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Pleiades cluster

Exploring the impact of new $^{12}C+^{12}C$ nuclear reaction rates on stellar evolution (in rotating models)

Thibaut Dumont

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Main collaborators: University of Geneva, University of Bruxelles

18th Russbach School on nuclear astrophysics

March 17th, 2023

Context

- New determinations of the nuclear reaction rates have been obtained with direct measurements for $^{12}C+^{12}C$ nuclear reaction at very low energies by STELLA collaboration (cf. talk A. Bonhomme)

- Stellar evolution codes now include non-standard dynamical processes (e.g. rotation, magnetic instabilities)

Context

- New determinations of the nuclear reaction rates have been obtained with direct measurements for $^{12}C+^{12}C$ nuclear reaction at very low energies by STELLA collaboration (cf. talk A. Bonhomme)

- Stellar evolution codes now include non-standard dynamical processes (e.g. rotation, magnetic instabilities)

Outline

- Key impact of rotation-induced mixing in stars

Exploring internal mixing: The solar lithium problem (introduced this week by Andreas Korn)

- Impact of new nuclear reaction rates of $^{12}C+^{12}C$ on standard evolution models ($12M_\odot$ and a $25M_\odot$)

(E. Monpribat et al. 2022)

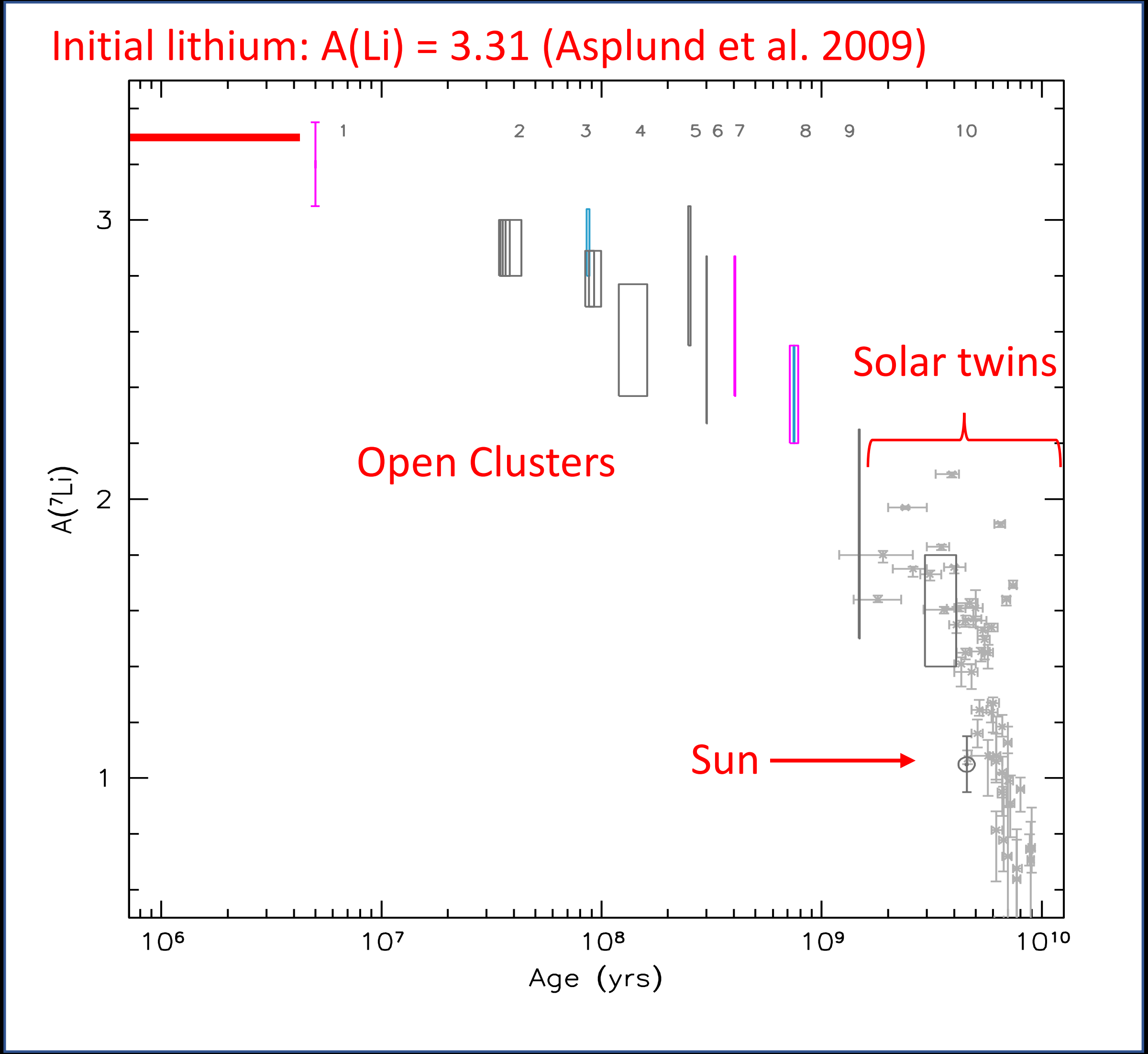
Transport by rotation: the case of lithium

Transport of chemicals:
Light elements as probes of internal transport.
Lithium: burning temperature of ≈ 2.5 MK

Solar-like stars

Li-depletion with time
(e.g. J.R. King et al. 1997, P. Sestito & S. Randich 2005, R. Smiljanic et al. 2011, J.D. Cummings et al. 2017)

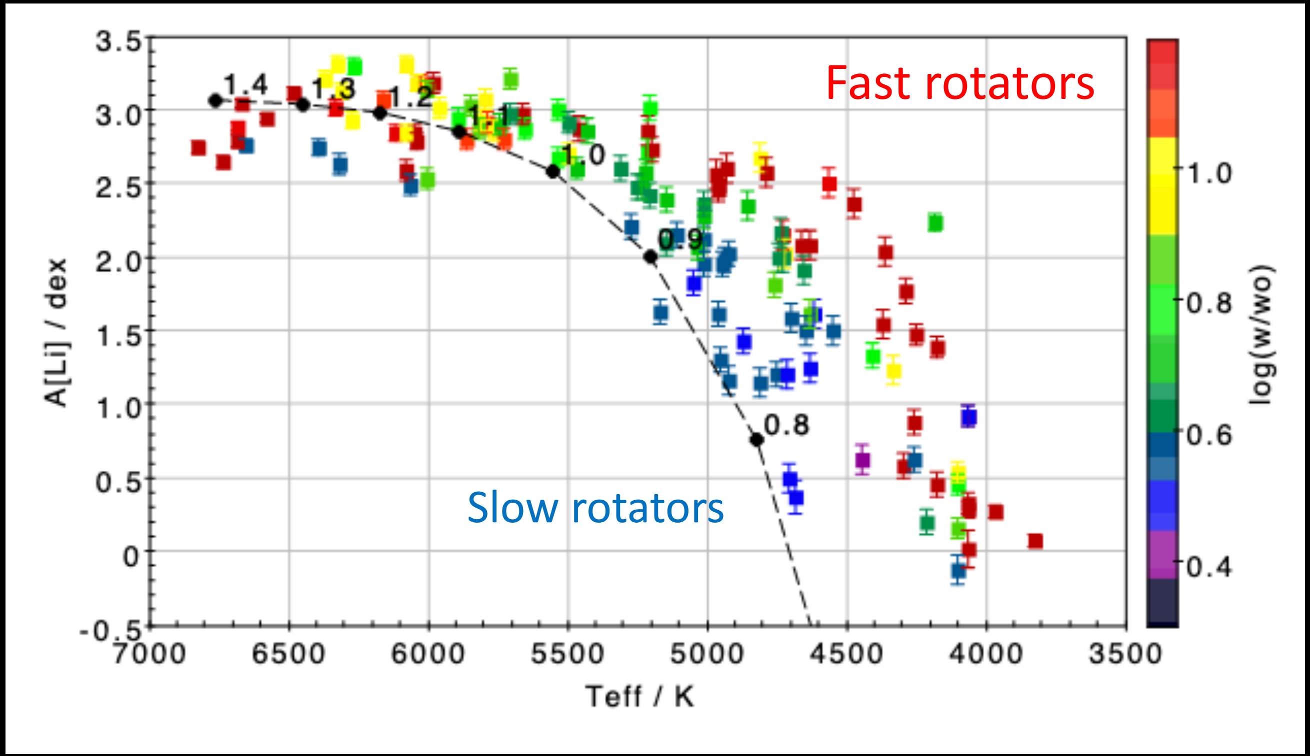
Adapted from T. Dumont et al. 2021



$$A(X) = log_{10}\left(\frac{N_X}{N_H}\right) + 12$$

N_X: number density of element X

Transport by rotation: the case of lithium



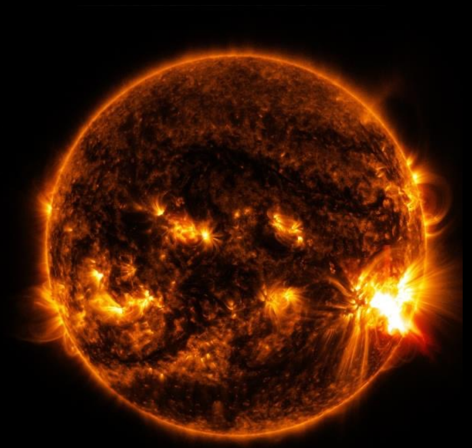
Pleiades cluster (125 Myrs)
J. Bouvier et al. (2018)

Anti-correlation between Li-depletion and rotation velocity

Slow rotators are more Li-poor than rapid-rotators

(e.g. D.R. Soderblom et al. 1993, J. Bouvier et al. 2008, 2018, J. Arancibia-Silvia et al. 2020)

Theoretical interpretation



Sun

Stellar evolution codes:

- model the stellar structure and the stellar evolution
- can include several dynamical processes to transport chemicals or angular momentum

