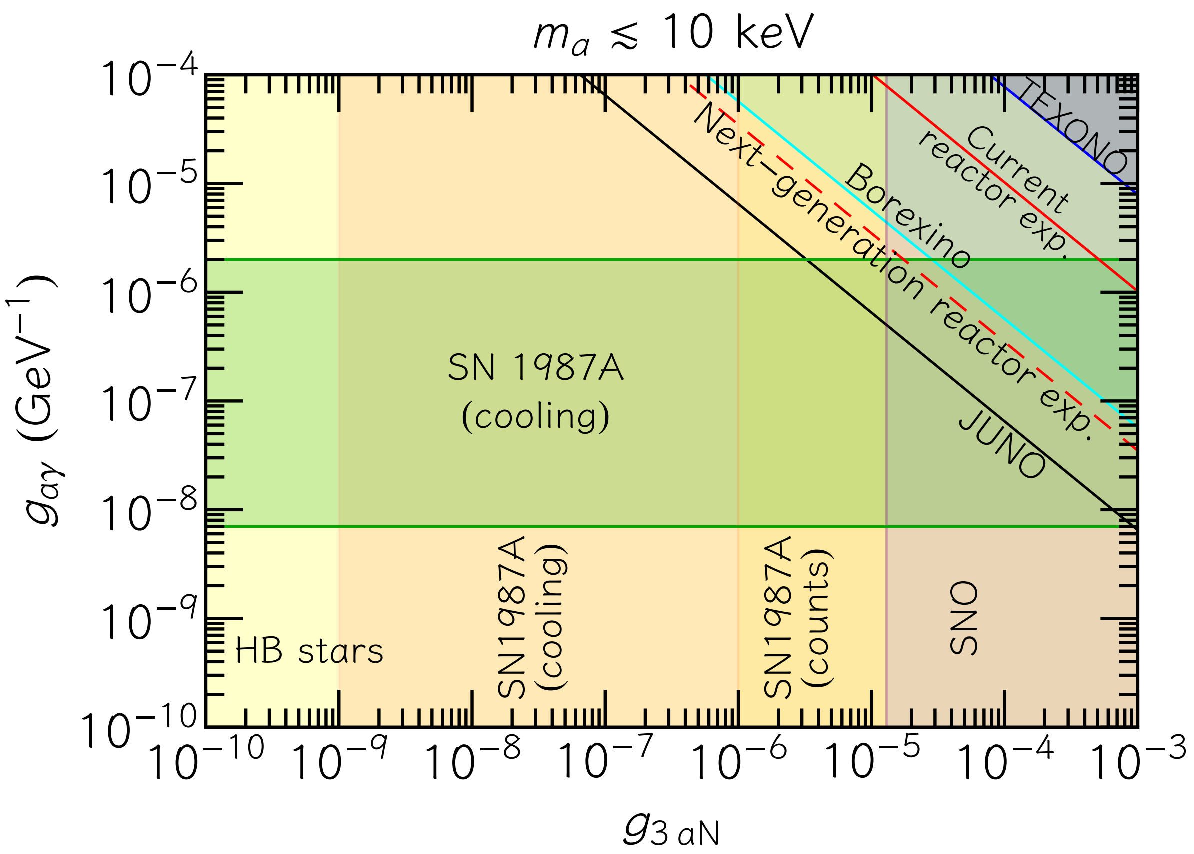
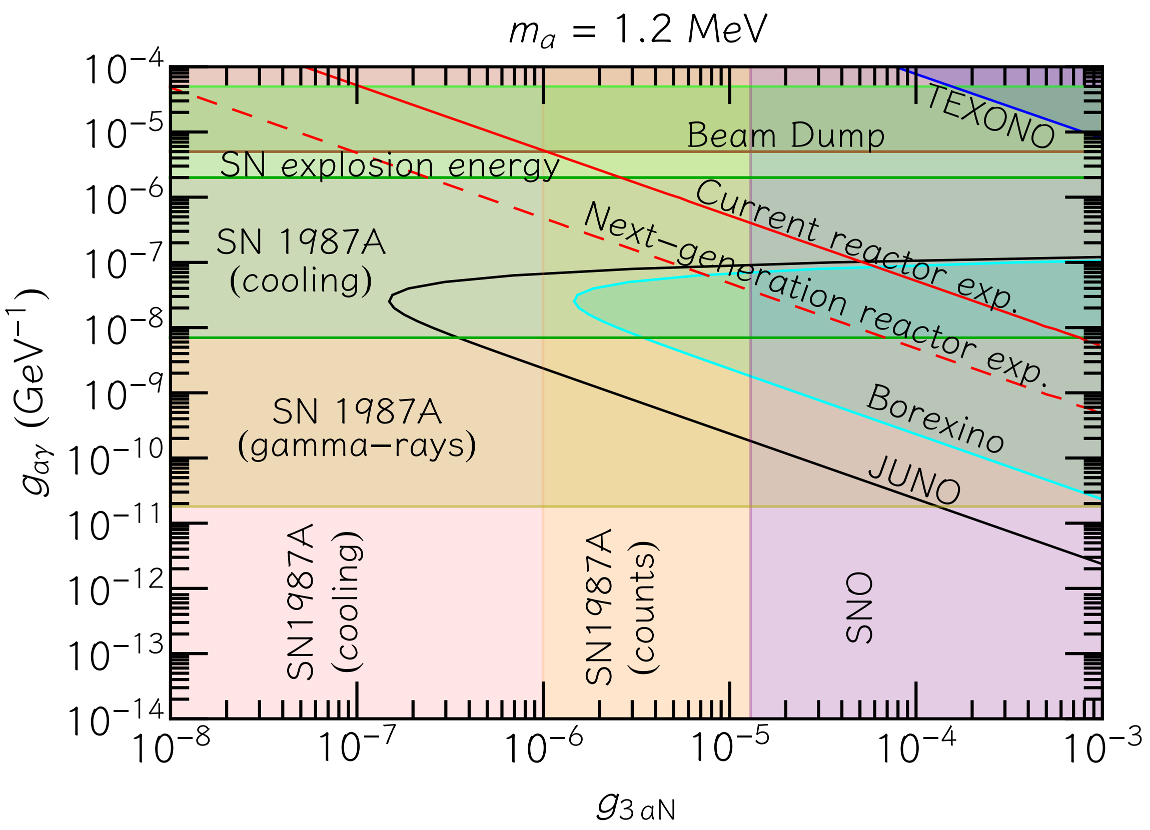


