The Sun as a laboratory of particle physics

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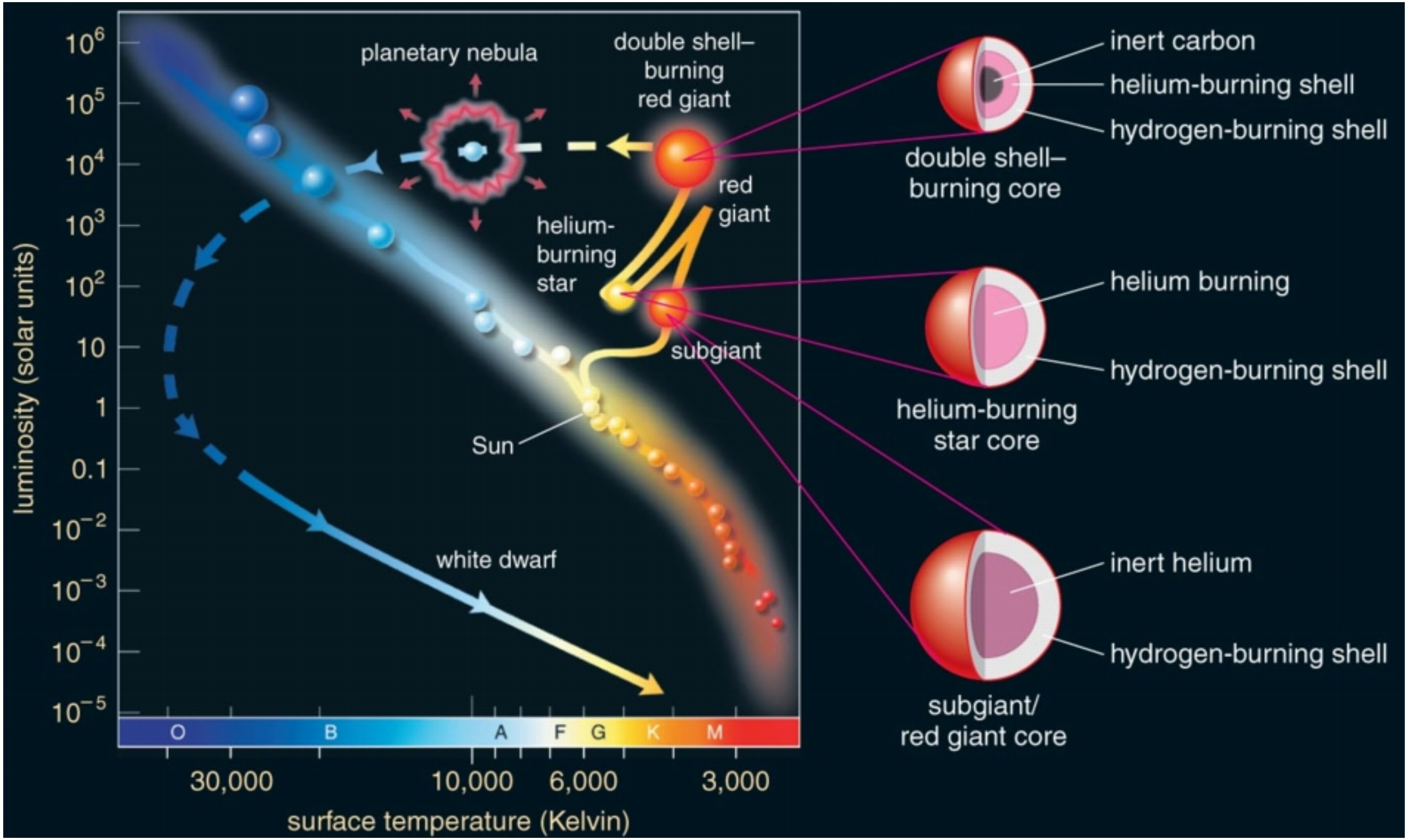
Outline

1. Stars as laboratories of particle physics
2. The Sun (Observations and theoretical models)
3. Particles: Axions, hidden photons and MCP particles
4. Statistical method
5. Results

Stars as laboratories of particle physics

- Stars have extreme temperatures and densities in their interior not reproducible in the Earth
- Low-mass weakly interacting particles ⟶ energy-loss argument
- New energy-loss channel leads to modifications on the structure and evolution of stars
- These changes can be used to constraint the properties of the studied non-standard particles
- The production rate of each particle depends differently on stellar conditions

Stars as laboratories



The Sun

What do we know from the Sun?

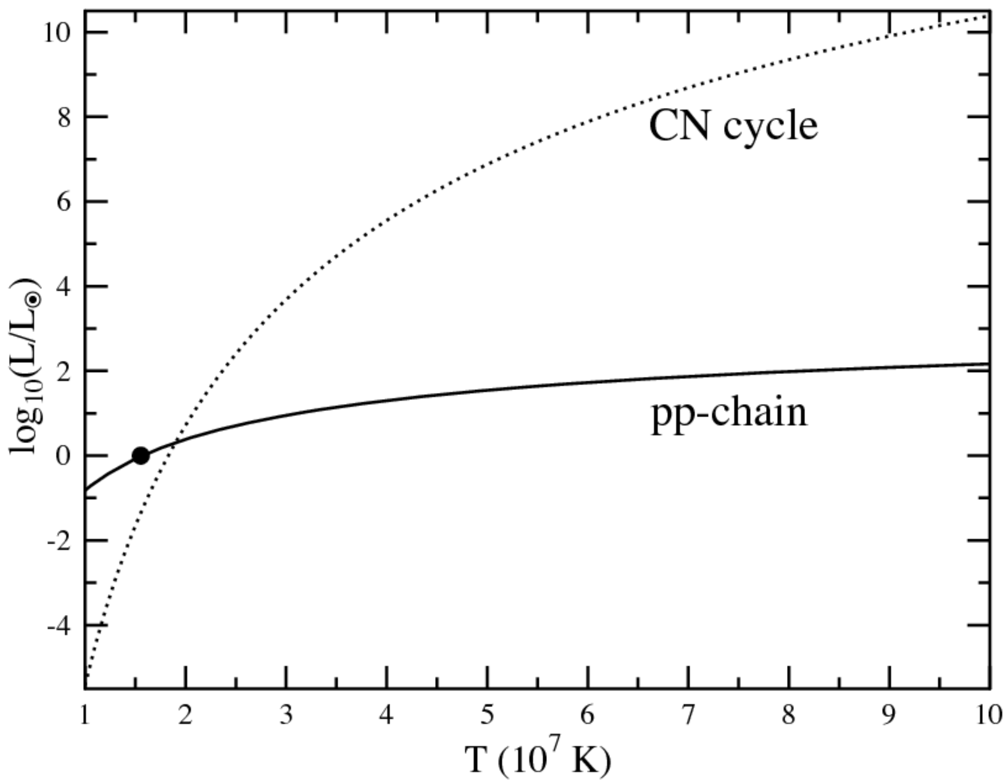
- Sun's properties (Luminosity, Radius, Mass, Age)
- Theoretical predictions: Solar Standard Models (SSM)
- Sun's other observations

    - Helioseismology

    - Neutrino fluxes

The Sun: Neutrino fluxes

Energy generation in the Sun results from the fusion of hydrogen to helium, 99% of pp chain.



The Sun: Neutrino fluxes

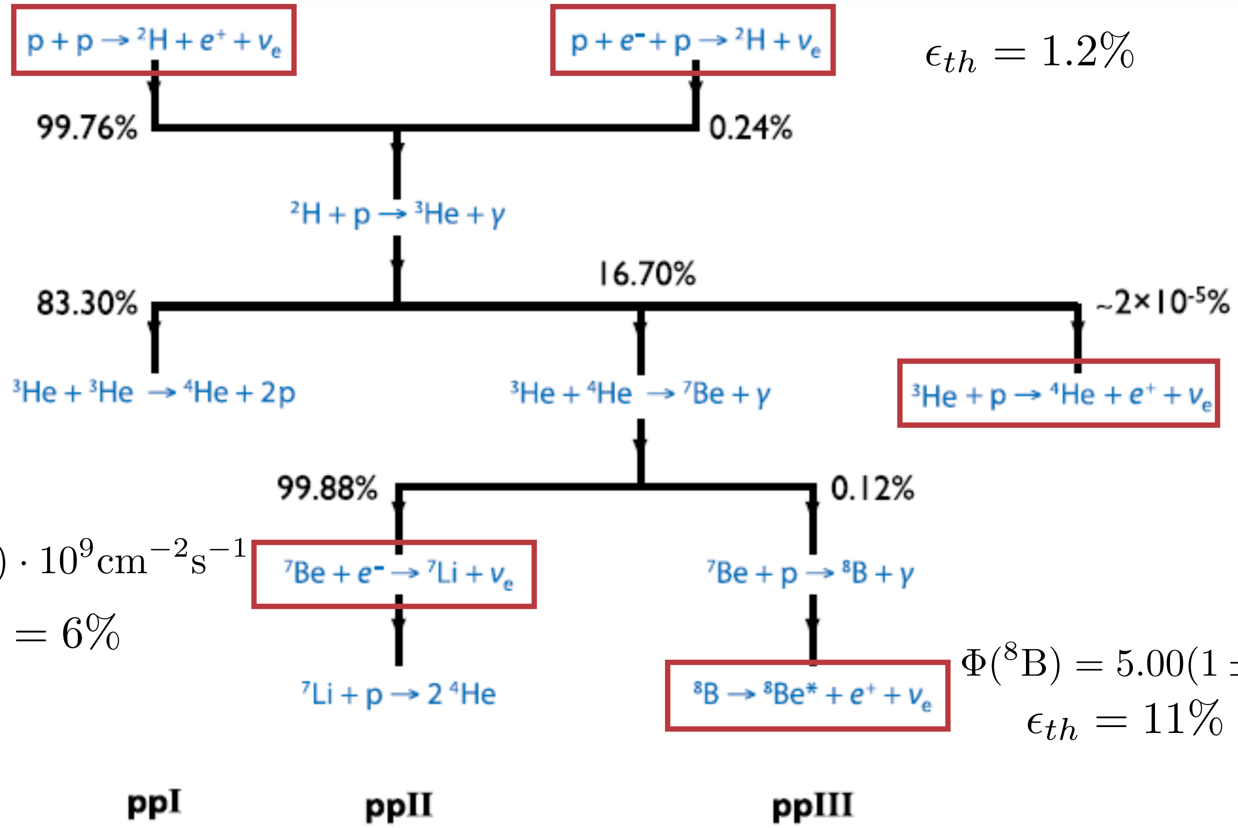
Neutrino fluxes

$\Phi(\text{pp}) = 6.6(1 \pm 0.1) \cdot 10^{10} \text{cm}^{-2}\text{s}^{-1}$

$\epsilon_{th} = 0.6\%$

$\Phi(\text{pep}) = 1.6(1 \pm 0.2) \cdot 10^{8} \text{cm}^{-2}\text{s}^{-1}$

$\epsilon_{th} = 1.2\%$



$\Phi(^7\text{Be}) = 4.82(1^{+0.05}_{-0.04}) \cdot 10^{9} \text{cm}^{-2}\text{s}^{-1}$

