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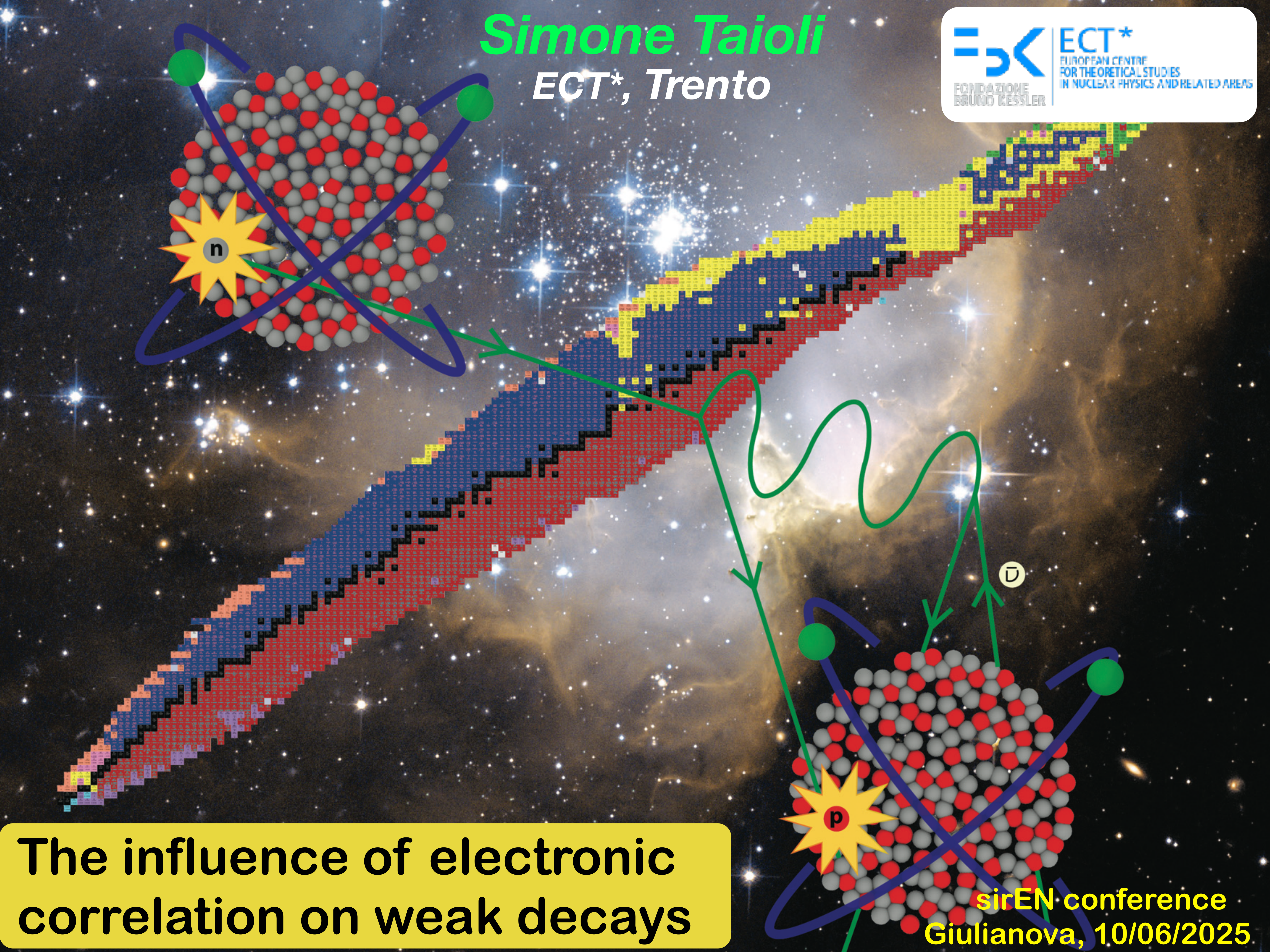

The influence of electronic correlation on weak decays

sirEN conference
Giulianova, 10/06/2025

I am deep in debt to ....

S. Simonucci
(Unicam)

S. Palmerini
(UniPG)

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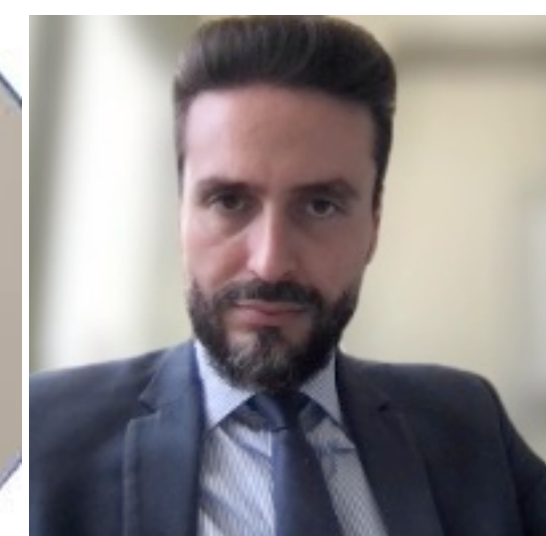


Outline

- **Introduction to our (relativistic) approach to weak decays in astrophysical scenarios**

- **β-decay and EC are not only nuclear but also atomic processes (electron correlation)**

- **Application of our approach to a number of β-decay processes of light (^{7}Be) and heavy (^{134}Cs and ^{135}Cs) atoms**

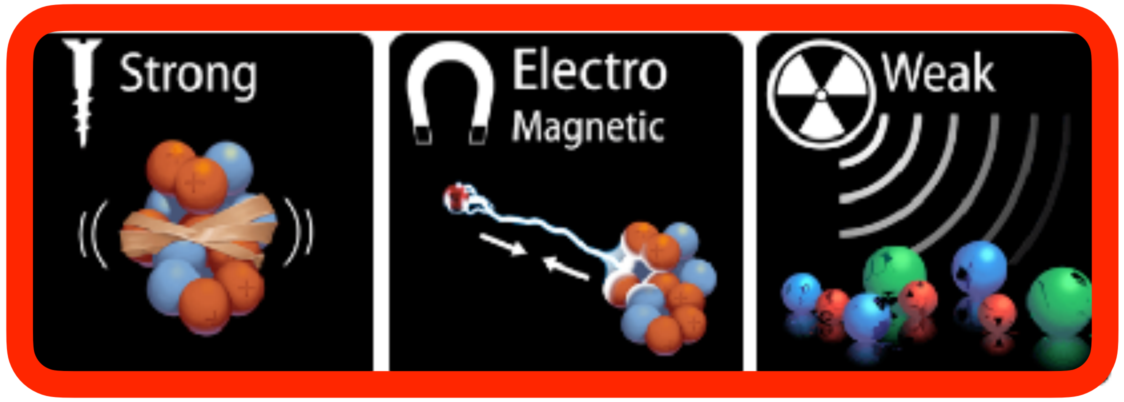
- **Perspectives, future developments**

β-decay: a multiscale scenario

10^{-2} (t=10^{-15} s, 10^{-10} m)

1

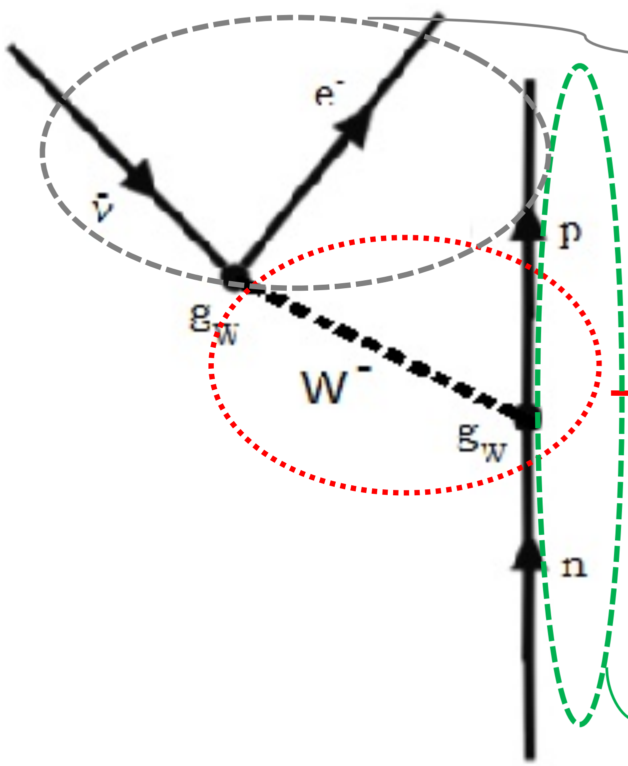
(W t=10^{-24} s, 10^{-15} m)



Coupl. const.=10^{-7}

(t>10^{-8} s, 10^{-18} m)

- **Standard model of particles: weak interaction is mediated by the emission or absorption of massive bosons**

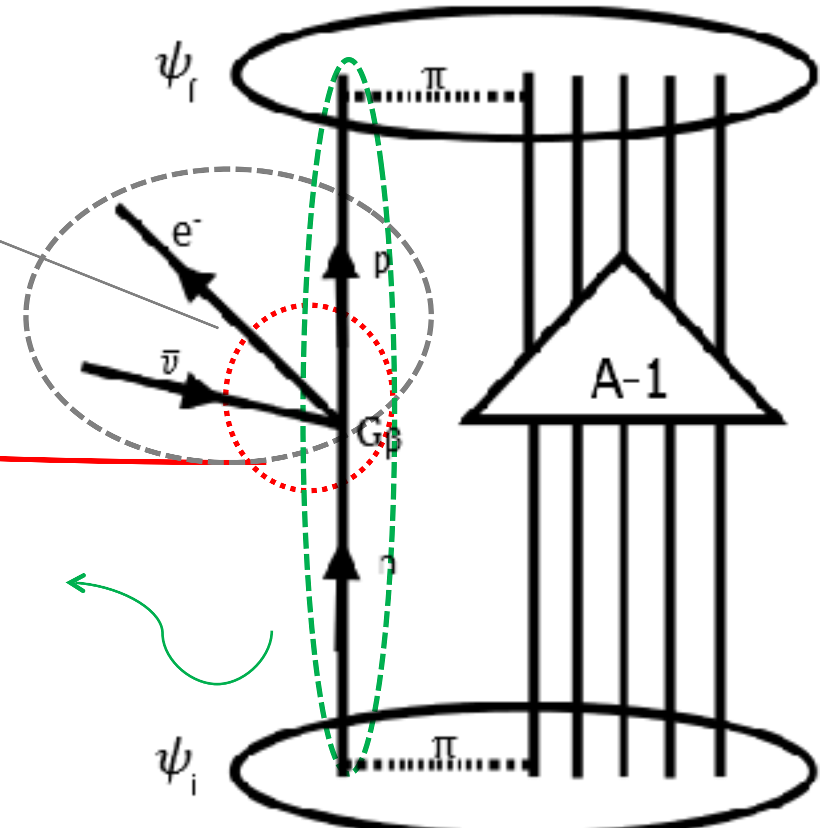


Weak leptonic

$$\frac{G_\beta}{\sqrt{2}} = \frac{g_W^2}{8M_W^2}$$

10^{-18}

Weak hadronic



W^- boson has a mass of $\sim 80\ \frac{GeV}{c^2}$

⟶ *Uncertainty principle*: W^- can only live $\Delta t \leq \frac{\hbar}{M_W c^2}$

⟶ During this time it can travel at most $c\Delta t \leq \frac{\hbar}{M_W \cdot c} \sim 10^{-3}\, fm \ll 1\, fm$

Short range = Fermi contact interaction

To accurately model weak decays you need to account for all these multiscale electronic-nuclear factors.

