Interplay between astrophysical and laboratory probes of MeV-scale ALPs

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in collaboration with:

Felix Kahlhoefer - arXiv: 2004.01193

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Outline

Motivation

- Extensions of the SM? Heavy new particles!
- Despite all experimental efforts so far, no (conclusive) evidence for heavy particles at TeV scale
- Maybe missed some physics along the way?

  $\rightarrow$ renewed attention for new, much lighter particles

  $\rightarrow$ remain to be discovered, if they have small interactions
- Popular candidate: Axion-like particle

Goldstone bosons

- Theoretical motivation: Goldstone's theorem
- Spontaneous breaking of an (approximate) global symmetry gives rise to (Pseudo−)Goldstone bosons
  - naturally light (or even massless)
  - interactions are suppressed by scale of symmetry breaking

$\rightarrow$ common explanation for small mass and tiny interactions

- Example: $U(1)_{\mathrm{PQ}}$ symmetry $\longleftrightarrow$ QCD axion

Axion-like particles

- Unlike QCD axion employ model-independent approach
  - Couplings are free parameters
  - Treat mass as an independent parameter

$\Rightarrow$ Axion-like particles (ALPs)

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- ALP couplings therefore include in general
  - SM fermions
  - SM Higgs
  - Gluons
  - Electroweak gauge bosons

General ALP EFT

- Write down general EFT

[H. Georgi et al., Phys.Lett. 169B (1986), M. Bauer et al., arXiv: 1708.00443]

$$\mathcal{L}_{\text{eff}} = \frac{1}{2}(\partial_\mu a)(\partial^\mu a) - \frac{m_{a,0}^2}{2} a^2 + \frac{\partial^\mu a}{\Lambda} \sum_F \bar{\Psi}_F \, C_F \, \gamma_\mu \, \Psi_F$$

$$+ g_s^2 \, C_{GG} \frac{a}{\Lambda} G_{\mu\nu}^a \tilde{G}^{\mu\nu,a} + g^2 \, C_{WW} \frac{a}{\Lambda} W_{\mu\nu}^a \tilde{W}^{\mu\nu,a} + g'^{\,2} \, C_{BB} \frac{a}{\Lambda} B_{\mu\nu} \tilde{B}^{\mu\nu}$$

- Ψ_F: chiral fermion fields
- $X_{\mu\nu}^a$: $SU(3)_C$, $SU(2)_L$ and $U(1)_Y$ field strength tensors

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Relations between couplings

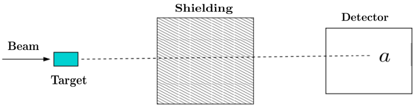
- EWSB generates couplings to W bosons, photons etc.
  - W boson $\leftrightarrow C_{WW}$
  - Photon coupling $C_{\gamma\gamma} = C_{WW} + C_{BB}$
  - $Z\gamma a$ coupling $C_{\gamma Z} = c_W^2 C_{WW} - s_W^2 C_{BB}$
- But also gluonic contribution ($m_a \lesssim \Lambda_{\mathrm{QCD}}$)
  - $C_{\gamma\gamma}^{\mathrm{eff}} \approx C_{WW} + C_{BB} - 1.92 C_{GG} - \frac{1}{3}\frac{m_a^2}{m_\pi^2 - m_a^2} C_{GG}$

[M. Bauer et al., arXiv: 1708.00443]

$\Rightarrow$ Strong correlation between interactions

Laboratory probes

- Which experiments do we consider?
  - Fixed-target experiments:

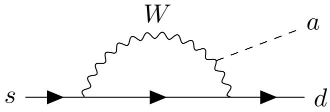


[S.N. Gninenko, arXiv: 1204.3583]

  - L3 at LEP performed search for $Z \to \gamma +$ inv. at Z resonance

Experimental and Observational Constraints

- Rare Meson decays:
  - Experimental constraints by E787/E949 on $K^+ \to \pi^+ a$
  - NA62 focusses on $K^+ \to \pi^+ \nu \bar{\nu}$
    $\to$ Assume improvement on bound by an order of magnitude
    [R. Fantechi et al., arXiv: 1407.8213]



