Looking into the dark universe with stars

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Outline

- ✧ Modern Particle Physics of today : the current status of Cosmology/Particle Physics/Astrophysics (Introduction)
- ✧ Dark Matter and Stars
- ✧ Stars as a probe of Gravitational Waves
- ✧ Conclusion

Modern Particle Physics of today

Gravity . Matter . Particle Physics

Modern Particle Physics of today

Einstein's Equation (ignoring constants):

$$G_{\mu\nu} = T_{\mu\nu}^{sp} + T_{\mu\nu}^{DM} + T_{\mu\nu}^{DE}$$

5% 27% 68%

$G_{\mu\nu}$ - Einstein tensor describing the curvature of space-time (and hence the effect of gravity)

$T_{\mu\nu}^{sp}$ – standard particles (baryons, photons and neutrinos)

$T_{\mu\nu}^{DM}$ – dark matter

$T_{\mu\nu}^{DE}$ – dark energy

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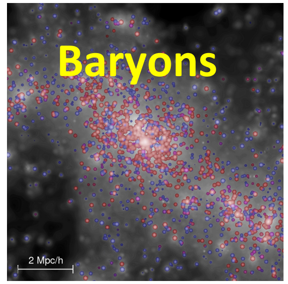
Formation of structure in the Universe

- **27% Dark Matter** creates the Gravitational web for the formation of structures with **5% of baryons**.

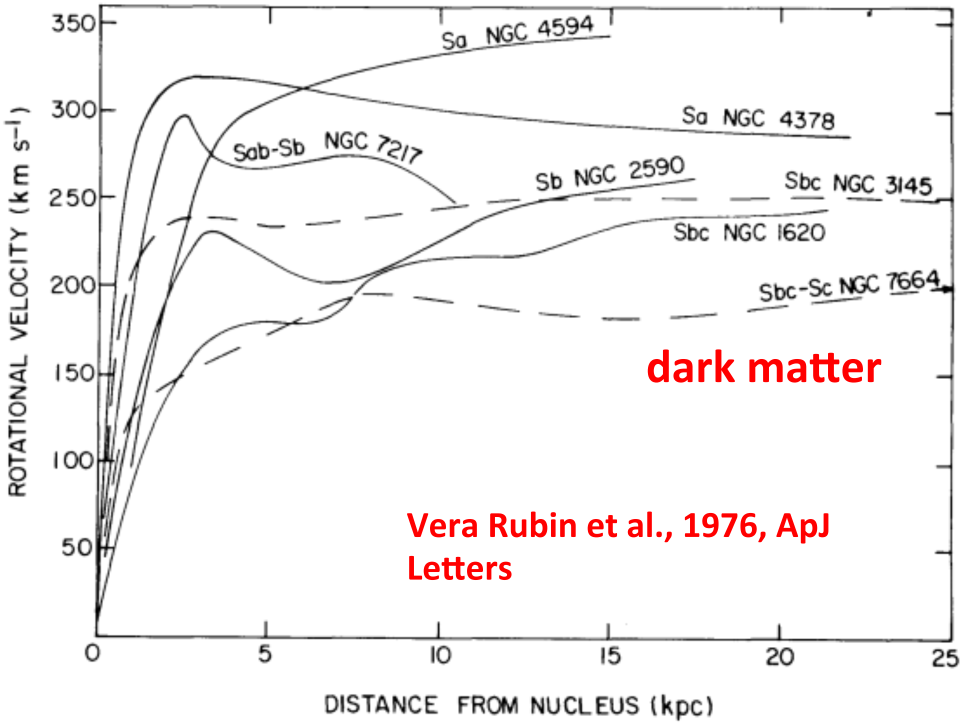
The Nature of Dark Matter: Cold dark matter weakly interacting particles

Reproduce the observed present baryonic structure: stars, stellar clusters, galaxies, galaxy clusters

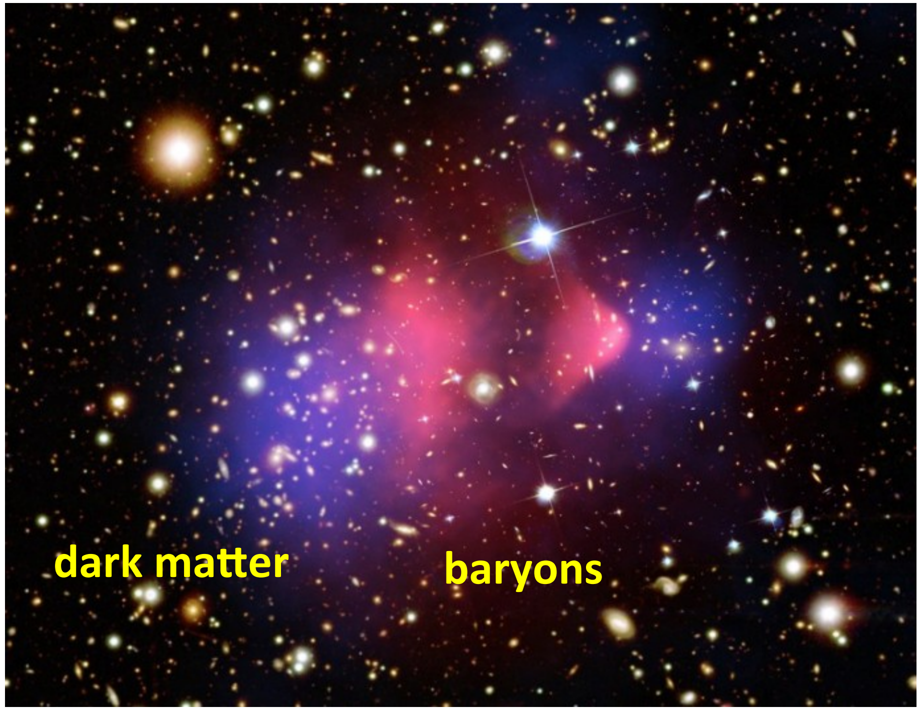


Confirmed by observations

Rotation curves for 7 spiral galaxies

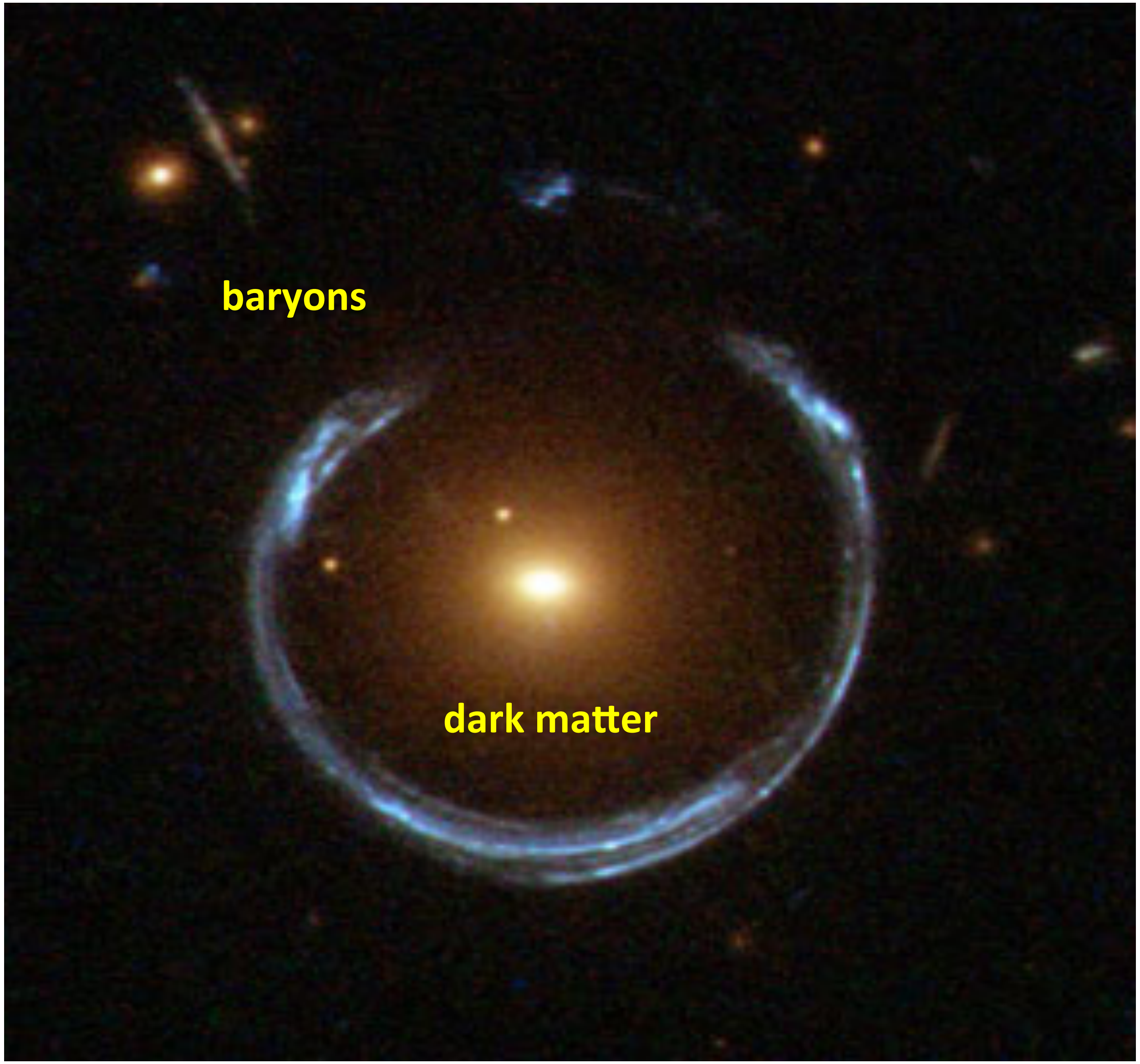


Bullet Cluster (two colliding clusters of galaxies)



Formation of structure in the Universe

Image LRG 3-757 (gravitational lens) obtained by the Hubble Space Telescope



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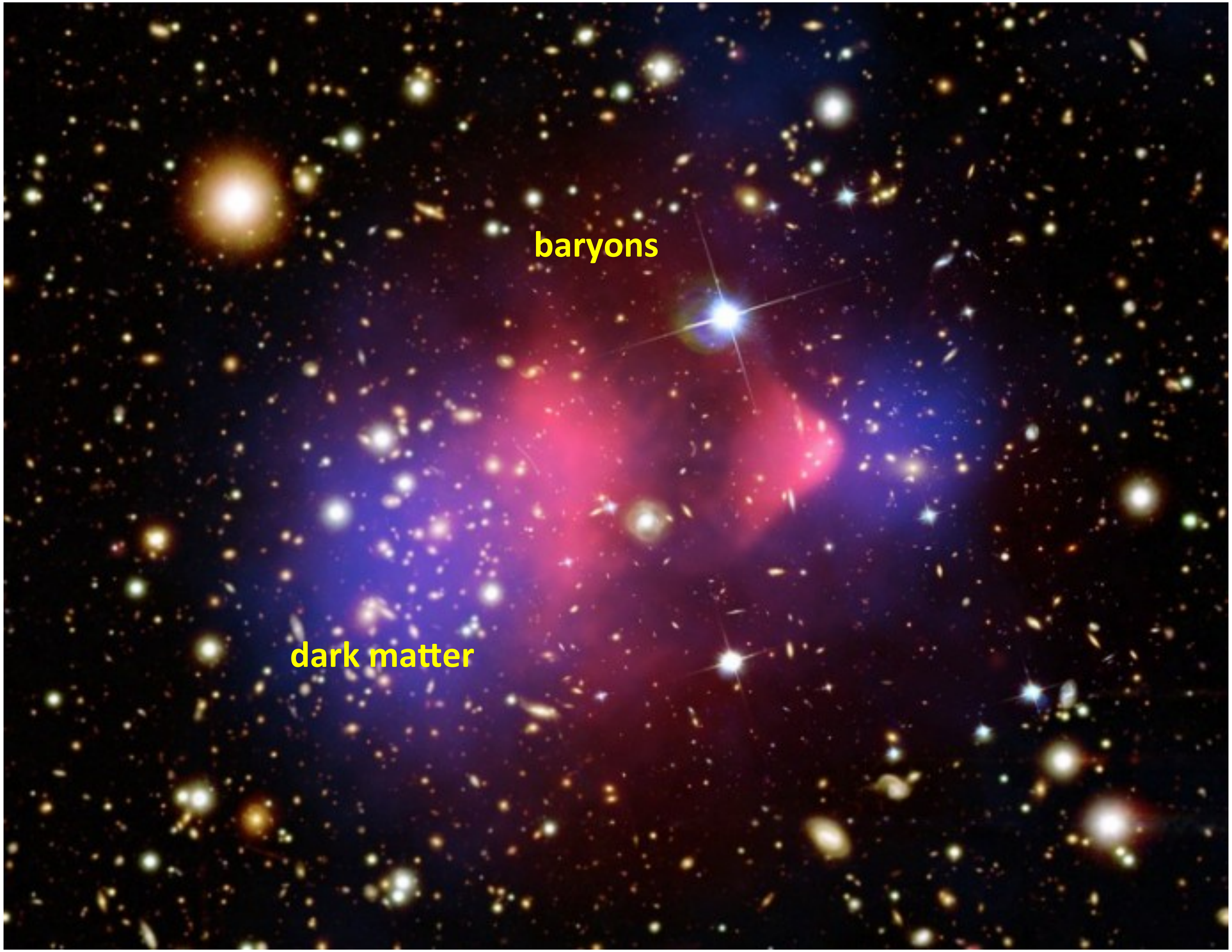

