Neutron Stars Surrouded by Dark Matter

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武汉 2017，6

- Dynamical Friction
- Accretion

DYNAMICAL FRICTION

- Orbital Motion of Binary Pulsars
- Breaking of Pulsars

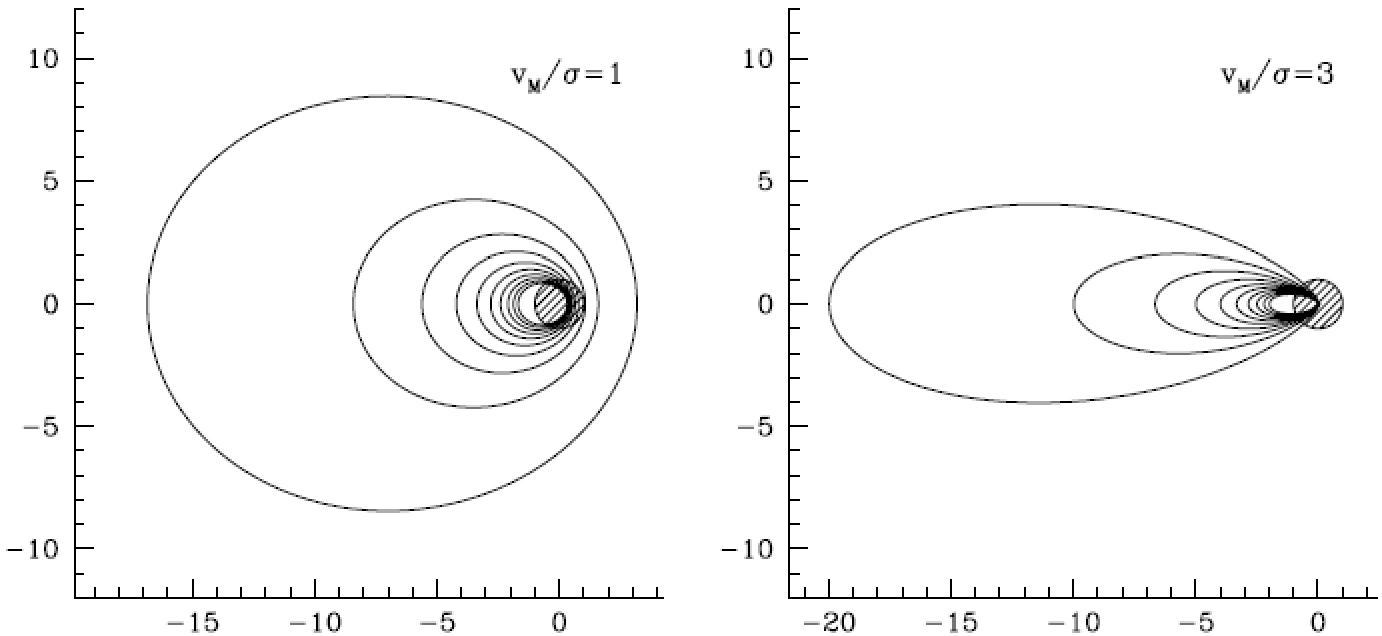
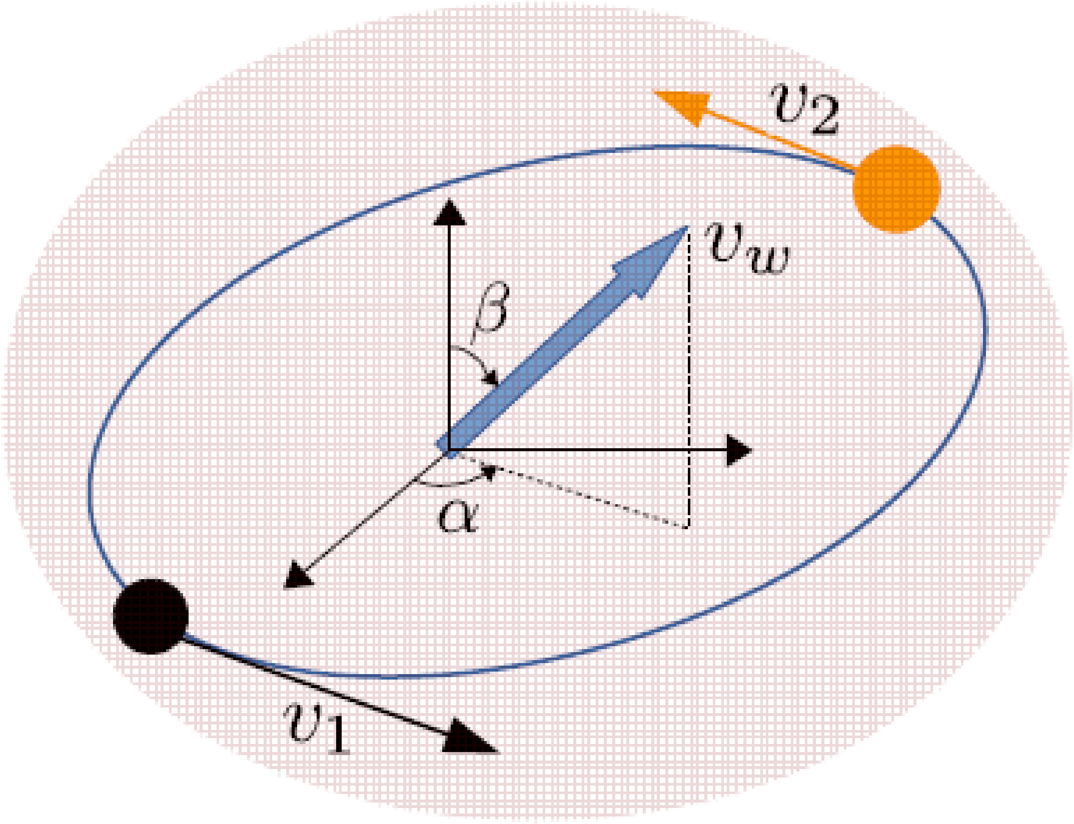