- Ensure invisible decay in experiment

$$\mathrm{BR}(K^+ \to \pi^+ a)^{\mathrm{exp}} = \mathrm{BR}(K^+ \to \pi^+ a)^{\mathrm{theo}}\, e^{-L_{\mathrm{det}}/L_{\mathrm{alp}}}$$

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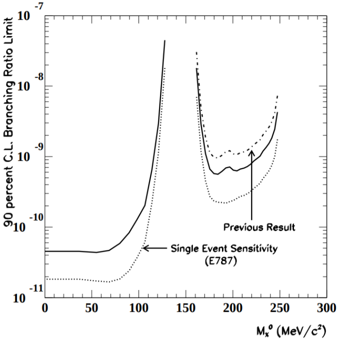

[S. Adler et al., E787, arXiv: 0403034]

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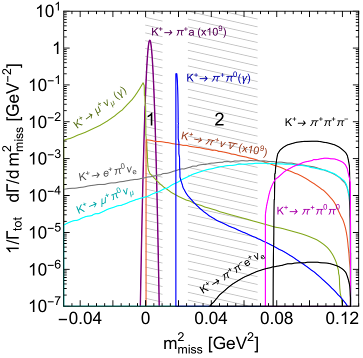

[E. C. Gil et al., NA62, arXiv: 1703.08501]

- Ensure invisible decay in experiment

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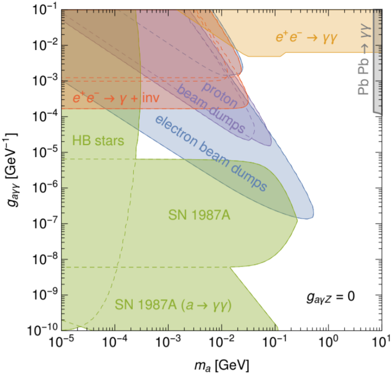
Experimental and Observational Constraints

- Electron beam dump (E137) strongest fixed-target bound
- HB star dominant for $m_a \lesssim 10\,keV$
- SN 1987A ("cooling" bound)
  - Formation of proto-neutron star
  - Most of energy liberated by neutrino emission



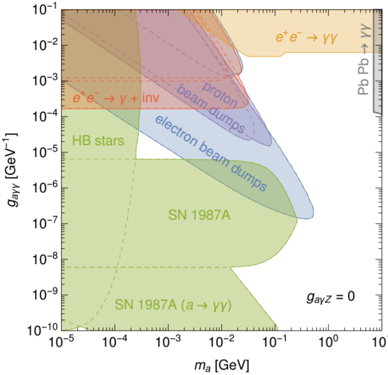
[M. Dolan et al., arXiv: 1709.00009]

Experimental and Observational Constraints

- SN bound rather simplistic
  - No temperature and density profiles
  - No radius and energy dependence of ALP trapping

    $\rightarrow$ improve calculation

    $\rightarrow$ consistent approach: $C_{\gamma\gamma}$ & C_{GG}
- Below cooling bound: missing ALP burst



[M. Dolan et al., arXiv: 1709.00009]

SN Bound

- Apply Raffelt criterion for SN bound: $L_{\text{ALP}} > L_\nu$ ↯
- ALP Luminosity reads schematically

[J.H. Chang et al., arXiv: 1611.03864]

$$L_{\text{ALP}} \sim \int_{r \leq R_\nu} dV\, Q\, e^{-\tau}$$

with Q as volume emission rate and optical depth τ

$$Q \sim \int \frac{d^3 k_a}{(2\pi)^3} E_a \Gamma_{\text{prod}}\,, \qquad \tau \sim \int_r^{R_{\text{far}}} dr'\, \Gamma_{\text{abs}}$$

ALP Luminosity Formula

- Luminosity formula is given by ($E_a \equiv \omega$)

$$L_{\mathrm{ALP}} = \int_{r \leq R_\nu} \mathrm{d}V \left(\int \frac{\mathrm{d}^3\mathbf{p}_a}{(2\pi)^3} \omega \Gamma_a e^{-\omega/T} \, \beta \, e^{-\tau} + \int \frac{2\mathrm{d}^3\mathbf{p}_\gamma}{(2\pi)^3} \frac{\omega \Gamma_{\gamma \to a}}{e^{\omega/T} - 1} \beta \, e^{-\tau} \right)$$

