Axions from Stellar Nuclear Transition

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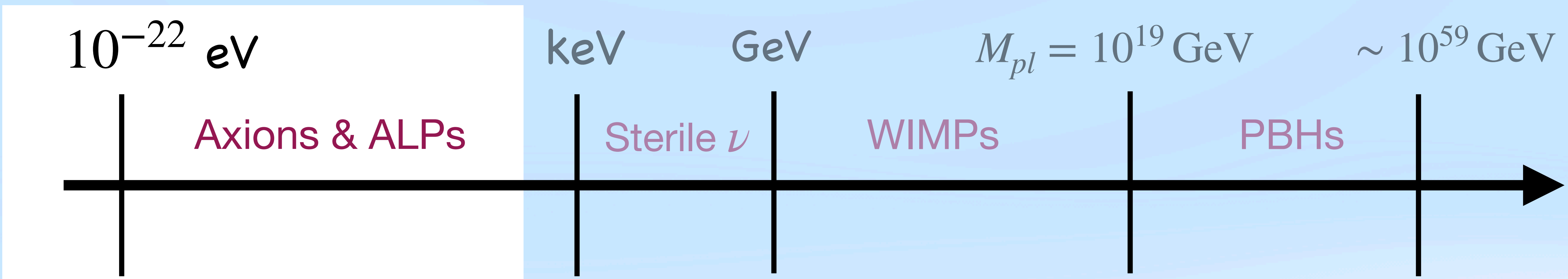
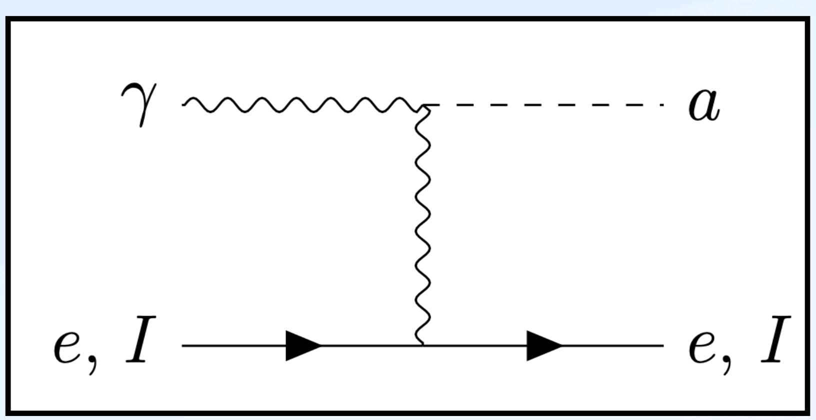
Axions & ALPs

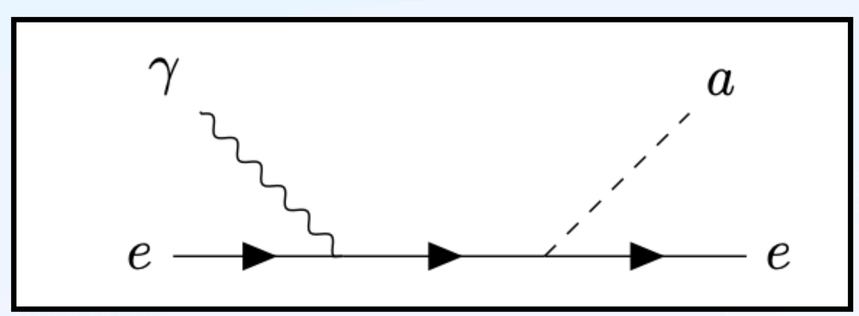
- Stars are natural laboratories for producing axions/ALPs.

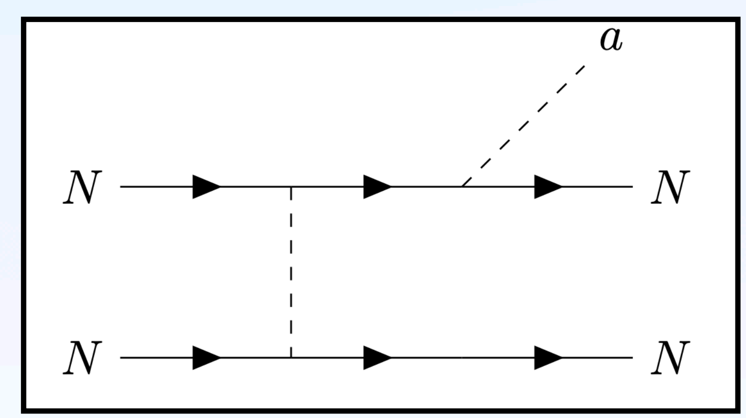


- Several Thermal processes:

Raffelt [1990], Turner [1990]...



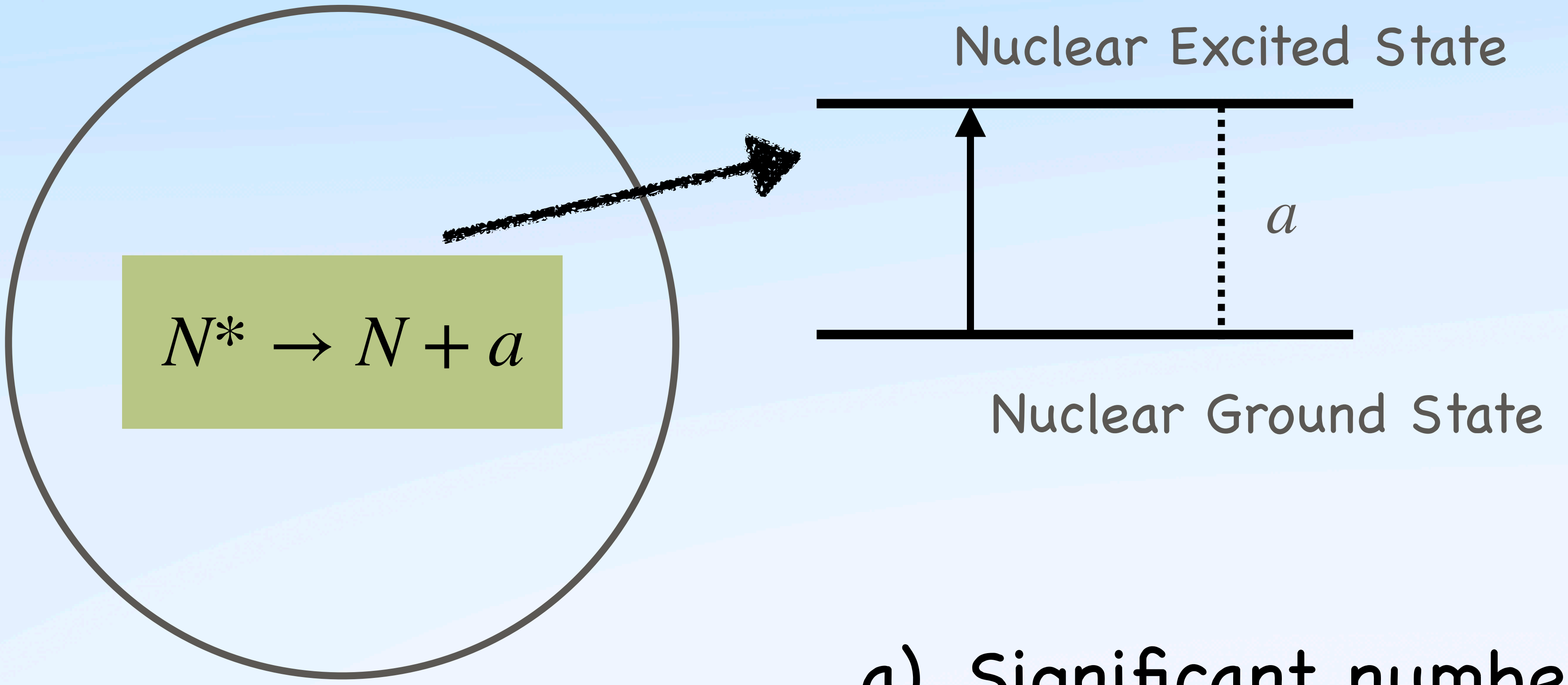




ALPs: Nuclear Transition

- ALPs can also be produced via nuclear transitions in the stars.

Haxton, Lee [PRL, 1991]



a) Significant number of nuclei

b) Hot core

ALPs: Nuclear Transition

- Lets take Sun as benchmark:

Typically, nuclear transitions are in ~MeV

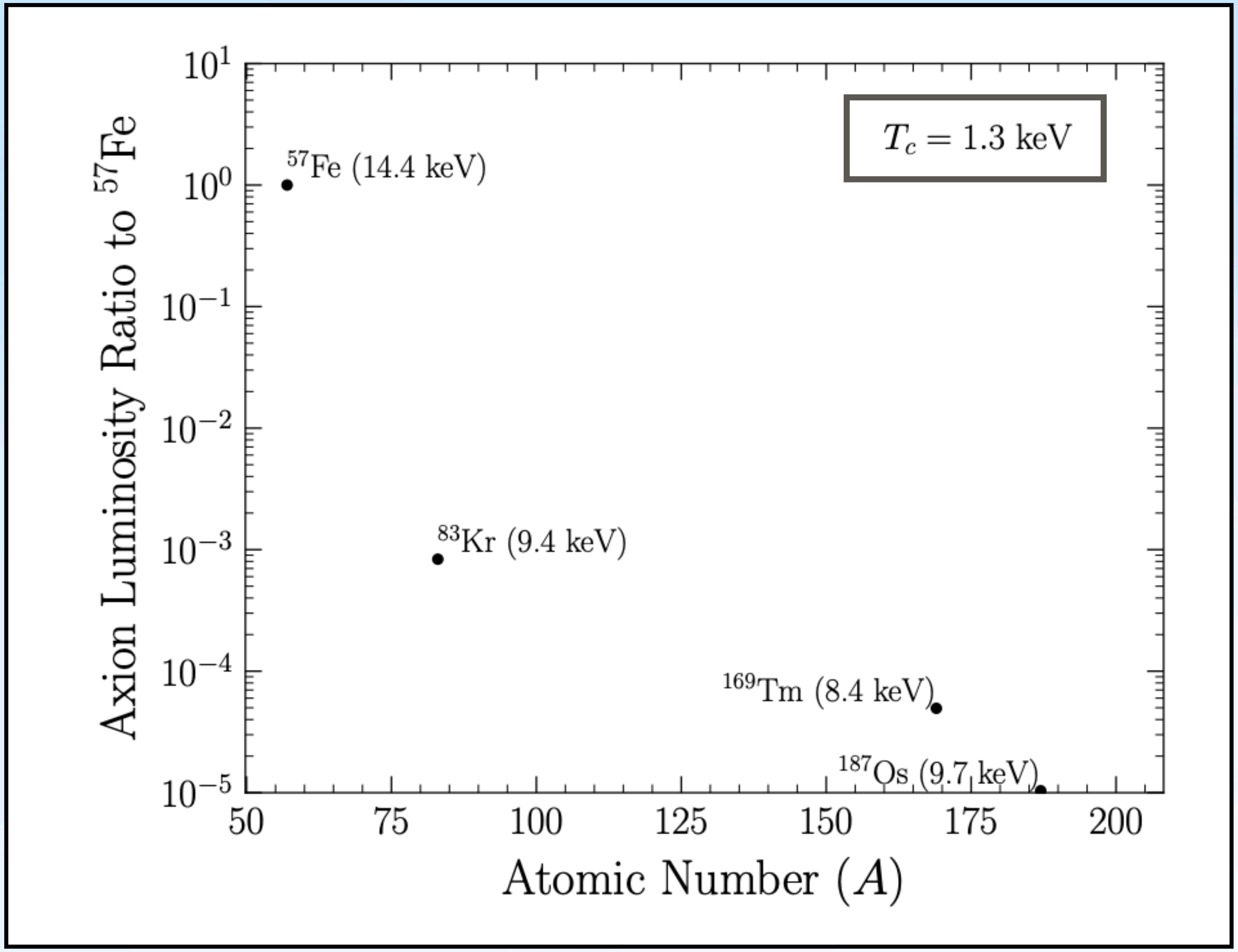
Solar core temperature: 1.3 keV

$$N_a \supset N e^{-E/k_B T_c}$$

Exponentially Suppressed Production!

