XENON1T vs. Astrophysics

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based on arXiv:2006.12487 in collaboration with:

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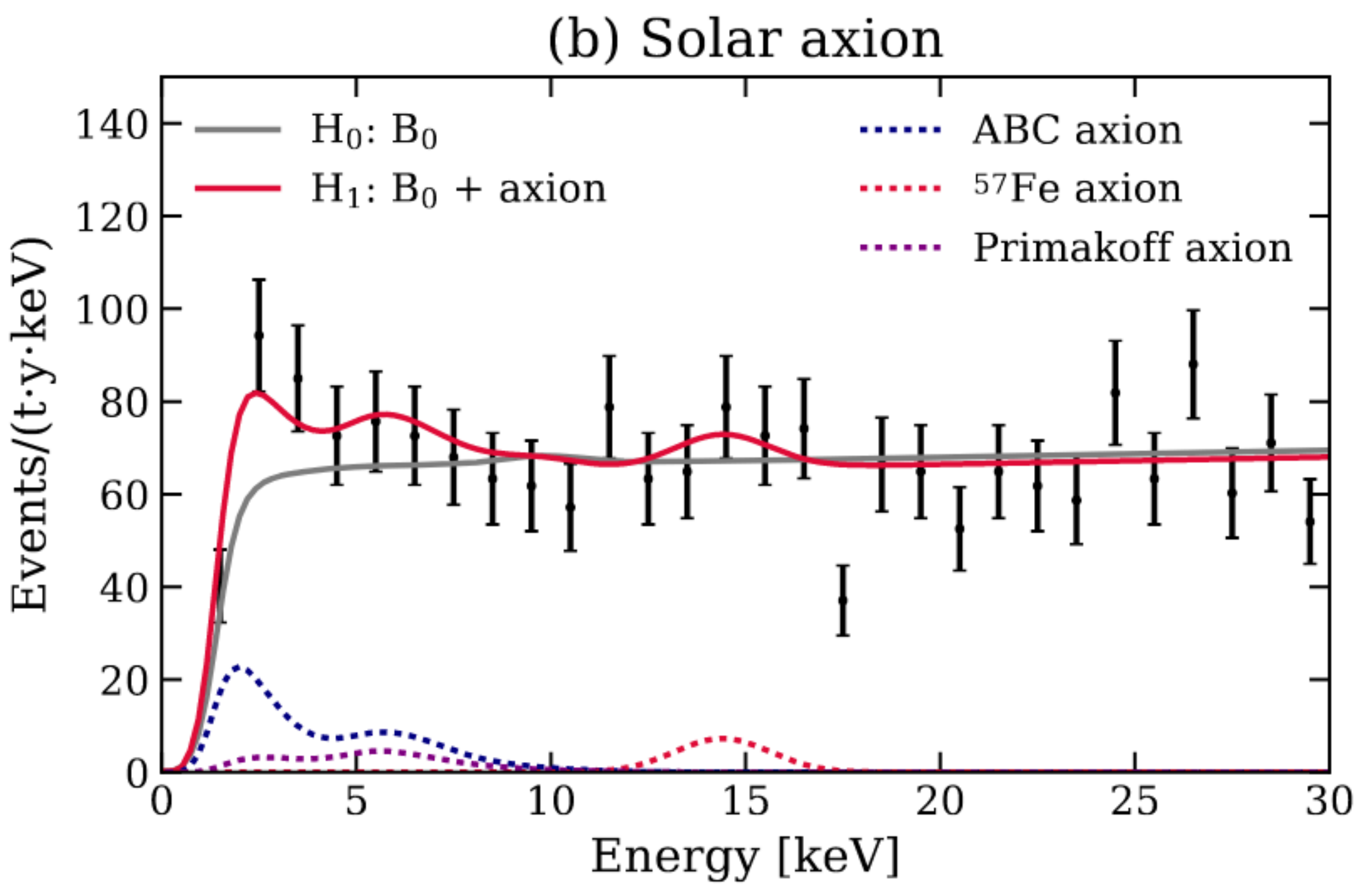
XENON1T anomaly as a hint of solar axions



$$\mathcal{L}_{\rm int} = \frac{1}{4} g_{a\gamma} a F_{\mu\nu} \tilde{F}^{\mu\nu} - g_{ae} a \bar{e} i \gamma_5 e$$

