Stars and Dark Matter

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Winter Workshop

MULTIMESSENGERS @ PRAGUE

TÉCNICO LISBOA

Center for Astrophysics and Gravitation

centra

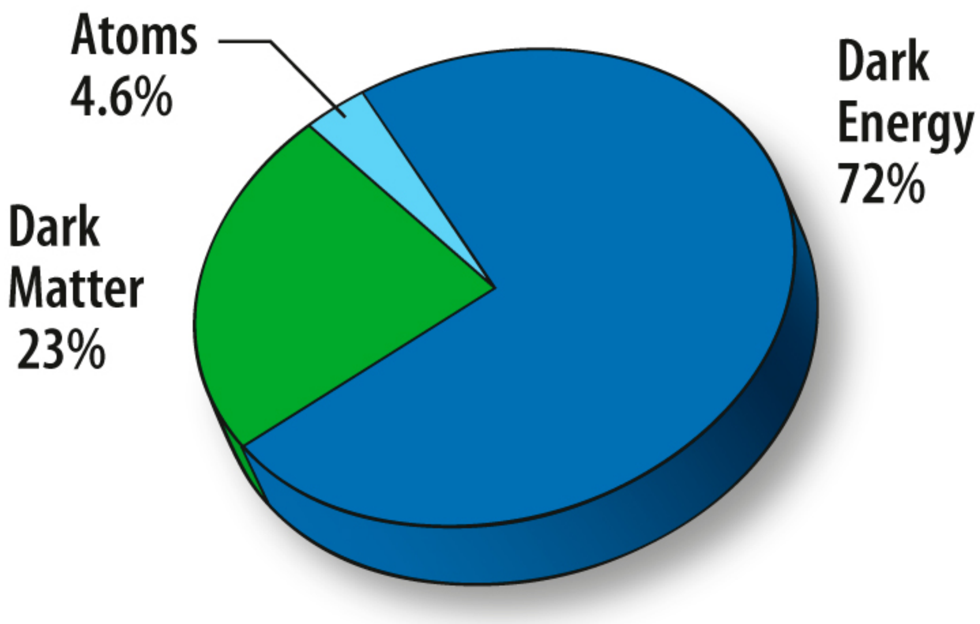
Outline

- Dark Matter in the Universe
  - Evidence in the Universe and Milky Way
  - Status of the standard model of particle physics and beyond.
- How Dark Matter affects Stars
  - Capture, annihilation and transport of energy.
- Dark Matter Constraints
  - Helioseismology, solar neutrinos, and Asteroseismology.
  - Stellar Clusters
- Conclusion
  - What we know, and what we can learn

Dark Matter in the Universe

Dark Matter in the Universe

Energy density



Today

https://wmap.gsfc.nasa.gov/universe/uni_matter.html

Lambda-CDM Model: The dark matter creates the gravitational web for the formation of structures that reproduces the observed present baryonic structure of the Universe, i.e., stars, stellar clusters, galaxies, galaxy clusters.

Dark Matter in the Universe

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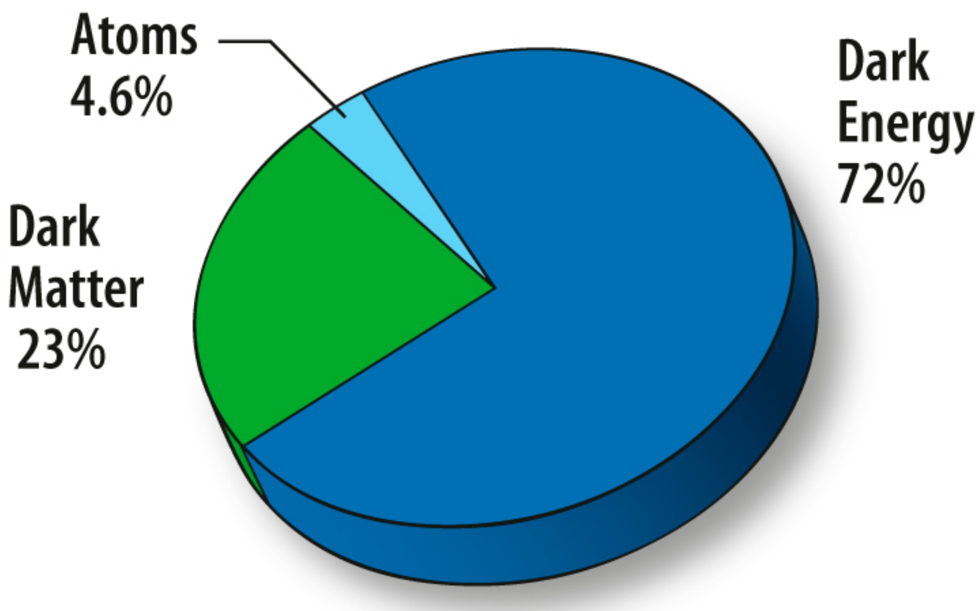

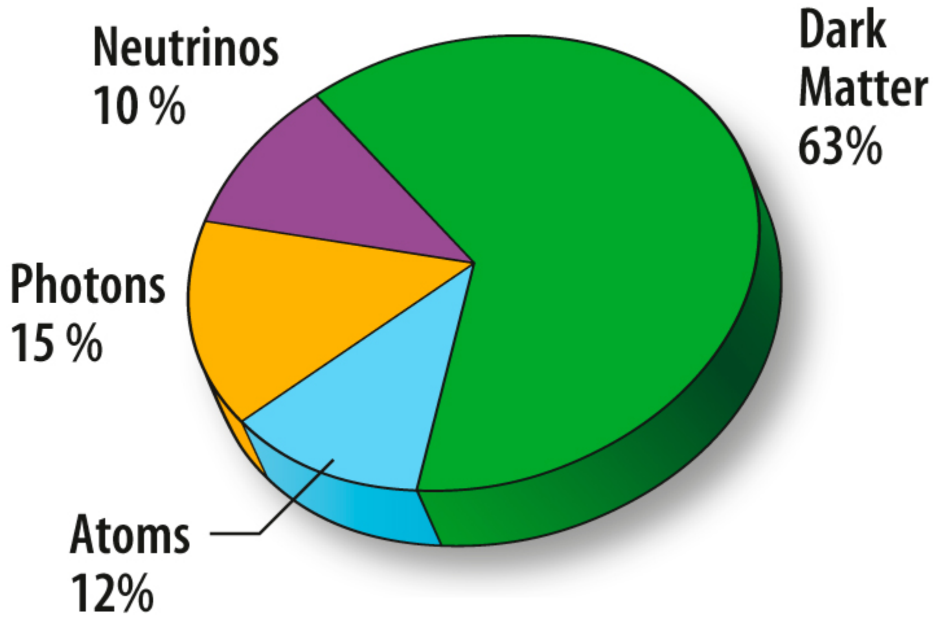

Today

~ 380 000 years (CMB)

https://wmap.gsfc.nasa.gov/universe/uni_matter.html

Nature of Dark Matter:

cold weakly interacting particles

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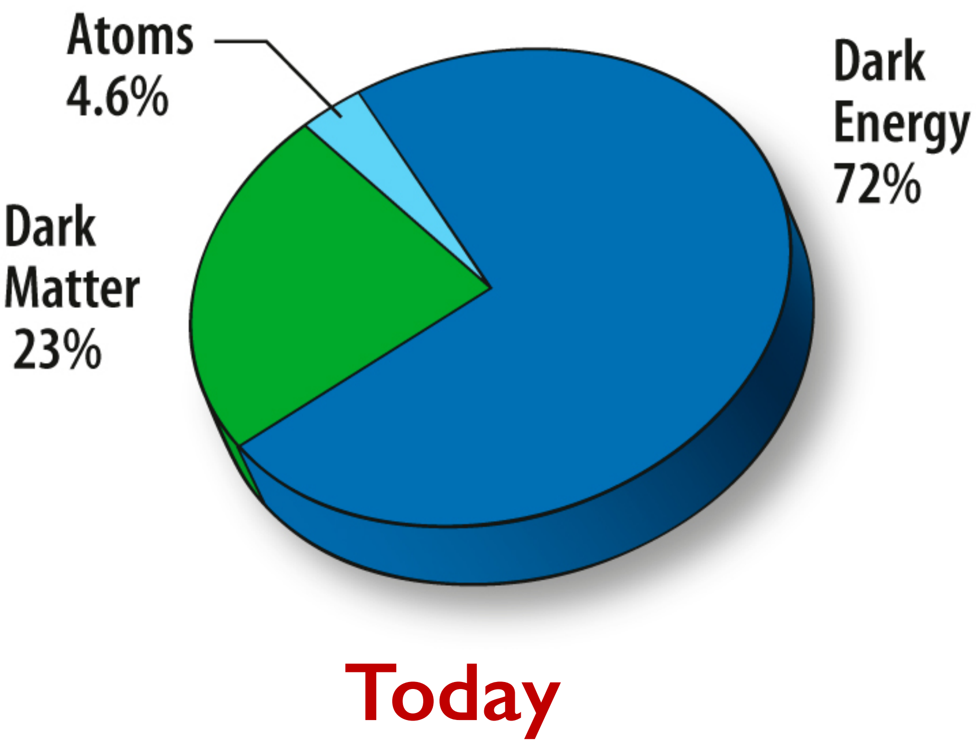
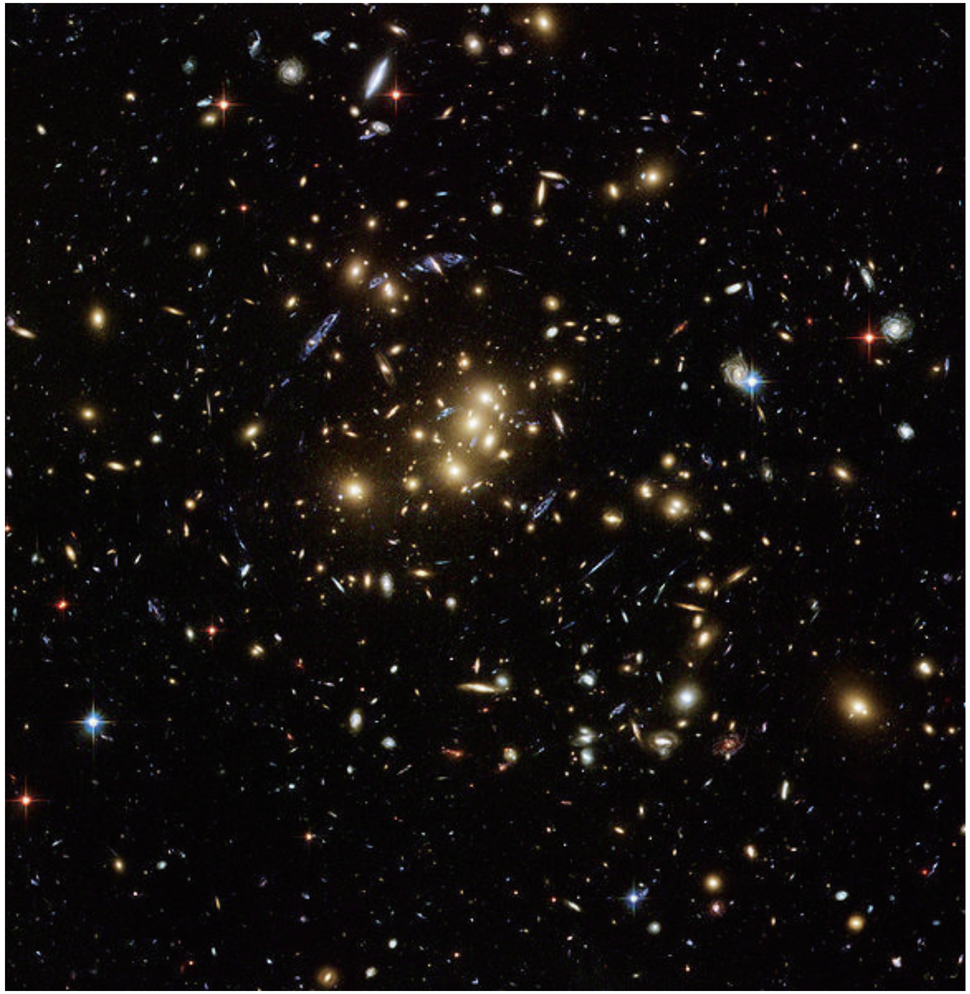
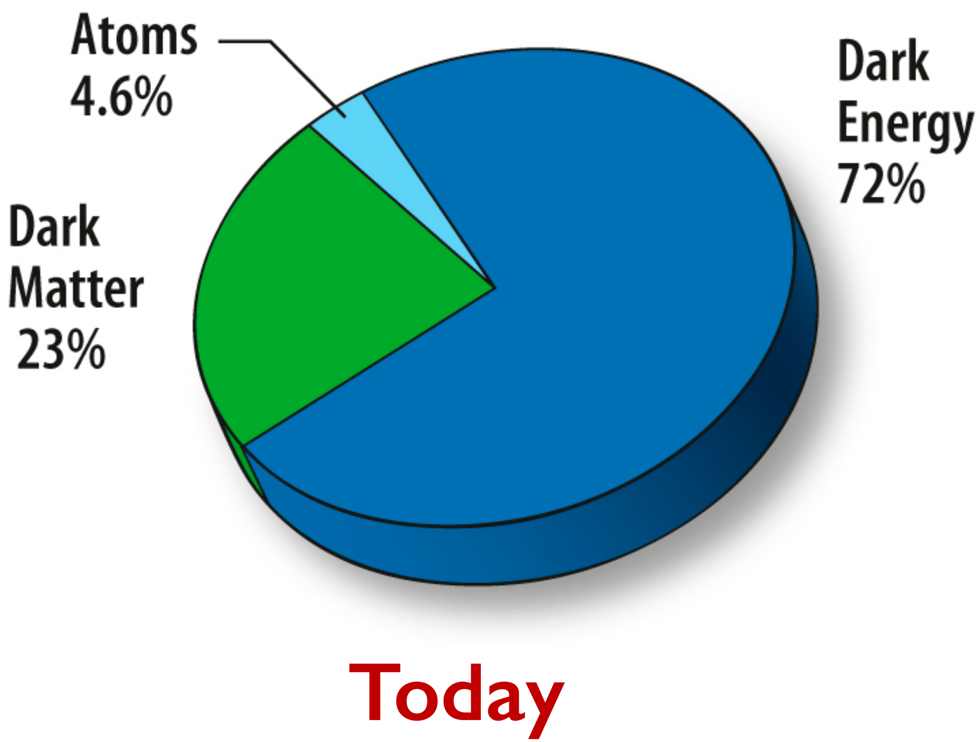




CL0024+17 cluster of galaxies (HST, 2004): Gravitational lensing, the bending of light rays by gravity, can also give us a cluster's mass.

Observational Evidence: This HST optical image of the galaxy cluster CL 0024+17 shows the gravitational lensing of faraway galaxies by the nearby galaxies. The dark matter clustered around each galaxy creates the gravitational lensing.

Dark Matter in the Universe (Zoom in)



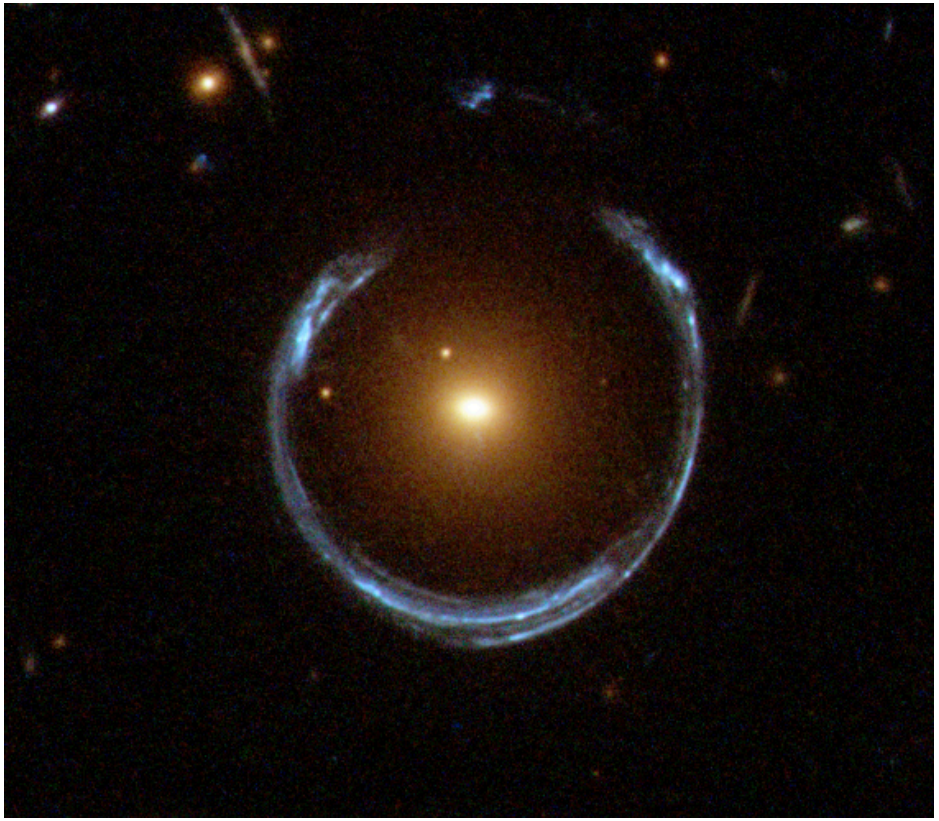


Image LRG 3-757 (HST): the gravitational field of an orange luminous galaxy gravitationally distorted the light from a much more distant blue galaxy. The almost perfect alignment between Earth and the blue galaxy gives rise to the resulting image that is an **almost complete Einstein ring** (Belokurov et al. ApJ 2007).

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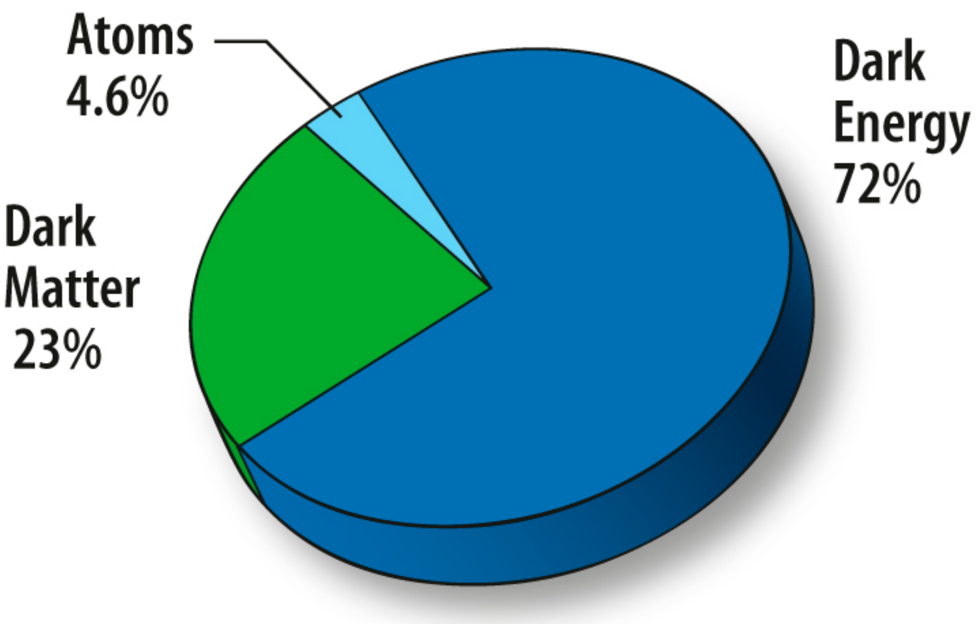

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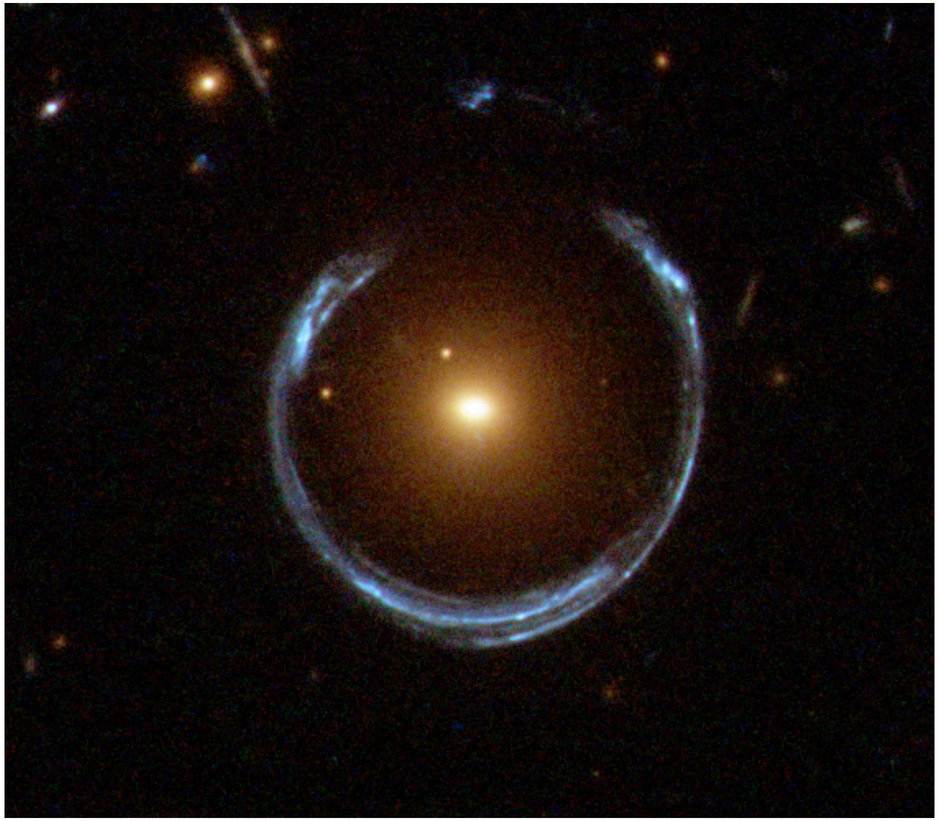