Modern Particle Physics of today

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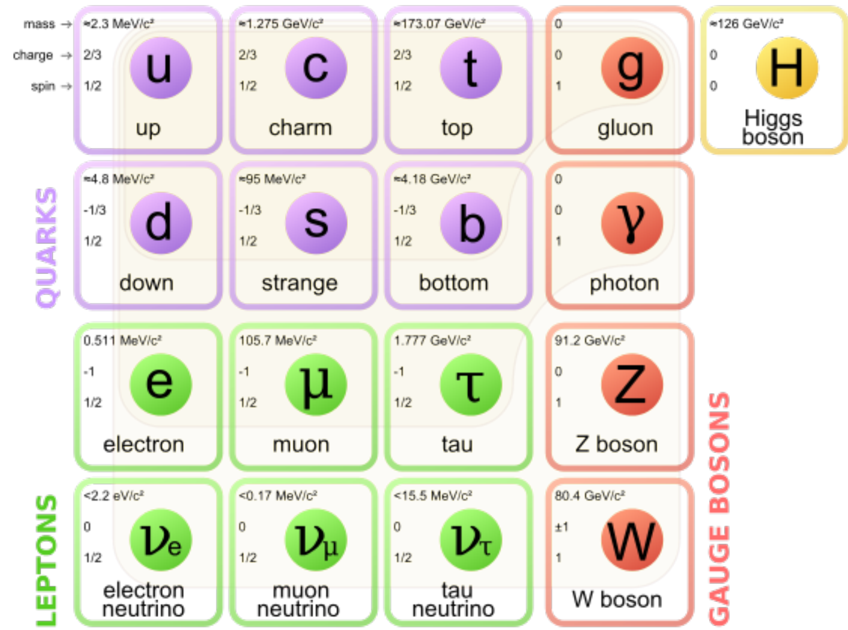
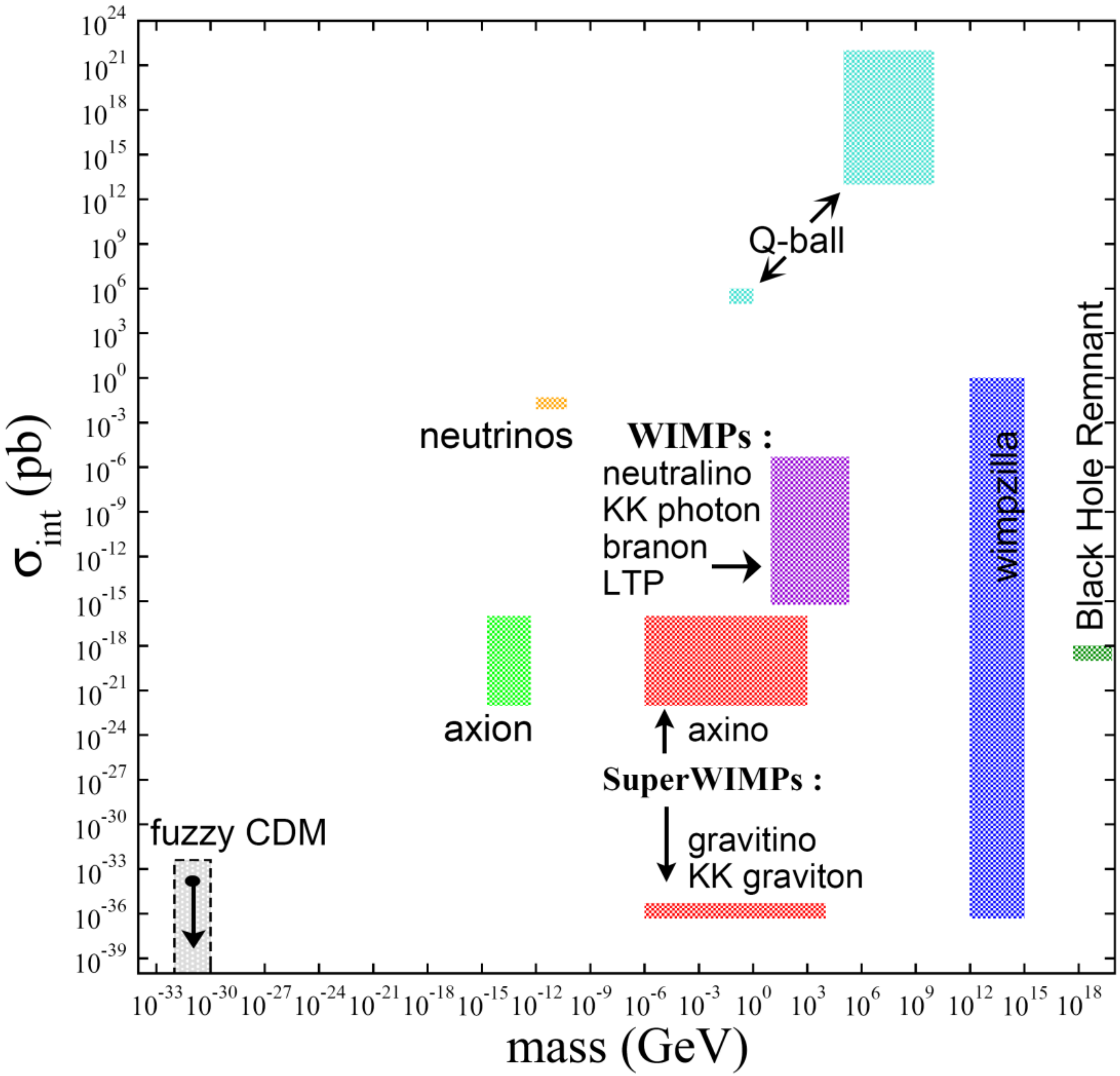


Modern Particle Physics of today

Candidates of dark matter particles



WIMPs (Weakly Interacting Massive Particles)

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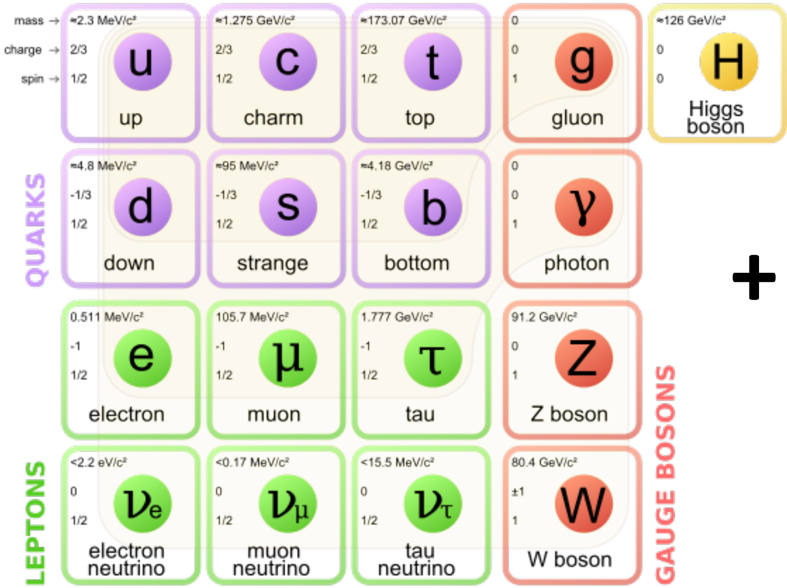
The Early Universe – dark matter particles

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 (5%).

Nevertheless, we choose to keep the dark matter world simple (dark particle + dark photon). The connection between the standard world and the dark world is done by a kinematic coupling term.

Lopes, Panci, Silk 2014 ApJ



+ Coupling. +

(dark particle + dark photon)

standard particles **mirror particles**

Dark Matter and Stars

Gravity . Matter . Particle Physics

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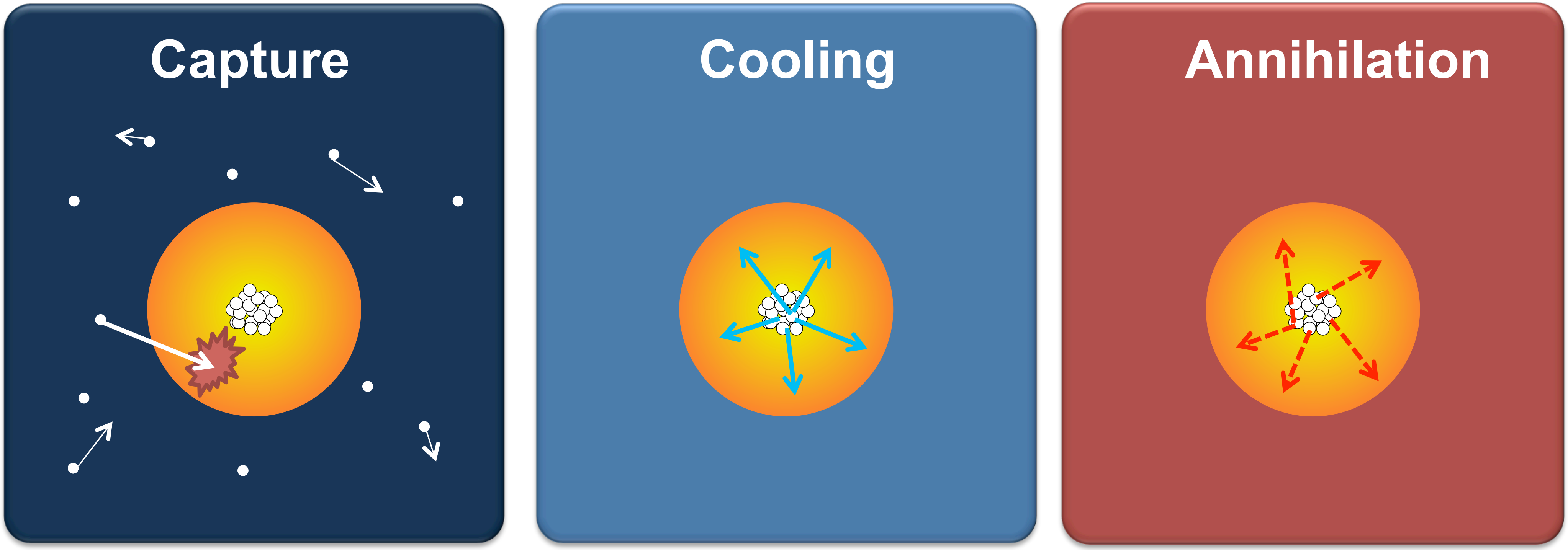
How does Dark Matter influence stars?

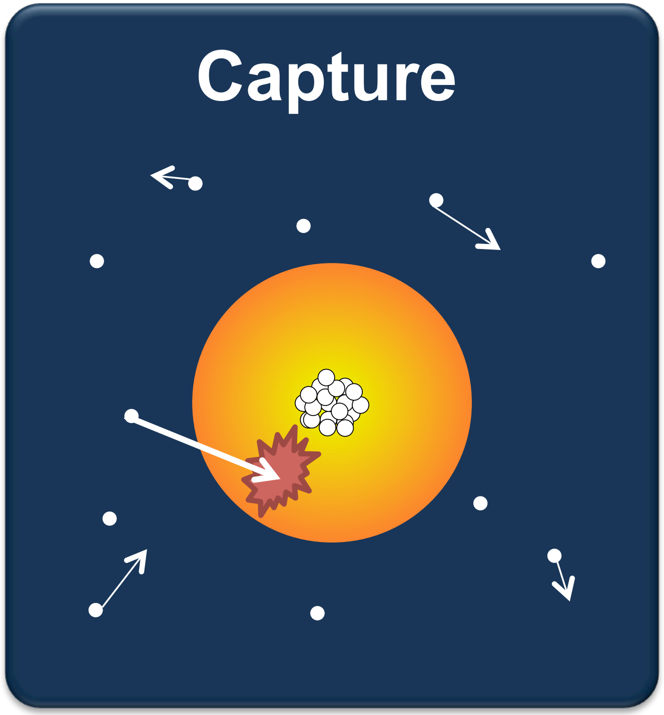


[Gould, ApJ 321 (1987)]

[Gould & Raffelt ApJ 352 (1990)]

[Salati & Silk ApJ 338 (1989)]

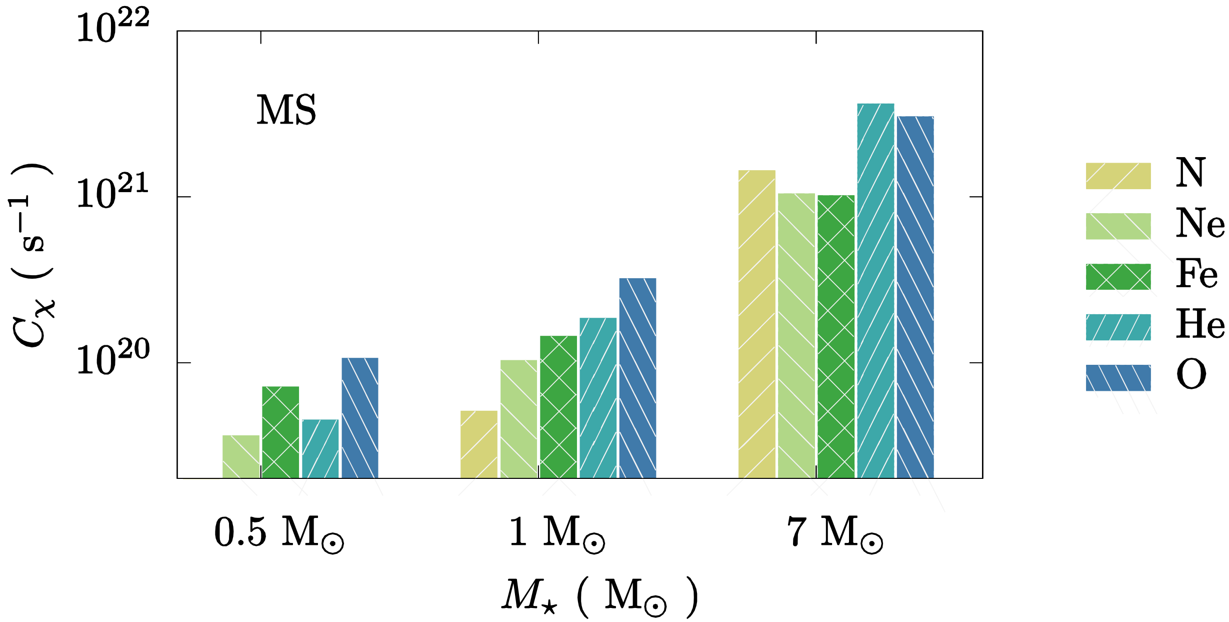
How does Dark Matter influence stars?