Nucleon-Scattering:
$N + N \to N + N + a$

Primakoff:
$\gamma + p \to a + p$

with $\beta = \sqrt{1 - m_a^2/\omega^2}$

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Nucleon-Scattering: $N + N \to N + N + a$

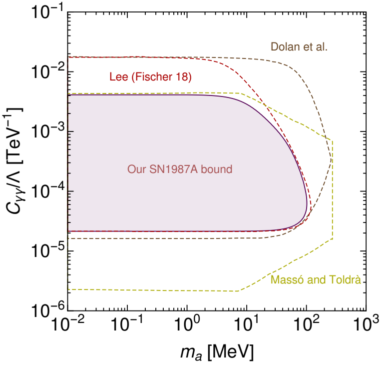
Primakoff: $\gamma + p \to a + p$

with $\beta = \sqrt{1 - m_a^2/\omega^2}$ and the optical depth τ reading

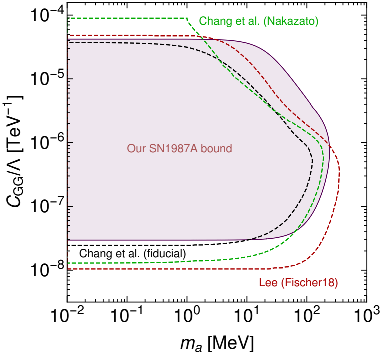
$$\tau = \beta^{-1} \int_r^{R_{\mathrm{far}}} dr' \left(2\Gamma_{\gamma\to a} + \gamma^{-1}\Gamma_{a\gamma\gamma} + \Gamma_a \right)$$

Comparison of SN bounds

Photon coupling



Gluon coupling



Reminder about couplings

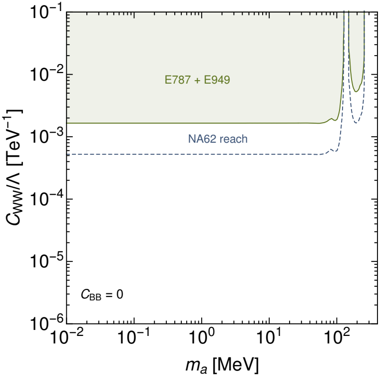
- Lagrangian before EWSB

$$\mathcal{L}_{\text{eff}} = g_s^2\, C_{GG} \frac{a}{\Lambda} G^a_{\mu\nu} \tilde{G}^{\mu\nu,a} + g^2\, C_{WW} \frac{a}{\Lambda} W^a_{\mu\nu} \tilde{W}^{\mu\nu,a} + g'^{\,2}\, C_{BB} \frac{a}{\Lambda} B_{\mu\nu} \tilde{B}^{\mu\nu}$$

- After EWSB
  - W boson $\leftrightarrow$ C_{WW}
  - $C^{\text{eff}}_{\gamma\gamma} \approx C_{WW} + C_{BB} - 1.92\, C_{GG} - \frac{1}{3} \frac{m_a^2}{m_\pi^2 - m_a^2} C_{GG}$
  - $Z\gamma a$ coupling $C_{\gamma Z} = c_W^2\, C_{WW} - s_W^2\, C_{BB}$

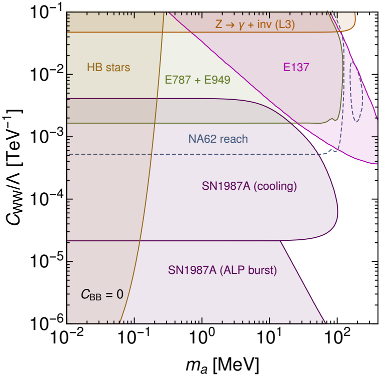
Couplings to electroweak gauge bosons only

- Consider sizeable C_{WW}



Couplings to electroweak gauge bosons only

- Consider sizeable C_{WW}
- Have $C_{\gamma\gamma}^{\text{eff}} \approx C_{WW}$
  $\to \text{BR}(a \to \gamma\gamma) \approx 1$
- How to open up more parameter space?
- Reminder:
  $C_{\gamma\gamma} = C_{WW} + C_{BB}$

