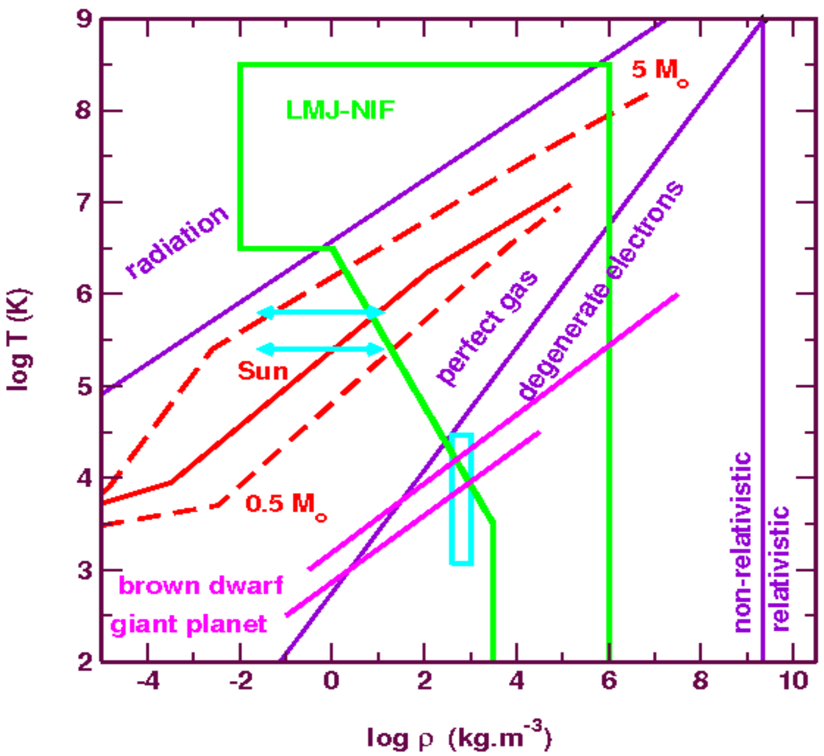
New perspectives in stellar physics: GAIA in the 2015 context

Yveline Lebreton
GEPI, Paris Observatory

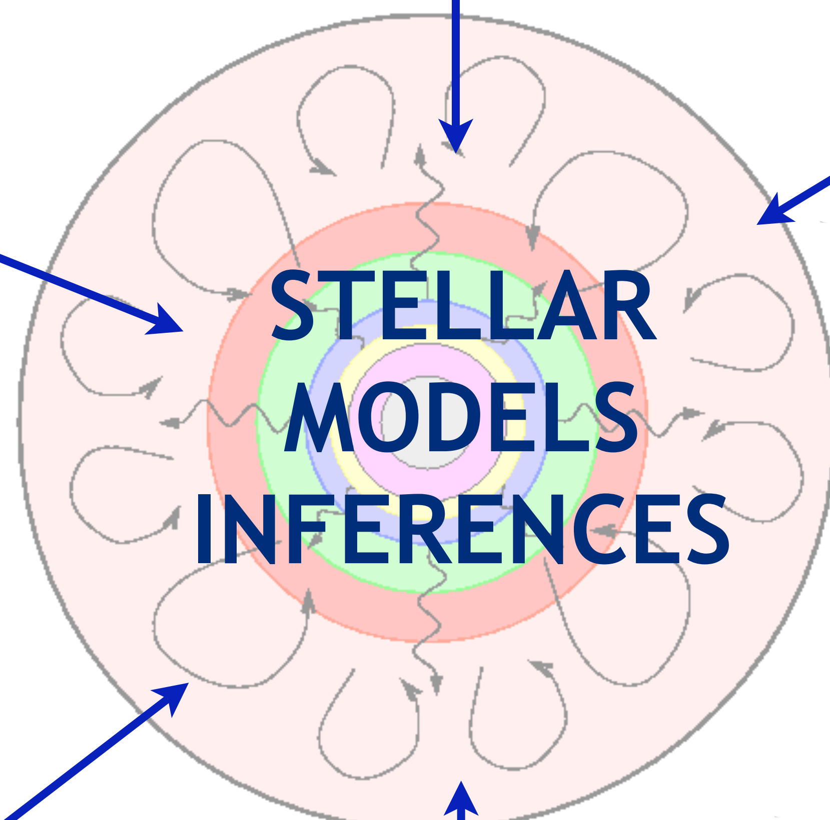


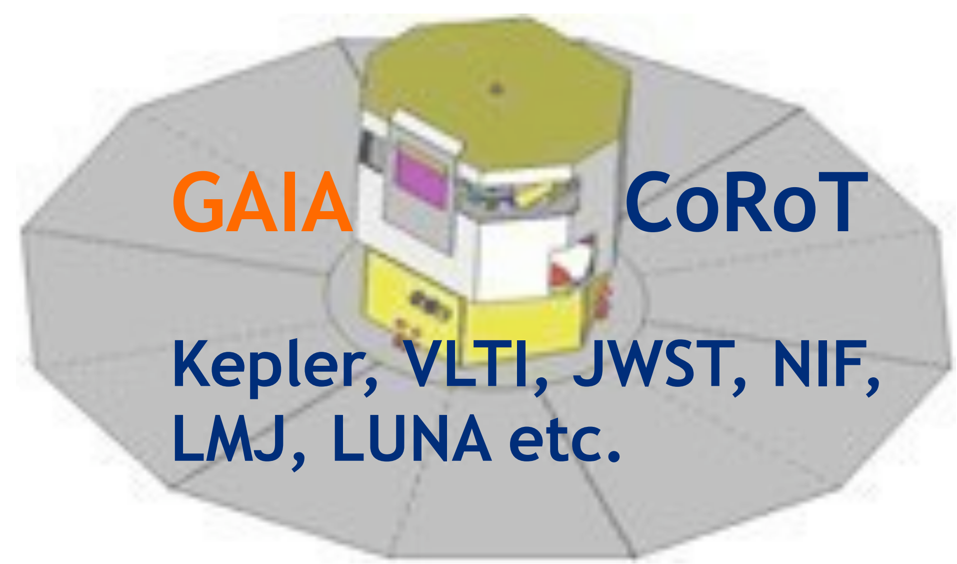
INPUT PARAMETERS
mass
initial composition
evolutionary state

INPUT PHYSICS
microscopic:
opacities
equation of state
nuclear reactions
microscopic diffusion

macroscopic:
convection, rotation
internal waves
magnetic field
&
related transport

OBSERVATIONAL CONSTRAINTS
distances
magnitudes
T_{eff}, log *g*
abundances
radii
masses
seismology
frequencies
amplitudes
lifetimes





BOUNDARIES
model atmospheres

NUMERICS

Opacities: progress is going on since 1990…

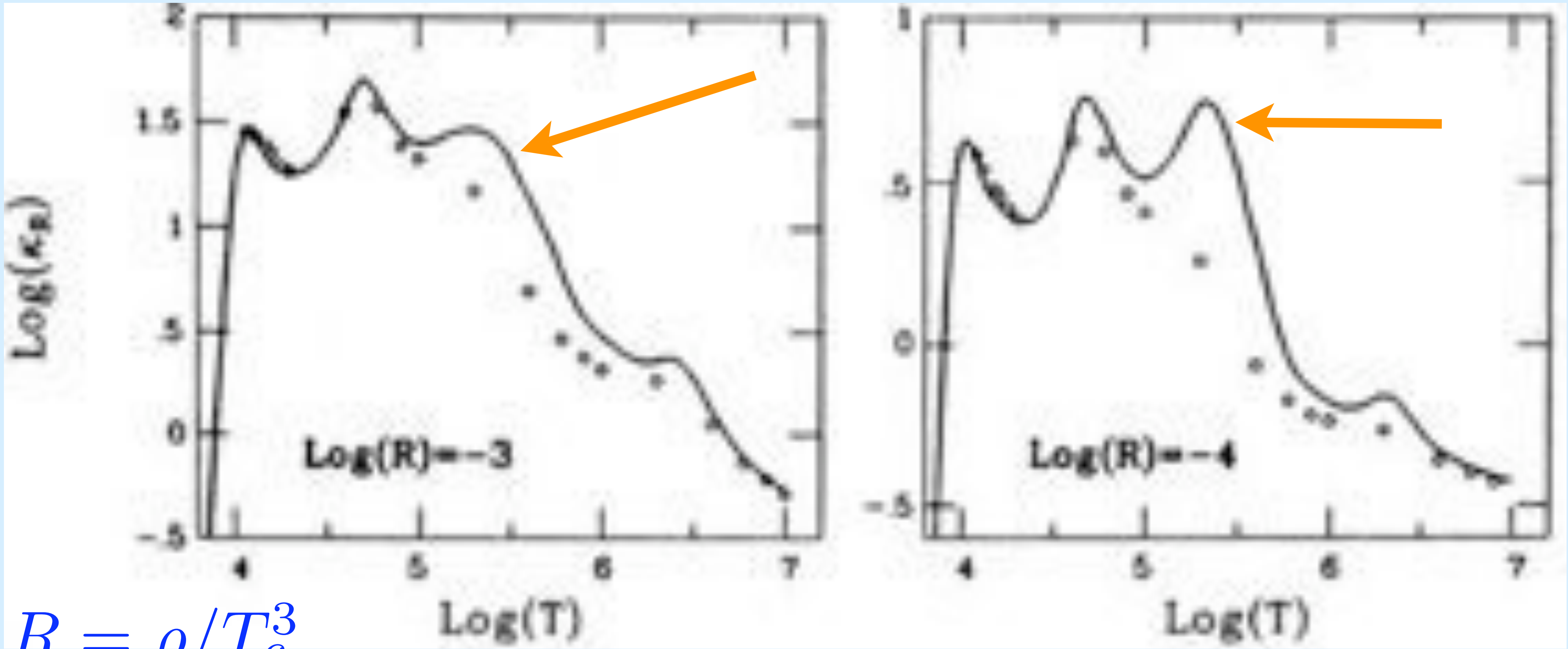
Badnell et al. 05, Iglesias Rogers 96, Ferguson et al. 04

Opacities: progress is going on since 1990...

bound-bound and bound free opacities: millions of lines included

- **interior: OPAL and OP data tables**
- **envelope/atmosphere: Wichita data tables, including molecules, grains**

1990: OPAL vs. LAOL



$R = \rho / T_6^3$

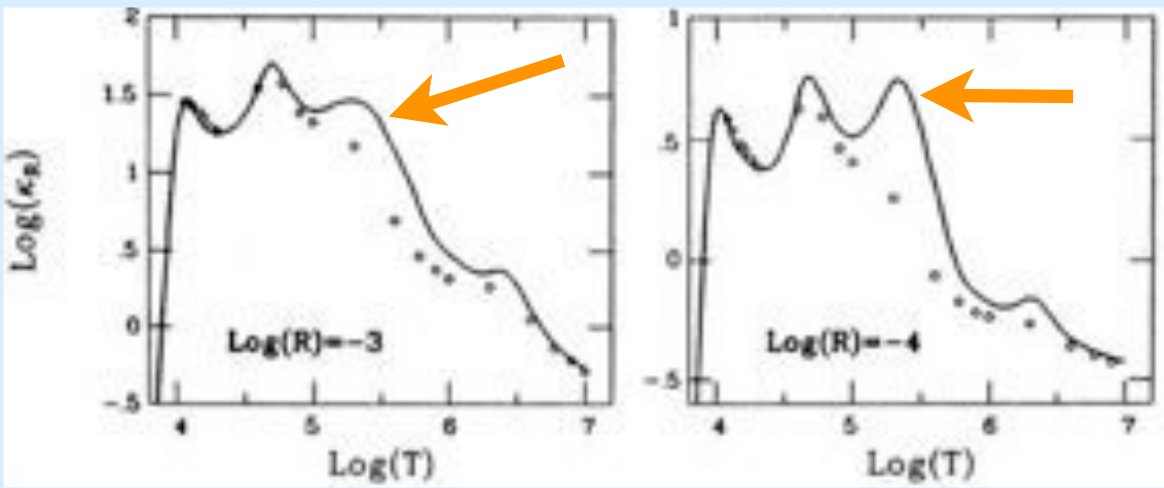
Badnell et al. 05, Iglesias Rogers 96, Ferguson et al. 04

Opacities: progress is going on since 1990...

bound-bound and bound free opacities: millions of lines included

- **interior: OPAL and OP data tables**
- **envelope/atmosphere: Wichita data tables, including molecules, grains**

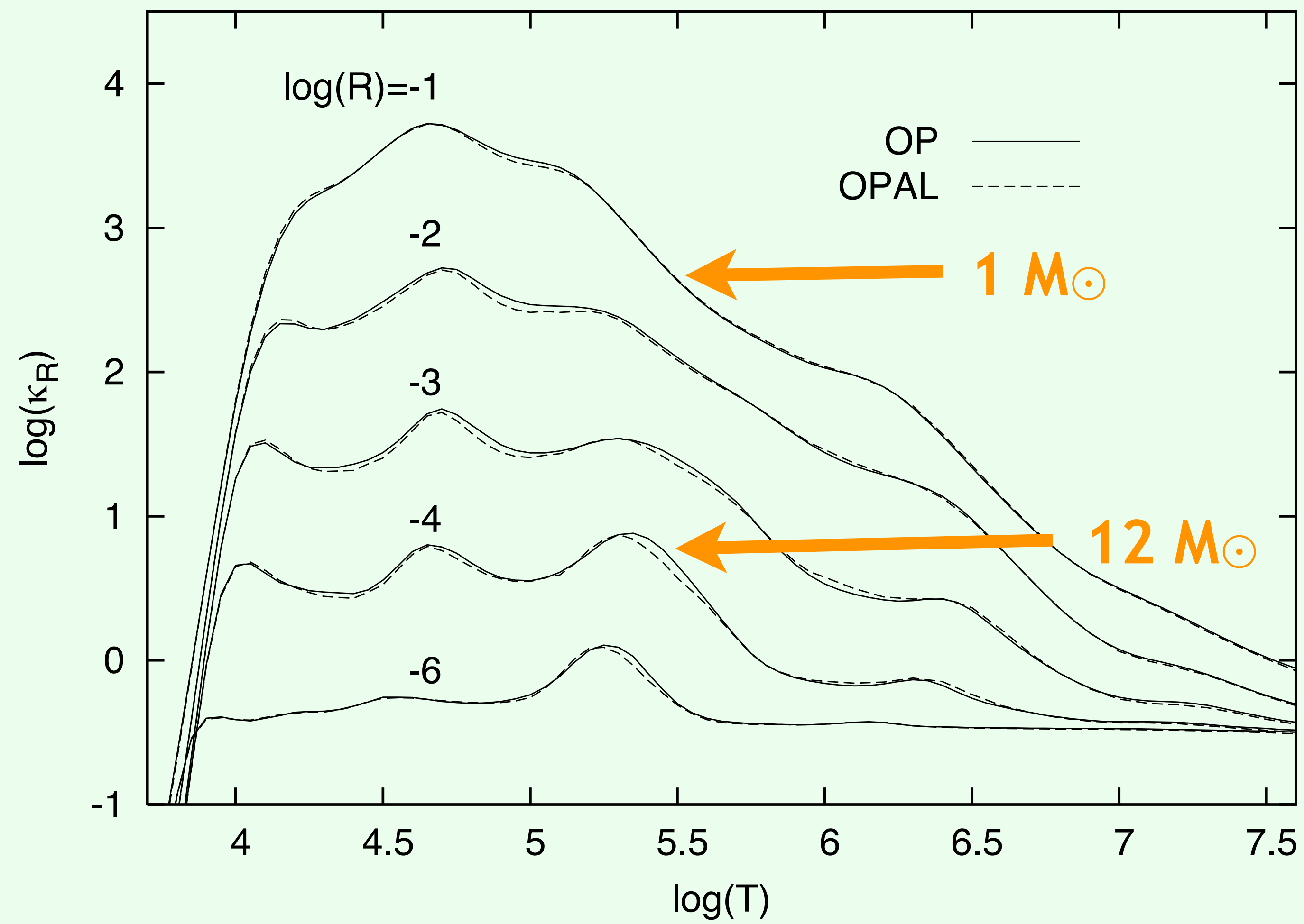
1990: OPAL vs. LAOL



$$R = \rho / T_6^3$$

2005: OP vs. OPAL

differences 5-10 % /locally Z-bump 30%



Badnell et al. 05, Iglesias Rogers 96, Ferguson et al. 04

Initial abundances: the solar mixture

Grevesse & Noels 93, Grevesse & Sauval 1998, Asplund et al. 05, Asplund & al 09, Lodders et al. 09, Caffau et al 10

Initial abundances: the solar mixture

1993-2010: several revisions of the photospheric solar mixture

2003: 3D model atmospheres + NLTE effects + improved atomic data

➥ decrease of C, N, O, Ne, Ar and (Z/X)

	GN93	GS98	AGS05	AGS09	Lod09	Caff10
Z/X	0.0245	0.0229	0.0165	0.0181	0.0191	0.0209

Grevesse & Noels 93, Grevesse & Sauval 1998, Asplund et al. 05, Asplund & al 09, Lodders et al. 09, Caffau et al 10

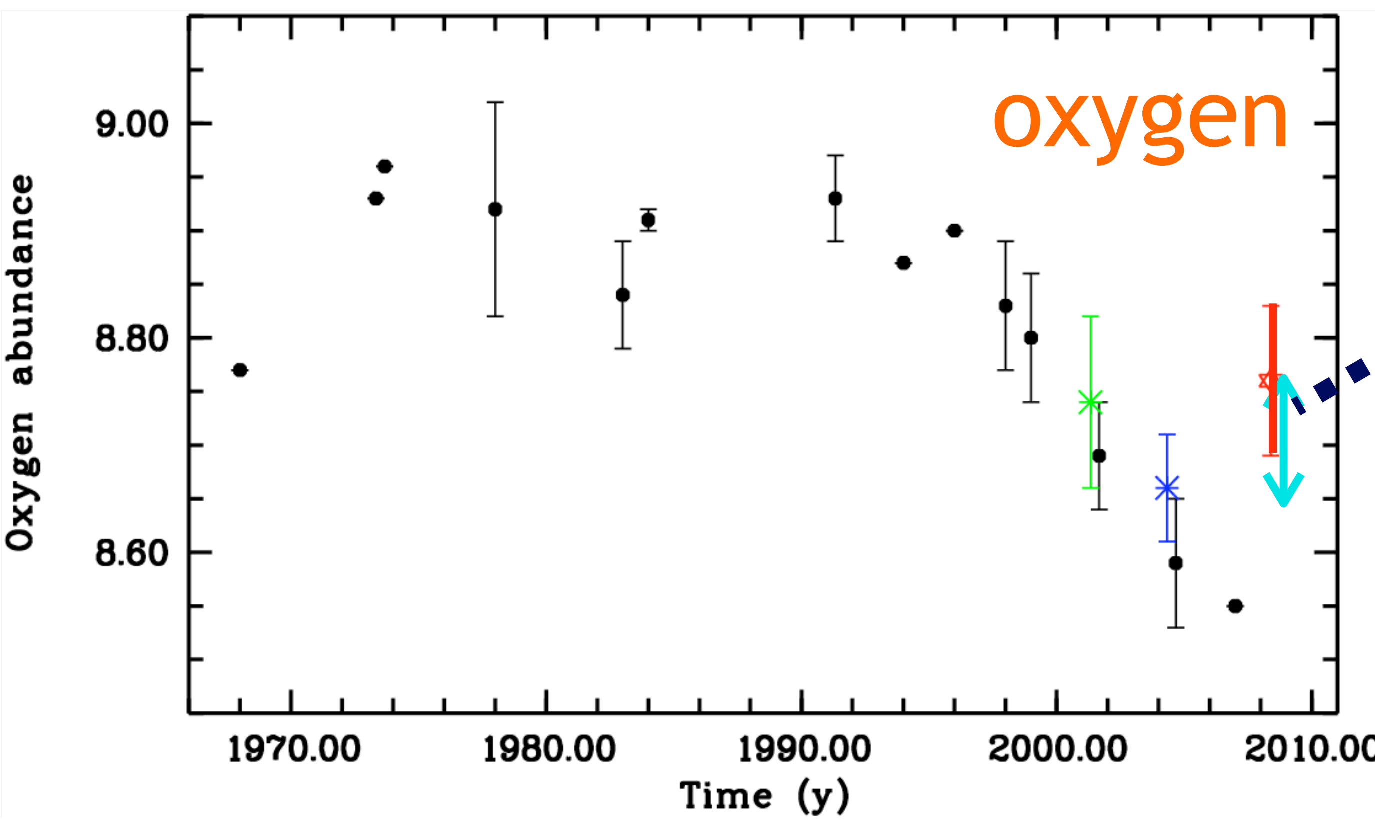
Initial abundances: the solar mixture

1993-2010: several revisions of the photospheric solar mixture

2003: 3D model atmospheres + NLTE effects + improved atomic data

➥ decrease of C, N, O, Ne, Ar and (Z/X)

	GN93	GS98	AGS05	AGS09	Lod09	Caff10
Z/X	0.0245	0.0229	0.0165	0.0181	0.0191	0.0209



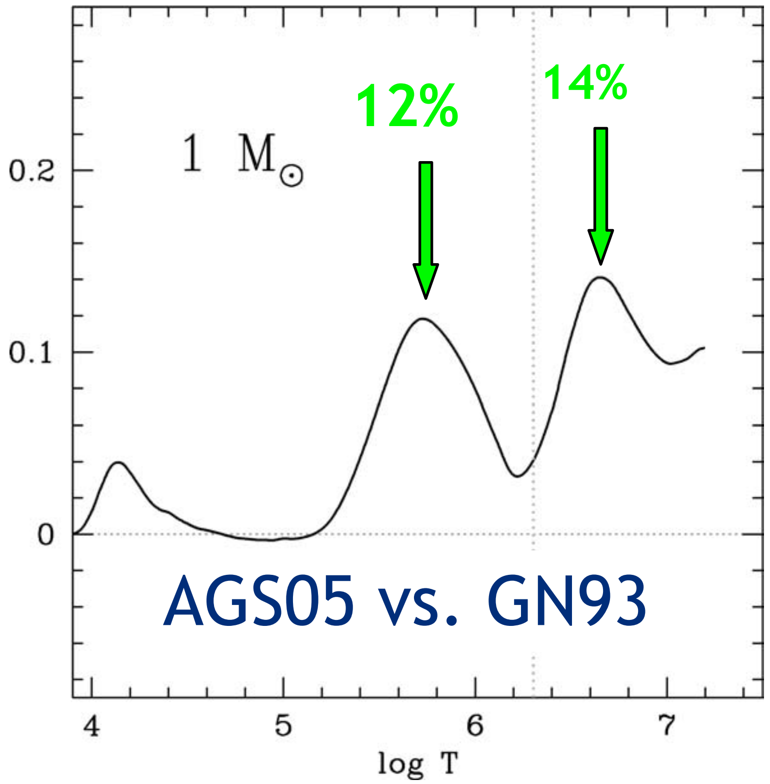
measure of lines EW
evaluation of NLTE effects
3D model atmosphere

stellar models
⇒ opacity changes

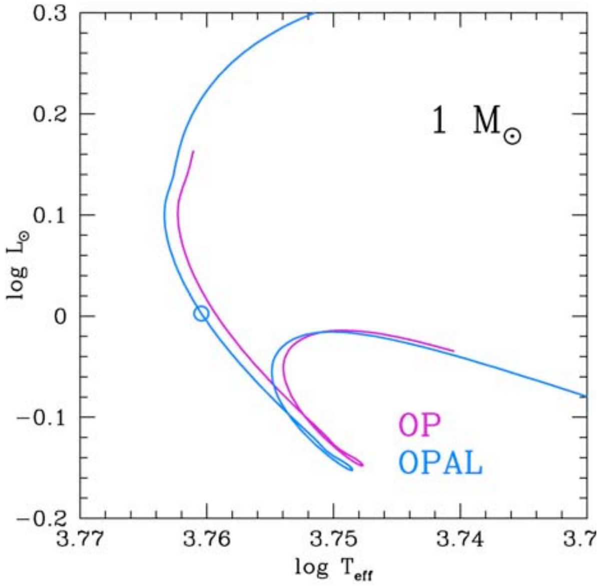
Grevesse & Noels 93, Grevesse & Sauval 1998, Asplund et al. 05, Asplund & al 09, Lodders et al. 09, Caffau et al 10

