CONSTRAINING DARK MATTER with ASTEROSEISMOLOGY

CoRoT 3 - KASC 7

Jordi Casanellas

in coll. with

Ilídio Lopes: Casanellas J. & Lopes I., ApJL 765 (2013) arXiv: 1212.2985

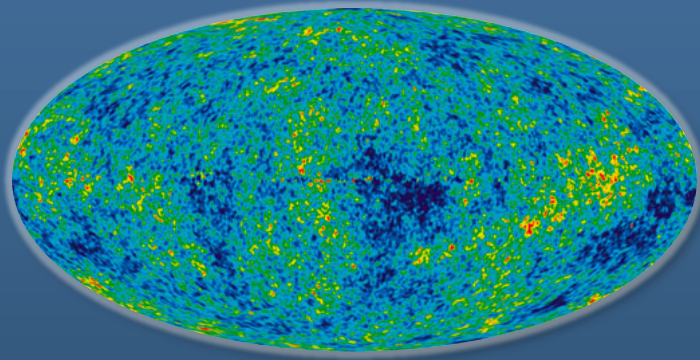
Isa M. Brandão: Casanellas J. & Brandão I., in preparation

Max-Planck-Institut für Gravitationsphysik (Albert-Einstein-Institut)

Unterstützt von / Supported by Alexander von Humboldt Stiftung / Foundation

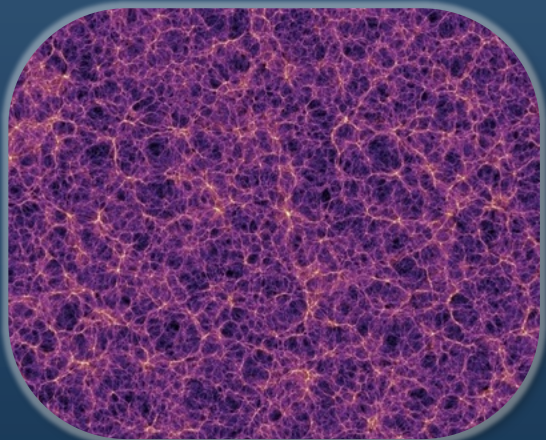
The Space Photometry Revolution, Toulouse 2014

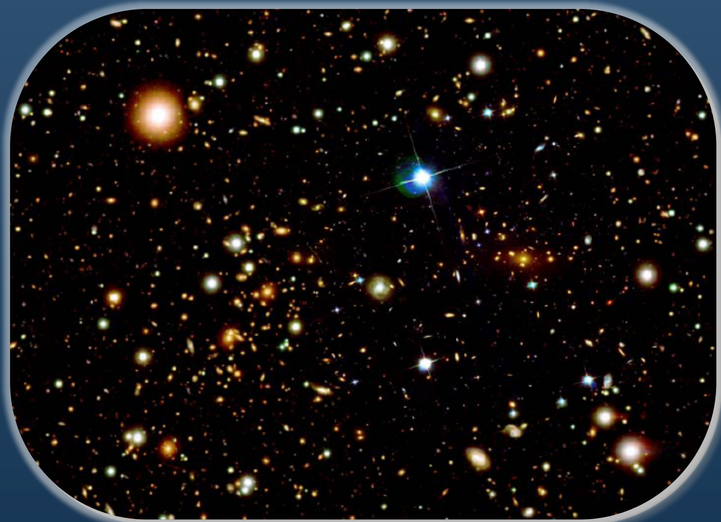
Dark Matter??

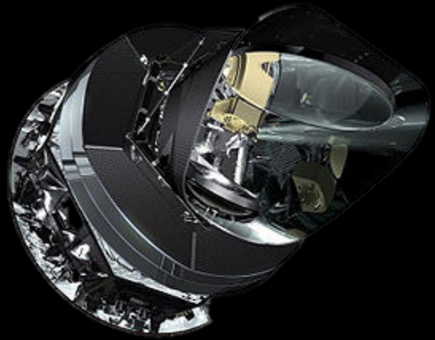


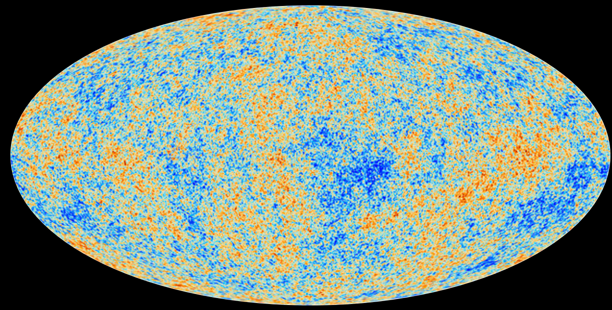
~ **80%** of all the matter exists in an **unknown form**

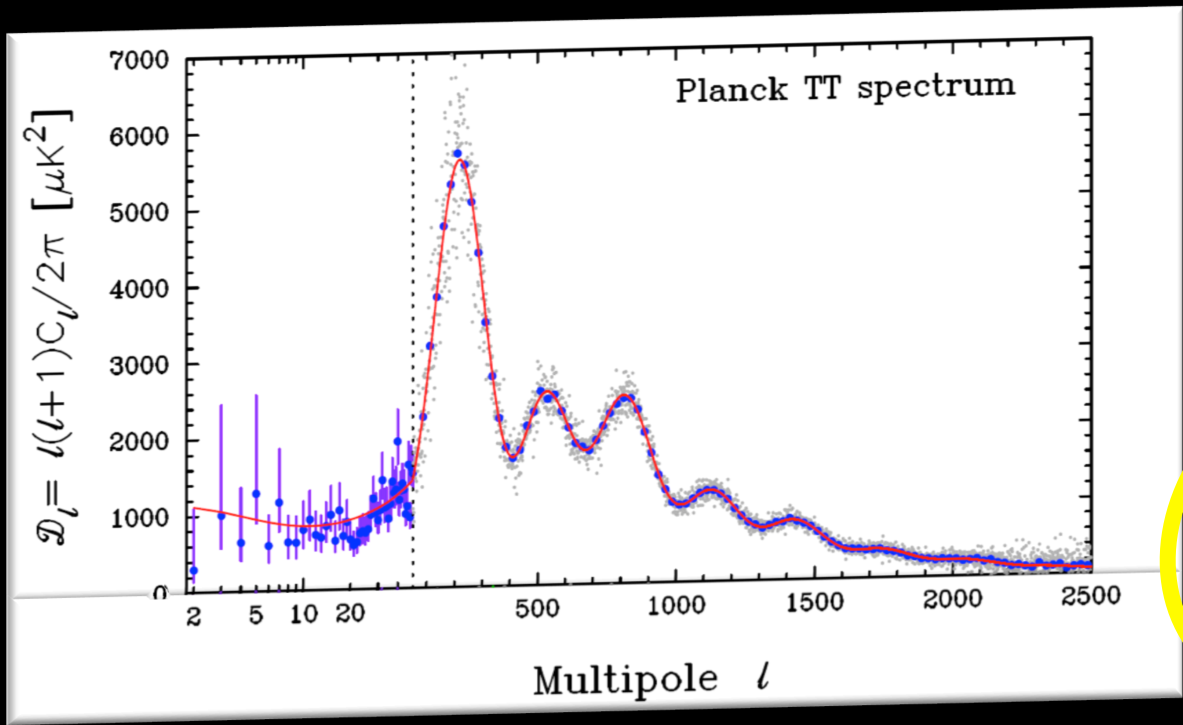
- Massive
- Abundant
- Stable
- Weakly interacting with photons (neutral) and baryons











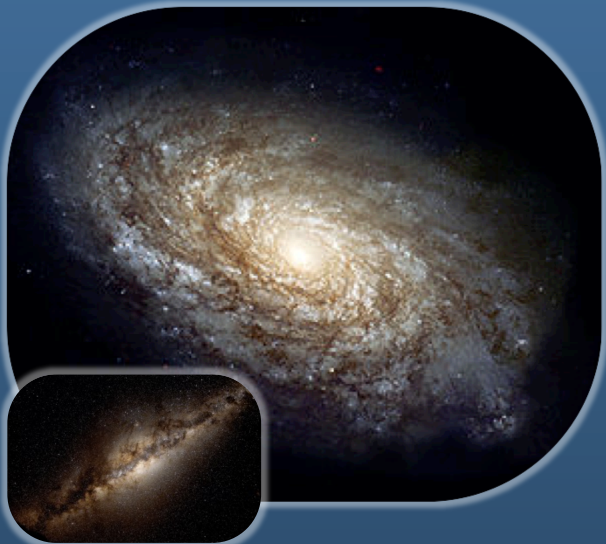
ting

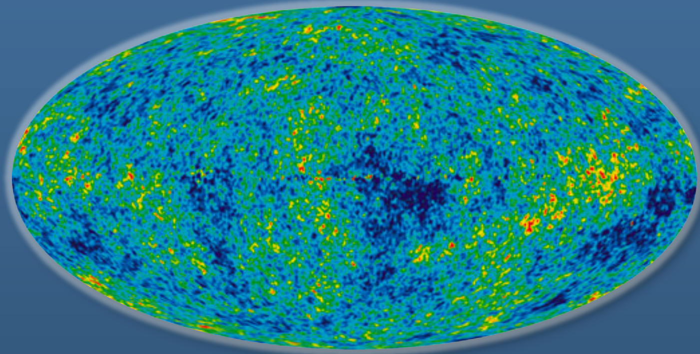
$\Omega_m = 0.315$

$\Omega_b = 0.049$

[PLANCK coll., arXiv:1303.5076 (2013)]

Dark Matter??





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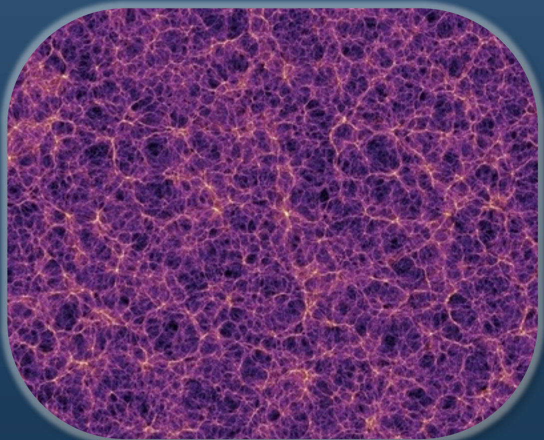
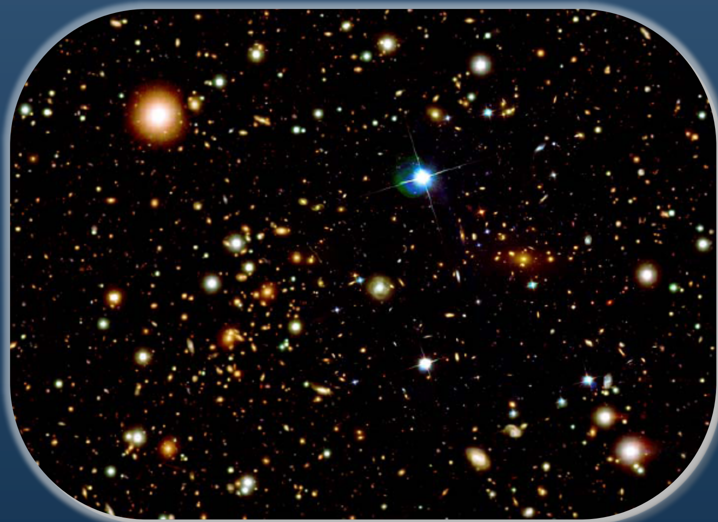
- Non baryonic





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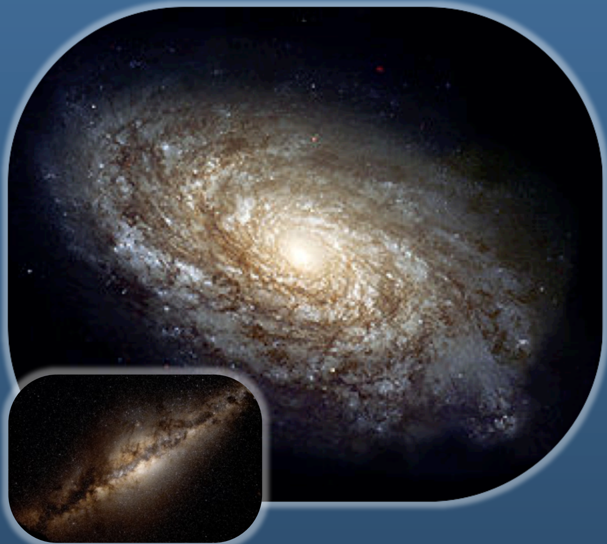

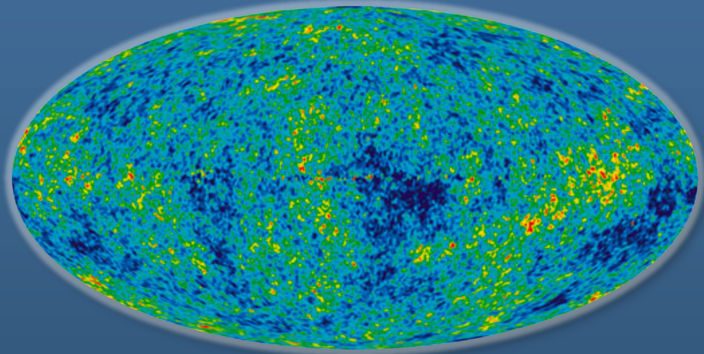

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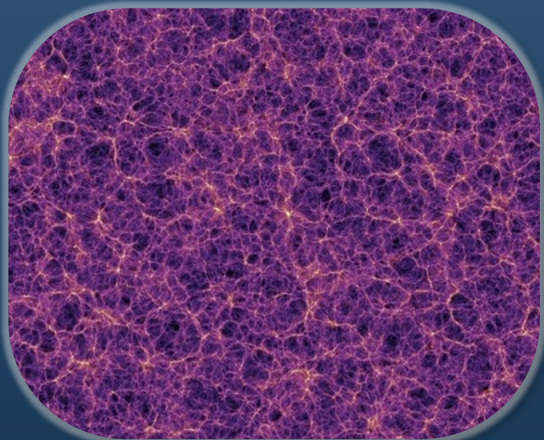

