Stellar evolution models in the Gaia sky

Corinne Charbonnel

Why do we care ?

Ages, masses, initial/present chemical composition

Stellar populations studies (Pop I, II, open and globular clusters)

→ Chemical tagging, age-metallicity relation

→ Population synthesis

→ Galactic archeology, dynamics

→ Formation, evolution, accretion of the various Galactic substructures

Nucleosynthesis yields

→ Chemical evolution

Variability

→ Galactic and extra-galactic distance scales

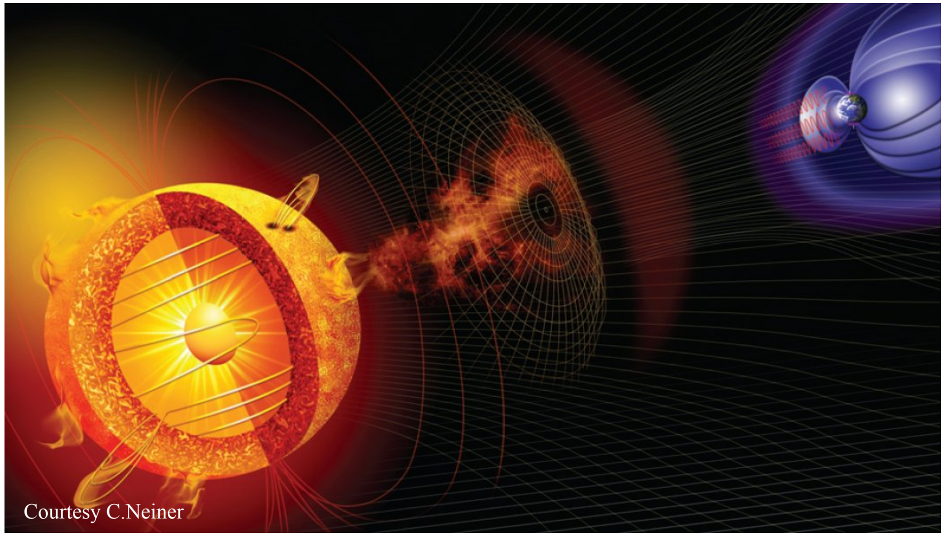
Star-planet interactions

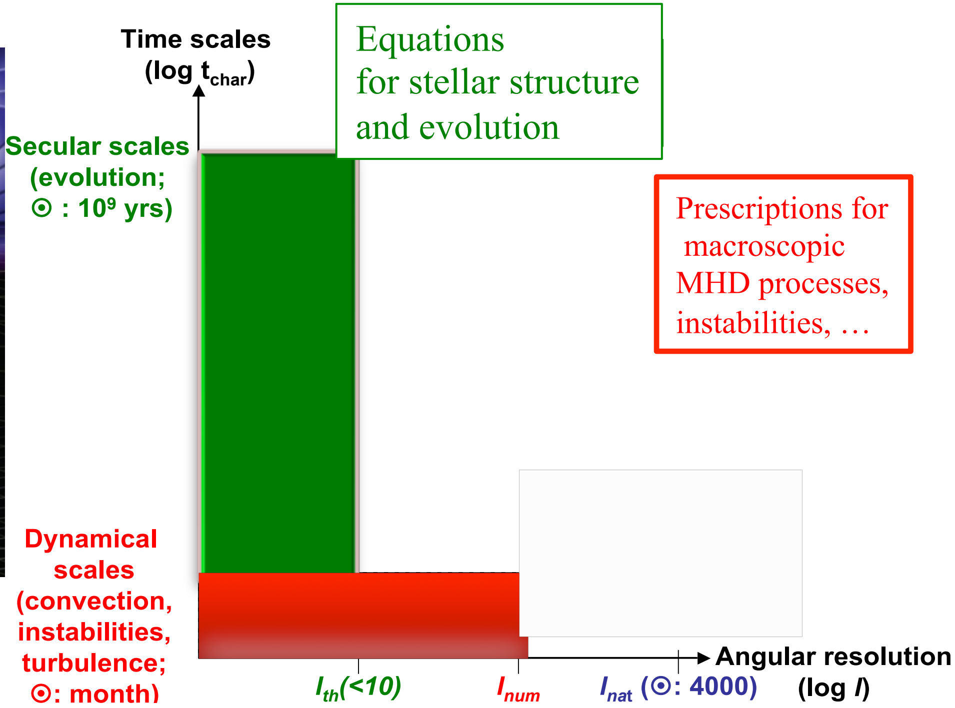
→ Formation and dynamics of the systems

→ Habitability

From the complex 3D

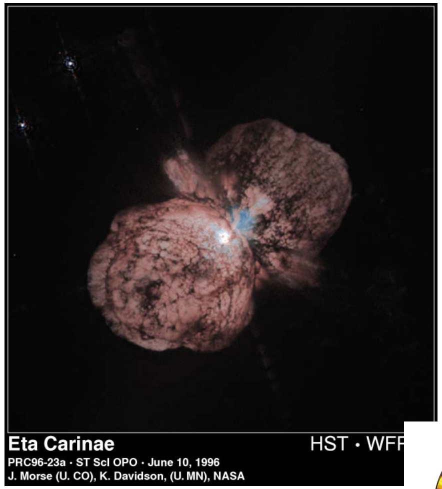
Stellar models

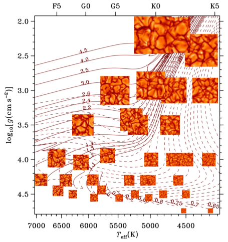


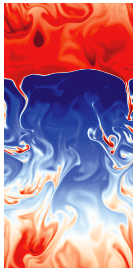


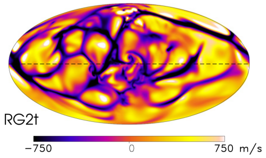
Equations
for stellar structure
and evolution

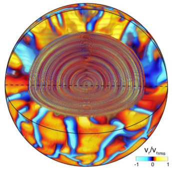
Prescriptions for
macroscopic
MHD processes,
instabilities, …







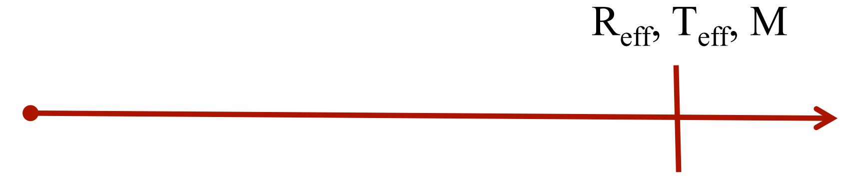




Alvan et al. (2014)

to the « simple » 1D

Spherically symmetric system in hydrostatic equilibrium



center
r = 0

photosphere
$r = R_*$

3D Euler hydro equations of fluid motion

+

Spherically symmetric system in quasi hydrostatic equilibrium

Equations – 1D

$$\frac{\partial r}{\partial m} = -\frac{1}{4\pi r^2 \boxed{\boldsymbol{\rho}}}$$

Mass conservation

$$\frac{\partial P}{\partial m} = -\frac{Gm}{4\pi r^4} + \frac{\boxed{\boldsymbol{\Omega}}^2}{6\pi r}$$

Hydrostatic equilibrium

$$\frac{\partial L}{\partial m} = \boxed{\boldsymbol{\epsilon_{\mathrm{nuc}}}} - \boxed{\boldsymbol{\epsilon_{\mathrm{grav}}}} - \frac{\partial \boxed{\boldsymbol{U}}}{\partial t} + \frac{P}{\boldsymbol{\rho}^2}\frac{\partial \boldsymbol{\rho}}{\partial t}$$

Energy conservation

$$\frac{\partial T}{\partial m} = -\frac{GmT}{4\pi r^4 P}\boxed{\boldsymbol{\nabla}}$$

$$\text{with } \nabla = \frac{\mathrm{d}\ln T}{\mathrm{d}\ln P} = \begin{cases} \nabla_{\mathrm{rad}} = \frac{3}{16\pi acG}\frac{\kappa L_P P}{m_P T^4} \\ \nabla_{\mathrm{con}} = \left(\frac{\partial \ln T}{\partial \ln P}\right)_{\mathrm{ad}} = \frac{P\delta}{C_P \rho T} \end{cases}$$

Energy transport

$$\left(\frac{\partial X_i}{\partial t}\right) = \left(\frac{\partial X_i}{\partial t}\right)_{\boxed{\mathrm{nuc}}} + \left(\frac{\partial X_i}{\partial t}\right)_{\boxed{\mathrm{transport}}}$$

Chemicals

Boundary conditions
m = 0 → r = 0, L = 0
m = $M_* - M_{\mathrm{atmos}}$,
Model atmosphere → R_*, L_*

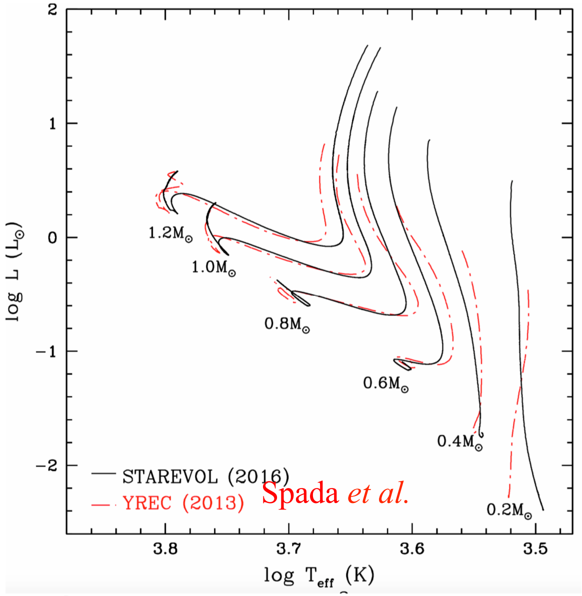
r radius of a sphere inside the star, m mass inside the sphere
L net luminosity escaping the sphere, U internal energy
Ω angular velocity, κ opacity (no magnetic field)

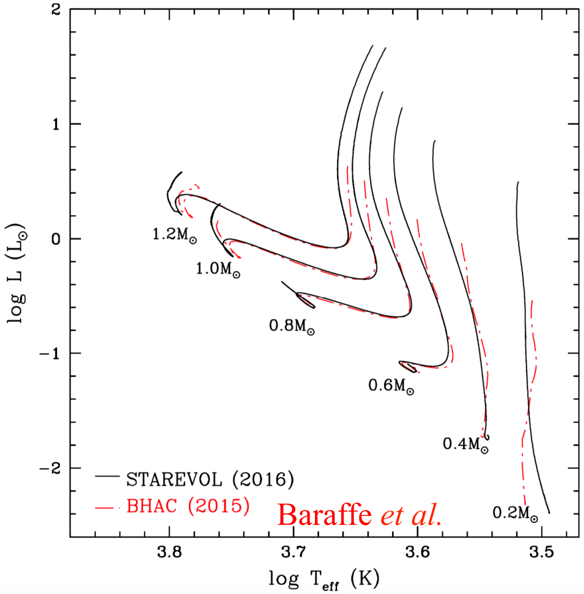
Each quantity depends on the position in the star, and evolves with time

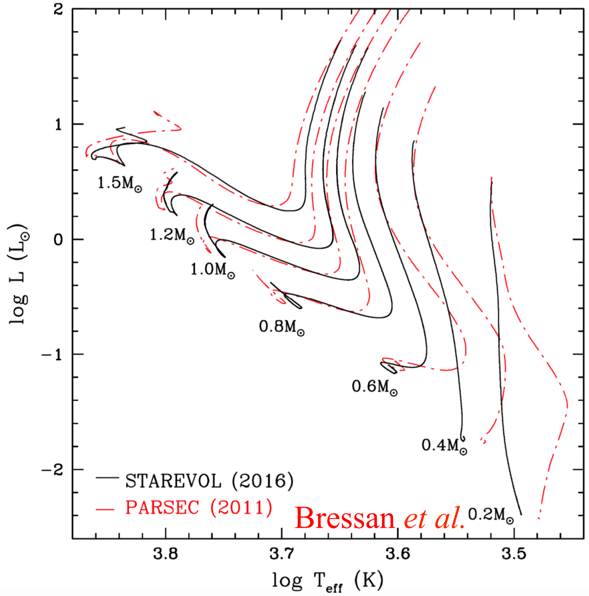
Lebreton et al. (2014) for the writing, Lagrangian form

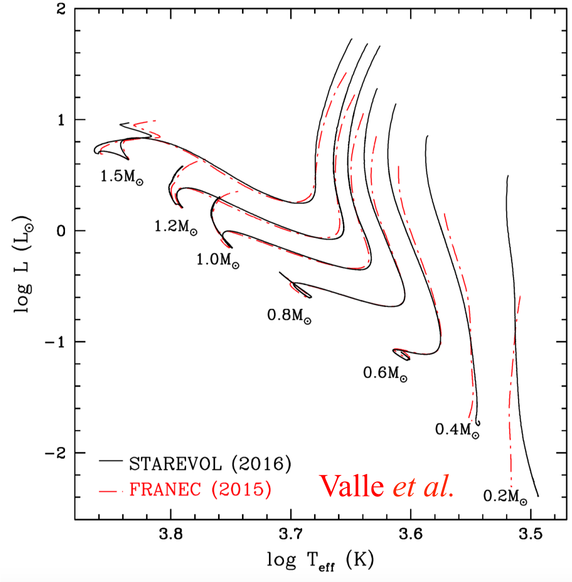
Modelling uncertainties

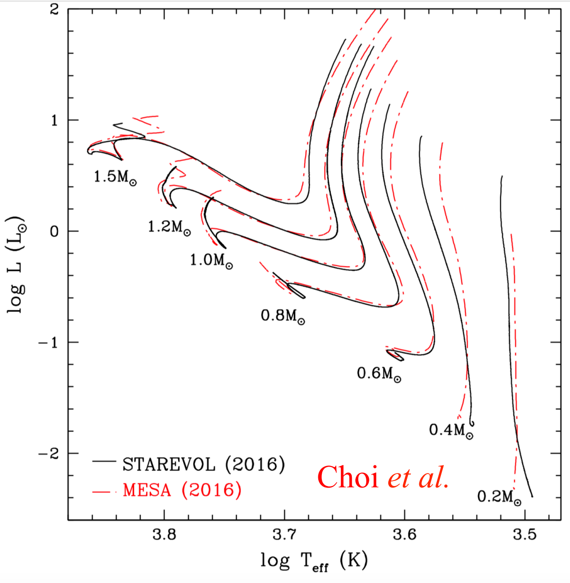
Comparison of $Z_\odot$ **standard** models for **low-mass stars** (PMS and MS)

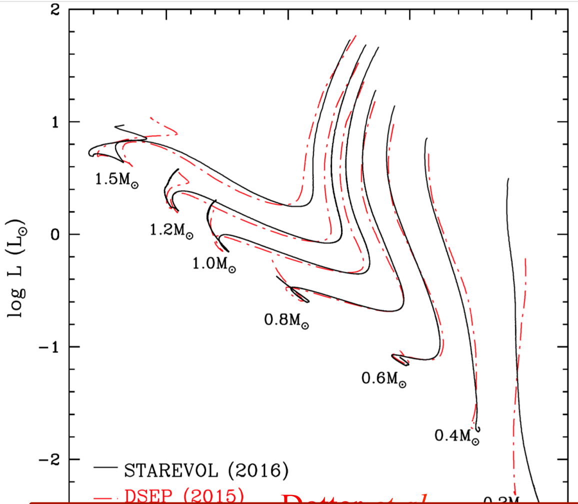












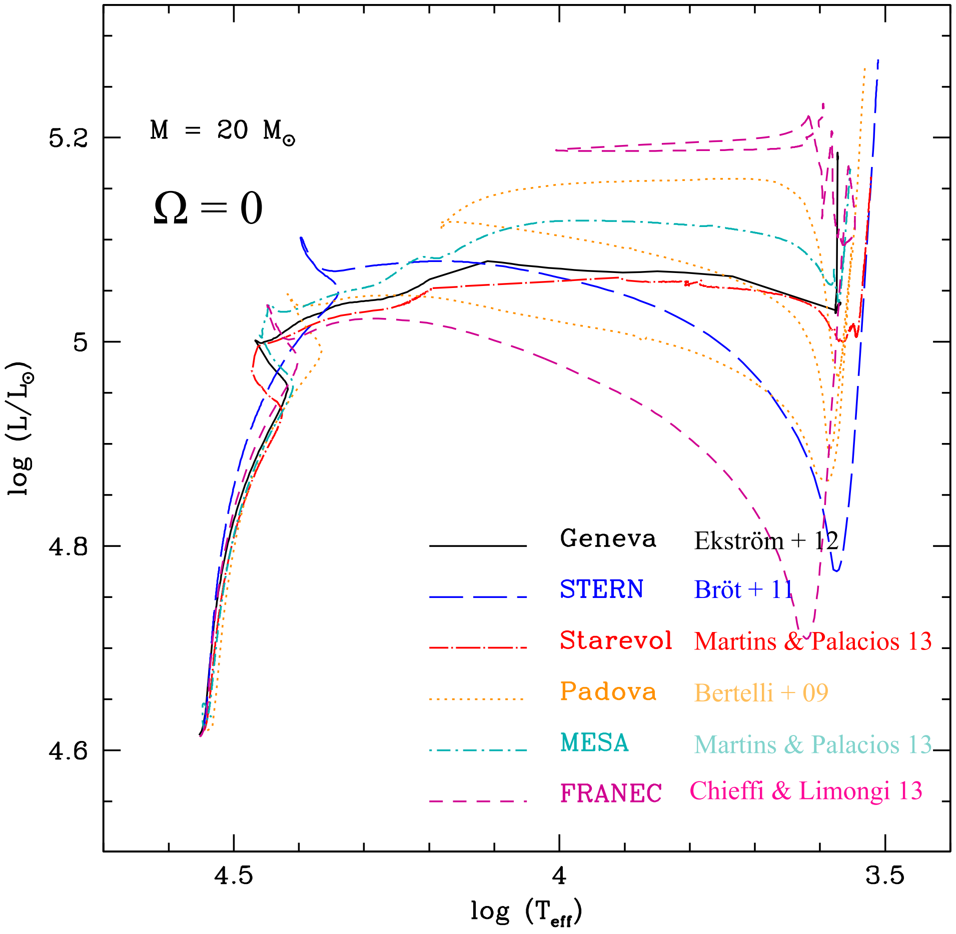
τ_{SP} $(1,2M_\odot)$
4,92Ga
4,49Ga
4,88Ga
4,85Ga
-
4,62Ga
4,58Ga
4,83Ga