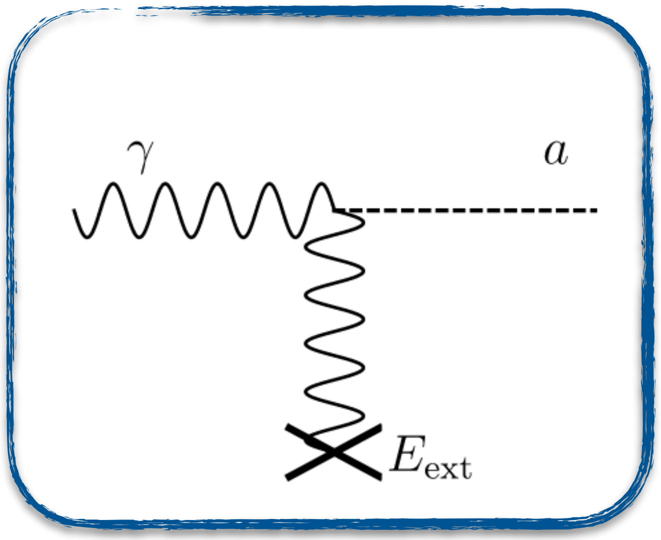
Theoretically motivated to explain dinamically the origin of the strong CP problem

- ABC emission, controlled by g_{ae}, is the main component
- Primakoff emission, controlled by $g_{a\gamma}$, is a non negligible component
- ^{57}Fe emission, controlled by g_{aN}, is a negligible component

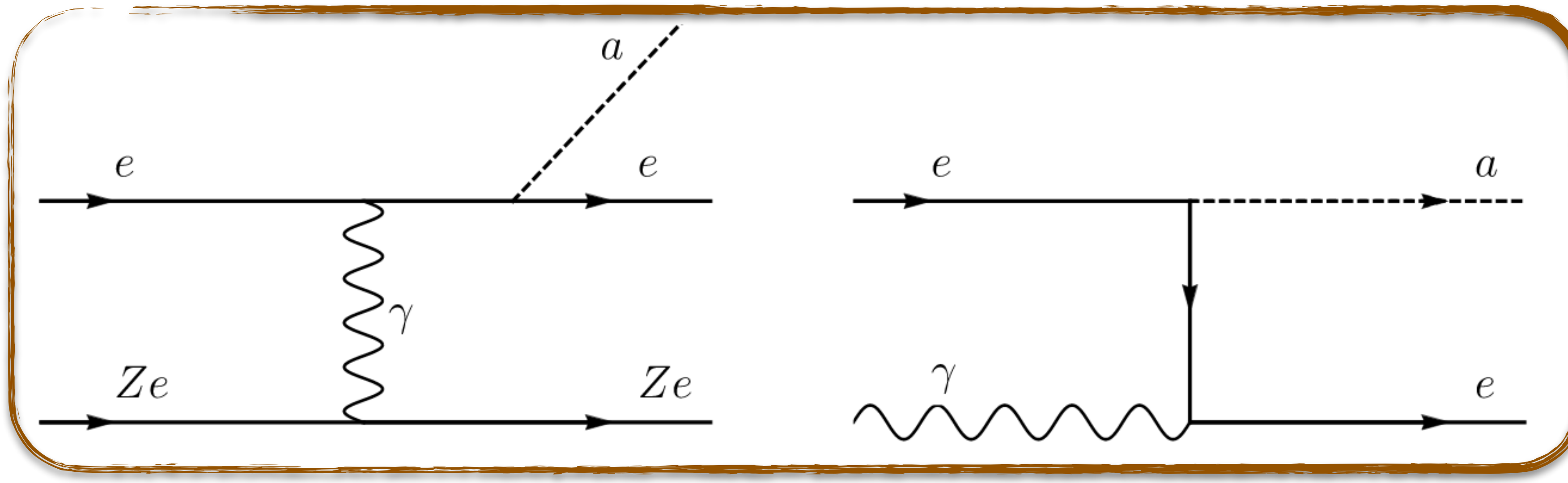
We will focus on the coupling with electrons and photons!