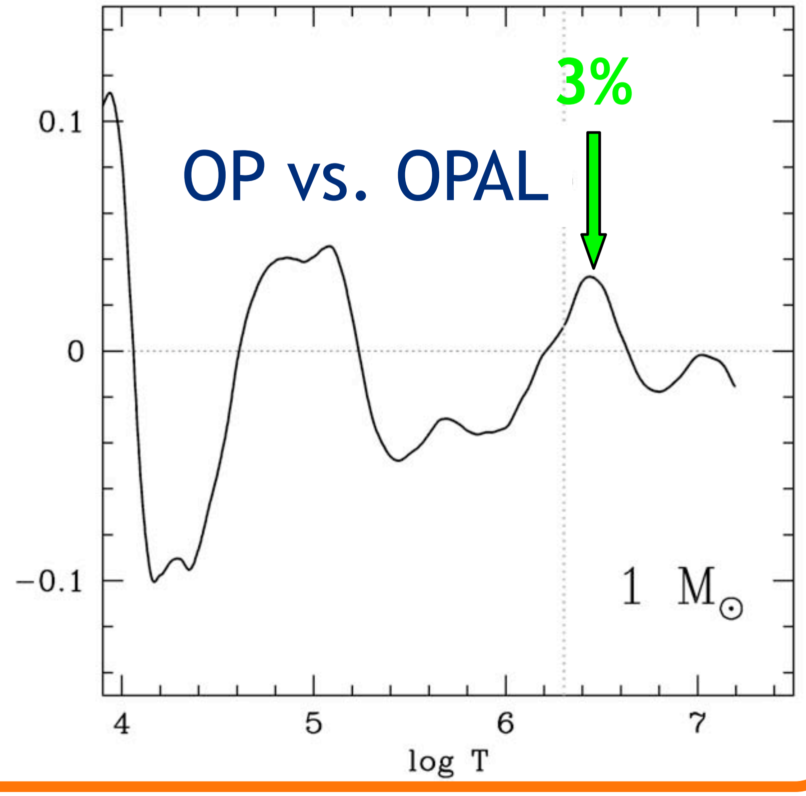
Opacities: mixture and choice of tables

Opacities: mixture and choice of tables



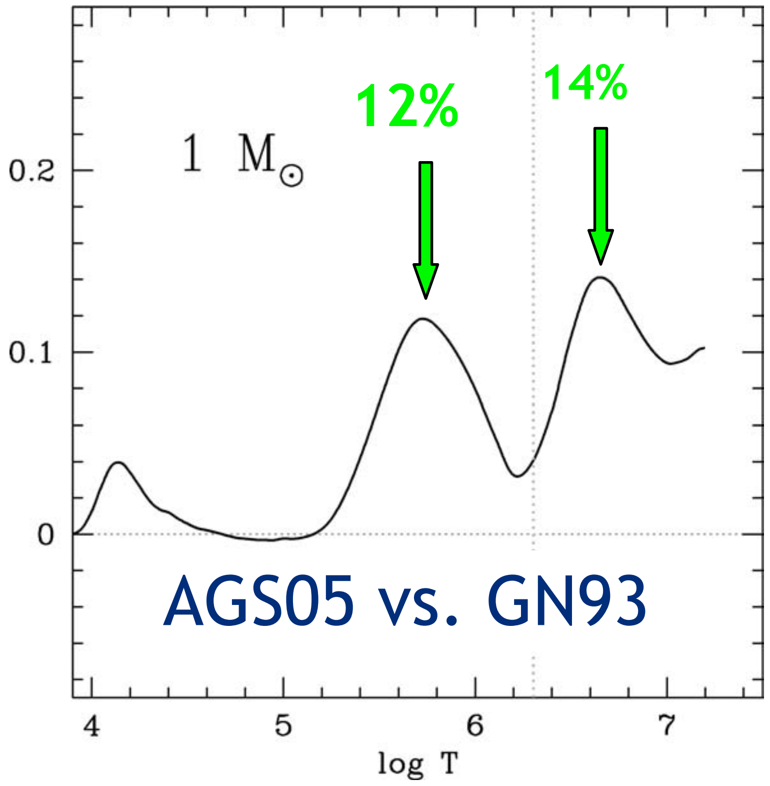
MODEL with M= 1 M⊙

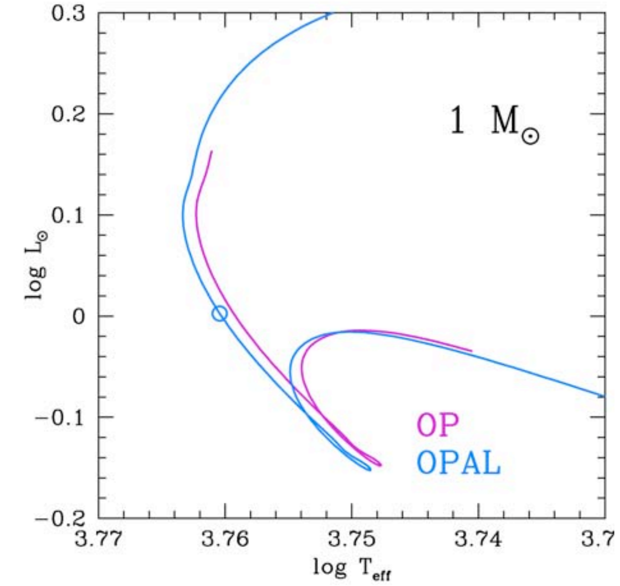


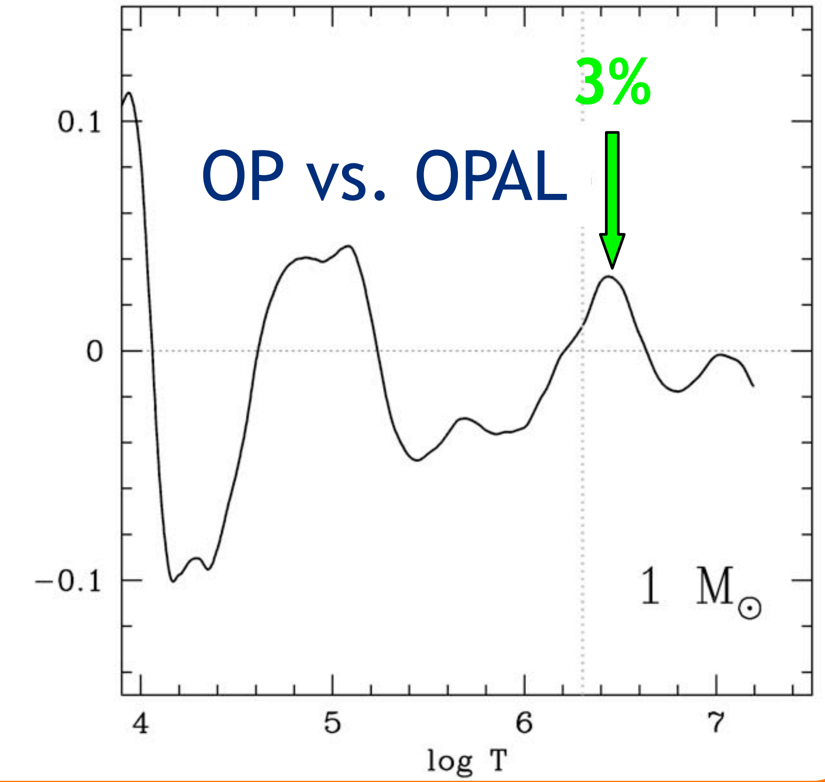


Opacities: mixture and choice of tables

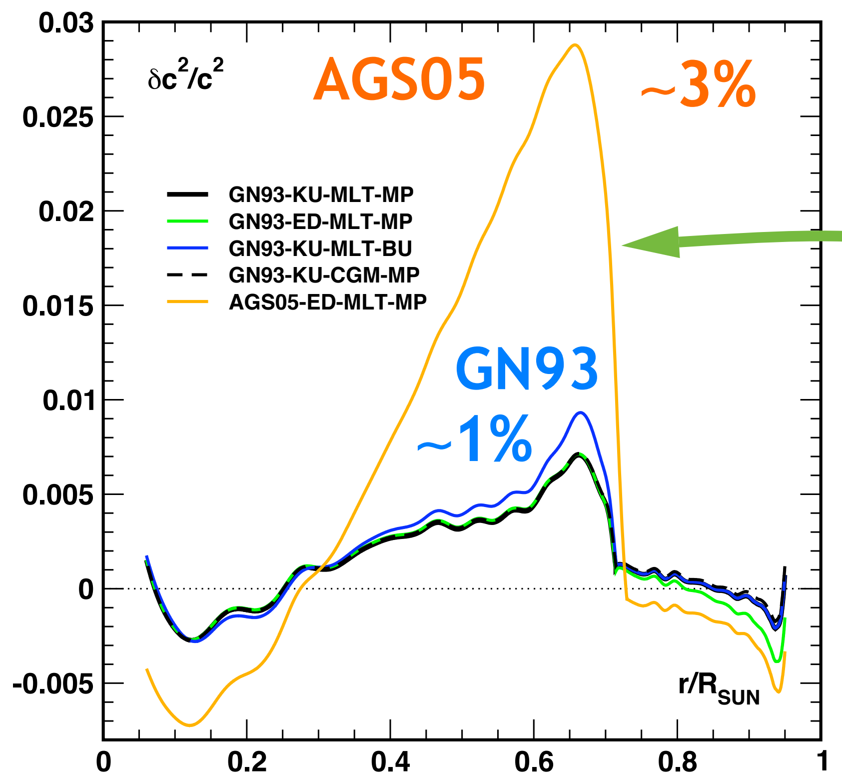
MODEL with M= 1 M$_\odot$







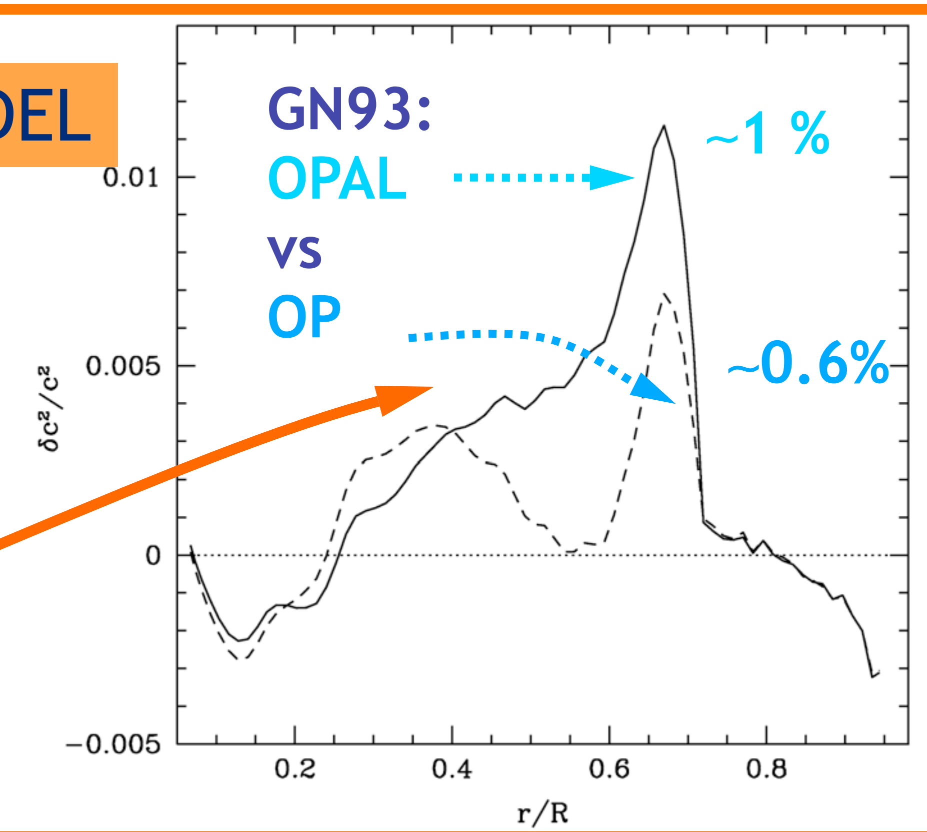
CALIBRATED SOLAR MODEL



mixture: ~1 to ~3%

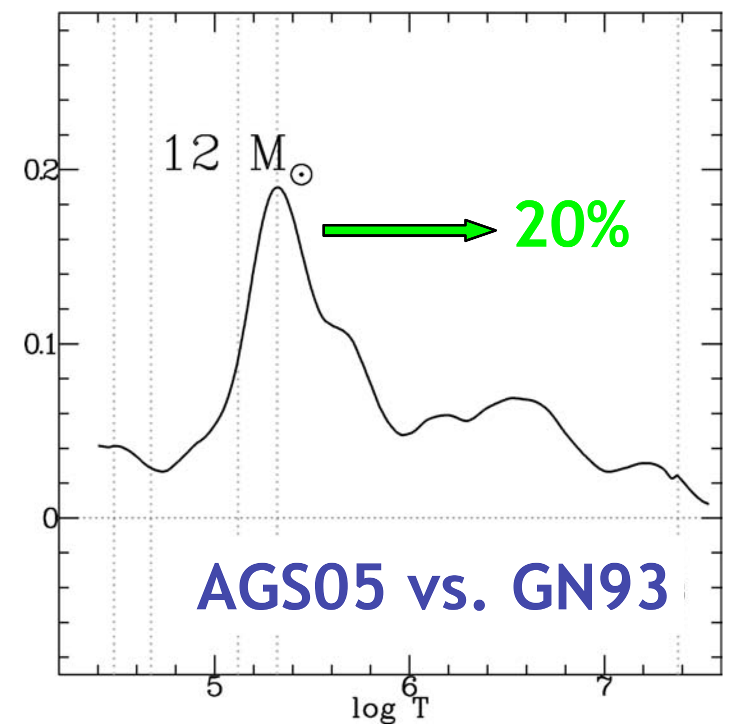
opacity tables

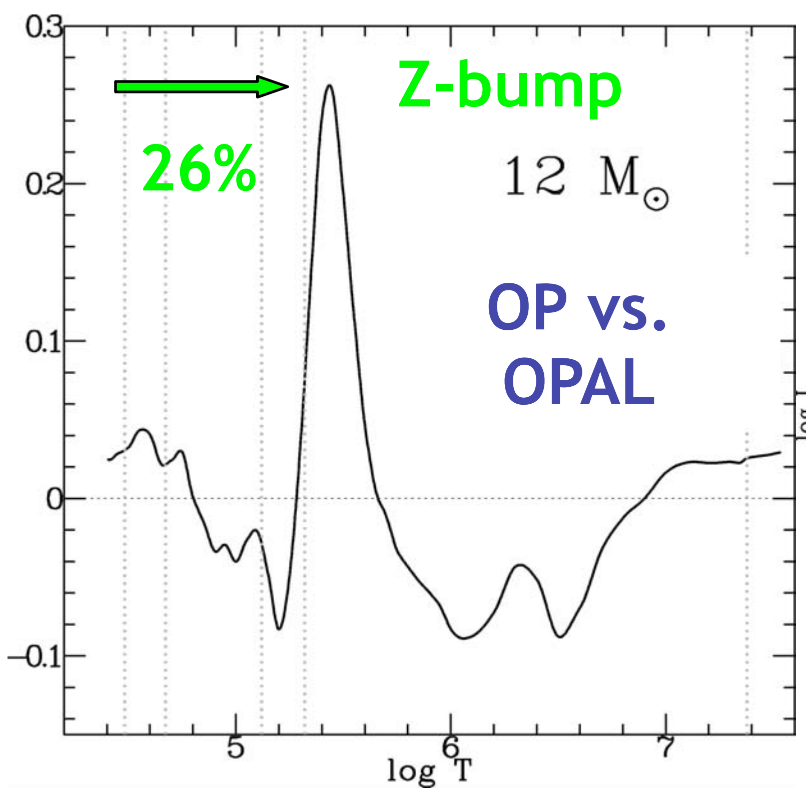
Miglio 07, Basu & Antia 08, etc.

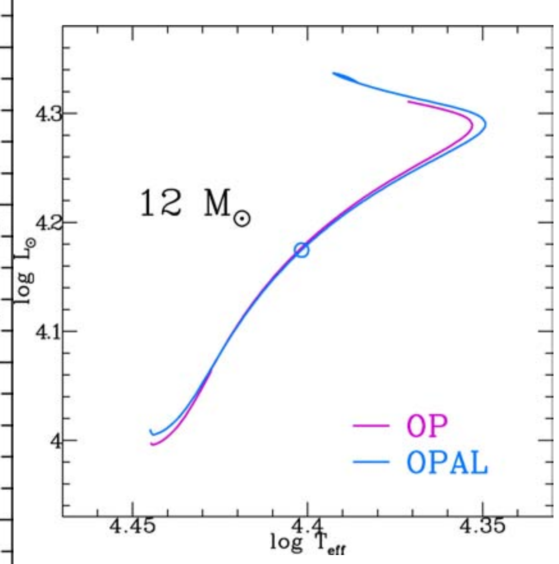


Opacities: mixture and choice of tables

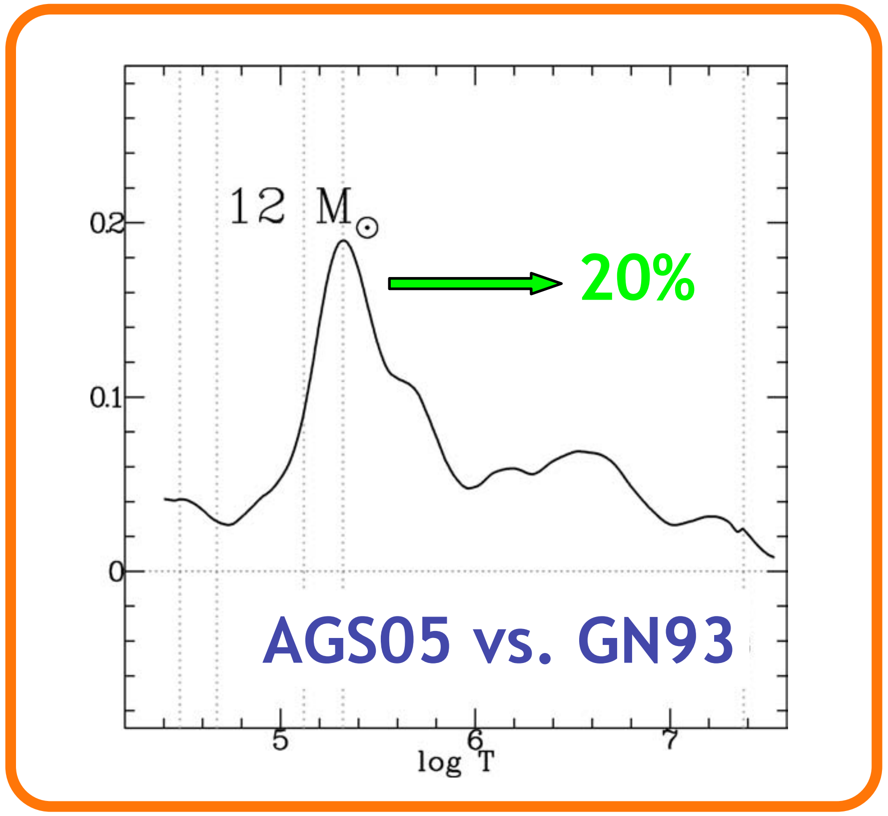
Opacities: mixture and choice of tables



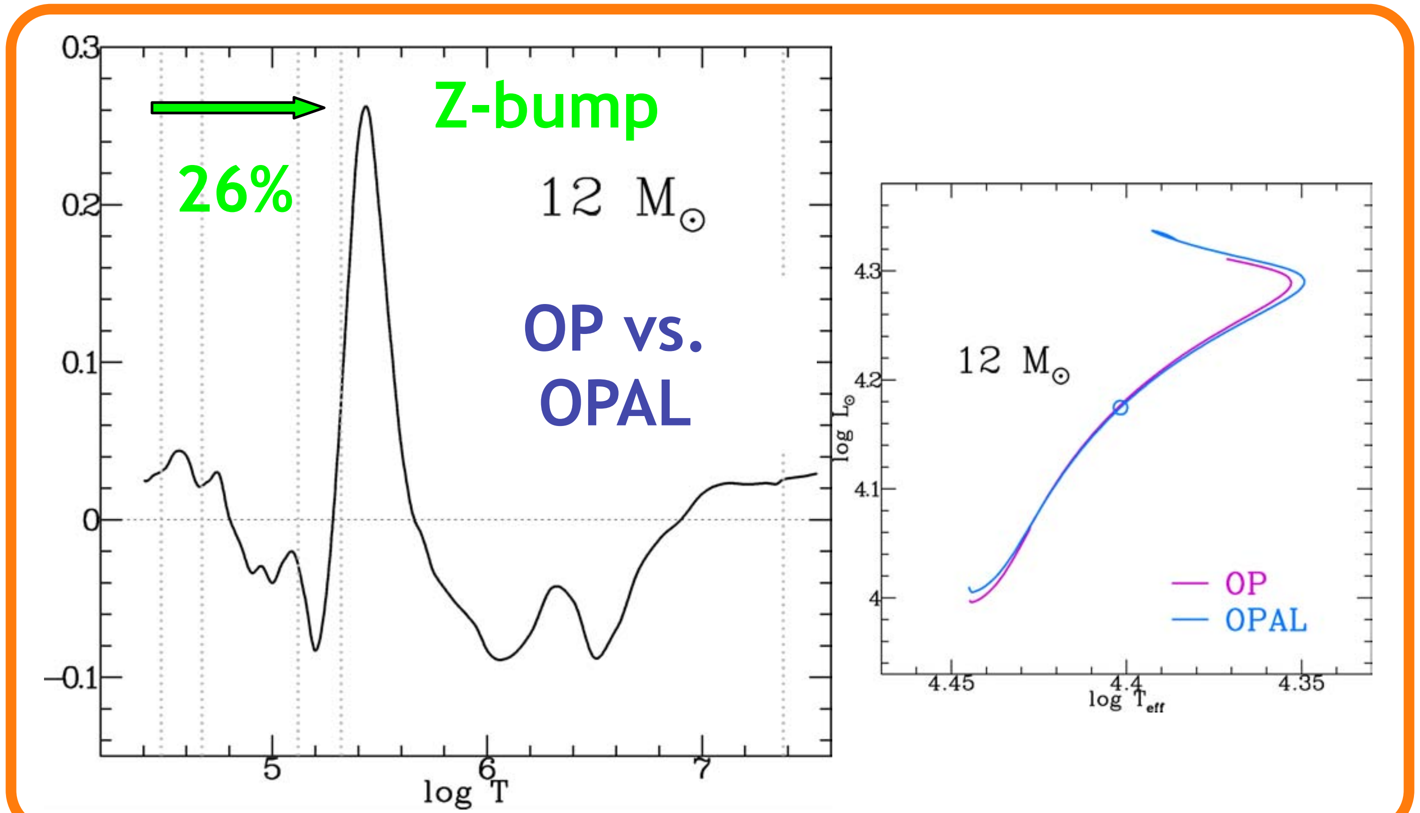


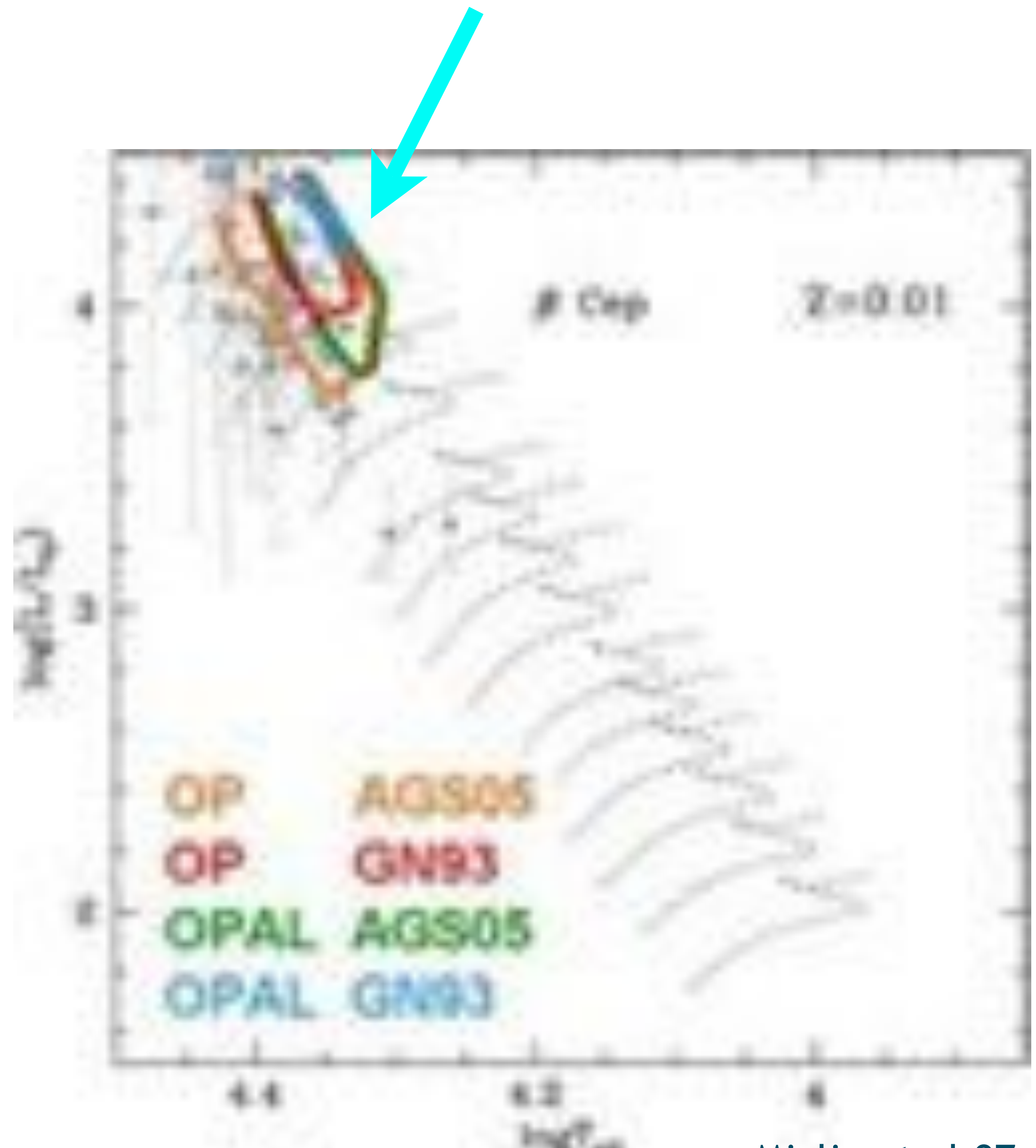


Opacities: mixture and choice of tables



Beta Cephei pulsators: region of excitation theoretical predictions vs. observations





