A new stellar constraint on axion-like particles

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Based on

M.J. Dolan, F.J. Hiskens and R.R. Volkas, *Constraining axion-like particles using the white dwarf initial-final mass relation,* JCAP 09 (2021) 010 [2102.00379]

Overview

1. Astrophysical ALP production & stellar cooling constraints
2. ALPs & asymptotic giant branch stars
3. Constraining ALPs using white dwarf the initial-final mass relation
4. Concluding remarks

Astrophysical ALP production & stellar cooling constraints

Axion-like particles

Axion-like particles (ALPs) are a class of pseudoscalar particle which appear frequently in extensions of the Standard Model (SM) of particle physics

A prominent dark matter candidate

Their masses and interactions with SM particles are model dependent

Studied in wide phenomenological range – particle physics, cosmology and **astrophysics**

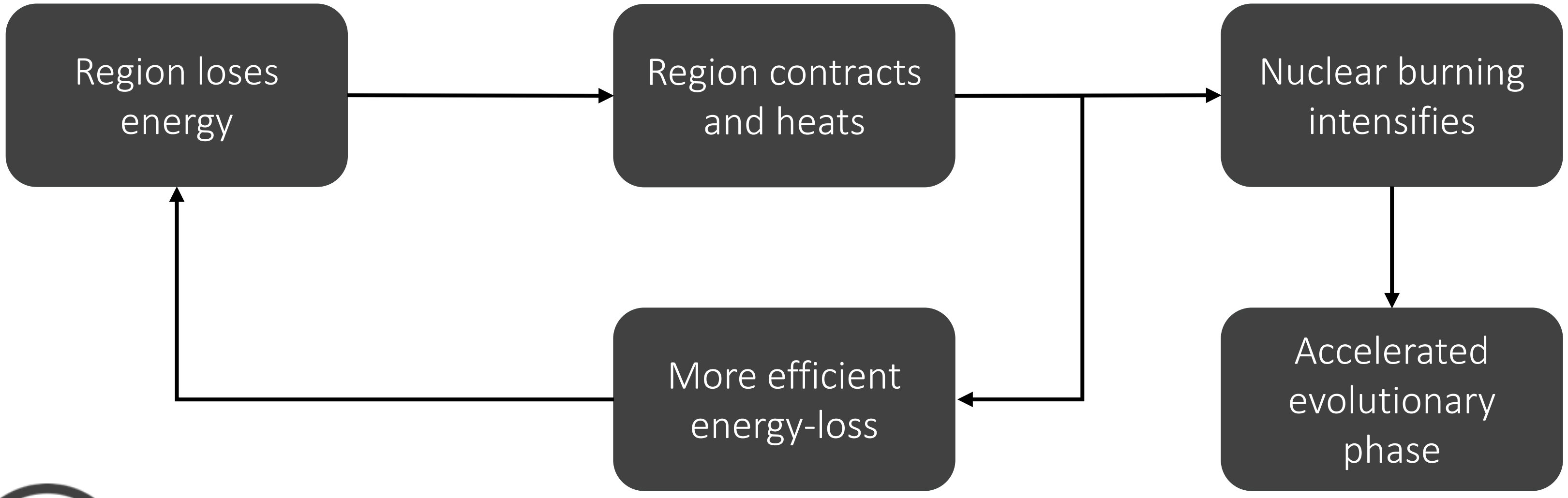
The energy-loss argument

It has long been realised that ALPs could be produced in deep stellar interiors

If sufficiently light and weakly interacting, they can freely escape the local stellar region

New source of energy-loss from stellar interior

Constraints derived in this manner are termed **stellar cooling** bounds



Exploring the parameter space

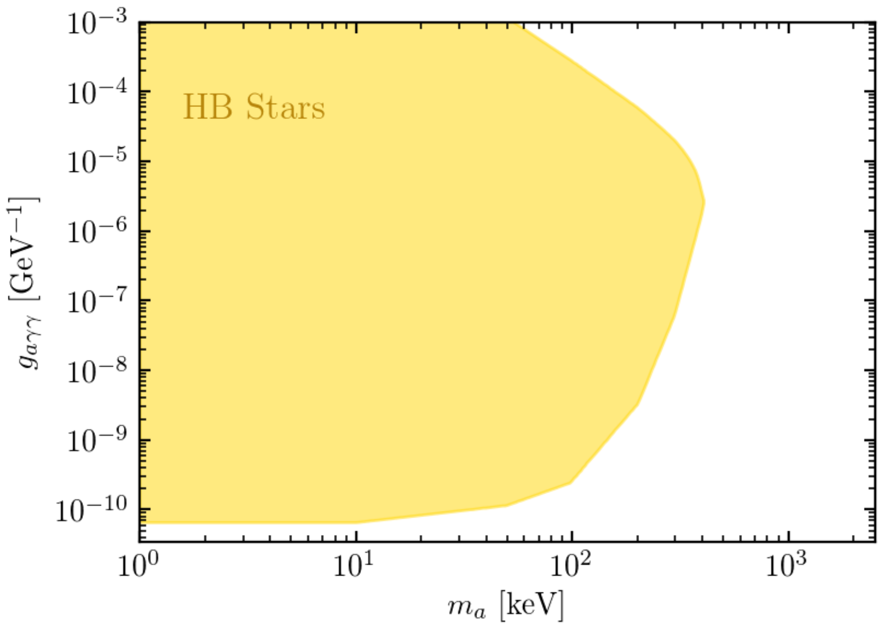
We are interested in ALPs which interact exclusively with electromagnetism via the two-photon vertex

$$\mathcal{L}_\gamma = -\frac{g_{a\gamma\gamma}}{4} a F_{\mu\nu} \tilde{F}^{\mu\nu}$$

Most restrictive stellar cooling constraint comes from observation of **horizontal branch** stars

ALPs produced in He-B core through **Primakoff mechanism** and **photon fusion**

Both Boltzmann suppressed when $m_a \gtrsim T$ – cause HB constraint to relax in keV-MeV mass range



