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Improved bounds on the bosonic dark matter with pulsars in the Milky Way

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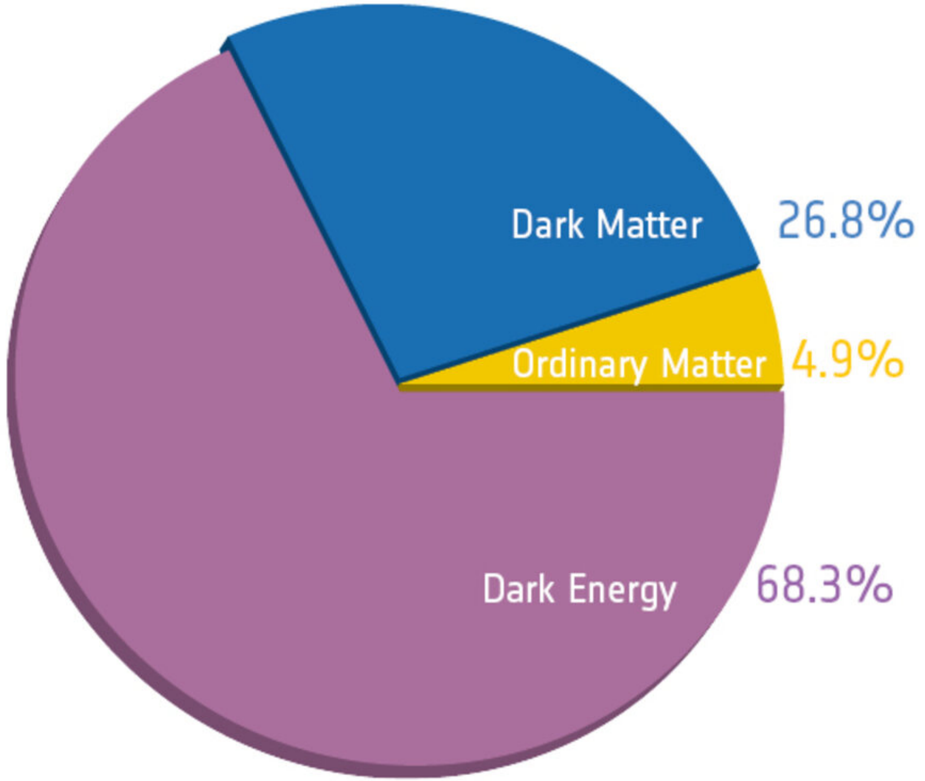
Outline

- Background
- Dark matter capture
- Black hole formation
- Results and discussions

Dark matter



(Credit: ESA & Planck Collaboration)

Dark matter captured by the Sun and the Earth

Press & Spergel, 1985; Gould, 1987a, 1987b, 1988 …

emission of neutrino

Dark matter captured by the white dwarf/ neutron star

Goldman & Nussinov, 1989; Gould, et al. 1990;
Kouvaris, 2008; Bertone & Fairbairn 2008;
McCullough & FairBairn, 2010; Bell, et al. 2018 …