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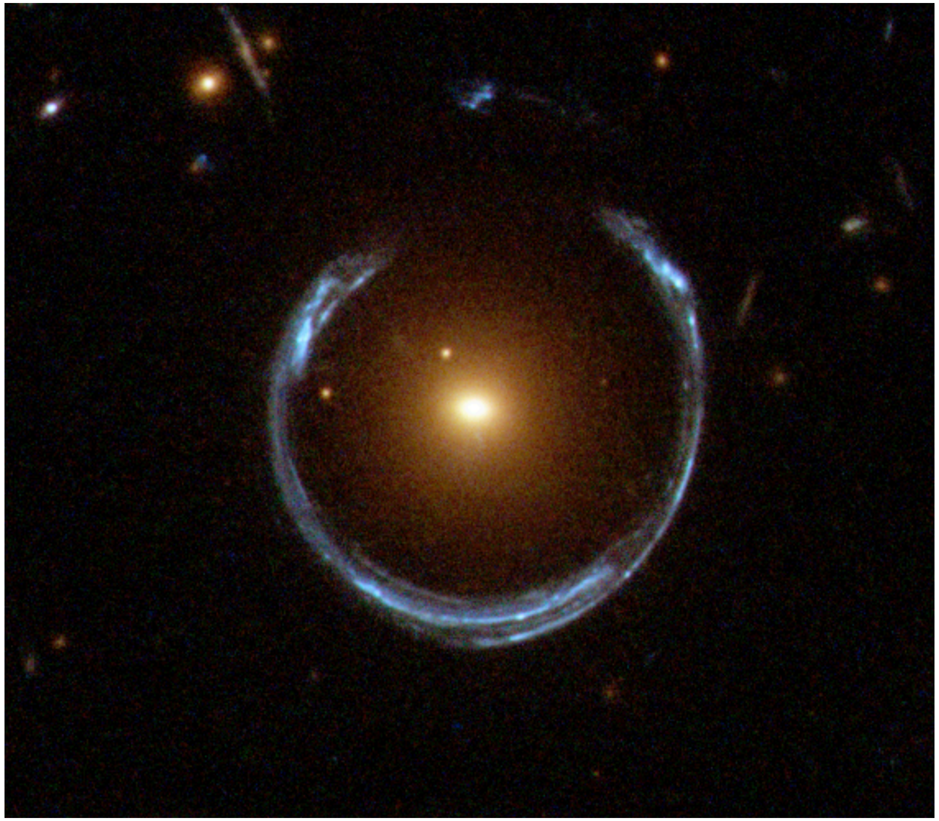
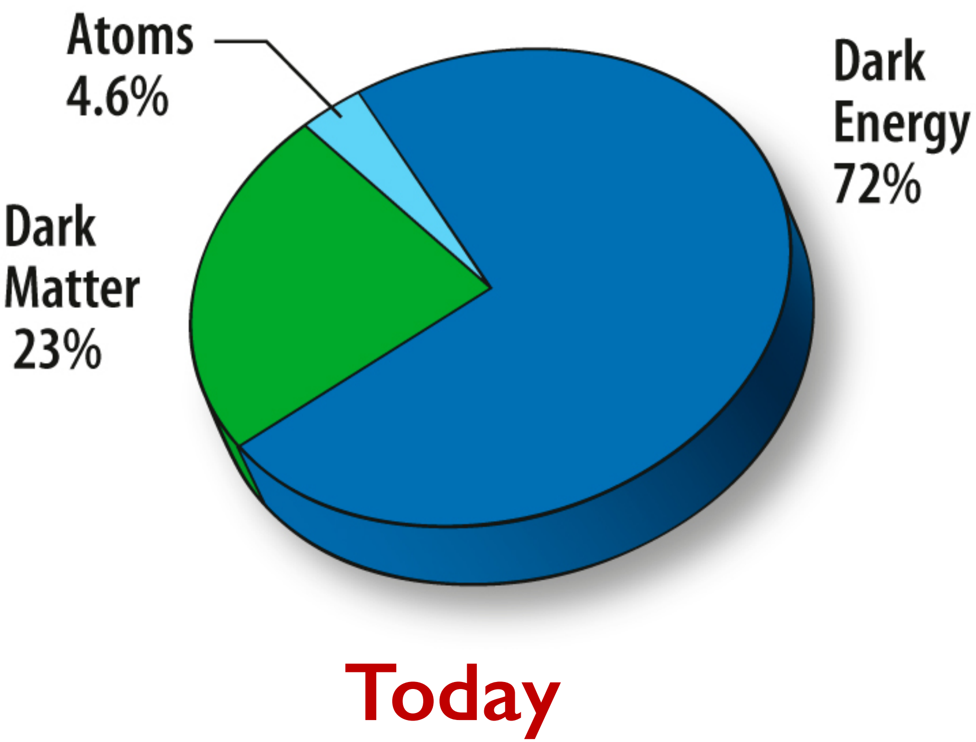
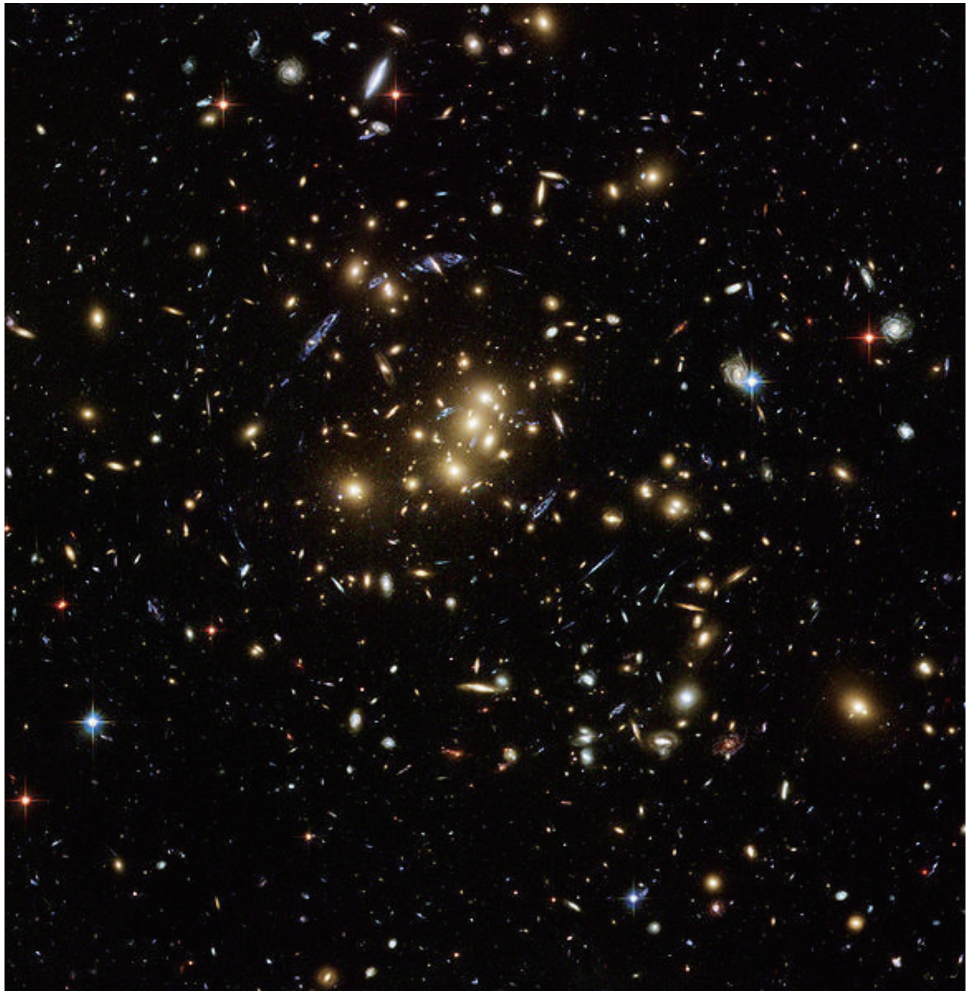


Image LRG 3-757 (HST)

What is the radial density profile of dark matter in this galaxy?

Dark Matter in the Universe





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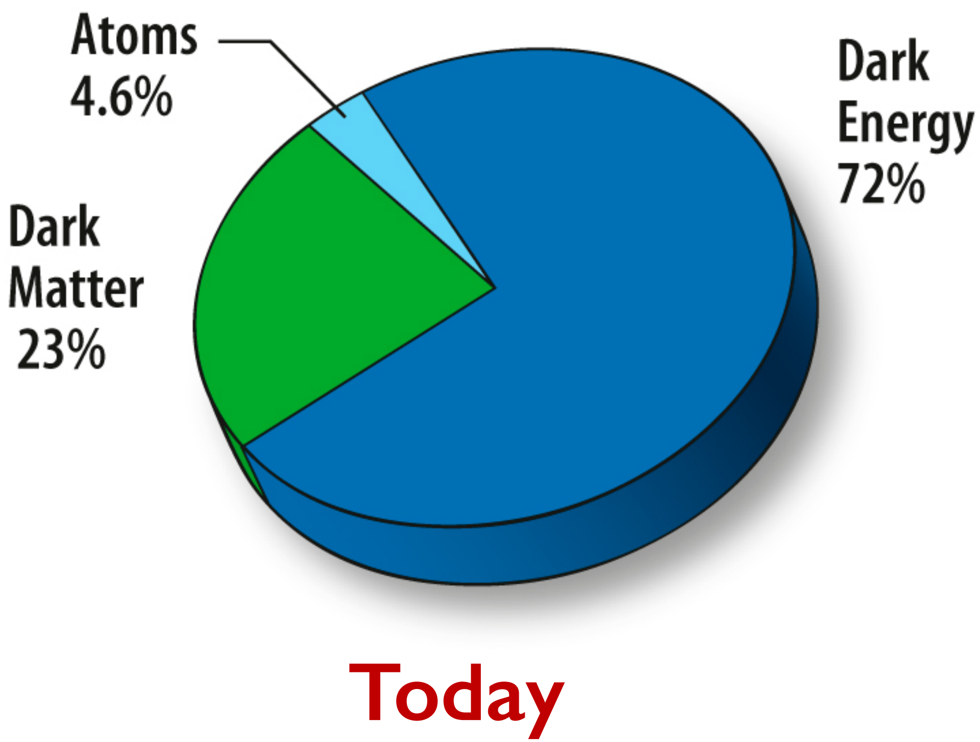
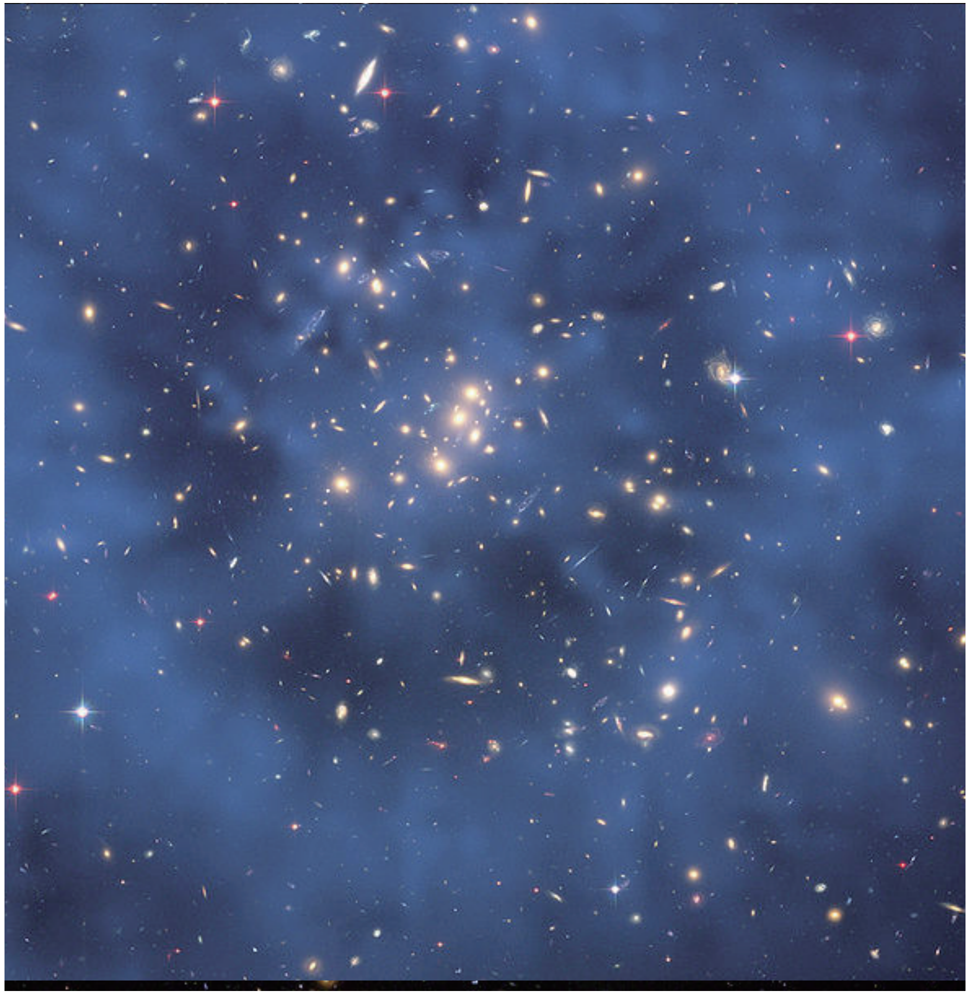


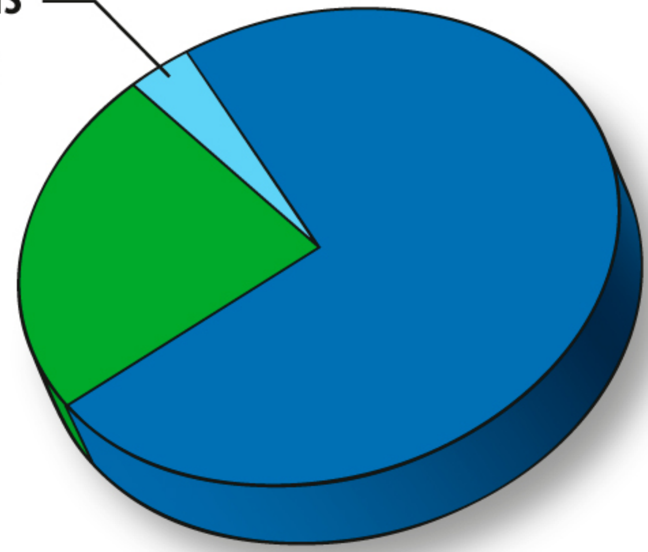


The gravity map super-imposed on the HST image which shows a dark matter distribution in the central region and a thick ring.

CL0024+17 cluster of galaxies (HST, 2004): Gravitational lensing, the bending of light rays by gravity, can also give us a cluster's mass.

Observational Evidence: A strong evidence of dark matter is the HST image of the galaxy cluster CL0024+17 as shown in this Figure. Because of their mutual gravitational attraction, dark matter and visible material are generally expected to be together, however in this image the dark matter distribution does not match with that of the stars and hot gas.

Dark Matter in the Universe



Today

Bullet cluster of galaxies 1E 0657-56

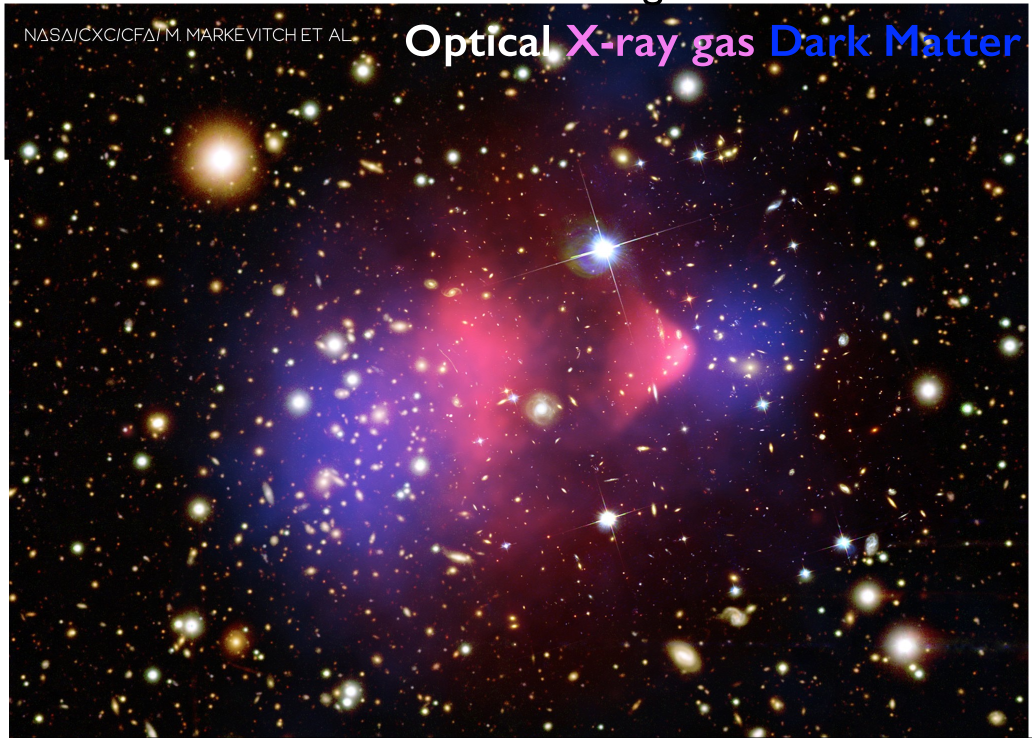


Image: optical, pink: X-ray gas, blue: lensing mass

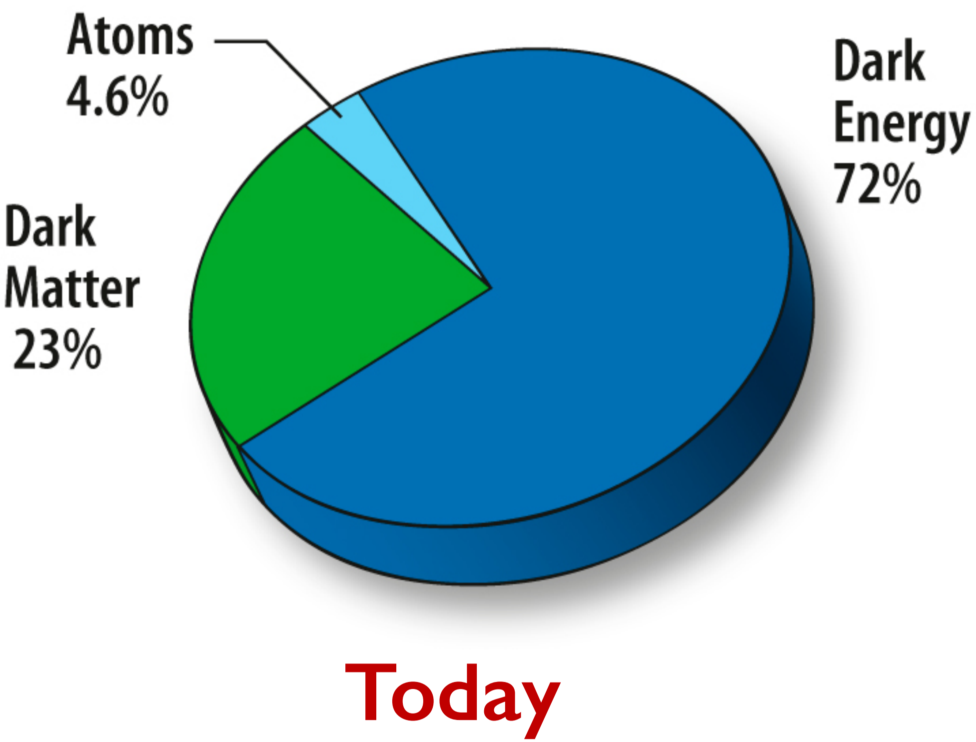
M_{total}: M_{gas}: M_{star} ~ 70:10:1

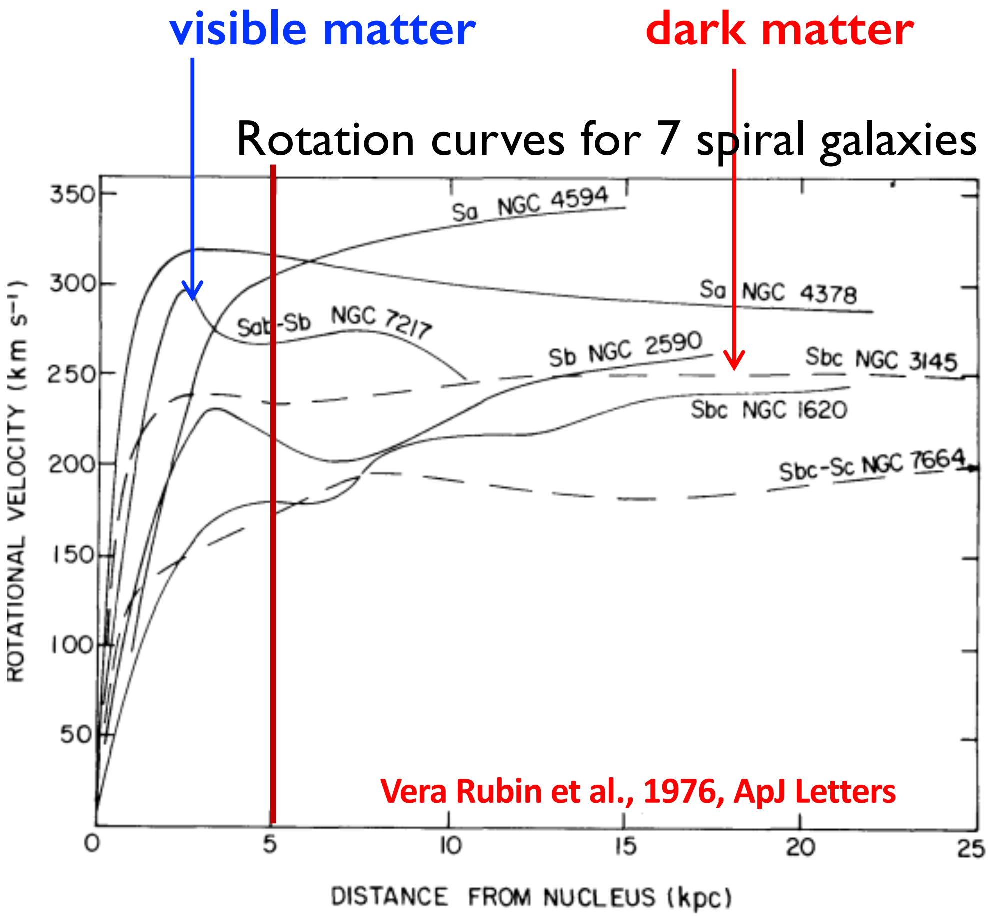
Clowe, Gonzalez & Markevitch ApJ 2004

+ 72 bullet clusters by Harvey et al. Science 2015

Observational Evidence: This image of the bullet cluster is a composite of optical (HST: white), X-ray (Chandra X-ray Observatory: pink), and a reconstructed mass map (lensing mass: blue). It shows that the total mass of the system (galaxies +dark matter) is not where is the X-ray gas. This fixes a lower limit for dark matter self-interaction cross-section: $\boldsymbol{\sigma_{\chi\chi}}/m_\chi < 8.3 \times 10^{-25}$ cm2/GeV at 95% CL.

Dark Matter in the Universe



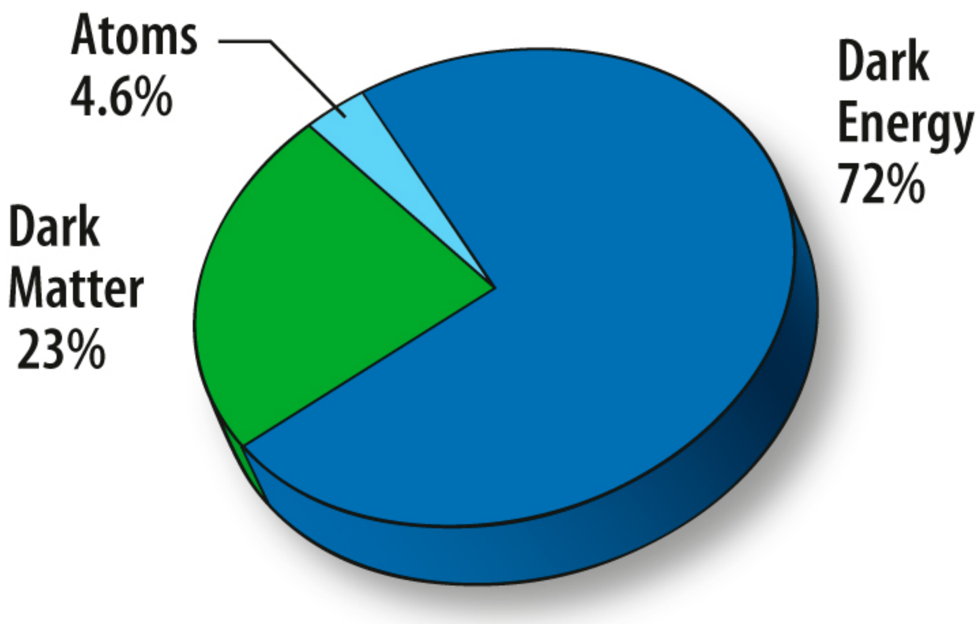


Vera Rubin and Kent Ford have made these critical observations in 1975.

The radius of 90% of the enclosed "visible matter" is shown as the vertical red line.

Observational Evidence: Galaxy Rotation Curves - dark matter exists within the galaxies themselves, where the velocity of stars (and gas) was found to be flat and not decreasing with the distance from the galaxy centre.

