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Constraints on ALPs from astrophysical probes

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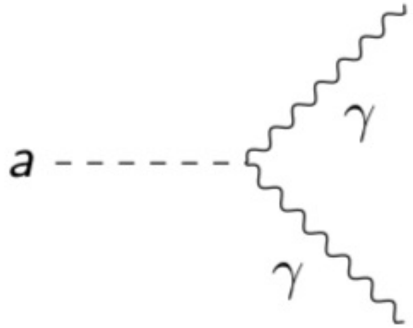
Based on
G.L., O. Straniero, P. Carenza, M. Giannotti, A. Mirizzi, PRL 129 (2022) 1, 011101
P. Carenza, G.L. et al., PLB 809 (2020) 135709, G.L. et al., JCAP 12 (2020) 008

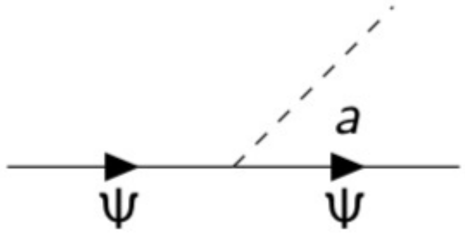
AXION-LIKE PARTICLES

Axion-like particles (ALPs) are pseudoscalar particles introduced in UV completions of the Standard Model (SM).

Possible interactions with SM particles

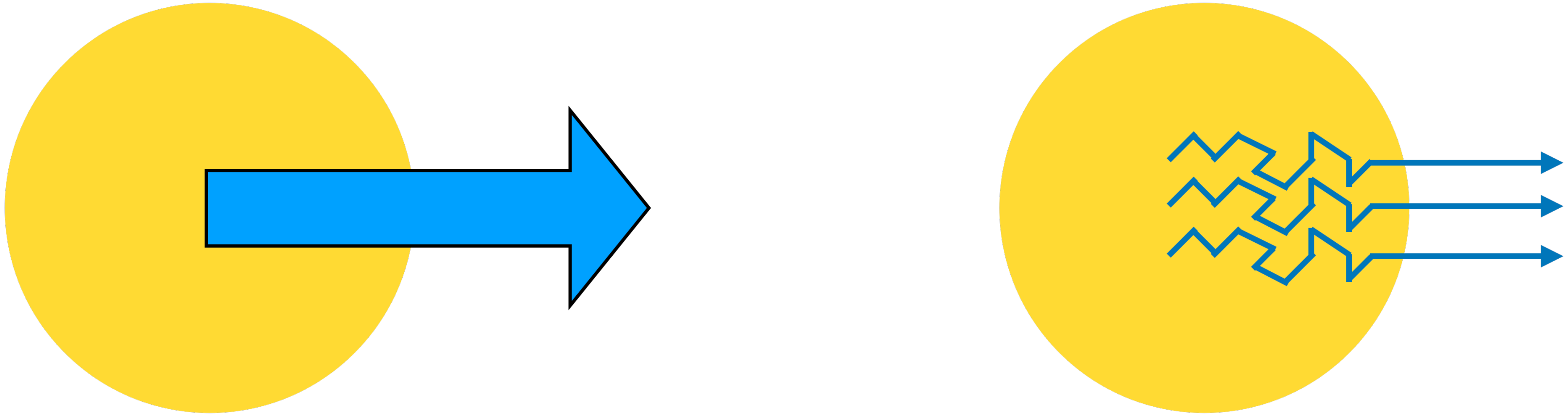
$$\boxed{\mathcal{L}_{int} = -\frac{1}{4} g_{a\gamma} \tilde{F}^{\mu\nu} F_{\mu\nu}\, a + \sum_{\psi=e,p,n} \frac{g_{a\psi}}{2\, m_\psi} (\bar{\psi}\gamma^\mu\gamma^5\psi)\partial_\mu a + \cdots}$$



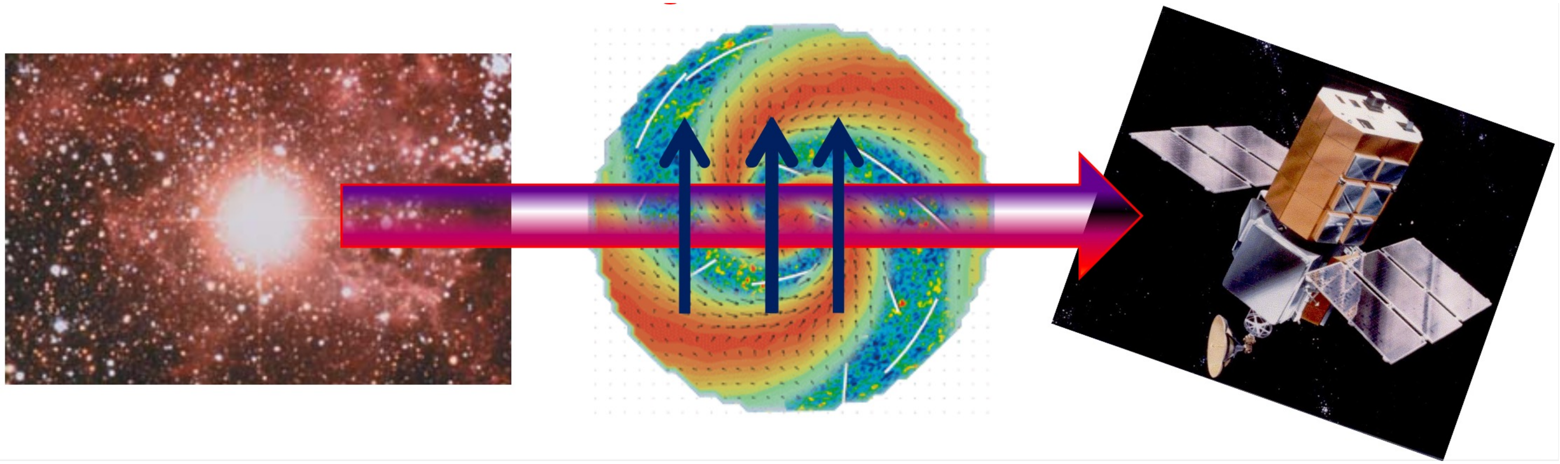


ALPs IN ASTROPHYSICS

- Impact on the standard stellar evolution



- Direct signature on Earth after photon conversion



ENERGY-LOSS ARGUMENT

- Weakly interacting ALPs: New energy-loss channel [Raffelt & Dearborn, PRD 36 (1987)]
- Energy flux equation

Net energy flux

$$\frac{dL_r}{dr} = 4\,\pi\, r^2\, \epsilon\, \rho, \qquad \epsilon = +(\epsilon_{\mathrm{nuc}} + \epsilon_{\mathrm{grav}}) - (\epsilon_\nu + \epsilon_a)$$

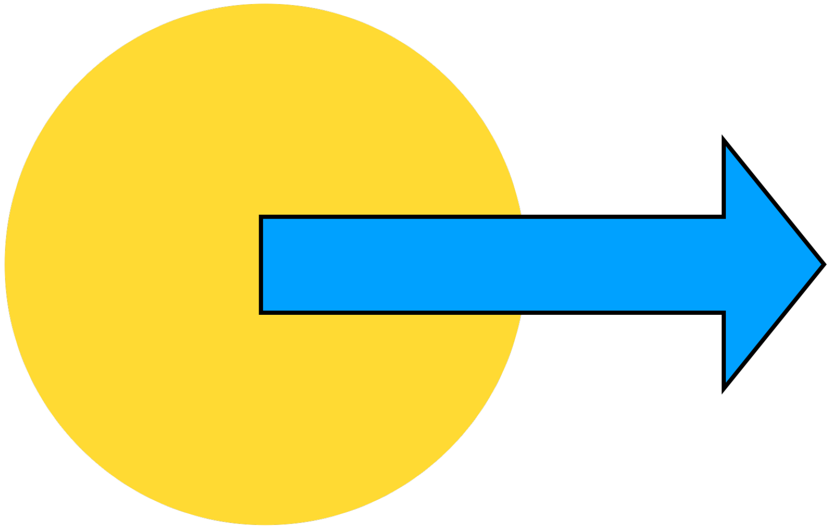
Sources

Sinks

<u>Backreaction</u> on stellar evolution

- Loss of pressure
- Heating
- Contraction
- Increased nuclear burning

→ Consumption of nuclear fuel is accelerated



ENERGY-TRANSFER ARGUMENT

Large interactions: ALPs trapped inside the star and contribute to energy transfer.

$$L_r = L_{conv} - \frac{4\,\pi\,r^2}{3\,\kappa\,\rho}\frac{d(aT^4)}{dr}, \qquad \kappa^{-1} = \kappa_\gamma^{-1} + \kappa_e^{-1} + \kappa_a^{-1}$$

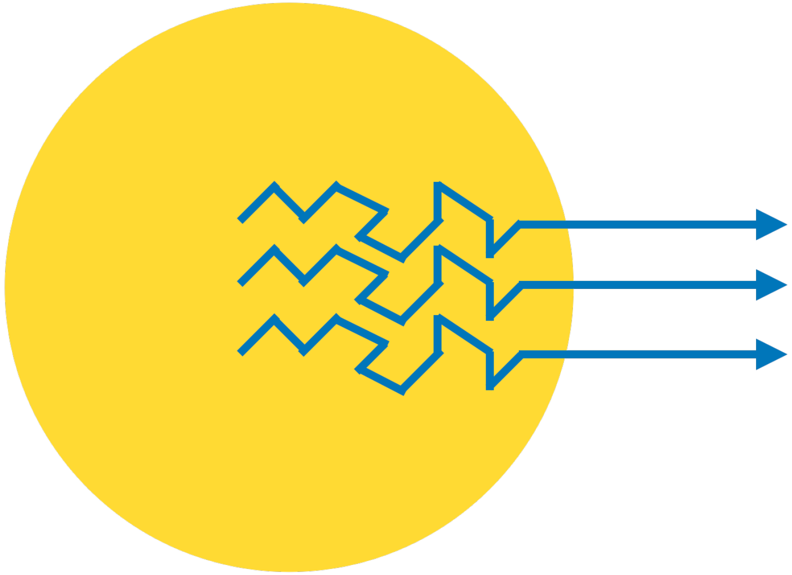
Radiative opacity

Electron conduction

ALPs

- L_{conv} energy transported by convection
- $(\kappa_x \rho)^{-1} = \lambda_x$ particle mean free path (mfp)
- ALPs must interact more strongly than standard particles in order not to change stellar properties:

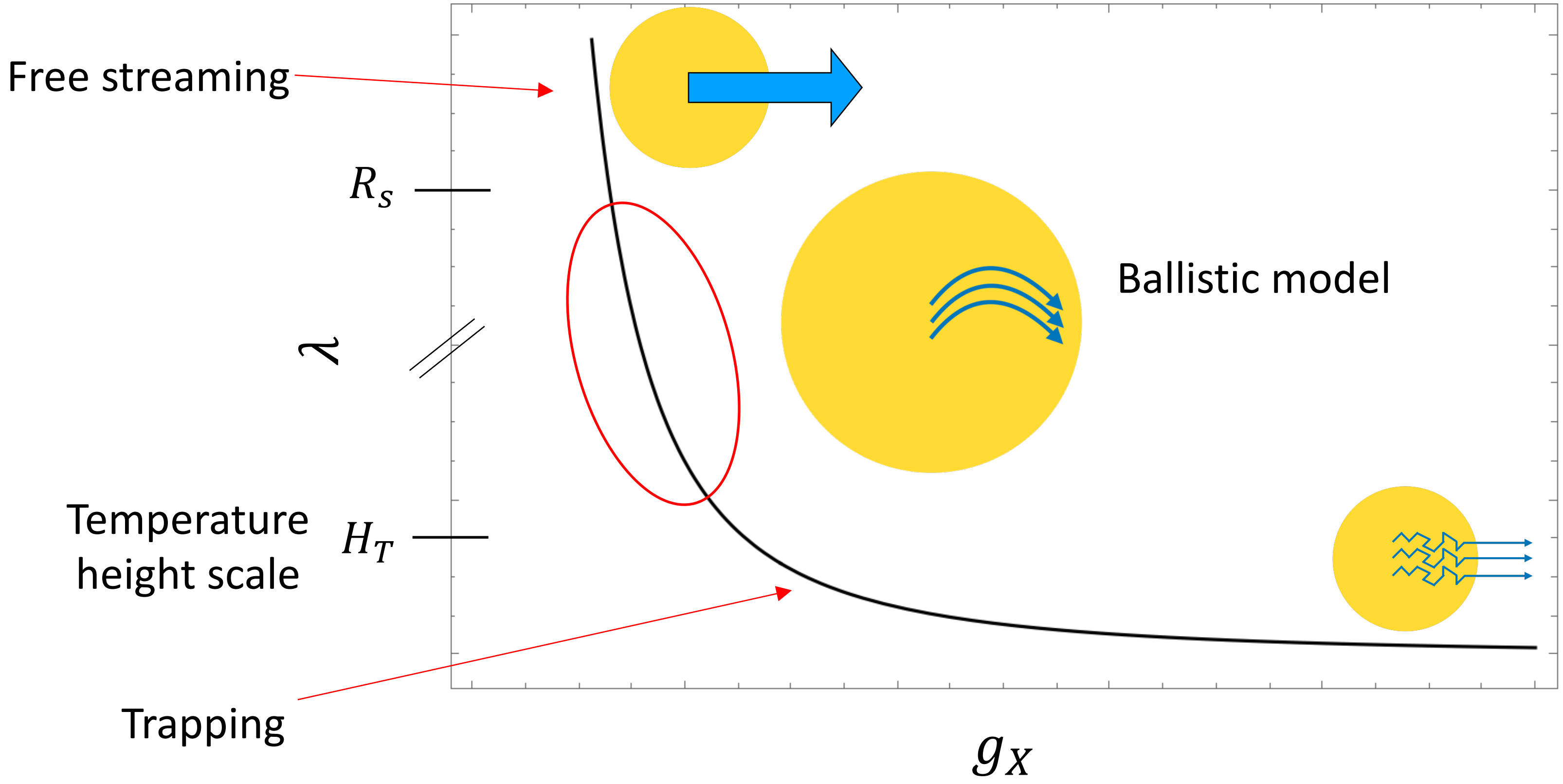
$$\kappa_a > \kappa_\gamma, \kappa_c$$



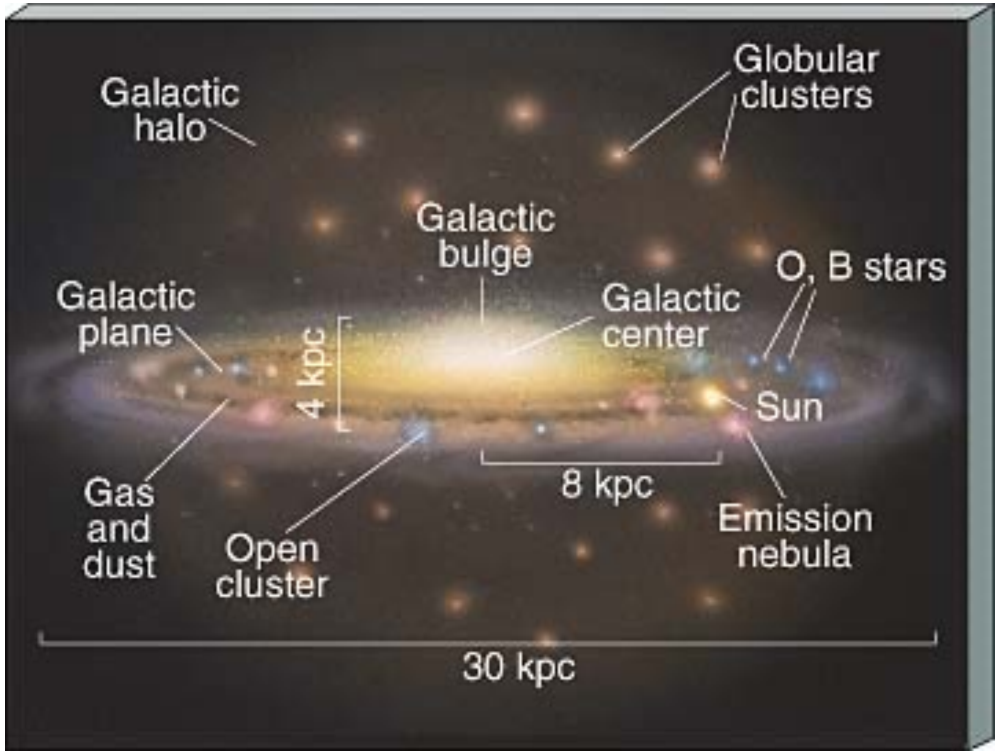
See [Caputo et al., JCAP 08 (2022)] for a recent review on the topic and application in the supernova context.

INTERMEDIATE REGIME

- For ALP mfp $\sim$ Stellar radius R_s, ALPs deposit energy far from the production region: intrinsic non-local problem
- **Ballistic model**: general method valid for any mfp (we apply it to Globular Cluster stars)

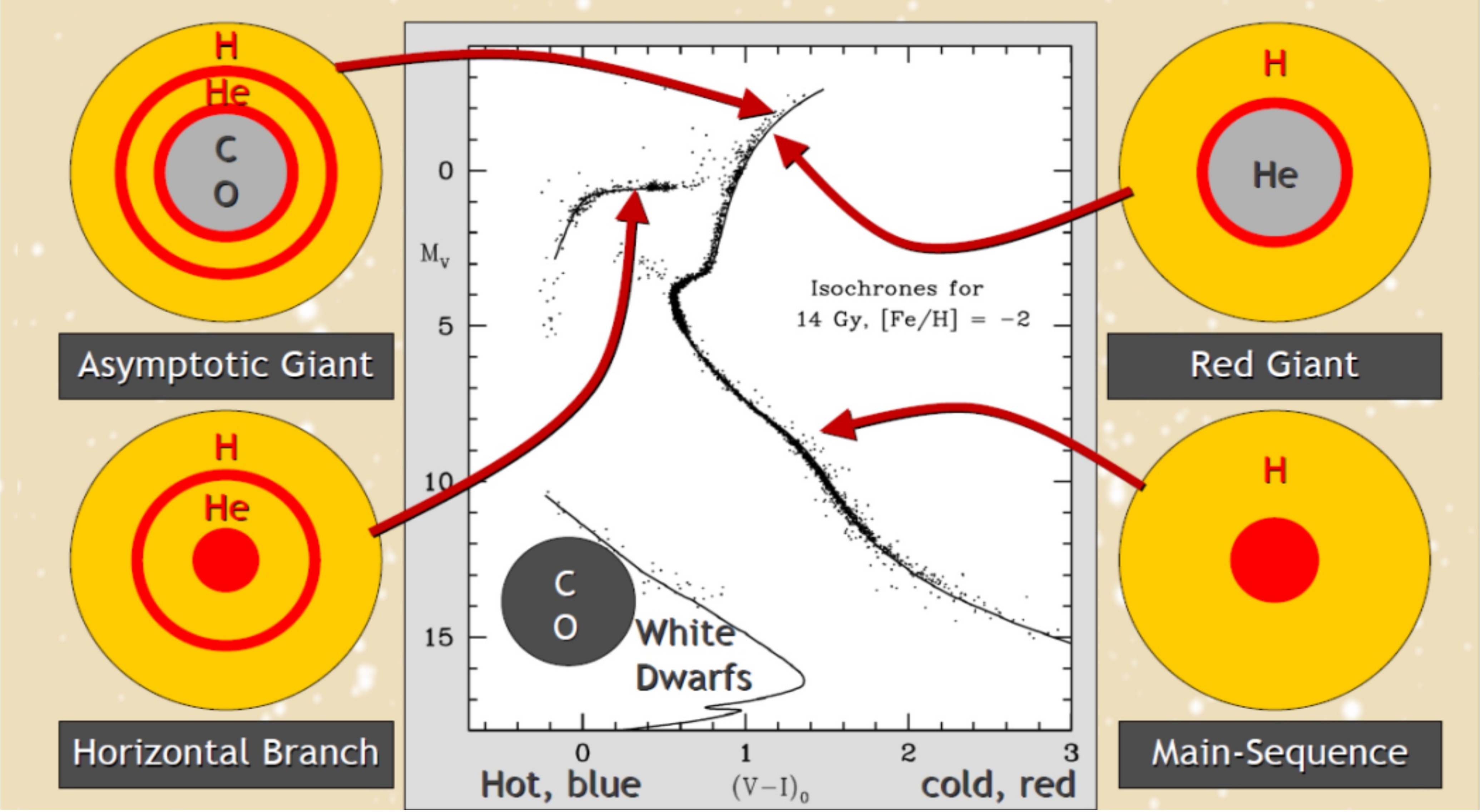


GLOBULAR CLUSTERS



- Gravitationally bound systems of $\sim 10^6$ coeval stars.
- Low metallicity $(Z = 10^{-4} - 10^{-2})$ related to great age.
- Fixed chemical composition $(Y \approx 0.25)$, only difference is mass.

COLOR MAGNITUDE DIAGRAM FOR GLOBULAR CLUSTERS



PRIMAKOFF PROCESS

Conversion of a thermal photon into an ALP in the Coulomb fields of nuclei and electrons.

The production rate is:

$$\frac{d^2 n_a}{dt\, dE} = \frac{g_{a\gamma}^2\, T\, \kappa_s^2}{32\pi^3 \left(e^{E/T} - 1\right)} \sqrt{E^2 - m_a^2}\sqrt{E^2 - \omega_{\mathrm{pl}}^2}\; G(E, m_a, \omega_{\mathrm{pl}}, \kappa_s)$$

- Temperature $T \approx 10$ keV in HB stars.
- Plasma frequency $\omega_{\mathrm{pl}} \approx 3$ keV in HB stars.
- Screening scale $\kappa_s^2 = \frac{4\,\pi\,\alpha}{T}\left(n_e^{eff} + \sum_j Z_j^2\, n_j^{\mathrm{eff}}\right)$

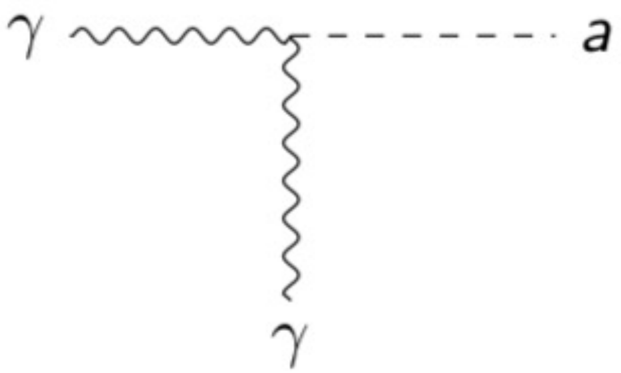
PHOTON COALESCENCE

In a medium of sufficiently high density, two photons can annihilate producing an ALP.

The production rate is:

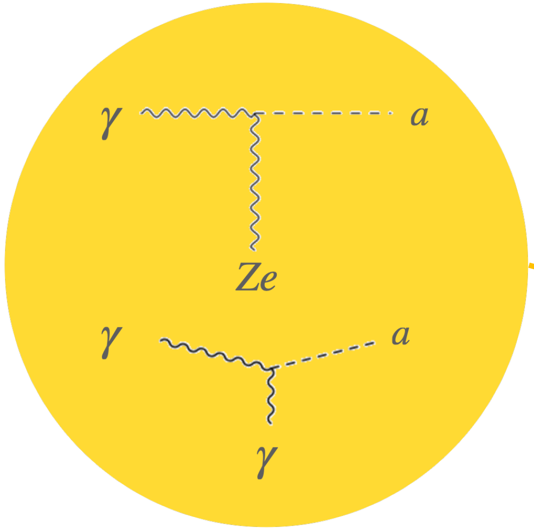
$$\frac{d^2 n_a}{dt\, dE} = g_{a\gamma}^2 \frac{m_a^4}{128\, \pi^3} \sqrt{E^2 - m_a^2} \left(1 - \frac{4\omega_{\rm pl}^2}{m_a^2}\right)^{3/2} e^{-E/T}$$

Threshold for $m_a < 2\omega_{\rm pl}$.



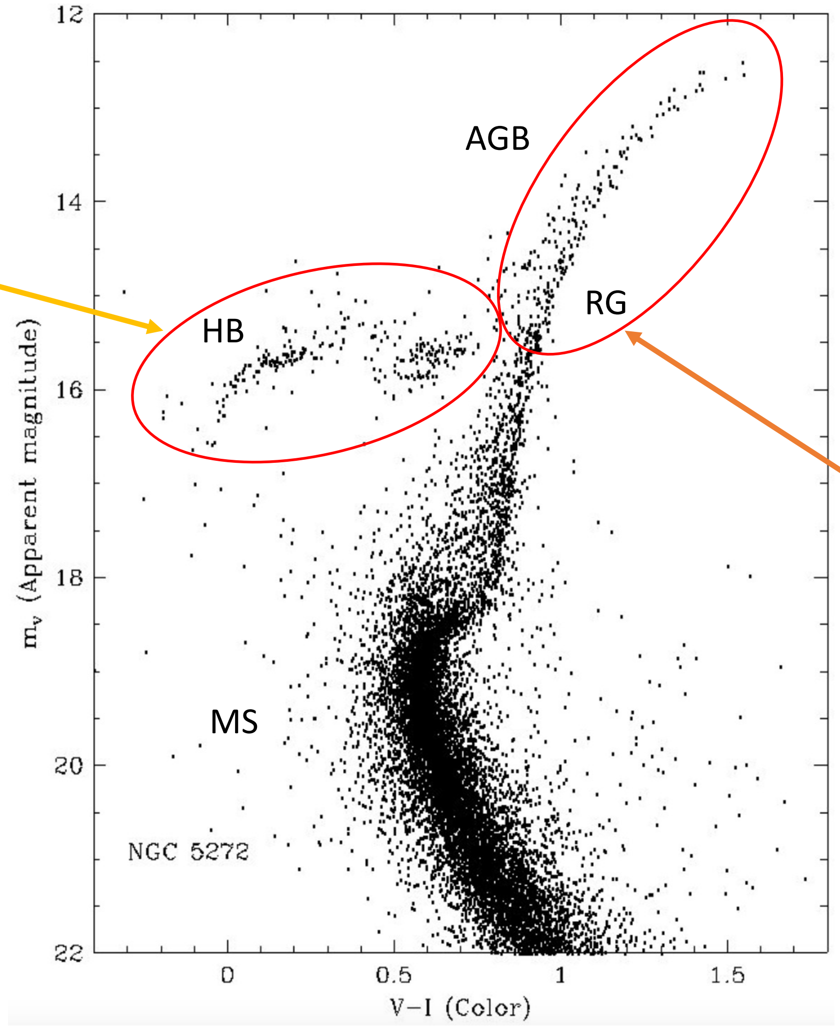
SENSITIVITY TO ALP EMISSION

[Raffelt & Dearborn, PRD 36 (1987)]



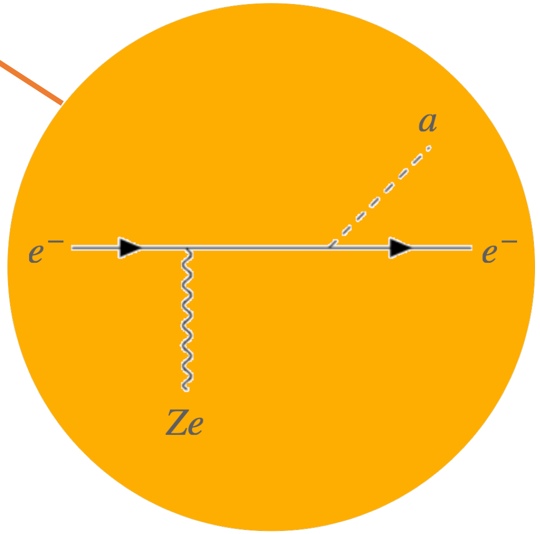
HB: non-degenerate core.
Sensitive to $g_{a\gamma}$.

$$\boxed{R = N_{HB}/N_{RG}}$$



RG: degenerate core.
Sensitive to g_{ae}.
Brightness of the tip of the RG branch.