$\epsilon_{th} = 6\%$

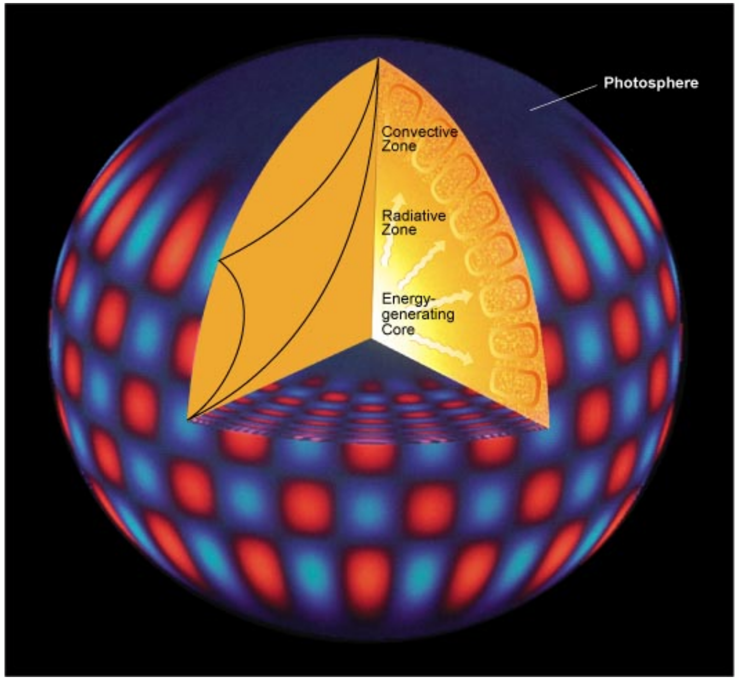
$\Phi(^8\text{B}) = 5.00(1 \pm 0.03) \cdot 10^{6} \text{cm}^{-2}\text{s}^{-1}$

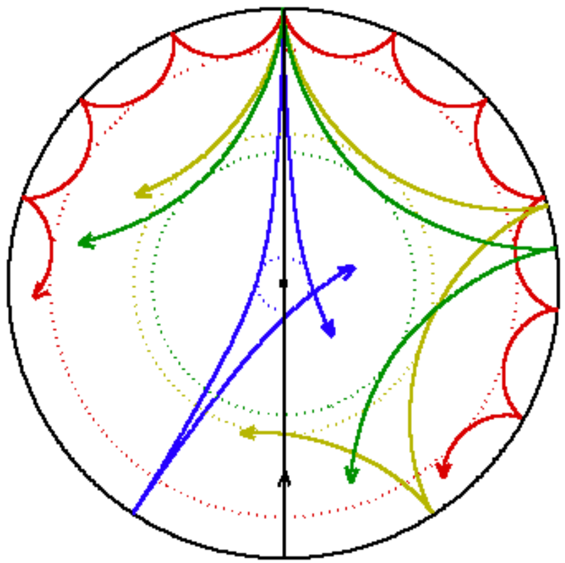
$\epsilon_{th} = 11\%$

The Sun: Helioseismology

Helioseismology

Study of the global oscillations of the Sun





Propagation acoustic pressure waves

adiabatic index

$$c_s^2 = \frac{\Gamma_1 p}{\rho}$$

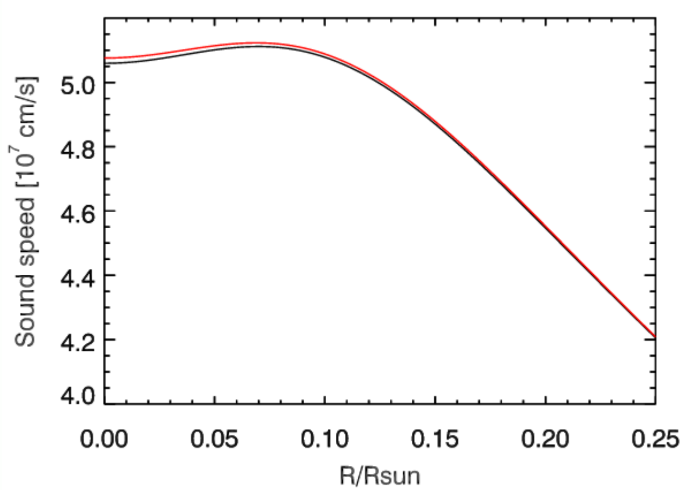
pressure

density

The Sun: Helioseismology

- **Sound speed profile:** From the observed frequencies and using inversion techniques

In our work, we use 30 points of the sound speed profile

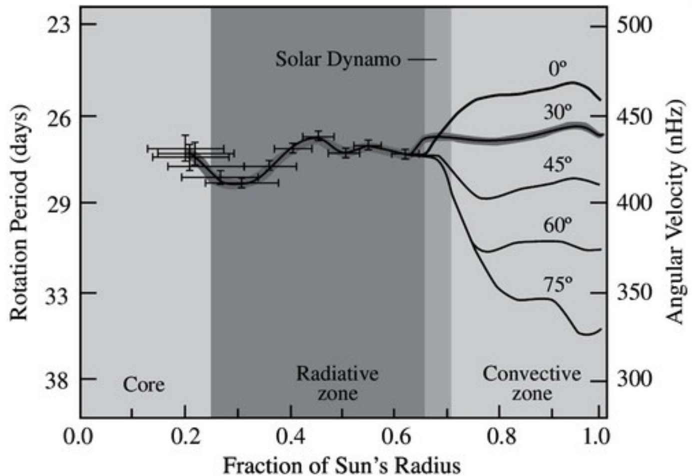


- **Surface Helium**: $Y_S = 0.2485 \pm 0.0035$

In the helium ionization zone on the solar envelope the adiabatic index Γ_1 variates ⟶ variation of the observed frequencies.

- **Radius of the convective envelope**:

$$R_{CZ} = 0.713 \pm 0.001$$



The Sun: Standard Solar Models (SSMs)

Theoretical descriptions of the Sun that are calibrated to **match the Sun's present status**

Adjust three initial quantities

↓

1. Mixing length parameter (α)

2. Initial Helium (Y_{ini})

3. Initial metallicity (Z_{ini})

The Sun: Standard Solar Models (SSMs)

Theoretical descriptions of the Sun that are calibrated to **match the Sun's present status**

To satisfy the present solar constraints

↓

1. Luminosity($L_\odot = 3.8418 \times 10^{33}$ erg s^{-1})
2. Radius ($R_\odot = 6.9598 \times 10^{10}$ cm)
3. Metal - hydrogen ratio

The Sun: Standard Solar Models (SSMs)

Theoretical descriptions

match the Sun's present status

To satisfy the present solar constraints

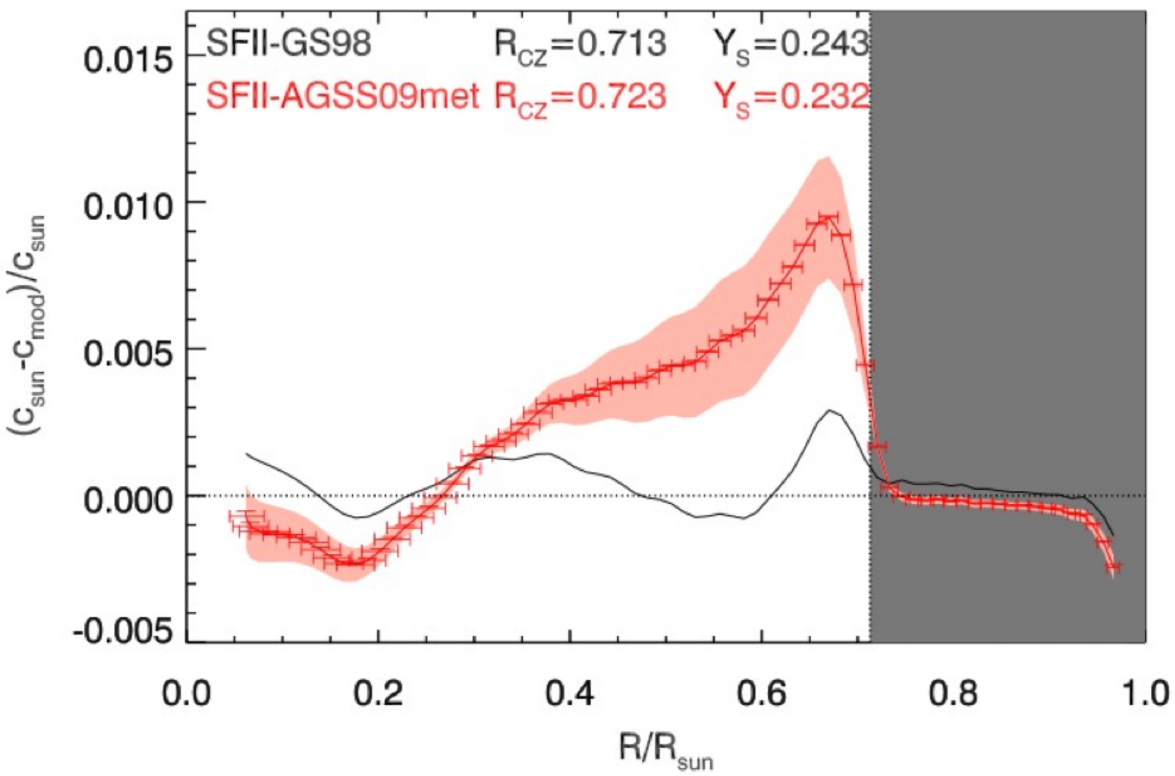
Solar Abundance Problem

2. Radius ($R_\odot = 6.9598 \times 10^{10}$ cm)

3. Metal - hydrogen ratio ?

The Sun: Solar Abundance Problem

- *Grevesse et al. 1998* **(GS98)** : 1-D solar atmosphere models
- *Asplund et al. 2009* **(AGSS09)** : 3-D hydrodynamical models of the solar atmosphere



Element	GS98	AGSS09+met
C	8.52	8.43
N	7.92	7.83
O	8.83	8.69
Ne	8.08	7.93
Mg	7.58	7.53
Si	7.56	7.51
Ar	6.40	6.40
Fe	7.50	7.45
Z/X	0.0229	0.0178

The Sun: Solar Abundance Problem

Possible sources of solar abundance problem:

- Observations
- Solar Models
    - Radiative opacities!