changing the temperature

changing the structure

forming mini black hole

Capture rate

Gould, 1987; McDermott, et al. 2012; Bramante, et al. 2014

Dark matter particles scatter at the surface of the neutron star

$$M_{\rm NS} \simeq 1.5\, M_\odot \qquad R_{\rm NS} \simeq 11\,{\rm km}$$

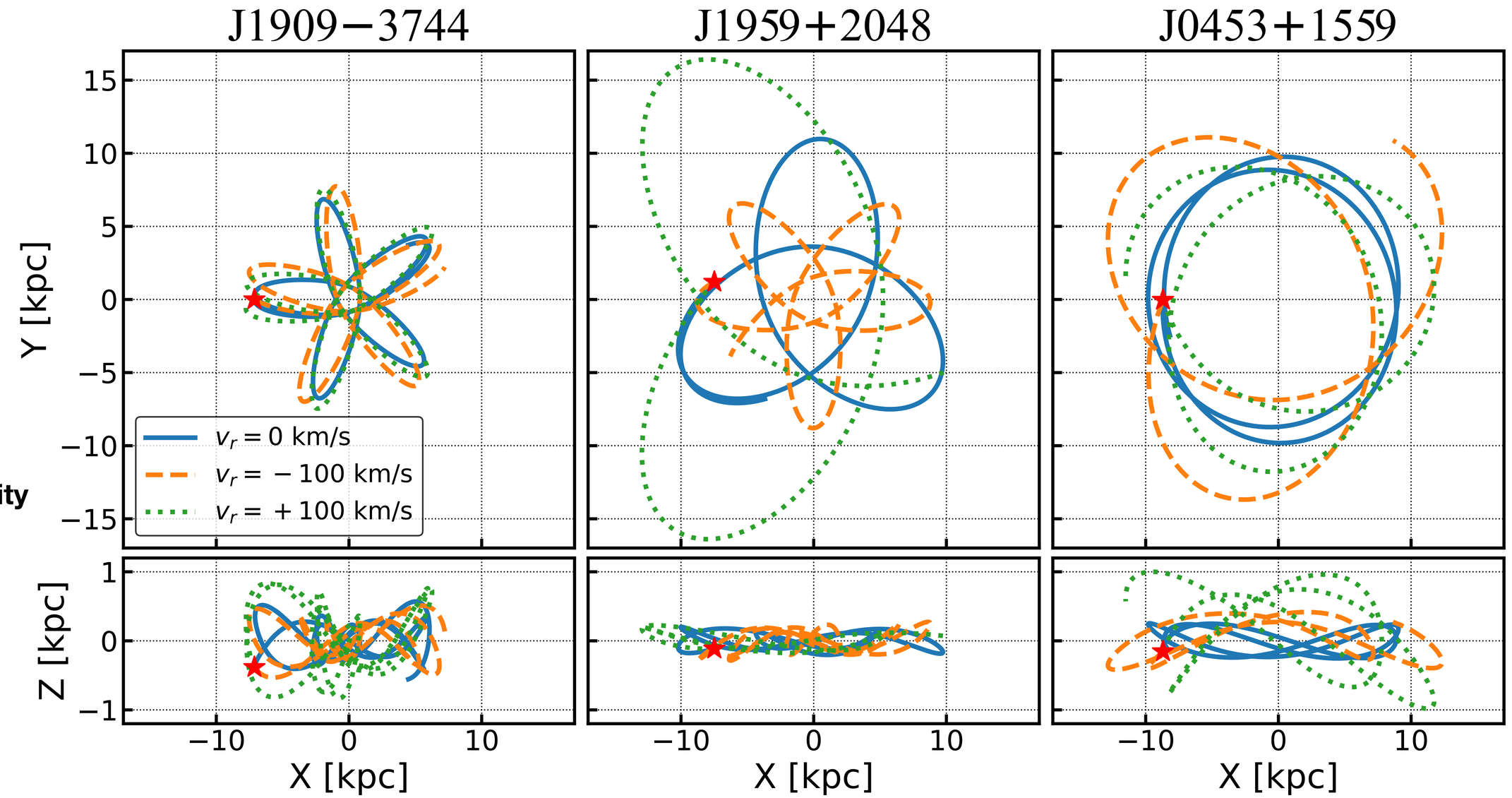
$$C_{X,0} = \sqrt{\frac{6}{\pi}} \left(\frac{\rho_{\rm DM}}{\bar{v}_X}\right) \frac{\xi N_B v_{\rm esc}^2}{m_X} \left[1 - \frac{1-\exp(-B^2)}{B^2}\right] f(\sigma_{nX})$$

$$B^2 = \frac{v_{\rm esc}^2}{\bar{v}_X^2} \frac{6 m_X m_B}{(m_X - m_B)^2} \qquad f(\sigma_{nX}) = \sigma_{\rm sat}\left[1 - e^{-\sigma_{nX}/\sigma_{\rm sat}}\right] \qquad \sigma_{\rm sat} = R_{\rm NS}^2/\left(0.45 N_B \xi\right)$$