The enrichment of Li in the Universe is still unexplained

Li is one of the primordial elements produced in Big Bang nucleosynthesis: very fragile

Galactic Cosmic Rays do not produce much ^{7}Li

BBN predicts a ^{7}Li abundance > 3 than observed in metal-poor objects and in low metallicity MS stars

Stellar nucleo-synthesis

Contrary to these expectations, observations of the Sun and solar-like stars reveal that they undergo extensive Li-depleting processes (Li-dip) during central hydrogen burning as well as in late stages (RGB and AGB)

In interstellar medium Li content is higher than that expected by BBN

For low mass star (below 2 - 3 M$_{\odot}$) Li is predicted to be destroyed in the early phases of evolution, preceding the MS

^{7}Li is produced in Novae and a small amount of ^{7}Li in H-burning intermediate mass stars at the base of their envelope, but is thought to be burned during MS as fast as produced when convective processes carry it to temperatures of a few millions K, where it undergoes p-captures.

The cosmic Li problem before BSM….

Thus, stellar burning may form and deplete Li and its abundance is strongly influenced by several nuclear burning mechanisms as well as by the extension of the convective envelope.

- Production of ^{7}Li via EC (hereinafter "EC") of ^{7}Be

$$^7\mathrm{Be} + e^- \longrightarrow {}^7\mathrm{Li} + \nu_e$$

- production of ^{7}Li via antineutrino capture of ^{7}Be

$$^7\mathrm{Be} + \overline{\nu}_e \longrightarrow {}^7\mathrm{Li} + e^+$$

- production of ^{7}Be via positron capture of ^{7}Li

$$^7\mathrm{Li} + e^+ \longrightarrow {}^7\mathrm{Be} + \overline{\nu}_e$$

- production of ^{7}Be via neutrino capture of ^{7}Li

$$^7\mathrm{Li} + \nu_e \longrightarrow {}^7\mathrm{Be} + e^-$$

These reactions are interesting since previous simulations, which didn’t account for electroweak processes at 10< $K_B T$<100 KeV, gave a too high (or low) ^{7}Li abundance compared to observations

State-of-the-art of ^{7}Be beta-decay in solar-like systems

- Bachall (1962): ~ 20% of ^{7}Be in the center of the Sun might have a bound electron —-> ^{7}Be lifetime in solar conditions for partially ionised atoms using DH screening for the e-e interaction: total-to-continuum capture ratio is 1.217

- Shaviv et al. (2001): ^{7}Be lifetime larger by ~ 20%–30% as compared to Bahcall due to fully ionized ^{7}Be is in the solar plasma

- Quarati et al. (2009): ^{7}Be lifetime shorter by about 10%, using a modified DH screening potential.

Despite the main decay channel in the Sun's interior is the free EC, bound e- can significantly change the decay probability of ^{7}Be

Out-of-solar conditions

Adelberger (2011): data extrapolation from Bahcall's calculations, a procedure rather insecure due to the very different conditions

The situation is unsatisfactory with a lot of scattered data and uncertainties, in particular related to the T and ϱ dependence of the rate.

Motivation of this work: provide the missing weak-interaction input data for Li nucleosynthesis calculations

$$ {}^{7}_{4}\mathrm{Be} + e^{-} \rightarrow {}^{7}_{3}\mathrm{L}i + \nu_e $$

At ambient conditions ^{7}Be decays in 53 days into the ground state of ^{7}Li (3/2-) for 89.7% of cases, 10.3% it decays into the first excited state (1/2-)

Decay may occur by capture of an orbital e^{-} through the following process:

$$ p + e^{-} \rightarrow n + \nu_e $$

change Z to Z-1 of an atom, keeping fixed A

$$ W \propto \delta(\vec{r}) $$

insensitive to extra-nuclear factors, such as chemical environment, ionization degree, pressure and temperature.

The driving force responsible for this decay is the weak interaction

One of the three β-decays mediated by the weak force.

Contrary to this simple view, there is evidence of changes in nuclear decay rates with these parameters

β-decay: standard approach

A typical nuclear β-decay process reads:

$$ {}^{A}_{Z}X_N \rightarrow {}^{A}_{Z+1}X'_{N-1} + e^- + \bar{\nu}_e $$

<u>Q-value</u>: total energy released by the reaction ($m_\nu = 0$)

$$ Q_{\beta^-} = m_N({}^{A}X) - m_N({}^{A}X') \qquad m_N({}^{A}X) = m({}^{A}X) - Zm_e + \sum_i^Z B_i $$

Extra-nuclear factor

$$ Q_{\beta^-} = \{[m({}^{A}X) - Z \cdot m_e] - [m({}^{A}X') - (Z+1) \cdot m_e] - m_e\} \cdot c^2 + \{\sum_{i=1}^{Z} B_i - \sum_{i=1}^{Z+1} B_i\} $$

In the traditional theory of β-decay processes, spectra are typically calculated as product of three factors:

$$ \frac{dN}{dW} \propto pWq^2F(Z,W)C(W) $$

- a phase-space factor to deal with the momentum sharing between the β-electron (p) and neutrino (q);
- a Fermi function F(Z,W) to take into account the static corrections due to the Coulomb field of the nucleus;
- a shape factor C(W) to include the coupling between nuclear and lepton dynamics.

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Extra-nuclear factor

$$ Q_{\beta-} = \{[m(^AX) - Z\cdot m_e] - [m(^AX') - (Z+1)\cdot m_e] - m_e\}\cdot c^2 + \{\sum_{i=1}^{Z} B_i - \sum_{i=1}^{Z+1} B_i\} $$

In the traditional theory of β-decay processes, spectra are typically calculated as product of three factors:

$$ \frac{dN}{dW} \propto pWq^2 F(Z,W) C(W) \qquad F(Z,W) = \frac{2\pi\nu}{1-\exp^{-2\pi\nu}} \qquad \nu = \pm Ze^2/\hbar v $$

- a phase-space factor to deal with the momentum sharing between the β-electron (p) and neutrino (q);
- a Fermi function F(Z,W) to take into account the static corrections due to the Coulomb field of the nucleus;
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β-decay: standard approach

$$\frac{dN}{dW} \propto pWq^2F(Z,W)C(W)$$

It works well to predict the lineshape of allowed transitions (ΔL=0,1 π conserved), at odds forbidden non-unique transitions (ΔL>1 and π can or cannot be conserved) are out of reach of this relation

Still a rigours treatment of these transitions including electronic and nuclear DOF is missing!!!

Our approach to beta-decay aims to solve these issues using first-principles simulations as in condensed matter

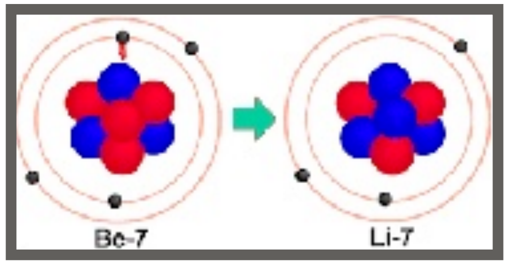
Open issues in Li depletion

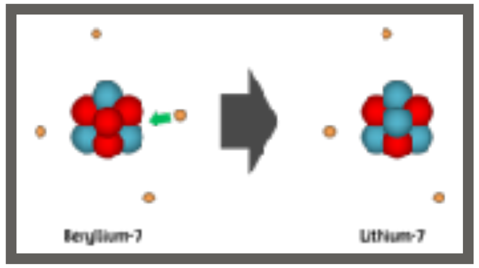
Li could be produced by coupled mixing and nucleosynthesis episodes, in which the depletion of Li by downward diffusion is over-compensated by an upward transport of 7Be from burning regions, at a pace fast enough to survive destruction by p- and e-captures, reaches the stellar envelope and eventually decays there

Poor knowledge of the Be decay rate dependence on the conditions below the envelopes of Red Giants (T=1:80 MK, ϱ =1:5 o.o.m. lower than the Sun), very different from our Sun (T_{core} = 10^7 K a nd ϱ~10^5 kg/m^3)

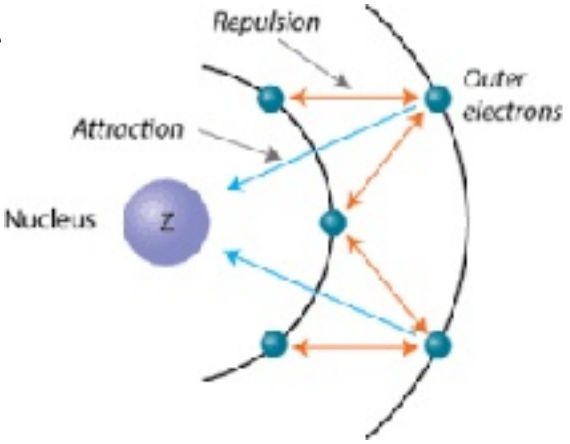
In calculating rates in these conditions you need to take into account conditions in which:

1. ^{7}Be can be partially or totally ionized, decay may occur by capturing an e^- fron both bound (excited) and continuum states;





2. the presence of other charged particles in the stellar plasma that screen the e^- motion;
3. the DH approx to model the e-e interaction may not hold and introduce large deviations in the capture rate



(degenerate Fermi gas ???)

Condition of the stellar material at high T

DEGENERACY CONDITIONS: CLASSICAL vs. QUANTUM

The electronic density must be >> N_Q
N_Q is the number of available quantum states

To have degeneracy $\rho_e >> n_{NQ} = (2\pi m_e kT/h^2)^{3/2}$

$$T << h^2 \rho_e^{2/3}/(2\pi m_e k) = 9.12 \times 10^6 \text{ K}$$

Solar core: T=15.6 X 10^6 K → ^{7}Be atoms are all ionized
(12000 K = 1 eV)!!!

In the solar core the temperature is marginally too high for degeneracy of electrons, classical gas, but decreasing R can set in...

