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EXPLORE DARK SECTOR PARAMETERS IN LIGHT OF NEUTRON STAR TEMPERATURES

ASTRO-PARTICLE AND COSMOLOGY

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G.-L. LIN AND Y.H. LIN, PHYS. REV. D 104 063021 (2021)

OUTLINE

- **Introduction:** (a) the advantage of applying neutron star (NS) temperature to constrain dark sector, (b) a general dark sector with a vector mediator.
- **NS cooling and dark matter (DM) heating:** (a) DM captured by NS, (b) NS temperature evolutions by SM processes and DM heating
- **Numerical results and detectability; JWST detector**
- **Summary and conclusions**

I.1: WHY INVOKING NEUTRON STAR?

- **Direct detections of DM in keV to TeV mass range involve many different physics effects and techniques: such as collective effects, electron recoils and nucleus recoils.**
- **Neutron star observation however can probe a very wide range of dark sector parameters.**

I.2: A GENERAL MODEL FOR SPIN-1 MEDIATOR CONNECTING DARK AND VISIBLE SECTORS

- Dark $U(1)_X$ field V mixes kinetically with SM $U(1)_Y$ and mixes with SM Z boson in mass terms

$$\mathcal{L}_{\text{gauge}} = -\frac{1}{4}B_{\mu\nu}B^{\mu\nu} + \frac{1}{2}\frac{\varepsilon_\gamma}{\cos\theta_W}B_{\mu\nu}V^{\mu\nu} - \frac{1}{4}V_{\mu\nu}V^{\mu\nu}$$

$$\mathcal{L}_{\text{mass}} = \frac{1}{2}m_Z^2 Z_\mu Z^\mu - \varepsilon_Z m_Z^2 Z_\mu V^\mu + \frac{1}{2}m_V^2 V_\mu V^\mu$$

$$\mathcal{L}_{\text{DM}} = i\bar{\chi}\gamma^\mu(\partial_\mu - i g_d V_\mu)\chi - m_\chi\bar{\chi}\chi$$

Holdom (1986)
Batel *et al.* (2009)
Davoudiasl *et al.* (2012)
Ilten et al. (2018)
Lin *et al.* 2102.11151

- Many ways to generate DM and V masses: extra scalar boson **s** may be introduced for generating DM and V boson masses