Figure 8.2 A mass M travels from left to right at speed v_M, through a homogeneous Maxwellian distribution of stars with one-dimensional dispersion σ. Deflection of the stars by the mass enhances the stellar density downstream, and the gravitational attraction of this wake on M leads to dynamical friction. The contours show lines of equal stellar density in a plane containing the mass M and the velocity vector $\mathbf{v}_M$; the velocities are $v_M = \sigma$ (left panel) and $v_M = 3\sigma$ (right panel). The fractional overdensities shown are $0.1, 0.2, \ldots, 0.9, 1$. The unit of length is chosen so that $GM/\sigma^2 = 1$. The shaded circle has unit radius and is centered at M. The overdensities are computed using equation (8.148), which is based on linear response theory; for a nonlinear treatment see Mulder (1983).

Friction Force

$$\mathbf{F}_i^{\mathrm{DF}} = -4\pi\rho_{\mathrm{DM}}\lambda\frac{G^2 m_i^2}{\tilde{v}_i^3}\left(\mathrm{erf}\left(x_i\right) - \frac{2x_i}{\sqrt{\pi}}e^{-x_i^2}\right)\tilde{\mathbf{v}}_i,$$

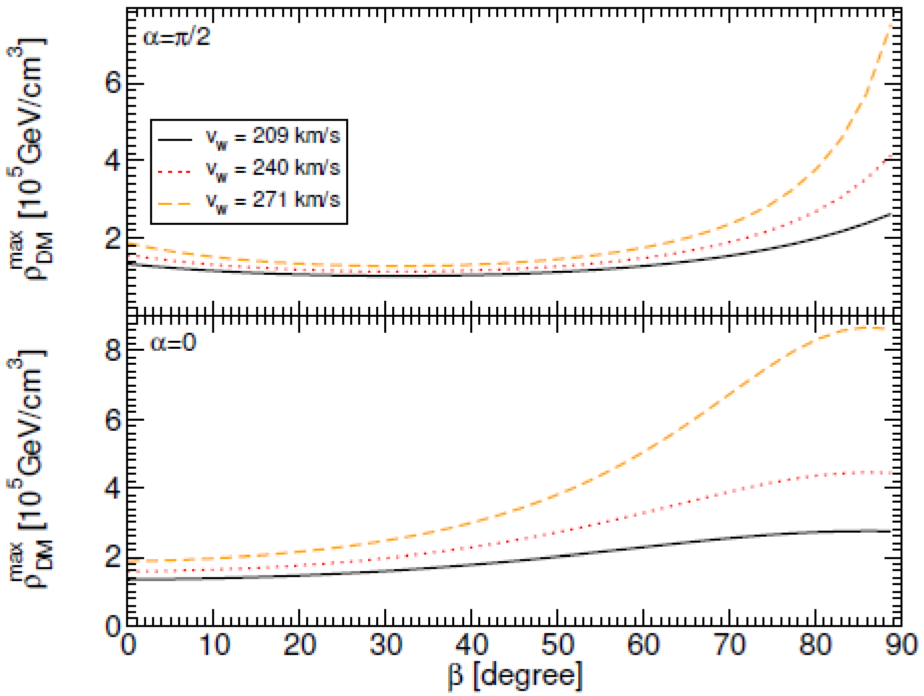
Orbital Motion



$$m_i\ddot{\mathbf{r}}_i = \pm\frac{Gm_1m_2}{r^3}\mathbf{r} + \mathbf{F}_i^{\mathrm{DF}},$$