Main sequence lifetime (~ 10 %)

Amard (2016)

Comparison of
$Z_\odot$ **standard** models for **massive stars**

Modelling uncertainties



MS lifetime (Myrs) : (~ 17 %)
7.819 – 8.173 – 8.535 – 9.100 – 8.598 – 9.085

Martins & Palacios (13)

Modelling

Initial conditions:
M, **chemical composition**, rotation

Equations, structure and evolution:
Spherical symmetry, quasi hydrostatic equilibrium
rotation, magnetic field, …

Boundary conditions:
Model atmosphere

Numerics

Calibration(s):
HRD (main sequence width,
red and blue populations,
HB morphology, …)
Surface abundances
Asteroseismology
Helioseismology

Full **description of the plasma**
through **microscopic processes**:
Eos, opacity, nuclear reactions
atomic diffusion, energy
production/loss/transport

Macroscopic MHD processes:
Convection, mass loss,
rotation, magnetic field,
internal gravity waves,
double-diffusive and other instabilities

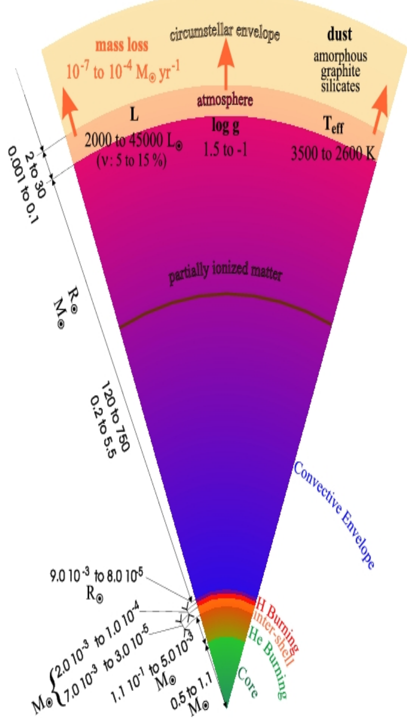


Fig AGB courtesy M.Forestini

Stellar parameters
L, Teff, R, age, P_{rot} ...
Stellar **structure**
P(r), T(r), …
Asteroseismic properties
Yields
Nucleosynthesis
wind, radiation, ...

$$\boxed{X + Y + Z = 1}$$

Initial chemical composition

$[M/H] = \log(\mathbf{Z/X}) - \log(Z/X)_\odot$

$[M/H] = [Fe/H]$

Solar abundance scale : $X_\odot + \mathbf{Y_\odot} + Z_\odot = 1$

Photospheric $\mathbf{Z_\odot/X_\odot}$

Calibration:
Solar model → $(\mathbf{Y_\odot}, \alpha_{MLT})$

$1M_\odot$, $R_\odot$, $L_\odot$ @ $t_\odot$

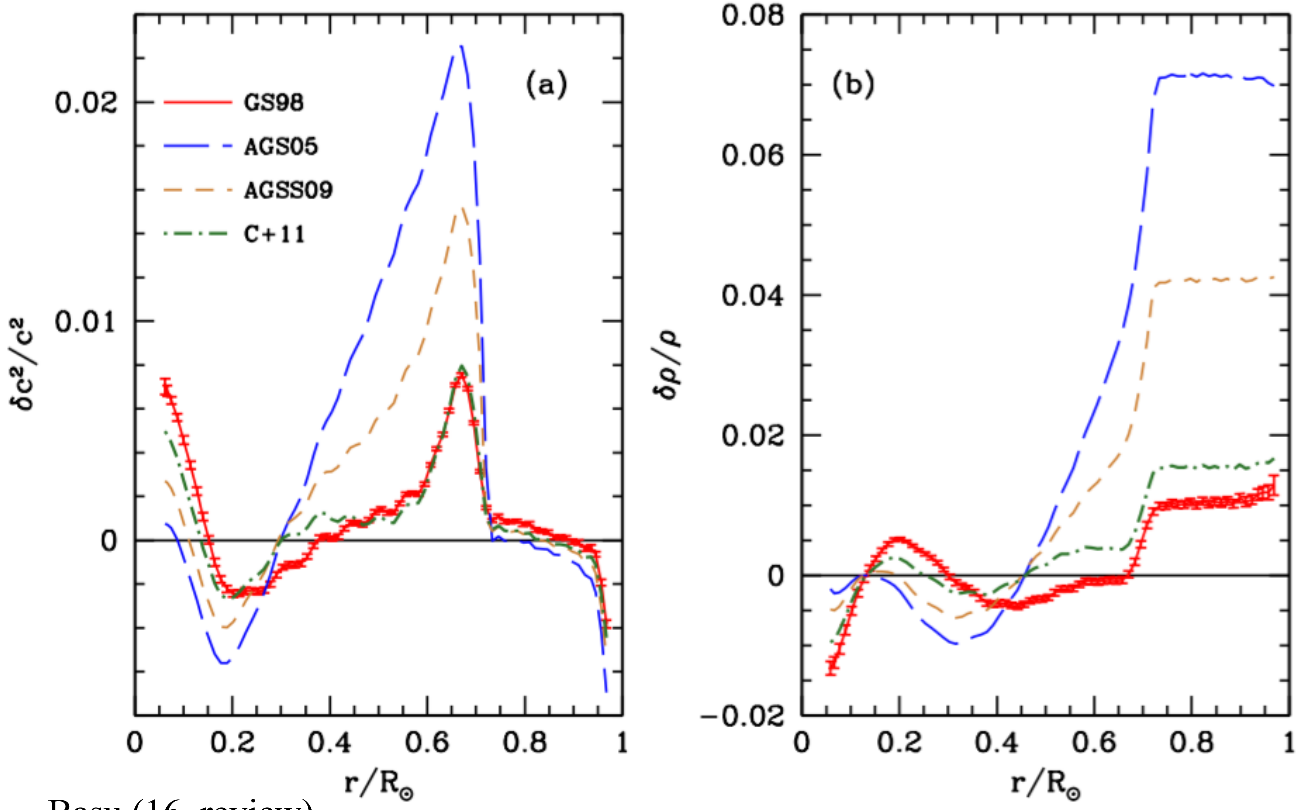
10^{-3} to 10^{-5}

3D model atmospheres, NLTE, improved atomic data

→ Decrease of C, N, O, Ne, Ar, (Z/X)

Decrease of O/H by 39% and of (Z/X) by 25 % from GS98 to AGSS 09

$\mathbf{Z_\odot/X_\odot}$ = 0.0245 (Grevesse & Noels 05)
0.0229 (Grevesse & Sauval 98; GS98)
0.0165 (Asplund *et al.* 05; AGS05)
0.0181 (Asplund *et al.* 09; AGSS09)
0.0209 (Caffau *et al.* 10, 11; C+11)
0.0191 (Lodders et al. 09)



Basu (16, review)

Initial chemical composition

$X + Y + Z = 1$

$[M/H] = \log(Z/X) - \log(Z/X)_\odot$

$[M/H] = [Fe/H]$

Calibration:
Solar model

$1M_\odot, R_\odot, L_\odot$ @ $t_\odot$
10^{-3} to 10^{-5}

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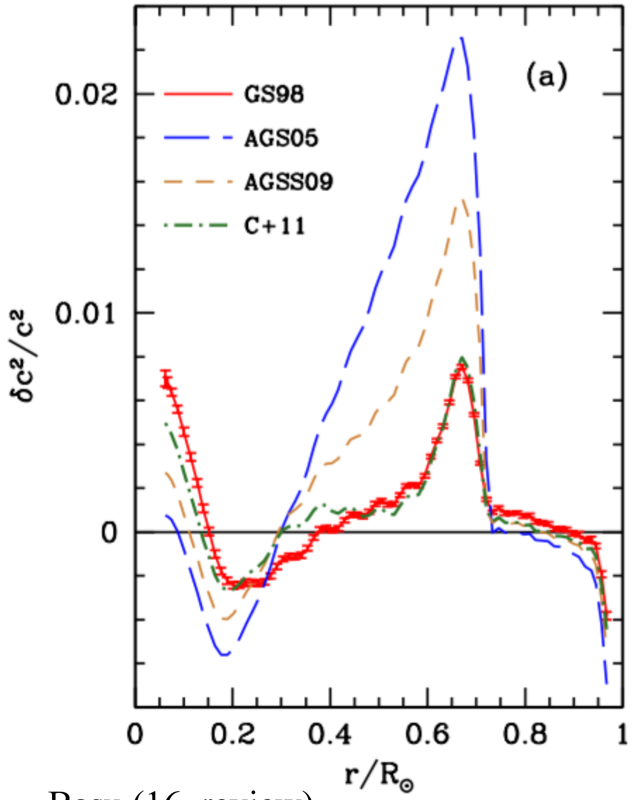

Basu (16, review)

Requires an **opacity increase**
(~ 15 % below the convective envelope, ~ 5 % in the core)
to compensate abundance corrections of AGSS09.
Not recovered yet, nor in the new generation of opacity tables by Los Alamos (OPLIB, Colgan *et al.* 16),
nor in recent innovative experiments (Bailey *et al.* 15)

Initial chemical composition

$\boxed{X + Y + Z = 1}$

$[M/H] = \log(Z/X) - \log(Z/X)_\odot$

$[M/H] = [Fe/H]$

Calibration:
Solar model $\rightarrow$ $(Y_\odot, \alpha_{MLT})$

$1M_\odot$, $R_\odot$, $L_\odot$ @ $t_\odot$
10^{-3} to 10^{-5}

Solar abundance scale : $X_\odot + Y_\odot + Z_\odot = 1$
Photospheric $Z_\odot/X_\odot$

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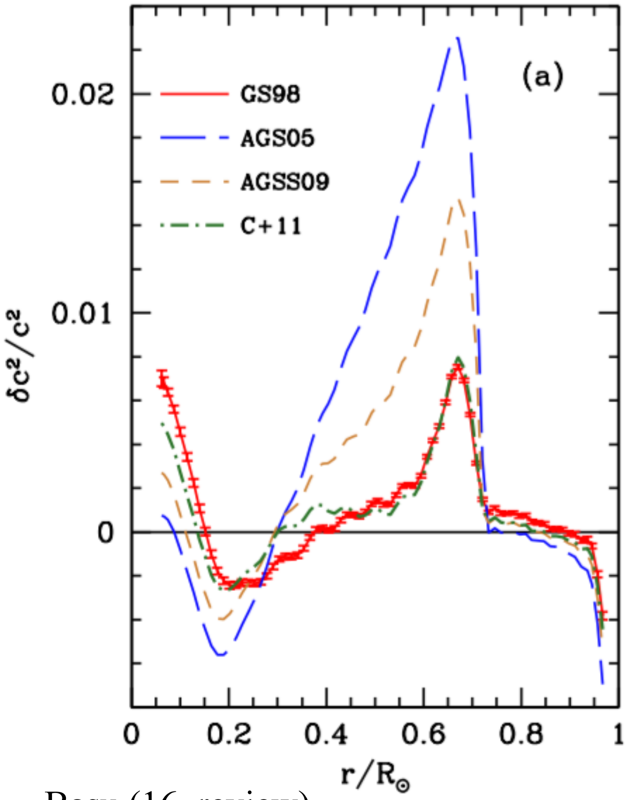


Basu (16, review)

Mixture	Z/X	$Y_\odot$
Helioseismic	-	0.273 ± 0.006
GS98	0.023	0.2755
AGS05	0.0165	0.2586
AGSS09	0.018	0.2650
C+11	0.0209	0.2711

Y for an arbitrary Z ?

$[M/H] = \log(Z/X) - \log(Z/X)_\odot$

Galactic chemical enrichment law

$$\mathbf{Y = Y_P + (\Delta Y / \Delta Z)\, Z}$$

$$= Y_P + \left(\frac{Y_{proto\odot} - Y_P}{Z_{proto\odot}} \right) Z$$

with $Y_P = 0.2485$
(Planck collaboration 2015)

Galactic chemical enrichment

Solar calibration
→ Galactic chemical enrichment law

$(\Delta Y / \Delta Z)$ = 1.0 – 2.0 (Christensen-D 08 – ASTEC)
= 1.35 (Dotter *et al.* 08)
= 1.4 (Weiss & Schlattl 08 – GARSTEC)
= 1.75 (Bressan *et al.* 12 – PARSEC)
= 1.56 (Spada *et al.* 13 – YREC)
= 0.33 (Valle *et al.* 15 – FRANEC)
= 1.53 (Choi *et al.* 16 – MESA)
= 1.7 (Amard *et al.* 17 – Starevol)

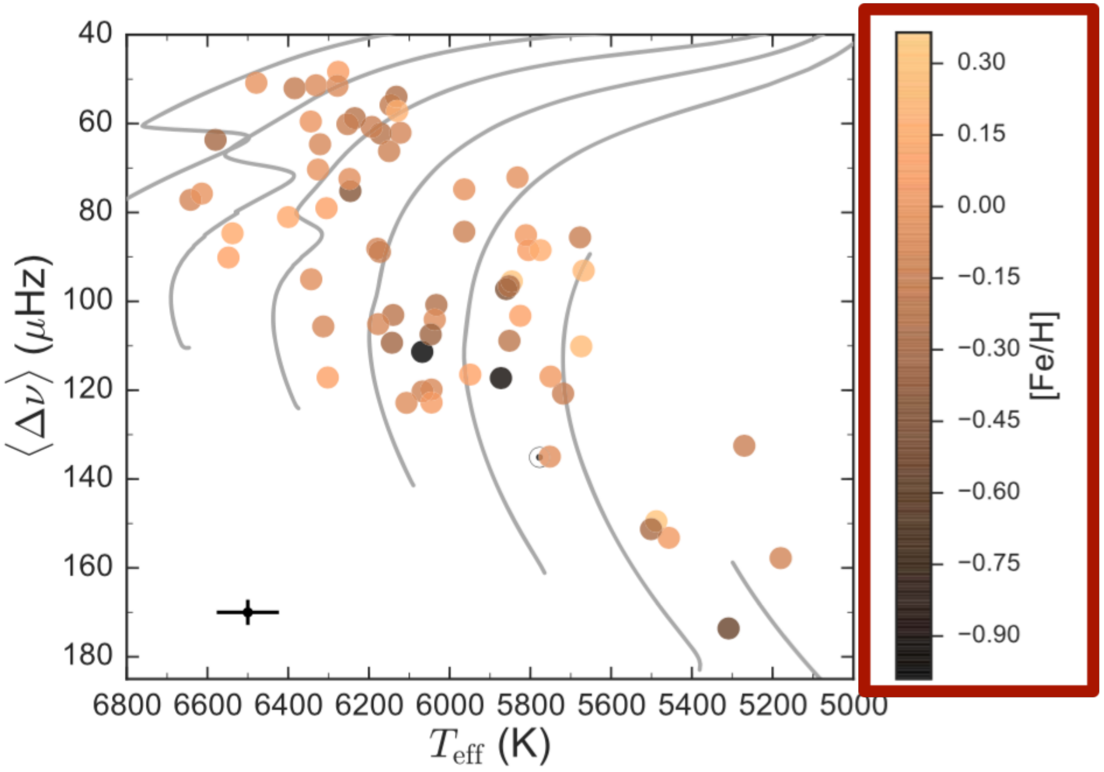
Strongly dependent on the input physics of the stellar models

Initial He content strongly impacts
the stellar **luminosity,**
(opacity and molecular weight)
lifetime, mass loss,
mass and composition of the remnant

Initial mixture of the models:
$Z_i / Z = (Z_i / Z)_\odot$
or observed ("à la carte" models),
or special mixture (α – enhanced for Pop II; CNONeNaMgAl for globular clusters; …)

Initial chemical composition

Kepler dwarfs LEGACY
Silva Aguirre *et al.* (2017)



"Best asteroseismic data available
among solar- like stars for at least another decade"
(i.e., until the PLATO mission)