$T \propto 1/R$ **and thus** $n_{QNR} \propto T^{(3/2)} \propto R^{-3/2}$**, which cannot keep the pace with** $\rho_e \propto R^{-3}$ **Cold? Fermi gas can be degenerate even at millions of K.**

THE DH model of e-e interaction is questionable

Inside a star I have a plasma of Be nuclei, protons, electrons in mutual interaction this means to solve the coupled el-nuc many-body

Nonrelativistic Schrödinger equation

$$\boxed{\hat{H}(\{\mathbf{r}\},\{\mathbf{R}\})\Psi_j(\{\mathbf{r}\},\{\mathbf{R}\}) = E_j\Psi_j(\{\mathbf{r}\},\{\mathbf{R}\})}$$

$$\hat{H}(\{\mathbf{r}\},\{\mathbf{R}\}) = \sum_{j=1}^{N_e}\left(-\frac{\nabla_j^2}{2} + V_e(\mathbf{r}_j)\right) + \frac{1}{2}\sum_{j\neq k}^{N_e}\frac{1}{|\mathbf{r}_j - \mathbf{r}_k|}$$ electronic Hamiltonian

$$+\sum_{j=1}^{N_n}\left(-\frac{\nabla_j^2}{2M_j} + V_{n,j}(\mathbf{R}_j)\right) + \frac{1}{2}\sum_{j\neq k}^{N_e}\frac{Z_j Z_k}{|\mathbf{R}_j - \mathbf{R}_k|}$$ nuclear Hamiltonian

$$-\sum_{j=1}^{N_e}\sum_{k=1}^{N_n}\frac{Z_k}{|\mathbf{r}_j - \mathbf{R}_k|}$$ electron-nuclear attraction

$V_e(\mathbf{r}), V_n(\mathbf{R})$: external scalar potentials acting on the electrons/nuclei.

This is a very tricky computational problem

Electronic Structure and BO approximation: panettone/plasma

Sponge keeps together panettone. Only sponge no taste...

The source of the interesting properties in stellar plasma is the rearrangement of electrons due to the arrangement of the nuclei

Sultana change the taste, but we assume that the taste does not depend much on their distribution (basically we still have a panettone).

$$M_N/m_e \geq 10^4$$

Electronic transitions ~10^{17} Hz

Ionic vibration ~ 10^{12} Hz .

$$\chi = \tau_p/\tau_e = 10^5$$

Timescales are not comparable: electronic and nuclear motion can be decoupled.

Nonrelativistic Schrödinger equation

$$\boxed{\hat{H}(\{\mathbf{r}\},\{\mathbf{R}\})\Psi_j(\{\mathbf{r}\},\{\mathbf{R}\}) = E_j \Psi_j(\{\mathbf{r}\},\{\mathbf{R}\})}$$

$$\left.\hat{H}(\{\mathbf{r}\},\{\mathbf{R}\}) = \sum_{j=1}^{N_e}\left(-\frac{\nabla_j^2}{2} + \cancel{V_e(\mathbf{r}_j)}\right) + \frac{1}{2}\sum_{j\neq k}^{N_e}\frac{1}{|\mathbf{r}_j - \mathbf{r}_k|}\right\}\text{electronic Hamiltonian}$$

$$\left.+\sum_{j=1}^{N_n}\left(\cancel{-\frac{\nabla_j^2}{2M_j}} + \cancel{V_{n_j}(\mathbf{R}_j)}\right) + \frac{1}{2}\sum_{j\neq k}^{N_e}\frac{Z_j Z_k}{|\mathbf{R}_j - \mathbf{R}_k|}\right\}\text{nuclear Hamiltonian}$$

$$\left.-\sum_{j=1}^{N_e}\sum_{k=1}^{N_n}\frac{Z_k}{|\mathbf{r}_j - \mathbf{R}_k|}\right\}\text{electron-nuclear attraction}$$

$V_e(\mathbf{r}), V_n(\mathbf{R})$: external scalar potentials acting on the electrons/nuclei.

Born-Oppenheimer approximation

- Decouple the electronic and nuclear dynamics. This is a good approximation since nuclei are much heavier than electrons.
- Treat the nuclei as classical particles at fixed positions.
- Write down electronic Hamiltonian for a given nuclear configuration (here we ignore any external fields):

$$\hat{H}_{BO}(\{\mathbf{r}\},\{\mathbf{R}\}) = -\sum_{j=1}^{N_e}\frac{\nabla_j^2}{2} + \frac{1}{2}\sum_{j\neq k}^{N_e}\frac{1}{|\mathbf{r}_j-\mathbf{r}_k|} + \underbrace{\frac{1}{2}\sum_{j\neq k}^{N_e}\frac{Z_j Z_k}{|\mathbf{R}_j-\mathbf{R}_k|}}_{\text{This is just a constant}}$$
$$-\sum_{j=1}^{N_e}\sum_{k=1}^{N_n}\frac{Z_k}{|\mathbf{r}_j-\mathbf{R}_k|}$$

The problem of doing realistic simulations of stellar plasma breaks into two questions: **first, how do you find the electronic states of the system of electrons when the Be nuclei are sitting in certain positions and second, how should the nuclei move?**

The electronic many-body problem

$\Psi(x_1, x_2, ..., x_N)$ $\qquad x_j = (\mathbf{r}_j, \sigma_j)$ space and spin coordinate

antisymmetric N-electron wave function

$$\boxed{\hat{H}\Psi_j(x_1, ..., x_N) = E_j \Psi_j(x_1, ..., x_N)}$$

$$\hat{H} = -\sum_{j=1}^{N} \frac{\nabla_j^2}{2} + \sum_{j=1}^{N} V(\mathbf{r}_j) + \frac{1}{2}\sum_{j \neq k}^{N} \frac{1}{|\mathbf{r}_j - \mathbf{r}_k|} \quad \equiv \quad \hat{T} + \hat{V} + \hat{W}$$

Even a two-electron problem (Helium) is very difficult:

$$\left\{-\frac{\nabla_1^2}{2} - \frac{\nabla_2^2}{2} - \frac{1}{r_1} - \frac{1}{r_2} + \frac{1}{|\mathbf{r}_1 - \mathbf{r}_2|}\right\}\Psi_j(\mathbf{r}_1, \mathbf{r}_2) = E_j \Psi_j(\mathbf{r}_1, \mathbf{r}_2)$$

This is a 6-dimensional partial differential equation!

Correlation within BO approximation

A first simple case: one electron hydrogen atom

The allowed energies are given by:

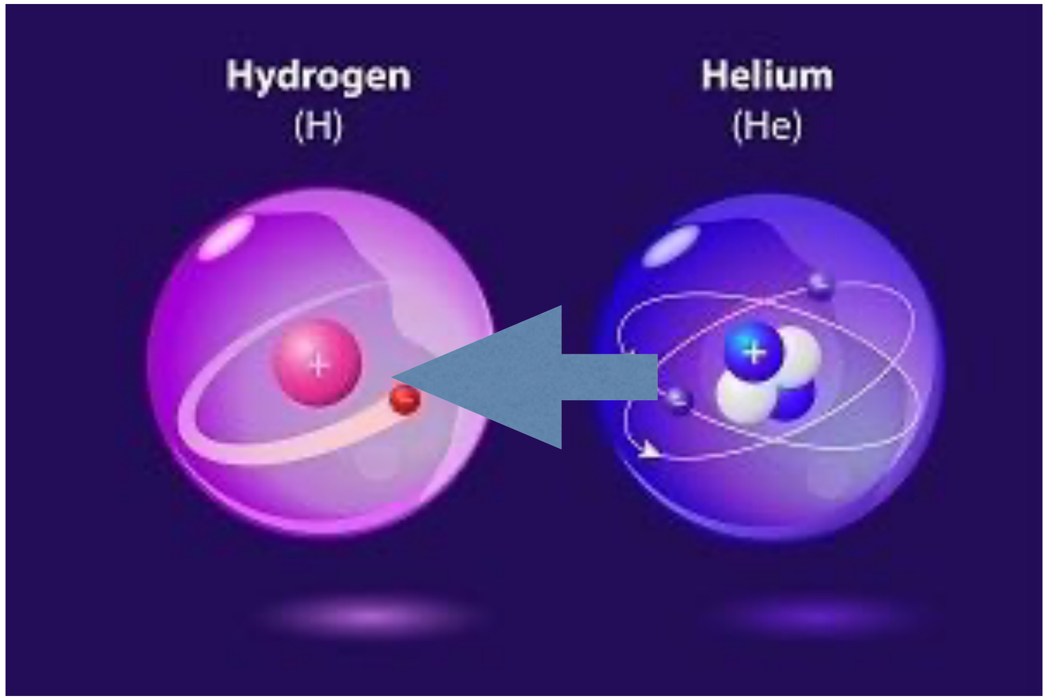
$$H_T|\Psi_n(r)\rangle = E_n|\Psi_n(r)\rangle$$

where

$$H_T = \frac{\hbar^2}{2m}\nabla^2 + V(r),\ V(r) = -e^2/(4\pi\epsilon r)$$

More than one electron (like bound and continuum electrons in a plasma with Be): attraction with the nuclei and repulsion with other e⁻

(1 $\AA$ = 14 eV)



Two one-body problem

$$|\Psi(r_1, r_2)\rangle = \psi_a(r_1)\psi_b(r_2)$$
$$E_{tot} = E_1 + E_2$$

One two-body problem

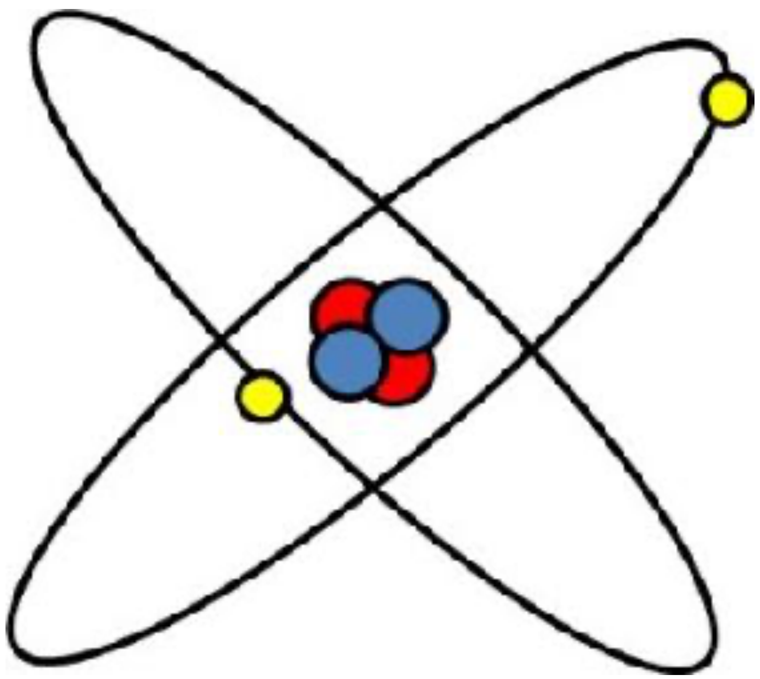
$$|\Psi(r_1, r_2)\rangle \neq \psi_a(r_1)\psi_b(r_2)$$
$$E_{tot} \neq E_1 + E_2$$

Repulsion destroys the independent particles model

Hartree-Fock within BO approximation

Hartree theory: include static repulsion, but ignore correlation

Electrons are independent and feel an average potential $V_m(r)$



Many-body problem has been replaced by many one-body problems with electrons moving in $V_m(r)$

Hartree-Fock: electrons are unsociable

$$\Psi(r) = \psi_{a\uparrow}(r_1)\psi_{b\uparrow}(r_2) - \psi_{b\uparrow}(r_2)\psi_{a\uparrow}(r_1)$$

There are two mechanisms to avoid each other: exchange and correlation and both lower the total energy and dress the electron-electron bare interaction.