Principal emission mechanism for solar axions

$$\frac{dN_a}{dtd\omega} = \left(\frac{g_{a\gamma}}{\mathrm{GeV}^{-1}}\right)^2 n_{a\gamma}(\omega) + g_{ae}^2\, n_{ae}(\omega)$$



Primakoff



Bremsstrahlung

Compton

$$n_{a\gamma}(\omega) \approx 1.69 \times 10^{58} e^{-0.829\,\omega} \omega^{2.45}\, \mathrm{keV}^{-1}\mathrm{s}^{-1}$$

$$n_{ae}^{B} \approx 7.4 \times 10^{62} \frac{\omega\, e^{-0.77\,\omega}}{1 + 0.667\,\omega^{1.278}}\, \mathrm{keV}^{-1}\mathrm{s}^{-1}$$

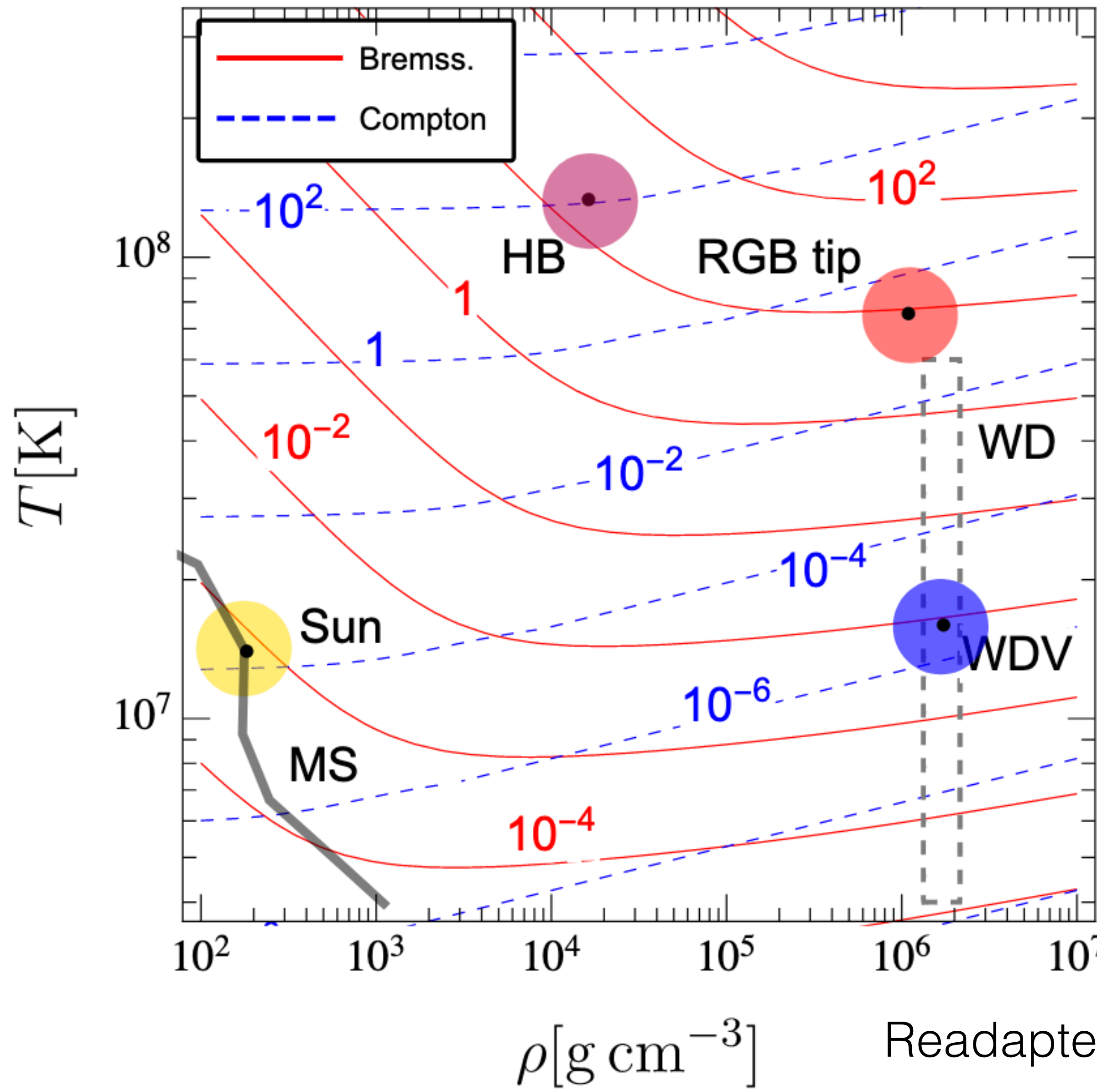
$$n_{ae}^{C} \approx 3.7 \times 10^{60} \omega^{2.987}\, e^{-0.776\,\omega}\, \mathrm{keV}^{-1}\mathrm{s}^{-1}$$