Pauli blocking $\xi \simeq \min\left\{m_X/(0.2\ {\rm GeV}), 1\right\}$

Galactic motion in the past 500 Myrs

ATNF pulsar catalogue + GalPot (McMillan 2017)



unknown radial velocity

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Suppression due to the relative motion

Gould, 1987

$$C_X = \zeta C_{X,0} \qquad \zeta \to 1 \quad \text{when} \quad \eta \to 0 \qquad \eta = \sqrt{3/2} v_\star / \bar{v}_X$$

$$\zeta = \left[1 - \frac{1 - \exp(-B^2)}{B^2}\right]^{-1} \left\{ \frac{(B_+ B_- - 1/2)[\chi(-\eta, \eta) - \chi(B_-, B_+)]}{2\eta B^2} + \frac{B_+ \exp(-B_-^2)/2 - B_- \exp(-B_+^2)/2 - \eta \exp(-\eta^2)}{2\eta B^2} \right\} \leq 1$$

$$\chi(a,b) \equiv \int_a^b \exp(-y^2) dy = \sqrt{\pi}[\mathrm{erf}(b) - \mathrm{erf}(a)]/2 \qquad B_\pm \equiv B \pm \eta$$

Dark matter distribution

Navarro, Frenk & White, 1997

$$\rho_{\rm DM}(r) = \frac{\rho_{0,h}}{(r/r_h)^\gamma (1 + 3r/r_h)^{3-\gamma}}$$

$\gamma = 1$ $\qquad r_h = 18.6\,\mathrm{kpc}$

$\rho_{\rm DM}(r = 8.20\,\mathrm{kpc}) = 0.38\,\mathrm{GeV/cm^3}$ McMillan, 2017

Velocity dispersion

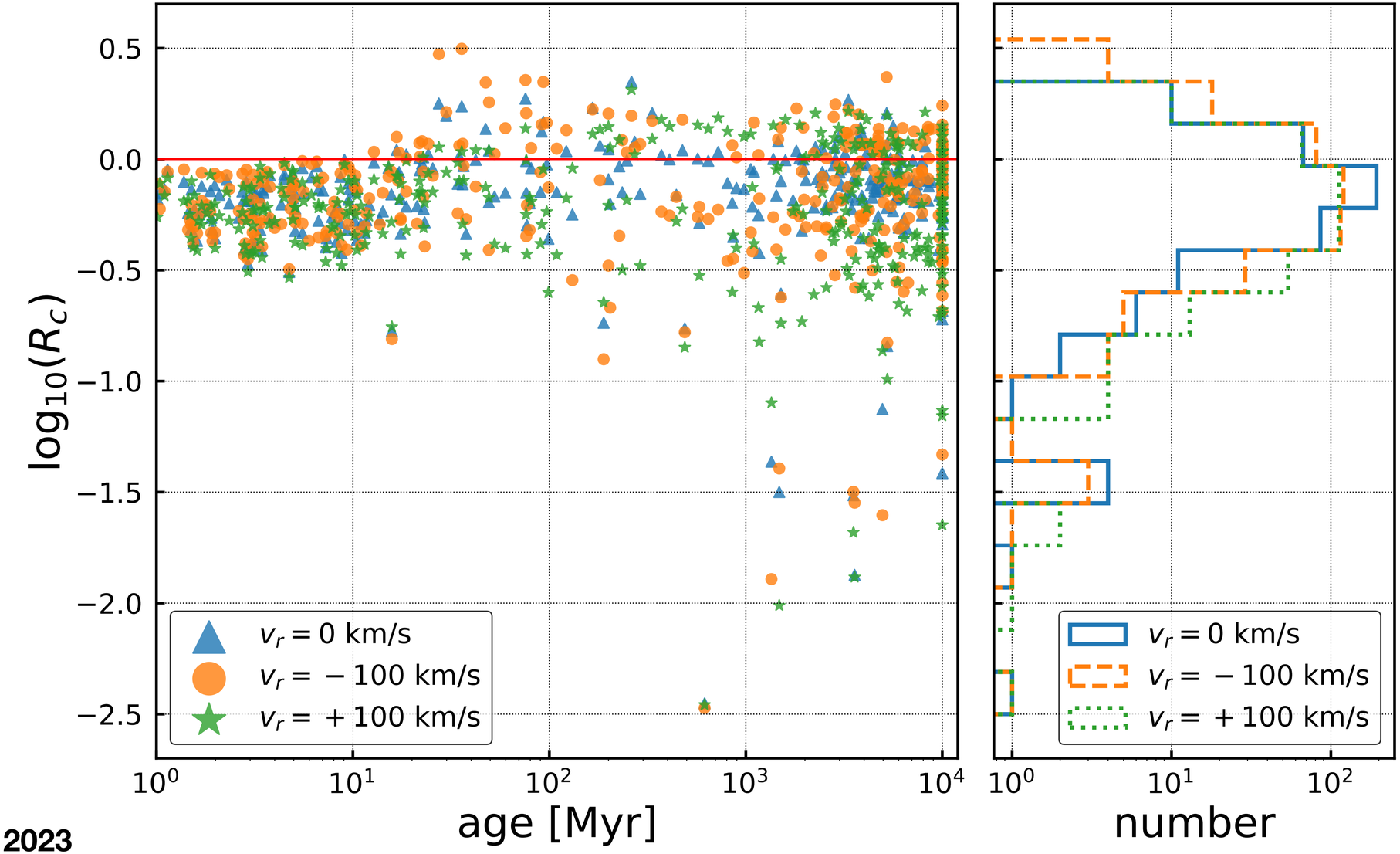
Green, 2010
Catena & Ullio, 2012

$$\bar{v}_X = \sqrt{3/2} v_c$$

Comparison with the static case