$$\dot{P}_b^{\rm DF} \approx -3 \times 10^{-14} \frac{\mu_1 \lambda_{20} \rho_{\rm DM}^{\rm GC} P_b^{(100)}}{\sigma_{150}^3}$$

$$|\langle \dot{P}_b^{\rm DF} + \dot{P}_b^{\rm cm} + \dot{P}_b^{\iota} \rangle| - \dot{P}_b^{\rm GW} \lesssim |\dot{P}_b^{\rm xs}|$$



$$|\langle \dot{P}_b^{\rm DF} + \dot{P}_b^{\rm cm} + \dot{P}_b^{\iota} \rangle| \lesssim 2 \times 10^{-13}$$

$$\rho_{\rm DM} \lesssim (1-8) \times 10^5 \, {\rm GeV/cm^3}$$

FIG. 6. Upper bounds on the DM density due to DM dynamical friction as a function of the angle β of the DM wind derived from the timing of binary pulsar J1713+0747. We adopted the observed values $P_b \approx 67.8\,$day, $e \approx 0$, $m_1 \approx 1.31 M_\odot$, $m_2 \approx 0.29 M_\odot$, $\iota \approx 75.3°$, $\omega \approx 176.2°$ and considered $v_w \sim (240 \pm 31)\,$km/s. The upper (lower) panel shows the case with $\alpha = \pi/2$ ($\alpha = 0$). The behavior is monotonic with α so these two cases bracket the minimum and the maximum upper bound.

Paolo， PRD 92,123530 2015

Braking

$$n(\Omega) \equiv \frac{\Omega \ddot{\Omega}}{\dot{\Omega}^2}$$

$$\dot{E}_d = -\frac{2{\mu_\perp}^2}{3c^3}\Omega^4$$

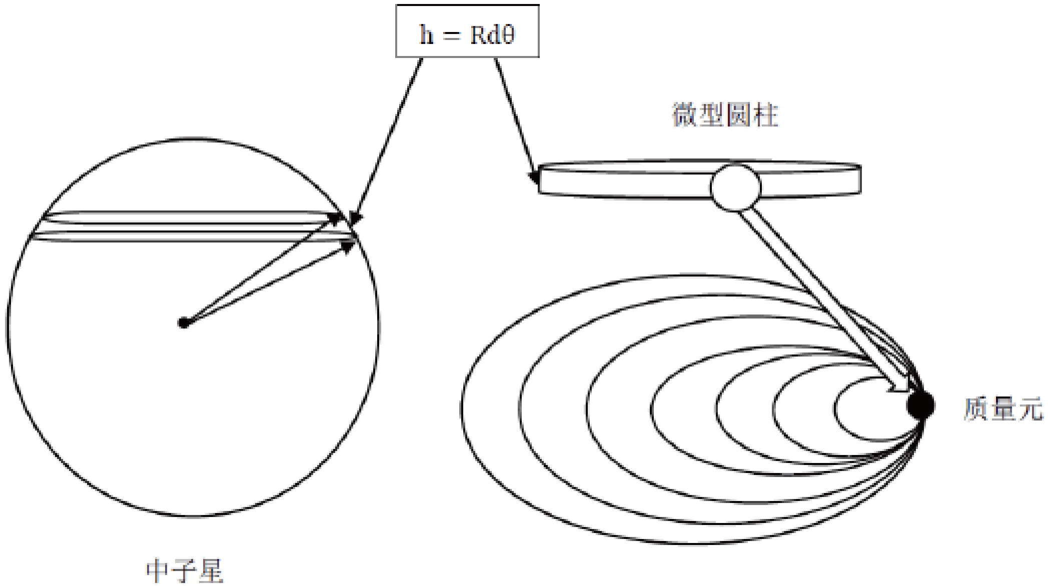
$$n = \frac{\ddot{\Omega}\Omega}{\dot{\Omega}^2} = 3$$

磁偶极制动

$$\dot{E}_{GW} = -\frac{2048\pi^6}{5}\frac{G}{c^5}I^2\varepsilon^2(\frac{\Omega}{2\pi})^6$$

$$n = \frac{\ddot{\Omega}\Omega}{\dot{\Omega}^2} = 5$$

引力波制动



$$\dot{E}_1 = \Omega M = \alpha \Omega^2$$

$$\dot{E}_2 = \Omega M = \beta \Omega^{-1}$$

$$\alpha = -\frac{16\pi^2 G^2 M^2}{3} \frac{n m_a \ln \Lambda R^2}{(2\pi\sigma^2)^{\frac{3}{2}}} \int_{\theta_c}^{\frac{\pi}{2}} \cos^2\theta d\theta$$

$$\beta = -4\pi G^2 M^2 n m_a \ln \Lambda \frac{1}{R} \int_0^{\theta_c} \frac{1}{\cos\theta} d\theta$$

$$n = 1 - \frac{3\beta}{\alpha\Omega^3 + \beta}$$

动力学摩擦制动

Zheng，Liu，in preparation

$$\dot{E}_{rot} = \dot{E}_d + \dot{E}_{DF} + \dot{E}_{GW}$$

$$n = 3 - \frac{2\dot{E}_{DF} + 3\beta\Omega^{-1} - 2\dot{E}_{GW}}{\dot{E}_d + \dot{E}_{DF} + \dot{E}_{GW}}$$