Dark Matter in the Universe



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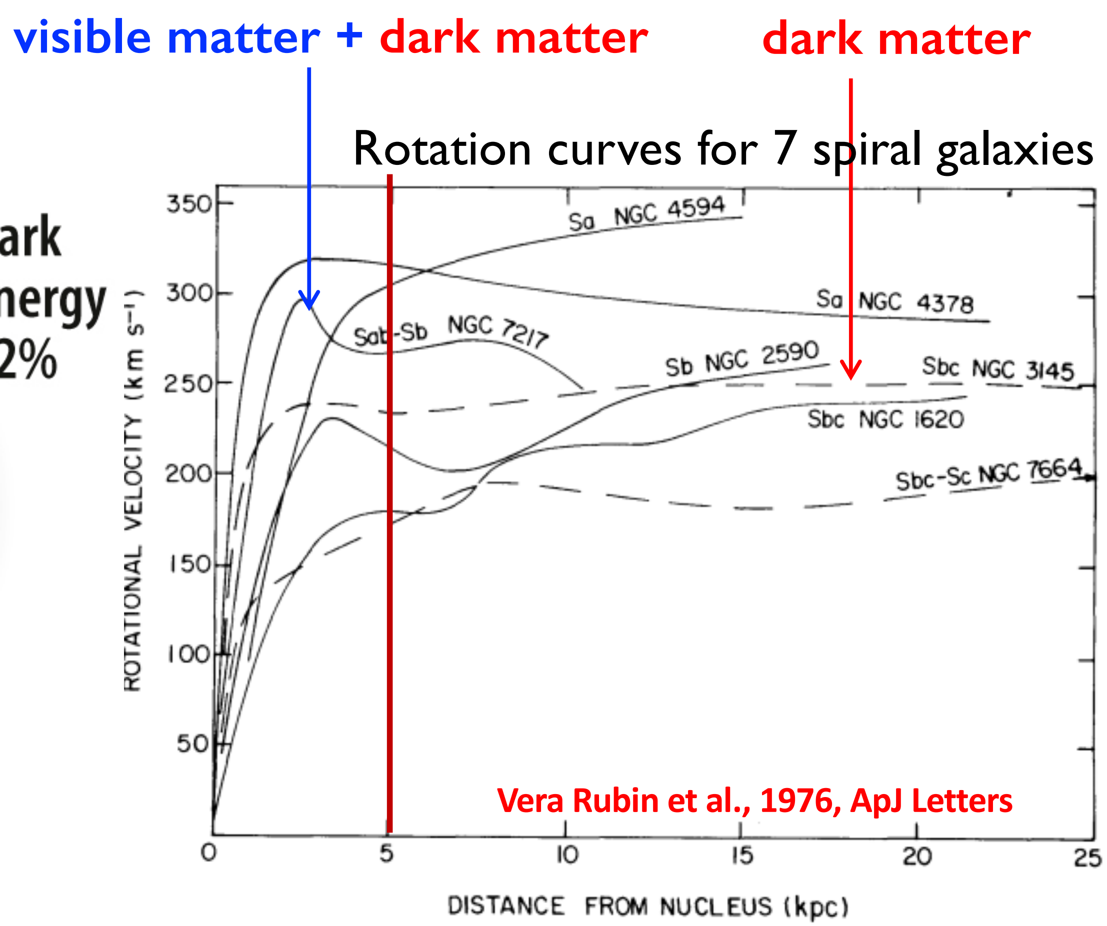

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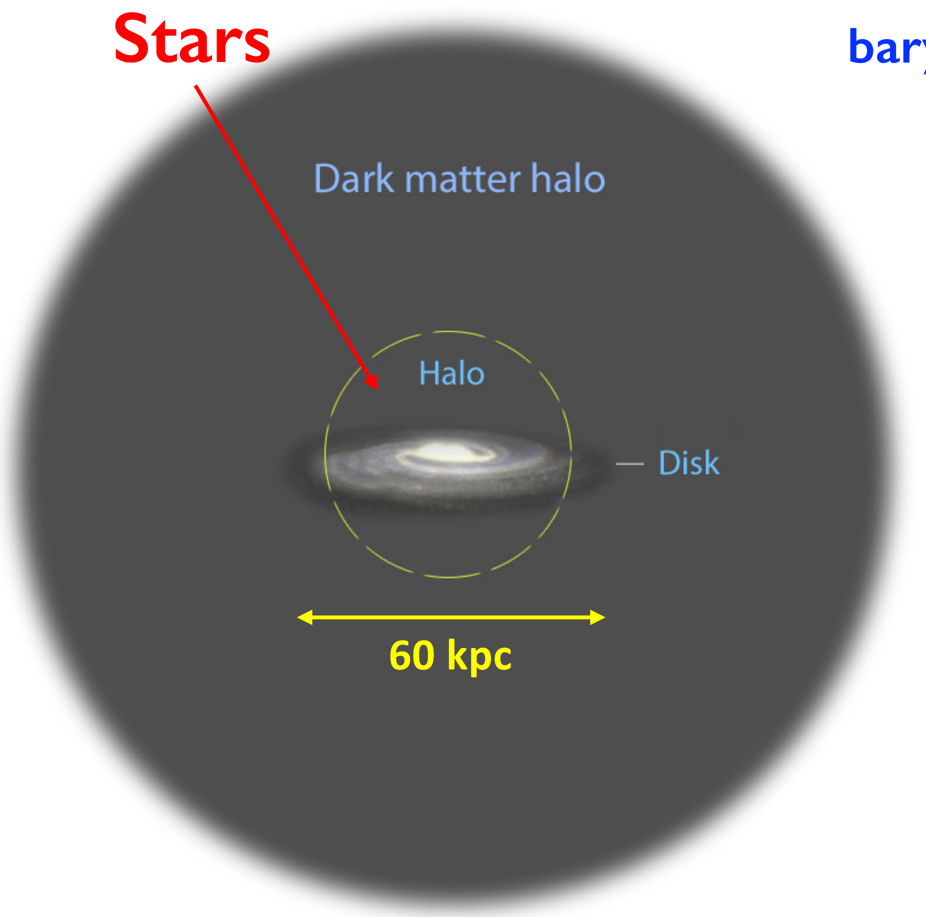
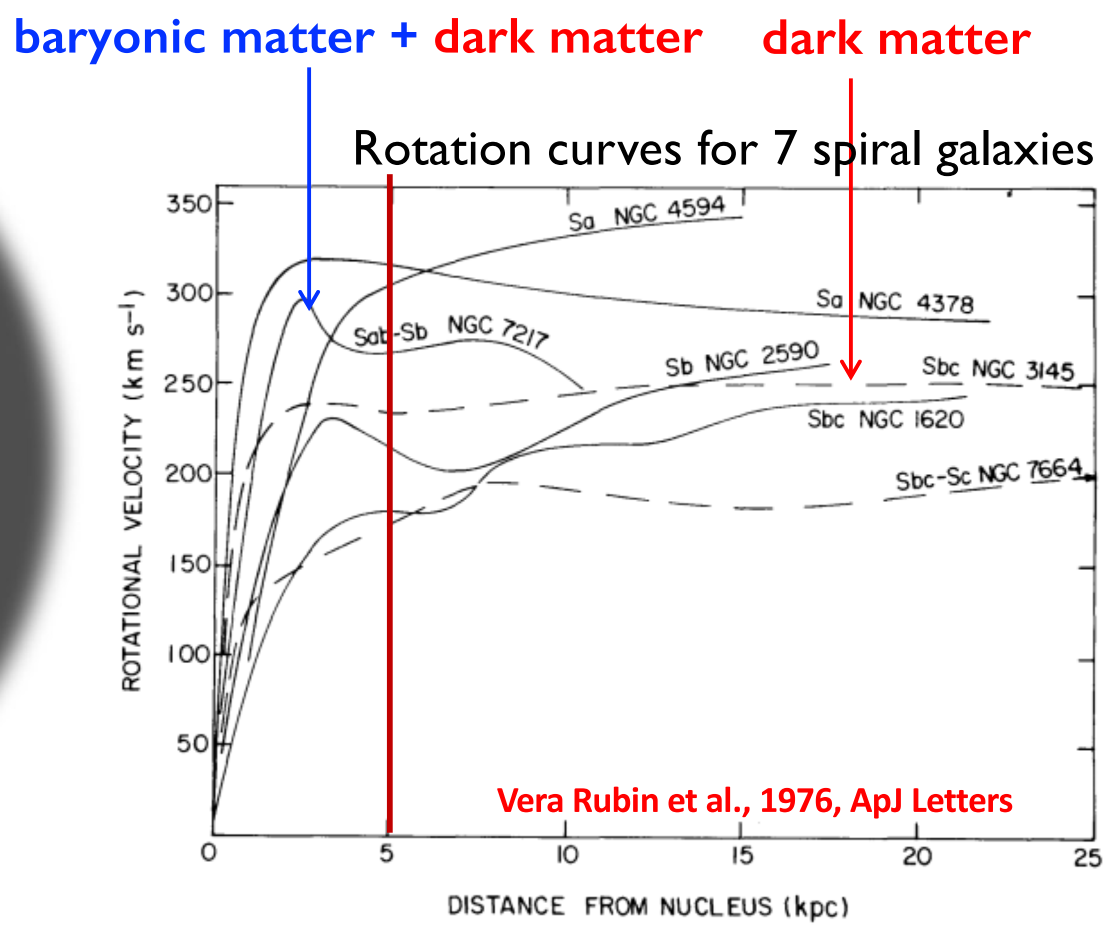
Observational Evidence: Inner galactic core (Milky Way), the comparison of the observed rotation curve (data from gas and stars kinematics) with the predictions of baryonic models strongly support the existence of dark matter (Iocco et al. 2015, Nature Physics).

Dark Matter in the Universe

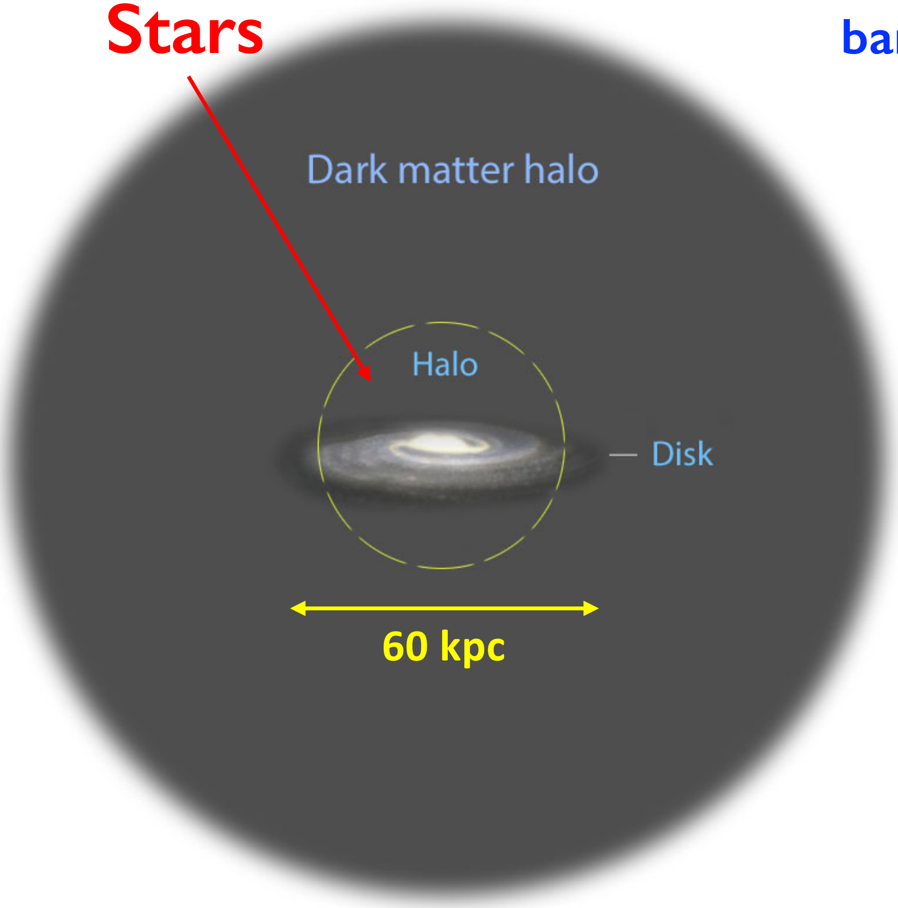


Milky Way : Standard DM Halo



In the standard cosmological model, **the dark matter halo** of a galaxy like the Milky Way forms from the merger and accretion of smaller sub-halos. These sub-units also harbour stars, typically old and metal-poor, that are deposited in the inner galactic regions by disruption events.

Dark Matter in the Universe



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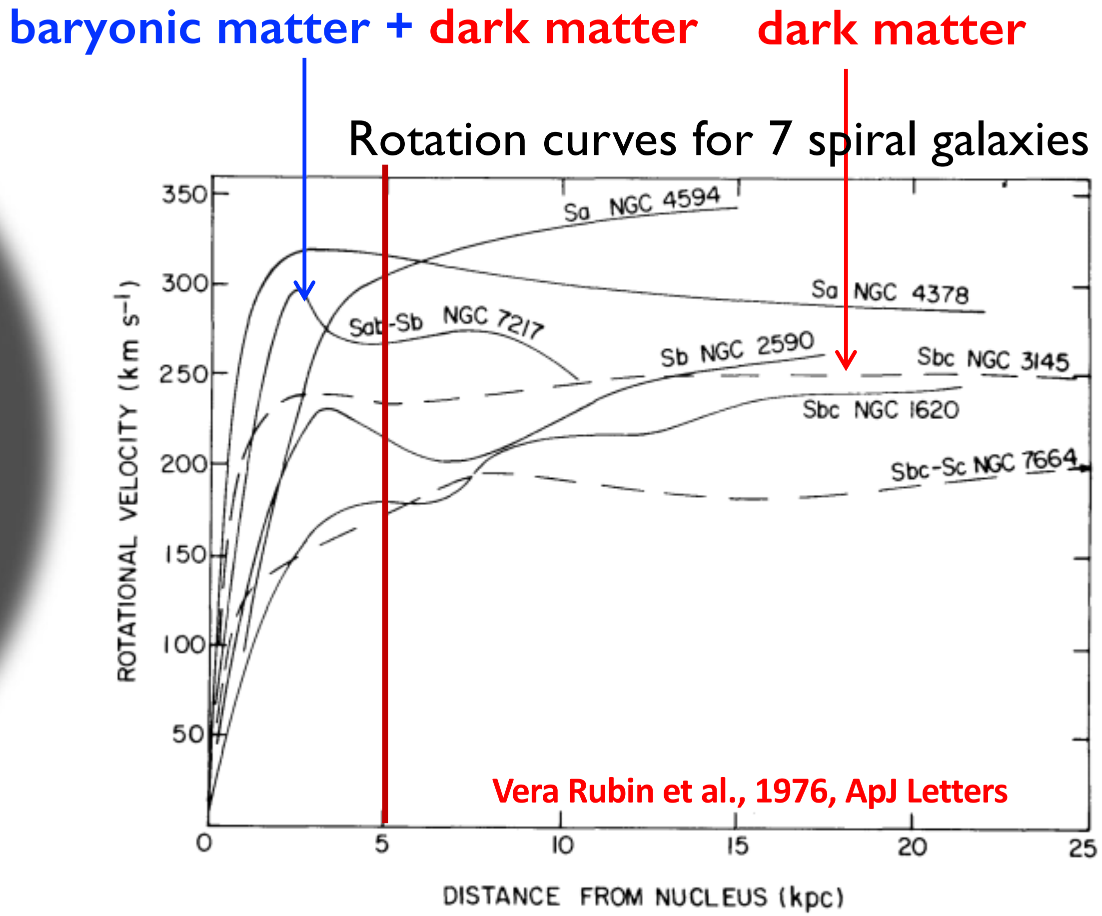
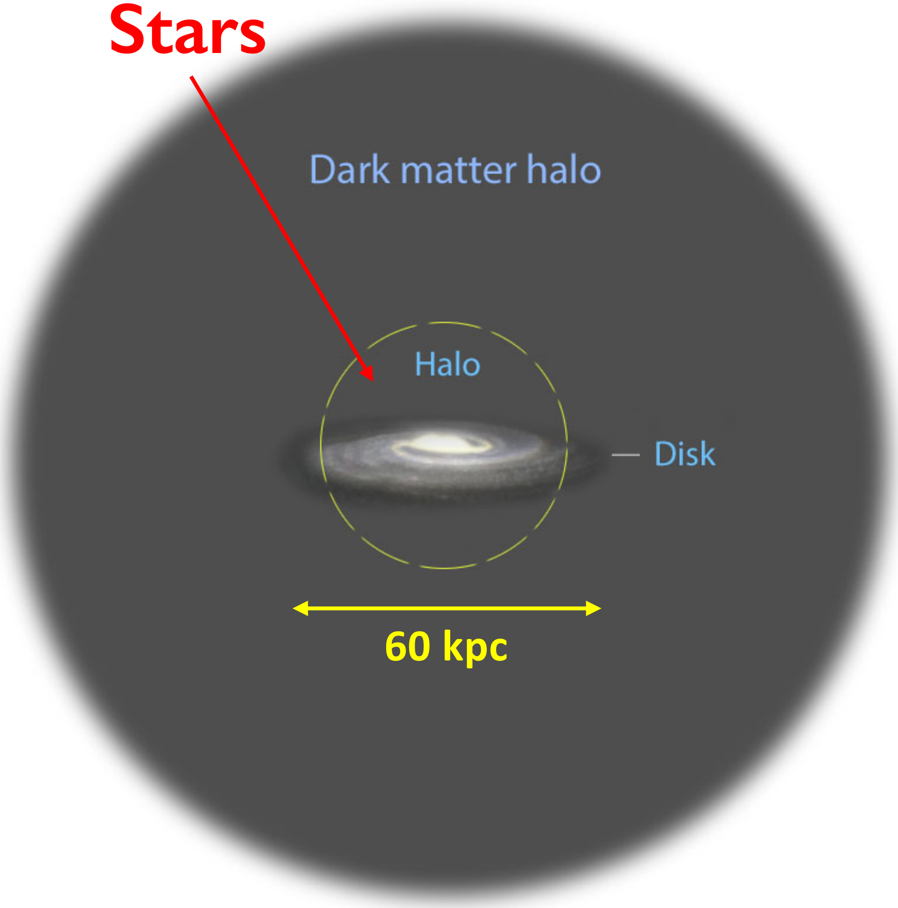


Dark Matter content of the Milky Way: Among other authors, Posti and Helmi (2018), using GAIA data (globular cluster motions), estimated that the total mass of the Milky Way within the region of 20 Kpc to be $1.91 \pm 0.17 \times 10^{11}$ M⊙ of which 70% is dark matter.

Important point: recent numerical simulations established that 90% - 95 % of the Milky Way mass is dark matter (up to 200 Kpc).

Dark Matter in the Universe



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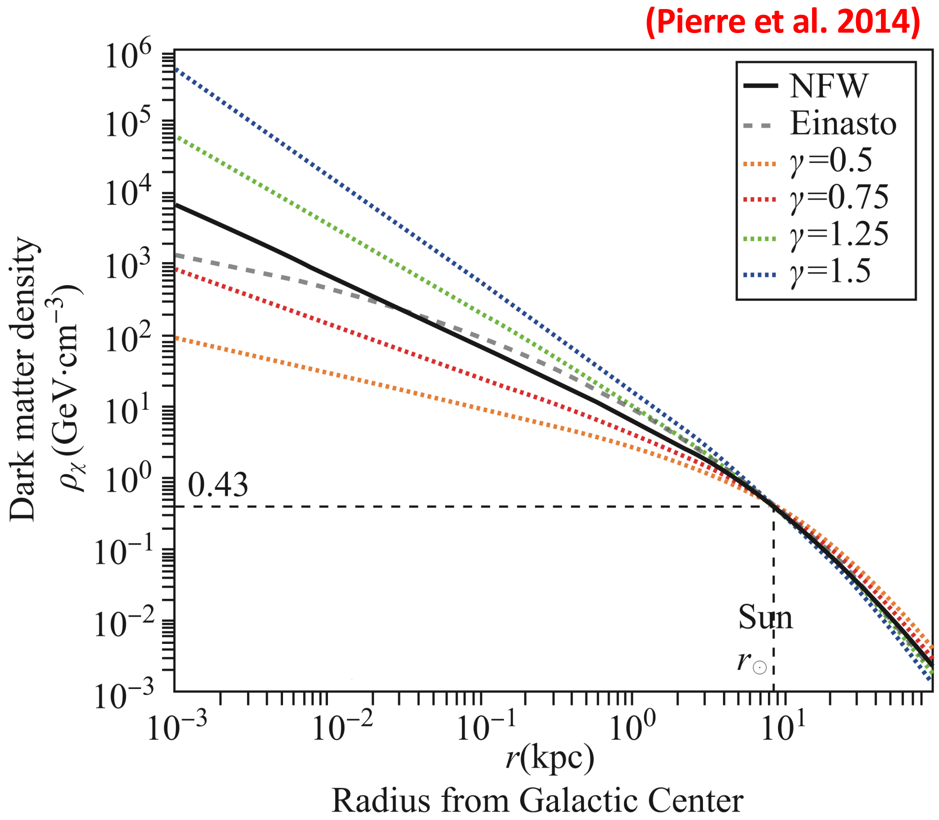
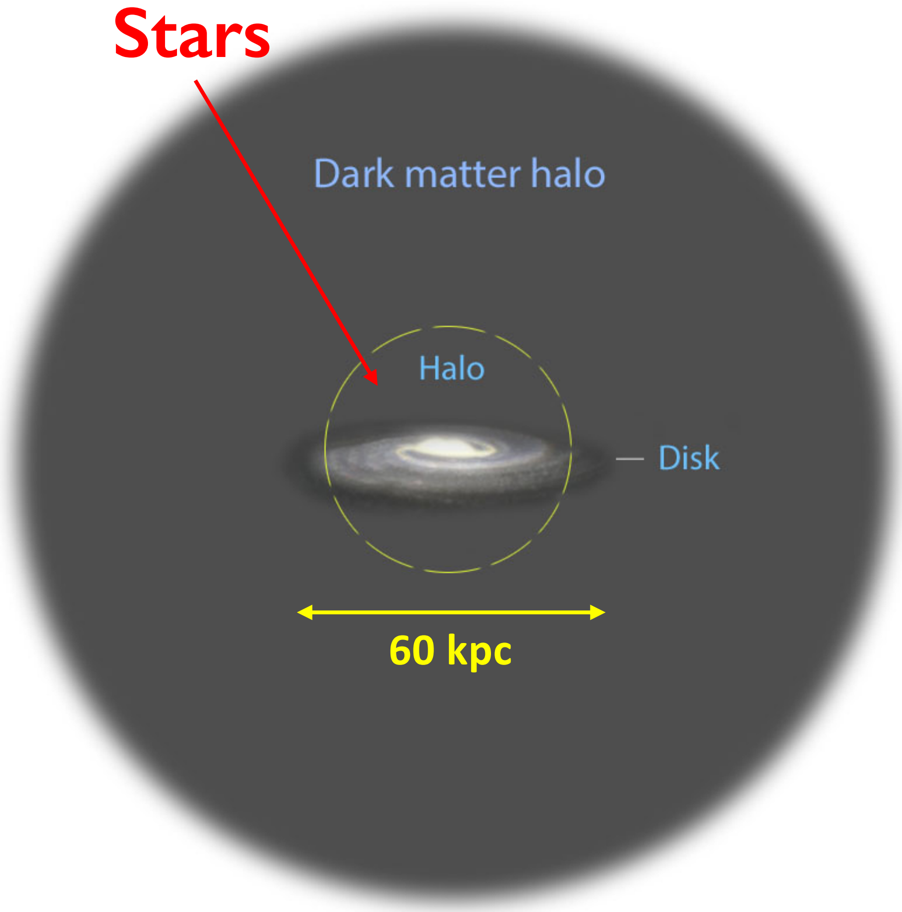


dark matter density at the Sun's position is ~ 0.4 GeV/cm^3

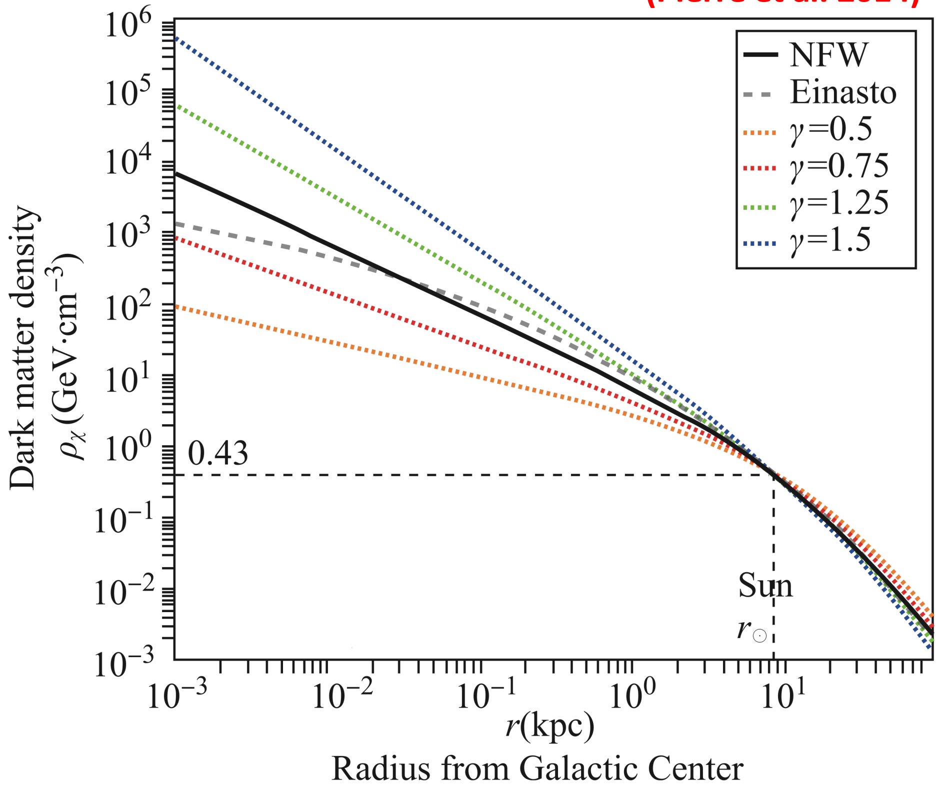
In light of the uncertainty in the DM distribution in the Inner Galaxy and the dependence of the signal on it, there is a range of possible density profiles. The most common benchmarks are N and Einasto profiles.