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

[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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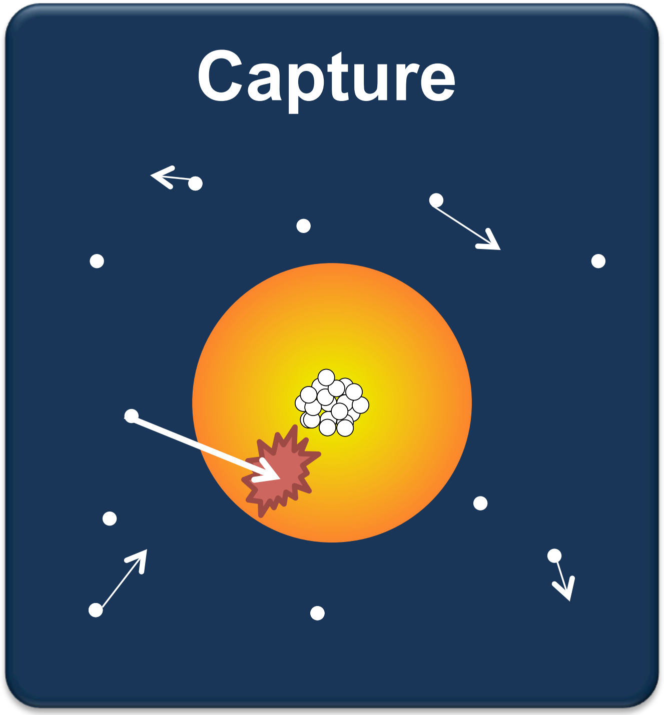

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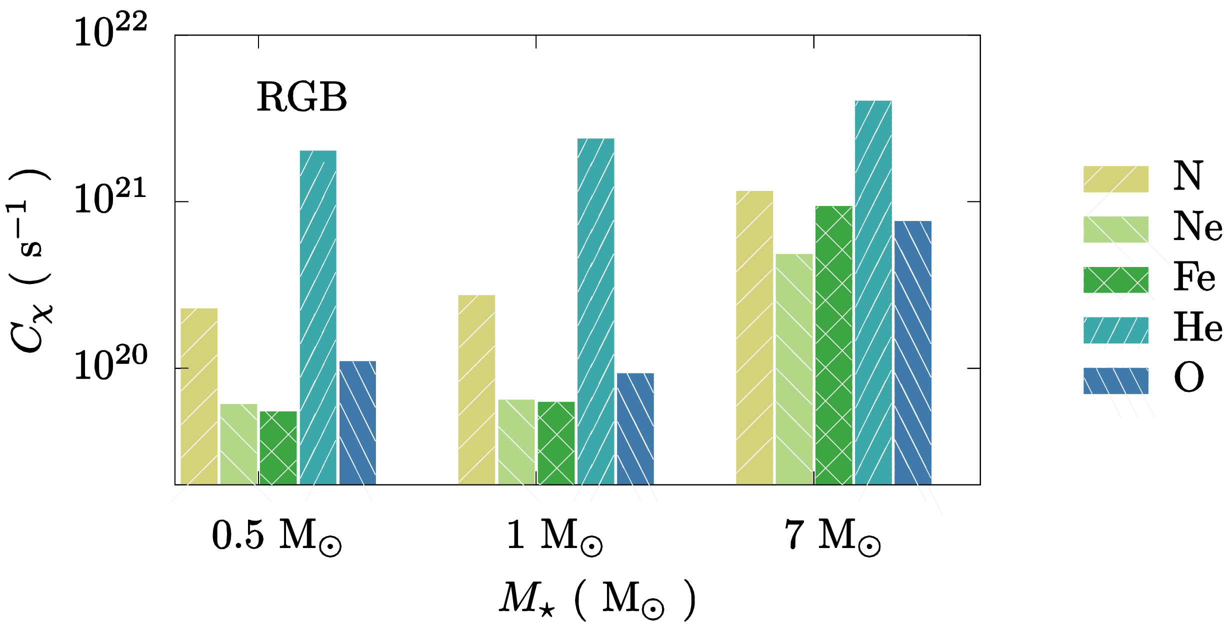
σ_χ m_χ ρ_χ $\bar{v}_\chi$ $V_\star$ n_i



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

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Dark Matter and Stars (few examples)

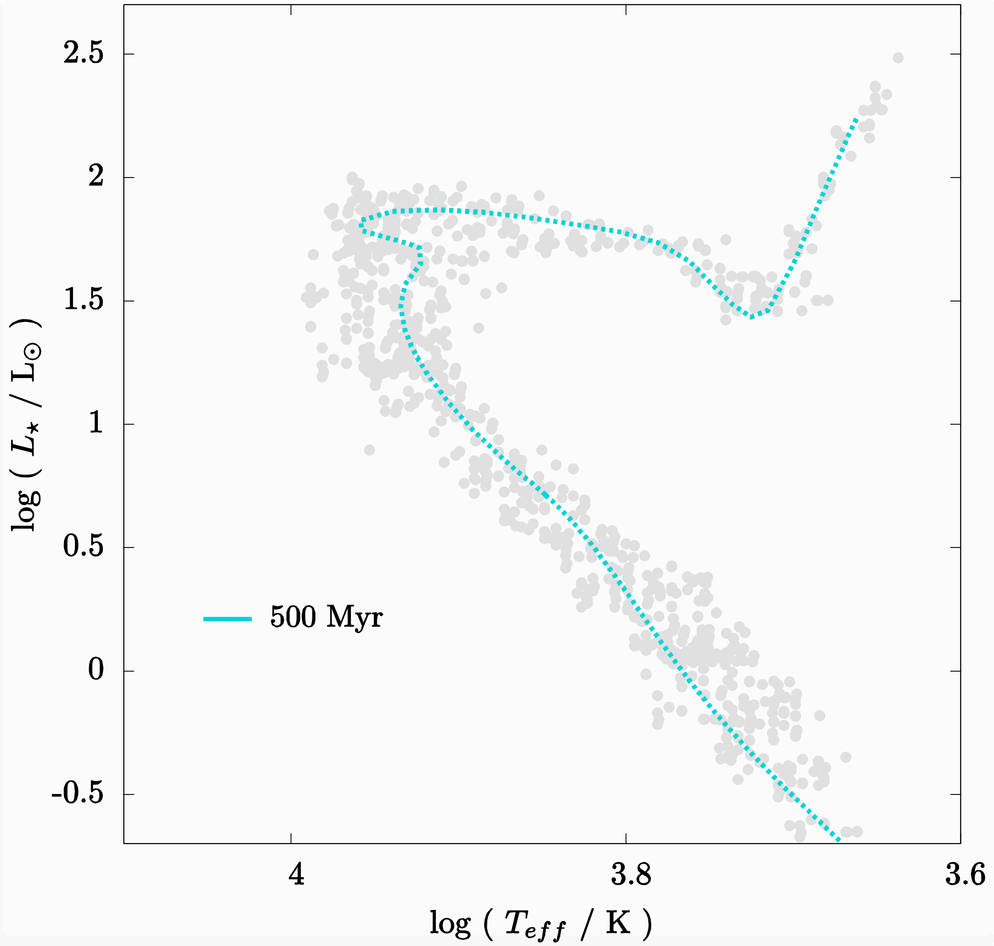
Gravity . Matter . Particle Physics

Prediction: dark matter effect on Population II stars

Stars form in the dense dark matter halos (primordi Universe and core of galaxies) have their lives exten (slower evolution in the HD diagram), due to the en 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 ~ 100 GeV and σ_{SD} (with protons) ~ 10^{-38} cm^2
- For a cluster of stars (0.7-3.5 $M_\odot$) in DM halo (ρ_x ~ 10^{10} GeV cm^{-3}, continuous lines) and classical scenario (dashed lines).



Stellar Cluster

Casanellas & Lopes (ApJ Letters 2011)

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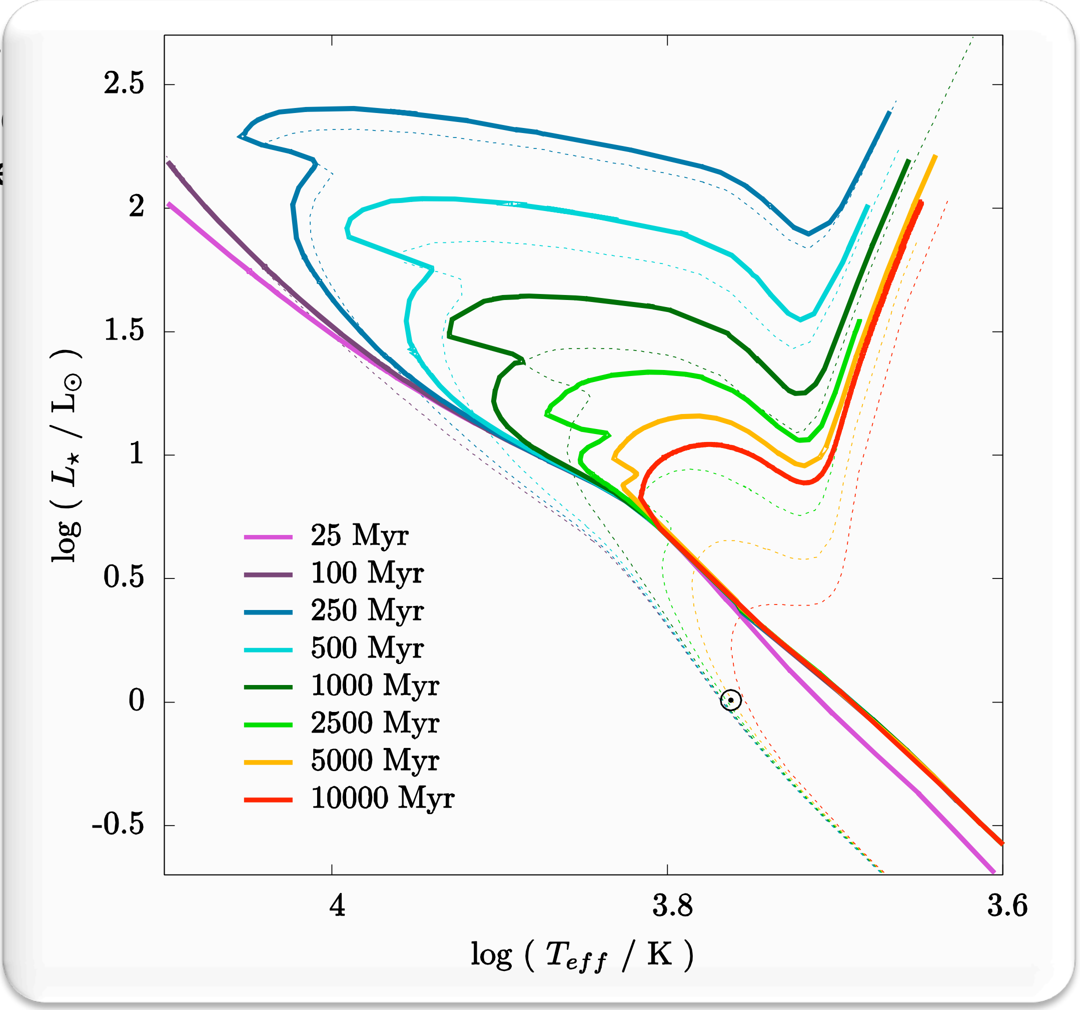
- DM particles with a $m_x \sim 100$ GeV and σ_{SD} (with protons) $\sim 10^{-38}$ cm^2
- For a cluster of stars (0.7-3.5 $M_\odot$) in DM halo ($\rho_x \sim 10^{10}$ GeV cm^{-3}, continuous lines) and classical scenario (dashed lines).



Stellar Cluster

Casanellas & Lopes (ApJ Letters 2011)

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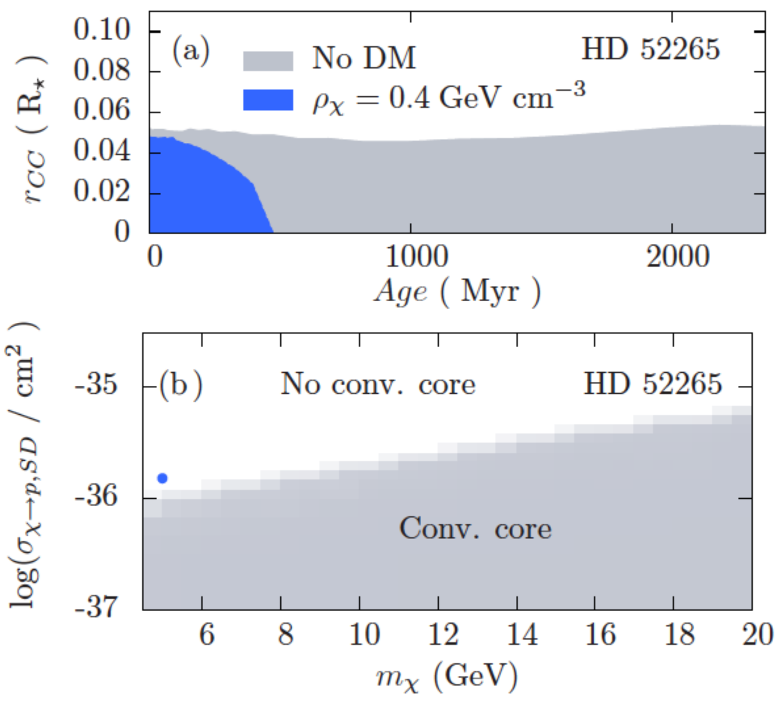
Prediction: dark matter effect on Population I stars

