Dark matter in stars

Impact and constraints from asteroseismology

Ilídio Lopes

CENTRA, Instituto Superior Técnico
University of Lisbon

Paris Workshop 2016

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centra
multidisciplinary center for astrophysics

Outline

- Using Sun and stars to investigate dark matter
- Asteroseismology
- Dark matter interaction with stars
- Future Missions
- Conclusion

Stars to investigate Dark Matter

- Pioneer works: Cosmions as a solution to the solar neutrino problem

  [Steigman *et al.* (83), Spergel and Press (85),

  Krauss *et al.* (85), Gilliland *et al.* (86), Dearborn *et al.* (91)]

  Use of helioseismology to test the WIMP hypothesis

  [Faulkner *et al.* (86), Dappen *et al.* (86)]

  Dark matter impact in Stars (Sun and red giant stars, . . .)

  [Gould, Bouquet, Dearborn, Freese, Raffelt, Salati, Silk, . . .]

- The Sun: solar neutrinos and helioseismology to constrain low-mass DM candidates

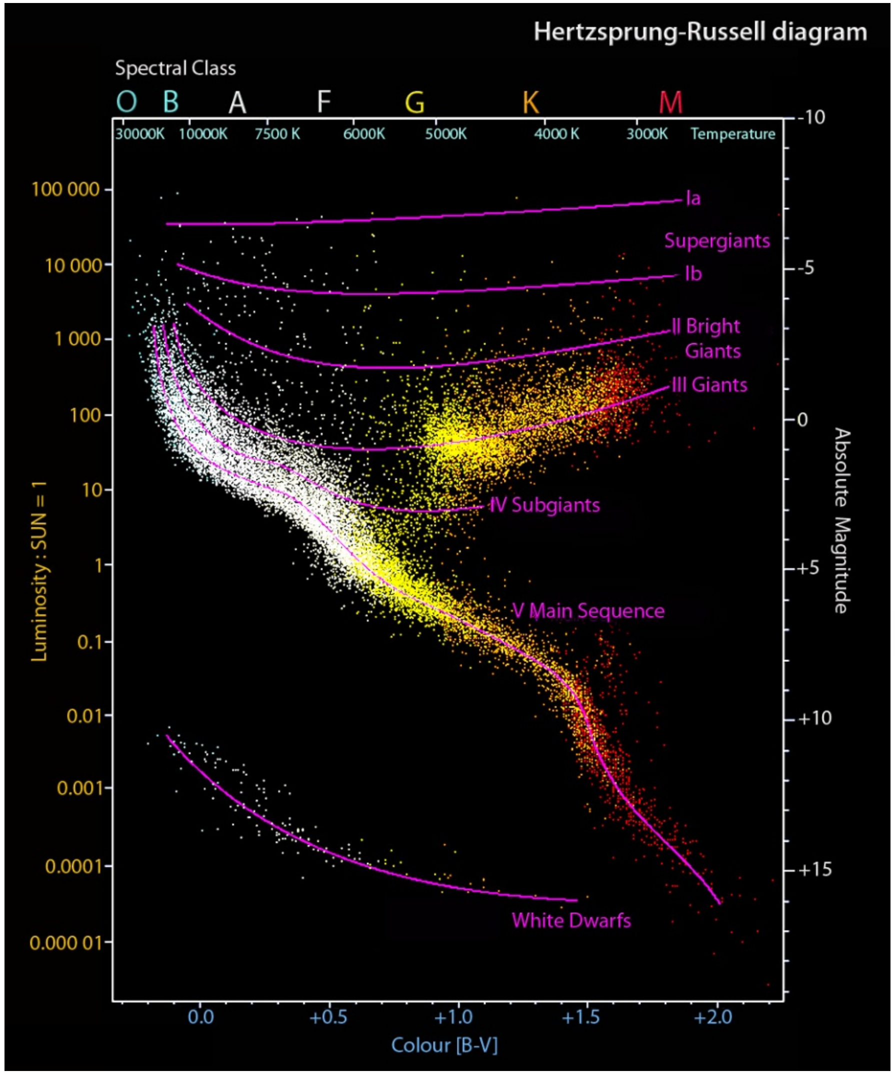
  [Bottino, Bertone, Casanellas, Cumberbatch, Frandsen, Guzik, Lopes, Iocco, Panci, Meynet, Ricci, Scott, Silk, Taoso, Turck-Chièze, Watson, Vincent]

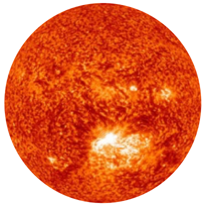
- Stars (including DM stars) and asteroseismology to constrain low-mass DM candidates

  [Lopes, Casanellas, Silk, . . . Iocco, Kouvaris, Scott , . . .]

Using Stars to investigate Dark Matter

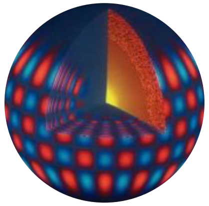
Stellar Modelling and Observations





Sun

EoS, opacities, nuc. reac. rates,...

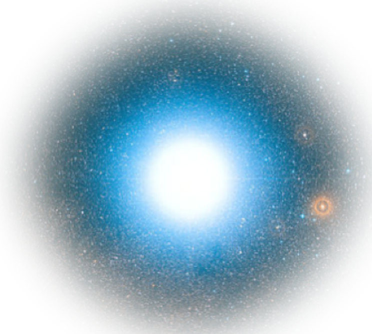


Helioseismology

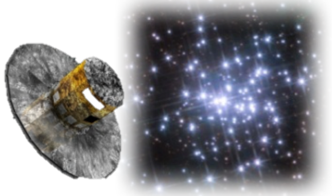
Prediction of c(r) better of 1%

Solar neutrinos

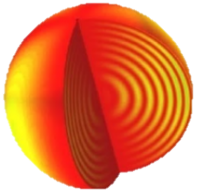
^{8}B flux with accuracy of 3%



Stars



Star clusters, isochrones



Asteroseismology

Solar-like osc. ident. in hundreds ★

Main sequence and red giants

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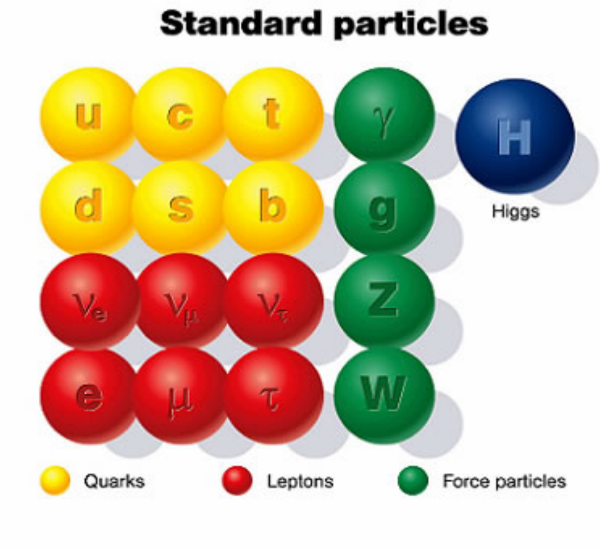
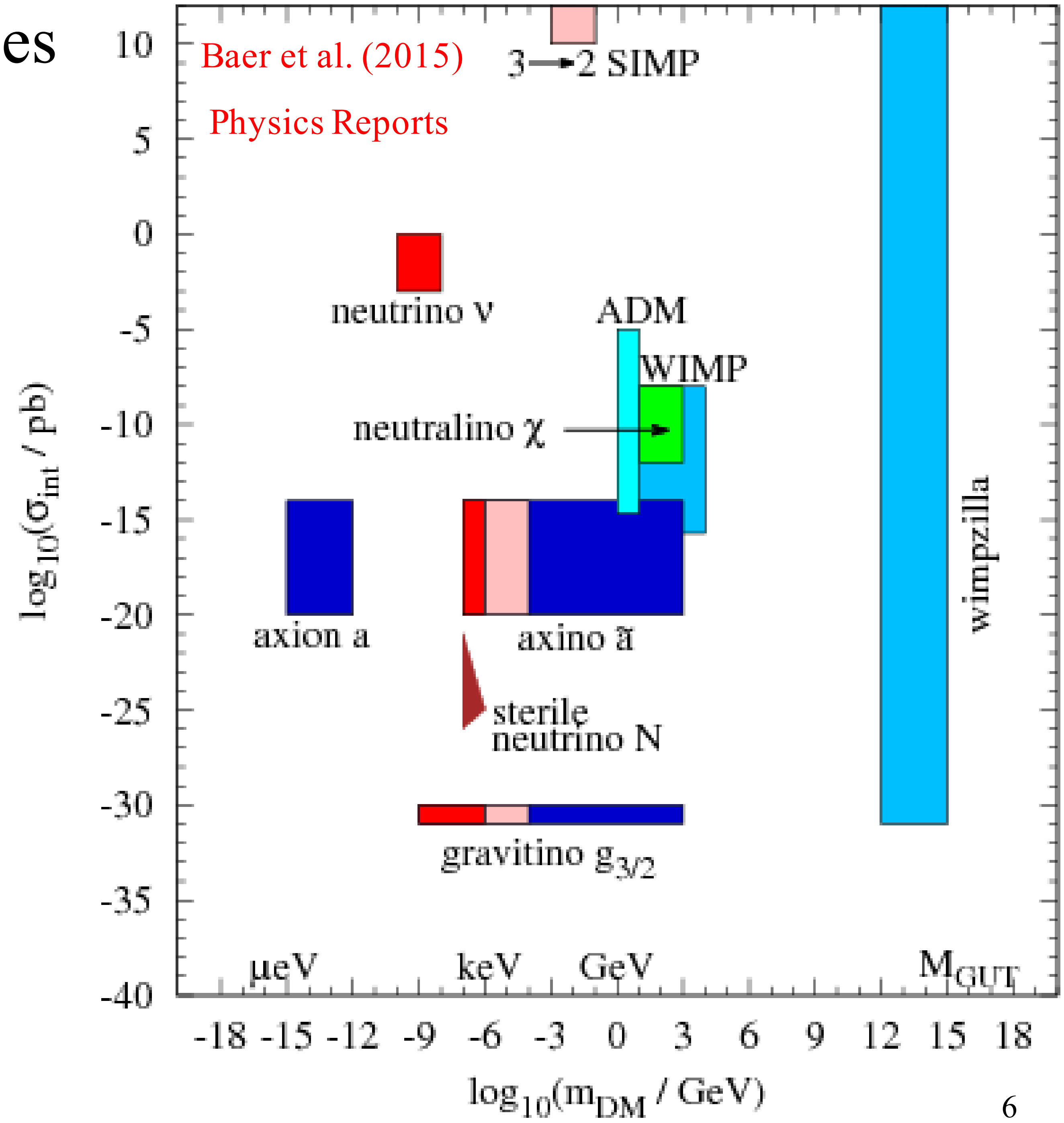
Dark matter particle candidates

Dark matter particles

(theoretical world)




Baer et al. (2015)

Physics Reports

DM 'well-motivated' candidates:
HDM (red), WDM (pink) and
CDM (blue)

picobarn [1E-36 cm^2].

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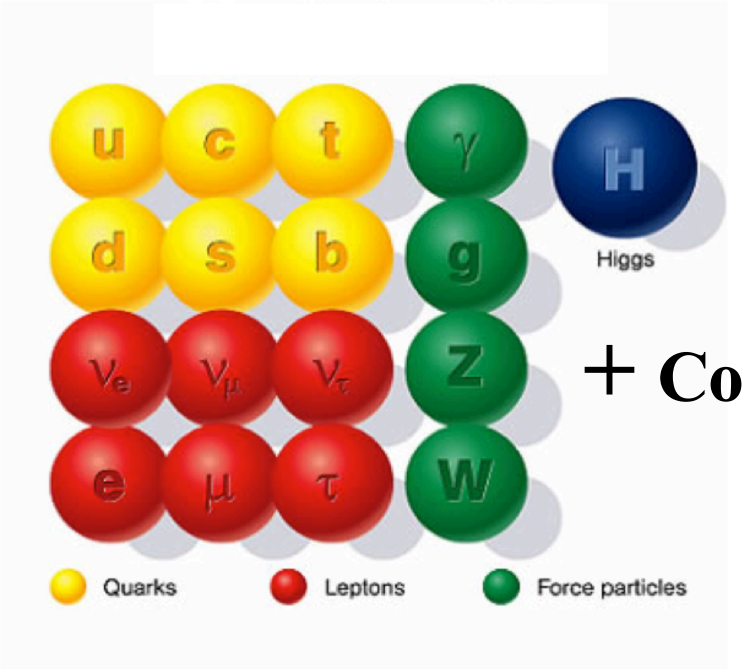
The Early Universe – dark matter particles

Following the evidence, let us now consider that our dark matter is somehow identical to the standard particles.

The obvious choice is to consider that dark matter (27%) is a mirror world of the standard particles (4%) - **supersymmetry**. However, the most complete models have 128 free parameters

Nevertheless, we choose to keep the dark matter world simple . . .



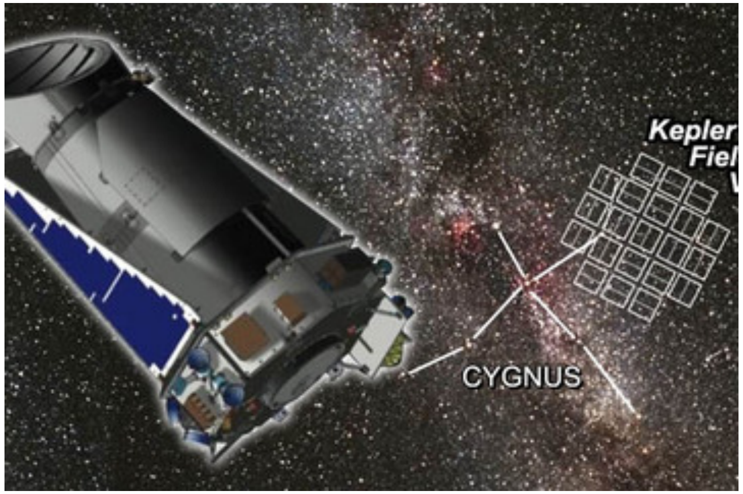
+ **Coupling/Interaction** + dark particle

standard particles

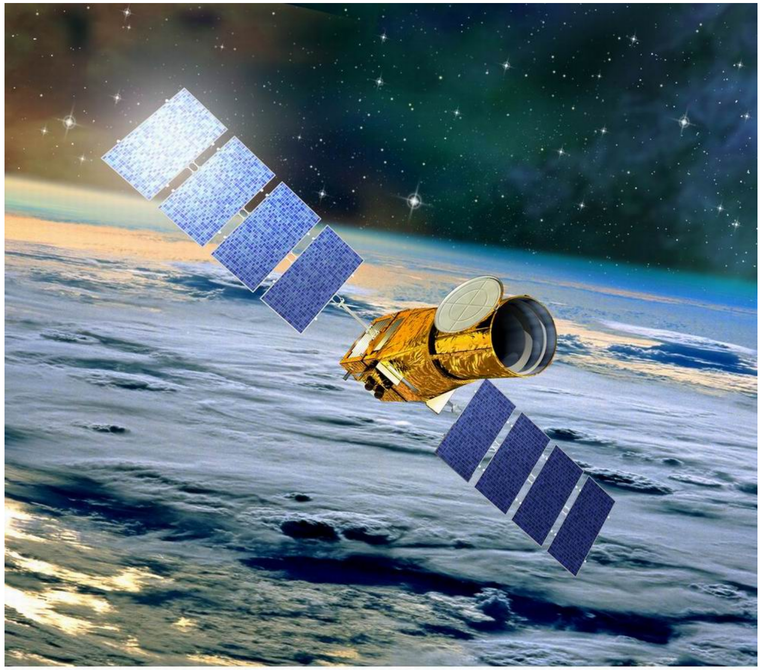
Asteroseismology

Asteroseismology

Kepler



COROT



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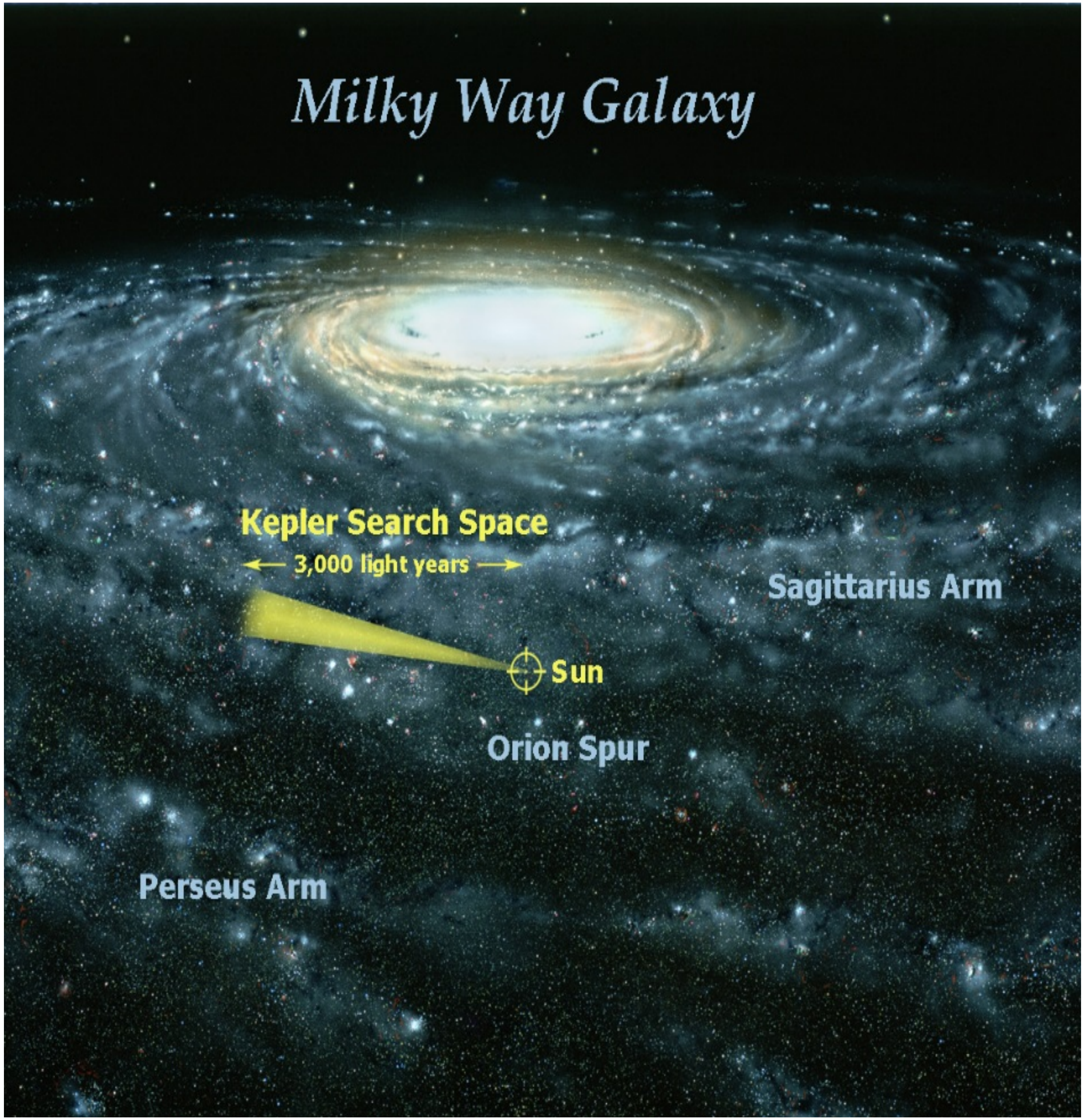
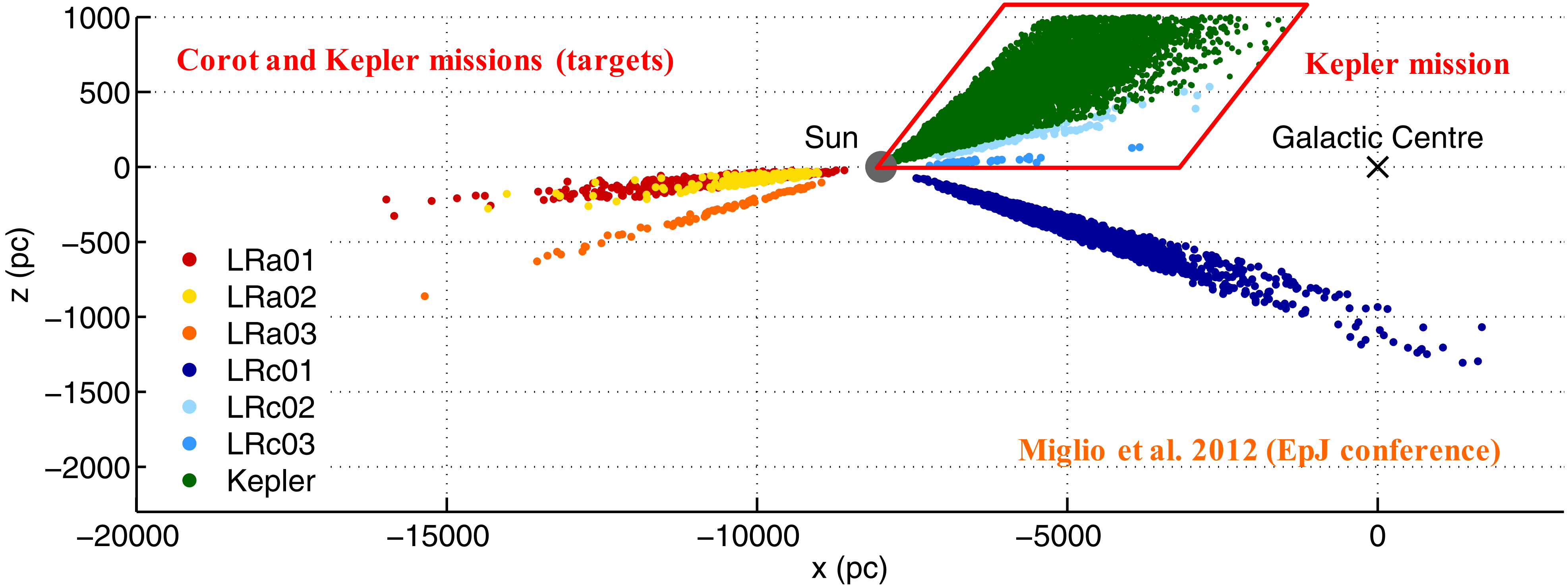


Stars as natural detectors – oscillating stars



Corot and Kepler missions (targets)

Kepler mission

Miglio et al. 2012 (EpJ conference)

- Corot’s objective search for extrasolar planets and to measure solar-like oscillations in stars. Launch: December 27, 2006

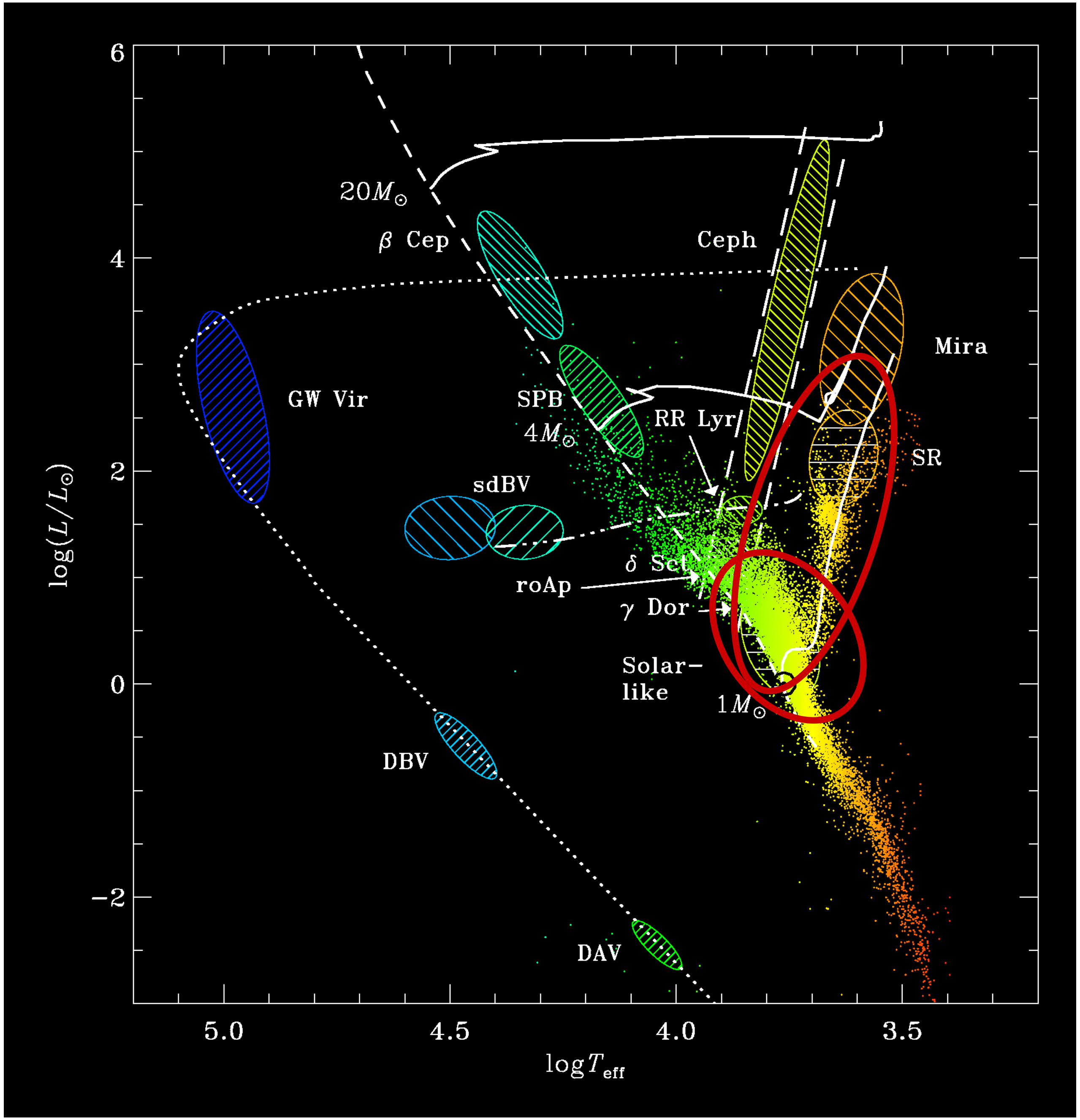
- Kepler has been pointed at a single point in the sky (near the constellation Cygnus) and has been constantly monitoring over 100,000 stars. Launch: March, 2009

- Sun-like oscillations were discovered in **700 main sequence and sub-giant stars** and in more than **16 000 red giant stars** in the solar neighbourhood.

Asteroseismology

Oscillating stars in the HR diagram

Sun-like oscillations…

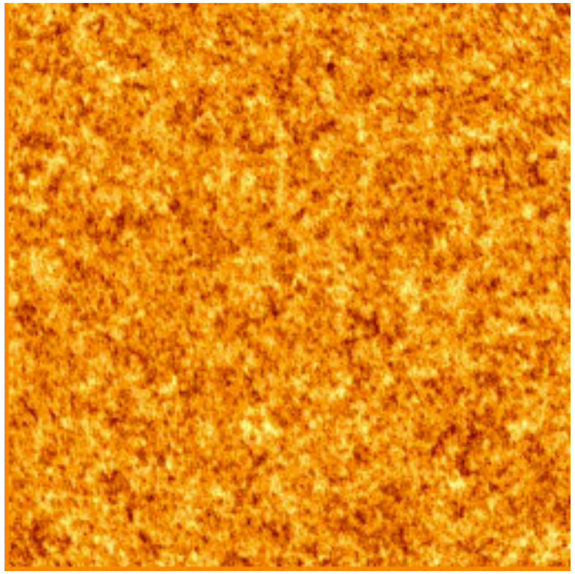


Helioseismology: Space Instruments

- SoHO: Solar and Heliospheric Observatory (2/12/1995) :
- Three seismic Instruments: MDI , GOLF, VIRGO

MDI-full-disk Dopplergram sequence shows solar "5-minute" oscillations.

MDI Dopplergrams from high resolution field show solar oscillations. This data was observed with a 12-second cadence.