HB stars: arXiv 2004.08399

Exploring the parameter space

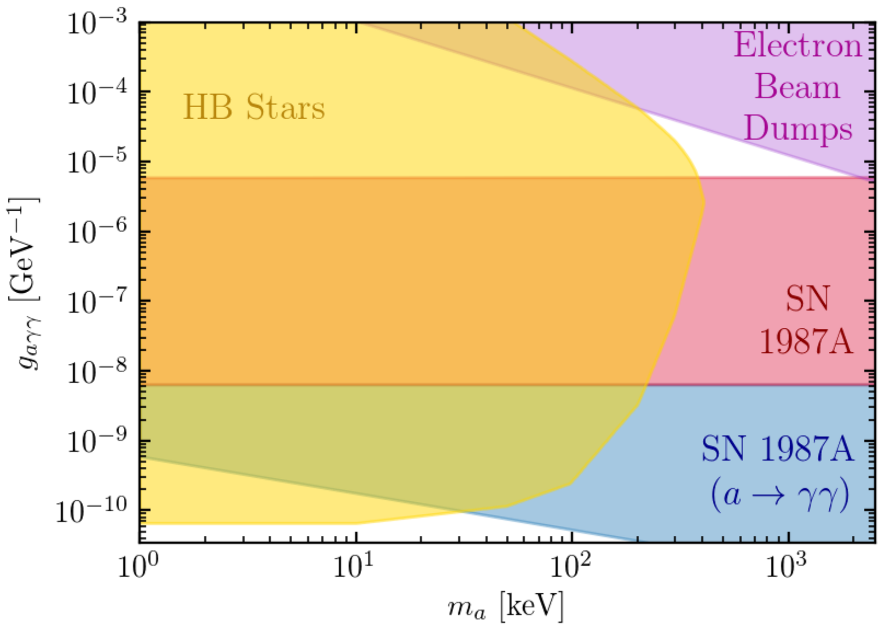
In keV-MeV mass there are other relevant constraints

Fail to exclude a small triangular region at $m_a \sim 1\ MeV$ and $g_{a\gamma\gamma} \sim 10^{-5}\ \ GeV^{-1}$ - the **cosmological triangle**

HB star constraint defines lower mass end of the cosmological triangle

Target subsequent (hotter) shell helium burning phase – the **asymptotic giant branch**

Investigate effects of ALPs using edited version of stellar evolution code **Modules for Experiments in Stellar Astrophysics** (MESA)



HB stars: arXiv 2004.08399
Beam dumps: Phys. Rev. D 38 (1988) 3375
SN1987A neutrino: arXiv 2008.04918
SN1987A visible: arXiv 1702.02964

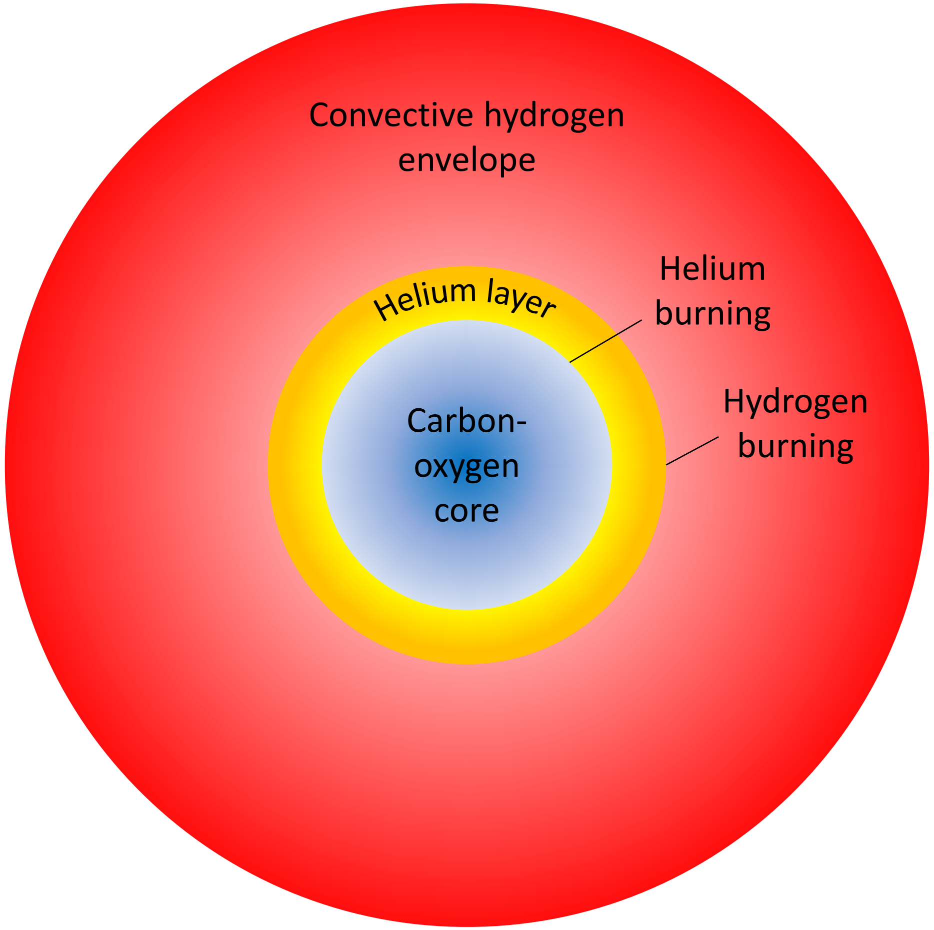
ALPs & asymptotic giant branch stars

The asymptotic giant branch

Evolutionary phase immediately following central helium burning in $0.6 - 8M_{\odot}$ stars

Separated into two phases

1. Early-AGB:
    - Evolution governed by activity of He-B shell
    - Shell progresses outward through helium layer
    - CO core & convective envelope grow
2. **Thermal pulsating-AGB:**
    - Strong stellar winds strip away star's outer layers
    - Bridges the gap between E-AGB and white dwarf phases



http://www.astro.uvic.ca/~fherwig/DATA/index.html#ARAA%20article%20-%20The%20evolution%20of%20AGB%20stars