Dark Matter in the Universe



Milky Way : Standard DM Halo

(Pierre et al. 2014)



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In light of the uncertainty in the DM distribution in the Inner Galaxy and the dependence of the signal on it, there is a range of possible density profiles. The most common benchmarks are NFW and Einasto profiles.

The density of the most **metal-poor stellar population** exhibits the same dependence on the radius as the dark matter near the Sun's position (Herzog-Arbeitman et al. 2018).

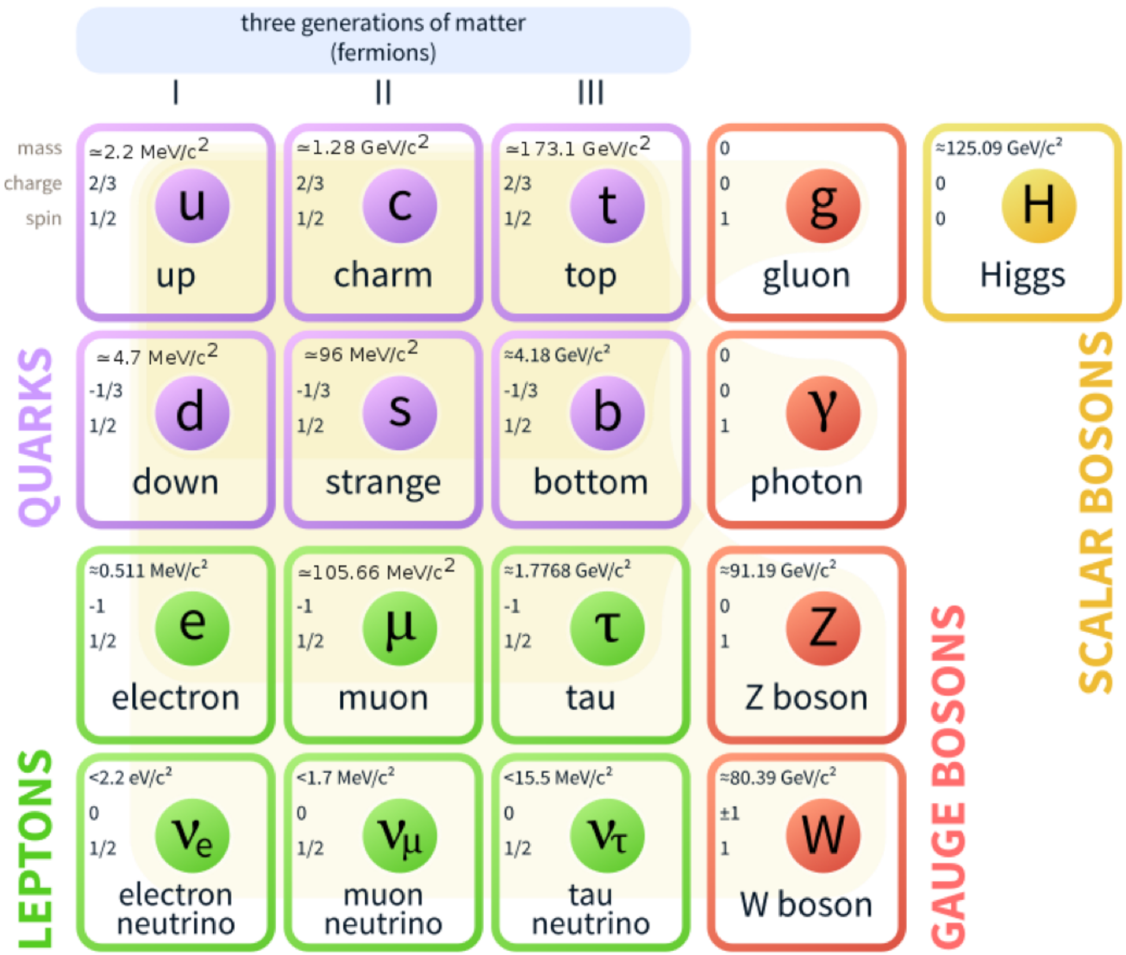
Dark Matter in the Milky Way

A large amount of the total mass of the Milky Way is dark matter

Dark Matter in the Universe

(What is dark matter made of ?)

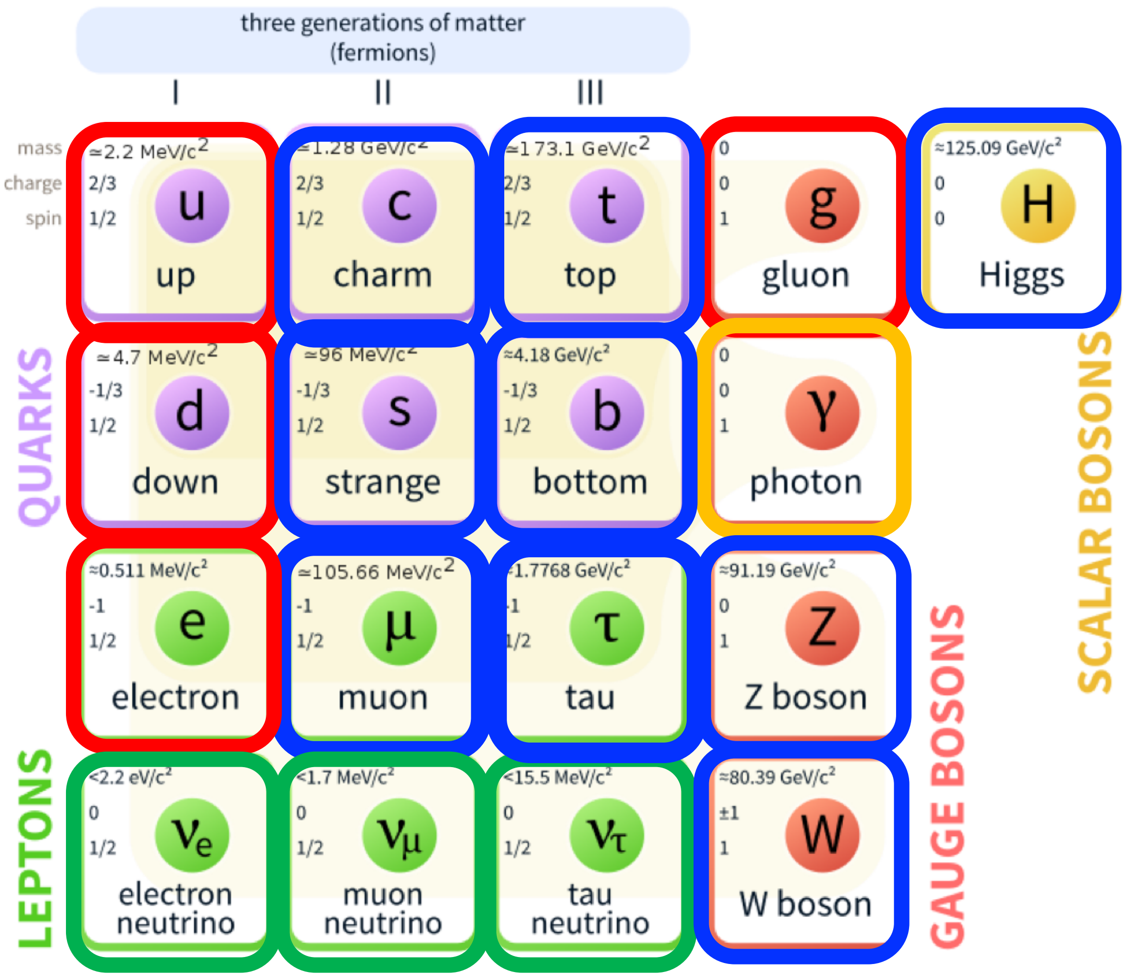
What is dark matter made of?



Standard Model of Elementary Particles

This table of elementary particles (with its rules) explains the origin of all known matter of the Universe (that corresponds to 4% of the cosmological density).

What is dark matter made of?



Standard Model of Elementary Particles

Light particle

Couples to the plasma

Disappears too quickly

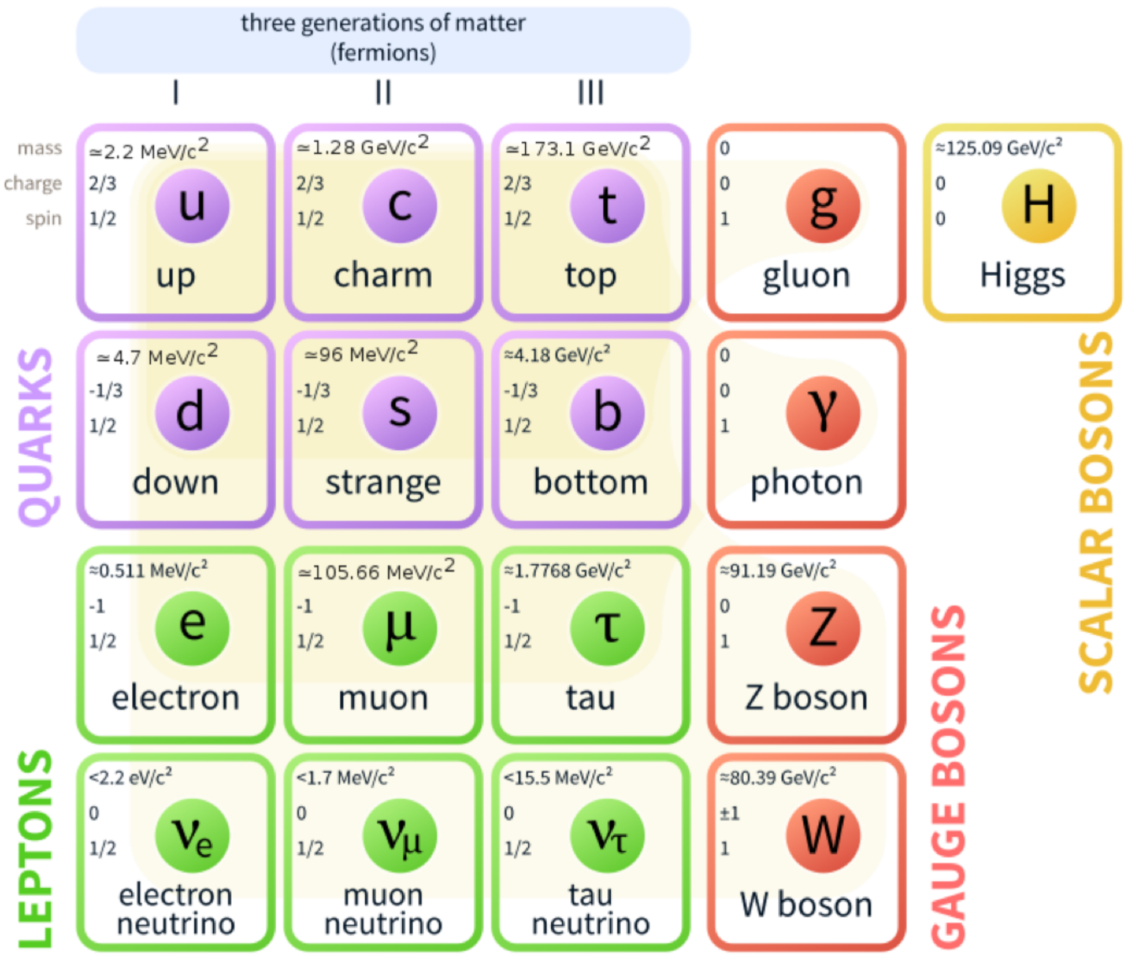
Hot dark matter

As the standard model is quite successful in explaining all the known interactions (other than gravity), let us now consider that these new particles have somehow identical properties to the ones found in the standard particles.

None of these particles can be constituents of dark matter..

If not standard particles, then how to proceed …

What is dark matter made of?



Visible sector

Standard Model
Extended

+

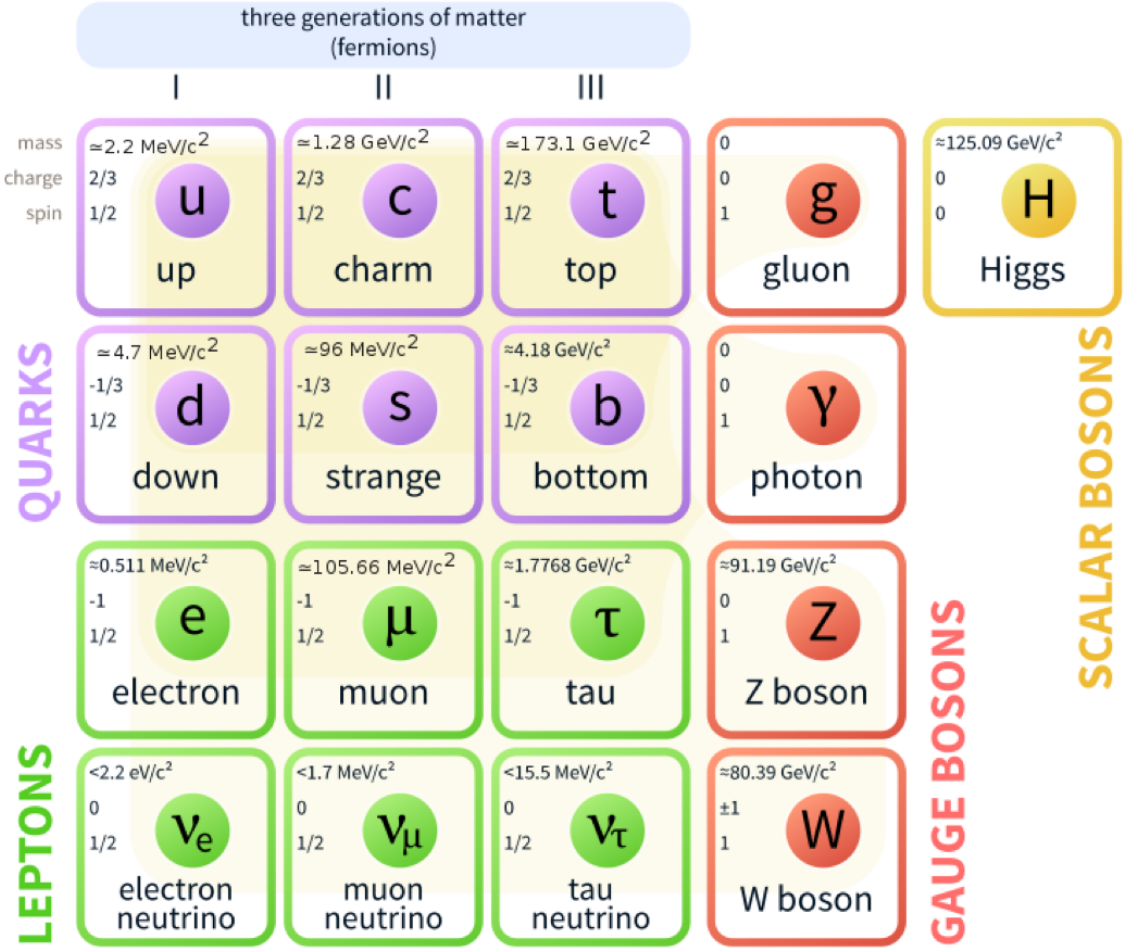
new fermions

new bosons

New particles

Dark (matter) sector

What is dark matter made of?



Standard Model Extended

+ new fermions

new bosons

New particles

Visible sector **Dark (matter) sector**

Expected properties of the Dark Matter particles: They should have the cosmic dark matter density have mass, weak interacting with ordinary matter, be non-relativistic, **be stable or very long-lived;** compatible with bounds coming from experimental (direct an indirect) detectors, astrophysics and cosmological data sets.

Ideally, it should be interesting to detect it in the outer space and produce it in the laboratory.

What is dark matter made of?

Dark Matter Candidates:

Theory

Cold particles (blue, cyan, green)

Warm particles (pink)

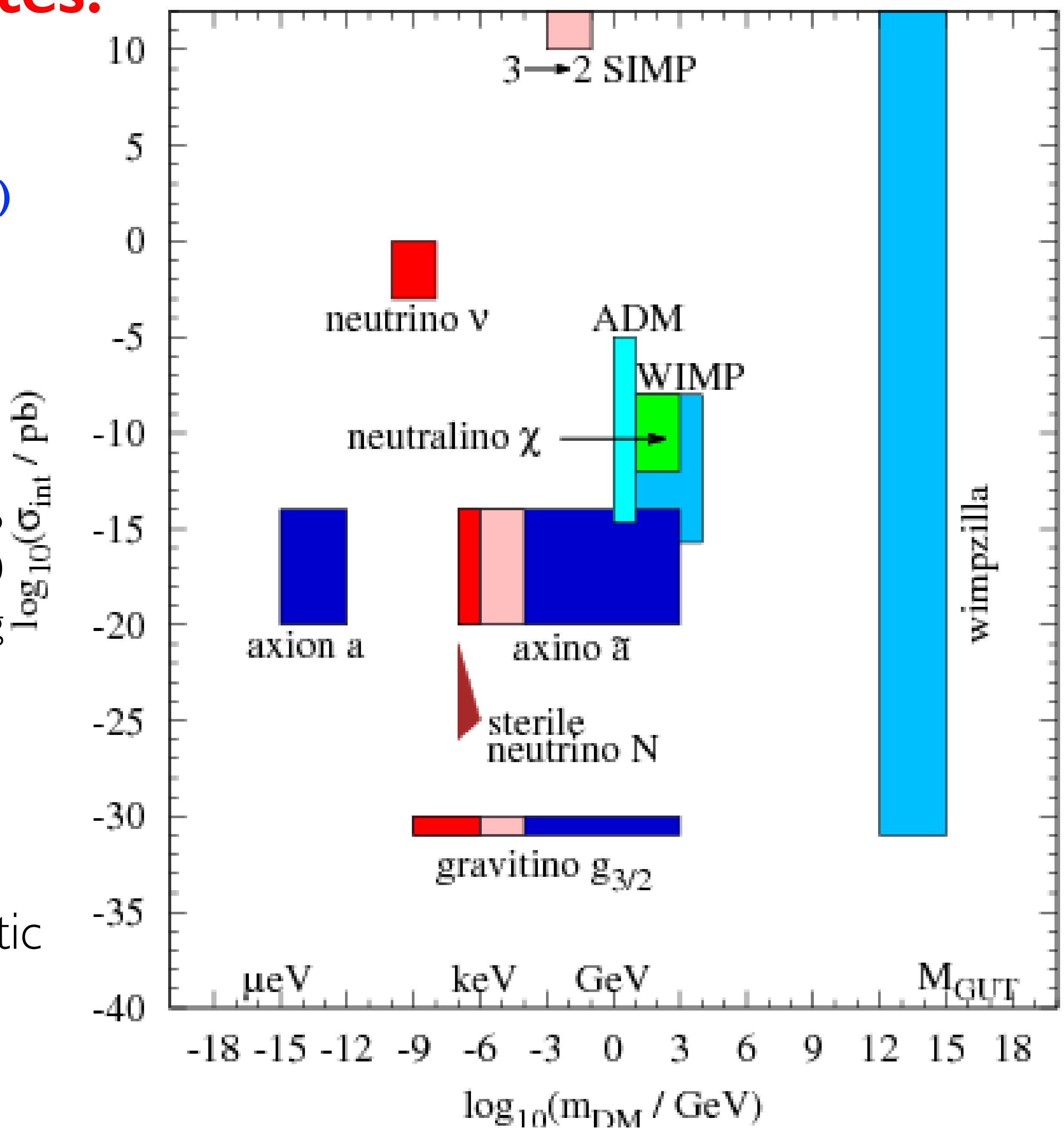
Hot particles (red)

The candidates span a range of 36 orders of magnitude in mass and 50 orders of magnitude in the scattering cross-section with baryons.

The best motivate dark matter candidates are the non-relativistic (cold) particles.

Picobarn=10^{-36} cm²

Baer et al. (2015)



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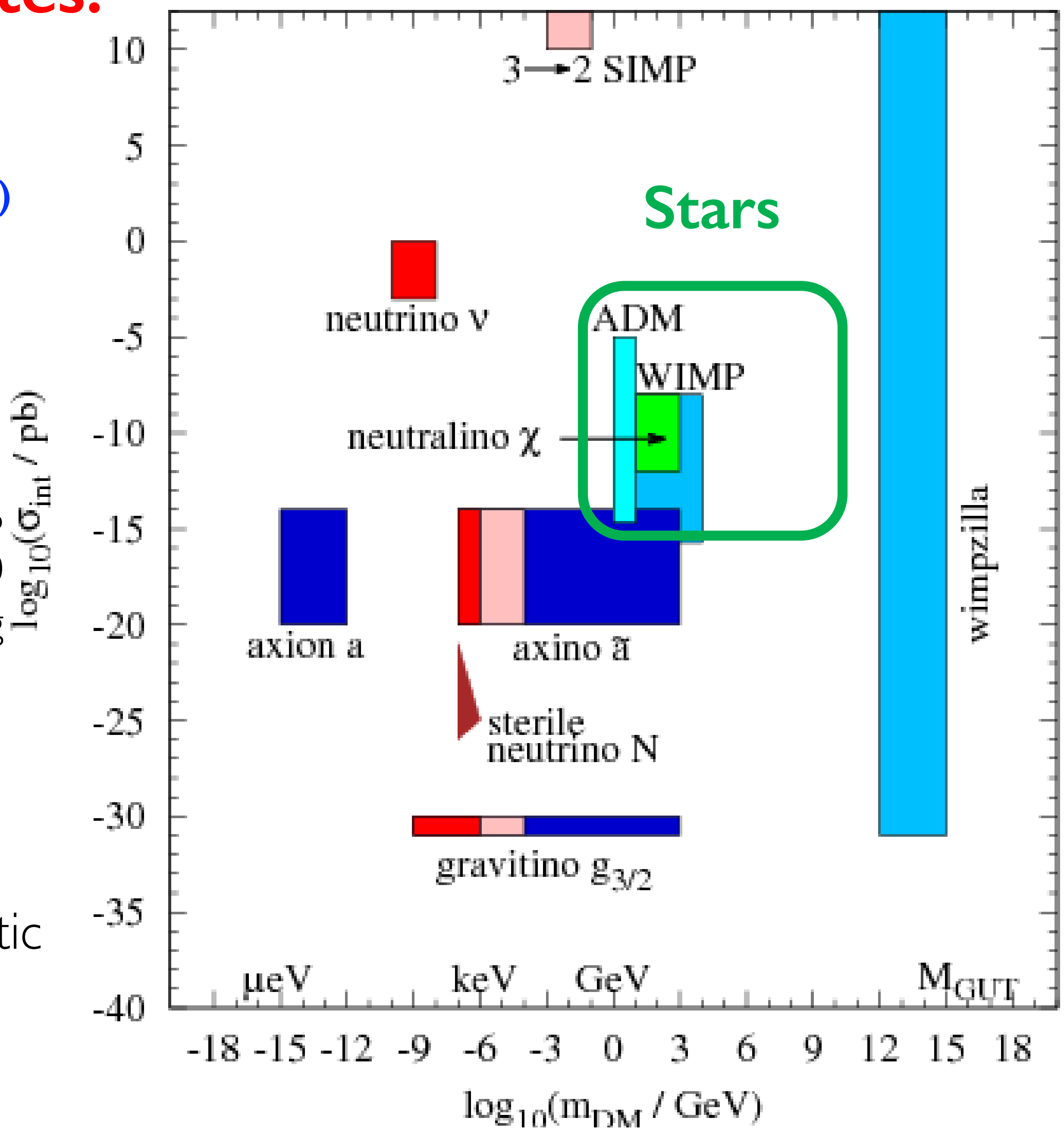
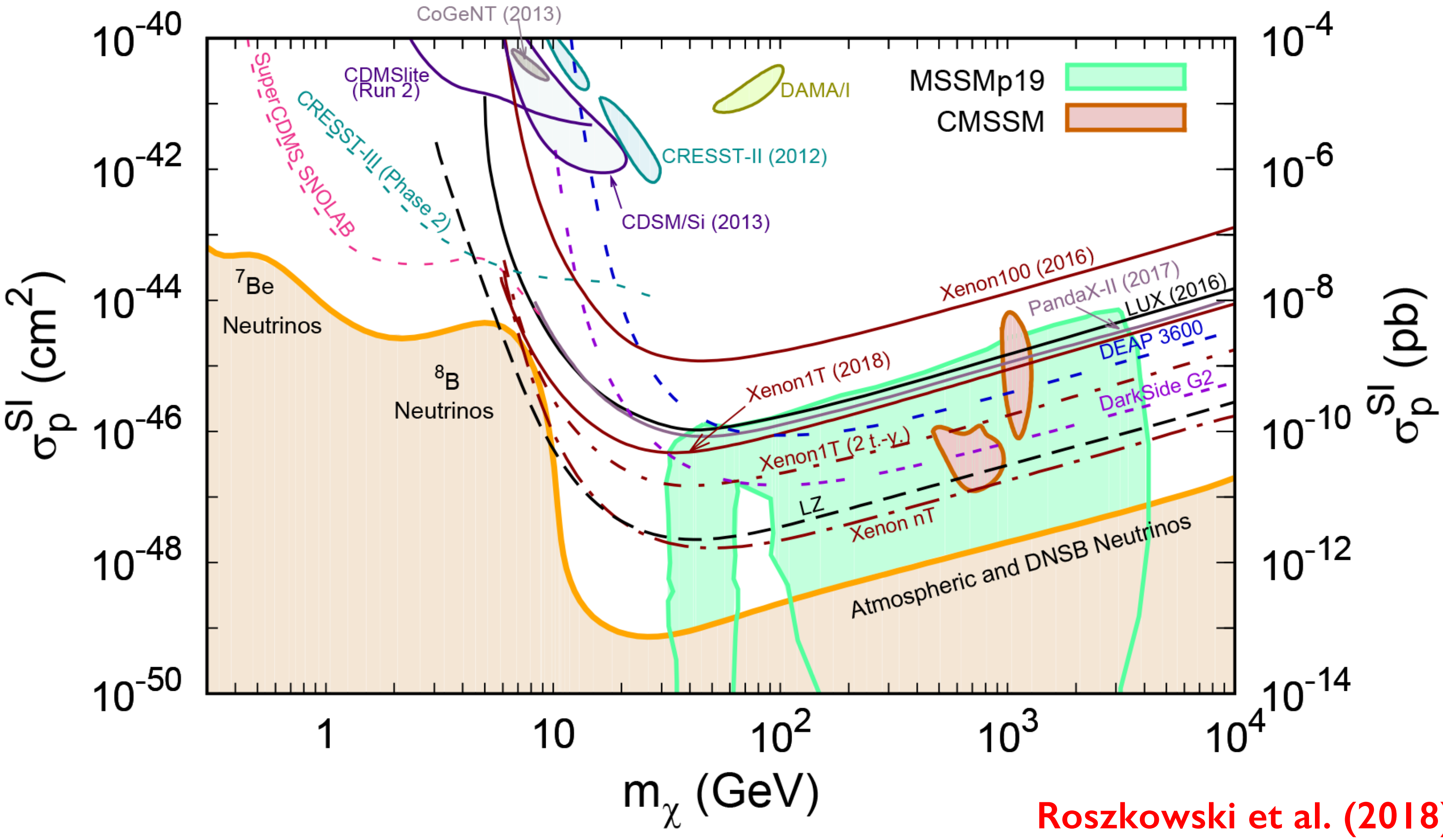


What is dark matter made of?