arXiv:hep-ex/0702006, 1302.6283

The atomic recomb.-deexc. does not have a nice analytical approximation

Axions production in the stars

Contours of the axion energy-loss rates per unit of mass, assuming $g_{e13} \sim 4.3$, for a pure He plasma



Stars in Main Sequence have a H core, so their position is approximate (biased towards large rates)

Readapted from arXiv:2003.01100

- The WD have ~ Compt. but > Bremss. than the Sun
- The RGB and HB have >> Compt. & Bremss. than the Sun

$\Longrightarrow$ Large emission from the sun would imply other stars being “axion lighthouses”

Axions and RGB

- Characterised by a degenerate He core and a burning H shell
- During the evolution, the He core is increased and the luminosity grows
- Once T ~ 10^8 K and ρ ~ 10^6 g cm^{-1}, the tip of the luminosity is reached, He ignition starts, and the star moves to the HB

Additional cooling mechanism (e.g. axion bremss.) in the core delays He ignition

$\Longrightarrow$ the star can reach higher luminosities

$\Longrightarrow$ the He core accrete a larger mass

$$M_{I,\mathrm{TRGB}} = -4.17 \pm 0.13 \text{ mag}$$

M5 cluster (NGC 5904)

arXiv:1311.1669

$$M_{I,\mathrm{TRGB}}^{\mathrm{theo}} = -4.03 - 0.25\left(\sqrt{g_{e13}^2 + 0.93} - 0.96 - 0.17 g_{e13}^{1.5}\right)$$

Analytic fit to simulations for 10 evolutionary track points reaching close to the RGB tip, corresponding to 10 different values of g_{e13} up to 9

Axions and HB

- Characterised by a non-degenerate burning He core
- Thermal press. balances the grav. pull: the larger the pull, the faster the burning rate
- Once the fuel is exhausted, the large grav. pull is no longer balanced and the star turns into a WD

Enhanced burning rate (due to Primakoff) and heavier core (due to longer RGB)

$\Longrightarrow$ the HB lifetime is reduced

$\Longrightarrow$ the # of HB stars over the # of the RGB ones decreases

$$R = 1.39 \pm 0.03$$

Average of 39 clusters

arXiv:1406.6053

$$R^{\rm theo} = 7.33Y - 0.095\sqrt{21.86 + 21.08 g_{\gamma 10}} + 0.02 - 1.61\delta\mathcal{M}_c - 0.005 g_{e13}^2$$

$$\delta\mathcal{M}_c = 0.024\left(\sqrt{g_{e13}^2 + 1.23^2} - 1.23 - 0.138\, g_{e13}^{1.5}\right) \qquad Y = 0.255 \pm 0.002$$

Analytic fit to simulations, which extrapolated would imply R ~ 0 for g_{e13} ~ 14 (15) for $g_{\gamma 10}$ ≃ 1 (0.1)