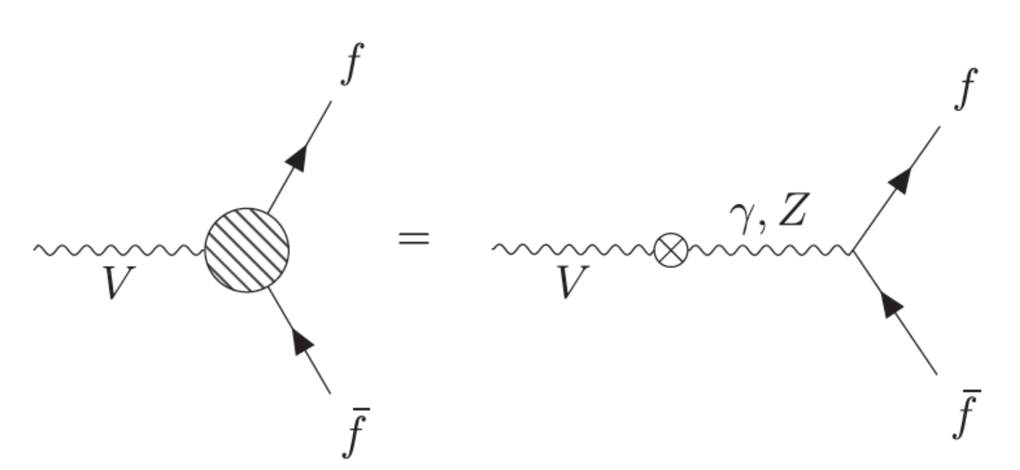
S: dark Higgs

N. F. Bell, Y. Cai, and R. K. Leane, (2016)

M. Duerr *et al.* (2016)

A GENERAL MODEL FOR SPIN-1 MEDIATOR CONNECTING DARK AND VISIBLE SECTORS

- **Effective interactions between dark boson and SM fermions:**

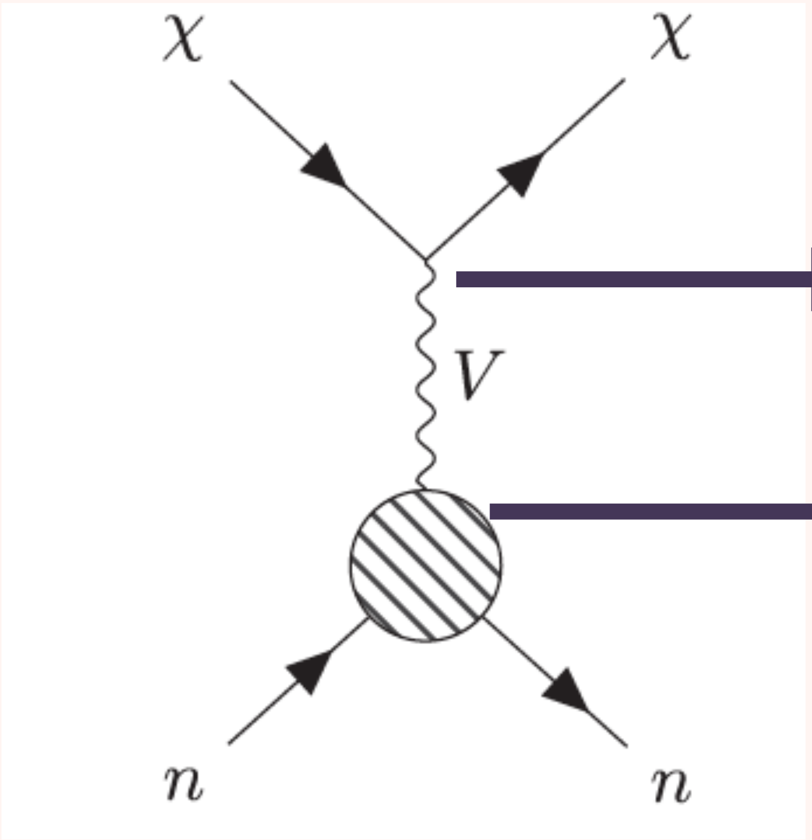


$$\mathcal{L}_{\mathrm{DS-SM}} = \left(\varepsilon_\gamma e J_\mu^{\mathrm{EM}} + \tilde{\varepsilon}_Z \frac{g_2}{\cos\theta_W} J_\mu^{\mathrm{NC}} \right) V^\mu$$

$$\tilde{\varepsilon}_Z = \frac{\varepsilon_Z + \varepsilon_\gamma \tan\theta_W (m_V^2/m_Z^2)}{(1 - m_V^2/m_Z^2)^2 + \Gamma_Z^2/m_Z^2} \left(1 - \frac{m_V^2}{m_Z^2} - i \frac{\Gamma_Z}{m_Z} \right)$$

$$\tilde{\varepsilon}_Z \to \varepsilon_Z \text{ for } m_V \ll m_Z$$

DM-NEUTRON INTERACTIONS—DETERMINING THE RATE OF DM CAPTURE BY NS



$$\mathcal{L}_{\bar{\chi}\chi V} = g_d \bar{\chi}\gamma_\mu \chi V^\mu \qquad \alpha_\chi = \frac{g_d^2}{4\pi}$$

$$\mathcal{L}_{\bar{n}nV} = e\bar{\psi}_n \gamma_\mu (a_f + b_f \gamma^5)\psi_n V^\mu$$

$$a_f = Q\varepsilon_\gamma + \frac{1}{\sin 2\theta_W}(I_3 - 2Q\sin^2\theta_W)\tilde{\varepsilon}_Z$$

$$b_f = -\frac{I_3}{\sin 2\theta_W}\tilde{\varepsilon}_Z$$

II.1 DM CAPTURE IN NEUTRON STAR

NS mass $M_0 = 1.4\ M_\odot$, Radius $R_0 = 12$ km

Bell *et al.* (2018)
Garani *et al.* (2020)

$$\frac{dN_\chi}{dt} = C_c - C_a N_\chi N_{\bar{\chi}}$$

C_c : capture rate, increases the numbers of DM

$$\frac{dN_{\bar{\chi}}}{dt} = C_c - C_a N_{\bar{\chi}} N_\chi$$

C_a : annihilation rate, decreases the numbers of DM

Solving the above equations gives

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

$\tau_{\rm eq} \equiv 1/\sqrt{C_c C_a}$ is the equilibrium time scale

$$C_c \propto \sigma_{\chi n}, C_a \propto \langle \sigma v \rangle.$$

$\tau_{\rm eq} = (10^2 - 10^3)$ yrs for $(\langle \sigma v \rangle, \sigma_{\chi n}) = (6 \times 10^{-26} \mathrm{cm}^3 \mathrm{s}^{-1}, 10^{-47} \mathrm{cm}^2)$

$$\mathrm{MeV} \le m_\chi \le \mathrm{TeV}$$

Equilibrium reached for t $\sim$ Gyr NS $\quad N_\chi = N_{\bar{\chi}} \to \sqrt{C_c/C_a}$

II.2 NEUTRON STAR COOLING

- **NS cools due to neutrino and photon emissions**
- **On the other hand, DM annihilating to SM particles could heat up NS**

$$\frac{dT_b}{dt} = \frac{-\epsilon_\nu - \epsilon_\gamma + \epsilon_\chi}{c_V}$$

$$T_s \approx 8.7 \times 10^5 \text{ K}(g_s/10^{14} \text{ cm s}^{-2})^{1/4}(T_b/10^8 \text{ K})^{0.55}$$

$$g_s \equiv \frac{GM_0}{R_0^2} \approx 1.85 \times 10^{14} \text{ cm s}^{-2}, \text{redshift corrections}$$

T_b : NS interior temperature

$\epsilon_\nu \approx 2.1 \times 10^4 \text{ erg} \cdot \text{cm}^{-3}\text{s}^{-1}(T_b/10^7\text{K})^8,$ Neutrino Emissivity

$\epsilon_\gamma \approx 1.8 \times 10^{14} \text{ erg} \cdot \text{cm}^{-3}\text{s}^{-1}(T_b/10^7\text{K})^{2.2},$ Photon Emissivity

ϵ_χ : heating induced by DM annihilation

c_V : heat capacity of NS

Gudmunsson *et al.* (1982)
Gudmunsson *et al.* (1983)
Page *et al.* (2004)
Kouvaris (2008)
Potekhin *et al.* (2015)
Chen *et al.* (2018)...

