Stars and new physics
Lecture II

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Summary of Lecture I

- star is a solution of simple equations
- coefficients in these equations are sensitive to new physics
  - ✓ energy production and loss
  - ✓ energy transfer
  - ✓ presence of new particles
  - ✓ ….
- strong constraints on new-physics contributions
  - ✓ even from very rough estimates of solar lifetime





Can we do better? Dig inside the Sun!

- chemical composition:
  - ✓ spectroscopy plus Boltzmann (for heavy elements)
- power of thermonuclear reactions:
  - ✓ solar neutrinos
- distribution of matter in the Sun:
  - ✓ helioseismology

[spoiler: these three constraints cannot be satisfied simultaneously]





Solar composition: what is actually measured?

Observed solar spectrum → **Atmosphere + line formation**
3D structure · NLTE · atomic data → **Element abundances**

Solar photosphere

- atomic and molecular absorption lines
- 3D atmospheric structure and radiative transfer
- non-LTE populations, oscillator strengths, collisions, blends

Essential for **volatile elements**:
H, He, C, N, O, noble gases

Primitive meteorites

- mass spectrometry gives very precise abundance ratios
- best constraints for refractory elements
- highly volatile elements are strongly depleted

Meteoritic scale is tied to the photospheric abundance scale

➢ solar abundances are model-dependent inferences — not direct observables

Solar composition: low or high metallicity?

AAG21 — LOW Z

- time-dependent 3D RHD Stagger atmosphere
- full 3D non-LTE for C, N, O, Fe and many key elements
- atomic and molecular diagnostics combined
- convective velocities predict line profiles: no micro-/macroturbulence

Z/X = 0.0187 ± 0.0009

MB22 — HIGH Z

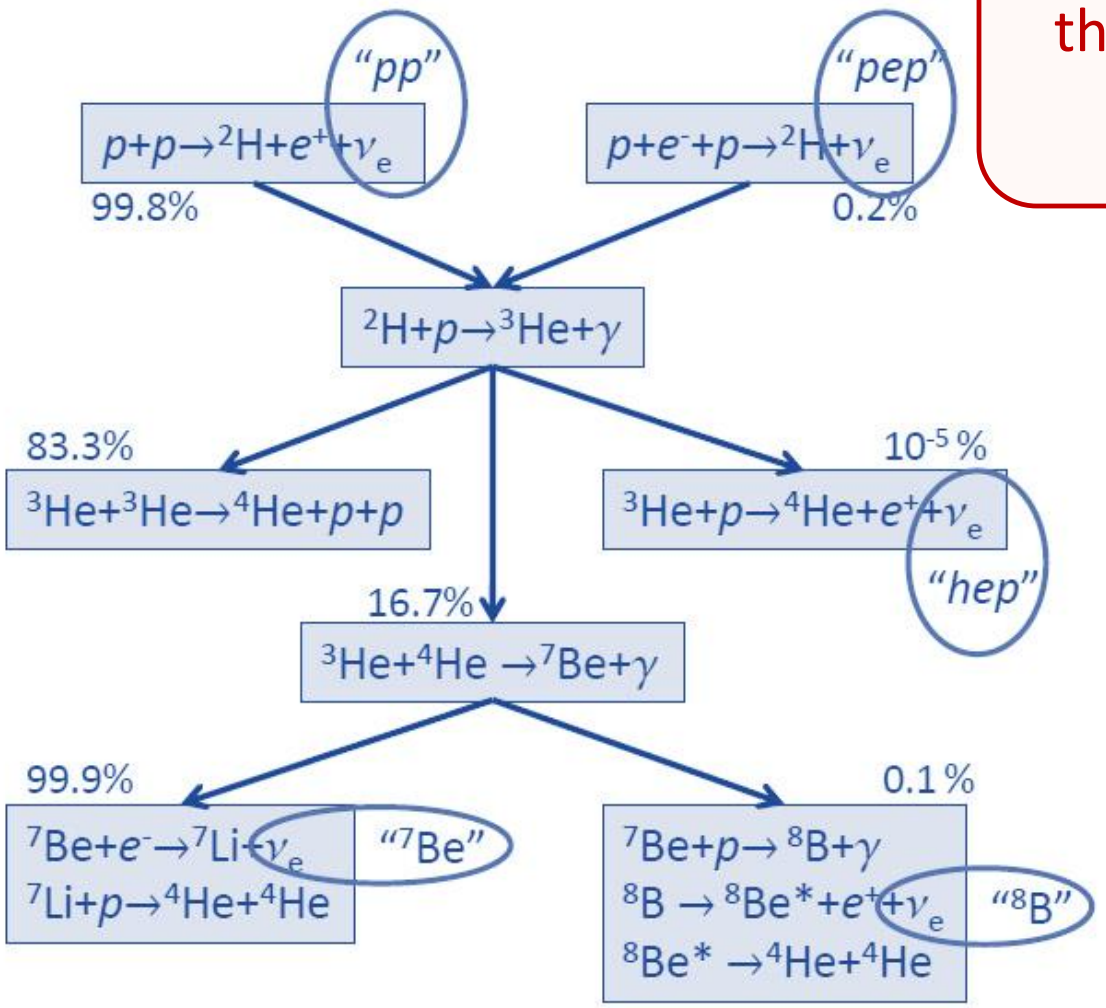
- MARCS 1D and averaged ⟨3D⟩ Stagger/CO5BOLD atmospheres
- new high-S/N IAG solar spectra
- non-LTE line formation
- new O I and N I oscillator strengths; different line selection and weighting

Z/X = 0.0225 ± 0.0014

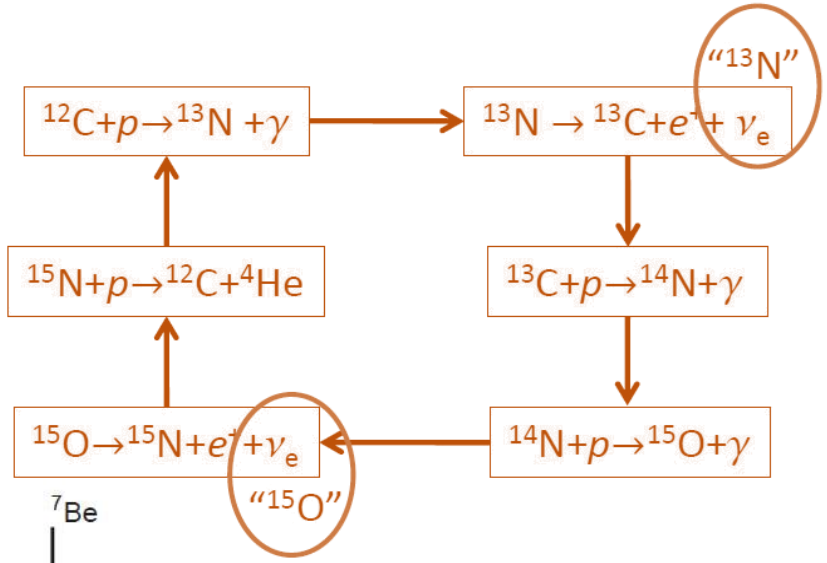
$$\Delta A(\mathrm{C,N,O}) = (+0.10, +0.15, +0.08)\,\mathrm{dex},$$