当$2\dot{E}_{DF}+3\beta\Omega^{-1}>2\dot{E}_{GW}$且$2\dot{E}_{d}+4\dot{E}_{GW}>3\beta\Omega^{-2}$时

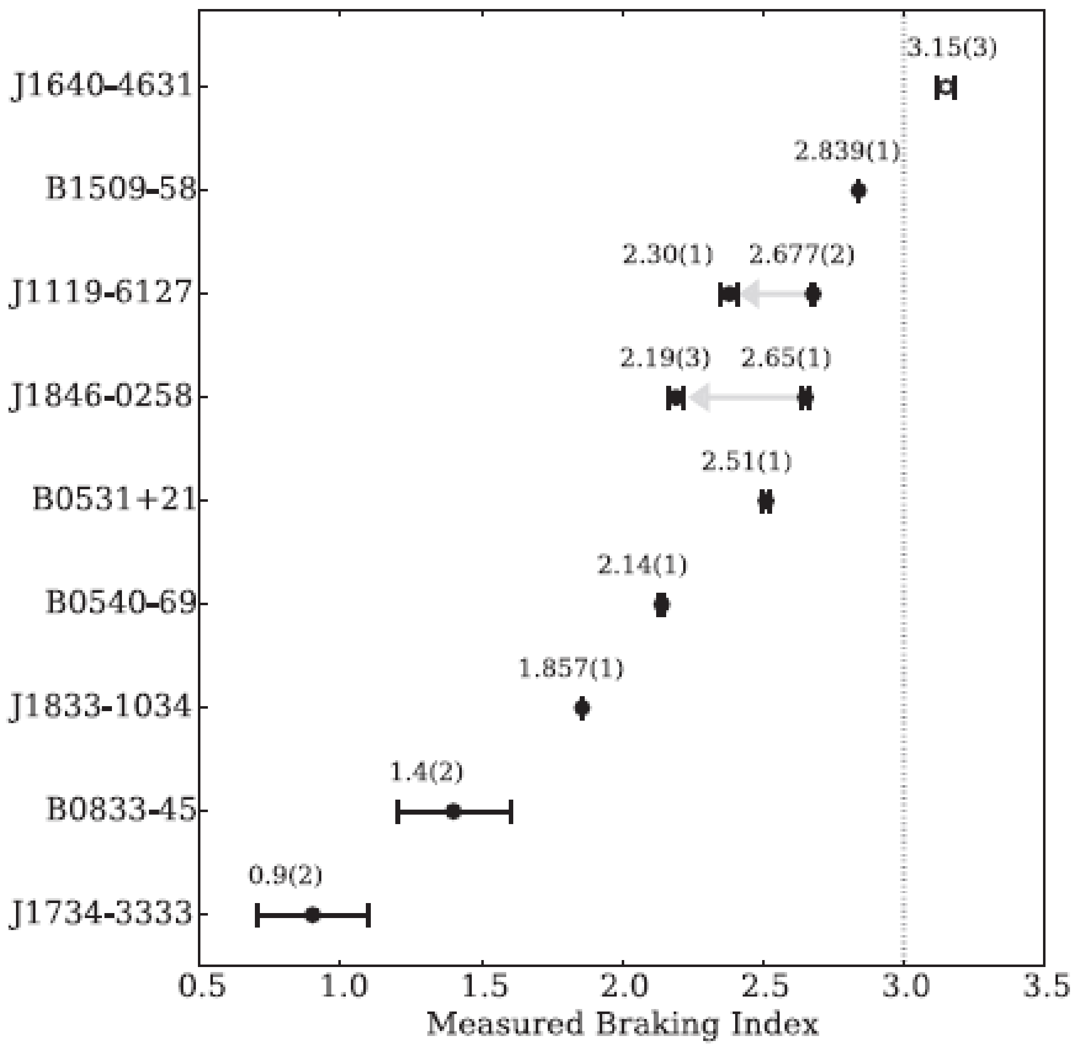
$$1<n<3$$

当$2\dot{E}_{DF}+3\beta\Omega^{-1}<2\dot{E}_{GW}$时

$$n>3$$

当$2\dot{E}_{d}+4\dot{E}_{GW}<3\beta\Omega^{-2}$且$3\dot{E}_{d}+5\dot{E}_{GW}+\dot{E}_{DF}>3\beta\Omega^{-2}$时