ALPs: Nuclear Transition

- Low-lying nuclear isotopes: ^{57}Fe (14.4 keV)



$$e^{-14.4/1.3} = 10^{-5} \neq 0$$

Ray (with Ning, Safdi) [PRD, 2026]

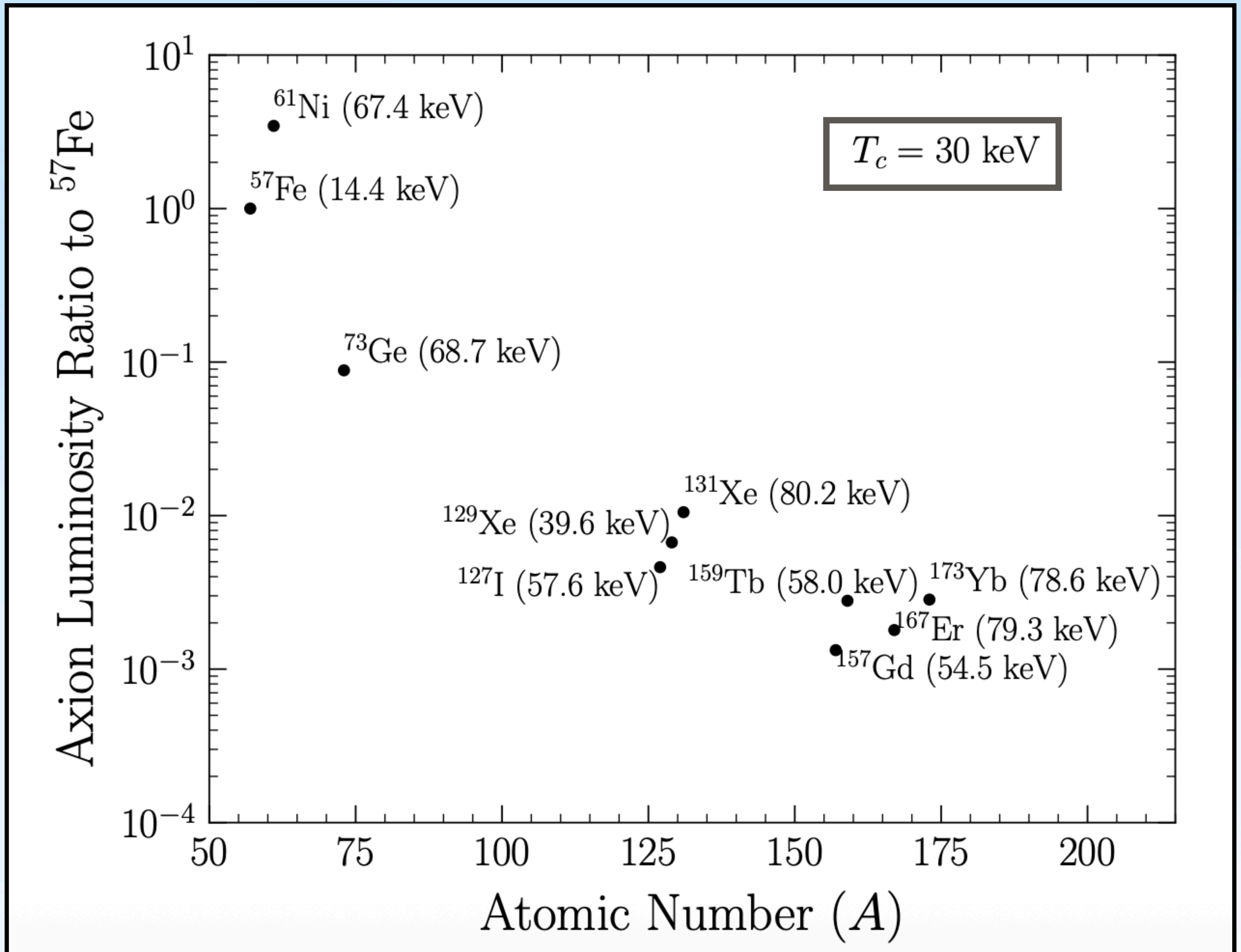
ALPs: Nuclear Transition

- Low-lying nuclear isotopes + hot stars:

^{57}Fe (14.4 keV),

^{61}Ni (67.4 keV),

^{73}Ge (68.7 keV)



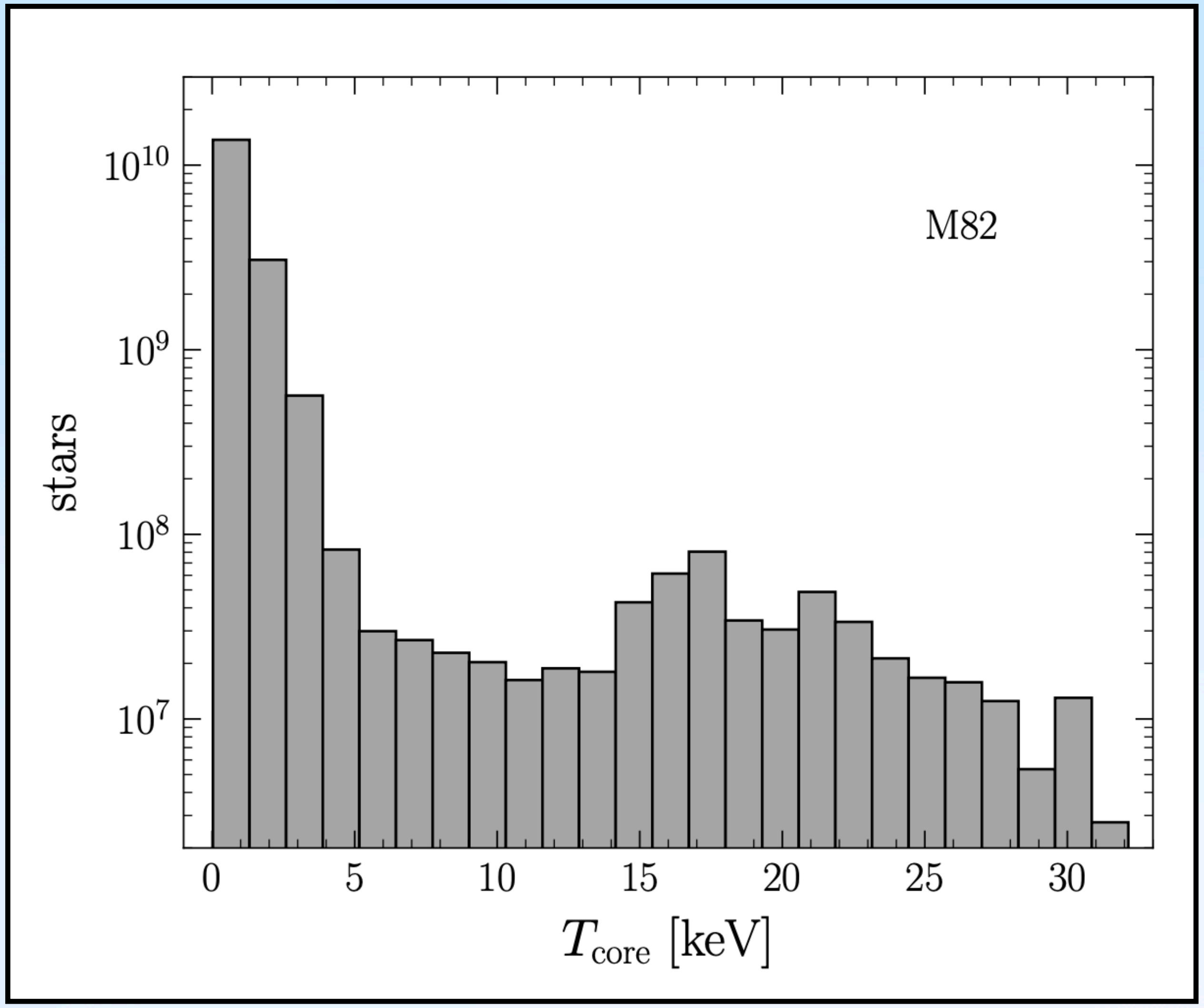
Many isotopes are important!

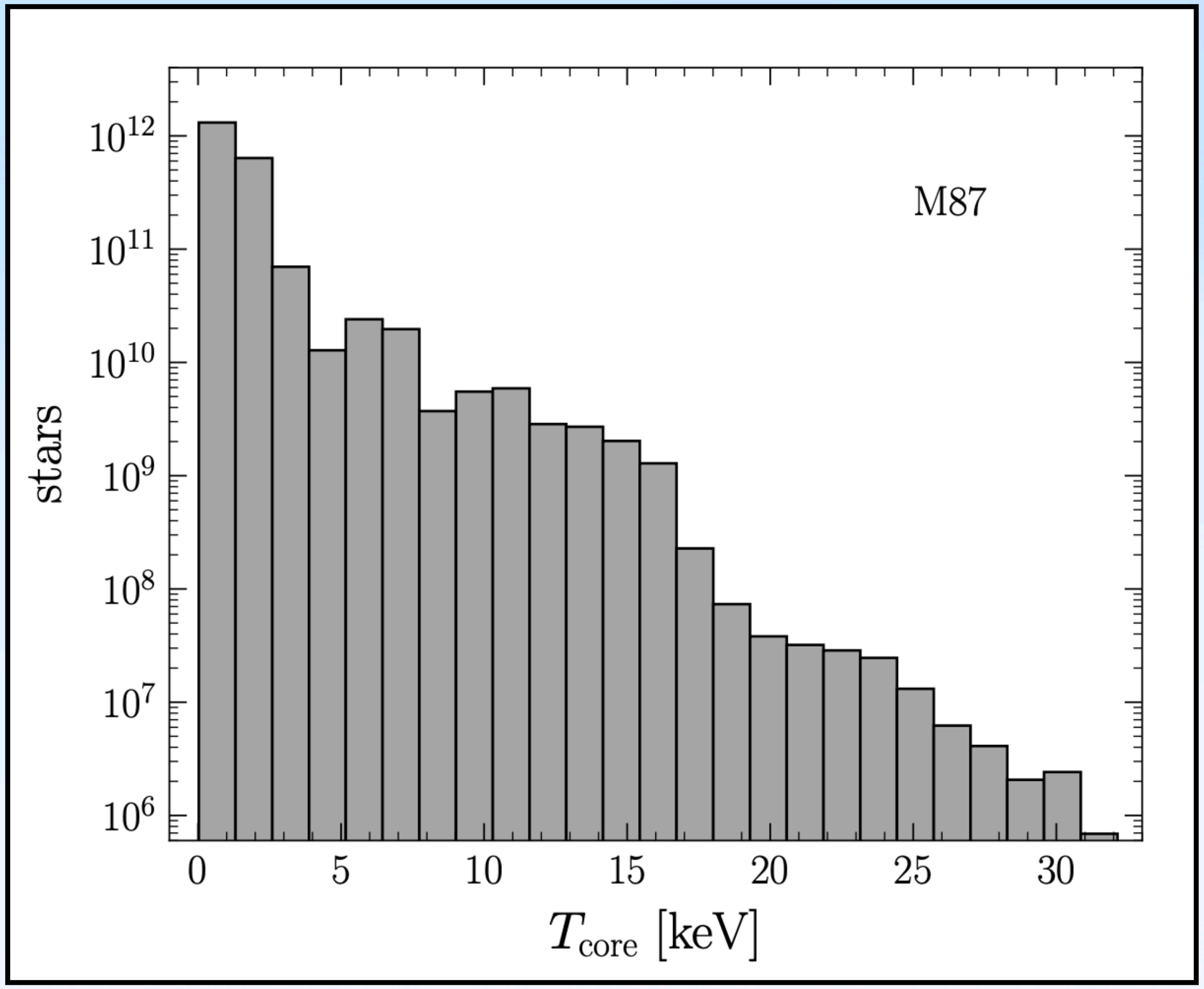
Ray (with Ning, Safdi) [PRD, 2026]