Transport processes: chemicals and angular momentum

Previous works have addressed the transport of chemicals or angular momentum in solar-type stars (e.g. Y. Lebreton & A. Maeder 1987, M. Pinsonneault et al. 1990, O. Richard et al. 1996, A. Palacios et al. 2003, S. Talon & C. Charbonnel 2005, P. Eggenberger et al. 2005, 2019, 2022, G. Somers & M. Pinsonneault 2016, L. Amard et al. 2016, 2019, I. Baraffe et al. 2017, A.C.S. Jørgensen et al. 2018, M. Deal et al. 2018, 2020)

Stellar evolution code: transport

Tool: 1D Stellar evolution code STAREVOL (Geneva-Montpellier)
(e.g. A. Palacios et al. 2003, N. Lagarde et al. 2012, W. Chantereau et al. 2015, L. Amard et al. 2019, T. Dumont et al. 2021a, b)

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Transport of chemicals

X_i: mass fraction of element i

$$\rho \frac{\partial X_i}{\partial t} = \underbrace{\frac{1}{r^2}\frac{\partial}{\partial r}\left(r^2 \rho D \frac{\partial X_i}{\partial r}\right)}_{\text{Turbulent diffusion}} - \underbrace{\frac{1}{r^2}\frac{\partial}{\partial r}\left(r^2 \rho X_i \mathrm{v}_\mathrm{i}\right)}_{\text{Atomic diffusion}} + m_i \underbrace{\left[\sum_j r_{ji} - \sum_k r_{ik}\right]}_{\text{Nuclear reactions}}$$

Transport of angular momentum

$\boldsymbol{\Omega}$: angular velocity

$$\rho \frac{d}{dt}(r^2\Omega) = \underbrace{\frac{1}{5r^2}\frac{\partial}{\partial r}(\rho r^4 \Omega U_2)}_{\text{Advection term}} + \underbrace{\frac{1}{r^2}\frac{\partial}{\partial r}\left(\nu_v r^4 \frac{\partial \Omega}{\partial r}\right)}_{\text{Diffusion term}}$$

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Initial abundances from M. Asplund et al. 2009 (Ne enhancement P.R. Young et al. 2018, M. Asplund et al. 2021)
Nuclear reactions rate for elements: NACRE II (Y. Xu et al.2013a, b), G. Caughlan & W. Fowler 1988

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Transport of angular momentum

Ω: angular velocity

$$\rho \frac{d}{dt}(r^2 \Omega) = \underbrace{\frac{1}{5r^2}\frac{\partial}{\partial r}(\rho r^4 \Omega U_2)}_{\text{Advection term}} + \underbrace{\frac{1}{r^2}\frac{\partial}{\partial r}\left(\nu_v r^4 \frac{\partial \Omega}{\partial r}\right)}_{\text{Diffusion term}}$$

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Nuclear reactions rate for elements: NACRE II (Y. Xu et al.2013a, b), G. Caughlan & W. Fowler 1988
Dynamical process: Rotation-induced mixing

Transport of chemicals

X_i: mass fraction of element i

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Turbulent diffusion $D = \sum_j D_j$ Sum of the turbulent coefficients from different dynamical processes

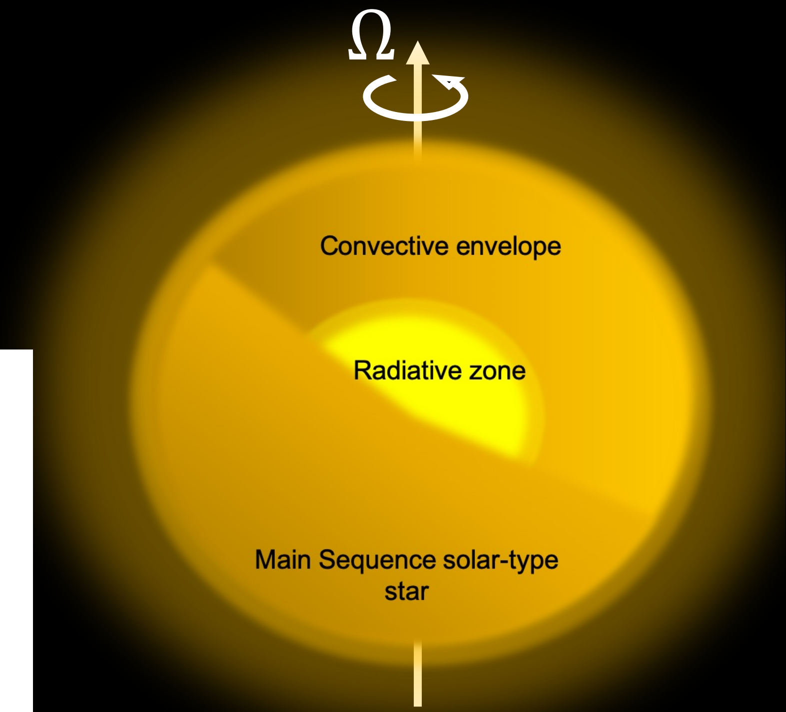
Transport of angular momentum

$\boldsymbol{\Omega}$: angular velocity

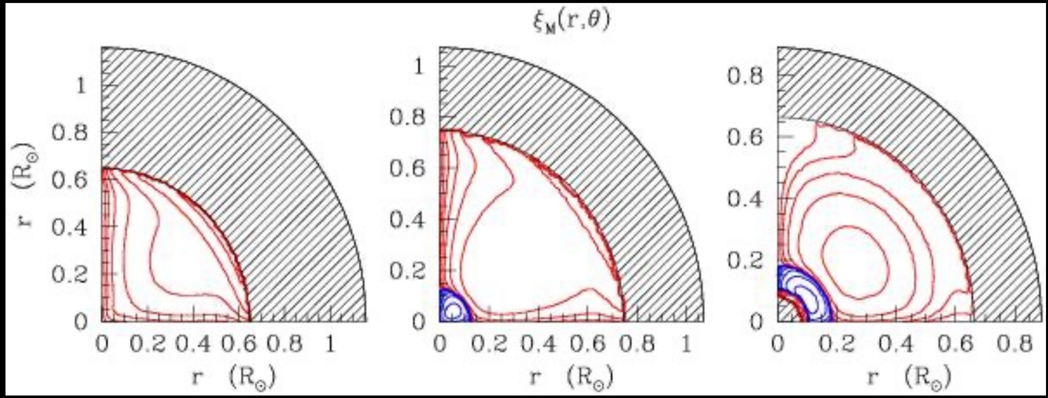
$$\rho\frac{d}{dt}(r^2\Omega) = \underbrace{\frac{1}{5r^2}\frac{\partial}{\partial r}(\rho r^4\Omega U_2)}_{\text{Advection term}} + \underbrace{\frac{1}{r^2}\frac{\partial}{\partial r}\left(\nu_v r^4\frac{\partial\Omega}{\partial r}\right)}_{\text{Diffusion term}}$$

Transport processes: Rotation

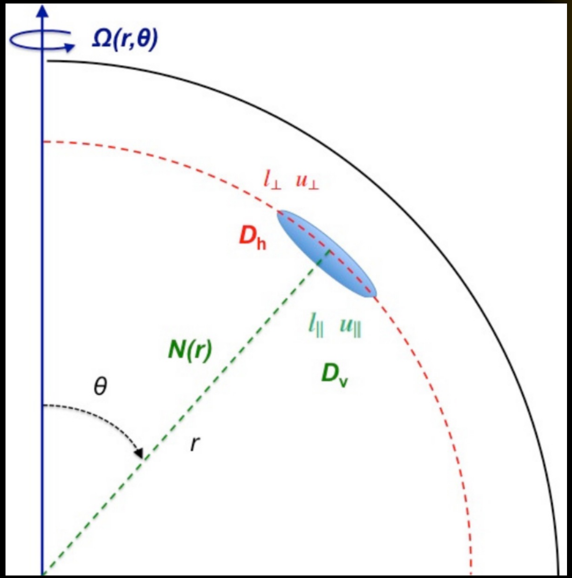
Rotation ⟶ internal transport of chemical species and angular momentum according to J.P. Zahn (1992) and A. Maeder & J.P. Zahn (1998)



Meridional circulation and shear induced turbulence



Meridional circulation in a solar model at three different ages. Blue: clockwise, red: counterclockwise.
(C. Charbonnel et al. 2013)



Anisotropic turbulent transport
(S. Mathis et al. 2018)