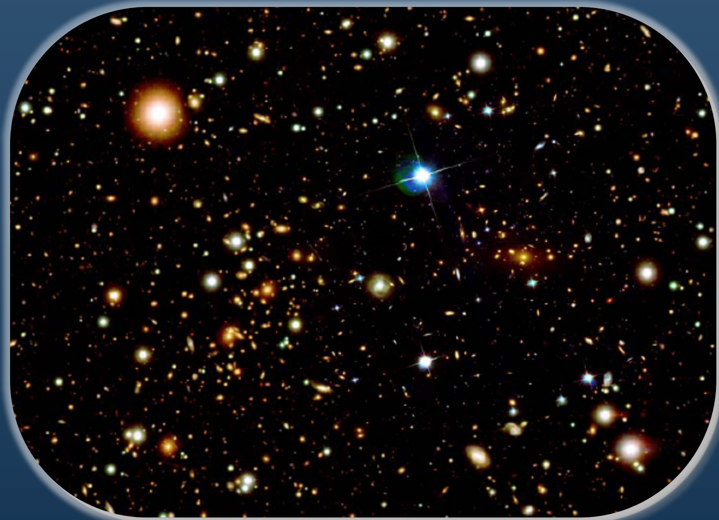

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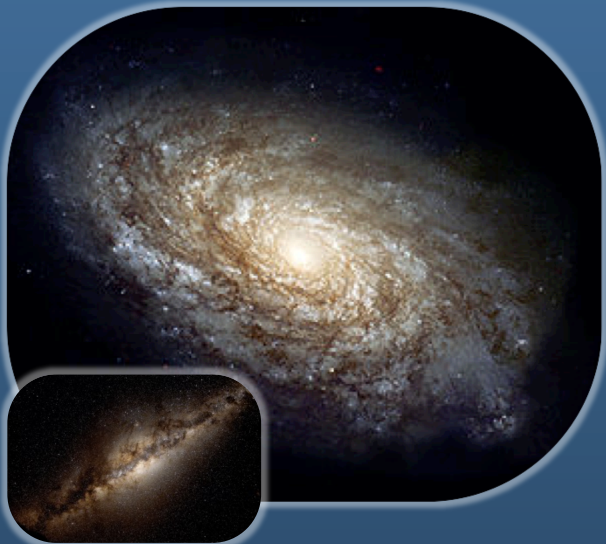
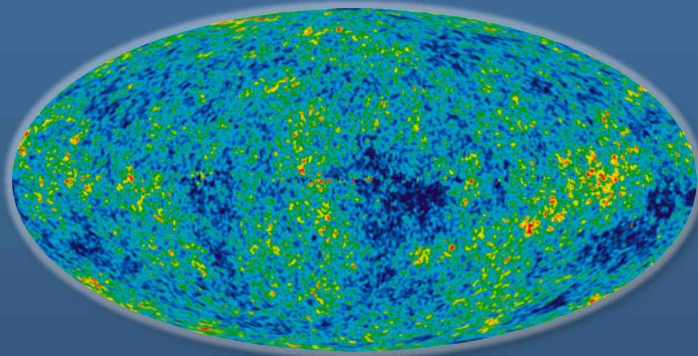
- Cold (very non-relativistic)

Dark Matter??





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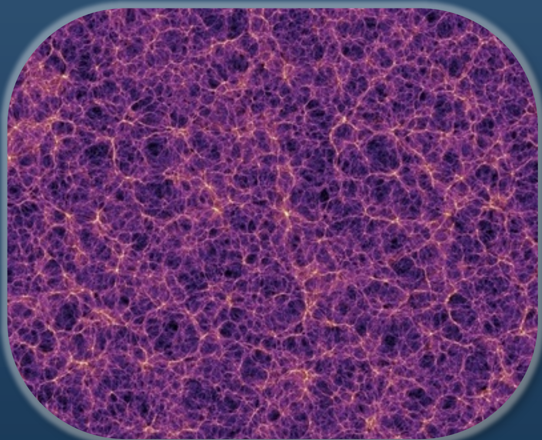

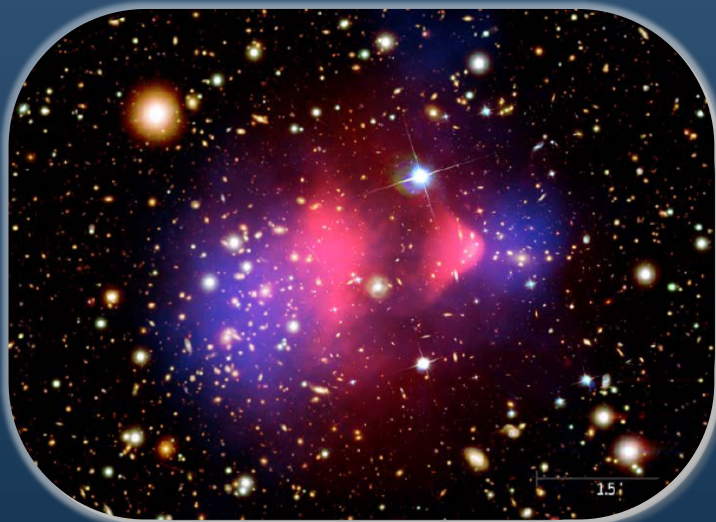

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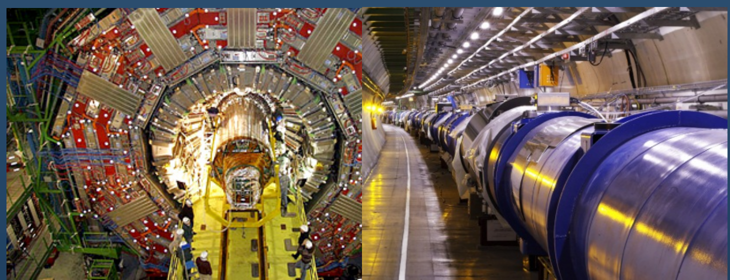
→ **WIMPs !**

axions,
sterile neutrinos,
gravitinos ...

Dark Matter searches

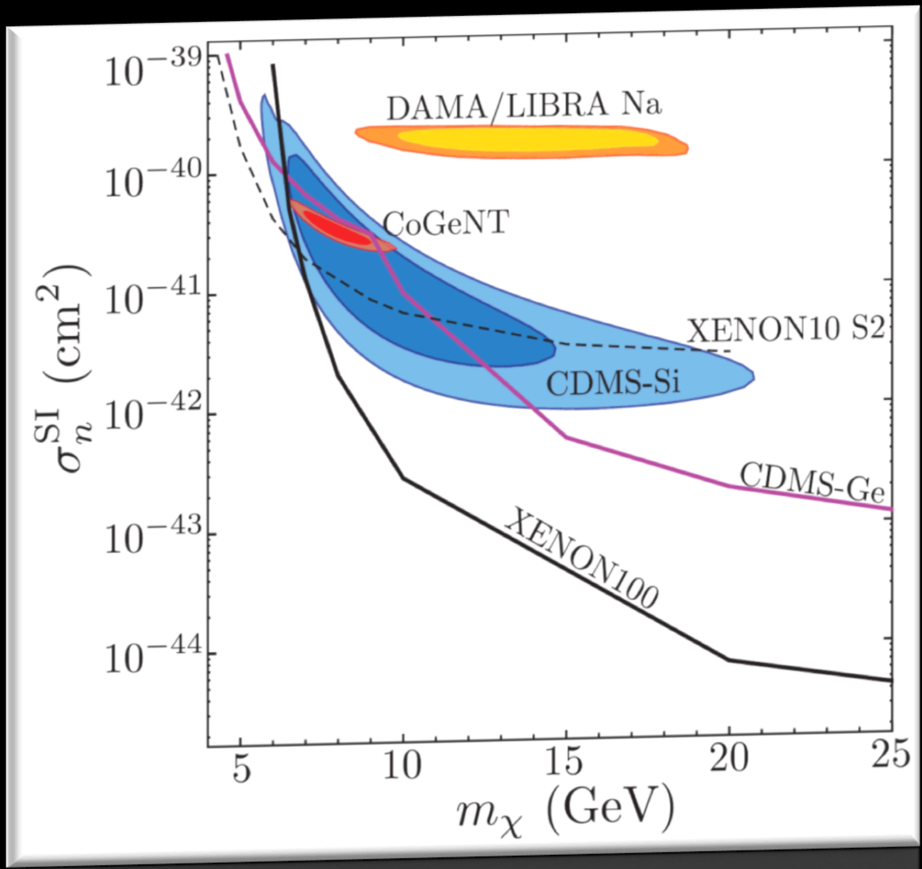
Direct detection

Indirect detection



Colliders

Astrophysical probes
(**STARS**)



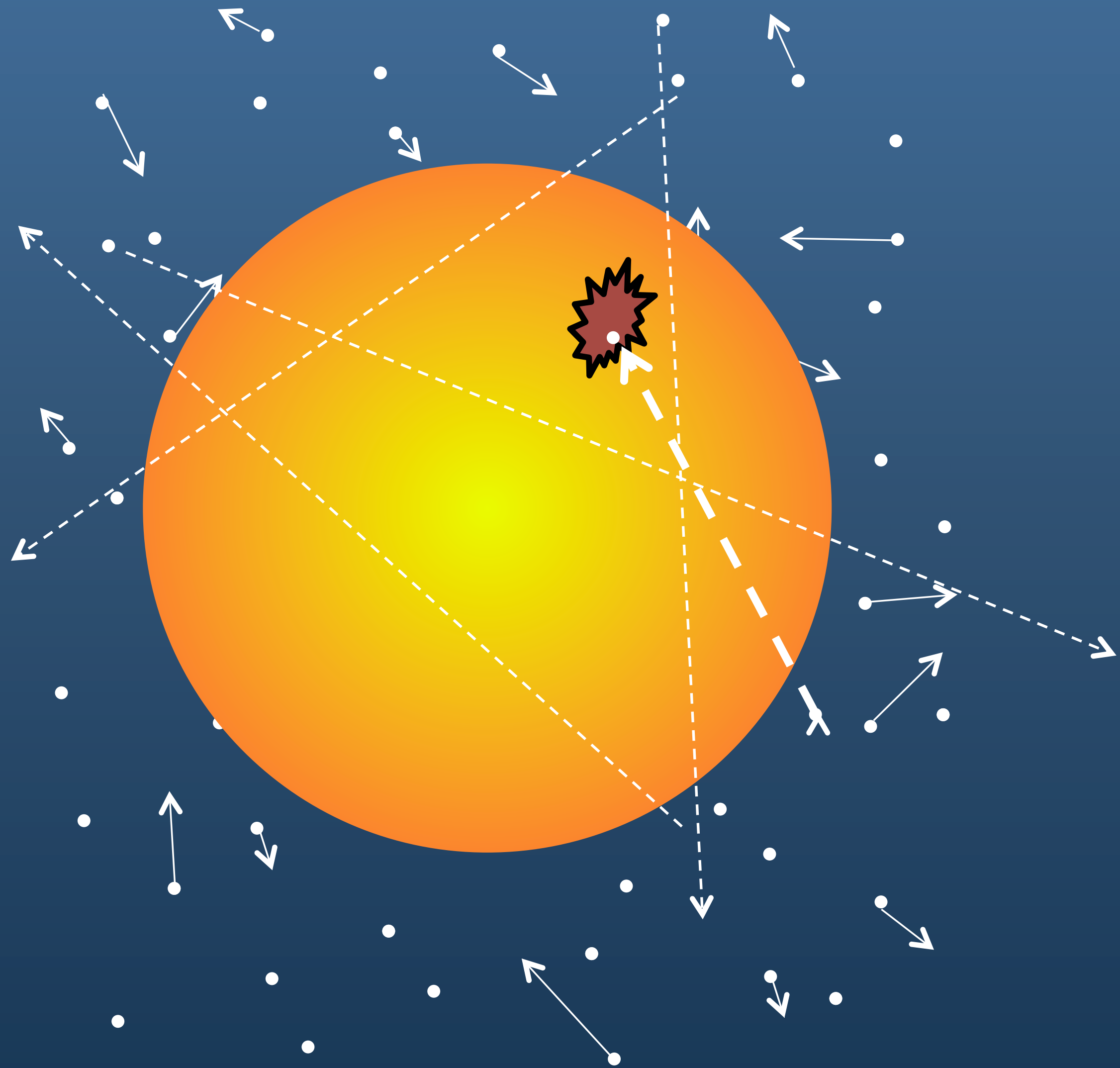
[Buckley M. & Lippincott W. H., Phys. Rev. D 88 (2013)]

Detection of Low-mass WIMPs ??

DAMA, CoGeNT, CRESST, CDMS

Tension with null results of XENON100, EDELWEISS

Impact of Dark Matter on stars



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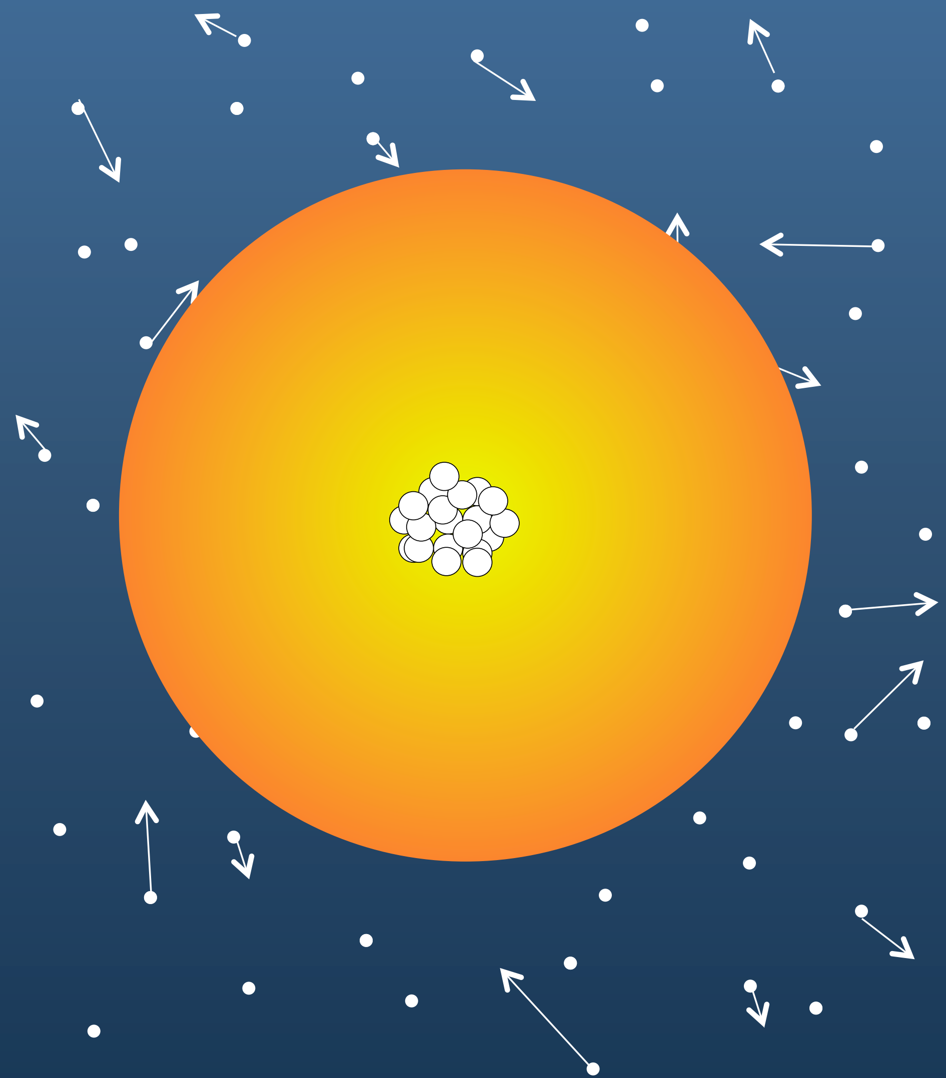