ALPs: Nuclear Transition

- We consider a population of stars in M82 and M87.

not very far and huge number of hot stars





Ray (with Ning, Safdi) [PRD, 2026]

ALPs: Nuclear Transition

- We calculate axion emission from each stars!

M82: 3.5 Mpc

M87: 16.5 Mpc

M82 galaxy (Source: HST)

ALP Luminosity

- ALP Luminosity:

Ray (with Ning, Safdi) [PRD, 2026]

$$L_a = E_a \sum_{\text{stars}} N\omega_*(T)\frac{1}{\tau_0}\frac{\Gamma_a}{\Gamma_\gamma}$$

N : Number of specific nuclei in the ground state

$\omega_*(T)$: Excitation probability

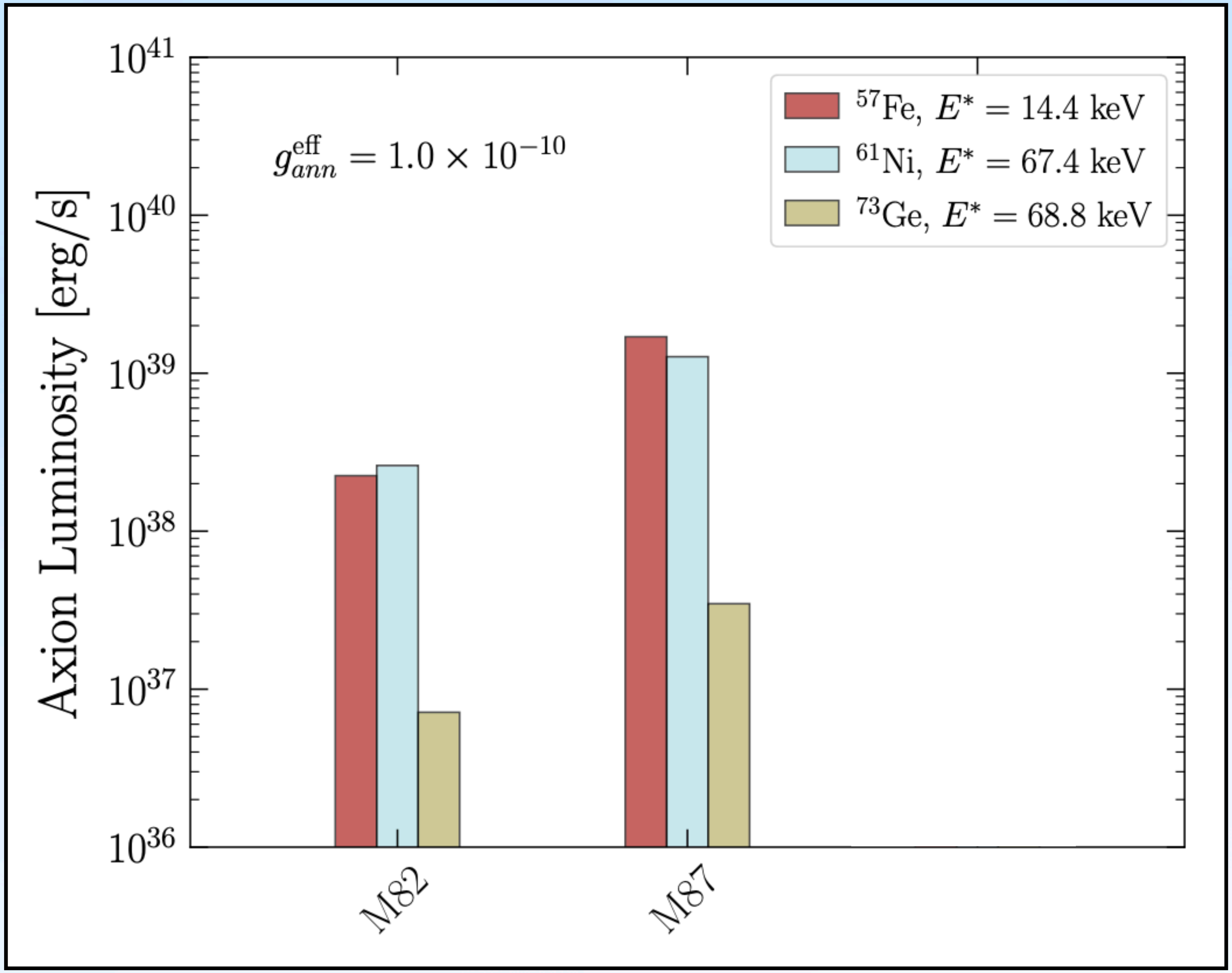
τ_0 : Mean life time of the excited state

Γ_a/Γ_γ : Axion photon branching ratio → Nuclear Shell model

M1 Transition provides maximal emission

ALP Luminosity

- ALP Luminosity:



Sun (^{57}Fe):

$L_a = 3 \times 10^{23}$ erg/s

Ray (with Ning, Safdi) [PRD 2026]

Photon Flux

- Mono energetic ALPs readily escape from the stars.

- Convert to line photons in the magnetic fields of M82 and M87.

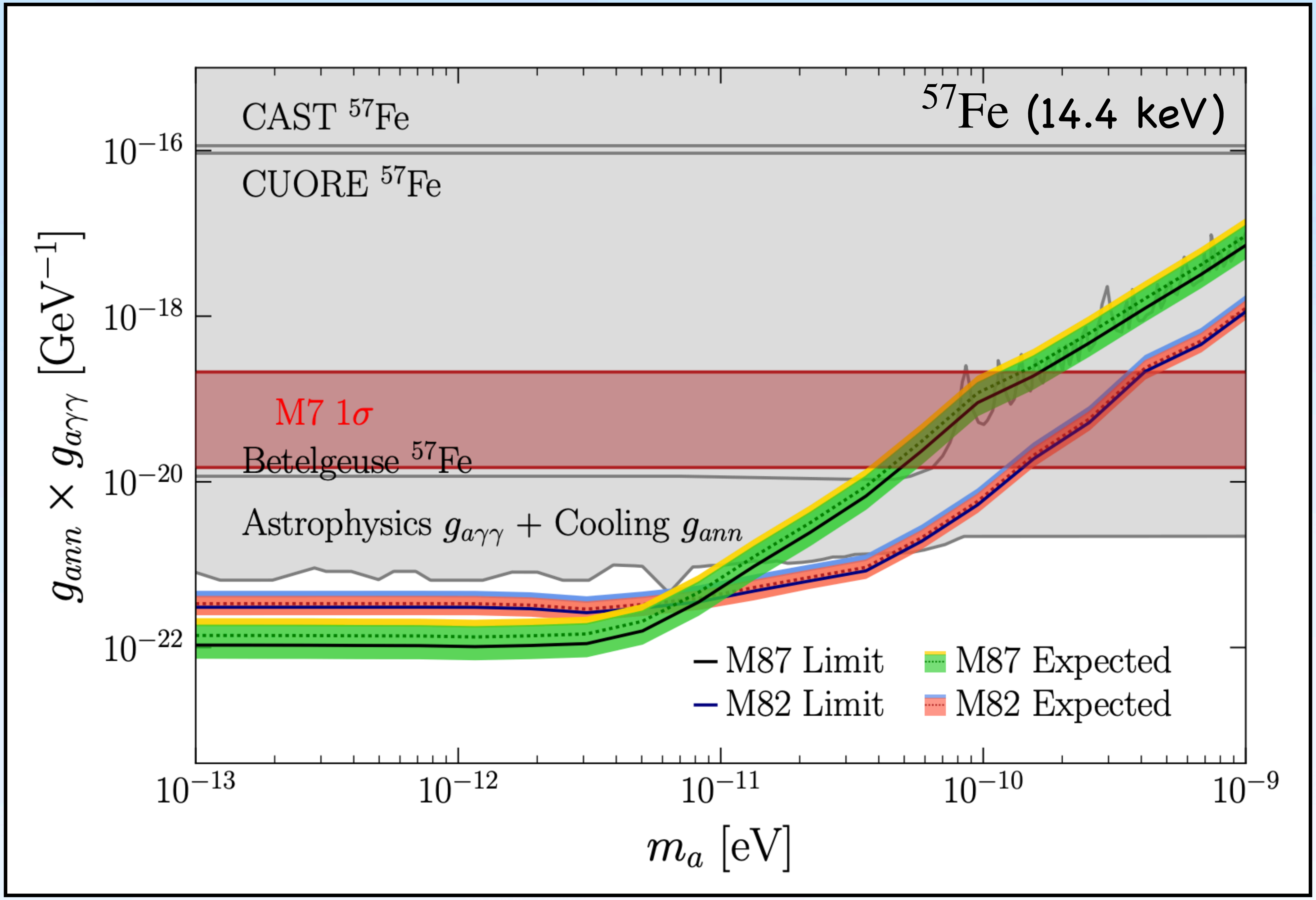
For ^{57}Fe: 14.4 keV X-ray line

- Photon Flux:

$$\Phi = L_a \times P_{a\to\gamma} \times \frac{1}{4\pi d^2}$$

Results

- We search these line photons in NuSTAR data.