Correlation is the remaining repulsion energy:

keeps electrons apart!!!

How do we actually calculate e-capture rates?

We can define the T-matrix of the weak interaction as:

$$\left\langle \psi^-_{f,\boldsymbol{k}} | W | \phi^+_{i,\boldsymbol{p}} \right\rangle = \left\langle \phi^-_{f,\boldsymbol{k}} | \mathrm{T}_W | \phi^+_{i,\boldsymbol{p}} \right\rangle$$

By multiplying the c.s. by the e$^-$ current one obtains the e-capture rate:

$$\Gamma_{i\to f} = \int 2\pi \frac{d^3k}{(2\pi)^3} \left| \left\langle \phi^-_{f,\boldsymbol{k}} | T_w | \phi^+_{i,\boldsymbol{p}} \right\rangle \right|^2 \delta\left(\frac{p^2}{2m_e} + E_i - E_f - ck \right) = \frac{\bar{k}^2}{\pi c} \left| t_{f,i} \langle i,0 | \phi^+_{i,\boldsymbol{p}}(0) \rangle \right|^2$$

$$= \frac{1}{\pi c^3} \left| t_{f,i} \right|^2 \langle i,0 | \phi^+_{i,\boldsymbol{p}} \rangle \left(\frac{p^2}{2m_e} + E_i - E_f \right)^2 \langle \phi^+_{i,\boldsymbol{p}} | i,0 \rangle$$

$|i,0><i,0|$

$T_W \propto \delta(\boldsymbol{r})$

$H_0 + V$

where $\bar{k} = \frac{1}{c}\left(\frac{p^2}{2m_e} + E_i - E_f \right)$ **and** $\langle \phi^+_{i,\boldsymbol{p}} | i,0 \rangle$ **is the electronic w.f. at the Be nucleus.**

Approximations made

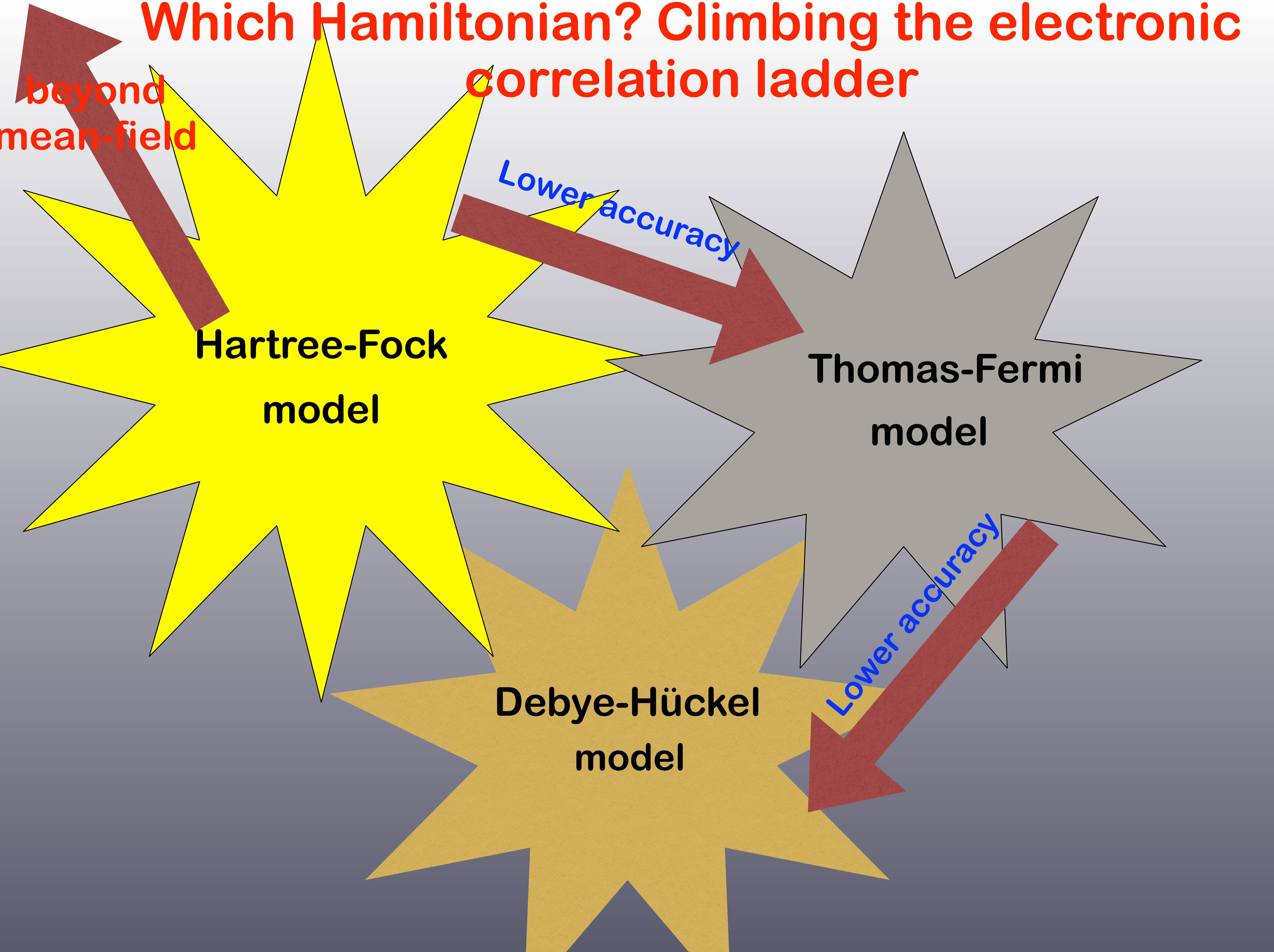
1. 1st Be e.s. is found at 429.4 keV=5X10^9 K above the ground state
2. $T_W \propto \delta(\boldsymbol{r})$ = very short range contact interaction
3. $t_{f,i}$ are chosen equal to those measured on the Earth, neglect dependence on T and $p^2/2m_e$

IMPORTANT OUTCOME!

^{7}Be-e$^-$ can be modelled as a two-body scattering process at a given relative electron momentum p.

The rate is proportional to $\rho_e(0)$.

Which Hamiltonian? Climbing the electronic correlation ladder



Some data…

Energy of the Isolated Beryllium Atom in Atomic Units and Spin-up Density at the Nucleus Obtained Through the HF and CI Calculations

	Energy	$\rho_{e\uparrow}(0)$
Hartree–Fock	−14.573	17.68521
Full-CI	−14.660	17.68060