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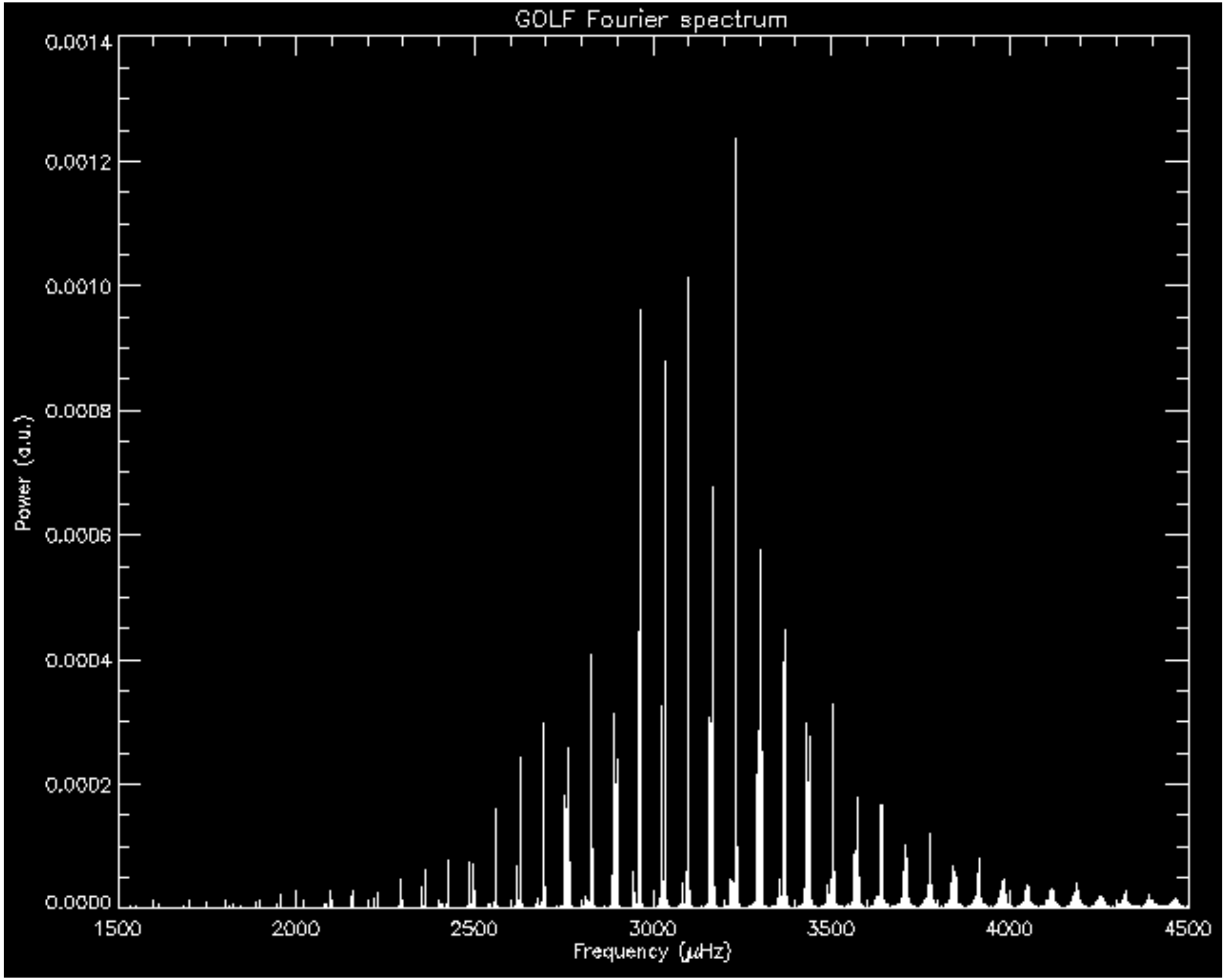
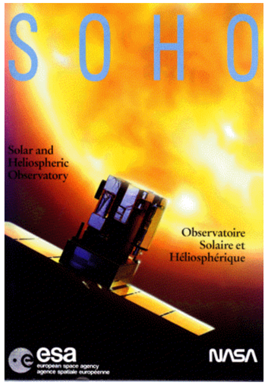
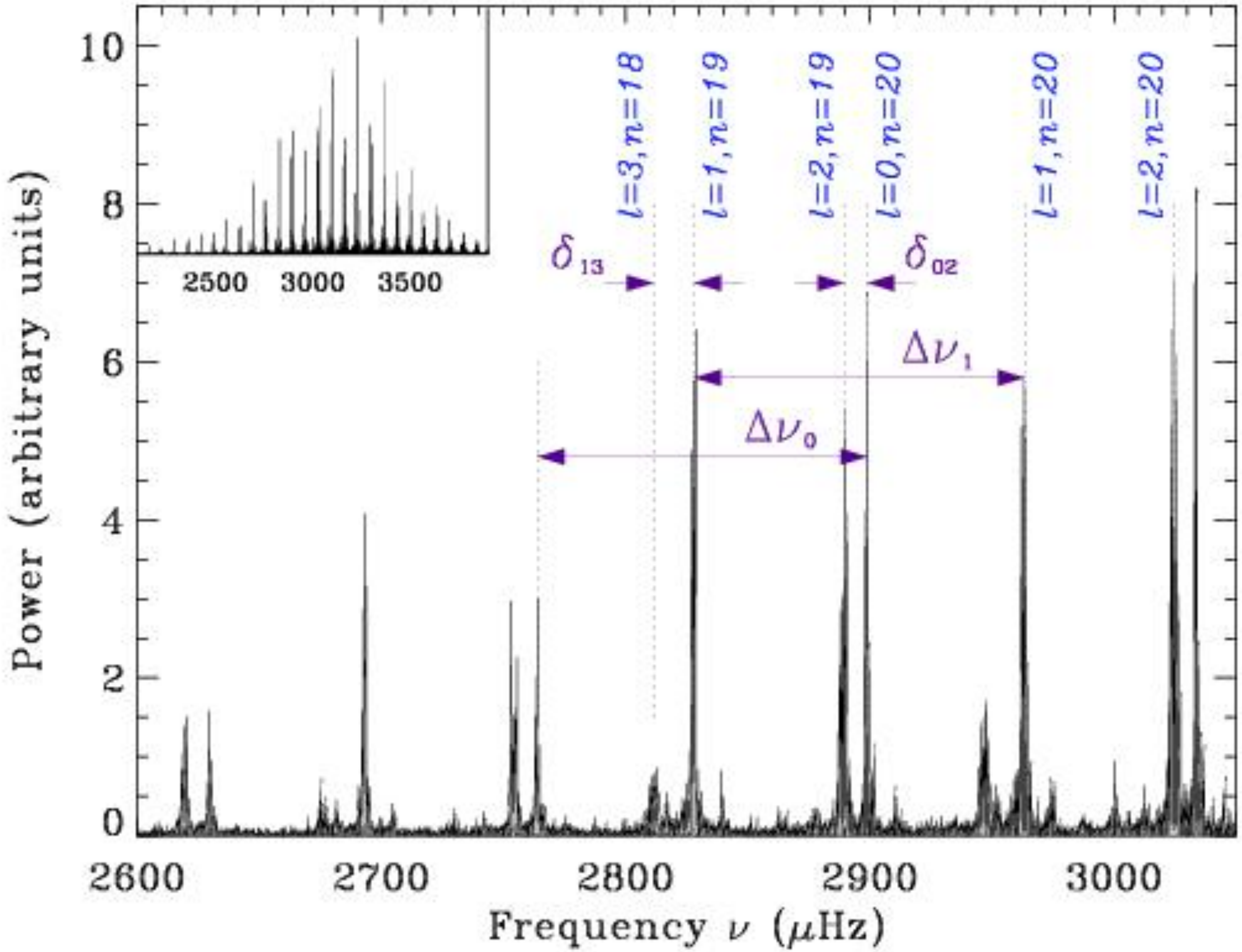
Asteroseismology

GOLF: Whole-disk power spectrum





Asteroseismology



Asteroseismology

p - mode eigenfrequency (low l and $l << n$) :

$$\nu_{l,n} = \left(n + \frac{1}{2}l + \varepsilon\right)\nu_o + \left[Al(l+1) - B\right]\frac{\nu_o^2}{\nu_{l,n}} + \cdots$$

(Tassoul 1980)

$$\nu_o = \left(2\int_0^R \frac{dr}{c}\right)^{-1} \qquad A = \frac{1}{2\pi\omega_o}\left[\frac{c(R)}{R} - \int_0^R \frac{1}{2}\frac{dc}{dr}dr\right]$$

Large separation

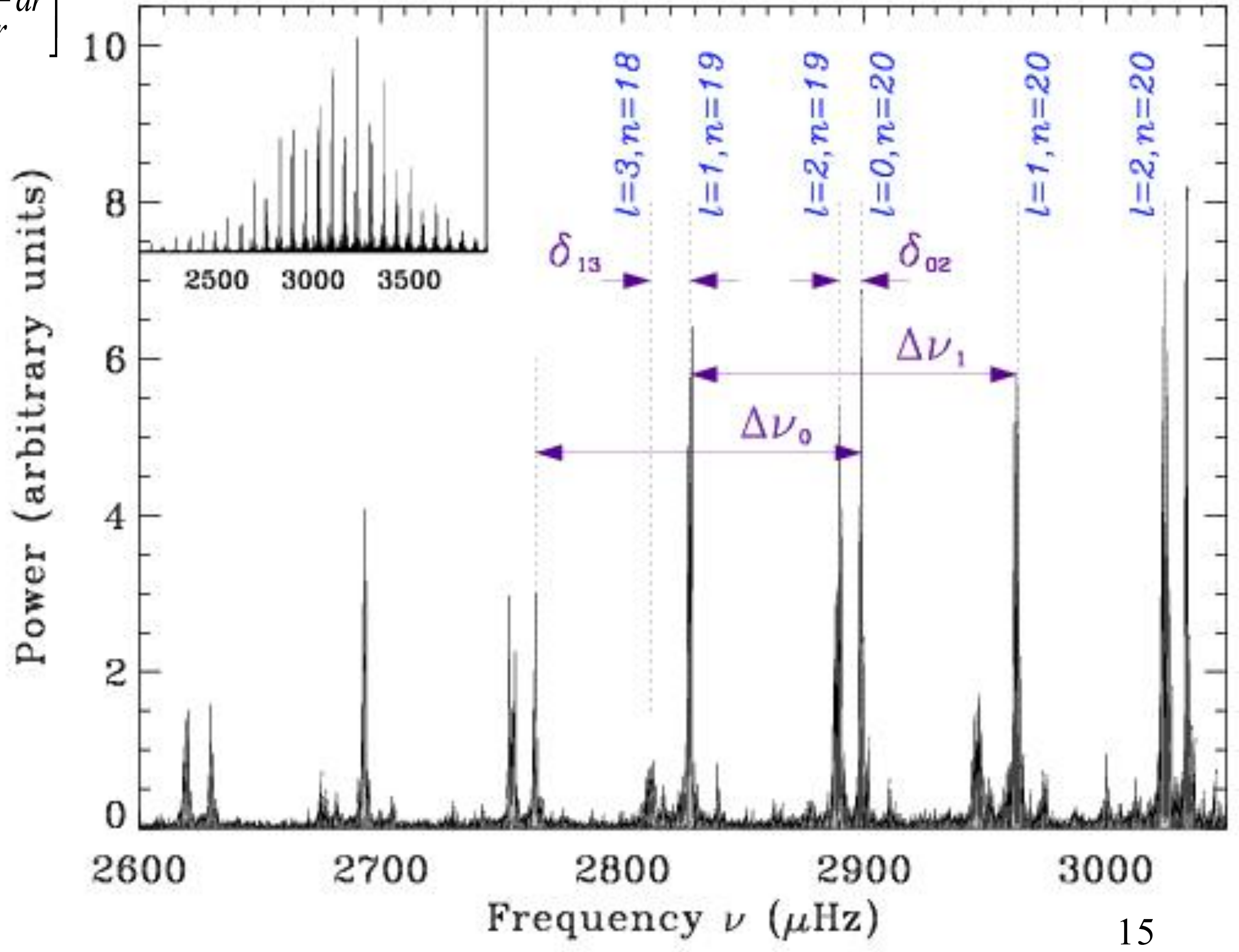
$$\Delta\nu_{l,n} = \nu_{l,n} - \nu_{l,n-1} = \nu_o$$

sensitive to sound speed in the surface

Small separation

$$\delta\nu_{l,n} = \nu_{l,n} - \nu_{l+2,n-1} \approx \frac{6\nu_o^2}{(n + l/2 + \varepsilon)}A$$

sensitive to sound speed gradients in the interior



Asteroseismology

p-mode eigenfrequency (low l and $l << n$):

$$\nu_{l,n} = \left(n + \frac{1}{2}l + \varepsilon\right)\nu_o + \left[Al(l+1) - B\right]\frac{\nu_o^2}{\nu_{l,n}} + \cdots$$ **(Tassoul 1980)**

$$\nu_o = \left(2\int_0^R \frac{dr}{c}\right)^{-1} \qquad A = \frac{1}{2\pi\omega_o}\left[\frac{c(R)}{R} - \int_0^R \frac{1}{2}\frac{dc}{dr}dr\right]$$

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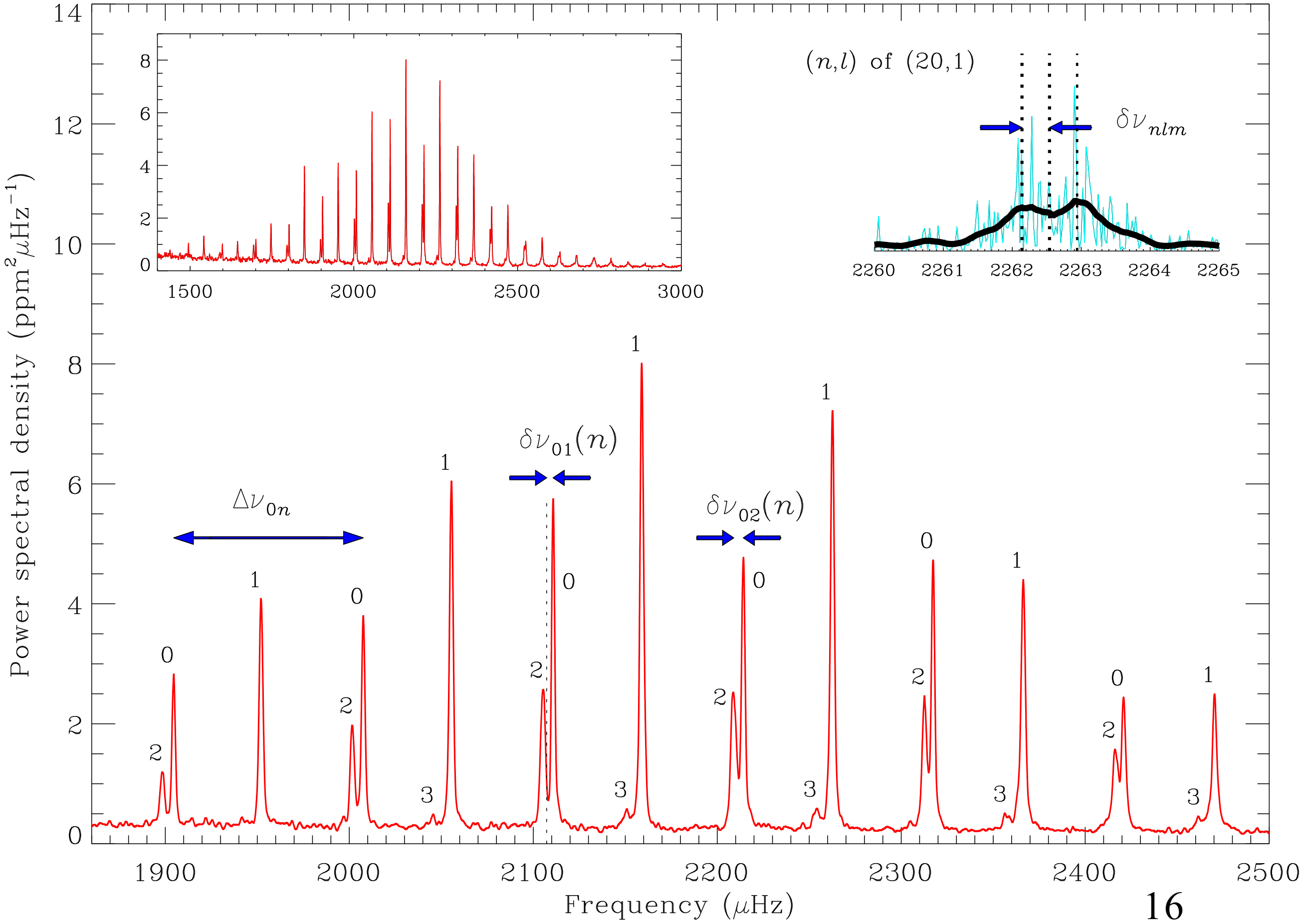
sensitive to sound speed gradients in the interior

Oscillation spectrum of the G-type main-sequence star in 16CygA as observed by Kepler

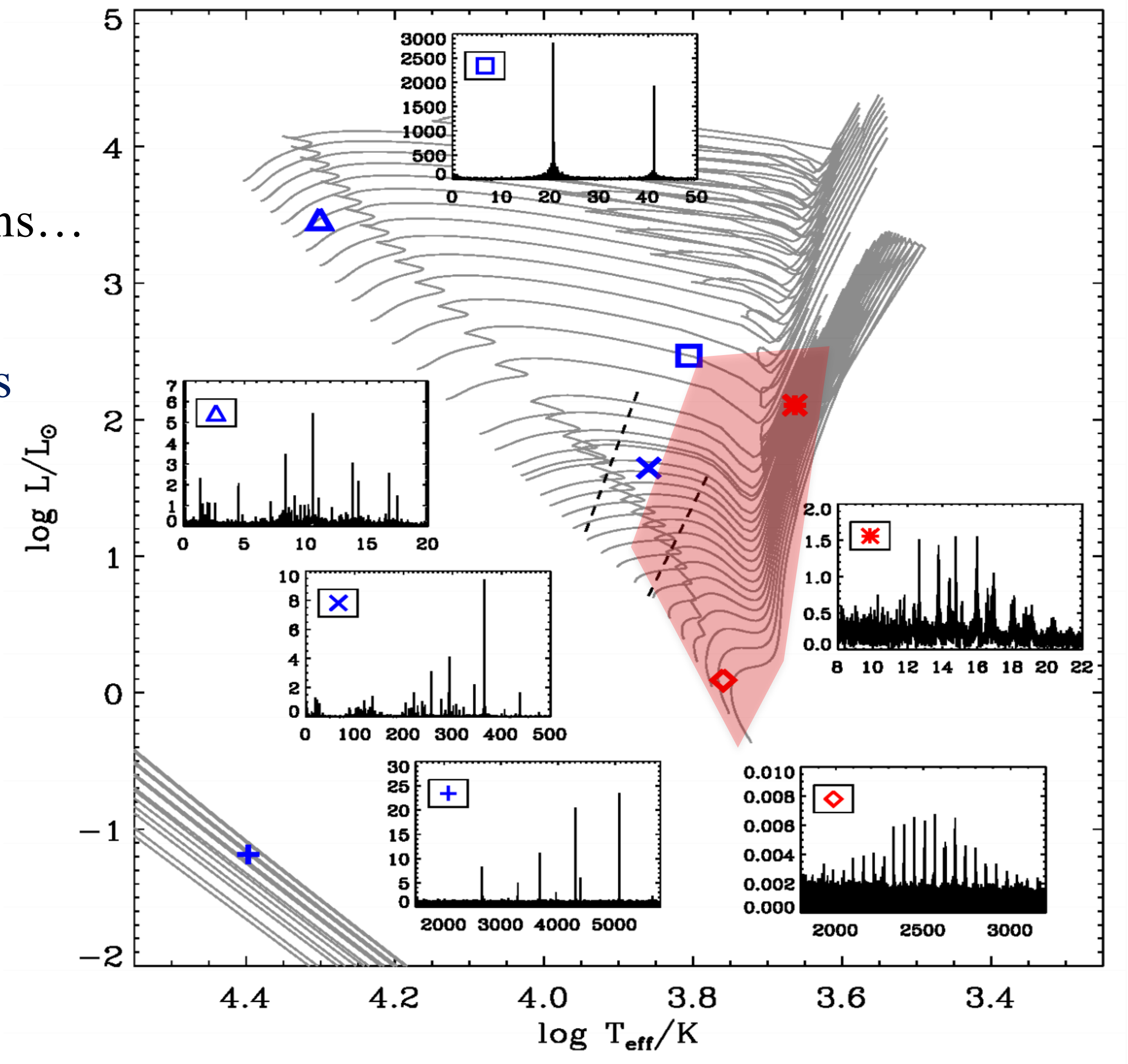


Asteroseismology

Huber (2014)

Sun-like oscillations…

Stochastically excited oscillations in stars with a convective envelope

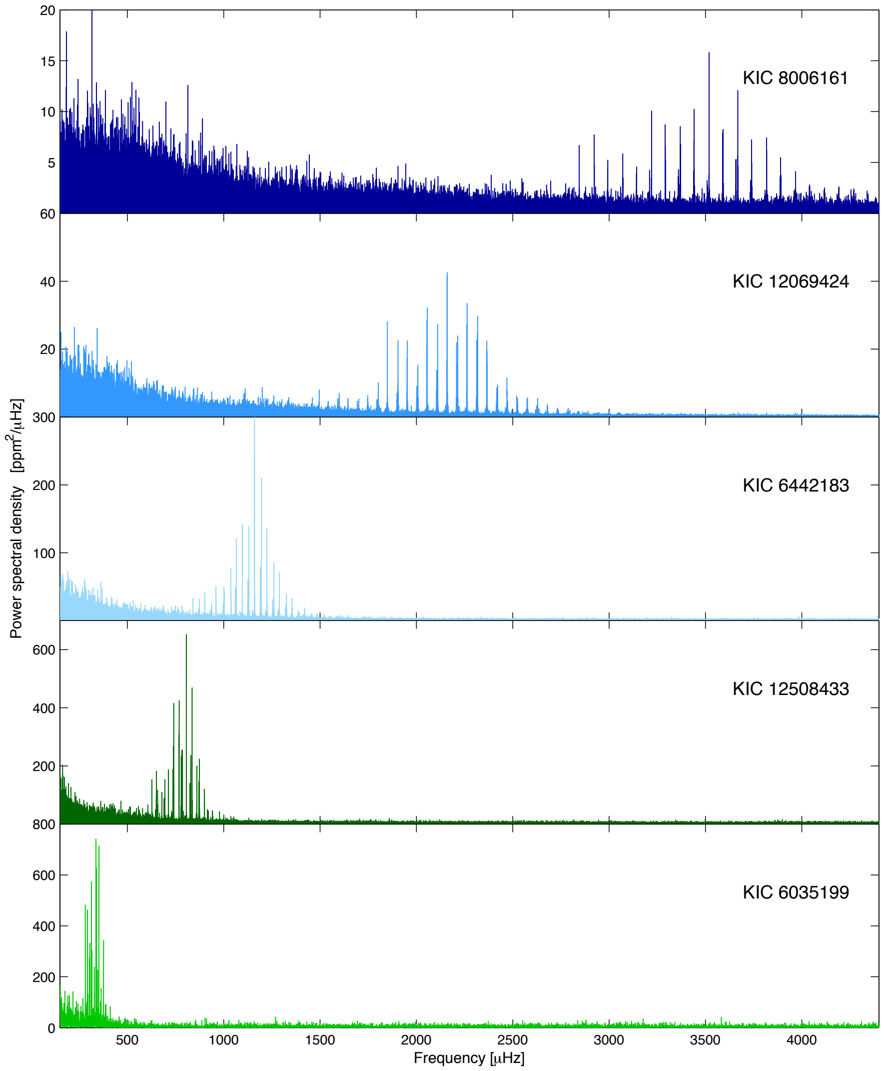


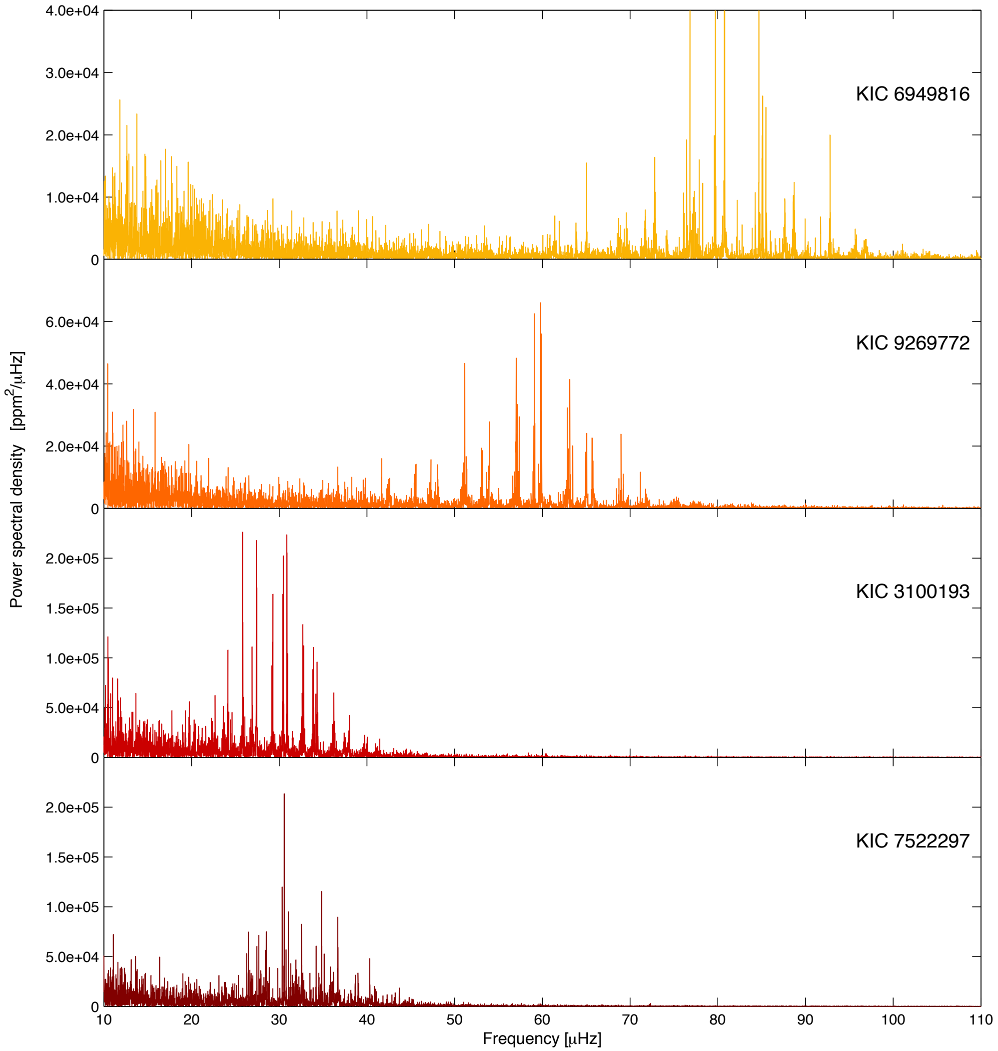
Asteroseismology

Kepler observations Solar-like oscillations

Main sequence and subgiant stars $(\sim 1M_\odot)$

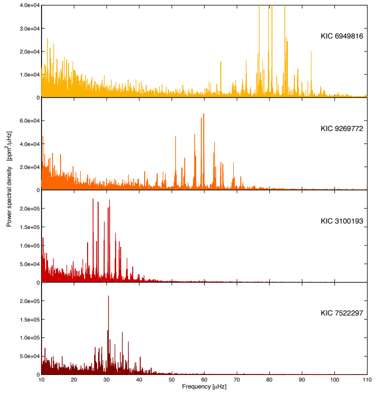
Red giant stars $(\sim 1M_\odot)$

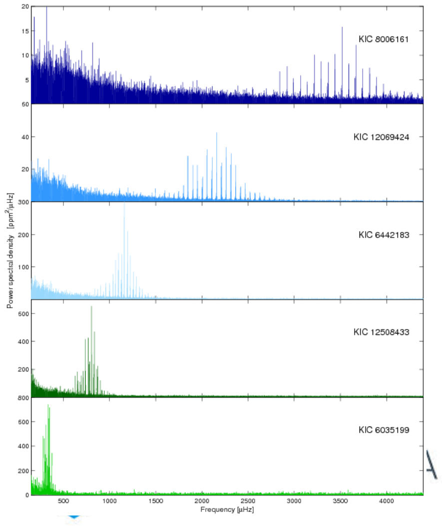




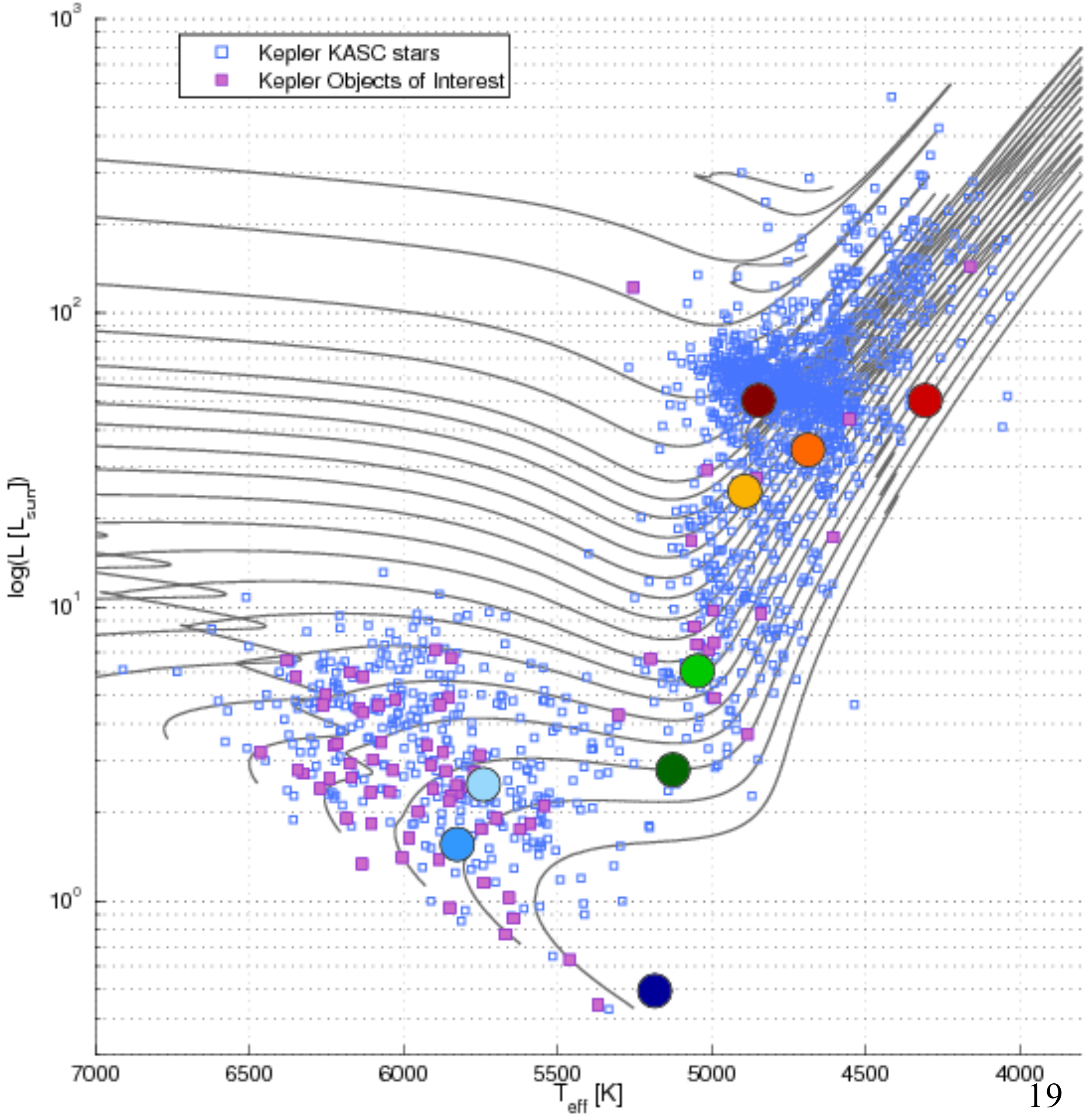
Asteroseismology

Hertzsprung-Russell diagrams showing populations of stars with detected solar-like oscillations (Detections made by the Kepler mission): The large coloured circles mark the stars whose spectra are plotted in the left Figure. Solid lines in both panels follow evolutionary tracks (Ventura, D'Antona & Mazzitelli 2008).