DM Capture [Gould, ApJ 321 (1987)]

Impact of Dark Matter on stars

DM Capture [Gould, ApJ 321 (1987)] + DM energy transport [Gould & Raffelt ApJ 352 (1990)]

Impact of asymmetric Dark Matter on stars

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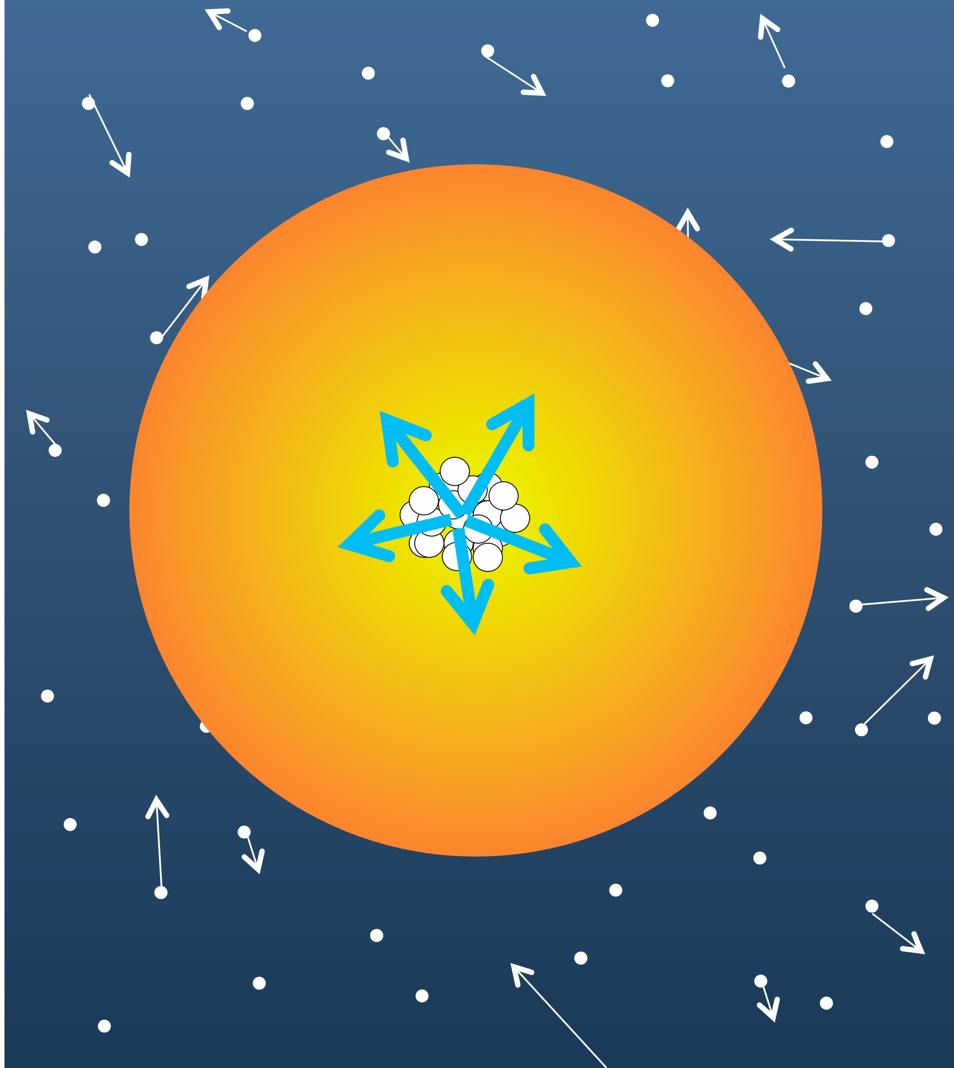
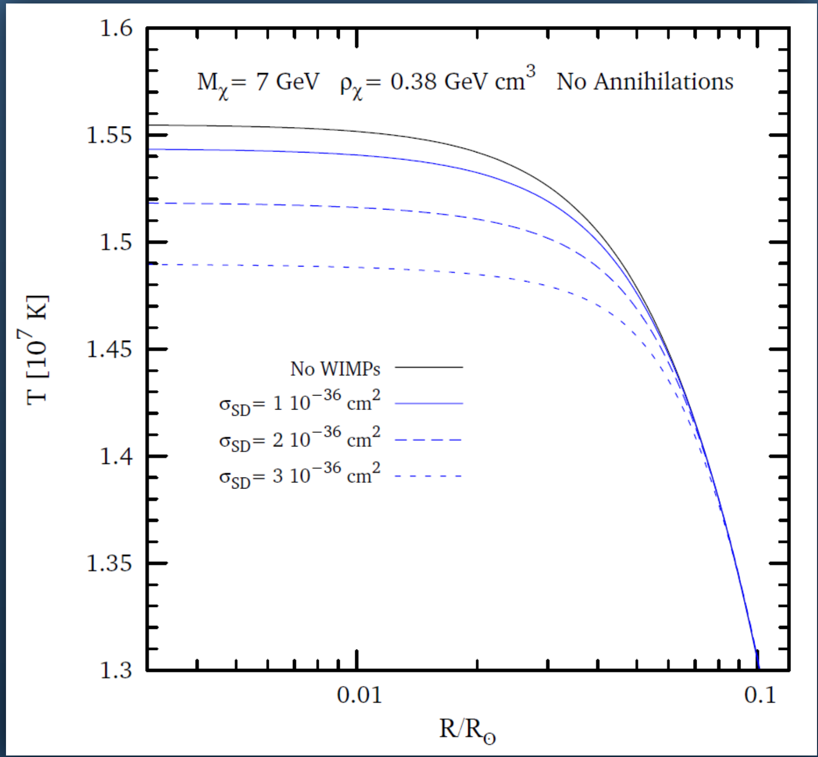


DM energy transport

[Gould & Raffelt ApJ 352 (1990)]

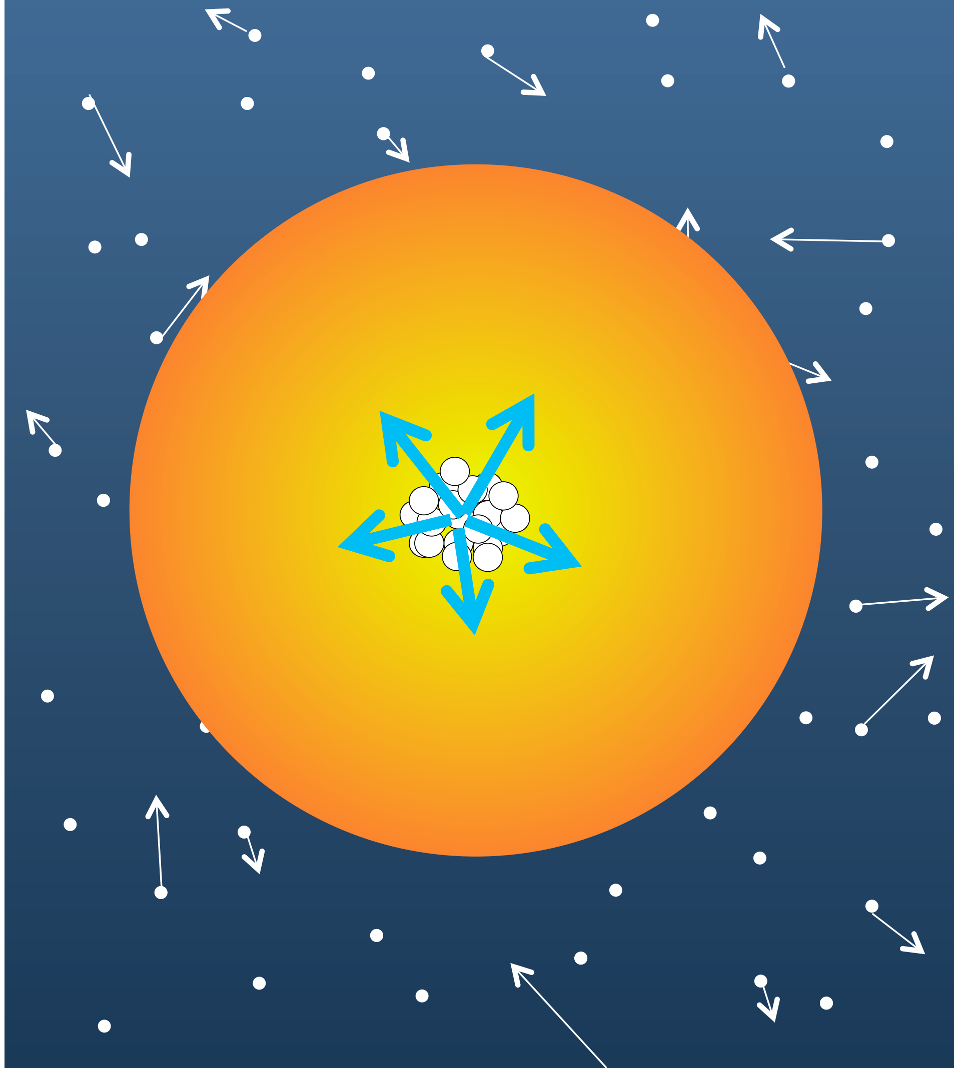
Reduction central temperature

SUN: [Spergel and Press, ApJ 294 (1985)
Lopes, Bertone & Silk, MNRAS 337 (2002)...]



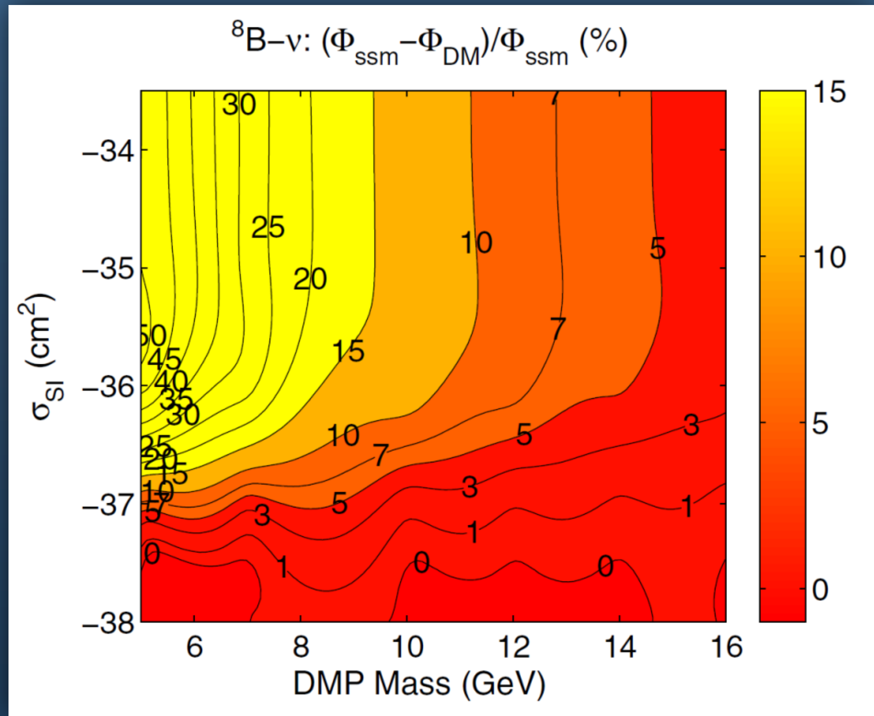
[Taoso *et al*. Phys. Rev. D 82 (2010)]

Impact of asymmetric Dark Matter on stars



Reduction central temperature

SUN: solar neutrinos, helioseismology



[Lopes & Silk, ApJL 752 (2012), Science (2012)]

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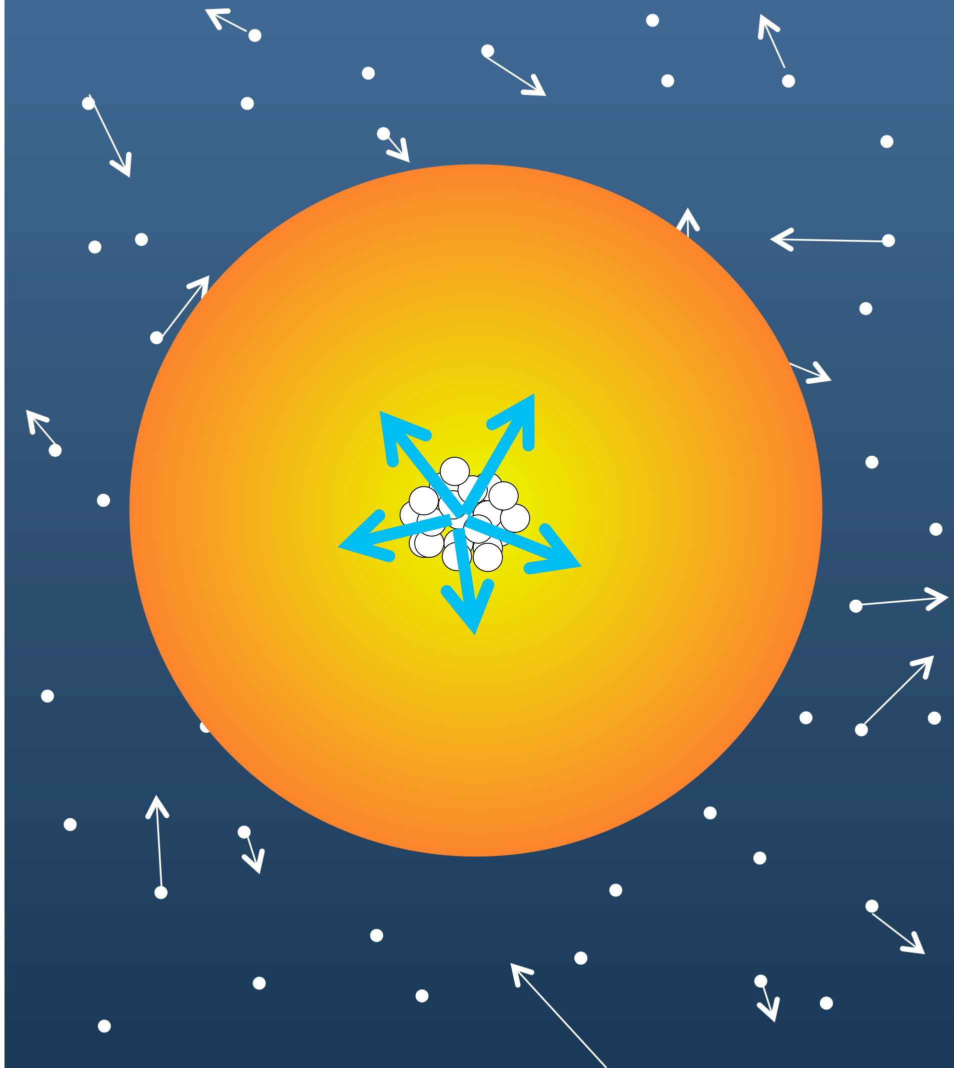