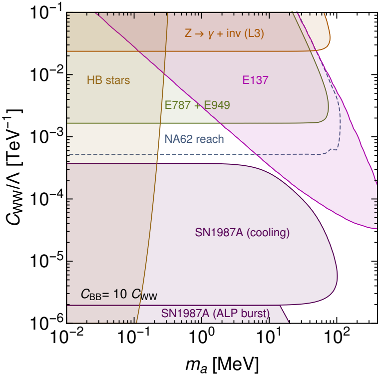


Couplings to electroweak gauge bosons only

- Consider $C_{BB} = 10 C_{WW}$
- $C_{\gamma\gamma} = C_{WW} + C_{BB}$

  $\rightarrow$ Shifts bounds dependent on $C_{\gamma\gamma}$

  $\rightarrow$ In particular SN bounds are shifted downwards
- Further Options?



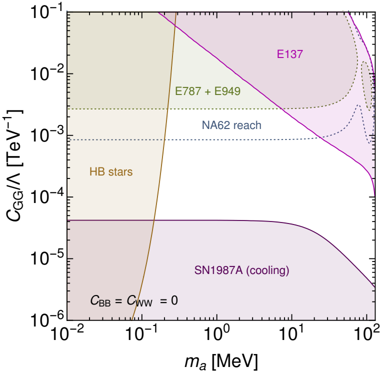
Couplings to gluons

- Turn on sizeable gluon coupling
  [G. Alonso-Alvarez et al., arXiv: 1811.05466]

- Contributes to photon coupling

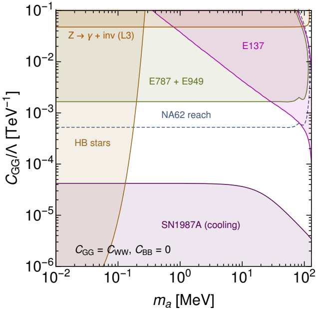
$$C_{\gamma\gamma}^{\text{eff}} \approx -1.92\, C_{GG} - \frac{1}{3}\frac{m_a^2}{m_\pi^2 - m_a^2} C_{GG}$$

- $K^+ \to \pi^+ a$ via π^0, η, η' mixing
  [D.S.M. Alves and N. Weiner, arXiv: 1710.03764]



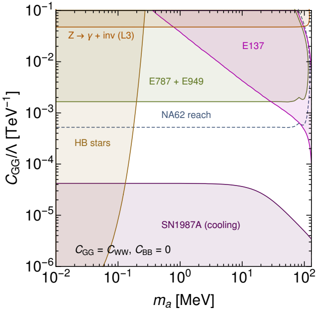
$\to$ How to circumvent the uncertainties?

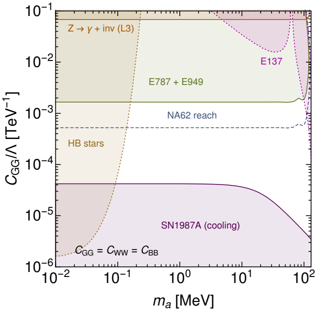
Couplings to all Standard Model gauge bosons



- $C_{GG} = C_{WW}$
- $K^+ \to \pi^+ a$ via C_{WW}

Couplings to all Standard Model gauge bosons

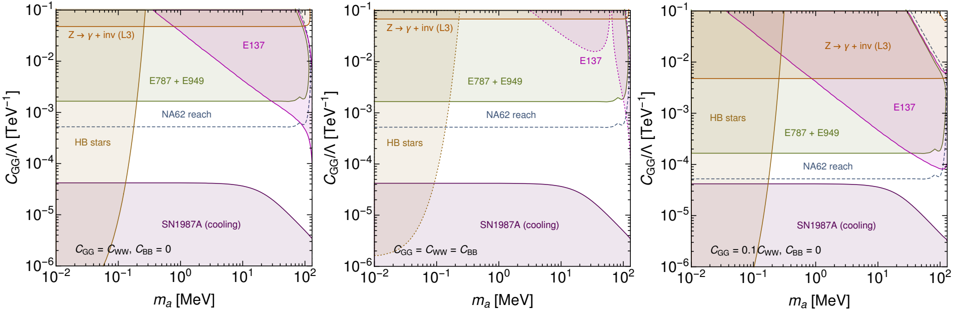




- $C_{GG} = C_{WW}$
- $K^+ \to \pi^+ a$ via C_{WW}

- $C_{GG} = C_{WW} = C_{BB}$
- Cancellation: $C_{\gamma\gamma}^{\text{eff}} \approx 0.08\, C_{GG}$