$$R_c := \frac{N_X^{(\mathrm{m})}}{N_X^{(\mathrm{s})}} = \frac{\int_0^{t_{\mathrm{NS}}} dt\ C_X(t)}{\int_0^{t_{\mathrm{NS}}} dt\ C_{X,0}} = \frac{\bar{A}}{A_0} \equiv \frac{\frac{1}{t_{\mathrm{NS}}}\int_0^{t_{\mathrm{NS}}} dt\ \rho_{\mathrm{DM}}(t)\zeta(t)\bar{v}_{X,s}/\bar{v}_X(t)}{\rho_{\mathrm{DM},0}\bar{v}_{X,s}/\bar{v}_{X,0}}$$

$t_{\mathrm{NS}} \leq 10\,\mathrm{Gyr}$



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Black hole formation

Thermalization **Bertoni, et al. 2013**

$$t_{\rm th} = \frac{105\pi^2\hbar^3}{16k_b^2T_{\rm NS}^2m_B\sigma_{nX}}\frac{m_X/m_B}{(1+m_X/m_B)^2} = 75\,{\rm yr}\left(\frac{10^{-45}\,{\rm cm}^2}{\sigma_{nX}}\right)\frac{m_X/m_B}{(1+m_X/m_B)^2}$$

Condition thermalization $t_{\rm th} < t_{\rm NS}$

Bose-Einstein Condensate **Jamison, 2013**

$$N_{\rm BEC} = \zeta(3)\left(\frac{k_BT_{\rm NS}}{\hbar\sqrt{4\pi G(\rho_B+3P_B)/3}}\right)^3 = 5.6\times10^{38}\left(\frac{T_{\rm NS}}{10^6\,{\rm K}}\right)^3$$

Condition BEC $N_X > N_{\rm BEC}$

Black hole formation

Chandrasekhar limit Colpi, et al. 1986

$$N_{\rm Cha} = \frac{2m_{\rm pl}^2}{\pi m_X^2}\left(1+\frac{\lambda m_{\rm pl}^2}{32\pi m_X^2}\right)^{1/2} \qquad \lambda = 10^{-30}$$

