Faint light of old neutron stars from dark matter capture and detectability at the James Webb Space Telescope (JWST)

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based on

"Faint light of old neutron stars from dark matter capture and detectability at the James Webb Space Telescope"

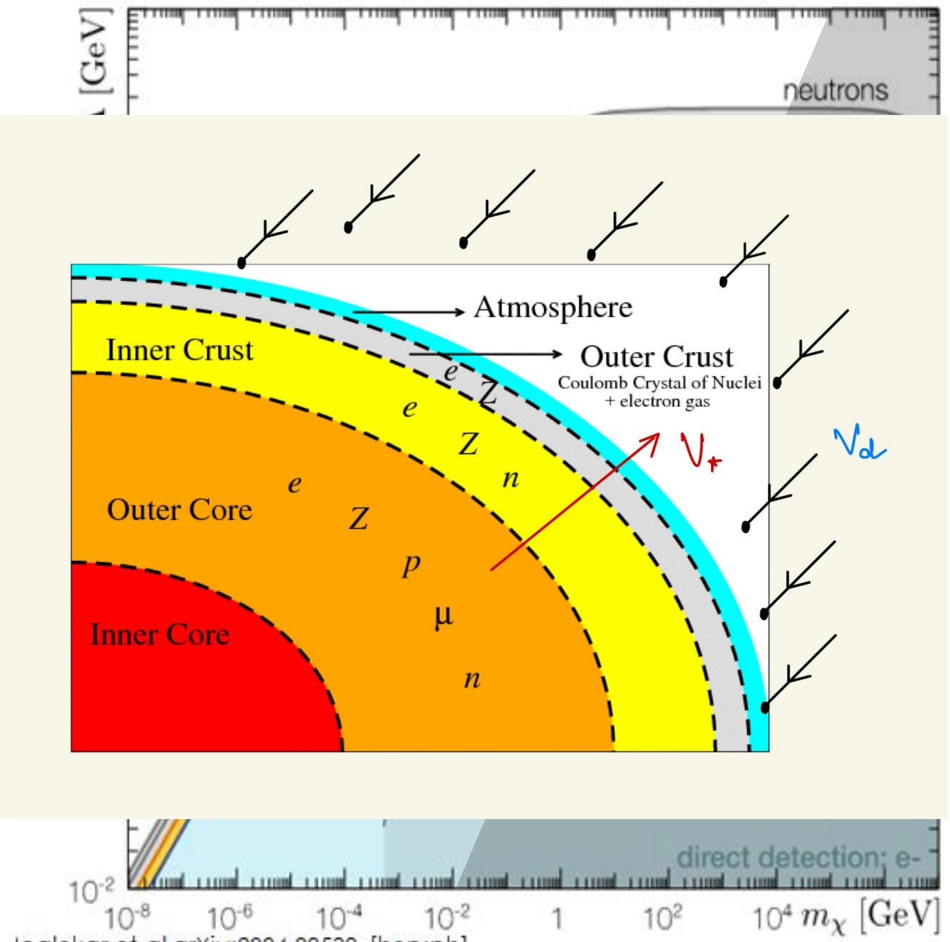
SC, Raghuveer Garani, Rajeev K. Jain, Brijesh Kanodia, M.S.N. Kumar, Sudhir K. Vempati **(arXiv: 2205.05048 [astro-ph.HE])**

Dark Interactions Workshop
November 15th, 2022

Overview:

- How can old Neutron Stars (NS) be probes for Dark Matter (DM)
- Goodness of probe:
  - Uncertainties that affect surface temperatures
  - Maximal heating and detectability at the James Webb Space Telescope (JWST)
- Results and Summary

Neutron Star Heating from DM: DM Probe



Joglekar et al arXiv:2004.09539 [hep:ph]

- For any astrophysical object existing in a DM-rich environment, DM particles can scatter with the constituents, get "captured" and deposit kinetic energy.
- Subsequently, thermalized DM can deposit energy via annihilation: Kinetic+Annihilation (KA) heating
- Neutron Stars are one of the most compact astrophysical objects known to us ⟹ efficient capture.
- Old neutron stars ($> 10^9$ years) are expected to have surface temperatures of $O(100)\,K$.
- Kinetic heating can bring up the surface temperatures to $O(1000) K \sim O(\mu m)$.
- Detection at infrared telescopes like the James Webb Space Telescope (JWST).
- Observation of a "cold" old NS will give *upper bounds* on DM interaction with SM (NS constituents).
- Complementary to Direct Detection (DD):
  - DD is limited by threshold recoil energy, while kinetic heating is dictated by chemical potential etc.
  - DM relative velocities are different $v_{DM}^{DD} \sim 10^{-3}, v_{DM}^{NS} \sim 0.2$