Dark Matter Candidates: Experimental Bounds



Roszkowski et al. (2018)

Expected properties of the dark matter particles: Current and future limits on DM direct detection: spin-independent cross section as a function of DM mass.

The region below of 20 GeV shown as the **vertical green** line is difficult to probe by experimental detectors and corresponds to dark matter candidates that most affect stars.

What is dark matter of?

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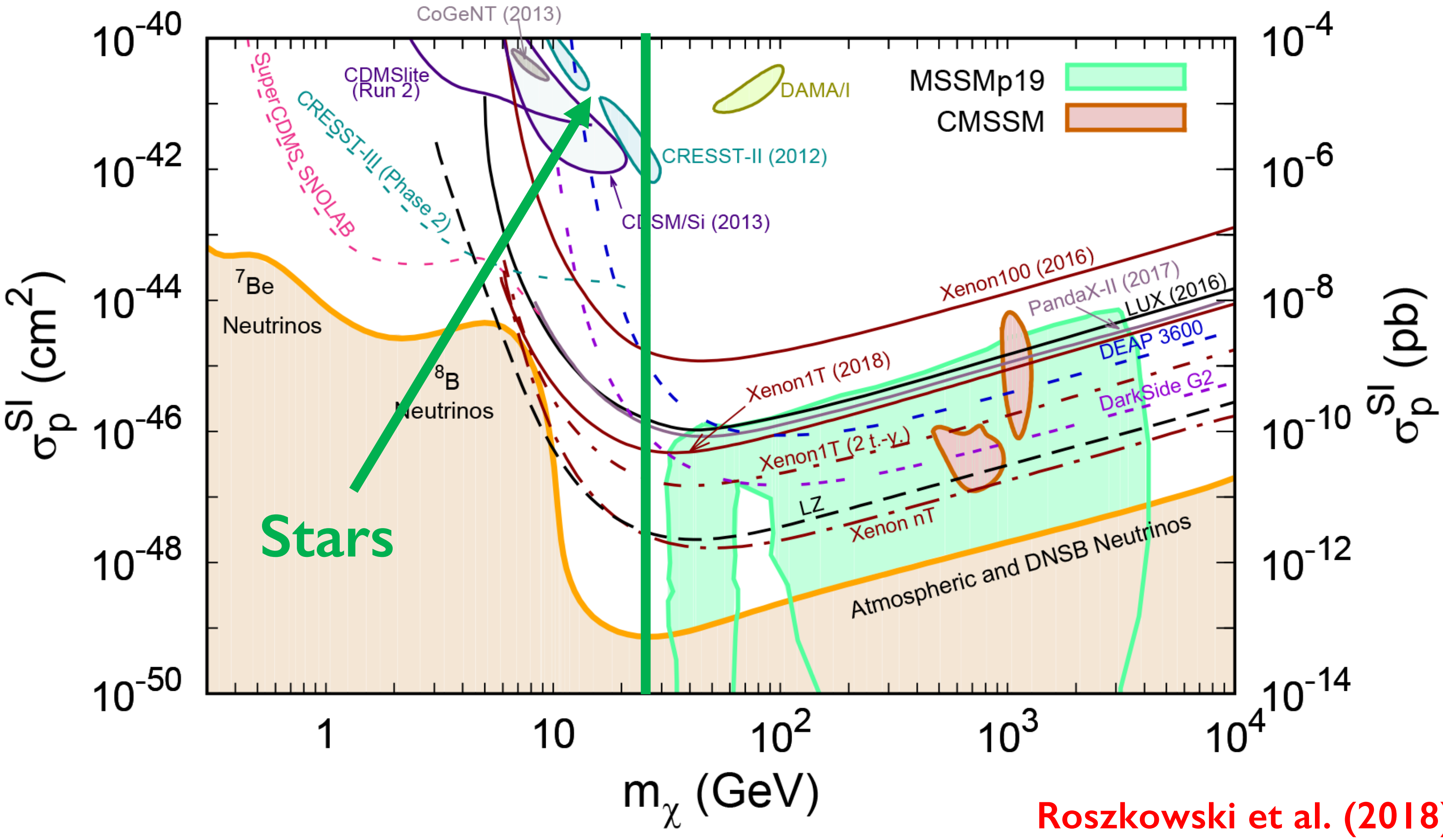

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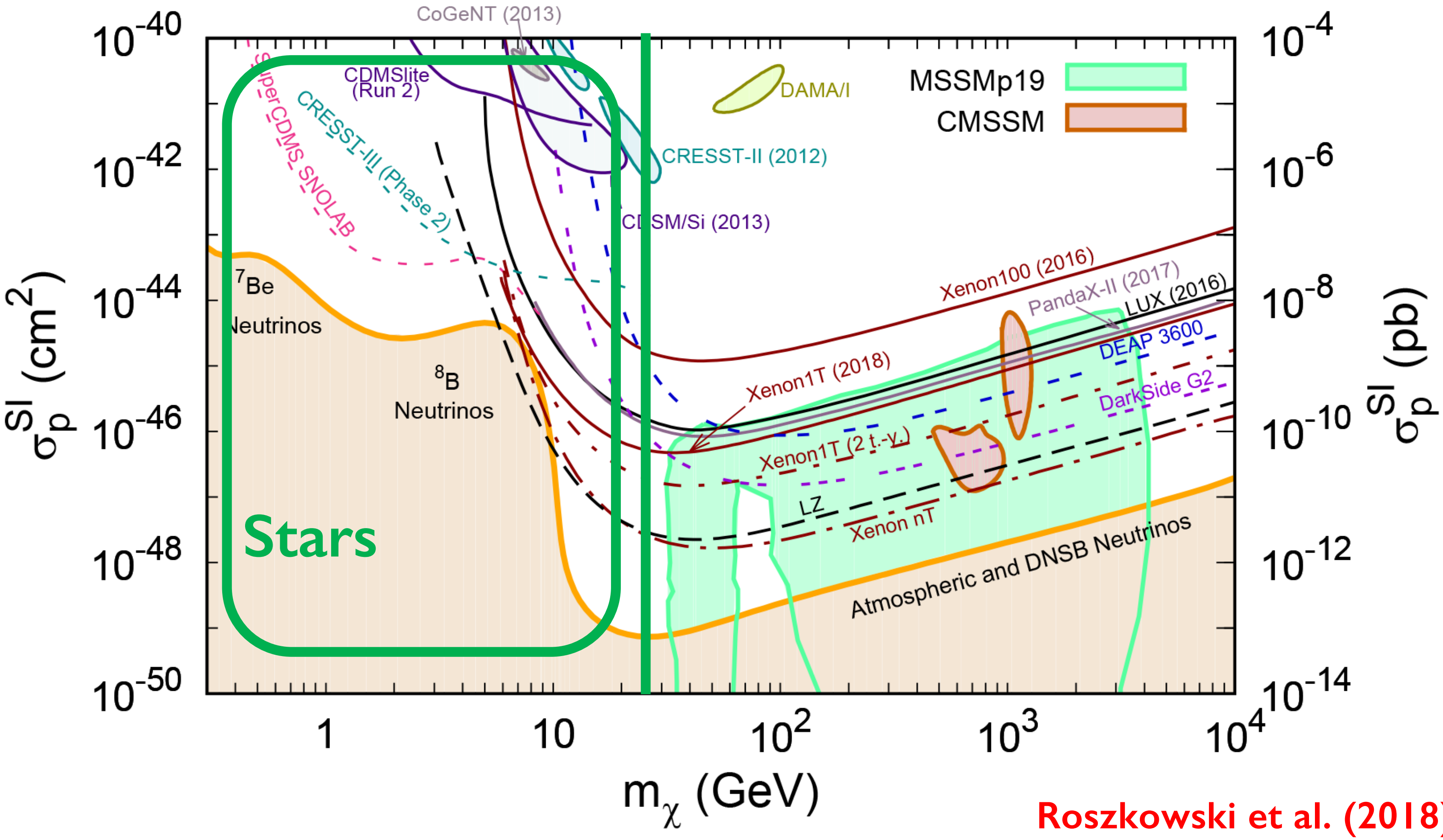

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Important Point

The Sun and stars are sensitive to light dark particles (with a mass of a few GeVs) which are difficult to probe by direct dark matter detection experiments.

How Dark Matter affects Stars

How does dark matter influence stars?

Pioneer Works:

Cosmions as a solution to the solar neutrino problem and dark matter problem [Steigman et al. (83), Spergel and Press (85), Krauss et al. (85), Gilliland et al. (86), Dearborn et al. (91), 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, . . .]

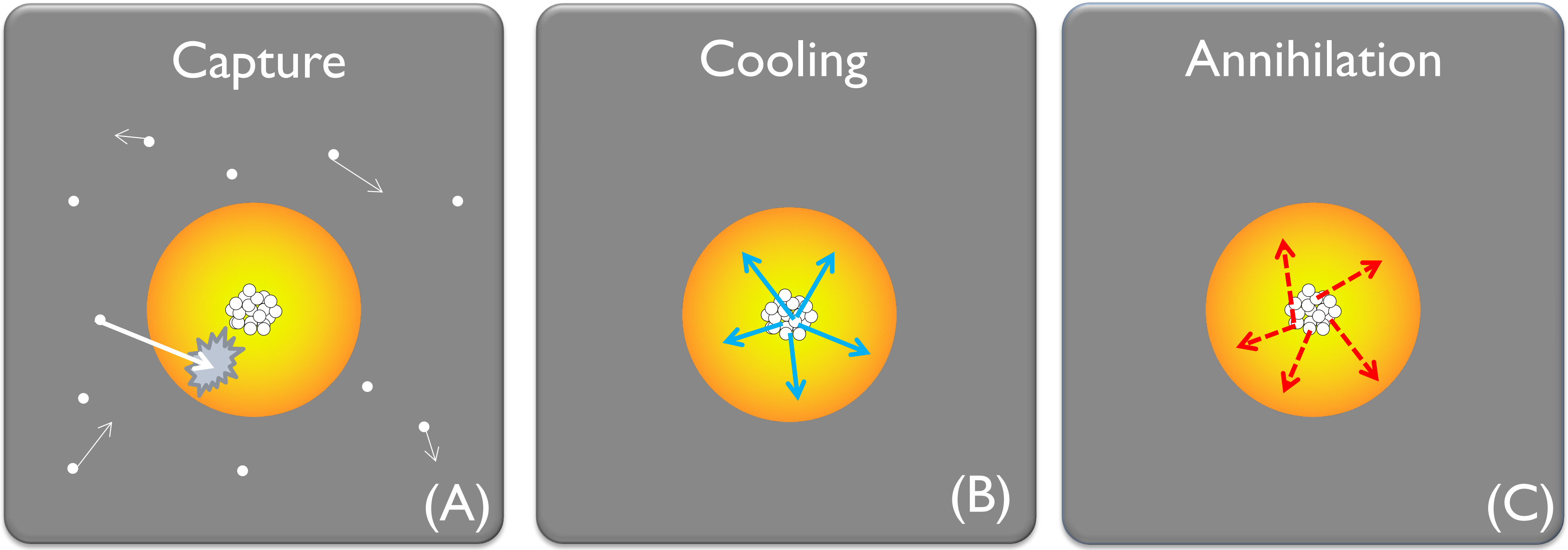
Recent Works:

Solar neutrinos and helioseismology: constraints low-mass DM candidates [Bottino, Bertone, Casanellas, Cumberbatch, Frandsen, Guzik, Lopes, Iocco, Panci, Meynet, Ricci, Sarkar, Scott, Silk, Vicent, Taoso, Turck-Chièze, Watson, Vincent]

Stars and asteroseismology: Constraints on low-mass DM candidates [Casanellas, Lopes, Silk, Brandão, Lebreton, . . .]

How does dark matter influence stars?

Generic properties



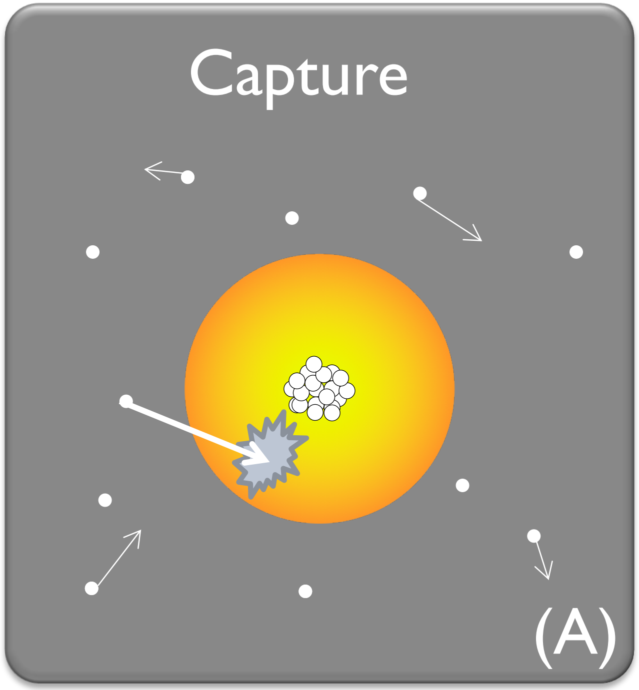
$C_\chi \propto f(\chi, \star)$ $L_{transp,\chi} \propto f(C_\chi, m_\chi)$ $L_{prod,\chi} = f_\chi \cdot C_\chi \cdot m_\chi$

Interaction of dark matter particles with stars: The interaction of dark matter with baryonic matter inside stars follows three basic processes: **capture** (A), **cooling** (B) and **annihilation** (C).

How does dark matter influence stars?

Gould, ApJ 321 (1987)

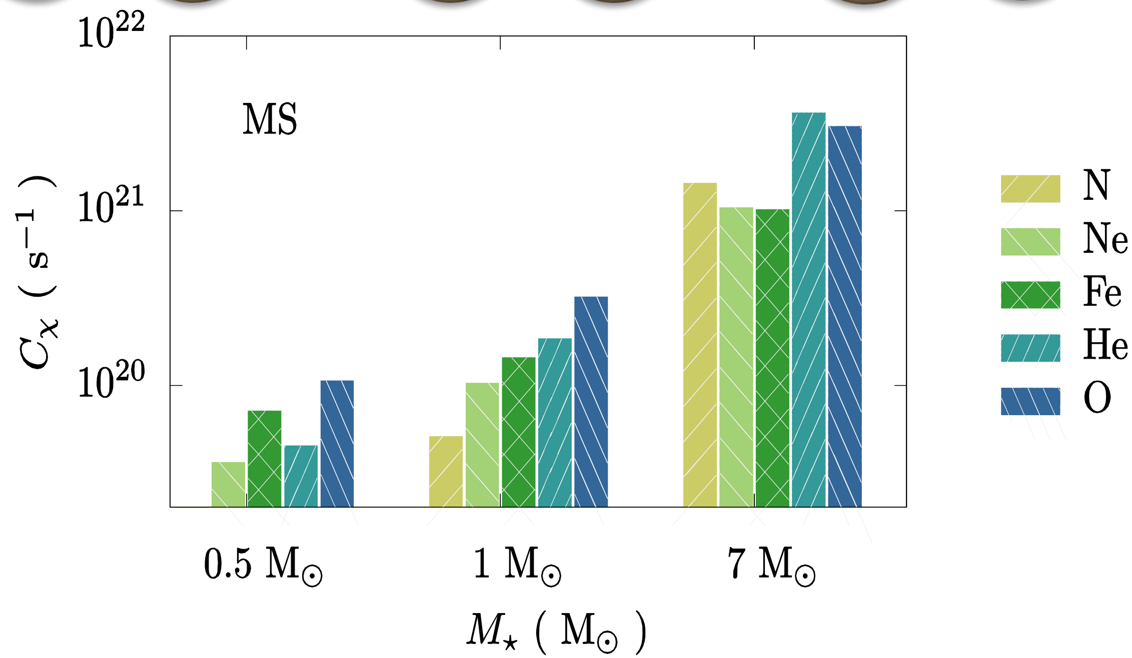
$$C_\chi(t) = \int_0^{R_\star} 4\pi r^2 \int_0^{\infty} \frac{f(u)}{u} w\Omega_v^-(w)\, \mathrm{d}u\, \mathrm{d}r$$



DM Particle Physics: σ_χ m_χ

DM Astrophysics: ρ_χ $\bar{v}_\chi$

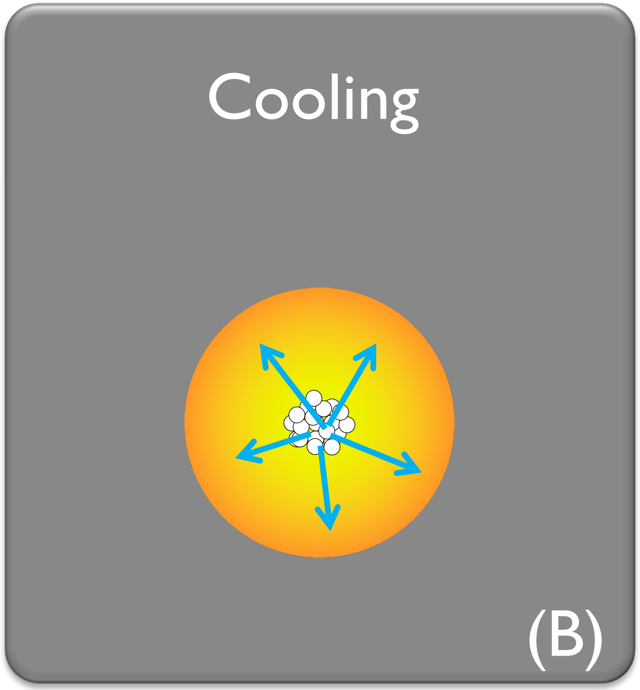
Stellar physics: $V_\star$ n_i

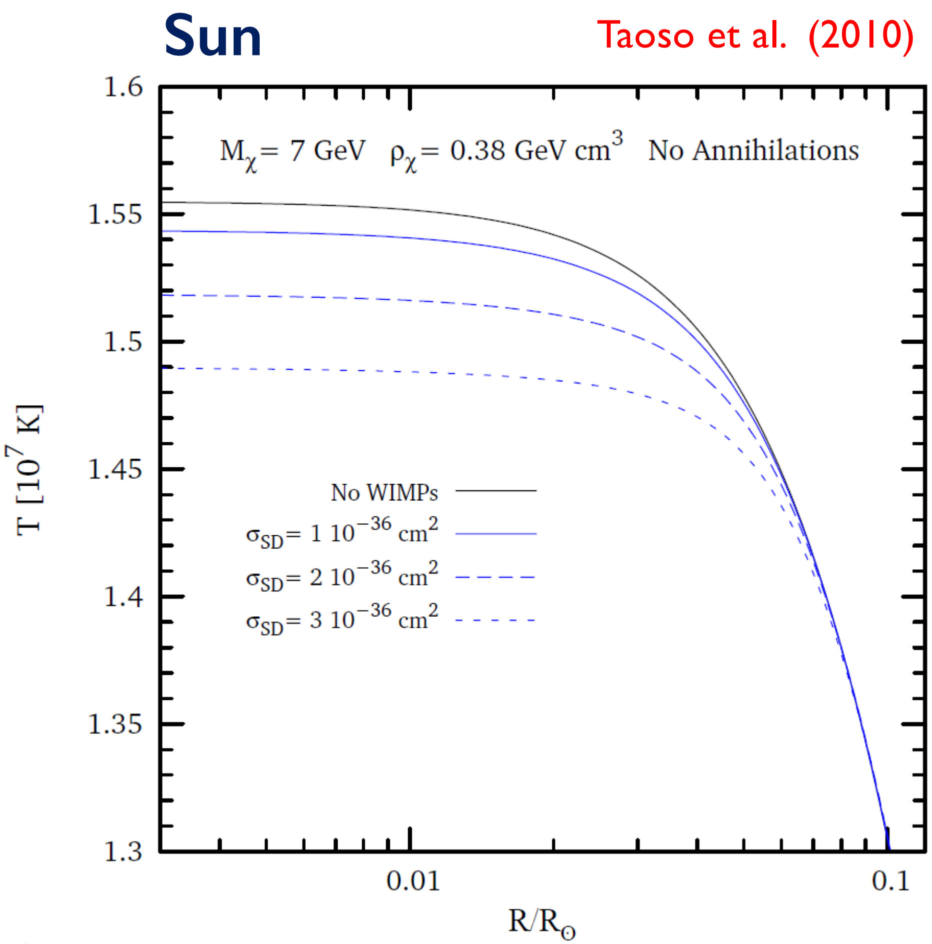


Lopes, Casanellas & Eugénio, (2011)]

Interaction of Dark Matter particles with stars: The interaction of dark matter with baryons depends on several factors that influence the capture and interaction dark matter with baryons on the star, properties of the dark matter particle, dynamics of the DM halo and internal properties of the star (including dynamical ones).

How does dark matter influence stars?