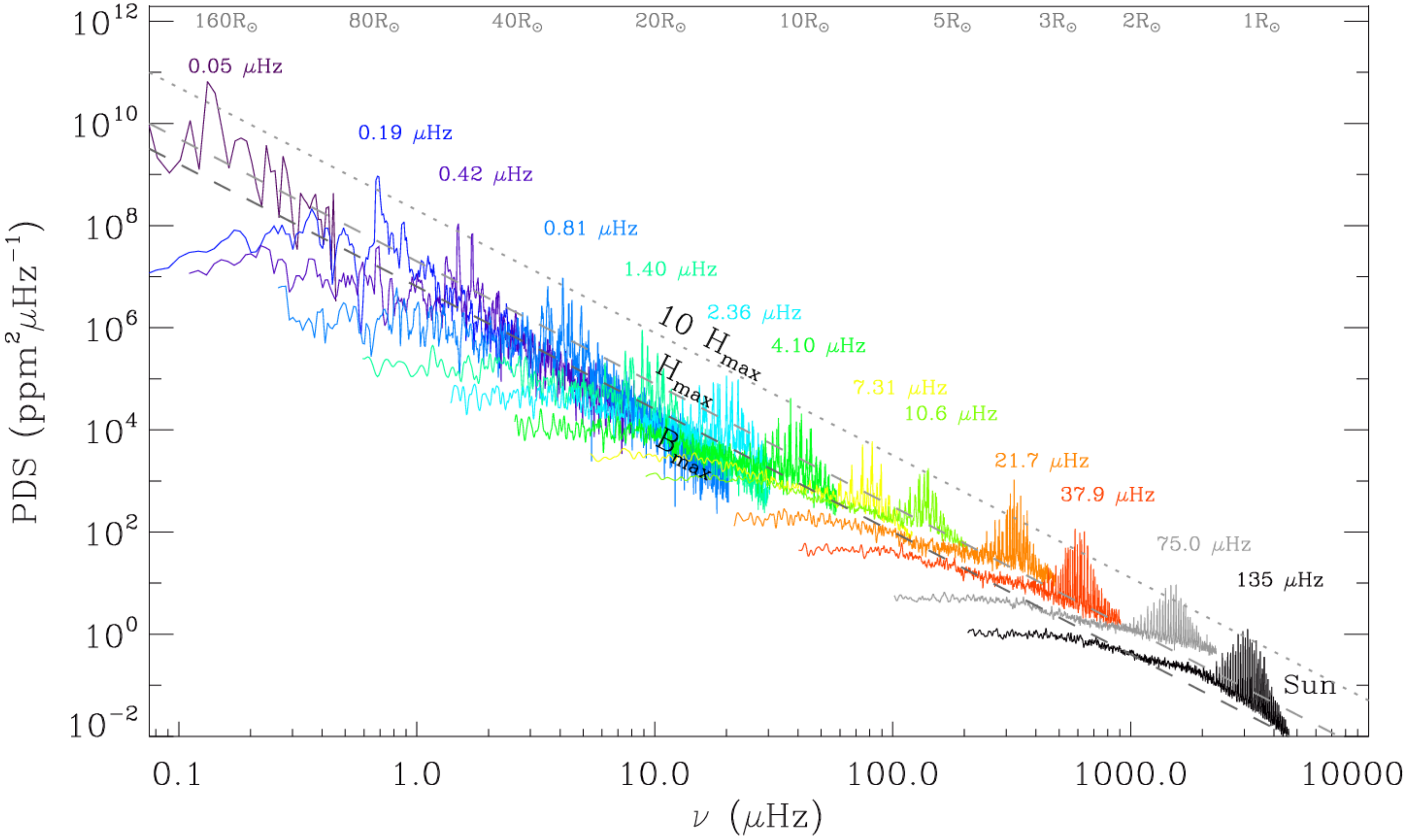
Chaplin & Miglio. (2014)



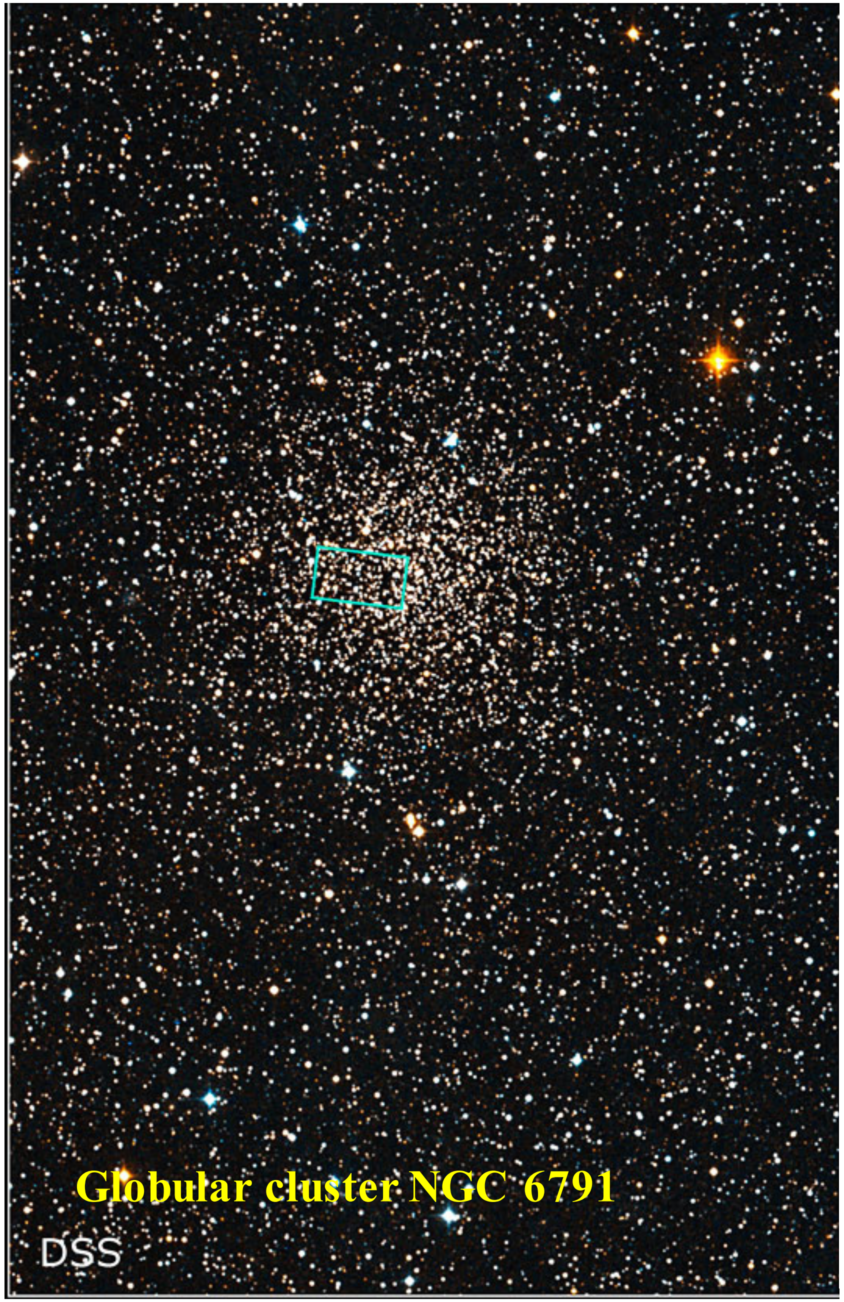
Asteroseismology

Sun-like oscillations…

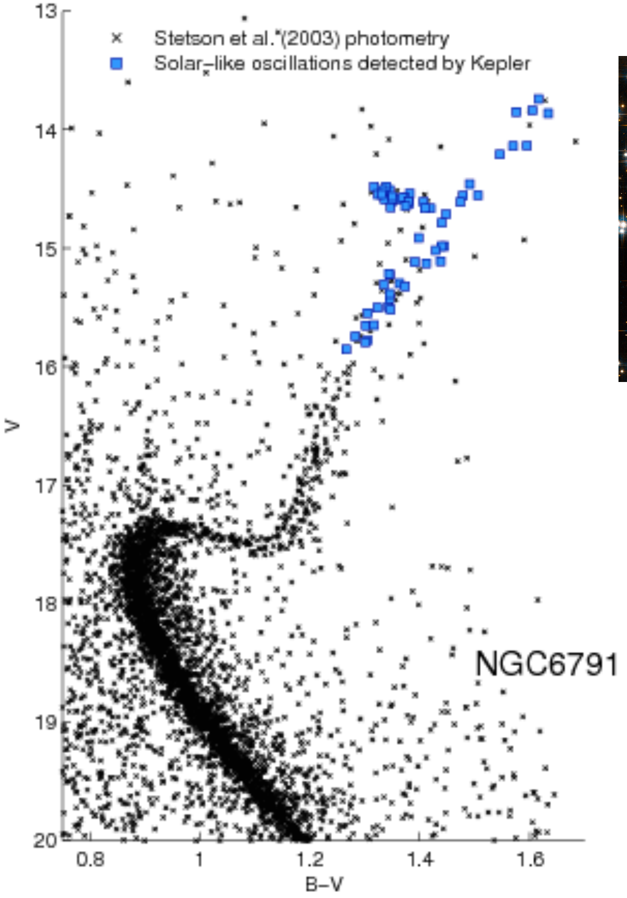
Mosser (2014)

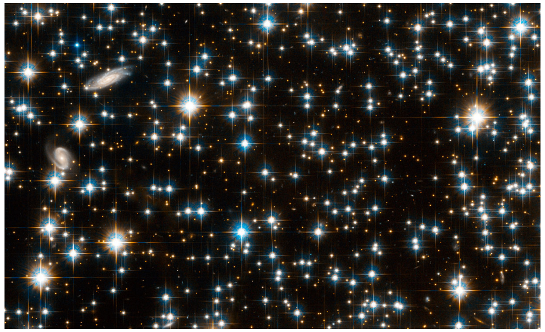


Asteroseismology
(red giants)

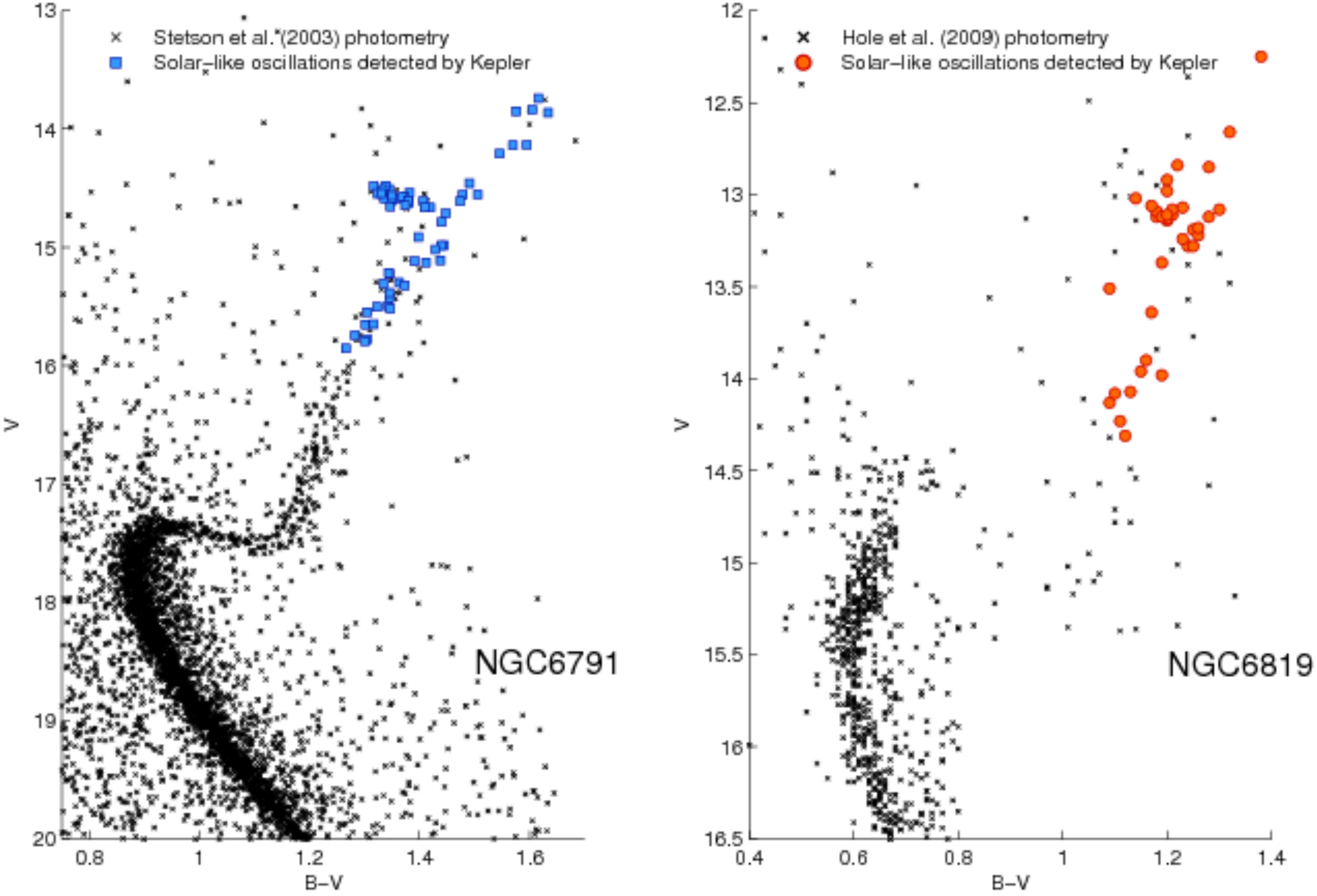


Globular star cluster NGC 6791 (NASA/ESA Hubble Space Telescope):[Left] - This is a ground-based telescopic view of NGC 6791, located 13,300 light-years away in the constellation Lyra. The green inset box shows the view with Hubble's Advanced Camera for Surveys.[Top right] - The full Hubble Advanced Camera for Surveys field is full of stars estimated to be 8 billion years old. Two background galaxies can be seen in upper left.[Bottom right] - A zoomed view of a small region of the Advanced Camera for Surveys field reveals very faint white dwarfs.





Asteroseismology
(red giants)



The blue circles identify hotter dwarfs that are 4 billion years old.

The red circles identify cooler dwarfs that are 6 billion years old.

Asteroseismology

Scaling relations

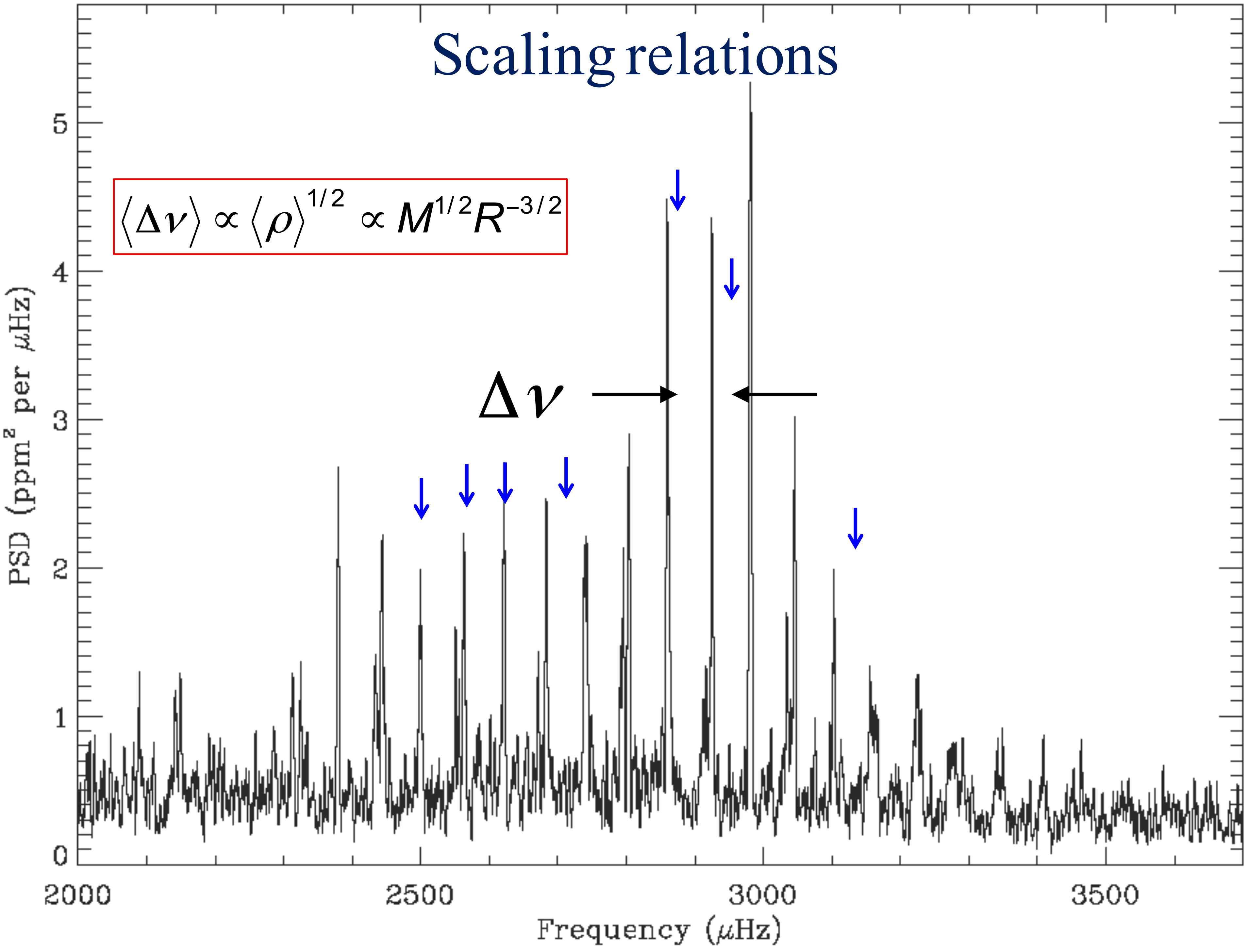
From the global seismic parameters stellar masses and radii,

$$\frac{R}{R_\odot} \simeq \left(\frac{\nu_{\rm max}}{\nu_{\rm max,\odot}}\right)\left(\frac{\Delta\nu}{\Delta\nu_\odot}\right)^{-2}\left(\frac{T_{\rm eff}}{T_\odot}\right)^{1/2}$$

$$\frac{M}{M_\odot} \simeq \left(\frac{\nu_{\rm max}}{\nu_{\rm max,\odot}}\right)^{3}\left(\frac{\Delta\nu}{\Delta\nu_\odot}\right)^{-4}\left(\frac{T_{\rm eff}}{T_\odot}\right)^{3/2}$$

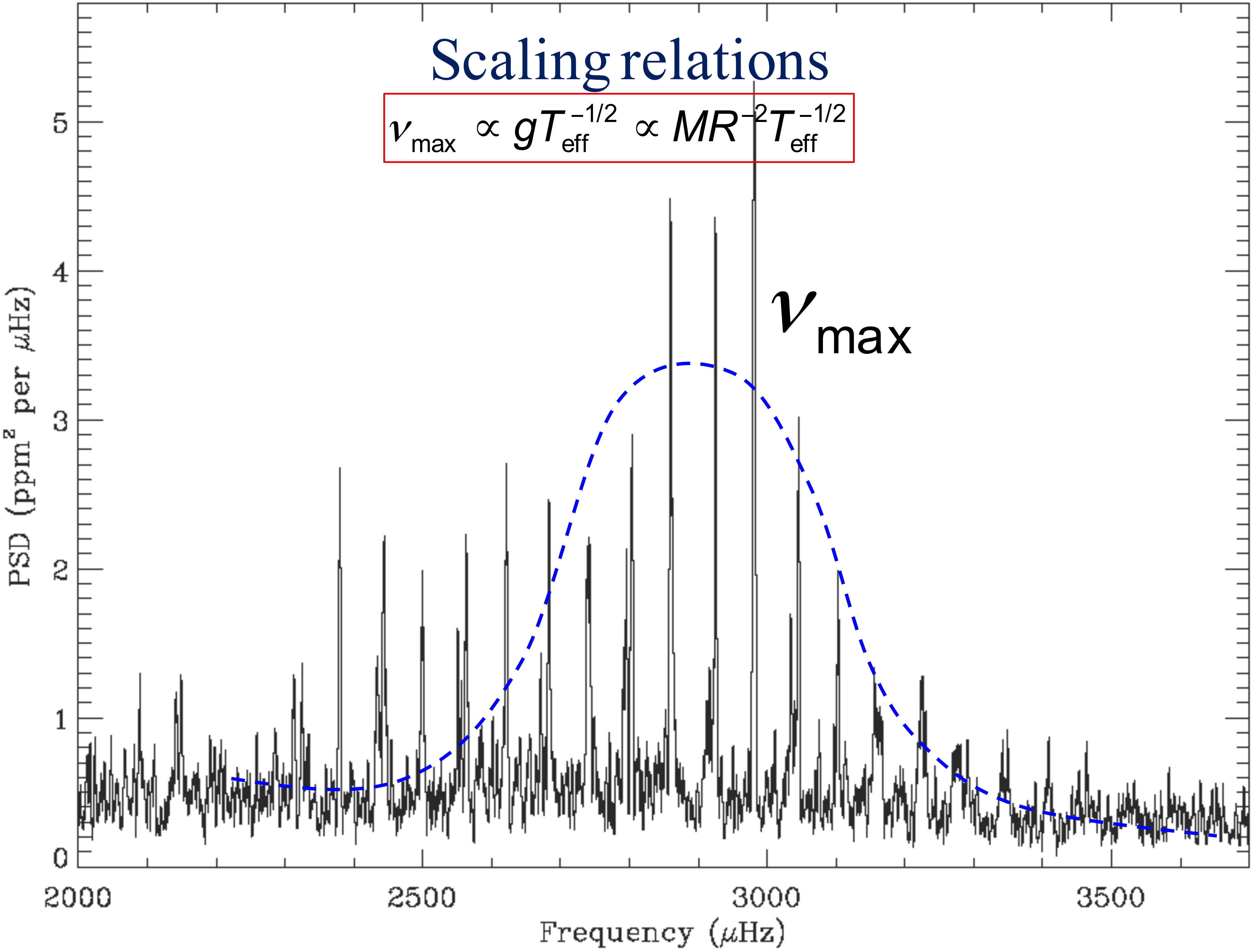
Scaling relations

$$\langle \Delta\nu \rangle \propto \langle \rho \rangle^{1/2} \propto M^{1/2} R^{-3/2}$$



Scaling relations

$$\nu_{\max} \propto g T_{\mathrm{eff}}^{-1/2} \propto M R^{-2} T_{\mathrm{eff}}^{-1/2}$$