The second dredge-up

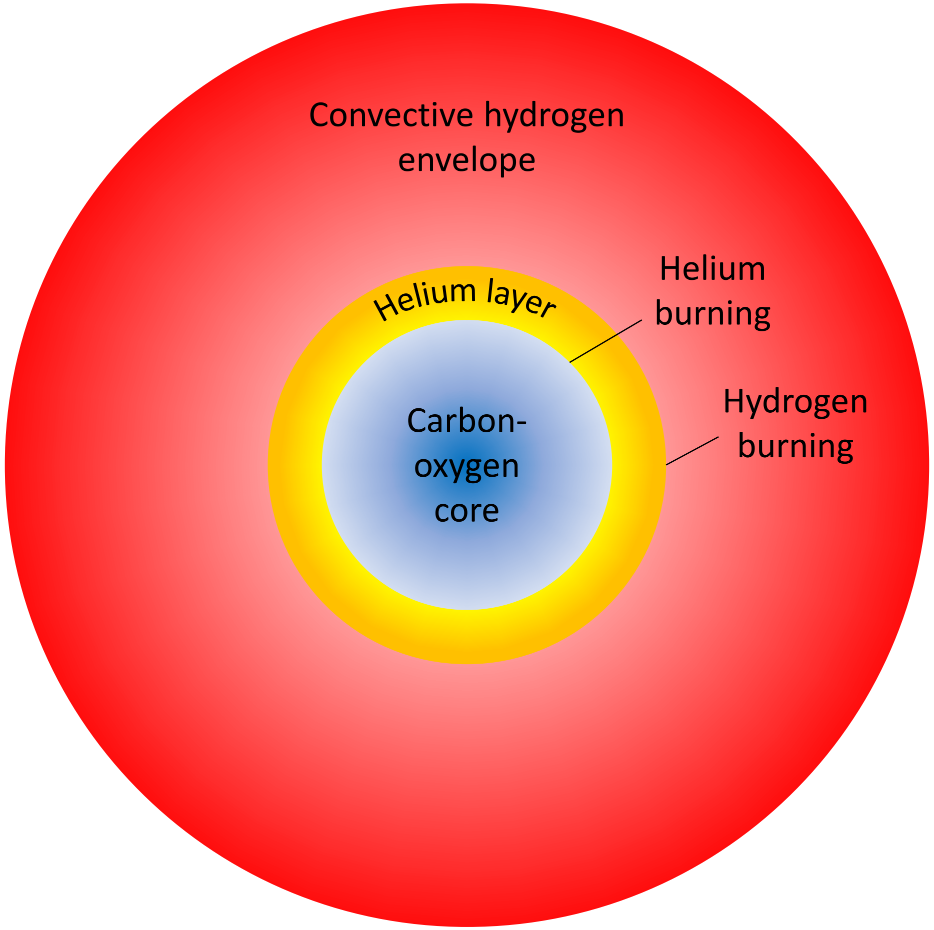
In the late E-AGB the convective envelope can breach the helium-rich layer – **the second dredge-up**

Disperses nuclear fuel throughout outer layer – curtails CO core growth

Arises due to intensifying activity of helium burning shell

Known that ALPs increase the efficiency of the second dredge-up [arXiv:9905033]

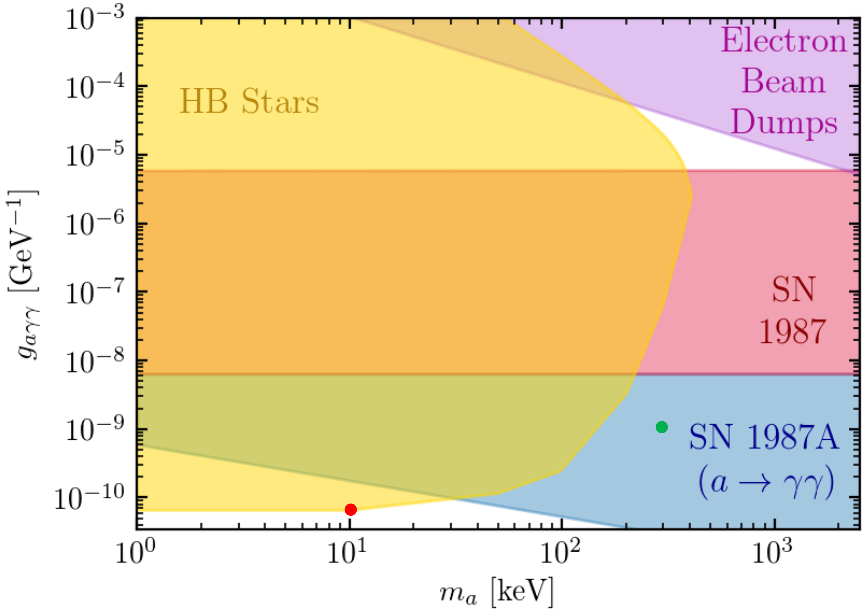
Investigate sensitivity of second dredge up to ALPs



http://www.astro.uvic.ca/~fherwig/DATA/index.html#ARAA%20article%20-%20The%20evolution%20of%20AGB%20stars

ALPs & the second dredge-up

M_{init}	m_a [keV]	$g_{a\gamma\gamma}$ [GeV^{-1}]	M_{CO} w/o ALPs	M_{CO} w ALPs
$4M_\odot$	10	0.66×10^{-10}	$0.80M_\odot$	$0.69M_\odot$
$4M_\odot$	300	10^{-9}	$0.80M_\odot$	$0.75M_\odot$
$6M_\odot$	300	10^{-9}	$0.96M_\odot$	$0.81M_\odot$



The second dredge-up is sensitive to ALPs in keV-MeV mass range – need a way to constrain this

The TP-AGB is short in intermediate mass stars – effects of ALPs persist through to final white dwarf mass