Reduction central temperature

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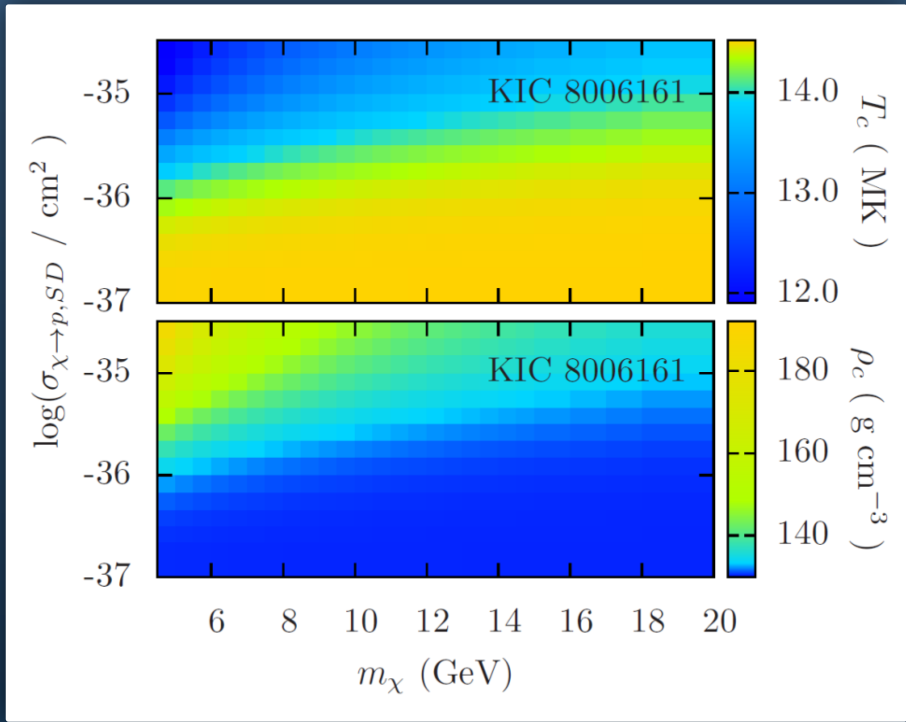
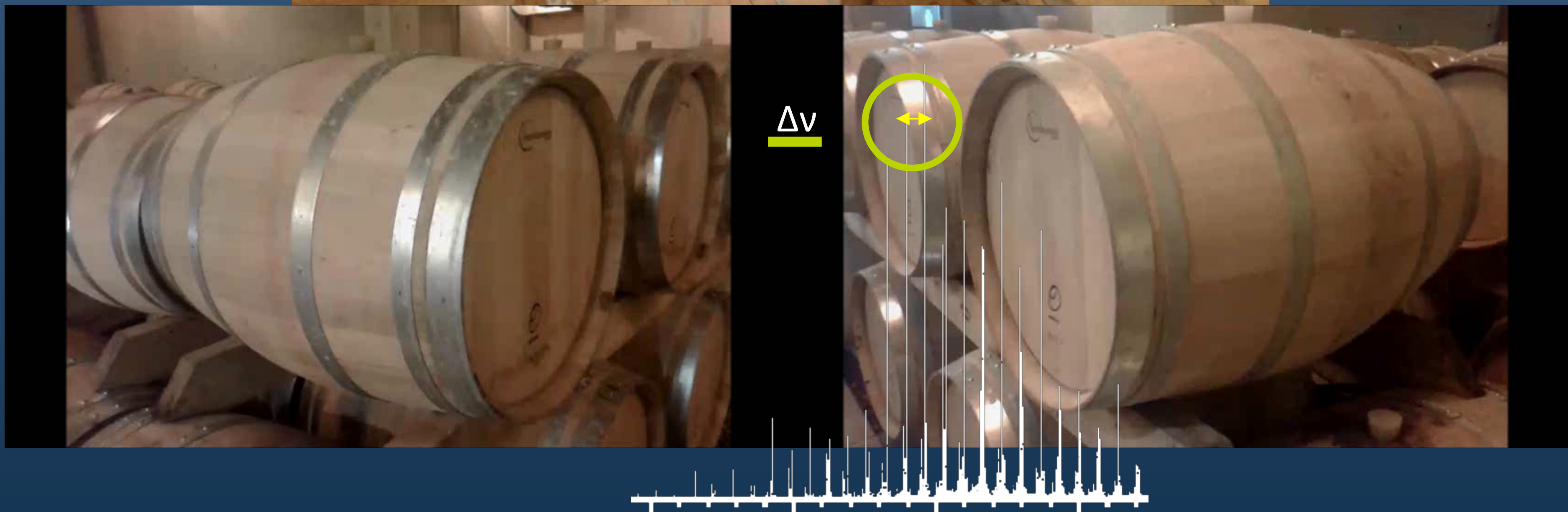
WHY OTHER STARS ?

- $M_\star \downarrow \Longrightarrow$ stronger DM impact



[**Casanellas** & Lopes , ApJL 765 (2013)]

How can asteroseismology constrain Dark Matter?



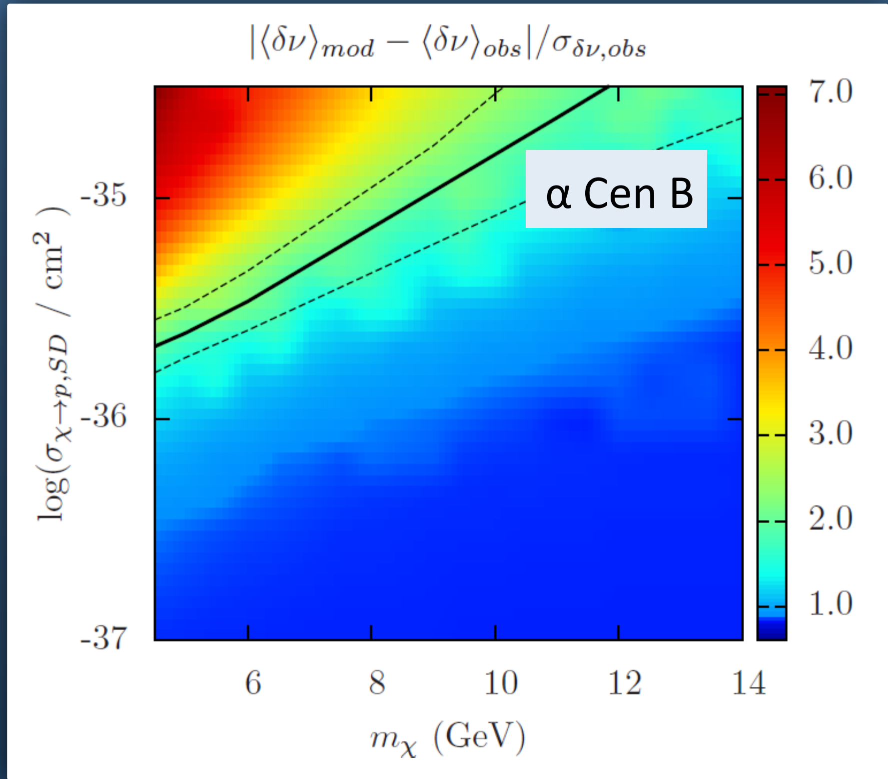
Constraining asym Dark Matter with asteroseismology

- Modelling of **α Cen B**

⇒ $M_\star \downarrow$, closest, binary

[**Casanellas** & Lopes , ApJL 765 (2013)]

$$\delta\nu_{n,l} = \nu_{n,l} - \nu_{n-1,l+2},$$



Asymmetric DM candidates with

$m_\chi = 6\ GeV$ and

$\sigma_{\chi,SD} \geq 3\cdot 10^{-36}\ cm^2$

excluded at 95% confidence level.

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)
α Cen B							
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

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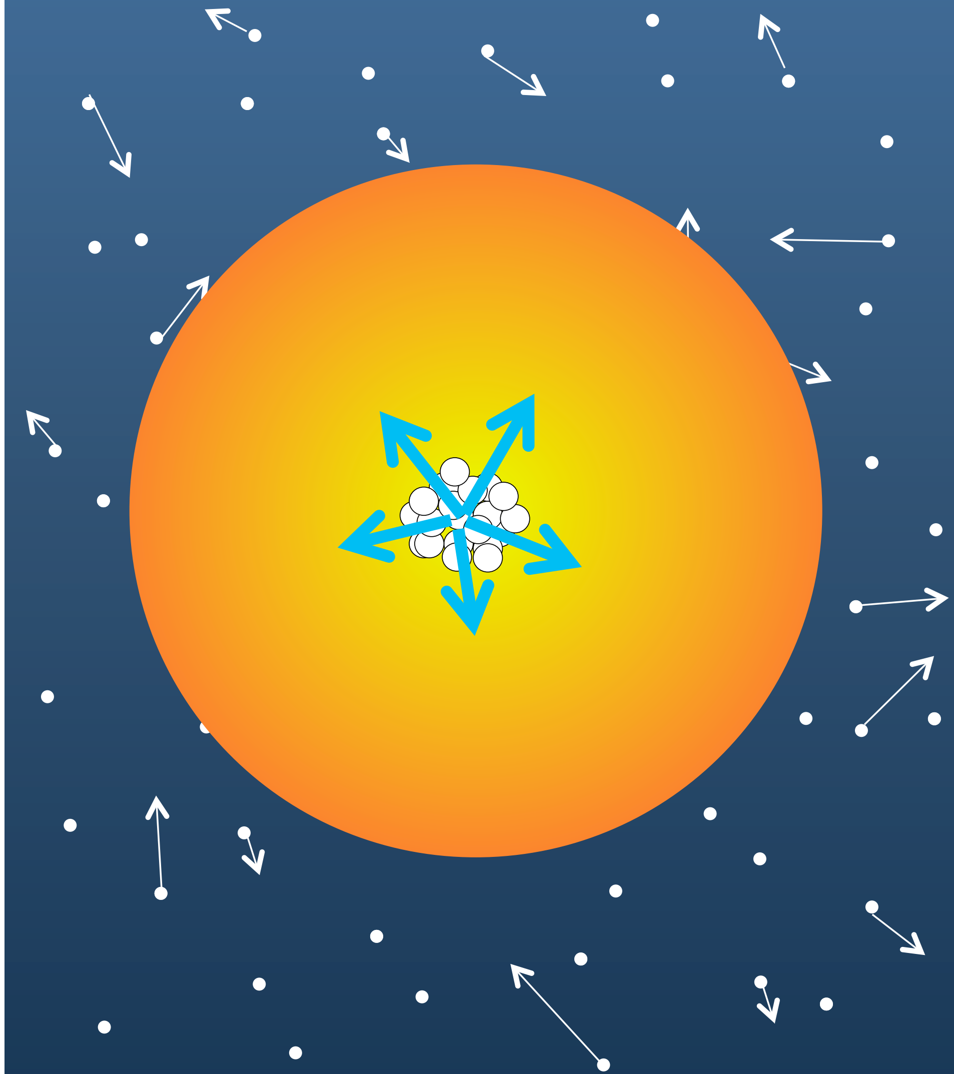

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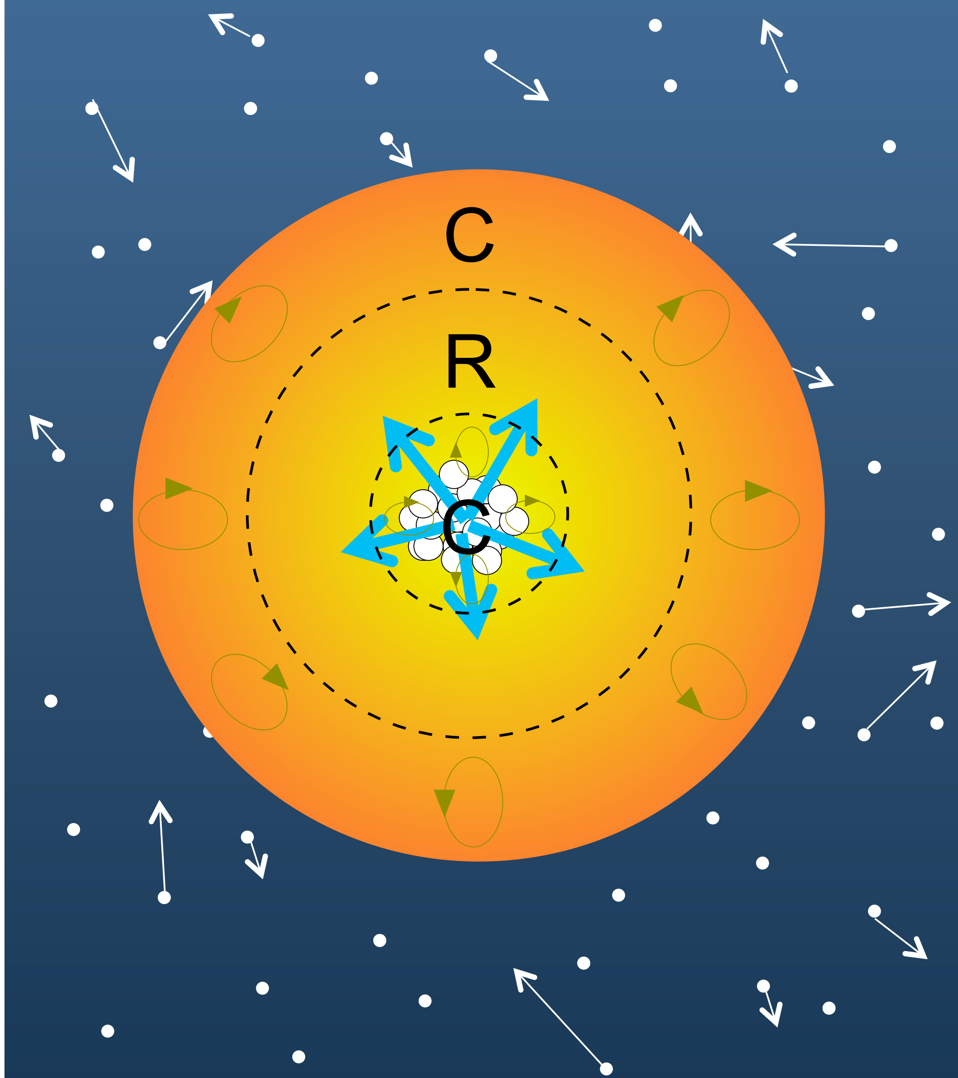