Condition collapse $N_X - N_{\rm BEC} > N_{\rm Cha}$

Growth of black hole

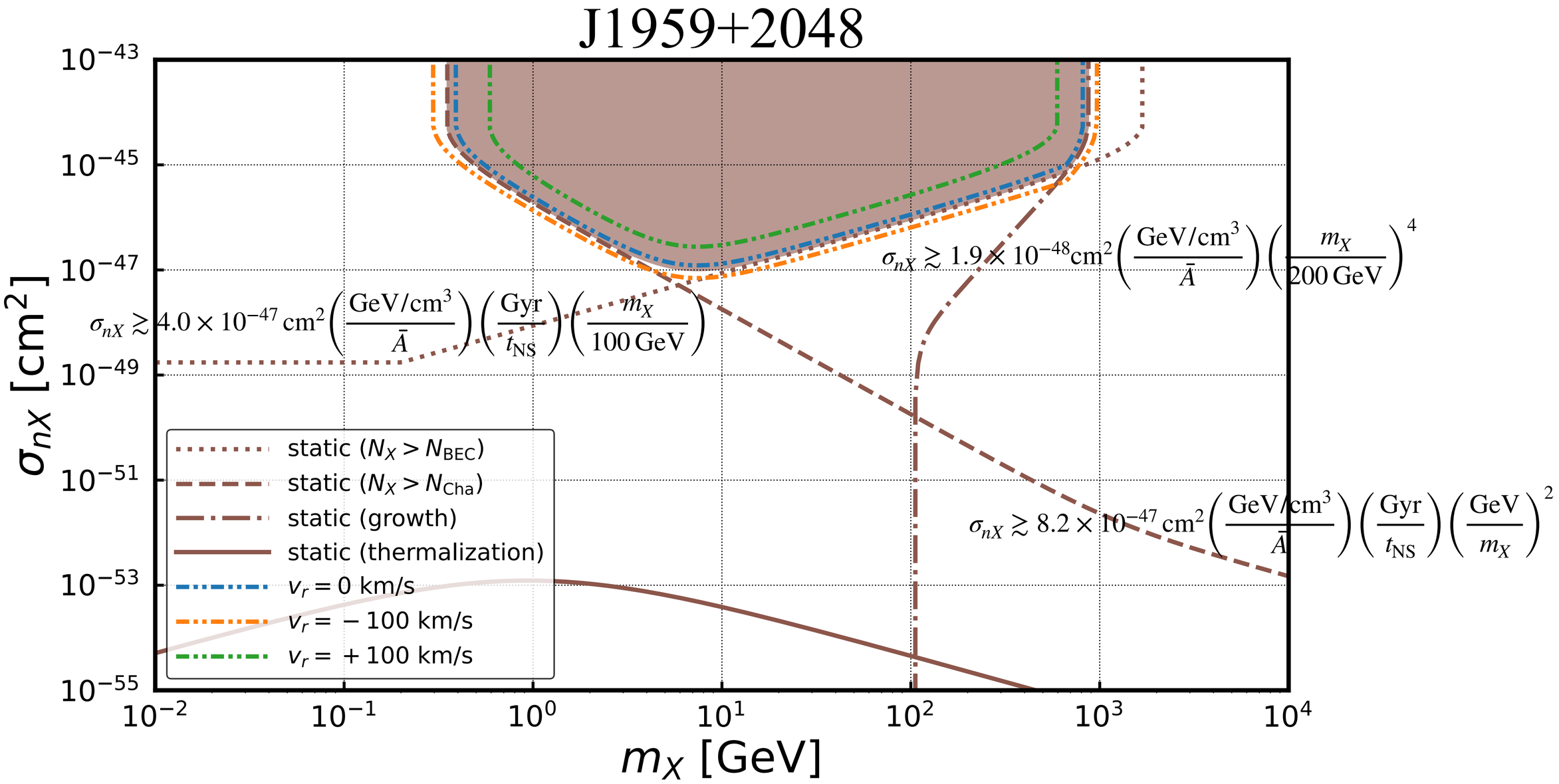
Condition growth

$$C_X m_X + \frac{4\pi\lambda_s \rho_B (GM_{\rm BH})^2}{v_s^3} - \frac{\hbar c^4}{15360\pi (GM_{\rm BH})^2} > 0$$