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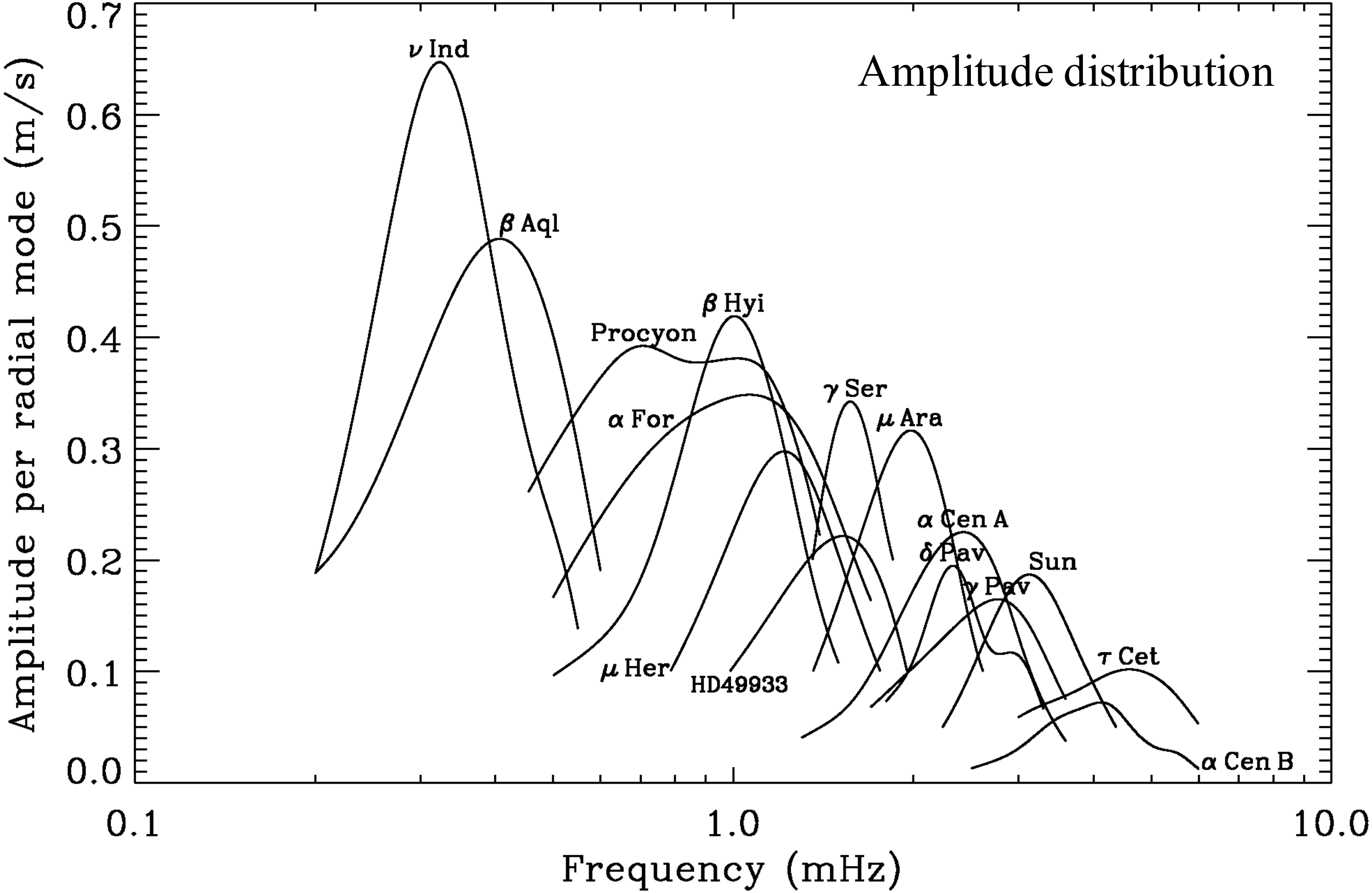
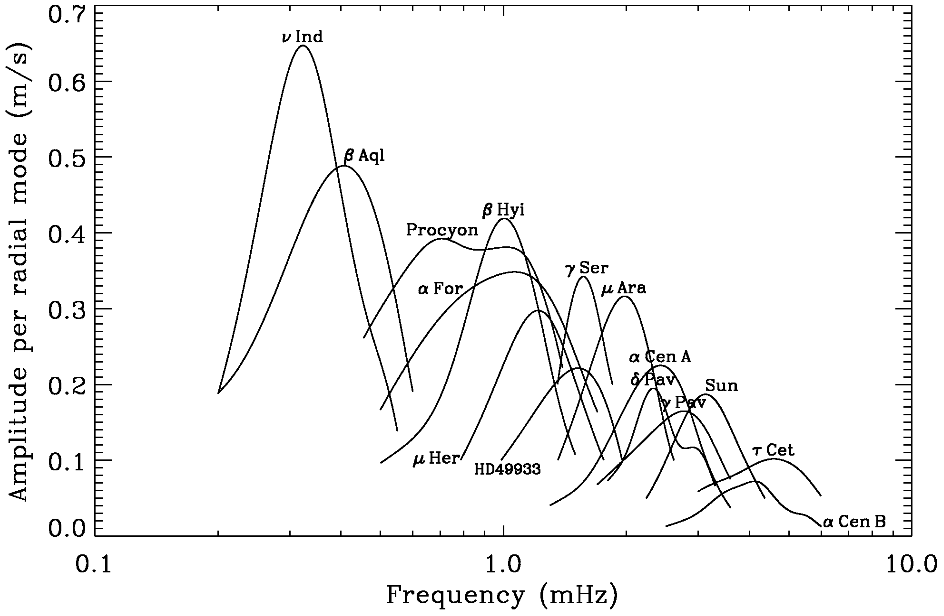
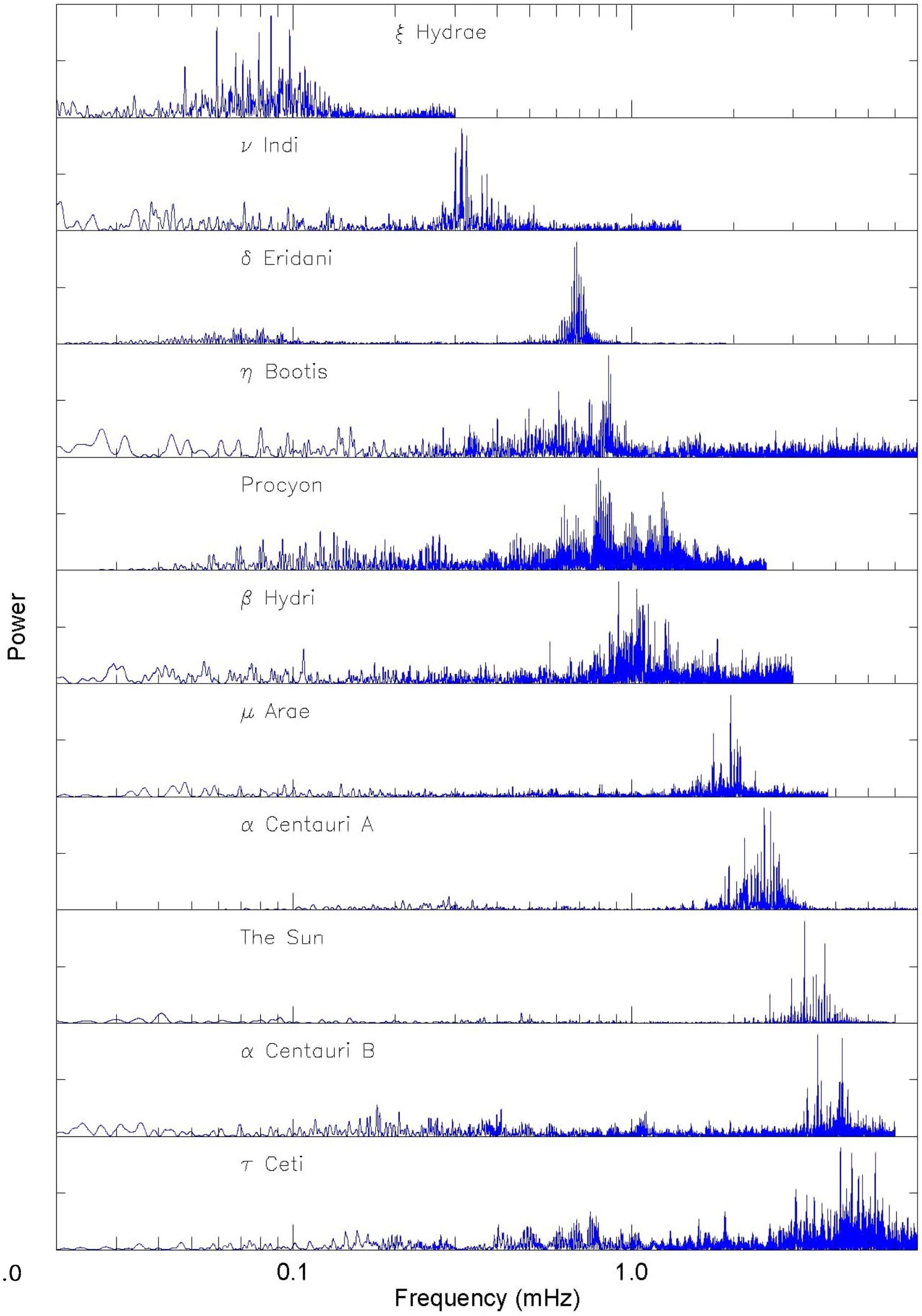


Scaling relations

Amplitude distribution





Asteroseismology

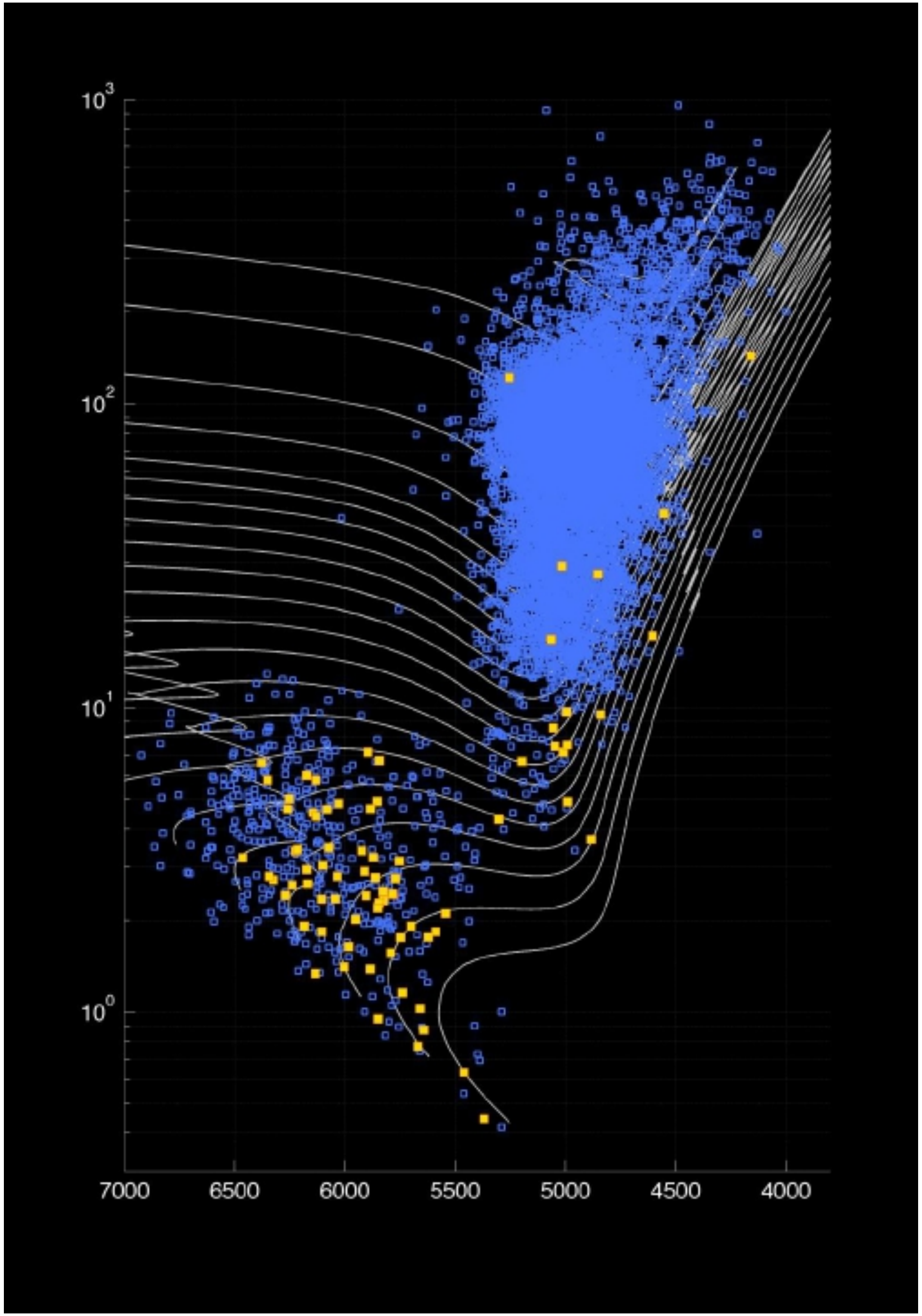
Asteroseismology of solar-like oscillators

🎬 *Kepler mission*

Approx. 700 solar-type stars

Approx. 16,000 red giants

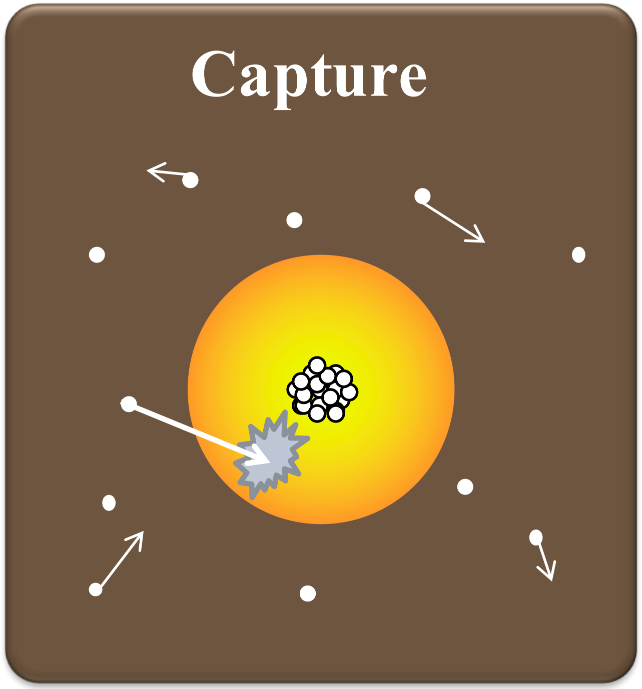
Over 100 planet-hosting stars



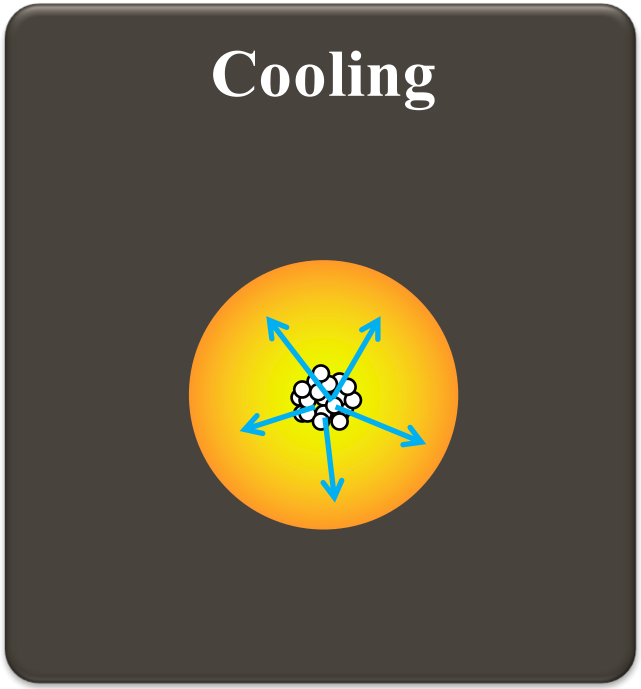
Dark matter interaction with stars

(Stellar structure)

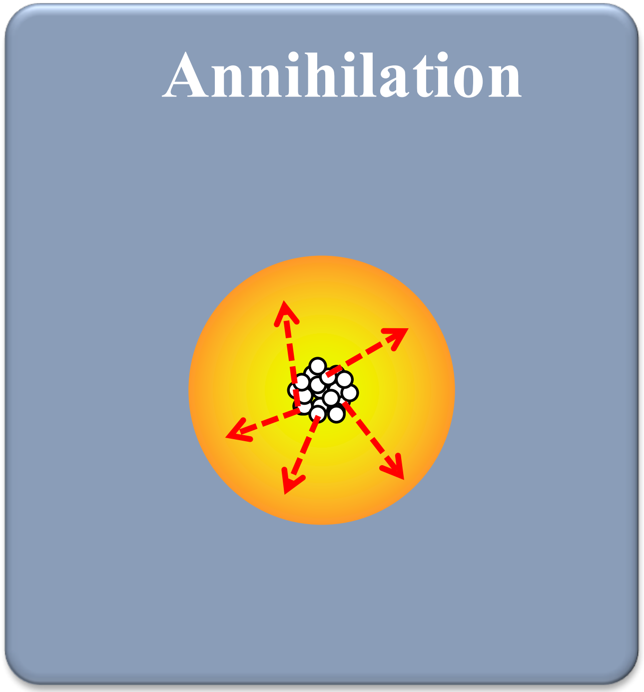
How does Dark Matter influence stars?



[Gould, ApJ 321 (1987)]

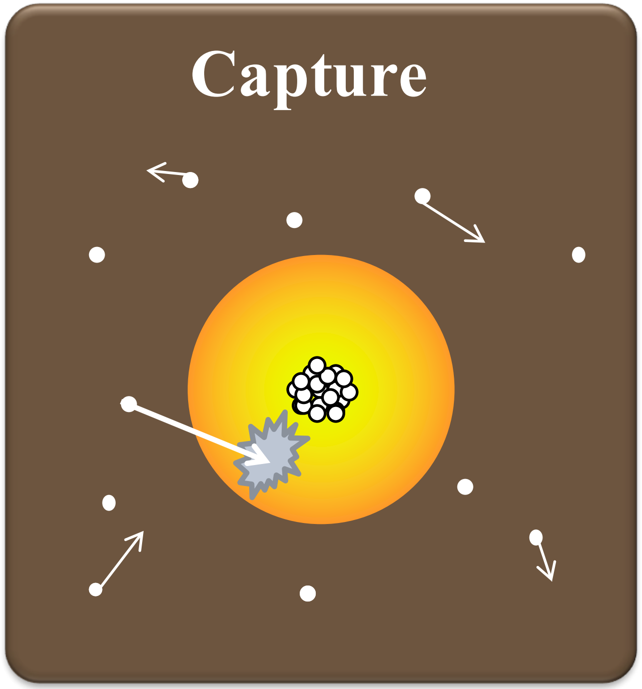


[Gould & Raffelt ApJ 352 (1990)]



[Salati & Silk ApJ 338 (1989)]

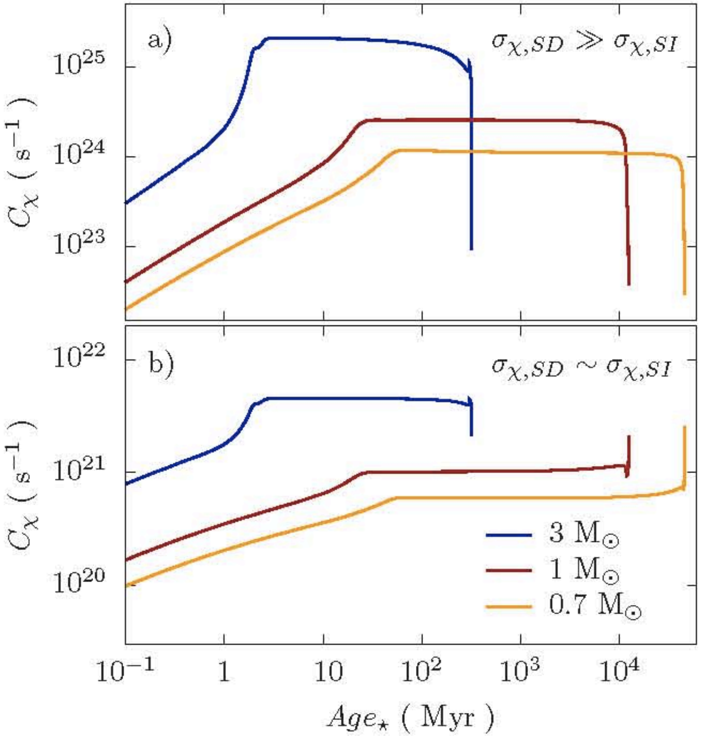
How does Dark Matter influence stars?



$$C_\chi(t) = \int_0^{R_\star} 4\pi r^2 \int_0^\infty \frac{f(u)}{u} w\Omega_v^-(w)\,\mathrm{d}u\,\mathrm{d}r$$

[Gould, ApJ 321 (1987)]

σ_χ m_χ ρ_χ $\bar{v}_\chi$ $V_\star$ n_i



[Lopes, Casanellas & Eugénio, PhysRevD 83 (2011)]

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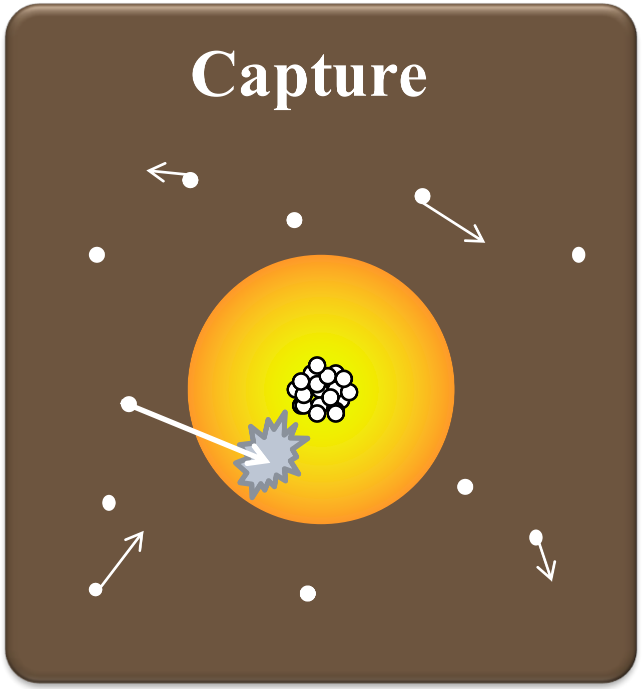
How does Dark Matter influence stars?



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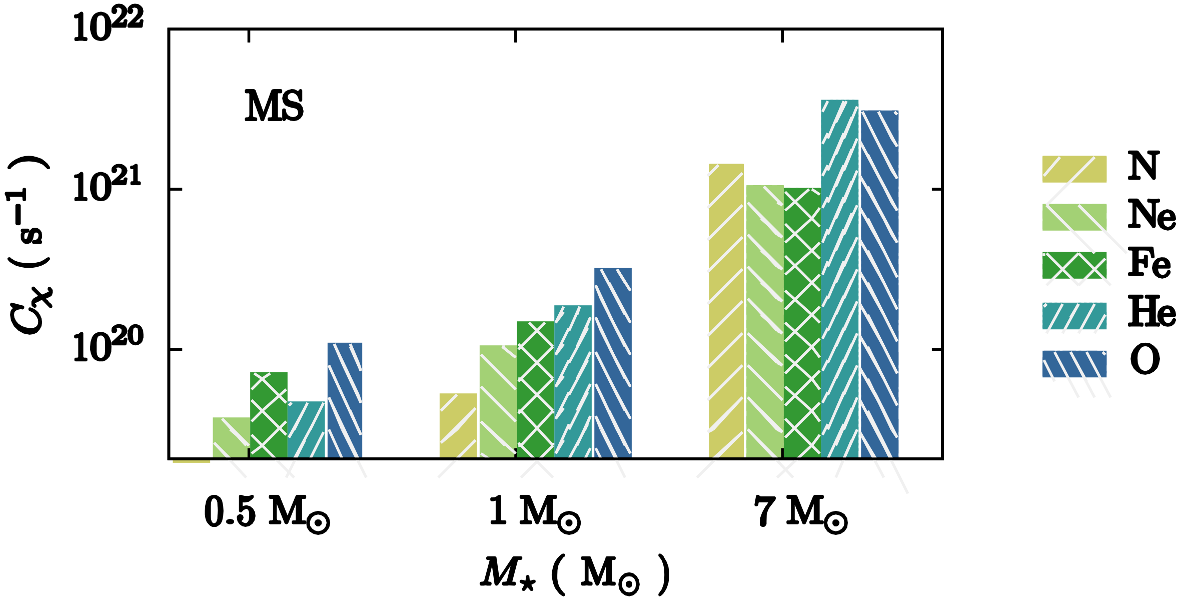
[Gould, ApJ 321 (1987)]

σ_χ m_χ ρ_χ $\bar{v}_\chi$ $V_\star$ n_i



[Lopes, Casanellas & Eugénio, PhysRevD 83 (2011)]

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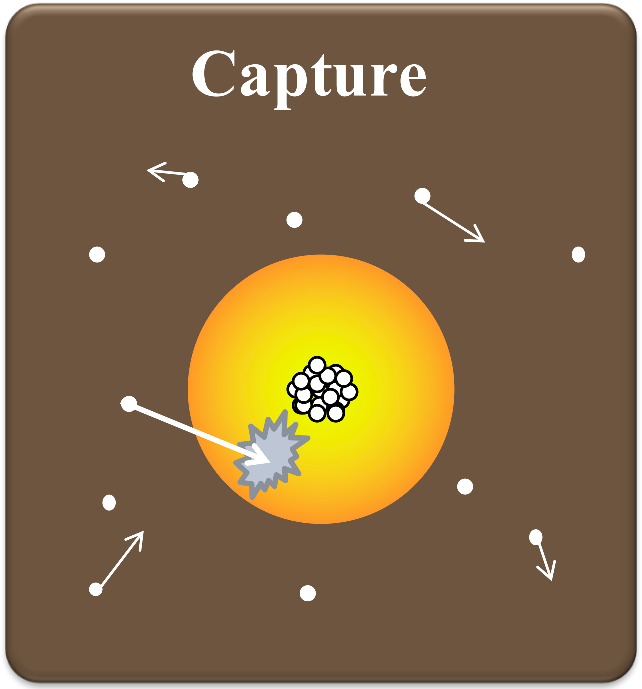
How does Dark Matter influence stars?



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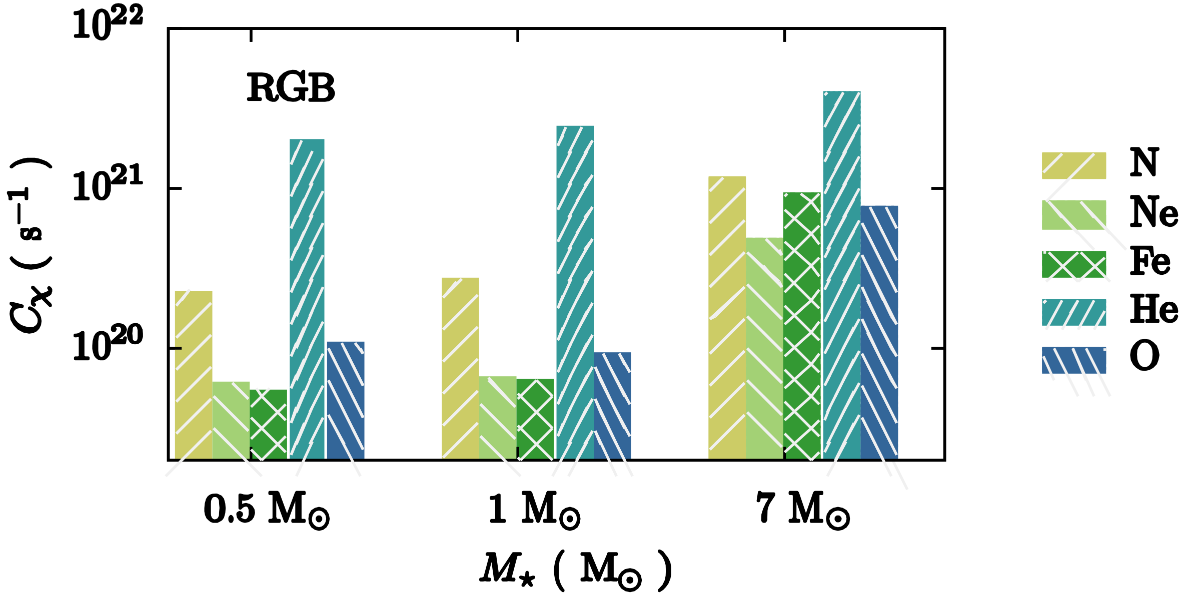
[Gould, ApJ 321 (1987)]

σ_χ m_χ ρ_χ $\bar{v}_\chi$ $V_\star$ n_i



[Lopes, Casanellas & Eugénio,
PhysRevD 83 (2011)]

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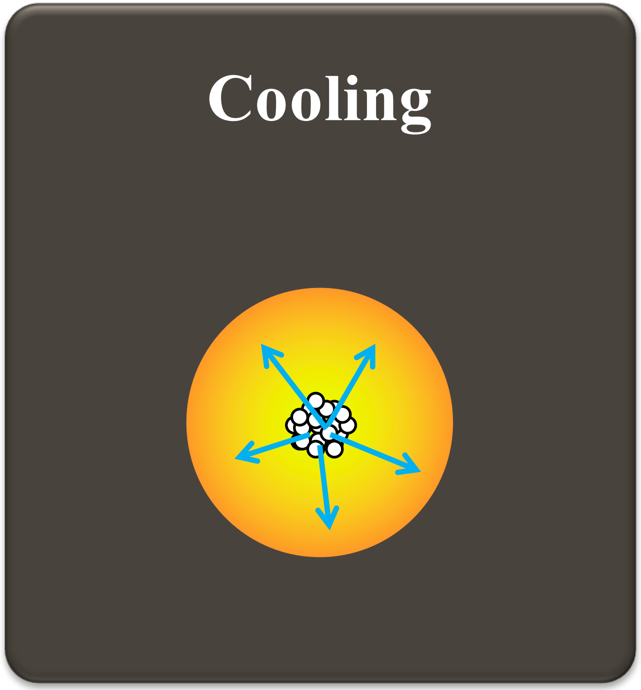
How does Dark Matter influence stars?



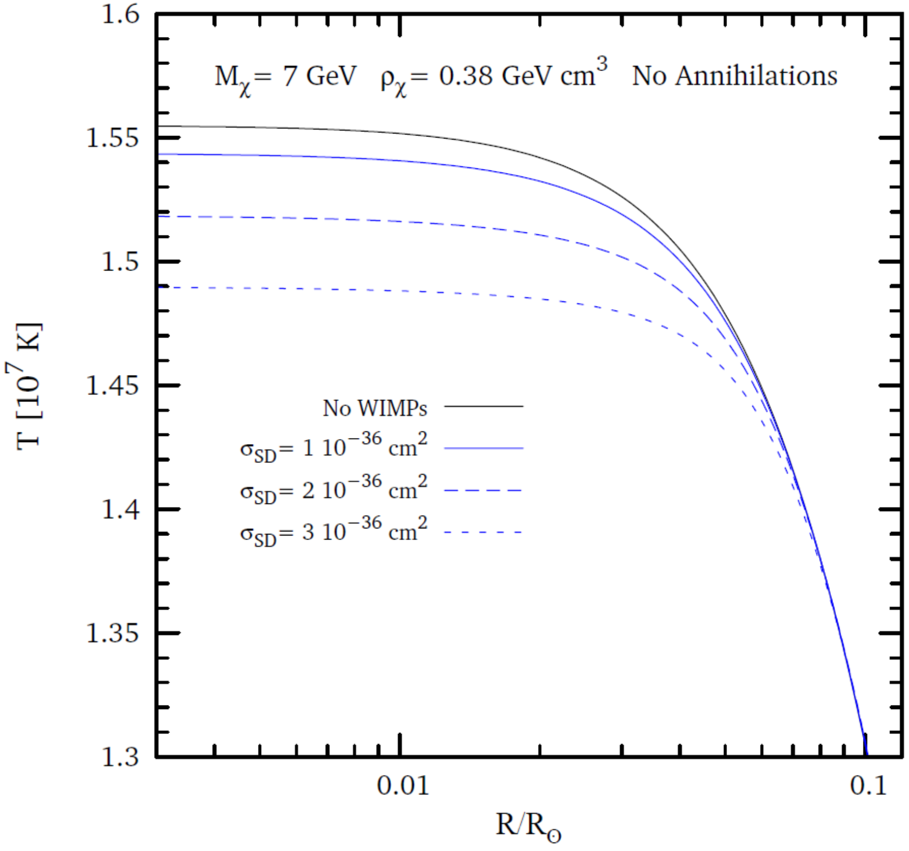
Cooling

SUN:[Spergel and Press, ApJ 294 (1985)

Lopes, Bertone & Silk, MNRAS 337 (2002) ...]