Reduction central temperature

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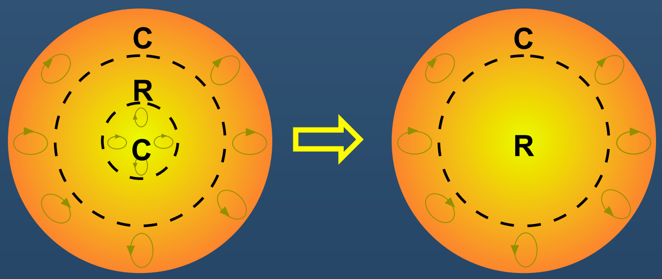
- Suppression of **convective core** in 1.1-1.3 Ms stars



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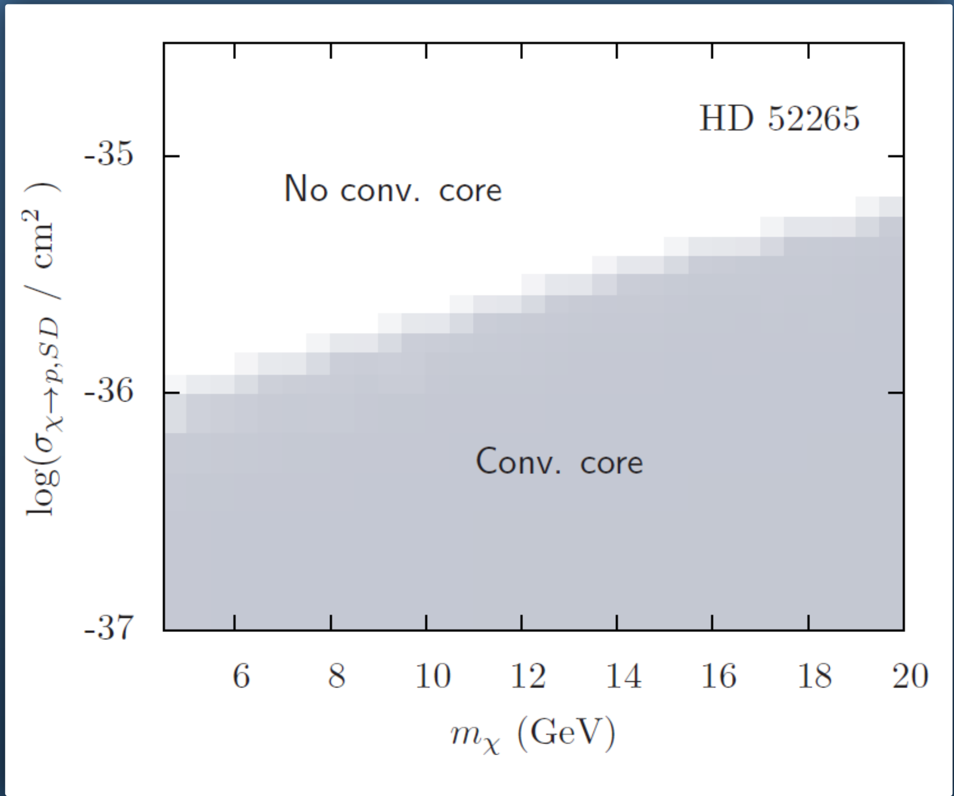

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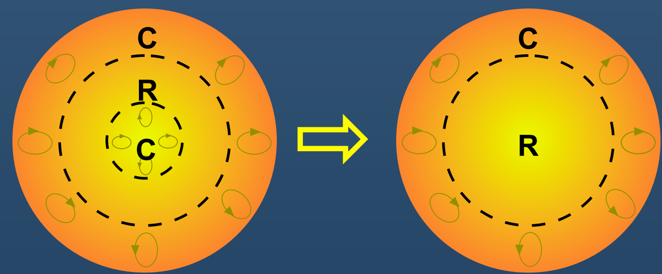


[**Casanellas** & Lopes , ApJL 765 (2013)]

Convective Core in HD 52265 ??

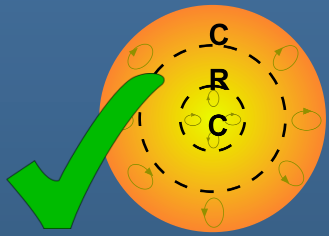
[Ballot *et al.*, A&A 530 (2011), Escobar *et al.*, A&A 547 (2012)]

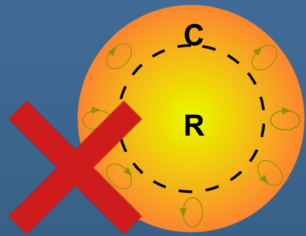
Star	M (M$_\odot$)	R (R$_\odot$)	L (L$_\odot$)	T_{eff} (K)	$(Z/X)_s$	$\langle\Delta\nu_{n,0}\rangle^a$ (μHz)	$\langle\delta\nu_{02}\rangle^a$ (μHz)
HD 52265							
Observ. [19, 23]	1.18-1.25^b	1.19-1.30^b	2.09 ± 0.24	6100 ± 60	0.028 ± 0.003	98.07 ± 0.19	8.18 ± 0.28
Stand. mod./DM mod.^{c}	1.18	1.30	2.22	6170	0.028	97.92/98.05	8.16/7.65

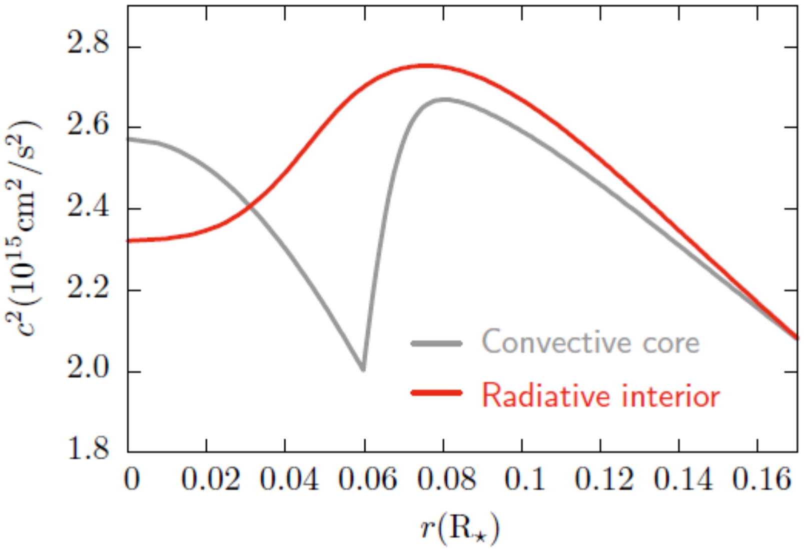
Constraining asym Dark Matter with asteroseismology

- Presence or absence of a **convective core** in KIC 12009504 (Dushera)

[Silva Aguirre *et al.*, ApJL 769 (2013)]







$$dr_{0213} = 6\left(\frac{D_{02}}{\Delta\nu_{n-1,1}} - \frac{D_{13}}{\Delta\nu_{n,0}}\right)$$

$$\text{where } D_{l,l+2} \equiv \delta\nu_{n,l}/(4l+6)$$

[Cunha M.S. & Metcalfe T.S. (2007), Cunha M.S. & Brandão I.M (2014)]

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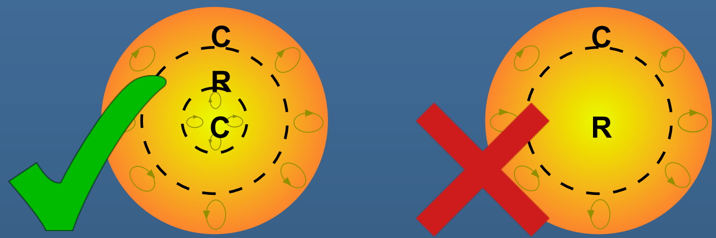

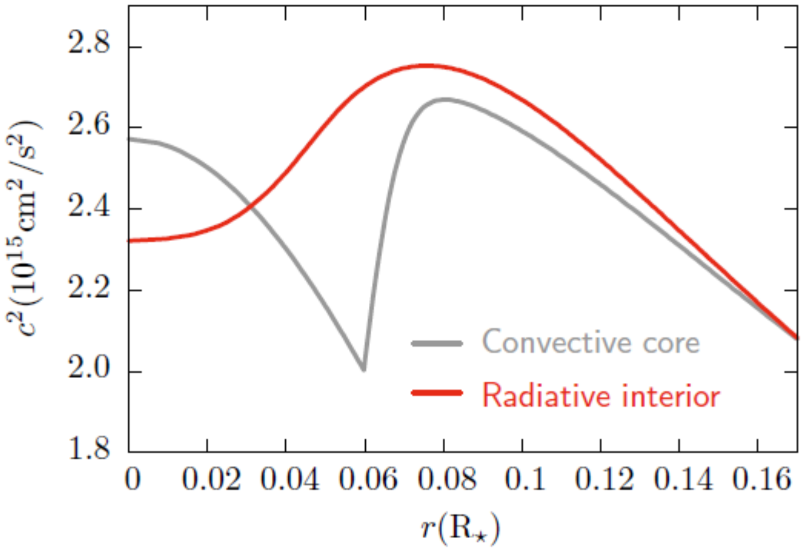

$$|S\{\Delta\nu\ r_{010}\}|$$

$$r_{01} = \frac{d_{01}}{\Delta\nu_{n,1}}, \qquad r_{10} = \frac{d_{10}}{\Delta\nu_{n+1,0}},$$

where

$$d_{01} = \frac{1}{8}(\nu_{n-1,0} - 4\nu_{n-1,1} + 6\nu_{n,0} - 4\nu_{n,1} + \nu_{n+1,0}),$$

$$d_{10} = -\frac{1}{8}(\nu_{n-1,1} - 4\nu_{n,0} + 6\nu_{n,1} - 4\nu_{n+1,0} + \nu_{n+1,1}).$$

[Roxburgh I. W. &Vorontsov S. V. (2003), Brandao I., Cunha M. &.Christensen-Dalsgaard J, MNRAS 438 (2014)]

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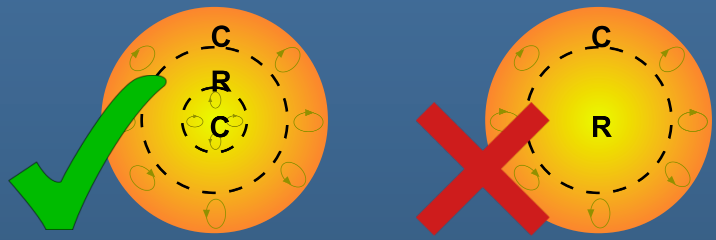

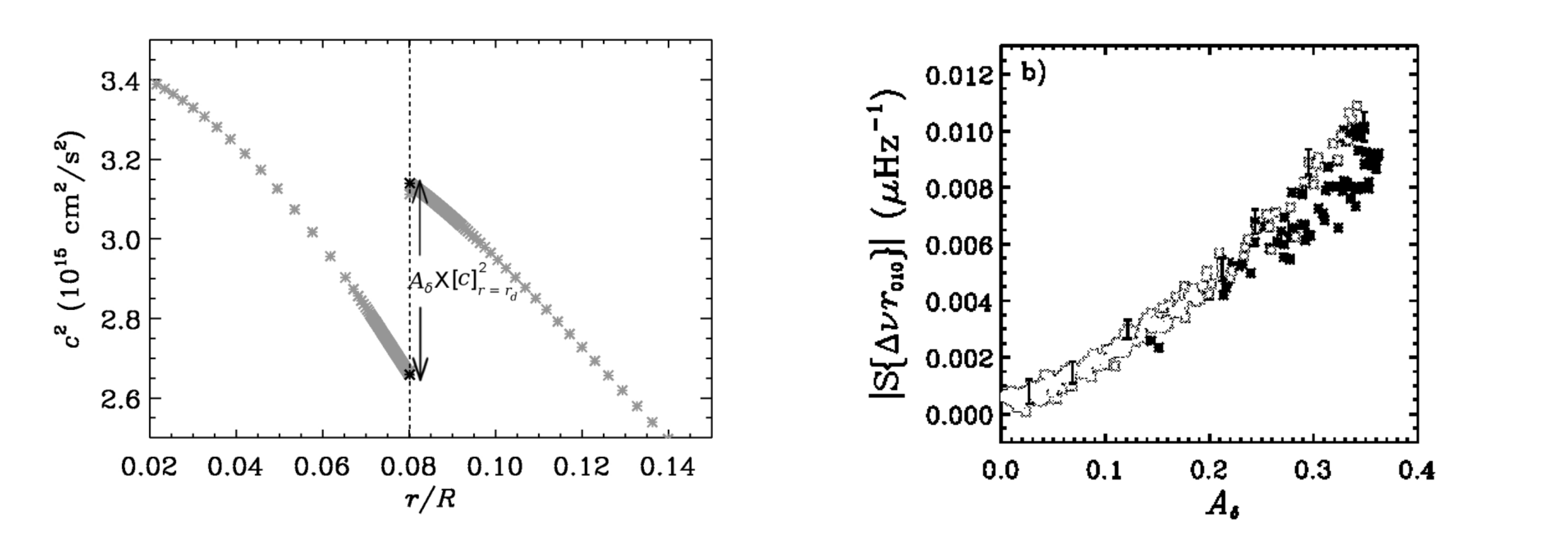

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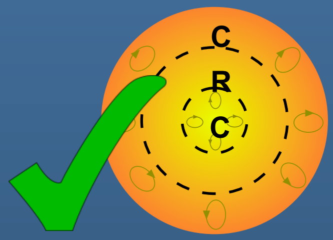

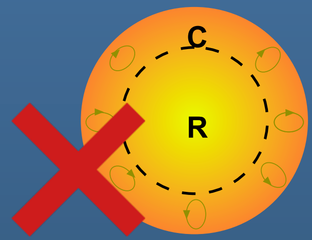

- Modelling of Dushera: Grid with CESAM (M, Z, age, α_{CONV} , α_{OV}) +

  [**Casanellas** & Brandao , in prep.]