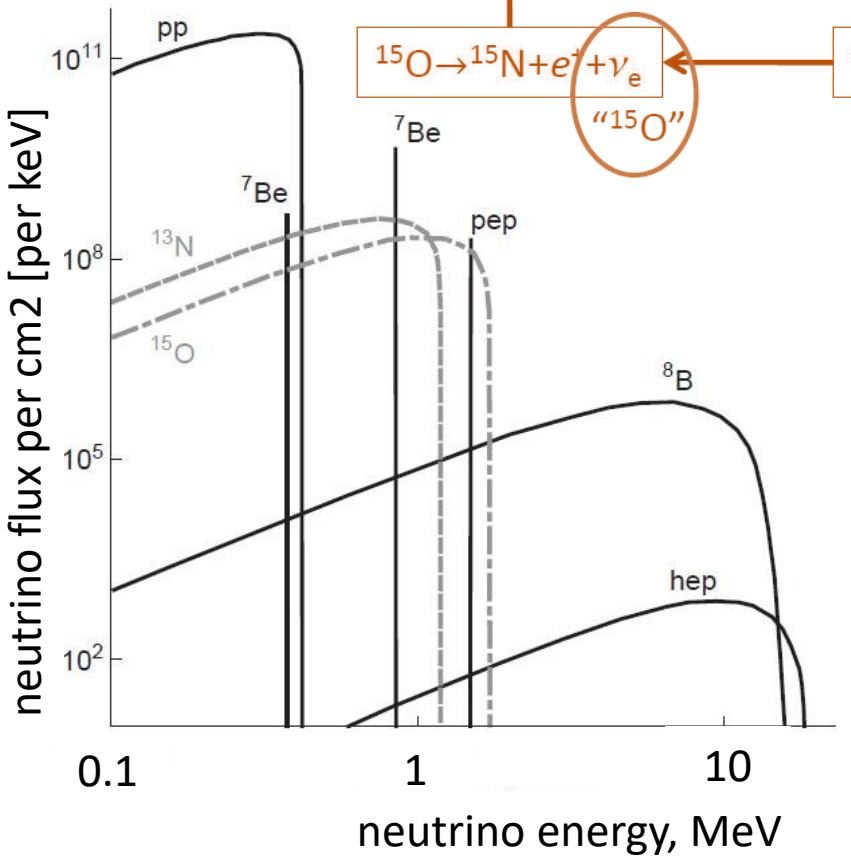
$$\frac{(Z/X)_{\mathrm{MB22}}}{(Z/X)_{\mathrm{AAG21}}} = \frac{0.0225}{0.0187} \simeq 1.20$$

Solar neutrinos



direct test of thermonuclear reactions!





Helioseismology

➢ small variations of stellar equations about the solution (now non-radial!):

pressure perturbations: $p'(r,\theta,\varphi,t) = p'(r)\, Y_\ell^m(\theta,\varphi)\, e^{i\omega_{n\ell m}t}$

shifts:

$$\boldsymbol{\xi}(r,\theta,\varphi,t) = \left(\xi_r(r),\ \xi_h(r)\frac{\partial}{\partial\theta},\ \frac{\xi_h(r)}{\sin\theta}\frac{\partial}{\partial\varphi}\right) Y_\ell^m(\theta,\varphi)\, e^{i\omega_{n\ell m}t}$$

where $\xi_h = \dfrac{1}{\omega_{n\ell m}^2 r}\left(\dfrac{p'}{\rho} + \Phi'\right)$ are horizontal shifts, Φ' is the gravitational potential

- Cawling approximation: background Φ' (not changed by the wave)
- wavelength much smaller than the solar size

➡ wave equation

the wave vector $|\boldsymbol{k}|^2 = k_r^2 + k_h^2,$

$$k_h^2 = \frac{S_\ell^2}{c_s^2}, \quad k_r^2 = \frac{1}{c_s^2}\left[S_\ell^2\left(\frac{N^2}{\omega_{n\ell m}^2} - 1\right) + \omega_{n\ell m}^2 - \omega_c^2\right]$$

where:

$$S_\ell^2 = \frac{\ell(\ell+1)c_s^2}{r^2} \qquad N^2 = g\left[\frac{1}{\Gamma_1}\frac{d\ln p}{dr} - \frac{d\ln\rho}{dr}\right]$$

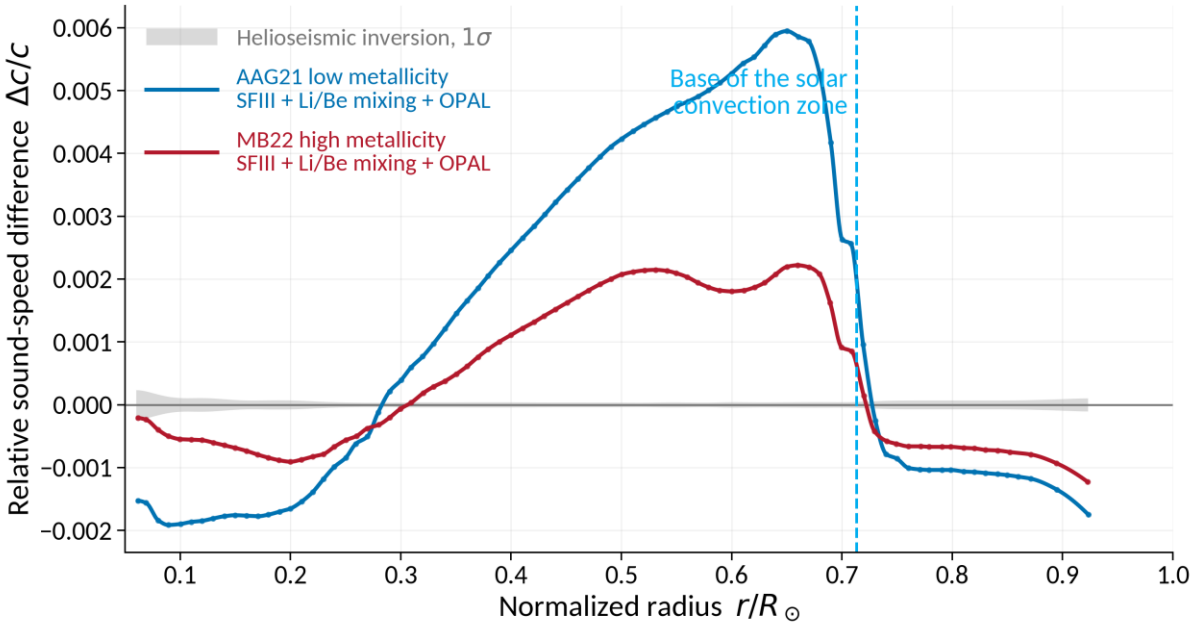
$$\omega_c^2 = \frac{c_s^2}{4H_\rho^2}\left(1 - 2\frac{dH_\rho}{dr}\right), \quad \frac{1}{H_\rho} = -\frac{d\ln\rho}{dr}, \quad c_s^2 = \frac{\Gamma_1 p}{\rho}$$