Here, we assume $e^{-d_\odot/l_\gamma} \approx 1$, i.e. $m_a^2(\mathrm{eV}) \times g_{a\gamma}(\mathrm{GeV}^{-1}) < 1.2 \times 10^4\ \mathrm{eV}^2\ \mathrm{GeV}^{-1}$.

SENSITIVITY ON $(g_{3aN}, g_{a\gamma})$

[G.L. et al., PRD 106 (2022) 12, 123007, arXiv:2209.11780]





$$S_P = \Phi_a\, \sigma_P\, N_C\, T \propto g_{3aN}^2\, g_{a\gamma}^2$$

$$S_{\gamma\gamma} = \Phi_a \frac{V}{l_\gamma}\, T$$

HIDDEN VECTORS

[Okun (1982), Holdom (1986), Davidson (1979), Fayet (1980), Fayet (1981), Fayet (1990)]

Massive spin-one particles introduced as gauge bosons of an additional Abelian symmetry.

$$\mathcal{L}_{\gamma'} = -\frac{1}{4} F'_{\mu\nu} F'^{\mu\nu} + \frac{m^2_{\gamma'}}{2} A'_{\mu} A'^{\mu} + \frac{\varepsilon}{2} F_{\mu\nu} F'^{\mu\nu} + e' \, J'^{\mu}(q'_{\mathrm{e}}) \, A'_{\mu}$$

- Kinetic mixing (ε): Dark photons.
- Plasma mixing (q'_{e}): Dark gauge bosons.

HIDDEN VECTORS

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- Kinetic mixing (ε): Dark photons.
- Plasma mixing (q'_Ψ): Dark gauge bosons.

DARK PHOTONS

- Massive vector particles: 2 transverse (T) and 1 longitudinal (L) polarization states.
- Interactions affected by in-medium effects. [Okun, Sov.Phys. JETP 56 (1982), Holdom, PLB 166 (1986)]

$$\mathcal{L}\Big|_{\mathrm{vacuum}} = \varepsilon e\, J^{\mu}_{\mathrm{EM}} A'_{\mu}$$

$$\mathcal{L}\Big|_{\mathrm{medium}} = \varepsilon \frac{m^2_{\gamma'}}{m^2_{\gamma'} - \pi_{\mathrm{T,L}}} e\, J^{\mu}_{\mathrm{EM}} A'_{\mu}$$