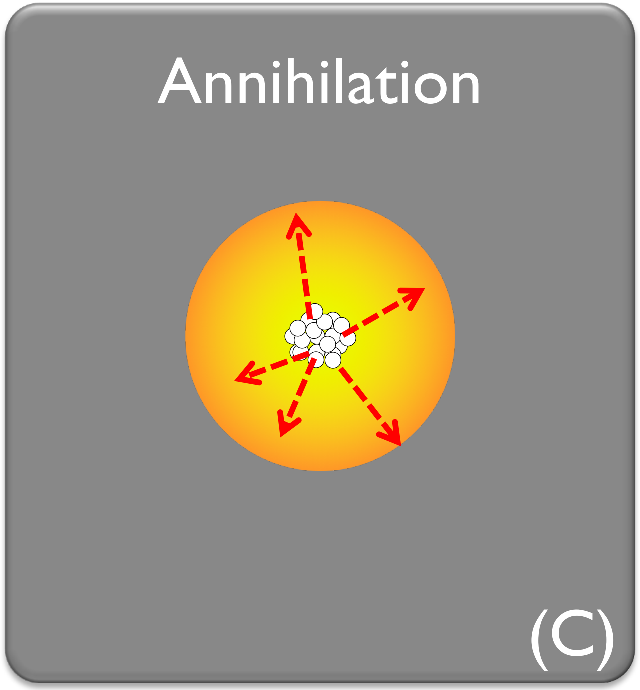




Reduction of the star's core temperature

Interaction of dark matter particles with stars: The presence of dark matter inside the star facilitates the energy transport outside of the core, leading to a reduction of the temperature in the centre. In extreme cases of the strong interaction of DM with baryons, it can lead to the creation of an isothermal core (Lopes & Silk 2002).

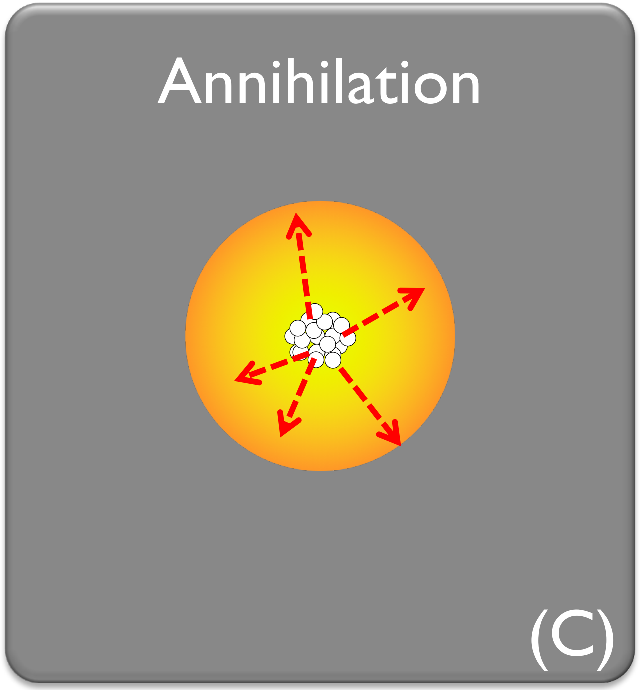
How does dark matter influence stars?



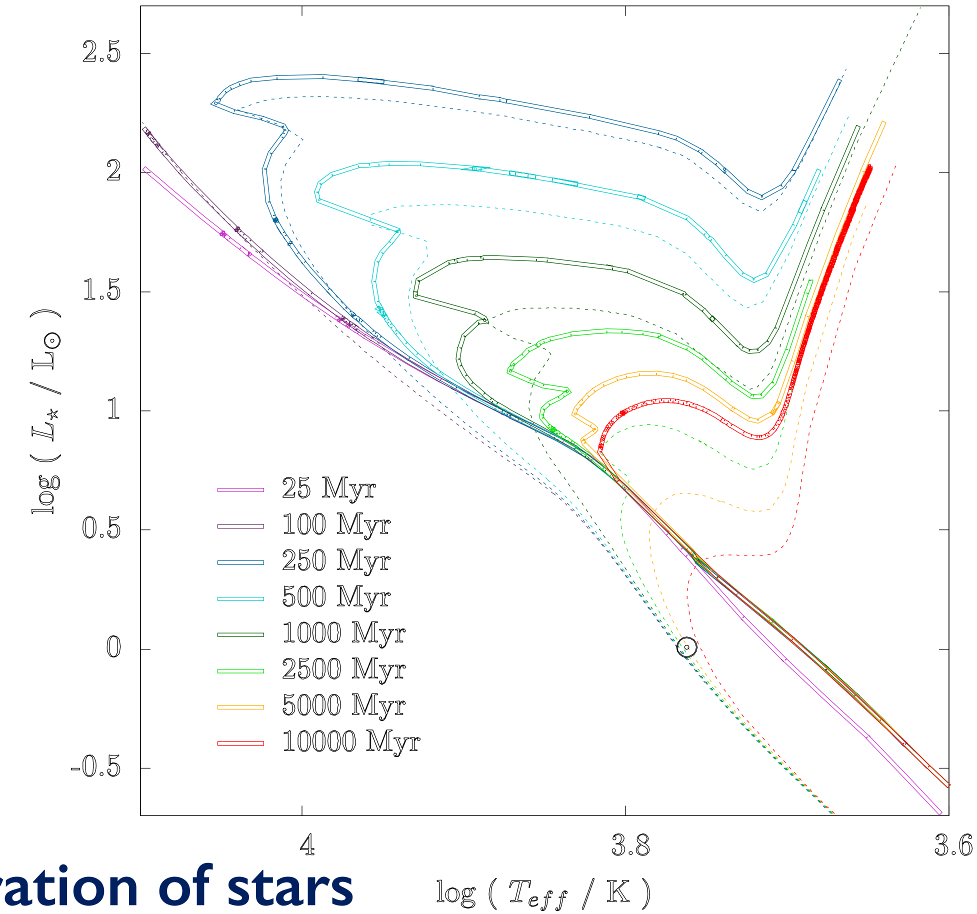
Relevant only in the first generation of stars

Interaction of Dark Matter particles with stars: The annihilation of dark matter as an energy source for stars in the Milky Way, will only reduce the efficiency of the cooling mechanism. Nevertheless, stars formed in the dense dark matter halos (primordial Universe) have their lives extended (slower evolution in the HD diagram), due to the energy produced by dark matter (Lopes & Silk 2014).

How does dark matter influence stars?



Stellar Cluster   Casanellas & Lopes (2011)



Relevant only in the first generation of stars

Example: For a cluster of stars (0.7-3.5 $M_\odot$) in DM halo (ρ ~ fix, continuous lines) and standard HR diagram (dashed lines). The DM halo constituted particles with a DM mass of ~ 100 GeV and σ_{SD} (with protons) ~ 10^{-38} cm^2 In the most dramatic cases lead to modifying the location of the main sequence in the HR diagram (Casanellas & Lopes 2011).

Dark matter constraints using stellar observables (a few examples)

Constraints on Asymmetric Dark Matter Interaction with Hydrogen

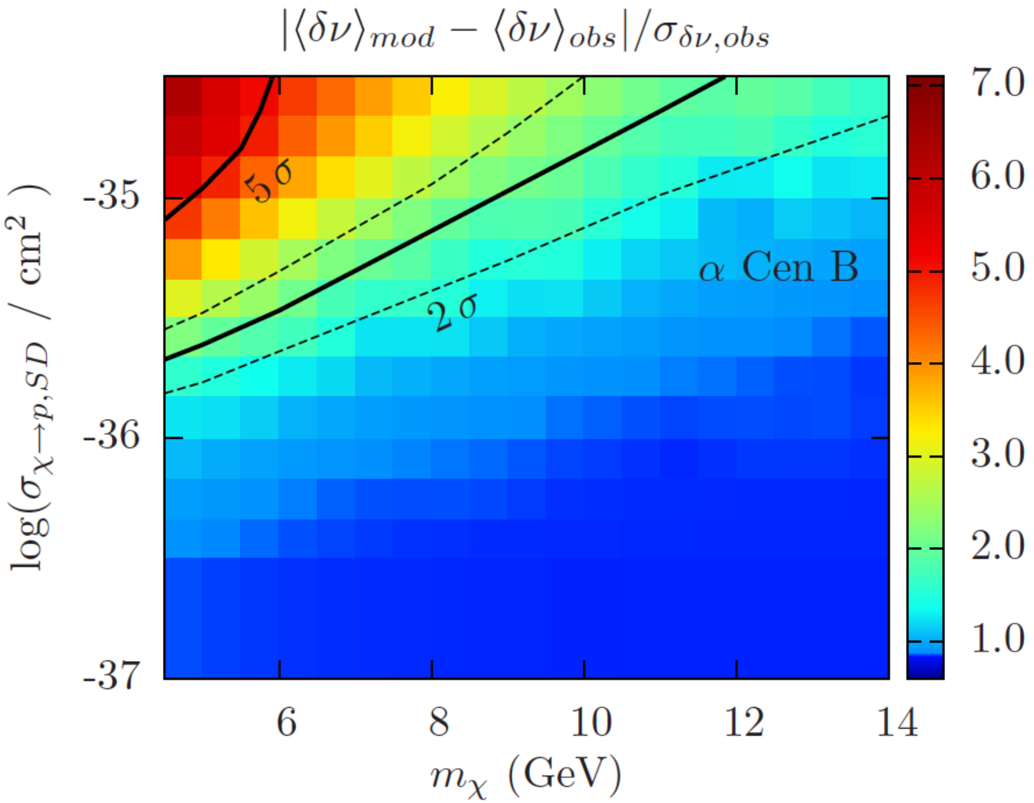
Asteroseismology

TÉCNICO LISBOA

Asteroseismology: limits to the DM characteristics

Dark sector: ADM particle (point-like interaction) – an interaction between a DM particle (with mass $\boldsymbol{m_\chi}$ and scattering cross-section $\boldsymbol{\sigma_{\chi p}}$) and a proton inside the star. Using the small frequency separations the following constraints were obtained for alpha Centauri B.

Casanellas & Lopes (2013)



Asteroseismology: The presence of dark matter (asymmetric) changes the transport of heat energy inside these stars (decreasing the central temperature). Using the asteroseismology data of Alpha Cent B (0.9 $M_\odot$), DM particles with $\mathrm{m}_\chi \sim$ 5 GeV and $\sigma_{\chi p}^{SD} \geq 3\ 10^{-36}$cm^2 are excluded at 95% CL.

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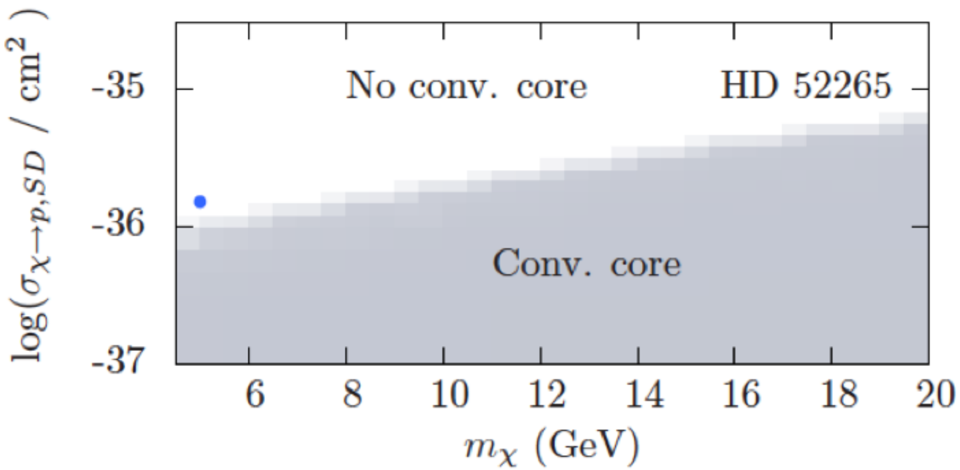

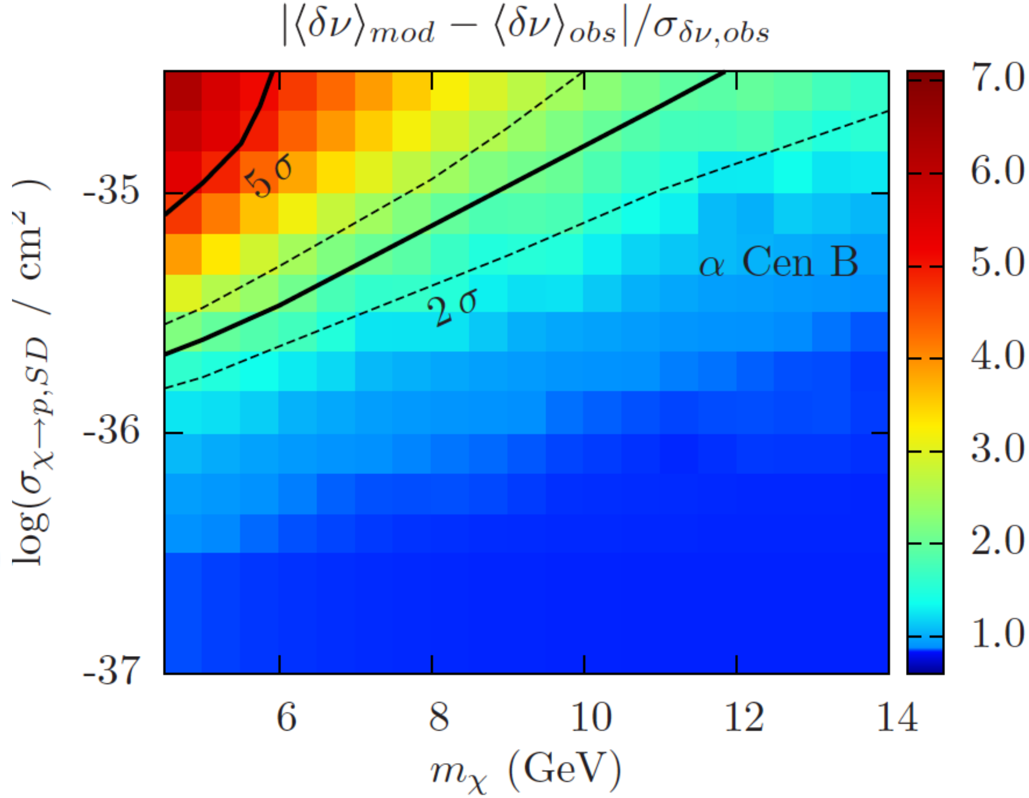

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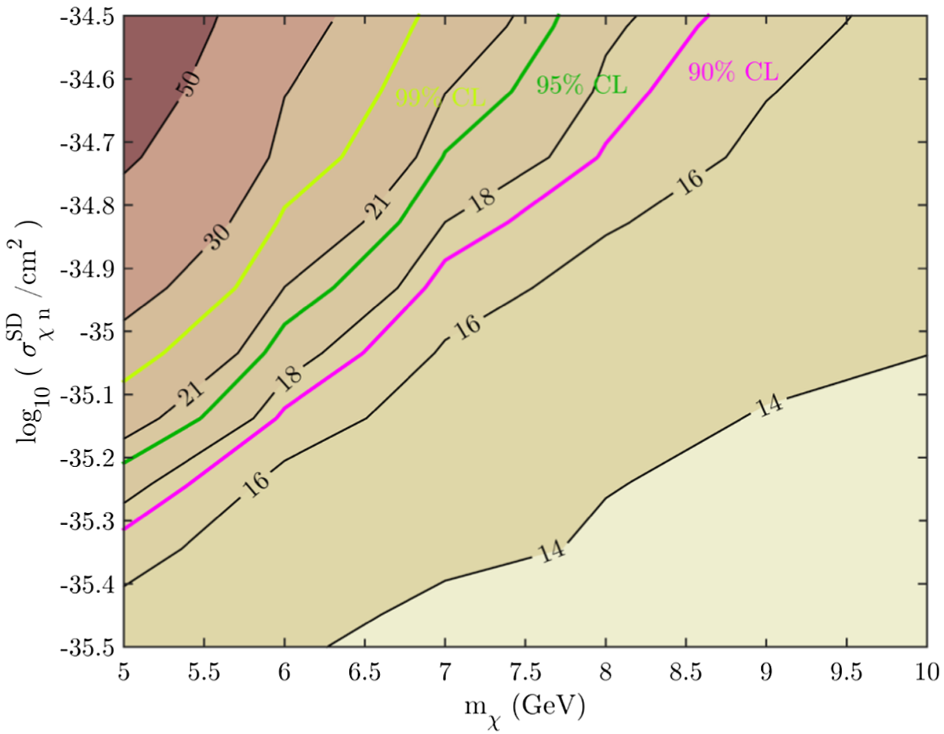
Changes in the central temperatures and densities lead to suppression of the convective core in 1.1-1.3 $M_\odot$ stars. This result was confirmed by Casanellas, Brandão & Lebreton 2015 using other stars.

Asteroseismology: limits to the DM characteristics

Dark sector: ADM particle **(point-like interaction)** - an interaction between a DM particle (with mass $\boldsymbol{m_\chi}$ and scattering cross-section $\boldsymbol{\sigma_{\chi p}}$) and a proton inside the star. This model includes also a self-interaction cross-section consistent with the constraint from self-interaction cross-section ($\sigma_{\chi\chi}/m_\chi \lesssim$ **8.3 × 10^{-25}** cm^2/GeV) obtained from the galaxy bullet clusters (Harvey et al. 2015).



Martins, Lopes & Casanellas (2017)

Asteroseismology: Sum of squared errors χ^2 for the r_{02} diagnostic of star KIC 8379927 **(1.12 M$_\odot$, 1.82 Gyr)** for these DM models with **$\sigma_{\chi\chi}$ = 10^{-24} cm^2**. Also shown are 90%, 95%, and 99% C.L.'s corresponding to these χ^2's.

Asteroseismology: limits to the DM characteristics

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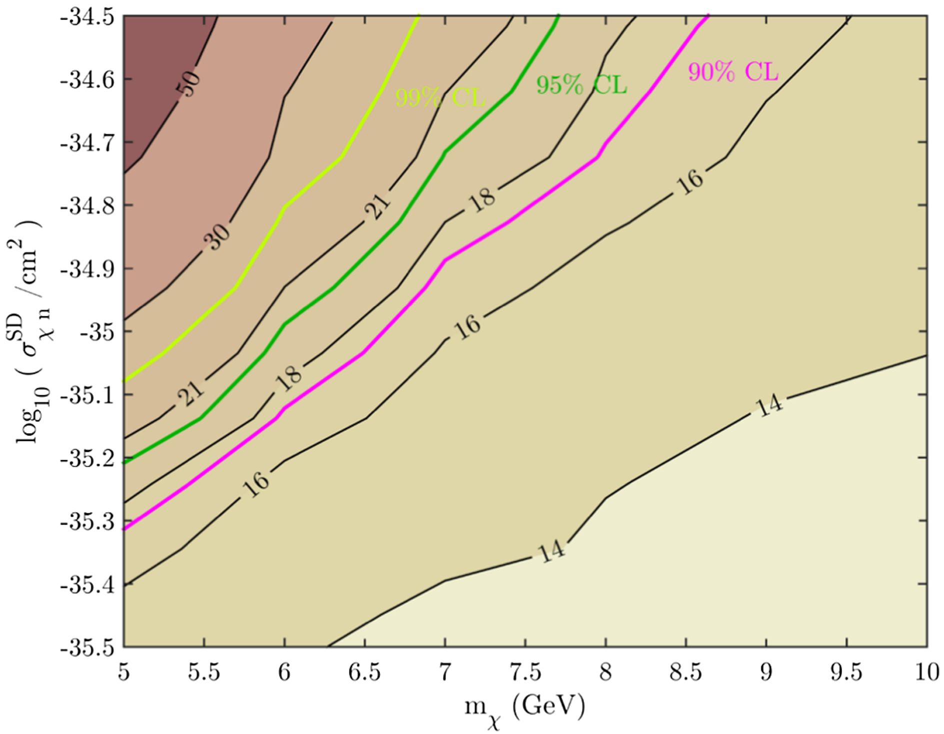

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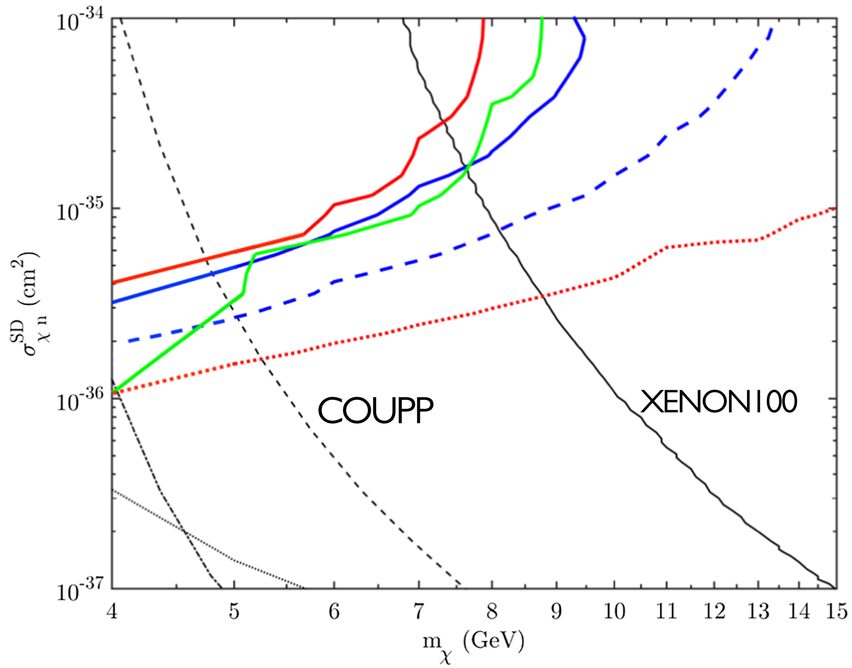


Asteroseismology: 90% C.L.'s ascertained from the ADM scenario for the Sun $\boldsymbol{\chi^2}$ Tc (dotted red), Sun $\boldsymbol{\chi^2}$ r_{02} (solid red), KIC 8379927 $\boldsymbol{\chi^2}$ r_{02} (solid blue), and KIC 7871531 $\boldsymbol{\chi^2}$ r_{02} (solid green). The dashed blue line is the projected 90% C.L. corresponding to a 10% increase in precision for the frequencies of the modes. For comparison, 90% C.L. limits from some direct detection experiments are also shown in black lines (like XENON100 and COUPP).