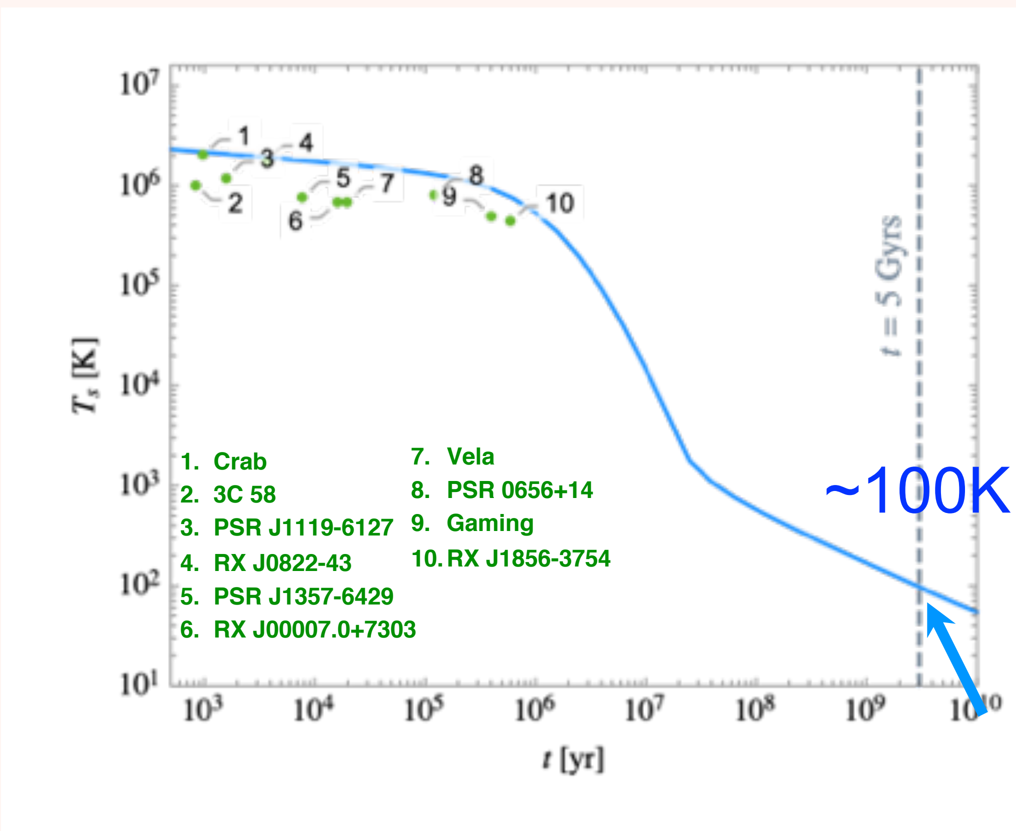
Shapiro & Teukolsky (1983)
Kouvaris (2008)

II. 2 NEUTRON STAR COOLING CURVE

$$\varepsilon_\chi = \frac{\mathcal{E}_\chi + \mathcal{K}_\chi}{V} \qquad \mathcal{E}_\chi = 2m_\chi \Gamma_a \sum_i b_i, \Gamma_a = C_a N_\chi N_{\bar{\chi}}$$

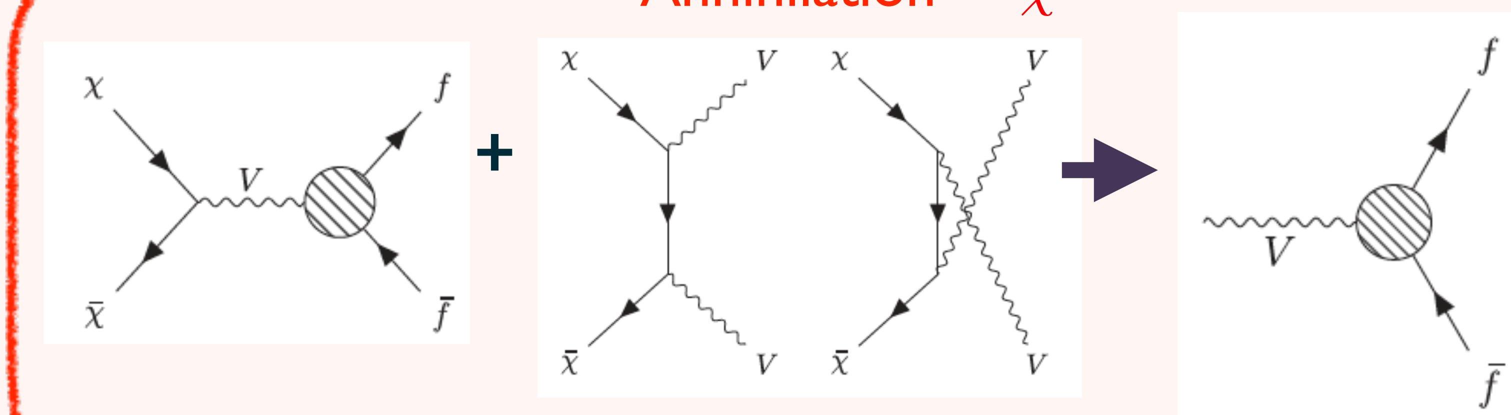
$$\mathcal{K}_\chi = C_c m_\chi (\gamma - 1)$$