We can use observation of white dwarfs to constrain ALP effects on the AGB

Constraining ALPs using the white dwarf initial-final mass relation

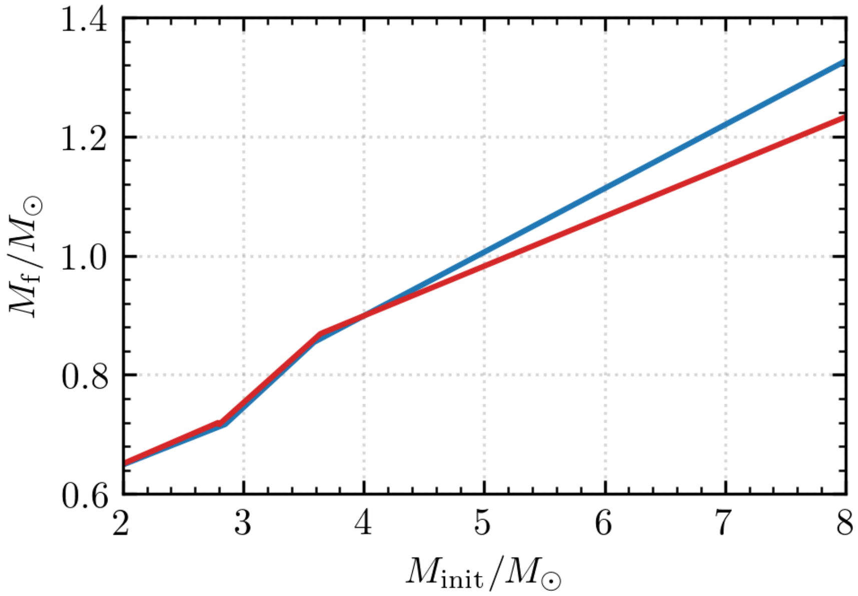
The initial-final mass relation

The **initial-final mass relation:** associates the mass with which a star forms on the Main Sequence to that of the white dwarf

Typically modelled as a three-piece linear function with breakpoints at 2-$2.8 M_\odot$ and 3.6-$4 M_\odot$

Numerous constraints on the IFMR exist - we use one derived from 14 wide double white dwarf binaries [1510.06107]

Minimises dependence on astrophysical uncertainties



Examples from [1809.01673]

ALPs & the IFMR

Simulate evolution of stars with initial masses between $2\text{-}8M_{\odot}$ and record their final masses

Apply a three-piece fit with flexible breakpoints to derive a theoretical IFMR

Recompute with 10 keV ALPs included in the models for

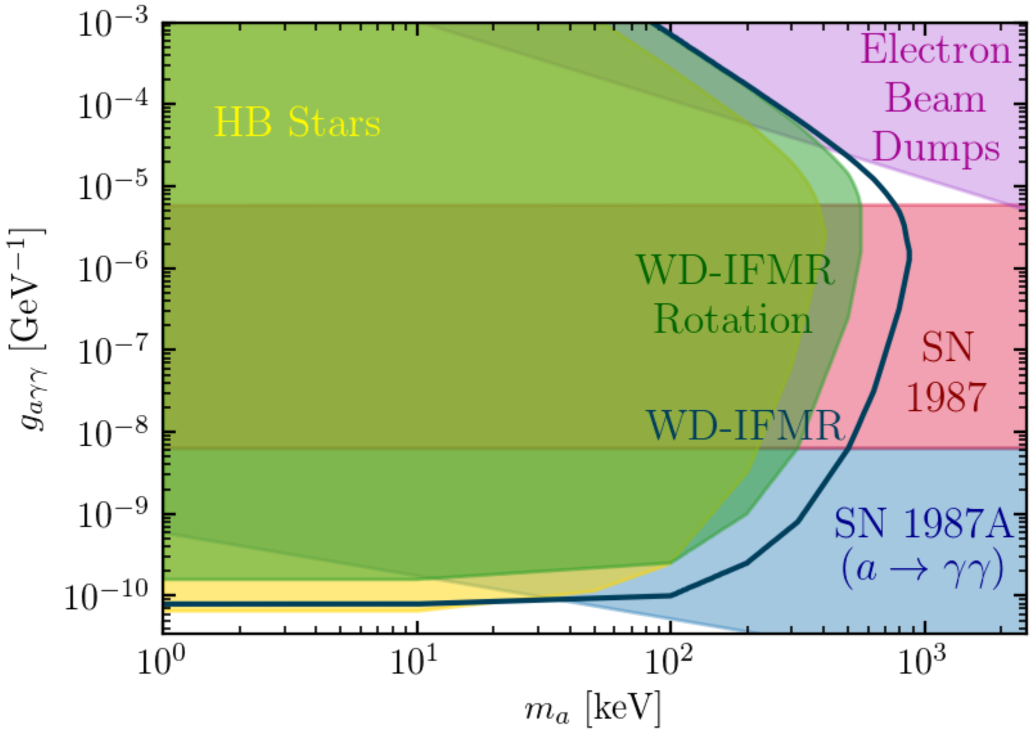
$$g_{a\gamma\gamma} = 0.316 \times 10^{-10}\ \mathrm{GeV}^{-1}$$
$$g_{a\gamma\gamma} = 0.631 \times 10^{-10}\ \mathrm{GeV}^{-1}$$
$$g_{a\gamma\gamma} = 10^{-10}\ \mathrm{GeV}^{-1}$$

Define constraint by identifying smallest excluded value of $g_{a\gamma\gamma}$ for fixed values of m_a

Relaxes when decay length falls below He-B shell radius

Need to account for possible effects of stellar rotation which shifts predicted IFMRs upward