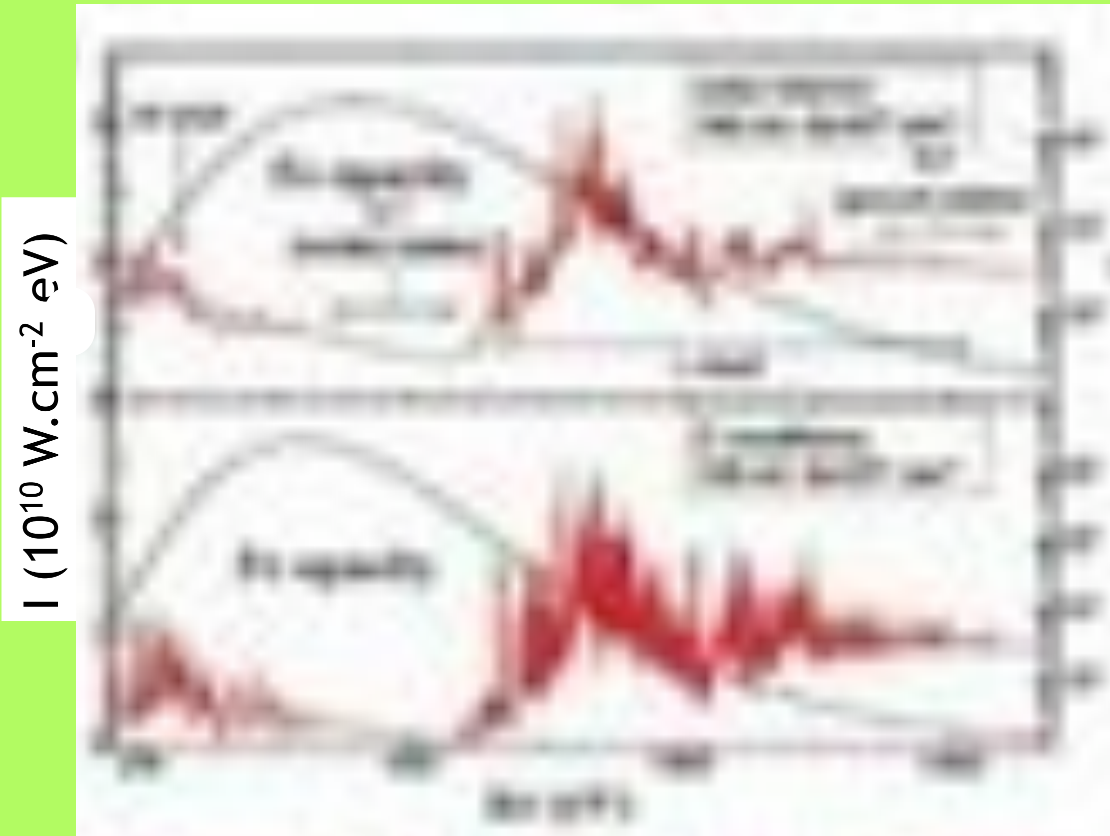
Miglio et al 07

Opacities: the future

Bailey et al. 07, Moses et al. 09

Opacities: the future

calculated iron plasma opacity



sun:
radiative-convective boundary

laboratory:
present reachable conditions

2010-2015: high-energy-density devices

- intense lasers, Z-pinches: NIF (March 2009), LMJ, ...

direct measurements at $T \geq 10^8$ K ; $\rho \approx 10^3$ g.cm^{-3}

Bailey et al. 07, Moses et al. 09

Nuclear reaction rates

Nuclear reaction rates

reaction cross section:

$$\sigma(E) = \frac{S(E)}{E}\exp(-2\pi\eta)$$

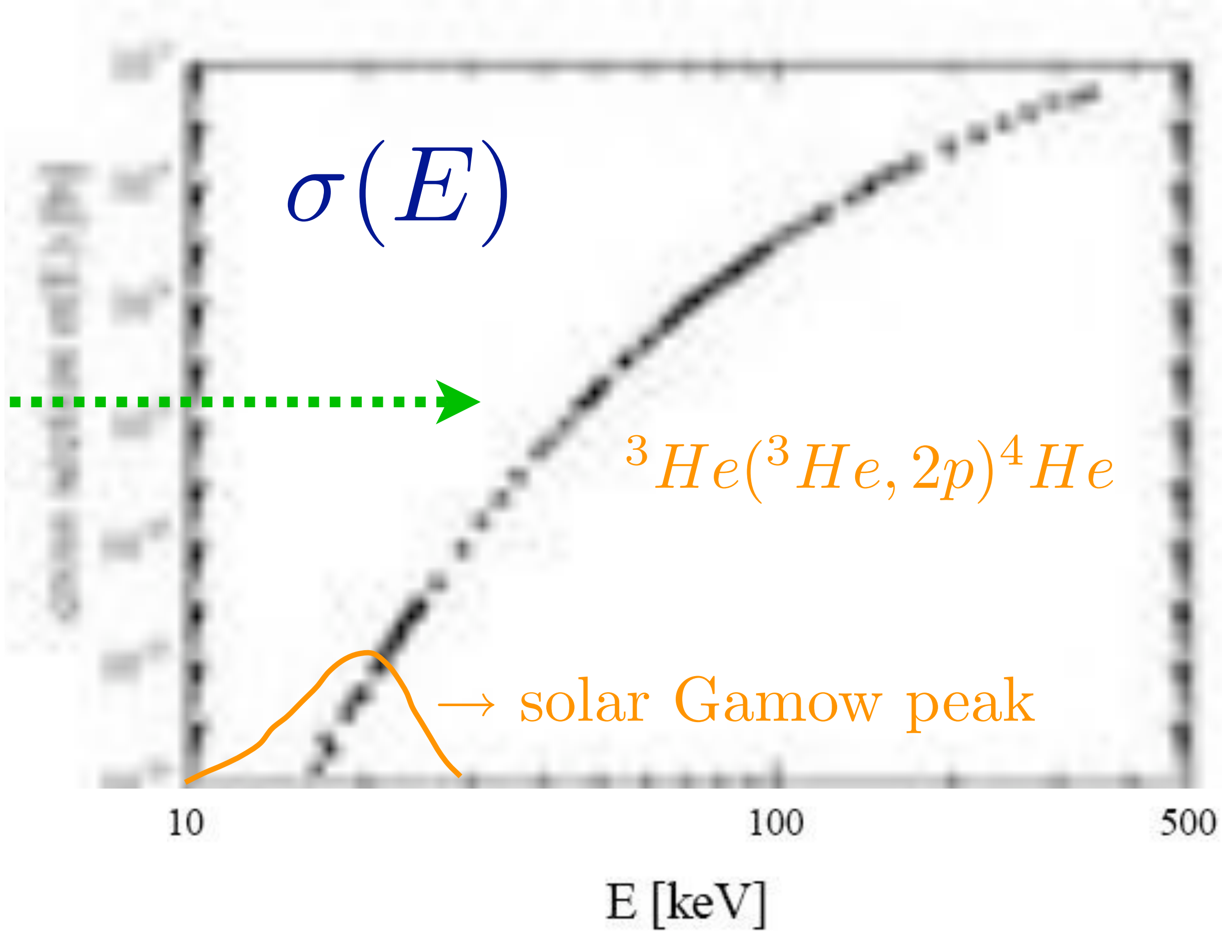
astrophysical factor (S-factor)

Nuclear reaction rates

reaction cross section:

$$\sigma(E) = \frac{S(E)}{E}\exp(-2\pi\eta)$$

astrophysical factor (S-factor)



in stars: reactions occur at low energy: few keV to 0.1 MeV

rates from:

- experimental data but to be extrapolated to low E
- theory

Nuclear reaction rates

Nuclear reaction rates

recent significant progress in laboratory and theory

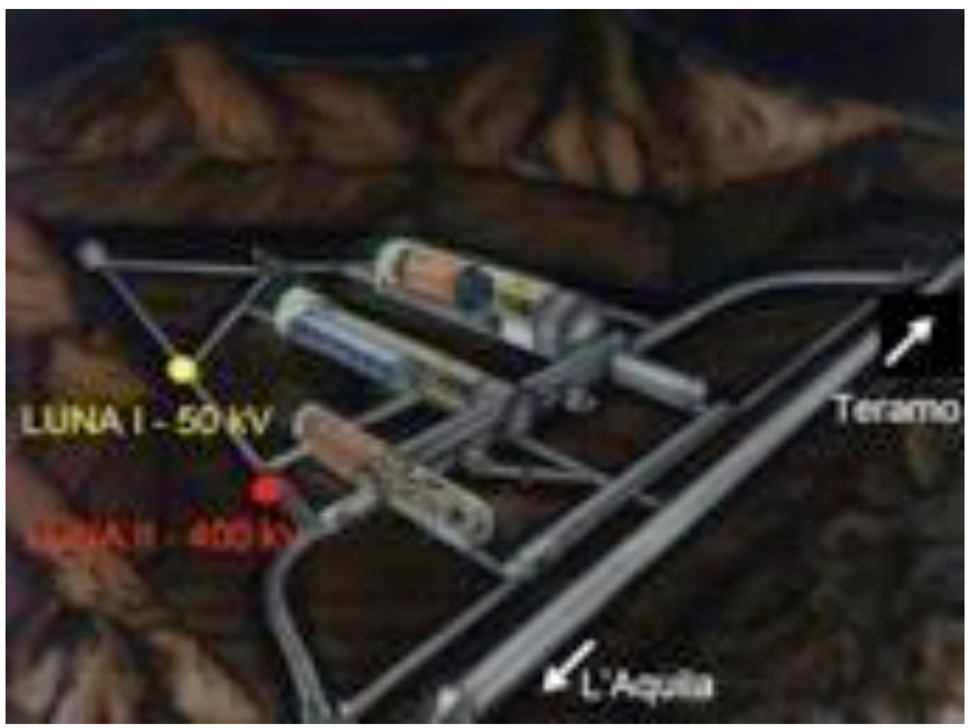
➥ S-factor + screening + extrapolation to the Gamow peak

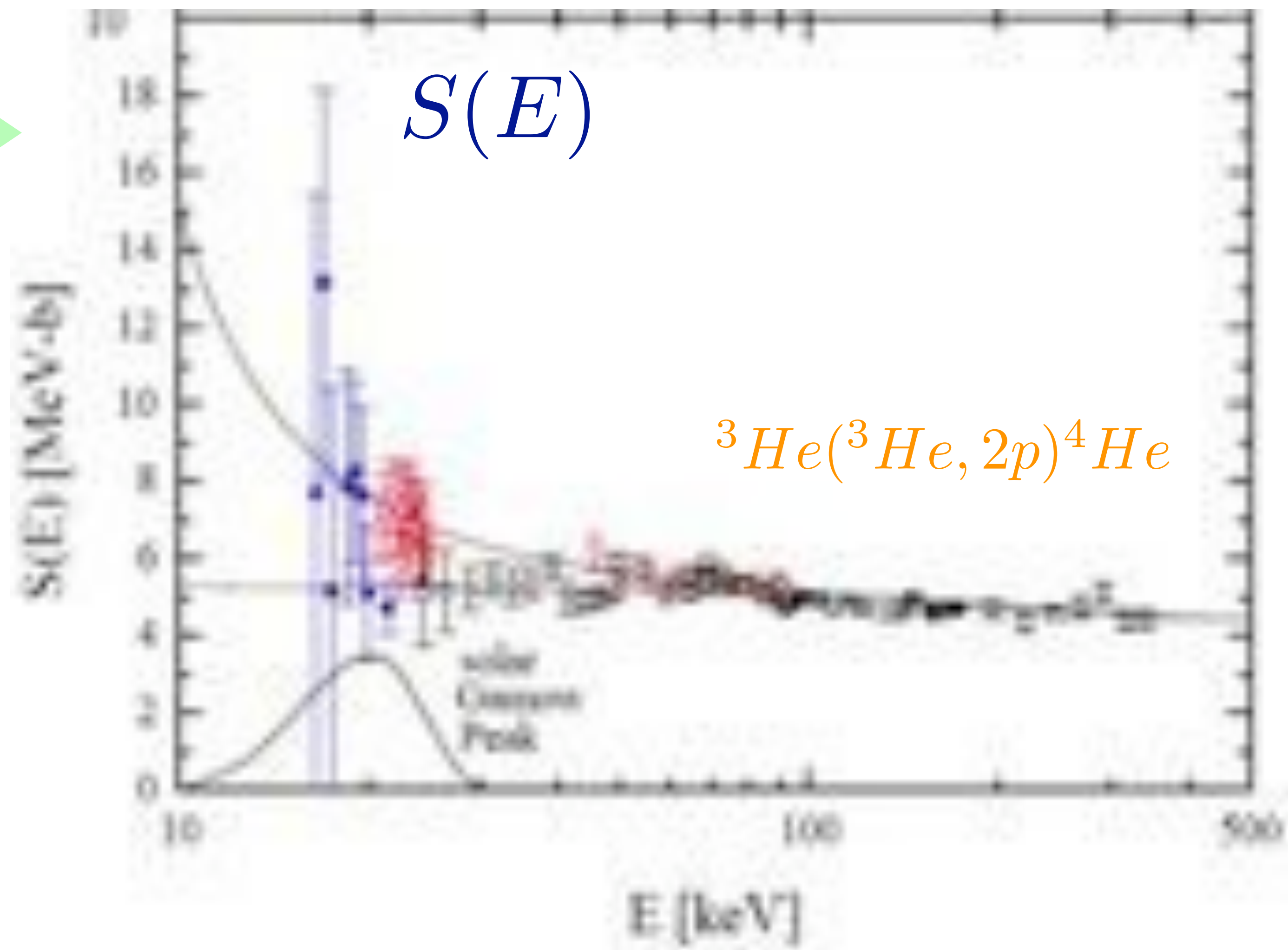
Nuclear reaction rates

recent significant progress in laboratory and theory

➥ S-factor + screening + extrapolation to the Gamow peak

NOW and FUTURE
low energy, high intensity
underground accelerators



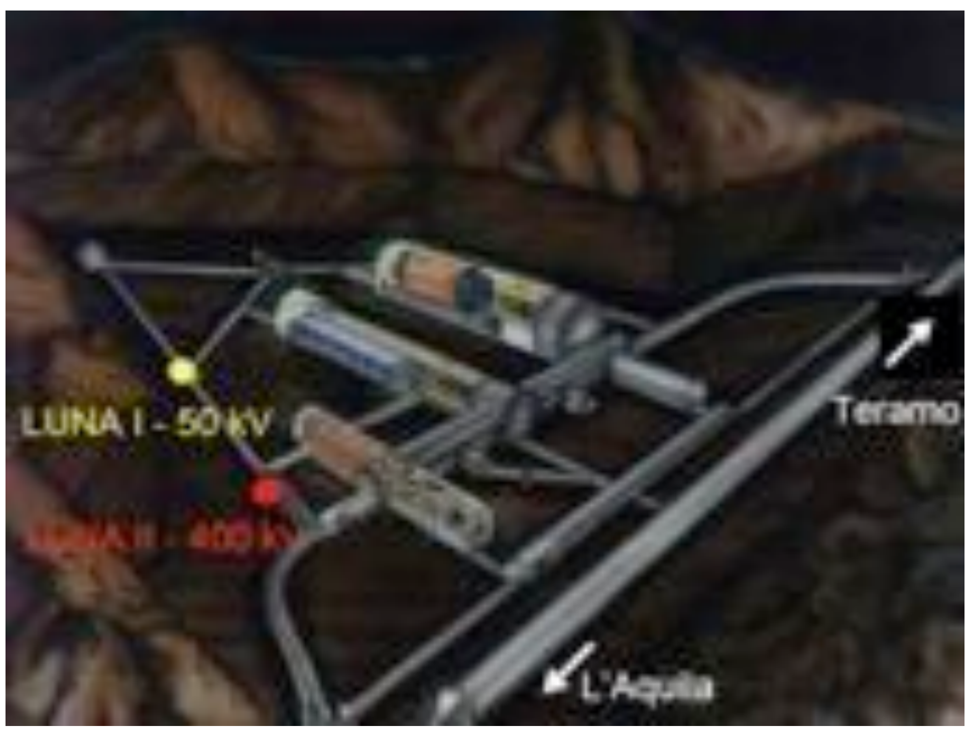


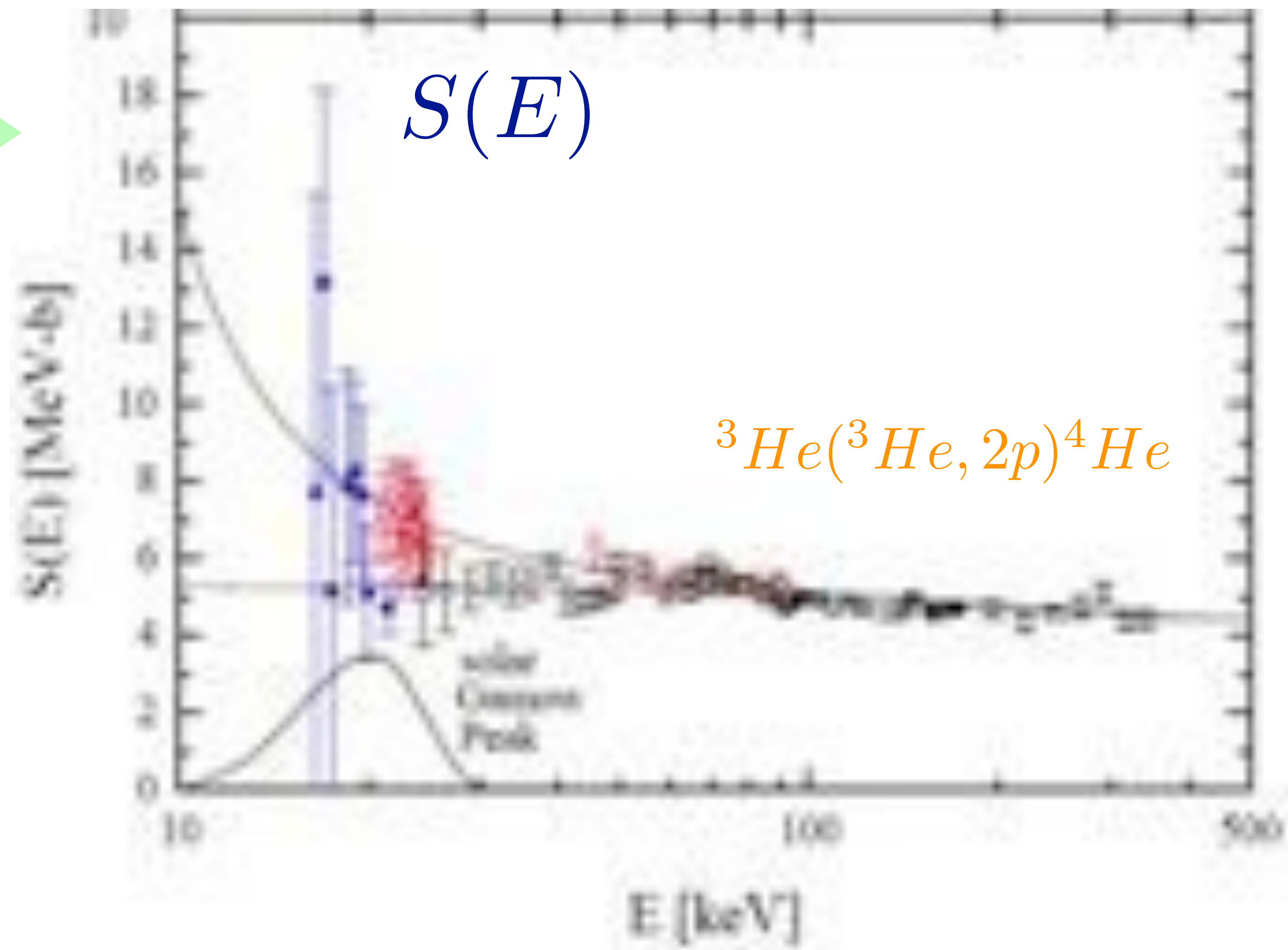
Nuclear reaction rates

recent significant progress in laboratory and theory

➥ S-factor + screening + extrapolation to the Gamow peak

NOW and FUTURE
low energy, high intensity underground accelerators



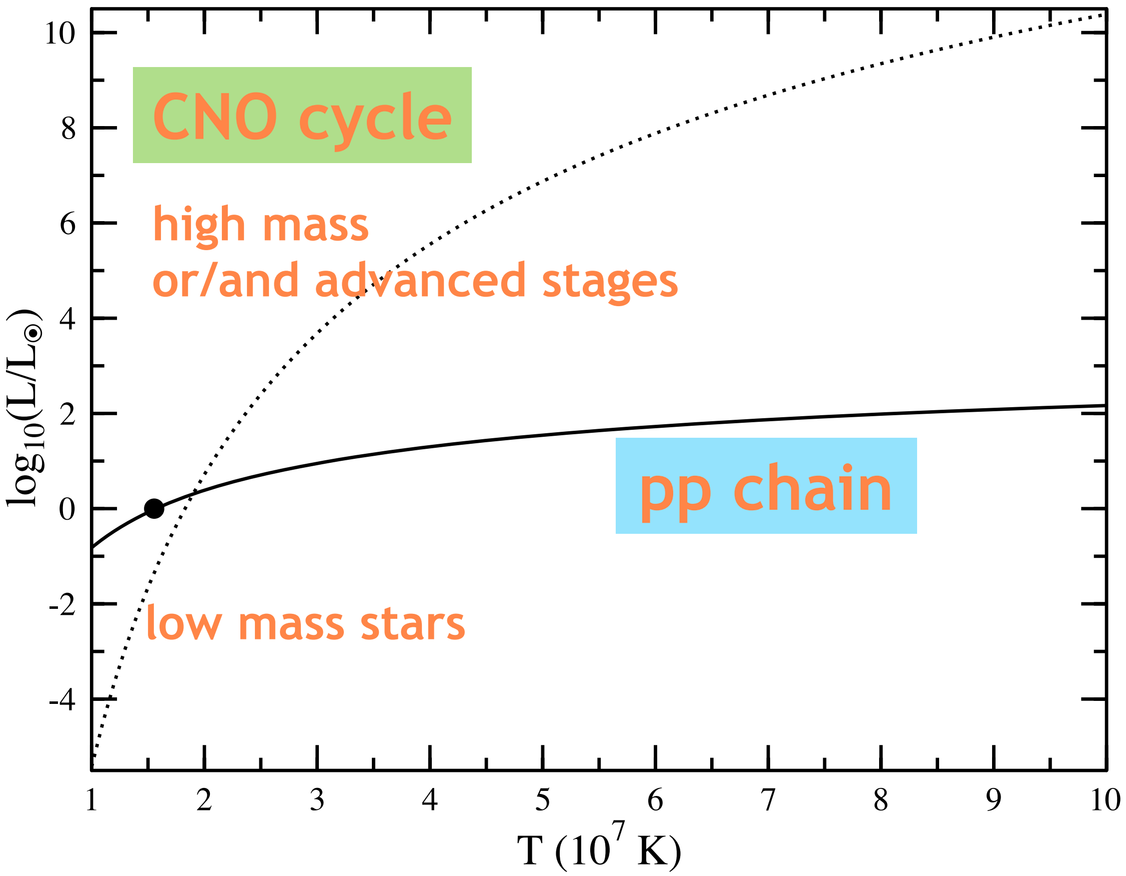


FUTURE
high-energy-density facilities: lasers, Z-pinches
⇒ measurements at stellar conditions!

