A Closer Look at the pp-chain reaction in the Sun

Anna M. Suliga

JCAP 07 (2021) 042

with S. Shalgar and G. M. Fuller

N3AS-PFC Fellow
University of California, Berkeley
University of Wisconsin-Madison

AstroDark 2021, IMPU, Tokyo, Dec. 6/7

Network for Neutrinos, Nuclear Astrophysics, and Symmetries
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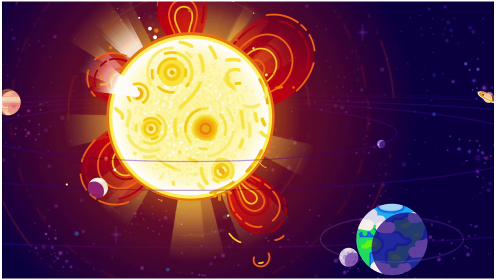
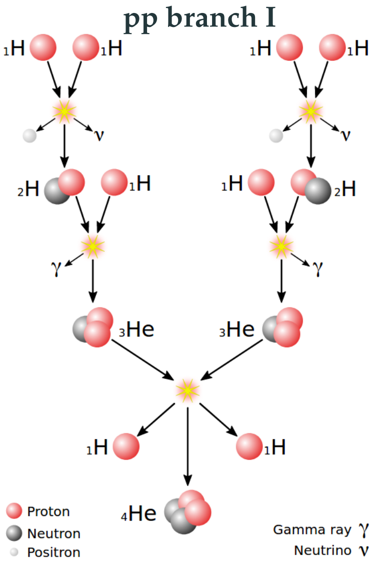
Why our sun is an interesting place to look at?



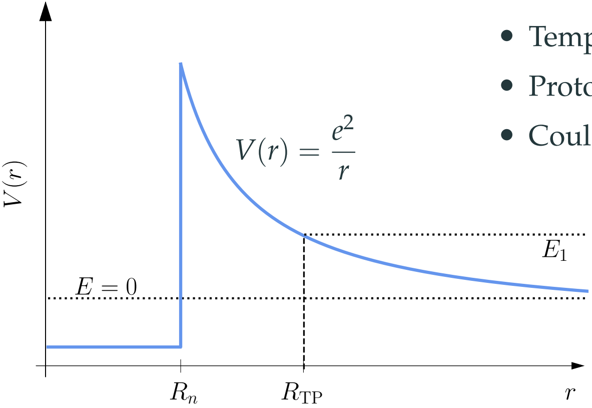
The Sun

- Closest star
- Well studied and well measured
- Better measurements will come
- *pp*-chain - primary channel (99.7%)



Pictures: Kurzgesagt, Wikipedia

Quantum tunneling through Coulomb barrier



- Temperature $\approx 1.56 \times 10^7$ K
- Proton energy $E \approx 10$ keV
- Coulomb barrier $E_c \approx 1$ MeV

Coulomb barrier penetration factor

$$P_{0,\mathrm{SM}} \approx \frac{E_c}{E} \exp\left[-\frac{2\pi e^2}{\hbar v}\right] \approx \frac{E_c}{E} \exp\left[-\frac{b}{\sqrt{E}}\right] = \frac{E_c}{E} \exp\left[-W_{0,\mathrm{SM}}\right]$$

Gamow (1928), Condon & Gurney (1929), Clayton (1968)

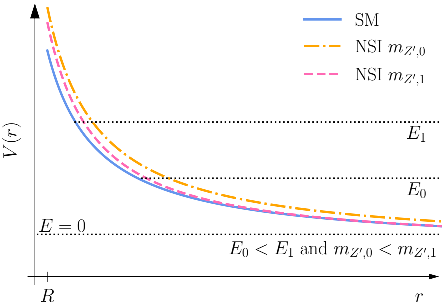
Non-standard mediators coupling to protons

vector boson (Z')

$$\mathcal{L}^{Z'} = g Z'_\mu \bar{\mathrm{p}} \gamma^\mu \mathrm{p}$$

scalar (ϕ)

$$\mathcal{L}^{\phi} = g \phi \bar{\mathrm{p}} \mathrm{p}$$



Interaction potential

$$V(r) = \frac{e^2}{r} \pm \frac{g^2}{r} \exp\left[-m_{\{Z',\phi\}} r\right]$$

Coulomb barrier penetration factor

$$P_{0,\mathrm{SM}} \approx \frac{E_c}{E} \exp\left[-\frac{2\pi e^2}{\hbar v}\right] \approx \frac{E_c}{E} \exp\left[-W_{0,\mathrm{SM}}\right]$$