T_{eff}	$\log(g)$	Z/X_s [1]	$\langle\Delta\nu\rangle_{012}$
6200 ± 200	4.30 ± 0.2	0.023 ± 0.09	88 ± 0.6

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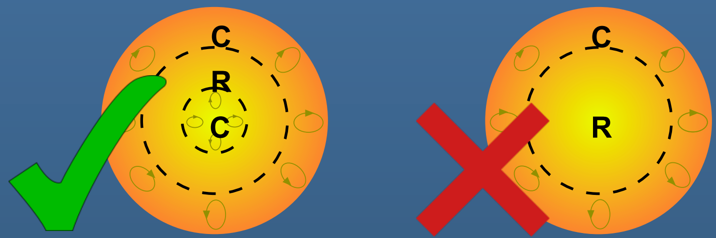

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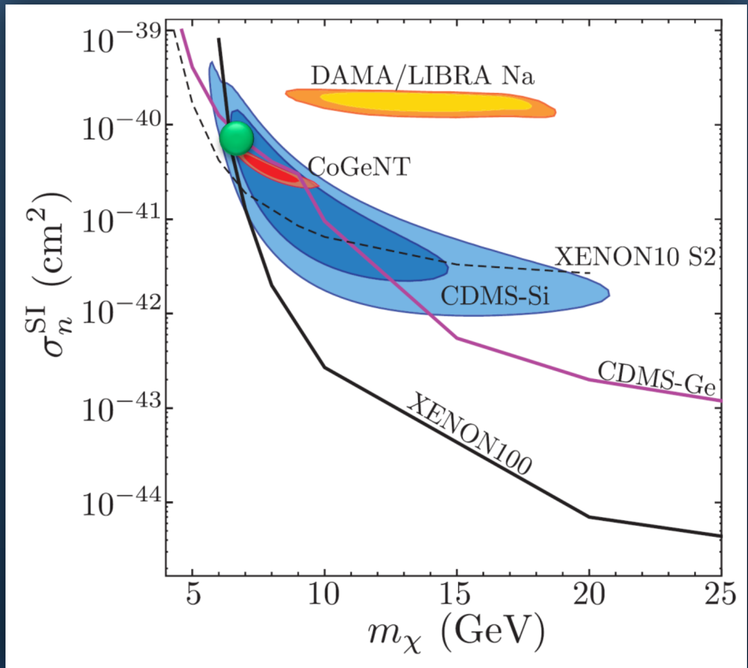
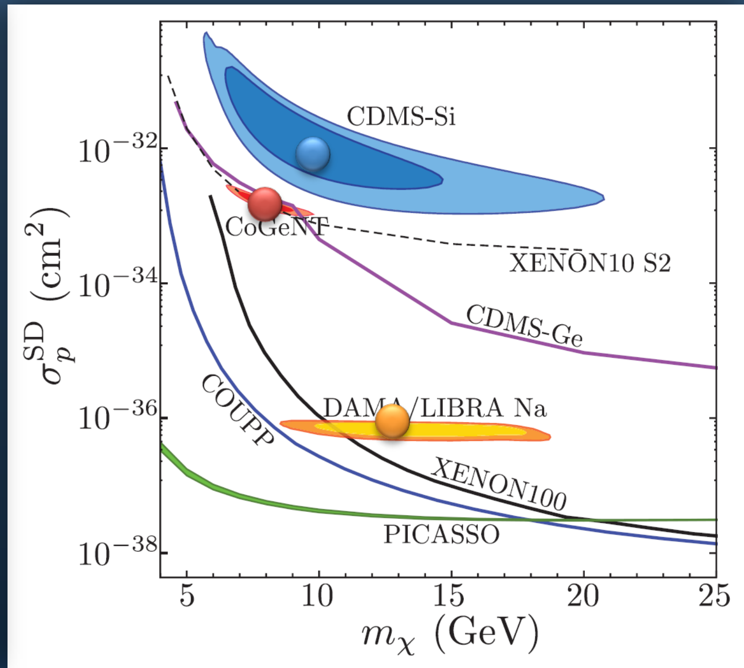
- DM model 1 (SI best fit)
- DM model 2 (DAMA)
- DM model 3 (CDMS)
- DM model 4 (CoGeNT)





[Buckley M. & Lippincott W. H., Phys. Rev. D 88 (2013), Arina , arXiv:1310.5718, (2013)]

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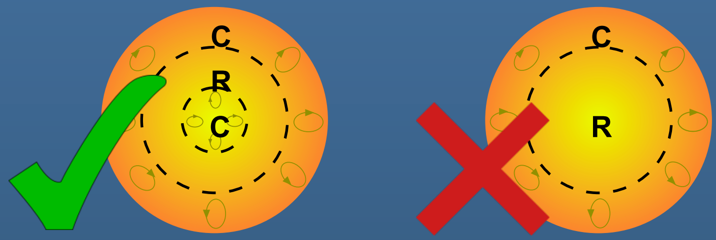

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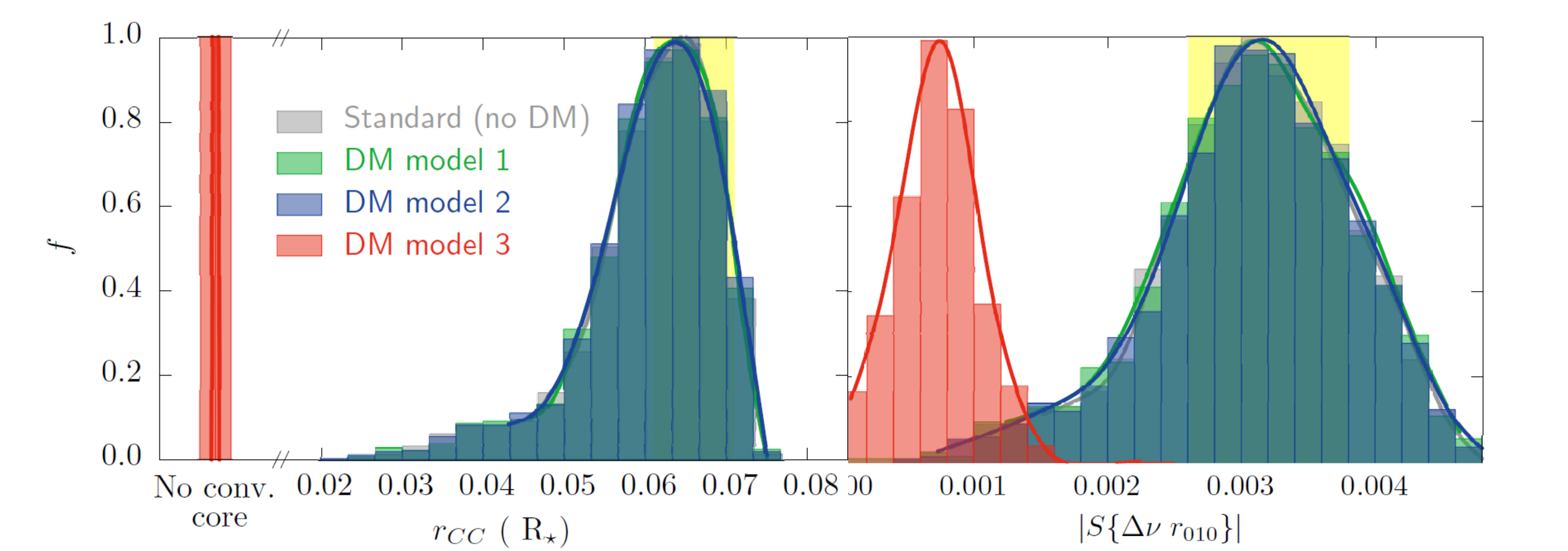


WORK IN PROGRESS, see also POSTER #40

Conclusion:

ASTEROSEISMOLOGY can be used to investigate **DARK MATTER**

Future directions:

- Solar-like oscillations in **low-mass stars** (0.7 Ms?) observed with high precision (detached eclipsing binaries?)
- Gravity modes in **Red Giants**
- Environments with **high Dark Matter densities**: the Galactic Center, Globular Clusters, dwarf Sph Galaxies

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

Capture

Gould (1987)

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

$$\Omega_v^-(w) = \sum_i \frac{\sigma_i n_i(r,t)}{w}\Big(v_{esc,r}^2 - \frac{\mu_{-,i}^2}{\mu_i}u^2\Big)\theta\Big(v_{esc,r}^2 - \frac{\mu_{-,i}^2}{\mu_i}u^2\Big)$$

$$\mu \equiv \frac{m_\chi}{m_\mathrm{n}}, \qquad \mu_\pm \equiv \frac{\mu \pm 1}{2} \qquad\qquad \sigma_{\chi,i} = \sigma_{\chi,SI} A_i^2 \left(\frac{m_\chi m_{\mathrm{n},i}}{m_\chi + m_{\mathrm{n},i}}\right)^2 \left(\frac{m_\chi + m_p}{m_\chi m_p}\right)^2$$

$$\sigma_{\chi,H} = \sigma_{\chi,SI} + \sigma_{\chi,SD}$$

$$\Omega_{v,i}^-(w) = \frac{\sigma_{\chi,i} n_i(r)}{w}\frac{2E_0}{m_\chi}\frac{\mu_{+,i}^2}{\mu_i}\left\{\exp\left(-\frac{m_\chi u^2}{2E_0}\right) - \exp\left(-\frac{m_\chi u^2}{2E_0}\frac{\mu_i}{\mu_{+,i}^2}\right)\exp\left(-\frac{m_\chi v_e^2}{2E_0}\frac{\mu_i}{\mu_{-,i}^2}\left(1 - \frac{\mu_i}{\mu_{+,i}^2}\right)\right)\right\}$$

$$f_0(u) = \frac{\rho_\chi}{m_\chi}\frac{4}{\sqrt{\pi}}\left(\frac{3}{2}\right)^{3/2}\frac{u^2}{\bar{v_\chi}^3}\exp\Big(-\frac{3u^2}{2\bar{v_\chi}^2}\Big)$$

$$f_{v_\star}(u) = f_0(u)\exp\Big(-\frac{3v_\star^2}{2\bar{v_\chi}^2}\Big)\frac{\sinh(3uv_\star/\bar{v_\chi}^2)}{3uv_\star/\bar{v_\chi}^2}$$

Equilibrium between capture and annihilation rates

$$\frac{dN_\chi}{dt} = C_\chi - 2A_\chi N_\chi^2 - E_\chi N_\chi \qquad A_\chi = 4\pi \int_0^{R_\star} r^2 \frac{\langle \sigma_a v \rangle n_\chi^2}{2} dr$$

$$N_\chi(t) = C_\chi \tau_{\chi,eq} \tanh\left(\frac{t}{\tau_{\chi,eq}}\right)$$

Equilibrium timescale: $\tau_{\chi,eq} \approx \sqrt{\pi^{3/2} r_\chi^3 / (C_\chi \langle \sigma_a v \rangle)}$

WIMPs distribution inside the star:

$$n_\chi(r) = \pi^{-3/2} r_\chi^{-3}\ e^{-r^2/r_\chi^2} \qquad r_\chi = \sqrt{3\kappa_B T_c / 2\pi G \rho_c m_\chi}$$

$$n_\chi(r) = \frac{T(r)}{T_c}^{3/2} \exp\left(-\int \frac{k_B \alpha(r) \frac{dT}{dr} + m_\chi \frac{d\phi}{dr} dr}{k_B T(r)}\right)$$

Rate of energy production by DM annihilation:

$$\varepsilon_\chi(r) = f_\chi\,(2m_\chi)\,\rho(r)^{-1} \frac{\langle \sigma_a v \rangle n_\chi(r)^2}{2} dr \qquad L_{\chi,prod} = \frac{2}{3} C_\chi m_\chi$$

Energy transport (DM cooling):

$$L_{\chi,trans}(r) = 4\pi r^2 n_\chi(r) l_\chi \kappa(r) \left(\frac{k_B T(r)}{m_\chi}\right)^{1/2} k_B \frac{dT}{dr} f(K) h(r)$$

Frequencies of the acoustic modes:

$$\nu_{n,l} \simeq \left(n + \frac{l}{2} + \epsilon_\nu\right) \nu_0 \; + O(\nu^{-2}), \qquad \nu_0 = [2 \int_0^R \mathrm{d}r/c]^{-1}$$

Large separation: $\Delta\nu_{n,l} = \nu_{n,l} - \nu_{n-1,l} \simeq \nu_0.$

Small separation: $\delta\nu_{n,l} = \nu_{n,l} - \nu_{n-1,l+2},$

Combinations to detect the convective core:

$$r_{01} = \frac{d_{01}}{\Delta\nu_{n,1}}, \qquad r_{10} = \frac{d_{10}}{\Delta\nu_{n+1,0}},$$

Roxburgh & Vorontsov (2003)

where

Silva Aguirre et. al (2010)

$$d_{01} = \frac{1}{8}(\nu_{n-1,0} - 4\nu_{n-1,1} + 6\nu_{n,0} - 4\nu_{n,1} + \nu_{n+1,0}),$$

$$d_{10} = -\frac{1}{8}(\nu_{n-1,1} - 4\nu_{n,0} + 6\nu_{n,1} - 4\nu_{n+1,0} + \nu_{n+1,1}).$$

$$dr_{0213} \equiv \frac{D_{02}}{\Delta\nu_{n-1,1}} - \frac{D_{13}}{\Delta\nu_{n,0}},$$

where $D_{l,l+2} \equiv \delta\nu_{n,l}/(4l + 6)$

Cunha & Metcalfe (2007)

Hidro. Eq.: $$\frac{dP}{dr} = -\rho(r)\frac{GM(r)}{r^2}$$

Therm. Eq.: $$\frac{dL}{dr} = 4\pi r^2 \rho(r)\ \varepsilon(r)$$

(rates and cross sections for pp, CNO and 3-alpha reactions)

Energy transport:

$$\frac{dT}{dr} = -\frac{L(r)}{4\pi r^2}\frac{\kappa_{cm}}{T^3}\frac{3}{16\sigma}$$

(radiative) when $\nabla_{ad} < \nabla_{rad}$

$$\frac{dT}{dr} = \nabla_{ad}\frac{T}{P}\frac{dP}{dr}$$

(convective) when $\nabla_{ad} > \nabla_{rad}$

Continuity: $$\frac{dm}{dr} = 4\pi r^2 \rho(r)$$

Boundary:

T(r=R) = 0 M(r=0) = 0

P(r=R) = 0 L (r=0) = 0

Equation of state: Tabulated (mixture, X,Y, p, ρ, T)

Opacities: Tabulated

Solar composition

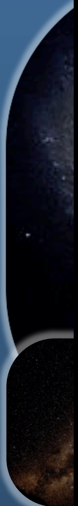
Chemical evolution

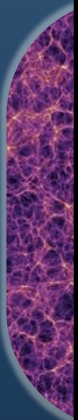
TABLE I. Variations in the total capture rate, C_χ, and in the ratio between the luminosities from DM annihilations and thermonuclear reactions, $L_\chi/L_{\rm nuc}$, when there is an uncertainty of 10% in the knowledge of one parameter of the DM characteristics or of the stellar structure. If not stated 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 $1M_\odot$ in the middle of the MS, with a metallicity $Z = 0.019$ and a velocity $v_\star = 220$ km s^{-1}.