Bondi accretion **Hawking radiation**

Shapiro & Teukolsky, 1983

Constraints from J1959+2048



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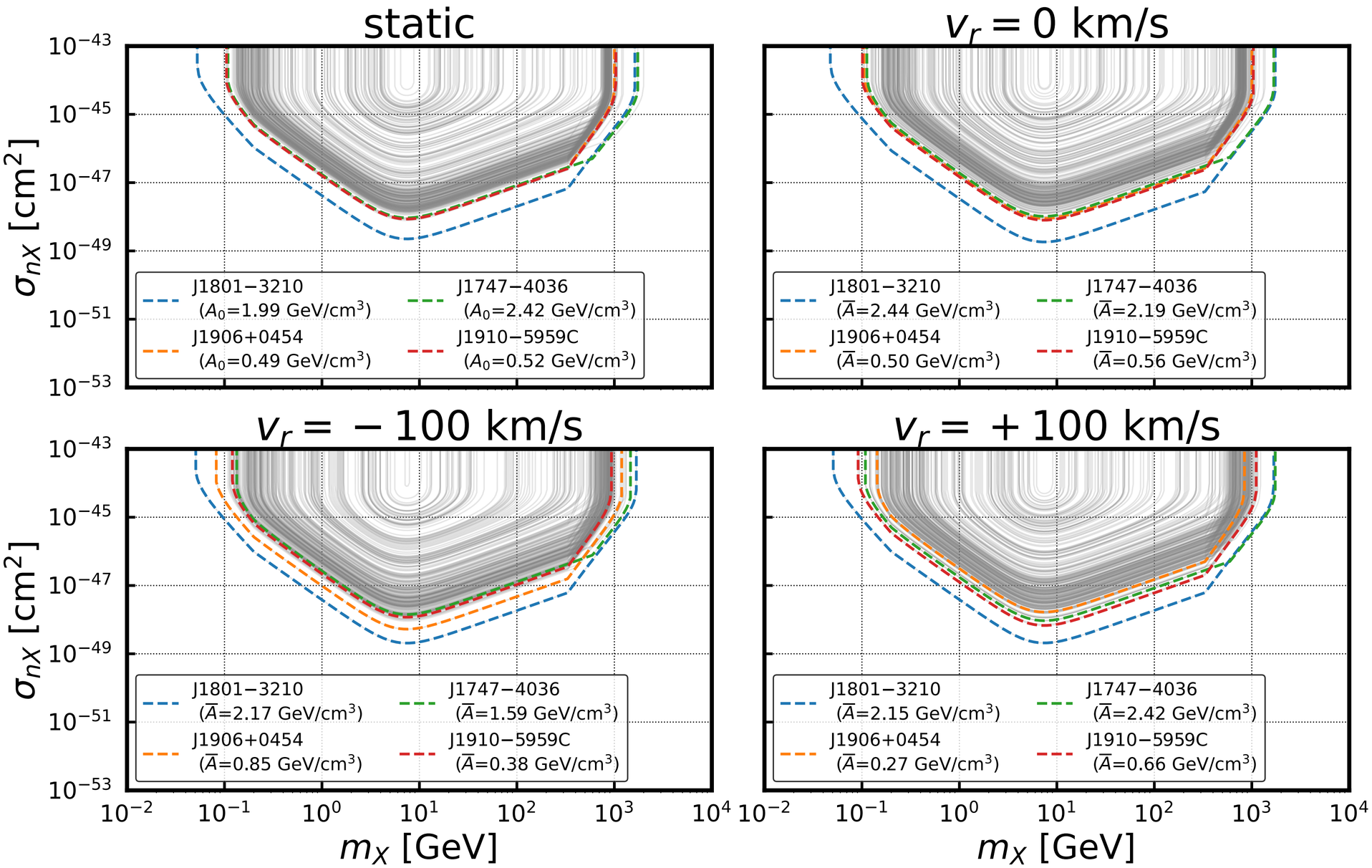
Constraints from 413 neutron stars



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Discussions

- Unknown radial velocity
- Imprecise age measurement

- Density-uniform NS ⟶ NS with different EoSs
- Bosonic dark matter ⟶ Fermionic dark matter


Thank You