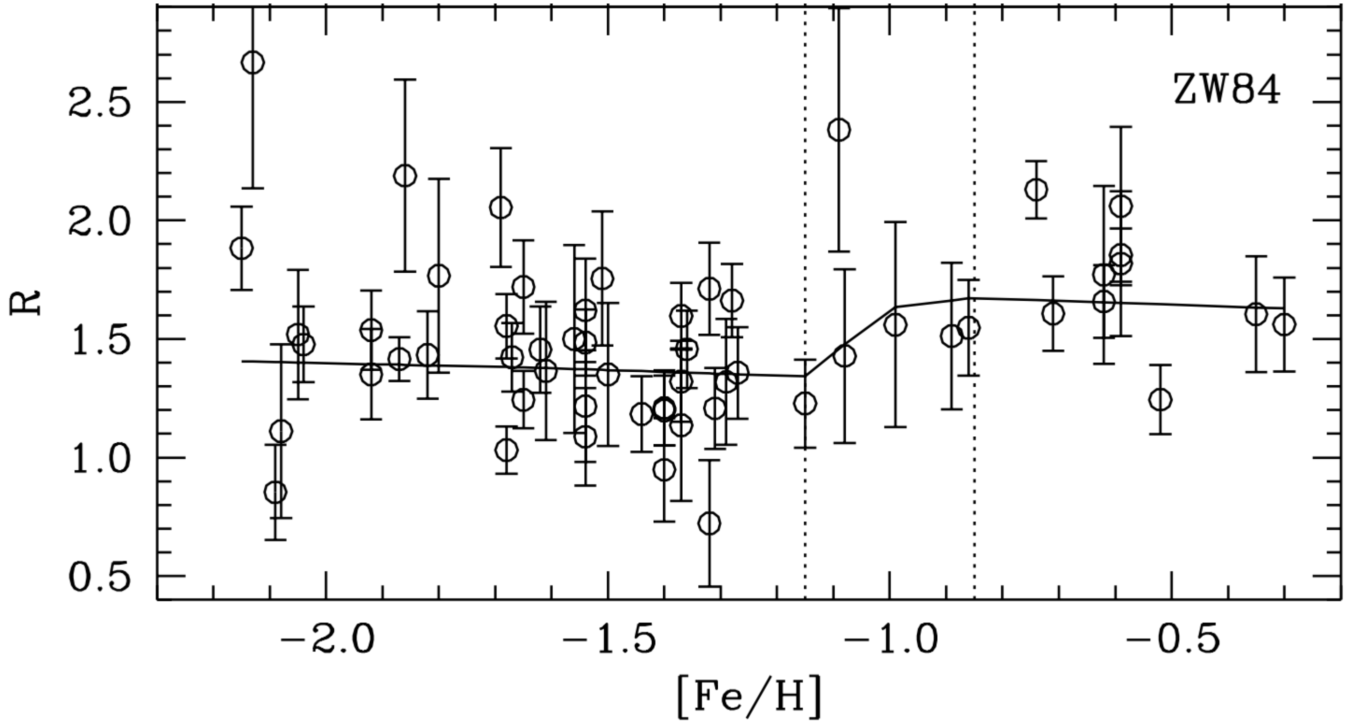
[Viaux et al., PRL 111 (2013)
Capozzi & Raffelt, PRD 102 (2020)
Straniero et al., Astron.Astrophys. 644 (2020)]



HELIUM BURNING LIFETIME

Analysis of 39 Globular Clusters [Salaris et al., Astron. Astrophys. 420 (2004)]

$$R_{\rm ave} = \frac{N_{HB}}{N_{RG}} = \frac{\tau_{HB}}{\tau_{RG}} = 1.39 \pm 0.03 \qquad \text{for } Y = 0.254 \text{ and } \left[\frac{\rm Fe}{\rm H}\right] < -1.1$$

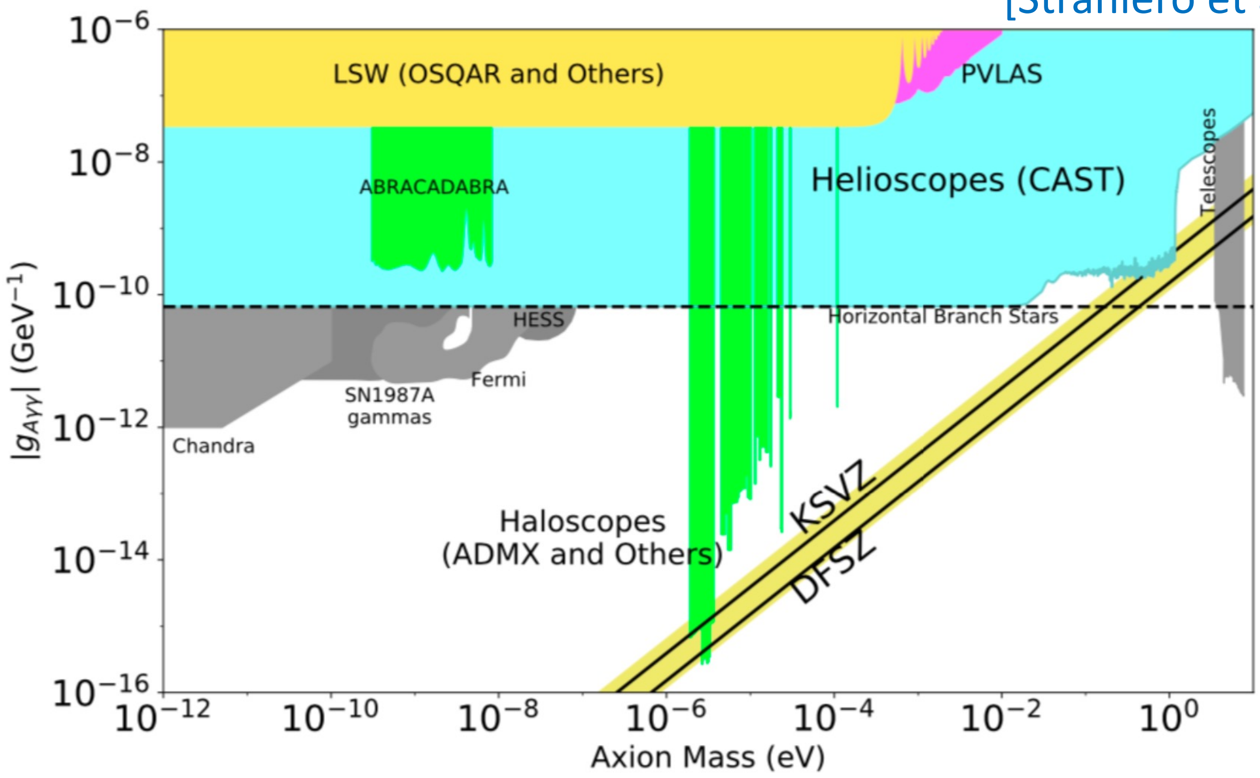


R parameter well reproduced by numerical models without ALPs.

HB STAR BOUND ON LIGHT ALPS

- ALPs included as new energy sink (ϵ_a) in hydrostatic 1D stellar evolution code: R reduces as $g_{a\gamma}$ increases.
- For $m_a < 10\ \text{keV}$: $g_{a\gamma} < 0.65 \times 10^{-10}$ GeV^{-1} (95% C. L.) [Ayala et al., PRL 113 (2014)]

[Straniero et al., proc. of XI Patras Workshop]

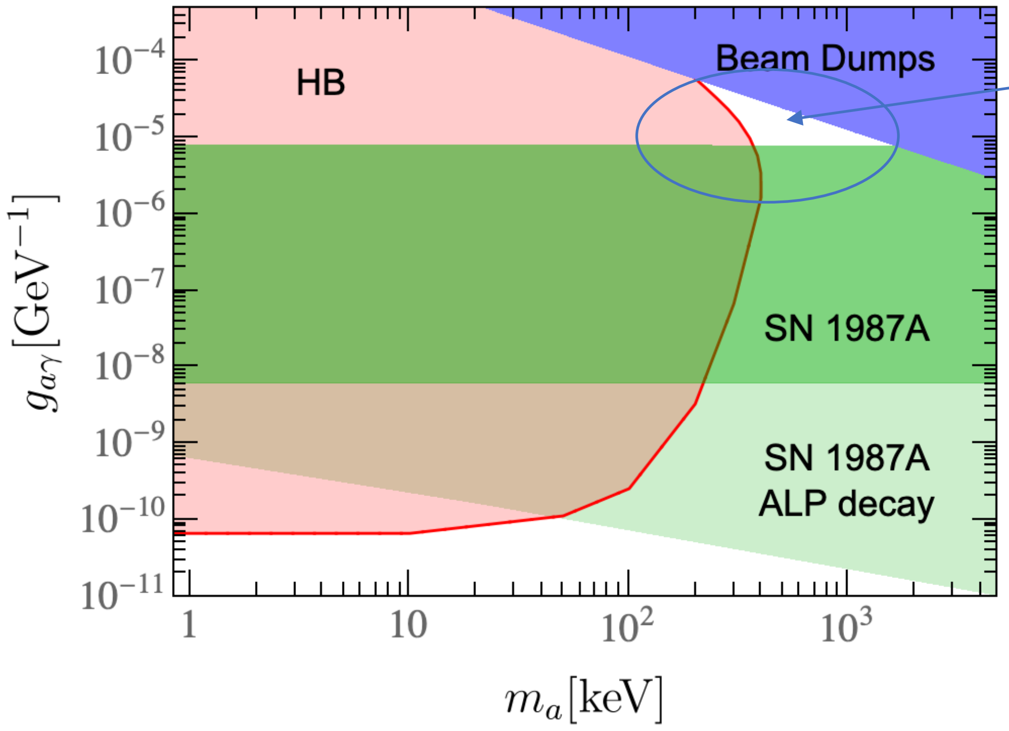


The strongest bound on $g_{a\gamma}$ comparable with CAST. [Anastassopoulos et al., Nature Phys. 13 (2017)]

BOUND ON HEAVY ALPs

[Carenza, G.L., et al., PLB 809 (2020)]

- For GC benchmark model with $Y = 0.26$ and $Z = 0.001$, light ALPs with $g_{a\gamma} = 0.65 \times 10^{-10}$ GeV^{-1} reduce τ_{HB} by $\sim 15\%$.
- For each mass m_a, the bound is obtained for $g_{a\gamma}$ giving the same reduction.



Cosmological triangle (probed only by cosmology)

Boltzmann suppression: the bound is relaxed for $m_a \gtrsim 10$ keV.

ALP DECAYS IN THE STAR: THE BALLISTIC MODEL

[Carenza, G.L., et al., PRL 129 (2022)]

For $m_a \gtrsim 300$ keV and $g_{a\gamma} \gtrsim 10^{-6}\ \mathrm{GeV}^{-1}$ ALPs decay inside the star.

A source term is added in the energy balance equation for the each shell of the star:

$$\epsilon_i = \cdots - \epsilon_{a,i} + < \epsilon_{dep,i} >$$

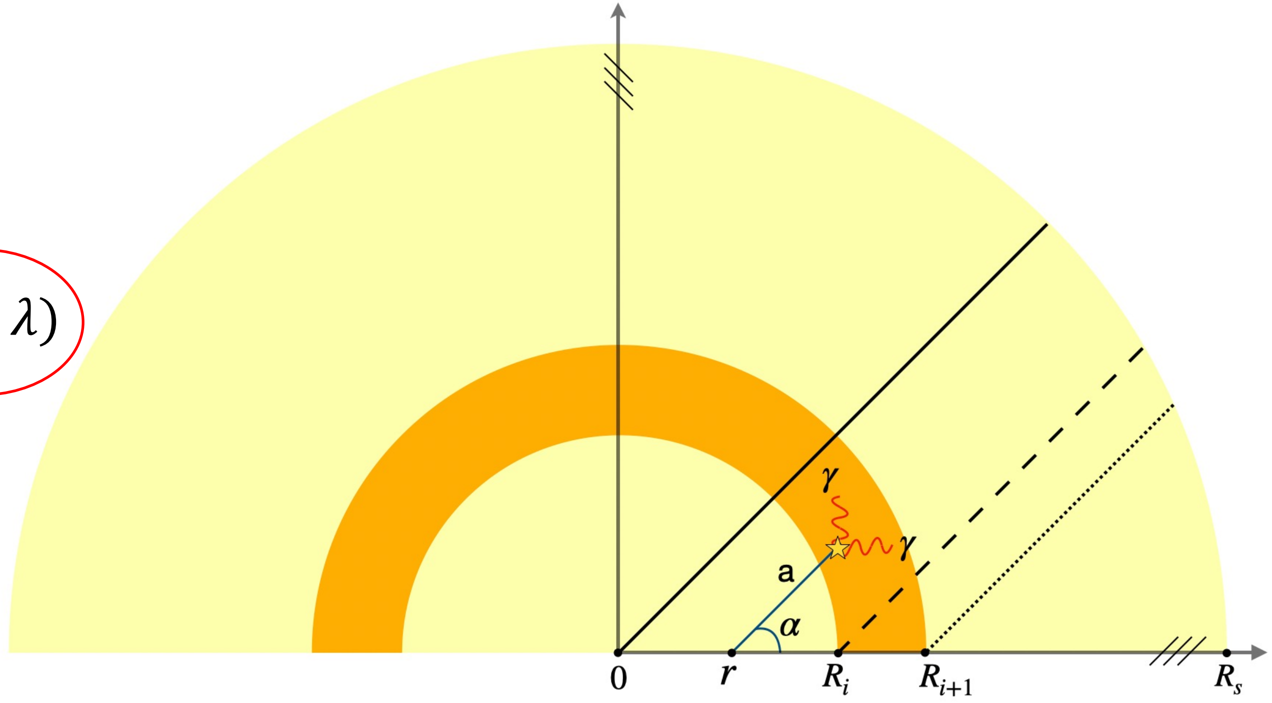
Average over the emission angle

$$\epsilon_{dep,i}(\eta) = \sum_d \frac{\Delta L_{i,d}(\eta)}{\Delta M_i}$$

$$\Delta L_{i,d}(\eta) = 2\pi \int_{I_{r,d}} dr\, r^2 \int_{m_a}^{\infty} dE\, E \frac{d^2 n_a(r)}{dt\, dE} \chi_d(l,\lambda)$$