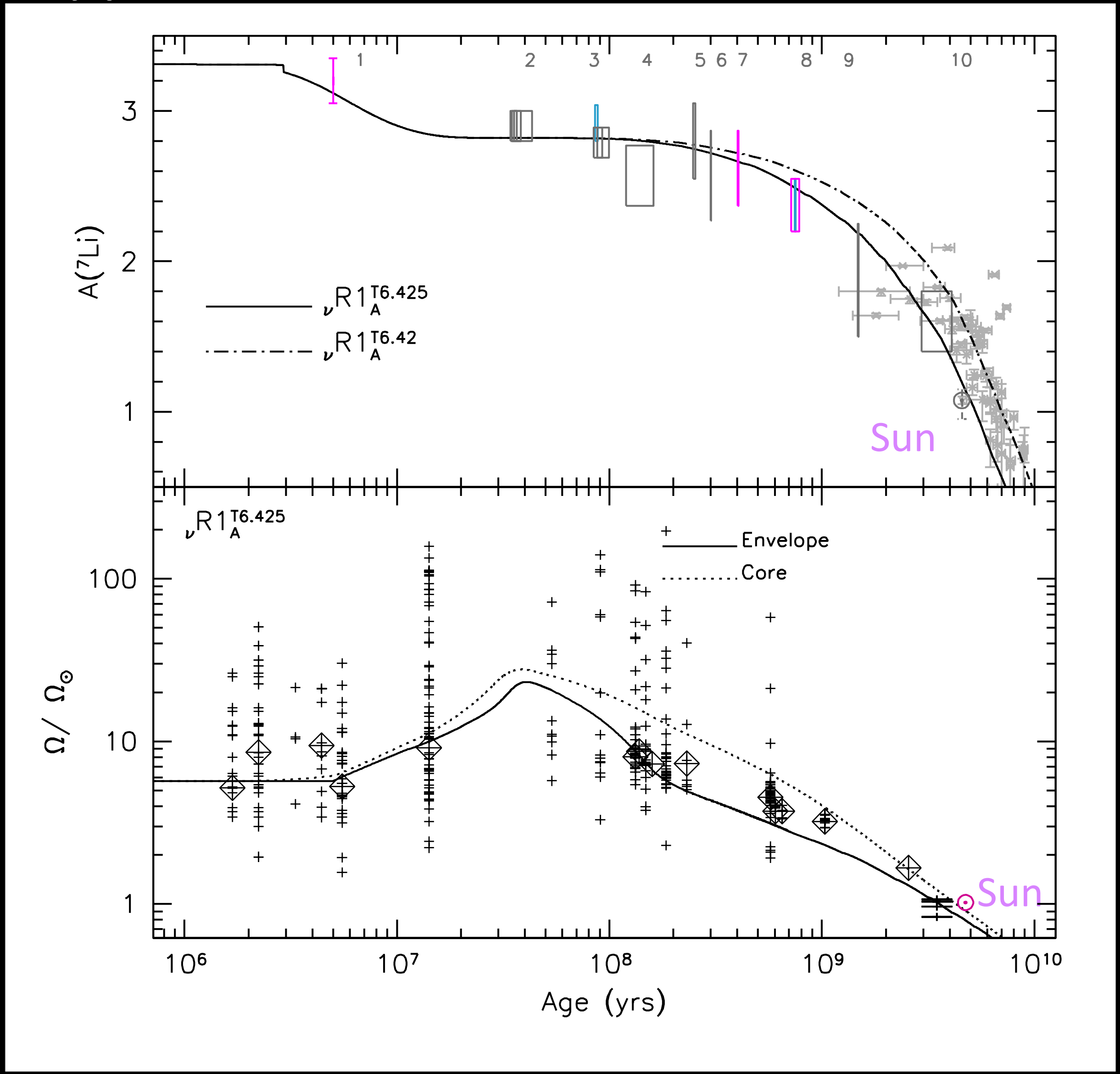
Lithium depletion and angular momentum transport in solar-type stars

Conclusions (T. Dumont et al. 2021a)

Rotation-induced mixing is required to describe Li-depletion

Additional transports (rotation-dependent) are also needed for both chemicals and angular momentum, namely:

- Overshoot
- Turbulence (cf. talk by A. Korn)
- Viscosity



◇ Median rotators

Stellar evolution code: nuclear reaction rates

Transport of chemicals

X_i: mass fraction of element i

$$\rho \frac{\partial X_i}{\partial t} = \underbrace{\frac{1}{r^2}\frac{\partial}{\partial r}\left(r^2 \rho D \frac{\partial X_i}{\partial r}\right)}_{\text{Turbulent diffusion}} - \underbrace{\frac{1}{r^2}\frac{\partial}{\partial r}\left(r^2 \rho X_i \mathrm{v}_\mathrm{i}\right)}_{\text{Atomic diffusion}} + \underbrace{m_i \left[\sum_j r_{ji} - \sum_k r_{ik}\right]}_{\text{Nuclear reactions}}$$

Nuclear reactions rate for elements usually in the stellar evolution codes
NACRE II (Y. Xu et al.2013a, b), G. Caughlan & W. Fowler 1988

➡ The case of $^{12}C+^{12}C$ during C-burning phase of massive stars (cf. Talk by A. Bonhomme)

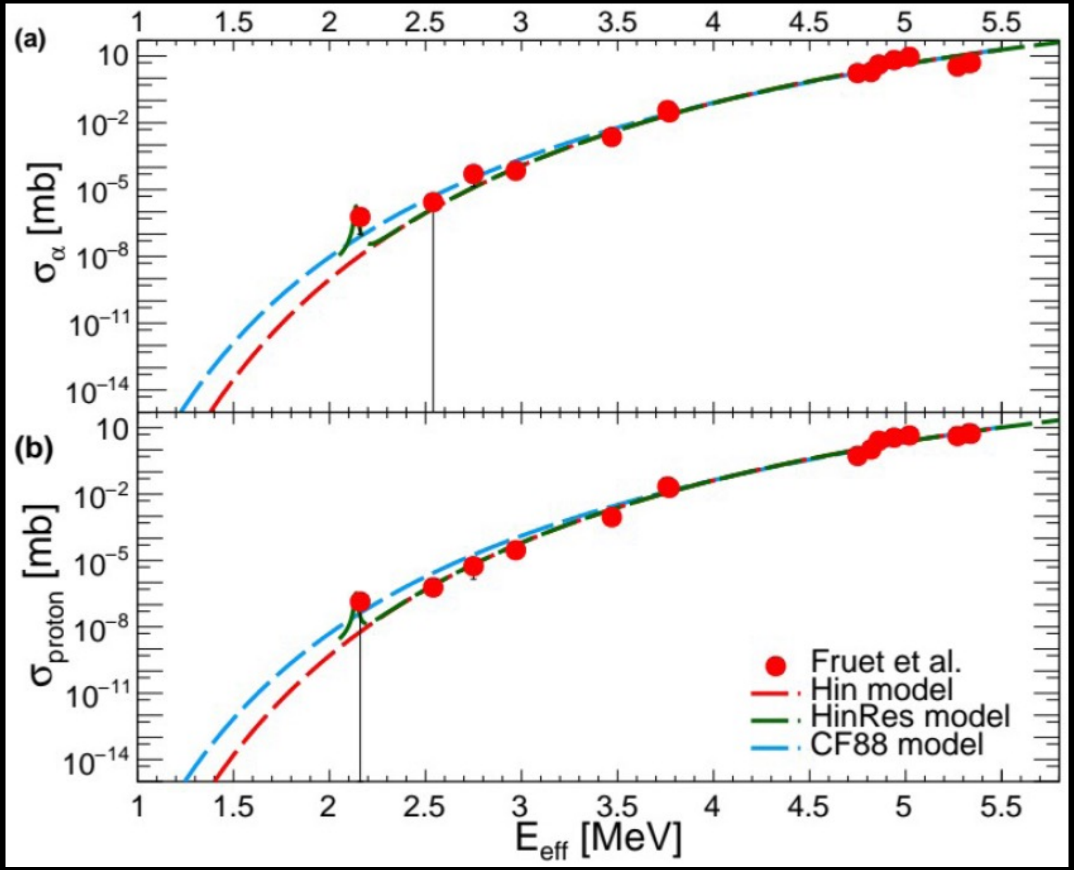
Exploring the impact of new $^{12}C+^{12}C$ nuclear reaction rates on stellar evolution

E. Monpribat et al. 2022 + cf. Talk by A. Bonhomme

G. Caughlan & W. Fowler 1988 (CF88): Original reaction rates

New nuclear reactions rate for $^{12}C+^{12}C$: G. Fruet et al. 2020
Hindrance: Hin
Hindrance+Resonance (T. Spillane et al. 2007): HinRes

(+ Neutron channel from B. Bucher et al. 2015)



Cross sections for alpha and proton channels

Courtesy of E. Monpribat

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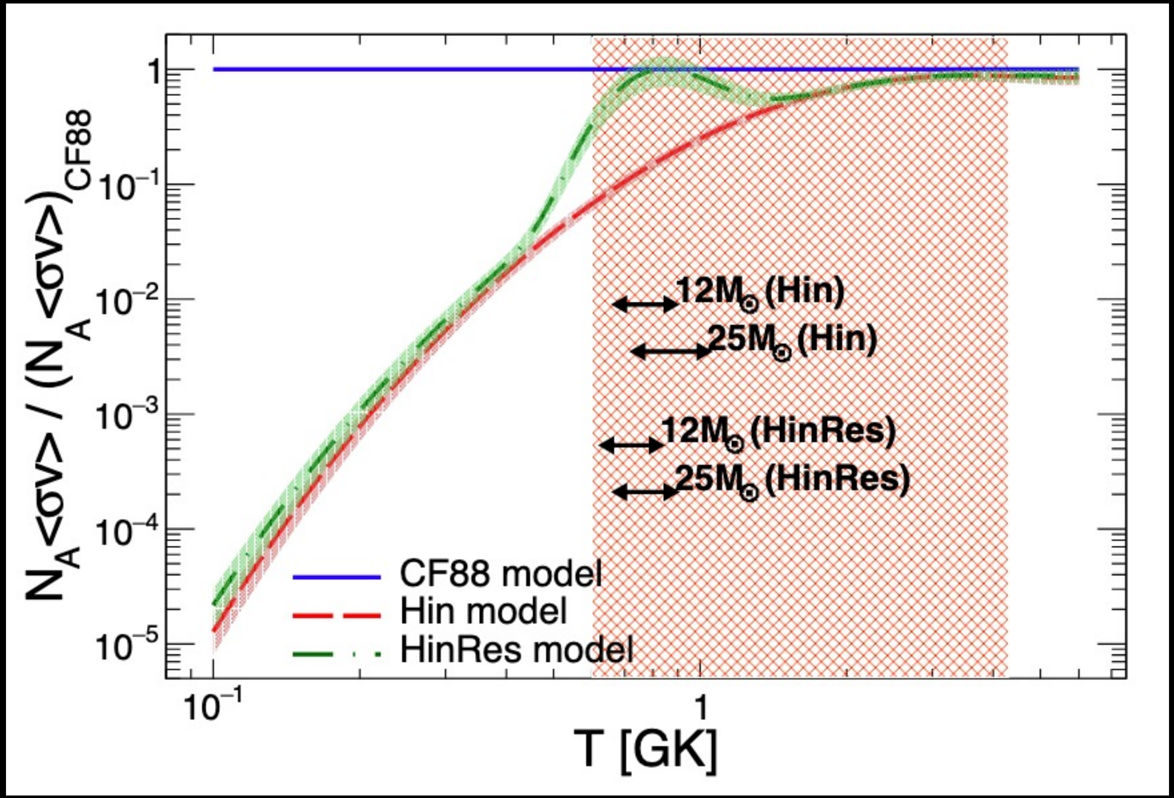