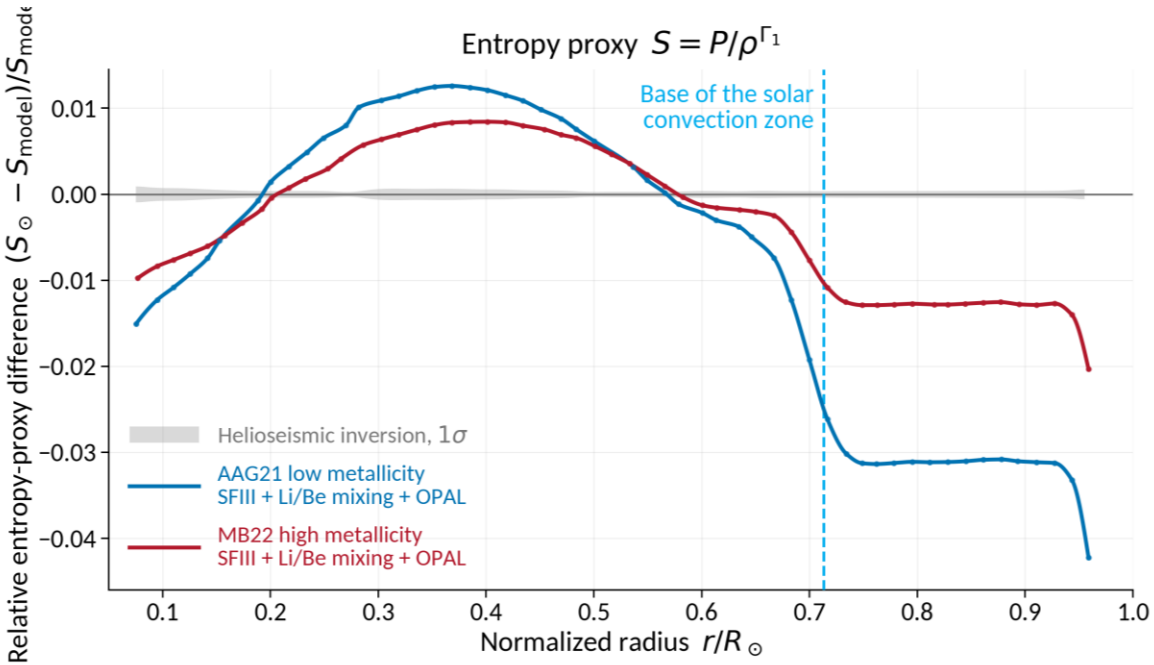


Dig inside the Sun: putting things together - helioseismology

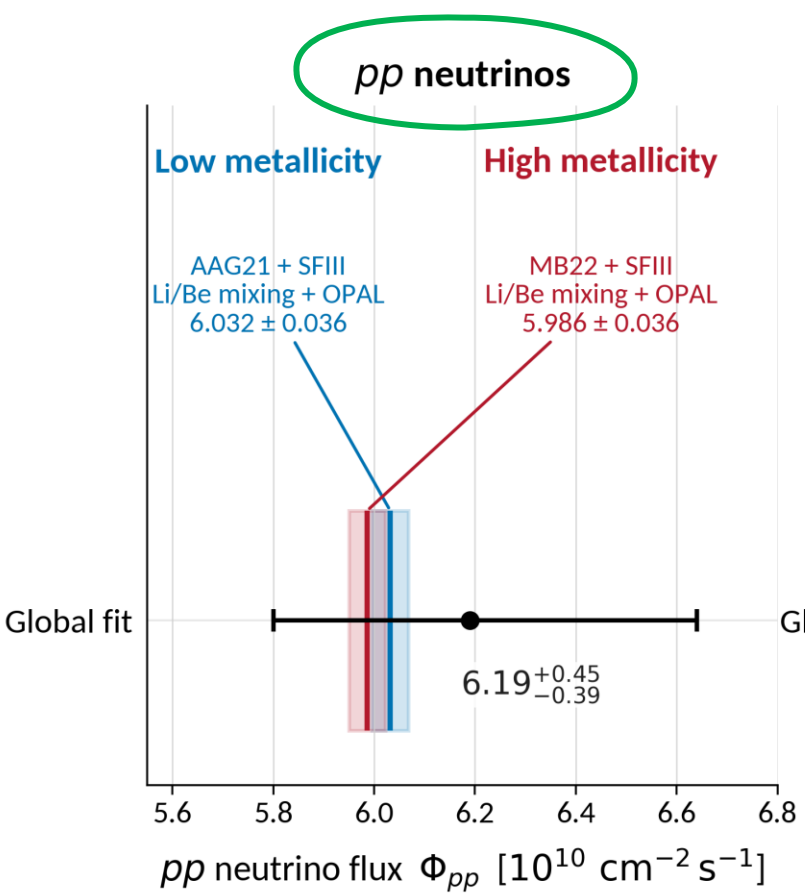
- several thousands of modes detected from surface velocities (Doppler), and…