Constraints on Asymmetric Dark Matter long-range interaction with Baryons (heavy elements)

Helioseismology

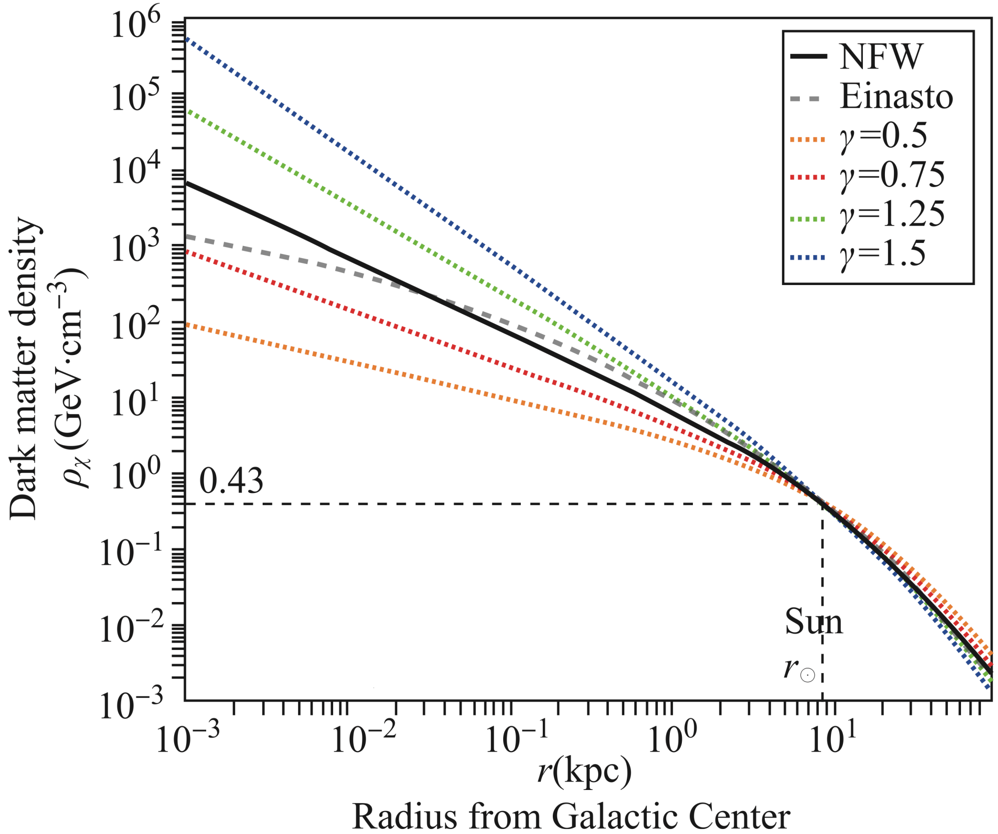
TÉCNICO LISBOA

Helioseismology: limits to the DM characteristics

Dark sector: DM particle (long-range interaction) - interaction between a DM particle (with mass $\boldsymbol{m_\chi}$ and charge $\boldsymbol{Z_\chi\, g_\chi}$) and a nucleus (with mass $\boldsymbol{m_n}$ and electric charge $\boldsymbol{Ze}$). The scattering cross section $\boldsymbol{\sigma_{\chi n}}$ depends on the relative velocity $\boldsymbol{v_{rel}}$ of the particles and there specific properties:

$$\boldsymbol{\sigma_{\chi n}(v_{rel}\, Z_\chi\, , m_\chi, g_\chi, Z, m_n \ldots)}$$

(Pierre et al. 2014)



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

Helioseismology: limits to the DM characteristics

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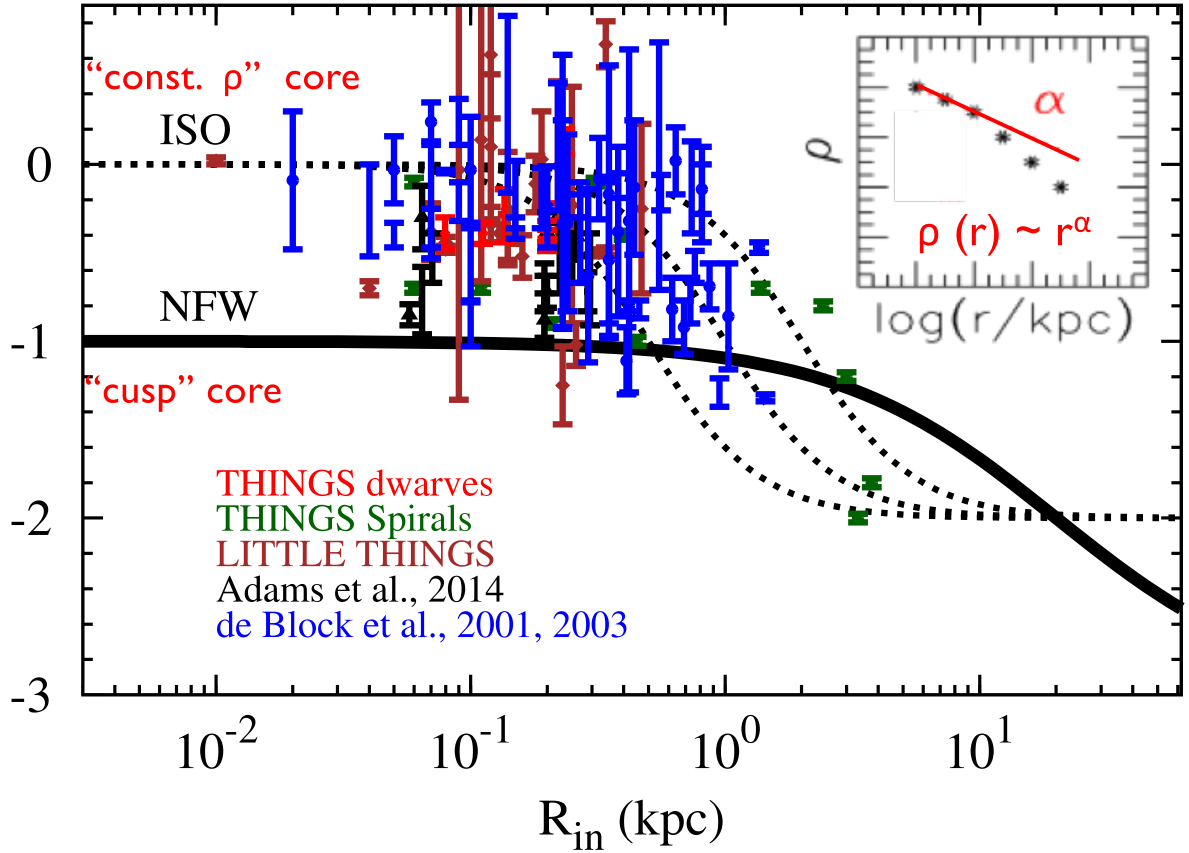
Popolo & Pace 2016 found that a baryonic clumps-DM interaction performs better than the one based on supernova feedback.



Experimental Detection evidence: These DM models can also "explain" the controversial 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);

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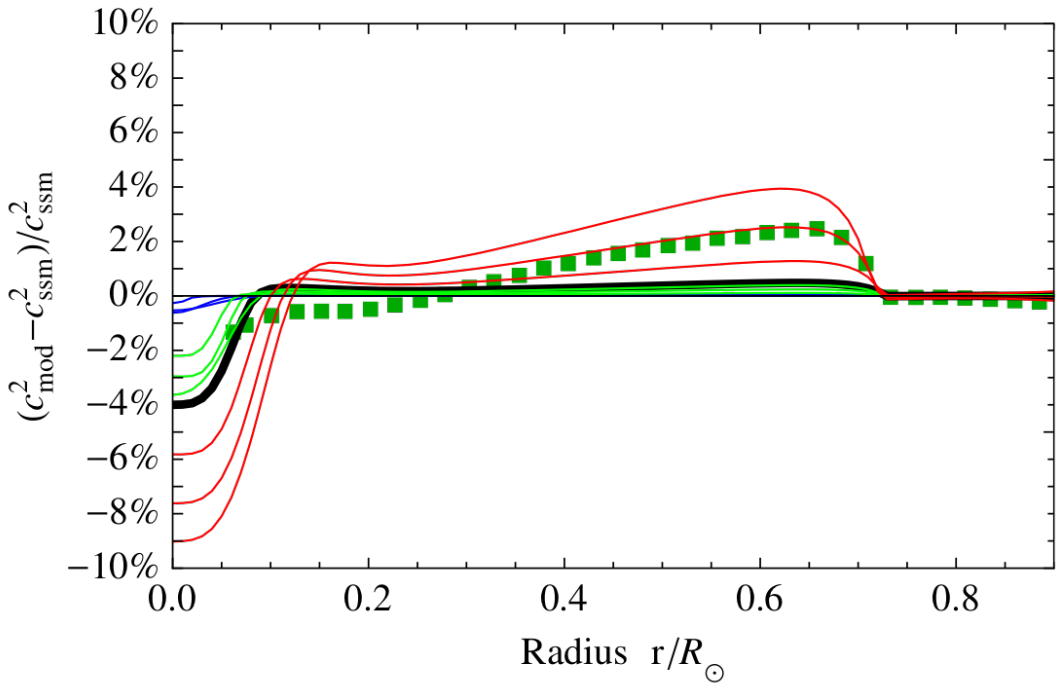
Lopes, Panci and Silk (2014)



Max $\boldsymbol{\delta} c^2_{obs}$ [$=(c^2_{obs}-c^2_{ssm})/c^2_{ssm}$] $\simeq$ 3%

Max $\boldsymbol{\delta} c^2_{dm}$ [$=(c^2_{dm}-c^2_{ssm})/c^2_{ssm}$] $\simeq$ 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. Possible **solution** to the **solar metallicity problem.**

Helioseismology: limits to the DM characteristics

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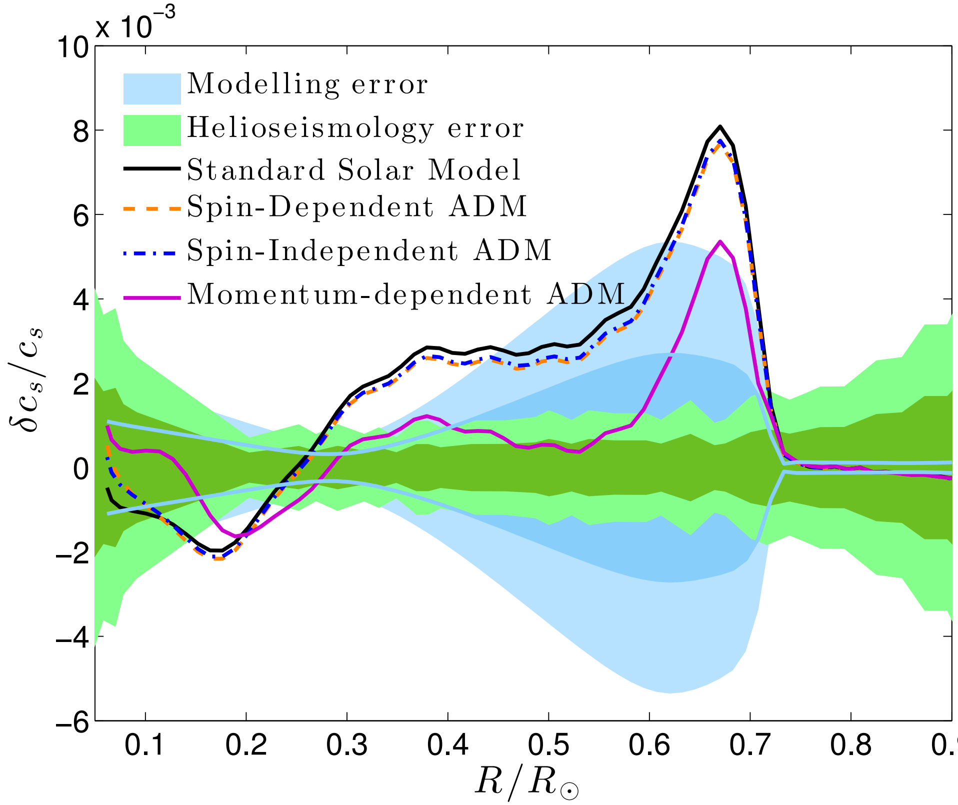
Vincent et. al. (2015)



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Helioseismology: Asymmetric dark matter coupling to nucleons has the square of the momentum q exchanged in the collision. Agreement with sound speed profiles, etc . . . . The best model corresponds to a dark matter particle with a mass of 3 GeV.

Helioseismology: limits to the DM characteristics

Dark sector (magnetic dipole dark matter): an interaction between DM particle (with mass $\boldsymbol{m_\chi}$ and magnetic dipole moment $\boldsymbol{\mu_\chi}$) and a baryon, this leads to the following expression for cross section: $\boldsymbol{\sigma_{\chi n}}(\ \boldsymbol{m_\chi}, \boldsymbol{\mu_\chi}\ , \ldots)$

Lopes, Kadota & Silk (2014)

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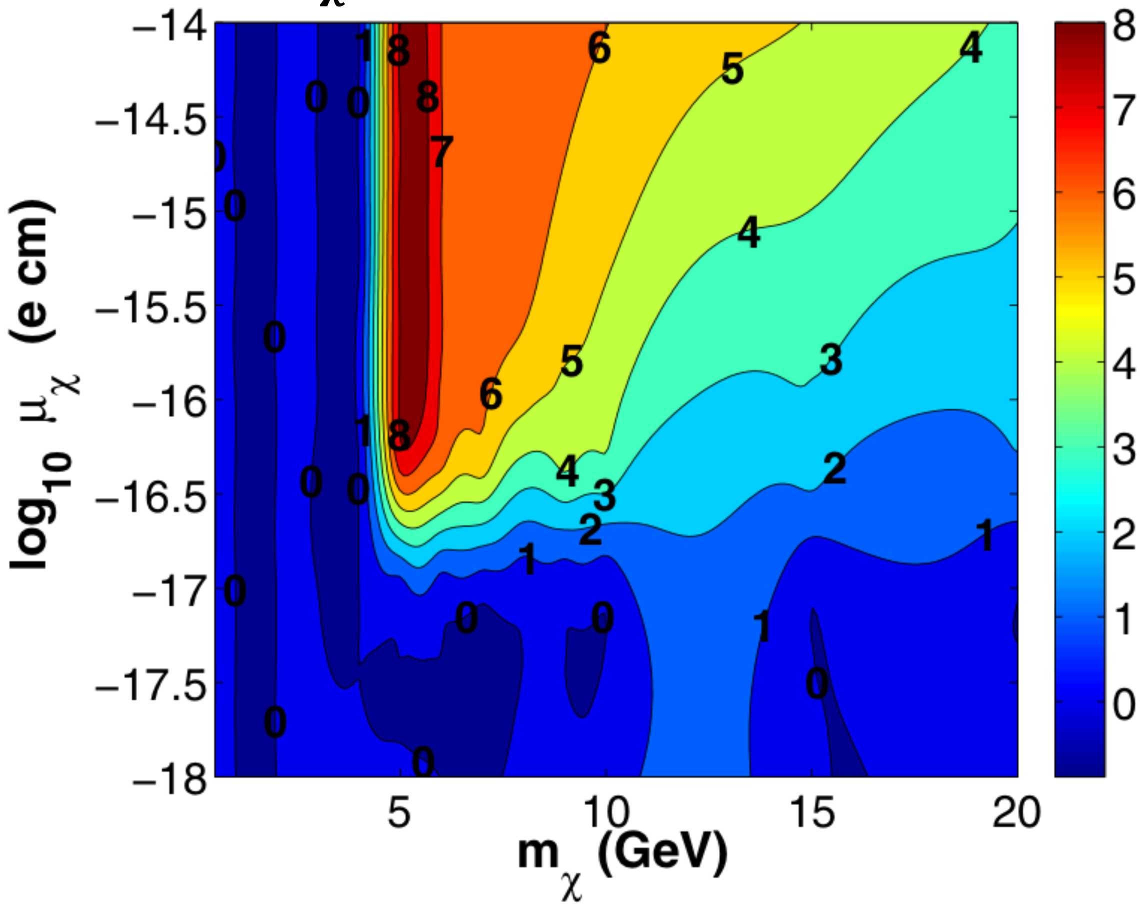
Max $\boldsymbol{\delta} c^2_{dm}\,[=(c^2_{dm}-c^2_{ssm})/c^2_{ssm}] \gtrsim\ 3\%$

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



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.

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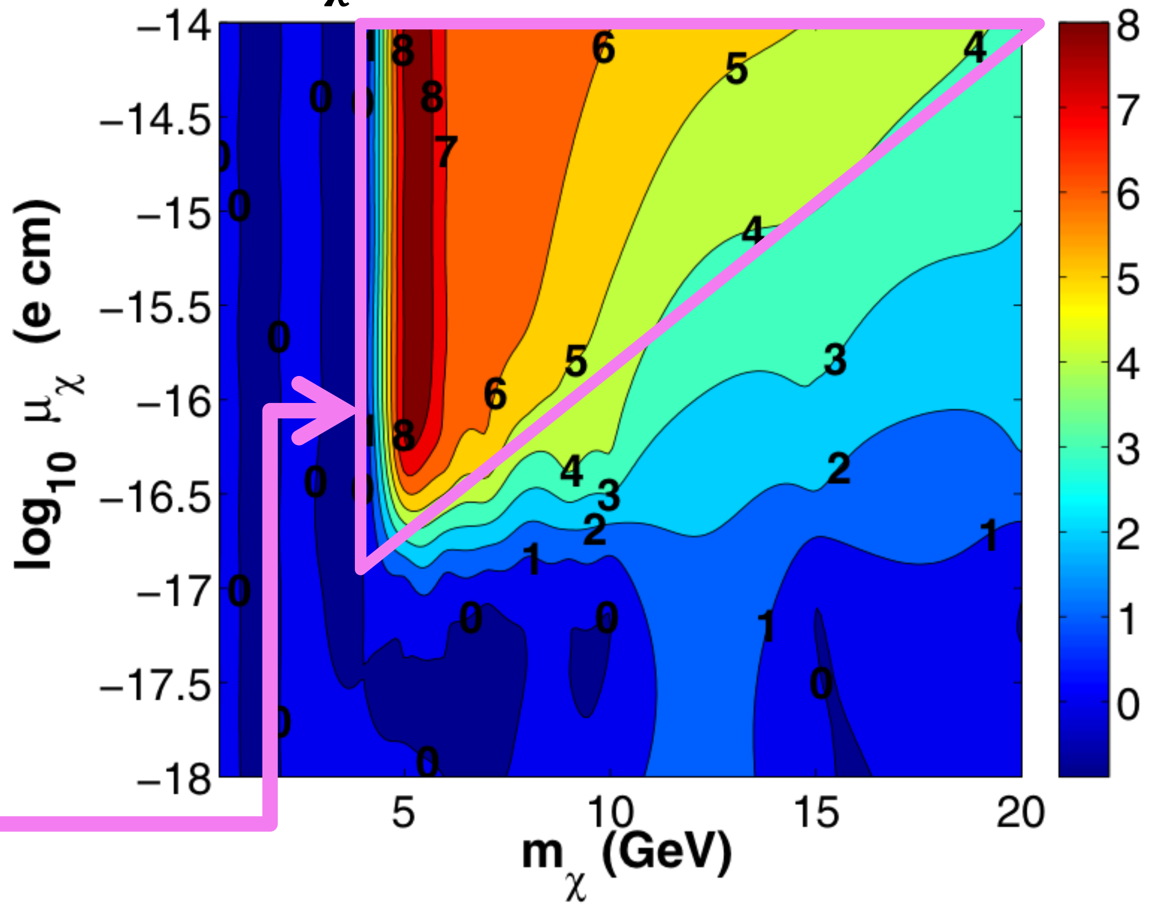

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Neutrinos from annihilating dark matter present in the Sun’s core

Helioseismology

Limits on Thermally Annihilating Dark Matter from Neutrino Telescopes

I. Lopes, J. Lopes (2016)

Dark sector: Neutrino flux (including neutrino flavour oscillations) resulting from the WIMP annihilation (with the annihilation rate $\langle \sigma v \rangle$) of two DM particles in the Sun is given by

$$\Phi_\nu = \frac{\Gamma_A}{4\pi r^2} \sum_i \mathrm{BR}_i \int \frac{dN_\nu}{dE_\nu} dE_\nu$$

$$\langle \sigma v \rangle(\mathrm{v}) = a + b \, \langle v^2 \rangle$$

s-wave annihilation (standard) p-wave annihilation

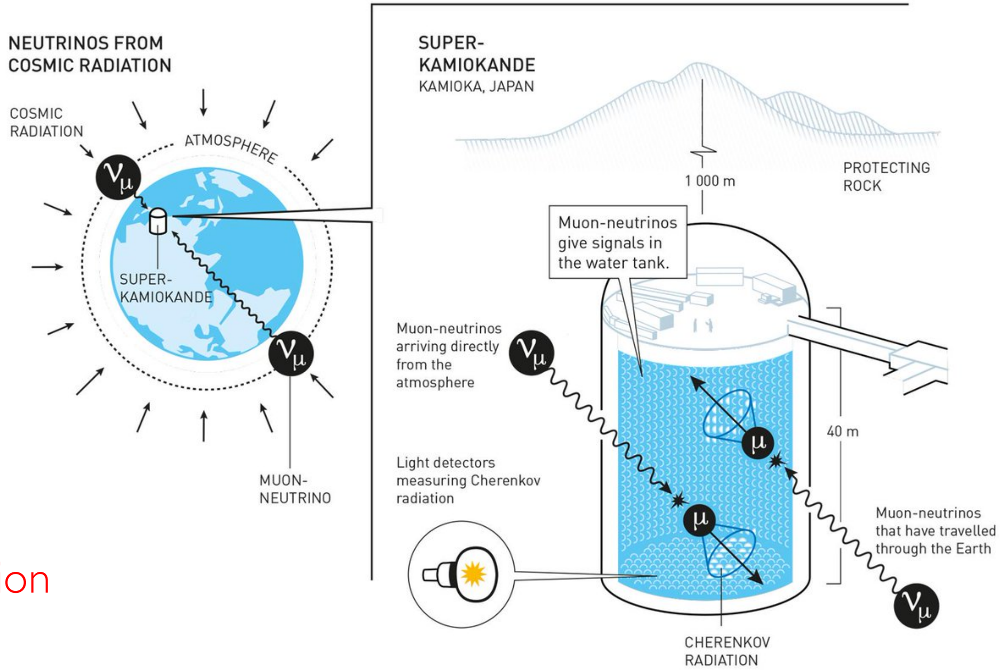

Illustration: © Johan Jarnestad/The Royal Swedish Academy of Sciences

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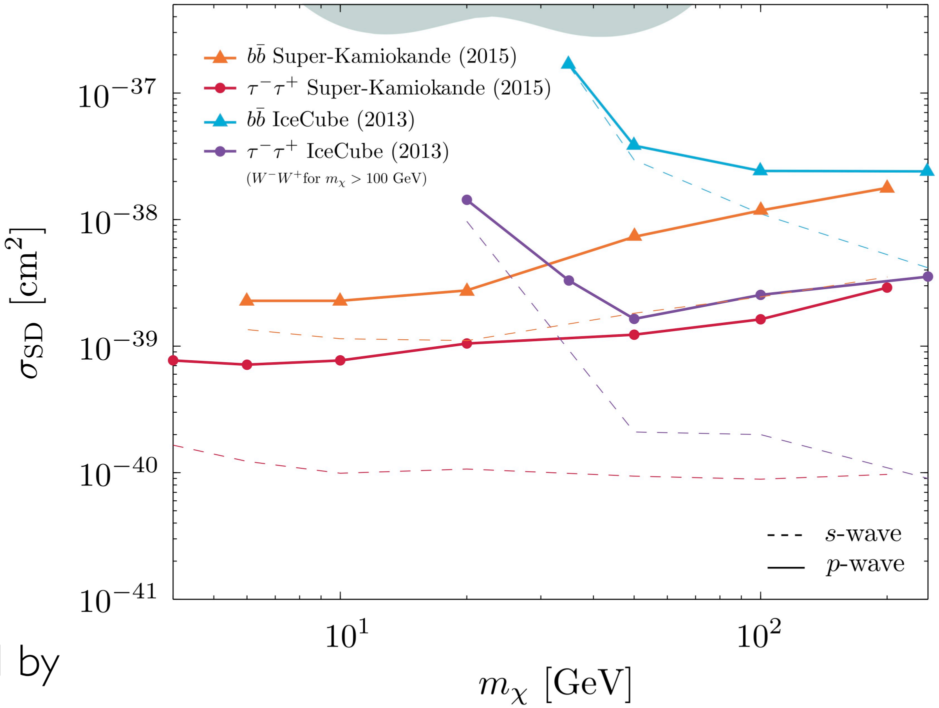
s-wave annihilation (standard)   p-wave annihilation

Limits in the $\sigma_{\chi n}^{SD}$ scattering cross-section placed by the **Super-Kamiokande** and **IceCube neutrino** detectors.



Spin dependent

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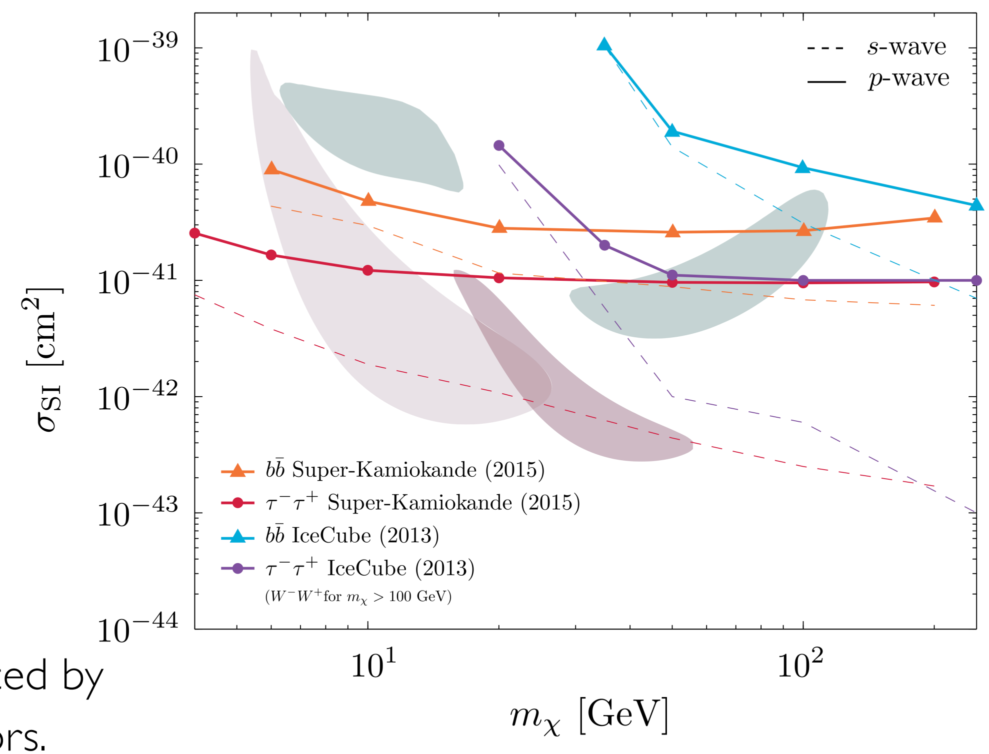
s-wave annihilation (standard) p-wave annihilation

Limits in the $\sigma^{SD}_{\chi n}$ and $\sigma^{SI}_{\chi n}$ scattering cross-section placed by the **Super-Kamiokande** and **IceCube neutrino** detectors.