Neutron star surface temperature

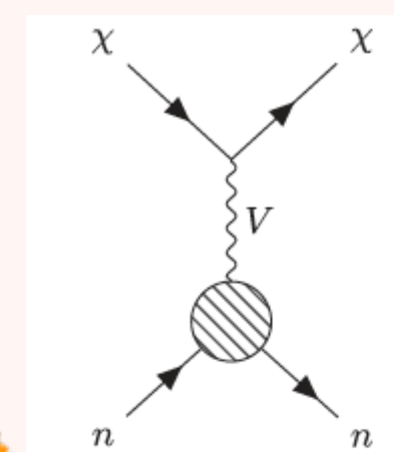


DM heating not included

Annihilation $\mathcal{E}_\chi$



Kinetic $\mathcal{K}_\chi$

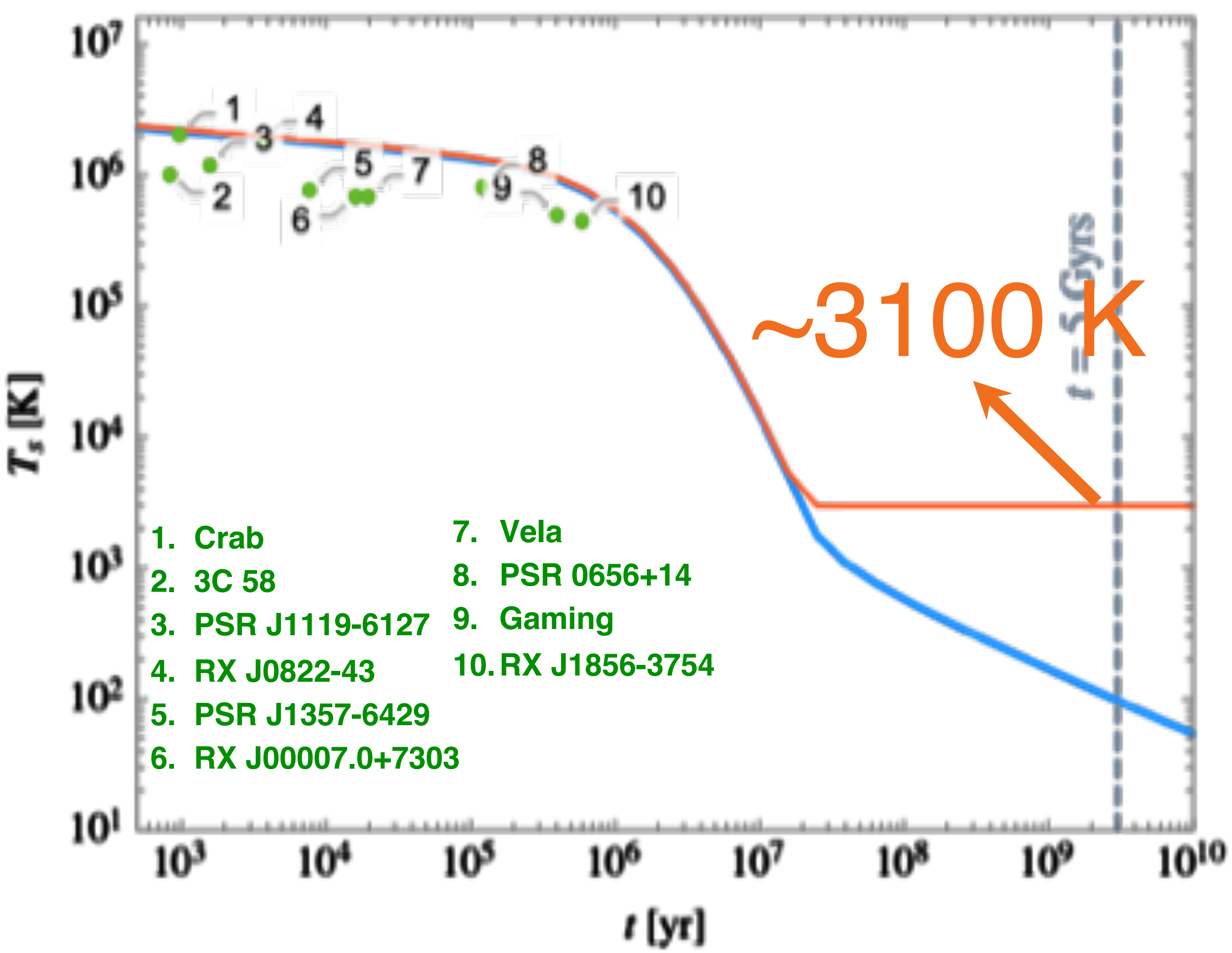


With DM heating

Baryakhtar *et al.* (2017)