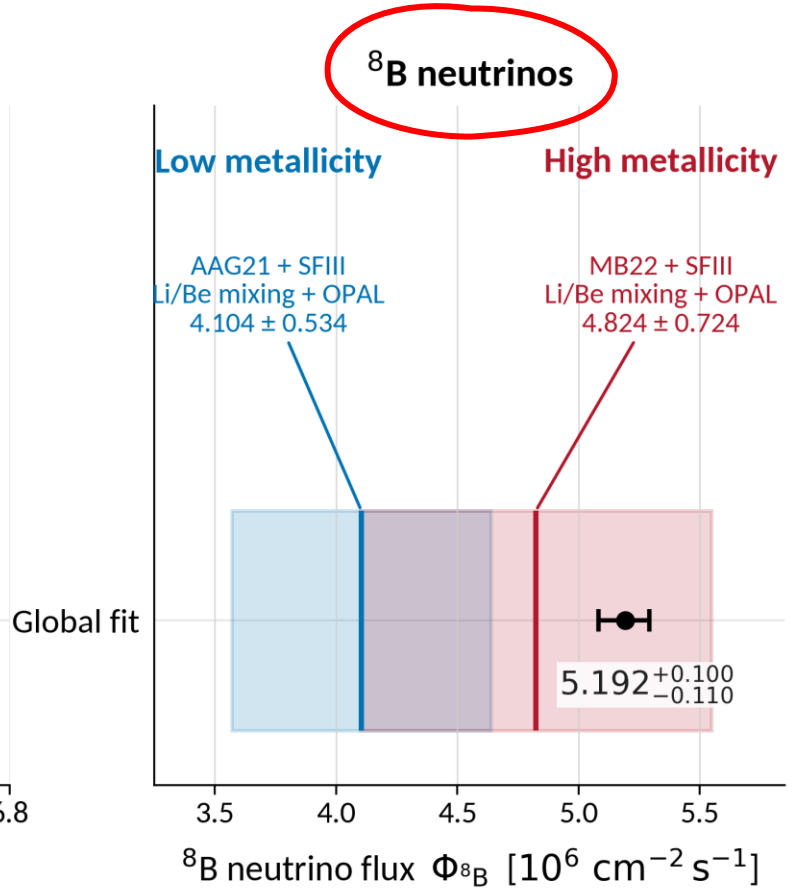
sound speed

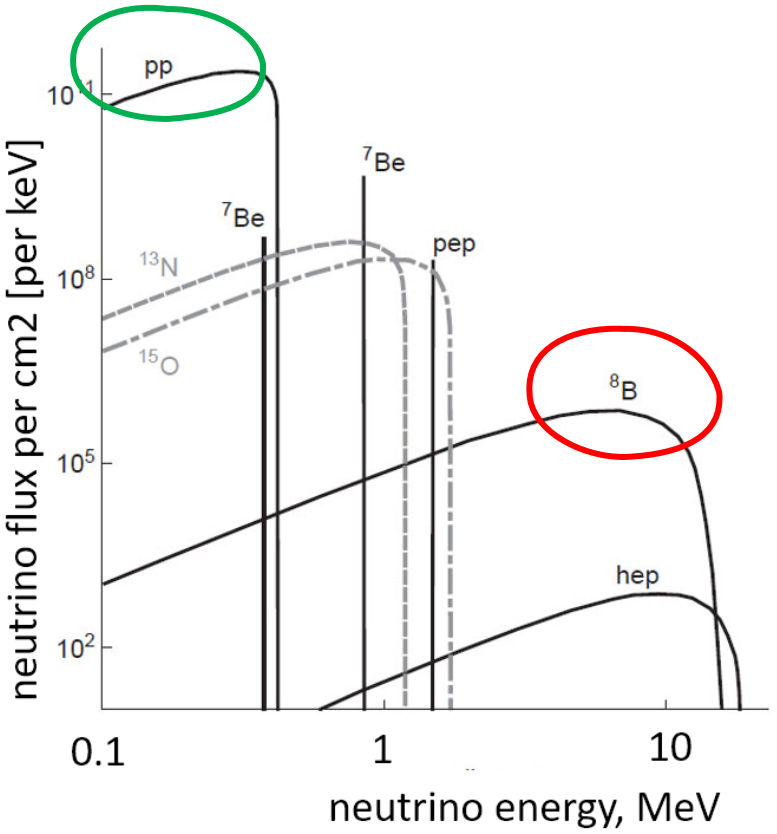




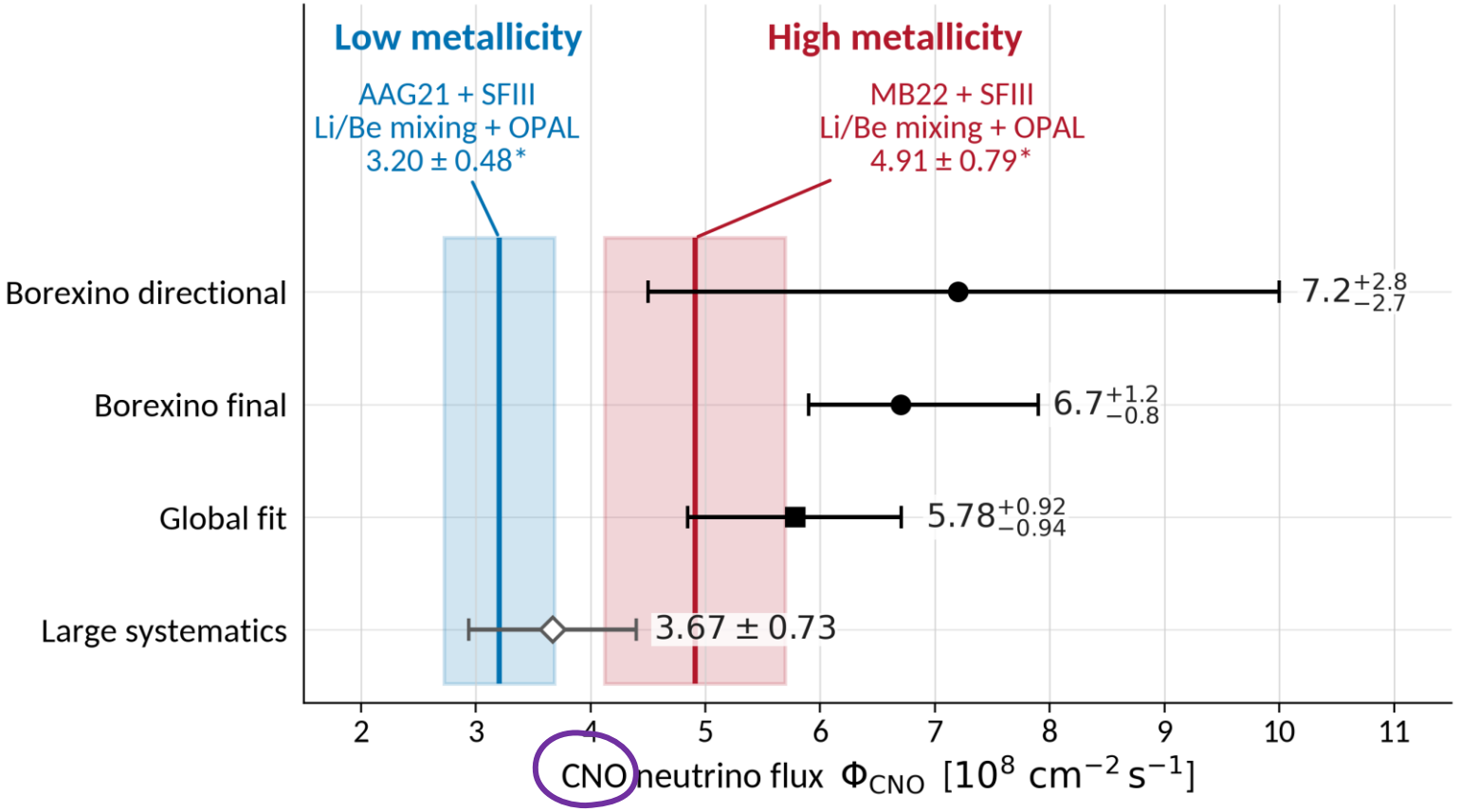
Dig inside the Sun: putting things together – neutrinos from the *pp* chain