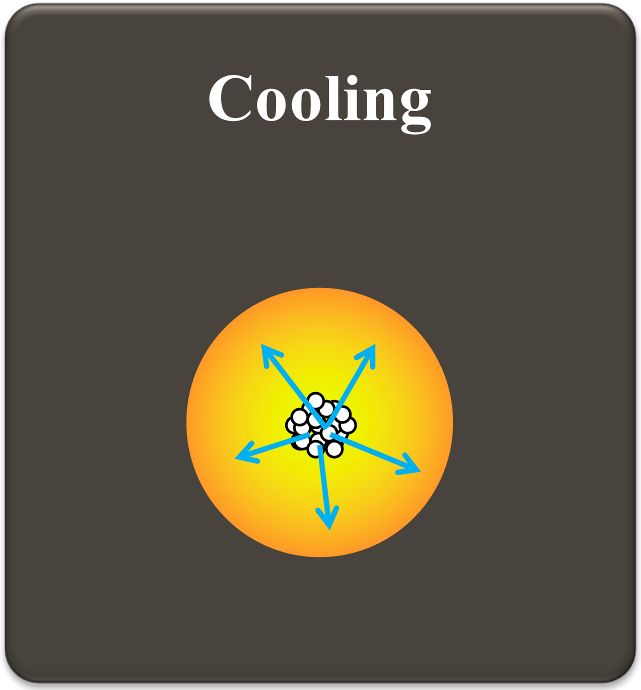
Impact of Dark Matter on stars

Reduction central temperature



[Taoso et al. Phys. Rev. D 82 (2010)]

How does Dark Matter influence stars?

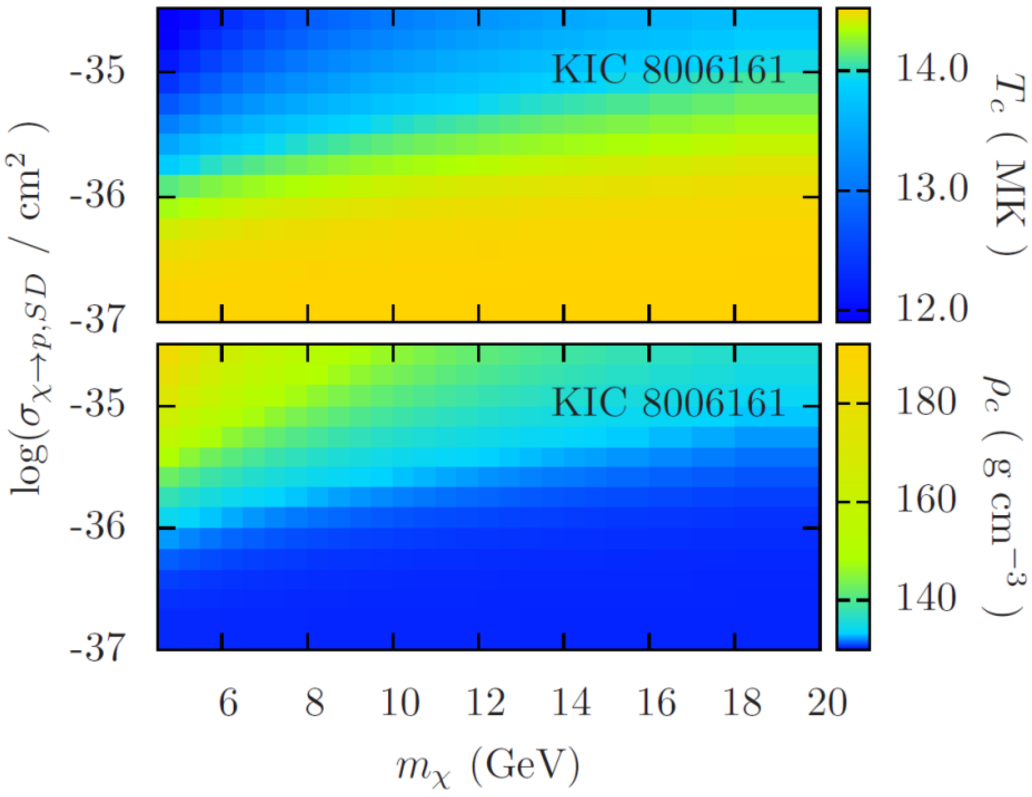


WHY OTHER STARS ?

M$_\star$ ↓ → stronger DM impact

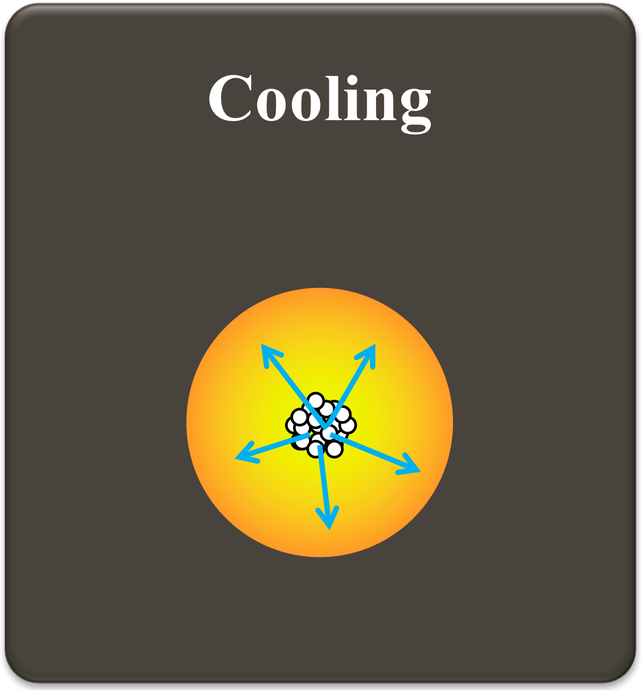
Impact of Dark Matter on stars

Reduction central temperature



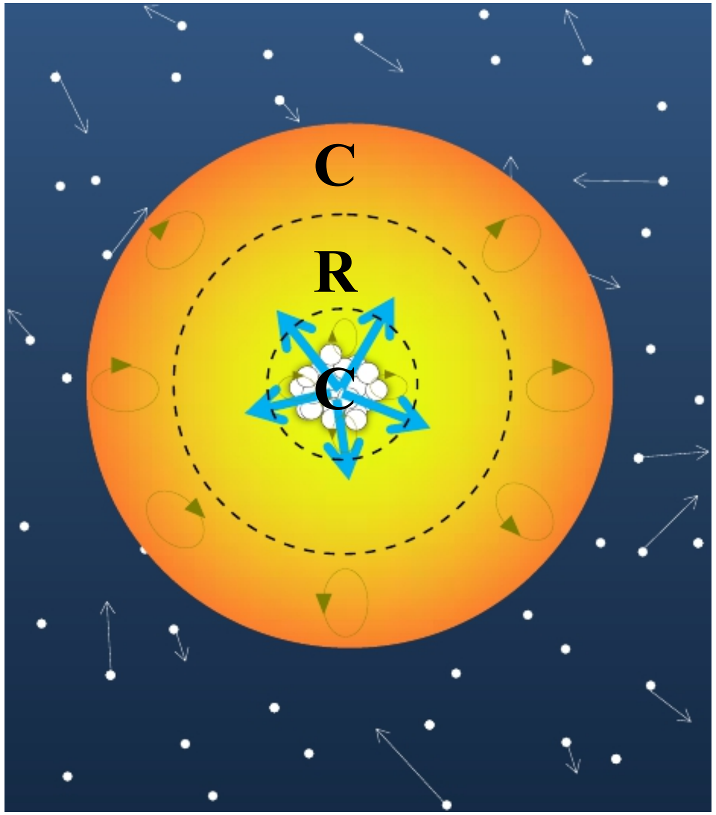
[Casanellas & Lopes , ApJL 765 (2013)]

How does Dark Matter influence stars?



Impact of Dark Matter on stars

Reduction central temperature



WHY OTHER STARS ?

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Suppression of convective core in 1.1-1.3 M_o

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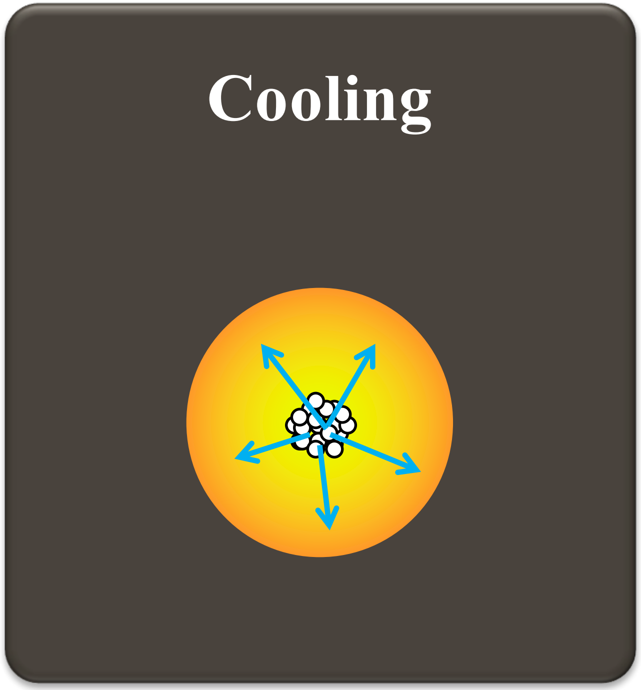
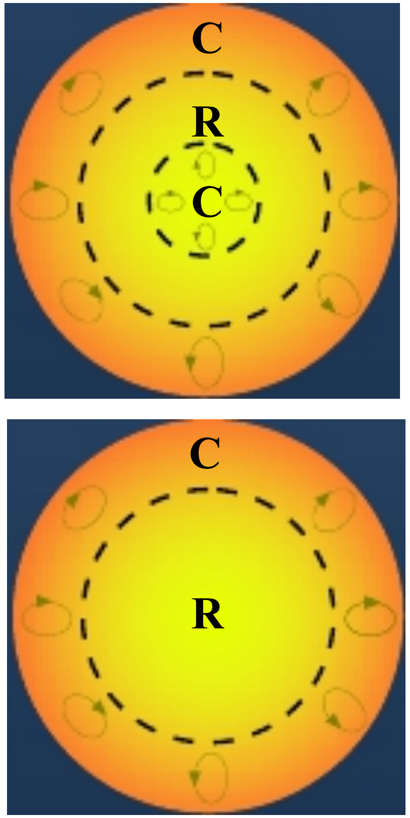


Impact of Dark Matter on stars

Reduction central temperature



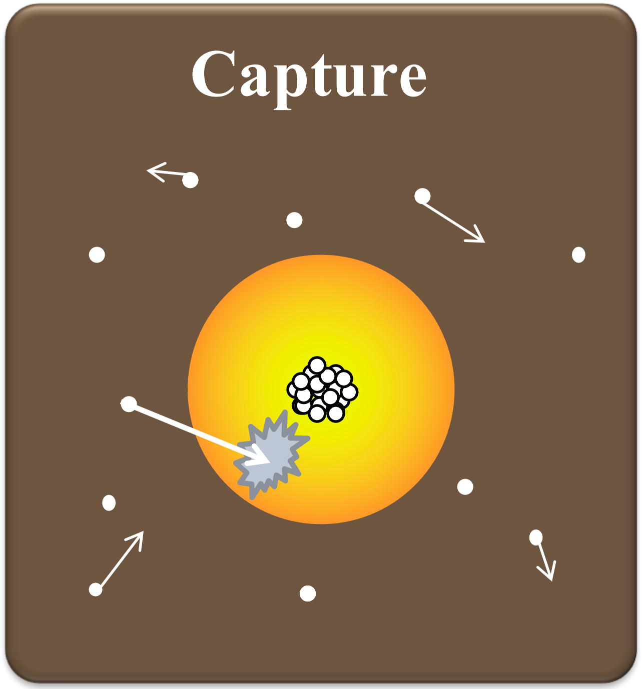
WHY OTHER STARS ?

$M_\star$ ↓ → stronger DM impact

Suppression of convective core in 1.1-1.3 M_o

How does Dark Matter influence stars?

Uncertainty in the physical parameters



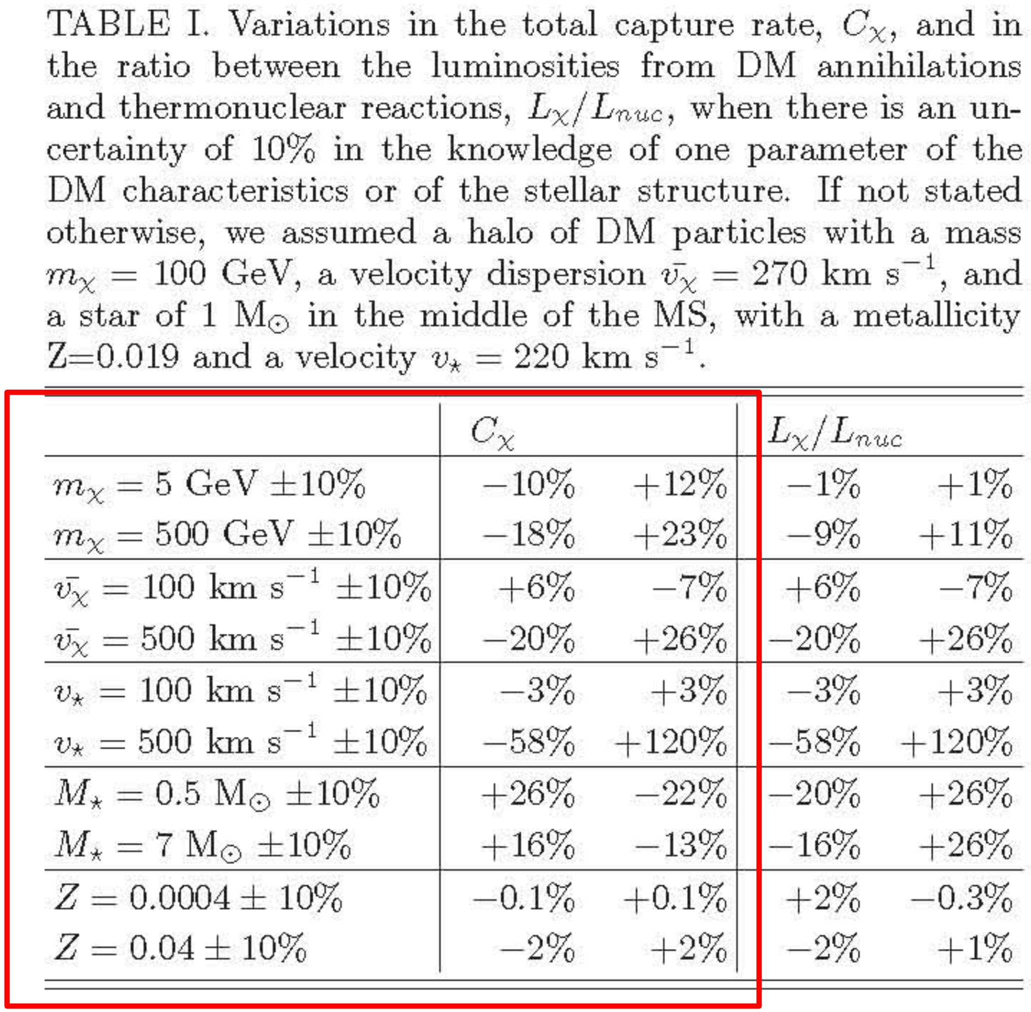
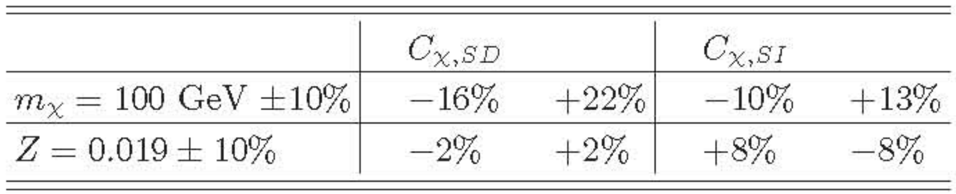


TABLE I. Variations in the total capture rate, C_χ, and in the ratio between the luminosities from DM annihilations and thermonuclear reactions, L_χ/L_{nuc}, when there is an uncertainty of 10% in the knowledge of one parameter of the DM characteristics or of the stellar structure. If not stated otherwise, we assumed a halo of DM particles with a mass $m_\chi = 100$ GeV, a velocity dispersion $\bar{v_\chi} = 270$ km s^{-1}, and a star of 1 M$_\odot$ in the middle of the MS, with a metallicity Z=0.019 and a velocity $v_\star = 220$ km s^{-1}.

	C_χ		L_χ/L_{nuc}	
$m_\chi = 5$ GeV ±10%	−10%	+12%	−1%	+1%
$m_\chi = 500$ GeV ±10%	−18%	+23%	−9%	+11%
$\bar{v_\chi} = 100$ km s^{-1} ±10%	+6%	−7%	+6%	−7%
$\bar{v_\chi} = 500$ km s^{-1} ±10%	−20%	+26%	−20%	+26%
$v_\star = 100$ km s^{-1} ±10%	−3%	+3%	−3%	+3%
$v_\star = 500$ km s^{-1} ±10%	−58%	+120%	−58%	+120%
$M_\star = 0.5$ M$_\odot$ ±10%	+26%	−22%	−20%	+26%
$M_\star = 7$ M$_\odot$ ±10%	+16%	−13%	−16%	+26%
$Z = 0.0004 \pm 10\%$	−0.1%	+0.1%	+2%	−0.3%
$Z = 0.04 \pm 10\%$	−2%	+2%	−2%	+1%



	$C_{\chi,SD}$		$C_{\chi,SI}$	
$m_\chi = 100$ GeV ±10%	−16%	+22%	−10%	+13%
$Z = 0.019 \pm 10\%$	−2%	+2%	+8%	−8%

[Lopes, Casanellas & Eugénio,

PhysRevD 83 (2011)]

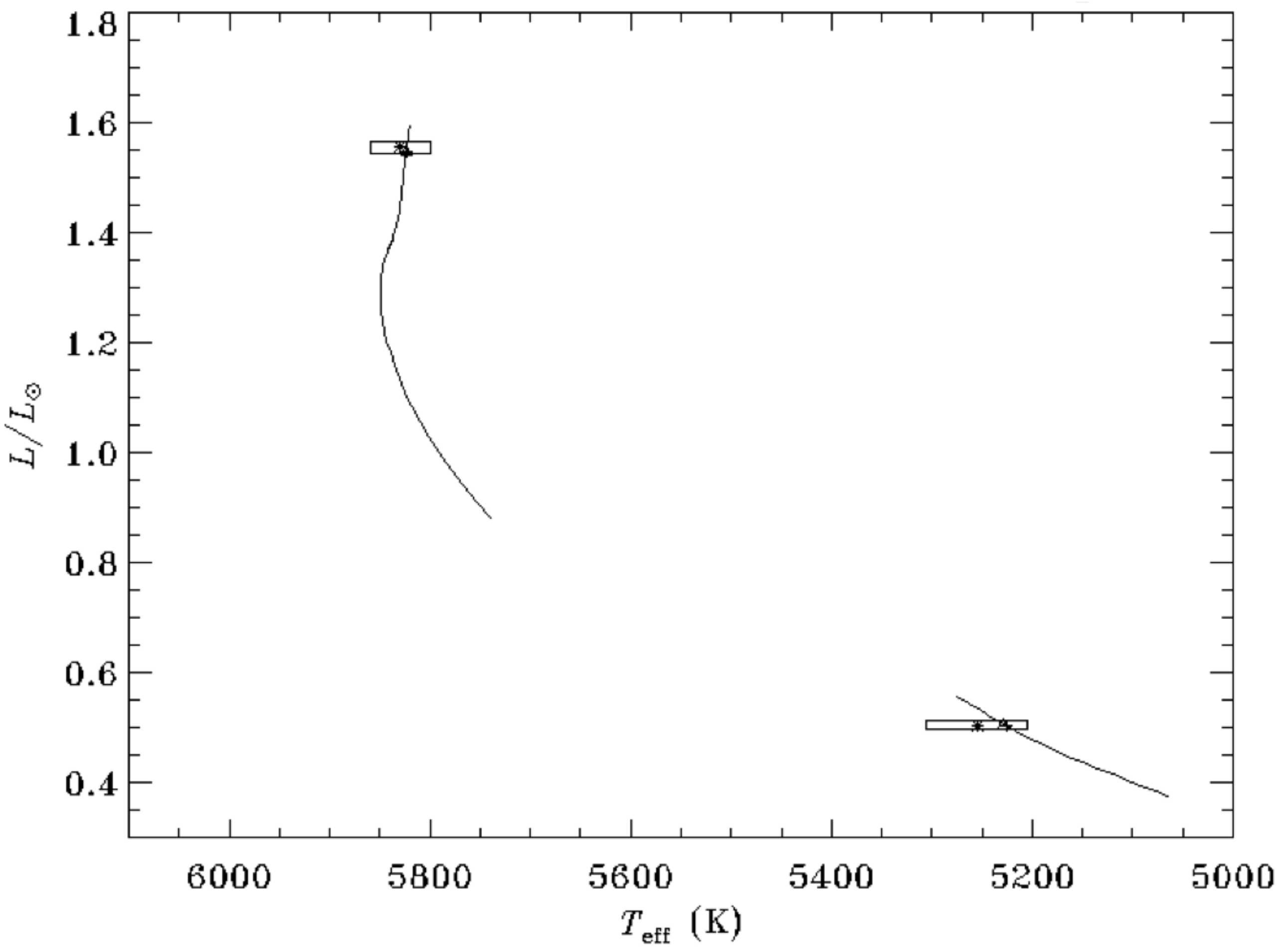
TÉCNICO LISBOA

Dark matter effects on a star’s observables

(Asteroseismology)

Asteroseismology: limits to the DM characteristics

α Centauri binary system



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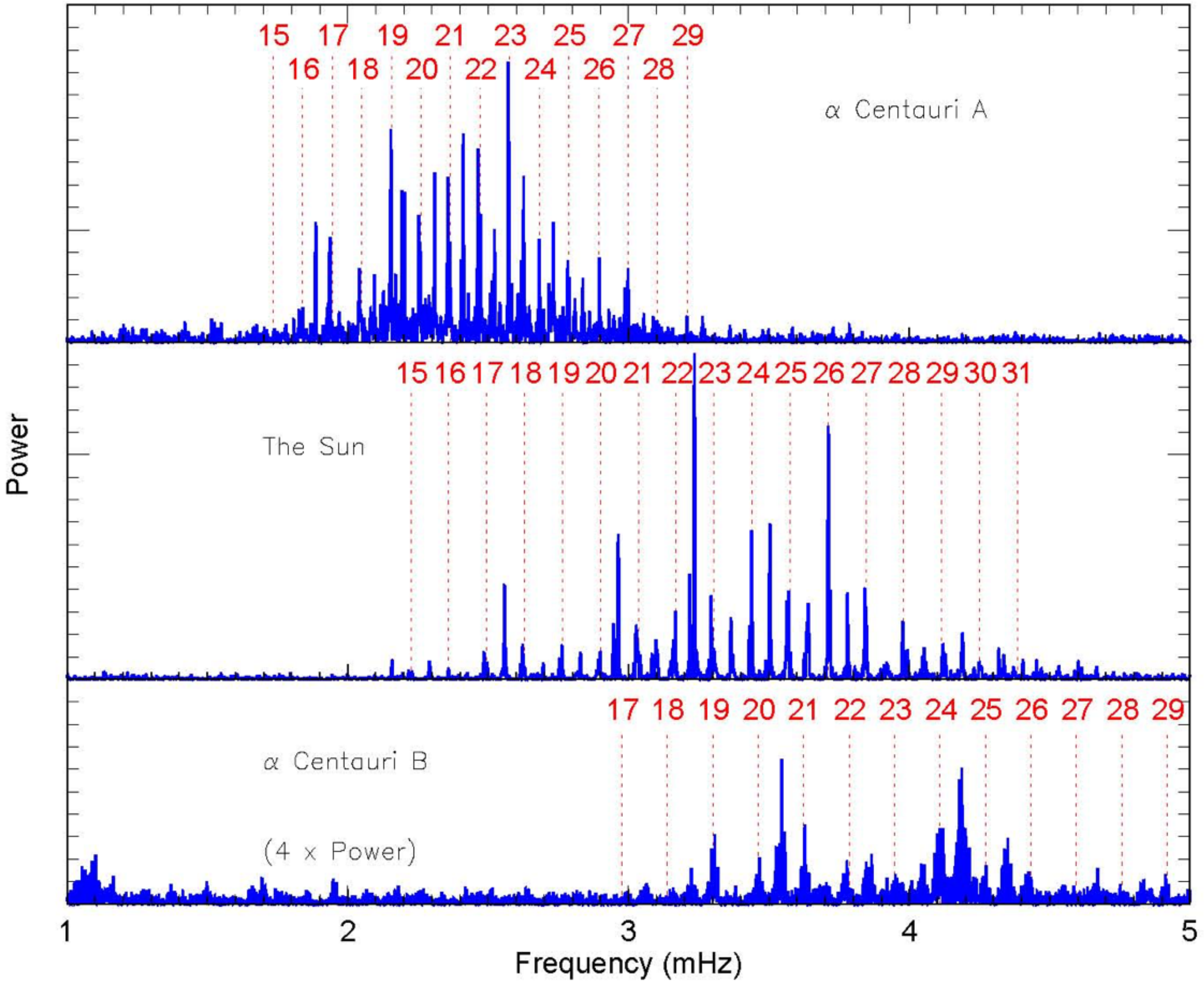
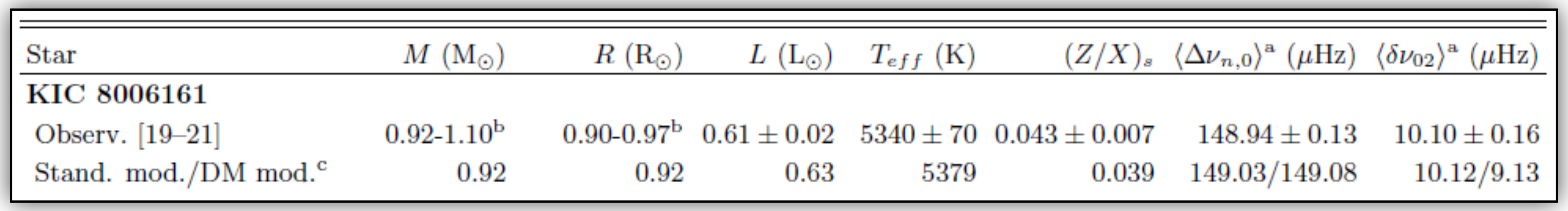


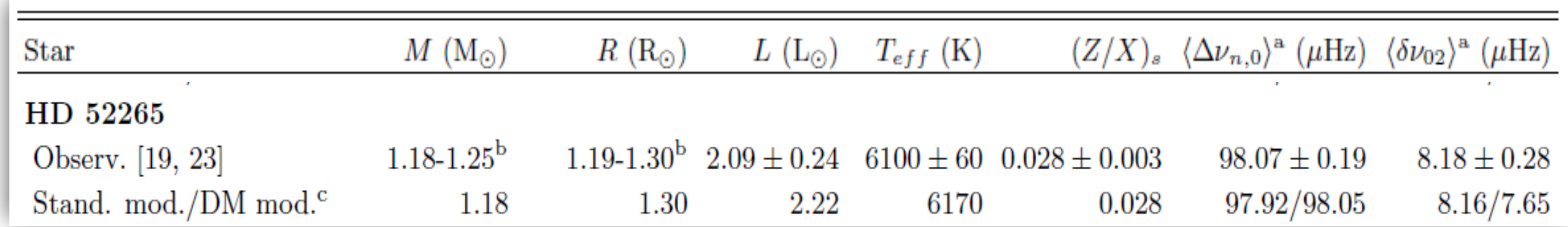
Radial p-mode (radial orders, l=0)

Asteroseismology: limits to the DM characteristics

Casanellas & Lopes (2013)



Star	M (M$_\odot$)	R (R$_\odot$)	L (L$_\odot$)	T_{eff} (K)	$(Z/X)_s$	$\langle\Delta\nu_{n,0}\rangle^a$ (μHz)	$\langle\delta\nu_{02}\rangle^a$ (μHz)
KIC 8006161							
Observ. [19–21]	0.92-1.10^b	0.90-0.97^b	0.61 ± 0.02	5340 ± 70	0.043 ± 0.007	148.94 ± 0.13	10.10 ± 0.16
Stand. mod./DM mod.^{c}	0.92	0.92	0.63	5379	0.039	149.03/149.08	10.12/9.13



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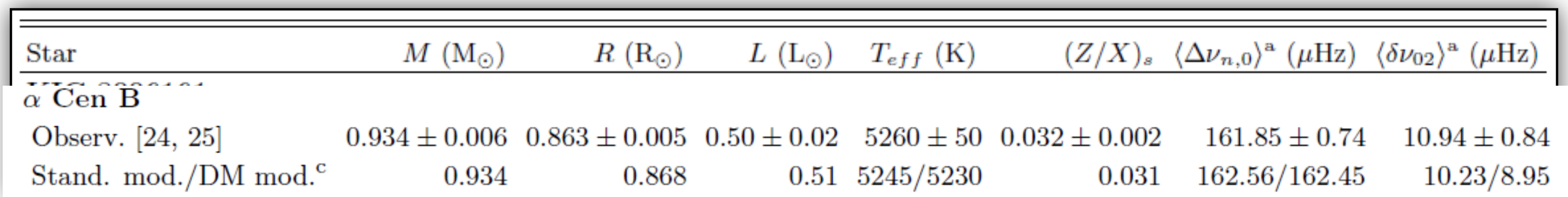
HD 52265							
Observ. [19, 23]	1.18-1.25^b	1.19-1.30^b	2.09 ± 0.24	6100 ± 60	0.028 ± 0.003	98.07 ± 0.19	8.18 ± 0.28
Stand. mod./DM mod.^{c}	1.18	1.30	2.22	6170	0.028	97.92/98.05	8.16/7.65