Medium effects accounted for in $\pi_{\mathrm{T,L}}$: [An et al., PLB 725 (2013), Redondo JCAP 07 (2008)]

$$\Re[\pi_{\mathrm{T}}] \simeq \omega^2_{\mathrm{pl}} \qquad \Re[\pi_{\mathrm{L}}] \simeq \omega^2_{\mathrm{pl}}\left(1 - \frac{k^2}{\omega^2}\right) \qquad \Im[\pi_{\mathrm{T,L}}] \simeq -\omega(1-\omega)\Gamma^{\mathrm{abs}}_{\mathrm{T,L}}$$

DARK PHOTON FLUX FROM DEUTERIUM FUSION

The 5.5 MeV dark photon flux on Earth is

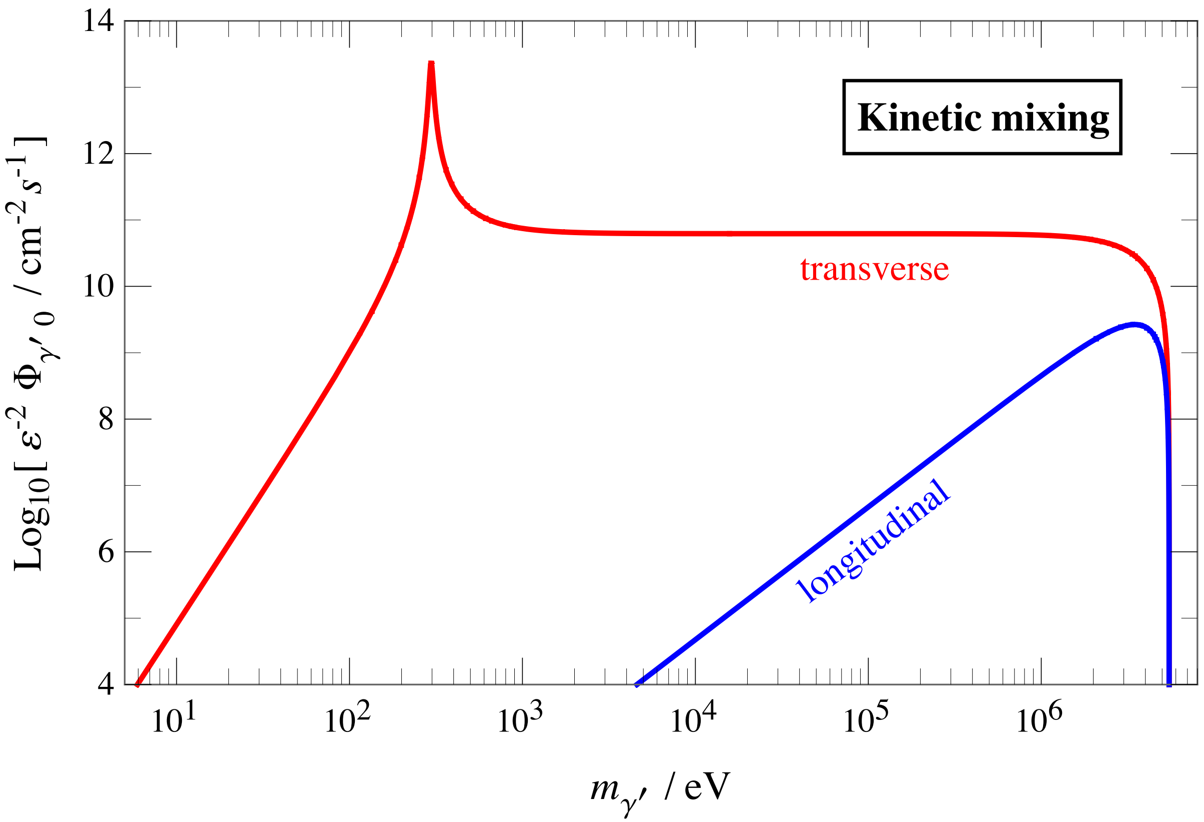
$$\Phi_{\gamma'} = \sum_{P=L,T} \Phi_{\gamma' P} = \sum_{P=L,T} \exp[-\tau_{\rm abs}] \exp\left[-\Gamma_{\gamma'} \frac{m_{\gamma'}}{\omega} \frac{d_\odot}{v_{\gamma'}}\right] \Phi_{\gamma' 0P}$$

[Donnelly et al., PRD 18 (1978), Avignone et al., PRD 37 (1988)]

$$\Phi_{\gamma' 0\rm T,L} \propto \left| \varepsilon e \frac{m_{\gamma'}^2}{m_{\gamma'}^2 - \pi_{\rm T,L}} \right|^2 \phi_\gamma$$

T states resonantly produced when $m_{\gamma'} \simeq \omega_{\rm pl} \simeq 0.3$ keV