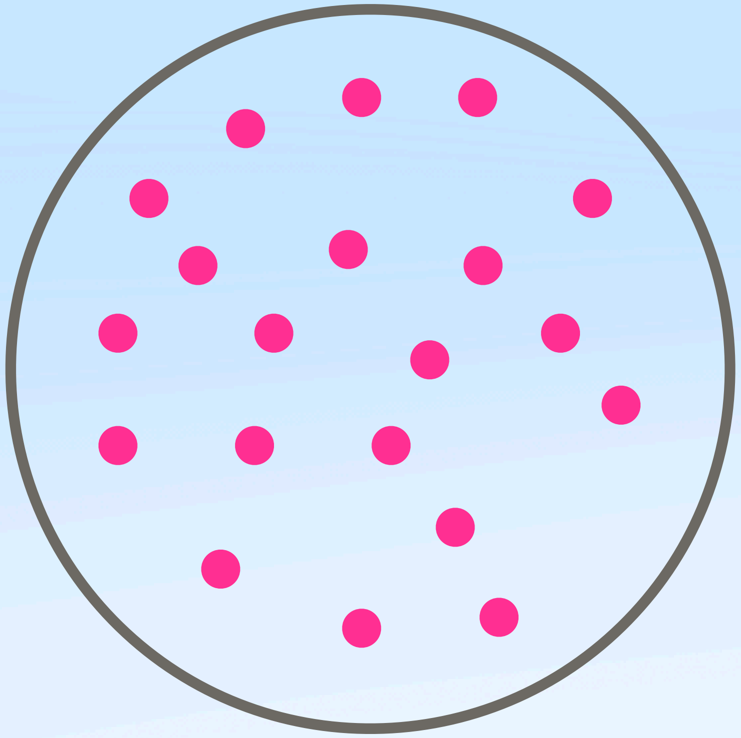


Significant limits on axion interactions

Ray (with Ning, Safdi) [PRD 2026]

^{23}Na: An Unsung Hero

- α-stable nuclei, ^{4}He, ^{12}C, ^{16}O, ^{20}Ne – dominate in the stars.

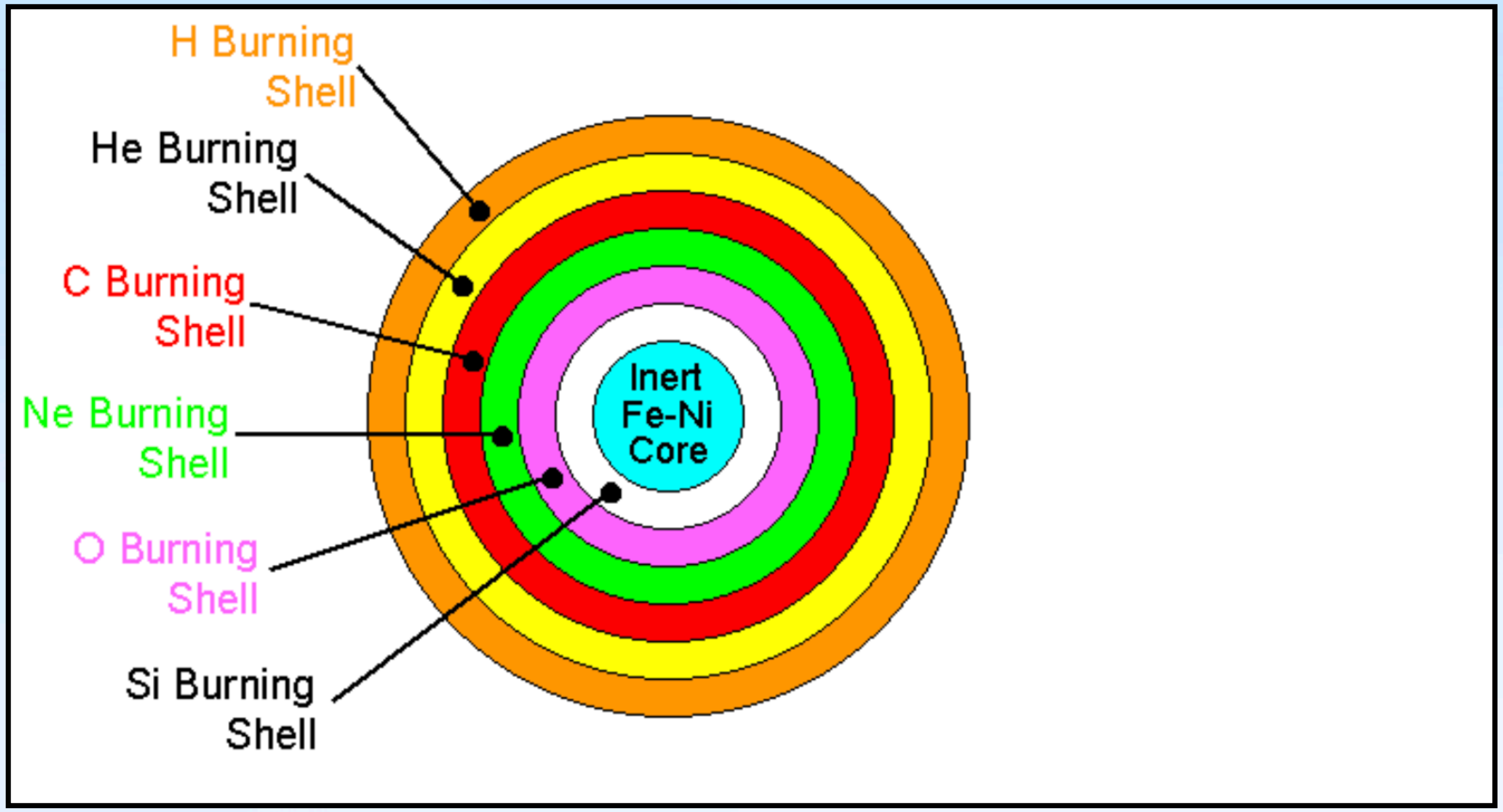


- odd-A isotopes are rare in stars (often burn up quickly), but, ^{23}Na is an exception.

Limonji et al [APJ, 2024]

^{23}Na: An Unsung Hero

- Massive stars (7.5 - 30 $M_\odot$) in their carbon burning phase synthesize significant amount of ^{23}Na.



Can be up to 0.1 $M_\odot$

$$^{12}\mathrm{C} + {}^{12}\mathrm{C} \to {}^{24}\mathrm{Mg}^* \to \begin{cases} {}^{20}\mathrm{Ne} + {}^{4}\mathrm{He} + 4.62\ \mathrm{MeV} \\ {}^{23}\mathrm{Na} + p \quad + 2.24\ \mathrm{MeV} \\ {}^{23}\mathrm{Mg} + n \quad - 2.60\ \mathrm{MeV} \end{cases}$$

^{23}Na: An Unsung Hero

- Temperature in the Carbon burning phase (60-120 keV) is favorable for ^{23}Na nuclear transition.

- Additionally, these hot stage is maintained for significantly longer amount of time.

For a $9M_\odot$ progenitor, it can occur up to $\sim$12,500 year.

^{23}Na: an unsung hero for stellar ALP emissions

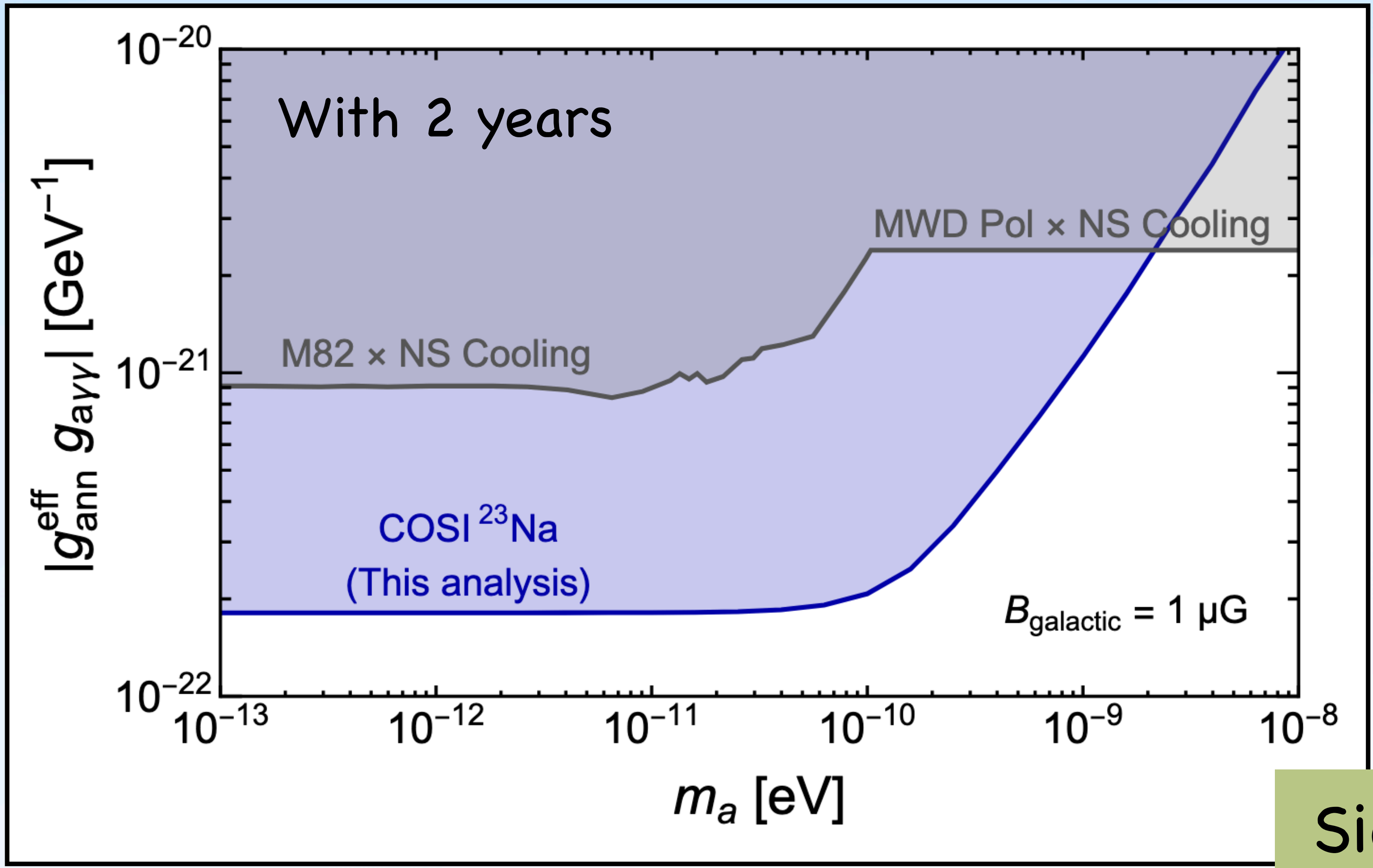
Ray (with Haxton, Liu, McCutcheon) [PRL, 2025]

Results

- ALPs from galactic populations escape and covert to line photons (440.2 keV) in Galactic B-field.

- Upcoming telescopes, such as, COSI can easily detect such line — providing a tantalizing science case.