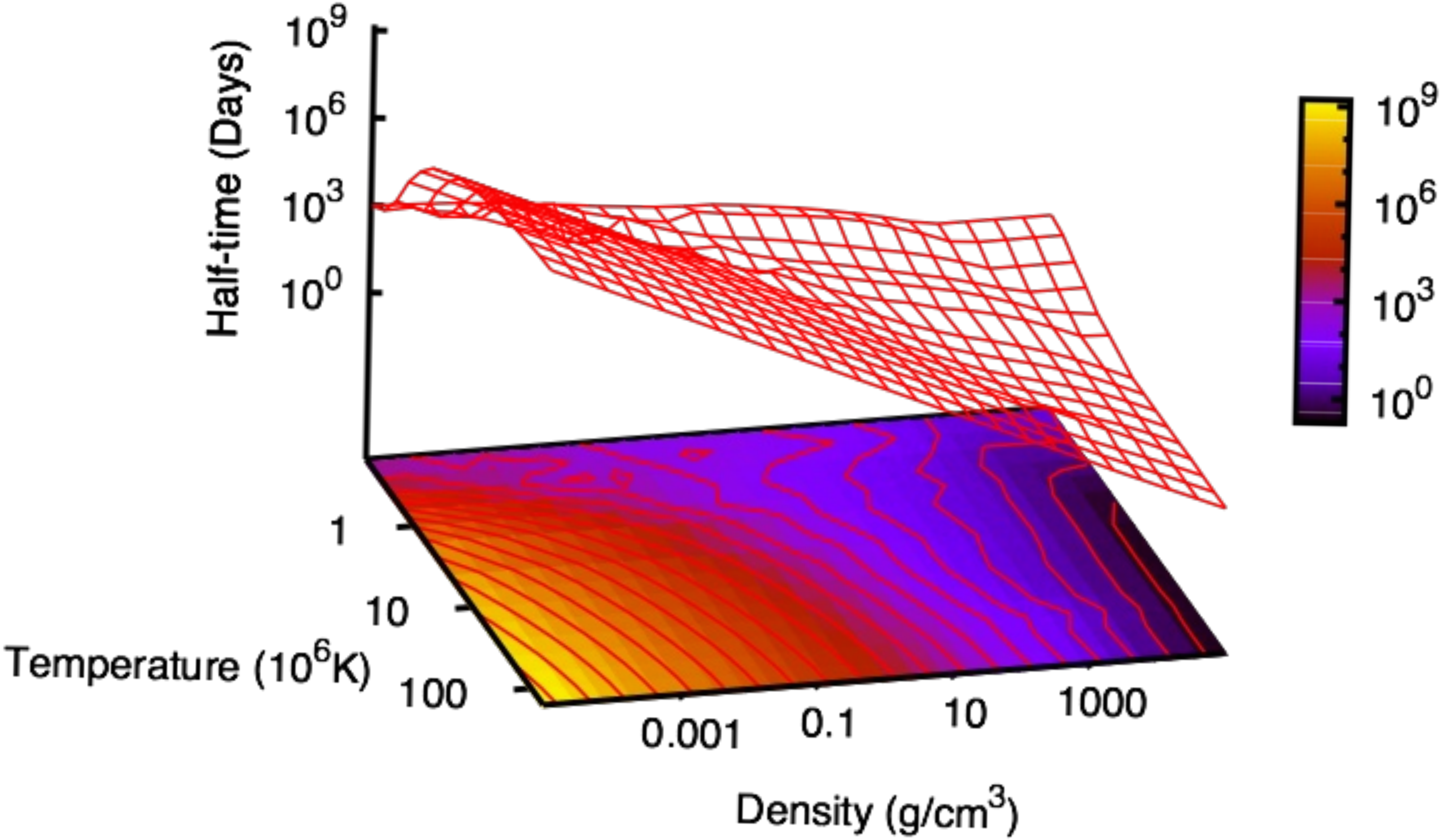
Degenerate condition

Solar condition

ρ (g cm^{-3})	T (10^6 K)	λ_{Debye} $a.u.$	$\lambda_{\mathrm{De\,Broglie}}$ $(e-p)$	$\rho_{\mathrm{HF}}(0)$ $a.u.$	$\rho_{\mathrm{TF}}(0)$	$\rho_B(0)$	$\rho_{\mathrm{DH}}(0)$
1000.	1.	0.038	1.409–0.0329	71.87 ÷ 71.97	68.99 ÷ 69.11	42.61 ÷ 42.74	47.46 ÷ 47.55
100.		0.119		33.52 ÷ 33.53	29.53 ÷ 29.55	4.027 ÷ 4.031	19.13 ÷ 19.14
10.		0.377		17.37 ÷ 17.37	13.83 ÷ 13.83	0.945 ÷ 0.945	13.33 ÷ 13.33
1.		1.193		7.839 ÷ 7.837	5.708 ÷ 5.707	0.184 ÷ 0.184	8.151 ÷ 8.149
0.1		3.771		1.940 ÷ 1.940	1.415 ÷ 1.415	0.044 ÷ 0.044	2.059 ÷ 2.058
0.01		11.93		0.278 ÷ 0.278	0.220 ÷ 0.220	0.0075 ÷ 0.0075	0.279 ÷ 0.279
0.001		37.71		0.0308 ÷ 0.0308	0.0264 ÷ 0.0264	0.0012 ÷ 0.0012	0.0303 ÷ 0.0303
1000.	10.	0.119	0.445–0.0103	122.43 ÷ 122.89	116.21 ÷ 116.68	51.77 ÷ 52.05	108.56 ÷ 109.01
100.		0.377		20.23 ÷ 20.27	19.53 ÷ 19.57	10.36 ÷ 10.39	19.54 ÷ 19.58
10.		1.193		2.578 ÷ 2.581	2.554 ÷ 2.558	2.515 ÷ 2.519	2.570 ÷ 2.573
1.		3.771		0.274 ÷ 0.275	0.274 ÷ 0.275	0.274 ÷ 0.274	0.274 ÷ 0.275
0.1		11.93		0.0281 ÷ 0.0282	0.0281 ÷ 0.0282	0.0281 ÷ 0.0282	0.0281 ÷ 0.0281
0.01		37.71		$(2.84 \div 2.84) \times 10^{-3}$	$(2.84 \div 2.84) \times 10^{-3}$	$(2.84 \div 2.84) \times 10^{-3}$	$(2.83 \div 2.83) \times 10^{-3}$
0.001		119.3		$(2.84 \div 2.84) \times 10^{-4}$	$(2.84 \div 2.84) \times 10^{-4}$	$(2.84 \div 2.84) \times 10^{-4}$	$(2.84 \div 2.84) \times 10^{-4}$
1000.	100.	0.377	0.141–0.0033	78.31 ÷ 80.39	78.24 ÷ 80.32	76.57 ÷ 78.64	78.22 ÷ 80.30
100.		1.193		9.051 ÷ 9.289	9.051 ÷ 9.288	9.031 ÷ 9.268	9.051 ÷ 9.288
10.		3.771		0.773 ÷ 0.787	0.773 ÷ 0.787	0.773 ÷ 0.787	0.773 ÷ 0.787
1.		11.93		0.0775 ÷ 0.0789	0.0775 ÷ 0.0789	0.0775 ÷ 0.0789	0.0775 ÷ 0.0789
0.1		37.71		$(7.75 \div 7.90) \times 10^{-3}$	$(7.75 \div 7.90) \times 10^{-3}$	$(7.75 \div 7.90) \times 10^{-3}$	$(7.75 \div 7.90) \times 10^{-3}$
0.01		119.3		$(7.75 \div 7.90) \times 10^{-4}$	$(7.75 \div 7.90) \times 10^{-4}$	$(7.75 \div 7.90) \times 10^{-4}$	$(7.75 \div 7.90) \times 10^{-4}$
0.001		377.1		$(7.75 \div 7.90) \times 10^{-5}$	$(7.75 \div 7.90) \times 10^{-5}$	$(7.75 \div 7.90) \times 10^{-5}$	$(7.75 \div 7.90) \times 10^{-5}$

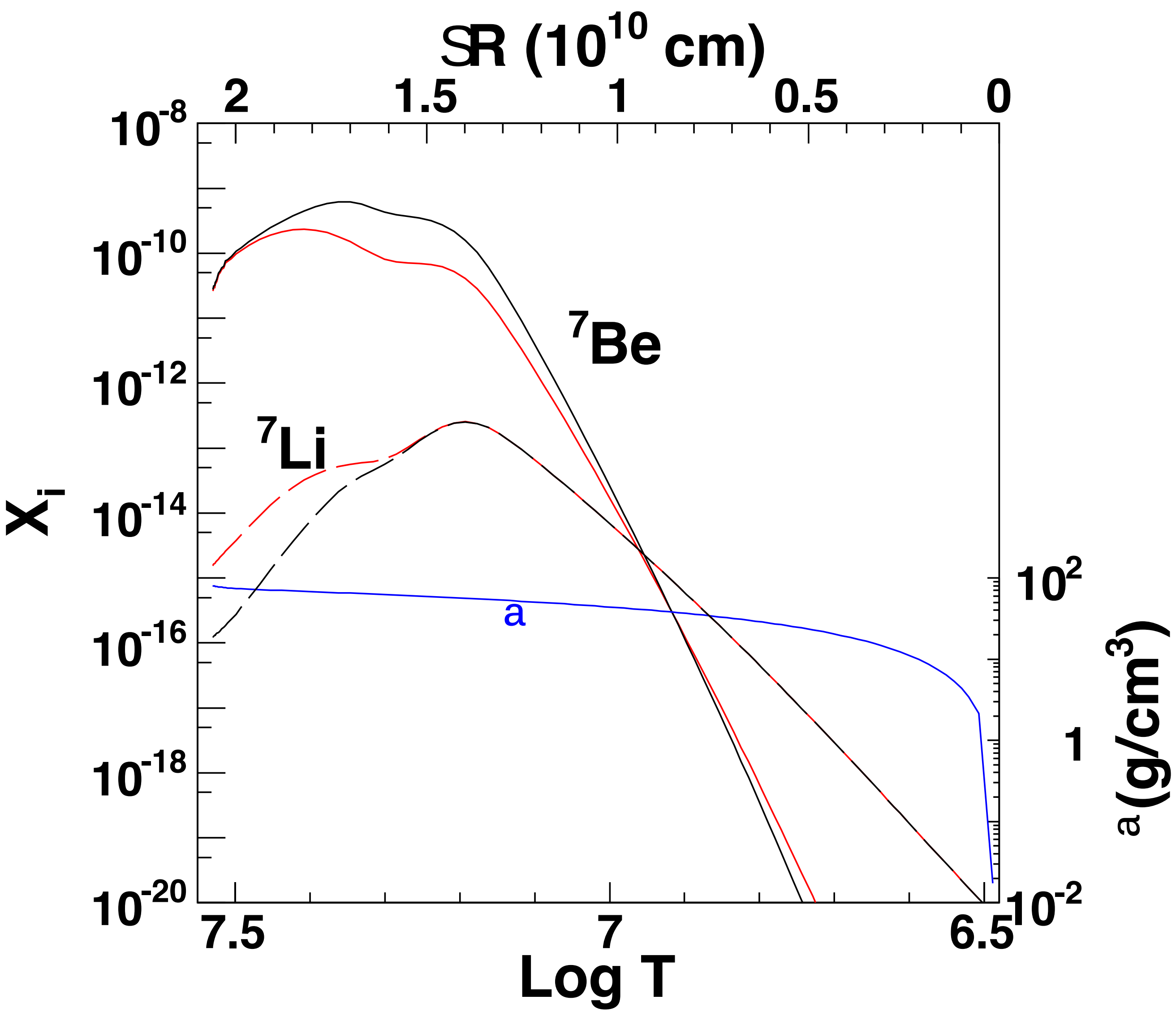
^{7}Be half-life

half-life (days)= 941.86881/ϱ(0)