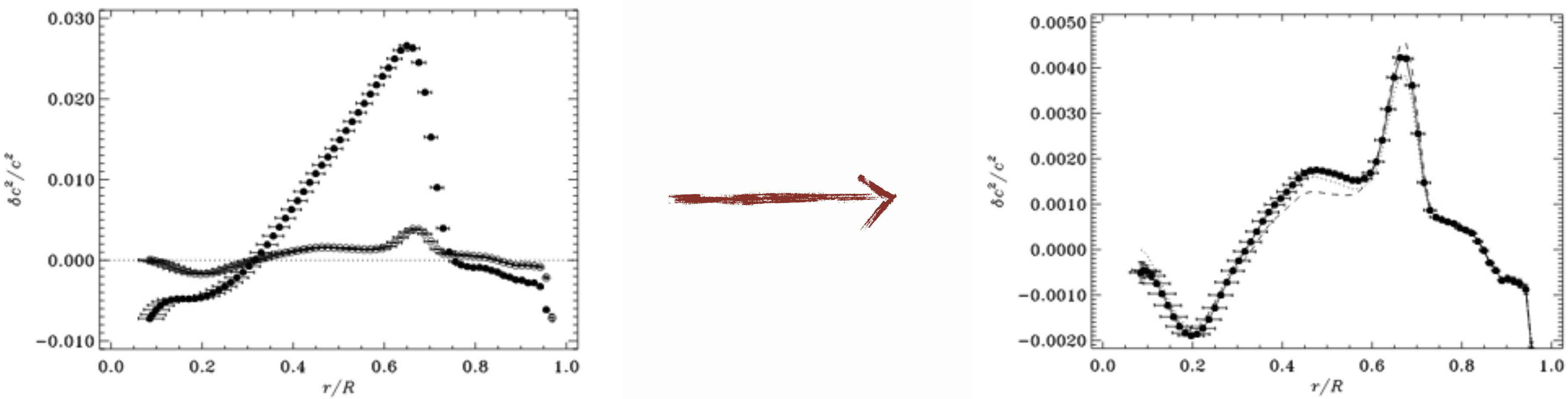
The Sun: Solar Abundance Problem

Thermal stratification of the Sun is defined by the **opacity profile**:

- Solar Composition (GS98, AGSS09, …)

- Radiative opacities (OP, OPAL)

Some works as *Christensen-dalsgaard et al. 2009* points that an increase of the the radiative opacities could change the opacity profile in a way that the helioseismological agreement is recovered.



The Sun: Solar Abundance Problem

Thermal stratification of the Sun is defined by the **opacity profile**:

- Solar Composition (GS98, AGSS09, …)

- Radiative opacities (OP, OPAL)

Latest experimental results go on this direction

Bailey et al. 2015: Gives a larger value (15%) for the iron opacity than the one predicted for solar interior temperatures → goes on the direction of relieving the solar abundance problem.

The Sun: Best Fit Model

Best fit model: Reproduces the thermal stratification of the Sun with the composition as free parameter

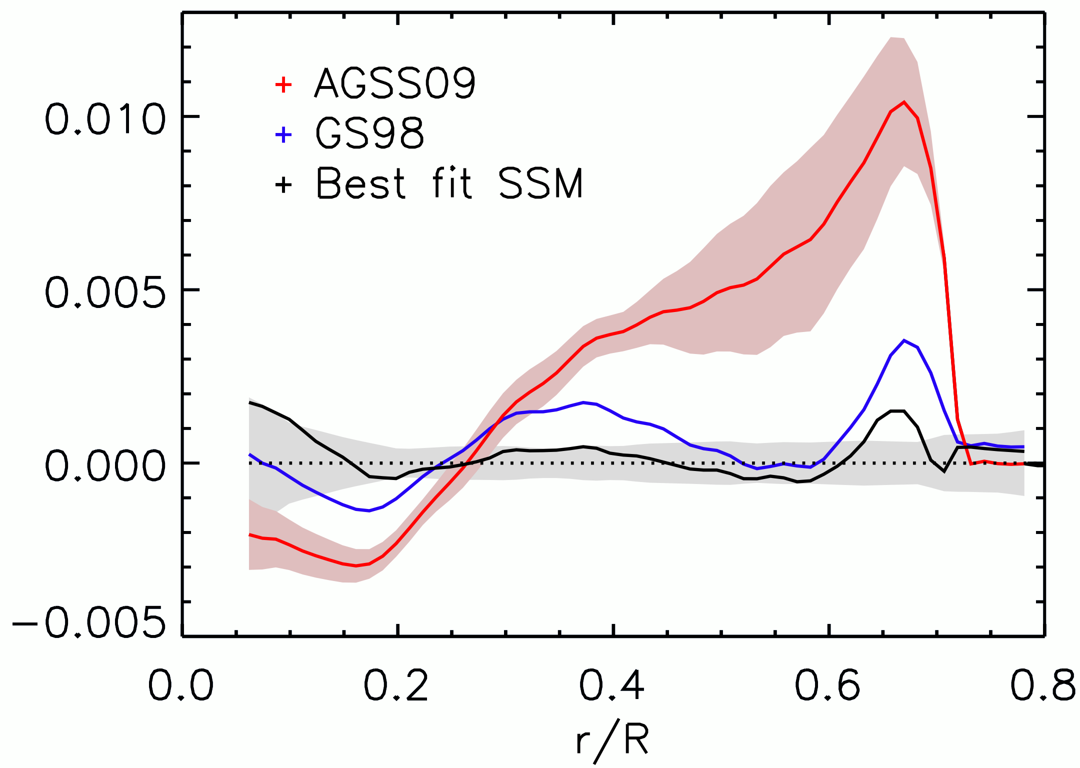
Minimize for the composition:

Group the composition in two groups:

- Refrectories (Mg, S, Si, Fe, …)
- Volatiles (C, N, O, Ne, …)

Results:

	Best Fit	GS98	AGSS09
Fe	7.52	7.5	7.45
O	8.85	8.83	8.69



Villante et al. 2014

Particles: Axions and hidden photons

Models with **axions** ⟶ Primakoff effect

$$Q_{a\gamma} = \frac{dE}{dm\,dt} = \frac{g_{a\gamma}^2}{4\pi}\frac{T^7}{\rho}F(\kappa^2)$$

Schlatt et al. 1999

$$F(\kappa^2) = 1.842(\kappa^2/12)^{0.31}$$

$$\kappa^2 = \pi\alpha\frac{n_B}{T^3}\left(Y_e + \sum_j Z_j^2 Y_j\right)$$

Longitudinal **hidden photons** ⟶ $\gamma \to \gamma'$ oscillations

$$\omega_p^2 = \frac{4\pi\alpha n_e}{m_e}$$

In the Sun:

$$\omega_P < 0.3\text{ keV}$$

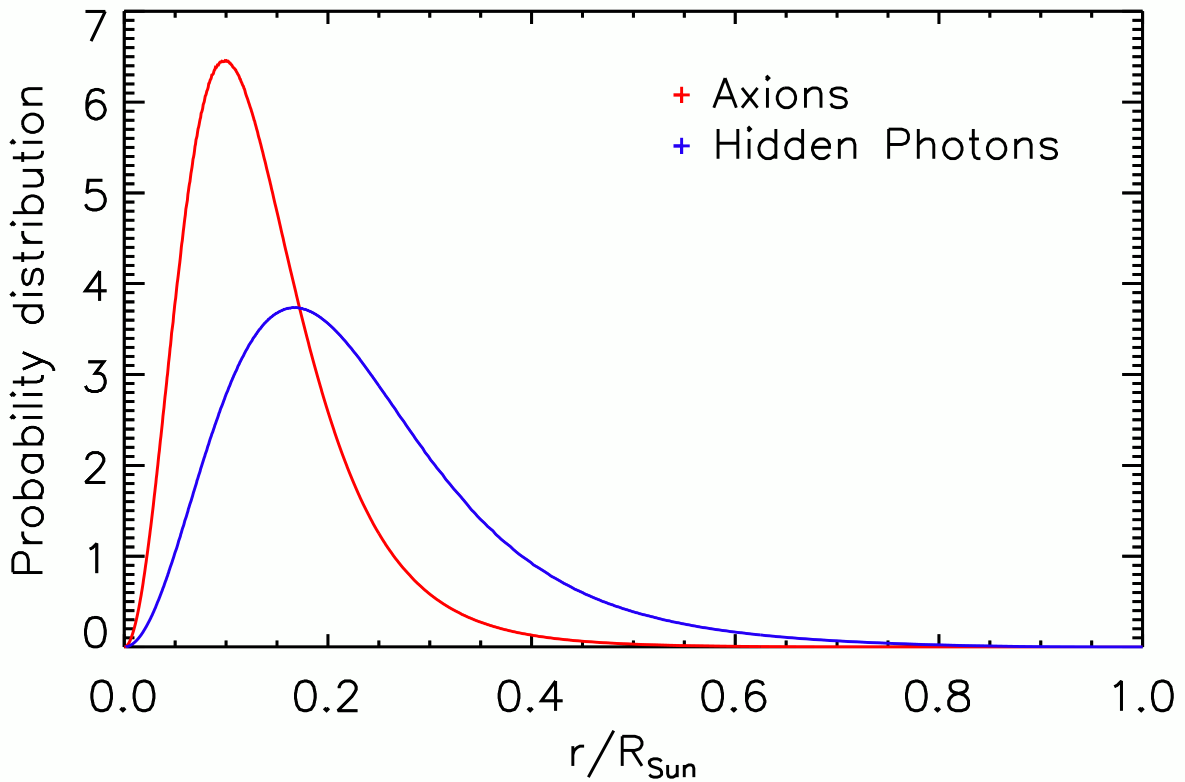
↓

$$m_{HP} < 0.3\text{ keV}$$

$$Q_{hp} = \frac{dE}{dm\,dt} = \frac{\chi^2 m^2}{e^{\omega_p/T}-1}\frac{\omega_p^3}{4\pi}\frac{1}{\rho}$$

Redondo et al. 2013

Particles: Axions and L-HP



Different dependences on density and temperature

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Different effects on the structure and evolution of the Sun

Particles: Minicharged particles

MCPs are dominantly produced through plasmon decay $\gamma^* \to f\bar{f}$

$\omega_p \geq 2m_f$ **On-shell emission**

$$Q_{MCP} = \frac{dE}{dm\,dt} = \frac{2}{2\pi^2}\int_0^\infty dk k^2 \frac{\omega\Gamma_{\gamma^*}}{e^{\omega/T}-1}\frac{1}{\rho}$$

$$\Gamma_{\gamma^*} = \frac{\epsilon^2\alpha}{3}\frac{Z}{\omega}(\omega_p^2+2m_f^2)\sqrt{1-\frac{4m_f^2}{\omega_p^2}}$$

$\omega_p < 2m_f$ **Off-shell emission**

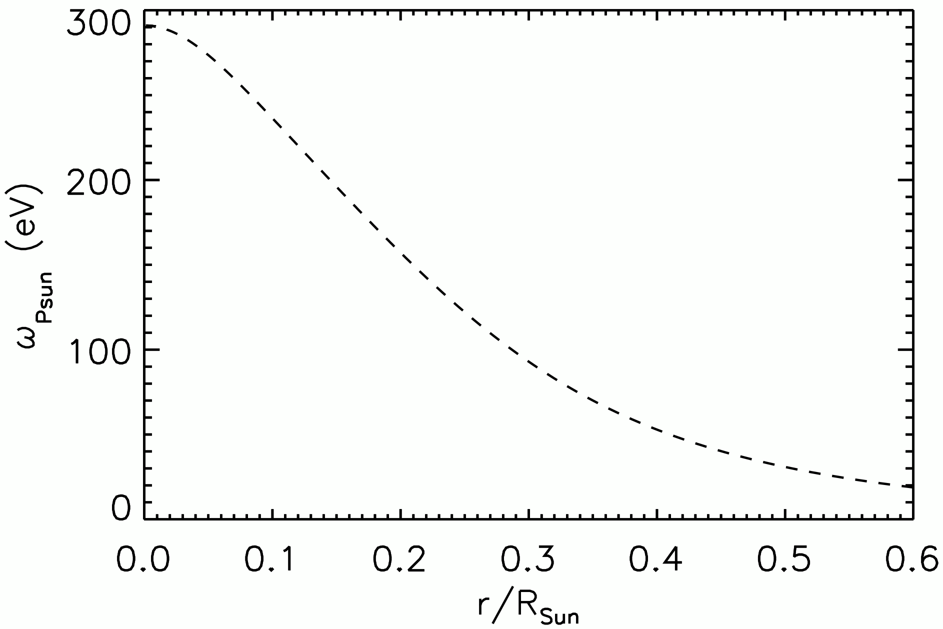
$$Q_{MCP} = \frac{dE}{dm\,dt} = \int_0^\infty \frac{dk k^2}{\pi^2}\int_{2m_f}^\infty \frac{d\omega^2}{\pi}\frac{\omega\Gamma_{Th}}{(K^2-\omega_p^2)+(\omega\Gamma_{Th})}\frac{\omega\Gamma_{\gamma^*}}{e^{\omega/T}-1}\frac{1}{\rho}$$