Large frequency separation (Ulrich 86; Gough 87)

$$\langle \Delta\nu \rangle \propto \left(\frac{M}{M_\odot}\right)^{1/2} \left(\frac{R}{R_\odot}\right)^{-3/2}$$

$$\Delta\nu_\ell(n) = \nu_{n,\ell} - \nu_{n-1,\ell}$$

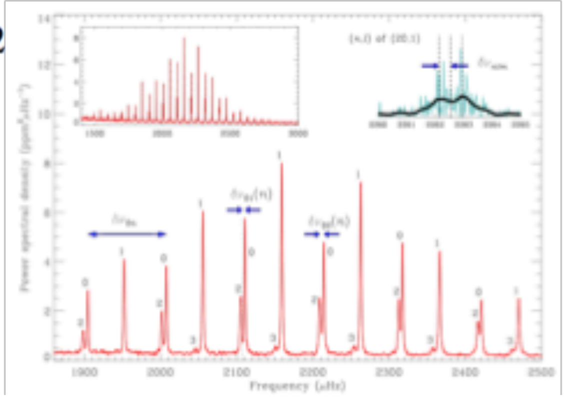
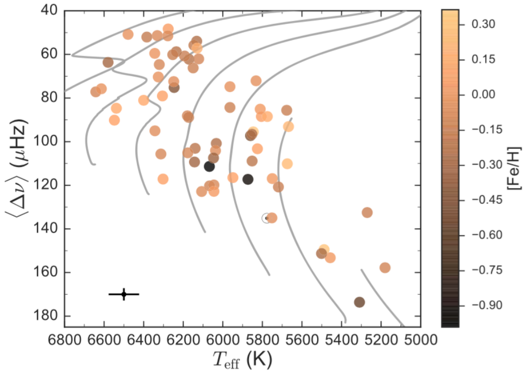


Fig MS star 16 Cygni (Chaplin & Miglio 13)

Galactic chemical enrichment

Kepler dwarfs LEGACY
Silva Aguirre *et al.* (2017)



“A la carte” models:
Initial helium and
heavy-metal abundances
freely varying the composition
as part of the optimization
for all target stars

Constraints:
individual oscillation frequencies
extracted of the time series of each
sample star
+ fit of the atmospheric parameters
$T_{\rm eff}$ and [Fe/H]

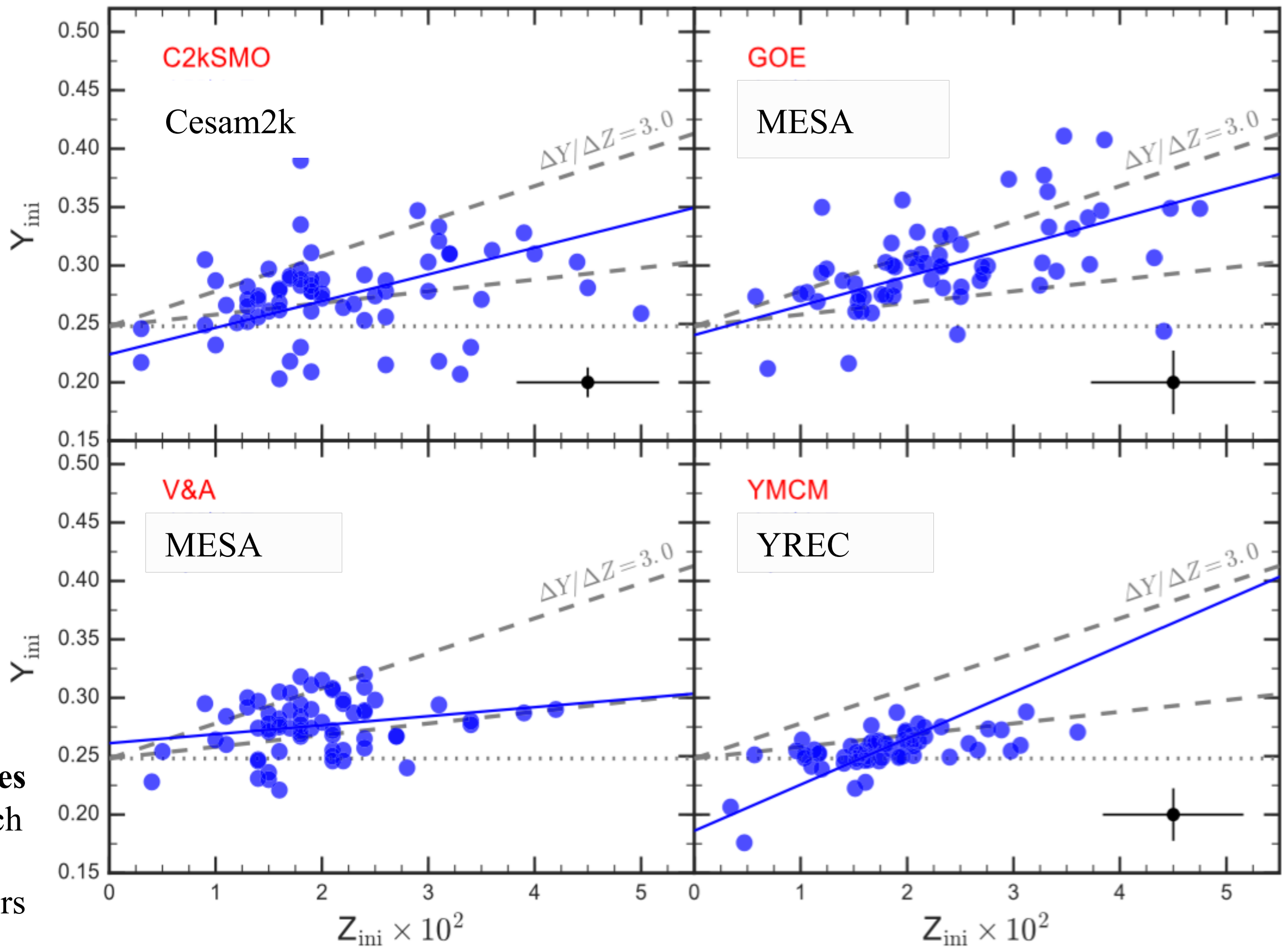
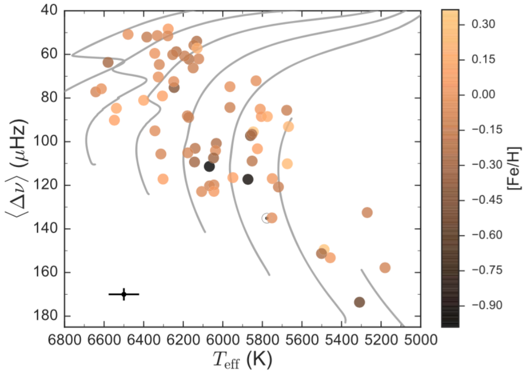
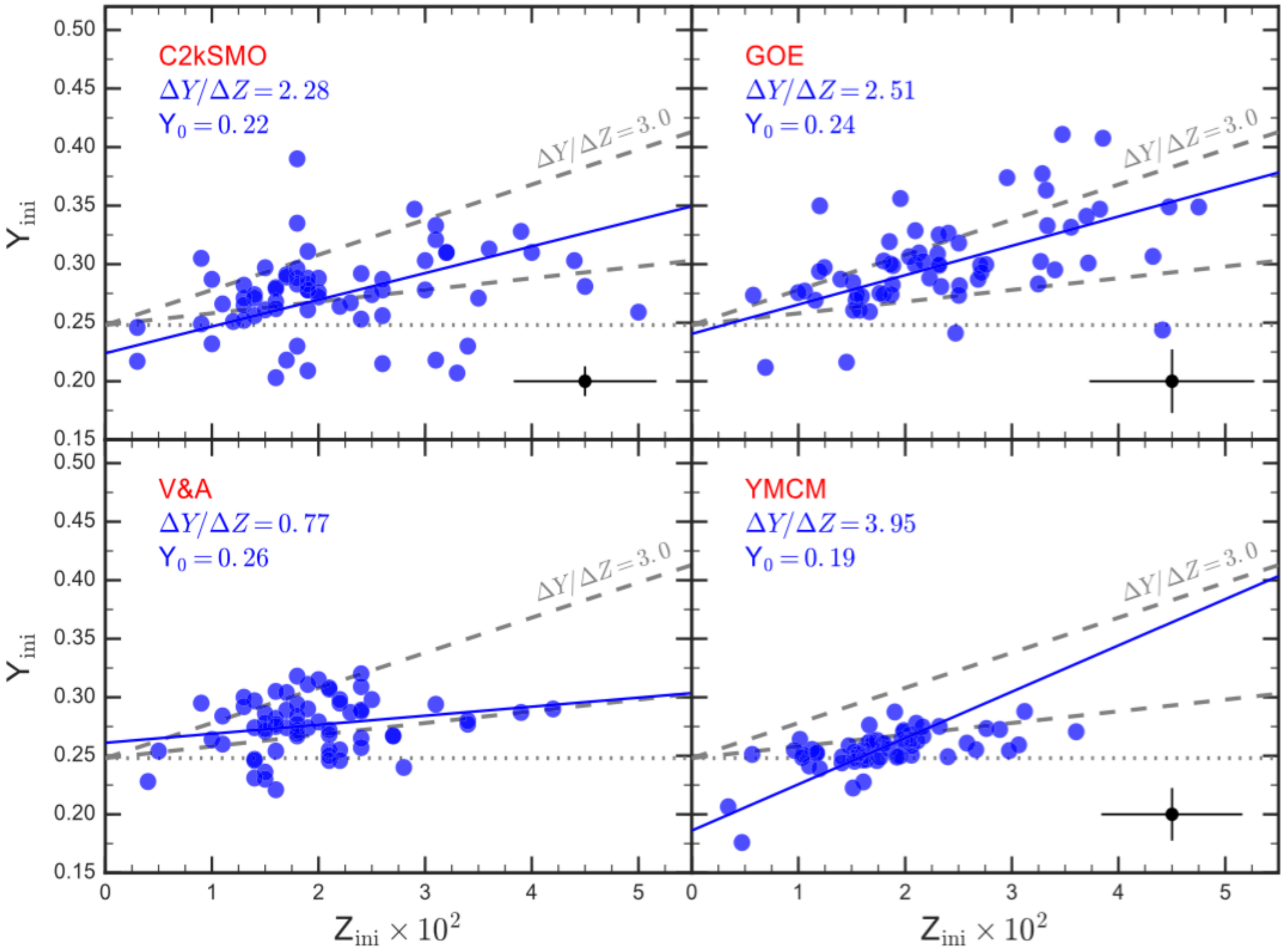


Figure 8. Initial helium abundance as a function of initial heavy-element abundance for the pipelines that do not constrain the chemical composition with a galactic enrichment law. Two dashed gray lines depict different slopes in the $\Delta Y/\Delta Z$ relation: 3.0 (upper), 1.0 (lower). The dotted gray line shows the primordial helium abundance predicted by SBBN (Steigman 2010), while the solid blue lines present a linear least-square fit to the results from each pipeline, characterized by the slope and intercept given in each panel. Median uncertainties are plotted to avoid clutter (black circles, except for V&A that does not provide them for these parameters). See the text for details.

Galactic chemical enrichment

Kepler dwarfs LEGACY
Silva Aguirre *et al.* (2017)





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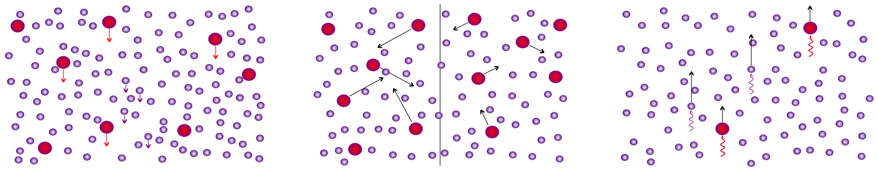
Galactic chemical enrichment law:
(ΔY / ΔZ)
between 0.77 and 3.95

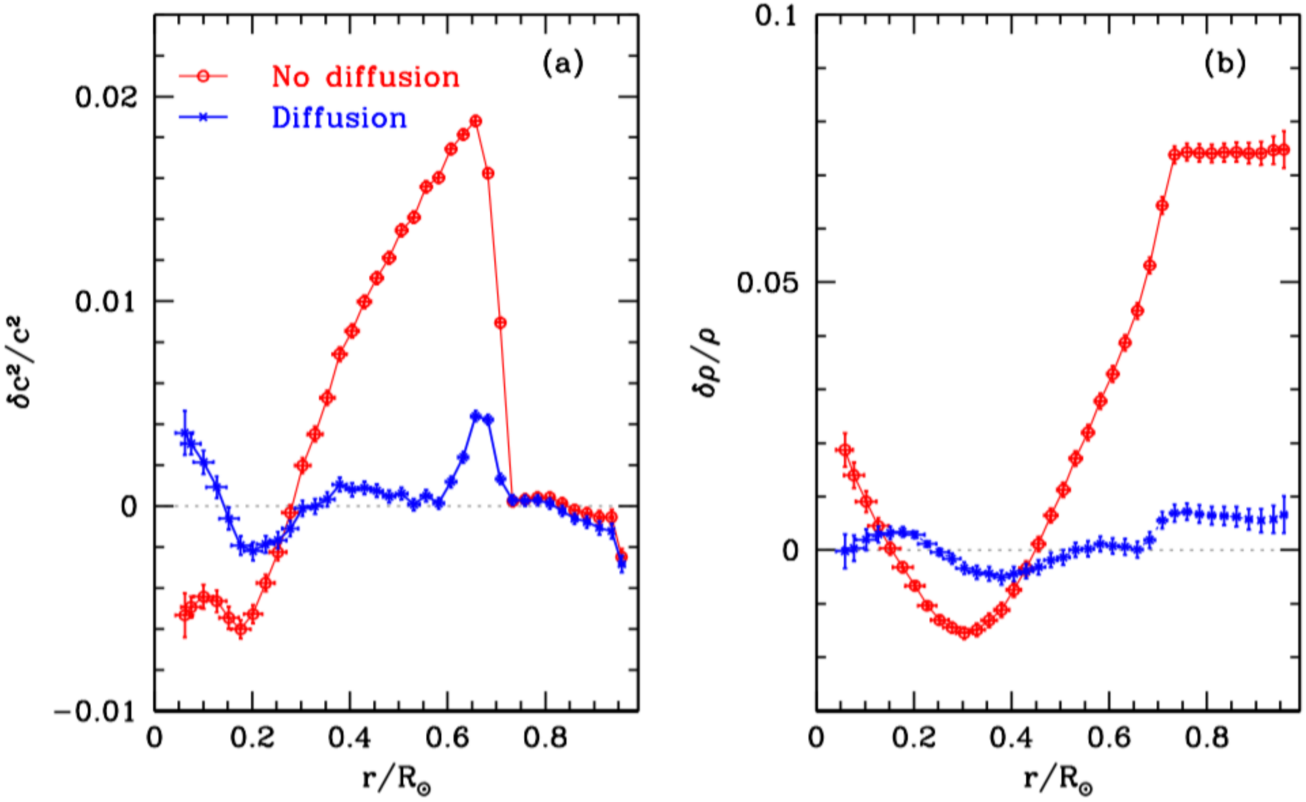
$Y_0 < 0.2485$ (Planck)
in 3 cases out of 4

Atomic diffusion, Sun



Processes driven by gradients (pressure, thermal, chemical)
+ radiative acceleration acting differently on individual species
Michaud, Vauclair, and collaborators

Sun : Proffitt & Michaud (91), Christensen-Dalsgaard *et al.* (93), Richard *et al.* (96)
Turck-Chièze *et al.* (10)



Basu (16, models of Basu *et al.* 00; solar abundances of Grevesse & Sauval 98)

Yini = 0.2755

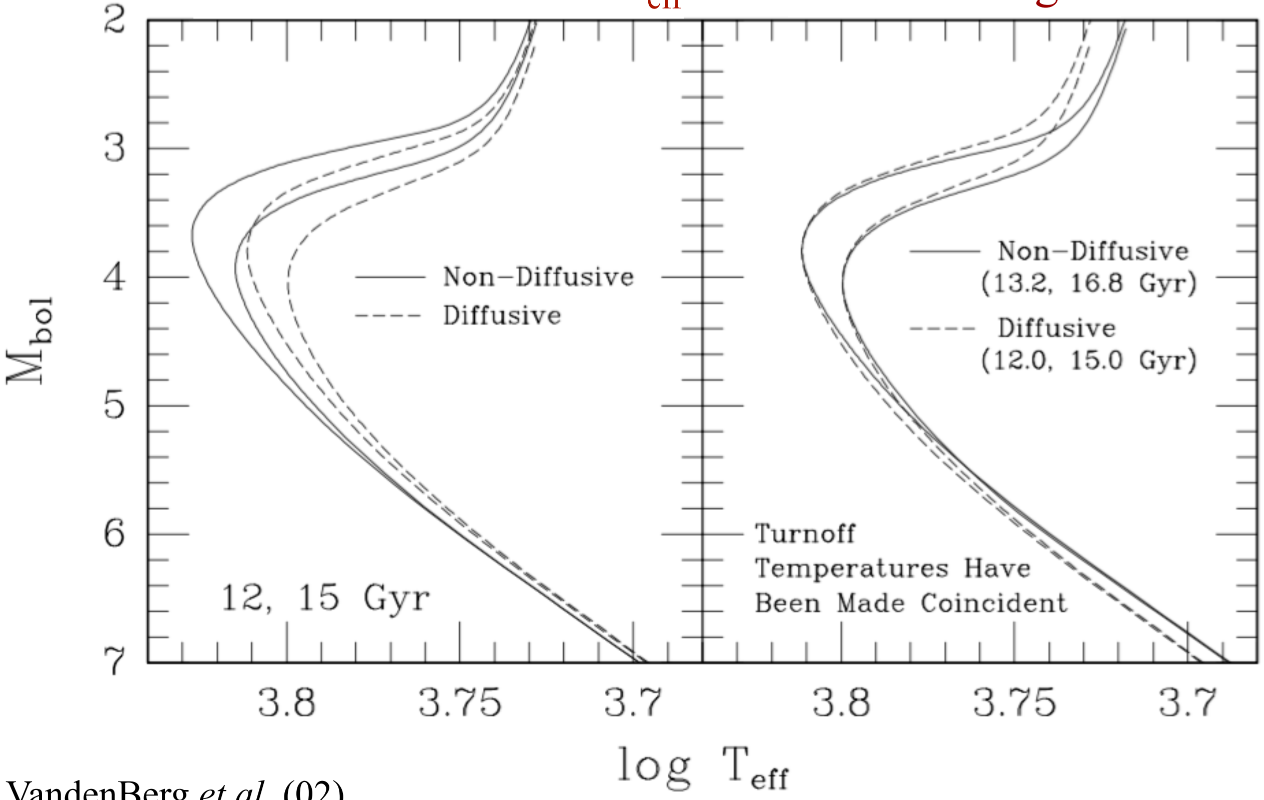
Helioseismology : $Y_{\odot,\ \mathrm{conv.envelope}} = 0.2485 \pm 0.034$ (Basu & Antia 2004)