Axions and WD

- Compact objects whose equilibrium is supported by electron degeneracy
- Pulsating WD (WDV) have their luminosity varying periodically, $\dot{\Pi}/\Pi \propto \dot{T}/T$
- The number distribution of WDs in function of their luminosity (WDLF) is affected by the velocity of the WDs evolution

Extra cooling sources (axion emission via coupling with electrons)

$\Longrightarrow$ variation in the period change

$\Longrightarrow$ faster evolution, resulting in a change in the WDLF shape

$$\dot{\Pi}_{\rm G117-B15A} = (4.2 \pm 0.7) \times 10^{-15} s/s$$
$$\dot{\Pi}_{\rm R548} = (3.3 \pm 1.1) \times 10^{-15} s/s$$
$$\dot{\Pi}_{\rm L19-2} = (3.0 \pm 0.6) \times 10^{-15} s/s$$
$$\dot{\Pi}_{\rm PG1351+489} = (2.0 \pm 0.9) \times 10^{-13} s/s$$

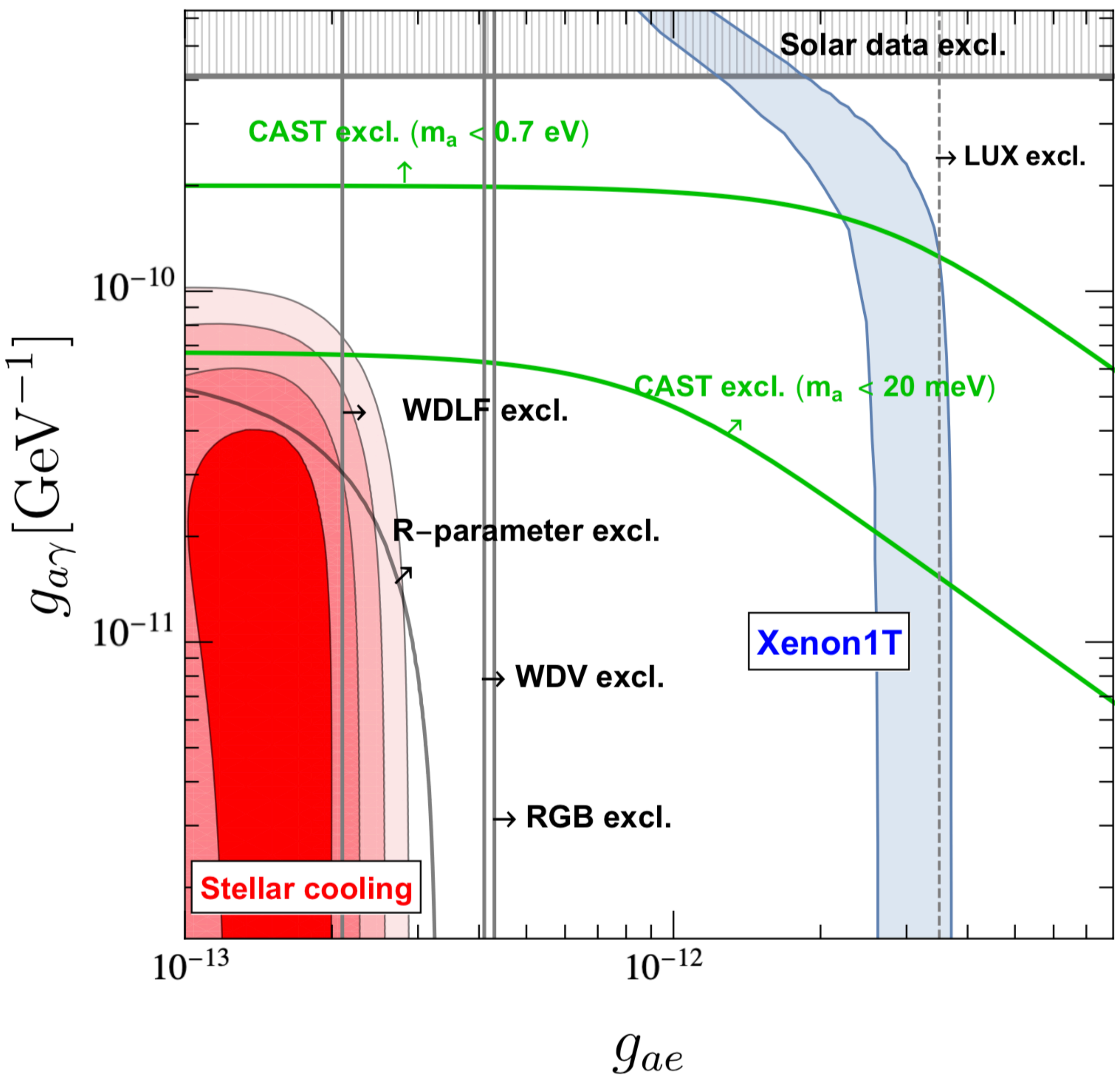
arXiv:1205.6180, arXiv:1211.3389, arXiv:1605.06458, arXiv:1605.07668