Hydrogen burning reaction rates

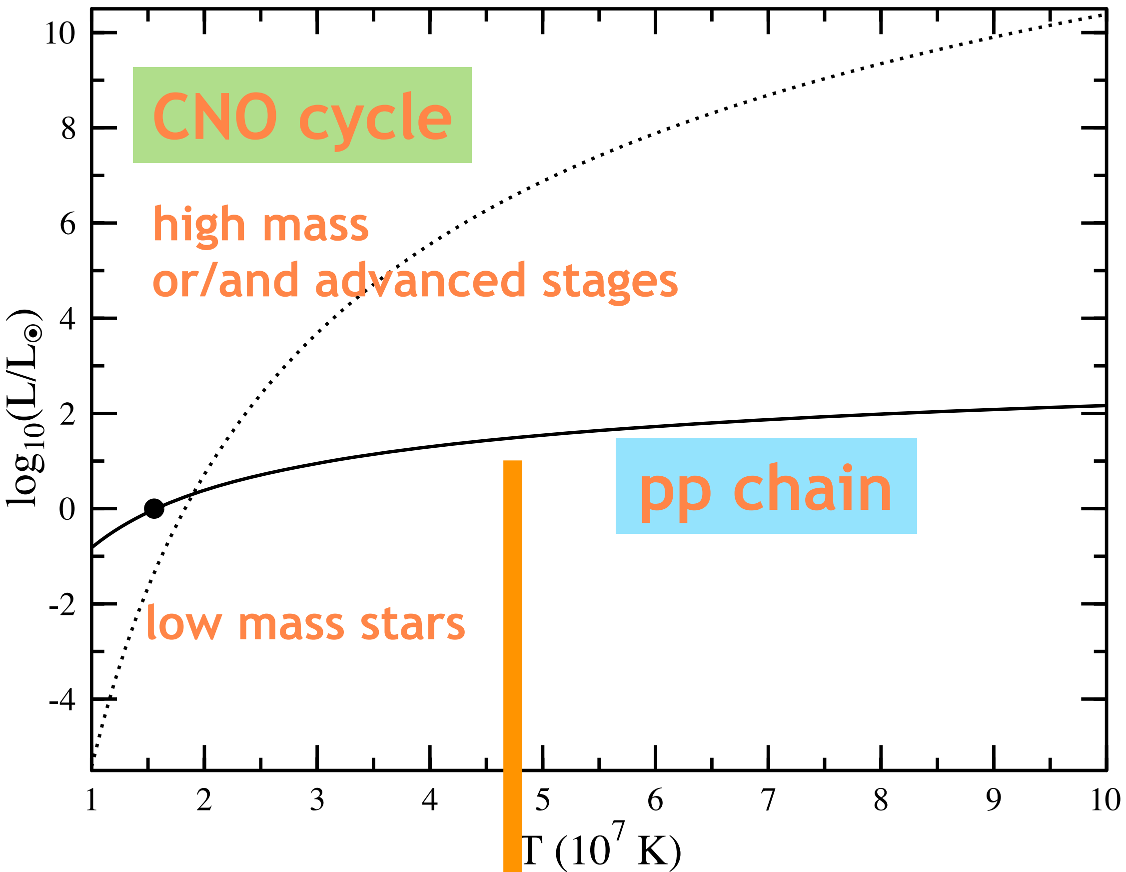
Adelberger et al. 2010

Hydrogen burning reaction rates



Adelberger et al. 2010

Hydrogen burning reaction rates

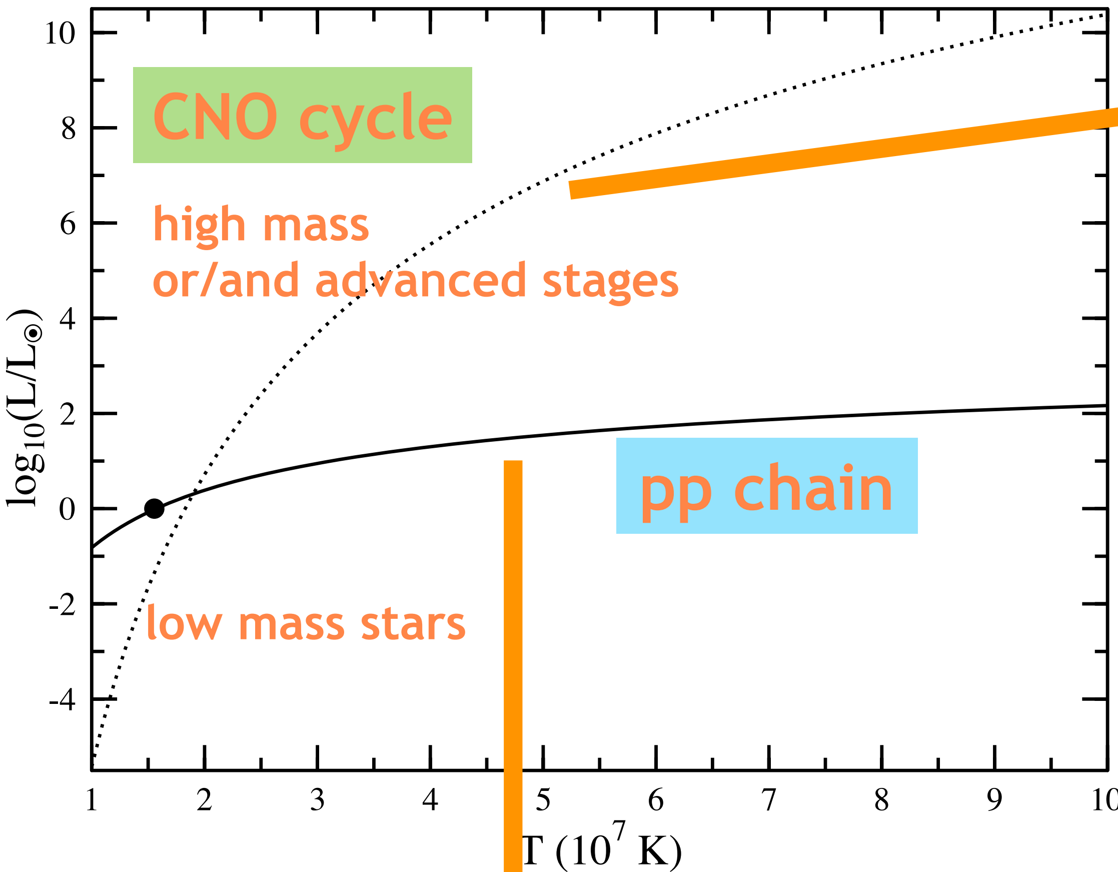


p(p, e⁺ ν)d

theoretical estimate only
but helioseismic validation
➡ rate constrained to ±15%

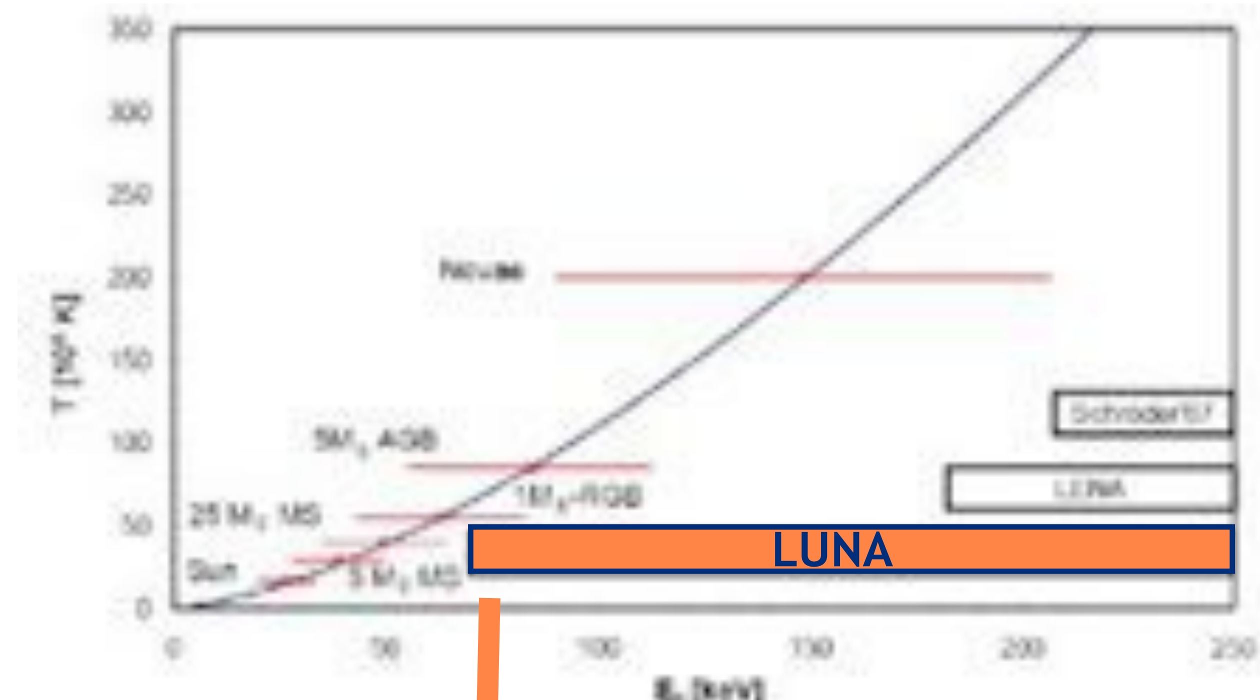
Adelberger et al. 2010

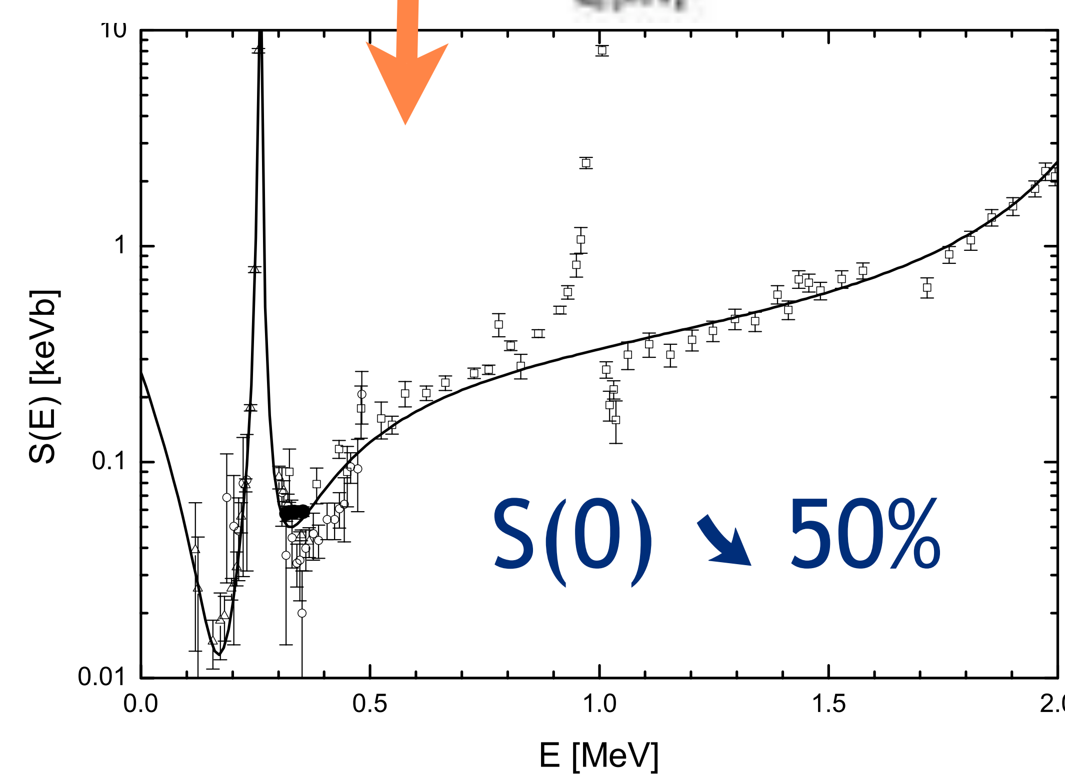
Hydrogen burning reaction rates



$^{14}N(p,\gamma)^{15}O$

experimental measurements





$p(p, e^+ \nu)d$

theoretical estimate only
but helioseismic validation
➡ rate constrained to ±15%

Adelberger et al. 2010

$^{14}N(p,\gamma)^{15}O$ burning reaction rate

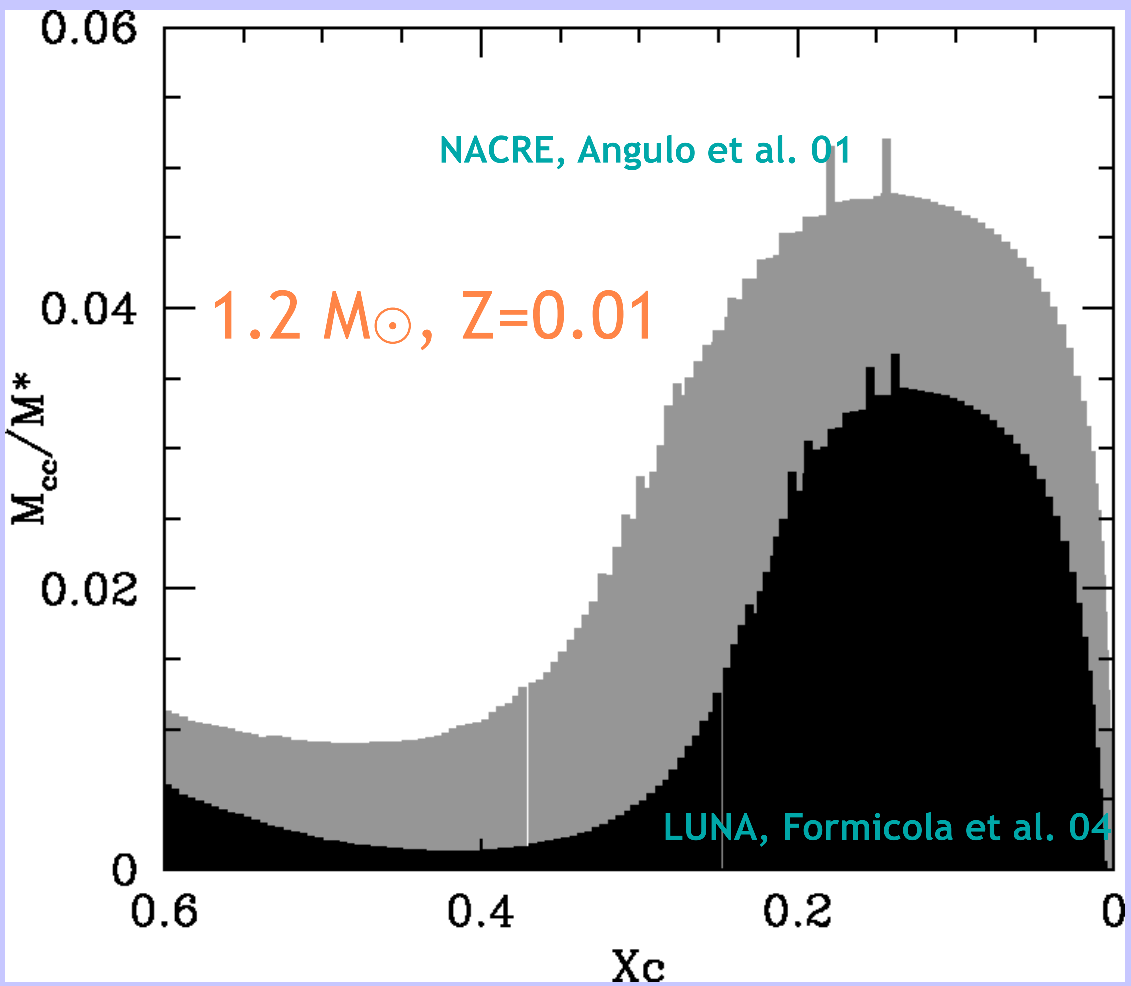
CNO cycle efficiency is reduced (Sun: E_{CNO}/E_{TOT}= 0.8% vs.1.6% before)

$^{14}N(p,\gamma)^{15}O$ burning reaction rate

CNO cycle efficiency is reduced (Sun: E_{CNO}/E_{TOT}= 0.8% vs.1.6% before)

convective core

- ✳ smaller at given mass
- ✳ appears at higher mass

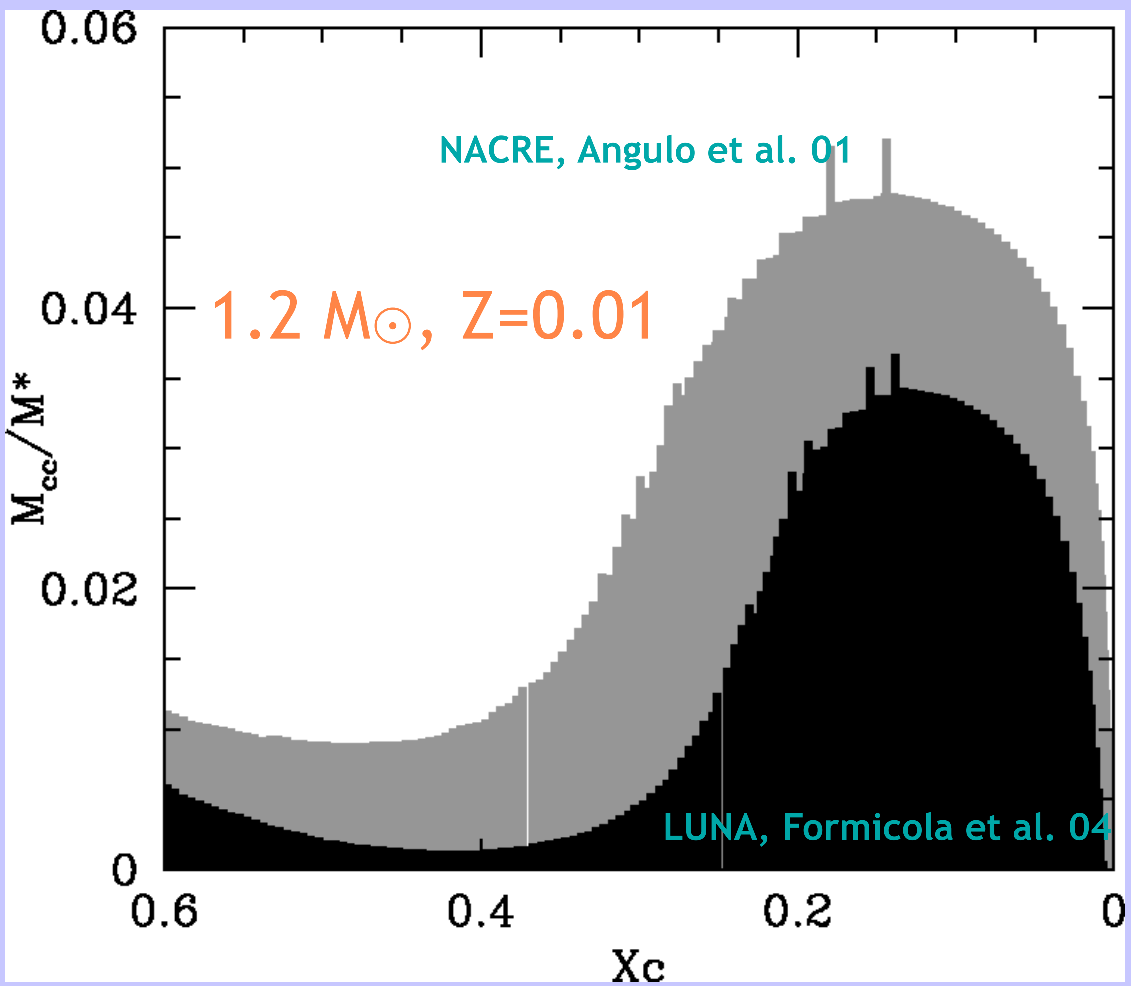


$^{14}N(p,\gamma)^{15}O$ burning reaction rate

CNO cycle efficiency is reduced (Sun: E_{CNO}/E_{TOT}= 0.8% vs.1.6% before)