Photospheric abundances ≠ initial abundances

Atomic diffusion, tracks, ages

Shifts evolution tracks towards lower L and T_{eff}

Decreases ages



VandenBerg *et al.* (02)
First PopII stellar models with both gravitational settling and radiative acceleration

10 – 12 % reduction in age at a given turnoff luminosity (Pop II stars, Globular Clusters)

Crucial for the age determination of the ages of star clusters

M.Pinsonneault (talk on Thursday)

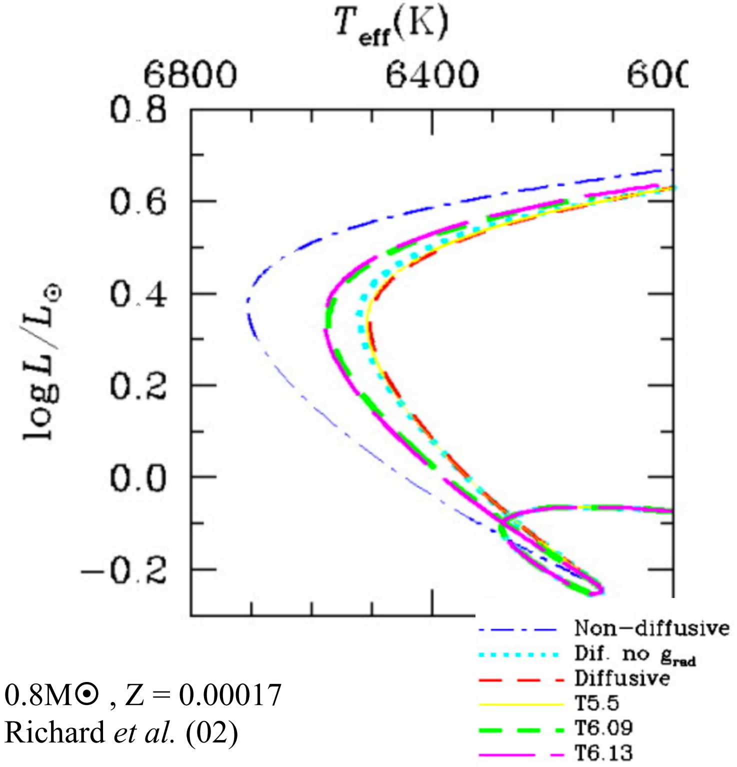
Turbulent processes are required
to account for surface chemical properties
(e.g. Li, CNO, heavy elements)

Atomic diffusion + turbulent processes

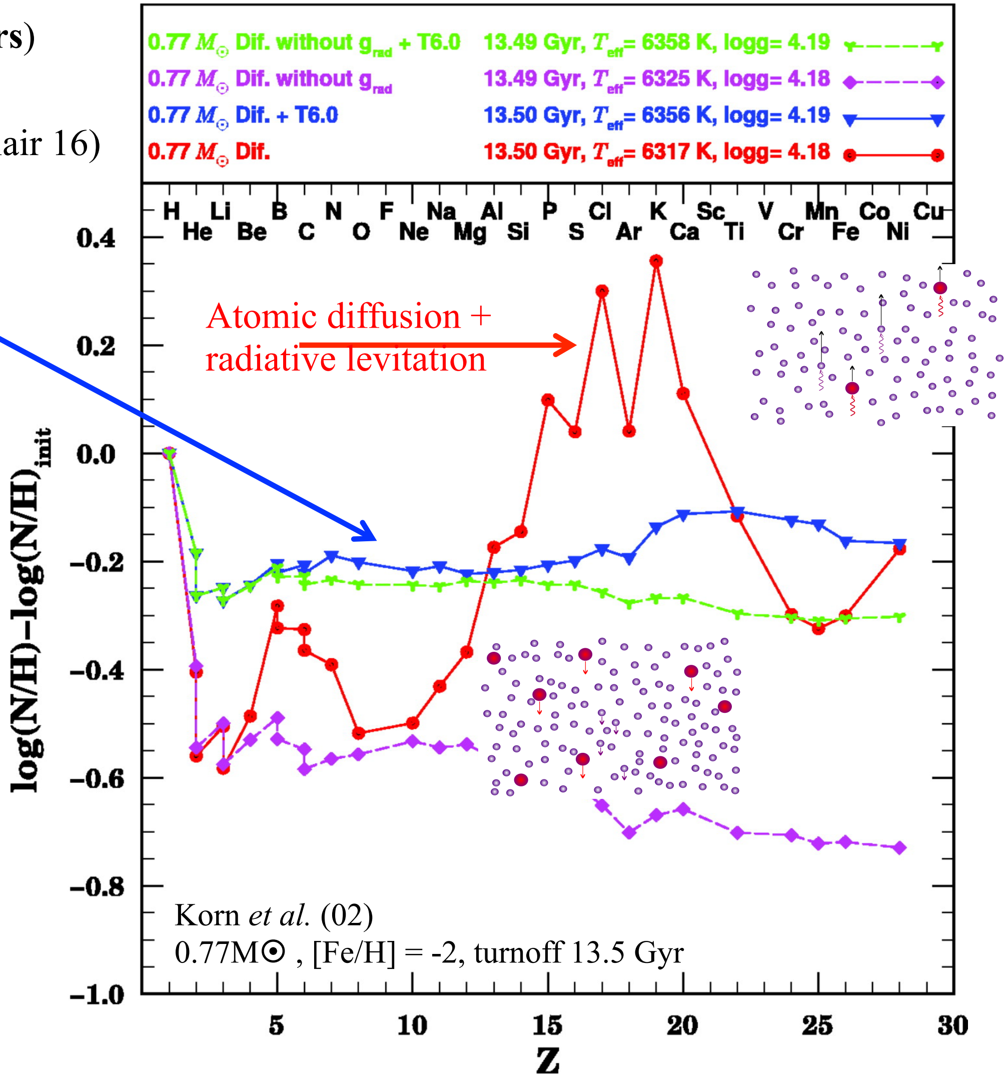
Eddington (1929, **Internal circulation in rotating stars**)

Atomic diffusion generates **instabilities**
that counterbalance its own effects (Deal *et al.* 16,Vauclair 16)

Parameterized
temperature (density) - dependent
turbulent mixing in the radiative layers



0.8M⊙ , Z = 0.00017
Richard *et al.* (02)



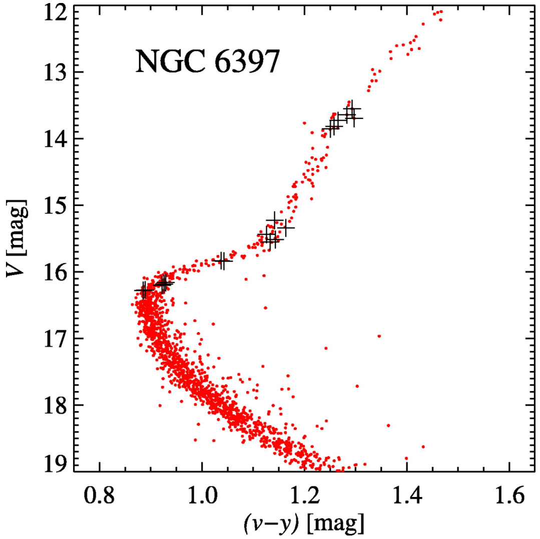
Korn *et al.* (02)
0.77M⊙ , [Fe/H] = -2, turnoff 13.5 Gyr

Proffitt & Michaud (91), VandenBerg *et al.* (02), Richard *et al.* (02, 05)

Parameterized density-dependent turbulent mixing

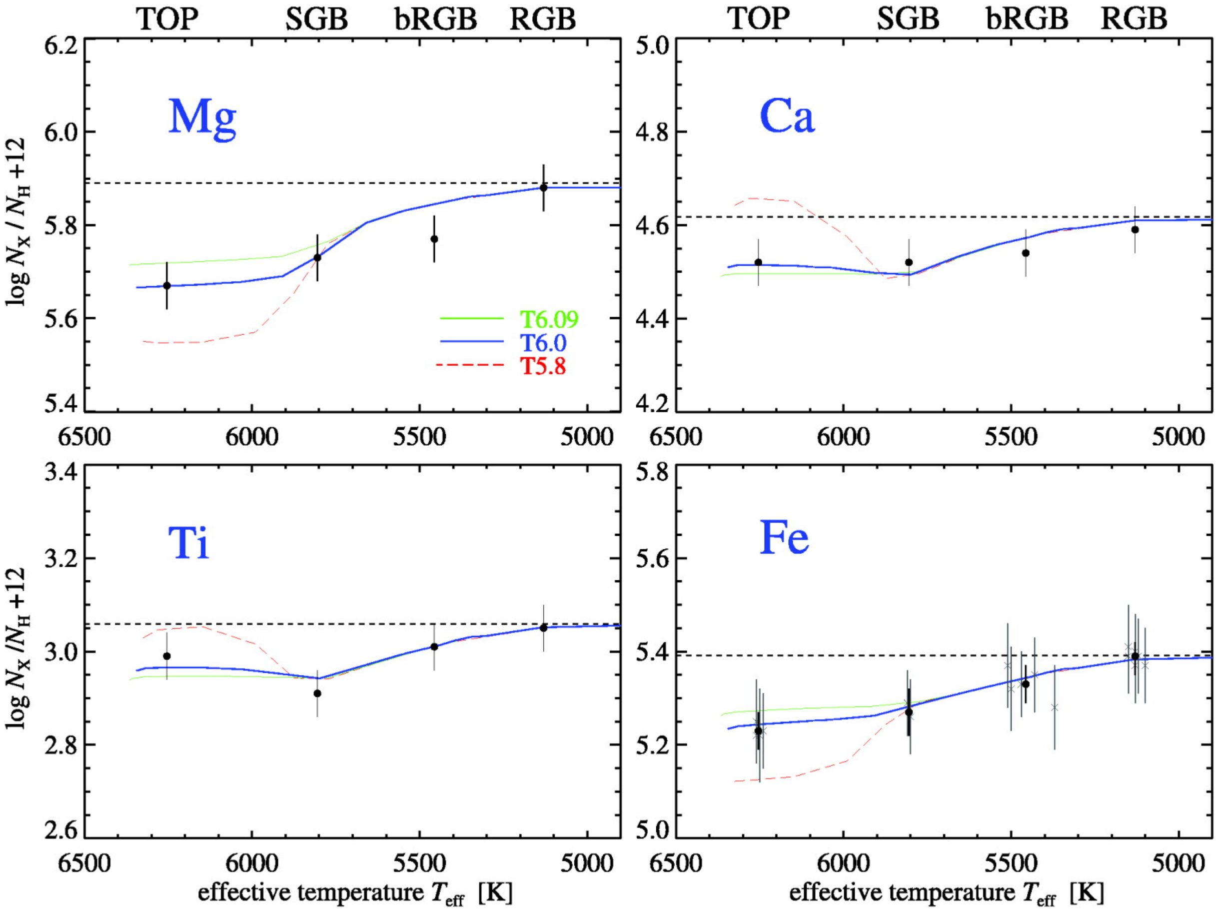
Atomic diffusion + turbulent processes

Calibration on spectroscopic analysis of stars along the evolutionary sequence of **globular clusters**



Korn *et al.* (07)

See also Nordlander *et al.* (12) NGC 6397
Gruyters *et al.* (13) NGC 6752
Gruyters *et al.* (16) M30



Consistent with **rotation-induced processes** (Talon *et al.* 06)

Photospheric abundances ≠ initial abundances
Signatures depend on the evolution phase

Chemical tagging

Photospheric abundances ≠ initial abundances
Signatures depend on the evolution phase

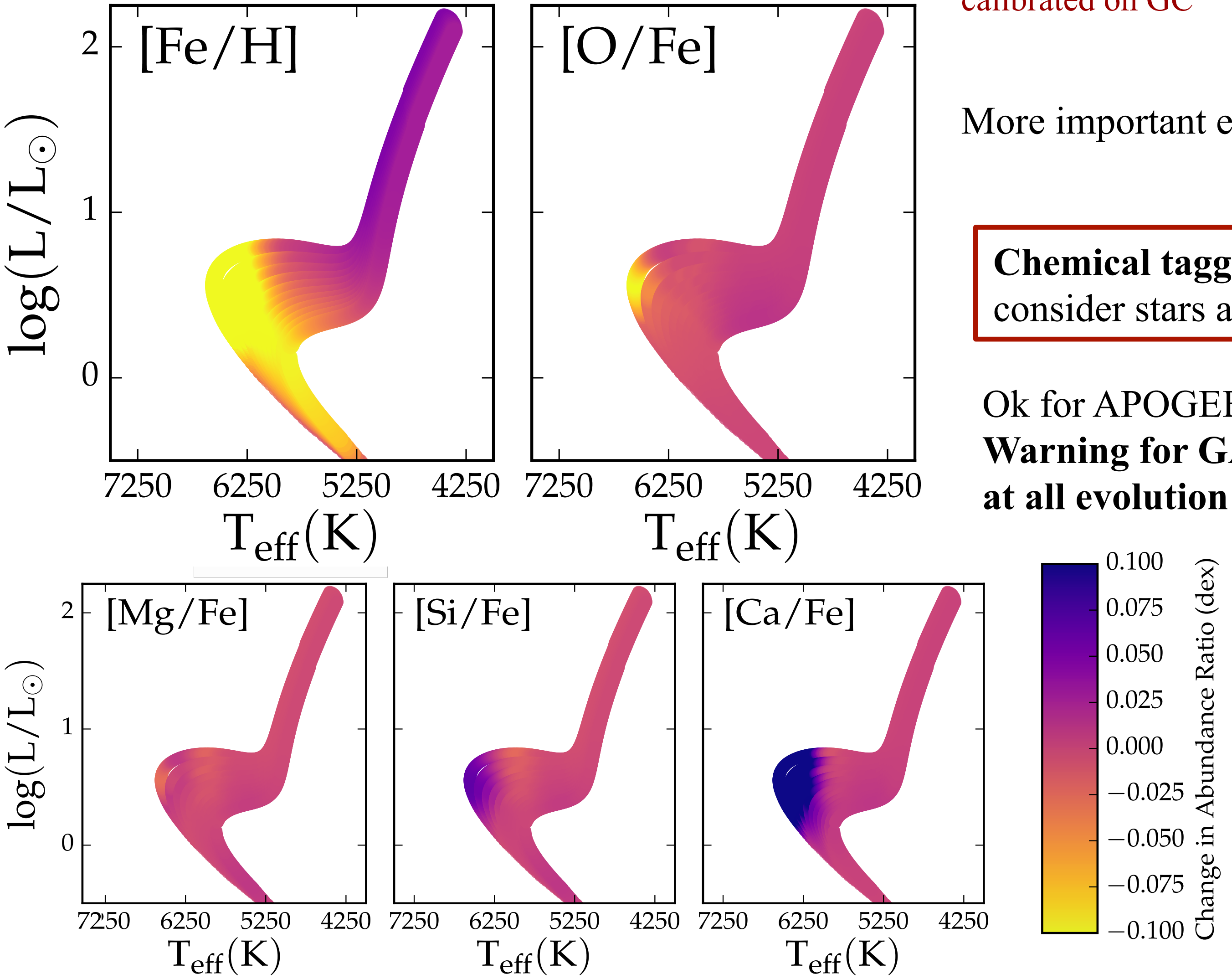
Parameterized density-dependent turbulent mixing calibrated on GC

$$D_T = D_0 \left(\frac{\rho_{CZ}}{\rho}\right)^3 \left(\frac{M_{CZ}}{M_*}\right)^{-3/2}$$

More important effects around the MS turnoff

Chemical tagging should
consider stars at the same evolution phase

Ok for APOGEE that targets red giant stars
Warning for GALAH that targets stars at all evolution phases