$$\dot{\Pi}^{\rm theo}_{\rm WD_i} = a_i + b_i \; g^2_{e13}$$

$$g^{\rm WDLF}_{e13} \leq 2.8$$

arXiv:1406.7712

XENON1T vs. Astrophysics



- Updated CAST exclusion limits, folded with the effect of g_{ae} increasing the solar axion flux (improvement of ~1.5)

  arXiv:1705.02290

- Updated solar data excl. limits, including flux of ^8B, ^7Be neutrinos and heliseismology observation (improvement of ~2)

  arXiv:1501.01639

Theoretically, XENON1T region is well parametrised by the relation

$$g_{e12}^2(g_{e12}^2 + 2g_{\gamma 10}^2) = \bar{g}_{e12}^4$$

with $\bar{g}_{e12} \in [2.82, 3.48]$ at 1σ

What does this imply for the astro obs.?

XENON1T vs. Astrophysics

Observable	Exp. value	Prediction	Tension
R-parameter	1.39 ± 0.03	≤ 0.83	$19\sigma^\star$
$g_{e13}^{\rm WDLF}$	≤ 2.8 (3σ)	29.7 ± 4.8	5.6σ
$M_{I,\rm TRGB}^{\rm M5}$ [mag]	-4.17 ± 0.13	≤ -4.87	$5\sigma^\star$
$\dot{\Pi}_{\rm L19-2}^{(113)}$	3.0 ± 0.6	57 ± 16	3.4σ
$\dot{\Pi}_{\rm L19-2}^{(192)}$	3.0 ± 0.6	95 ± 27	3.4σ
$\dot{\Pi}_{\rm PG1351+489}$	200 ± 90	19620 ± 5730	3.4σ
$\dot{\Pi}_{\rm G117-B15A}$	4.2 ± 0.7	113 ± 33	3.3σ
$\dot{\Pi}_{\rm R548}$	3.3 ± 1.1	87 ± 25	3.3σ

* = Predictions for RGB tip and R-parameter given as an upper bound, assuming the limit value $g_{e13} = 9$.

Smooth extrapolation to $g_{e13} \sim 15$ (still < g_{e13}(XE1T)) would give R~0 (46 σ tension)

Addendum: Inverse Primakoff effect

It has recently been pointed out that the Inverse Primakoff effect might help reducing the tension between the solar axion interpretation and Astro. obs. (see next talk by Wei Xue on 2006.14598, or 2006.15118)

The inclusion of this effect is currently under investigation by the XENON1T collaboration (XENON1T, private communication)

However, while the observed range for g_{ae} would allow also for lower values capable to remove the tension with WD and RGB, the allowed range for $g_{a\gamma}$ would still imply a conservative tension for the R-parameter at ~8σ, hence still ruling out the interpretation of QCD solar axions without any additional help