$$0<n<1$$



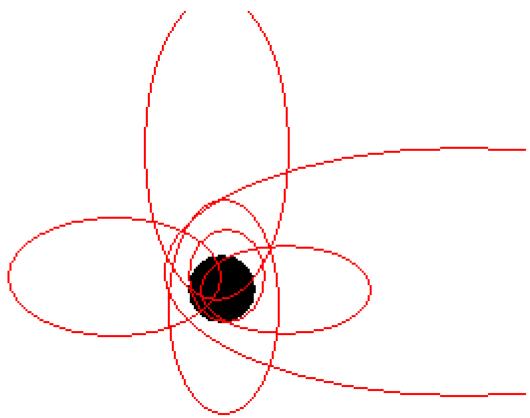
J1640-4631
B1509-58
J1119-6127
J1846-0258
B0531+21
B0540-69
J1833-1034
B0833-45
J1734-3333
3.15(3)
2.839(1)
2.30(1)
2.677(2)
2.19(3)
2.65(1)
2.51(1)
2.14(1)
1.857(1)
1.4(2)
0.9(2)
0.5
1.0
1.5
2.0
2.5
3.0
3.5
Measured Braking Index

ACCRETION

- Capture of WIMPs by Central Objects
- Bondi Accretion

Capture of WIMPs by Central Objects

轨道束缚暗物质吸积



$$p(v)dv = n_0 \left(\frac{3}{2\pi\bar{v}^2}\right)^{3/2} 4\pi v^2 \exp\left(\frac{-3v^2}{2\bar{v}^2}\right) dv,$$

$$d\mathcal{F} = 4\pi R^2 dF = n_0 \left(\frac{3}{2\pi\bar{v}^2}\right)^{3/2} \exp\left(\frac{-3E}{\bar{v}^2}\right) 4\pi^2 dE dJ^2.$$

太阳（Press and Spergel 1985,ApJ， 296）

$$\mathcal{F}_{\odot} = n_0 \left(\frac{3}{2\pi\bar{v}^2}\right)^{3/2} 4\pi^2 (2GMR) \min\left(\frac{1}{3}\bar{v}^2, E_0\right)$$

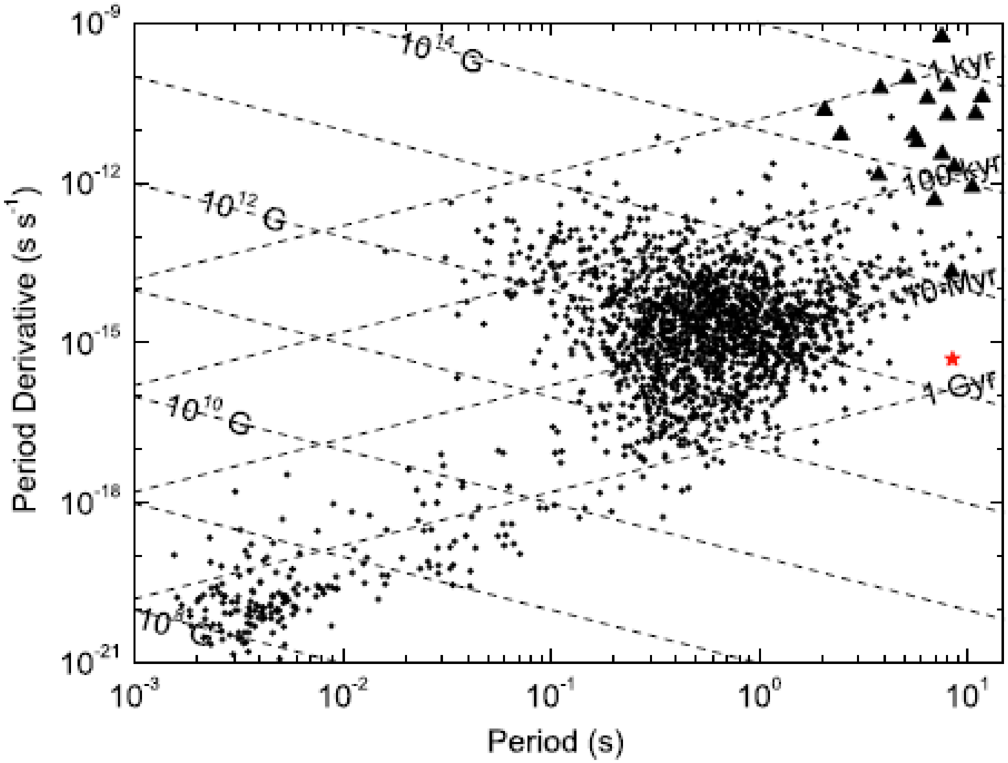
中子星（ Kouvaris 2008，PRD，77 ）

$$\mathcal{F}_{N} = n_0 \left(\frac{3}{2\pi\bar{v}^2}\right)^{3/2} 4\pi^2 (2GMR) \frac{1}{1 - 2GM/R} \min\left(\frac{1}{3}\bar{v}^2, E_0\right).$$