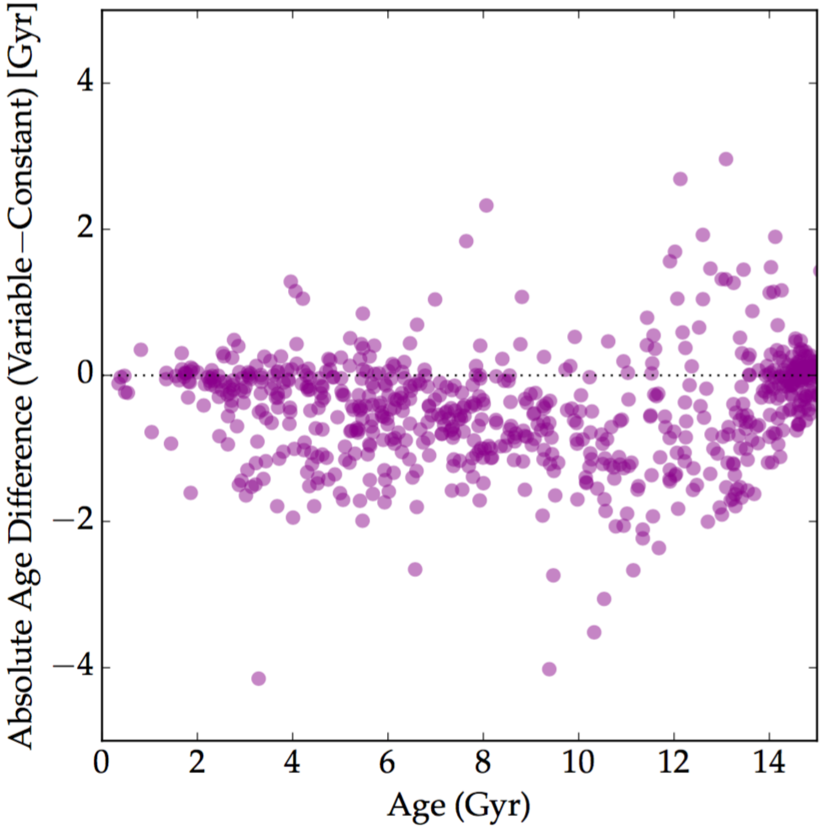


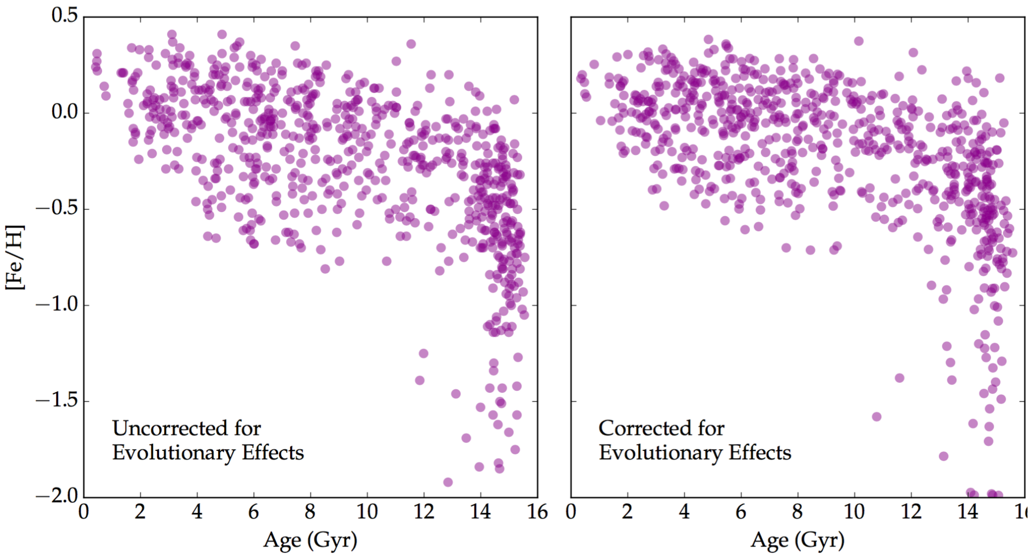
Dotter *et al.* (17) – Models with ages between 5 and 15 Gyr, and $[Fe/H]_{ini}$ = -0.5

Photospheric abundances ≠ initial abundances

Chemical tagging and AMR

Use isochrones
with tabulated surface abundance variations
to derive age-metallicity relations



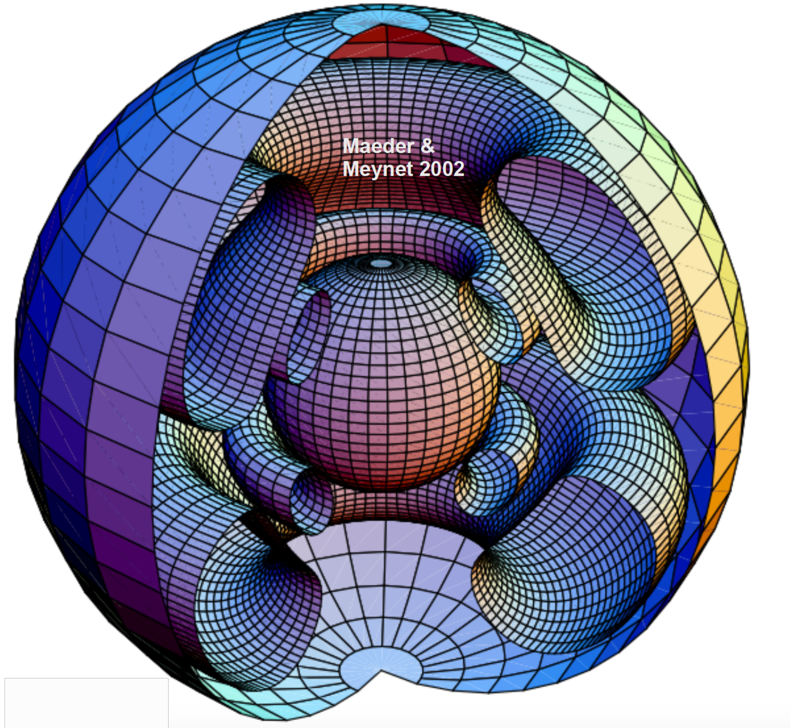


Difference in **ages** using variable and constant metallicity isochrones
→ **decrease by up to 20 %**
Bensby et al. (14) catalog for the Galactic disk

Dotter *et al.* (17)

Stellar evolution
is a function of M, Z, and Ω

Rotation



Stellar parameters

L, Teff, R, age, P_{rot} ...

Stellar **structure**

P(r), T(r), …

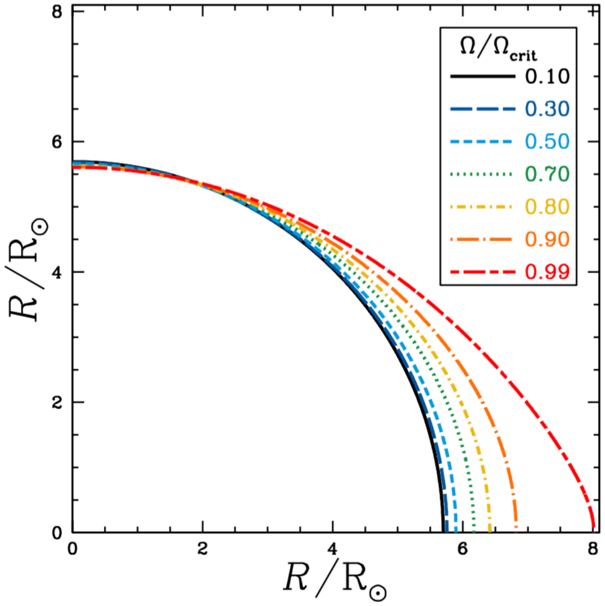
Asteroseismic properties

Yields

Nucleosynthesis

wind, radiation, ...

Rotation



Centrifugal effects

→ Deformation of the surface

→ Modification of the effective gravity g_{eff} (Ω,θ)

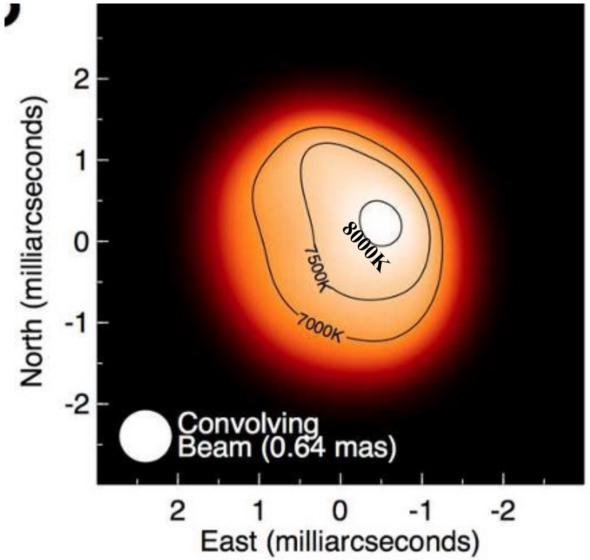
→ Modification of the effective temperature

$T_{eff}(\Omega,\theta) \alpha\ g_{eff}^{\beta}(\Omega,\theta)$

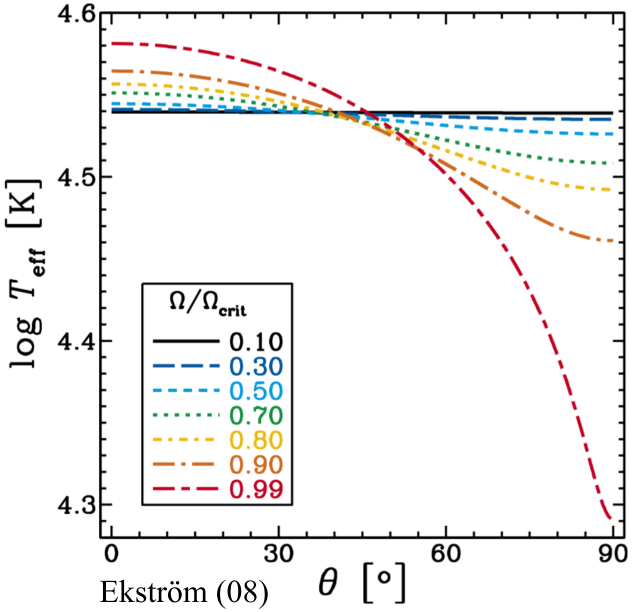
$\beta = 1/4$, Von Zeipel (1924); more complex, Espinosa Lara *et al.* (2011)

→ Modification of the mass loss

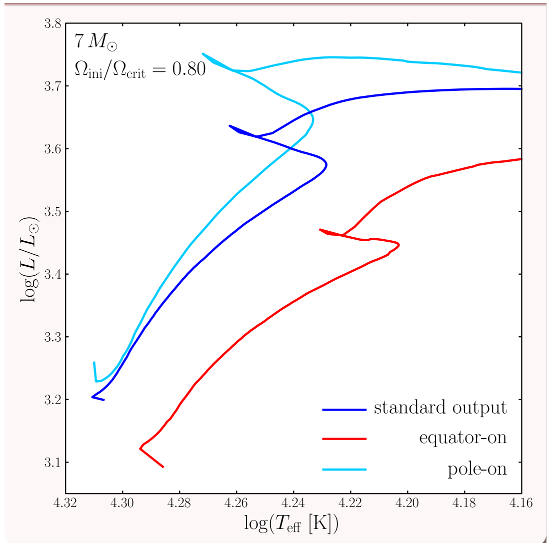
(radiatively-driven + mechanical)



Altair, Chara
Gravity darkening induced by fast rotation
Monnier *et al.* (07)

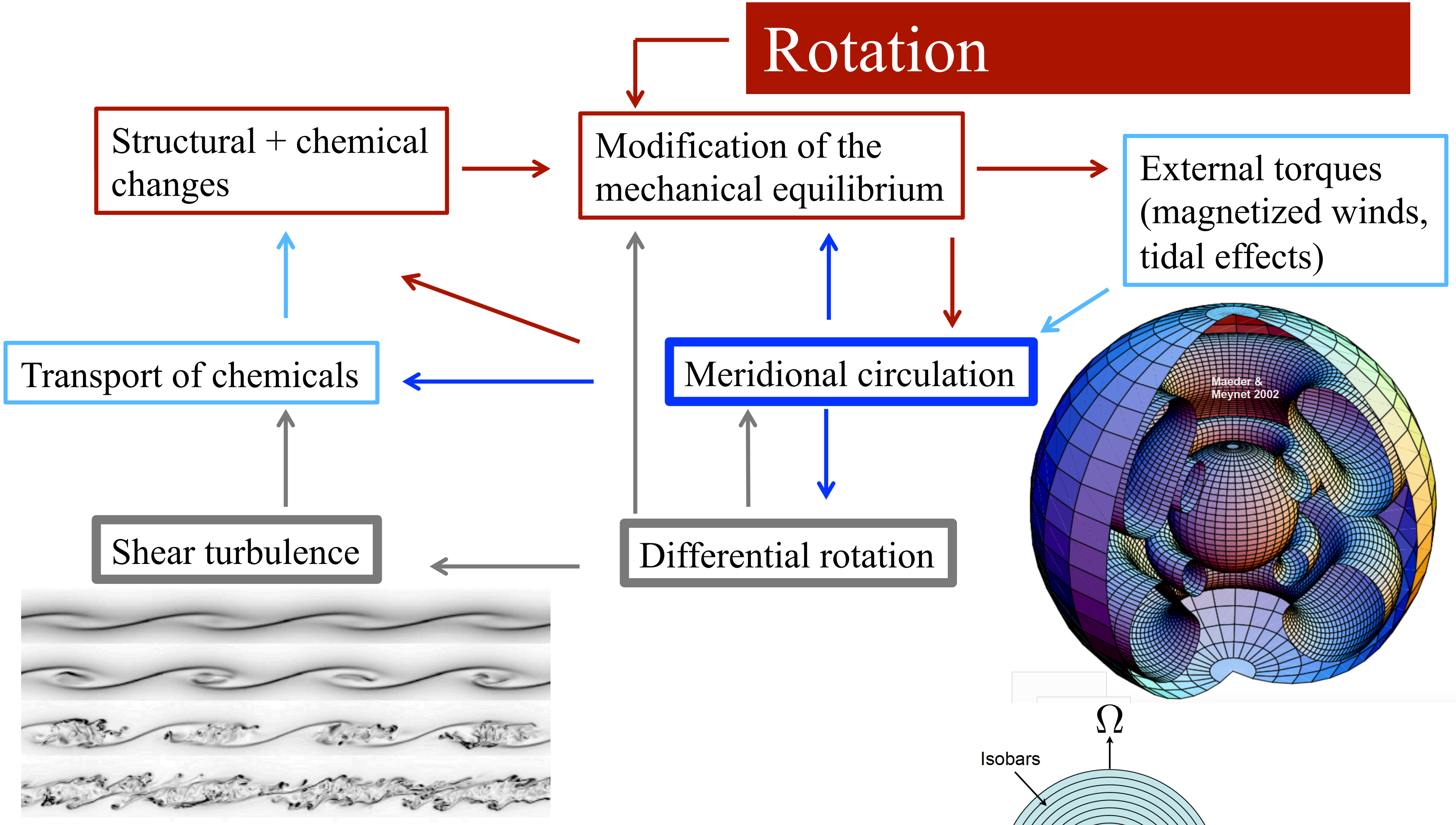


Ekström (08)
20 $M_\odot$, $Z_\odot$, ZAMS



Georgy *et al.* (13), correction for limb darkening (Claret 10)

Rotation



Structural + chemical changes

Modification of the mechanical equilibrium

External torques (magnetized winds, tidal effects)

Transport of chemicals

Meridional circulation

Shear turbulence

Differential rotation

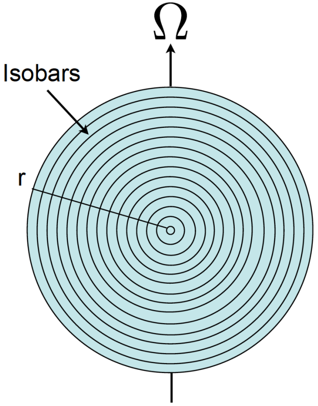
Different formalisms Kippenhahn & Thomas (1970) Zeng (2002)

Zahn (1992), Maeder & Meynet (1997) – Shellular rotation

Turbulence is highly anisotropic (horizontal >> vertical)

→ Angular velocity is constant on isobars

→ Any quantity can be expressed as a function of pressure only



Stellar structure with rotation

Shellular rotation

$$\boxed{\begin{aligned}
\frac{\partial P}{\partial m_P} &= -\frac{Gm_P}{4\pi r_P^4} f_P \\
\frac{\partial r_P}{\partial m_P} &= \frac{1}{4\pi r_P^2 \bar{\rho}} \\
\frac{\partial L_P}{\partial m_P} &= \epsilon_n - \epsilon_\nu + \epsilon_g \\
\frac{\partial T}{\partial m_P} &= -\frac{G m_P T}{4\pi r_P^4 P} \nabla_P
\end{aligned}}$$

$$F_{rad} = -\frac{4\alpha c T^3}{3\kappa\rho}\frac{\partial T}{\partial n} = -\frac{4\alpha c T^3}{3\kappa}\left\langle g^{-1}\right\rangle S_P g \frac{\partial T}{\partial m_P}$$

$$L_P = -\frac{4\alpha c}{3}\left\langle g^{-1}\right\rangle S_P^2 \left\langle \frac{T^3 g}{\kappa}\frac{\partial T}{\partial m_P}\right\rangle$$