Particles: MCPs in the Sun

MCP emission depends on the plasma frequency in the Sun

$$\omega_p^2 = \frac{4\pi\alpha n_e}{m_e}$$

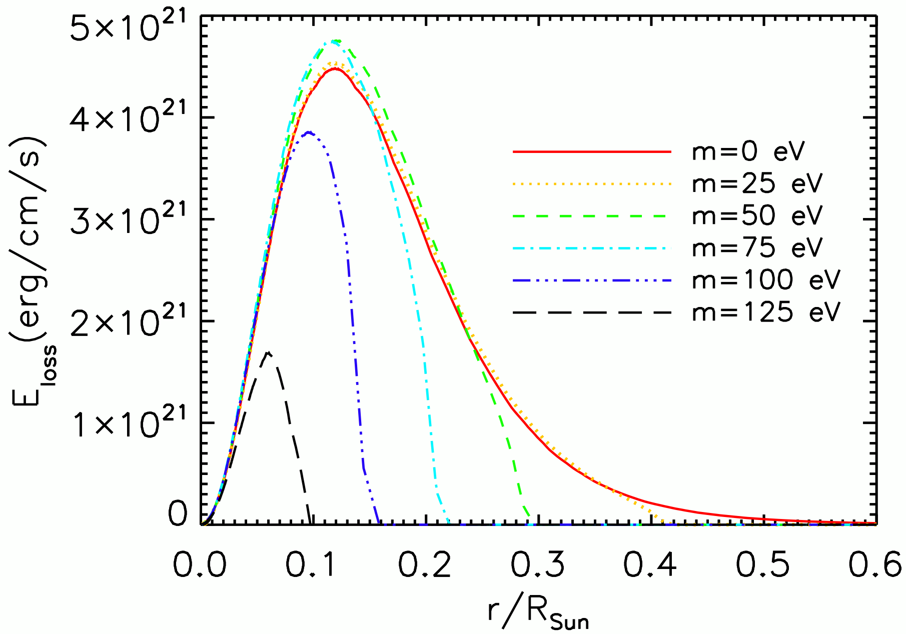
$$\omega_{p,max} \sim 290 \text{ eV}$$



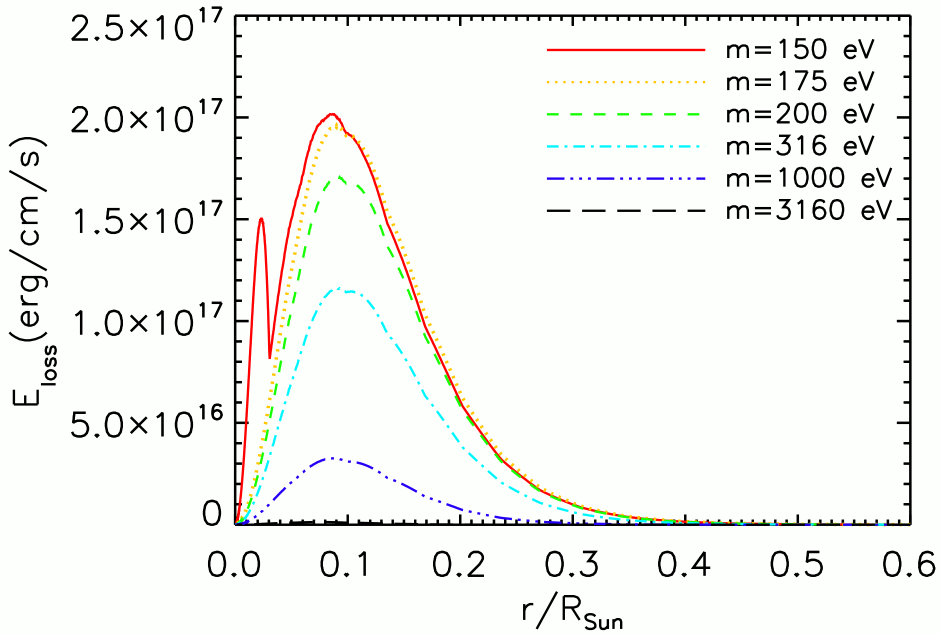
On - shell emission: $2m_f < \omega_p \longrightarrow m_f < 150 \text{ eV}$
Off - shell emission: $2m_f > \omega_p \longrightarrow m_f > 150 \text{ eV}$

Particles: MCPs in the Sun

On-shell emission

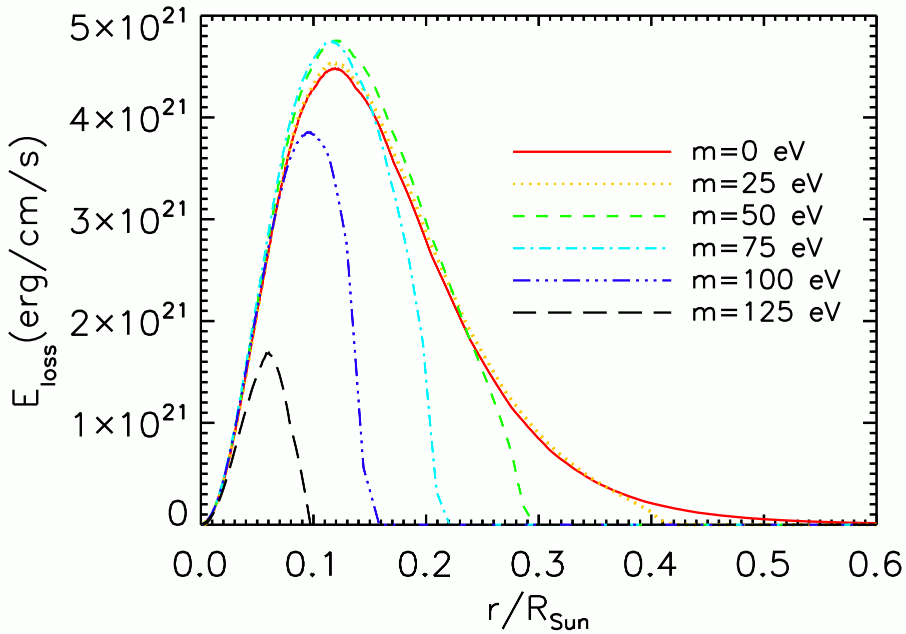


Off-shell emission

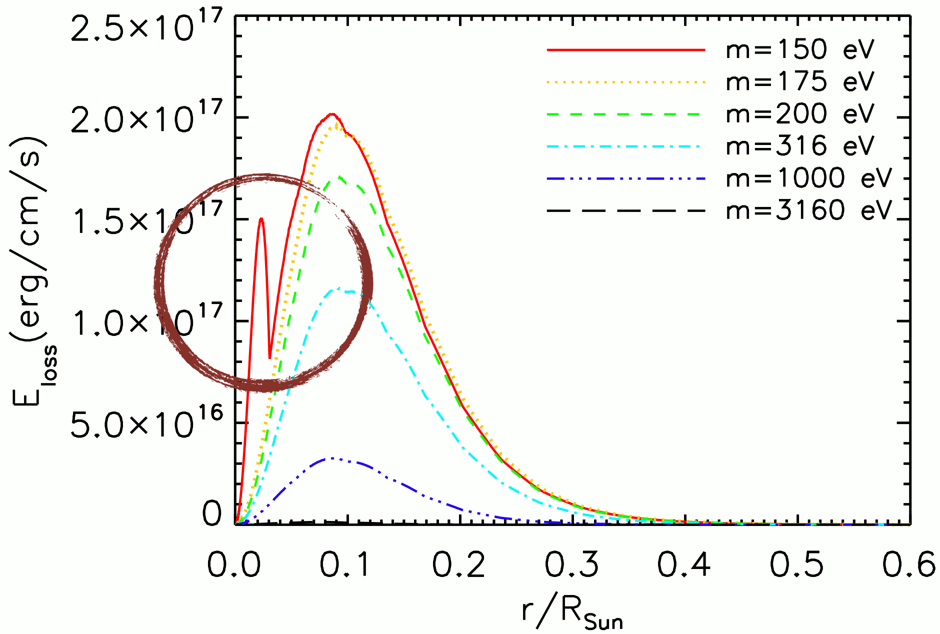


Particles: MCPs in the Sun

On-shell emission



Off-shell emission



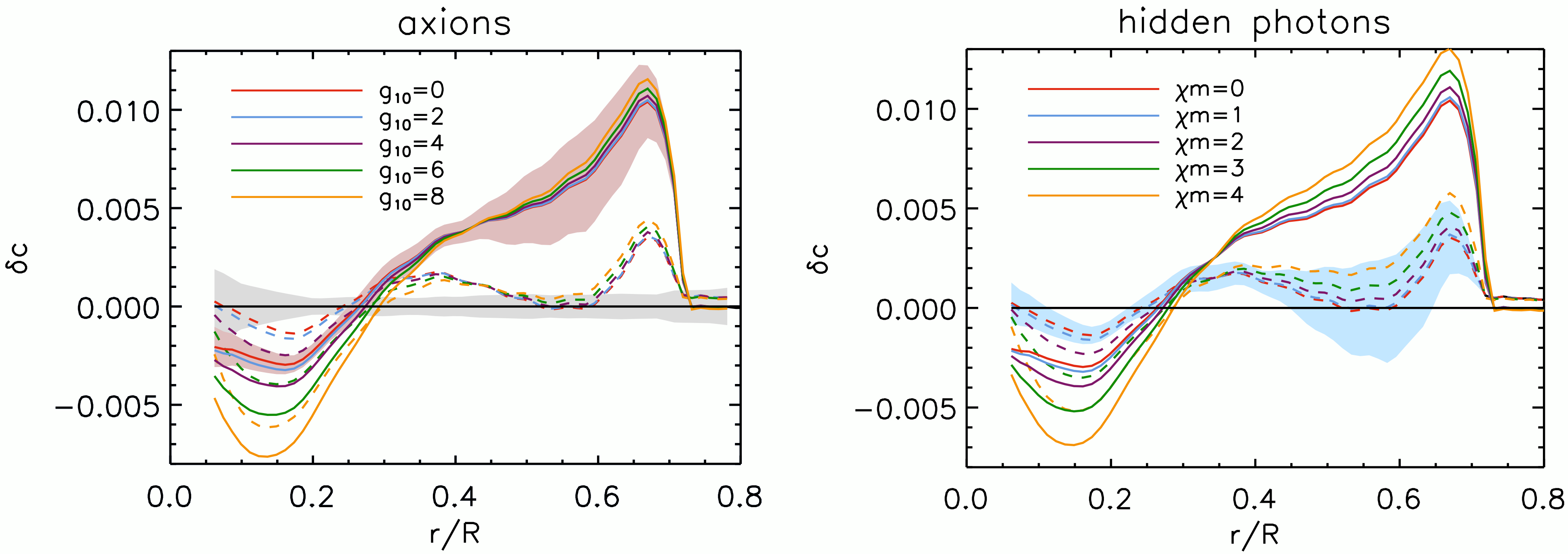
Results: Solar Models with extra energy-loss