Millicharged Particles

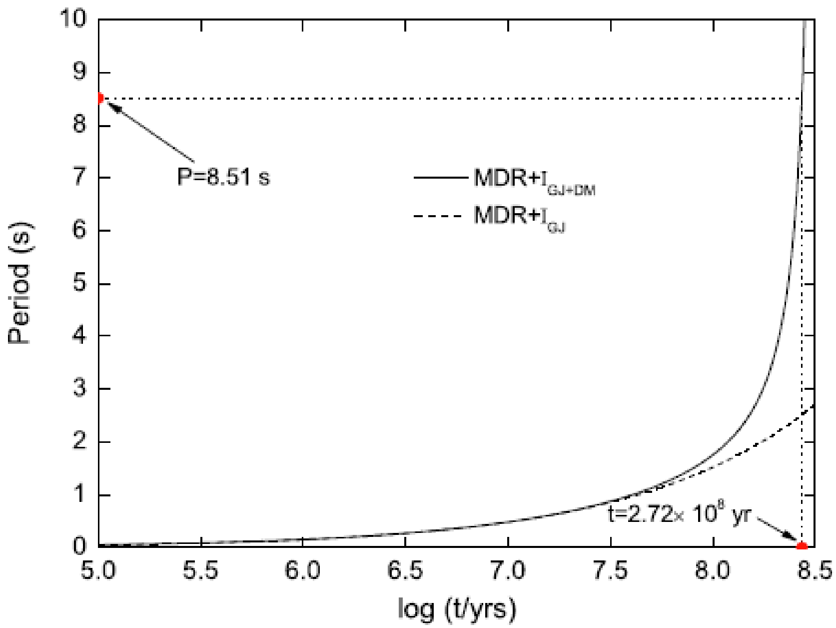
$$L_{\mathrm{orth}} = \frac{B_0^2 \Omega^4 R^6}{4c^3}, \qquad L_{\mathrm{align}} = \frac{B_0 \Omega (\Omega - \Omega_{\mathrm{death}}) R^3 I}{2c^2}$$

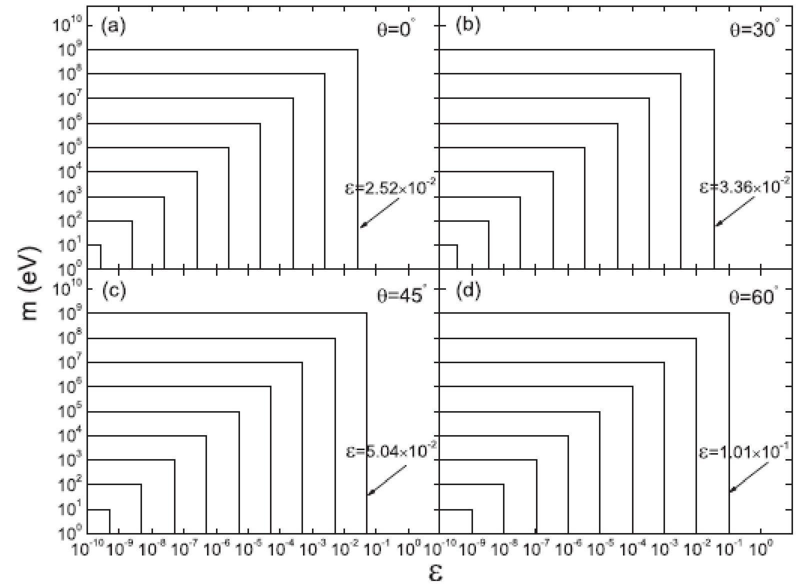
$$\frac{\mathrm{d}\Omega}{\mathrm{d}t} = -\frac{B_0^2 \Omega^3 R^6}{4\mathcal{I} c^3} \left[\sin^2\theta + \left(1 - \frac{\Omega_{\mathrm{death}}}{\Omega}\right)\left(1 + \frac{I_{\mathrm{DM}}}{I_{\mathrm{GJ}}}\right) \cos^2\theta \right].$$