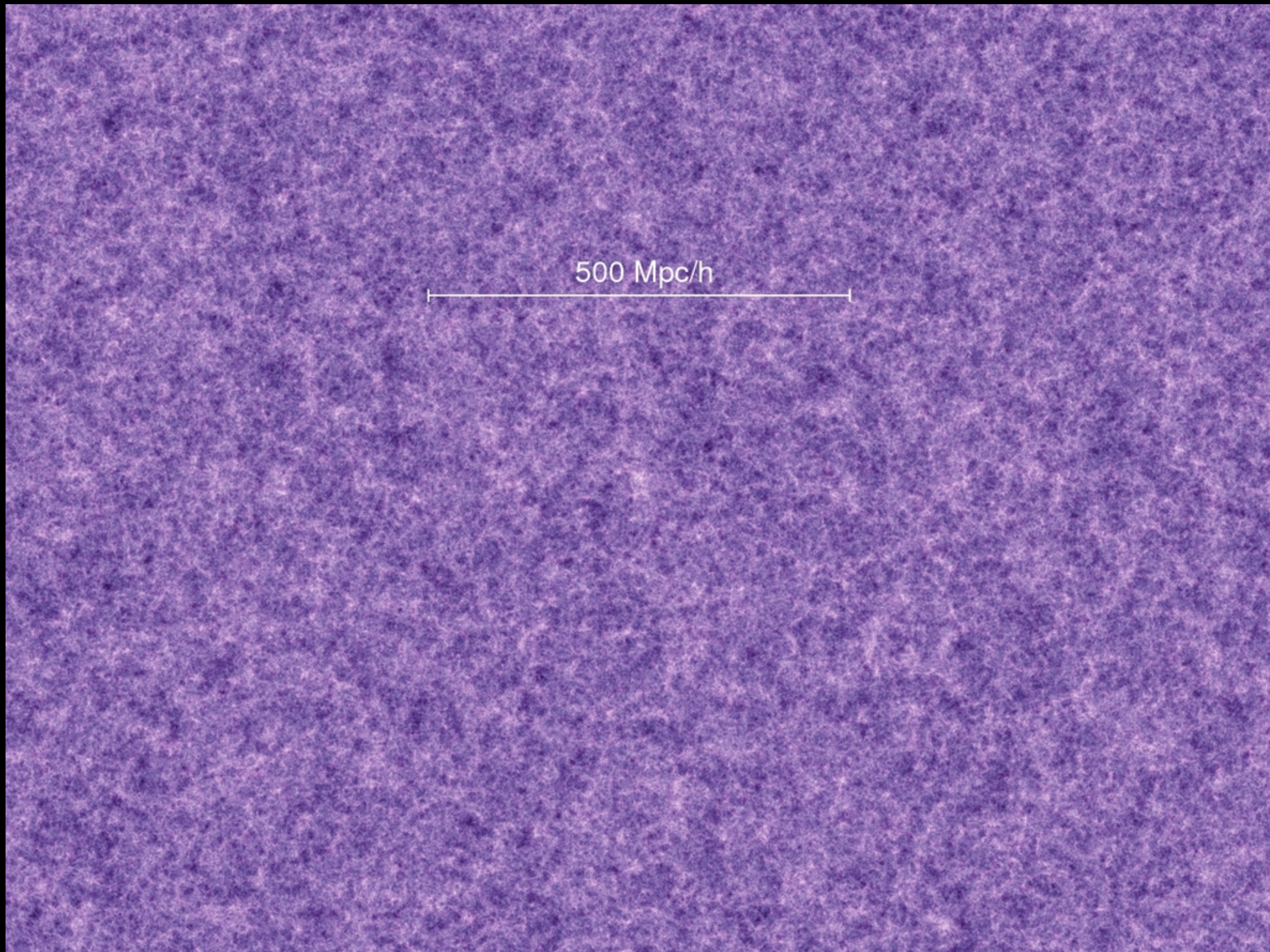
	C_χ		$L_\chi/L_{\rm nuc}$	
$m_\chi = 5$ GeV $\pm10\%$	−10%	+12%	−1%	+1%
$m_\chi = 500$ GeV $\pm10\%$	−18%	+23%	−9%	+11%
$\bar{v}_\chi = 100$ km s^{-1} $\pm10\%$	+6%	−7%	+6%	−7%
$\bar{v}_\chi = 500$ km s^{-1} $\pm10\%$	−20%	+26%	−20%	+26%
$v_\star = 100$ km s^{-1} $\pm10\%$	−3%	+3%	−3%	+3%
$v_\star = 500$ km s^{-1} $\pm10\%$	−58%	+120%	−58%	+120%
$M_\star = 0.5M_\odot$ $\pm10\%$	+26%	−22%	−20%	+26%
$M_\star = 7M_\odot$ $\pm10\%$	+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%

TABLE II. Variations in the capture rate due to SD and SI interactions of the stellar elements with the DM particles ($C_{\chi,\rm SI}$ and $C_{\chi,\rm SD}$) when there is an uncertainty of 10% in the knowledge of the mass of the DM particles or on the stellar metallicity.

	$C_{\chi,\rm SD}$		$C_{\chi,\rm SI}$	
$m_\chi = 100$ GeV $\pm10\%$	−16%	+22%	−10%	+13%
$Z = 0.019 \pm 10\%$	−2%	+2%	+8%	−8%







Redshift z=18.3 (t = 0.21 Gyr)

Millenium Simulation [Springel *et al.*, Nature 435 (2005)]

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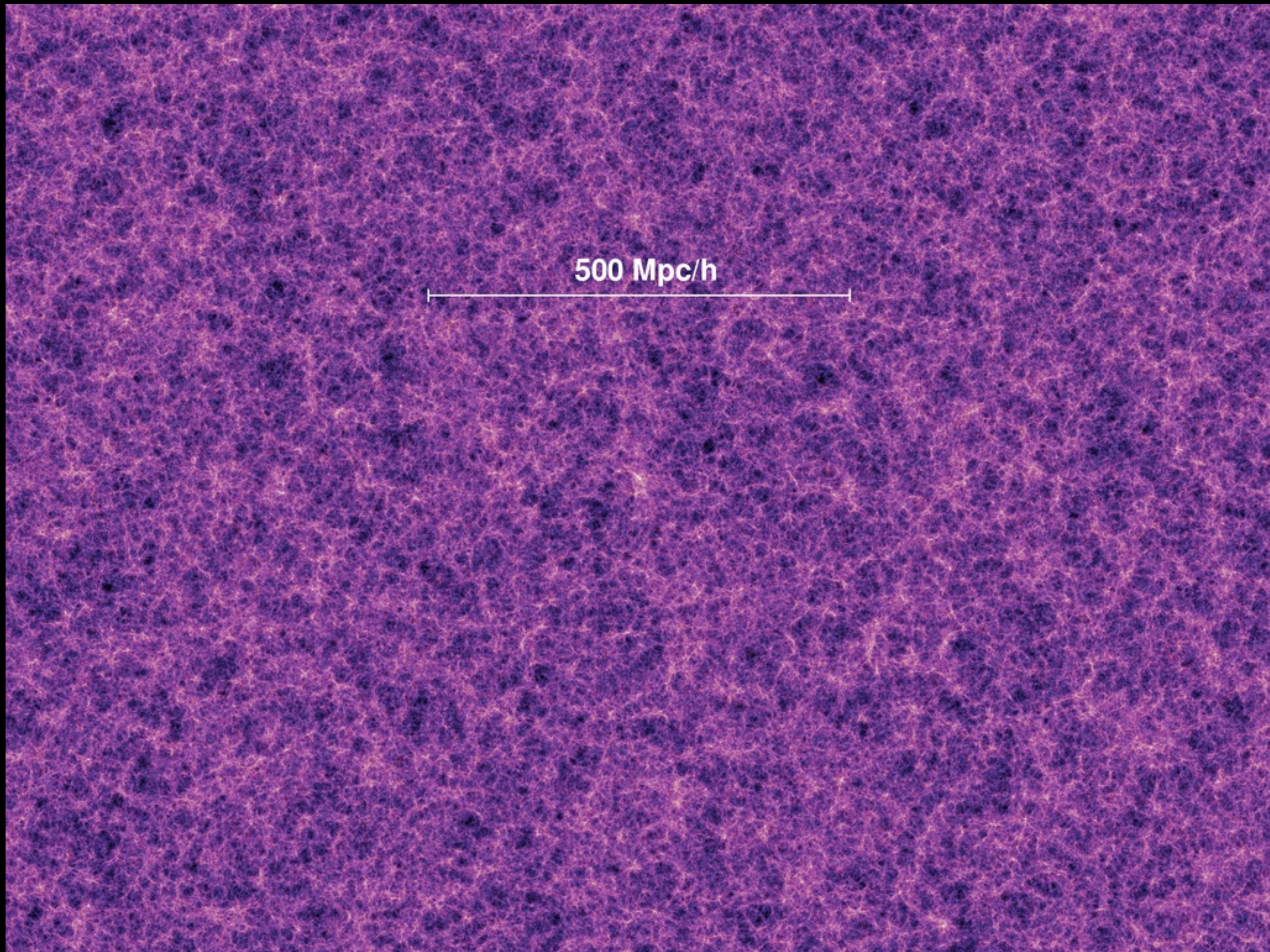

Redshift z=5.7 (t = 1.0 Gyr)

Millenium Simulation [Springel *et al.*, Nature 435 (2005)]

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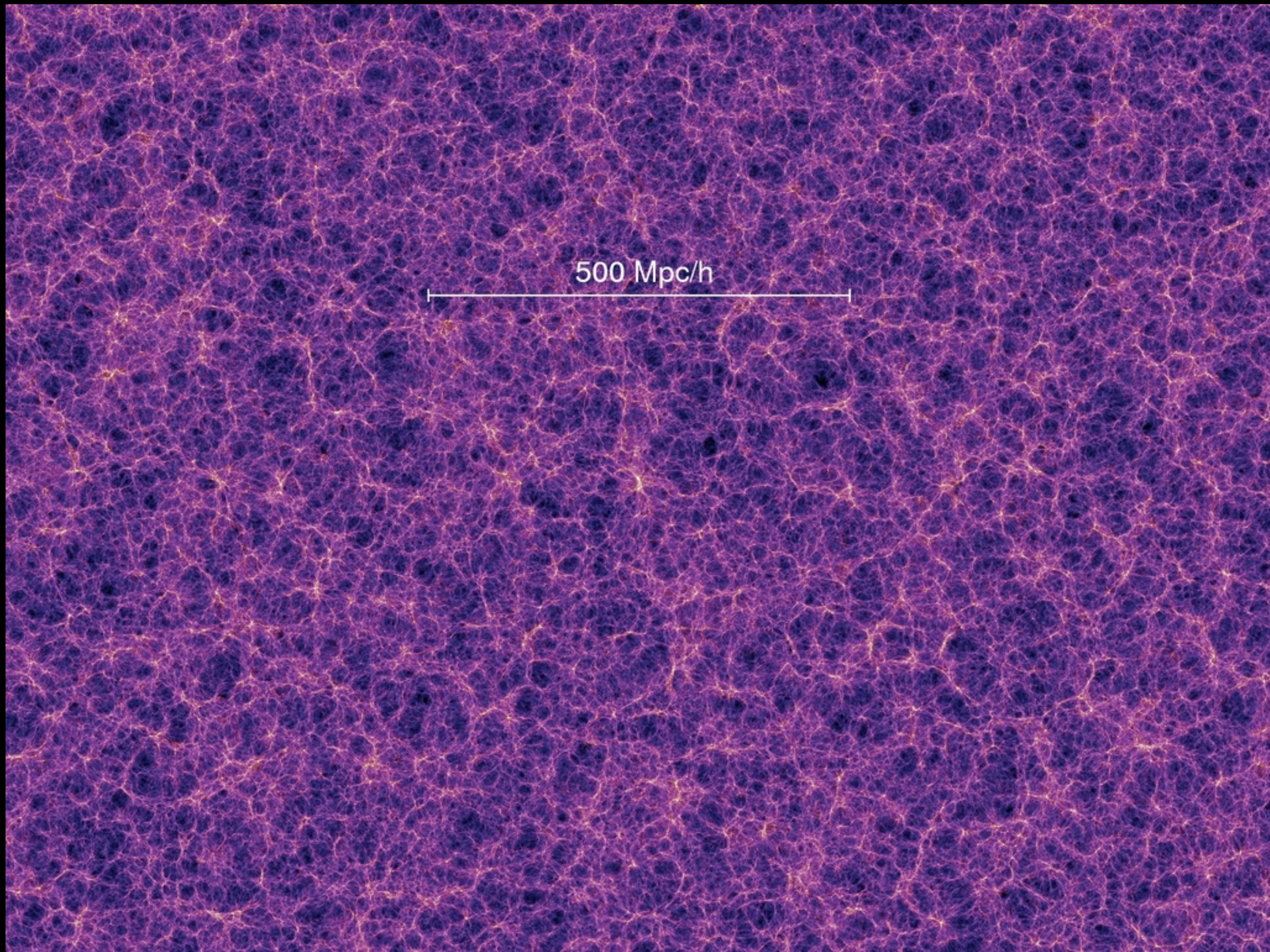