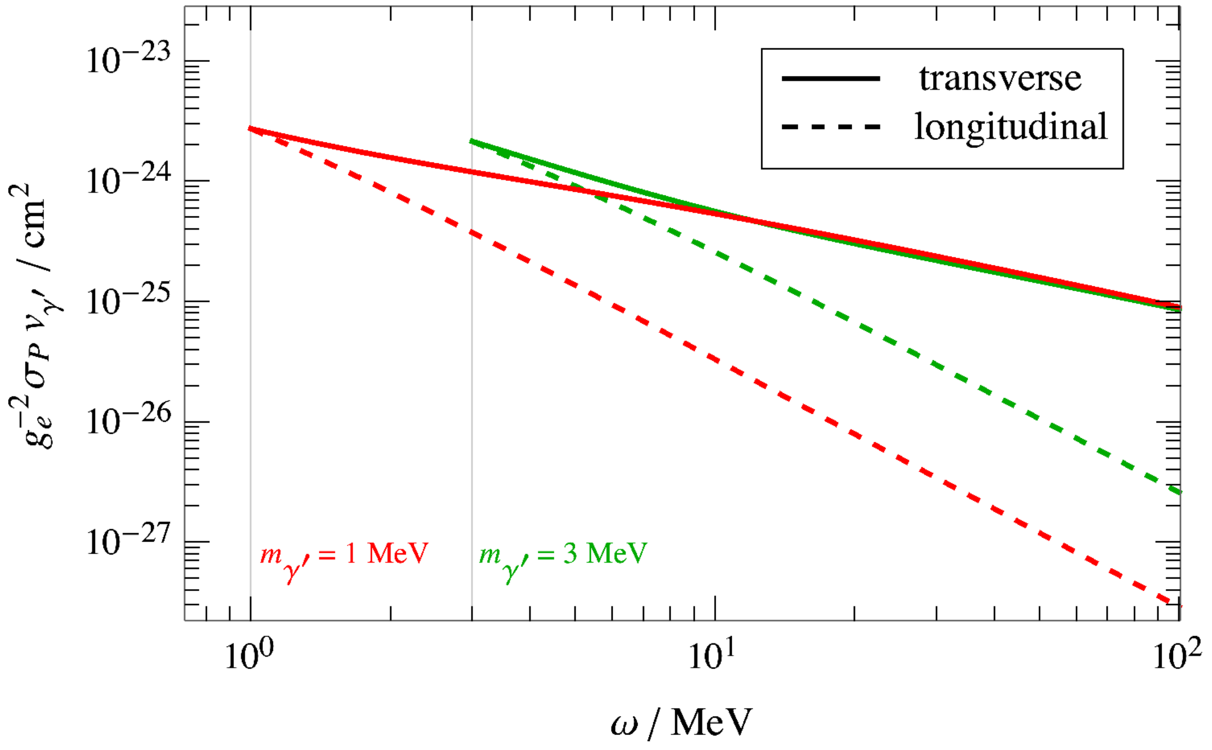
No resonance for L states since $\omega = 5.5$ MeV $\gg \omega_{\rm pl}$



TERRESTRIAL DETECTION

The 5.5 MeV Dark Photons will give an observable signal in JUNO via $\gamma' + e \to \gamma + e$.