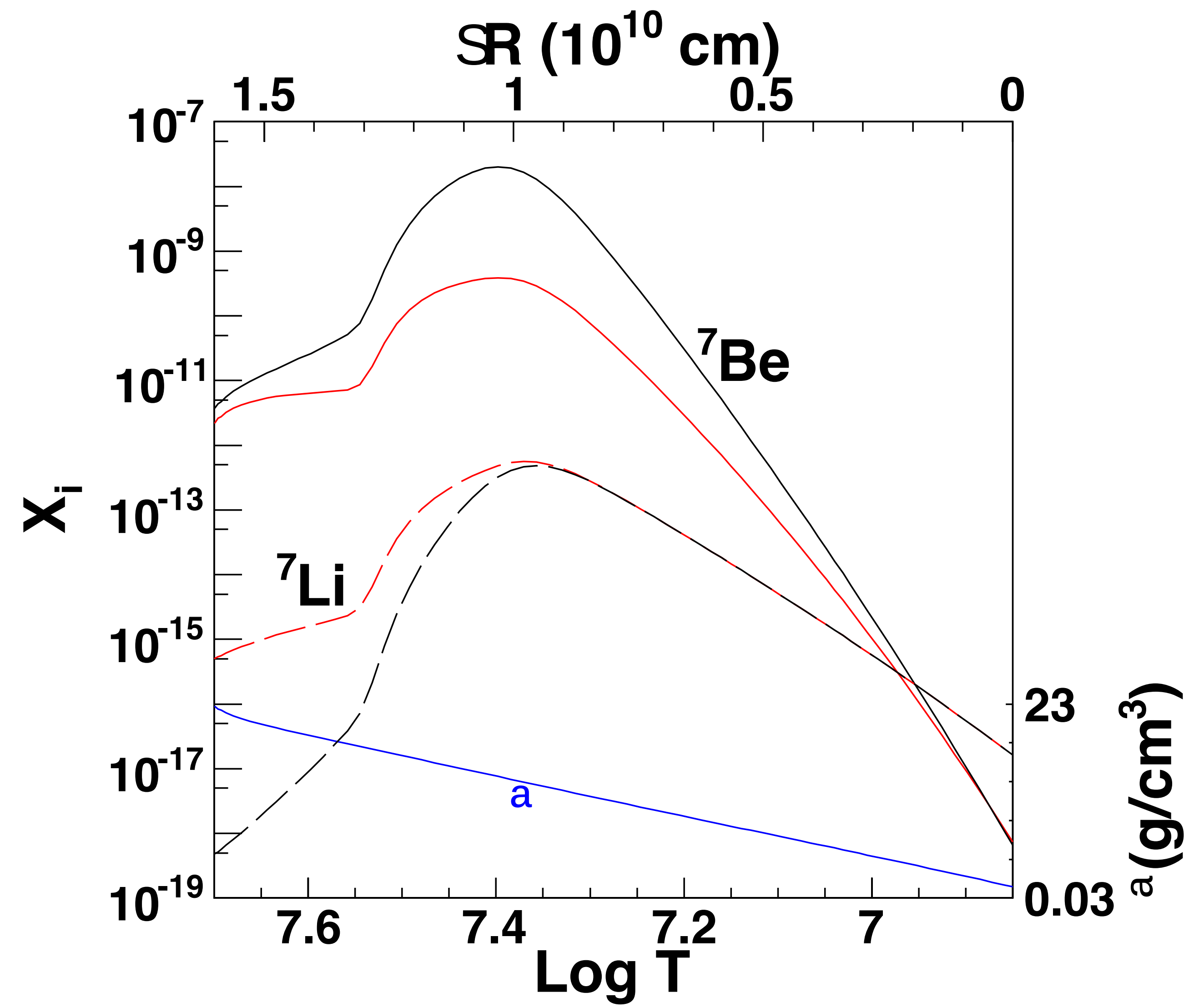


S Simonucci, S Taioli, et al., The Astrophysical Journal 764 (2), 118

Astrophysical consequences of the new rate



typical RGB conditions

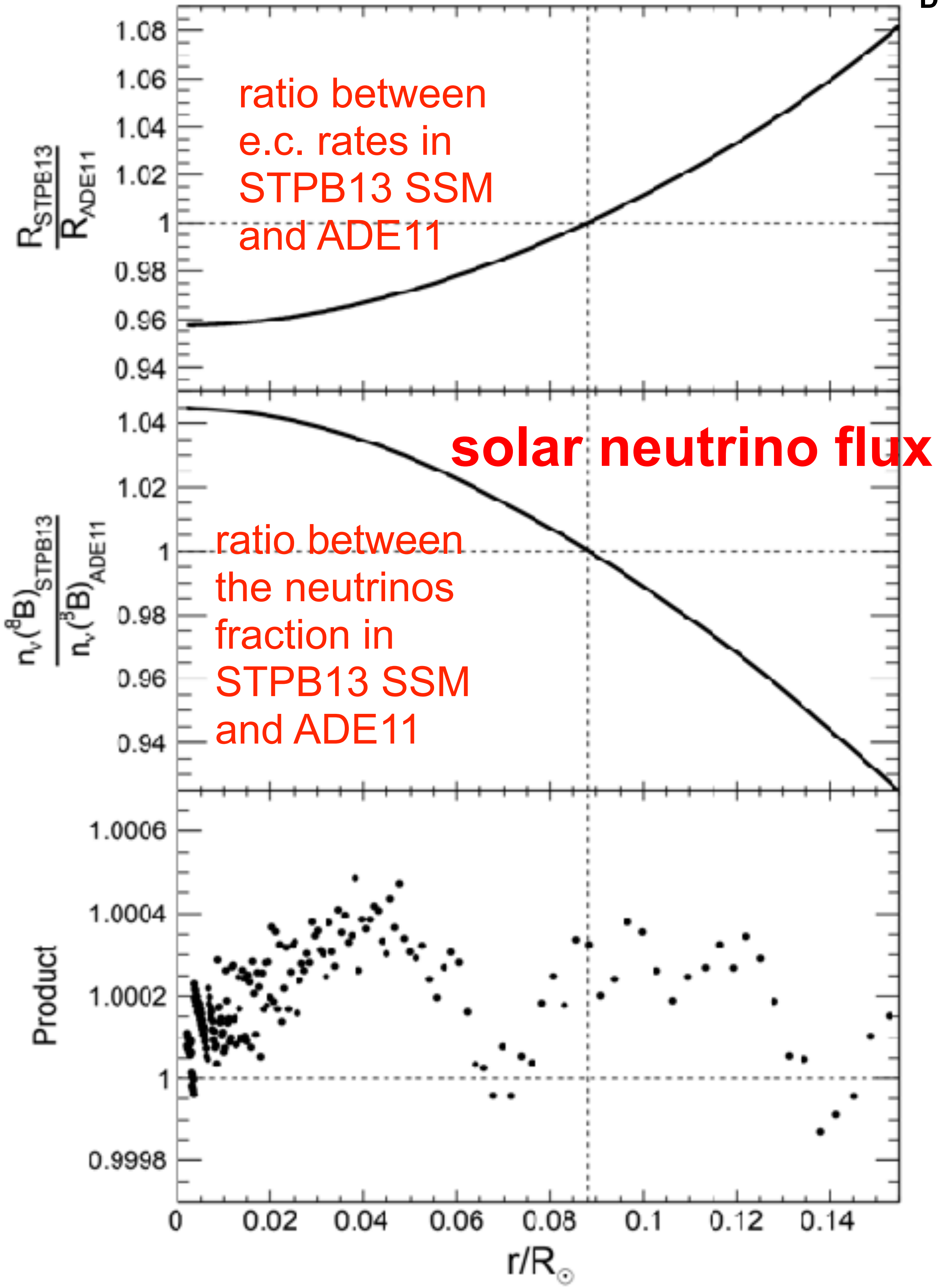


AGB stages

Equilibrium abundances of ^{7}Be and ^{7}Li in the layers above the H-burning shell using our ^{7}Be life-time (red line) and the solar extrapolated rate (black line), in a 2 M⊙ evolved star of solar metallicity. The matter density is also shown (blue line), and is referred to the scale on the right axis.

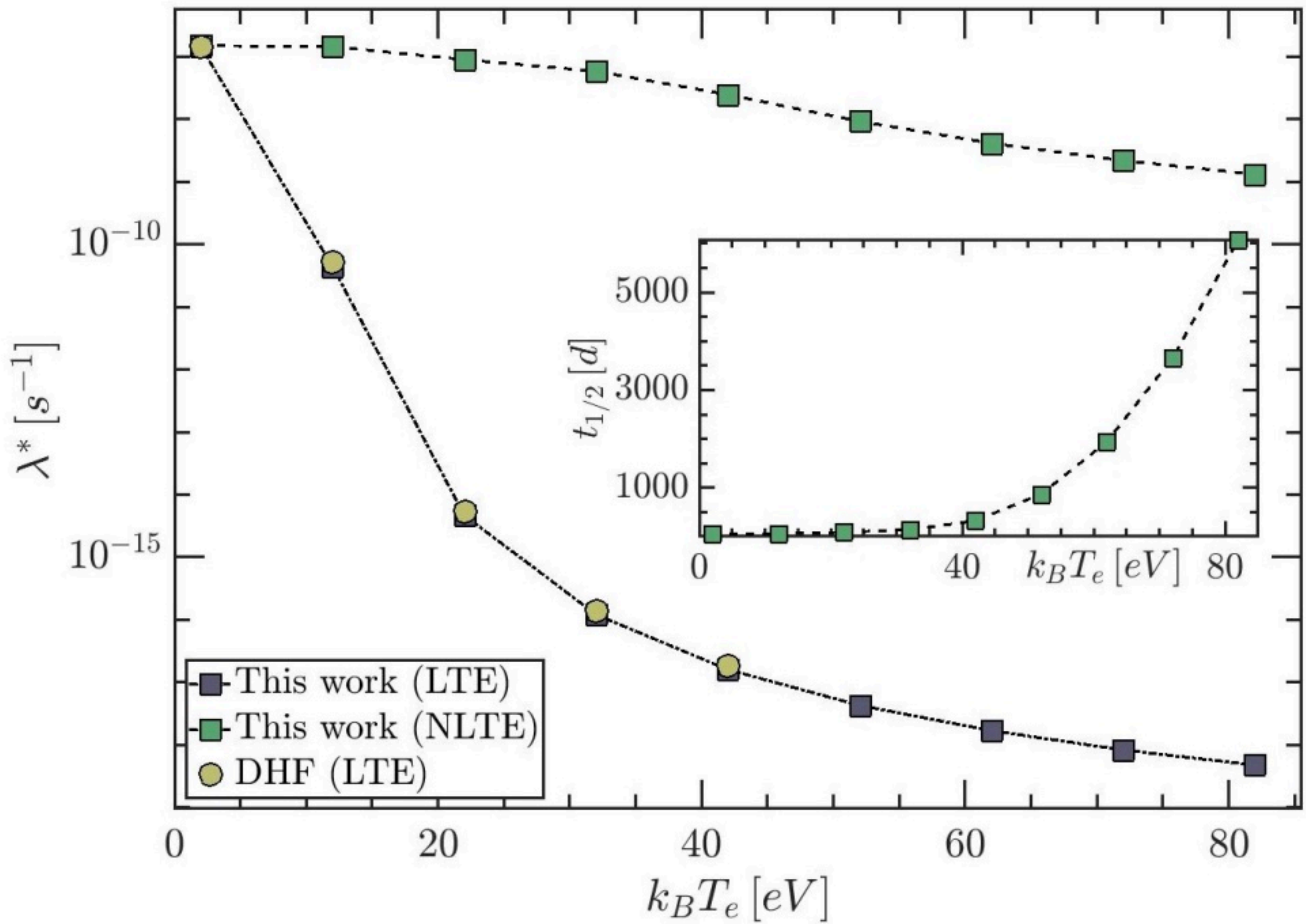
AGB: the HF values of $\rho_e(0)$ are > than those of the DH model; the half-life is smaller and the e-capture is therefore faster; a lower equilibrium abundance of ^{7}Be is established

D Vescovi, et al., Astron. & Astroph. 623 (A126), 7 (2019)



- A smaller lifetime of ^{7}Be EC: less destruction via the ^{7}Be(p, γ)^{8}B changing the yield of the solar neutrino flux.