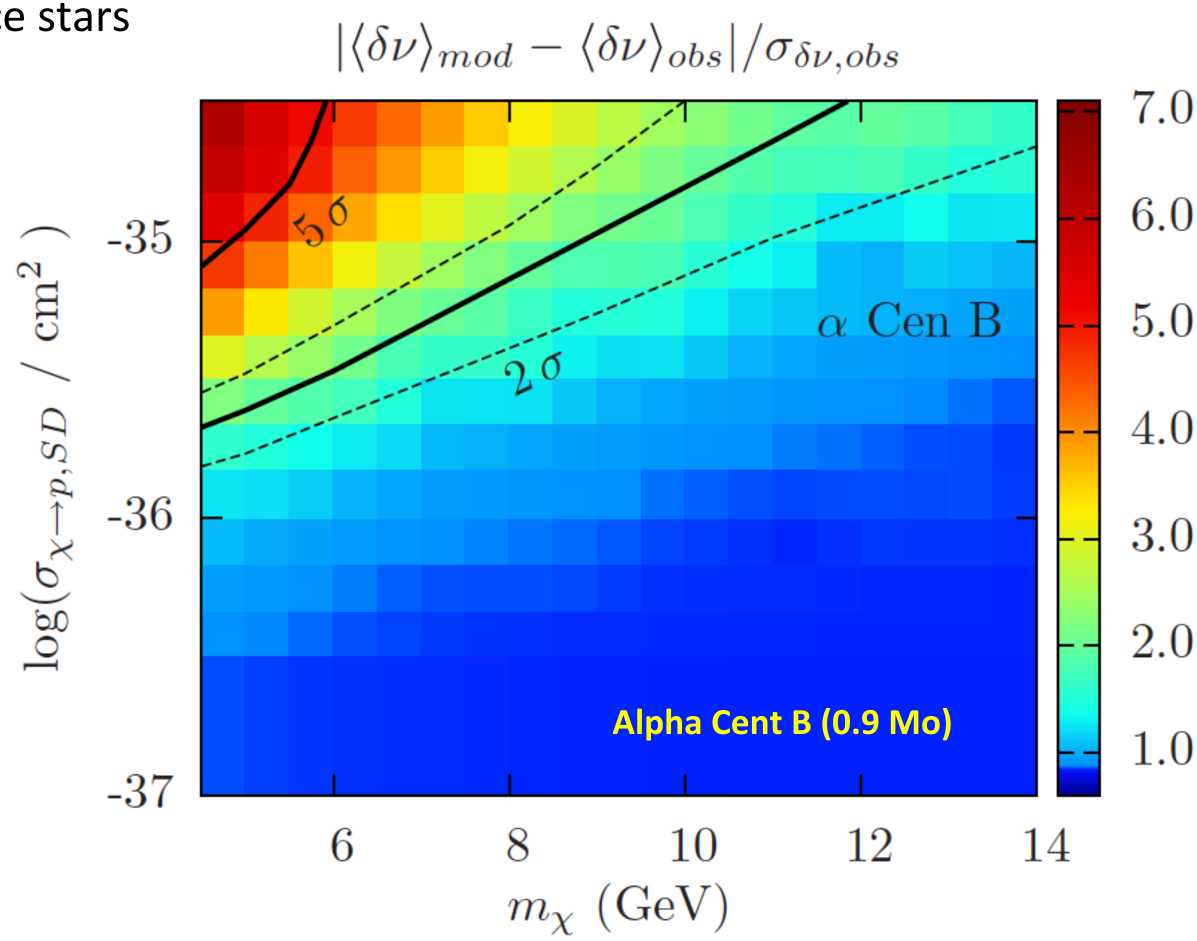
Dark matter (asymmetric) changes the transport of heat energy inside these stars (decreasing the central temperature).

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



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

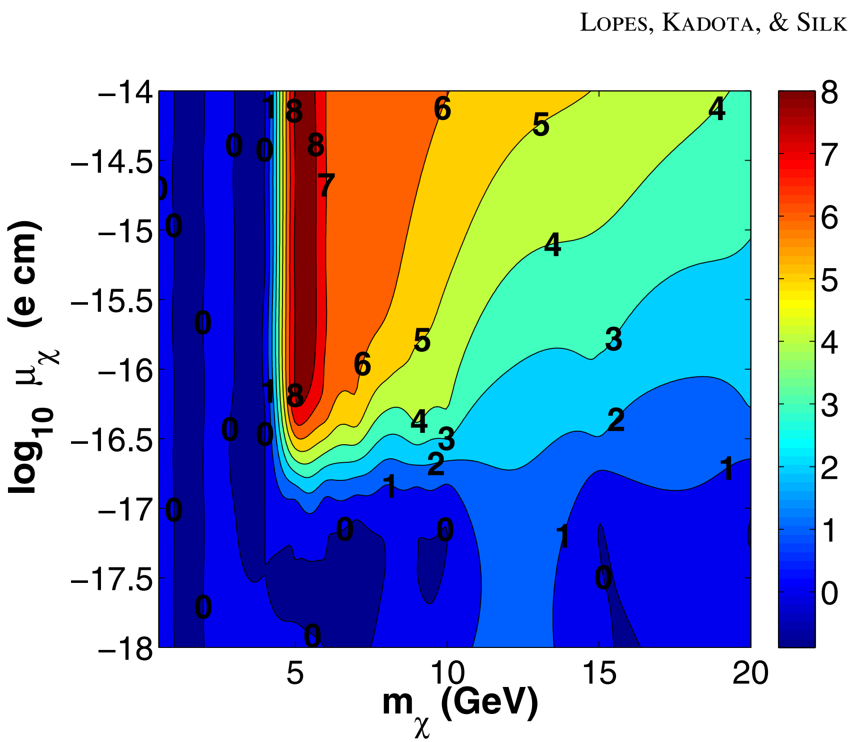
Asteroseismology

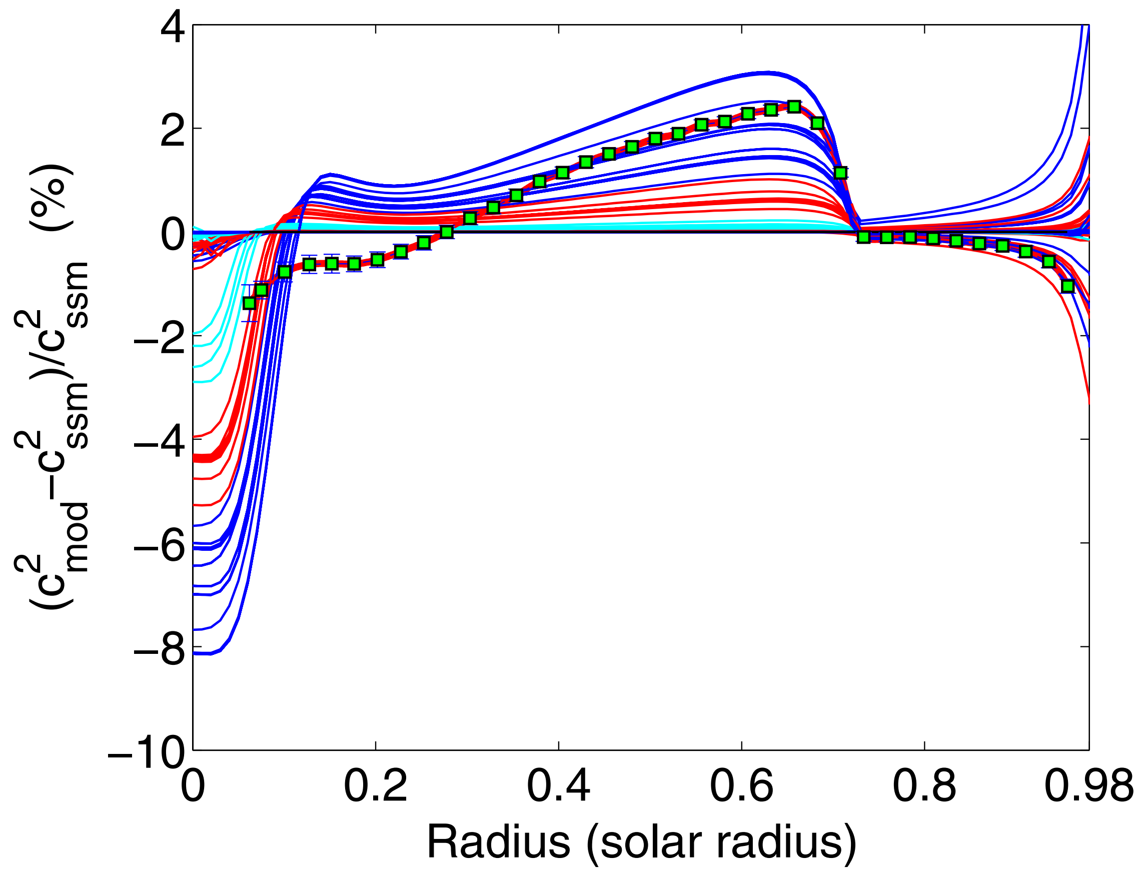


Casanellas & Lopes (ApJ Letters, 2013)

Prediction: dipole dark matter effect on the Sun

Constraint on Light Dipole Dark Matter from Helioseismology", Lopes, Kadota & Silk , ApJ Letters 2014)



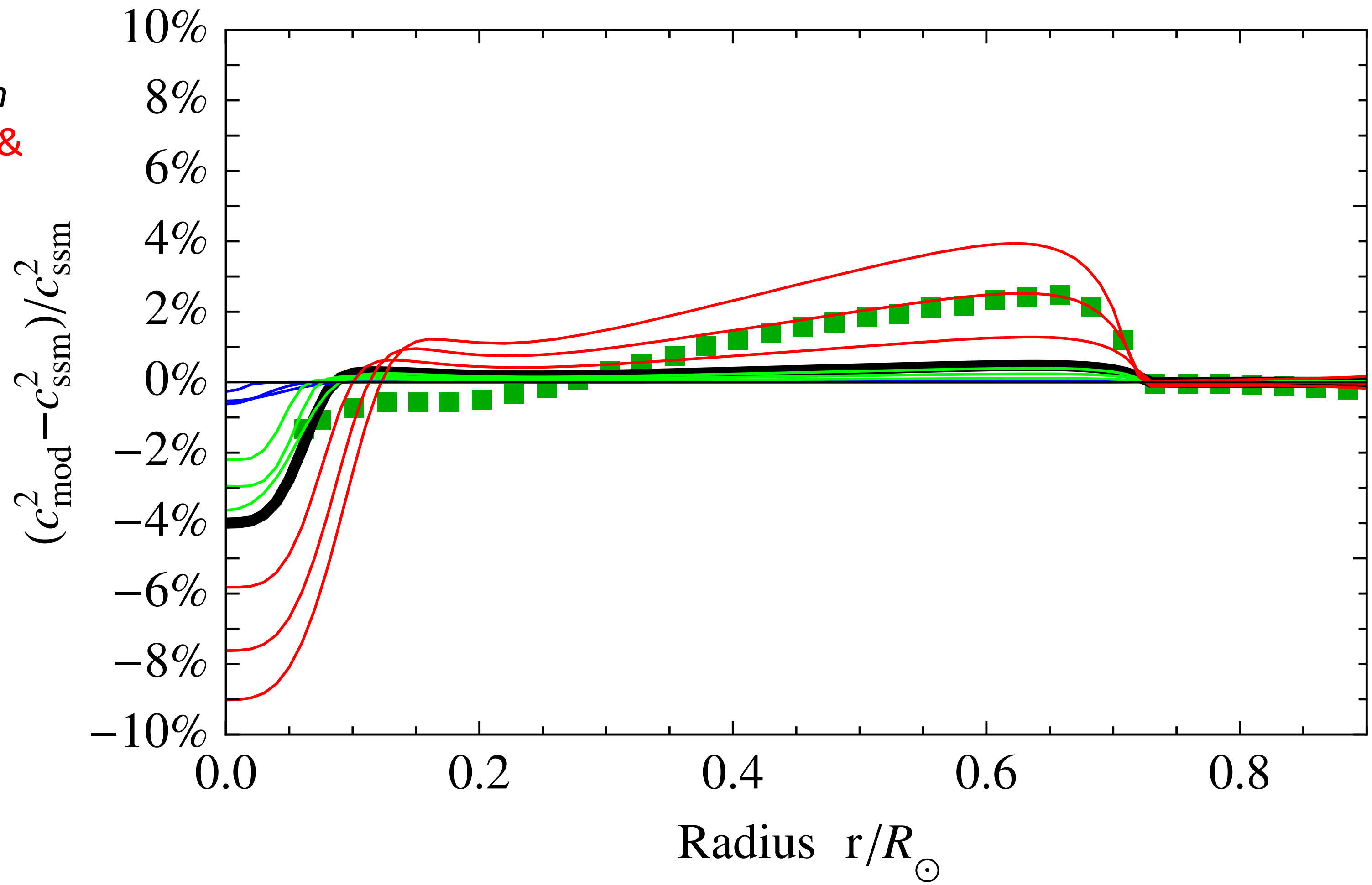


Helioseismology: The dipole interaction can lead to a sizable DM scattering cross section even for light DM, and asymmetric DM can lead to a large DM number density in the Sun. We find that solar model precision tests, using as diagnostic the sound speed profile obtained from helioseismology data, exclude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