Normalised reaction rates ($^{12}C+^{12}C$)

Exploring the impact of new $^{12}C+^{12}C$ nuclear reaction rates on stellar evolution

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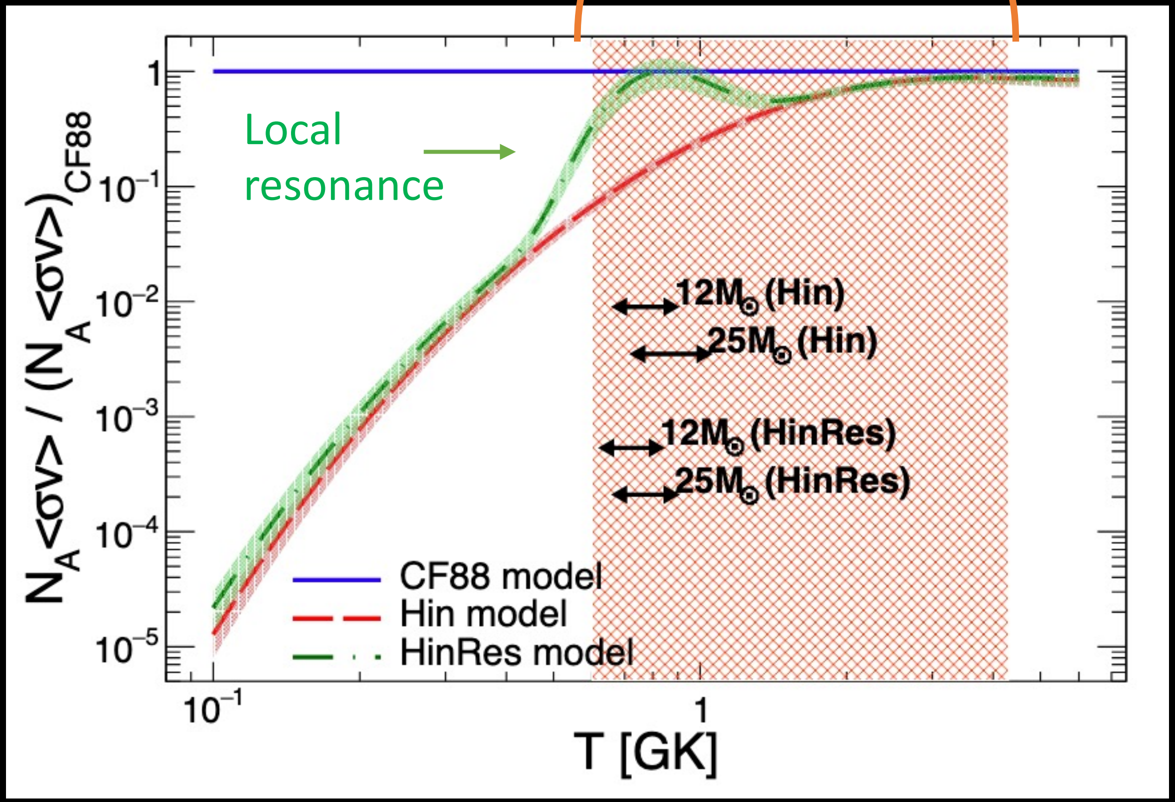
Temperature region explored by STELLA



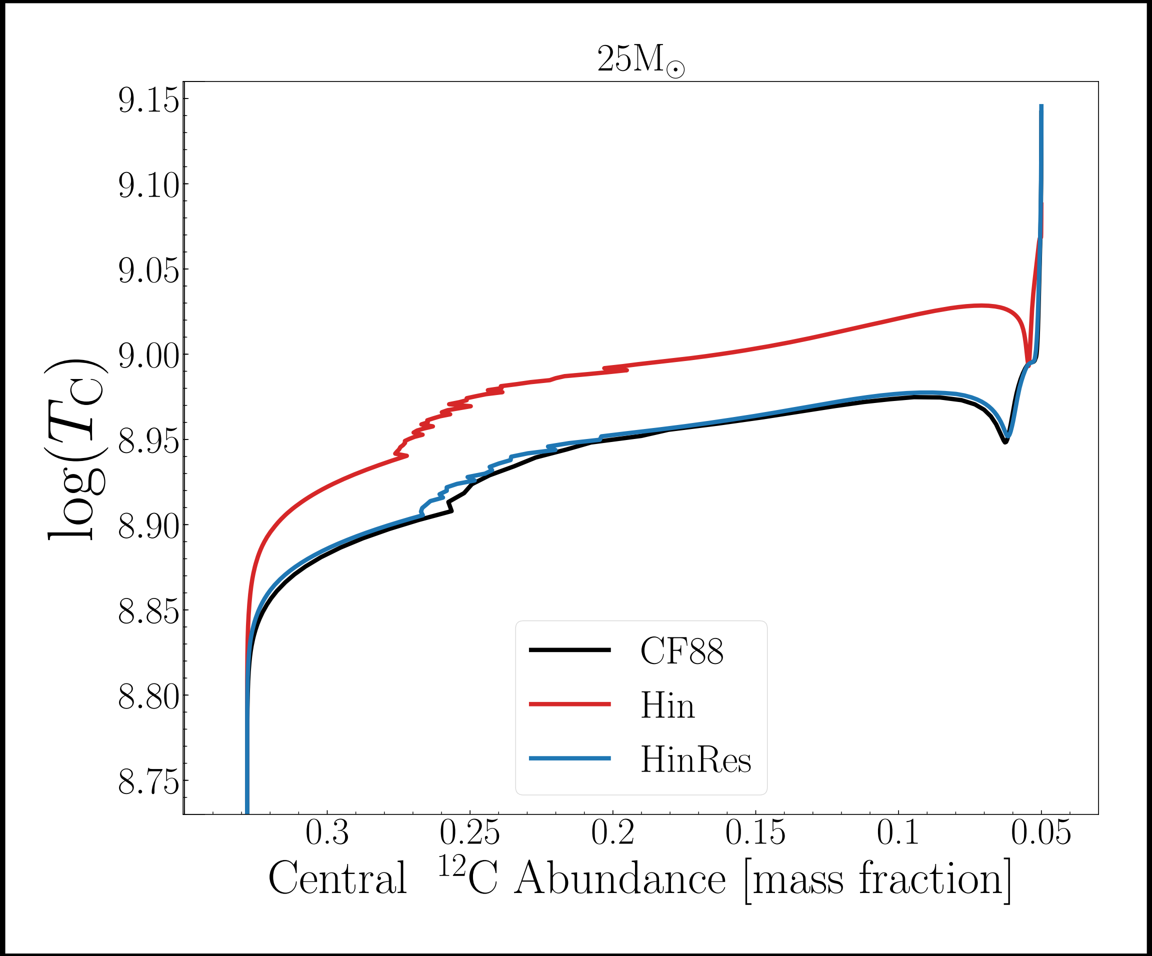
Normalised reaction rates ($^{12}C+^{12}C$)

Exploring the impact of new $^{12}C+^{12}C$ nuclear reaction rates on stellar evolution

E. Monpribat et al. 2022

C-burning phase (GENEC code, S. Ekström et al. 2012)

- Central temperature higher for the Hin model (+10%) resulting of a shorter lifetime (env. /2), but not for the HinRes model
- Modest structural changes due to readjustment of the star
- Impact on nucleosynthesis

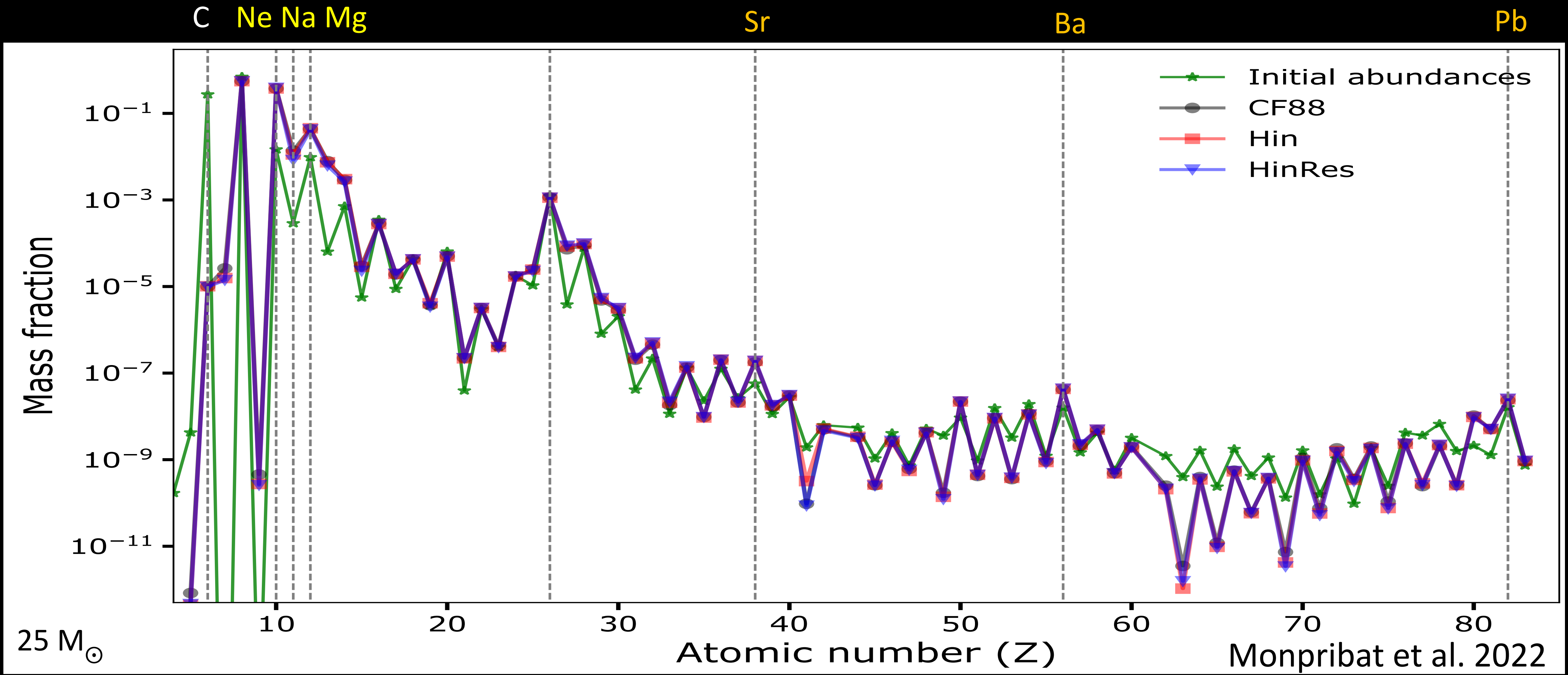


Nucleosynthesis analysis

C-burning phase (nucleosynthesis code, 1454 isotopes, A. Choplin et al. 2016)