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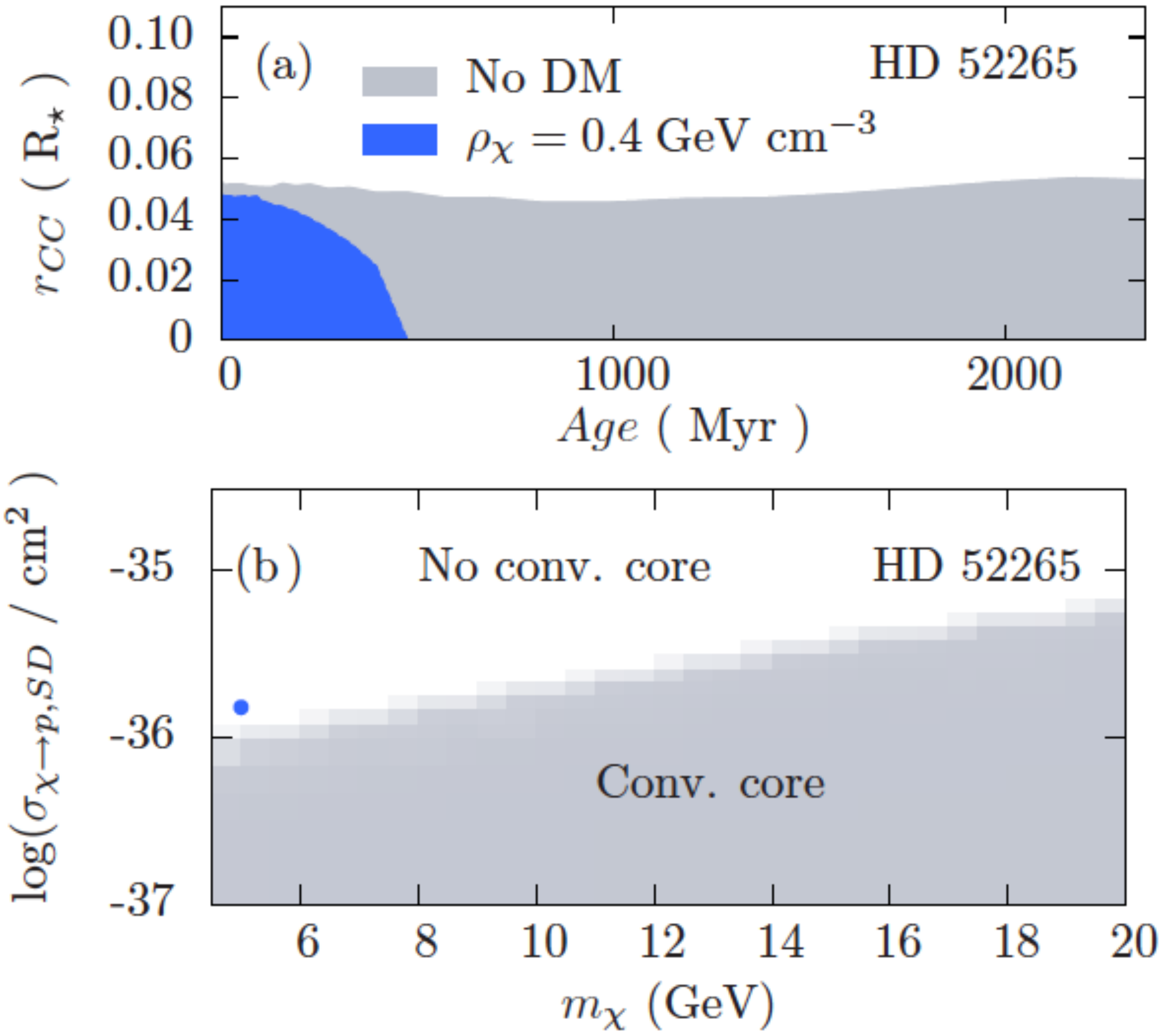
Observ. [24, 25]	0.934 ± 0.006	0.863 ± 0.005	0.50 ± 0.02	5260 ± 50	0.032 ± 0.002	161.85 ± 0.74	10.94 ± 0.84
Stand. mod./DM mod.^{c}	0.934	0.868	0.51	5245/5230	0.031	162.56/162.45	10.23/8.95

Asteroseismology: limits to the DM characteristics

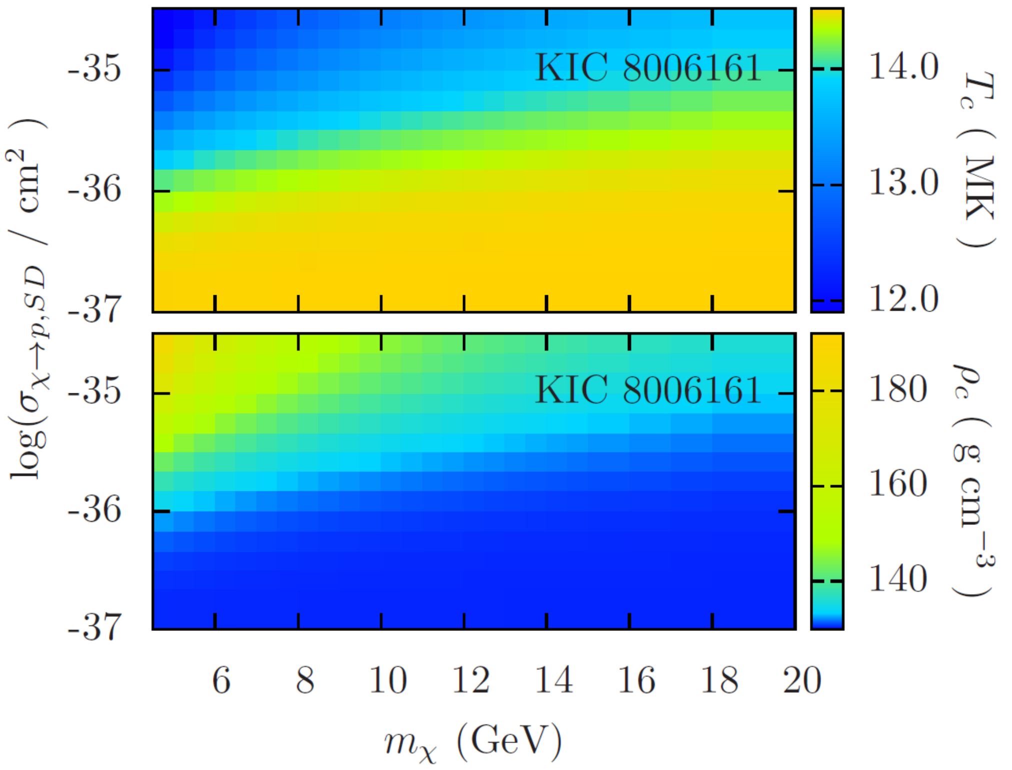
Observational prediction:
Suppression of the convective core in 1.1-1.3Mo Main sequence stars

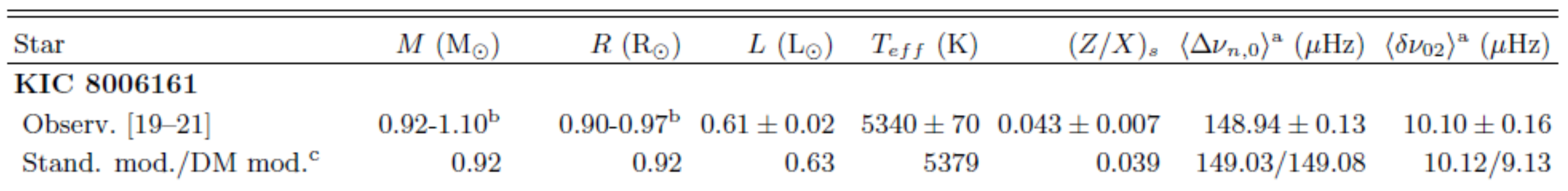


Asymmetric dark matter (with m_x ~ 5 GeV, σ_{SD}> 3 10^{-36} cm^2) are excluded at 95% CL.

Asteroseismology: limits to the DM characteristics

- **Changes in the central temperatures and densities**





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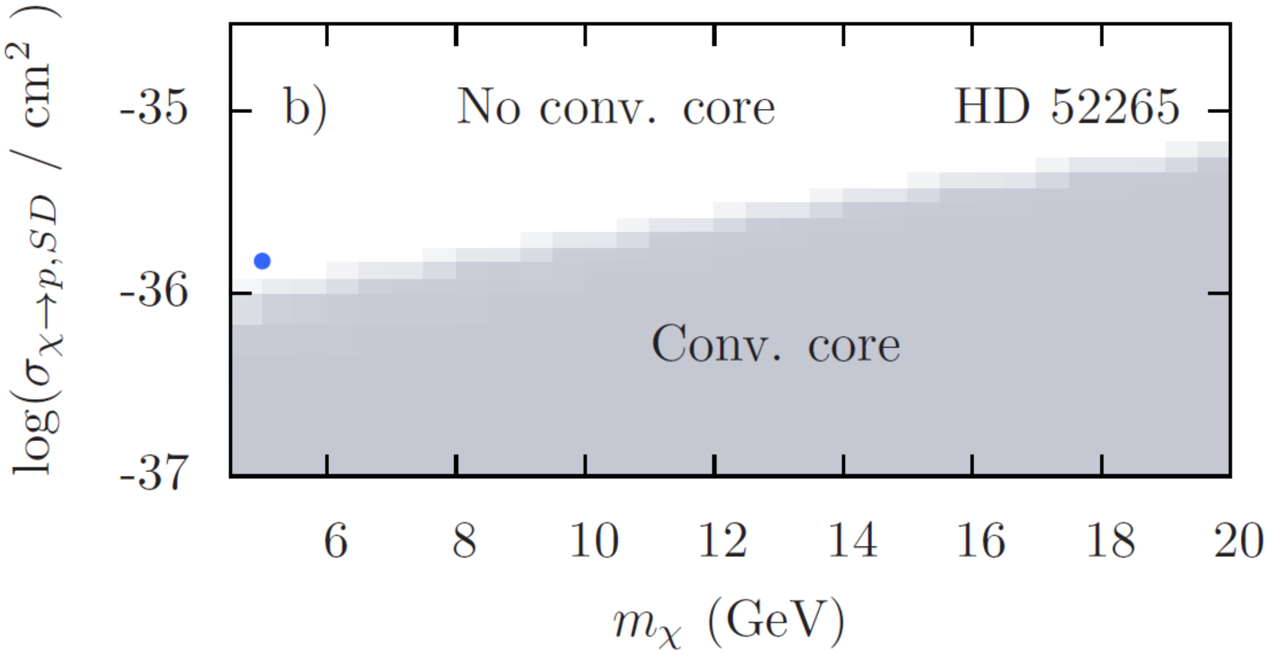
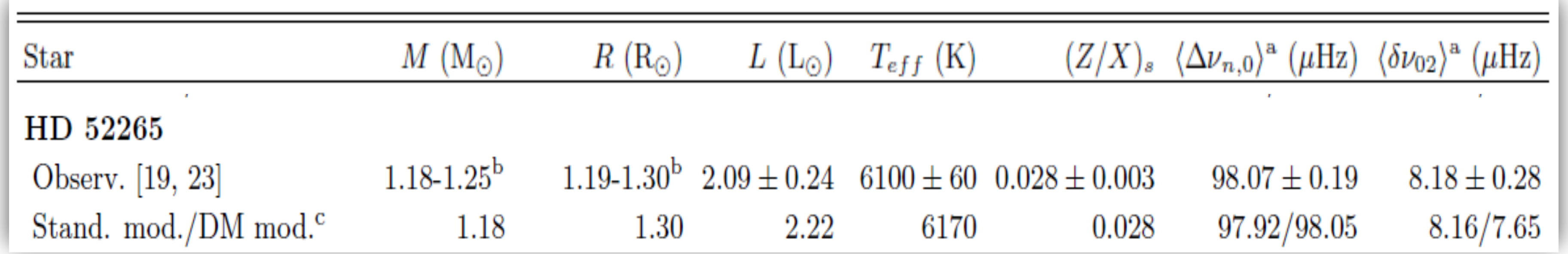
Asteroseismology: limits to the DM characteristics

- **Changes in the central temperatures and densities**
- **Suppression of the convective core in 1.1-1.3 Ms stars**





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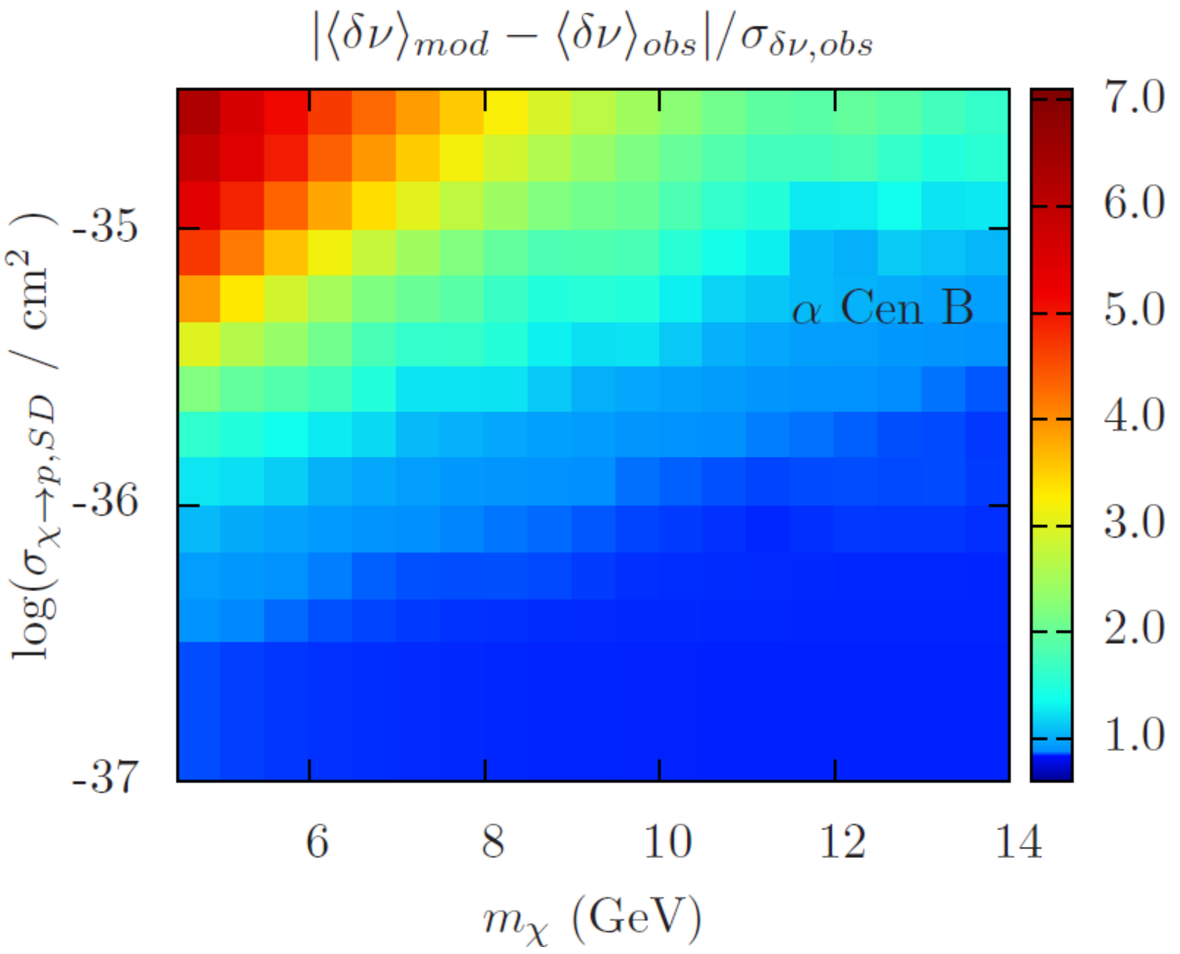

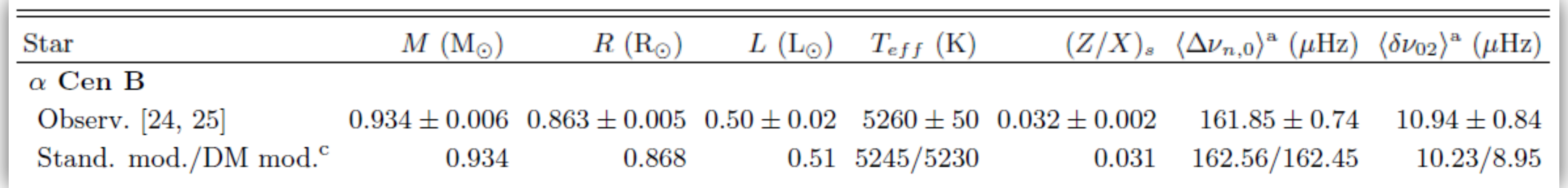

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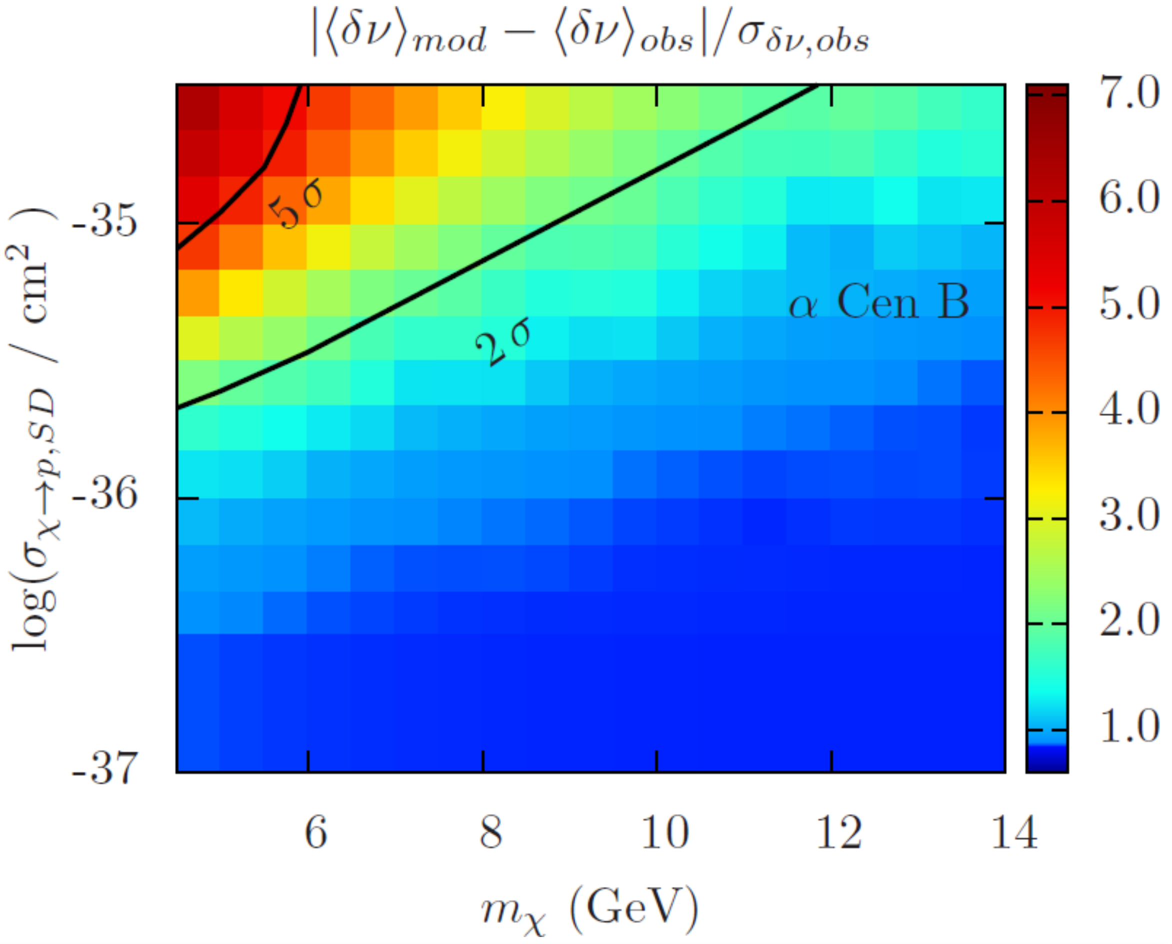

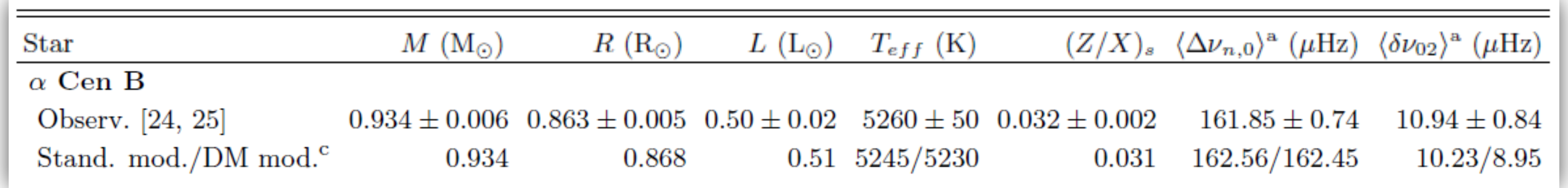

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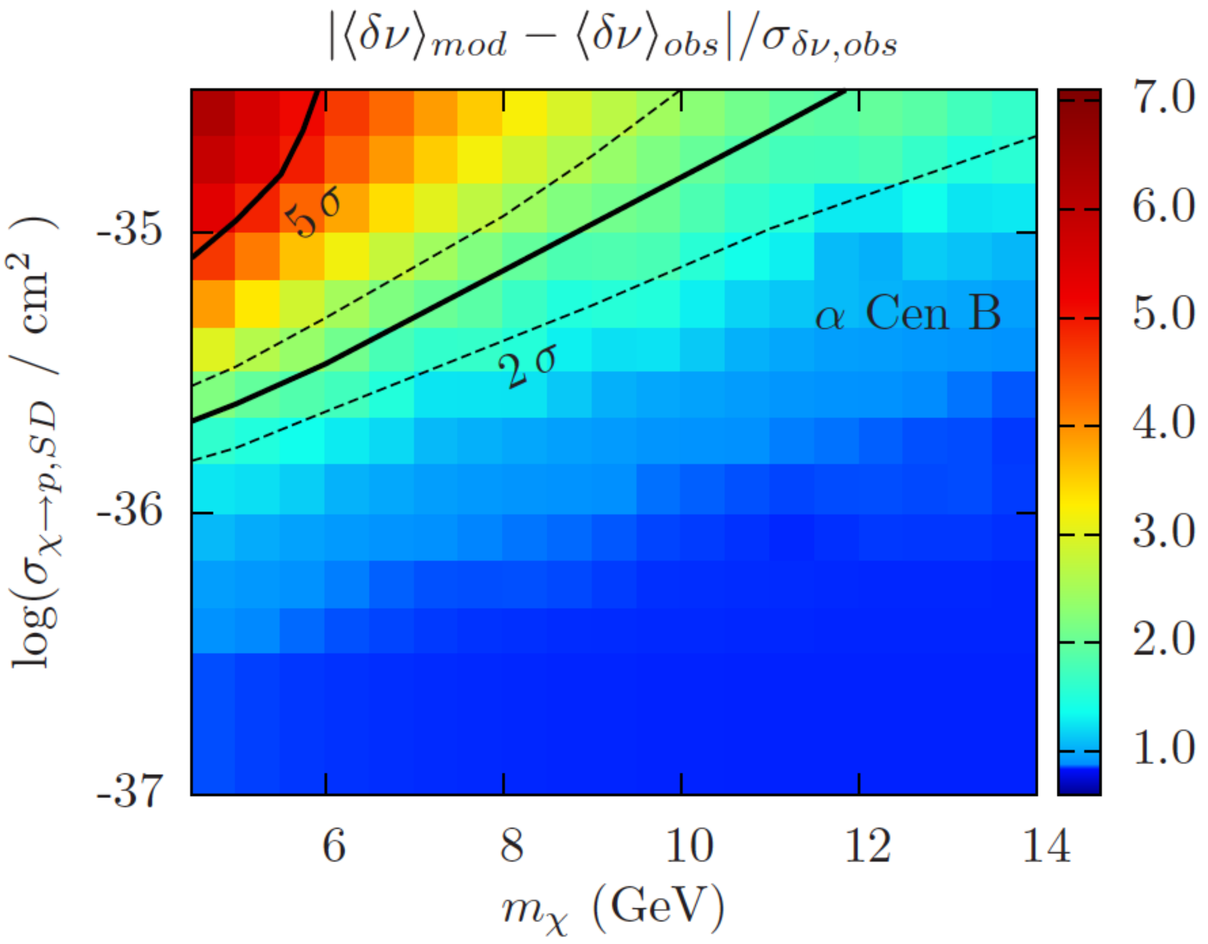

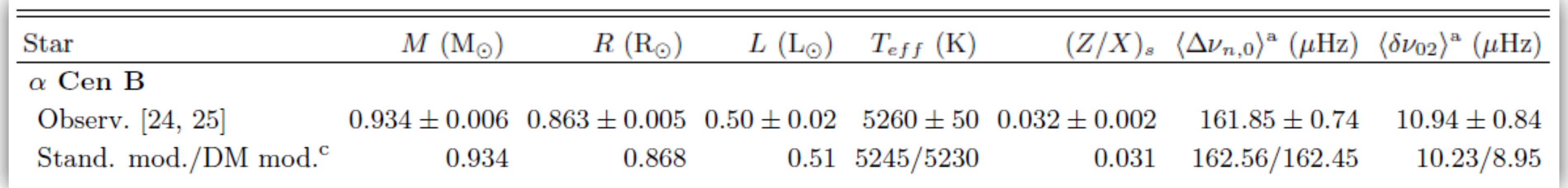

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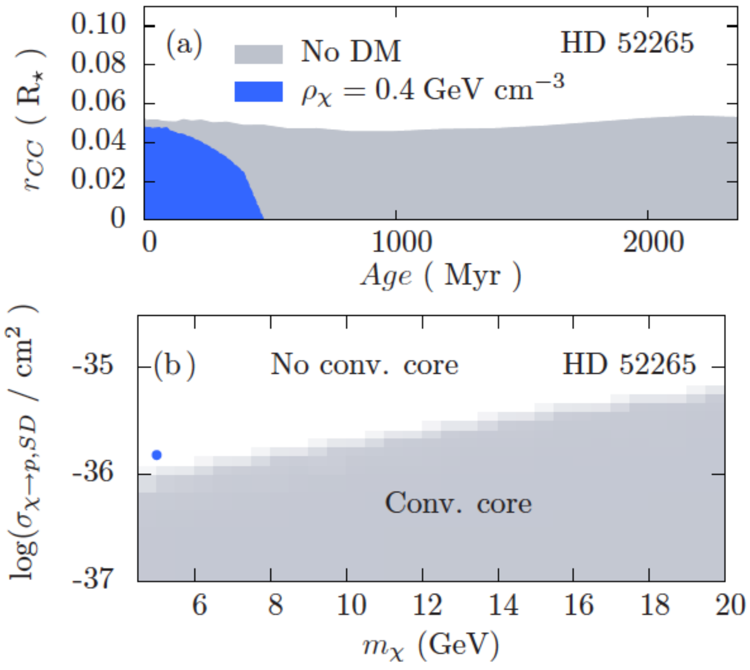
Asteroseismology: limits to the DM characteristics

Dark matter (asymmetric) changes the transport of heat energy inside these stars (decreasing the central temperature).