Prediction: asymmetric dark matter effect on the Sun

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

THE ASTROPHYSICAL JOURNAL, 795:162 (11pp), 2014 November 10



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

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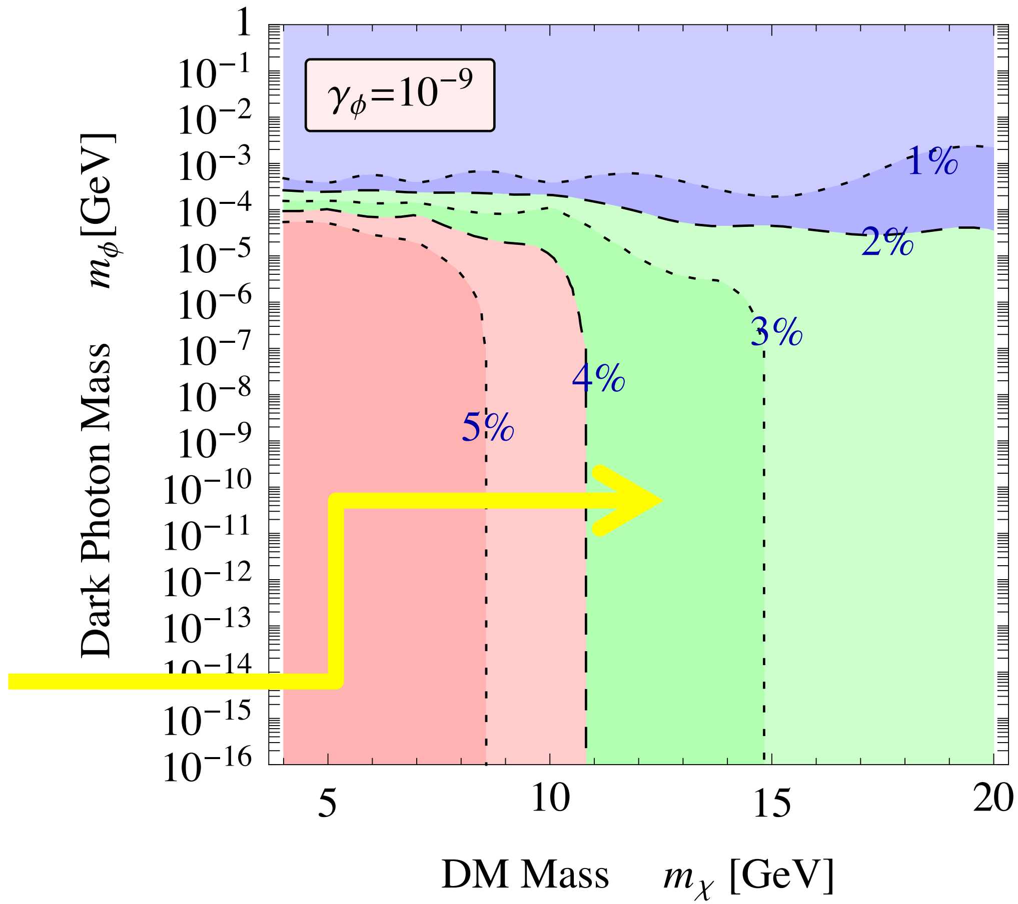

$(c^2_{dm}-c^2_{ssm})/c^2_{ssm}$ ~

$(c^2_{obs}- c^2_{ssm})c^2_{ssm}$ ≈ 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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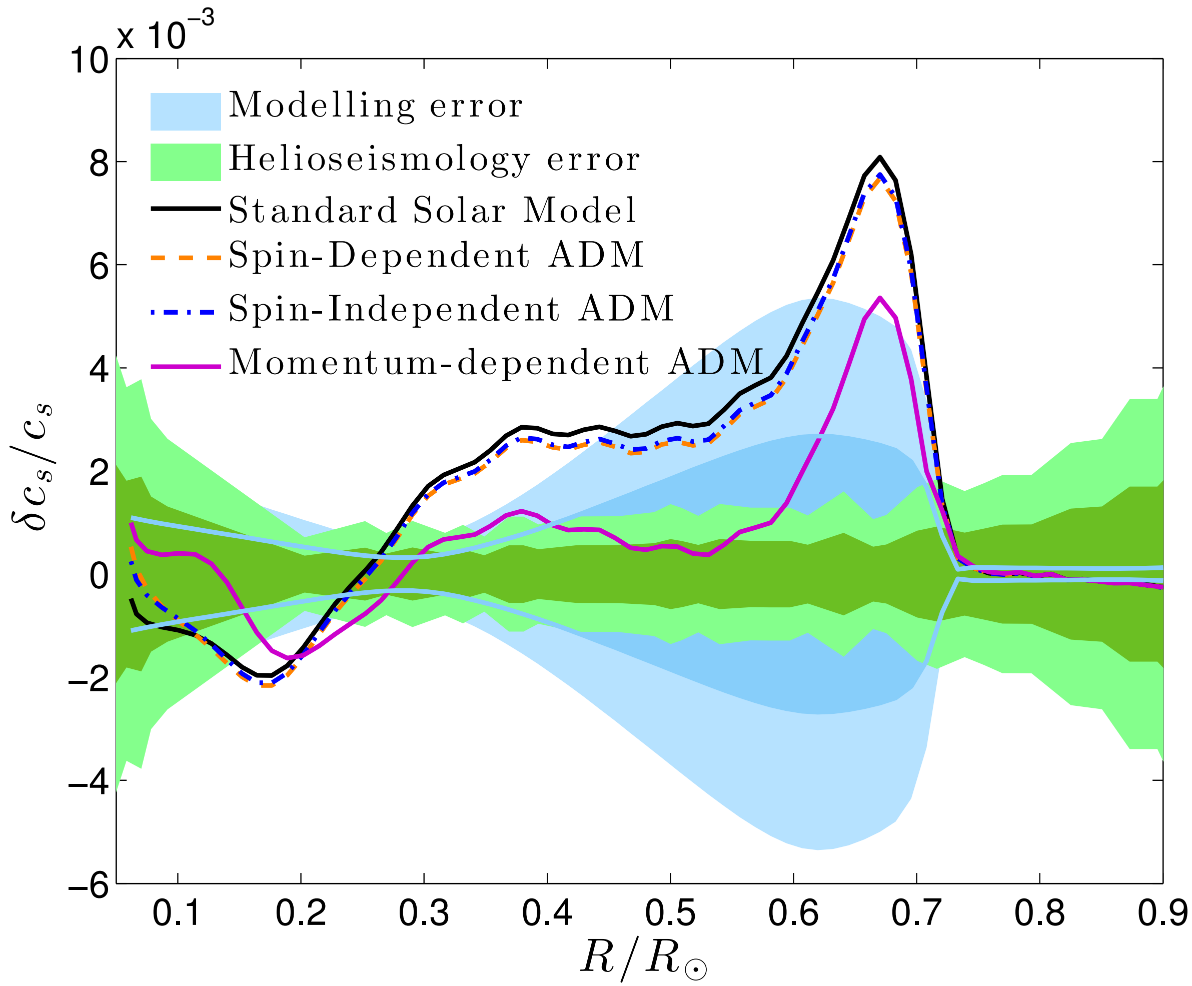
Prediction: asymmetric dark matter effect on the Sun



Helioseismology: Asymmetric dark matter coupling to nucleons as the square of the momentum q exchanged in the collision. Agreement with **sound speed profiles**, neutrino fluxes, small frequency separations, surface helium abundances, and convective zone depths for a number of models. 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) are within the region of parameter space allowed by both direct detection and collider searches.

(A. Vincent et. al. 2015)

Posters

- ✧'Asteroseismology of Kepler stars: a study of the outer layers', Ana Brito, Ilidio Lopes
- ✧Asking stars about Dark Matter',
  Andre Martins, Jordi Casanellas, Ilidio Lopes
- ✧'The Sun as a detector for dark matter',
  Jose Lopes, Ilidio Lopes

Stars as Gravitational Waves Detectors

Gravity . Stellar seismology

Stars as gravitational waves detectors

Einstein's Equation (ignoring constants):

$$G_{\mu\nu} = T_{\mu\nu}^{sp} + T_{\mu\nu}^{DM} + T_{\mu\nu}^{DE}$$

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$T_{\mu\nu}^{sp}$ – standard particles (baryons, electrons, photons and neutrinos)

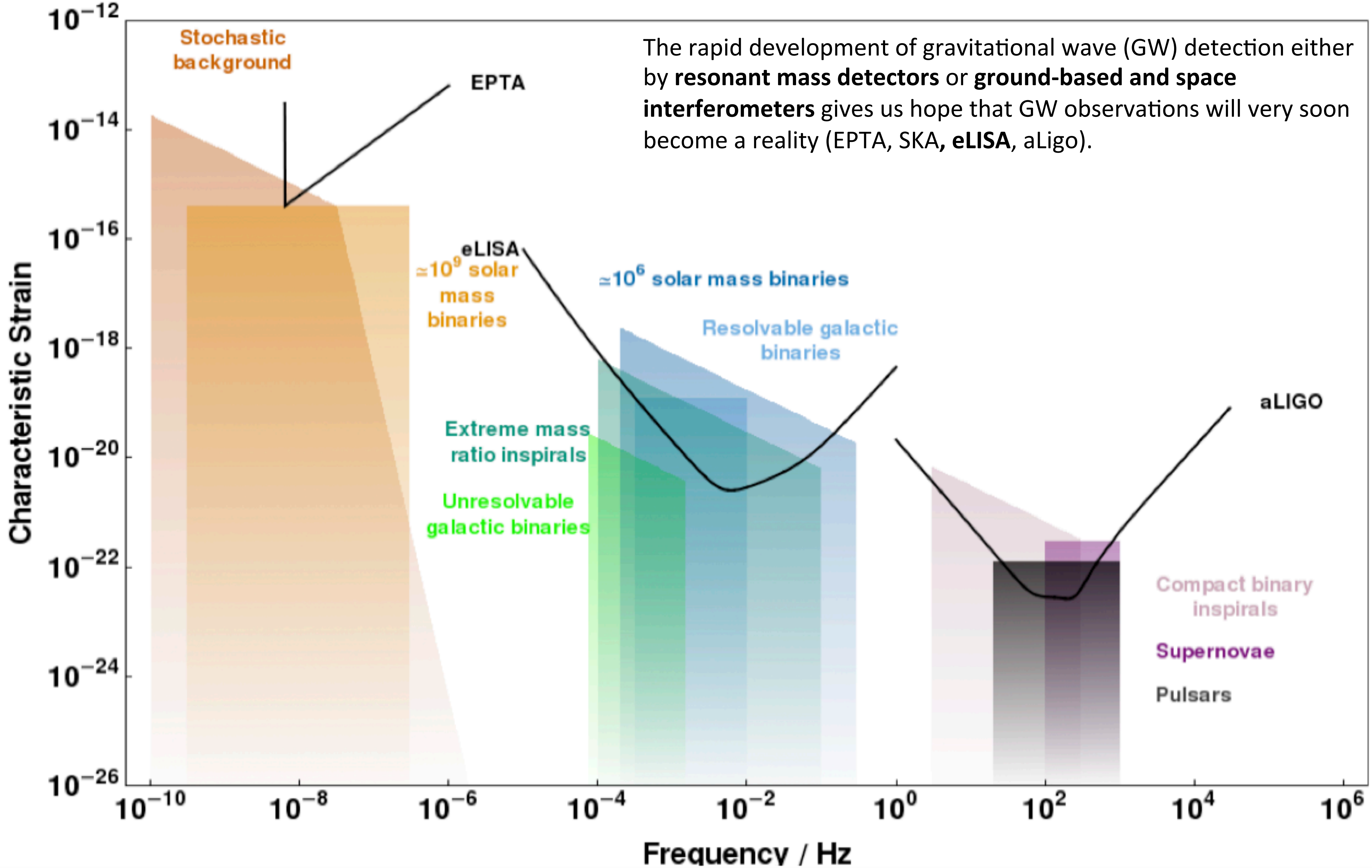
Gravitational waves are generated in many astrophysical systems like binary systems of Black holes, neutron stars and white dwarfs.

- GWs a **new window** to understand the Universe -- the formation of structure and galaxies, stellar evolution, the early universe, and the structure and nature of spacetime itself (e.g., Gair et al. 2013; Sathyaprakash & Schutz 2009).

Gravitational waves detectors and sources

Moore et al. 2014

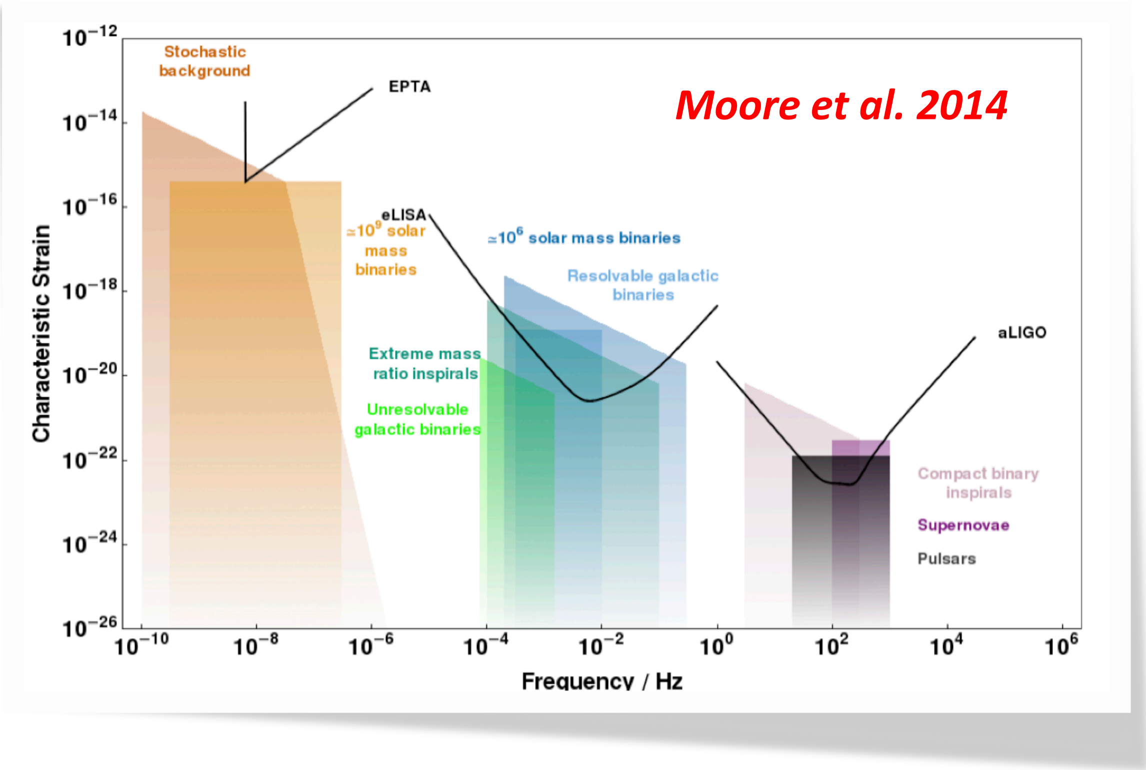
The rapid development of gravitational wave (GW) detection either by **resonant mass detectors** or **ground-based and space interferometers** gives us hope that GW observations will very soon become a reality (EPTA, SKA**, eLISA**, aLigo).