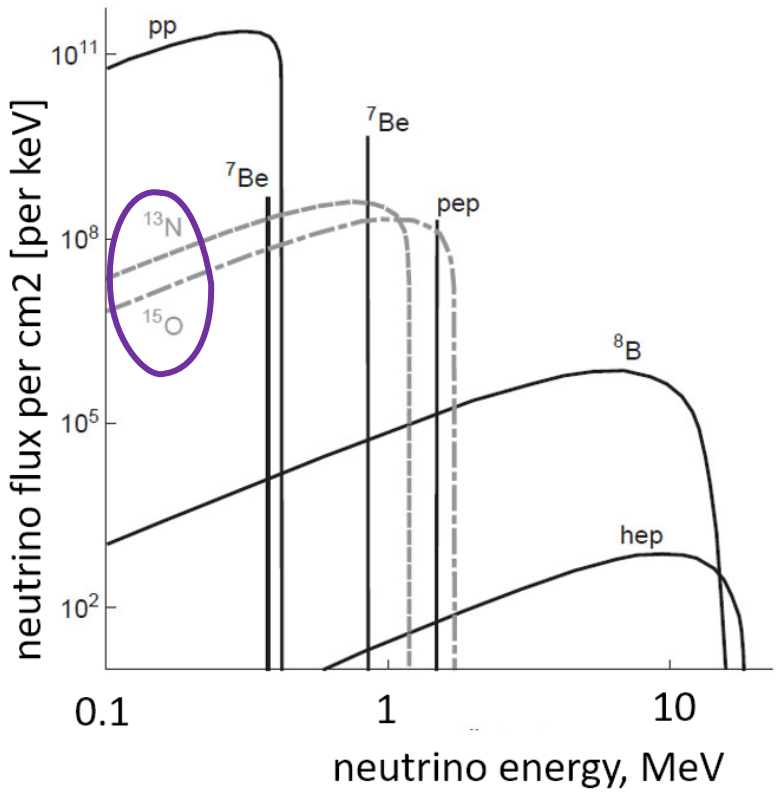






Dig inside the Sun: putting things together – neutrinos from the CNO cycle





Solar model problems

Low metallicity: composition +, structure – , neutrino +–

High metallicity: composition – , structure +– , neutrino +

New physics: composition +, structure +, neutrino –

new/missing physics remains required

Part II: stellar evolution

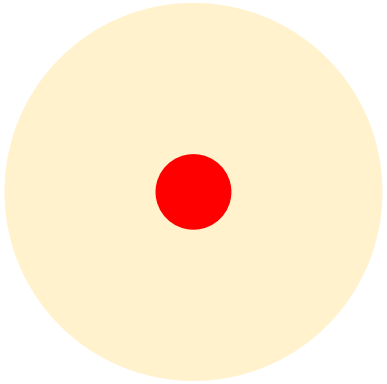
Stars are not born equal

- ➢ they have different masses $$\boxed{\frac{dN}{dM} \propto M^{-2.3}, \qquad M \gtrsim 0.5\, M_\odot}$$
- cutoff at low masses, no thermonuclear reactions for $M/M_\odot < 0.08$
- cutoff at high masses, haven't seen above $M_{\rm max} \sim 200\text{–}300\, M_\odot$
- R136a1 in a young stellar cluster in Tarantula nebula in Large Magellanic Cloud:

  $M_{\rm current} \simeq 233\, M_\odot$, $M_{\rm init} \gtrsim 250\, M_\odot$
- ➢ they have different chemical composition
- primordial 0.75 H, 0.25 He, but they are not primordial
- ➢ mass and composition determine everything (see stellar equations)



Hydrogen burning: main sequence versus red giants



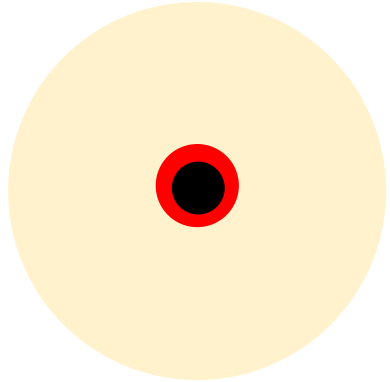
main sequence: H burns in the central part, produces He

- temperature, size, luminosity constant (determined by mass and stellar equations)
- may take billions of years
- all stars go through this stage

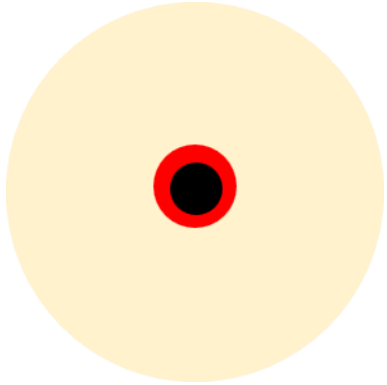
Further evolution depends on the mass, we focus on masses about (0.5 – 2) solar

red giant:
degenerate (electrons!) He core, H burns in a shell

- temperature, size, luminosity change (see next slide)
- fast evolution



Red giants: fast and interesting evolution



H burns in the shell, He falls on the core, core mass grows

- degenerate core: $R_c \propto M_c^{-1/3}$
- temperature at the shell: $T_{\rm shell} \propto \dfrac{M_c}{R_c} \propto M_c^{4/3}$
- hydrogen burning strongly temperature-dependent:

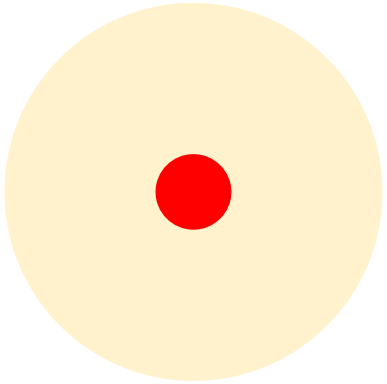
$$\varepsilon(\rho, T) \propto \rho^{\alpha_1} T^{\alpha_2} \qquad \alpha_1 = 1, \;\; \alpha_2 \simeq 5$$

- higher temperature ➡ faster burning ➡ more He falls (positive feedback!)

- energy needs to be transferred to the surface, convection
- energy needs to be emitted from the surface, $L = 4\pi R^2 \sigma T_{\rm eff}^4$
- but opacity does not allow to increase the surface temperature: $\kappa \propto \rho T^{-7/2}$

➡ need to increase area to have the required luminosity! red giant (warm and huge)

Helium flash and helium burning: TRGB and horizontal branch



high temperature allows for helium burning

- again non-degenerate, strong temperature dependence,
- flash at roughly fixed core mass
- stars with different shell masses but the same core mass have same luminosities (horizontal branch in any luminosity plot)

$$\alpha + \alpha \rightleftharpoons {}^{8}\mathrm{Be}$$

$${}^{8}\mathrm{Be} + \alpha \longrightarrow {}^{12}\mathrm{C}^{*} \longrightarrow {}^{12}\mathrm{C} + \gamma$$

then the story repeats, this time with carbon core, but no more flashes

New physics to be constrained with stars

axions and axion-like particles (interact with photons and maybe electrons, but very weakly)
hidden photons (like photons, but slightly massive and almost isolated)
neutrino magnetic moment (beyond the Standard Model may be large)
millicharged particles (like electrons, but with charge million times smaller)
chameleons, Kalutza-Klein gravitons, WIMPs,…

white-dwarf luminosity function
average rate of WD cooling
Blinnikov, Vysotsky 1990

HB stars to red giants ratio
time scale of helium burning
Dicus et al. 1978

pulsating white dwarf period change
rate of individual WD cooling
Isern et al. 1992

tip of the red-giant branch
time of helium ignition
Raffelt 1990

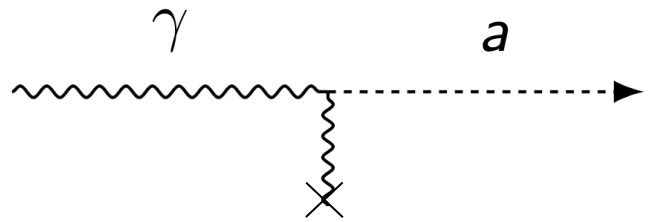
Axion-photon interactions: the Primakoff-Sikivie process

$$\mathcal{L}_{a\gamma} = -\frac{g}{4}\, a\, F_{\mu\nu}\widetilde{F}^{\mu\nu}\,, \qquad F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu\,, \qquad \widetilde{F}^{\mu\nu} = \frac{1}{2}\,\epsilon^{\mu\nu\rho\sigma} F_{\rho\sigma}$$

Electromagnetic field-strength tensor

a = new pseudoscalar particle (axion)

Assumptions:
nonrelativistic, nondegenerate plasma, $T \ll m_e$



$$\gamma + (Z, e) \longrightarrow a + (Z, e).$$

External electric field of nuclei and electrons

$$\frac{\mathrm{d}\sigma_{\gamma\to a}}{\mathrm{d}\Omega} = \frac{1}{2}\left(\frac{gZe}{4\pi}\right)^2 \frac{\left|\boldsymbol{k}_\gamma \times \boldsymbol{k}_a\right|^2}{q^4}$$

$$\boldsymbol{q} = \boldsymbol{k}_\gamma - \boldsymbol{k}_a$$

(diverges at $q \to 0$, screening required)