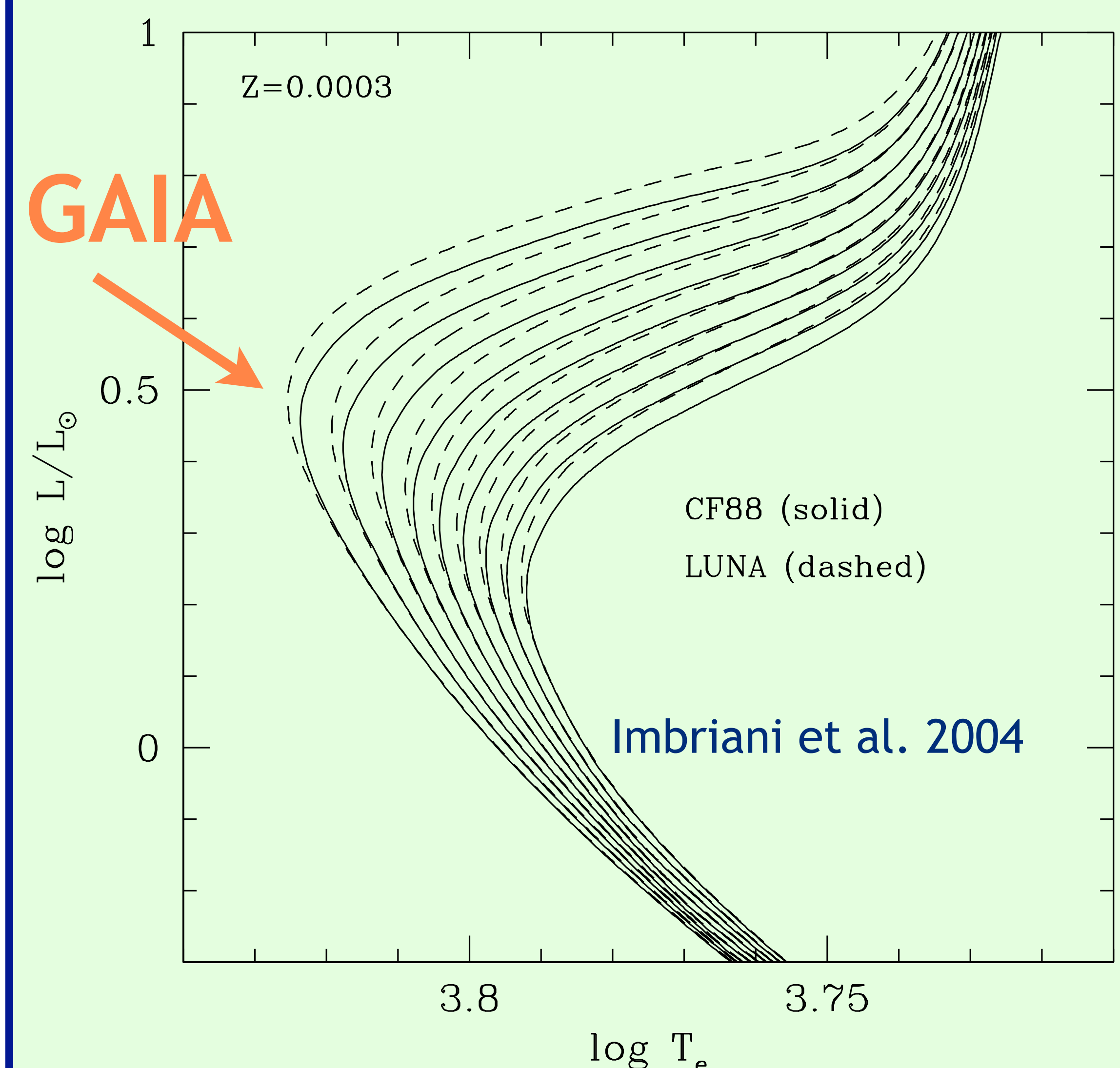
convective core

- ✳ smaller at given mass
- ✳ appears at higher mass



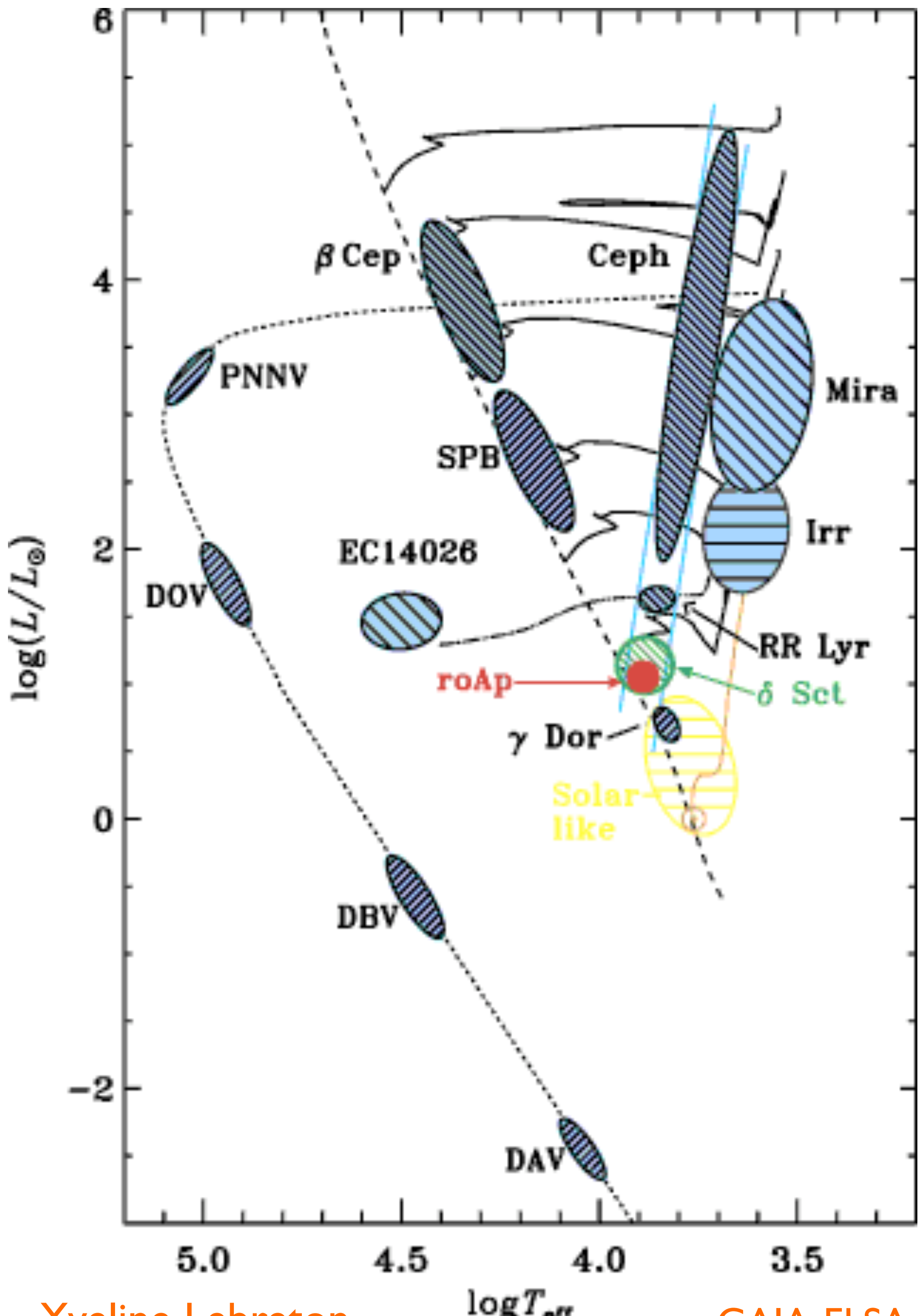
globular clusters

- ✳ brighter and bluer turn-off
- ✳ age increased by 0.7-1 Gyr

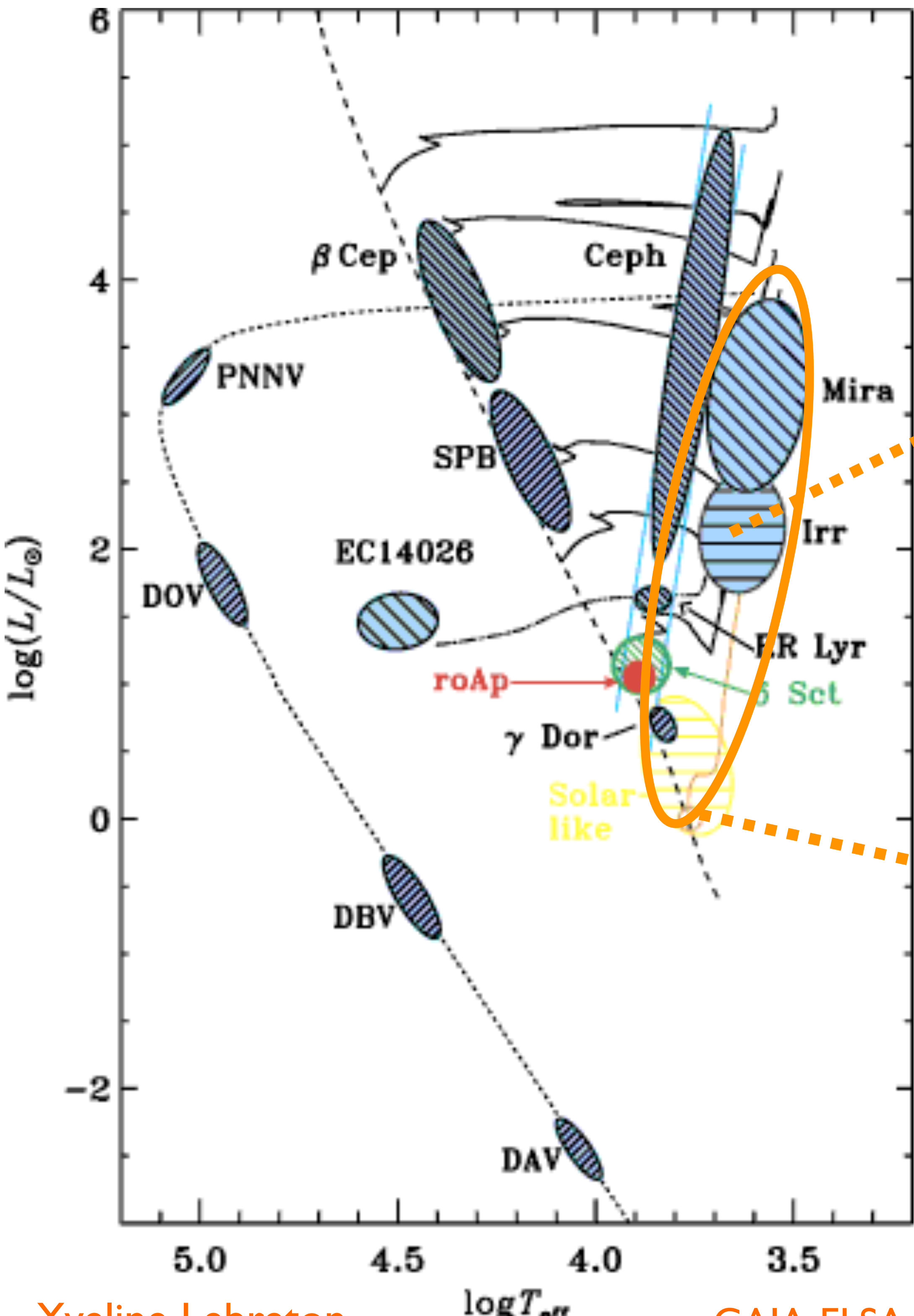


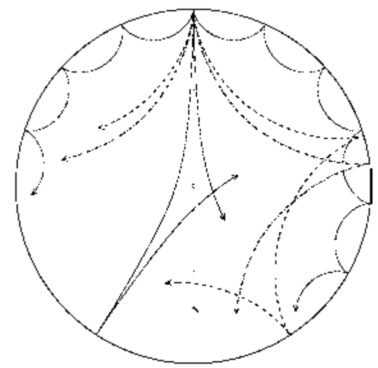
Asteroseismology: diagnostics all across the HR diagram

Asteroseismology: diagnostics all across the HR diagram



Asteroseismology: diagnostics all across the HR diagram

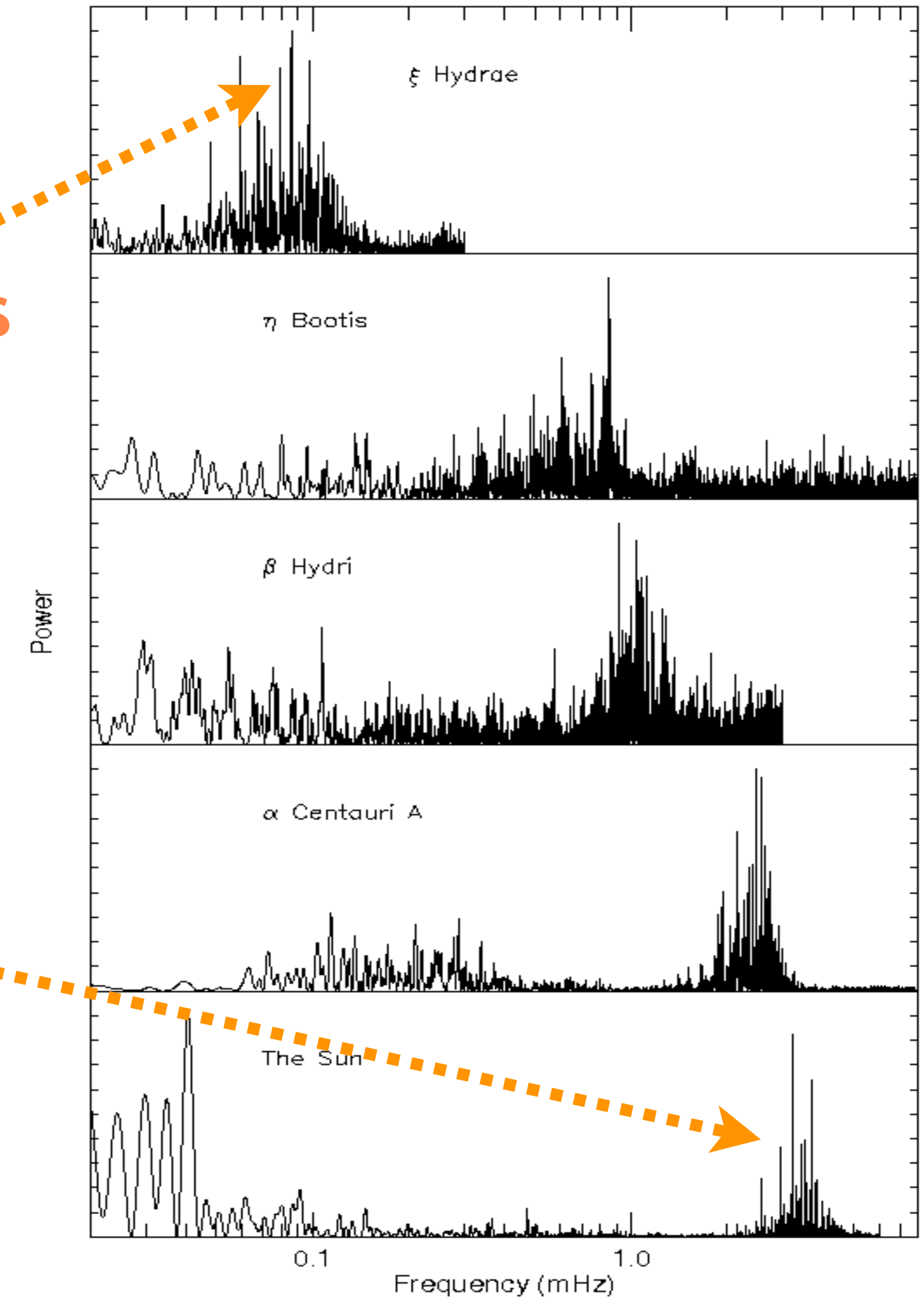




solar-like oscillations

red giants

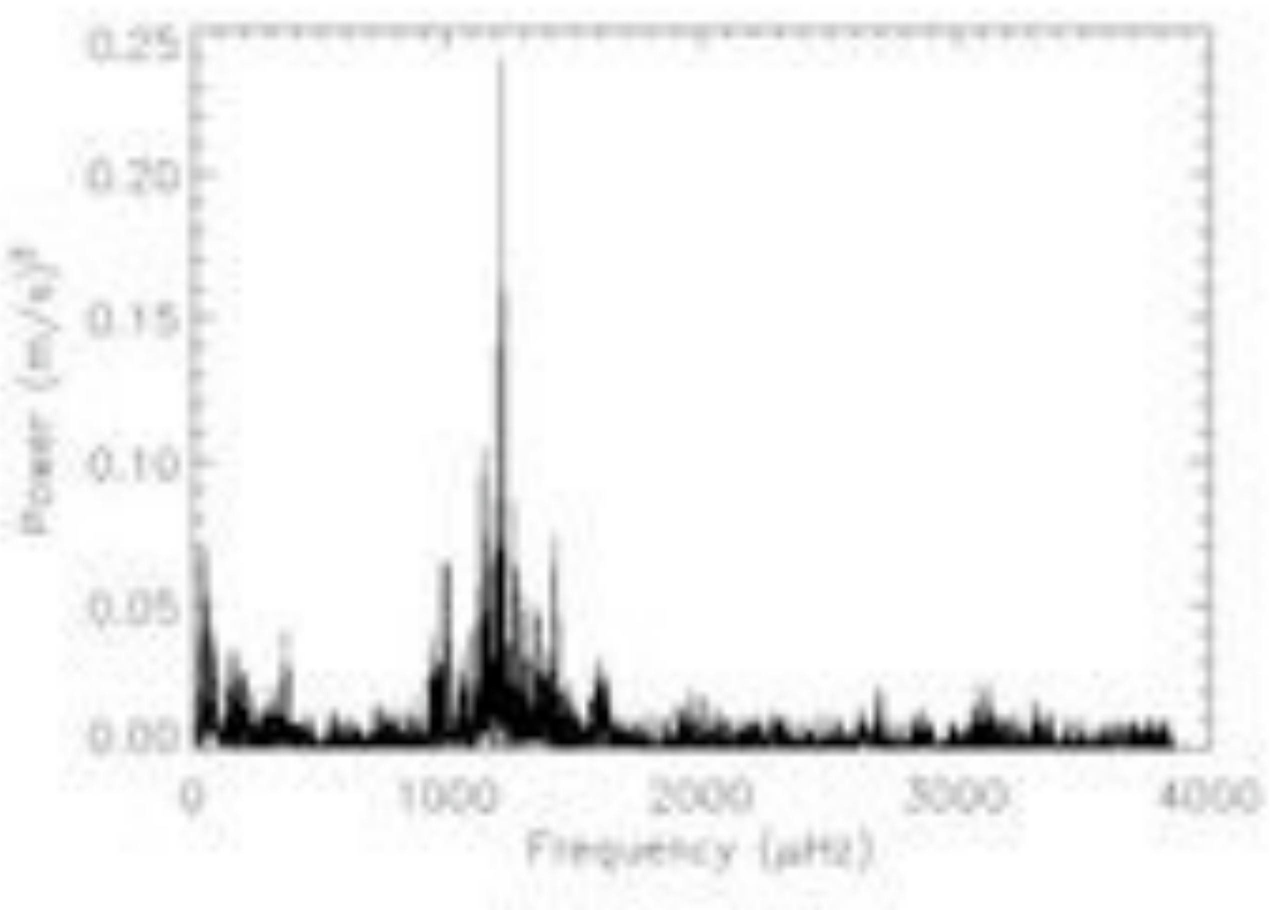
main sequence



Asteroseismology: acoustic modes spectrum

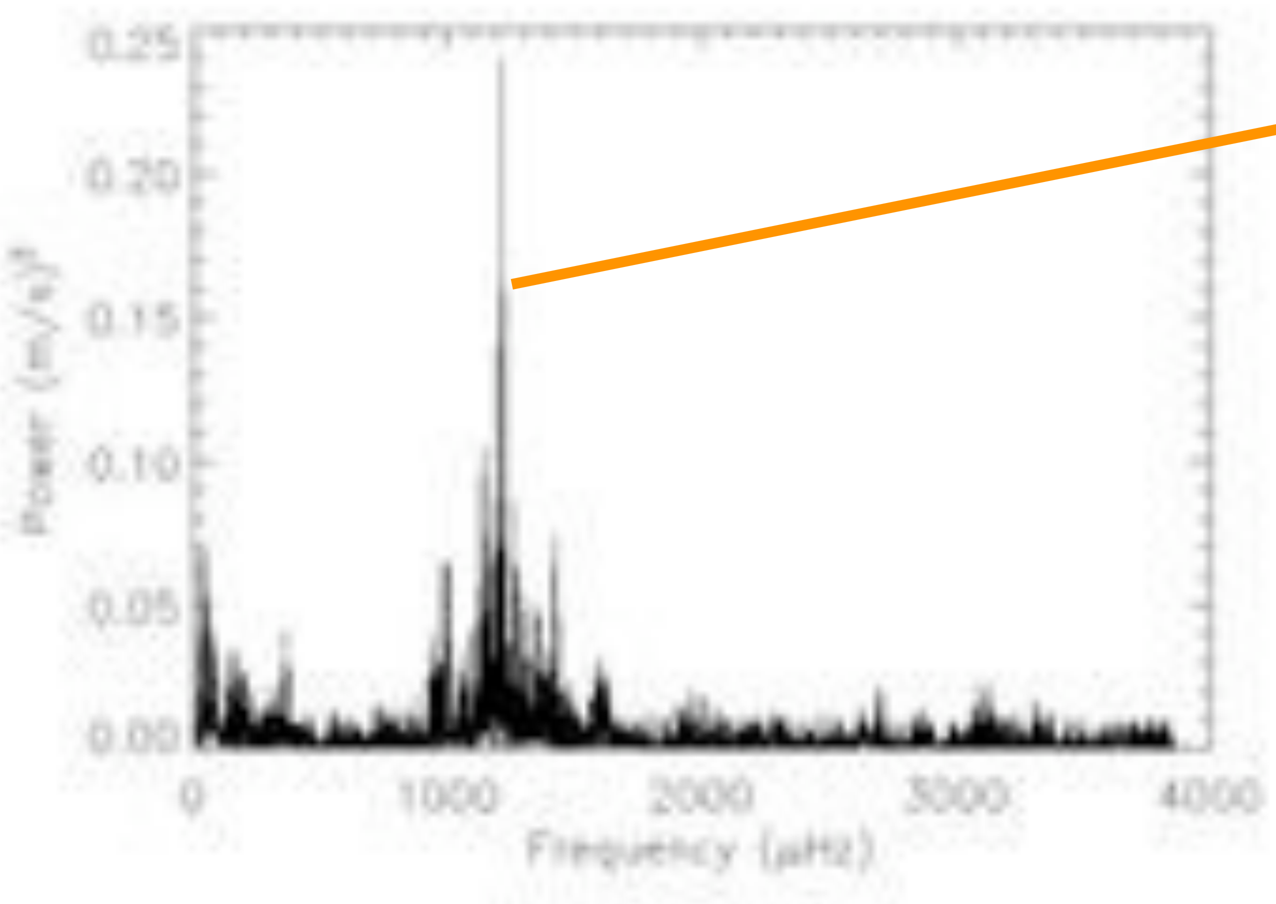
Kjeldsen & Bedding, 1995

Asteroseismology: acoustic modes spectrum



Kjeldsen & Bedding, 1995

Asteroseismology: acoustic modes spectrum

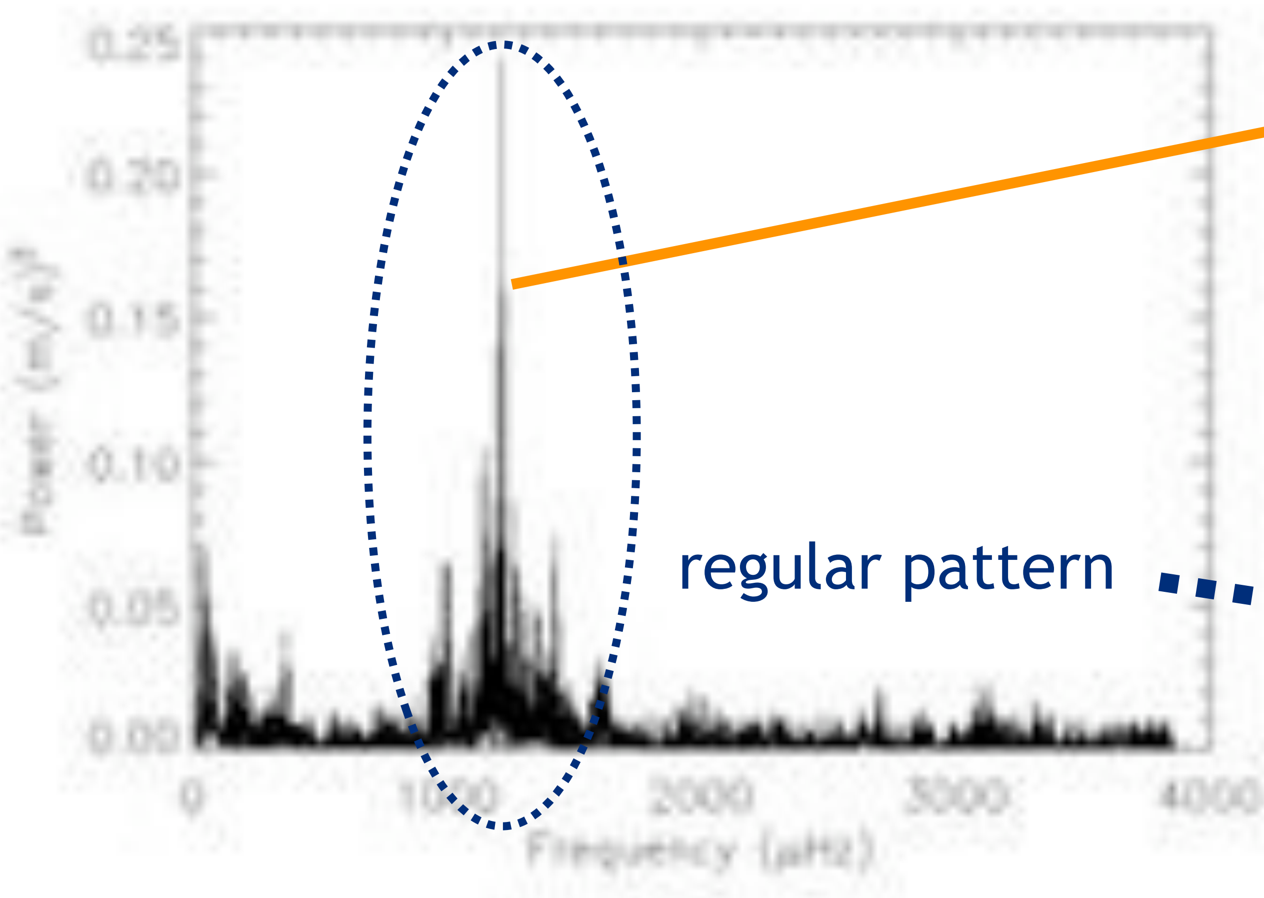


frequency for maximum power
scales as the acoustic cutoff frequency

$$\nu_{\max} = \frac{M/M_\odot}{(T_{\rm eff}/5777)^{1/2}\,(R/R_\odot)^2} \times 3.05\ {\rm mHz}$$