- **Axions**: SSM models changing $g_{10} = 10^{-10} \cdot g_{a\gamma}$
- **L-HP**: SSM models changing the product $\chi \mathrm{m}$
- **Minicharged particles**: SSM with fixed $\mathrm{m_f}$ $(1 < \log_{10}(\mathrm{m_f}/\mathrm{eV}) < 3.5)$ changing ϵ

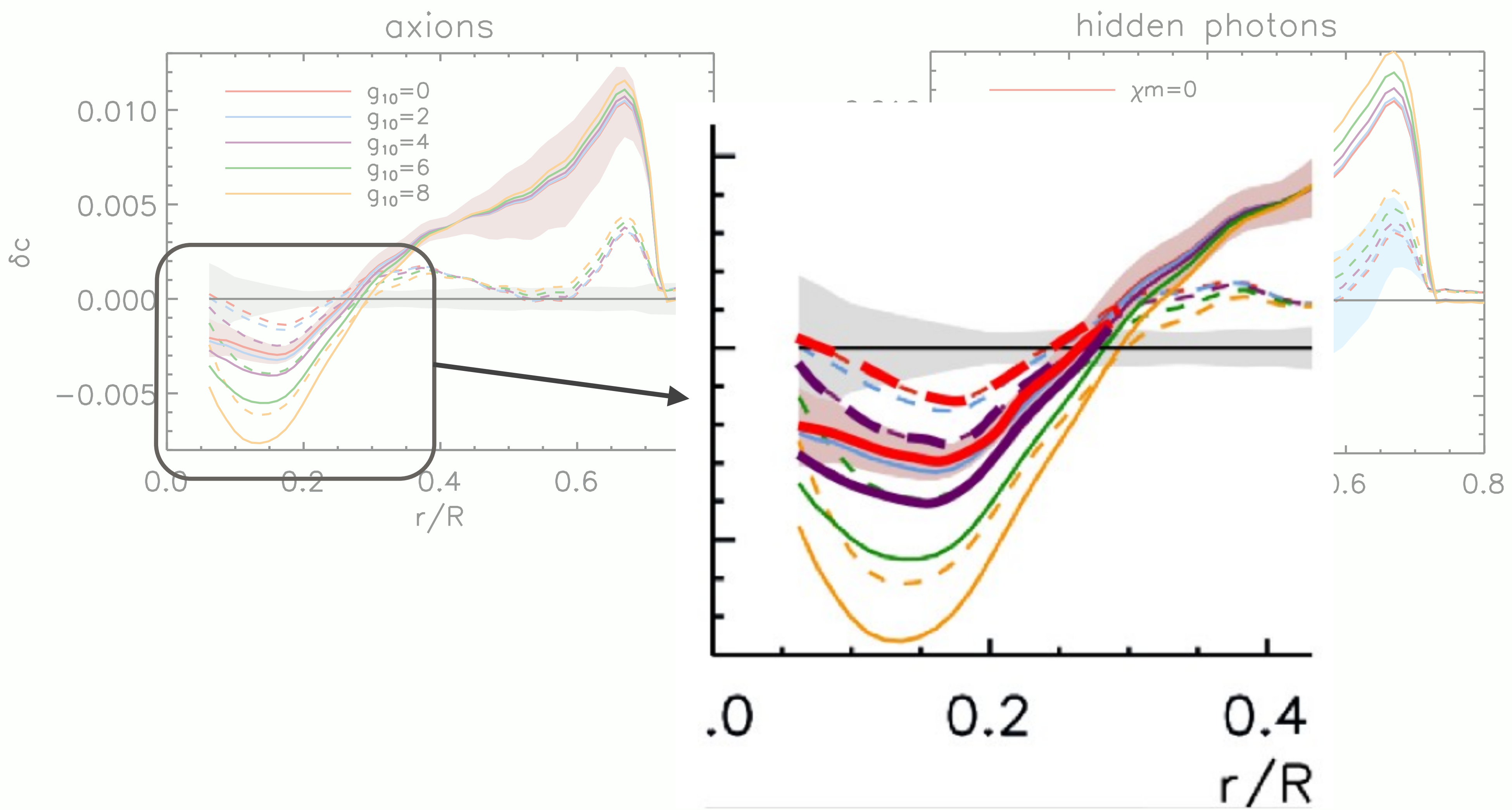
$$\frac{\partial l}{\partial m} = \epsilon_{nuc} + \epsilon_g - \epsilon_\nu - \boxed{\epsilon_{ex}}$$