Period Derivative (s s⁻¹)
Period (s)
10^14 G
10^12 G
10^10 G
1 kyr
100 kyr
10 Myr
1 Gyr

$$0.3\ \mathrm{GeV/cm^3}$$





Huang，Zheng PRD 91 123513 2015

球对称吸积

质量吸积率

$$\dot{M}_B = \Gamma \rho_\infty \frac{G^2 M^2}{{v_{s,\infty}}^3}$$

$$\gamma = \frac{5}{3}, v_s^2 = \frac{1}{3}\overline{v}^2 \text{（ig）}$$

总流量

$$\mathcal{F}_B = \frac{\sqrt{3}\pi}{5} \rho_\infty \frac{G^2 M^2}{v_\infty^3 m_\chi}$$

$$M_N = 1.4 M_{\odot}, R = 10\text{km}, R_{\odot} = 7 \times 10^5 \text{km}$$

$$\mathcal{F}_N = \frac{3.042 \times 10^{25}}{m_\chi(\text{GeV})} \times A \times f,$$

$$\mathcal{F}_{NB} = \frac{8.43 \times 10^{29}}{m_\chi} \times A \times f$$

$$\mathcal{F}_{\odot} \sim \frac{10^{30}}{m_\chi} \times A \times f \qquad \mathcal{F}_{\odot B} \sim \frac{10^{29}}{m_\chi} \times A \times f$$

其中*f* 散射因子

$$f = \left\langle 1 - \exp\left[- \int \frac{\sigma_\chi \rho}{m_n} dl \right] \right\rangle \simeq \left\langle \int \frac{\sigma_\chi \rho}{m_n} dl \right\rangle.$$

Simulation of Cooling Neutron Star

- Cooling Equation
- Standard Scenarios
- Heating

Cool equation

$$C_V \frac{dT}{dt} = -L_\nu - L_s + H$$

$$\frac{dT}{dP} = \frac{3}{16} \frac{\kappa}{T^3} \frac{T_s^4}{g_s}$$

$$\frac{1}{\kappa} = \frac{1}{\kappa_{\mathrm{rad}}} + \frac{1}{\kappa_{\mathrm{cond}}}$$