Couplings to all Standard Model gauge bosons



- $C_{GG} = C_{WW}$
- $K^+ \to \pi^+ a$ via C_{WW}
- $C_{GG} = C_{WW} = C_{BB}$
- Cancellation: $C^{\text{eff}}_{\gamma\gamma} \approx 0.08\, C_{GG}$
- $C_{GG} = 0.1\, C_{WW}$
- Lab-Experiment reaches region of SN1987A

Conclusion

- Studied MeV-scale ALPs in EFT framework

  $\rightarrow$ Particular focus on $K^+ \rightarrow \pi^+ a$

- Consistent approach to calculation of SN cooling bound

  $\rightarrow$ Bound on $C_{\gamma\gamma}$ more conservative, while on C_{GG} in agreement with literature

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- Overall ALP phenomenology depends on the couplings that are generated

  $\rightarrow$ Improved this approach by including all relevant operators

Thank you for your attention!

Questions?

Backup

Photophobic ALP

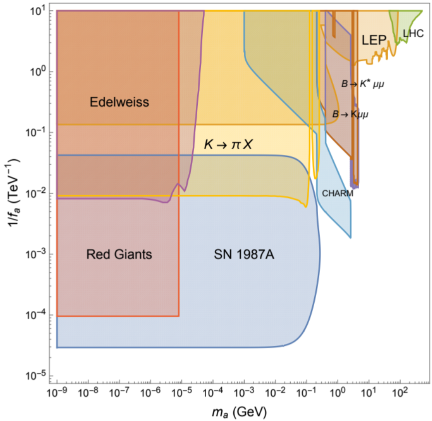
- Set $C_{WW} = -C_{BB}$

  $\rightarrow C_{\gamma\gamma}|_{\text{tree}} = 0$

  $\rightarrow$ "photophobic ALP"

  $\rightarrow$ nearly no parameter space open

- Note $1/f_a \sim C_{WW}$



[N. Craig et al., arXiv: 1805.06538]

Octet Enhancement

- Hierarchy encountered in Kaon decays

$$\Rightarrow \Gamma(K^0 \to \pi^+\pi^-),\, \Gamma(K^0 \to \pi^0\pi^0) \gg \Gamma(K^+ \to \pi^+\pi^0)$$

- The very same operators in ChPT lead to an enhanced mixing contribution of η and η'

$$i\mathcal{M}(K^+ \to \pi^+ a) \approx \theta_{a\pi}\, i\mathcal{M}(K^+ \to \pi^+\pi^0) + \theta_{a\eta}\, i\mathcal{M}(K^+ \to \pi^+\eta) + \theta_{a\eta'}\, i\mathcal{M}(K^+ \to \pi^+\eta')$$

[Bardeen et al., Nucl. Phys. B279 (1987)]

Mixing angles

- The mixing effects can be written as

$$\pi^0 \to \pi^0 + \theta_{a\pi} a \approx \pi^0 + \epsilon \frac{K_{a\pi}\, m_a^2}{m_a^2 - m_\pi^2} a$$

$$\eta \to \eta + \theta_{a\eta} a \approx \eta + \epsilon \frac{K_{a\eta}\, m_a^2 + m_{a\eta}^2}{m_a^2 - m_\eta^2} a$$

$$\eta' \to \eta' + \theta_{a\eta'} a \approx \eta' + \epsilon \frac{K_{a\eta'}\, m_a^2 + m_{a\eta'}^2}{m_a^2 - m_{\eta'}^2} a$$

[D. Aloni et al., arXiv: 1811.03474]