- Enhancement of s-process elements (Sr, Ba, Pb) and production of C-burning products (Ne, Na, Mg)

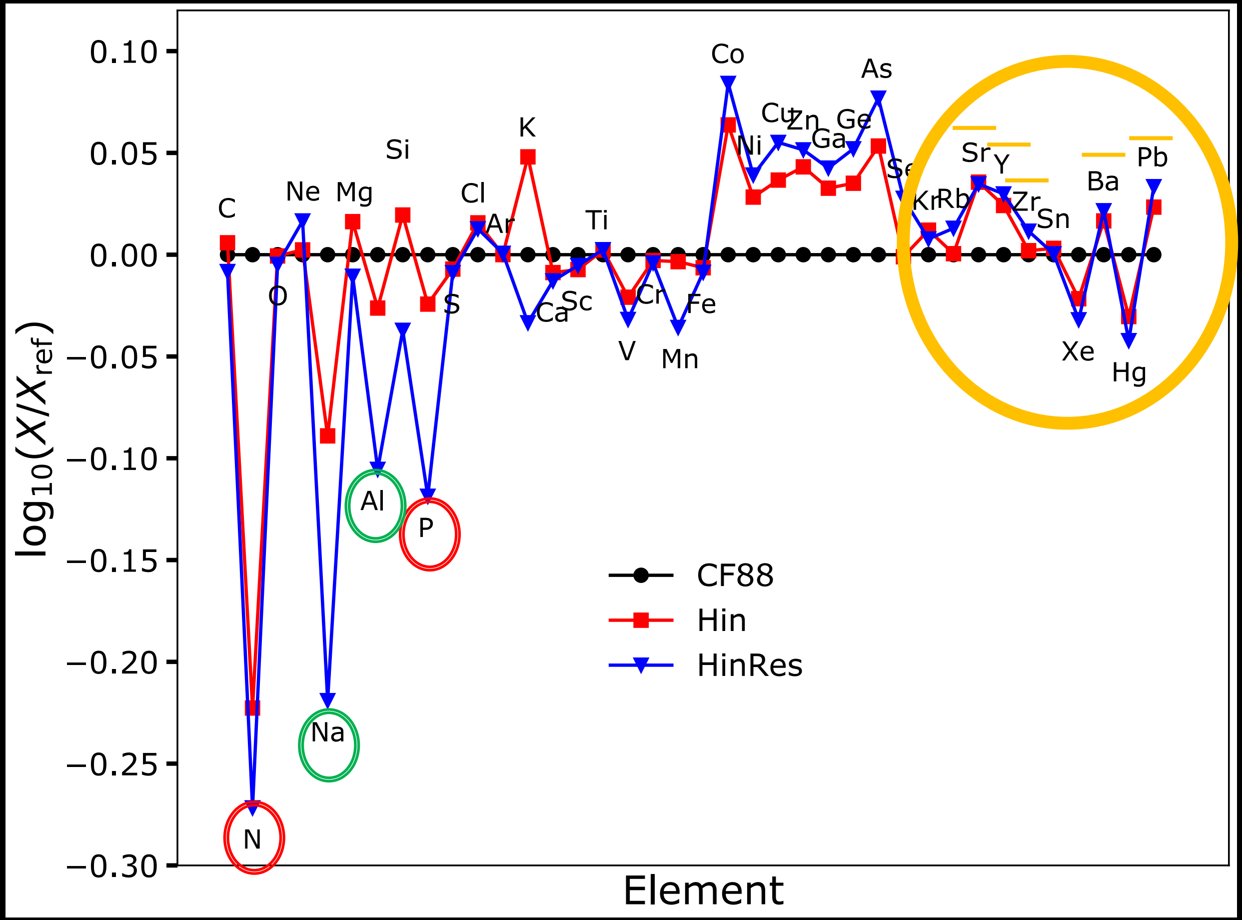
(see e.g. M. Pignatari et al. 2013)



Nucleosynthesis analysis

C-burning phase (nucleosynthesis code, 1454 isotopes, A. Choplin et al. 2016)

- Higher production of s-process elements (Y, Zr, Ba, Pb) and smaller amount of Na, Al with the HinRes model



25 $M_\odot$

> 10^{-2} mass fraction

~ 10^{-5} mass fraction

s-elements

< 10^{-7} mass fraction

E. Monpribat et al. 2022

Conclusion / Perspectives

Conclusion

- Rotation is a main process for chemical evolution in stars (like lithium)

- New nuclear reaction rates for $^{12}C+^{12}C$

Perspectives

- New models including both rotation and new $^{12}C+^{12}C$ rates

- In the future: $^{12}C+^{16}O$ and $^{16}O+^{16}O$ (cf. Talk A. Bonhomme)

The end

Merci ! Thanks! Danke!

Questions

Stellar evolution code: transport

Tool: 1D Stellar evolution code STAREVOL (Geneva-Montpellier)
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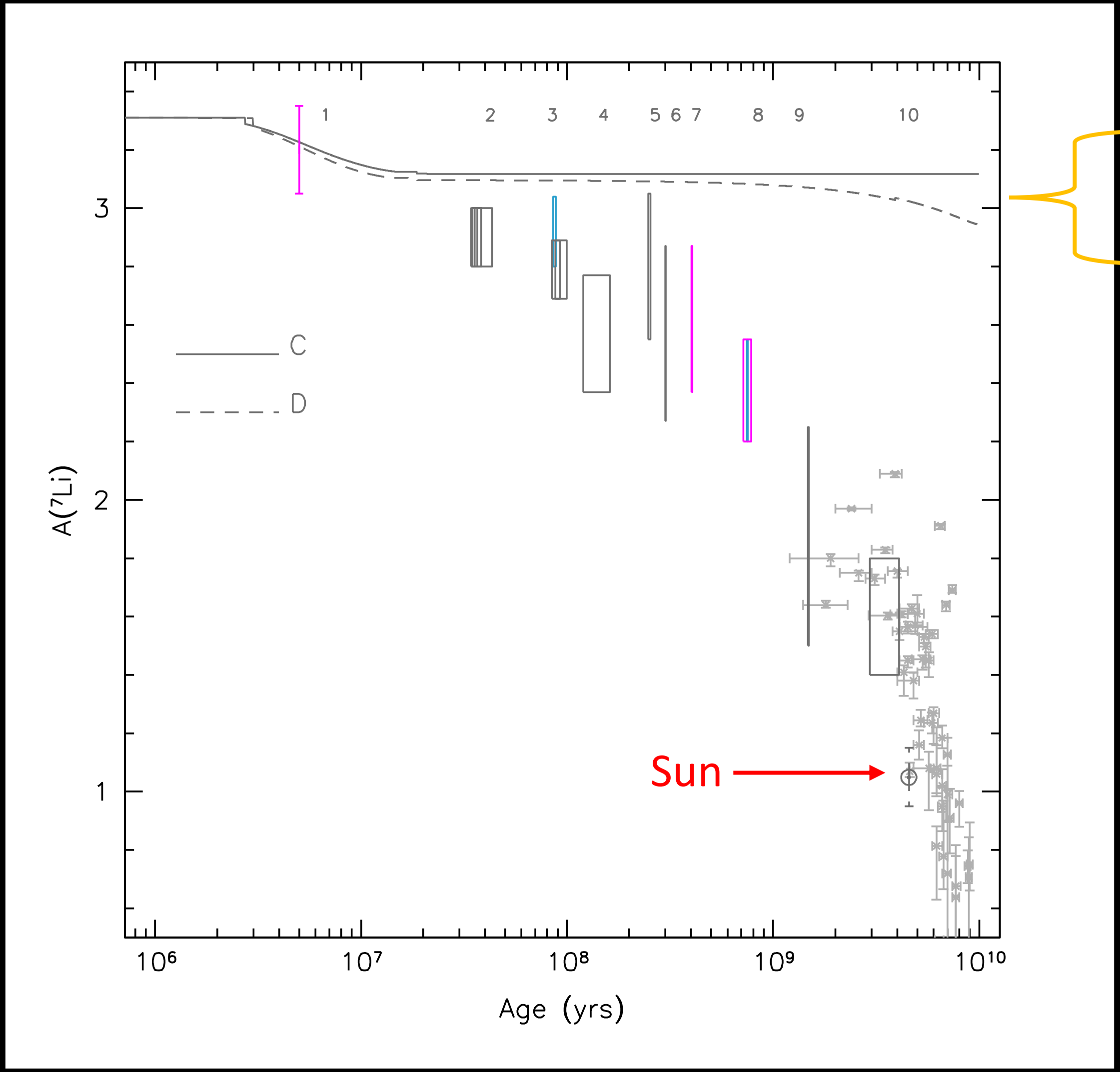
Atomic diffusion

Diffusion of heavy elements to the centre and hydrogen to the surface.