Axion-photon interactions: the Primakoff-Sikivie process (continued)

screening: $\dfrac{Ze}{4\pi r} \longrightarrow \dfrac{Ze}{4\pi r} e^{-k_s r}$,

k_s^{-1} is the Debye–Hückel screening length

$$k_s^2 = \frac{4\pi\alpha}{T} n_B \left(Y_e + \sum_j Z_j^2 Y_j \right).$$

n_B: baryon number density,

Y_e, Y_j: number abundances per baryon.

screened cross section:

$$\frac{\mathrm{d}\sigma_{\gamma\to a}}{\mathrm{d}\Omega} = \frac{g^2 Z^2 \alpha}{8\pi} \frac{\left|\boldsymbol{k}_\gamma \times \boldsymbol{k}_a\right|^2}{q^4} \frac{q^2}{q^2 + k_s^2}$$

energy production rate:

$$\epsilon\rho = \int_0^\infty \mathrm{d}\omega\, \omega\, \sigma_{\mathrm{tot}}(\omega)\, n_{\mathrm{target}}\, n'_\gamma(T,\omega) \Rightarrow \boxed{\epsilon\rho \simeq \frac{g^2}{4\pi} T^7 F\left(\frac{k_s^2}{4T^2}\right)}$$

$$n'_\gamma(T,\omega) = \frac{1}{\pi^2} \frac{\omega^2}{e^{\omega/T} - 1}.$$

In a HB star: $T \sim 10^8$ K, $\rho \sim 10^4$ g cm^{-3} $\Rightarrow$ $\boxed{\epsilon_a \sim 30 \left(\dfrac{g}{10^{-10}\ \mathrm{GeV}^{-1}}\right)^2 \mathrm{erg\,g^{-1}\,s^{-1}}}$

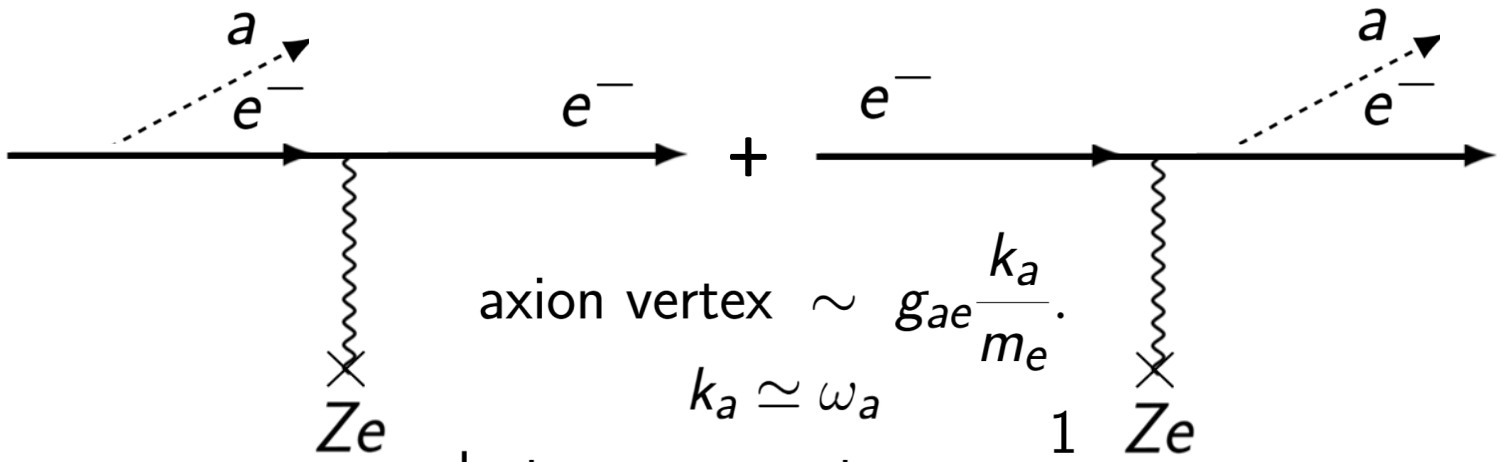


Axion-electron interactions: Bremsstrahlung

$$\mathcal{L}_{ae} = \frac{g_{ae}}{2m_e}\,\bar{e}\gamma^\mu\gamma_5 e\,\partial_\mu a$$

$$\simeq -ig_{ae}\,a\,\bar{e}\gamma_5 e$$

for an on-shell electron line



$$\text{axion vertex} \sim g_{ae}\frac{k_a}{m_e}.$$

$$k_a \simeq \omega_a$$

$$\text{electron propagator} \sim \frac{1}{\omega_a}$$

$$\mathcal{M}_{\rm brem} \sim \mathcal{M}_{\rm Coul}\,\frac{g_{ae}}{m_e} \times (\text{angular factor})$$

Important for red giants: Pauli blocking
(only electrons close to Fermi surface can scatter to empty space)

$$\epsilon_a \propto g_{ae}^2\,T^4.$$

$$\epsilon_a^{\rm D} = \frac{\pi\alpha^2 g_{ae}^2}{60\,\rho m_e^2}\,T^4\left(\sum_j n_j Z_j^2\right)F$$

Before the helium ignition: $T \simeq 10^8$ K, $\rho \simeq 2\times10^5$ g cm^{-3}.

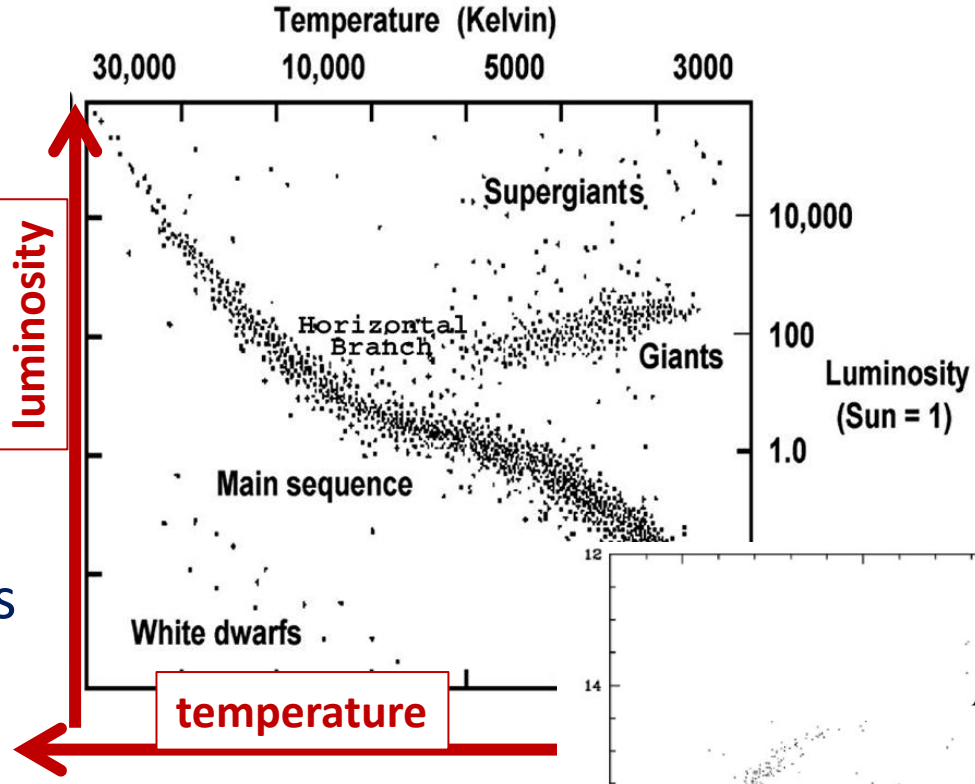
$$\epsilon_a^{\rm TRGB} \sim 1.3\,g_{13}^2\ {\rm erg\,g^{-1}\,s^{-1}}$$