$n_e = 10^{12}$ cm^{-3}

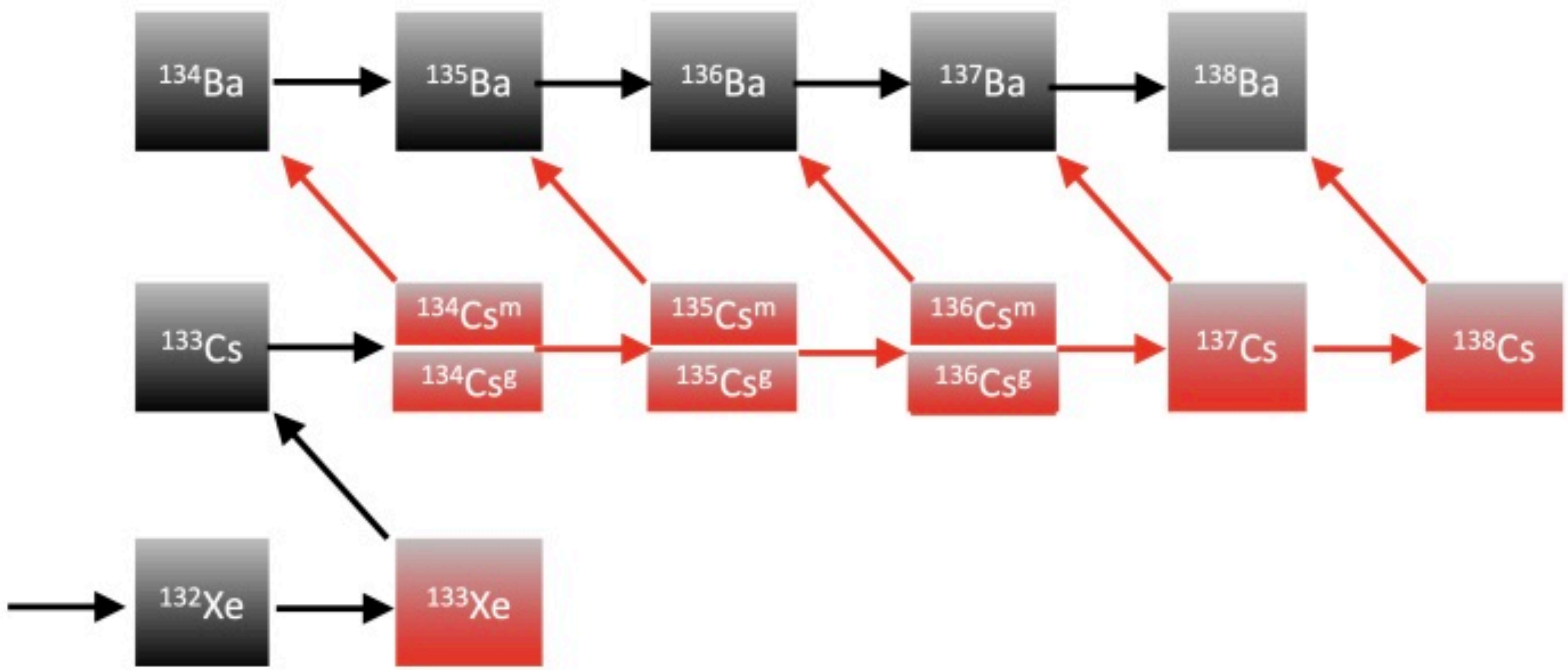


$\lambda^* \, [s^{-1}]$
10^{-10}
10^{-15}
0
20
40
60
80
$k_B T_e \, [eV]$
$t_{1/2} \, [d]$
5000
3000
1000
0
40
$k_B T_e \, [eV]$
80
This work (LTE)
This work (NLTE)
DHF (LTE)

OK for light nuclei! What about heavy ones?

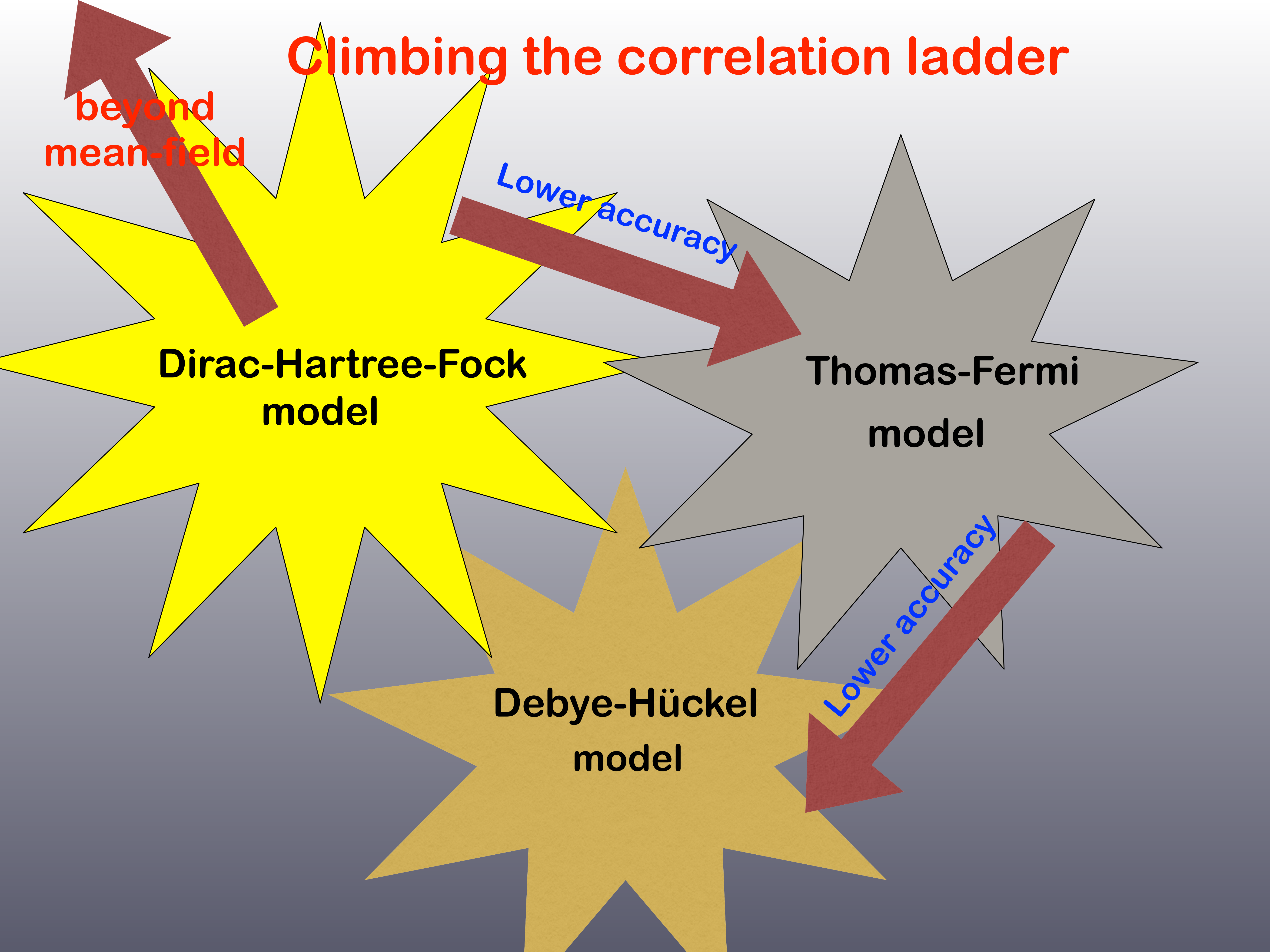
The s-process represents the mechanisms by which heavy nuclei are produced

The presence of several branching points along the s-process path require accurate rates of the competing β-decays and n-capture reactions



A new estimate of the 134Cs and 135Cs half-lives to reproduce isotopic ratios of heavy elements measured in presolar SiC grains. The abundance of Ba in AGB stars depends only on slow n-captures.

Climbing the correlation ladder



Standard Model β-decay theory

β-decay rate is calculated by using Fermi's Golden Rule:

$$P_{i\to f} = 2\pi \int |\langle f|\hat{H}_\beta|i\rangle|^2 \rho(W_f)\delta(W_f - W_i)dW_f$$

Probability P per unit time that a system undergoes a transition from an initial state, *i*, to a number of final states, *f*, under the influence of a perturbation described by the Hamiltonian H_β

Weak Interaction Hamiltonian

$$\mathcal{H}_\beta = \frac{G_\beta}{\sqrt{2}}(\bar{\psi}_{f,p}(\mathbf{r})\gamma^\mu(1 - x\gamma^5)\hat{\psi}_{i,n}(\mathbf{r})) \cdot (\bar{\psi}_{f,e}(\mathbf{r})\gamma_\mu(1 - \gamma^5)\hat{\psi}_{i,\nu}(\mathbf{r})) + h.c.$$

Creates a proton

Destroys a neutron

Creates an electron

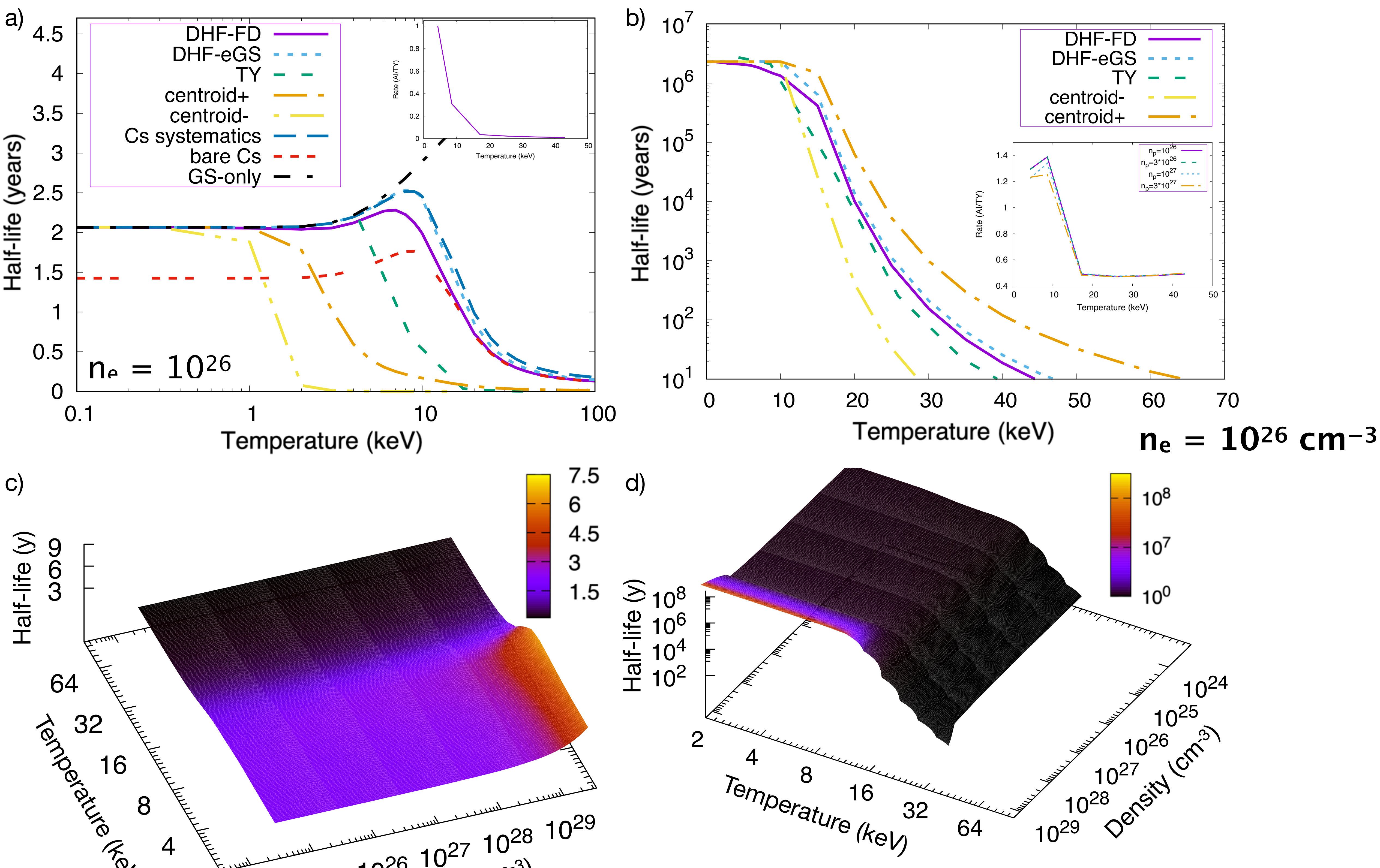
Destroys a neutrino (creates an antineutrino)