Key effect for solar calibration (position of the base of the convective zone and surface helium constrained by helioseismology)

Stellar modelling predictions

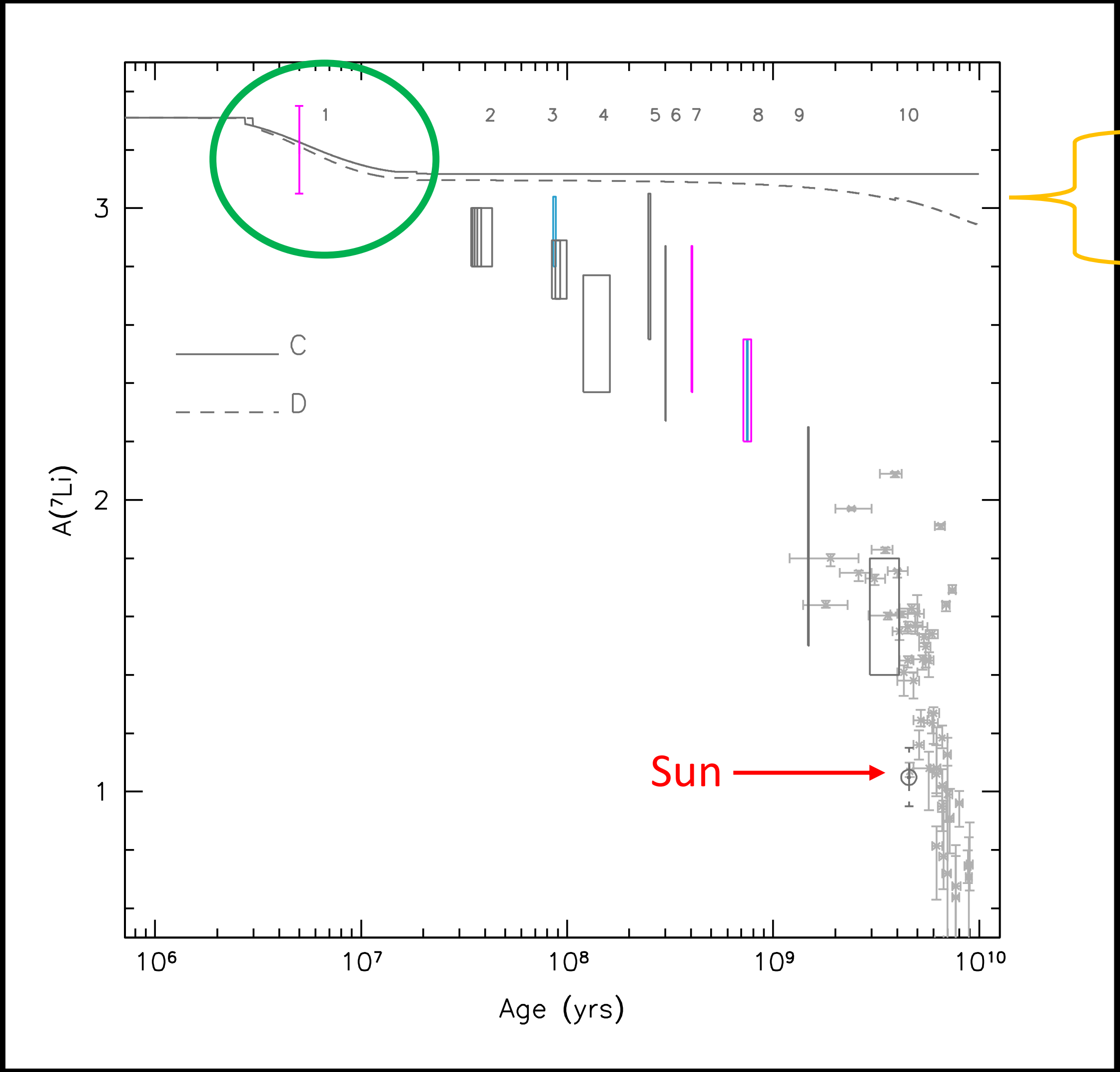


STAREVOL stellar evolution code (Geneva-Montpellier)

Classical model: C (Only convection)
Atomic diffusion model: D (Convection + atomic diffusion)

Adapted from T. Dumont et al. 2021

Stellar modelling predictions



STAREVOL stellar evolution code (Geneva-Montpellier)

Classical model: C (Only convection)
Atomic diffusion model: D (Convection + atomic diffusion)

Prediction of Li depletion during the PMS

Adapted from T. Dumont et al. 2021a

Solar-type Li depletion and angular velocity

Conclusions (Dumont et al. 2021a, A&A 646, A48)

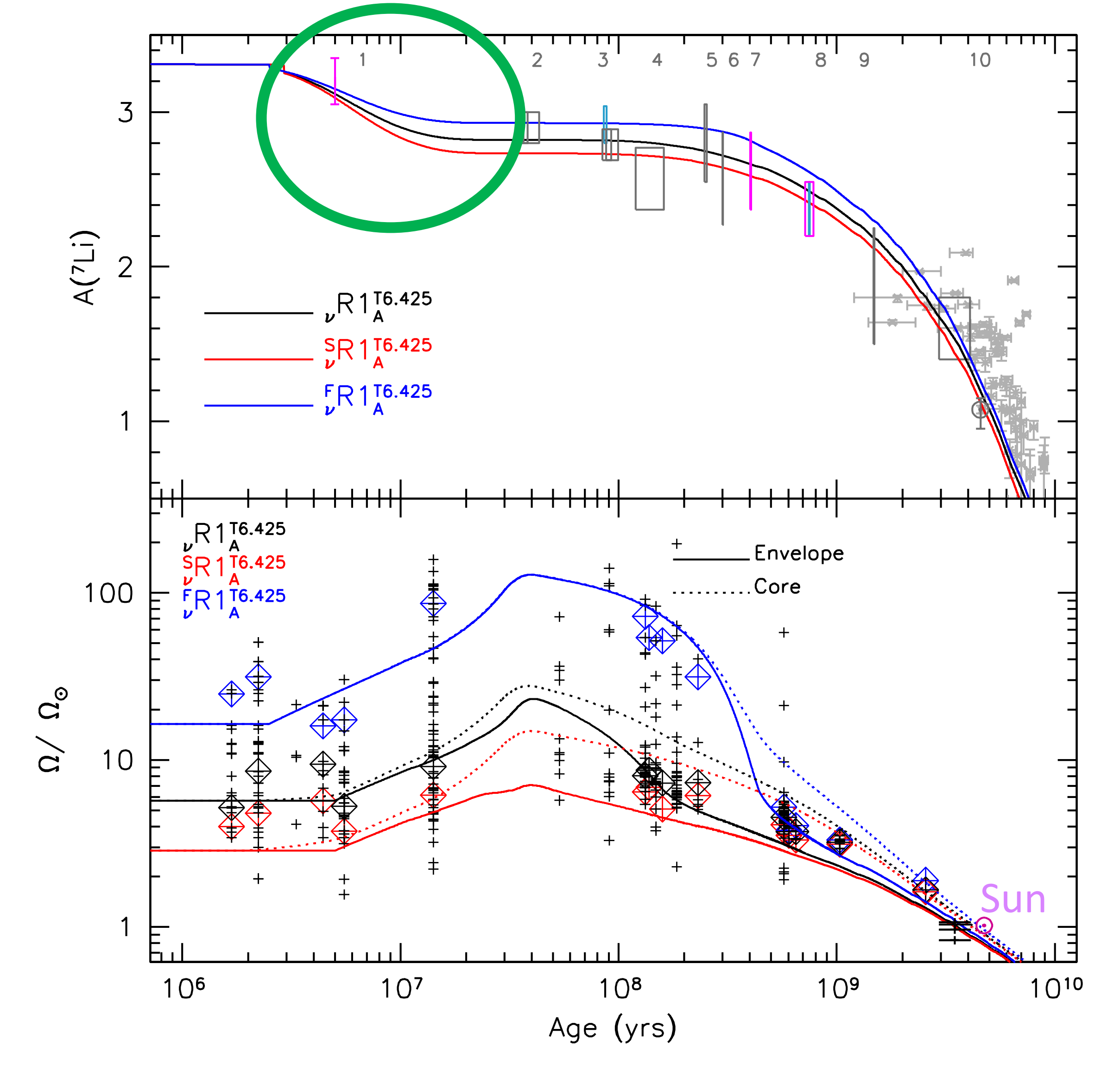
Different initial rotation velocities

- Slow: $Prot_{ini}$ = 9.0 days
- Median: $Prot_{ini}$ = 4.5 days

τ_{disc} = 5.0 Myrs

- Fast: $Prot_{ini}$ = 1.6 days → τ_{disc} = 2.5 Myrs

Anti-correlation Li-depletion and rotation velocity. Penetrative convection (rotational dependence) is shown as a key process that explains the anti-correlation Li-rotation



Fast rotators

Median rotators

Slow rotators

Transport processes: Rotation

Turbulent diffusion $D = \sum_j D_j$ Sum of the turbulent coefficients from different dynamical processes

Rotation → internal transport of chemical species and angular momentum according to J.P. Zahn (1992) and A. Maeder & J.P. Zahn (1998)