Stellar structure equations written on isobars
(instead of equipotentials)

$$\boxed{f_P = \frac{4\pi r_P^4}{G m_P S_P}\frac{1}{\left\langle g^{-1}\right\rangle}}$$

$$\boxed{f_T = \left(\frac{4\pi r_P^2}{S_P}\right)^2 \frac{1}{\left\langle g\right\rangle\left\langle g^{-1}\right\rangle}}$$

$$\bar{\rho} = \frac{\rho\left(1 - r^2\sin^2\vartheta\,\Omega\alpha\right)\left\langle g^{-1}\right\rangle}{\left\langle g^{-1}\right\rangle - \left\langle g^{-1} r^2 \sin^2\vartheta\right\rangle \Omega\alpha}$$

$$\vec{\nabla}\Omega = \alpha\vec{\nabla}\Psi \quad , \quad \alpha = \frac{d\Omega}{d\Psi}$$

$$g = \left(1 - r^2\sin^2\vartheta\,\Omega\alpha\right)\frac{d\Psi}{dn}$$

$$\nabla_P = -\frac{3\kappa}{16\pi\alpha c G}\frac{P}{T^4}\frac{L_P}{m_P}\frac{f_T}{f_P}$$

Palacios (EES2012)

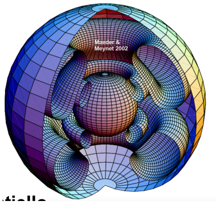
Rotation – 1.5 D

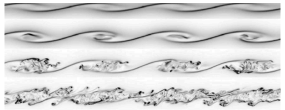
Transport of angular momentum

Zahn, Maeder, + formalism

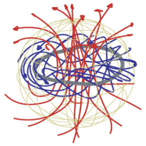
$$\rho \frac{\mathrm{d}(r^2\bar{\Omega})}{\mathrm{d}t} = \frac{1}{5r^2}\frac{\partial}{\partial r}\left(\rho r^4 \bar{\Omega} U_2(r)\right)$$

Advection
- Meridional circulation

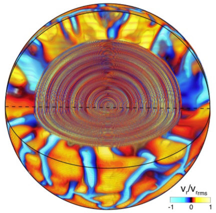




$$+\frac{1}{r^2}\frac{\partial}{\partial r}\left(\rho(\nu_v+\nu_B) r^4 \frac{\partial \bar{\Omega}}{\partial r}\right)$$



Diffusion
- Shear instability
- Magnetic instability



Alvan et al. (2014)

$$\pm 2\frac{3}{8\pi}\frac{1}{r^2}\frac{\partial}{\partial r}\mathscr{L}_J(r)$$

Internal gravity waves

$$\frac{\partial}{\partial t}\left[\Omega \int_{r_t}^{R} r^4 \rho \,\mathrm{d}r\right] = -\frac{1}{5} r^4 \rho \Omega U_2 + \mathscr{F}_\Omega$$

Surface condition
- AM extraction,
  stellar wind - $\mathscr{F}_\Omega$

Transport of chemical species

Rotation

$$\rho \frac{\mathrm{d}c_i}{\mathrm{d}t} = \rho \dot{c}_i + \frac{1}{r^2}\frac{\partial}{\partial r}\left[r^2 \rho V_{ip} c_i\right] + \frac{1}{r^2}\frac{\partial}{\partial r}\left[r^2 \rho \left(D_{\mathrm{eff}} + D_v\right) \frac{\partial c_i}{\partial r}\right]$$

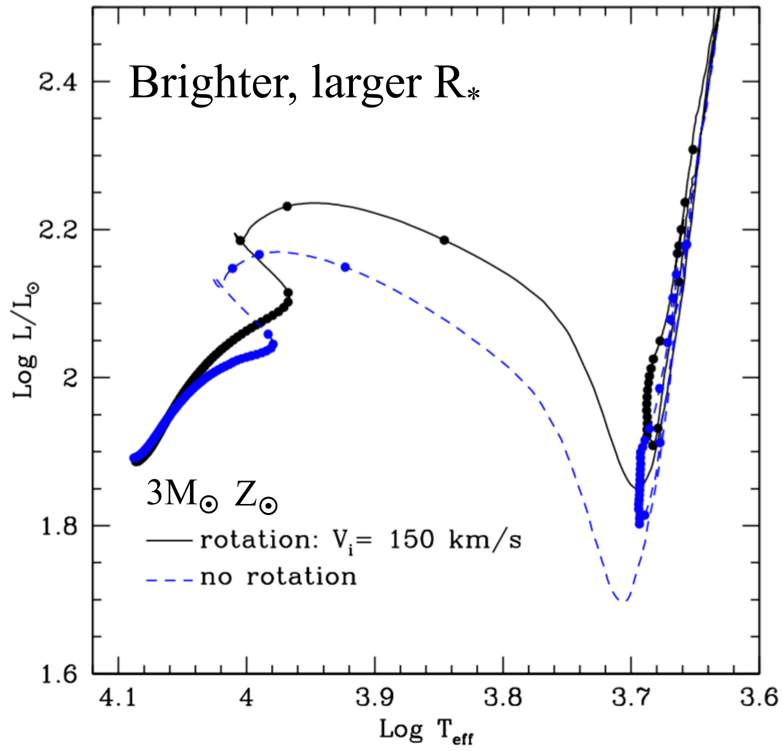
Nuclear

Atomic diffusion

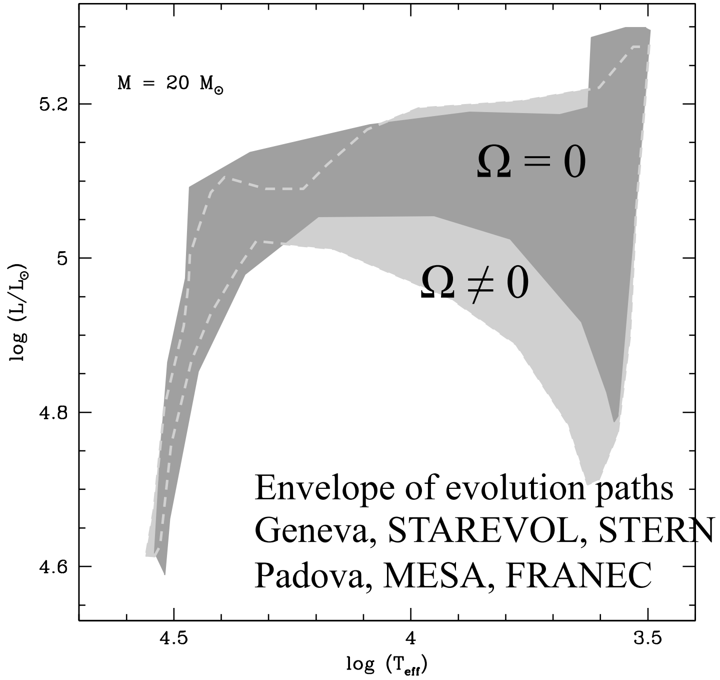
Circulation and turbulence

Zahn (92); Maeder & Zahn (98); Mathis & Zahn (04)

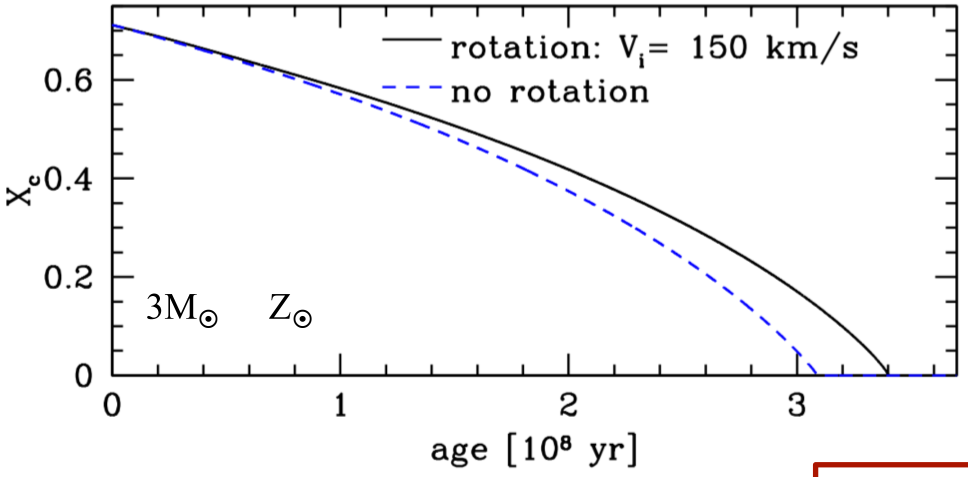
Rotation – HRD – Mass – Age


Brighter, larger R_*

Mass estimate ↘ 10 %



Envelope of evolution paths
Geneva, STAREVOL, STERN
Padova, MESA, FRANEC



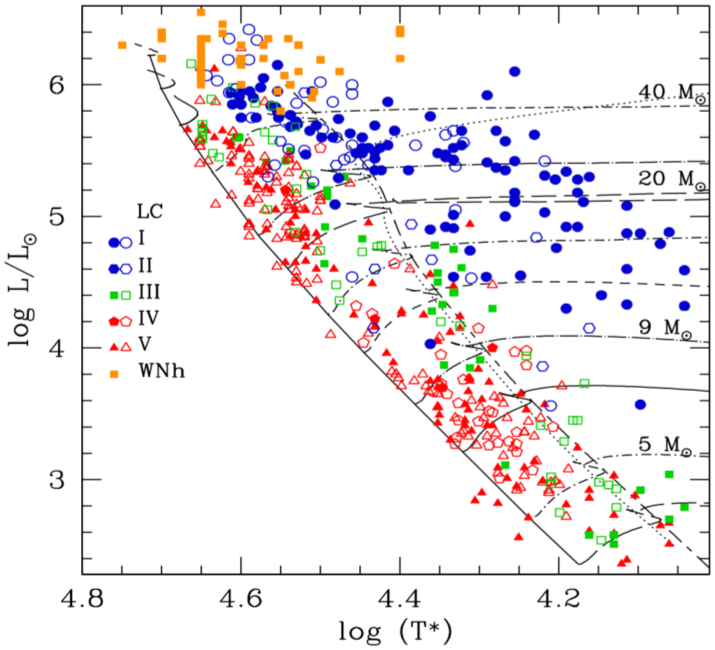
Martins & Palacios (13)

Age estimate ↗ 10 %

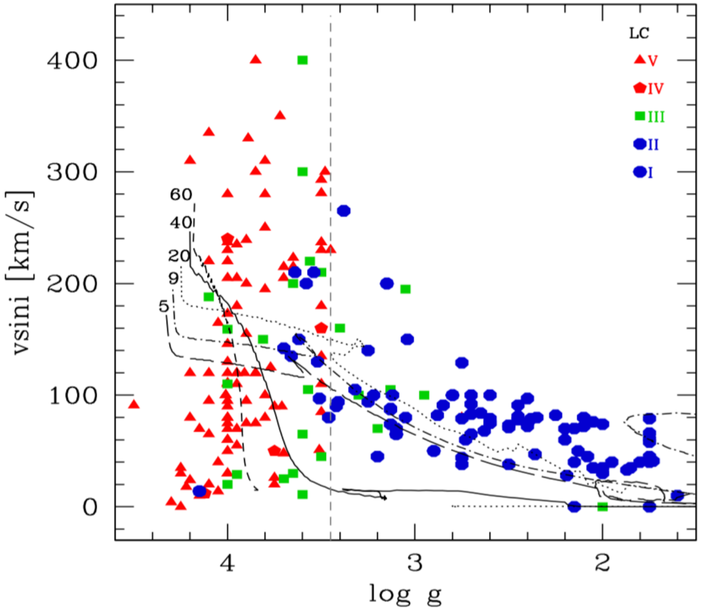
Eggenberger *et al.* (10b)

Constraints for massive stars

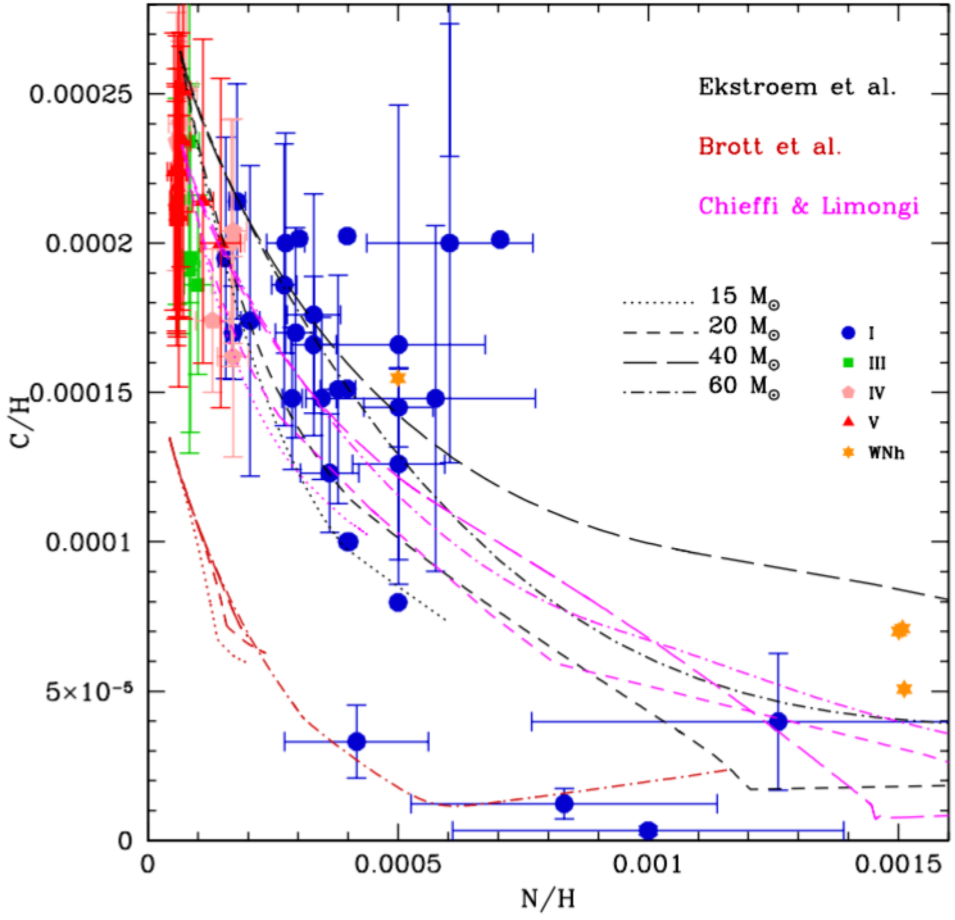
Width of the MS, surface rotation and abundances



Evolution tracks from Ekström *et al.* (12)



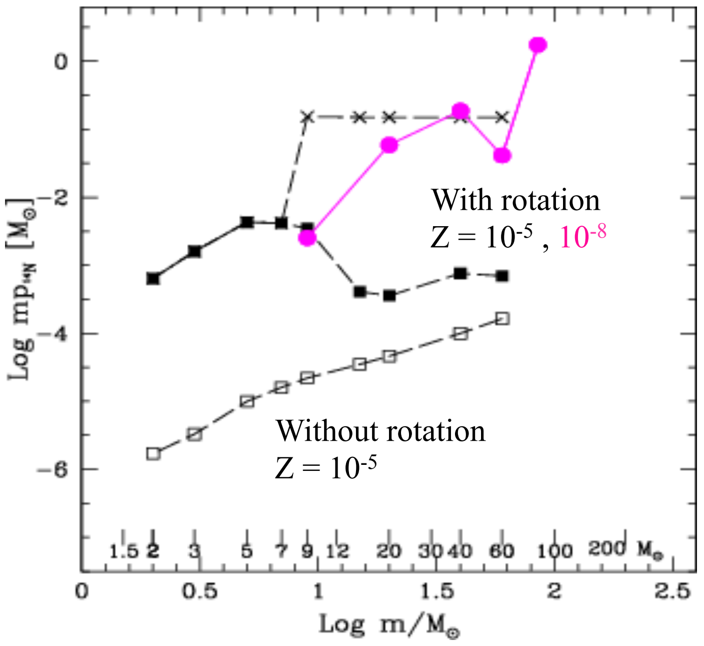
Martins & Palacios (13)