Observational prediction: Suppression of the convective core in 1.1-1.3Mo Main sequence stars



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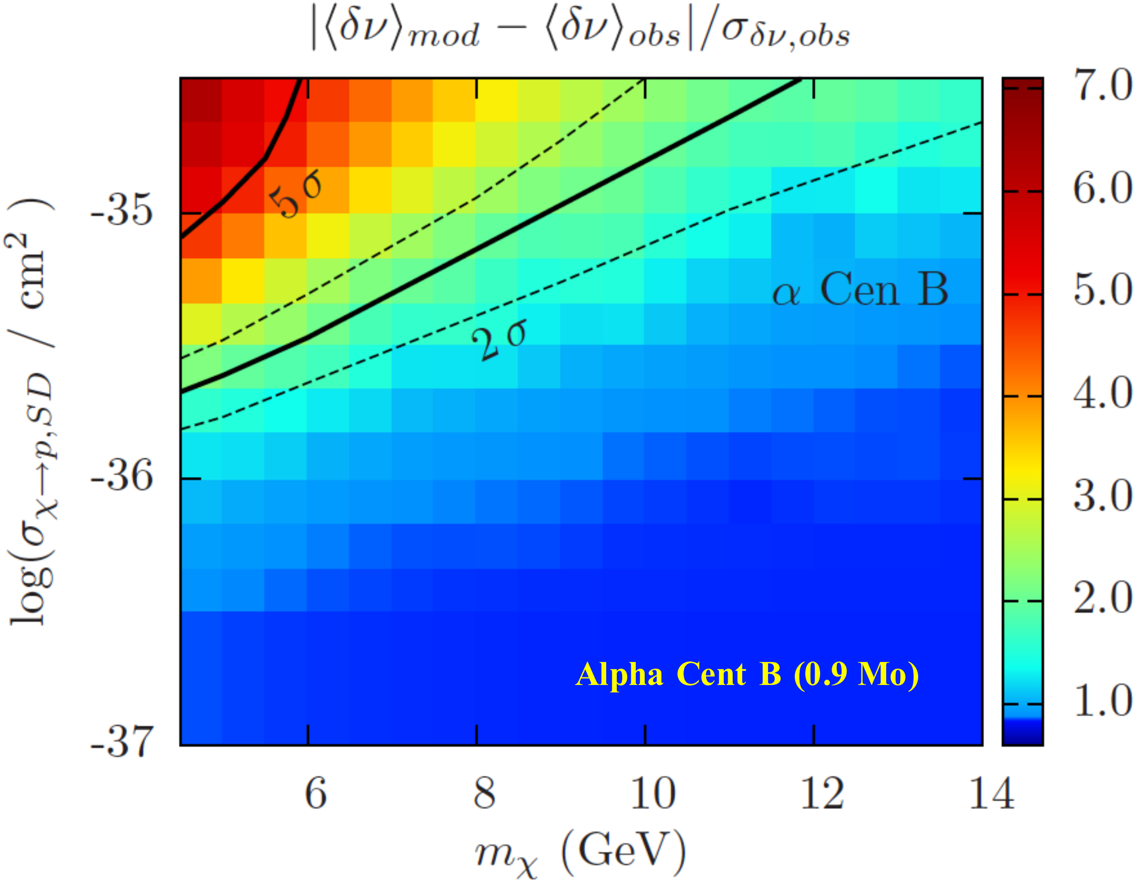


Casanellas & Lopes (ApJ Letters, 2013)

Dark matter effects on a star’s observables

(Stellar populations)

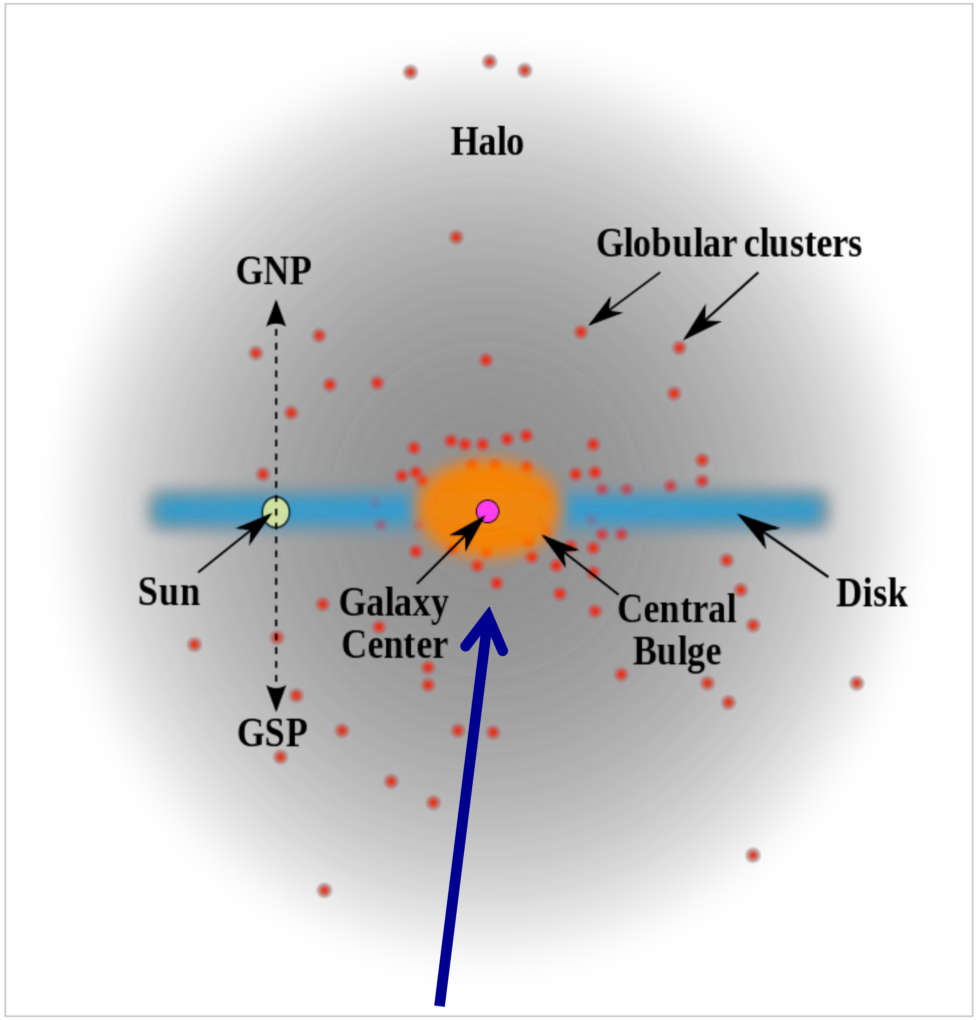
Prediction: dark matter effect on a population of stars

Stars formed in the dense dark matter halos (primordial Universe and core of galaxies) have their lives extended (slower evolution in the HD diagram), due to the energy produced by dark matter.

Observational prediction: The main sequence of these stars in the HR diagram will be different from the one known for population I stars.

- DM particles with a $m_x \sim 100$ GeV and σ_{SD} (with protons) $\sim 10^{-38}$ cm^2
- For a cluster of stars (0.7-3.5 $M_\odot$) in DM halo ($\rho_x \sim 10^{10}$ GeV cm^{-3}, continuous lines) and classical scenario (dashed lines).

dark matter halo



Stellar Population

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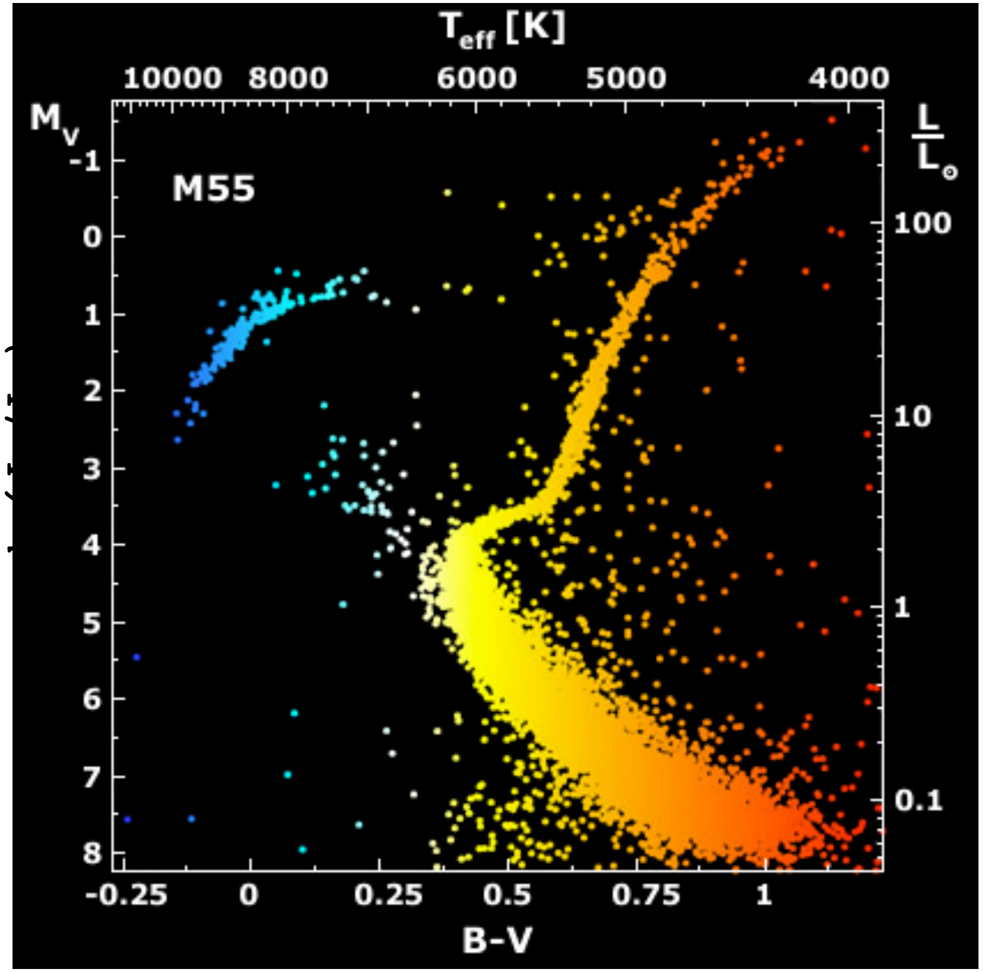

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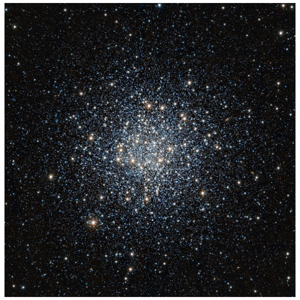
Stellar Cluster

M55 : $2.69 \times 10^5 M_\odot$,
Age 12.3 Gyr



TÉCNICO LISBOA

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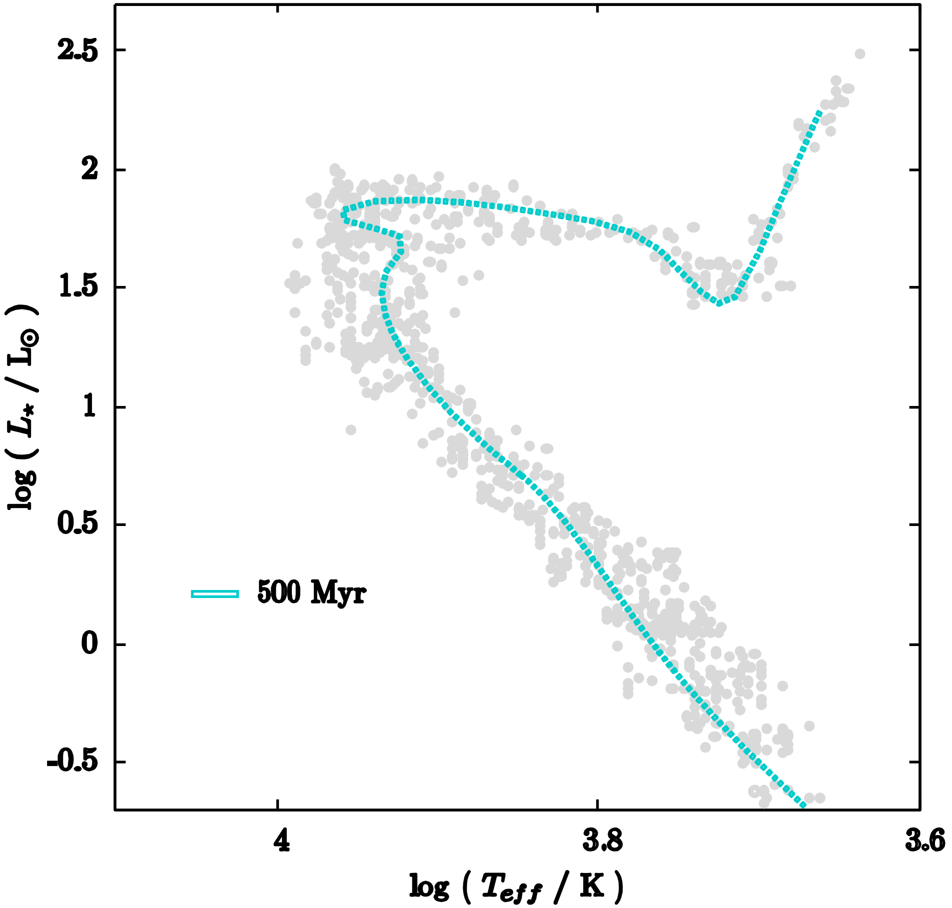

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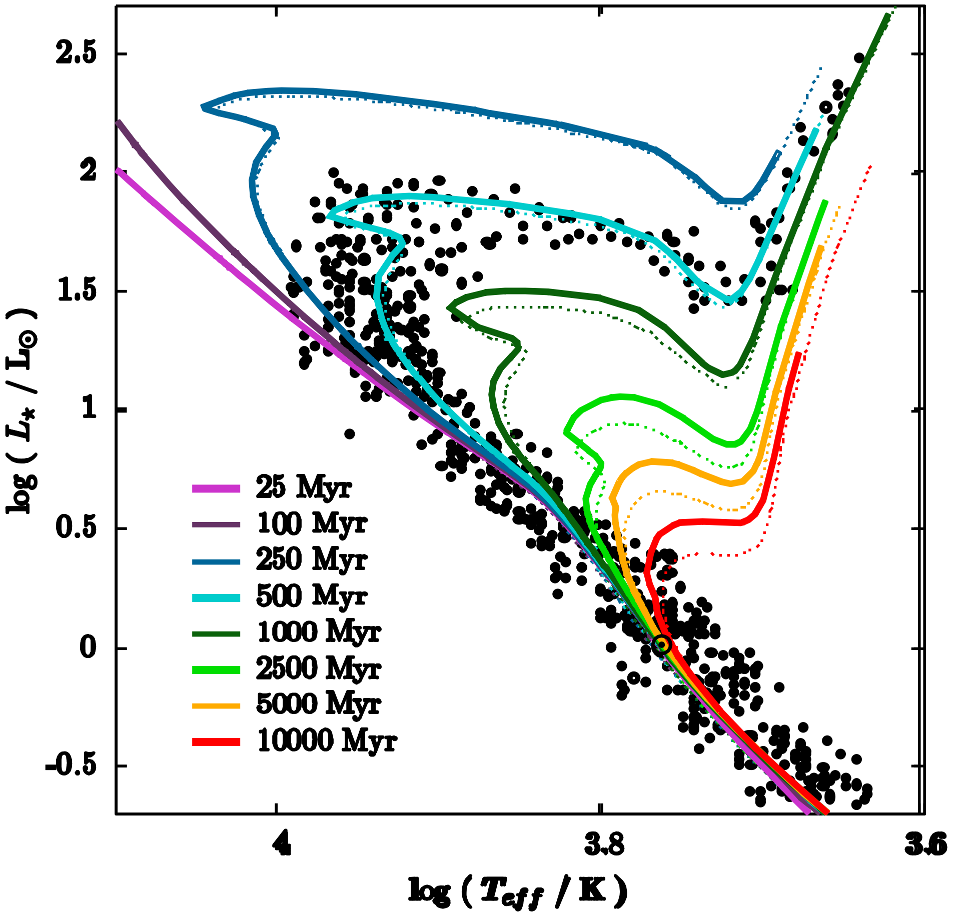

TÉCNICO LISBOA

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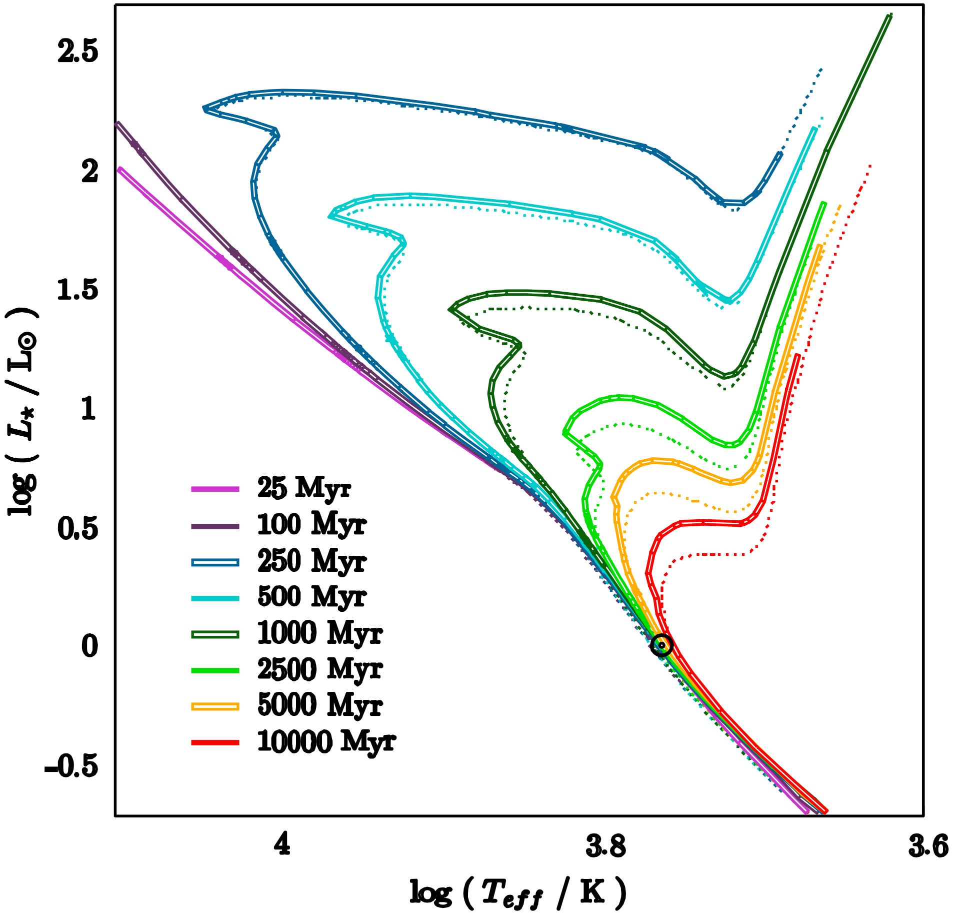

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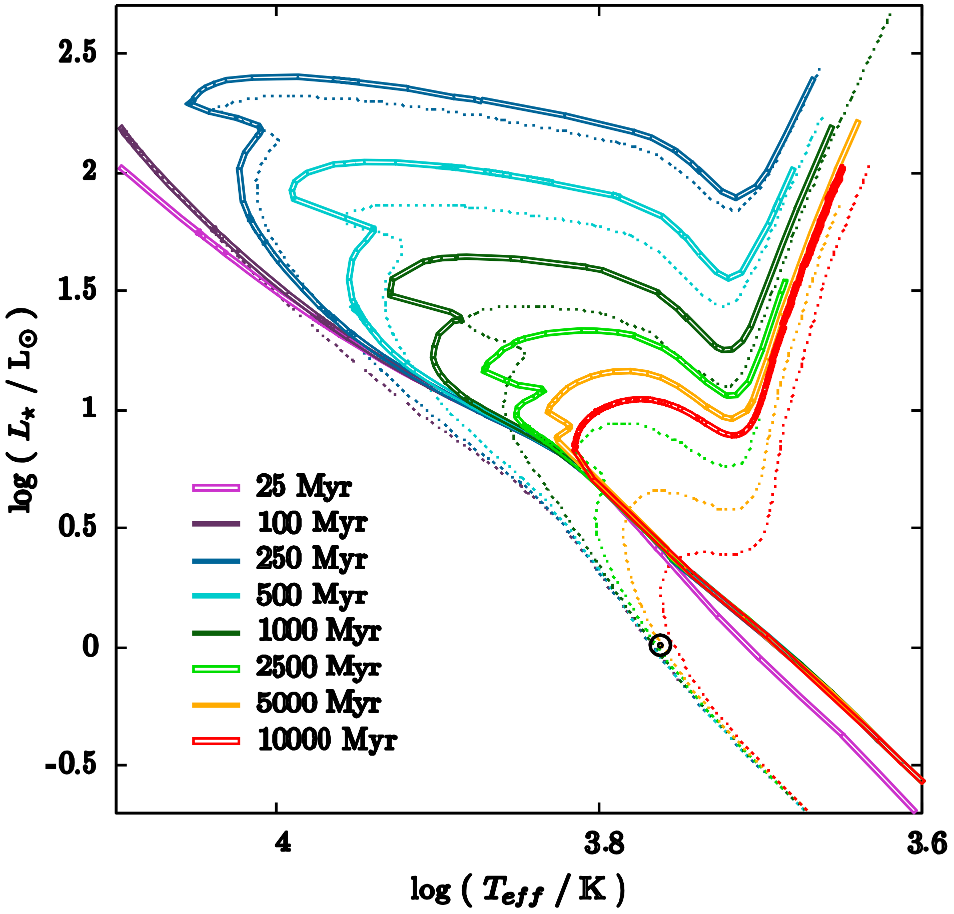


Stellar Cluster

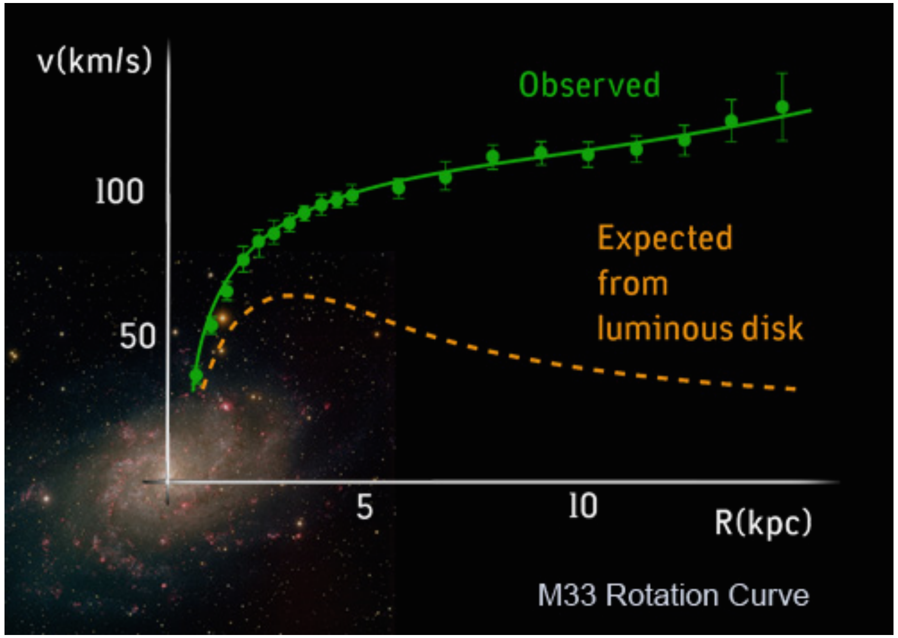
Casanellas & Lopes (ApJ Letters 2011)

Dark matter effects
on a star’s observables

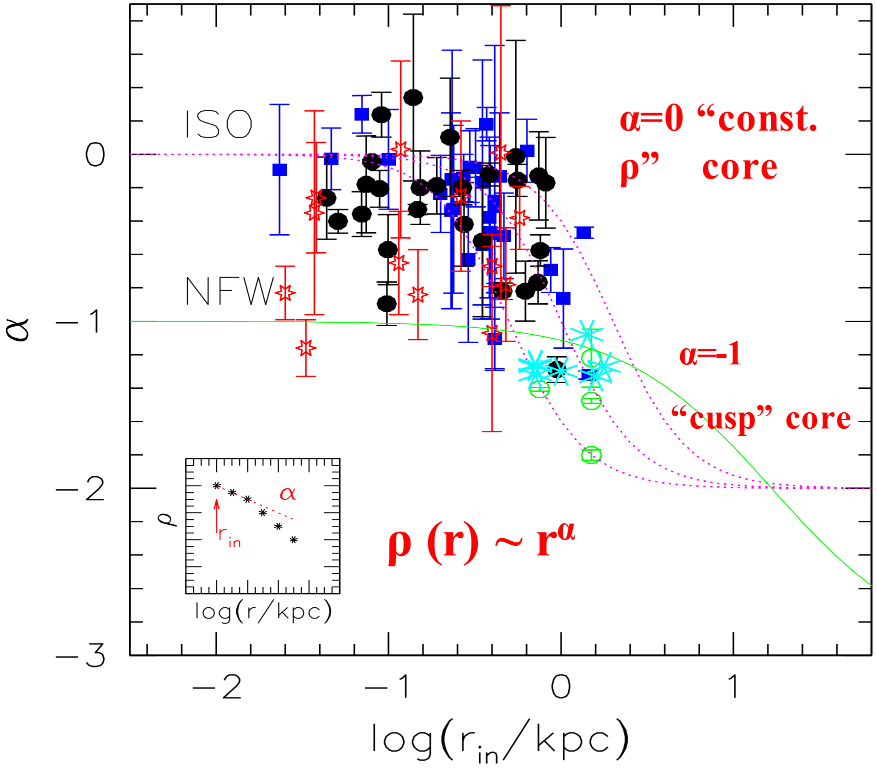
(Helioseismology & Solar Neutrinos)

Prediction: asymmetric dark matter effect on the Sun

Observational consequences (Galaxies cores): Resolves the cusp halo problem – DM becomes collisional: as a consequence the core of galaxies becomes in agreement with observations (see e.g. de Blok 2010), unlike numerical simulations (see e.g. Navarro et al. 2010)



Large scales - gravity dominates;
Small scales – dark matter (and baryons) interact



Experimental Detection evidence: These DM models can also "explain" the positive results of direct detection experiments: DAMA. CoGeNT, CRESST and CDMS-Si experiments, and the constraints coming from null results (CDMSGe , XENON100 and very recently LUX);

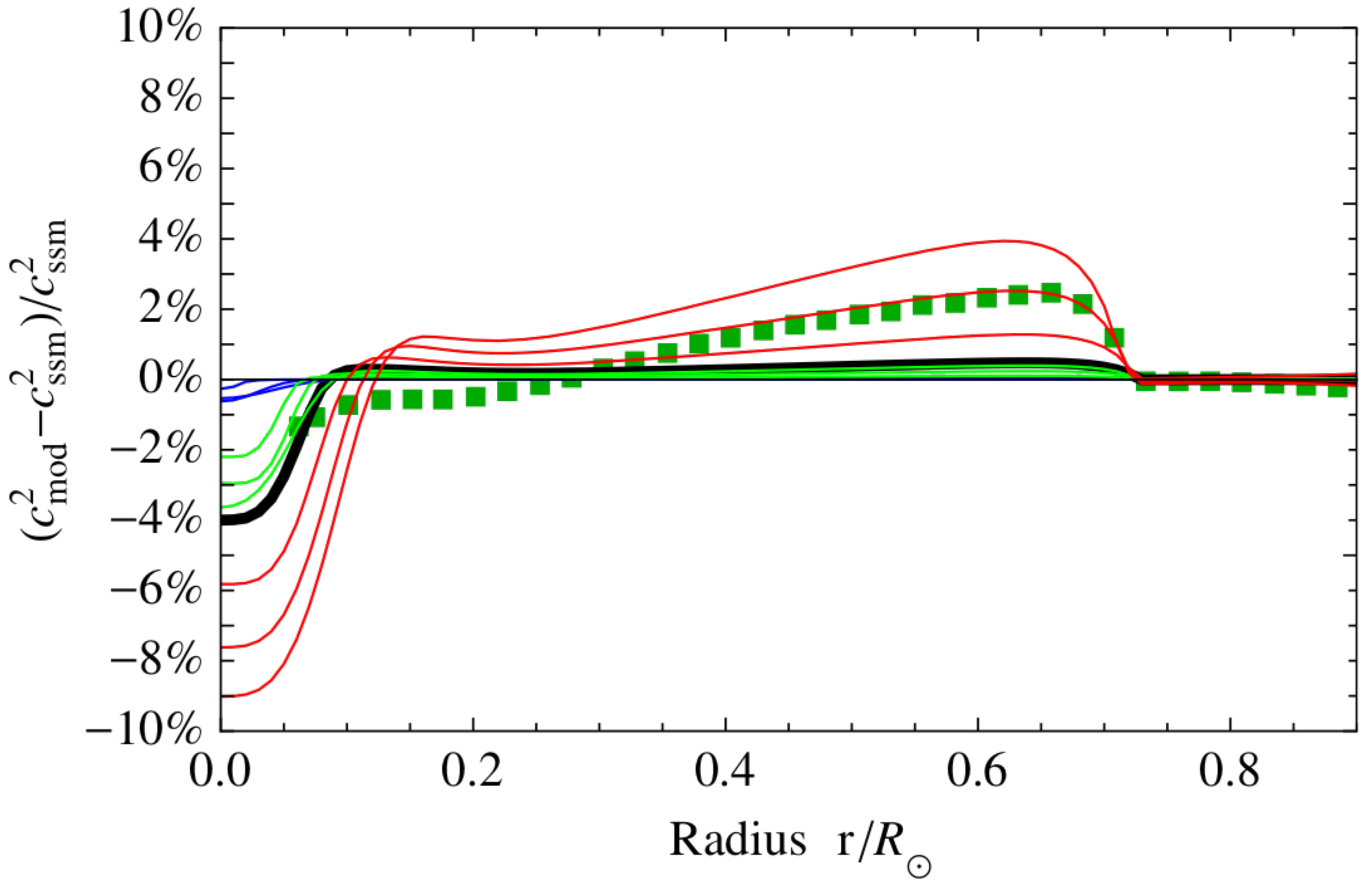
Prediction: asymmetric dark matter effect on the Sun

DM-baryon **velocity dependent** interaction:

$$\sigma_T(v_{\rm rel}) = \frac{2\pi\beta_\phi^2}{m_\phi^2}\left[\ln\left(1+r_\phi^2\right) - \frac{r_\phi^2}{1+r_\phi^2}\right]$$

$$r_\phi = 2\mu v_{\rm rel}/m_\phi,$$

$$\beta_\phi = \xi_\chi m_\phi/(2\mu v_{\rm rel}^2),$$



Helioseismology with Long Range Dark Matter Baryon Interaction",

(Lopes, Panci & Silk 2014)

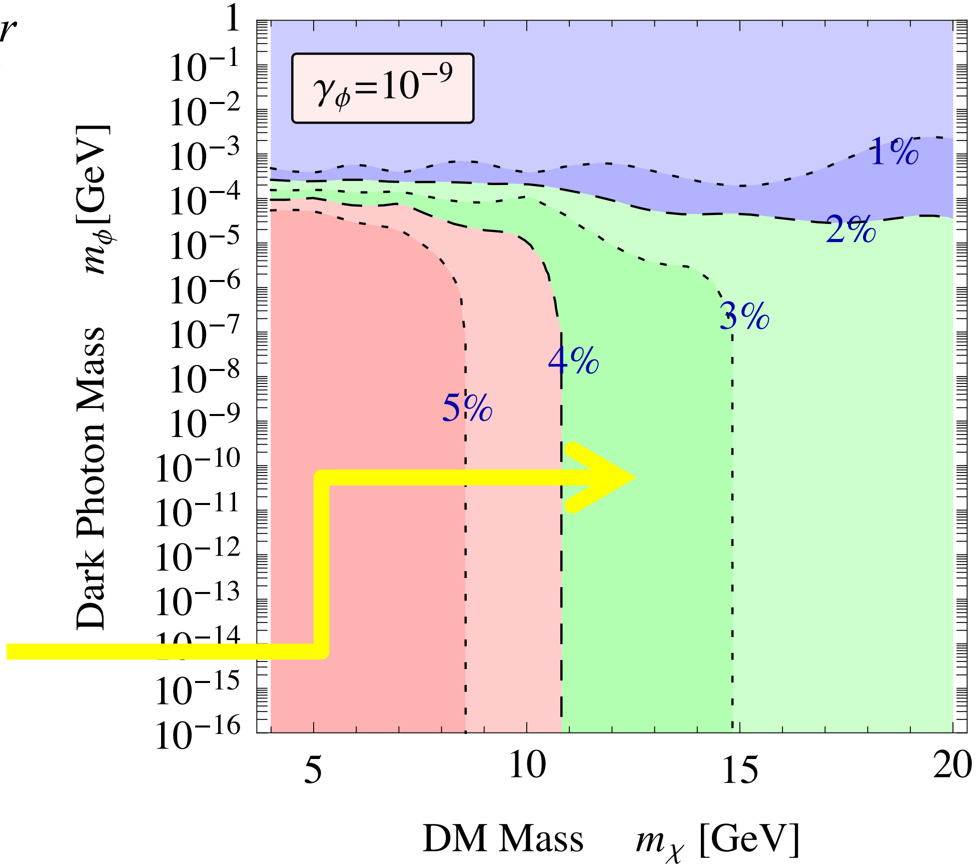
Helioseismology: DM particles with a **mass of 10 GeV and a long–range interaction with ordinary matter mediated by a very light mediator (below roughly a few MeV)**, can have an impact on the Sun's sound speed profile without violating the constraints coming from direct DM searches.