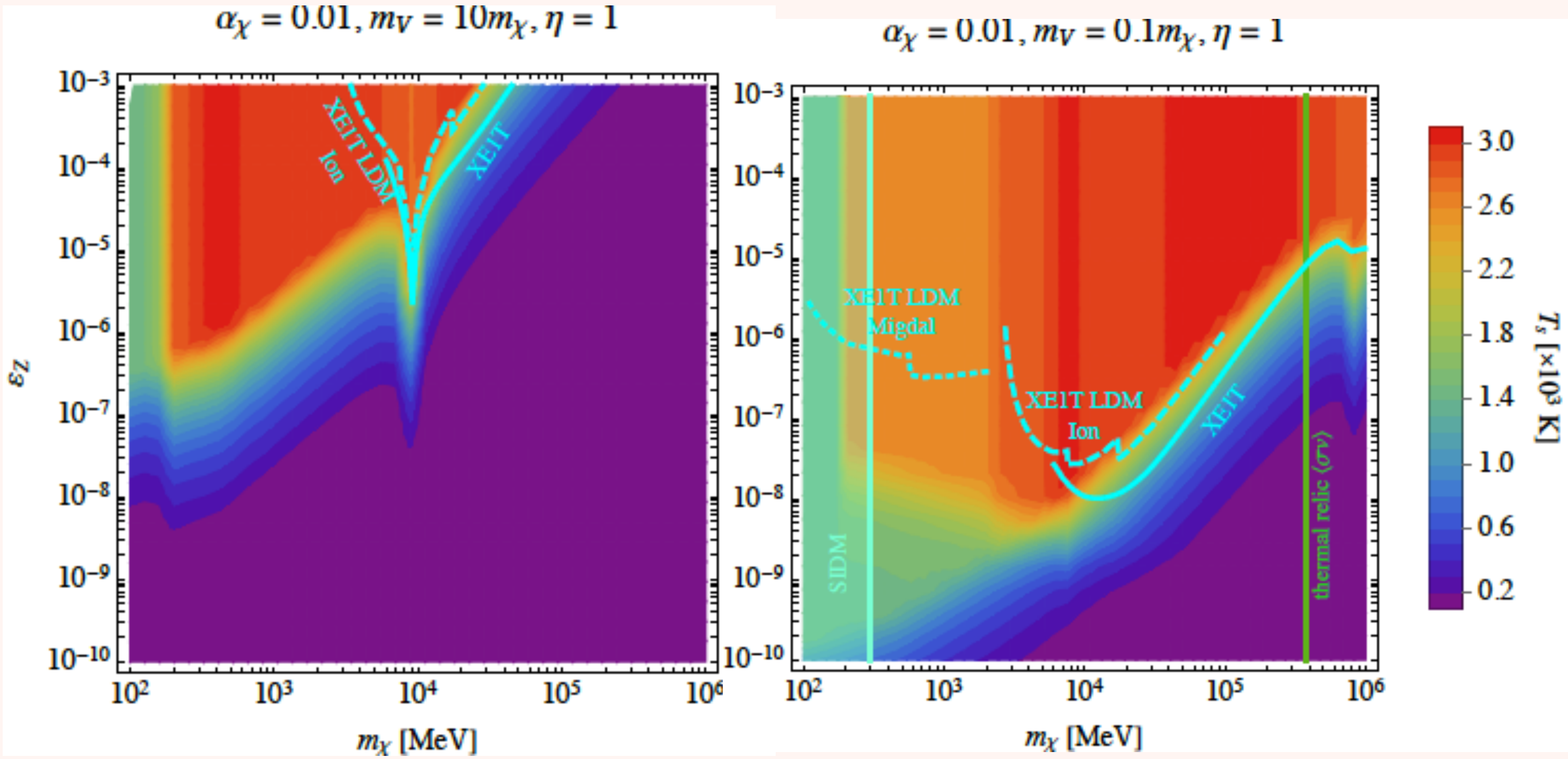
II-2 NEUTRON STAR COOLING CURVE—EFFECTS OF DM HEATING INCLUDED

Neutron star surface temperature



III NUMERICAL RESULTS AND DETECTABILITY OF NS TEMPERATURE (JWST)

$\varepsilon_\gamma = \varepsilon_Z$



Heavy mediator $m_V = 10 m_\chi$

$\chi\bar{\chi} \to f\bar{f}$

Light mediator $m_V = 0.1 m_\chi$

$\chi\bar{\chi} \to VV \to 2f\bar{f}$

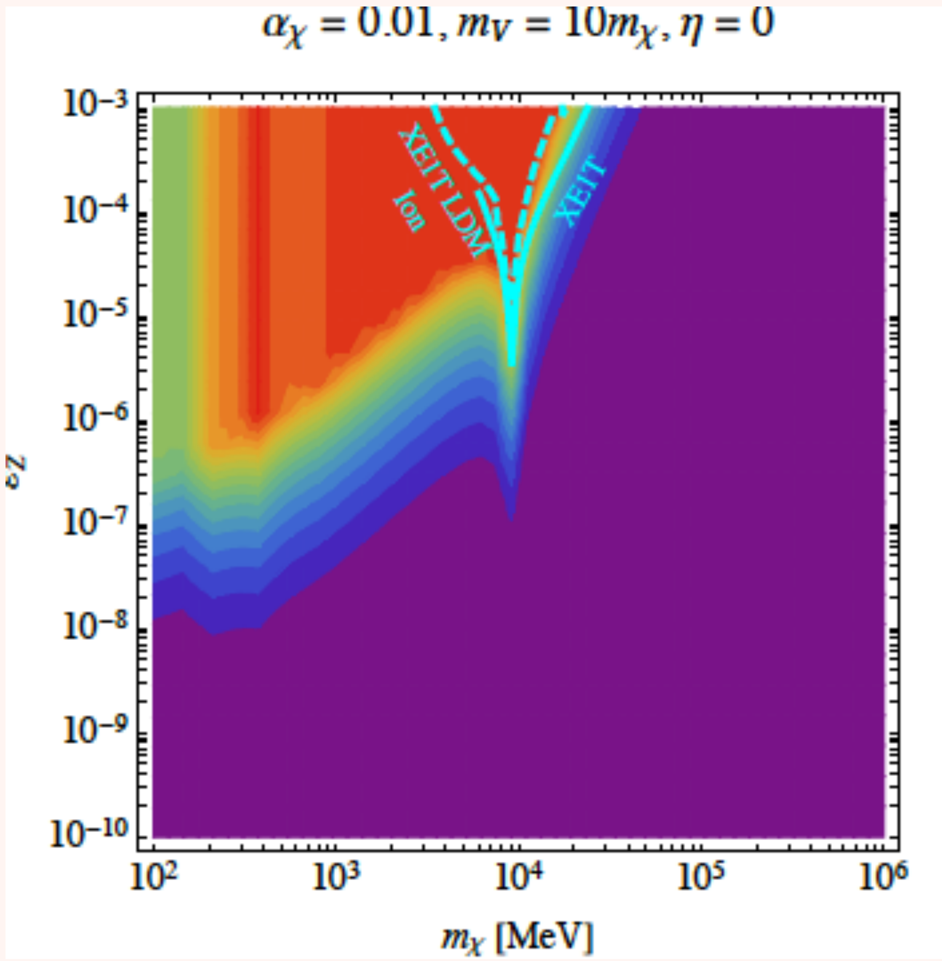
This thermal relic constraint applies only if $\chi\bar{\chi} \to VV$ dominates. The parameter space here is not constrained if $\chi\bar{\chi} \to ss$ dominates.