Meridional circulation and shear induced turbulence

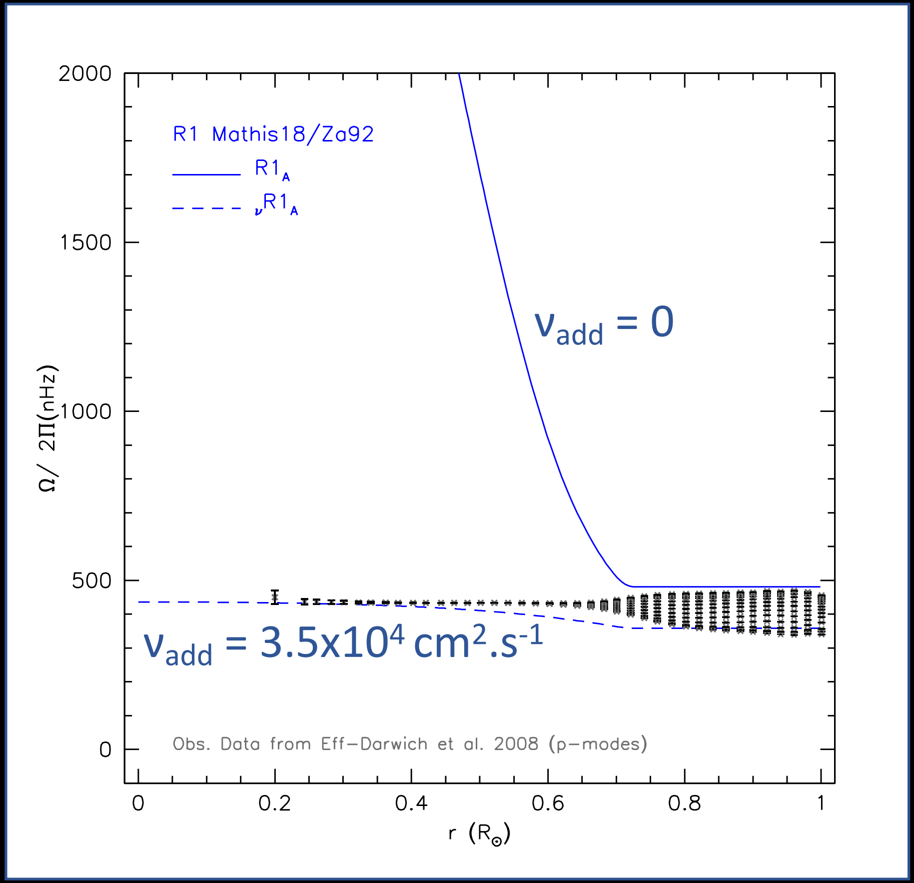
$$\rho \frac{\partial X_i}{\partial t} = \frac{1}{r^2}\frac{\partial}{\partial r}\left(r^2\rho\left(\boxed{D_{eff}}+\boxed{D_v}\right)\frac{\partial X_i}{\partial r}\right) - \frac{1}{r^2}\frac{\partial}{\partial r}\left(r^2\rho X_i \mathrm{v}_{\mathrm{Dmic,i}}\right) + m_i\left[\sum_j r_{ji} - \sum_k r_{ik}\right]$$

$$D_{\mathrm{eff}}(\underline{U_2}, \underline{D_h})$$

$$\rho\frac{d}{dt}(r^2\Omega) = \frac{1}{5r^2}\frac{\partial}{\partial r}(\rho r^4\Omega \boxed{U_2}) + \frac{1}{r^2}\frac{\partial}{\partial r}\left(\boxed{\nu_v} r^4 \frac{\partial\Omega}{\partial r}\right)$$

Simultaneous constraint of angular momentum and Li transports: Solar-type stars

Almost flat rotational profile of the Sun



Extra viscosity ν_{add}

(e.g. Eggenberger et al. 2012, Spada et al. 2016)

Transport of angular momentum

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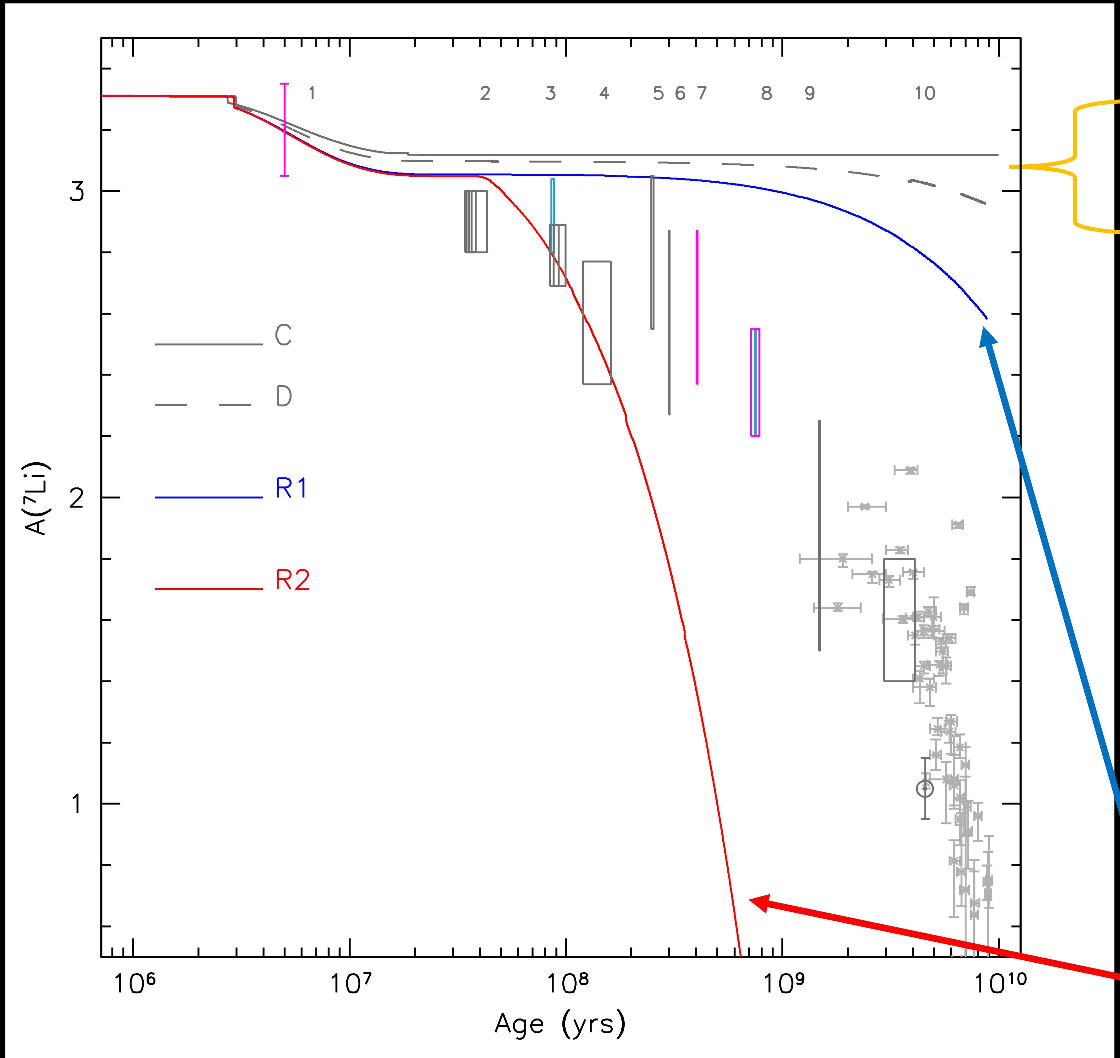
Dumont et al. 2021a, A&A 646, A48

Stellar modelling predictions



Adapted from Dumont et al. 2021a

Classical model: C (Only convection)
Atomic diffusion model: D (Convection + atomic diffusion)

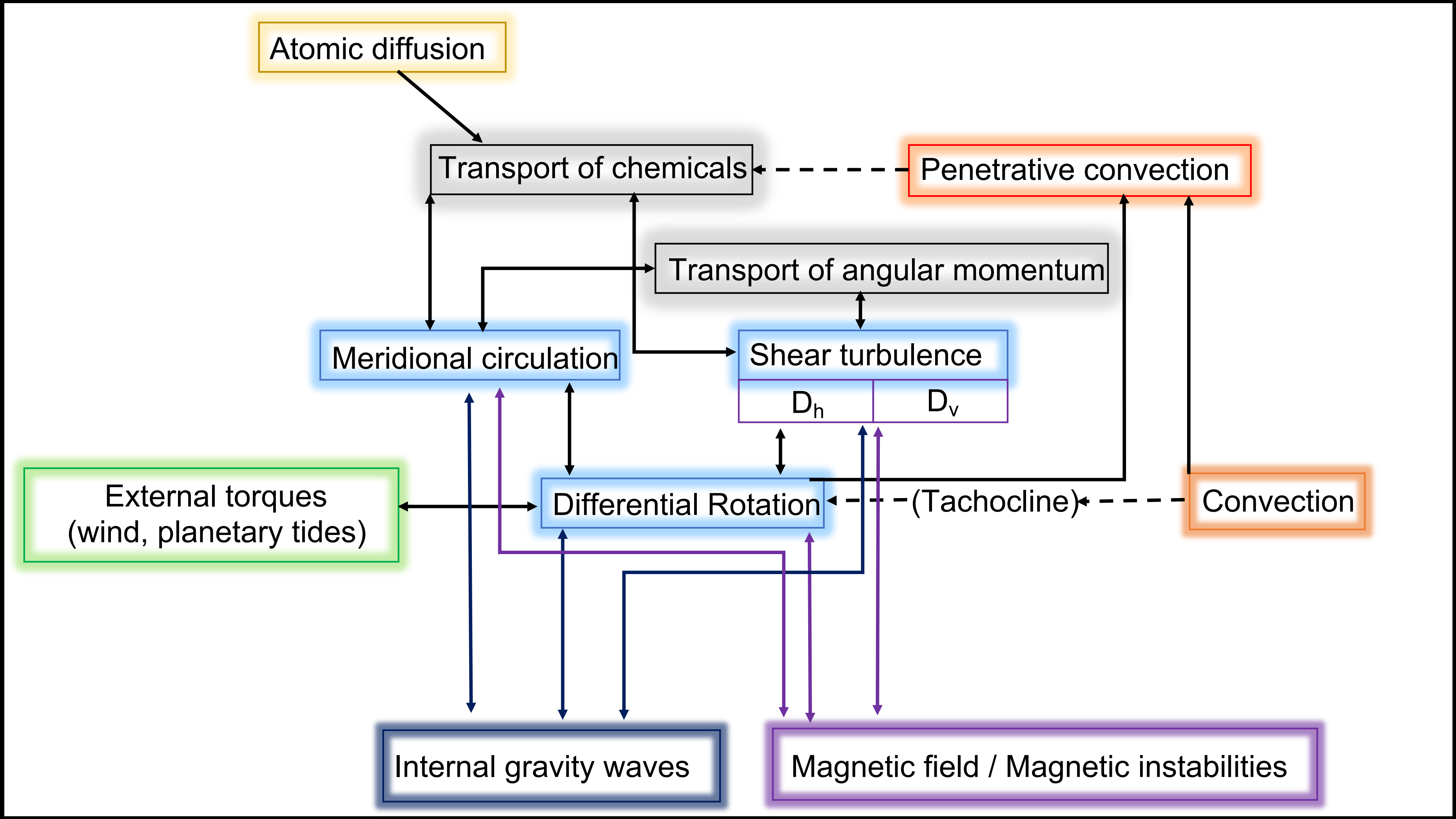
Non-standard Transport
Rotational mixing following Zahn 1992