Integration domain for production radius

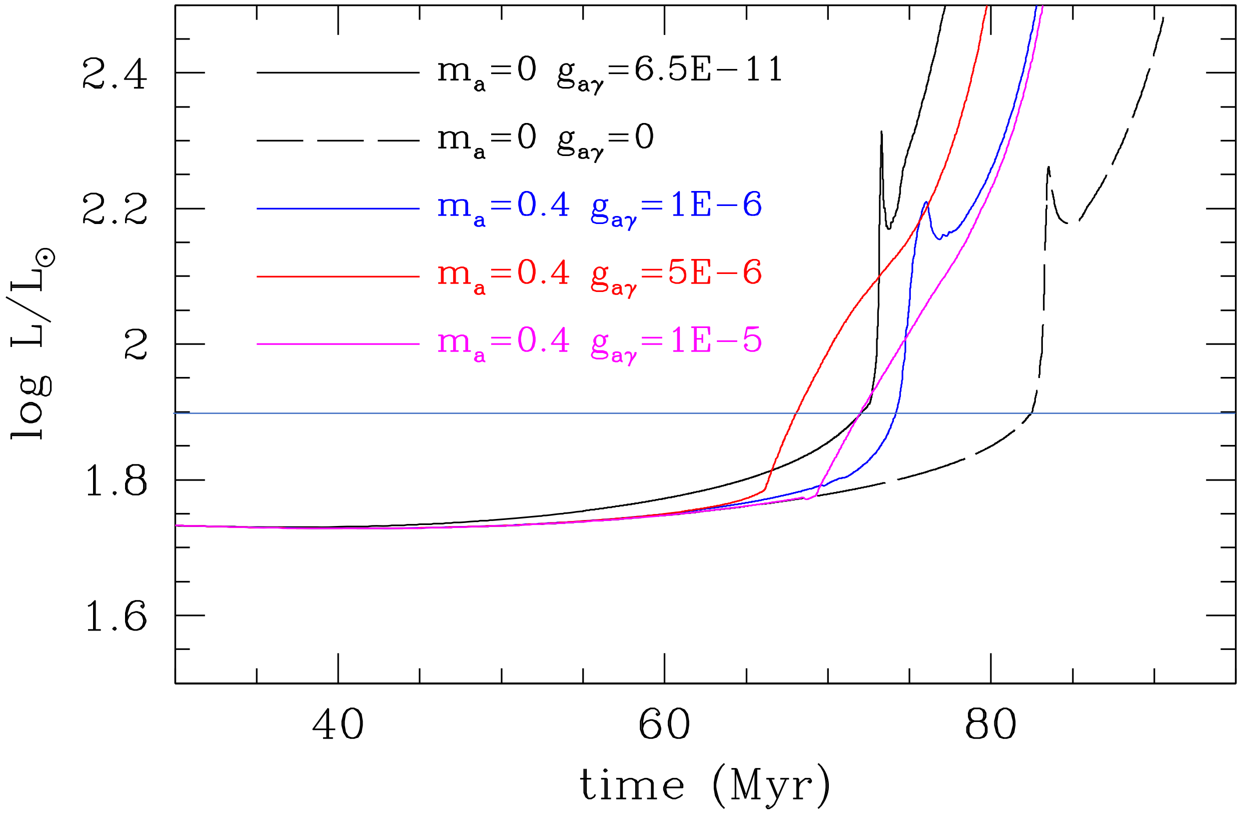
Fraction of ALPs decaying in the shell



ALP energy-transfer produces a premature disappearance of star convective core.

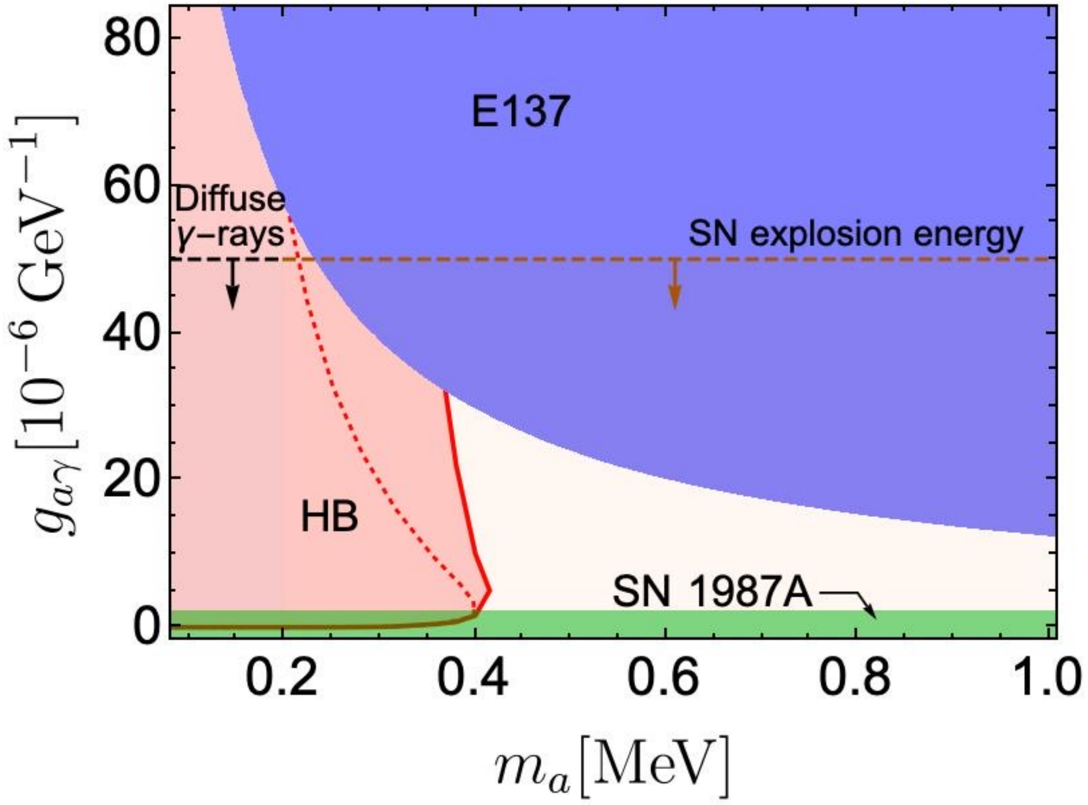
LUMINOSITY EVOLUTION

- Models rejected when the lifetime is shorter than that of the model with light ALPs.
- HB lifetime evaluated when $\log \frac{L}{L_{\odot}} = 1.9$
- For each value of m_a a pair of $g_{a\gamma}$ reproduce the light ALP bound.



UPDATED BOUND

Our new bound restricts the cosmological triangle.



- Future experiments could probe the cosmological triangle (e.g. DUNE [Brdar et al., PRL 126 (2021)]).
- Cosmological triangle closed by the SN explosion energy bound: energy deposited by ALPs in the SN envelope must not exceed $\sim 10^{50}$ erg (back-of-the-envelope estimation). [Caputo et al., PRD 105 (2022), PRL 128 (2022)]

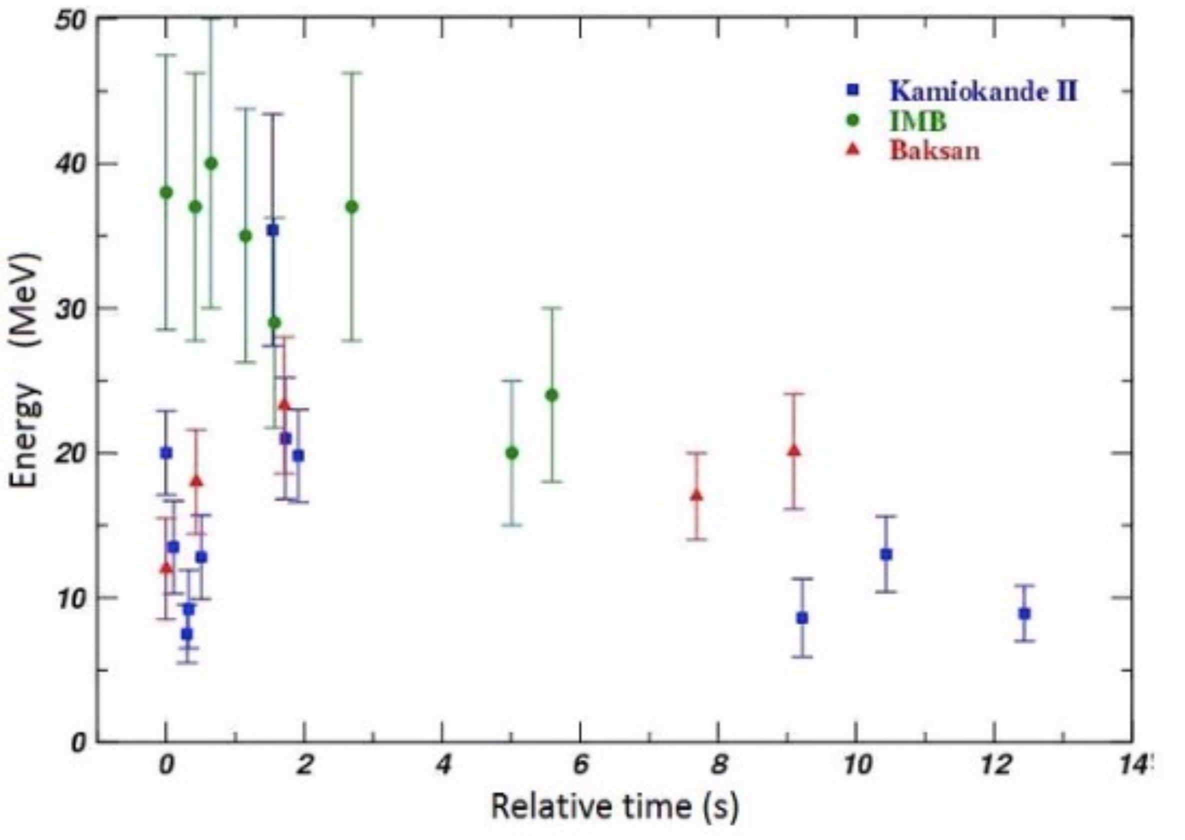
SUPERNOVAE

Core collapse supernovae (SNe) corresponds to the terminal phase of a massive star [$M \gtrsim 8\ M_\odot$] which becomes unstable at the end of its life. It collapses and ejects its outer mantle in a shock wave driven explosion.

- **ENERGY SCALES:** 99% of the released energy (~ 10^{53} erg) is emitted by ν and $\bar{\nu}$ of all flavors, with typical energies E ~ O(15 MeV).
- **TIME SCALES:** Neutrino emission lasts ~10 s
- **EXPECTED:** 1-3 SN/century in our galaxy (d $\approx$ O (10) kpc).

SN 1987A NEUTRINO SIGNAL

Observation of neutrino signal from SN 1987A in agreement with standard picture of SN explosion. [Loredo & Lamb, PRD 65 (2002)]



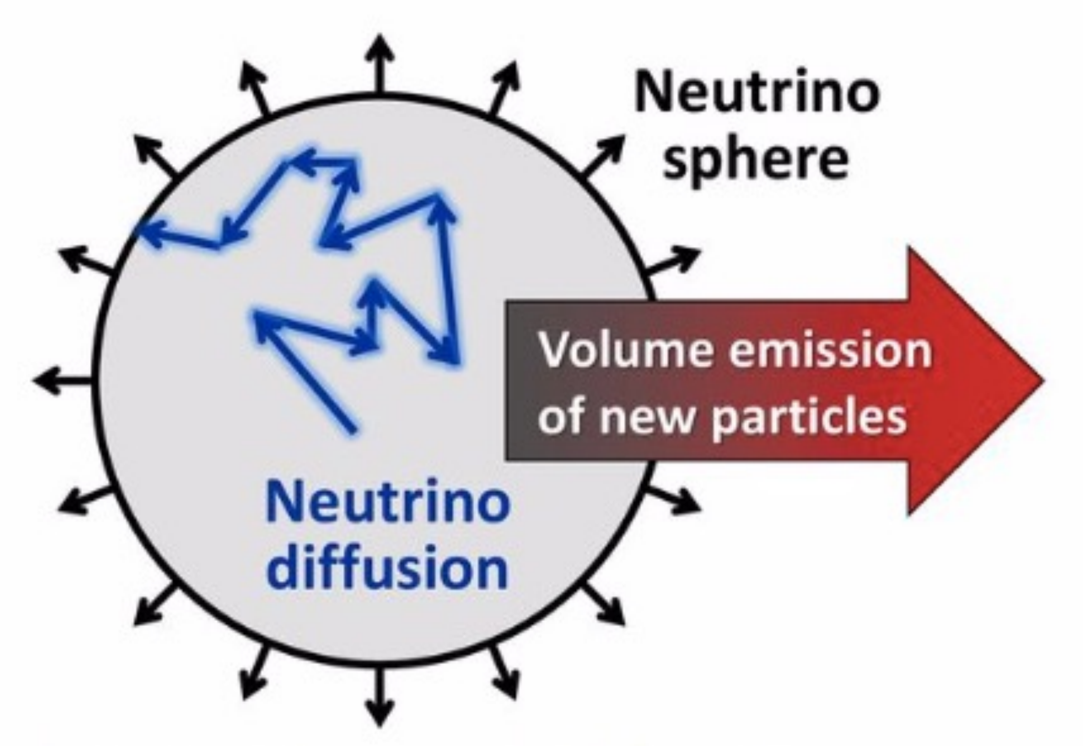
THE *ENERGY-LOSS* ARGUMENT

- Emission of weakly interacting particles would "steal" energy from the neutrino burst and shorten it. [Raffelt, Lect. Notes Phys. 741 (2008)]

- Assuming that the SN 1987A neutrino burst was not shortened by more than $\sim 1/2$ leads to an approximate requirement on the ALP luminosity

$$L_a \lesssim L_\nu \approx 3\times 10^{52}\ \mathrm{erg/s}$$

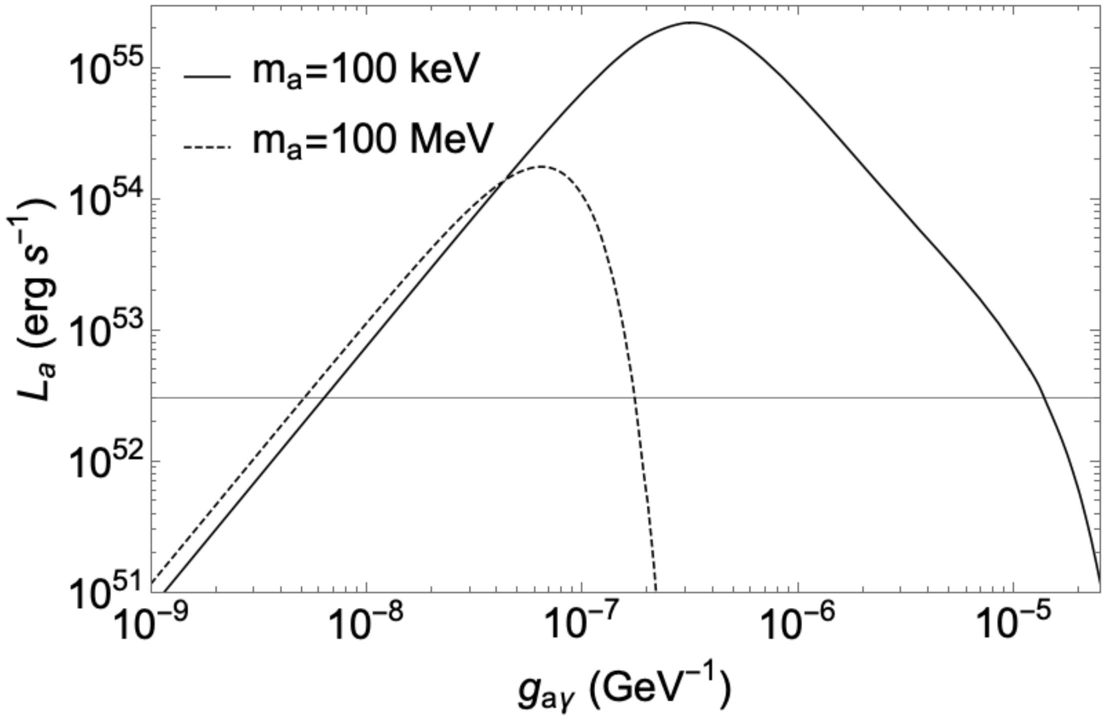
at $t = 1$ s.