Ray (with Haxton, Liu, McCutcheon) [PRL,2025]

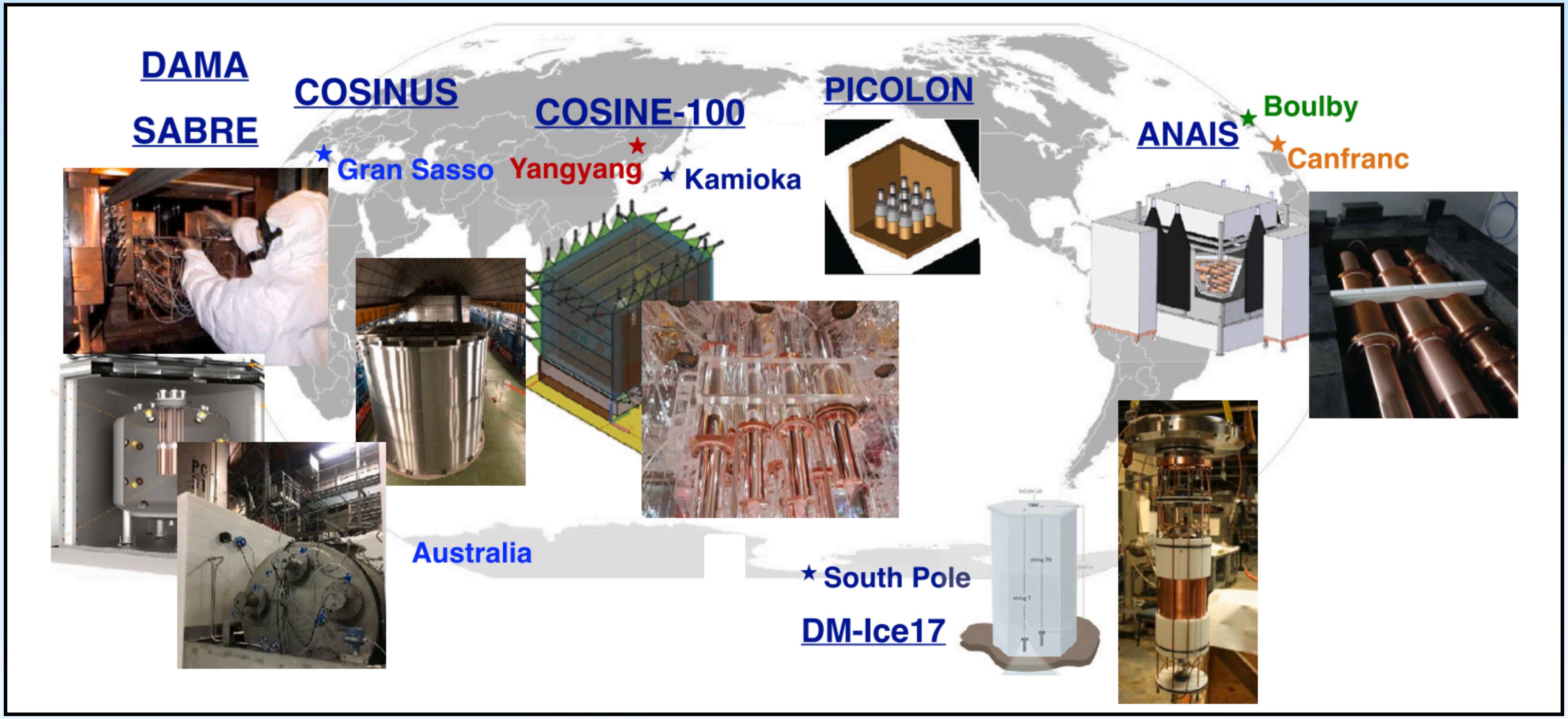


Significant sensitivity

Detecting Axions with NaI

- Followed by DAMA/LIBRA, significant investment with NaI detectors worldwide.

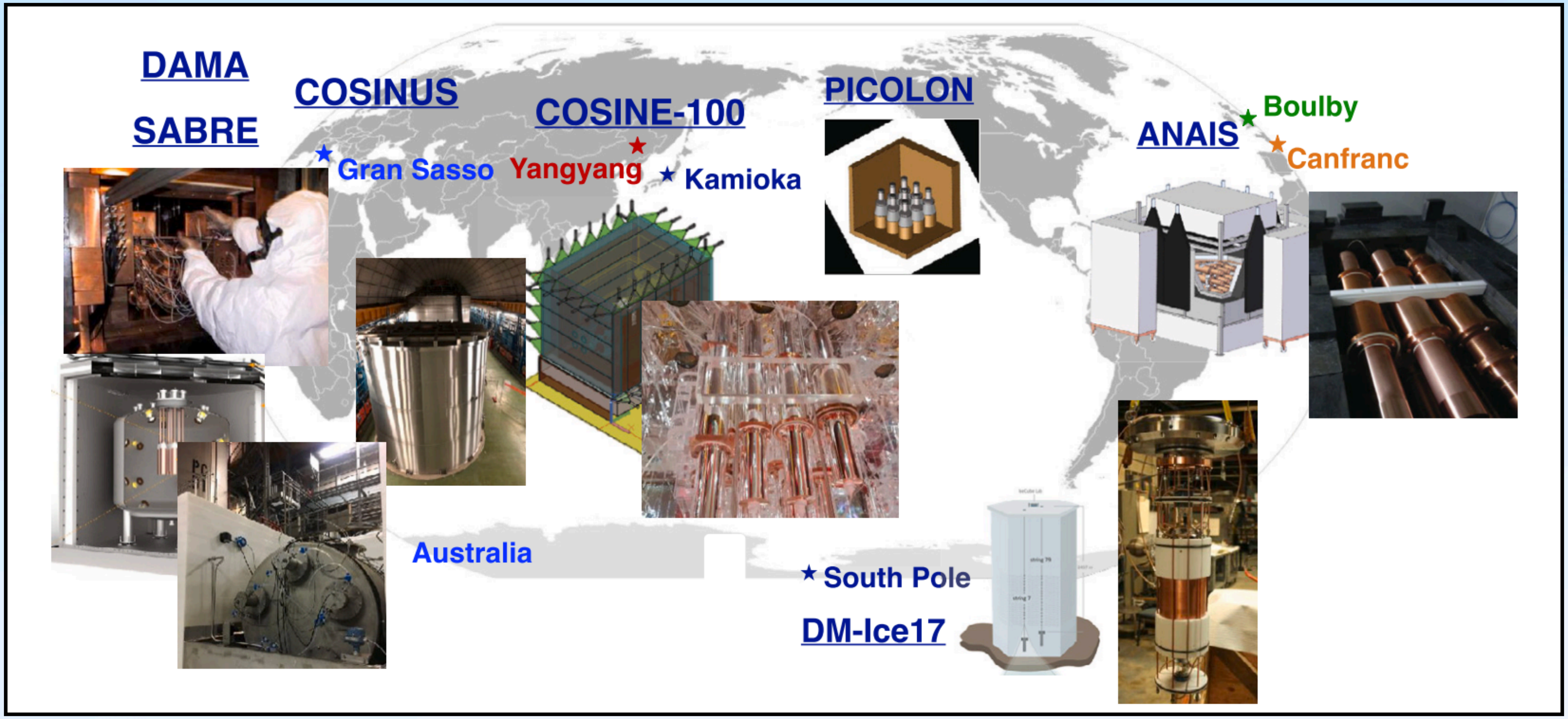
Fig: Maruyama (Nucl Phys B, 2024)



Only null result in WIMP searches

Detecting Axions with NaI

- What to do with these?



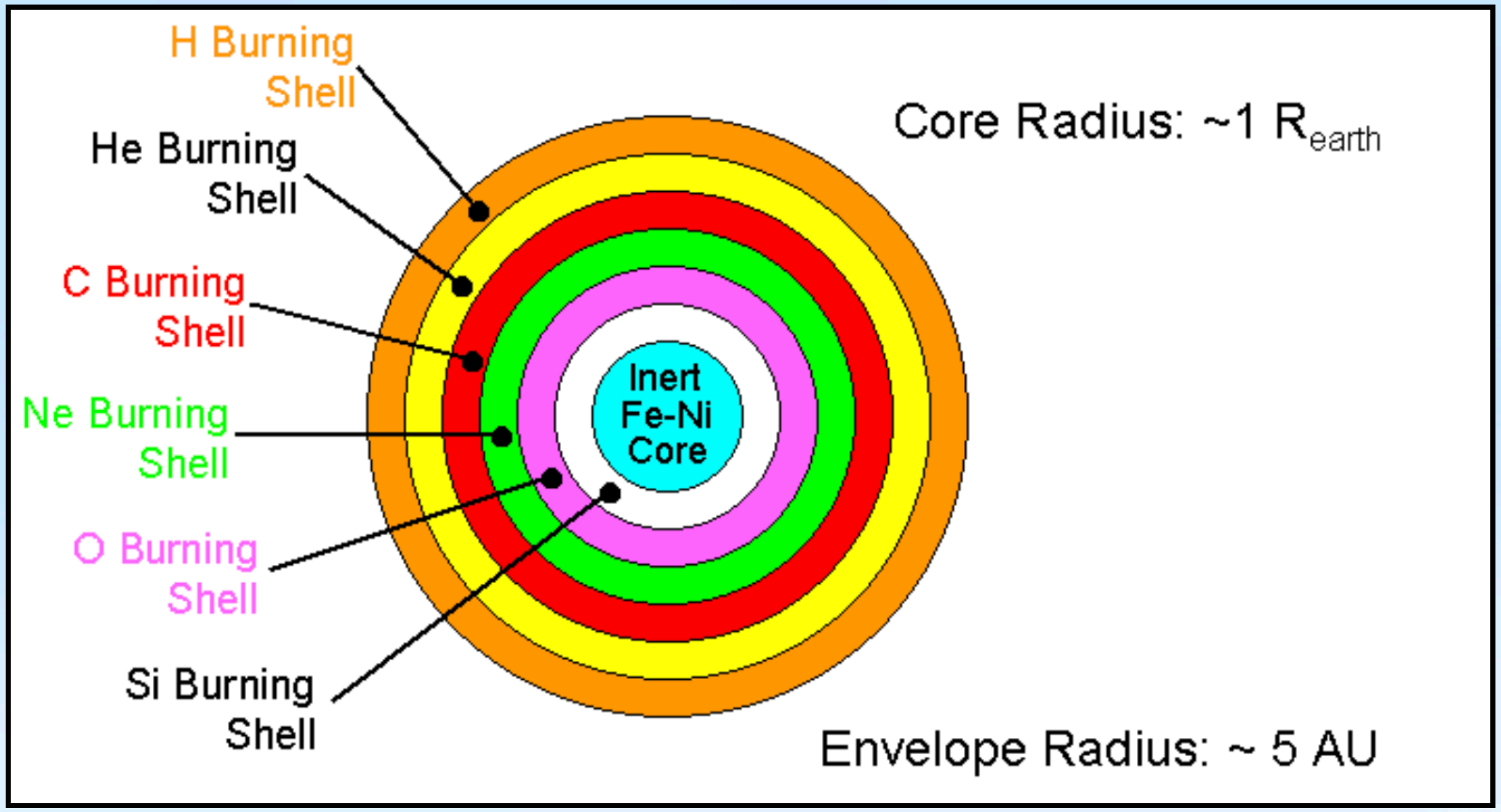
- Our proposal: Utilize as axion detectors.