- meridional circulation
- turbulence shear (horizontal and vertical, different couples Dh/Dv)

Prescription	Reference horizontal shear D_h , ν_h	Reference vertical shear D_v , ν_v
R1	Mathis et al. 2018	Zahn 1992
R2	Zahn 1992	Talon & Zahn 1997

Recent simulations are supporting R1 but it stays an open question: see ??? et al. 2022

Simultaneous transport of chemicals and angular momentum



Solar calibration

Classical model C

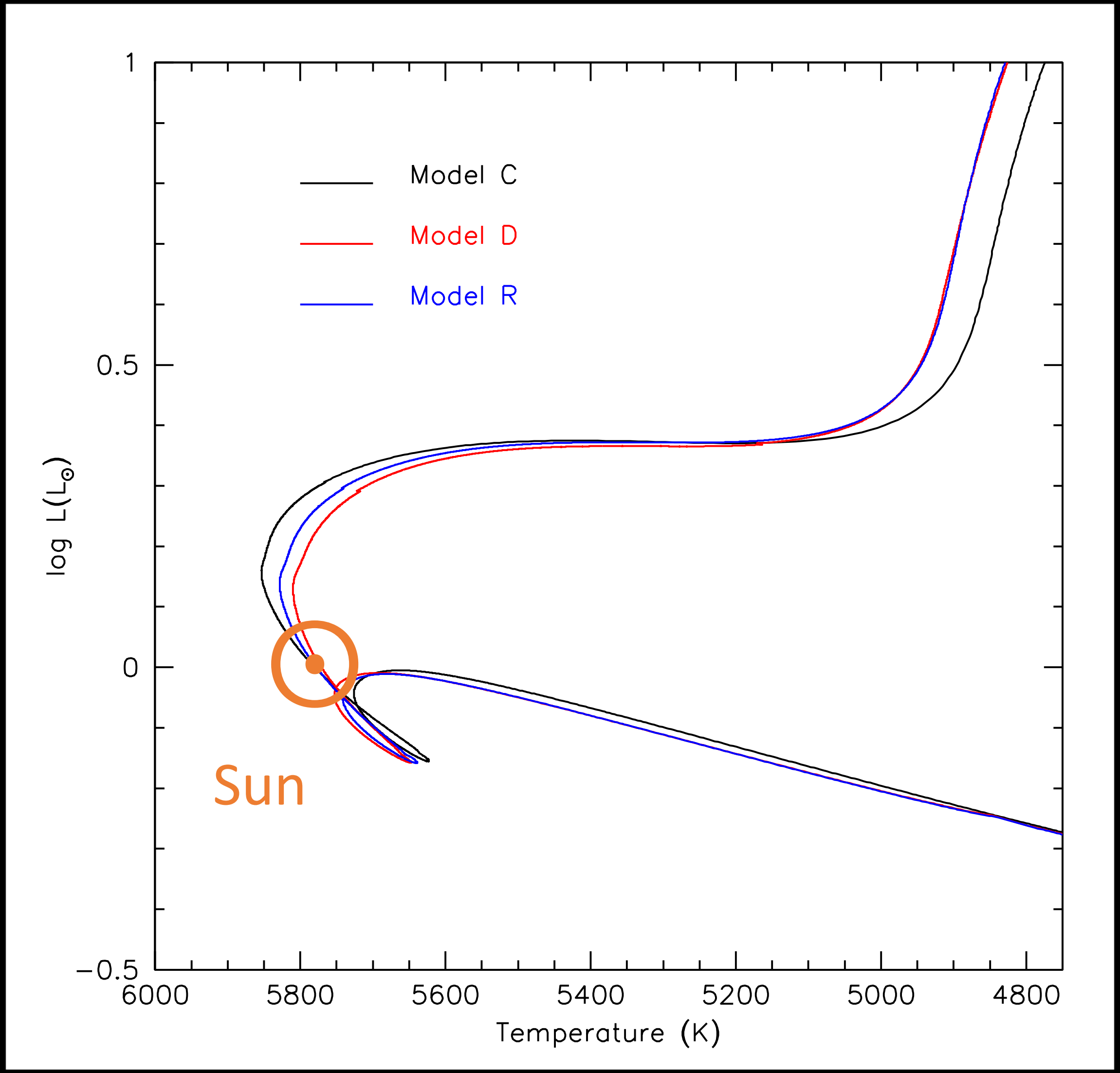
Standard model D

Non-Standard model R

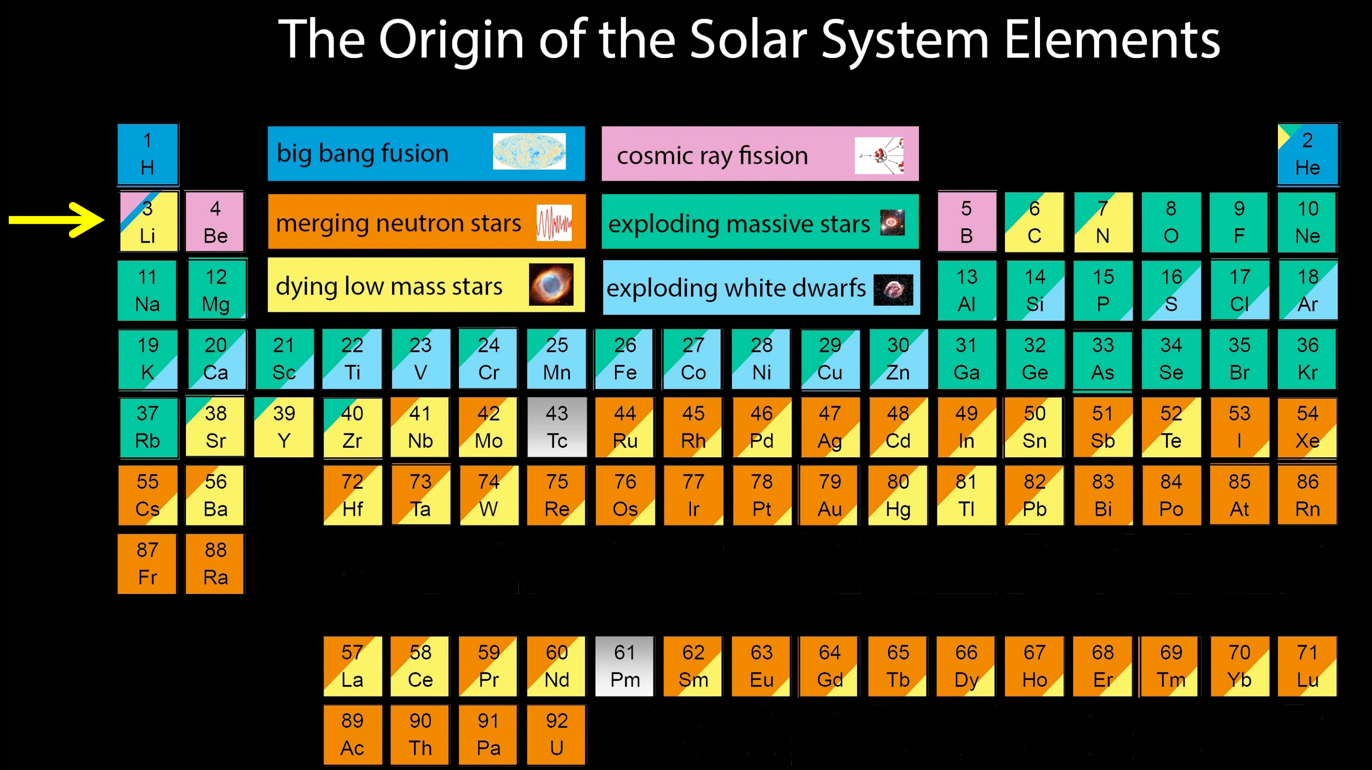
Solar calibration

Reach for a 1 $M_\odot$, $Z_\odot$ model and solar age the luminosity $L_\odot$, the radius $R_\odot$ and the $(Z/X)_\odot$ ratio of the Sun

Free parameters: Y_{ini}, α_{MLT}, Z_{ini}/X_{ini}



Transport of chemicals: Lithium



Graphic created by Jennifer Johnson

Astronomical Image Credits: ESA/NASA/AASNova

Lithium: third lightest element in the universe

$^{1}H = 0.7516$

$^{4}He = 0.2484$

$^{7}Li/^{1}H = 5.61 \times 10^{-10}$

(mass fractions from Coc & Vangioni 2017)

“We continue to find it slightly disconcerting that so uncommon an element as lithium should be so important for studying the structure of outer layers of stars, not to mention the early Universe. But so it is”

Trimble & Leonard (1994)