Redshift z=1.4 (t = 4.7 Gyr)

Millenium Simulation [Springel *et al.*, Nature 435 (2005)]

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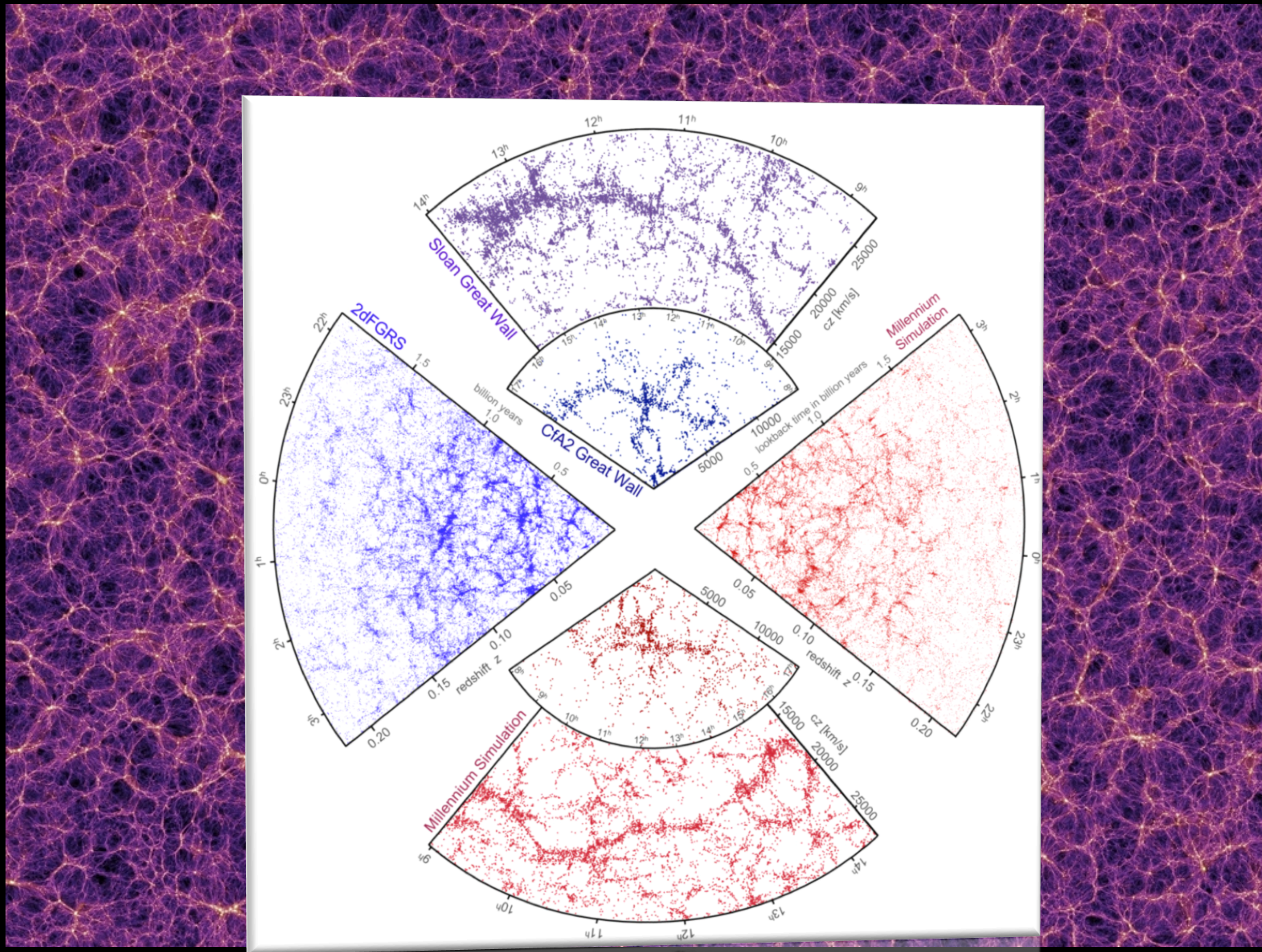

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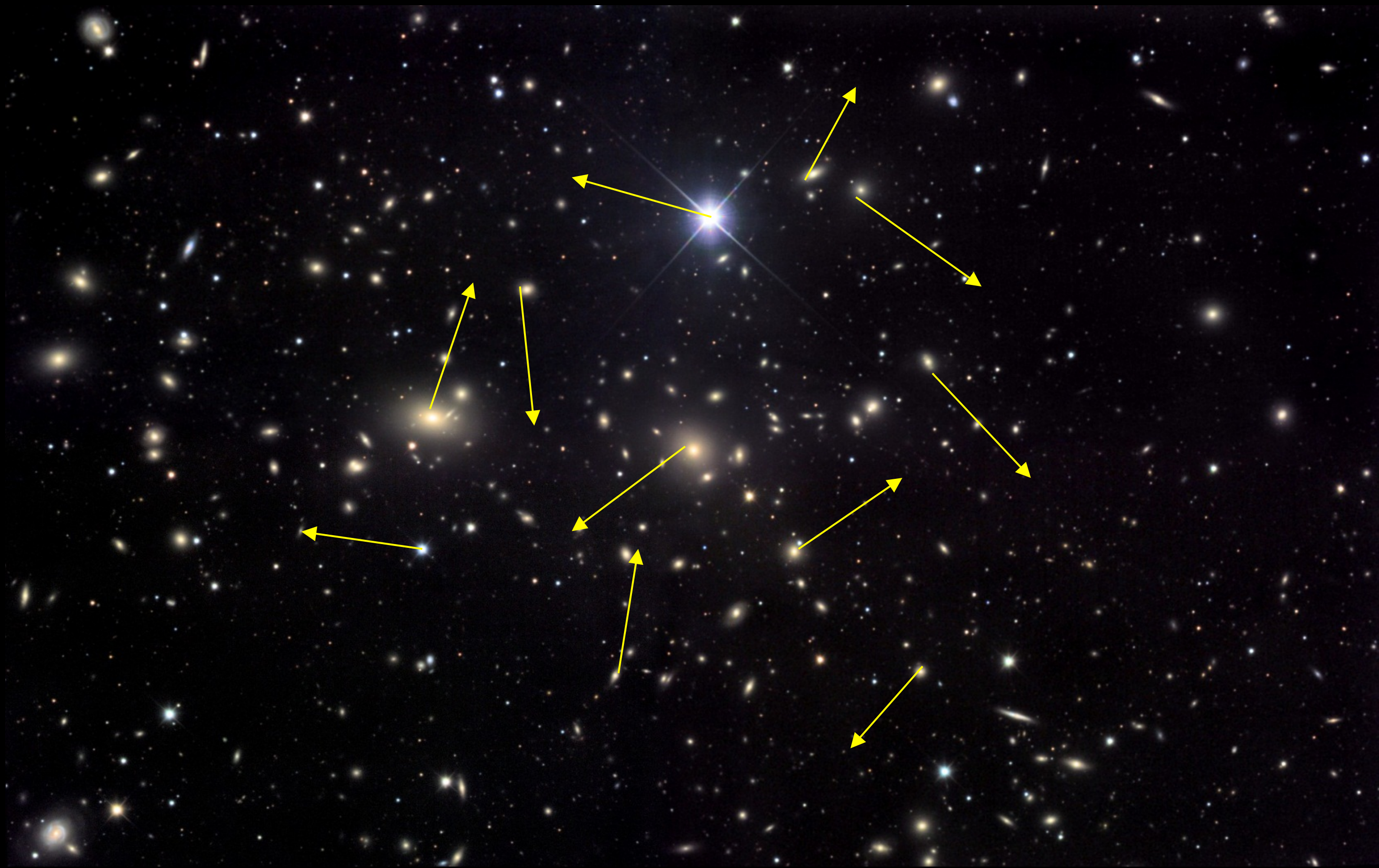
Redshift z=0 (t = 13.6 Gyr)

Millenium Simulation [Springel, et al., Nature 435 (2005)]
[Springel, Frenk & White, Nature 440 (2006)]



Dark Matter = 400 x Luminous Matter

[Zwicky, Helvetica Physica Acta 6 (1933)]

Coma Cluster

[Jim Misti, Misti Mountain Observatory]

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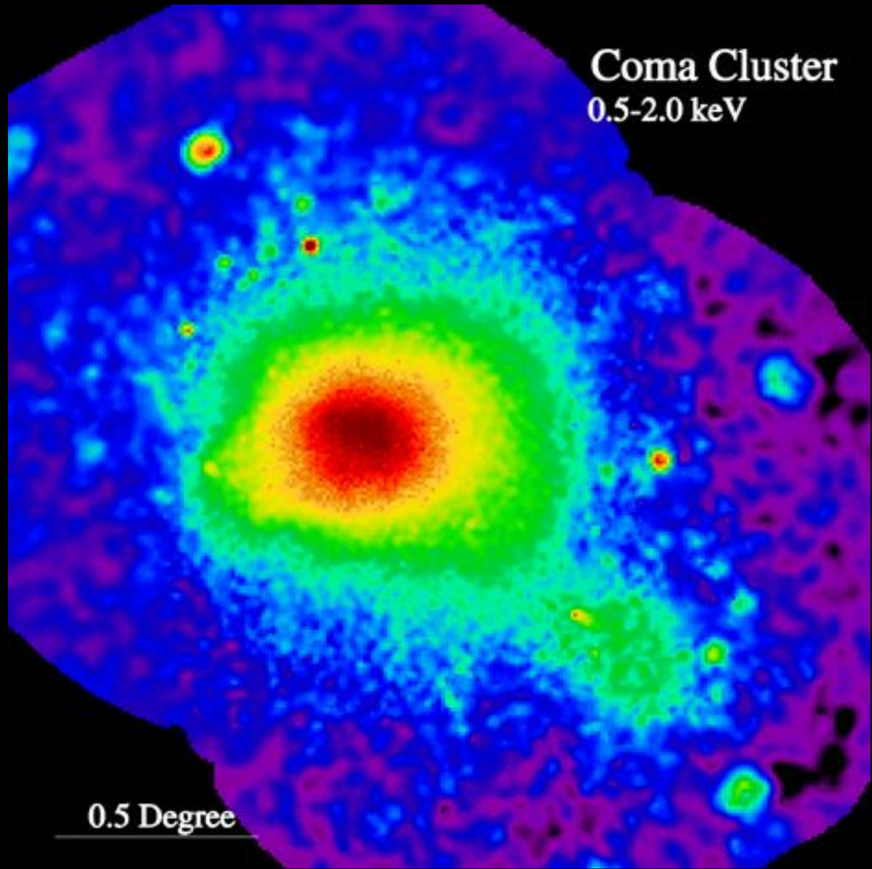

X-rays from ROSAT telescope

[Voges *et al.*, Astron.Astrophys. 349 (1999)]

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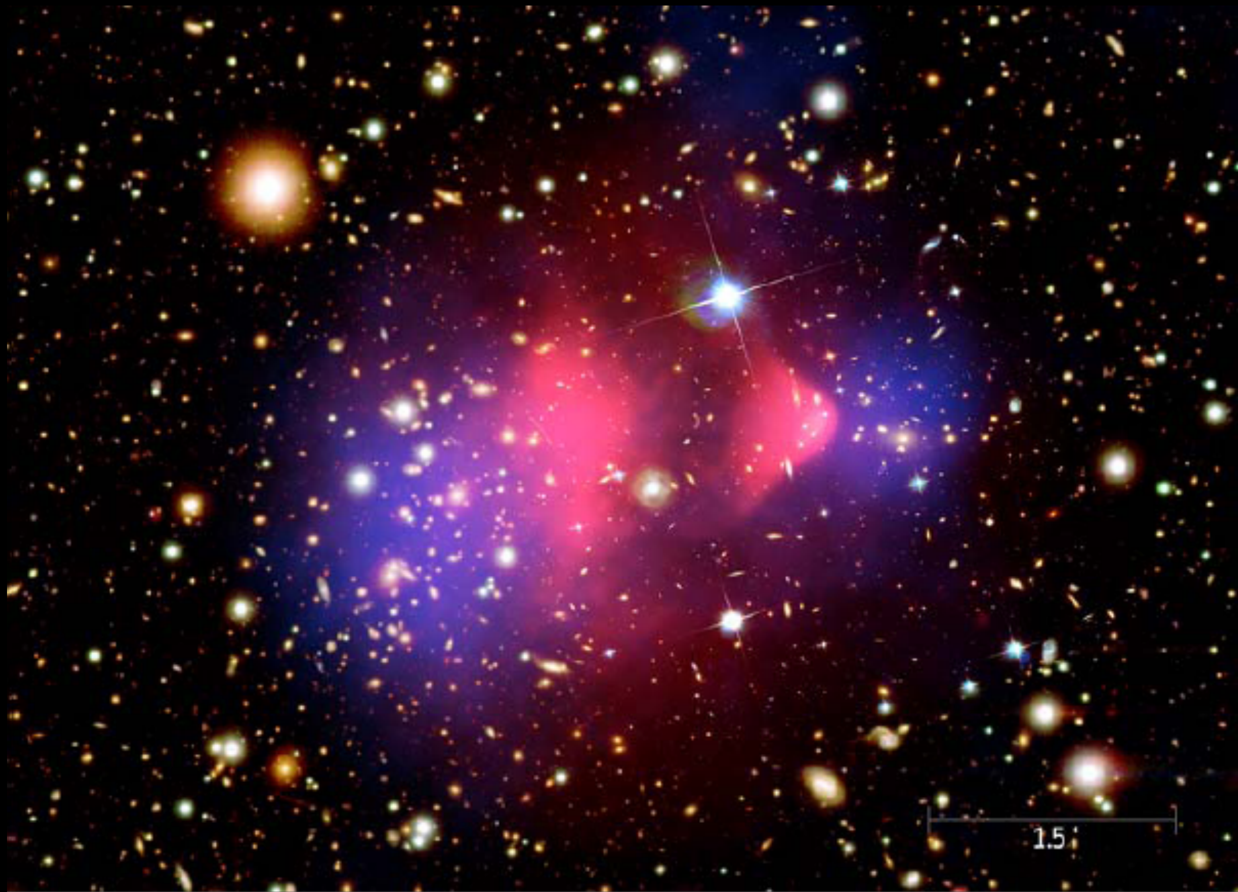

[Clowe *et al.*, ApJ 648 (2006), Markevitch, ESA SP-604 (2006)]

[Clowe *et al.*, ApJ 648 (2006)]

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