MODIFIED LUMINOSITY CRITERION

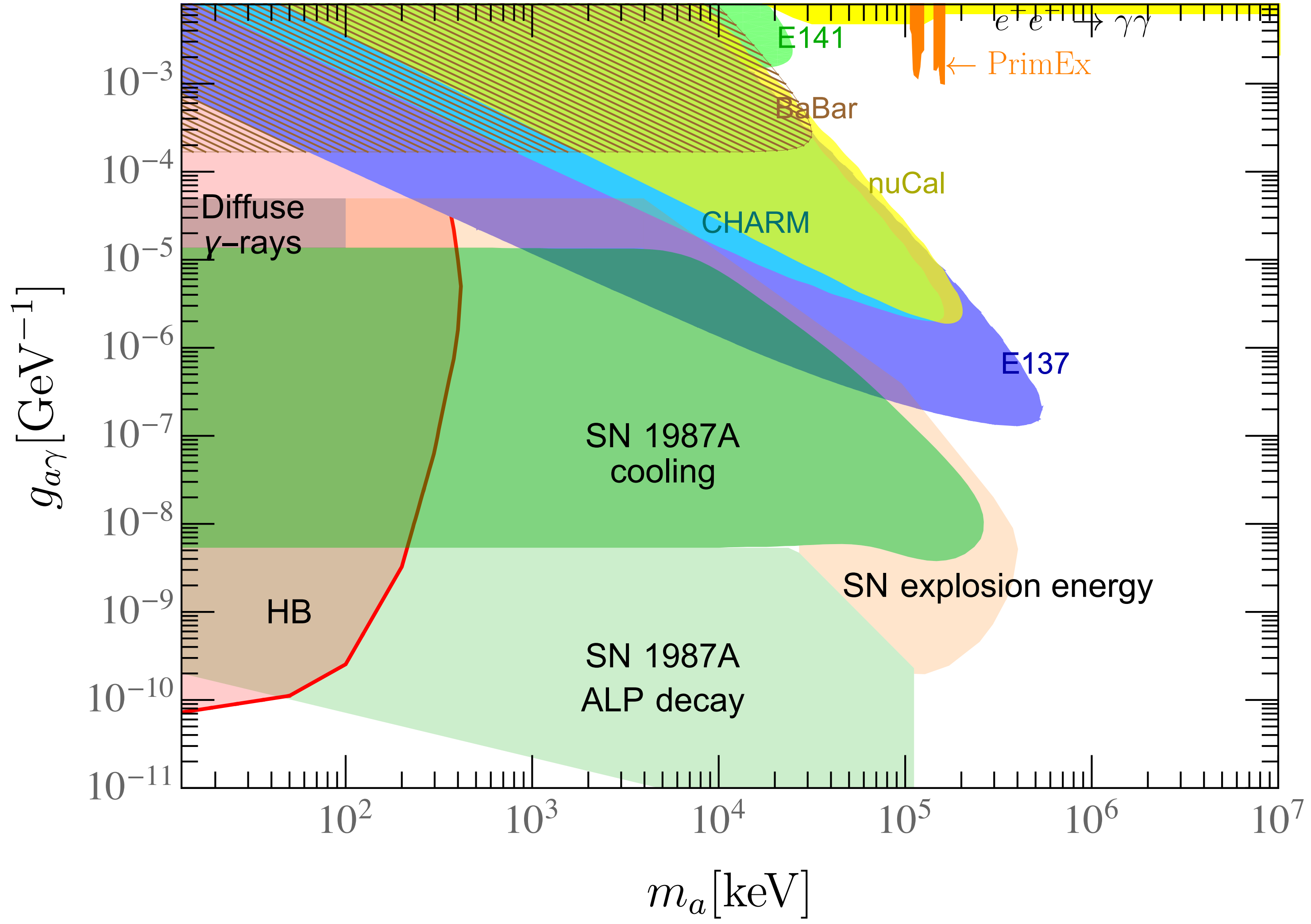
Only the ALP energy which cannot be reprocessed efficiently as neutrino one is relevant for constraining the ALP parameter space. [Chang et al, *JHEP* 01 (2017)]

$$L_{a,mod} = 4\pi \int dr\, r^2 \int_{m_a}^{\infty} dE\, E\, \underbrace{\frac{d^2 n_a}{dt\, dE}}_{\text{Production}}(r)\, \underbrace{e^{-\tau(r,E)}}_{\text{Absorption}}$$



BOUNDS ON HEAVY ALPs

[G.L. et al, JCAP 12 (2020)]



CONCLUSIONS

- Production of ALPs coupled with photons: impact on the stellar evolution.
- The lifetime of HB star is shortened and the R parameter is reduced: constraints on ALPs with mass $m_a \lesssim 300\ \mathrm{keV}$.
- ALPs production must not modify the duration of SN neutrino burst: constraints on ALPs with mass $m_a \lesssim 300\ \mathrm{MeV}$.
- Astrophysical constraints complementary to experimental bounds: interplay between Astrophysics and direct searches.

Thanks for your attention

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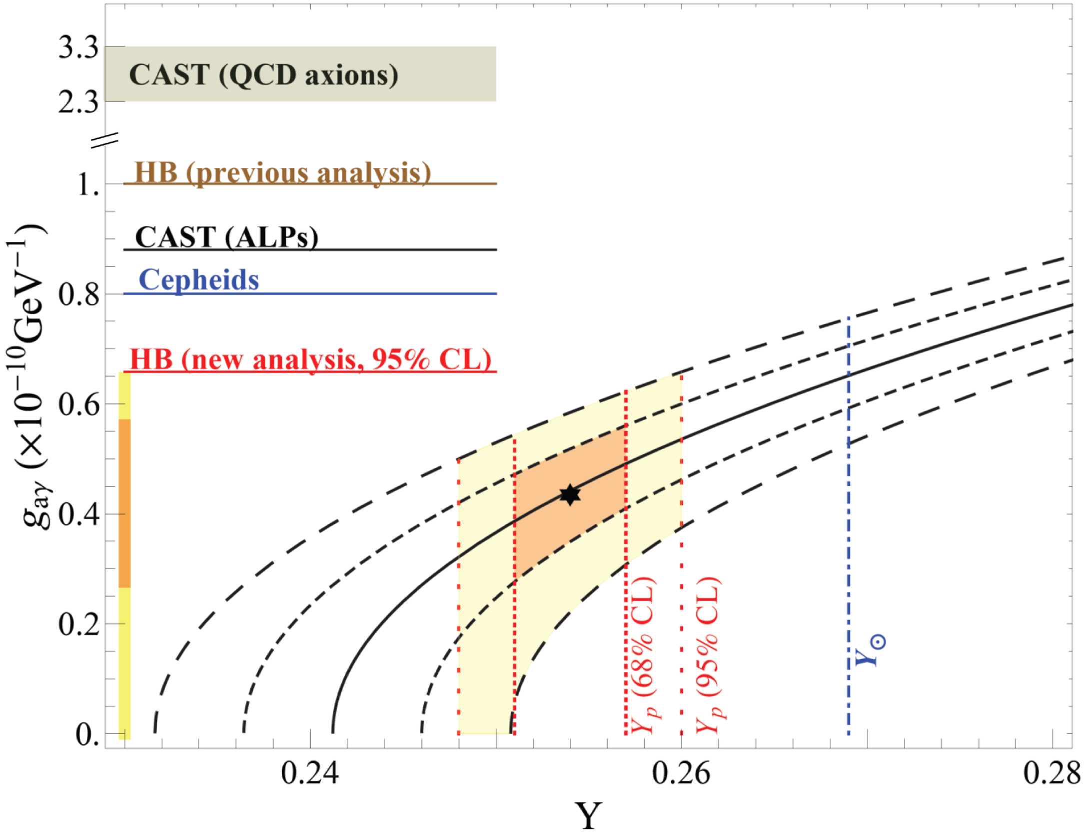
HINT FOR LOW-MASS ALPs

[Ayala et al., 1406.6053]

$$R(g_{a\gamma}, Y) = 6.26\,Y - 0.41\,g_{10}^2 - 0.12$$

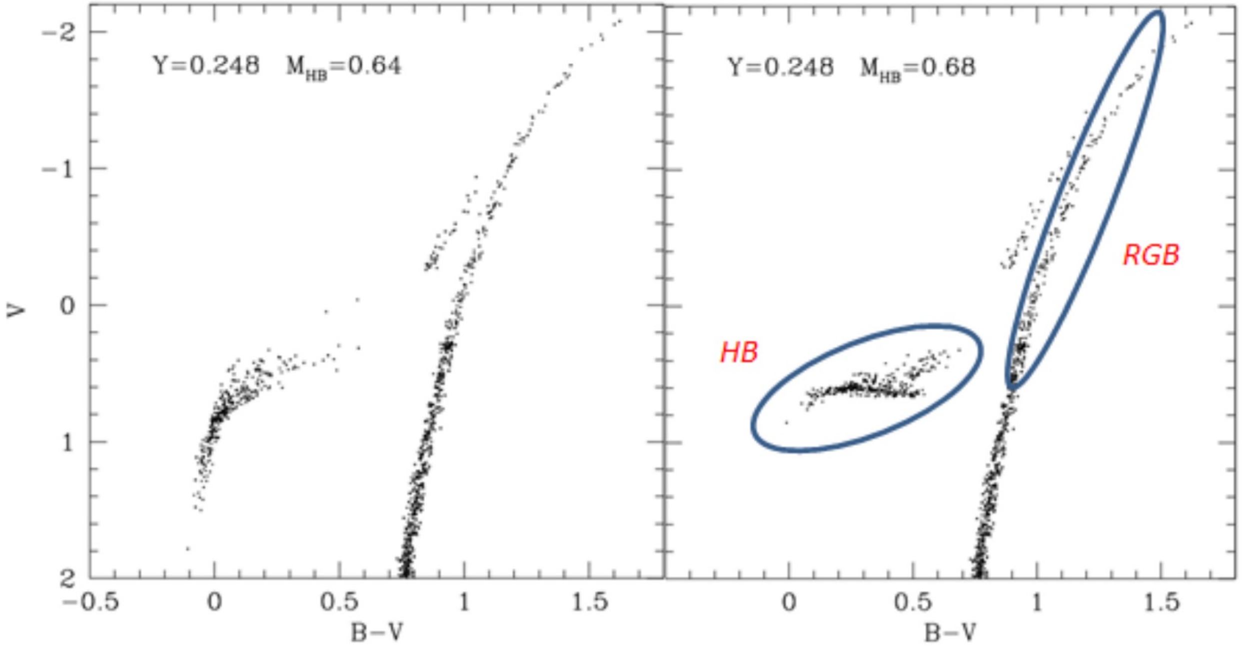


$Y = 0.254 \pm 0.003$

[Aver et al., 1309.0047]