Kjeldsen & Bedding, 1995

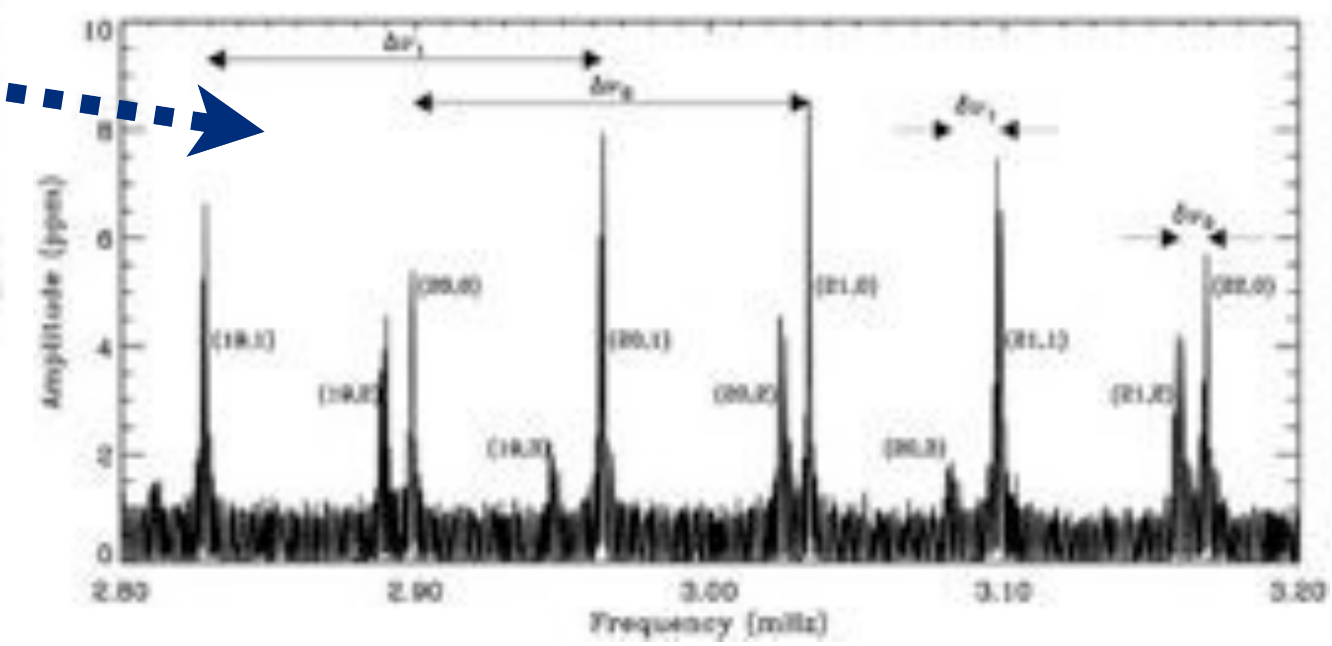
Asteroseismology: acoustic modes spectrum



frequency for maximum power
scales as the acoustic cutoff frequency

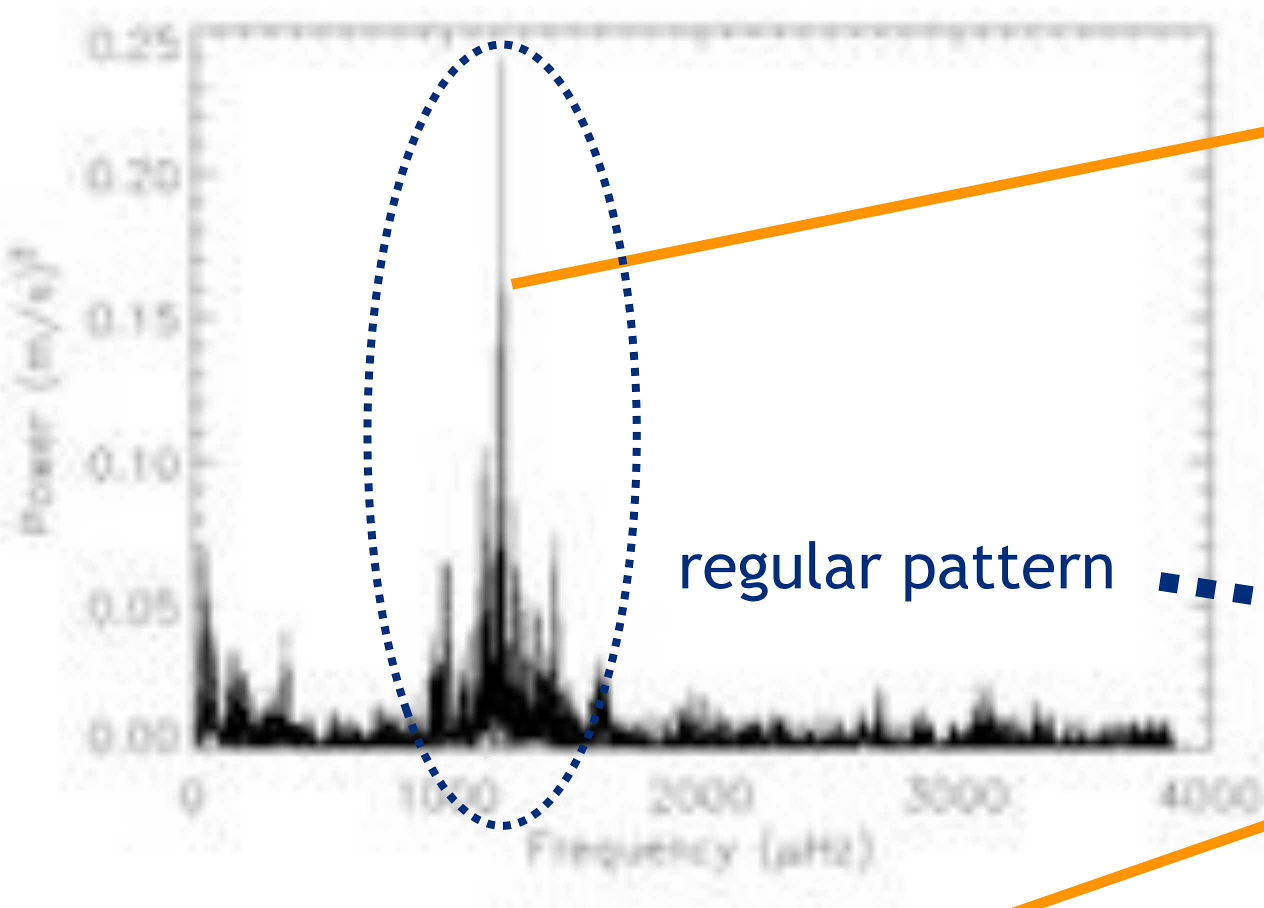
$$\nu_{\max} = \frac{M/M_\odot}{(T_{\rm eff}/5777)^{1/2}\,(R/R_\odot)^2} \times 3.05\ {\rm mHz}$$

regular pattern



Kjeldsen & Bedding, 1995

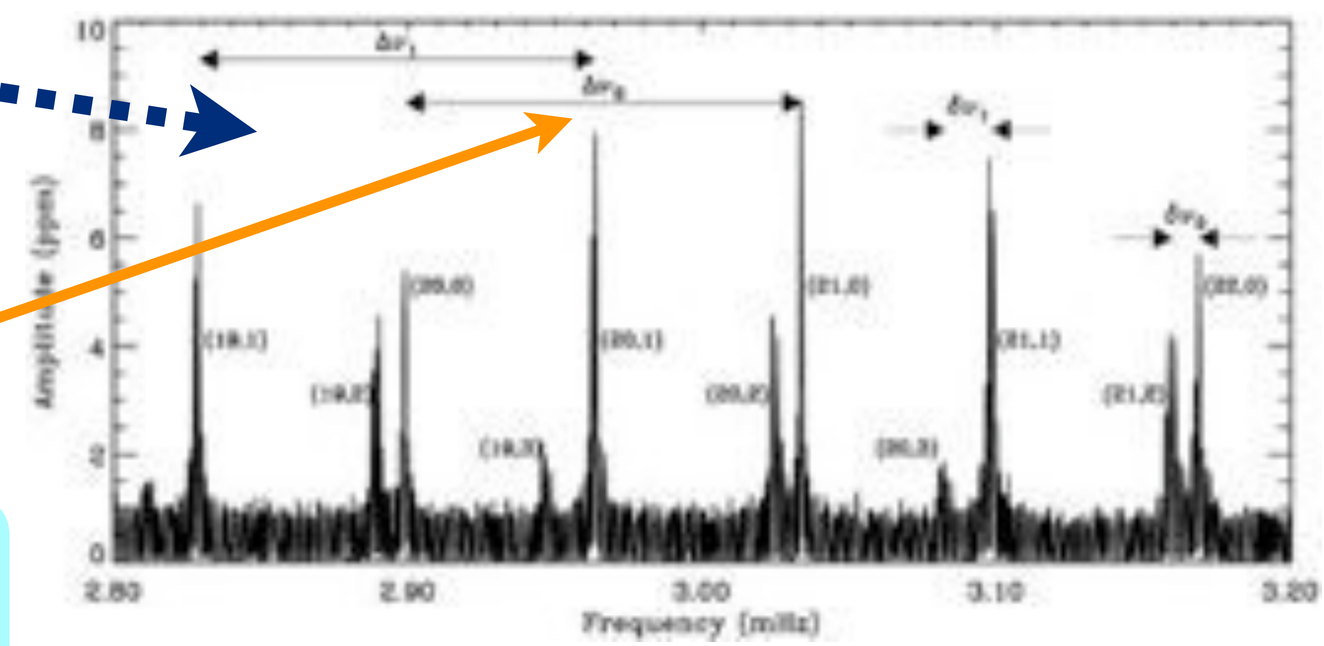
Asteroseismology: acoustic modes spectrum



frequency for maximum power
scales as the acoustic cutoff frequency

$$\nu_{\max} = \frac{M/M_\odot}{(T_{\rm eff}/5777)^{1/2}\,(R/R_\odot)^2} \times 3.05\ \mathrm{mHz}$$

regular pattern



large frequency separation

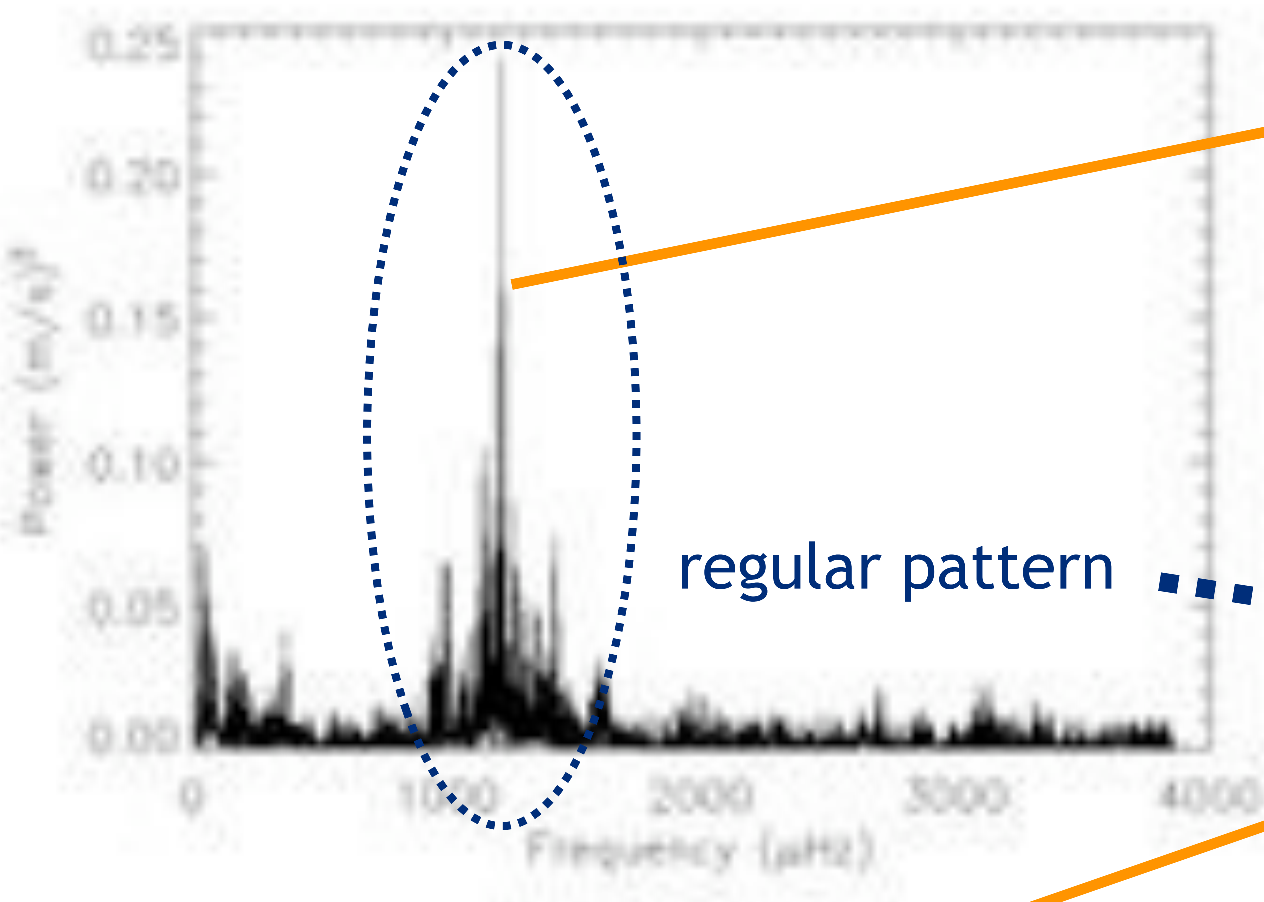
$$\Delta\nu \simeq \left(2\int_0^R \frac{dr}{c}\right)^{-1}$$

scales as mean density

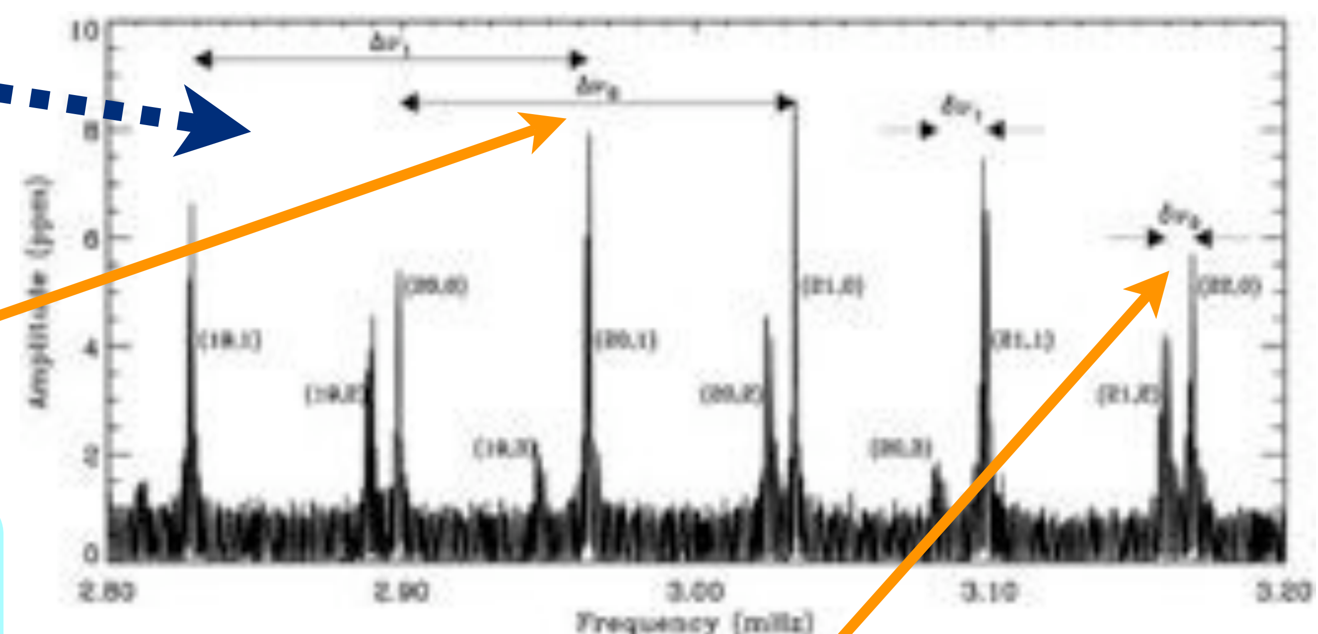
$$\Delta\nu = (M/M_\odot)^{1/2}\,(R/R_\odot)^{-3/2} \times 134.9\ \mu\mathrm{Hz}$$

Kjeldsen & Bedding, 1995

Asteroseismology: acoustic modes spectrum



regular pattern



<u>frequency for maximum power</u>
scales as the acoustic cutoff frequency

$$\nu_{\max} = \frac{M/M_\odot}{(T_{\rm eff}/5777)^{1/2}\,(R/R_\odot)^2} \times 3.05\ \mathrm{mHz}$$

<u>large frequency separation</u>

$$\Delta\nu \simeq \left(2\int_0^R \frac{dr}{c}\right)^{-1}$$

scales as mean density

$$\Delta\nu = (M/M_\odot)^{1/2}\,(R/R_\odot)^{-3/2} \times 134.9\ \mu\mathrm{Hz}$$

<u>small frequency separation</u>
➥ sound speed gradient

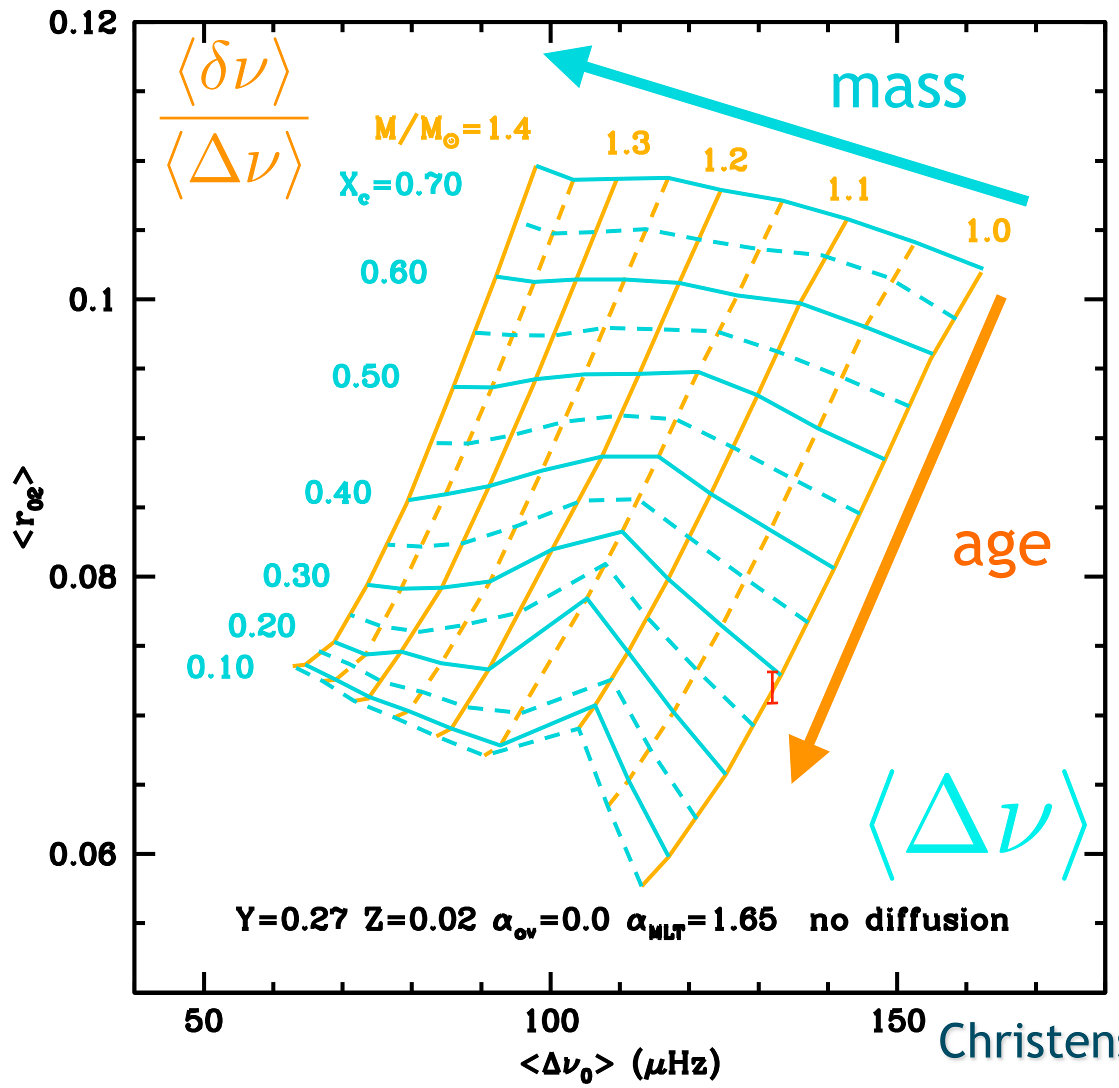
$$\delta\nu \propto -\int_0^R \frac{dc}{dr}\frac{dr}{r}$$