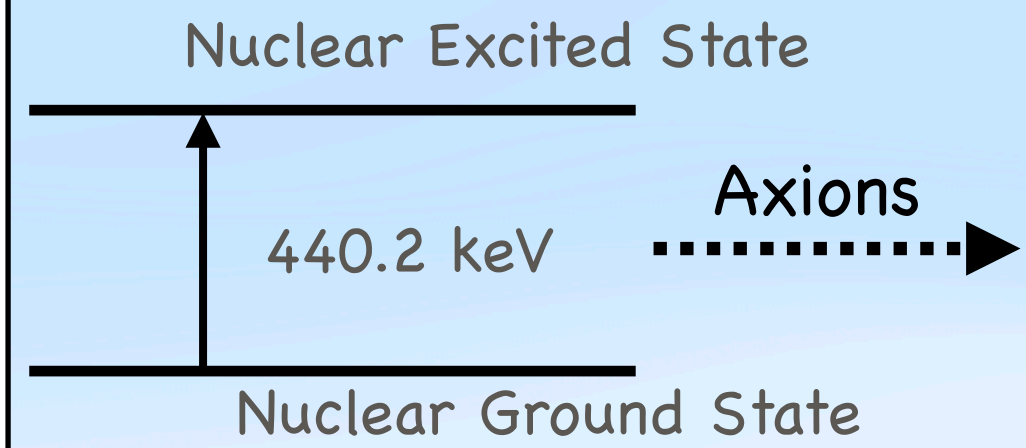
Ray (with Haxton, Liu, Rule) [2603.16998]

Ray (with Haxton, Liu, Rule) [2604.26004]

Detecting Axions with NaI

Same production mechanism: axions from stellar nuclear transition



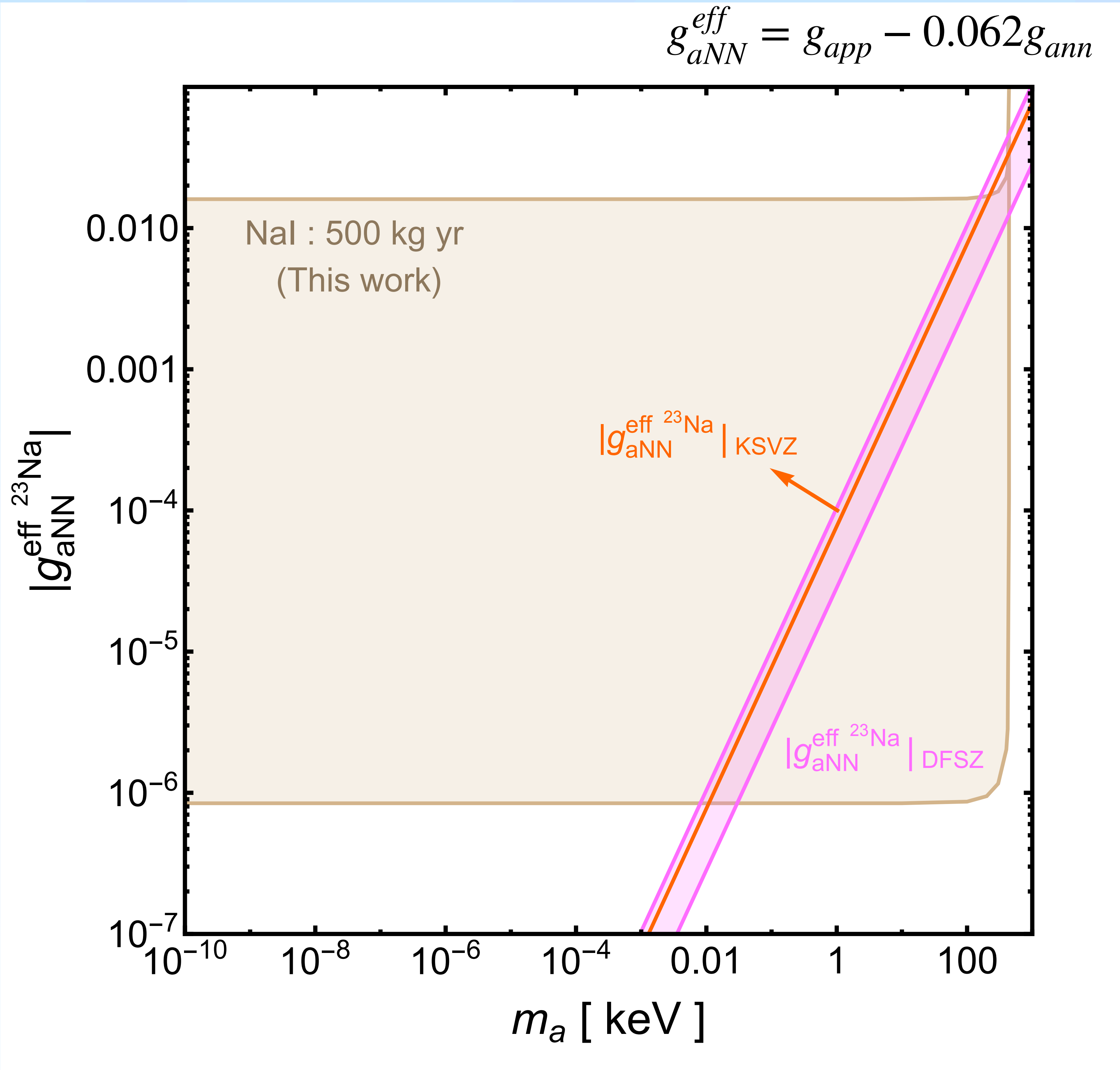


- These axions can propagate to the Earth and gets resonantly absorbed in the NaI detectors.

Ray (with Haxton, Liu, Rule) [2603.16998]

Ray (with Haxton, Liu, Rule) [2604.26004]