General Formula for Volume Emission Rate

- The energy loss rate Q (energy per volume and unit time) is defined by

$$Q = \int \frac{\mathrm{d}^3\mathbf{p}_a}{2\omega_a(2\pi)^3}\omega_a \left(\prod_i \int \frac{\mathrm{d}^3\mathbf{p}_i}{2\omega_i(2\pi)^3} f_i(\omega_i)\right)\left(\prod_f \int \frac{\mathrm{d}^3\mathbf{p}_f}{2\omega_f(2\pi)^3}[1 \pm f_f(\omega_f)]\right)$$
$$\times\ S \sum_{\text{spins/pol.}} |M|^2 \, (2\pi)^4 \, \delta^{(4)}\Big(\sum_i p_i^\mu - \sum_f p_f^\mu - p_a^\mu\Big)$$

[G. Raffelt, Phys. Rept. 198 (1990)]

General Formula for Optical Depth

- The optical depth is given by

$$\tau = \beta^{-1} \int \mathrm{d}r \, \Gamma_{\mathrm{abs}} \, ,$$

[G. Raffelt, Phys. Rept. 198 (1990)]

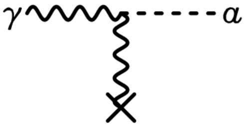
where the absorption rate reads

$$\Gamma_{\mathrm{abs}} = \frac{1}{2\omega_a} \left(\prod_i \int \frac{\mathrm{d}^3 \mathbf{p}_i}{2\omega_i (2\pi)^3} f_i(\omega_i) \right) \left(\prod_f \int \frac{\mathrm{d}^3 \mathbf{p}_f}{2\omega_f (2\pi)^3} [1 \pm f_f(\omega_f)] \right) \times S \sum_{\mathrm{spins/pol.}} |M|^2 \, (2\pi)^4 \, \delta^{(4)} \left(\sum_i p_i^\mu - \sum_f p_f^\mu - p_a^\mu \right)$$

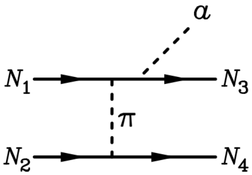
[H. Weldon, Phys. Rev. D28 (1983)]

Primakoff and Bremsstrahlung processes

Primakoff

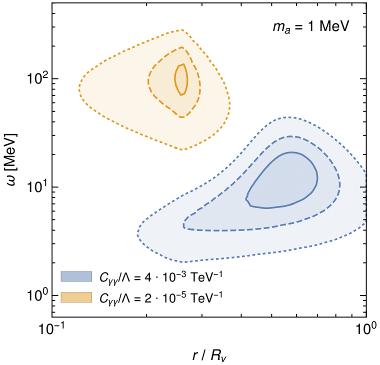


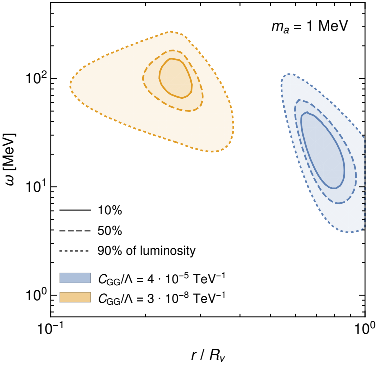
Bremsstrahlung (OPE)



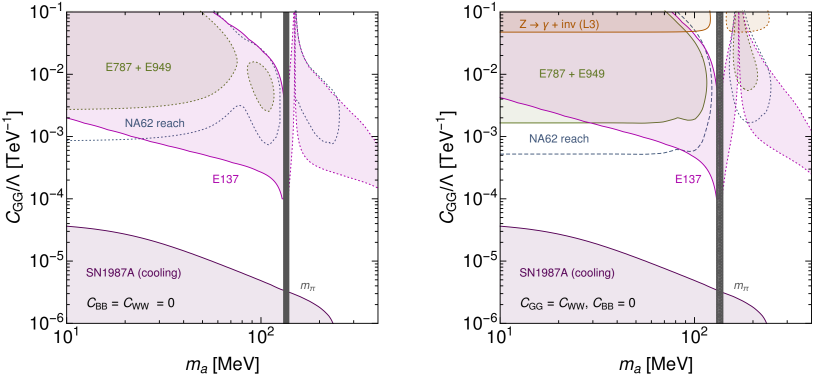
ALP Luminosity Distribution

What are typical energies for ALPs produced in SN core?





NA62: Signal Region 2 (1/2)



NA62: Signal Region 2 (2/2)