Constraint relaxes – still able to exclude region of the cosmological triangle



Concluding remarks

Concluding remarks

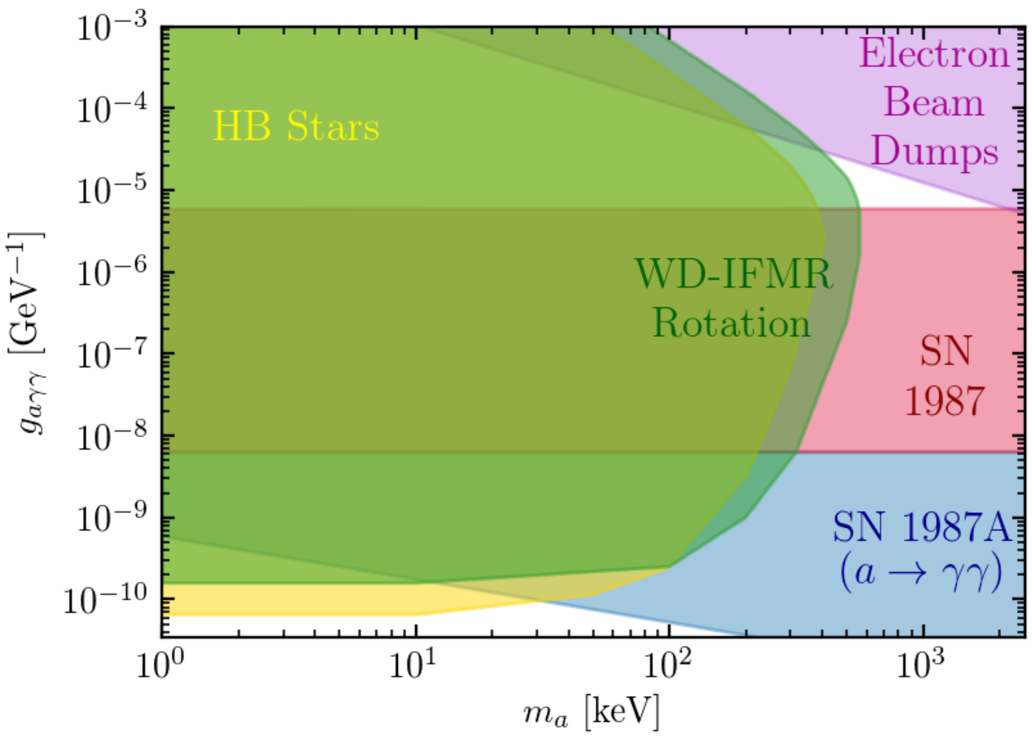
Stellar evolution simulations are a potent source of constraints on ALPs

AGB stars are excellent probes of keV-MeV scale ALPs

Their influence can be constrained via the white dwarf initial-final mass relation

Adopting a conservative approach we are still able to exclude part of the cosmological triangle

Stands to improve significantly as theoretical and observational uncertainties are better understood



Backup Slides

Astrophysical ALP production

Restrict our attention to ALPs which couple solely to electromagnetism via the two photon interaction

$$\mathcal{L}_\gamma = -\frac{g_{a\gamma\gamma}}{4} a F_{\mu\nu}\tilde{F}^{\mu\nu}$$

Have two production mechanisms of importance in stellar plasmas

Affects stellar structure by reducing the local energy production rate per unit mass ϵ

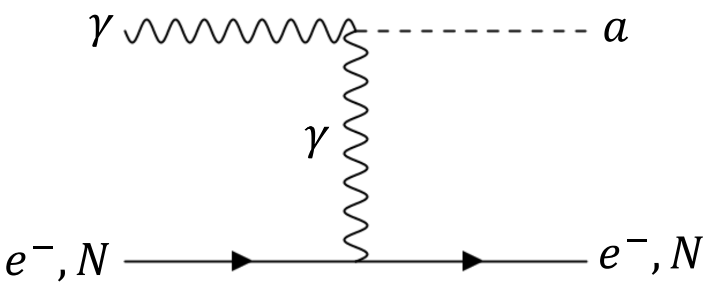
Magnitude of energy-loss given by

$$\epsilon_a = \frac{g_{a\gamma\gamma}^2 T^7}{4\pi\rho}\left(F_P(\xi,\mu\,) + F_F(\mu)\right)$$

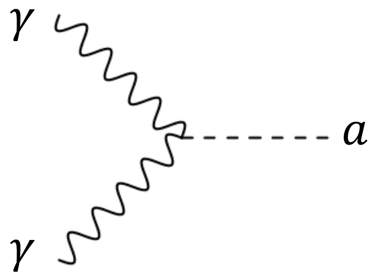
Strong temperature dependence

Contain entire mass and composition dependence

ϵ_a is Boltzmann suppressed when $m_a \gg T$



Primakoff production



Photon fusion

Evolution of intermediate mass stars

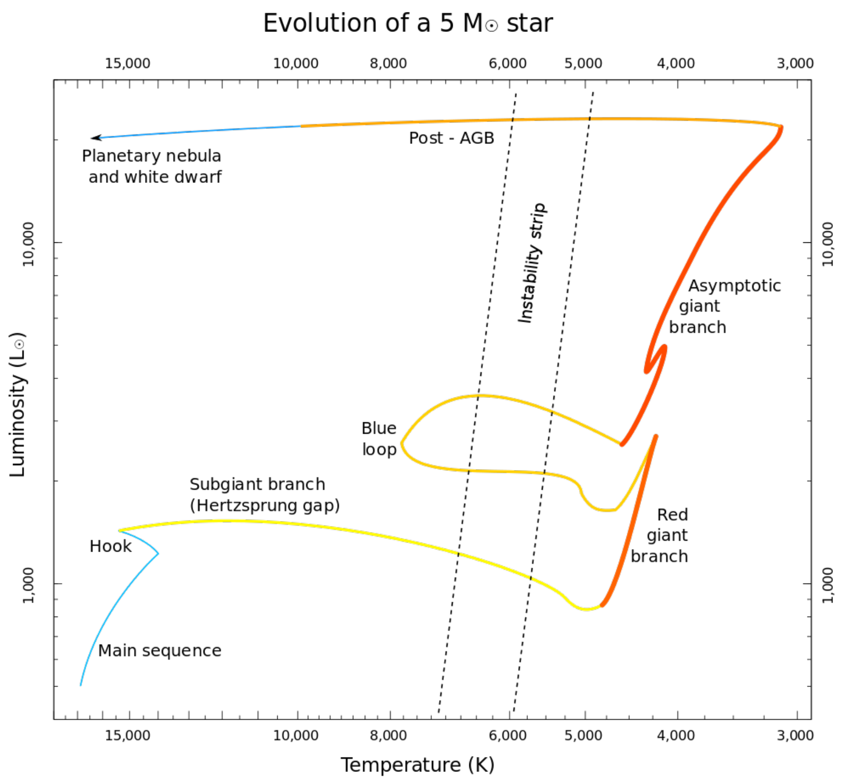
Consider the evolution of stars in the mass range 2-8$M_\odot$

A star's evolution is principally governed by its initial mass M_{init} and metallicity Z

Described though observable parameters L and T_{eff} which define the Hertzsprung-Russell diagram

Distinct phases in HR diagram arise due to different internal stellar structure:

1. **Main sequence:** H burning in core
2. **Subgiant & red giant branches:** rapidly contracting He core, H burning shell
3. **Central helium burning:** He burning core and H burning shell – blue loop
4. **Asymptotic giant branch (AGB):** double shell structure, inert CO core
5. **Post-AGB and white dwarf:** no further fusion, star cools



Towards a constraint

Demonstrated that the second dredge-up is sensitive to ALPs outside of the HB constraint

Need to find a way to constrain this behaviour

The AGB is a relatively short evolutionary phase in this mass range – sparsely populated

The TP-AGB is short in intermediate mass stars – little change to the core occurs

Can use observation of white dwarfs to constrain AGB astrophysics and the influence of ALPs!