Detecting Axions with NaI

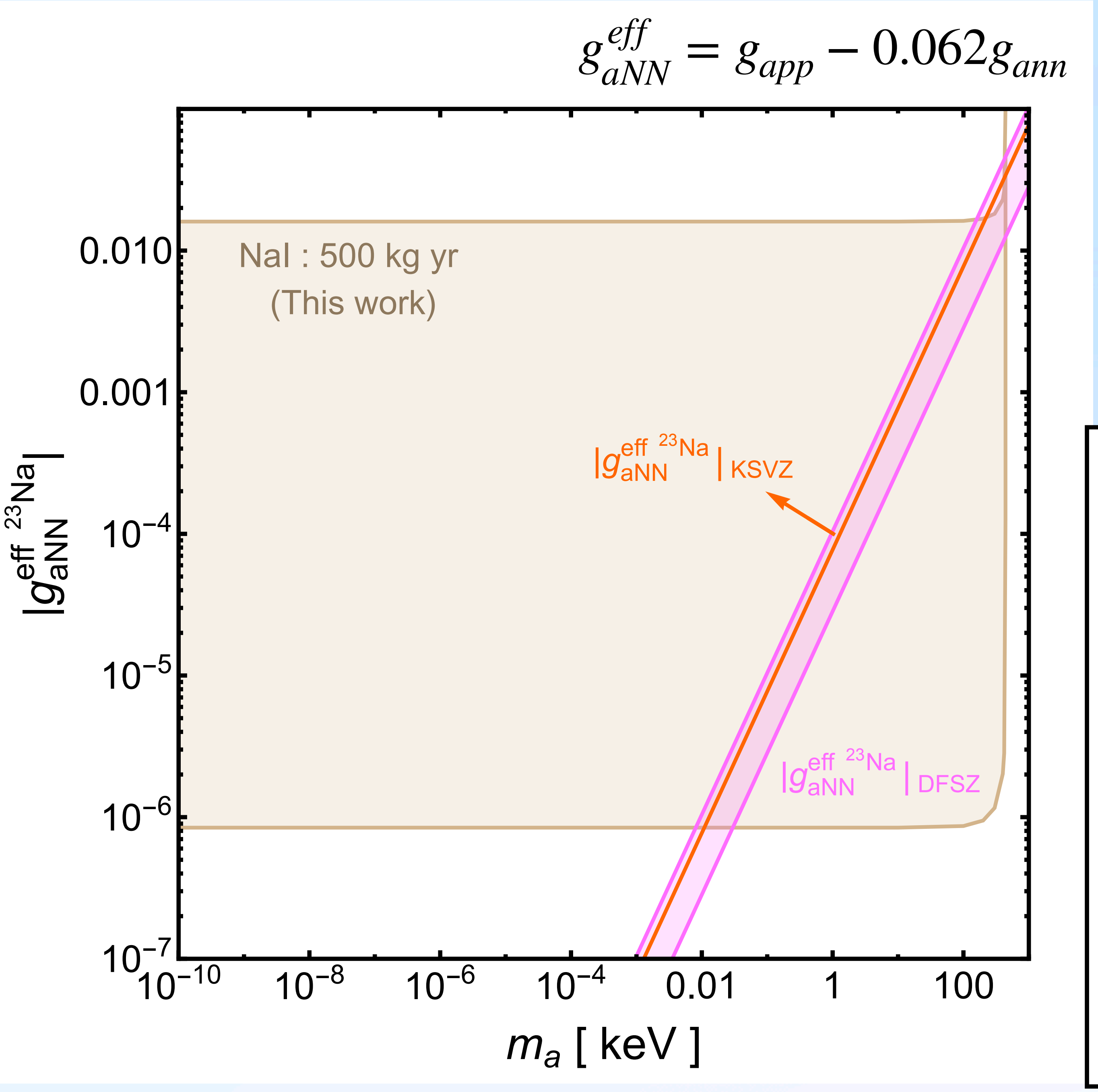


Covers significant region

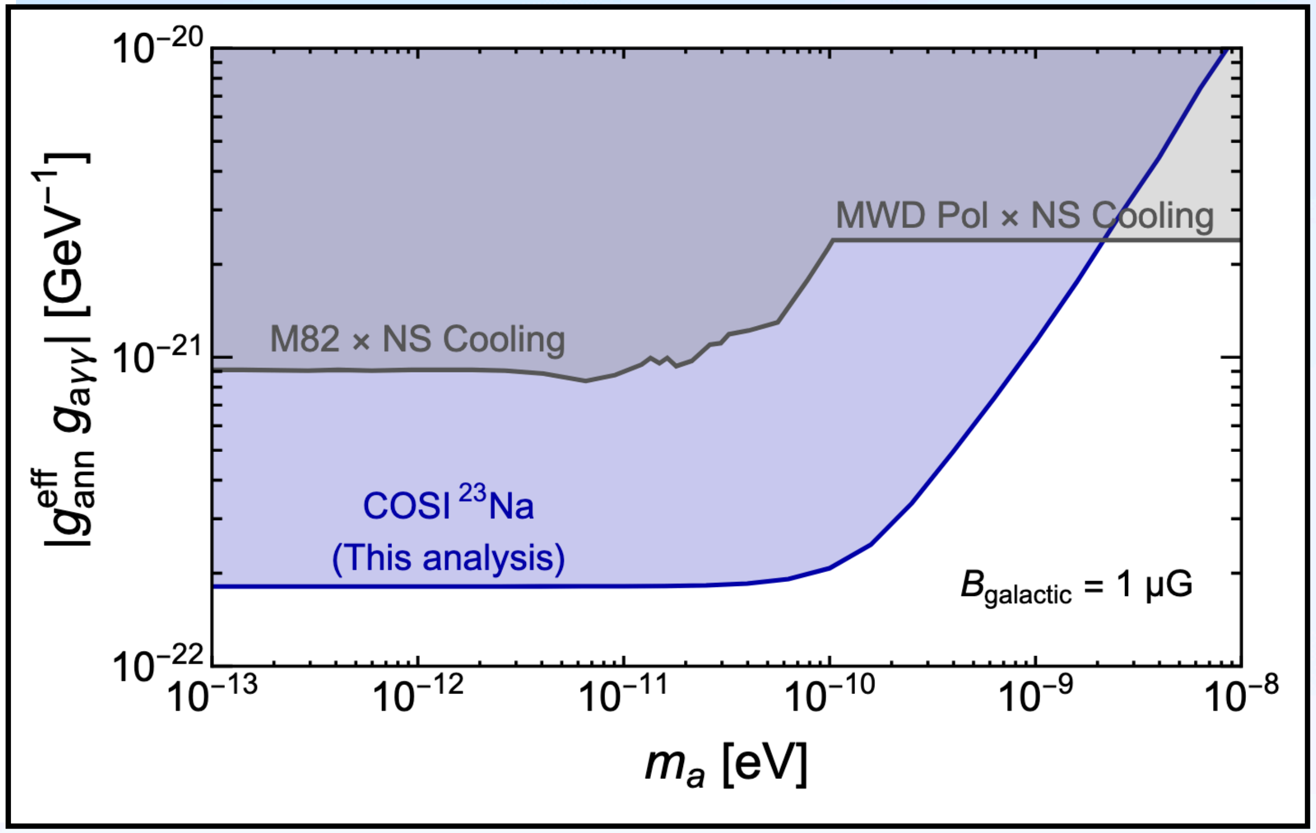
Can probe QCD axions!

Ray (with Haxton, Liu, Rule) [2604.26004]

Detecting Axions with NaI



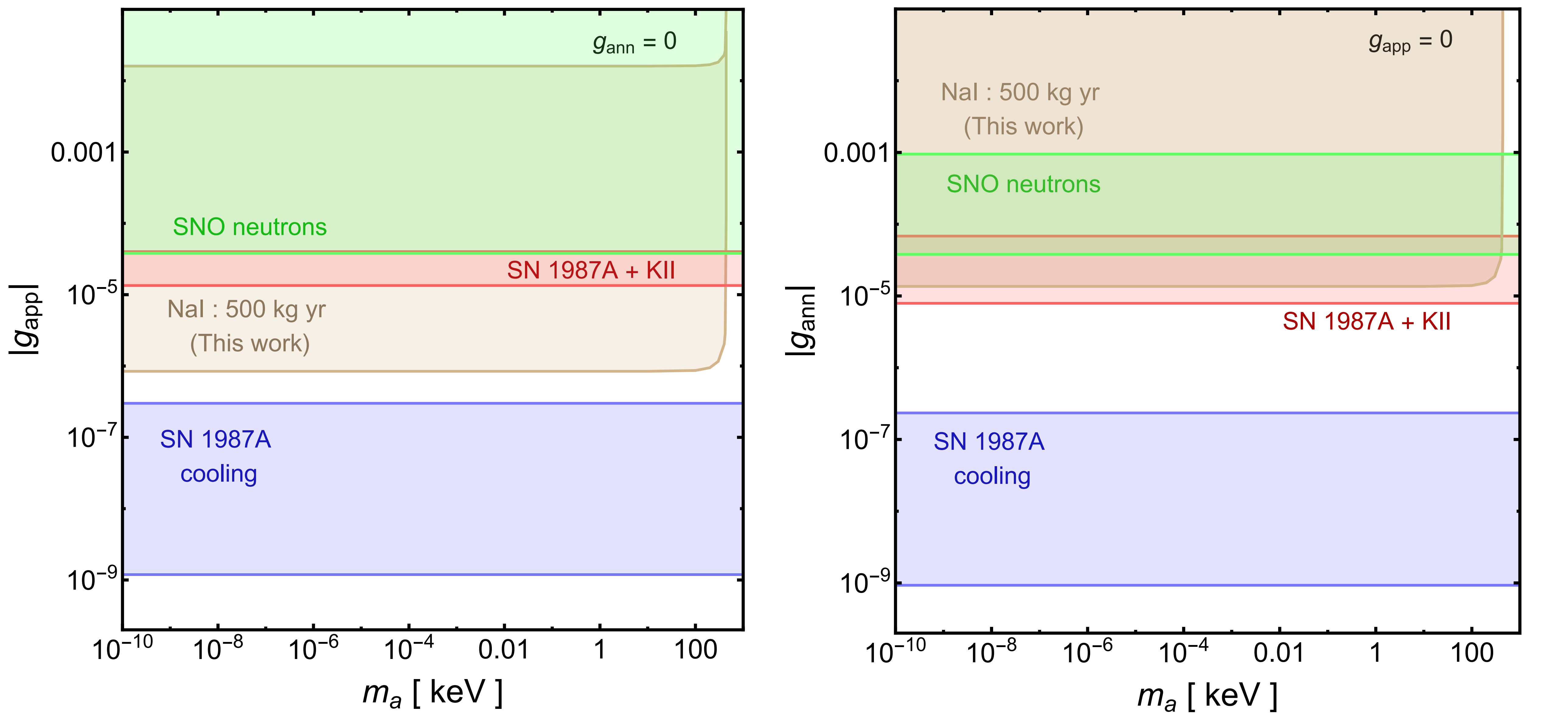
Unlike axion-photons, covers heavier axions too



Ray (with Haxton, Liu, Rule) [2604.26004]

Detecting Axions with NaI

Ray (with Haxton, Liu, Rule) [2604.26004]



Lets use NaI detectors to look for axions

ALP Absorption on Nuclei

Ray (with Haxton, Liu, Rule) [2604.26004]

- While deriving SN exclusions, a crucial effect is often neglected.

Axion absorption on nuclei (bound nucleons)

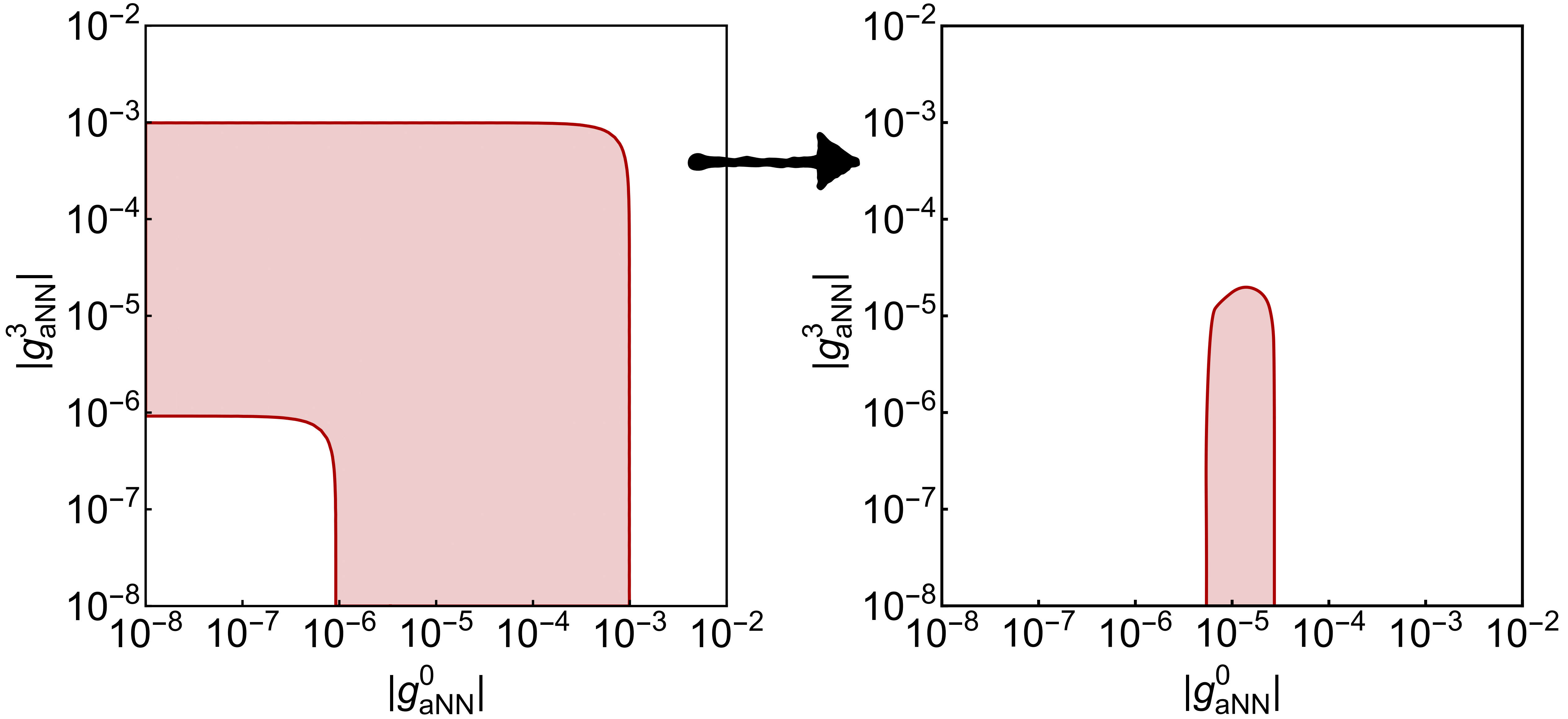
- Unlike free nucleons, nuclei exist in the SN for a much wider region and therefore extremely crucial for absorption.

Opacity channels are exponentially sensitive

^{4}He, ^{28}Si, ^{56}Ni and ^{16}O — excellent absorber

ALP Absorption on Nuclei

- Revised limit from SN1987+ KII with the inclusion of axion absorption in nuclei.