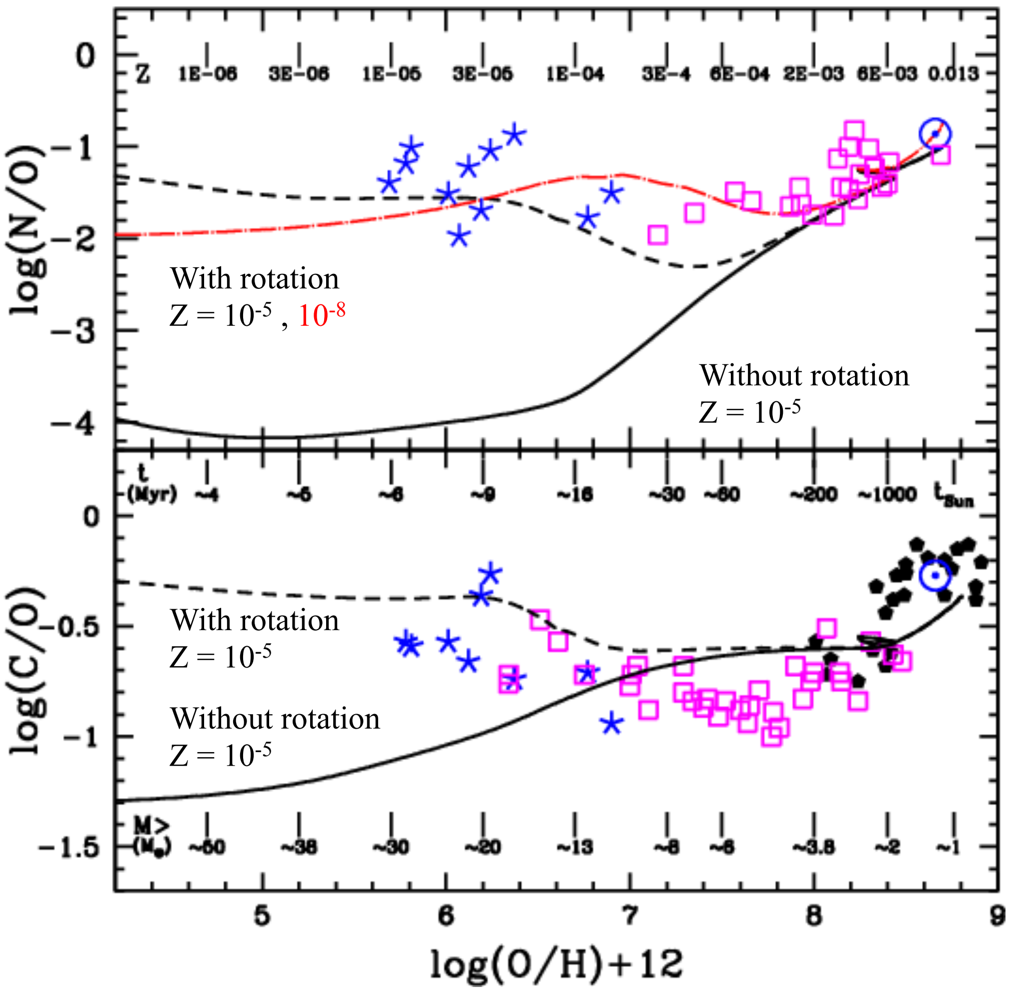
Blue to red ratio, spin of the remnants (WD, neutron stars), surface magnetic fields, chemical evolution, …

Primary production of ^{14}N, ^{13}C, ^{22}Ne
Production of s-process elements

Yields and chemical evolution



^{14}N yields

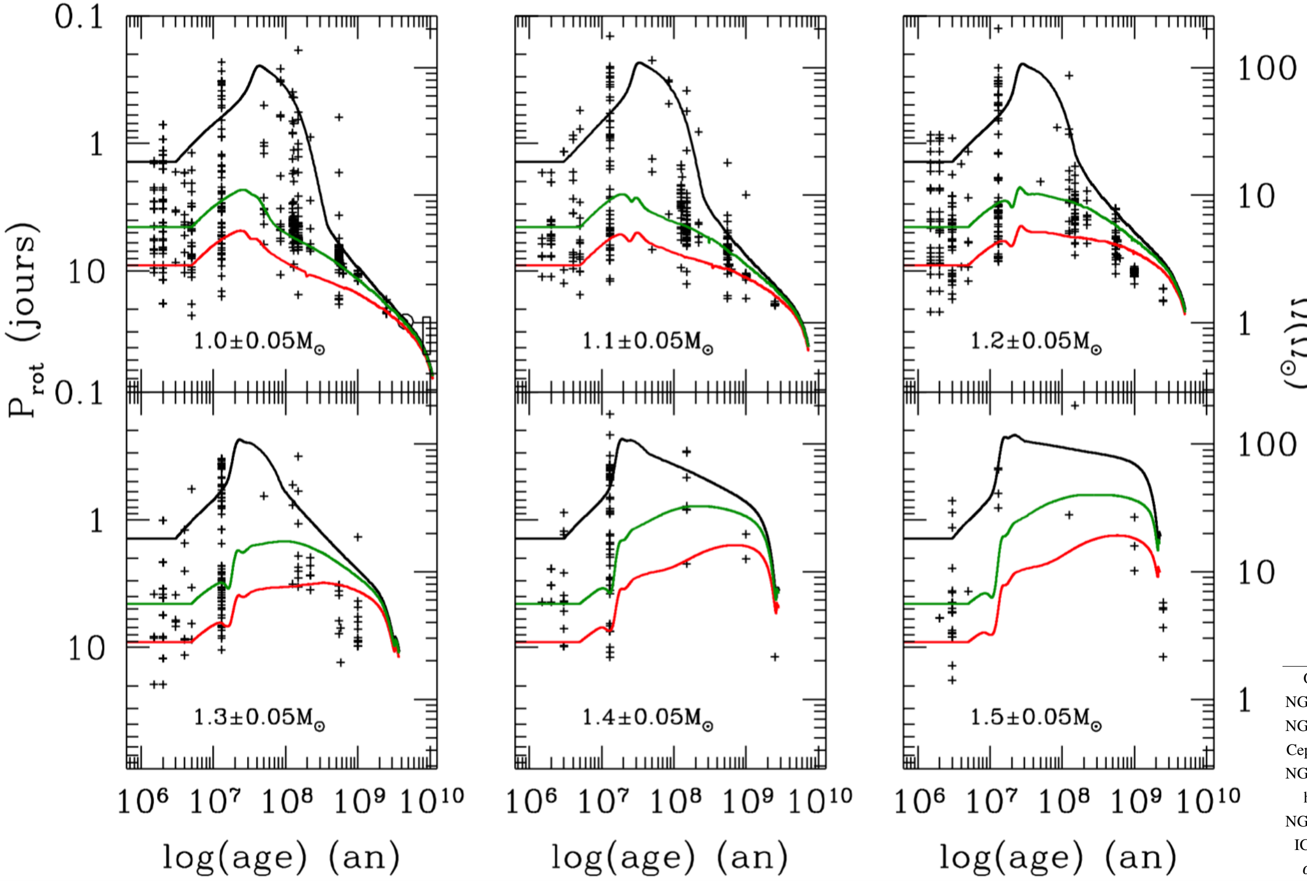


Solar vicinity (data Israelian *et al.* 04, Spite *et al.* 04)

Chiappini *et al.* (06)

Constraints for low-mass stars

Surface rotation

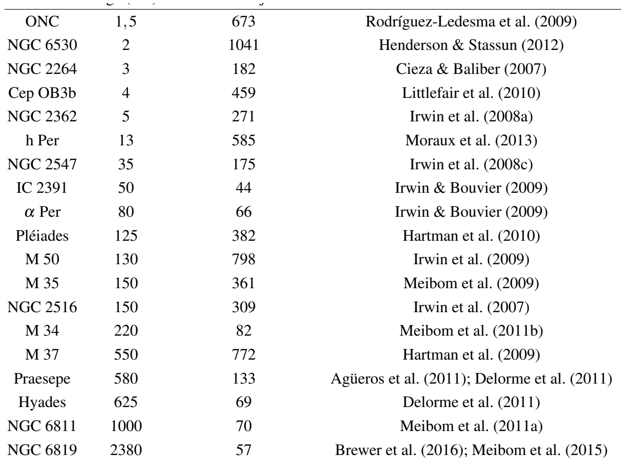


Models including
- Disk coupling
- Magnetized stellar wind torque, 2D MHD simulations
  (Matt *et al.* 15)
- Internal transport of angular momentum “ à la Zahn & Maeder”

Large dispersion on the PMS and the early-MS

slow, moderate, and fast rotators

Convergence on the main sequence

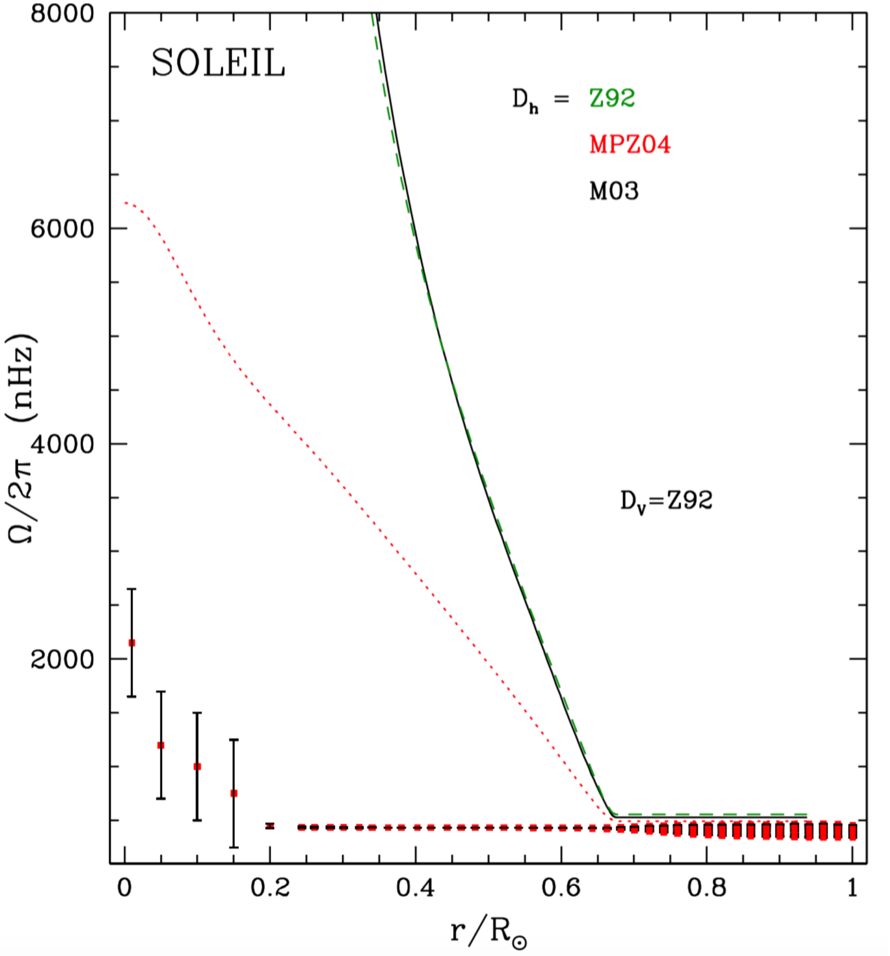


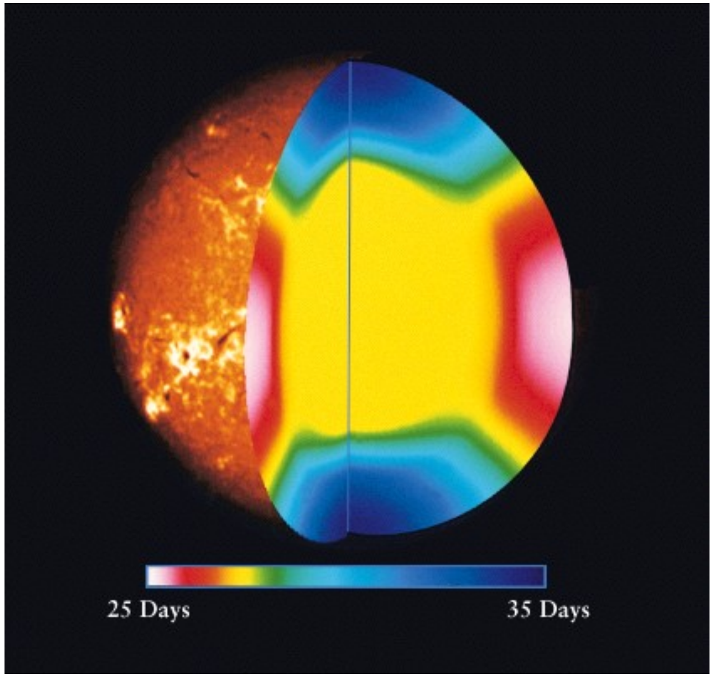
ONC	1,5	673	Rodríguez-Ledesma et al. (2009)
NGC 6530	2	1041	Henderson & Stassun (2012)
NGC 2264	3	182	Cieza & Baliber (2007)
Cep OB3b	4	459	Littlefair et al. (2010)
NGC 2362	5	271	Irwin et al. (2008a)
h Per	13	585	Moraux et al. (2013)
NGC 2547	35	175	Irwin et al. (2008c)
IC 2391	50	44	Irwin & Bouvier (2009)
α Per	80	66	Irwin & Bouvier (2009)
Pléiades	125	382	Hartman et al. (2010)
M 50	130	798	Irwin et al. (2009)
M 35	150	361	Meibom et al. (2009)
NGC 2516	150	309	Irwin et al. (2007)
M 34	220	82	Meibom et al. (2011b)
M 37	550	772	Hartman et al. (2009)
Praesepe	580	133	Agüeros et al. (2011); Delorme et al. (2011)
Hyades	625	69	Delorme et al. (2011)
NGC 6811	1000	70	Meibom et al. (2011a)
NGC 6819	2380	57	Brewer et al. (2016); Meibom et al. (2015)

Amard *et al.* (17)
Data collected by Gallet & Bouvier (13), Bouvier & Gallet (14)

Constraints for low-mass stars

Internal rotation – Sun

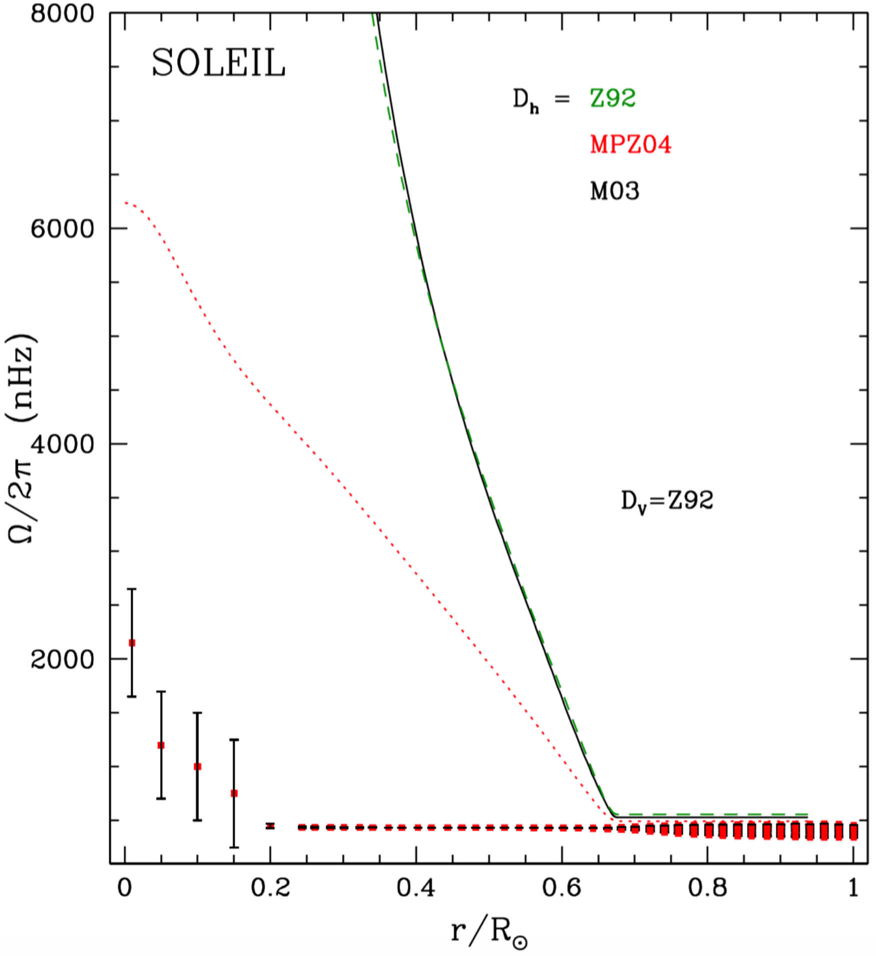




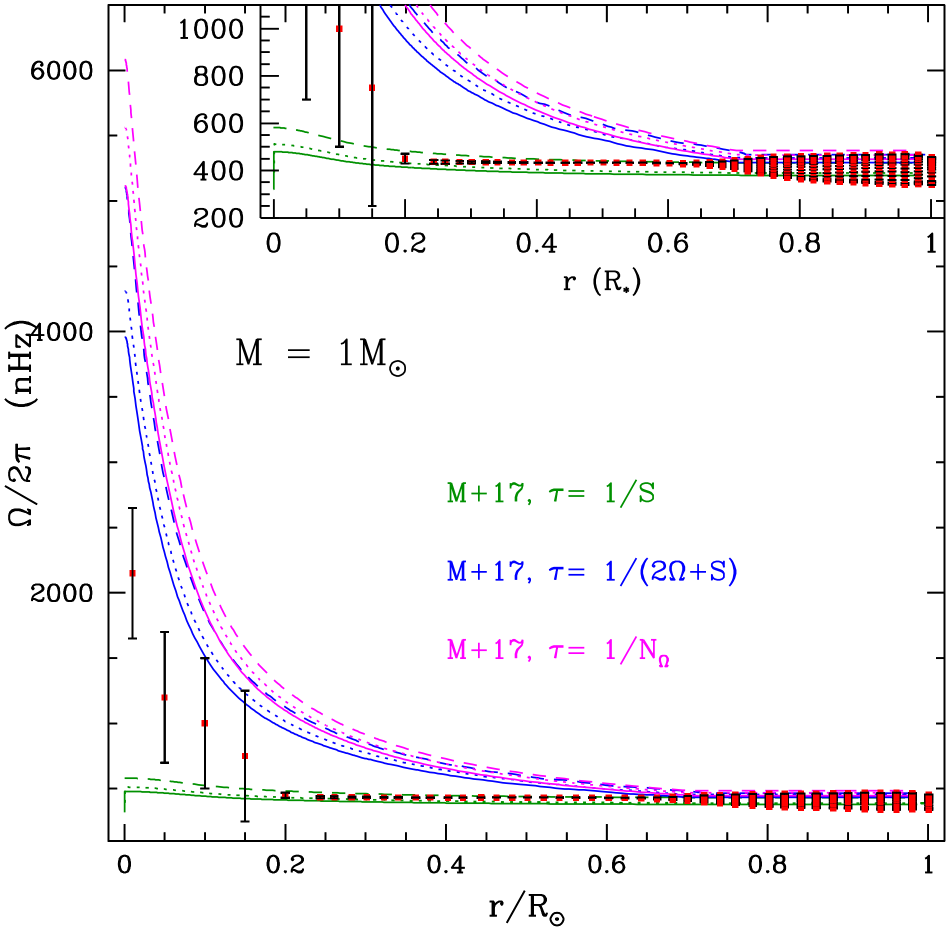
Mathis *et al.* (17) : **Previous prescriptions for turbulence → Too steep gradient of angular momentum**
Data Garcia *et al.* (07)
Similar problem in all models
(Pinsonneault et al. 89, Chaboyer et al. 95; Talon 97;
Charbonnel & Talon 05; Turck-Chièze et al. 10; …)