Kjeldsen & Bedding, 1995

Asteroseismology: age & mass diagnostics

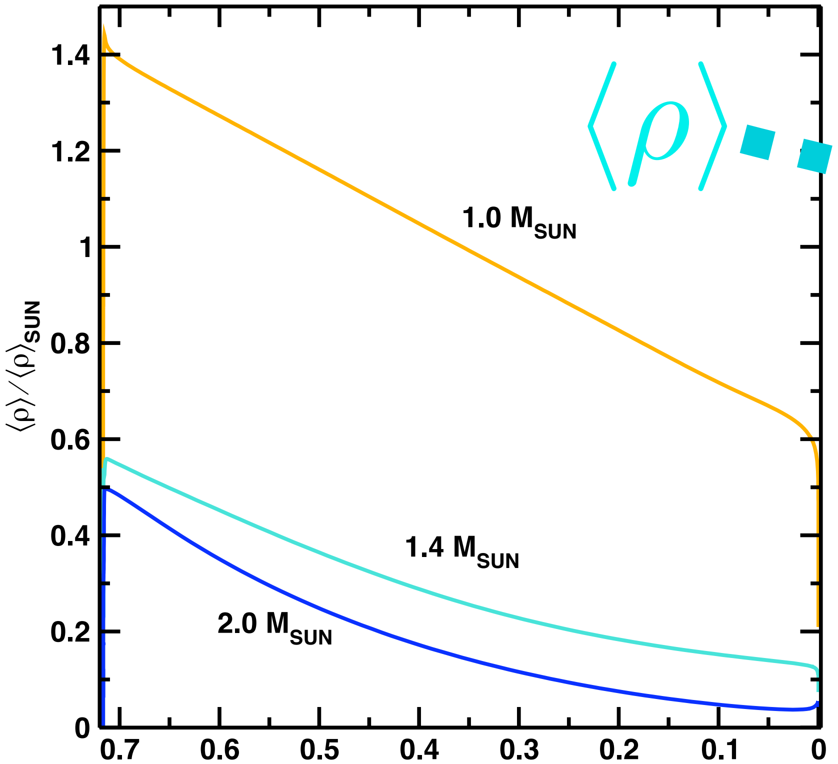
Christensen-Dalsgaard 88, 93

Asteroseismology: age & mass diagnostics

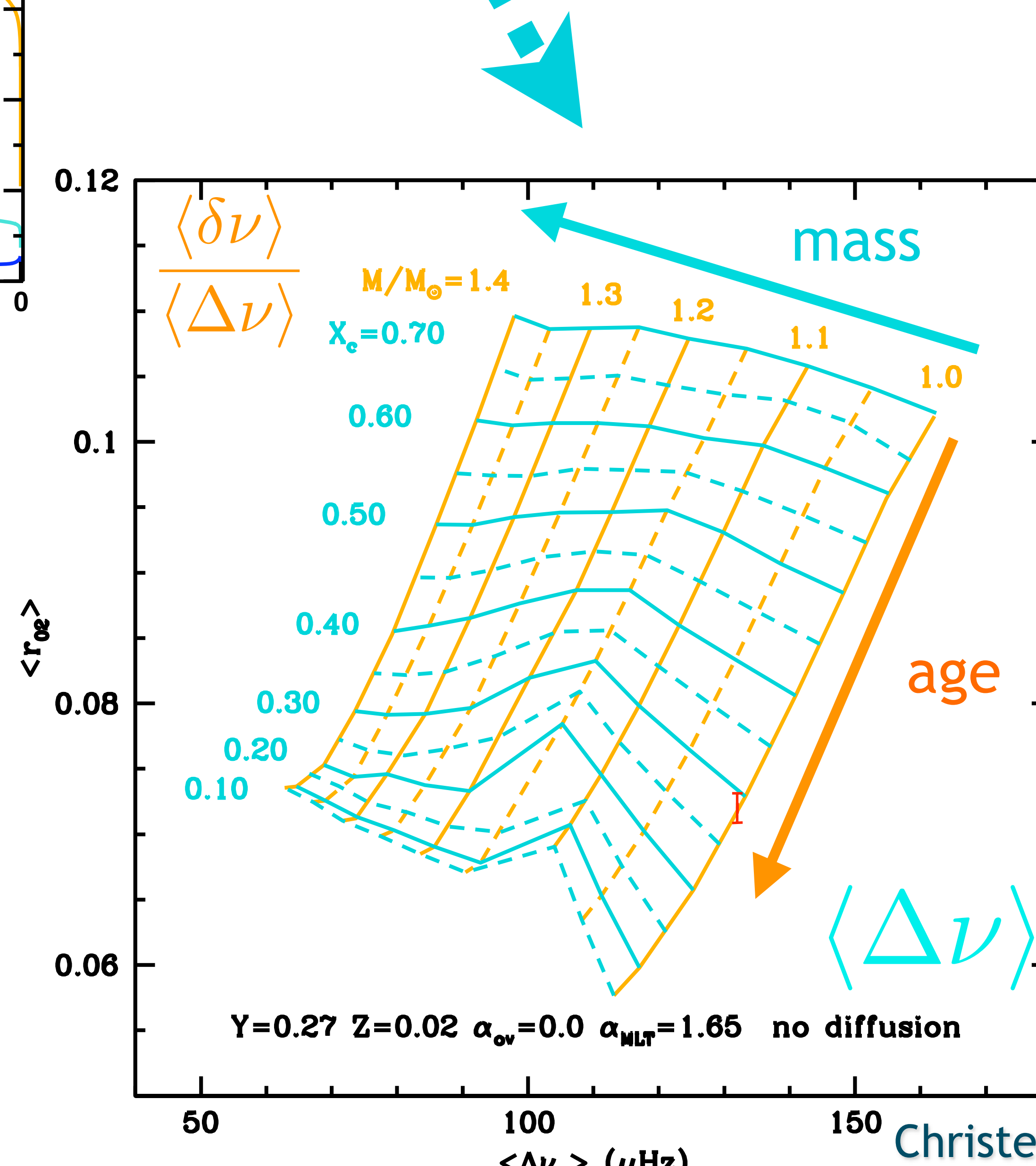


Christensen-Dalsgaard 88, 93

Asteroseismology: age & mass diagnostics

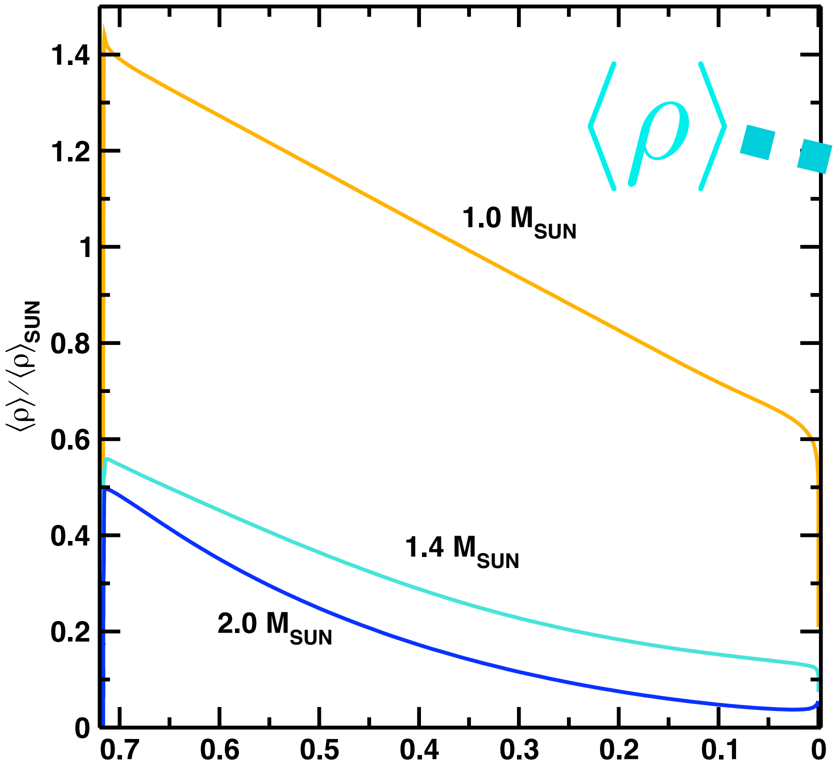


(M/R^3)
⇒ mass

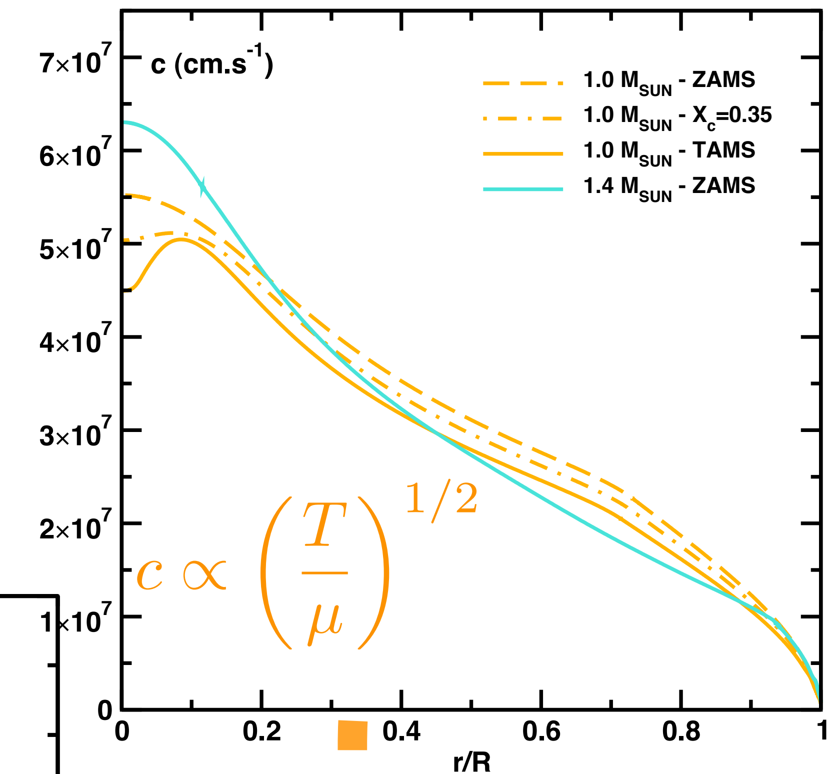


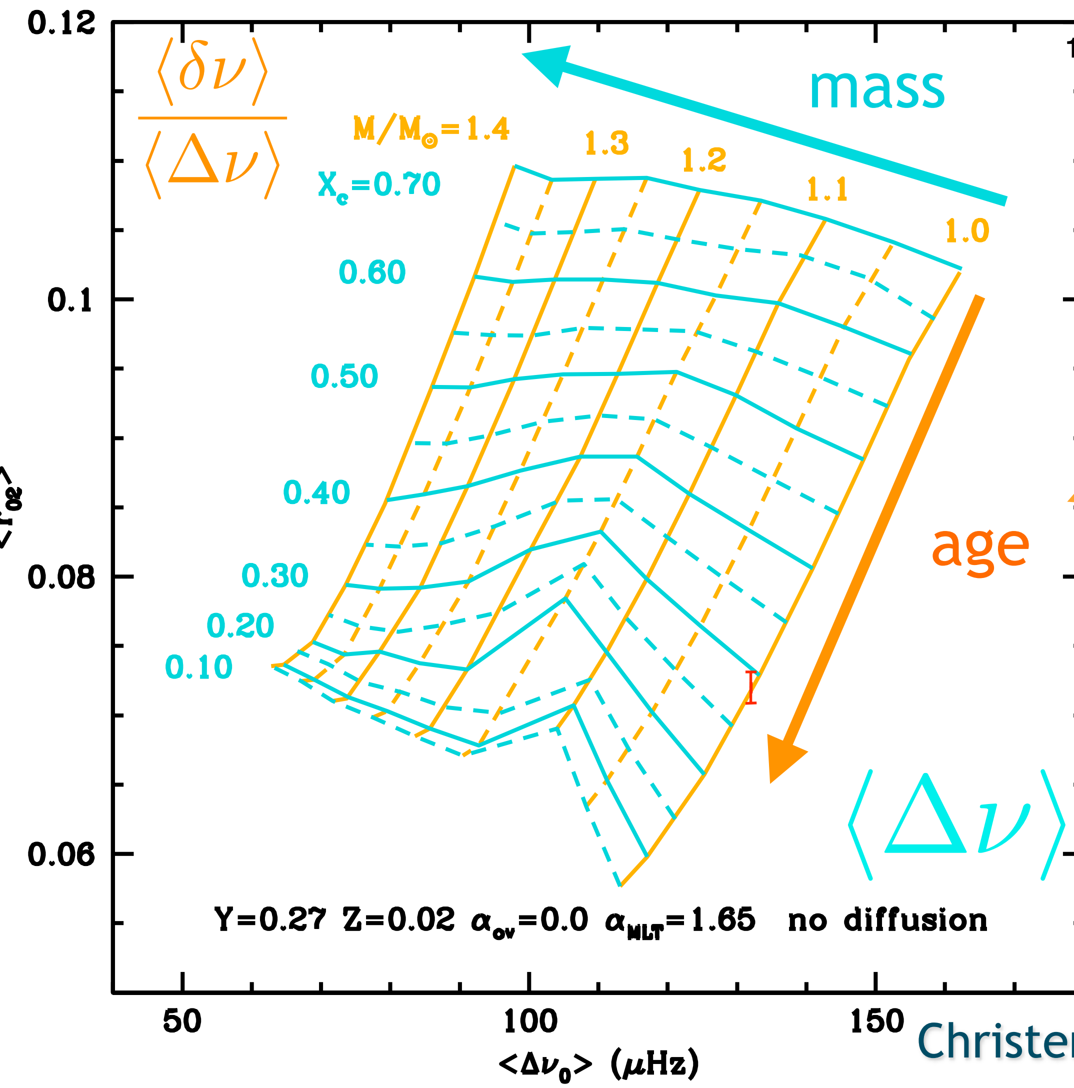
Christensen-Dalsgaard 88, 93

Asteroseismology: age & mass diagnostics



(M/R^3)
⇒ mass



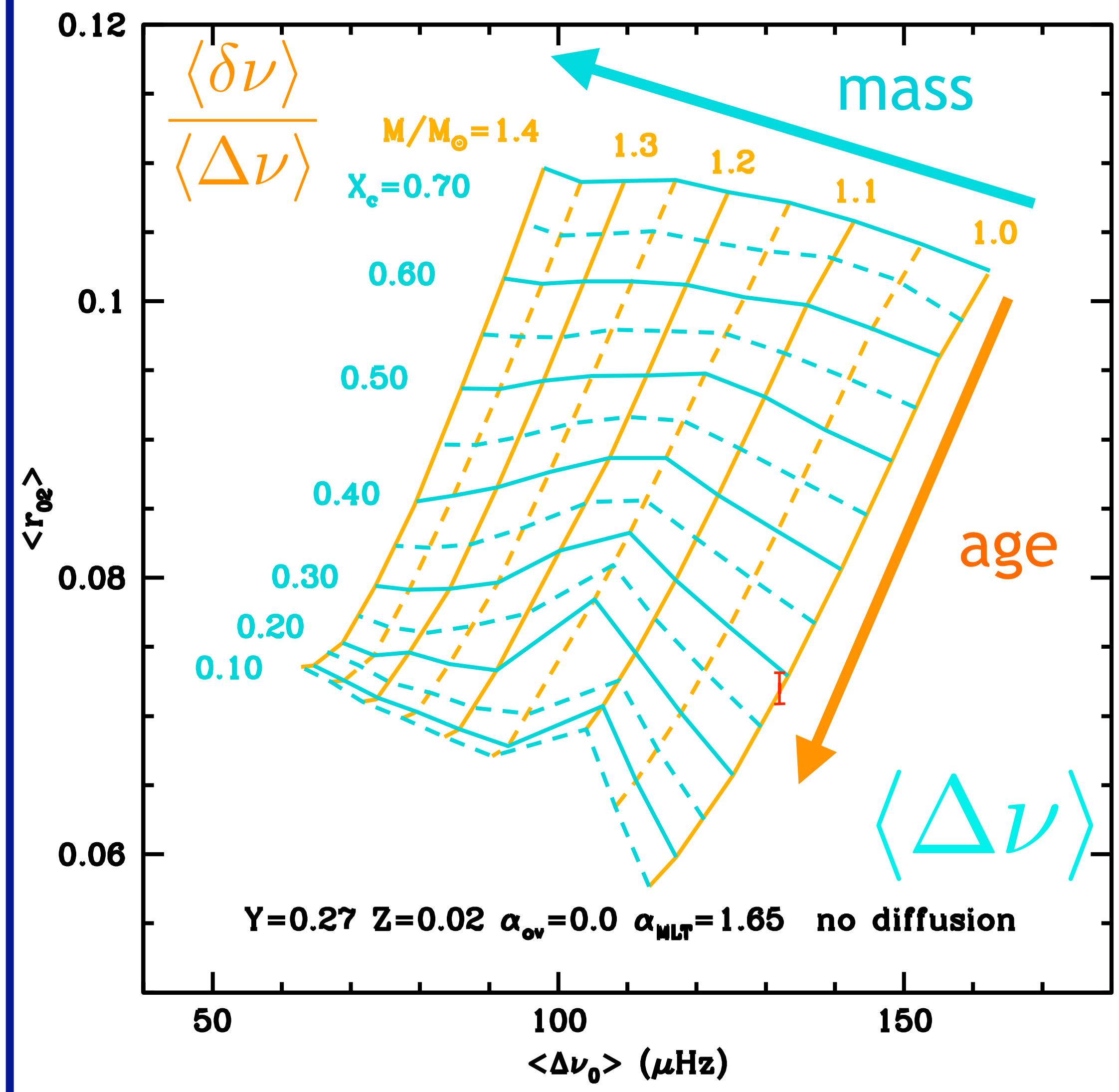


size of the mixed core
⇒ age

Christensen-Dalsgaard 88, 93

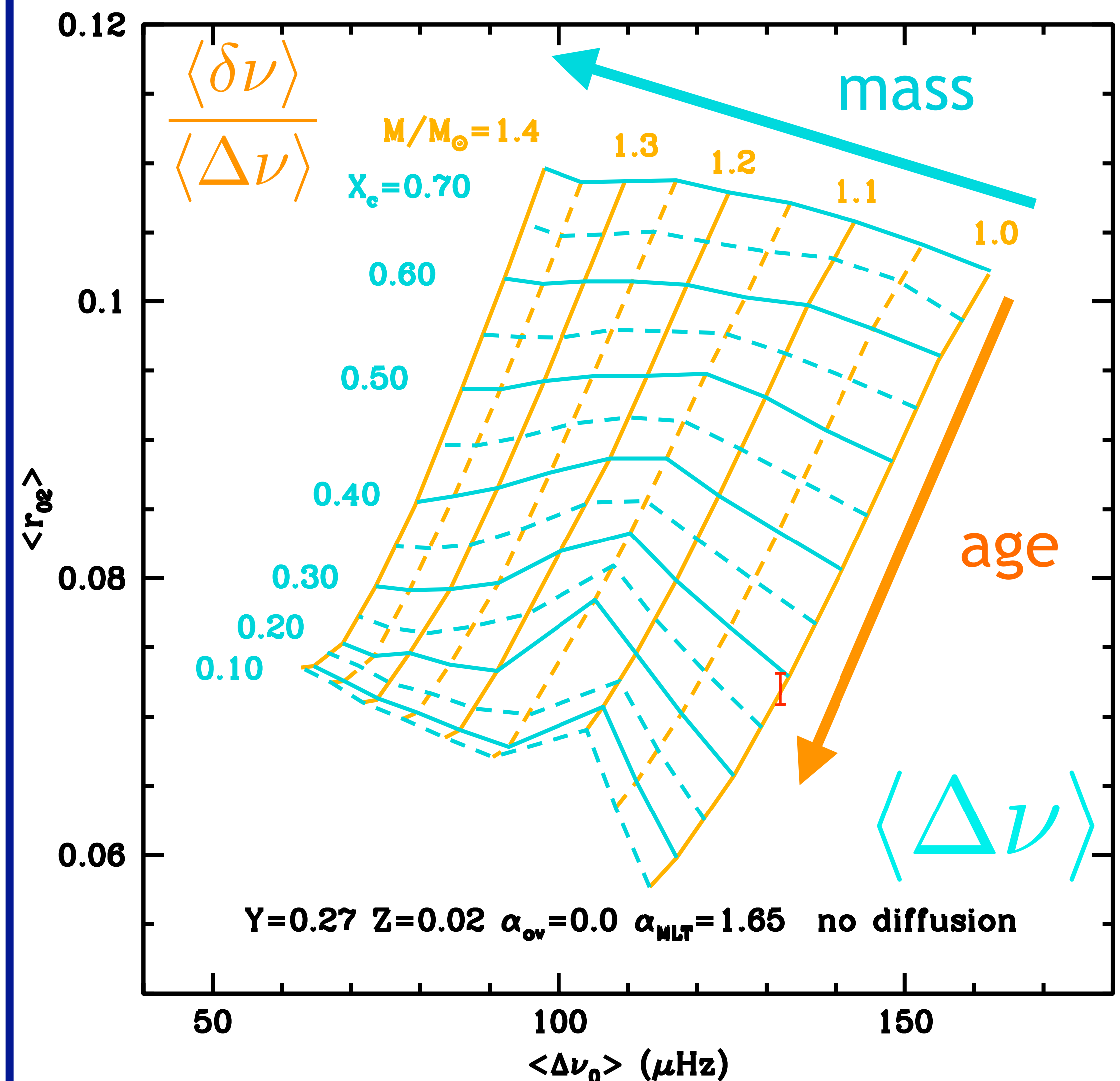
Asteroseismology: age & mass diagnostics

Asteroseismology: age & mass diagnostics

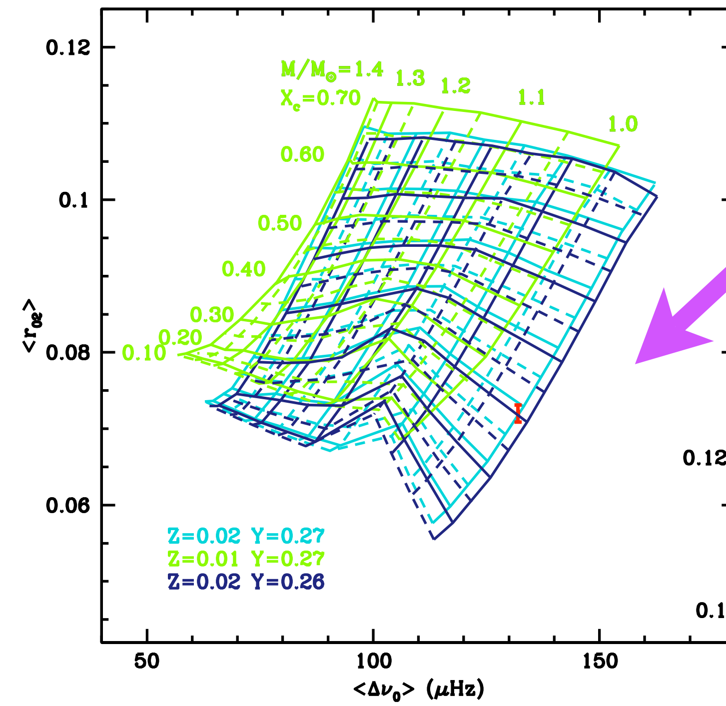


If $\sigma_\nu/\nu \approx 10^{-4}$ (CoRoT, Kepler)
$\Rightarrow \sigma_M/M \leq 5\%$; $\sigma_{age}/age \leq 10\%$

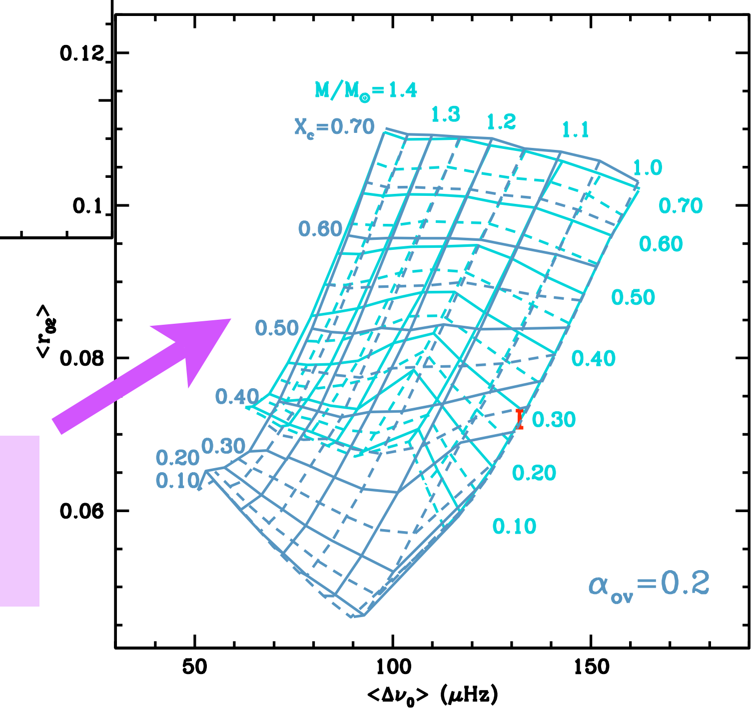
Asteroseismology: age & mass diagnostics