Gravitational waves detectors and sources

Current GW models predict waves with frequencies from 10^{-10} t0 10^{6} Hz and amplitude of the order of 10^{-18}.

The strain h is given by the ratio $\Delta L/L$, accordingly, for $h=\Delta L/L=10^{-18}$ a bar with a length L=1 m has $\Delta L=10^{-18}$ m or L=10 Km has $\Delta L=10^{-14}$ m (radius of a proton (fermi) ~ 10^{-15} m).



However, if L=7 10^{8} m (solar radius) $\Delta L=10^{-18} \times 7\ 10^{8} = 7\ 10^{-10}$ m.

Equally, L=20 × 7 10^{8} m (red giant radius), $\Delta L=20 \times 7\ 10^{-10} = 1.4\ 10^{-8}$ m.

Gravitational waves detectors and sources

Preliminary studies:

- The idea that gravitational radiation could excite the normal modes of vibration of celestial bodies such as the Earth and the Sun was originally discussed by Dyson (Dyson 1969). More recently, other authors have followed up this idea (e.g., Dyson1969; Zimmerman & Hellings 1980; Boughn & Kuhn 1984; Khosroshahi & Sobouti 1997).

- Boughn & Kuhn (1984) were the first to compute the impact of GW on solar gravity and acoustic modes, for which they also put upper limits on the stochastic gravitational background from the observed solar oscillations. Recently this results have been update by Siegel & Roth (2011-2014).

- McKernan et al. (2014) estimate the gravitational radiation that is absorbed by stars; In particular, they found that stars near massive black hole binaries (MBHB) can act as GW-charged batteries, cooling radiatively.

Gravitational waves detectors and sources

The Sun, as is the case for many other stars, is a natural massive GW detector with an isotropic sensitivity to GWs – able to absorb GWs from any direction of the sky.

Gravitational waves detectors and sources

Gravitational waves excitation of acoustic modes

- In a Galilean coordinate reference frame, whose origin coincides with the center of the star, the stellar material experiences a “Newtonian force” proportional to the perturbative space (-time) metric tensor h_{ij} (Misner et al. 1973).
- Only, quadrupole modes of vibration of the star (l=2, m=0,± 1, ± 2) will be excited by gravitational waves when the frequency of the incoming GW is close to the eigenfrequency of the mode.

Stellar oscillations in stars (e.g., Chaplin et al. 2005)

$$\boldsymbol{\xi}_N(\mathbf{r}, t) = A(t)\boldsymbol{\xi}_N(\mathbf{r})\ e^{-i\omega_{\rm N}t}$$

Stellar oscillations excited by a Gravitational Wave

$$\frac{d^2 A}{dt^2} + 2\eta_N \frac{dA}{dt} + \omega_N^2 A = \mathcal{S}_{\rm conv}(t) + \delta_2^l\ \mathcal{S}_{\rm gw}(t),$$

Lopes & Silk (ApJ 2014, 794 , 32)

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Gravitational waves detectors and sources

$$V_n(\omega_n) = \frac{h_\star L_n}{\alpha_s} \frac{\omega_n^2}{\eta_n}$$

Lopes & Silk (ApJ 2014)

- V_n – maximum amplitude of the photospheric velocity
- Acoustic mode (asteroseismology): frequency ω_n and damping rate μ_n
- Gravitational wave (monochromatic): frequency ω (~ω_n) and strain h_*
- L_n – "modal length" (sensitivity of the acoustic mode to the gravitational wave)

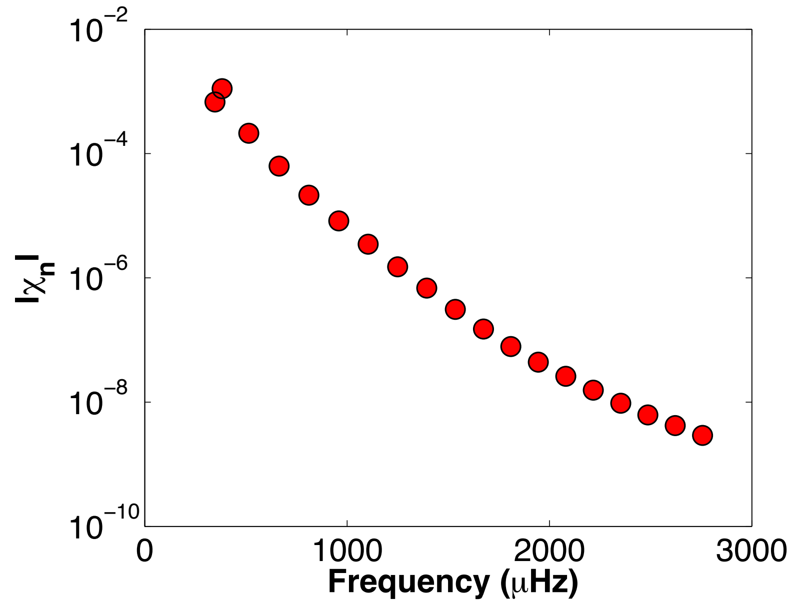
Gravitational waves detectors and sources

Internal Physics of the Star:

L_n – "modal length"

$$V_n(\omega_n) = \frac{h_\star L_n}{\alpha_s} \frac{\omega_n^2}{\eta_n}$$

$$L_n = 1/2 \, R \, \chi_n$$



$$\chi_n = \frac{3}{4\pi\bar{\rho}_\star} \int_0^1 \rho(r) \left[\xi_{r,n2}(z) + 3\xi_{h,n2}(z)\right] r^3 dr$$

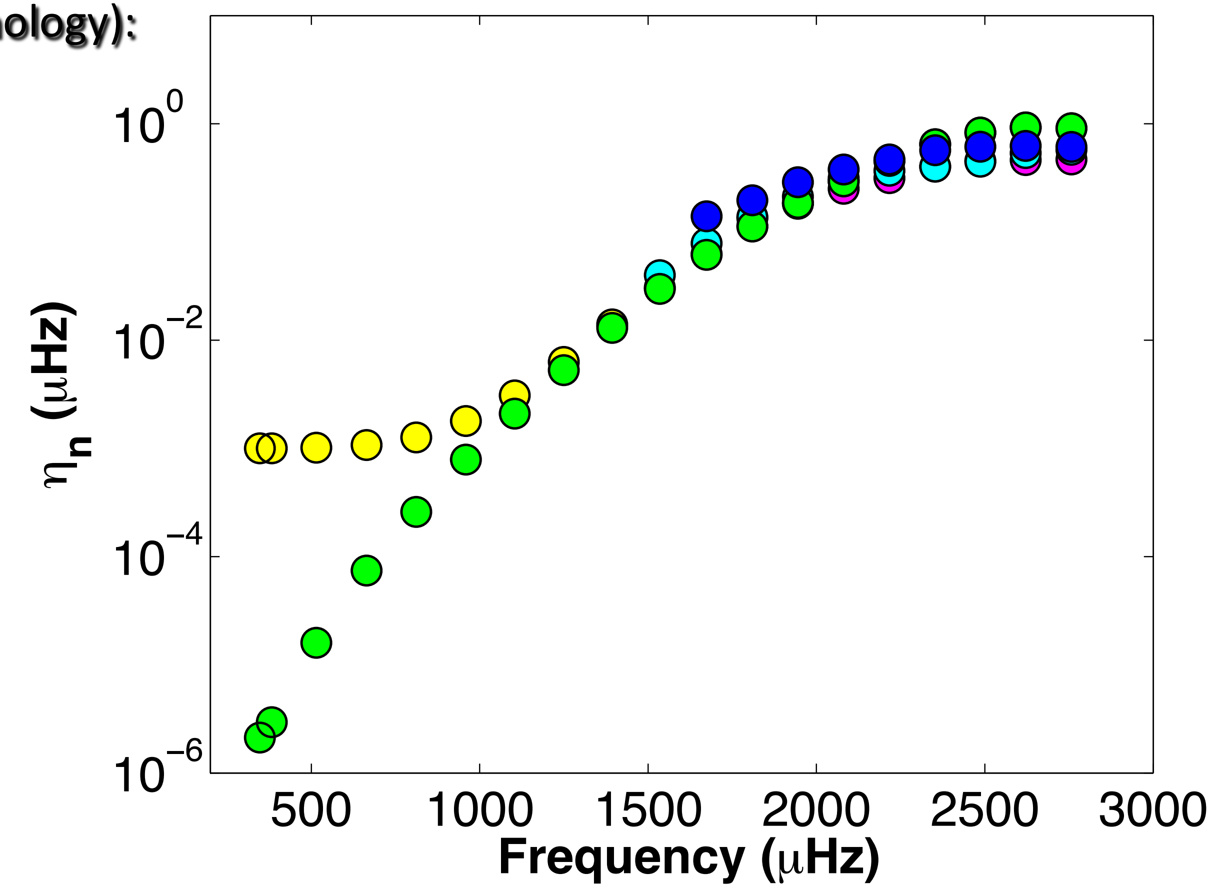
- For instance, the largest of the $|\chi_n|$ coefficients, $|\chi_1|$ has a value of 0.0011 for the Sun and 0.328 in the case of a resonant sphere (Maggiore 2008).
- $|L_n|$ takes values from 10^7 cm (n = 0) to 100 cm (n = 18).
- Quadrupole gravity modes (in the Sun) with larger $|\chi_n|$ are also potential GW probes (Siegel & Roth 2011), although the damping mechanism of these waves is poorly known.

Stars as gravitational waves detectors

Damping rates as a function of the frequency for the Sun.

Internal Physics of the Star (Astereoseismology):

$$V_n(\omega_n) = \frac{h_\star L_n}{\alpha_s} \frac{\omega_n^2}{\eta_n}$$



- Acoustic mode (asteroseismology): frequency ω_n and damping rate μ_n
- L_n – "modal length" (sensitivity of the acoustic mode to the gravitational wave)

The magenta, cyan, and blue dots correspond to the measurements made by Baudin et al. (2005), Chaplin et al. (1997), and Libbrecht (1988), and the green dots correspond to the theoretical predictions (Houdek et al. 1999;Houdek & Gough 2002; Belkacem et al. 2009).

Stars as gravitational waves detectors (sun-like stars)

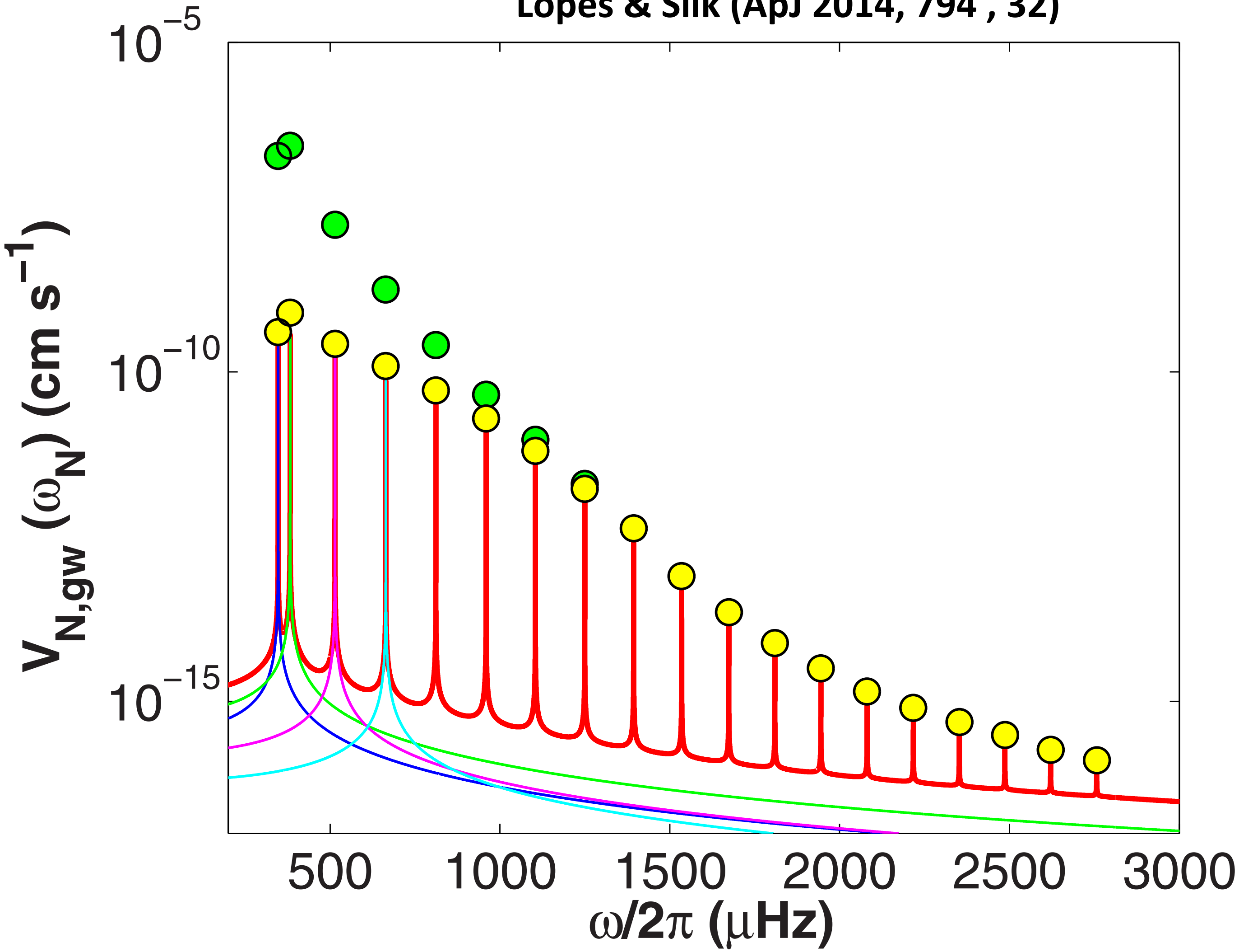
Green (and yellow) dots

$$V_n(\omega_n) = \frac{h_\star L_n}{\alpha_s} \frac{\omega_n^2}{\eta_n}$$

Only low order (acoustic) quadruple modes have sensitivity to gravitational waves.