Prediction: asymmetric dark matter effect on the Sun

Helioseismology with Long Range Dark Matter Baryon Interaction", Lopes, Panci & Silk, ApJ 2014)

$(c^2_{dm}-c^2_{ssm})/c^2_{ssm}$ ~

$(c^2_{obs}- c^2_{ssm})/c^2_{ssm} \approx$ **4% - 3 %**



Helioseismology: DM particles with a mass of 10 GeV and a long–range interaction with ordinary matter mediated by a very light mediator (below roughly a few MeV), can have an impact on the Sun's sound speed profile without violating the constraints coming from direct DM searches.

Prediction: Solar models for which the DM particles have a mass of 10 GeV and the mediator a mass smaller than 1 MeV, improve the agreement with helioseismic data.

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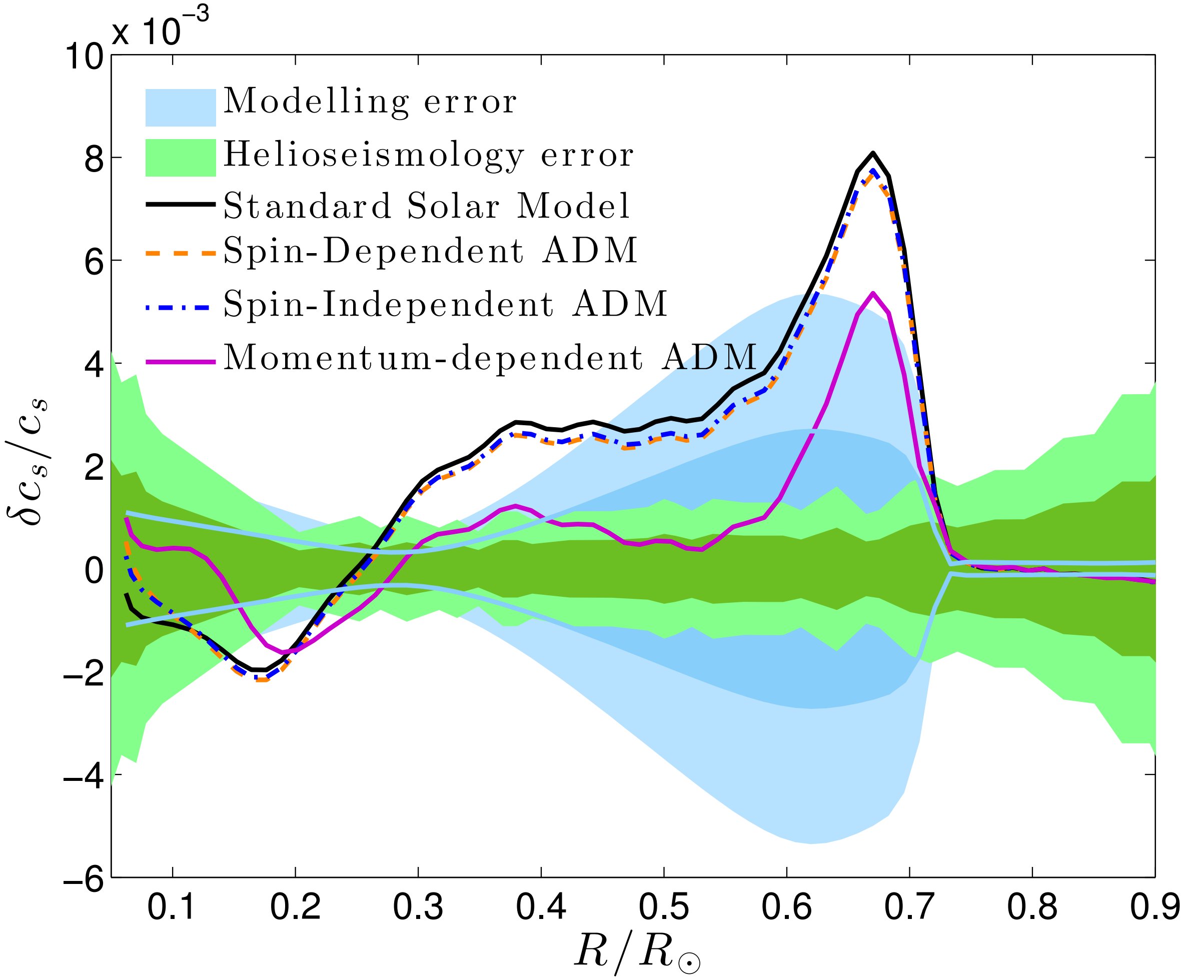
Prediction: asymmetric dark matter effect on the Sun

DM-baryon **velocity dependent** interaction:

$$\sigma_{\chi-\mathrm{nuc}} = \sigma_0 \left(\frac{q}{q_0}\right)^2$$

"A possible indication of momentum-dependent asymmetric dark matter in the Sun", (A. Vincent et. al. 2015)



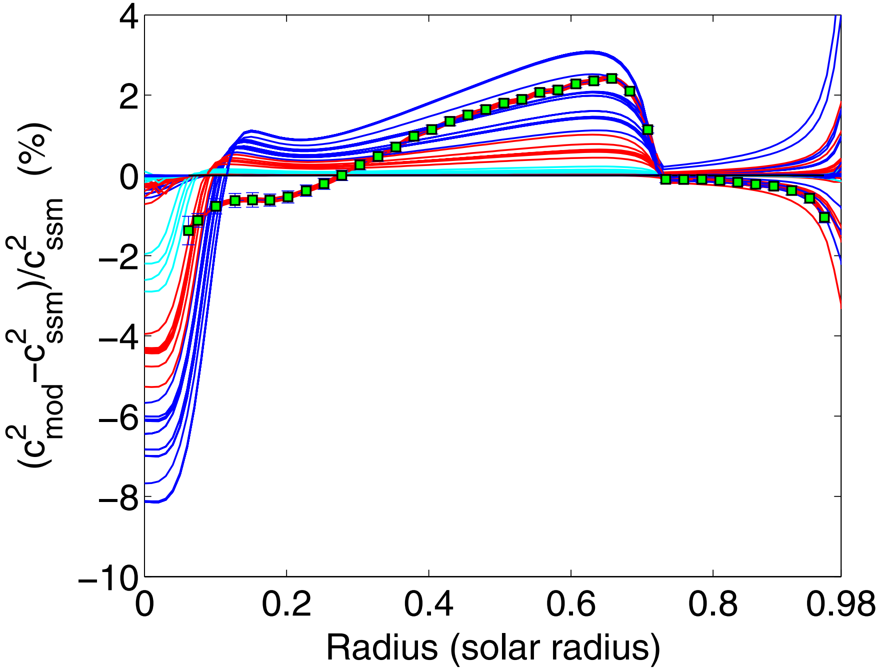
Helioseismology: Asymmetric dark matter coupling to nucleons as the square of the momentum q exchanged in the collision. Agreement with **sound speed profiles**, ect . . . . The best model correspond to a dark matter particle with a mass 3 GeV and reference dark matter-nucleon cross-section (10^{-37} cm^2 at q_0 = 40 MeV)

Prediction: dipole dark matter effect on the Sun

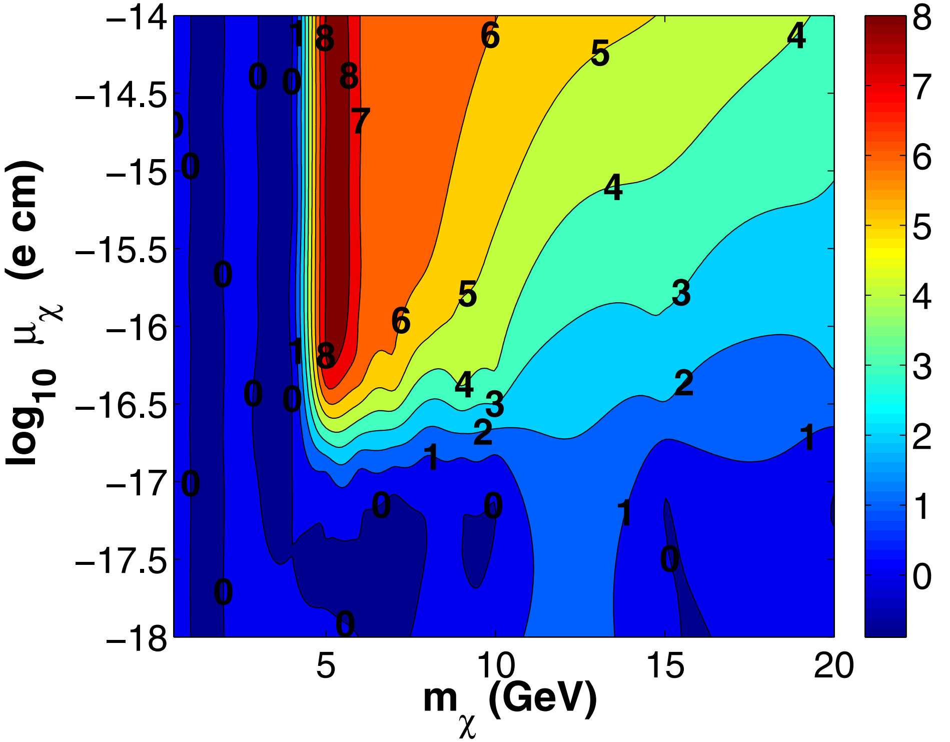
*"Constraint **on Light Dipole Dark Matter** from Helioseismology"*, Lopes, Kadota & Silk , ApJL 2014

$$\mathcal{L}_{\mathrm{MDDM}} = (\mu_\chi/2)\bar{\chi}\sigma_{\mu\nu}F^{\mu\nu}\chi$$

$\boldsymbol{\mu_\chi}$ is the magnetic dipole moment



Lopes, Kadota, & Silk



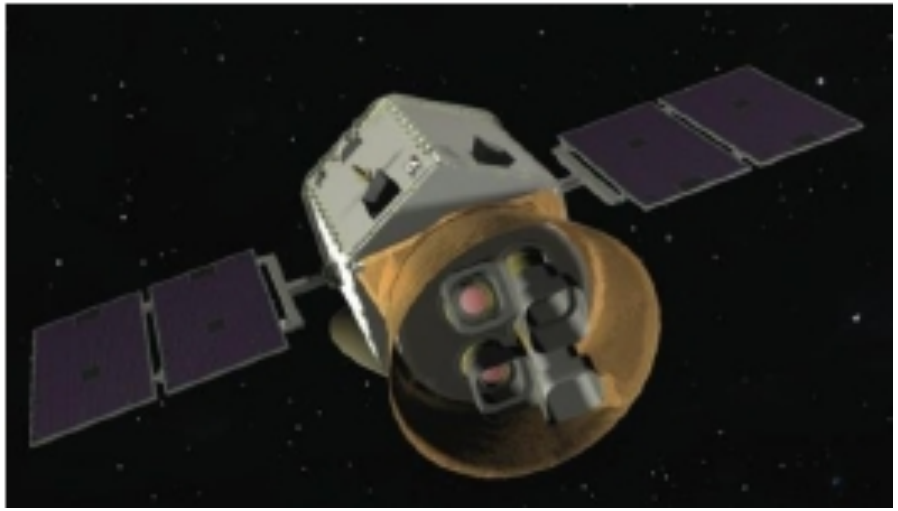
Helioseismology: The dipole interaction can lead to a sizable DM scattering cross section even for light DM, and asymmetric DM can lead to a large DM number density in the Sun. We find that solar model precision tests, using as diagnostic the sound speed profile obtained from helioseismology data, **exclude dipolar DM particles with a mass larger than 4.3 GeV and magnetic dipole moment larger than 1.6 × 10^{-17} e cm.**

Future Missions

(Asteroseismolgy)

Future Missions

- K2: Kepler observing near the ecliptic (done)
- TESS (launch in 2017)
  - All-sky survey, 1 min. cadence for all targets

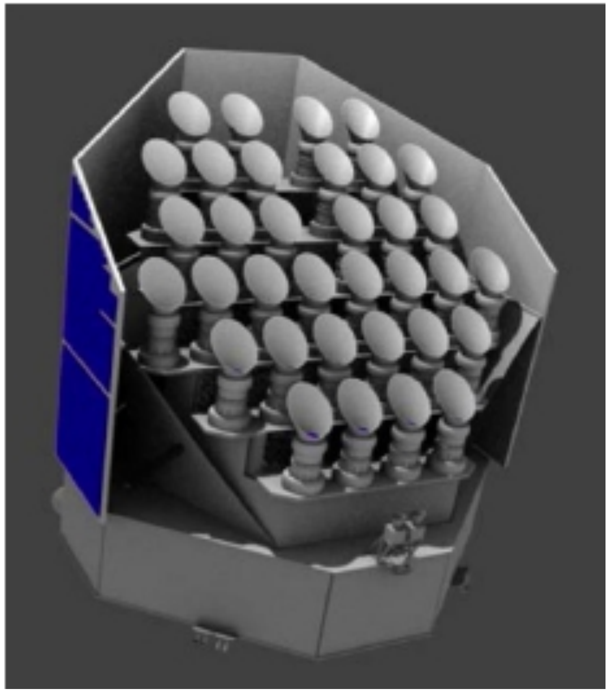


- PLATO (possible launch 2022 – 2024)
  - Large fields, bright stars.

Asteroseismology of planet hosts

an integrated part of the project

ESA M3 selection in Febr. 2014



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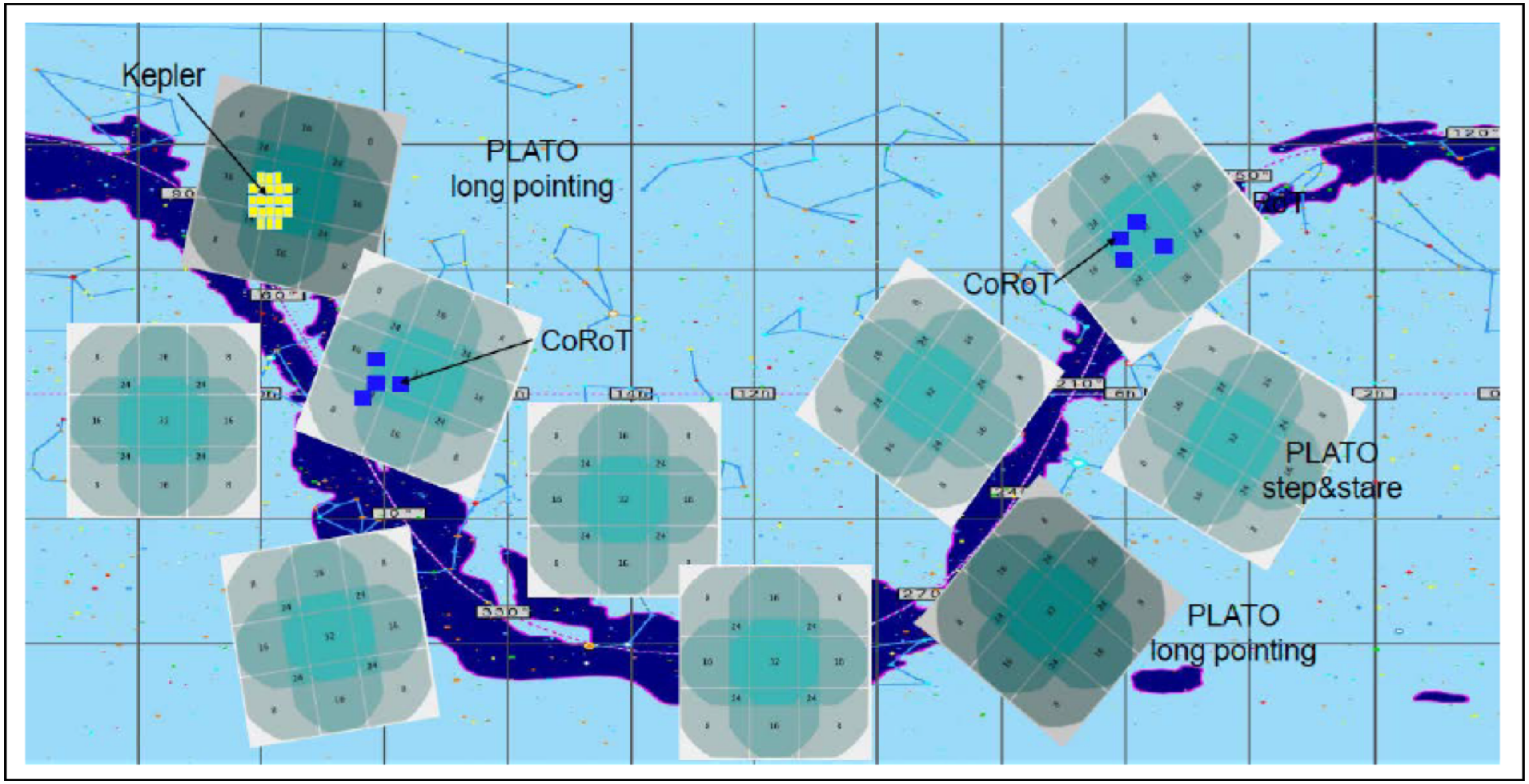
PLATO observing strategy

Baseline observing strategy:

- 6 years nominal science operation
- 2 long pointings of 2-3 years + step-and-stare phase (2-5 months per pointing)



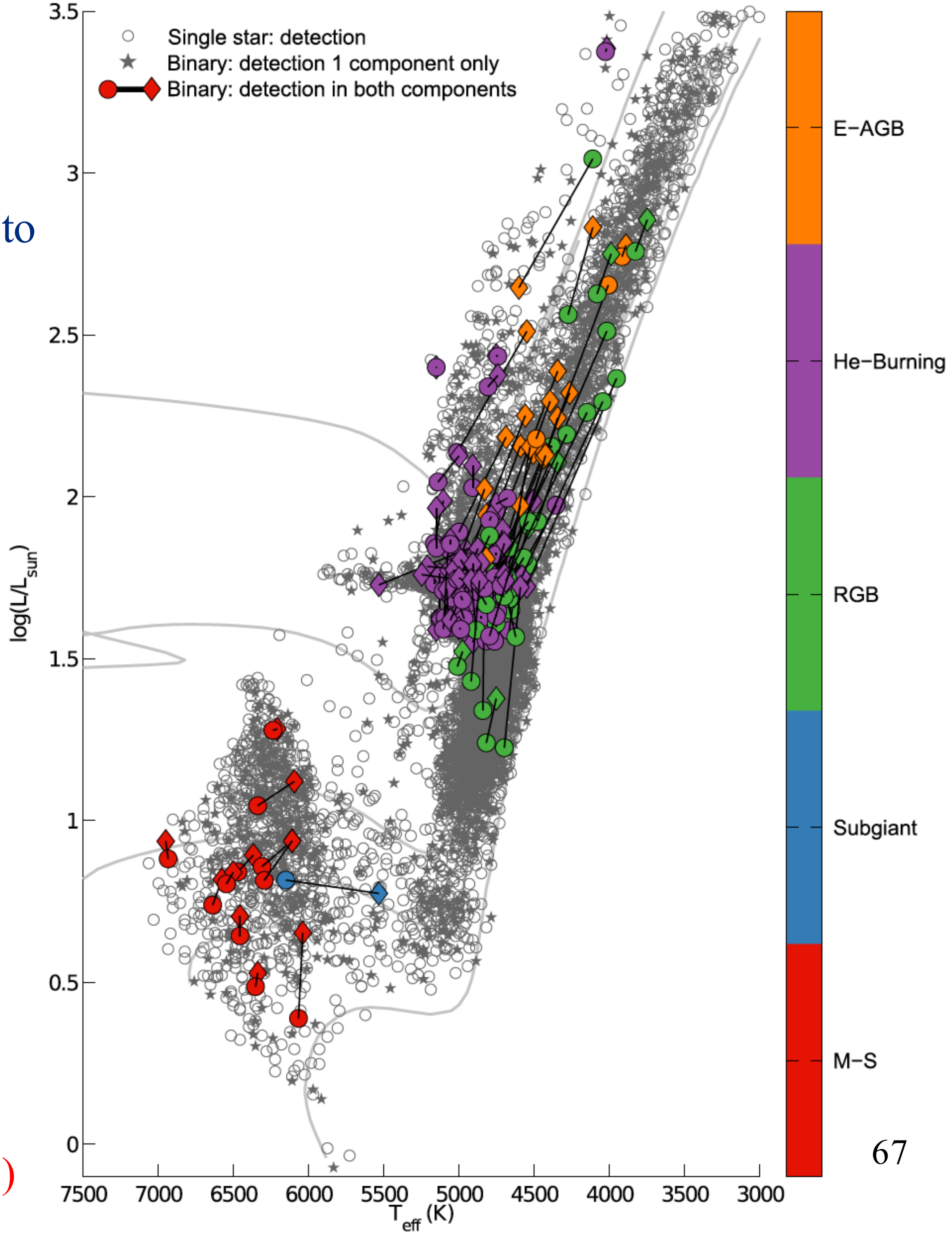
Conclusion

Asteroseismology and Dark matter in Stars

Asteroseismology opens a new way to put constraints to dark matter particles

Stellar Physics Caveats need to be improved to make more reliable DM constraints.

- Internal rotation (Subgiant stars, MS star)
- Helium ionization and convection zones
- Excitation and damping (mode physics)
- Stellar cycle and activity
- Atmosphere: surface effect, asymmetries
- Stellar Radius, Mass and Age
- Clusters and Binary stars



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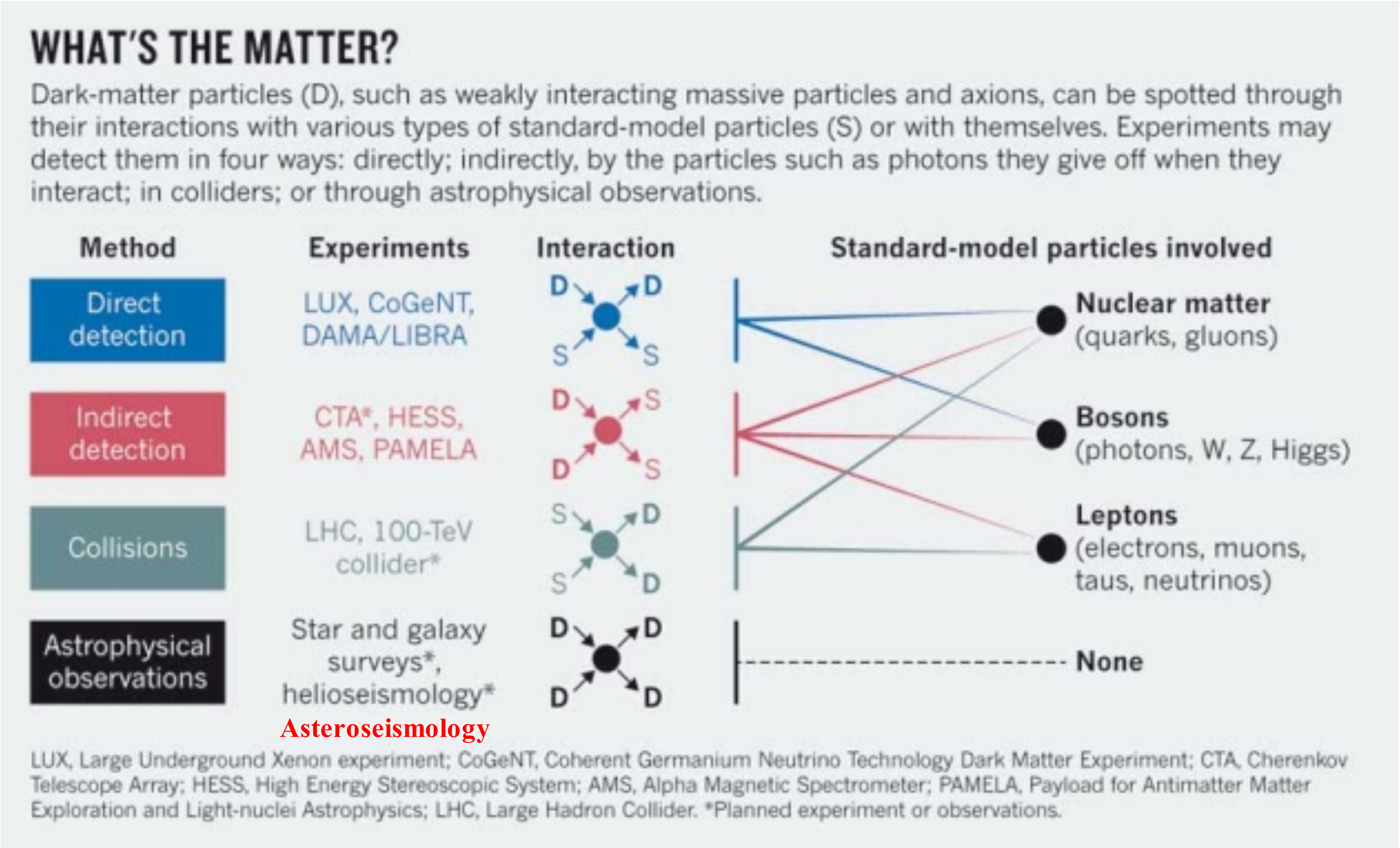
Chaplin et. al. (2014)

Asteroseismology and Dark matter in Stars



WHAT'S THE MATTER?

Dark-matter particles (D), such as weakly interacting massive particles and axions, can be spotted through their interactions with various types of standard-model particles (S) or with themselves. Experiments may detect them in four ways: directly; indirectly, by the particles such as photons they give off when they interact; in colliders; or through astrophysical observations.

Method	Experiments
Direct detection	LUX, CoGeNT, DAMA/LIBRA
Indirect detection	CTA*, HESS, AMS, PAMELA
Collisions	LHC, 100-TeV collider*
Astrophysical observations	Star and galaxy surveys*, helioseismology*

Standard-model particles involved

Nuclear matter (quarks, gluons)

Bosons (photons, W, Z, Higgs)

Leptons (electrons, muons, taus, neutrinos)

None

Asteroseismology

LUX, Large Underground Xenon experiment; CoGeNT, Coherent Germanium Neutrino Technology Dark Matter Experiment; CTA, Cherenkov Telescope Array; HESS, High Energy Stereoscopic System; AMS, Alpha Magnetic Spectrometer; PAMELA, Payload for Antimatter Matter Exploration and Light-nuclei Astrophysics; LHC, Large Hadron Collider. *Planned experiment or observations.

M. Livio & J. Silk Nature (2014)

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Thank You

TÉCNICO LISBOA