Stellar rotation

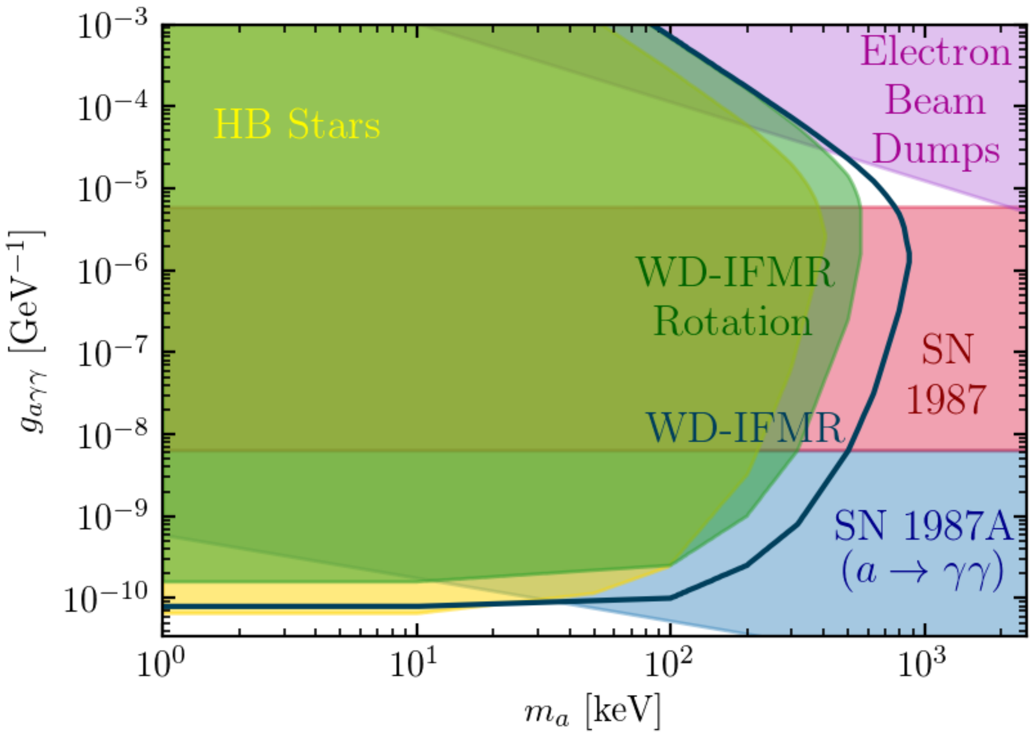
Our 1D simulations do not account for stellar rotation

Enhanced mixing during Main Sequence increases core mass – shifts IFMR upwards

Average IFMR shifted upwards by between $0.04\text{-}0.08 M_\odot$ [1901.02904]

Recompute constraint, shifting all theoretical IFMRs up by $0.08 M_\odot$

Still able to rule out region of cosmological triangle



The AGB

The E-AGB:

E-AGB evolution predominantly governed by activity of He-B shell

Causes CO core growth, inhibition of H-B shell and further penetration of convective region

Terminates when He-B shell reaches H/He discontinuity

Ending hastened by the **second dredge-up**

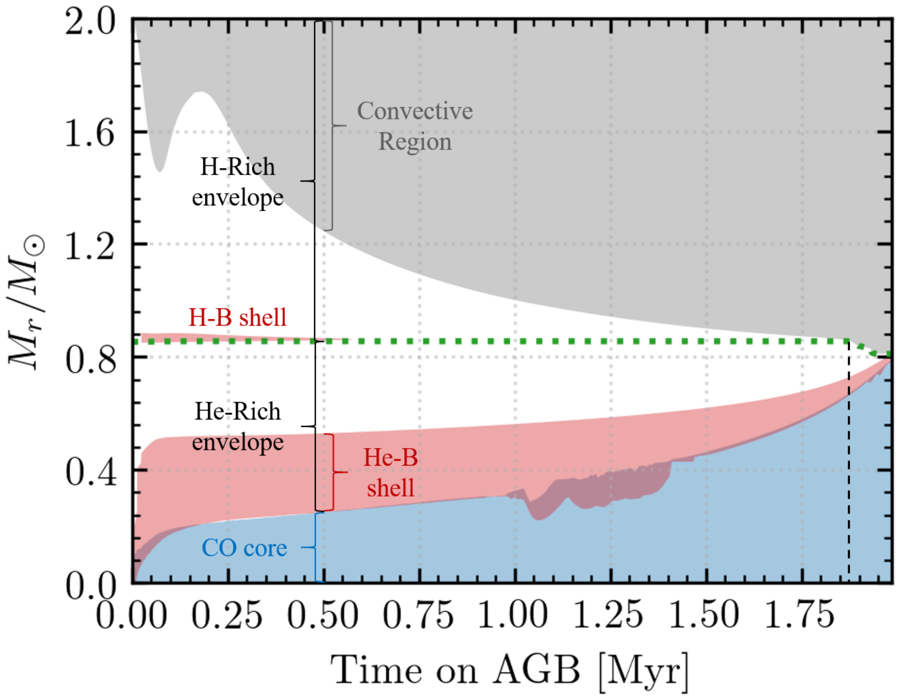
The TP-AGB:

Long periods of stable hydrogen-shell burning interrupted by unstable helium-shell flashes