Hint: $g_{10} = 0.45^{+0.12}_{-0.16} \times 10^{-10}\ \mathrm{GeV}^{-1}$

ANALYSIS WITH SYNTHETIC CM DIAGRAMS

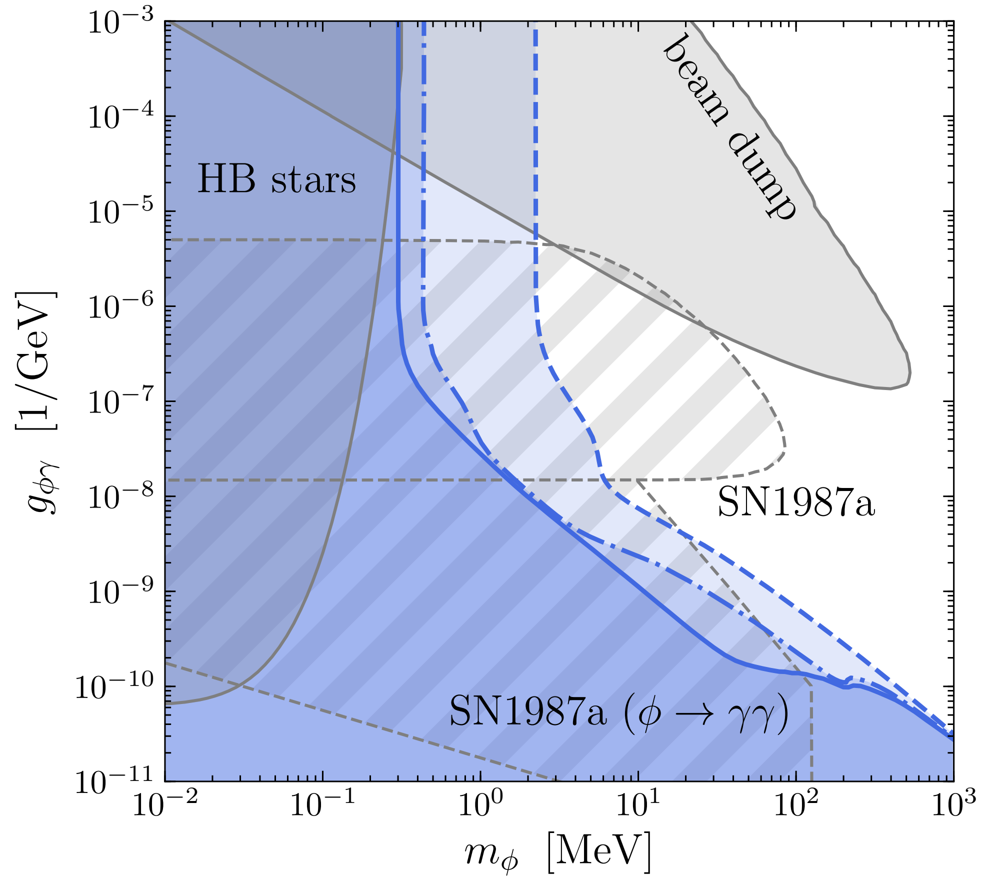


Parameter	error	Reference
$^{14}\mathrm{N}(p,\gamma)^{15}\mathrm{O}$	7%	[1]
$^{4}\mathrm{He}(2\alpha,\gamma)^{12}\mathrm{C}$	10%	[2]
$^{12}\mathrm{C}(\alpha,\gamma)^{16}\mathrm{O}$	20%	[6]
R	1.39 ± 0.03	[4]
Y	0.255 ± 0.002	[5],[3]

Hint: $g_{a\gamma} = (0.29 \pm 0.18\,)\times 10^{-10}\ \ \mathrm{GeV}^{-1}$

THE COSMOLOGICAL TRIANGLE

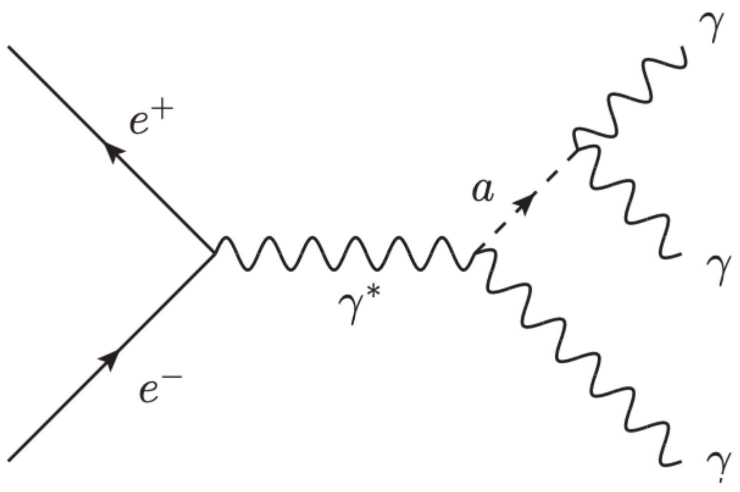
- ALPs modify cosmological evolution of the universe.
- Non-standard scenarios would weaken bounds on ALPs. [Depta et al., 2002.08370]

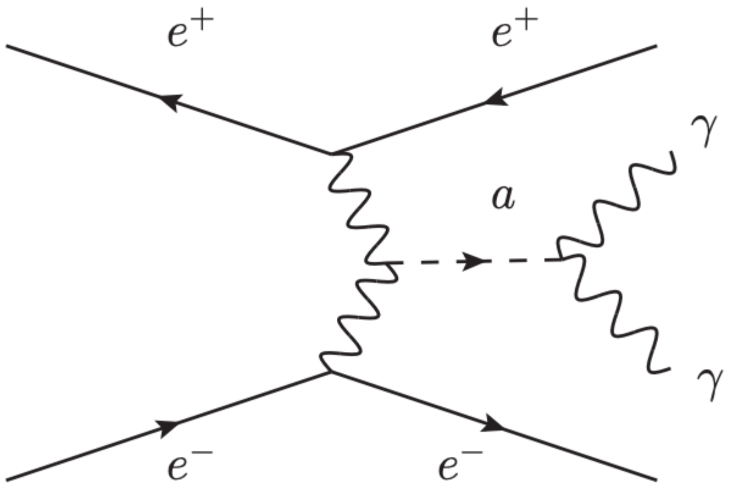


BEAM DUMP EXPERIMENTS

[Dolan et al., 1709.00009]

- An electron or positron beam produces ALPs which may decay into the detector.
- Too short and too long lifetimes cannot be probed: nose-like shape.





At the moment, the strongest bound is from E137. [Bjorken et al., PRD 38 (1988) 3375
Dolan et al., 1709.00009]

Future experiments, such as DUNE [Brdar et al., 2011.07054], will probe lower couplings.

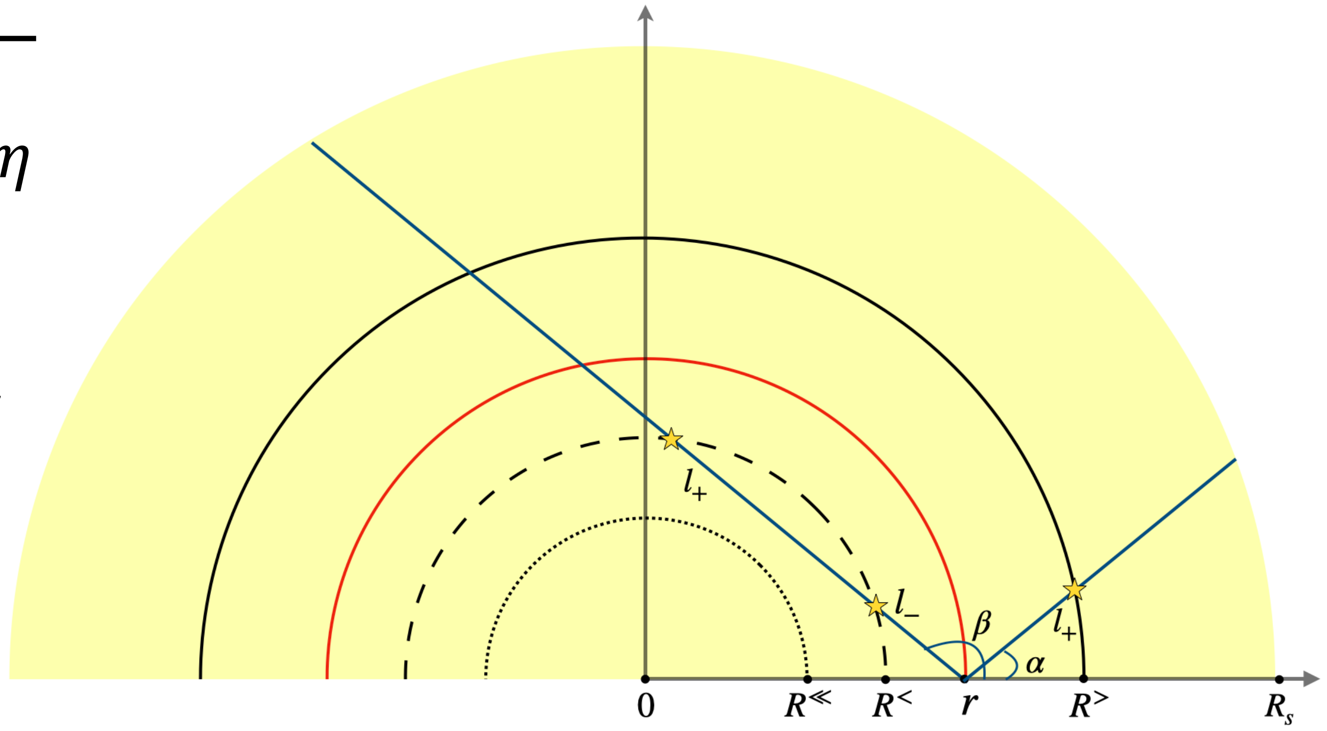
MORE ON THE BALLISTIC MODEL

- For $m_a \gtrsim 300$ keV and $g_{a\gamma} \gtrsim 10^{-6}\ \mathrm{GeV}^{-1}$ ALPs decay inside the star and they deposit energy into photons far from their production region: non-local energy transport.
- Fraction of survived particles after a path l is $e^{-l(r,R,\eta)/\lambda}$

$$l_{\pm} = -r\cos\eta \pm R\sqrt{1-\left(\frac{r}{R}\right)^2 \sin^2\eta}$$

η is the angle between particle trajectory and the outward radial direction

- Forward emission $\eta \in \left[0, \frac{\pi}{2}\right]$
- Backward emission $\eta \in \left[\frac{\pi}{2}, \pi\right]$



ENERGY DEPOSITION IN A SHELL

The star envelope is discretized in N shells, delimited by radii R_i and R_{i+1} ($R_1 = 0\ \mathrm{km}$, $R_{N+1} = R_S$).
In the i-th shell energy is deposited by decaying ALPs Forward ($r < R_{i+1}$) or Backward ($r > R_i$) emitted.

- A source term is added in the energy balance equation for the i-th shell:

$$\epsilon_i = \cdots - \epsilon_{a,i} + < \epsilon_{dep,i} >$$

Average over the emission angle

- Rate of energy deposited per unit mass $\epsilon_{dep,i}(\eta) = \sum_d \frac{\Delta L_{i,d}(\eta)}{\Delta M_i}$

$$\Delta L_{i,d}(\eta) = 2\pi \int_{I_{r,d}} dr\, r^2 \int_{m_a}^{\infty} dE\, E \frac{d^2 n_a(r)}{dt\, dE} \chi_d(l,\lambda)$$

Integration domain for production radius

Fraction of ALPs decaying in the i-th shell

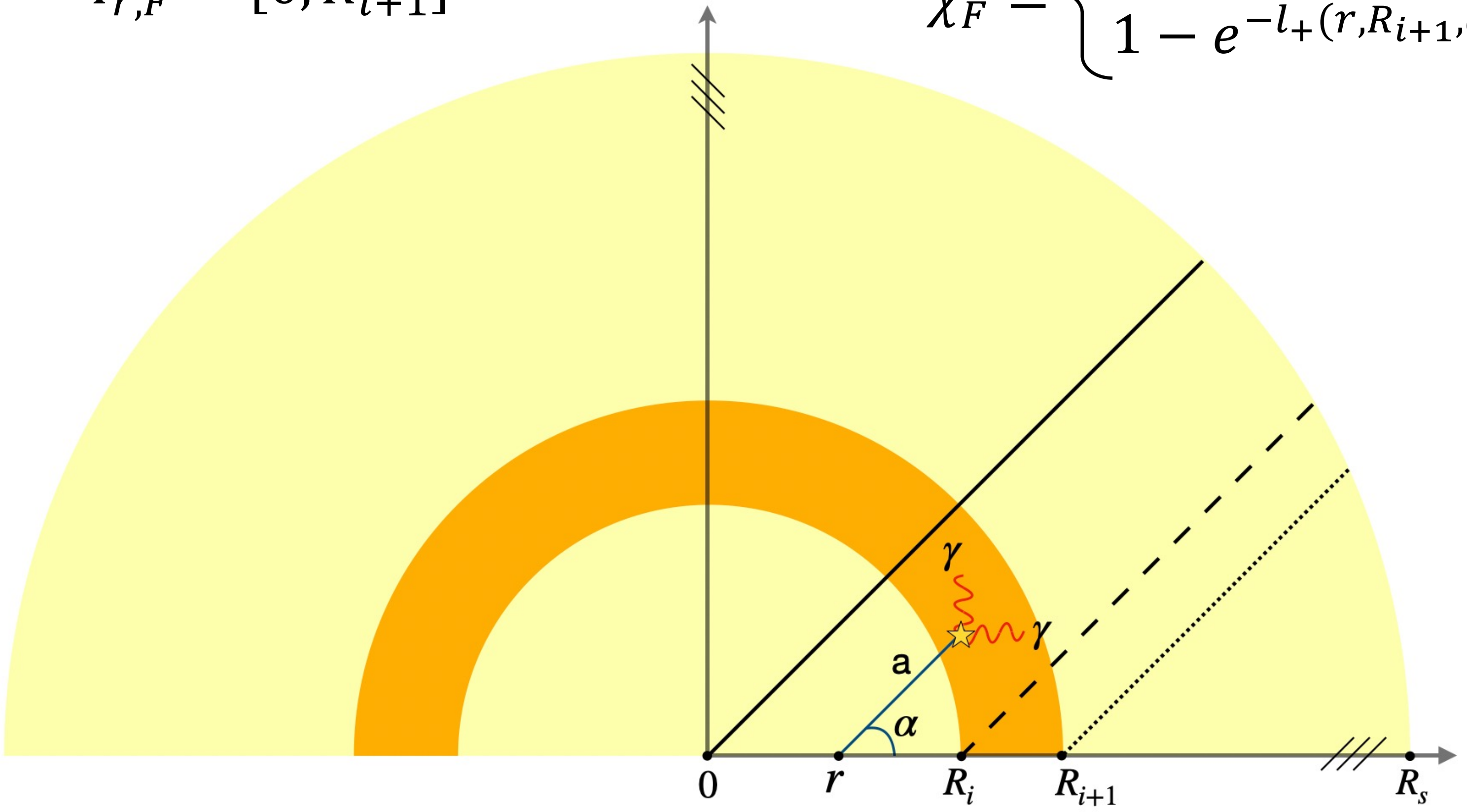
FORWARD EMISSION

Energy deposited by ALPs emitted by inner shells.

$$I_{r,F} = [0, R_{i+1}]$$

$$\chi_F = \begin{cases} e^{-l_+(r,R_i,\alpha)} - e^{-l_+(r,R_{i+1},\alpha)}, & r \in [0, R_i) \\ 1 - e^{-l_+(r,R_{i+1},\alpha)/\lambda}, & r \in [R_i, R_{i+1}) \end{cases}$$