Baryakhtar et al arXiv:1704.01577 [hep-ph]
Garani et al arXiv: 1906.10145 [hep-ph]
Bell et al: arXiv: 1904.09803 [hep-ph]
Joglekar et al arXiv:2004.09539 [hep-ph]
Baryakhtar et al arXiv: 2203.07984v2 [hep-ph]

Neutron Stars as Dark Matter Probes

- The extent of heating of a NS from DM scattering and annihilation depends on:
  1. DM model
  2. Equation of State of the Neutron star: NS mass and radius and radial profile of scattering target in the NS
  3. Astrophysical: Ambient DM distribution (energy density and dispersion velocity) and velocity of the NS

Neutron Stars as Dark Matter Probes

While in the geometric limit in which all DM particles incident upon the NS get captured

- The extent of heating of a NS from DM scattering and annihilation depends on:

  1. ~~DM model~~
  2. Equation of State (EoS) of the Neutron star: NS mass and radius ~~and radial profile of scattering target in the NS~~
  3. Astrophysical: Ambient DM distribution (energy density and dispersion velocity) and velocity of the NS

- The goodness of such a probe can be understood by asking:
  - How do the astrophysical and EoS uncertainties play into the DM predictions that can be made from the observation of a heated, old Neutron Star?
  - What are the prospects for actually observing said heated, old and isolated Neutron Star?

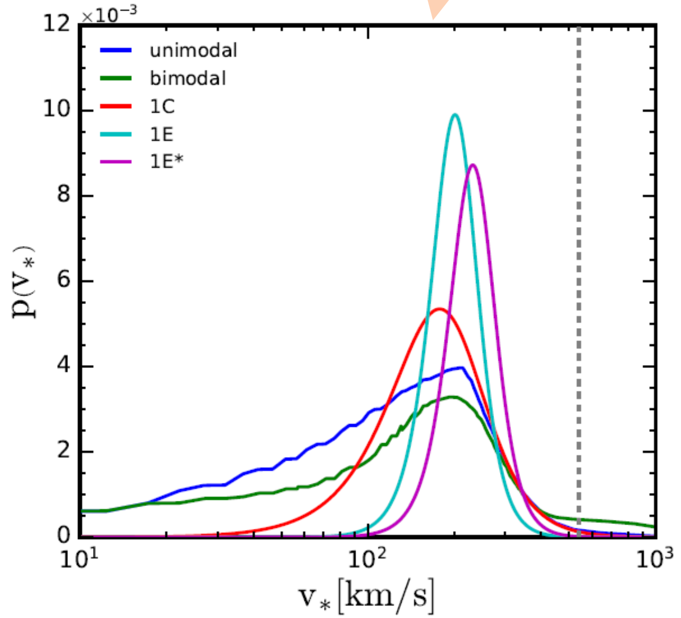
- This entails an accounting of known uncertainties from astrophysics $(v_{NS}, v_d^{DM}, \rho^{DM})$ and Neutron Star Equation of State $(M_{NS}, R_{NS}, v_{esc})$.

- A careful analysis exploiting the features of the James Webb Space Telescope, using their exposure time calculator to arrive at realistic SNR.

Accounting for Uncertainties:

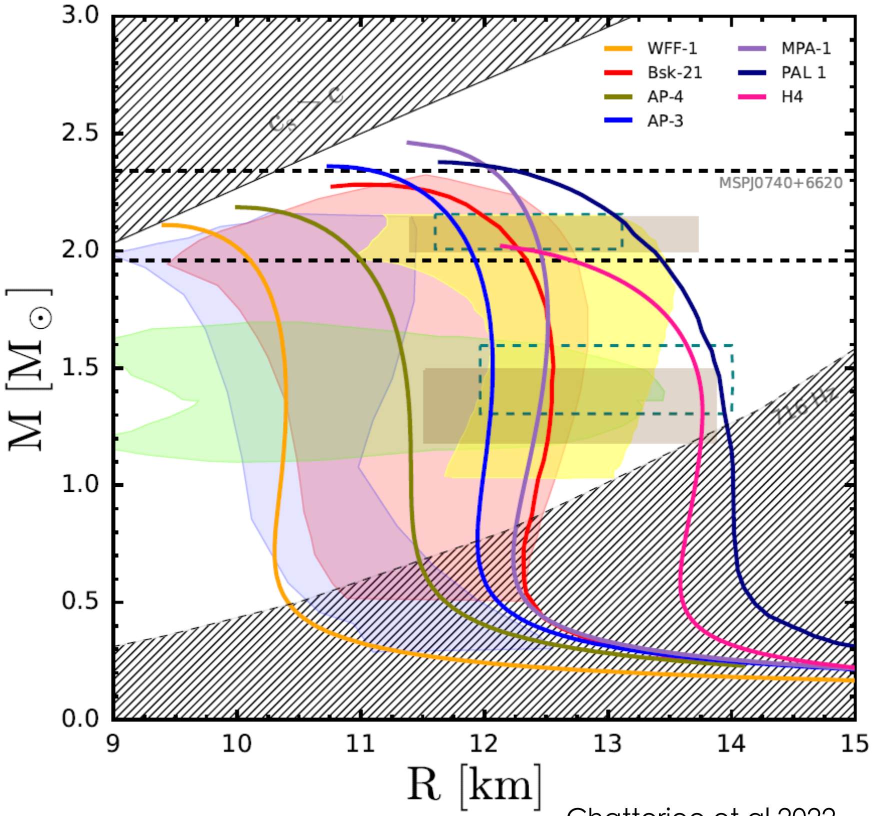
- Observed quantity: Flux from old, isolated neutron star, i.e. its surface temperature with a blackbody spectrum

$$T_{surface}^{observed} \propto \text{astrophysics} \times \text{Nuclear Equation of State}$$



Chatterjee et al 2022

DM dispersion velocity v_d (km/s)	DM energy density at solar radius ρ_{DM} (GeV/cm^3)
260	0.39
316	0.52



Chatterjee et al 2022

Ofek et al 2009
Sartore et al 2009
Bozorgnia et al 2016
Ozel and Freire, 2016

(II) Maximum temperatures and detectability:

- Observed quantity: Flux from old, isolated neutron star, i.e. its surface temperature, assuming a blackbody spectrum

$$T_{surface}^{observed} \propto \text{astrophysics} \times \text{Nuclear EoS} \times \text{particle physics}$$

- For large enough DM-SM coupling such that the the surface temperature is determined by geometric rates alone:

$$T_{kin}^{\infty} \simeq 1787K \left(\frac{\alpha_{kin}}{0.08} \left(\frac{\rho_{DM}}{0.42\ GeV/cm^3} \right) \frac{220\ km/s}{v_*} Erf\left(\frac{270\ km/s}{v_d} \frac{v_*}{220\ km/s} \right) \right)^{1/4}$$

where $\alpha_{kin} = \frac{(\gamma-1)(\gamma^2-1)}{\gamma^4}$

$$T_{KA}^{\infty} \simeq 2518K \left(\frac{\alpha_{KA}}{0.33} \left(\frac{\rho_{DM}}{0.42\ GeV/cm^3} \right) \frac{220\ km/s}{v_*} Erf\left(\frac{270\ km/s}{v_d} \frac{v_*}{220\ km/s} \right) \right)^{1/4}$$