DM-*V* coupling $\alpha_\chi = \frac{g_d^2}{4\pi}$

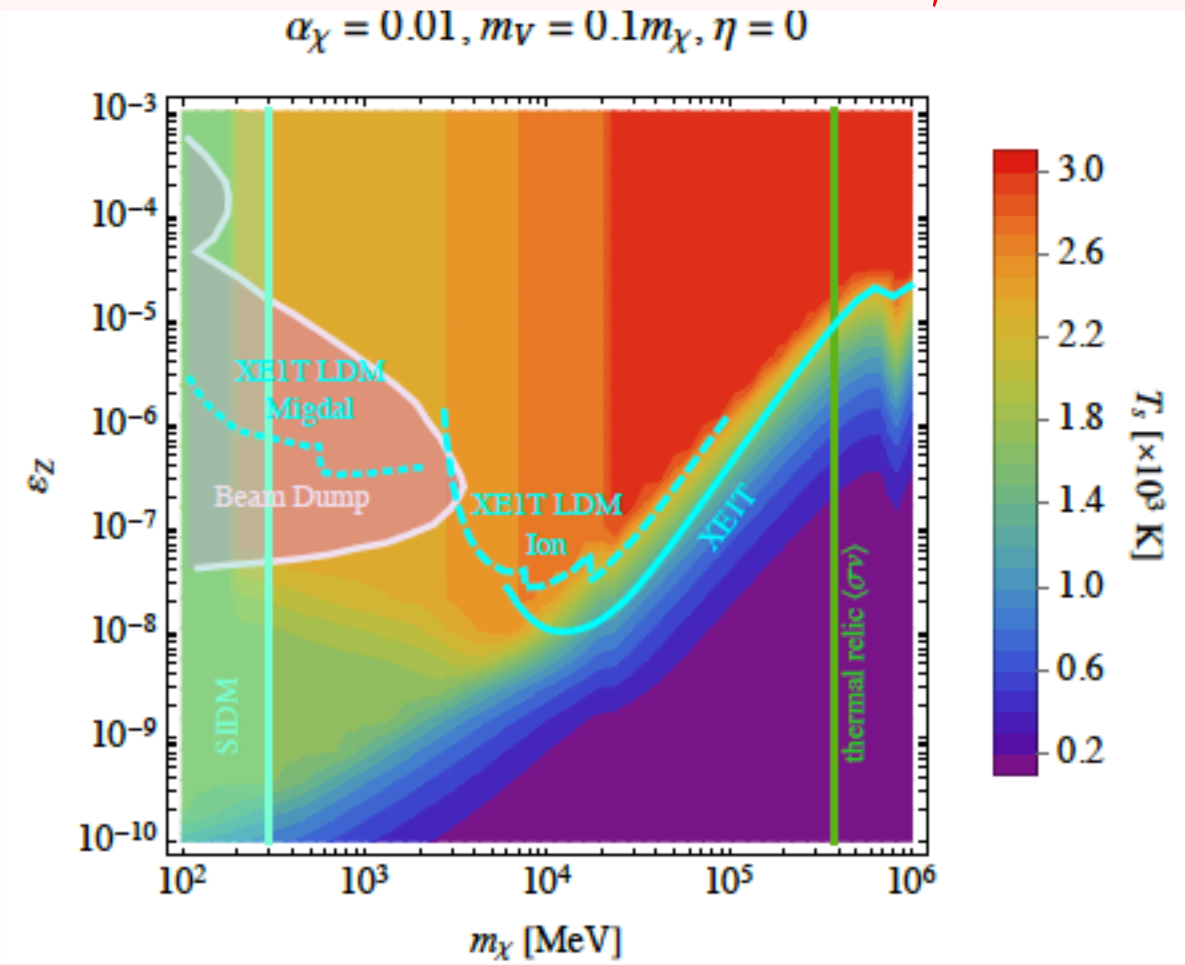
- $\varepsilon_\gamma = \varepsilon_Z$: $\sigma_{\chi n} \sim 0.36 \sigma_{\chi p}$
- Comparing to the current direct searches, NS gives better sensitivities for lighter DM

III NUMERICAL RESULTS AND DETECTABILITY OF NS TEMPERATURE (JWST)