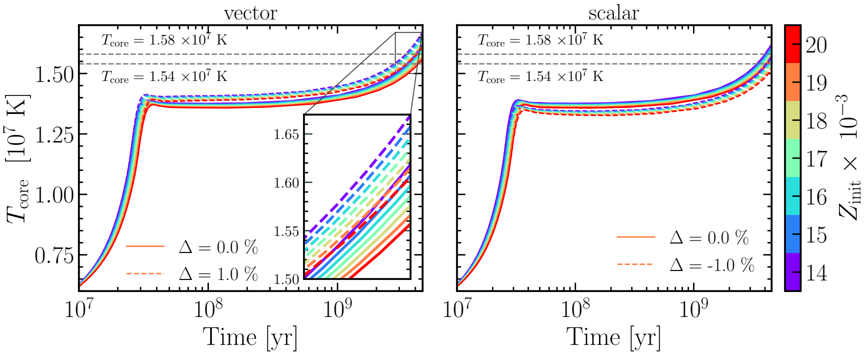
$$\Delta \approx \frac{\left| W_{0,\mathrm{NSI}}^{\frac{2}{3}} - W_{0,\mathrm{SM}}^{\frac{2}{3}} \right|}{W_{0,\mathrm{SM}}^{\frac{2}{3}}}$$

pp interaction rate

$$\Gamma_{pp} \propto \exp\left(-3.381(1 \pm \Delta) \ \left(\frac{T}{10^9\ \mathrm{K}}\right)^{\frac{1}{3}}\right)$$

D. D. Clayton (1968)

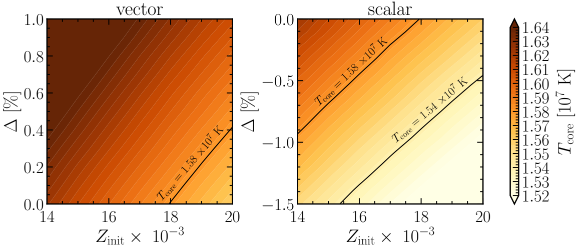
Temporal evolution of the solar core's temperature



- Modules for Experiments in Stellar Astrophysics *MESA*
- The evolution has been followed until the current solar age
- Changes in the barrier and metallicity due to NSI affect the outcome