where $\alpha_{KA} = \frac{\gamma(\gamma^2-1)}{\gamma^4}$

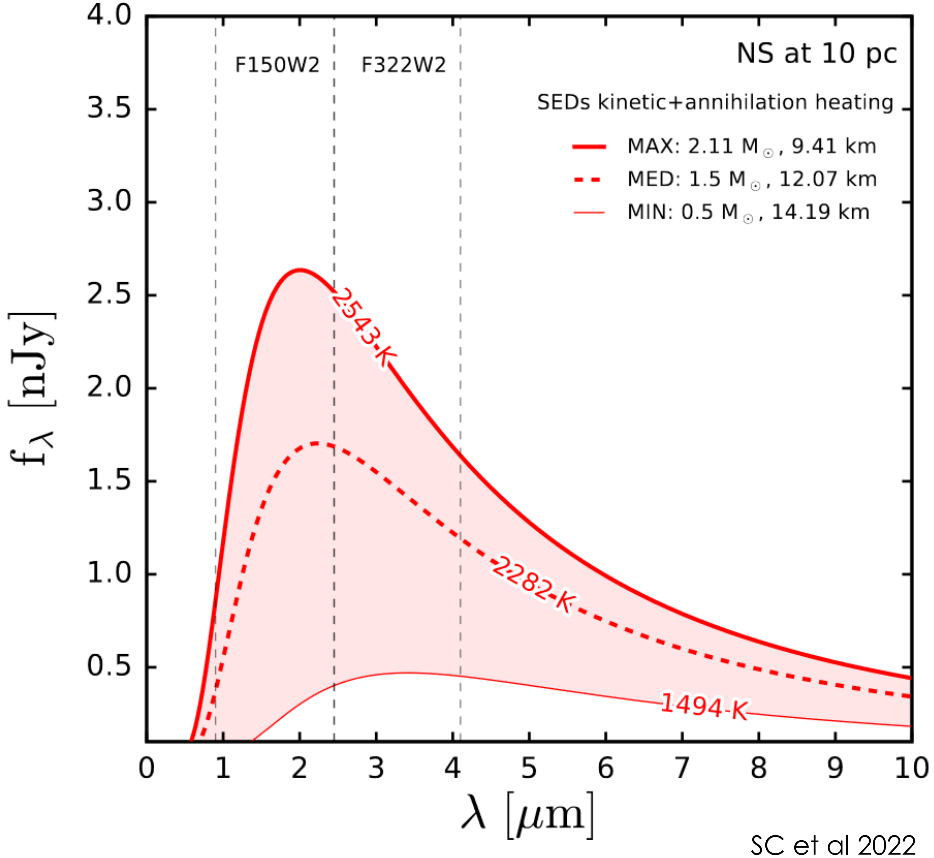
($M = 1.5\ M_{\odot}, R = 10\ km$ for $\alpha_{KA} = 0.33$)

(II) Maximum temperatures and detectability:

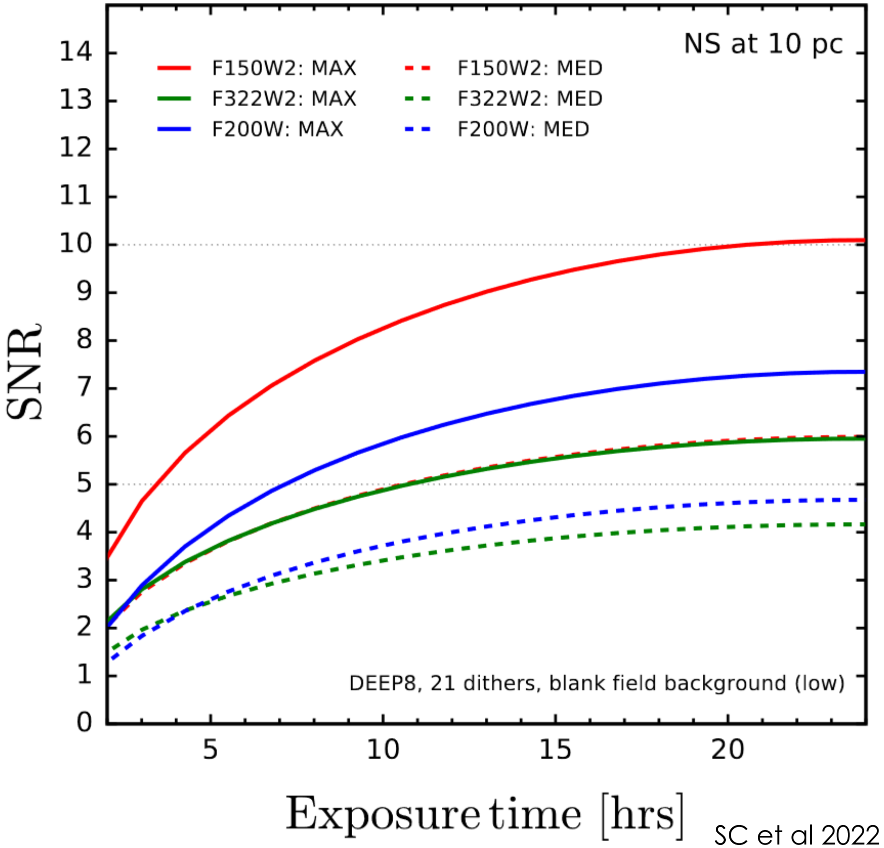
- Observed quantity: Flux from old, isolated neutron star, i.e. its surface temperature, assuming a blackbody spectrum

$$T_{surface}^{observed} \propto \text{astrophysics} \times \text{Nuclear EoS}$$

- Choose a NIRCAM filter that falls on the peak of the spectrum: Broad filters F150W2 and F322W2