$$S_{\rm ev} = \sum_{P={\rm T,L}} \Phi_{\gamma' P}\, N_e\, \sigma_P\, T$$

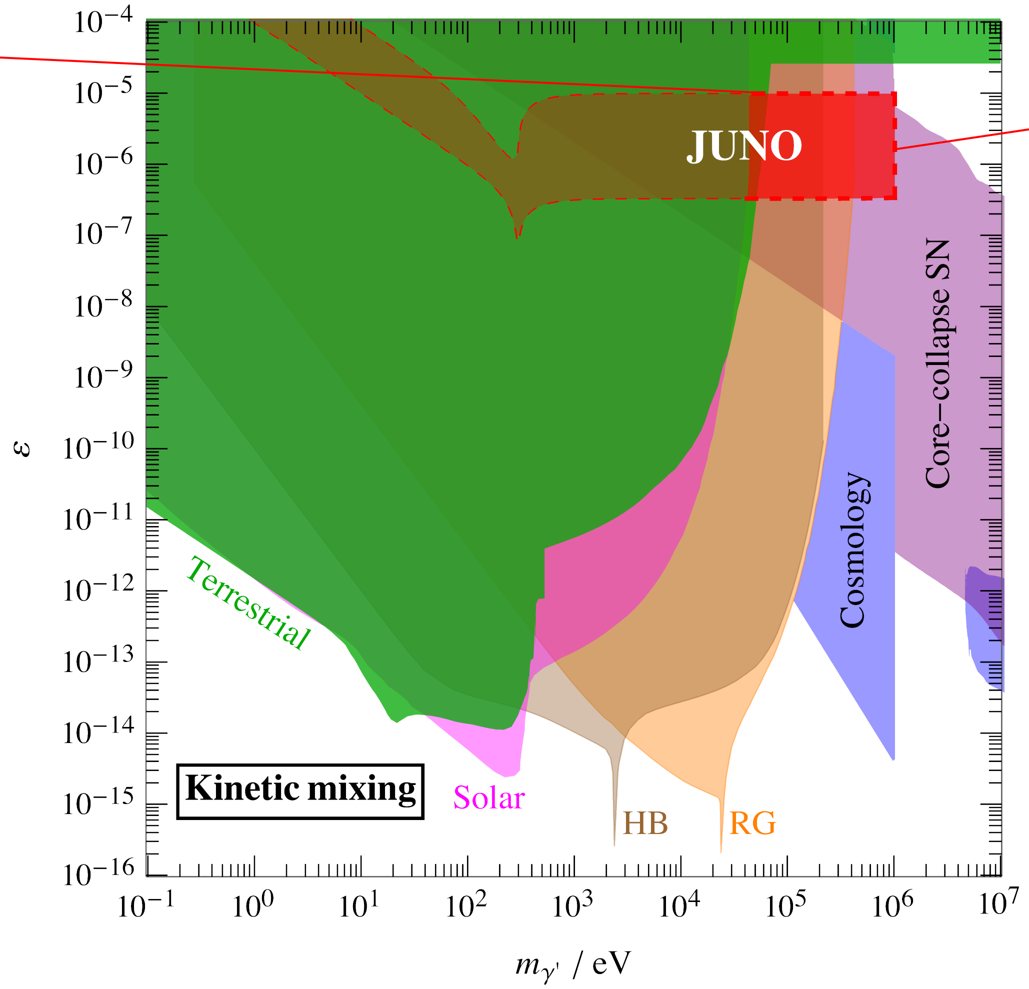


$$\sigma_P \propto g_e^2 \equiv \varepsilon^2 e^2$$

JUNO SENSITIVITY ON DARK PHOTONS

[F. D'Eramo, G.L., N.Nath and S. Yun, arXiv:2305.14420]

Dark photons reabsorbed in the Sun



Dark photon flux suppressed by $\gamma' \to e^+e^-$

JUNO will set the strongest terrestrial limits for $m_{\gamma'} \gtrsim 50$ keV.

CONCLUSIONS

- Nuclear reactions in the Sun can produce feebly interacting particles (FIPs).
- The forthcoming neutrino detector JUNO can detect 5.5 MeV FIPs emitted in the deuterium fusion $\mathrm{p}(d,\ {}^{3}\mathrm{He})X$.
- JUNO is ideal to probe 5.5 MeV FIPs due to its large fiducial volume and excellent energy resolution.
- Projected limits on different combinations of axion couplings and hidden vectors (e.g., dark photons).

Thank you for your attention

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SUMMARY SLIDE

Abstract: Solar nuclear reactions can occasionally produce feebly interacting particles (FIPs) X that escape the solar interior without further interactions. In this talk, we focus on the second stage of the solar proton-proton chain and evaluate the fluxes of monochromatic 5.49 MeV FIPs produced by the p(d, He^3)X reaction, analyzing the potential to detect them with the forthcoming large underground neutrino oscillation experiment Jiangmen Underground Neutrino Observatory (JUNO). In particular, we forecast the JUNO sensitivity on different combinations of the axion couplings and on hidden vectors, identifying the regions of the parameter space where current terrestrial bounds will be improved.

Based on:

1. G. Lucente, N. Nath, F. Capozzi, M. Giannotti and A. Mirizzi, ``*Probing high-energy solar axion flux with a large scintillation neutrino detector*,'' Phys. Rev. D **106** (2022) no.12, 123007, doi:10.1103/PhysRevD.106.123007 [arXiv:2209.11780 [hep-ph]].
2. F. D'Eramo, G. Lucente, N. Nath and S. Yun, ``*Terrestrial detection of hidden vectors produced by solar nuclear reactions*,'' [arXiv:2305.14420 [hep-ph]].

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Key-Words and topic: Neutrino Theory and Cosmology, Neutrino Detectors, Feebly Interacting Particles.

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