If $\sigma_\nu/\nu \approx 10^{-4}$ (CoRoT, Kepler)
$\Rightarrow \sigma_M/M \leq 5\%$; $\sigma_{age}/age \leq 10\%$



BUT ONLY IF ACCURATE M/H



AND PHYSICS STILL TO BE VALIDATED

Improvement if radius/mass known independently

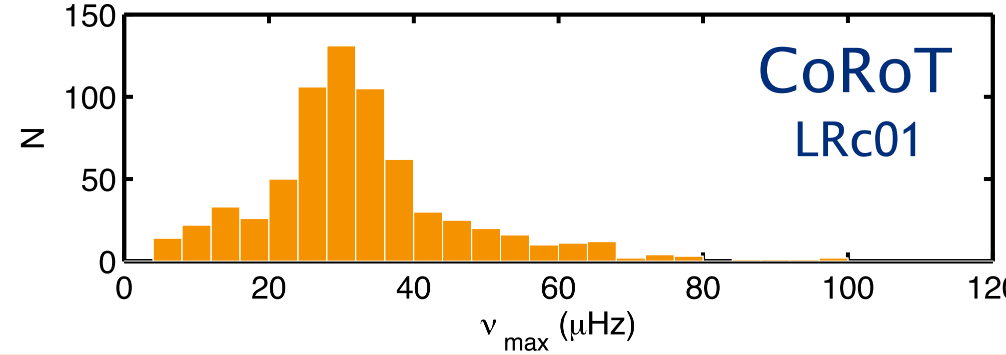
binaries, exoplanet hosts, interferometric R, R(L,T_{eff})
GAIA, interferometry, HARPS, CoRoT, Kepler, Plato

Asteroseismology: stellar populations

Asteroseismology: stellar populations

CoRoT, Kepler: solar-like oscillations in large samples of red giants

$$\nu_{\rm max} = \frac{M/M_\odot}{(T_{\rm eff}/5777)^{1/2}\,(R/R_\odot)^2} \times 3.05\ {\rm mHz}$$

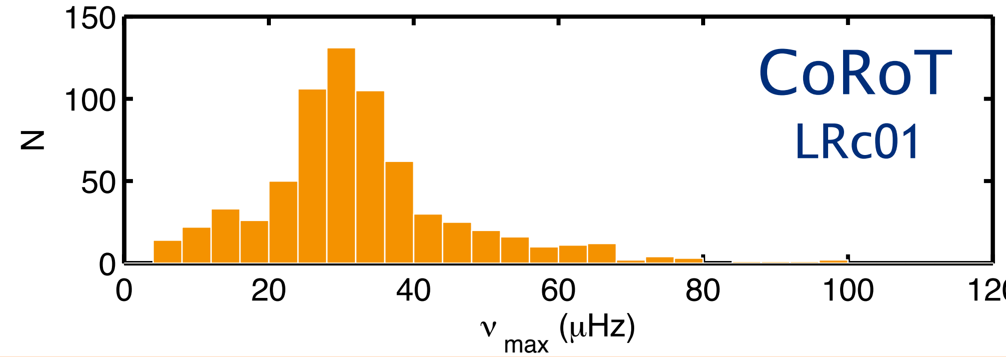


also $\Delta\nu = (M/M_\odot)^{1/2}\,(R/R_\odot)^{-3/2} \times 134.9\ \mu{\rm Hz}$

Asteroseismology: stellar populations

CoRoT, Kepler: solar-like oscillations in large samples of red giants

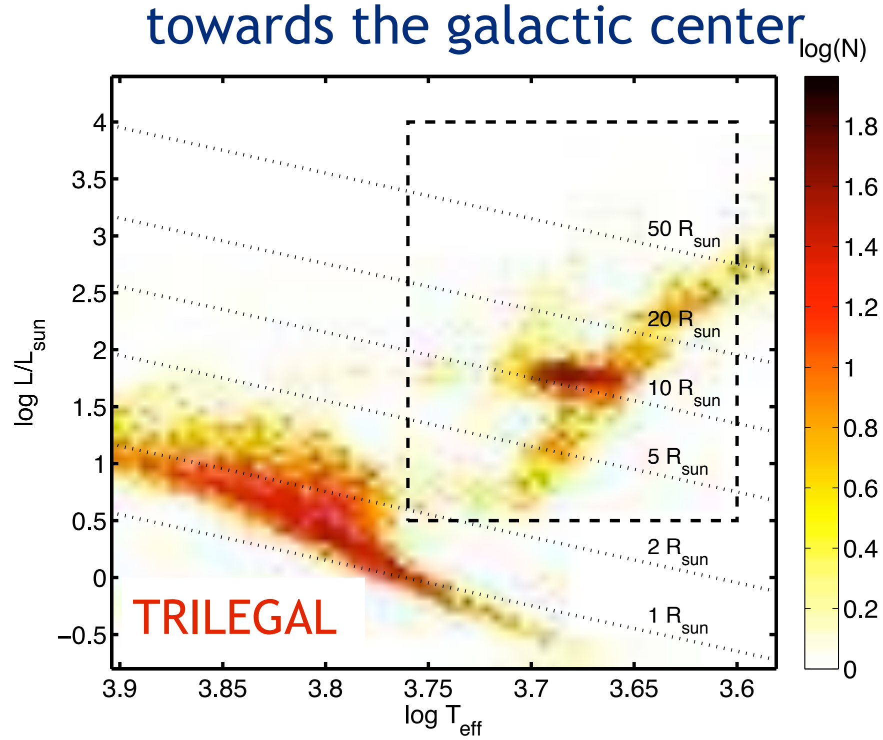
$$\nu_{\max} = \frac{M/M_\odot}{(T_{\rm eff}/5777)^{1/2}\,(R/R_\odot)^2} \times 3.05\ \mathrm{mHz}$$



also $\Delta\nu = (M/M_\odot)^{1/2}\,(R/R_\odot)^{-3/2} \times 134.9\ \mu\mathrm{Hz}$

Population synthesis: CoRoT field

towards the galactic center

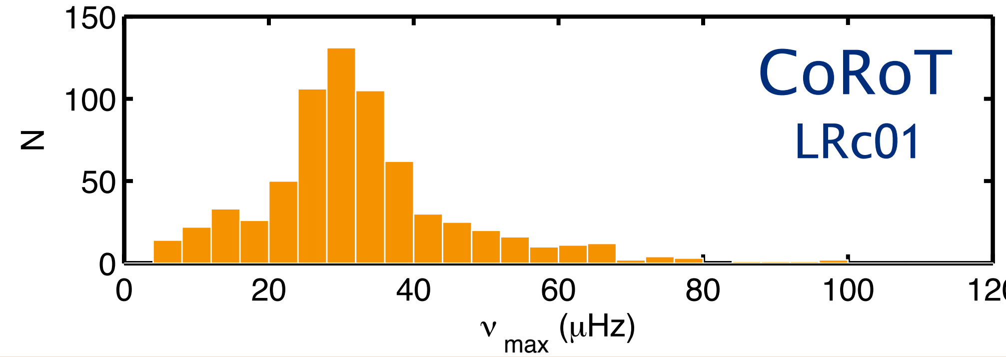


Miglio et al 2009

Asteroseismology: stellar populations

CoRoT, Kepler: solar-like oscillations in large samples of red giants

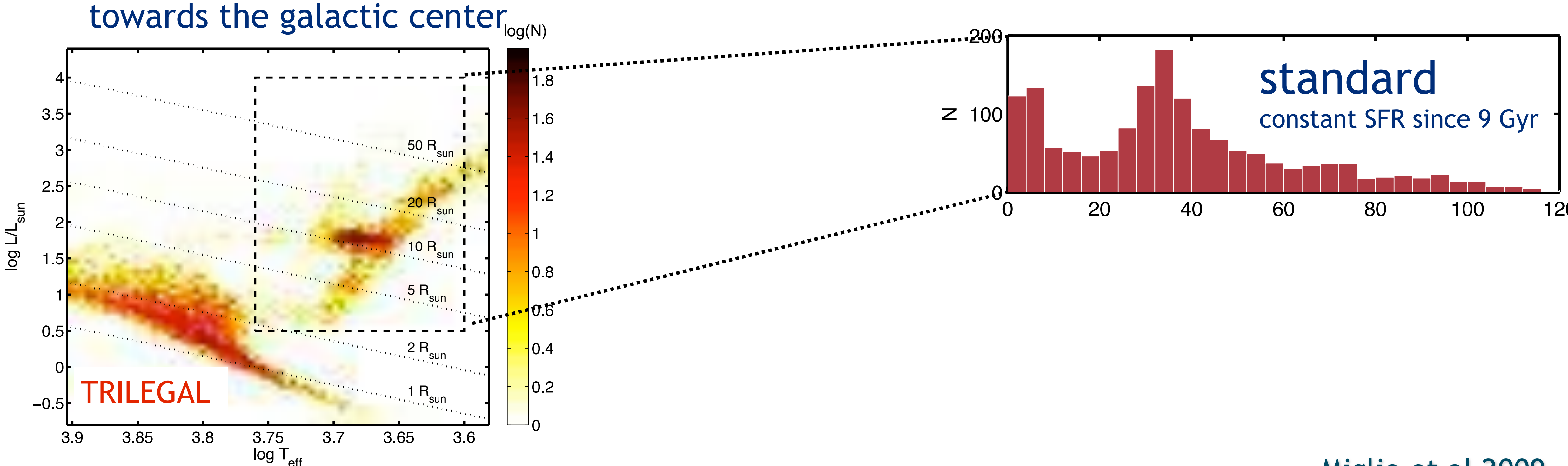
$$\nu_{\max} = \frac{M/M_\odot}{(T_{\rm eff}/5777)^{1/2}(R/R_\odot)^2} \times 3.05\ \mathrm{mHz}$$



also $\Delta\nu = (M/M_\odot)^{1/2}(R/R_\odot)^{-3/2} \times 134.9\ \mu\mathrm{Hz}$

Population synthesis: CoRoT field

towards the galactic center

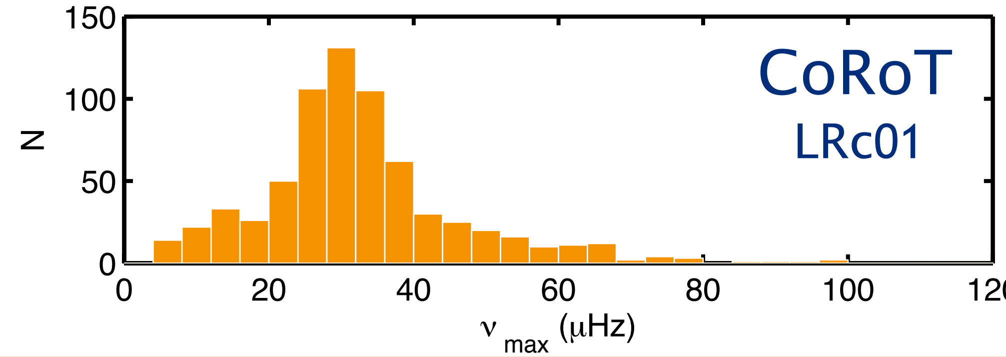


Miglio et al 2009

Asteroseismology: stellar populations

CoRoT, Kepler: solar-like oscillations in large samples of red giants

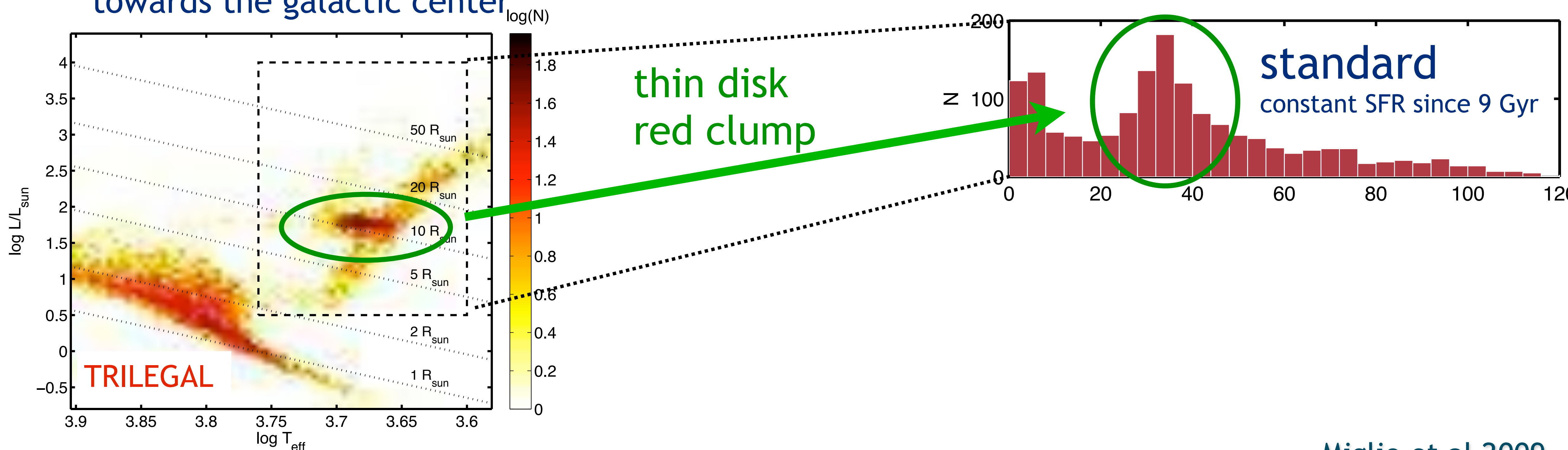
$$\nu_{\max} = \frac{M/M_{\odot}}{(T_{\rm eff}/5777)^{1/2}\,(R/R_{\odot})^{2}} \times 3.05\ \mathrm{mHz}$$



also $\Delta\nu = (M/M_{\odot})^{1/2}\,(R/R_{\odot})^{-3/2} \times 134.9\ \mu\mathrm{Hz}$

Population synthesis: CoRoT field

towards the galactic center



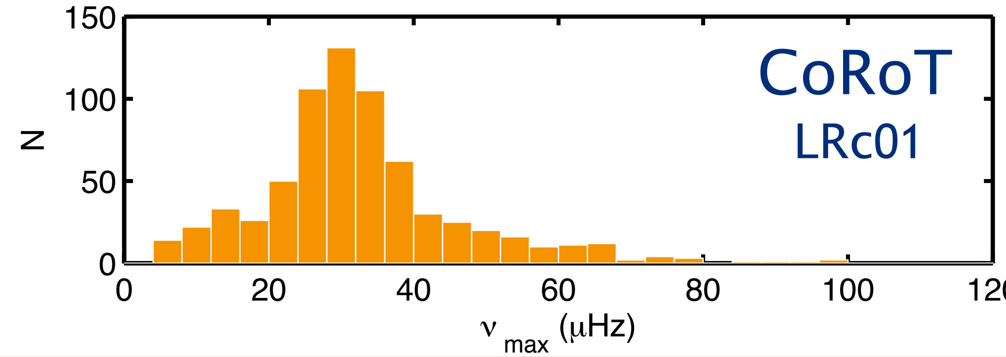
Miglio et al 2009

Asteroseismology: stellar populations

CoRoT, Kepler: solar-like oscillations in large samples of red giants

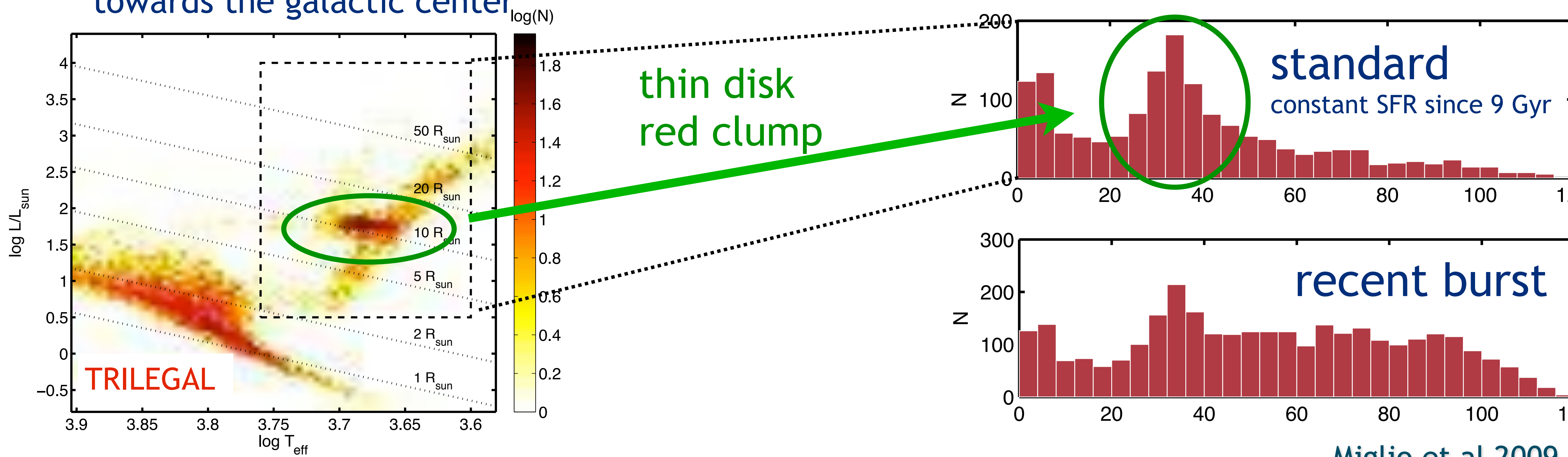
$$\nu_{\max} = \frac{M/M_{\odot}}{(T_{\rm eff}/5777)^{1/2}\,(R/R_{\odot})^{2}} \times 3.05 \text{ mHz}$$

also $\Delta\nu = (M/M_{\odot})^{1/2}\,(R/R_{\odot})^{-3/2} \times 134.9\ \mu\text{Hz}$



Population synthesis: CoRoT field

towards the galactic center



Miglio et al 2009

RGB: distribution of R and M, mass loss rate
DISC: probes of age and star formation rate

To come: giants in other galactic fields, old open clusters...

Exoplanets hosts

Exoplanets hosts

Transit: $M_{STAR}^{1/3}/R_{STAR}$, R_{PLANET}/R_{STAR} ➤ accuracy 10^{-3} (CoRoT, Kepler)
Radial velocity: M_{PLANET}^2/M_{STAR}^3 ➤ accuracy: a few $m.s^{-1}$ (Harps)
Spectroscopy: T_{eff}, log *g*, Fe/H ➤ still rather inaccurate
Astrometry, photometry: distance, luminosity ➤ presently unavailable

Exoplanets hosts

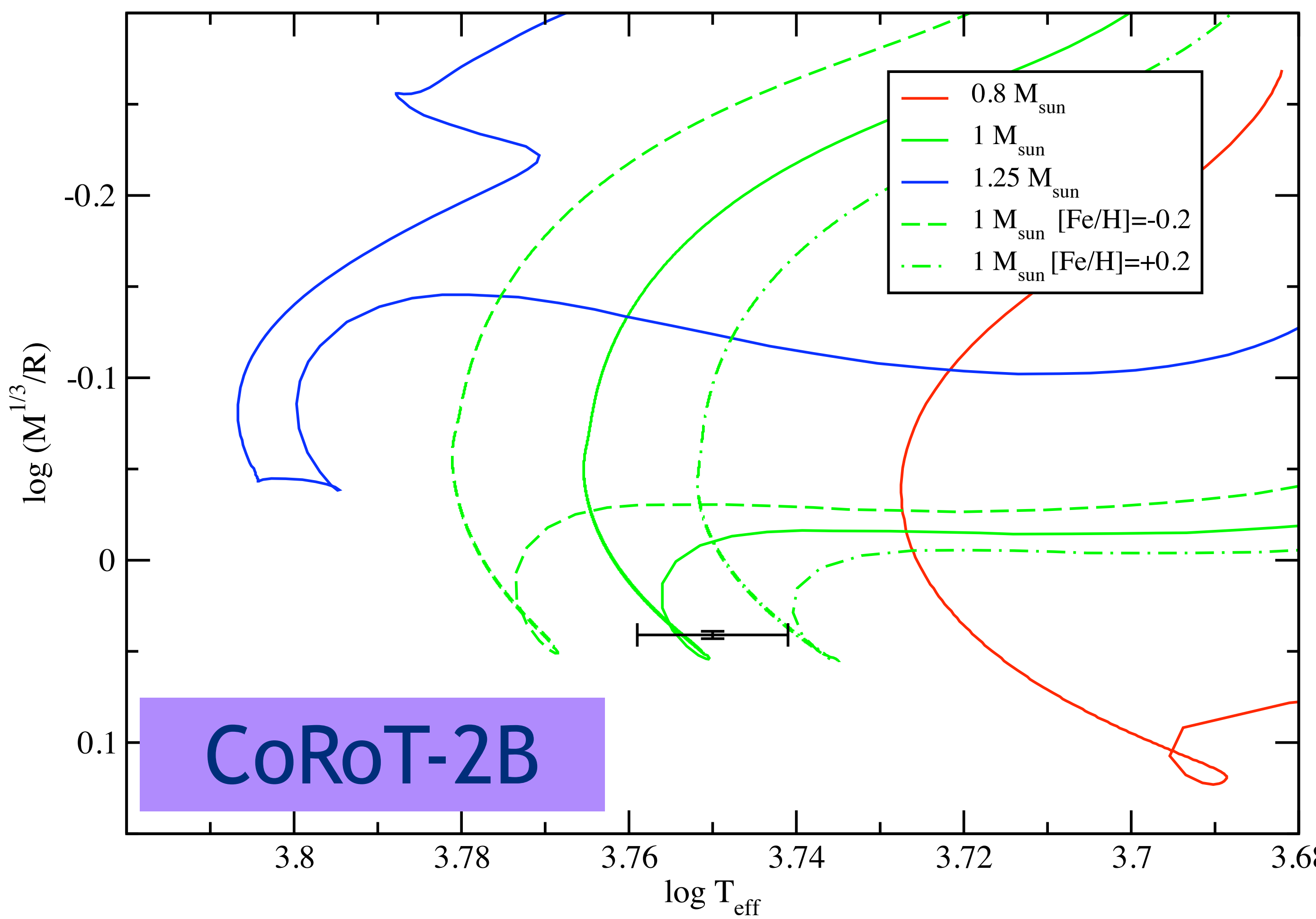
Transit: $M_{STAR}^{1/3}/R_{STAR}$, R_{PLANET}/R_{STAR} ➤ accuracy 10^{-3} (CoRoT, Kepler)
Radial velocity: M_{PLANET}^2/M_{STAR}^3 ➤ accuracy: a few $m.s^{-1}$ (Harps)
Spectroscopy: T_{eff}, log *g*, Fe/H ➤ still rather inaccurate
Astrometry, photometry: distance, luminosity ➤ presently unavailable

M_{STAR}
↓
STELLAR MODELS

ΔT_{eff}=50 K → ΔM=0.06
ΔFe/H=0.10 → ΔM=0.05
$\Delta\alpha_{MLT}$=0.2 → ΔM=0.05

+ transport processes

at least
15-20% for mass, 5% for radius
age: 30 Myr to 4 Gyr ➤ undetermined



GAIA + high resolution spectroscopy (radius) + PLATO (sismo: physics understanding)

From 2010 to 2015 and beyond

1D stellar models:

- further improvements in the physics and boundaries (atmospheres)
- validation of numerics

2 and 3D stellar models: currently under development

Observational constraints:

- global data will be improved: GAIA, VLT-I, TMT & ELT, JWST...
  distance, luminosity, effective temperature, abundances, gravity
  mass, radius
- oscillations: CoRoT 2007-12, Kepler 2009-14, Plato 2017-23
  individual frequencies but also amplitudes, lifetimes
  statistics: ν_{max}; $\Delta\nu$
  increased number of stars (150 000 to 500 000)
  longer duration of observations (150 d to 5 yr)

New diagnostics are expected