Standard scenarios

$t_\nu \sim 10^2 - 10^4\,\mathrm{yr}$

$t_\gamma \sim 10^5 - 10^6\,\mathrm{yr}$

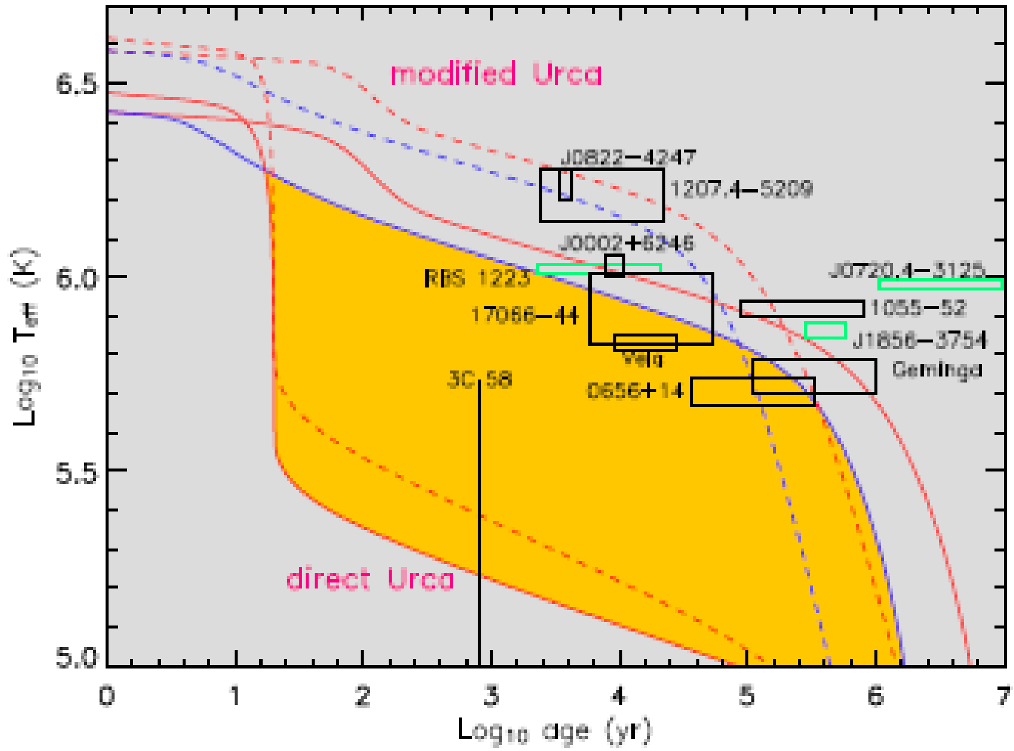


FIG. 4: Observational estimates of neutron star temperatures and ages together with theoretical cooling simulations for $M = 1.4\,M_\odot$. Models (solid and dashed curves) and data with uncertainties (boxes) are described in [43]. The green error boxes indicate sources from which thermal optical emissions have been observed in addition to thermal x-rays. Simulations with Fe (H) envelopes are displayed by solid (dashed) curves; those including (excluding) the effects of superfluidity are in red (blue). The upper four curves include cooling from modified Urca processes only, the lower two curves allow cooling with direct Urca processes and neglect the effects of superfluidity. Models forbidding direct Urca processes are relatively independent of M and superfluid properties. The yellow region encompasses cooling curves for models with direct Urca cooling including superfluidity.

Lattimer, Prakash
Science Vol. 304
2004 (536-542)

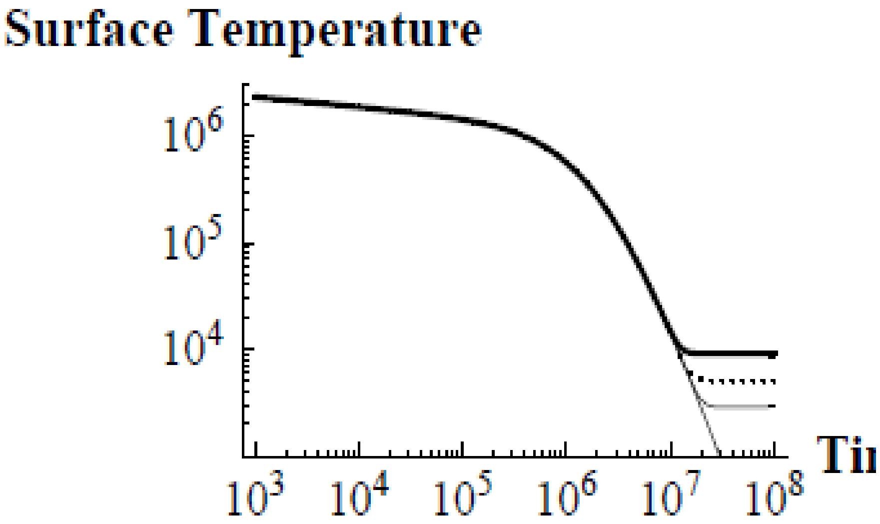
Heating- WIMP annihilation

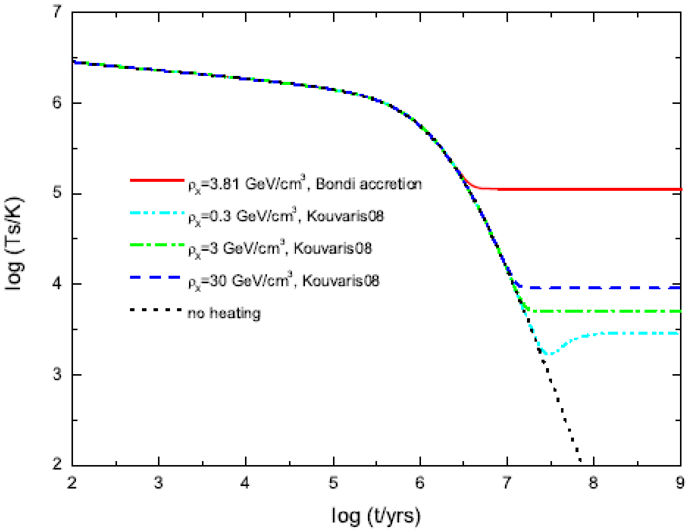
$$\frac{dN}{dt} = \mathcal{F} - C_A N^2.$$

$$N(t) = \sqrt{\frac{\mathcal{F}}{C_A}} \tanh(\frac{t}{\tau})$$

$$H = C_A N^2 m_\chi = \mathcal{F} \tanh^2(t/\tau) m_\chi.$$

$$C_A = \langle \sigma_\chi v \rangle / V \qquad \tau = 1/\sqrt{\mathcal{F} C_A}.$$





KouVars PRD77, 023006(2008)

Huang，Zheng In preparation

In Contrast

Star	$p(ms)$	$d^b(kpc)$	$t_{sd}(Myr)$	$T^\infty(10^5K)$
PSR J0437-4715	5.76	139^{+3}_{-3}	4900	1.2
PSR J2124-3358	4.93	270	7200	< 4.6
PSR J0030+0451	4.87	320	7700	< 9.2

表 5.2　老年毫秒脉冲星旋转周期、年龄、距离与表面温度观测数据。引自文献[70]。

Speculation

- 中子星作为暗物质粒子探针？
- 表面辐射与转动演化

谢谢