Spin independent

Helioseismology: Limits on the scattering cross-section for WIMPs for s-wave (dashed) and p-wave (dotted) annihilations, obtained from the IceCube (Aartsen et al. 2013) and Super-Kamiokande (Choi et al. 2015). The regions of interest obtained by direct detection experiments are also shown.

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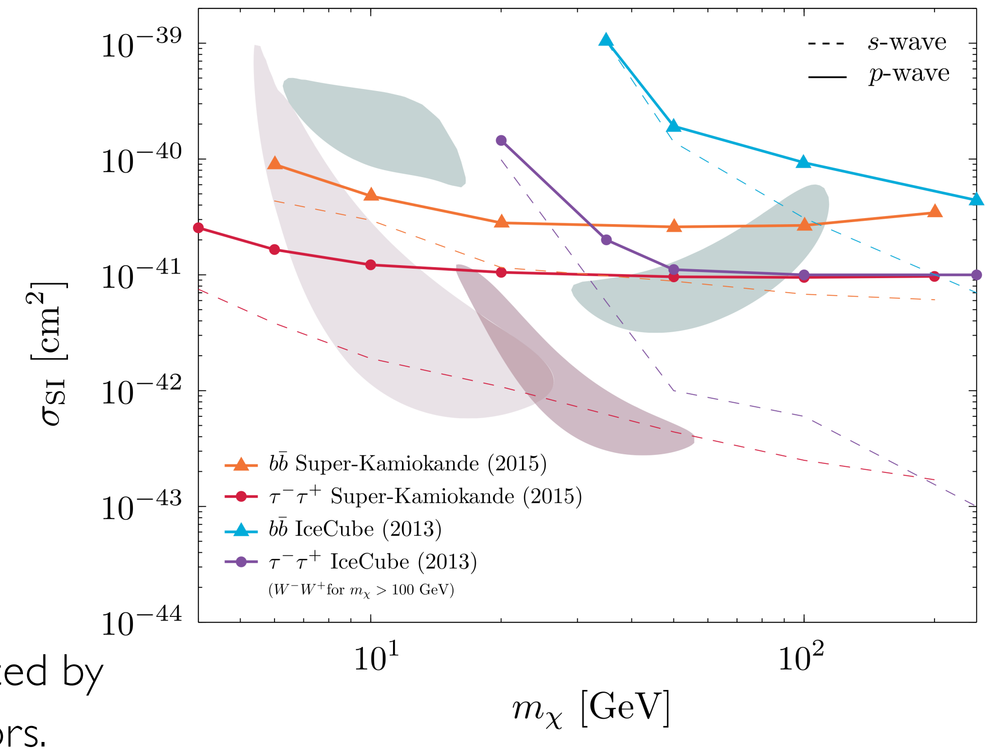

Spin independent

The favoured regions from different direct detection are also shown. Pink: CDMS II Si at 2σ C.L. (Agnese et al. 2013); Green: DAMA/LIBRA at 3σ C.L. (Bernabei et al. 2008); Purple: CRESSTII at σ C.L. (Angloher et al. 2012).

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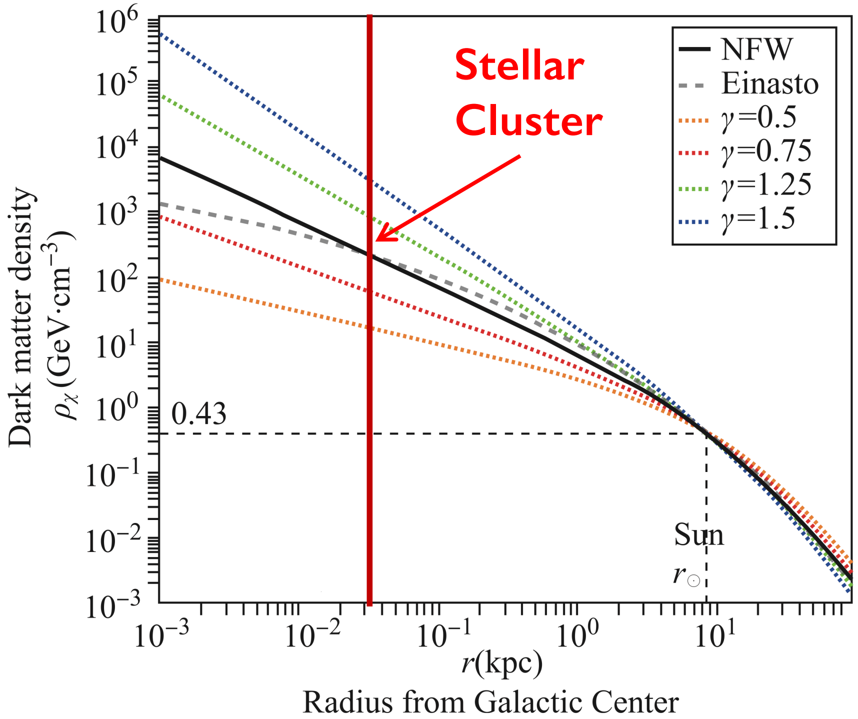
Constraints on Asymmetric Dark Matter

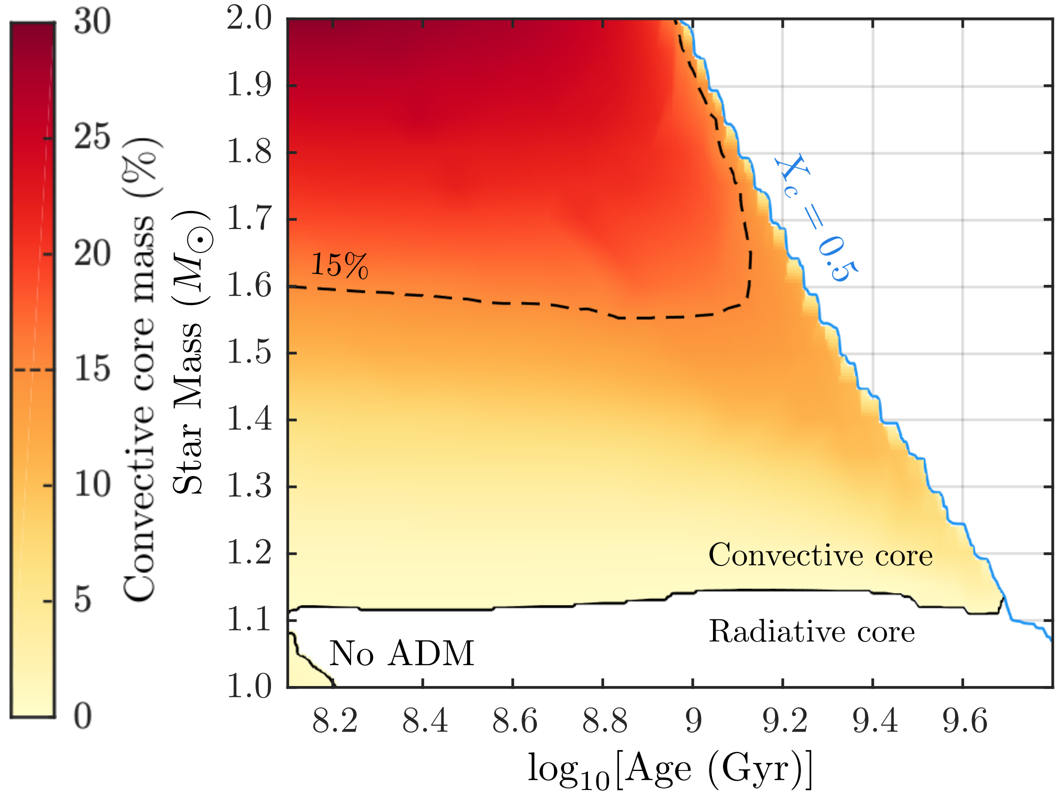
Stars in the Galactic Centre

TÉCNICO LISBOA

Stellar Cluster: limits to the DM characteristics

Dark sector: DM particle (point-like interaction) – an interaction between a DM particle (with mass $\boldsymbol{m_\chi}$ and scattering cross-section $\boldsymbol{\sigma_{\chi p}}$) and a proton inside a low-mass main-sequence star in the Milky Way's nuclear stellar cluster. Lopes & Lopes (ApJ, 2019)





The solid black line separates stars with radiative core from stars with a convective core. We also show the contour (black dashed line) for which the mass of the convective region represents 15% of the total mass of the star.

Stellar Clusters: If we consider $\boldsymbol{\rho_\chi} > 10^3$ GeV cm^{-3} (corresponding to the inner 5 pc of the Milky Way), stars lighter than the Sun will have a main-sequence lifespan comparable to the current age of the universe. Stars more massive than 2 $M_\odot$ are not sensitive to the dark matter particles.

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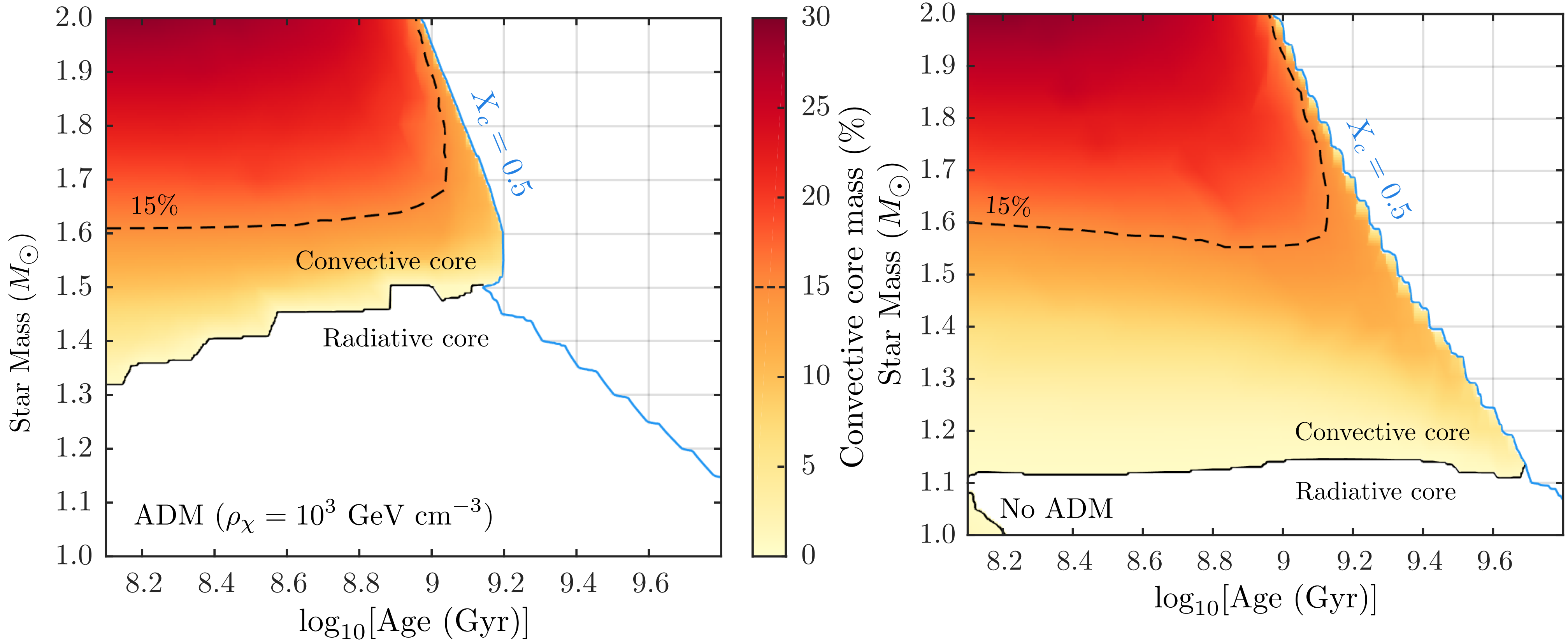

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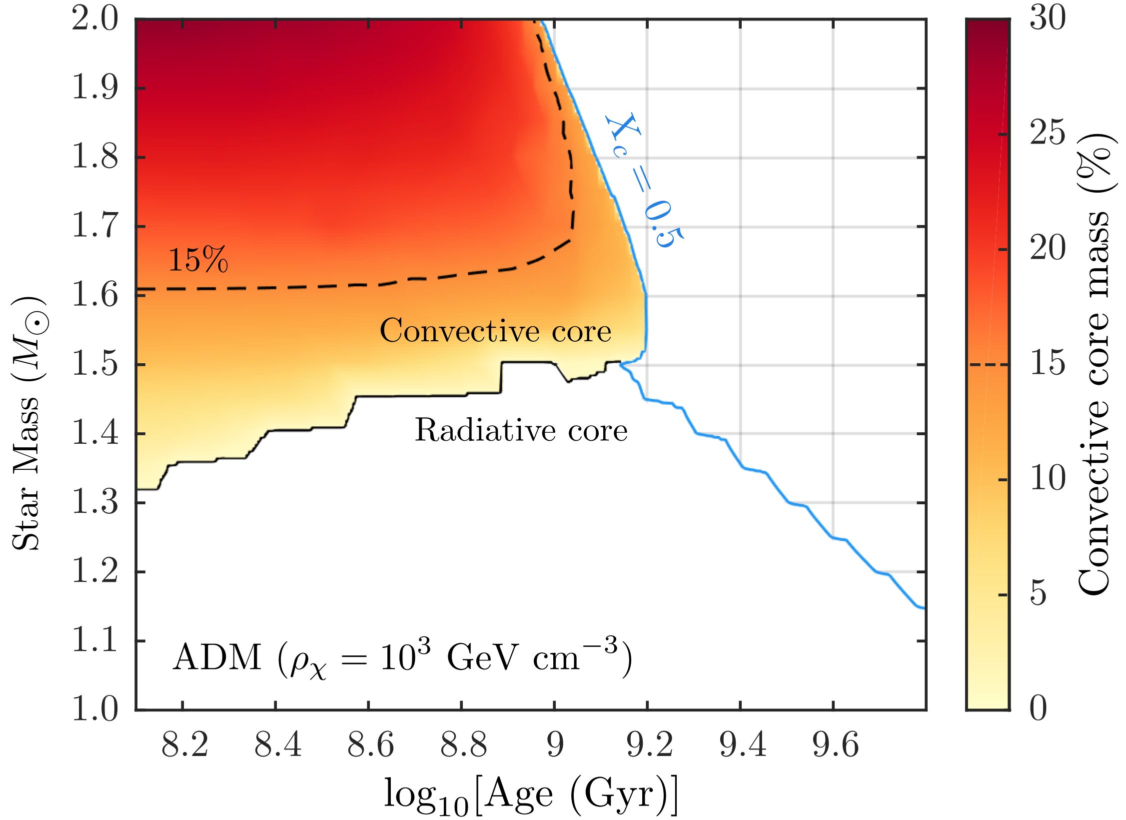

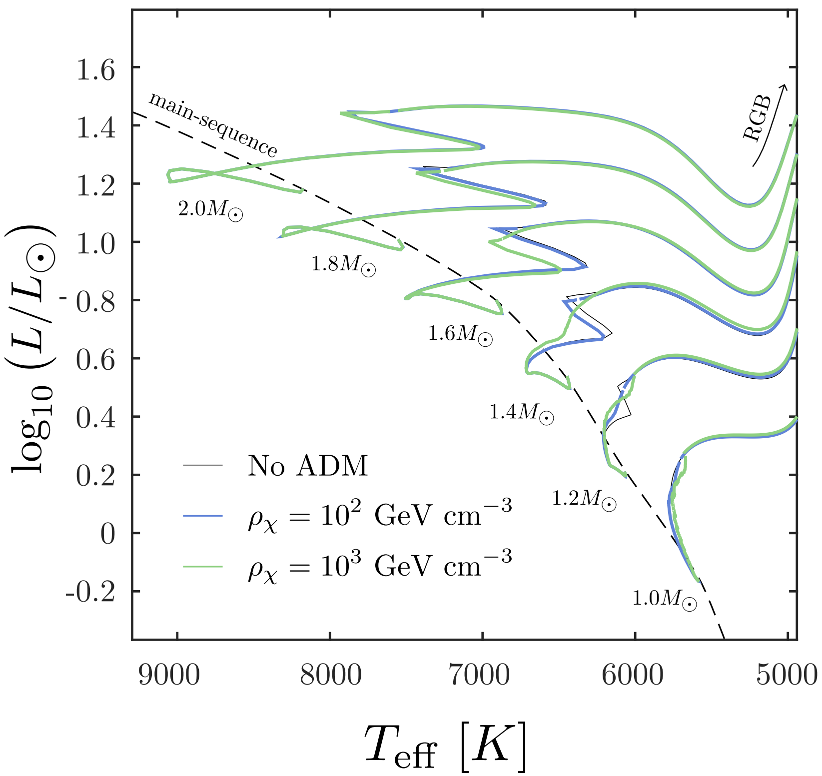

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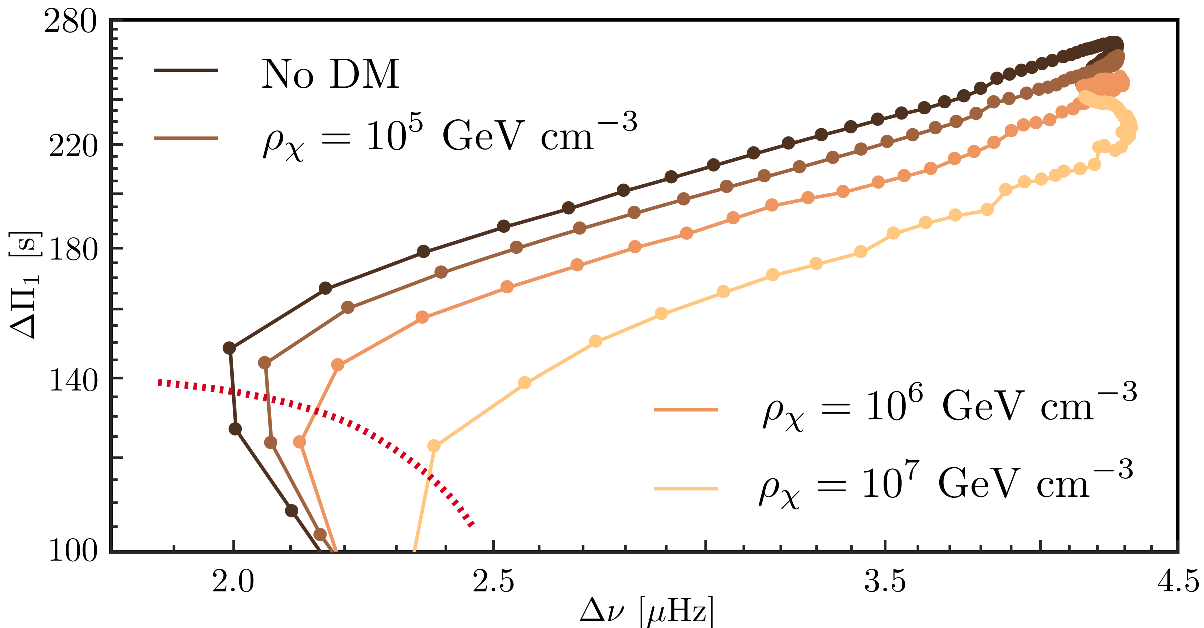
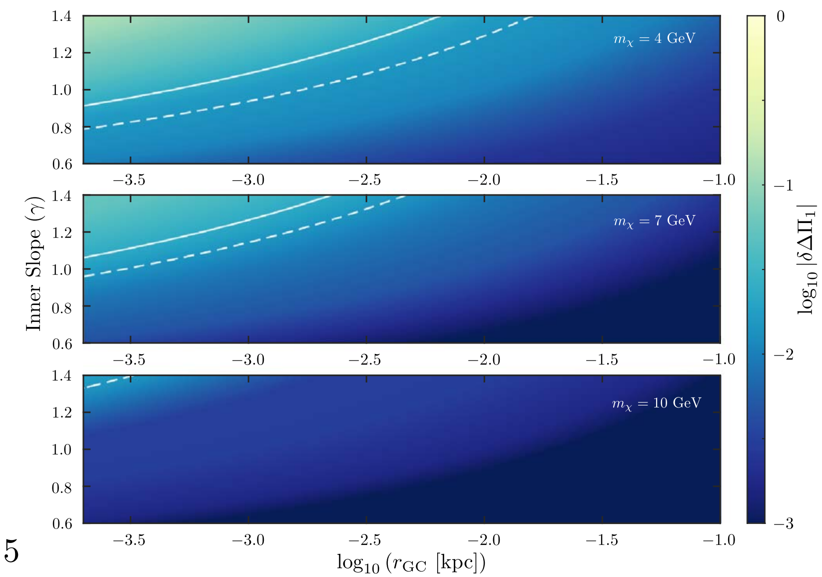
Stellar Cluster: limits to the DM characteristics

Dark sector: DM particle (point-like interaction) – Thermally produced DM particles in the mass range 4-10 GeV with spin-independent annihilation and scattering cross-sections that are close to the observational upper limits from direct detection experiments. Lopes & Lopes, Silk (ApJL, 2019)

Red Clump stars, in some cases with $L \sim 10^2\ L_{sun}$, can be observed throughout the galaxy and thus can give us insight into the DM conditions found in situ.





G-mode period spacing $\Delta\Pi_1$ vs. p-mode large frequency separation $\Delta\nu$ for an HB star with M=1.0 Msun from the ZAHB phase until the beginning of the asymptotic giant branch evolved in different DM densities. The considered DM particle has m_χ=4 GeV, $\sigma_{\chi,SI}=10^{-39}$ cm2 and $<\sigma v> = 3\ 10^{-26}$ cm^3 s^{-1}. The red dashed line flags the approximate region where the HB phase ends.

Stellar Clusters: "Asteroseismology of Red Clump Stars as a Probe of the Dark Matter Content of the Galaxy Central Region"

Constraints on dark matter and sterile neutrinos interaction with Hydrogen

Solar neutrinos

I. Lopes (EPJC 2018) and I. Lopes (ApJ 2019)

TÉCNICO LISBOA

Conclusion

Conclusion

The resolution of the dark matter problem will possibly be achieved through the development of an extension to the standard model of elementary particles, i.e., a dark matter sector made of one or more particles (stable and unstable) with their own set of rules.

A final resolution will be possible, not through efforts by a single field of research only, but more likely through an interdisciplinary approach to this problem, where the Sun and stars can play an important complementary role to Cosmology and Particle Physics.

Conclusion

Helioseismology and solar neutrinos can be used to test the different dark matter candidates. Moreover, the next generation of **solar neutrinos telescopes** has the potential of being even more stringent in fixing those constraints. More importantly, the combination of previous data sets could help us to disentangle the different physical processes operating in the Sun's core (rotation, magnetic field, gravity waves . . . and dark matter)

Asteroseismology provides a new method to probe the physics inside MS and post-MS stars. Therefore, stellar oscillation data (of a future mission like PLATO) can be used to put constraints on the same (and new) dark matter candidates. The **diversity of stars** and their distribution in the **Milky Way disk** and **Halo** (Globular clusters) provides a new way to constrain the properties of dark matter on locations other than **the solar neighbourhood**.

TÉCNICO LISBOA

Thank You

stars
solar
neutrino
Sun
matter
dark
helioseismology
physics
particles
modes
DM
mass
Solar
core
asteroseismology
oscillations
oscillation
model
acoustic
impact
data
evolution
stellar
density
neutrinos
Sun's
waves
flux
different
fluxes
interior
new
red
better
seismic
order
masses
asymmetric
asteroseismic
results
search
approach
light
study
nuclear
diagnostic
particular
spectra
amplitude
surface
massive
GW
giants
star
frequency
scattering
low
found
structure
measurements
range
high
small
observations
gravitational
atmospheric
precision
GeV
possibility
reactions
smaller
potential
variation
used
detection
propose
dynamo
possible
standard
first
Earth's
magnetic
glitch
using
New
Universe
electronic
time
profile
formed
detectors
speed
Dark
local
ionization
properties