$\varepsilon_\gamma = 0$



Heavy mediator $m_V = 10m_\chi$



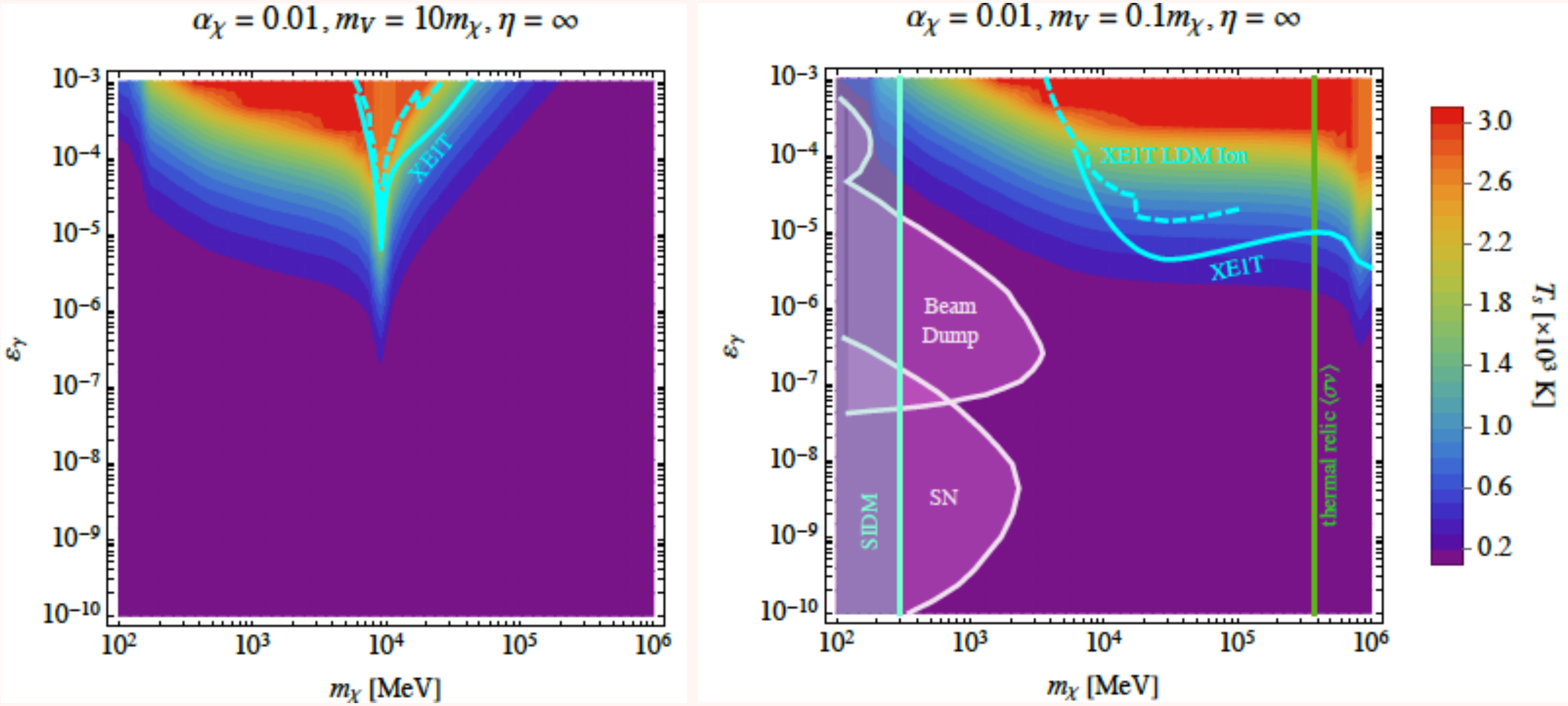
Light mediator $m_V = 0.1m_\chi$

DM-V coupling $\alpha_\chi = \frac{g_d^2}{4\pi}$

- $\varepsilon_\gamma = 0$: $\sigma_{\chi p} \sim 0$
- However, to a NS, $Y_n \sim 100 Y_p$, proton contribution to Cc (capture rate)
- is much less than that of neutron unless $\sigma_{\chi p} \gg \sigma_{\chi n}$

III NUMERICAL RESULTS AND DETECTABILITY OF NS TEMPERATURE (JWST)

$\varepsilon_Z = 0$



Heavy mediator $m_V = 10m_\chi$

Light mediator $m_V = 0.1m_\chi$

- $\varepsilon_Z = 0$: $\sigma_{\chi n} = 0$, only DM-proton scattering remains
- Since $Y_p \sim 0.01Y_n$, it needs bigger kinetic mixing coupling ε_γ to compensate the suppression of neutron contributions
- No Z-mixing exists, DM will not annihilate to neutrinos
- All the energy released from annihilation in NS will be fully absorbed by the star

EXISTING CONSTRAINTS SHOWN ON THE PLOTS FOR COMPARISONS

XENON1T

E. Aprile *et al.* (XENON Collaboration), Phys. Rev. Lett. **121**, 111302 (2018).

XENON LDM Ionization

E. Aprile *et al.* (XENON Collaboration), Phys. Rev. Lett. **123**, 251801 (2019).

XENON LDM Migdal effects

E. Aprile *et al.* (XENON Collaboration), Phys. Rev. Lett. **123**, 241803 (2019).

SIDM

S. W. Randall, M. Markevitch, D. Clowe, A. H. Gonzalez, and M. Bradac, Astrophys. J. **679**, 1173 (2008).

M. G. Walker and J. Penarrubia, Astrophys. J. **742**, 20 (2011).

M. Boylan-Kolchin, J. S. Bullock, and M. Kaplinghat, Mon. Not. R. Astron. Soc. **415**, L40 (2011).

M. Boylan-Kolchin, J. S. Bullock, and M. Kaplinghat, Mon. Not. R. Astron. Soc. **422**, 1203 (2012).

O. D. Elbert, J. S. Bullock, S. Garrison-Kimmel, M. Rocha, J. Oñorbe, and A. H. Peter, Mon. Not. R. Astron. Soc. **453**, 29 (2015).