Lead to further CO core growth

Ends when strong stellar winds strip away the star's outer layers

TP-AGB short in intermediate mass stars



ALPs & the AGB I

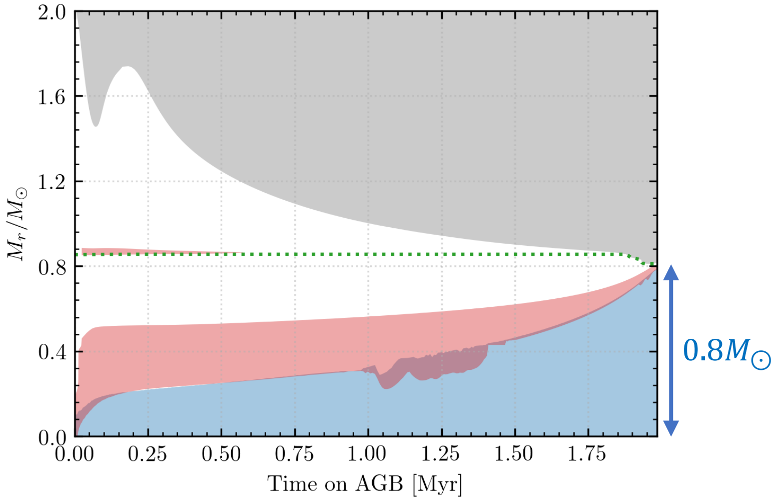
First consider effect of ALP on the edge of HB star constraint

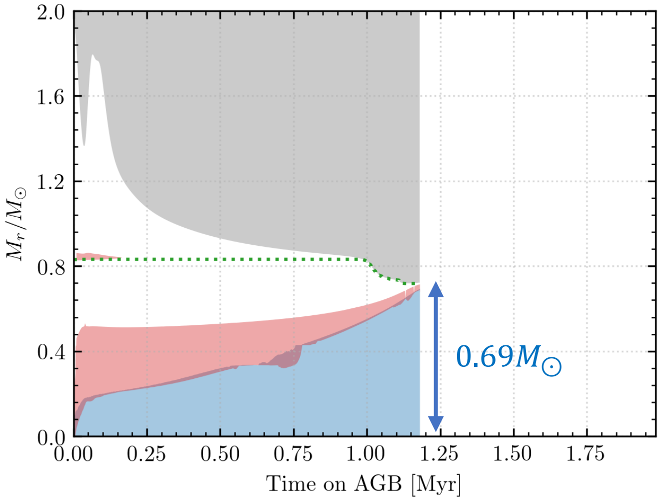
Duration of E-AGB shortened considerably

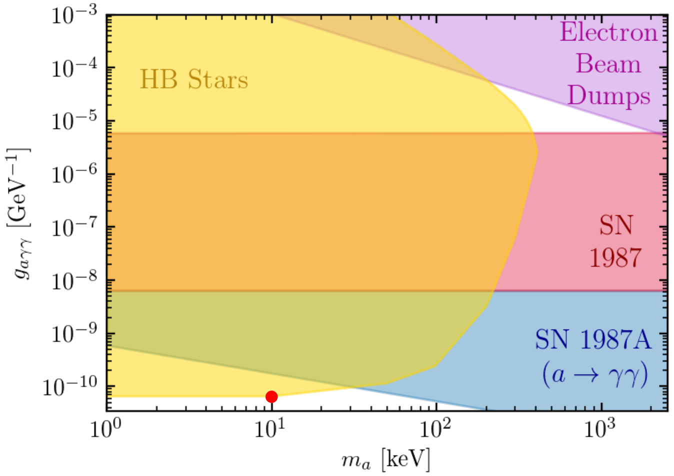
Second dredge-up occurs earlier and penetrates to greater depths

Both occur due to enhanced energy-loss within the He-B shell

Effects like this originally studied in 1999 [9905033]







ALPs & the AGB II

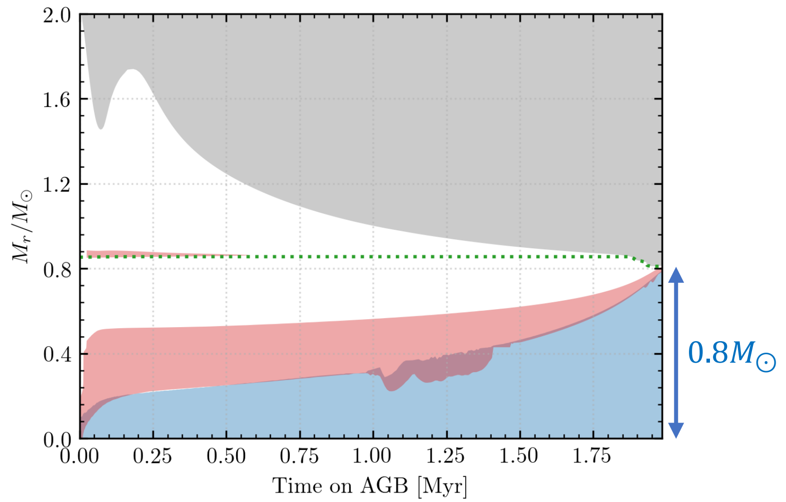
Now consider heavier ALPs which are unconstrained by HB stars

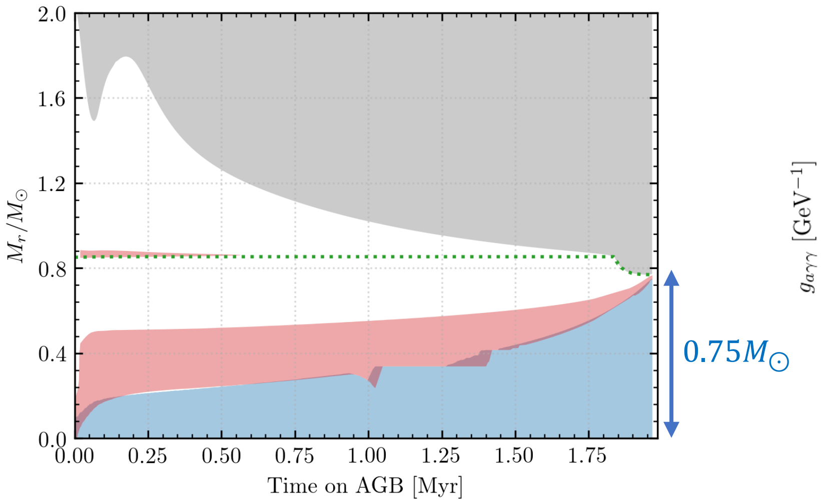
Reduction in E-AGB duration no longer present