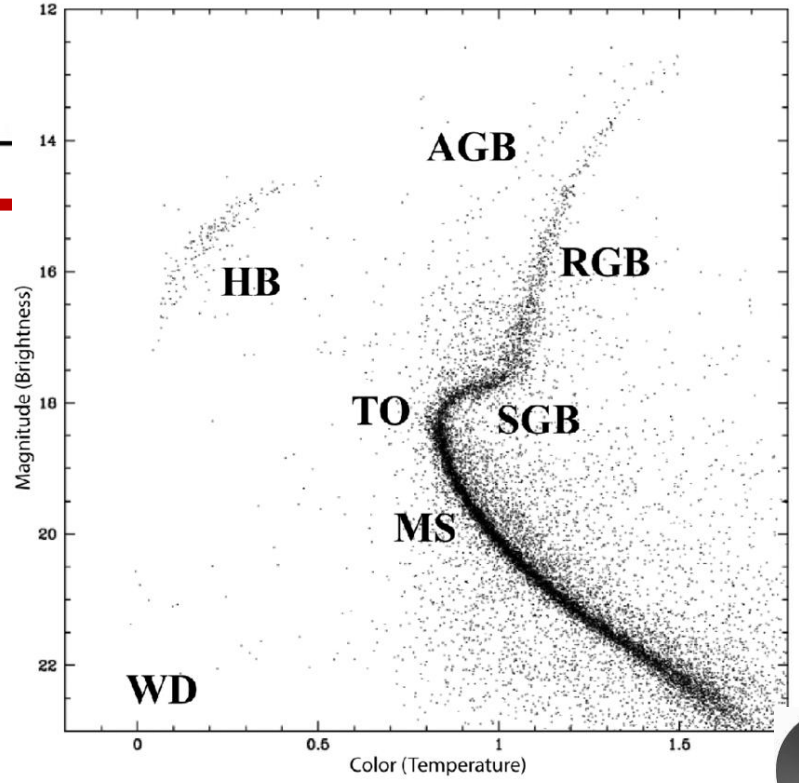
$$g_{13} \equiv \frac{g_{ae}}{10^{-13}}$$

Globular clusters

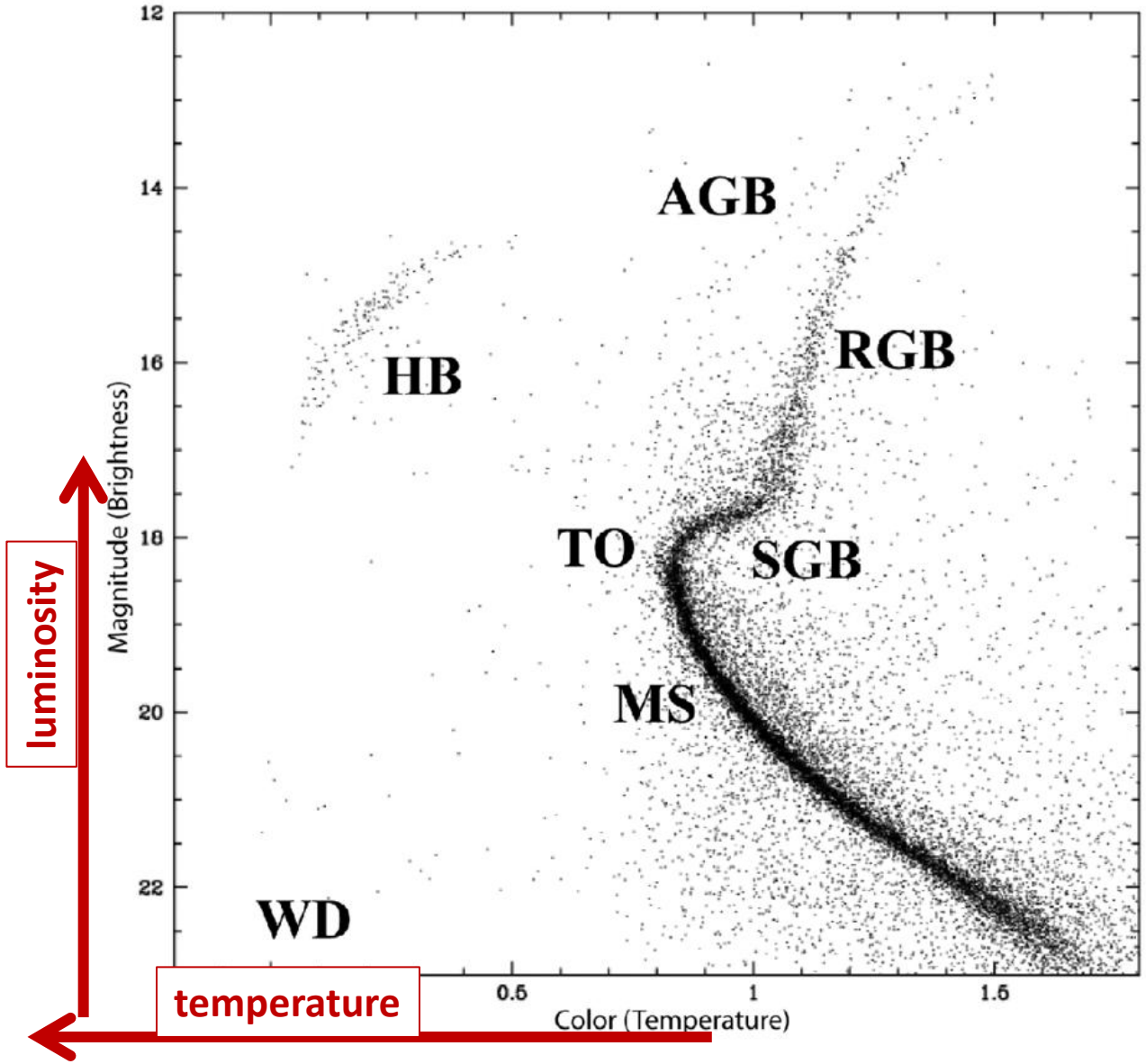
- millions of stars formed at the same time from the same gas
- star formation stopped (remaining gas blown by supernova explosions)
- color-magnitude diagram shows evolutionary tracks of very similar stars





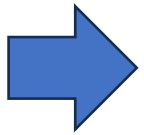


Globular clusters



Tip of the Red Giant Branch (TRGB)

• the brightest red giant indicates the moment of the helium ignition
• extra losses due to axions make the brightest red giant brighter than expected
• important to know the distance (GAIA parallaxes change the game)



- axion-electron interactions
- neutrino magnetic moment
- millicharged particles

…

The R parameter (ratio of HB to RG stars)