The rapid decrease of V_n with n is related with the low sensitivity of acoustic modes (L_n) to the core of the star.

Lopes & Silk (ApJ 2014, 794 , 32)



$$V_{N,gw}^2(\omega) = \frac{1/2\ \gamma_s\ h_o^2\ L_n^2\ \omega^6}{\left(\omega^2 - \omega_N^2\right)^2 + 4\eta_N^2\omega^2}$$

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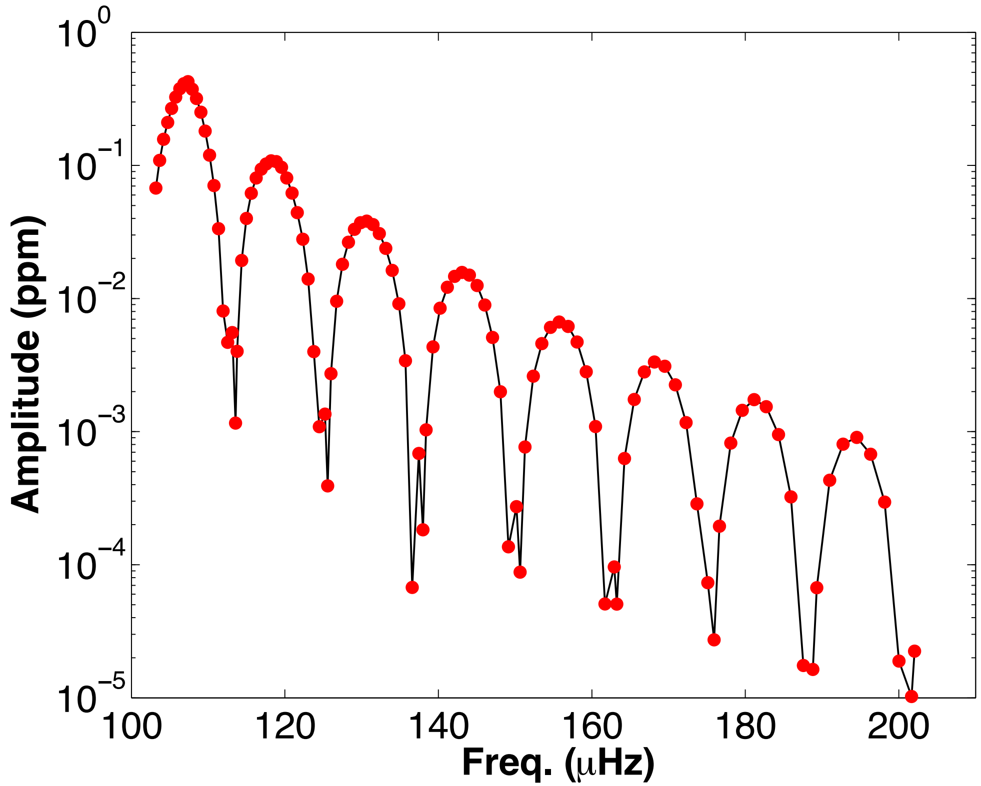
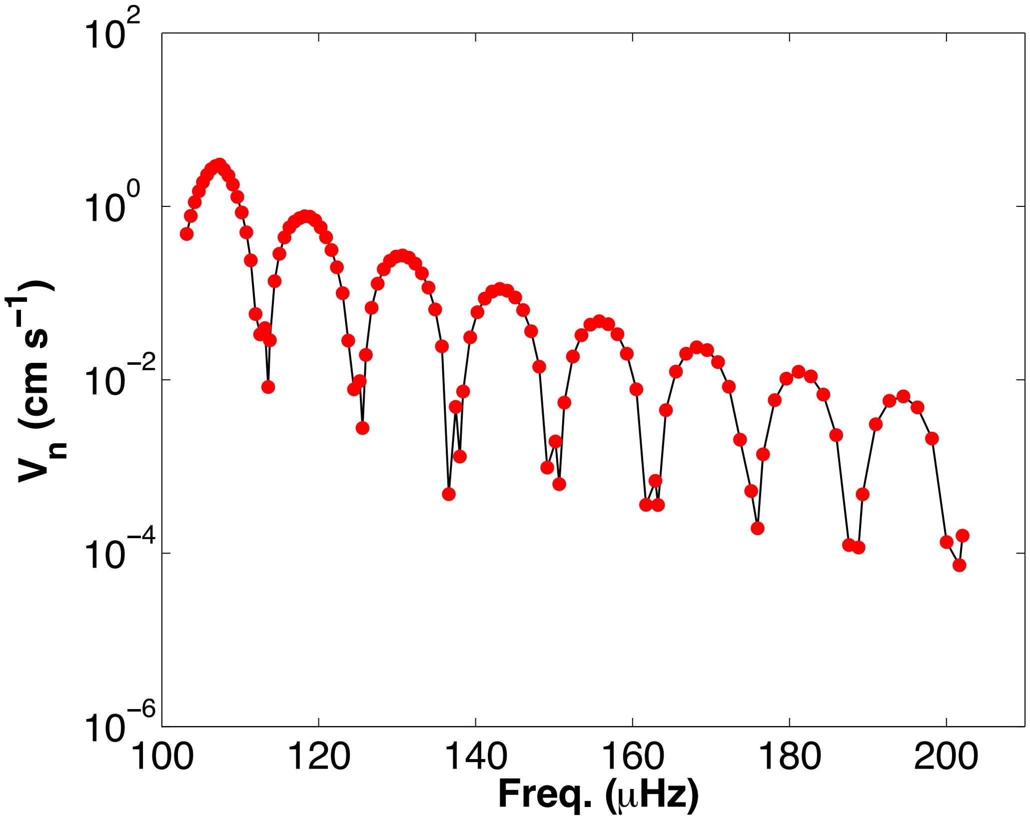
Stars as gravitational waves detectors (red giant stars)



Lopes et al. (in progress 2015)



$$V_n(\omega_n) = \frac{h_\star L_n}{\alpha_s} \frac{\omega_n^2}{\eta_n}$$

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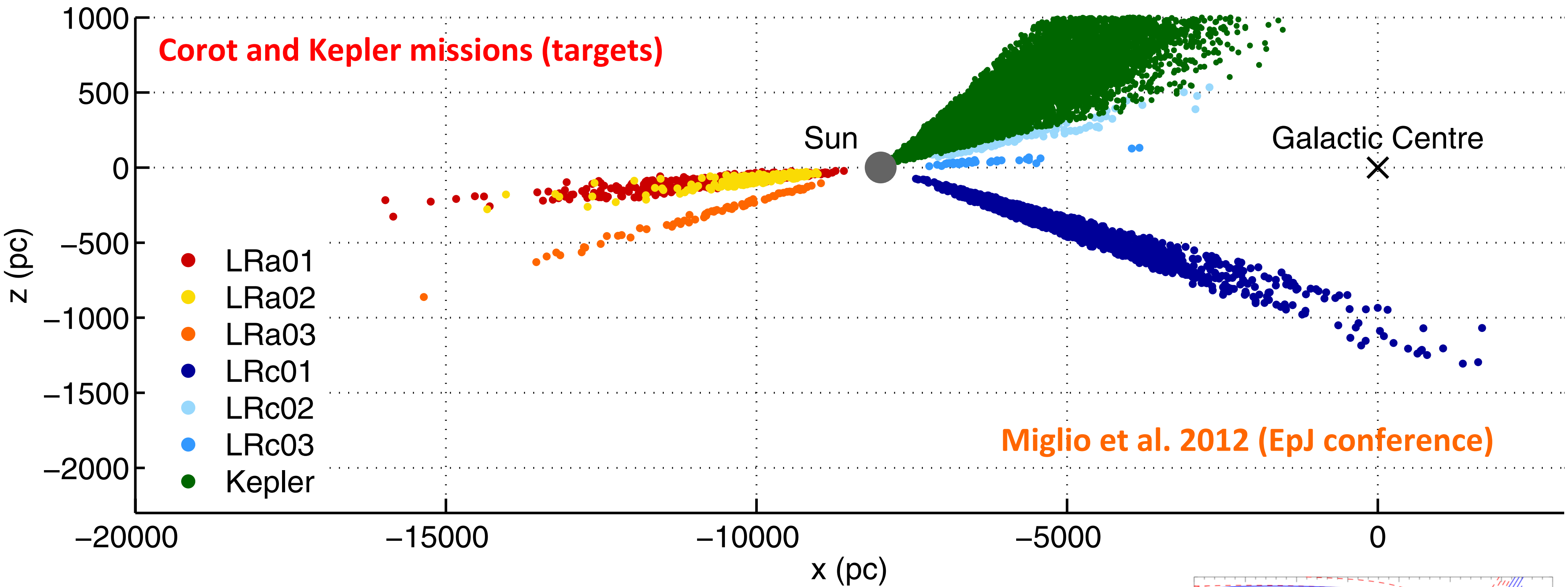
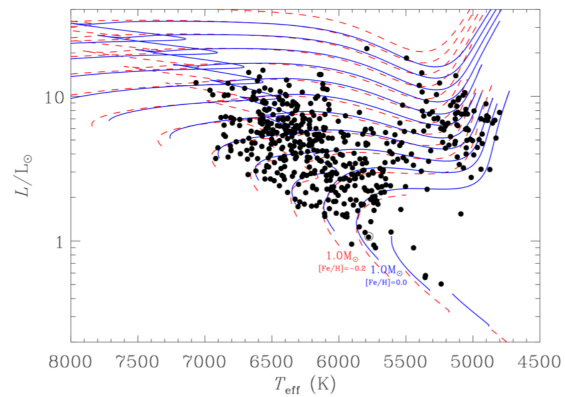
Stars as gravitational waves detectors – oscillating stars



Discovery of oscillations in Main sequence, sub-giant stars (~ 500) and red giant stars (~ 12 000) in the solar neighbourhood.



For many of these stars, a few tens of acoustic modes are measured with precision frequencies and damping rates (l=0,1,2 and 3)

Chaplin et al. (ApJ Sup. 2014)

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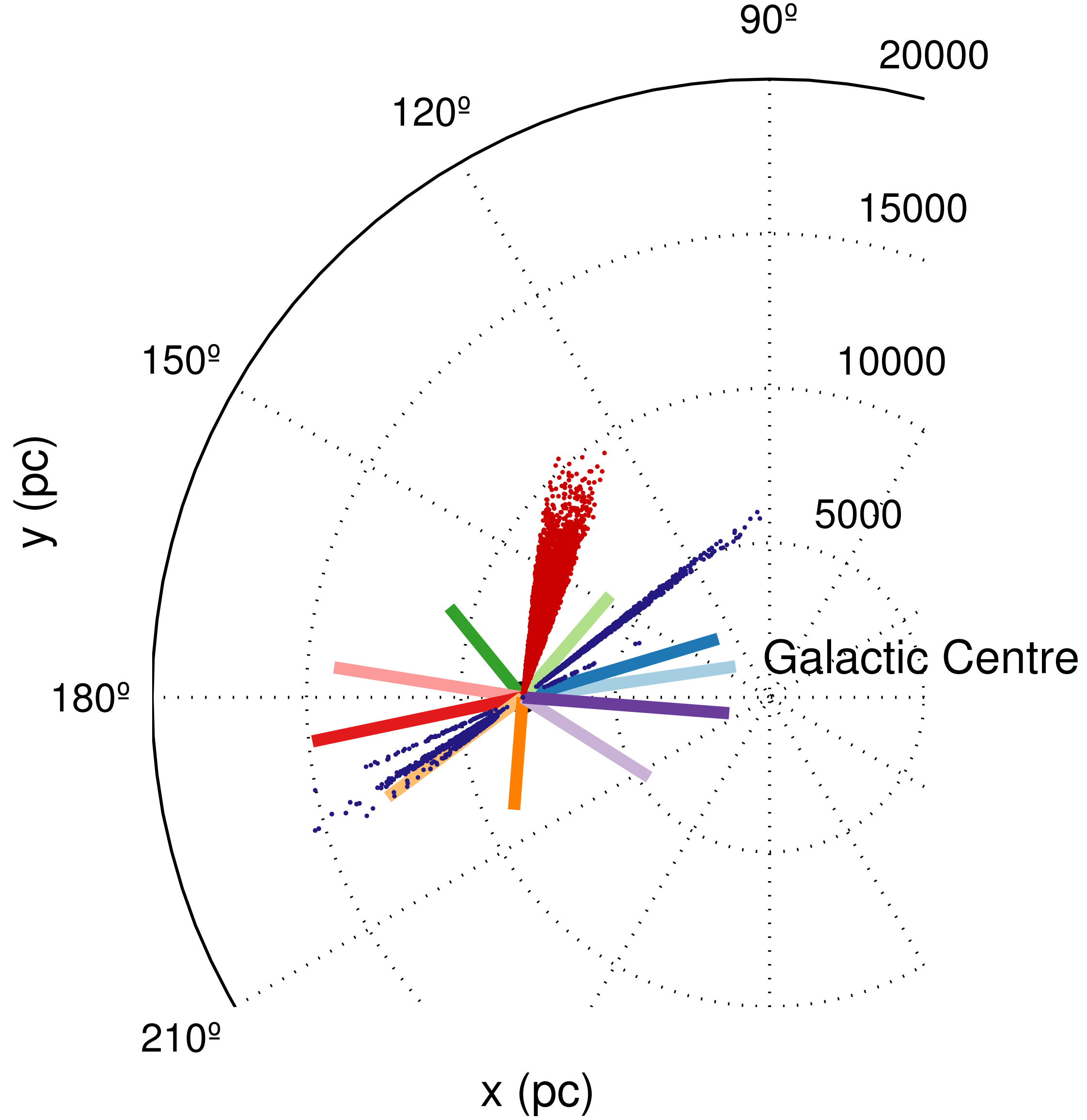
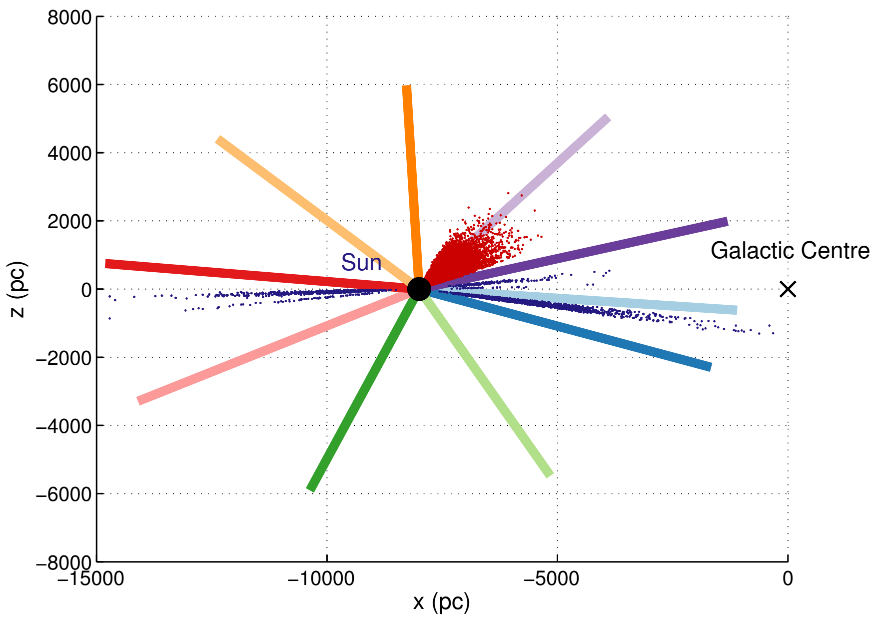
Stars as gravitational waves detectors – oscillating stars