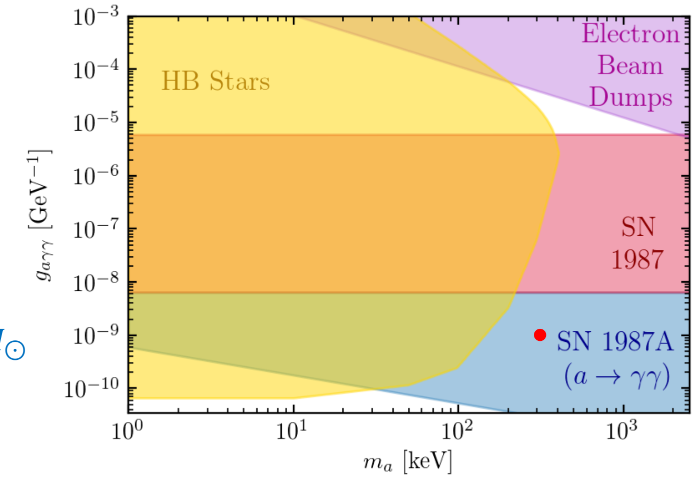
Models still predict a deeper dredge-up event

The second dredge-up is more sensitive to MeV scale ALPs than HB or E-AGB lifetimes

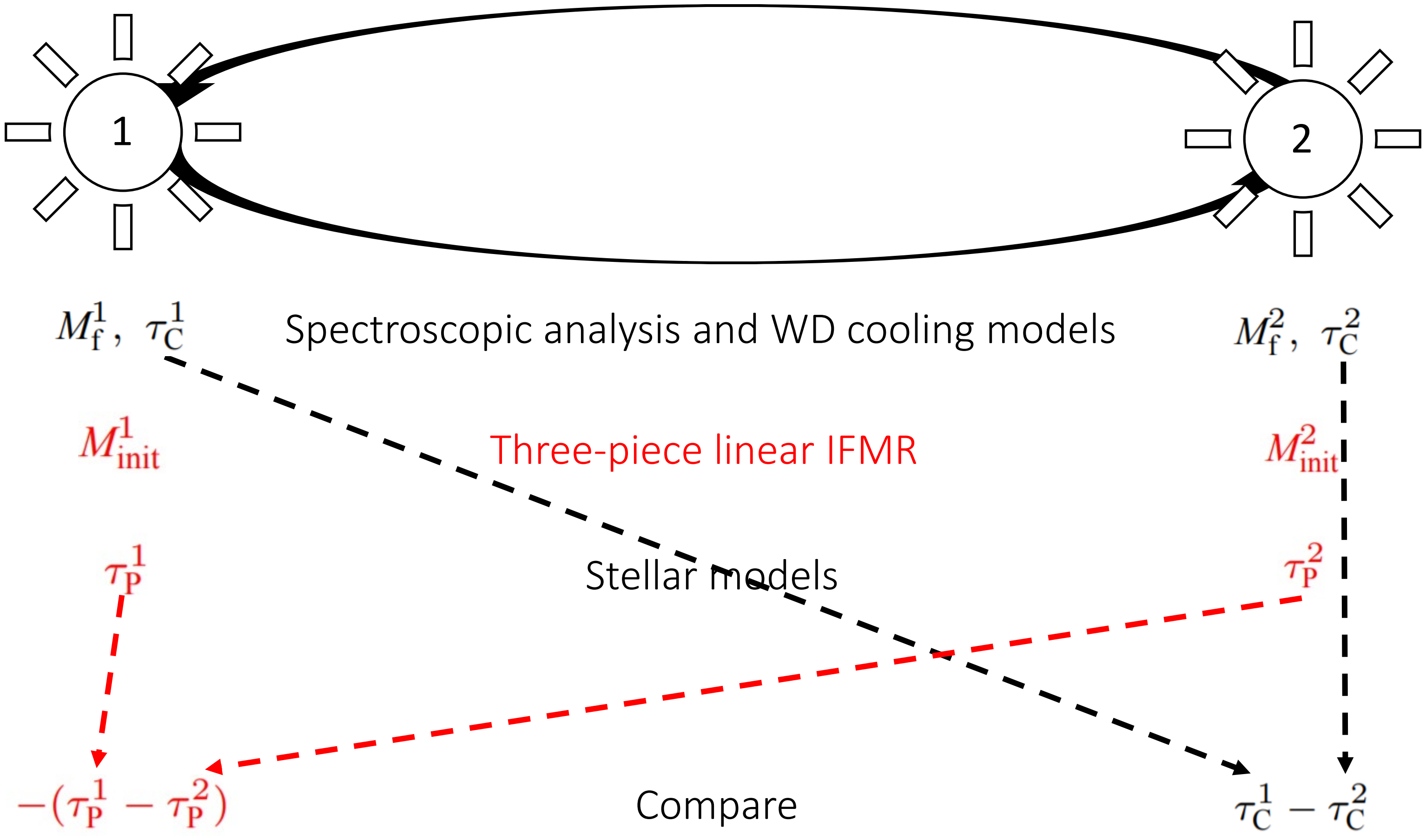
Predict larger reduction in more massive stars, e.g. reduction from $0.96M_{\odot}$ to $0.81M_{\odot}$







Wide double white dwarf binaries



Observed properties
Guessed properties

Decay

$$\lambda_a = 5.7 \times 10^{-5} g_{a\gamma\gamma}^{-2} m_{keV}^{-3} \frac{\omega}{m_a} \sqrt{1 - \left(\frac{m_a}{\omega}\right)^2}\, R_{\odot}$$

$$\epsilon_a^P = \frac{2}{\rho} \int \frac{dp\, p^2}{2\pi^2} \Gamma_P \omega f(\omega)$$

$$\epsilon_a^P = \frac{2}{\rho} \int \frac{dp\, p^2}{2\pi^2} \Gamma_P \omega f(\omega) e^{-\lambda_a/R_{region}}$$