Conclusions

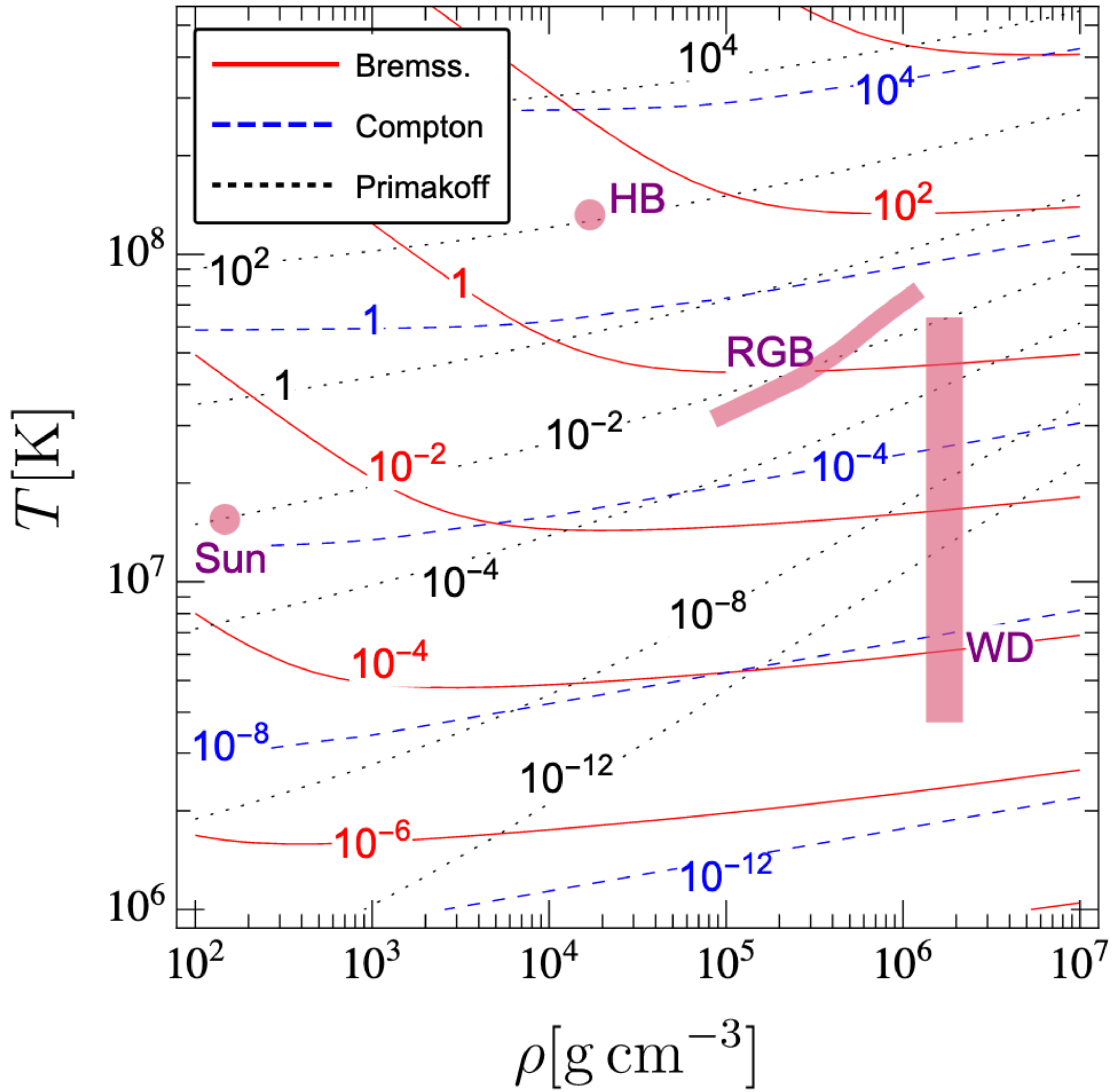
- XENON1T reported an intriguing excess, with the tritium background hypothesis easily testable in the first few months of the XENONnT program

- Interpreting the signal as an effect from solar axions is at stakes with data coming from astrophysics, with tensions going up to ~19σ

- Similar NP explanations based on solar production of light particles (hidden photons/bosons) or on modifications of neutrino properties (such as a neutrino magnetic moment) are also prone to severe astrophysical constraints, and are similarly excluded

Backup

Axions production in the stars



arXiv:2003.01100