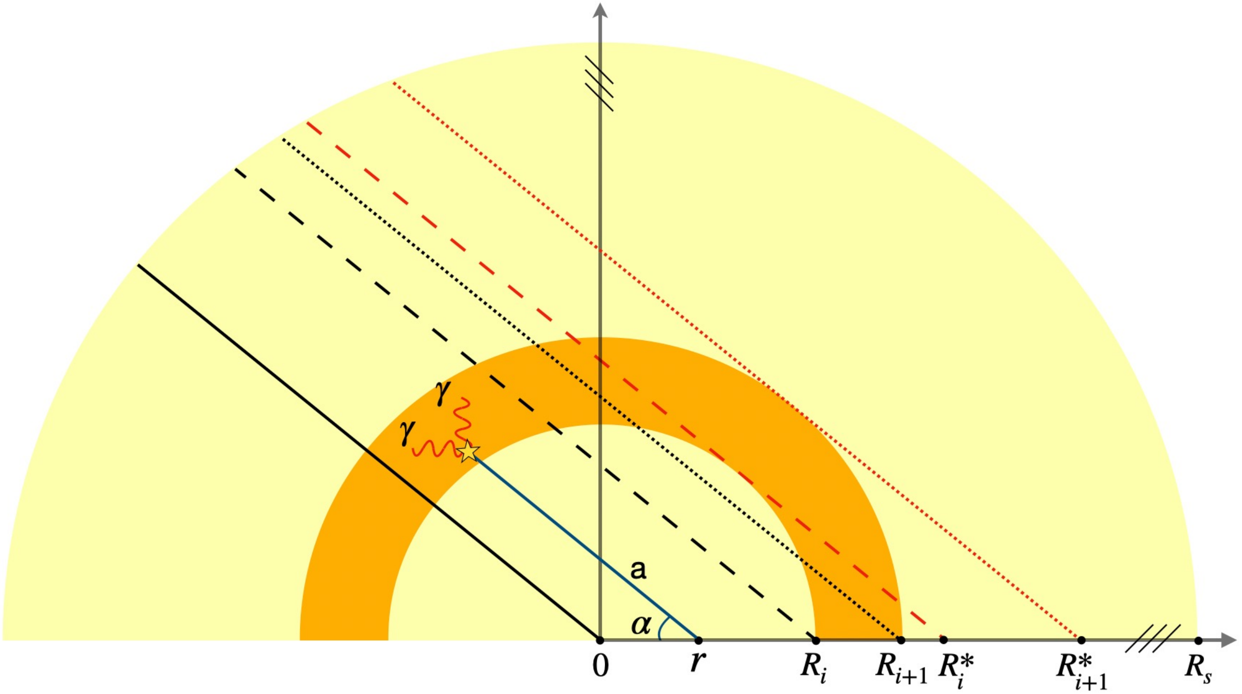
Contribution due to the finite size of the shell

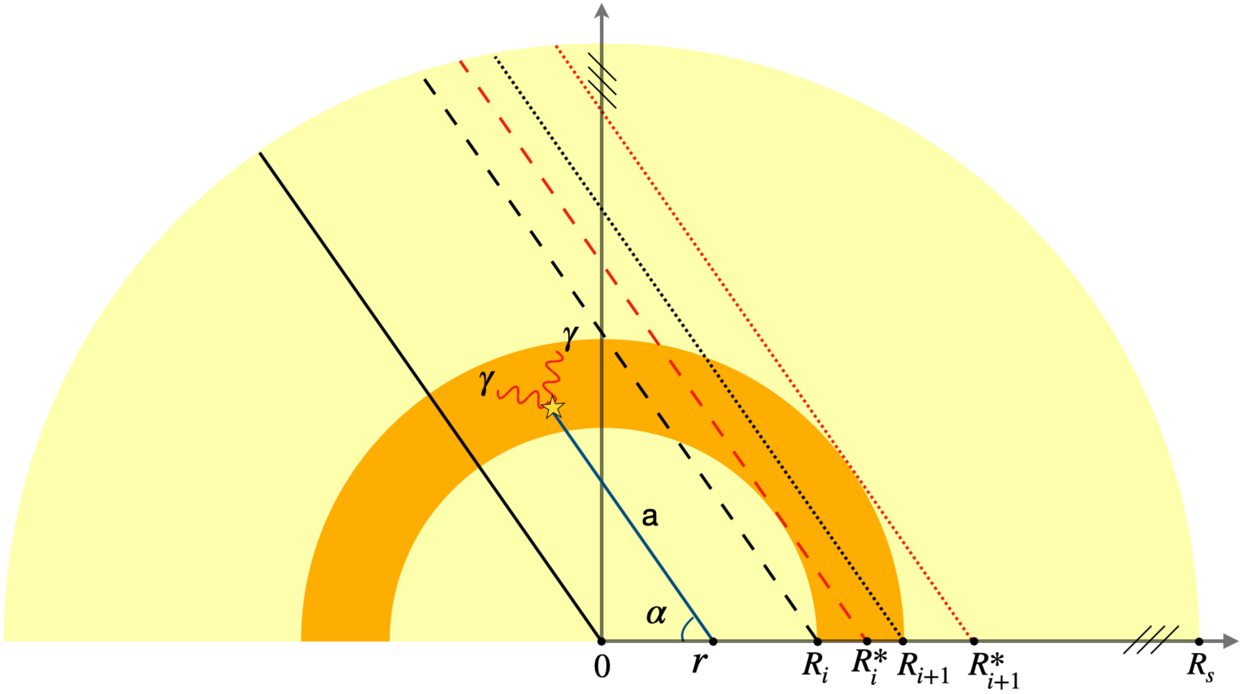


BACKWARD EMISSION

Trickier case: ALPs emitted at a radius $r > R^* = R/\sin(\alpha)$ with emission angle $\pi - \alpha$ never intersect a sphere of radius R.

- No contribution to $\epsilon_{dep,i}$ from particles emitted at $r > R^*_{i+1}$: $I_{r,B} = [0, R^*_{i+1}]$
- The explicit expression of χ_B depends on the position of R^*_i with respect to R_{i+1}



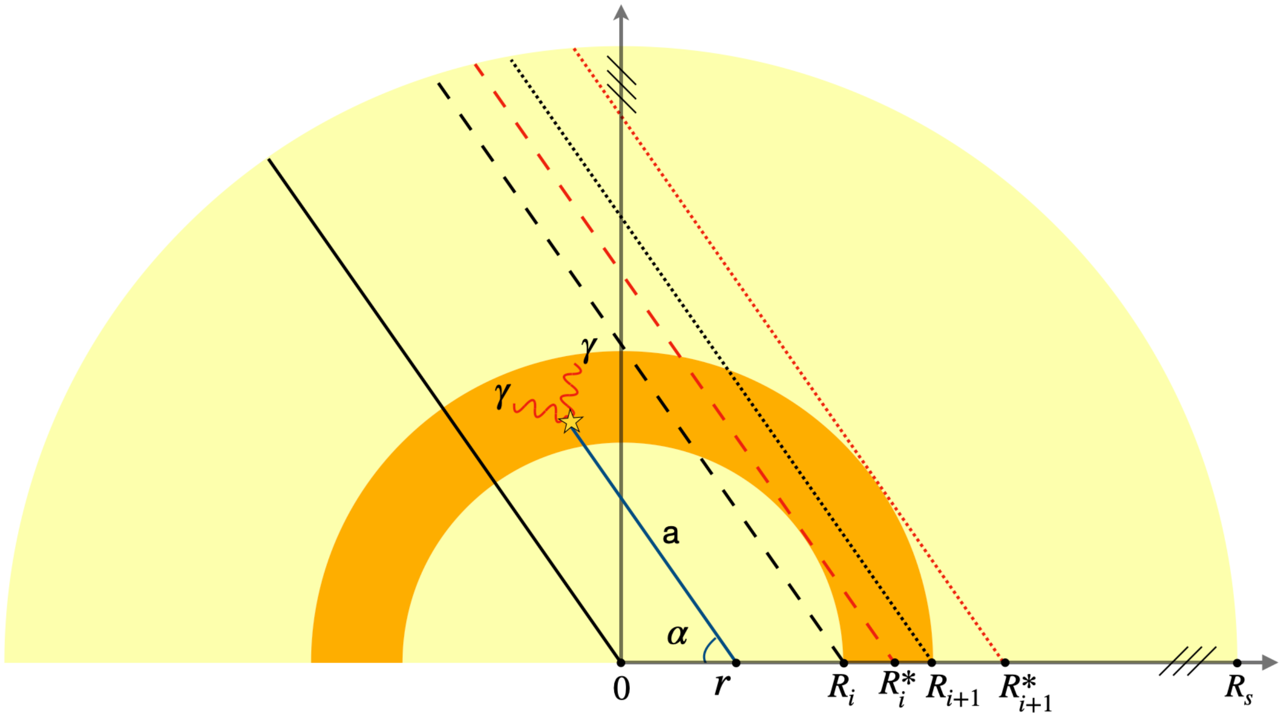


BACKWARD EMISSION (1)

- $R_i^* < R_{i+1}$

$$I_{r,B_1} = [0, R_{i+1}^*]$$

$$\chi_{B_1} = \begin{cases} f_+(\pi-\alpha), & r \in [0, R_i] \\ g_{-,i}(\pi-\alpha) + f_+(\pi-\alpha), & r \in (R_i, R_i^*] \\ g_{+,i+1}(\pi-\alpha), & r \in (R_i^*, R_{i+1}] \\ g_{+,i+1}(\pi-\alpha) - g_{-,i+1}(\pi-\alpha), & r \in (R_{i+1}, R_{i+1}^*] \end{cases}$$



$$f_\pm(\eta) = e^{-l_\pm(r,R_i,\eta)/\lambda} - e^{-l_\pm(r,R_{i+1},\eta)/\lambda}$$

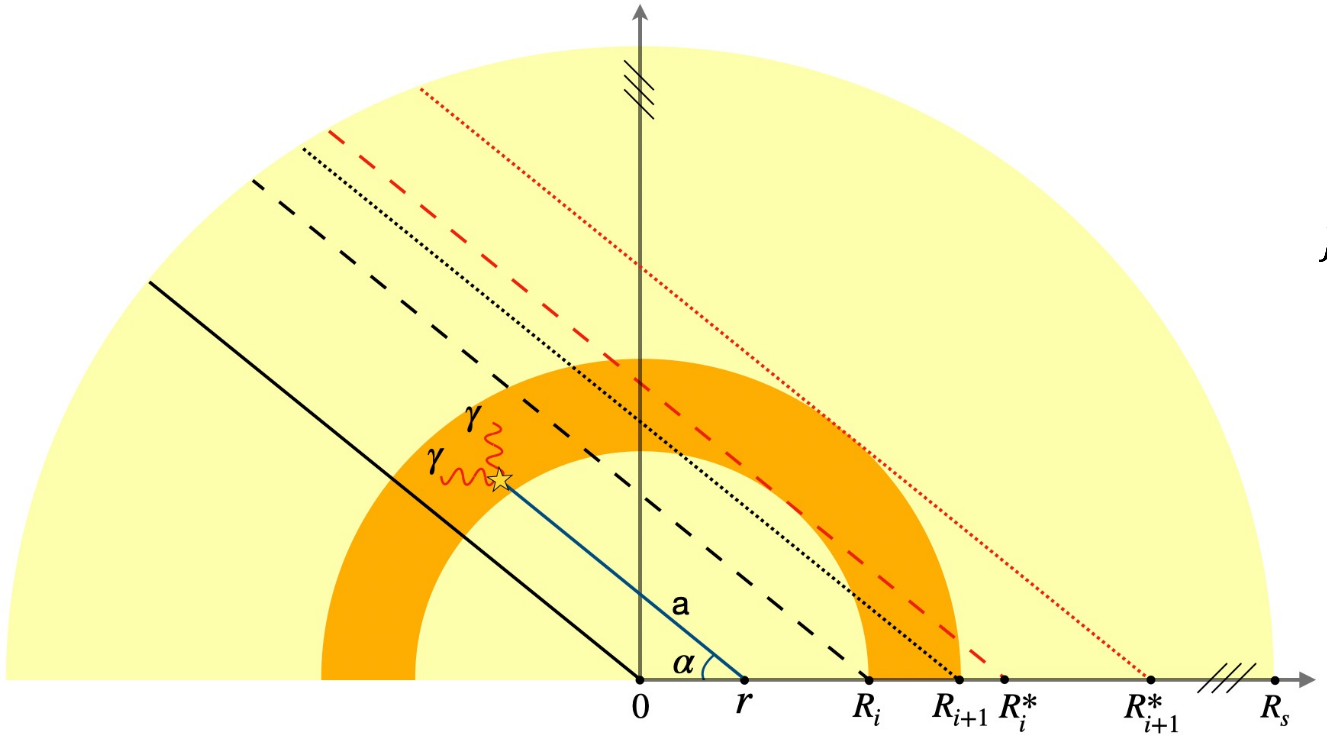
$$g_{\pm,i}(\eta) = 1 - e^{-l_\pm(r,R_i,\eta)/\lambda}$$

BACKWARD EMISSION (2)

- $R_i^* > R_{i+1}$

$$I_{r,B_1} = [0, R_{i+1}^*]$$

$$\chi_{B_2} = \begin{cases} f_+(\pi-\alpha), & r \in [0, R_i] \\ g_{-,i}(\pi-\alpha) + f_+(\pi-\alpha), & r \in (R_i, R_{i+1}] \\ f_+(\pi-\alpha) - f_-(\pi-\alpha), & r \in (R_{i+1}, R_i^*] \\ g_{+,i+1}(\pi-\alpha) - g_{-,i+1}(\pi-\alpha), & r \in (R_i^*, R_{i+1}^*] \end{cases}$$