SN 1987A

A. Sung, H. Tu, and M. R. Wu, Phys. Rev. D **99**, 121305 (2019).

Beam Dump Experiments

E. M. Riordan, M. W. Krasny, K. Lang, P. De Barbaro, A. Bodek, S. Dasu, N. Varelas, X. Wang, R. G. Arnold, D. Benton *et al.*, Phys. Rev. Lett. **59**, 755 (1987).

A. Bross, M. Crisler, S. H. Pordes, J. Volk, S. Errede, and J. Wrbanek, Phys. Rev. Lett. **67**, 2942 (1991).

M. Abdullah, J. B. Dent, B. Dutta, G. L. Kane, S. Liao, and L. E. Strigari, Phys. Rev. D **98**, 015005 (2018).

III.2 DETECTABILITY AT JWST DETECTOR

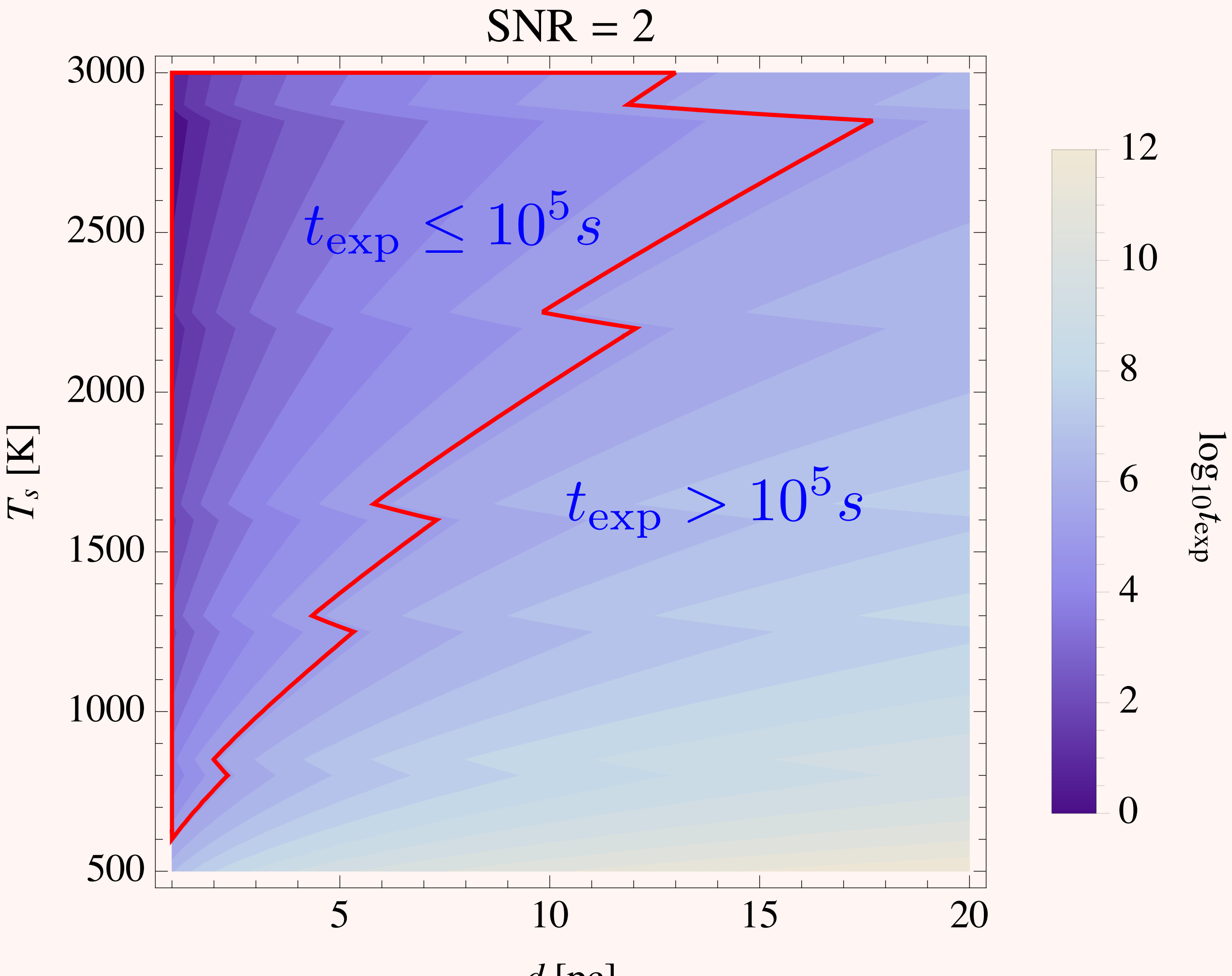
Gardner *et al.* 0606175 (2006)
JWST pocket guide (June 2020)
Lin *et al.* 2102.11151

$$\mathrm{SNR} = \frac{N_s}{\sqrt{N_b}} \propto f_\nu \sqrt{t_{\mathrm{exp}}}$$

Spectral flux density: $f_\nu(\nu, T_s, d) = \frac{(k_B T_s)^3}{2\pi}\left(\frac{a^3}{e^a - 1}\right)\left(\frac{R_0 \gamma}{d}\right)^2$

$a = 2\pi\nu / k_B T_s \qquad \gamma \approx 1.35$

R_0 : NS radius $\qquad d$: NS distance



JWST detector

IV SUMMARY

- NS has a wide sensitivity on DM mass m_χ: from keV to TeV
- NS has high sensitivity on DM-SM interaction cross section σ
- The existence of DM can alter the surface temperature of old NS
- The framework can be used to test various phenomenology models
- JWST is capable of detecting nearby low temperature NS and therefore set constraints on dark sector parameters