Internal rotation – Sun

Constraints for low-mass stars



Mathis *et al.* (17)
Data Garcia *et al.* (07)
Similar problem in all models
(Pinsonneault et al. 89, Chaboyer et al. 95; Talon 97;
Charbonnel & Talon 05; Turck-Chièze et al. 10; …)



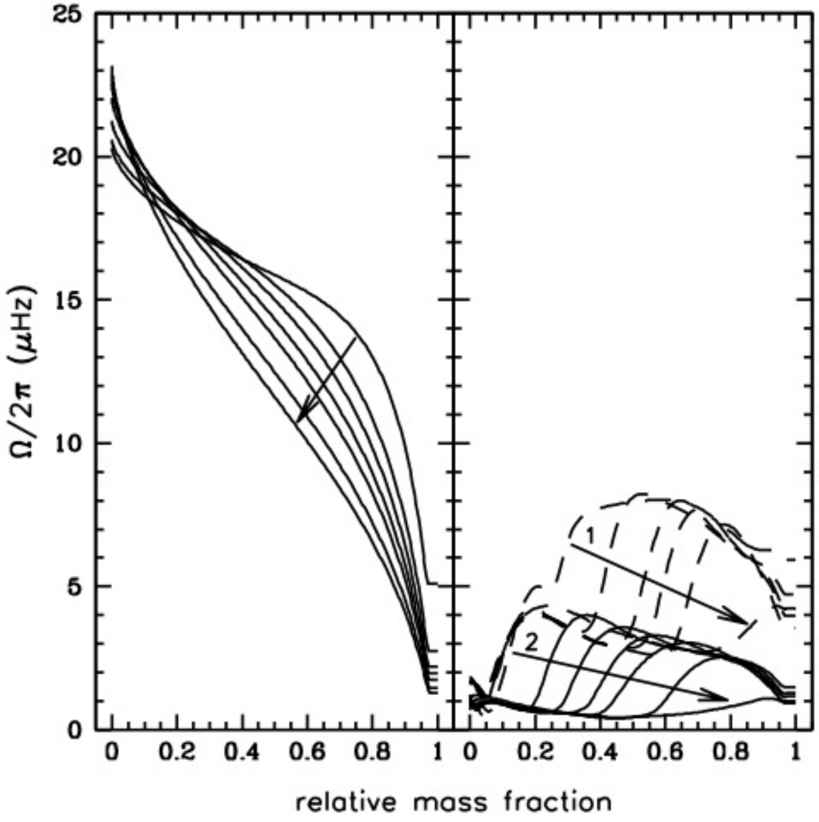
Mathis *et al.* (17)

Anisotropic Geostrophic Stratified Turbulence

Theoretical scaling laws and numerical simulations in fundamental fluid dynamics for stratified and rotating turbulent flows

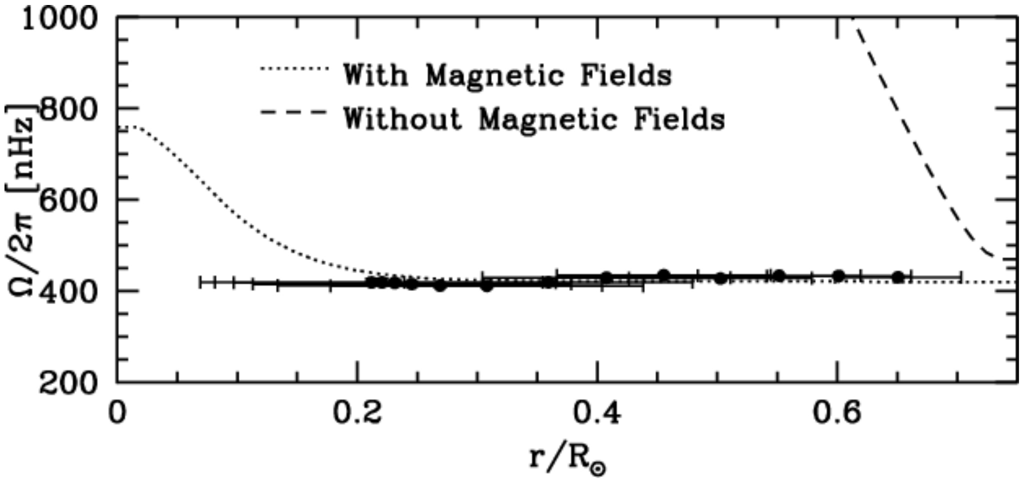
Constraints for low-mass stars

Additional processes for the transport of angular momentum inside stars



Charbonnel & Talon (05)

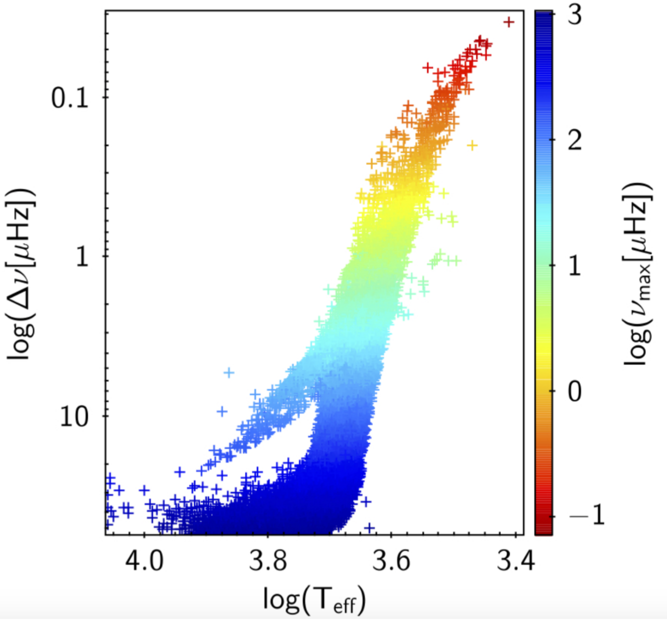
Internal gravity waves

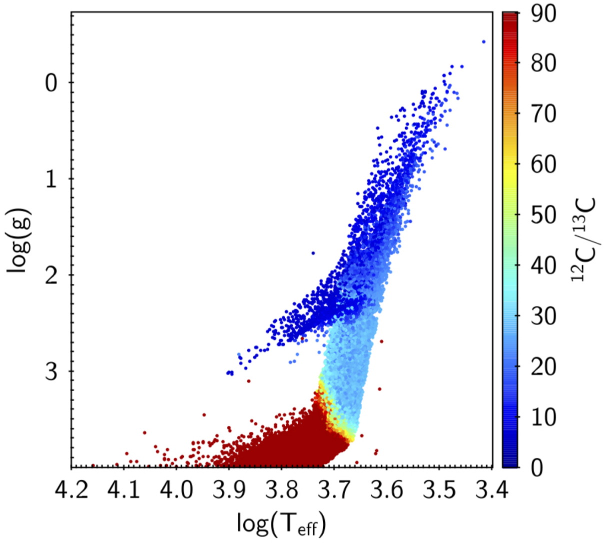


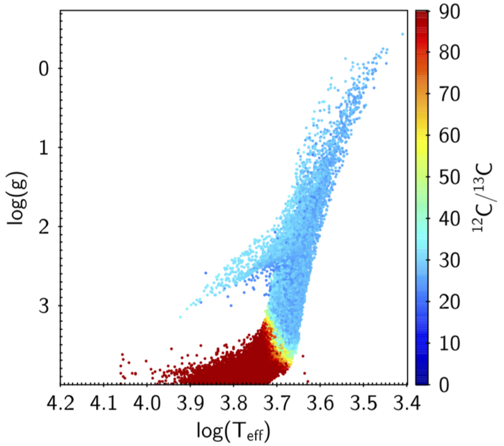
Eggenberger *et al.* (05)

Magnetic fields

Combined analysis of constraints from astrometry, asteroseismology, spectroscopy





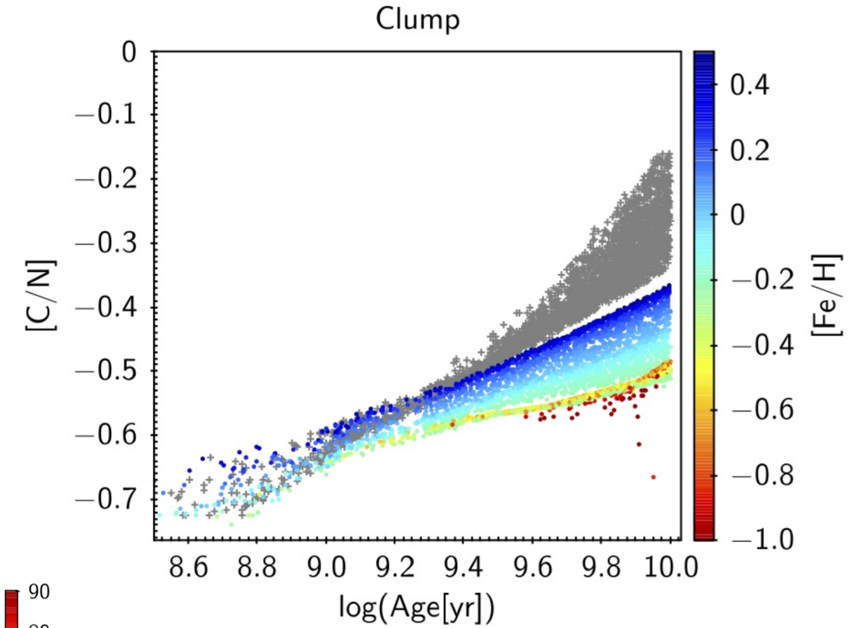


Population synthesis

Besançon Galaxy model including models of rotating stars with thermohaline instability – Lagarde *et al.* (17)

Basic ingredients:

IMF, SFR, 3D extinction map, Age-Z relation

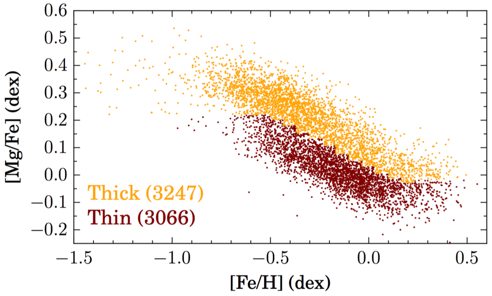


Stellar astrophysics is being revolutionized by large scale surveys

Golden age for stellar models

Spectroscopy

Stellar parameters
Abundances
Rotation

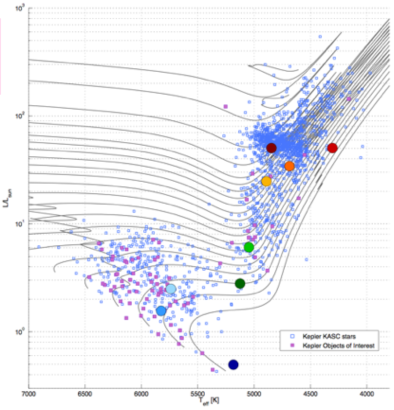


Spectropolarimetry

Magnetic field, rotation

Asteroseismology

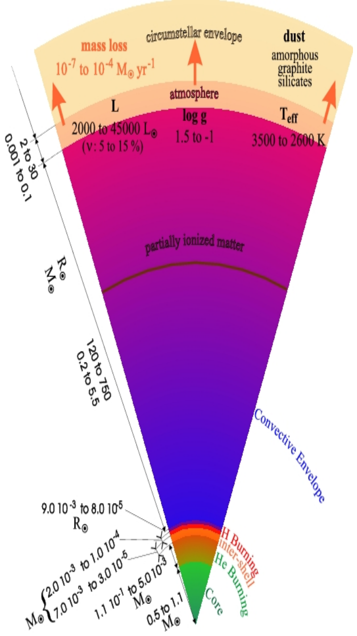
Internal properties
M, R, distance, age
Evolution state
Rotation



Models

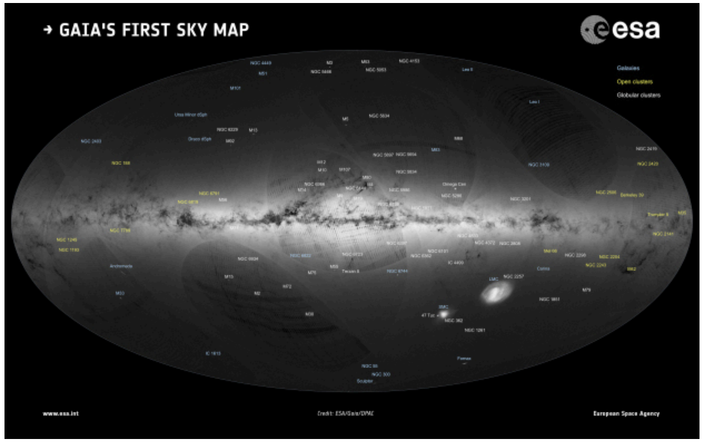
Macroscopic physical processes
Prescriptions from multiD MHD simulations

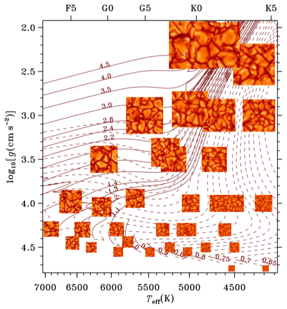
Full **description of the plasma**
Laser, nuclear reaction experiments

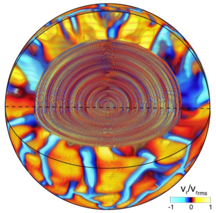


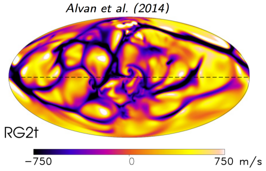
Astrometry

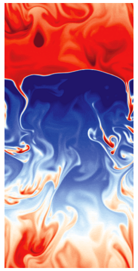
Distance, proper motion, CMD



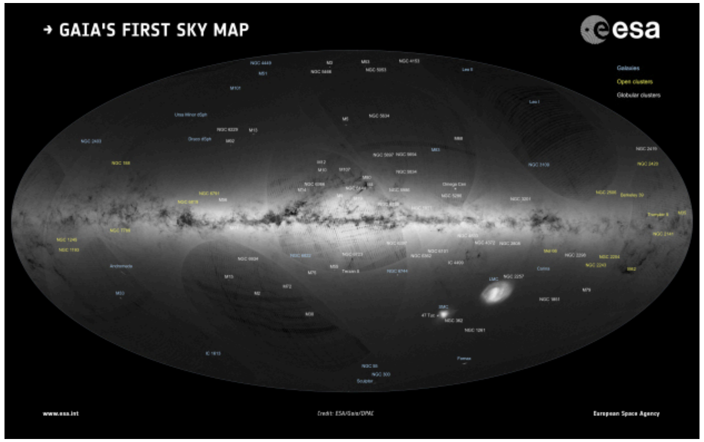








Take home messages



Use stellar models with great caution

Input physics counts !

→Ages, masses, initial composition

→ Stellar populations studies :

Chemical tagging , age-metallicity relation

→ Galactic archeology, dynamics

→ Nucleosynthesis : Chemical evolution

Use stellar models under guidance

Well selected, reliable, complementary constraints count !

The details are making the perfection, and perfection is not a detail
Leonard de Vinci