SC et al 2022



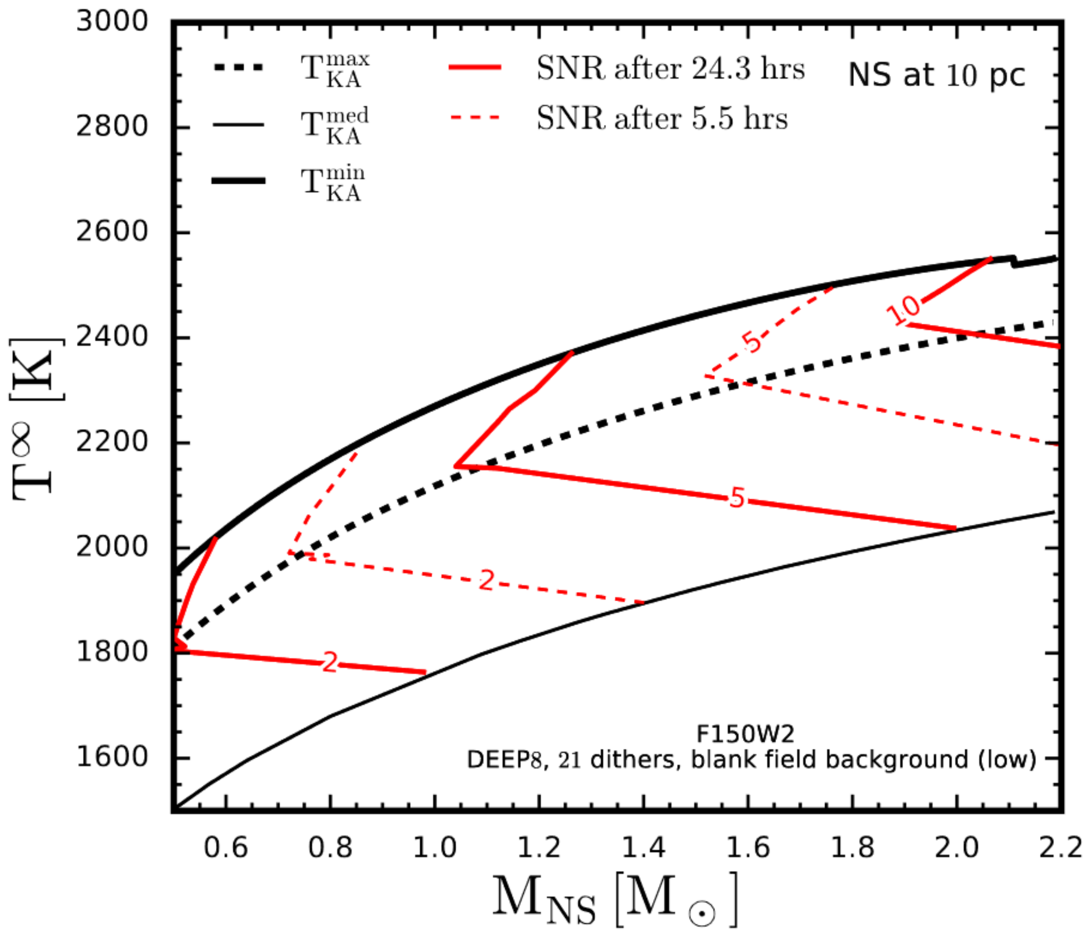
SC et al 2022

(II) Maximum temperatures and detectability:

- Observed quantity: Flux from old, isolated neutron star, i.e. its surface temperature, assuming a blackbody spectrum

$$T_{surface}^{observed} \propto \text{astrophysics} \times \text{Nuclear EoS}$$

- We choose a filter that falls on the peak of the spectrum
  - Broad filter F150W2 fares the best
- We calculate the SNR using JWST Exposure Time Calculator. This demonstrates the detection prospect of a NS with ~1800-2600 K surface temperature with a JWST small program ($t_{exposure} < 25\ hours$).