Results: Axions and hidden photons

Sound speed profile *Vinyoles et al. 2015*



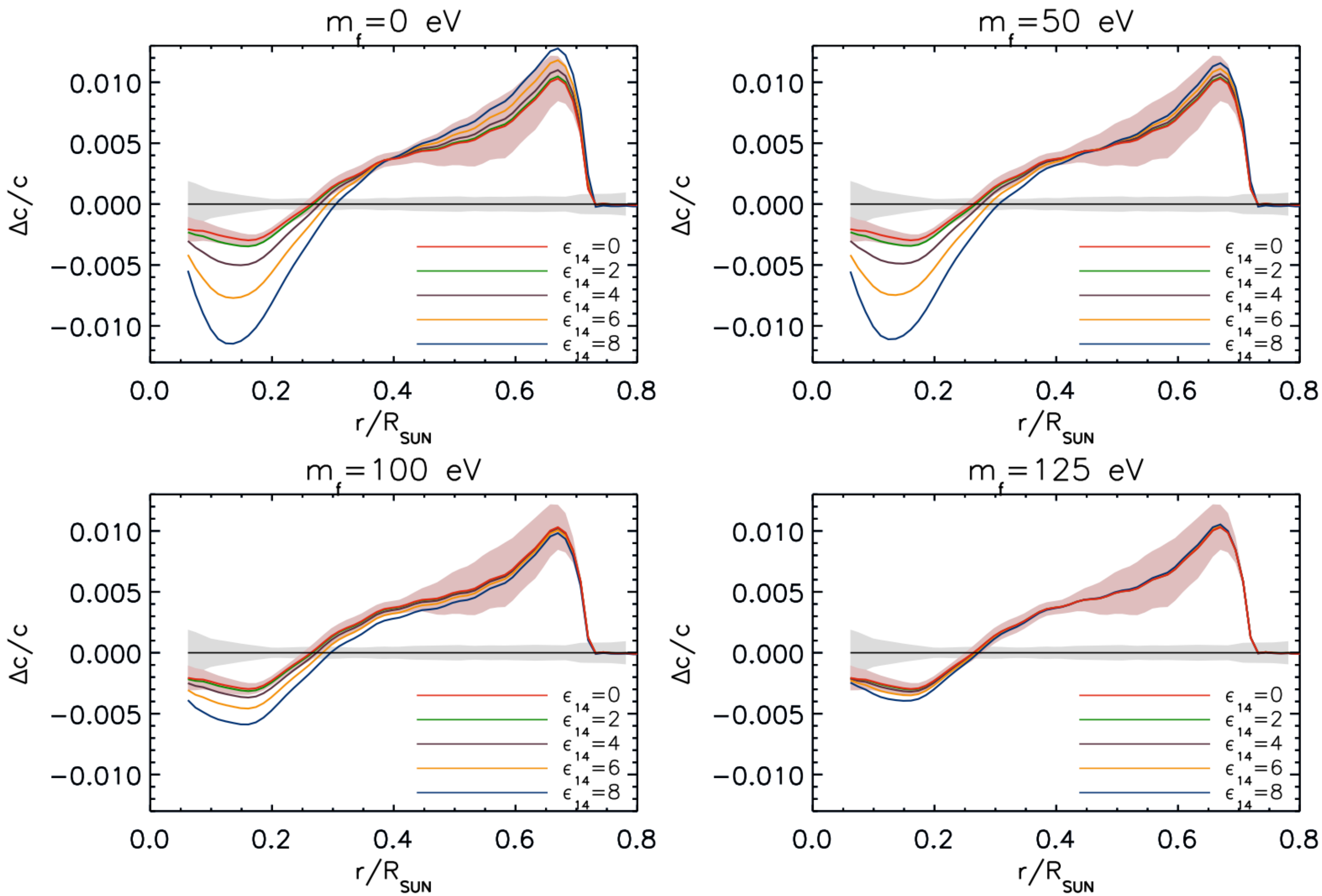
Results: Axions and hidden photons



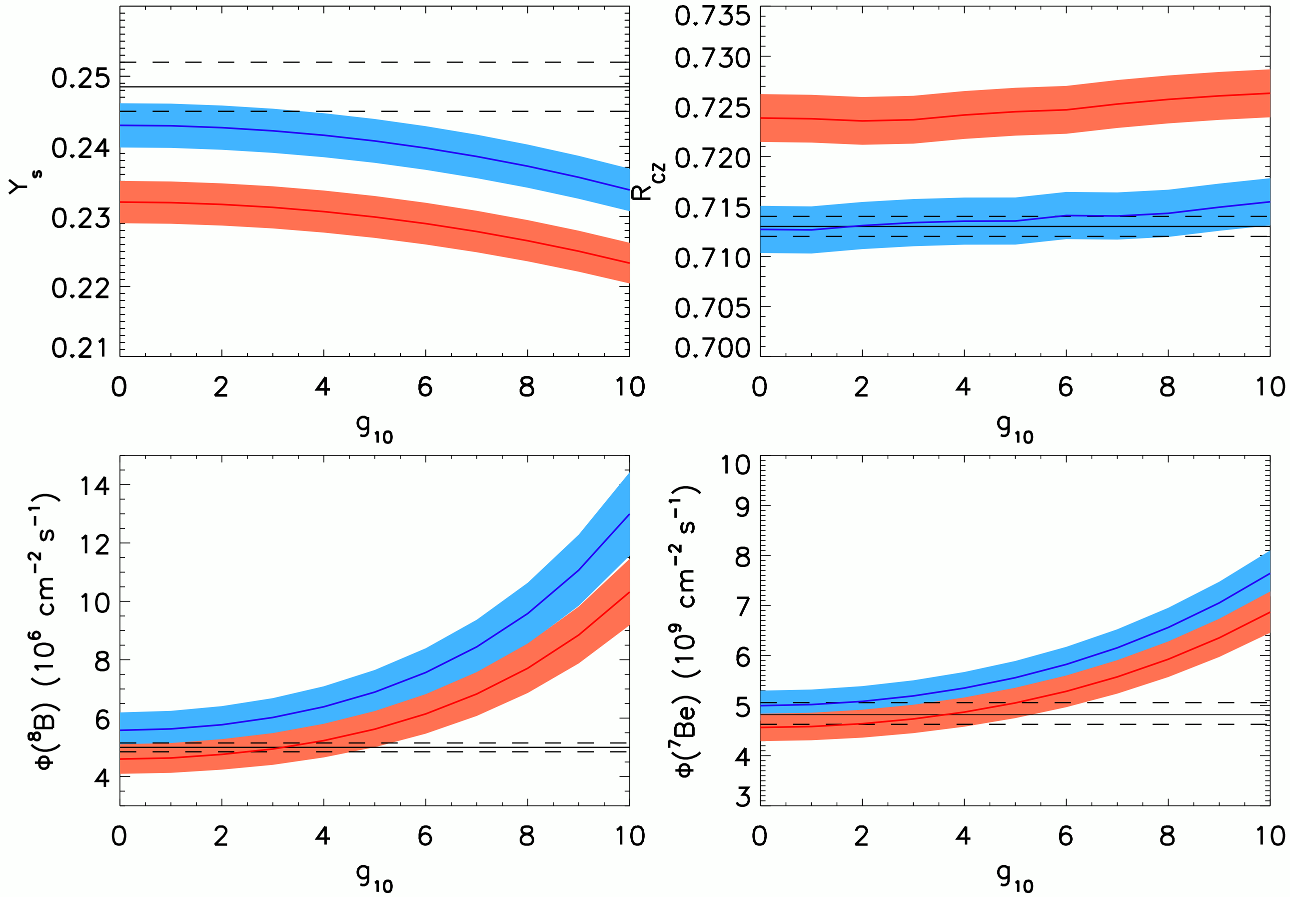
Results: MCPs

Sound speed profile

Vinyoles & Vogel 2015



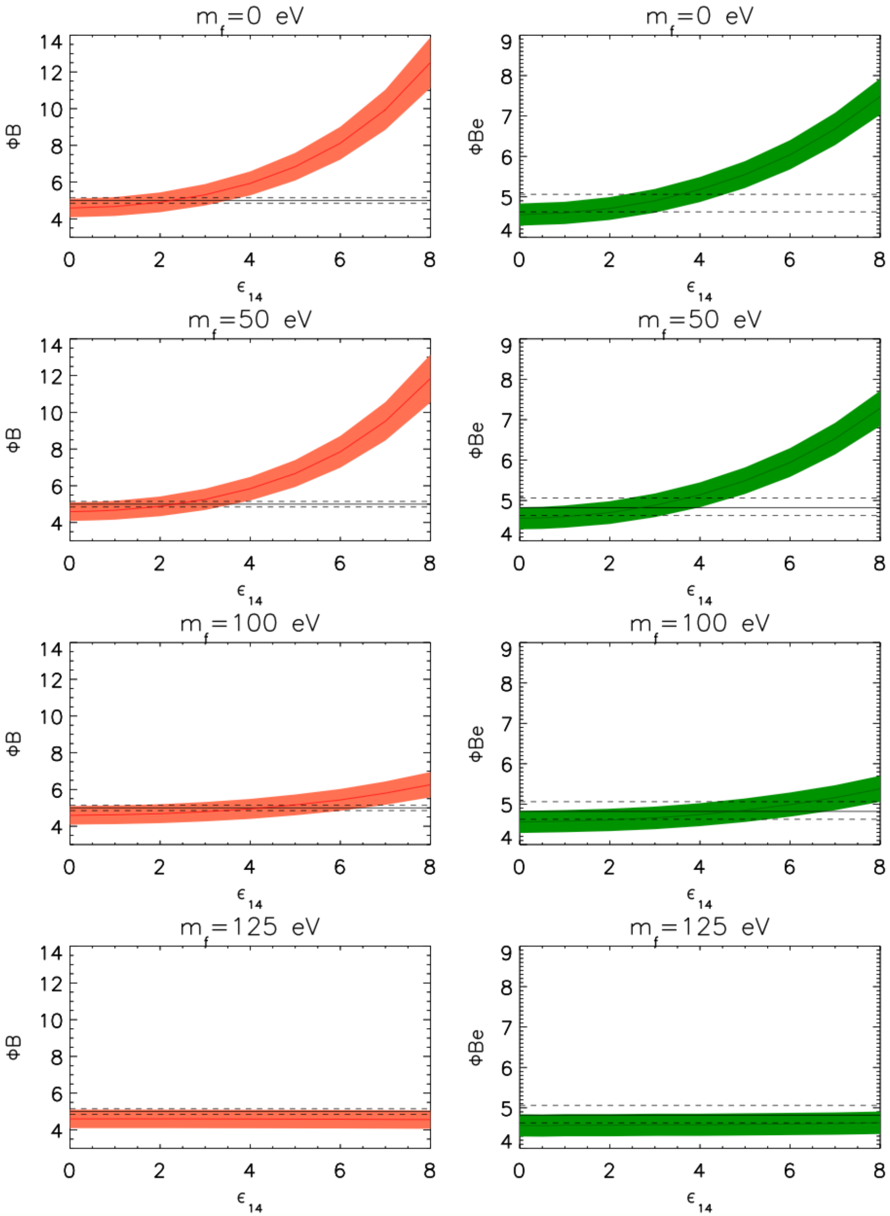
Results: Axions



When we add some extra energy-loss to a solar model, we need to increase the energy production through nuclear reactions in order to reach the observed solar luminosity.

$$L_\odot = L_{\rm nuc} + L_{\rm ex}$$

Results: MCPs



Results: Axions and hidden photons

$$\chi^2 = \min_{\{\xi_I\}} \left[\sum_Q \left(\frac{\delta_Q - \sum_I \xi_I C_{Q,I}}{U_Q} \right)^2 + \sum_I \xi_I^2 \right]$$

Observables: 30 points of the sound speed profile, $\Phi(^7\mathrm{Be})$, $\Phi(^8\mathrm{B})$, R_{CZ} and Y_s

1. For each model with different g_{10} or χm, minimize with respect of the composition to find the **best fit model**

2. Construct the χ^2 function using those **best fit models**

3. Use the relation between χ^2 function and the confidence level for 1 d.o.f problem $N\sigma = \sqrt{(\chi^2 - \chi^2_{min})}$ to derive the bounds

Results: MCPs

$$\chi^2 = \min_{\{\xi_I\}} \left[\sum_Q \left(\frac{\delta_Q - \sum_I \xi_I C_{Q,I}}{U_Q} \right)^2 + \sum_I \xi_I^2 \right]$$

Observables: 30 points of the sound speed profile, $\Phi(^7\mathrm{Be})$, $\Phi(^8\mathrm{B})$, R_{CZ} and Y_s

1. For a given $\mathrm{m_f}$, for each model with different ϵ minimize with respect of the composition to find the **best fit model**

2. For each value of $\mathrm{m_f}$, we construct a χ^2 function using the corresponding **best fit models**

3. Use the relation between χ^2 function and the confidence level for 2 d.o.f problem $\Delta\chi^2 = 2.3, 6.2, 11.8, \ldots$ to derive the bounds for each $\mathrm{m_f}$

Statistical method

Villante et al. 2014

$$\delta Q = 1 - \frac{Q_{th}}{Q_{obs}}$$

Seismic and neutrino observables

Model correlations

$$\chi^2 = \min_{\{\xi_I\}} \left[\sum_Q \left(\frac{\delta_Q - \sum_I \xi_I C_{Q,I}}{U_Q} \right)^2 + \sum_I \xi_I^2 \right]$$

Observables uncertainties

Pulls of input parameters

Input parameters of the SSMs

age, diffusion coefficients, luminosity, opacity

Astrophysical S-factors: S11, S33, S34, S17, Se7, S114

Statistical method

Villante et al. 2014

Seismic and neutrino observables

Model correlations

$$\chi^2 = \min_{\{\xi_I\}} \left[\sum_Q \left(\frac{\delta_Q - \sum_I \xi_I C_{Q,I}}{U_Q} \right)^2 + \sum_I \xi_I^2 \right]$$