Changes in the solar parameters

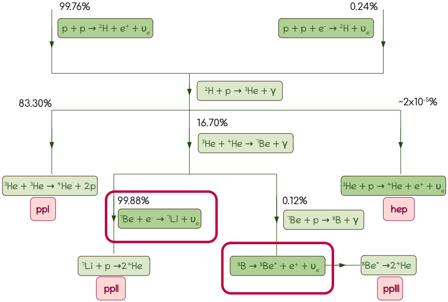
Sun's core temperature

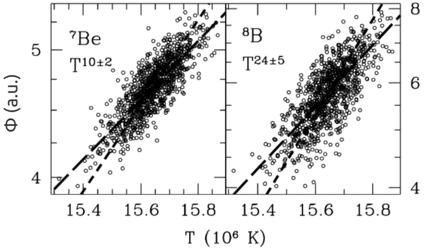


- vector boson mediator

  temperature increase
- scalar mediator

  temperature decrease

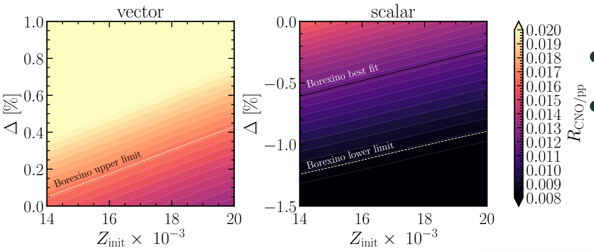




J. N. Bahcall, A. Ulmer (1996)

Changes in the solar parameters

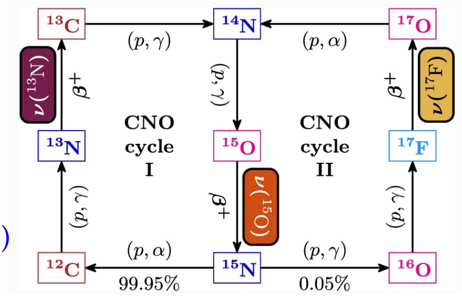
CNO to *pp* ratio, $R_{CNO/pp}$



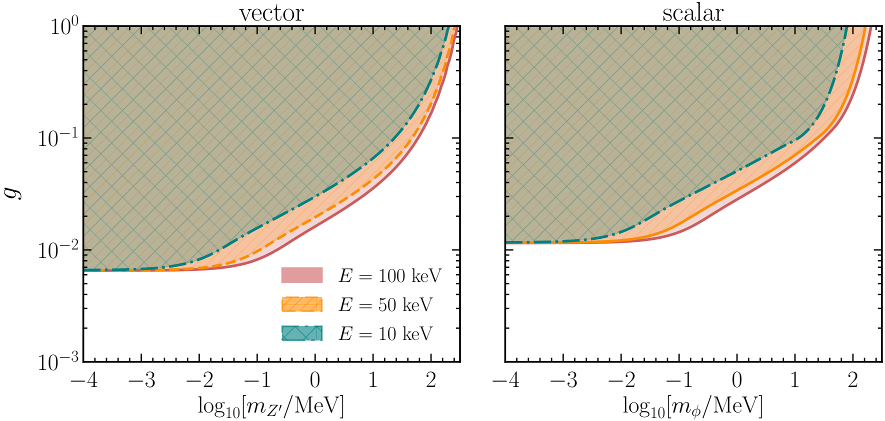
- $R_{CNO/pp}$ – the same trends
- degeneracy between initial metallicity and NSI

CNO cycle

- sub-percent contribiution to the solar energy generation
- neutrinos recently observed by the Borexino collaboration (2020)



Sensitivity bounds on the non-standard mediators



- low mediator mass → limits are insensitive to the mediator mass
- higher proton energies → the excluded region grows
- conservative bounds → there is room for improvement

Sensitivity of the results

Bottelnecks:

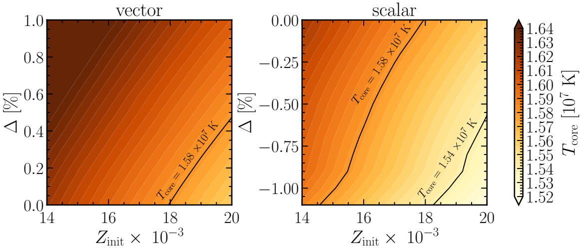
- pp-chain: $\mathrm{p} + \mathrm{p} \rightarrow \mathrm{D} + \nu_e + e^+$
  easy to calculate, not measured
- CNO cycle: $\mathrm{p} + {}^{14}\mathrm{N} \rightarrow {}^{15}\mathrm{O} + \gamma$
  not calculated exactly yet, possible to measure

Question marks in the extrapolated cross section

- measurements at higher energies than in the solar interior
- extrapolation procedures
- plagued by high uncertainty $\mathcal{O}(10)\%$

Changes in the solar parameters

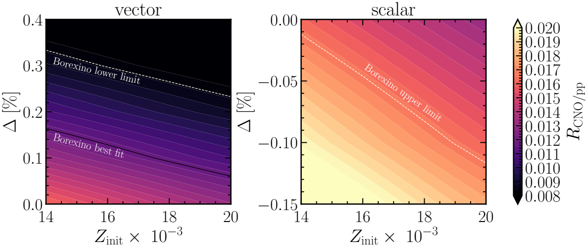
Sun's core temperature



- vector boson mediator
  temperature increase
- scalar mediator
  temperature decrease

CNO to *pp* ratio, $R_{CNO/pp}$

- $R_{CNO/pp}$ – flipped trends
- more robust changes in CNO bottelneck reaction



Conclusions: non-standard mediators coupling to protons

Non-standard mediators

- affect the Coulomb potential felt by the charged particles
- change the temperature of the core of the Sun
- can be constrained with the solar neutrino fluxes
- can affect nuclear reactions in less/more massive objects

The perspective sensitivity bounds for protons

- most constraining for mediators with masses above 50 keV
- will improve with better measurements of the metallicity and CNO neutrinos

Our work calls for improved measurements of the solar reactions involving Coulomb barriers