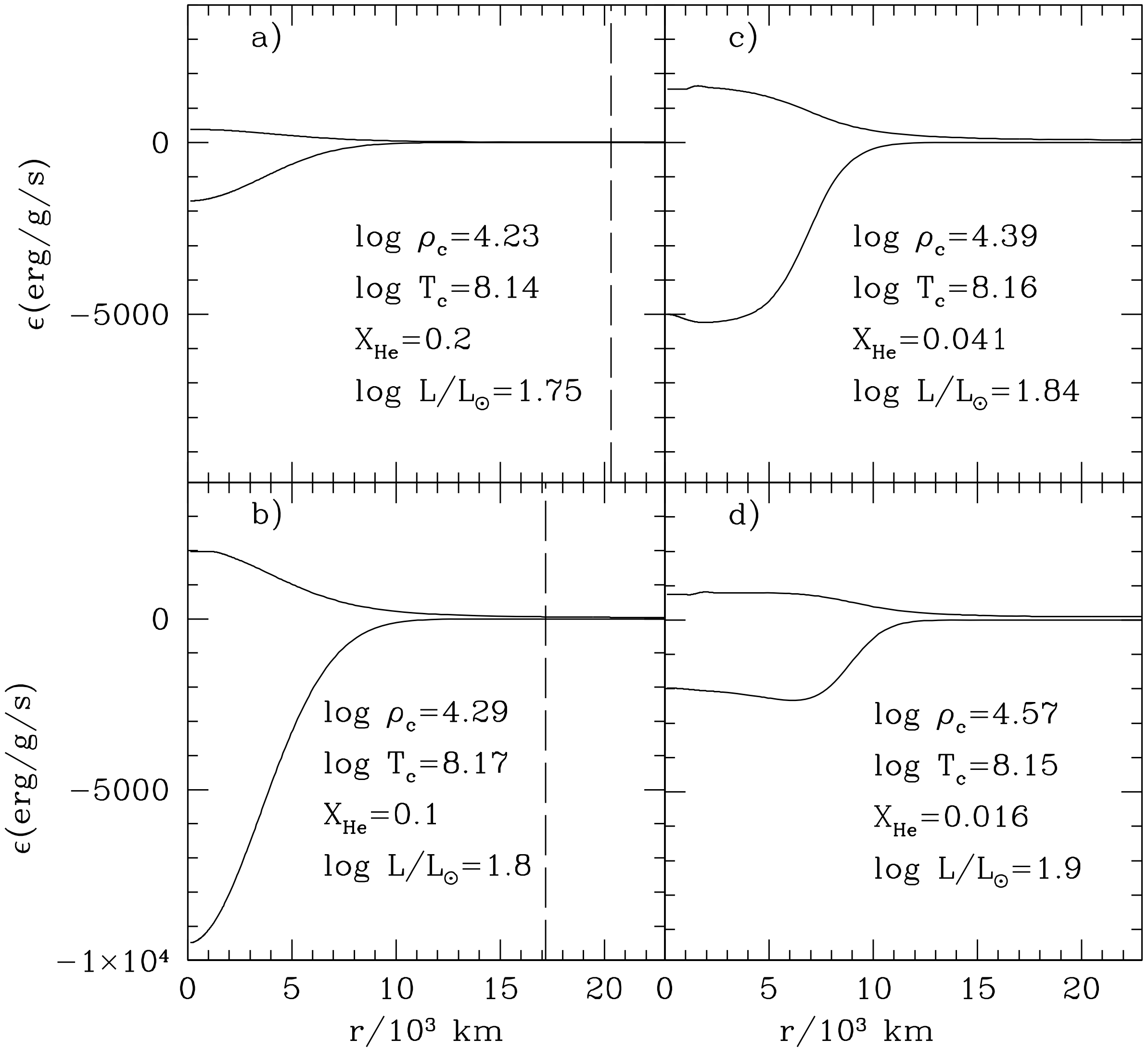


$$f_\pm(\eta) = e^{-l_\pm(r,R_i,\eta)/\lambda} - e^{-l_\pm(r,R_{i+1},\eta)/\lambda}$$

$$g_{\pm,i}(\eta) = 1 - e^{-l_\pm(r,R_i,\eta)/\lambda}$$

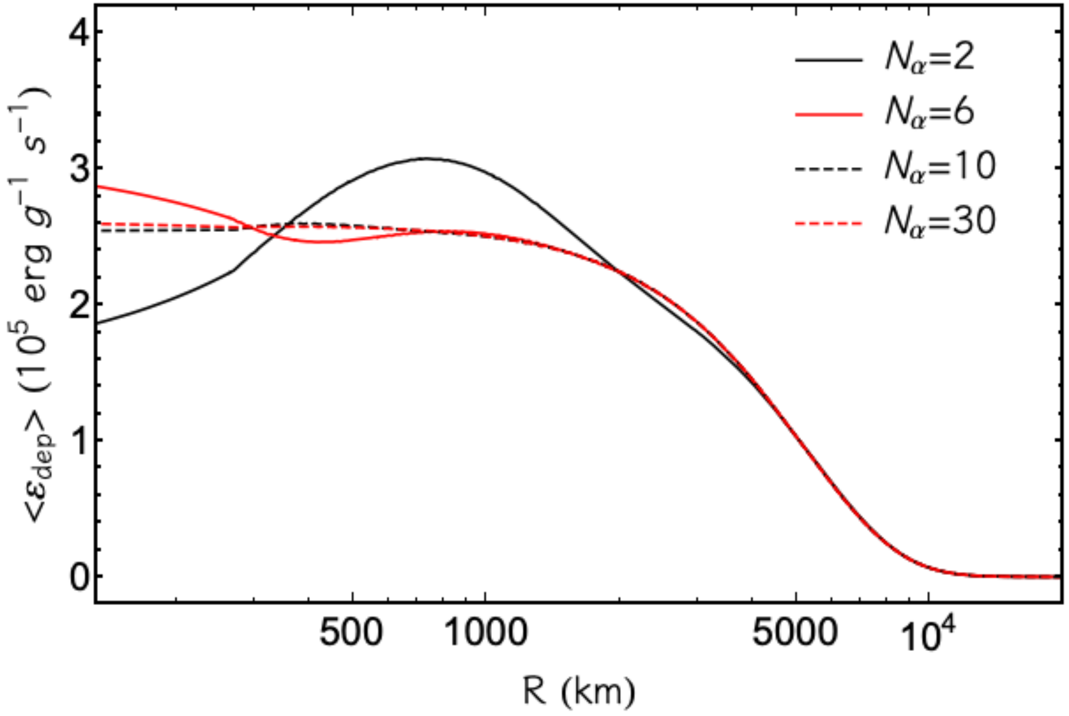
EFFECT ON THE STAR EVOLUTION

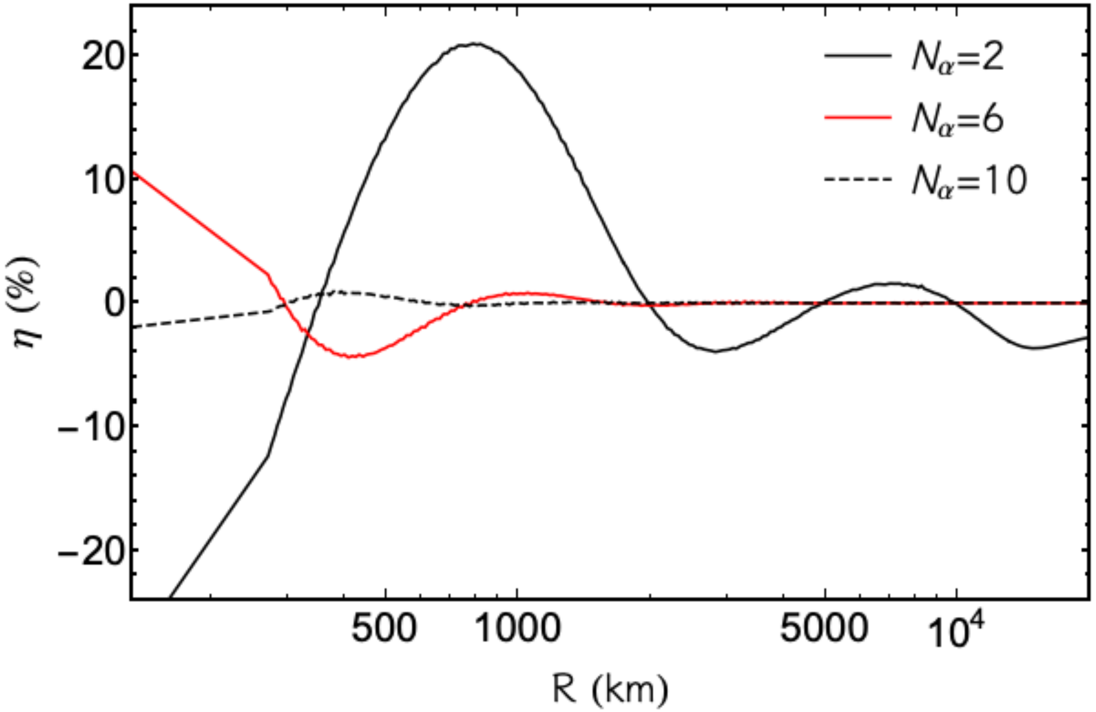
$m_a = 0.4$ MeV
$g_{a\gamma} = 3\times10^{-6}$ GeV^{-1}



- ALP energy transfer produces a premature disappearance of the star convective core
- Rapid contraction of the star and decrease in the core temperature

EFFECT OF THE DISCRETIZATION





$$\eta = \left(\frac{< \epsilon_{dep} > |_{N_\alpha}}{< \epsilon_{dep} > |_{N_\alpha \to \infty}} - 1 \right) \times 100$$

OPACITY CRITERION

$$\lambda \ll H_p, H_T \quad \text{where} \quad H_p = \left|\frac{dr}{d\ln P}\right| \quad H_p = \left|\frac{dr}{d\ln T}\right|$$

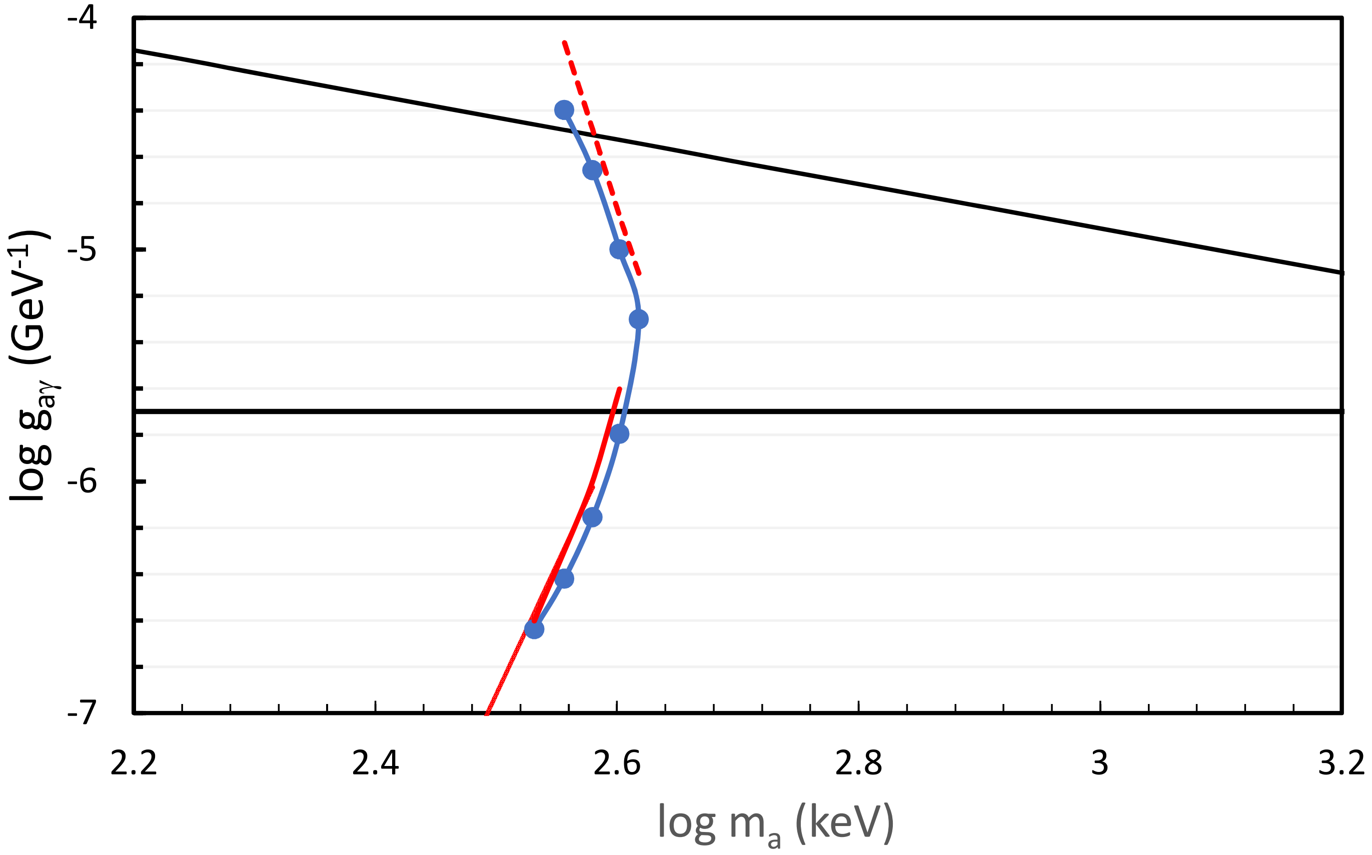
Energy flux at radius r $\quad L_r = L_{\rm conv} - \frac{4\pi r^2}{3\kappa\rho}\frac{d(aT^4)}{dr}, \quad \kappa^{-1} = \kappa_e^{-1} + \kappa_\gamma^{-1} + \kappa_a^{-1}$

ALP opacity

$$(\kappa_a\rho)^{-1} = \frac{1}{4aT^3}\int_{m_a}^{\infty} dE\, \beta_E\, \lambda_E \frac{\partial B_E}{\partial T} \quad \text{where} \quad B_E = \frac{1}{2\pi^2}\frac{E^2\sqrt{E^2 - m_a^2}}{e^{E/T} - 1}$$

$$\kappa_a^{-1} = 1.4\times 10^5\ \mathrm{g\ cm^{-2}}\ \rho\ g_{a\gamma}^{-2} \left(\frac{m_a}{T}\right)^{-5/2} T^{-3}\, e^{-m_a/T} \left[35 + \frac{m_a}{T}\left(15 + 2\frac{m_a}{T}\right)\right]$$

COMPARISON WITH OPACITY APPROACH



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