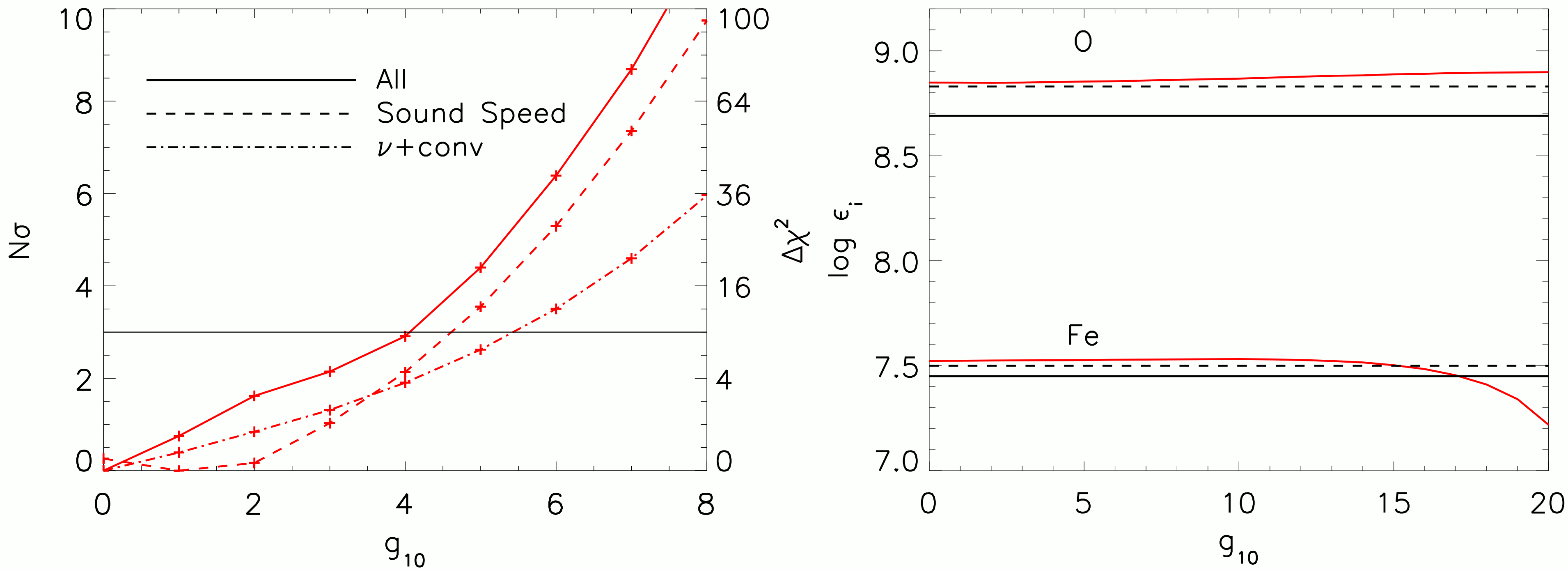
Observables uncertainties

Pulls of input parameters

ξ_I: **Pulls of the input parameters of the SSMs**

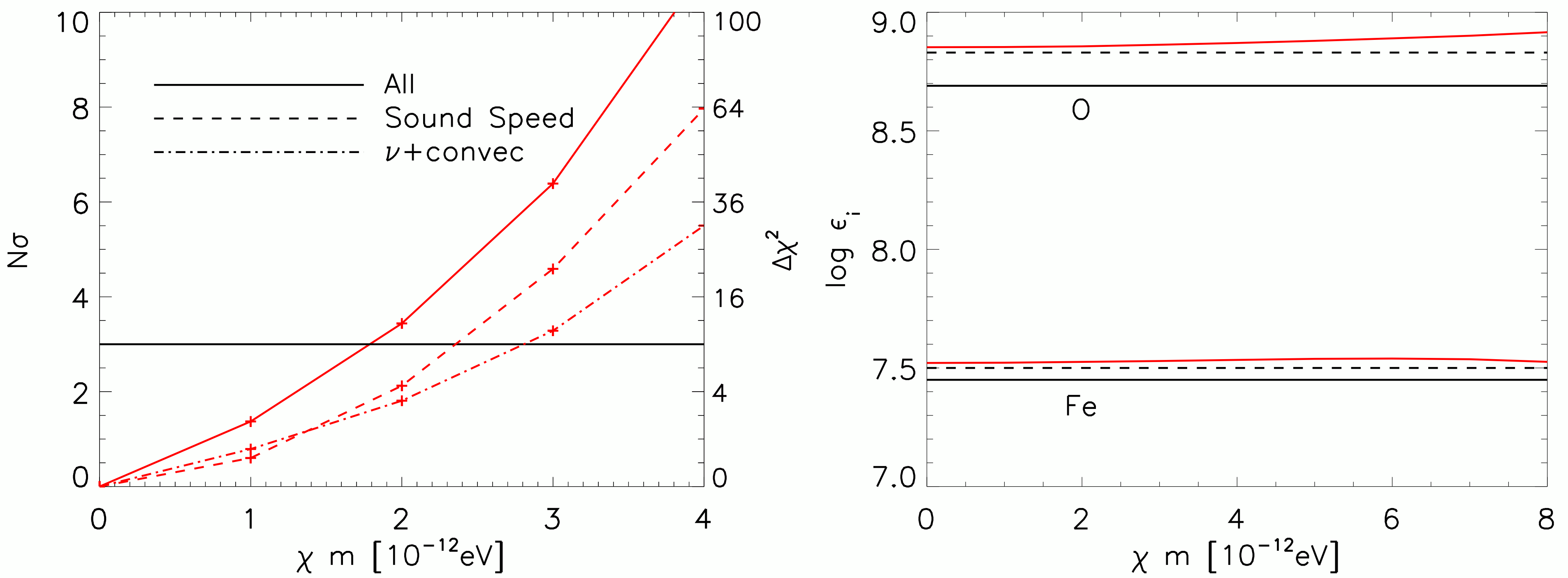
Minimize χ^2 and give information about tensions between parameters and data.

Results: Axions



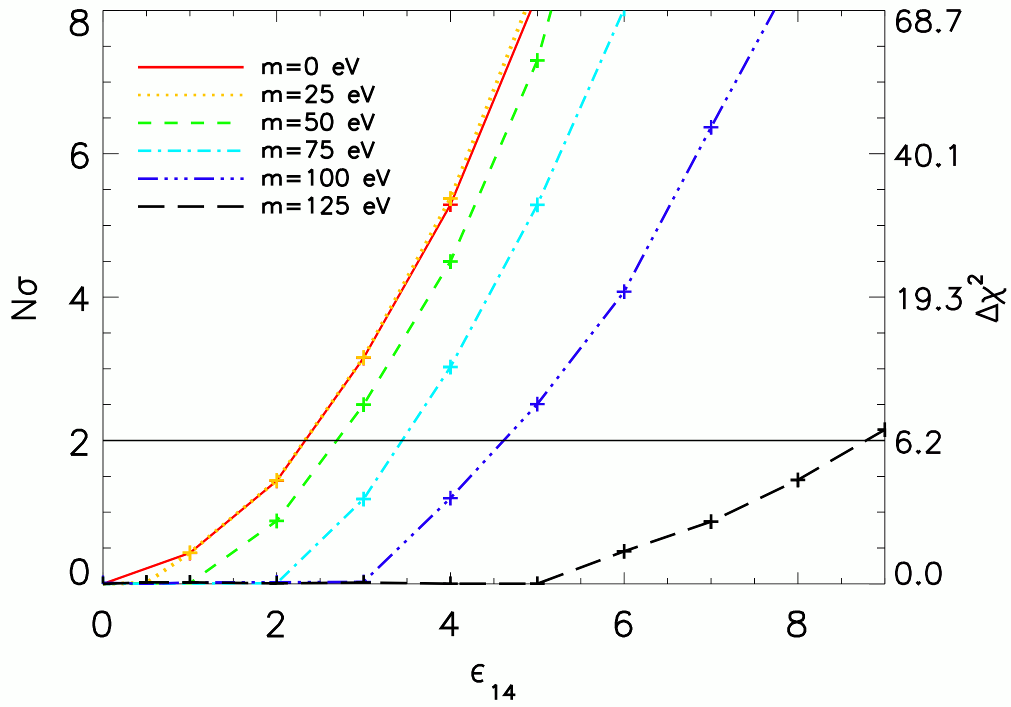
$$g_{a\gamma} < 4.1 \cdot 10^{-10} \mathrm{GeV}^{-1} \quad \text{at} \quad 3\sigma$$

Results: Hidden photons



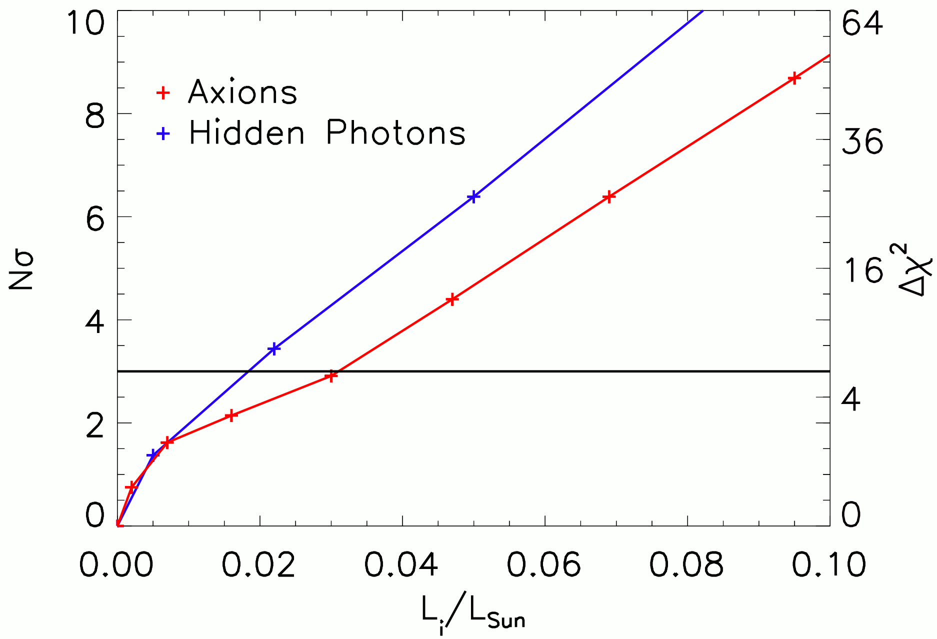
$$\chi m < 1.8 \cdot 10^{-12}\text{eV} \;\; \text{at} \;\; 3\sigma$$

Results: Milicharged particles

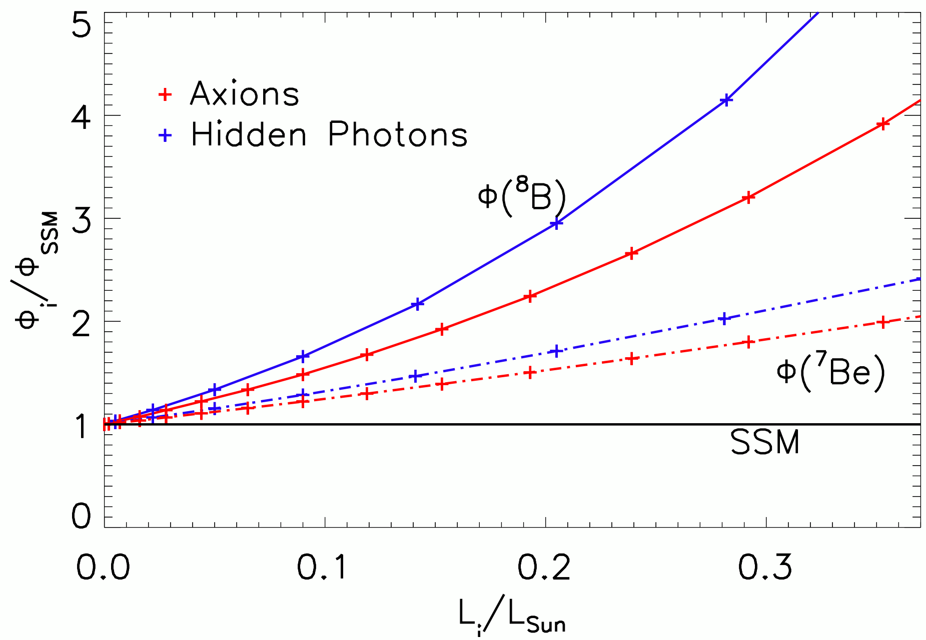


m_f(eV)	$\epsilon \times 10^{14}$ at 2σ	$L_{\rm MCP}/L_\odot(\%)$	m_f(eV)	$\epsilon \times 10^{14}$ at 2σ	$L_{\rm MCP}/L_\odot(\%)$
0	2.2	1.5	150	460	-
25	2.2	1.5	175	460	2.3
50	2.6	2.0	200	500	2.4
75	3.4	2.7	316	600	2.3
100	4.5	2.6	1000	1090	2.3
125	8.7	2.6	3160	7720	2.8

Results:



Luminosity constraint depends on the emission rate of the particle studied



$$\frac{\Phi(^8\mathrm{B})}{\Phi_{\mathrm{SSM}}(^8\mathrm{B})} = \left(\frac{L_a + \mathrm{L}_\odot}{\mathrm{L}_\odot}\right)^\alpha$$