Corot, Kepler (+K2) missions (targets)





Miglio et al. 2014

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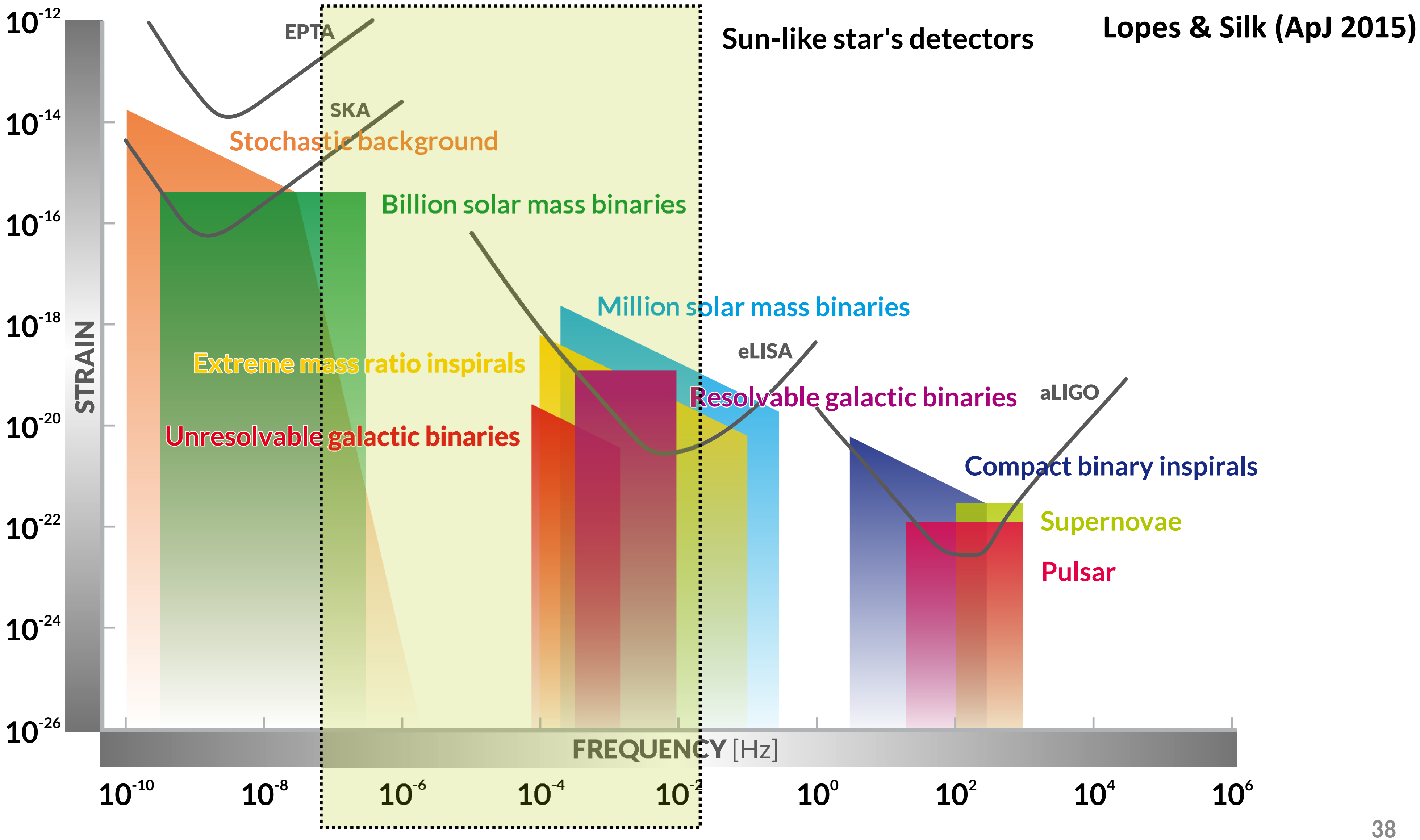
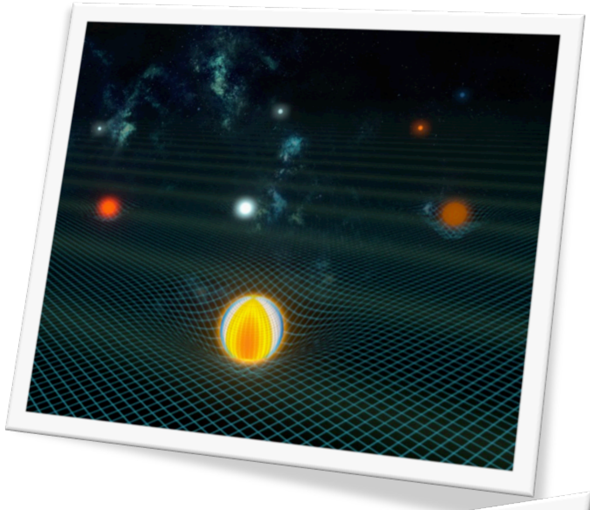
Gravitational Wave Detectors and Sources

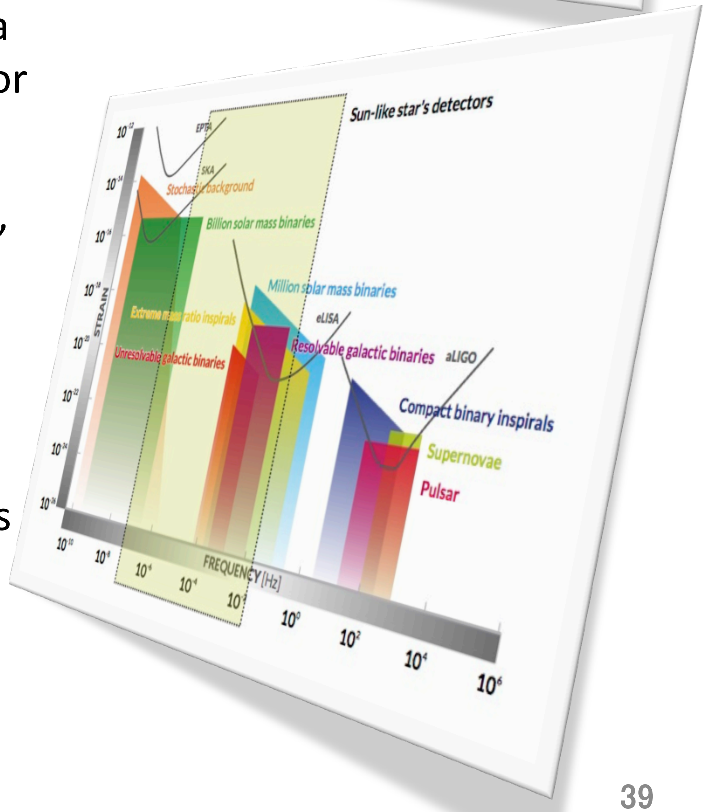
Main sequence, sub-giants and red giant stars (seismology): In principle can be used as detectors of gravitational waves



Gravitational Waves

- Stars and GW detectors:
- Sun-like oscillations were discovered in five hundred main sequence and sub-giant stars and in more than twelve thousand red giant stars in the solar neighbourhood.
- Sun-like oscillating stars form a set of natural detectors that can be used to search for gravitational waves in a large frequency range of the spectrum, from 10−7 Hz to 10−2 Hz.
- The group of all oscillating stars in the solar neighbourhood within a five thousand parsecs radius, constitutes the largest detector ever for gravitational radiation.
- There are thousands of oscillating stars scattered throughout space, some of which can be found relatively near gravitational wave sources.
- Alignments of stars between the source and the Solar System can monitor the progression of gravitational waves throughout space, which can be used as a test to probe General Relativity, a goal that is difficult to achieve with present man-made detectors.

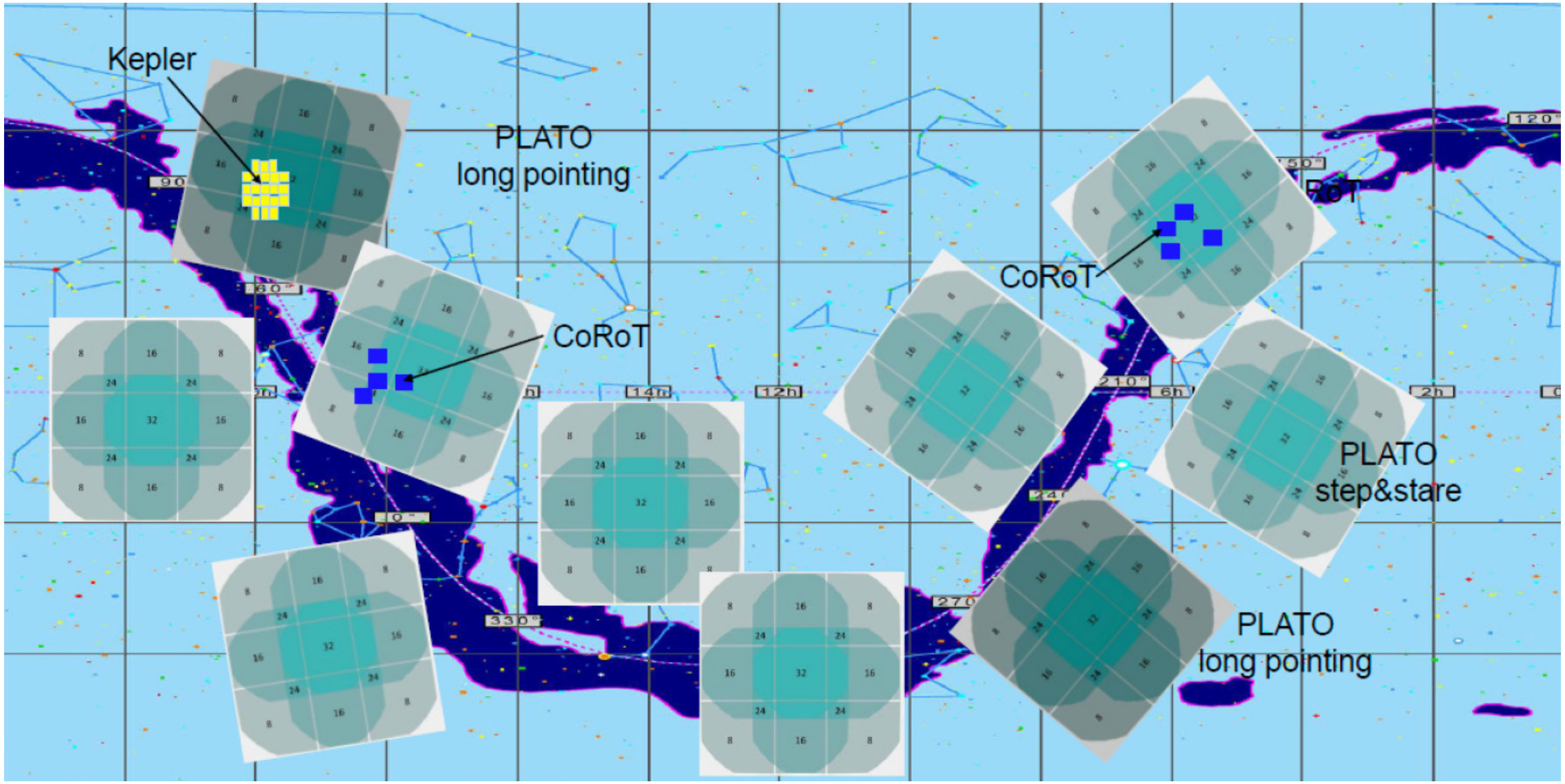




Conclusion

Fundamental Physics . New Detectors

Plato (2024)



Schematic comparison of PLATO 2.0, CoRoT and Kepler's fields of view and observational strategy. With a combination of short (step-and-stare) and long duration pointings PLATO 2.0 will cover a large fraction of the sky. Note that the final locations of long and step-and-stare fieldswill be defined after mission selection and are drawn here for illustration only.

(By detecting solar-like oscillations in 85,000 nearby dwarfs and an even larger number of giants)

Conclusion

Stars are a fundamental tool to probe the nature of fundamental physics.

- In the last 50 years*, **Helioseismology*** revealed a very complex and dynamical Sun.
- In the following decades, ***Asteroseismology*** will change our view about the formation and evolution of stars as well our understating of fundamental physics.
- **(Optimistic View)**: "The continuous observation and monitoring of the oscillation spectra of the stars around us, within a sphere of up to one thousand parsecs, could lead to the discovery of gravitational waves originating in our Galaxy or even elsewhere in the Universe."

Thank you