Engel, Seckel, Hayes (PRL, 1990)

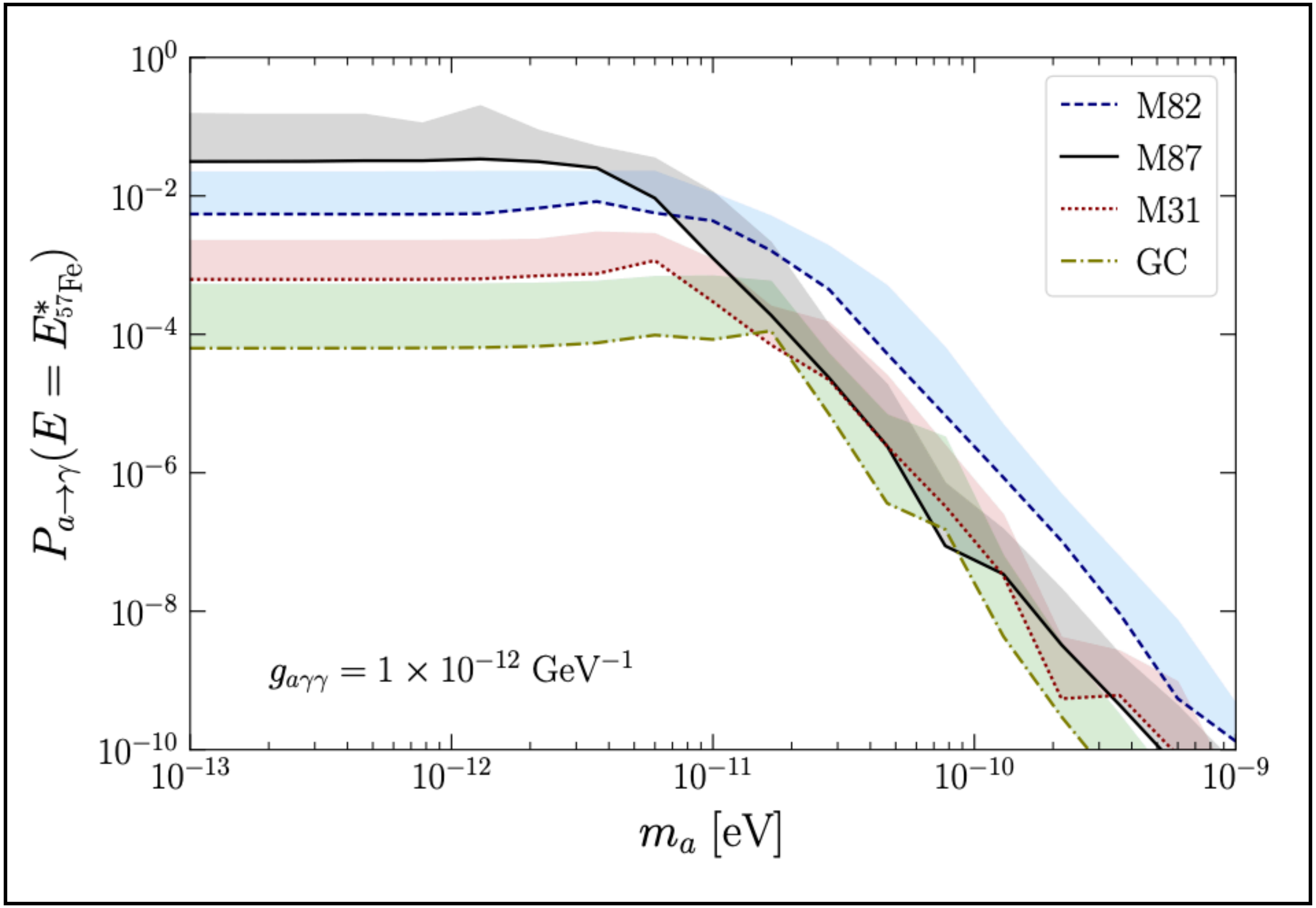
Ray (with Haxton, Liu, Rule) [2604.26004]

Summary

- Nuclear transition in stars: a key channel for axion production.
- Axions are monochromatic unlike other thermal production processes.
- X-ray line signature via axion-photon conversion can be searched in existing/upcoming telescopes — leading sensitivity.
- Direct detection with existing NaI-WIMP detectors provides another compelling avenue (can even probe QCD axions).

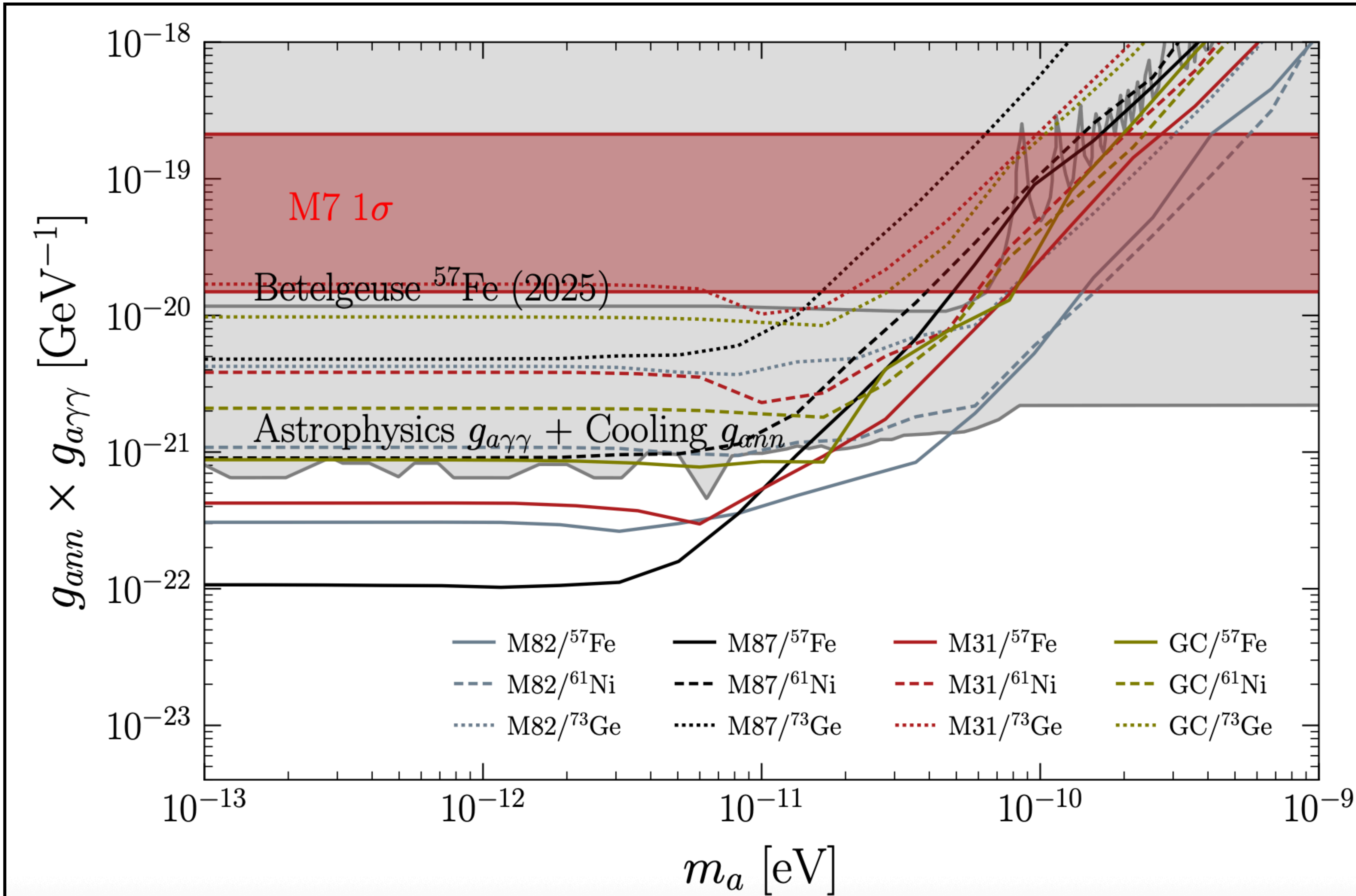
Extra Slides

ALPs: Nuclear Transition



Conversion Probability

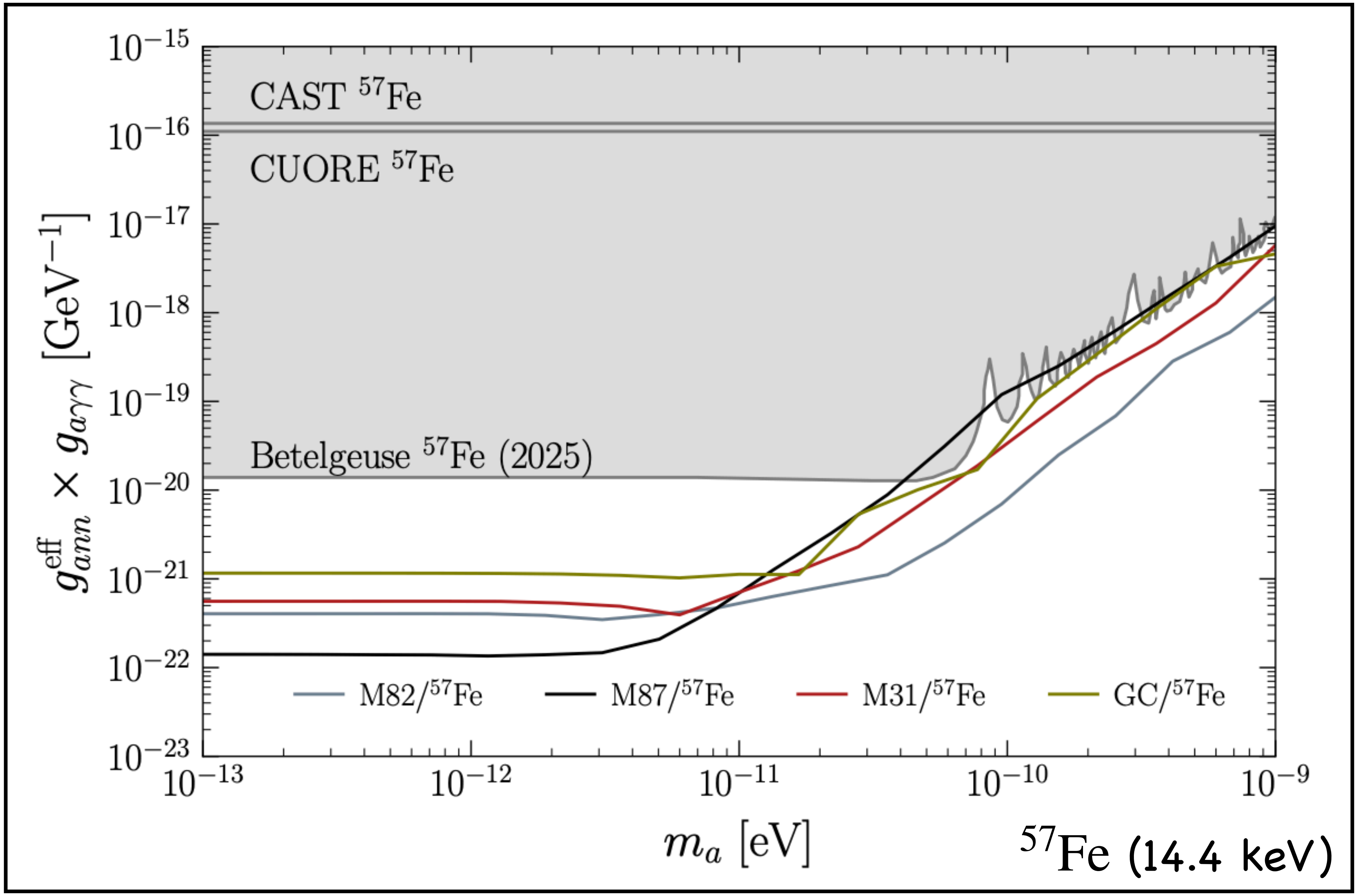
ALPs: Nuclear Transition



Other isotopes

ALPs: Nuclear Transition

- We also search these line photons from M31 and GC.



Ray (with Ning, Safdi) [2507.15271]