- axion-photon interactions
- nuclear processes

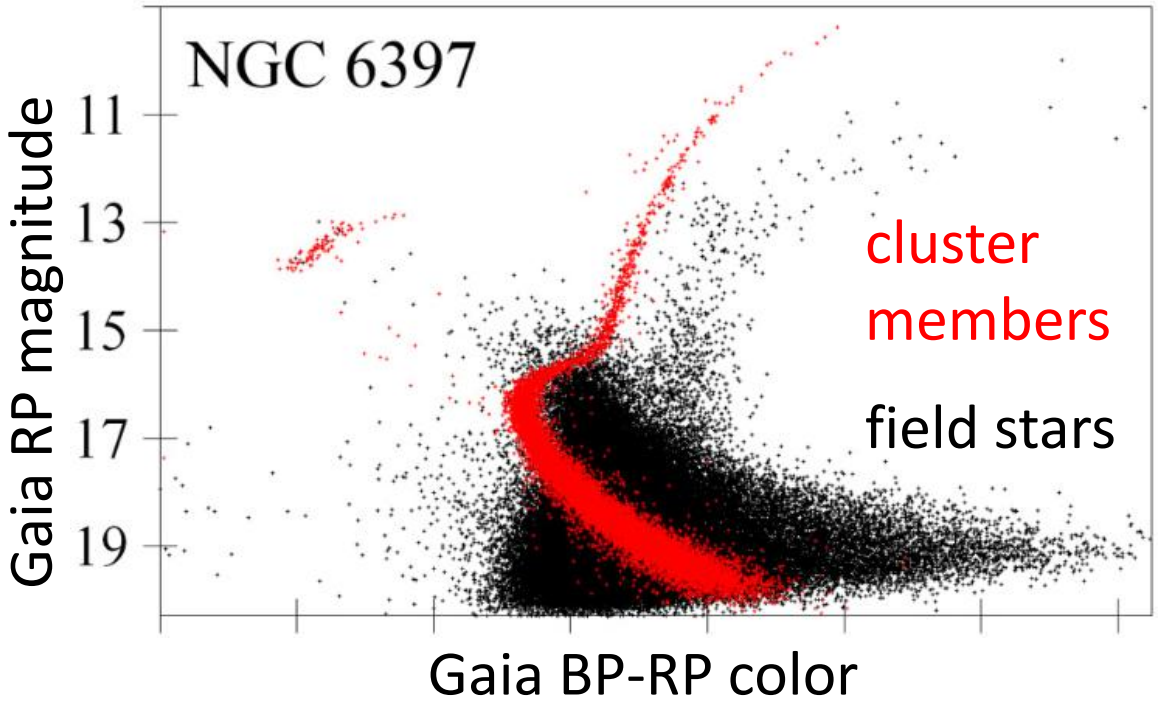
…

• ratio of the number of He burning stars to the number of red giants
• CMD gives a “stroboscopic” view of the evolutionary track
• many uncertainties cancel in the ratio
• losses due to axions accelerate He burning and reduce R

Globular clusters with Gaia

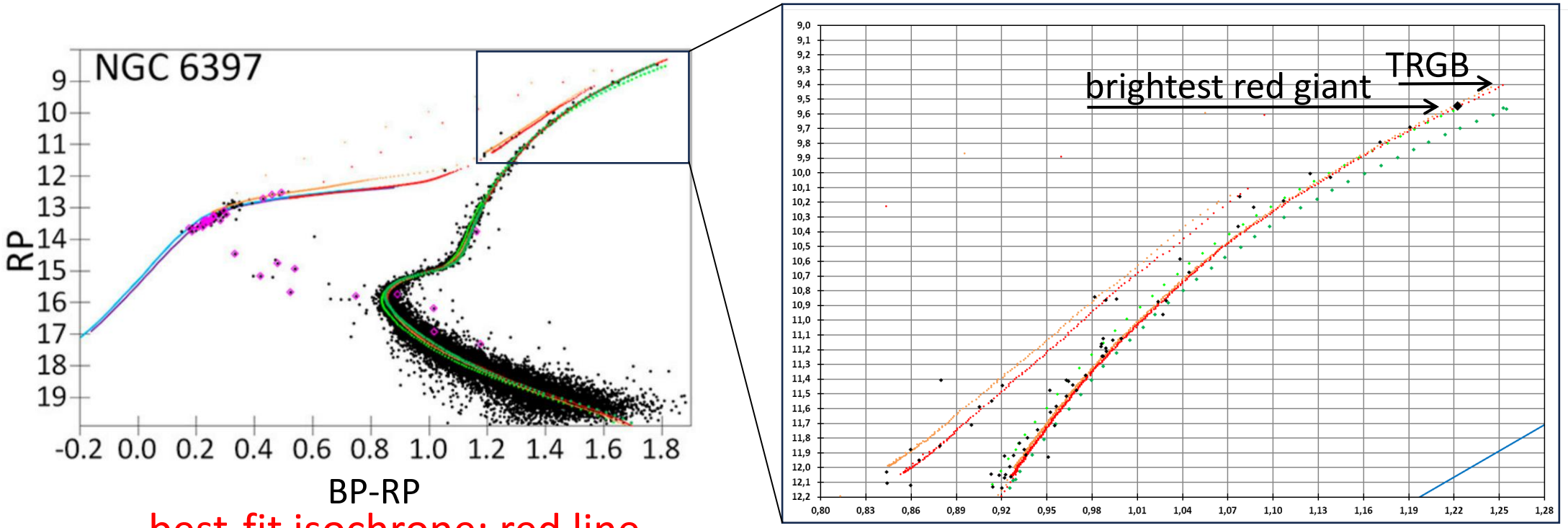
- Gaia DR3: parallaxes and proper motions for 1.9 billion stars
- easy selection of confirmed cluster members
- combination with HST and terrestrial photometry (Stetson) to resolve the very center





Isochrone fitting

- isochrone: model color-magnitude diagram (CMD) for a cluster as it is observed
- depends on cluster parameters, is produced by stellar evolution codes
- fits of the observed clean CMD ➡ the set of **parameters of each cluster**



best-fit isochrone: red line

Comparison of axion constraints

ALP-electron coupling			
group	experiment (technique)	Ref.	g_{ae}, 10^{-13}
laboratory	torsion pendulum	[31]	< 74500
solar	XENONnT	[32]	< 19
stellar	TRGB	[16]	< 1.48
this work			< 0.52

ALP-photon coupling			
group	experiment (technique)	Ref.	$g_{a\gamma}$, 10^{-11} GeV^{-1}
laboratory	OSQAR	[33]	< 3550
solar	CAST	[34, 35]	< 5.7
stellar	AGB stars	[23]	< 4.7
B field	pulsars	[36]	< 0.4
this work			$6.5^{+1.1}_{-1.3}$

from ST 2024

- red giants: the strongest limits on the axion-electron coupling
- horizontal branch: persistent indications for anomalous losses (but we probably will understand them very soon…)



Summary

- star is a solution of simple equations
- coefficients in these equations are sensitive to new physics
  - ✓ energy production and loss
  - ✓ energy transfer
  - ✓ presence of new particles
  - ✓ ….
- strong constraints on new-physics contributions
  - ✓ even from very rough estimates of solar lifetime
  - ✓ still have unsolved problems with structure of the Sun!
- stellar evolution can be studied observationally
  - ✓ strongest constraints on exotic energy losses
- physical models to test include exotic light particles, nonstandard properties of neutrino, dark matter etc.

Thank you! (for your understanding)