Gondolo et al. 2009

$$\alpha_{\mathrm{ax}} = 4.6 \qquad \alpha_{\mathrm{hp}} = 5.7$$

Results: MCPs

Luminosity constraint is different depending on the MCP mass

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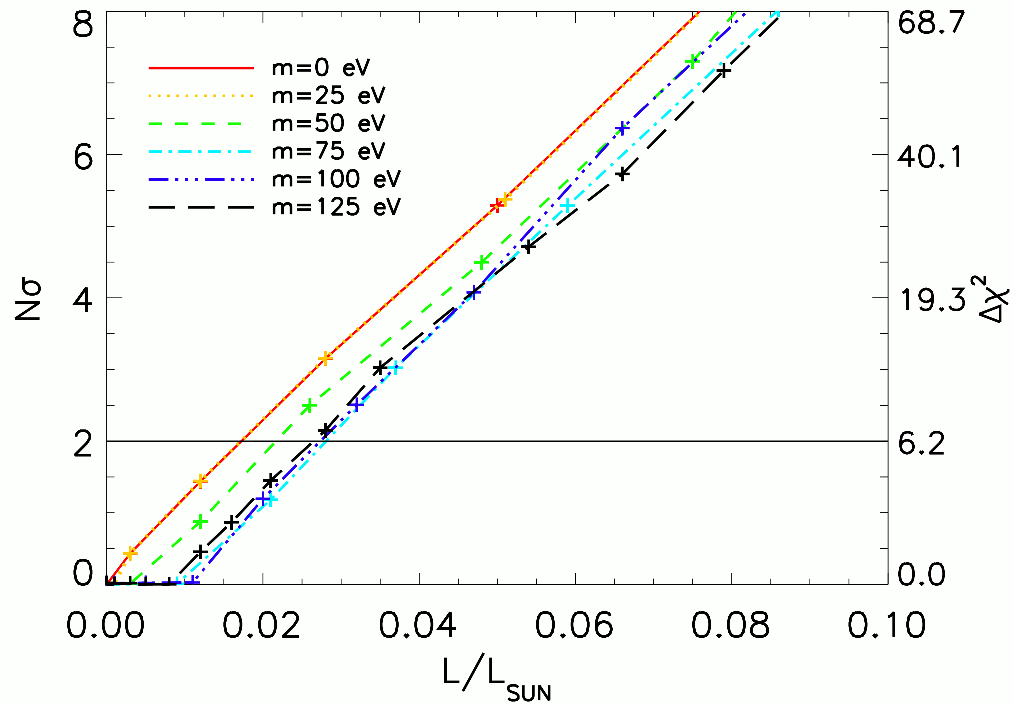
Not universal: Depends on the emission rate of the particle studied.



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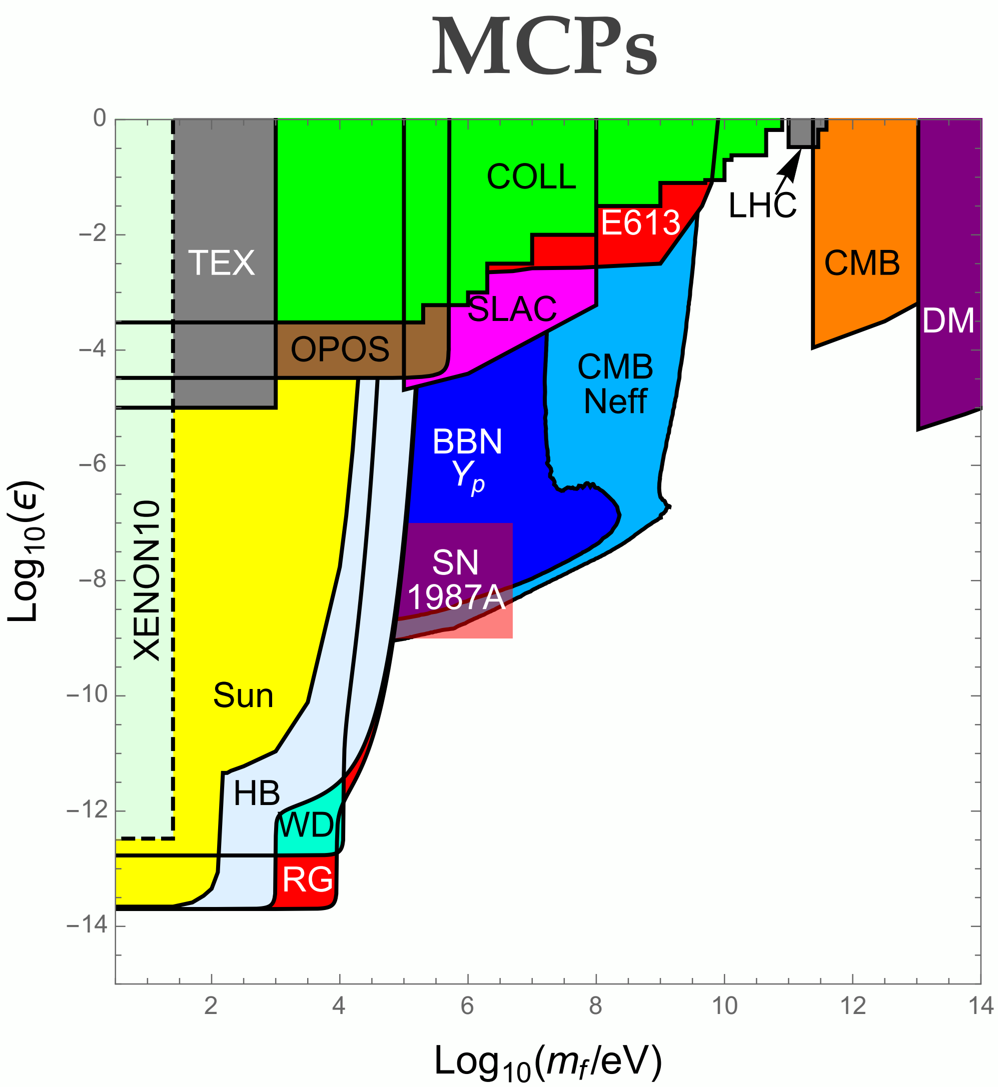
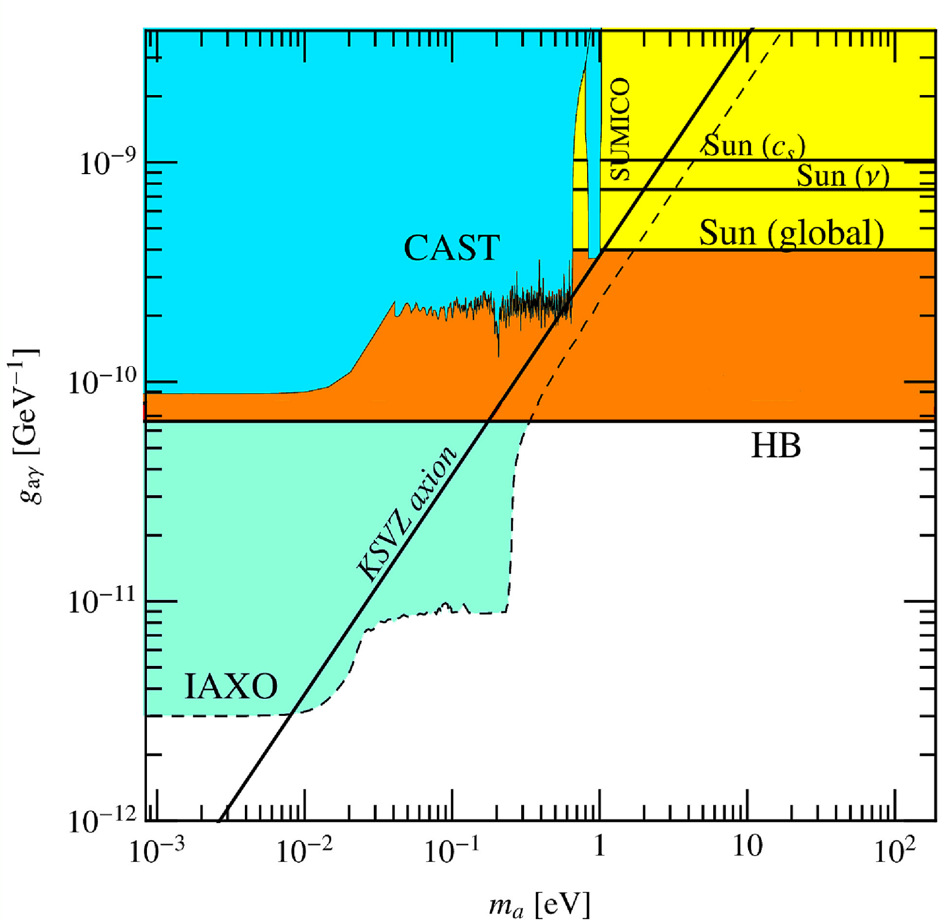
Results: Constaints on MCPs

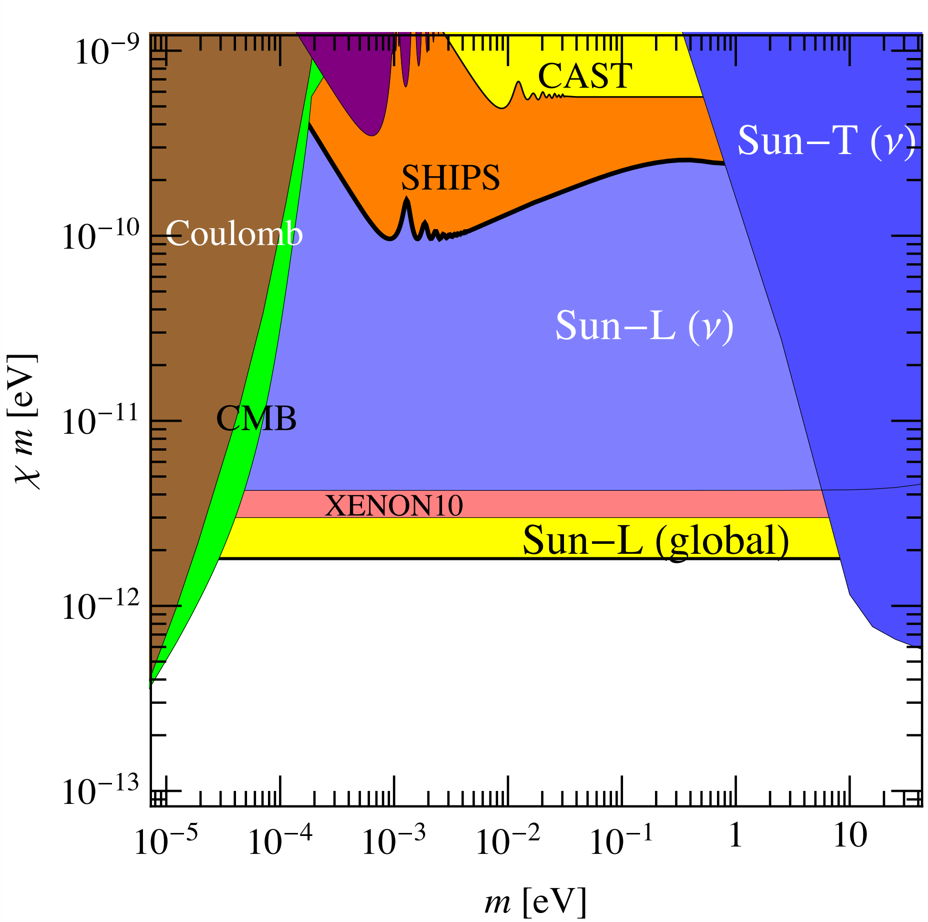


Results: Constraints on ALPs and HPs

ALPs



L-HPs



Summary

- Global fit using all the available observables of the Sun
- Improvement on the previous results based on the Sun
- Importance of self-consistent solar models
- Results not affected by the solar abundance problem
- Can be extended it to other cases with exotic energy-loss