$\gamma^\mu \to$ Dirac gamma matrices

$G_\beta = G \cdot c_V \sim 1.13 \cdot 10^{-5} GeV^{-2}$; $x = \frac{c_A}{c_V} \sim 1.27$;

All the wavefunctions will be written as Dirac spinors

While nuclear excited state dynamics is the most relevant, with rate increasing by a factor of 15 at 100 KeV due to populating fast-decaying nuclear excited states, e^- temperature has the most pronounced impact at [0:15] keV, decreasing the half-life by 20% with respect to e-GS (cyan)

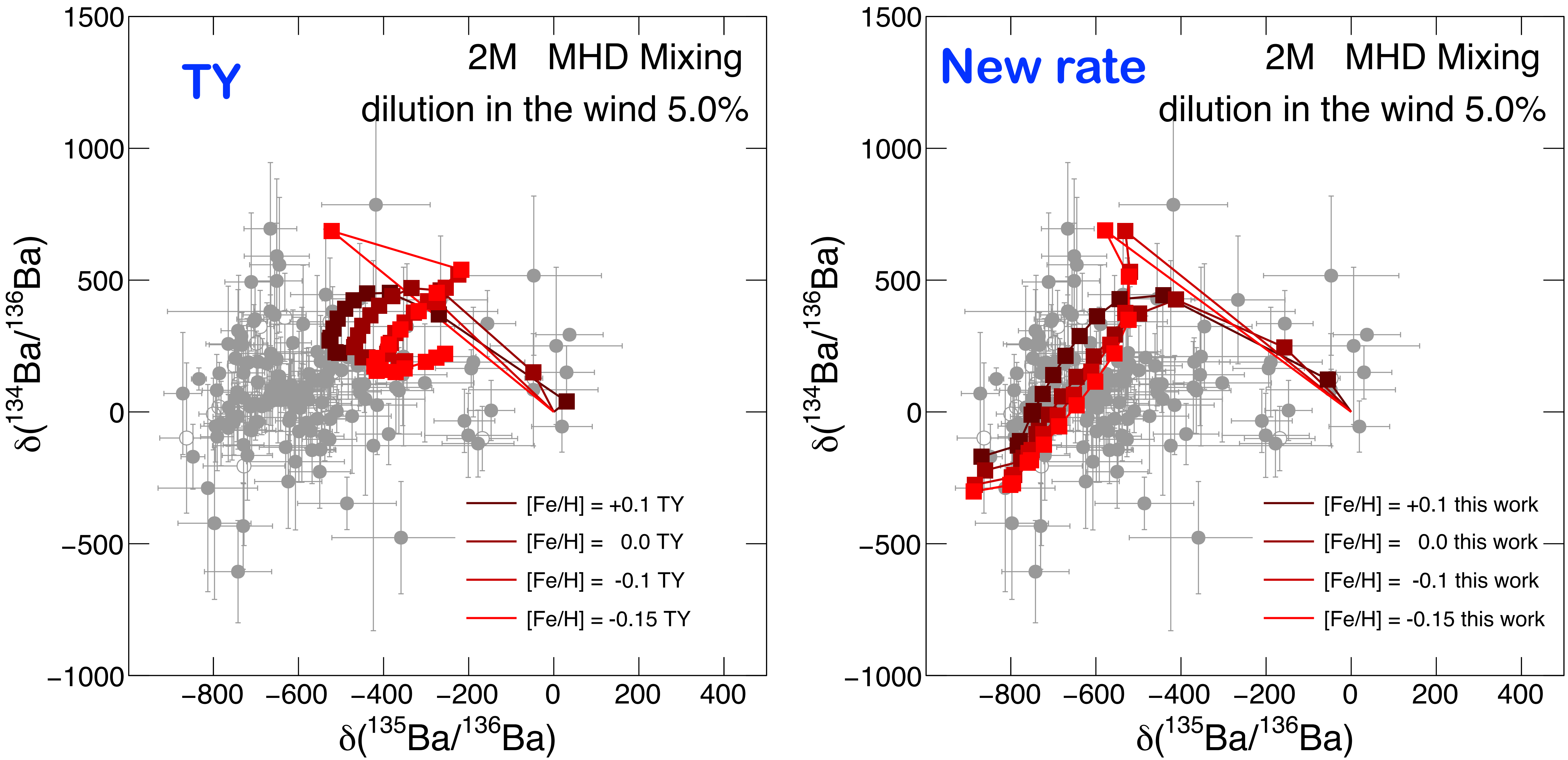


S Taioli, et al., The Astrophysical Journal, 933:158 (2022)

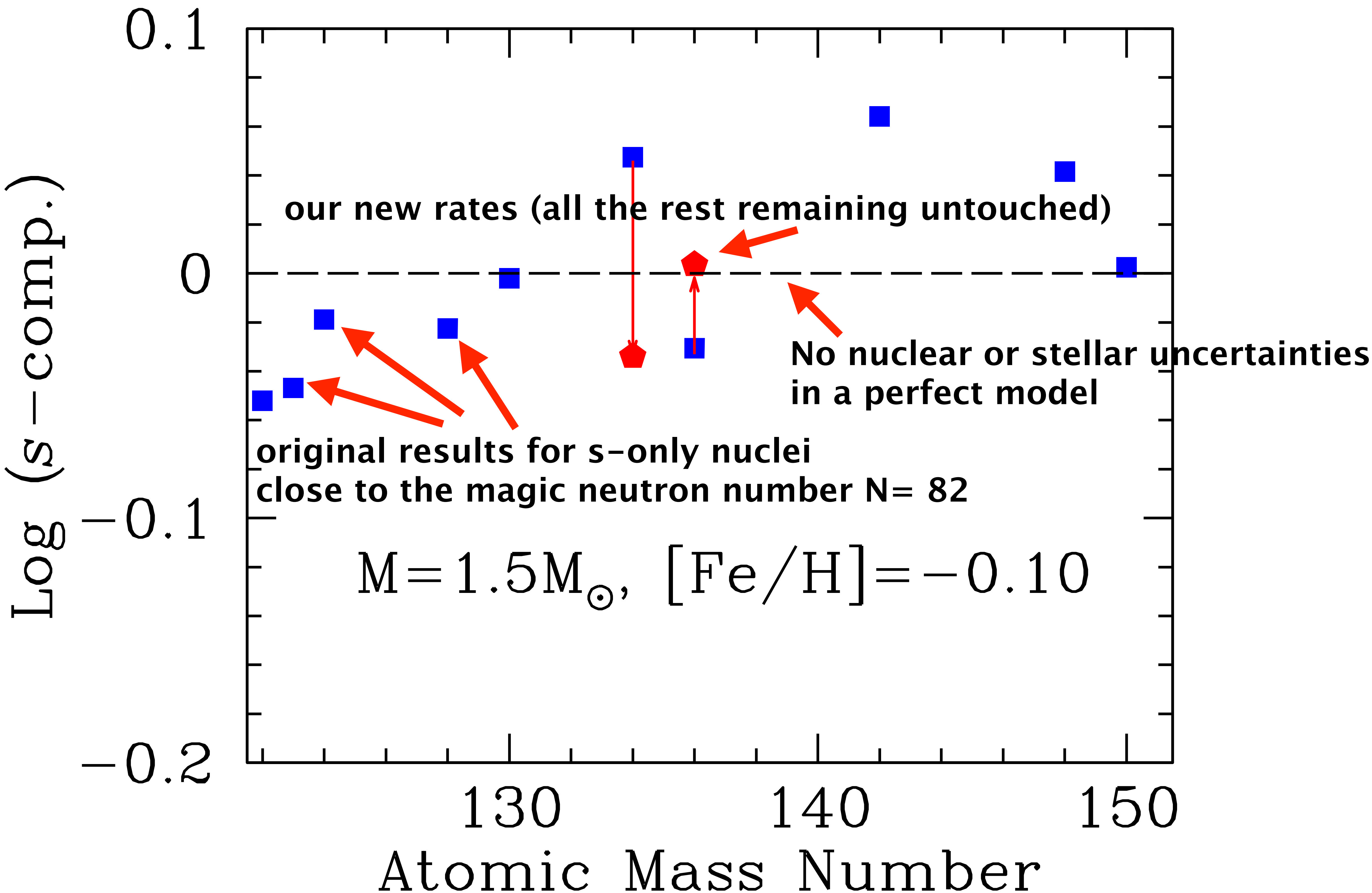
Astrophysical implications

Left panel: isotopic ratios of ^{134}Ba and ^{135}Ba with respect to ^{136}Ba, displayed as part-per-mil deviations (indicated by the symbol δ), with decay rates from TY.

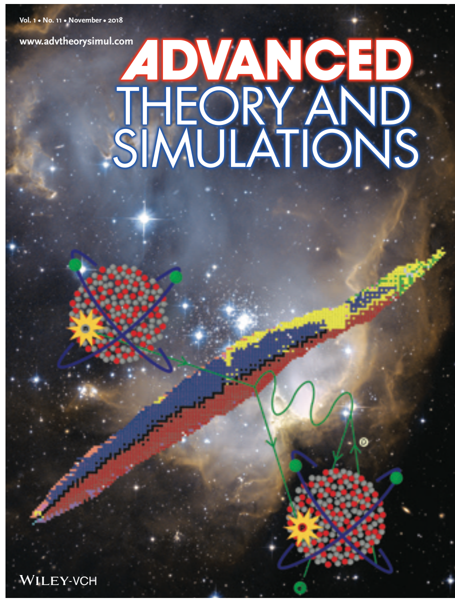
Right panel: the results of the same models, where only the decay rates for ^{134}Cs and ^{135}Cs are changed, using those of the present work. Computations are for 2 M stars, where magneto-hydrodynamic processes induce the penetration of protons into He-rich layers, producing ^{13}C then releasing neutrons through $^{13}C(\alpha,n)^{16}O$. Abundances are computed in stellar winds, where magnetic blobs further add 5% of C-rich material in flare-like episodes.The symbol [Fe/H] indicates $Log(X_{Fe}/X_{H})_{star}$ - $Log(\ ^{13}C)_{sun}$



Percentage of s-process contributions (blue dots) to the isotope production (134,136Ba) as computed by M. Busso et al. ApJ 908, 55 (2021) for s-only nuclei near the magic neutron number N= 82.



Conclusions



- A new method for calculating β- and e^--capture decay spectra in both light to heavy nuclei, which extends the standard approach in several ways
- This method can be applied to any nuclear beta decay and includes relativistic, many-body screening and post-collisional effects
- It works also in astrophysical environment by including temperature, density and charge state distribution
- Our approach can also take into account plasma induced variations of beta decay!

Outlook

- Inclusion of electro-nuclear dynamic correlation beyond mean-field approximation; DONE for electron! ECGBF; quantum neural network to estimate nuclear matrix elements
- Estimate of beta-decay rates of different elements (^{176}Lu, ^{94}Nb, any other suggestion from the Pandora collaboration AND you!)


That's all Folks!