SC et al 2022

Summary

- We have *quantified* the observational prospects for maximal (kinetic and annihilation) DM heating scenario of NS, corresponding to geometric values of scattering cross section.
- The DM heating from kinetic+annihilation processes can raise the NS surface temperature to a maximum of $\sim$ 2550 K in the best case scenario.
- We have studied the robustness of using old neutron stars as probes of DM and found that the maximal temperature varies at most by ~40%.
- We find that NS with temperatures $\gtrsim$ 2400 K at 10 pc can be detected by JWST at SNR $\gtrsim 10$ within 24 hours of exposure time using the F150W2 filter of NIRCAM.
- Observational implementation will require assembling candidate target lists for such objects through deep surveys from space and ground based facilities, such as the WFIRST or Vera C. Rubin observatory.

Thank you!

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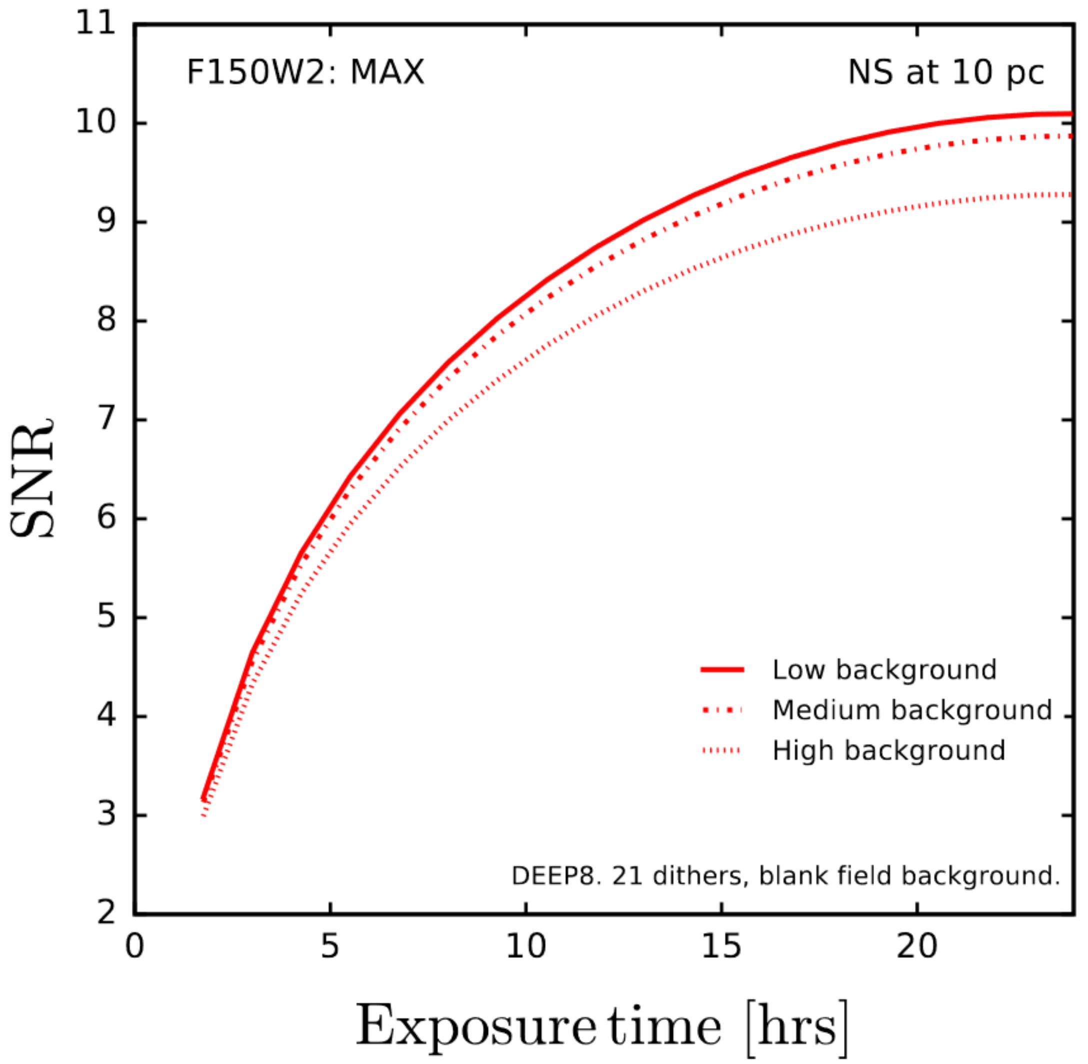
Back-up slides

Background effects

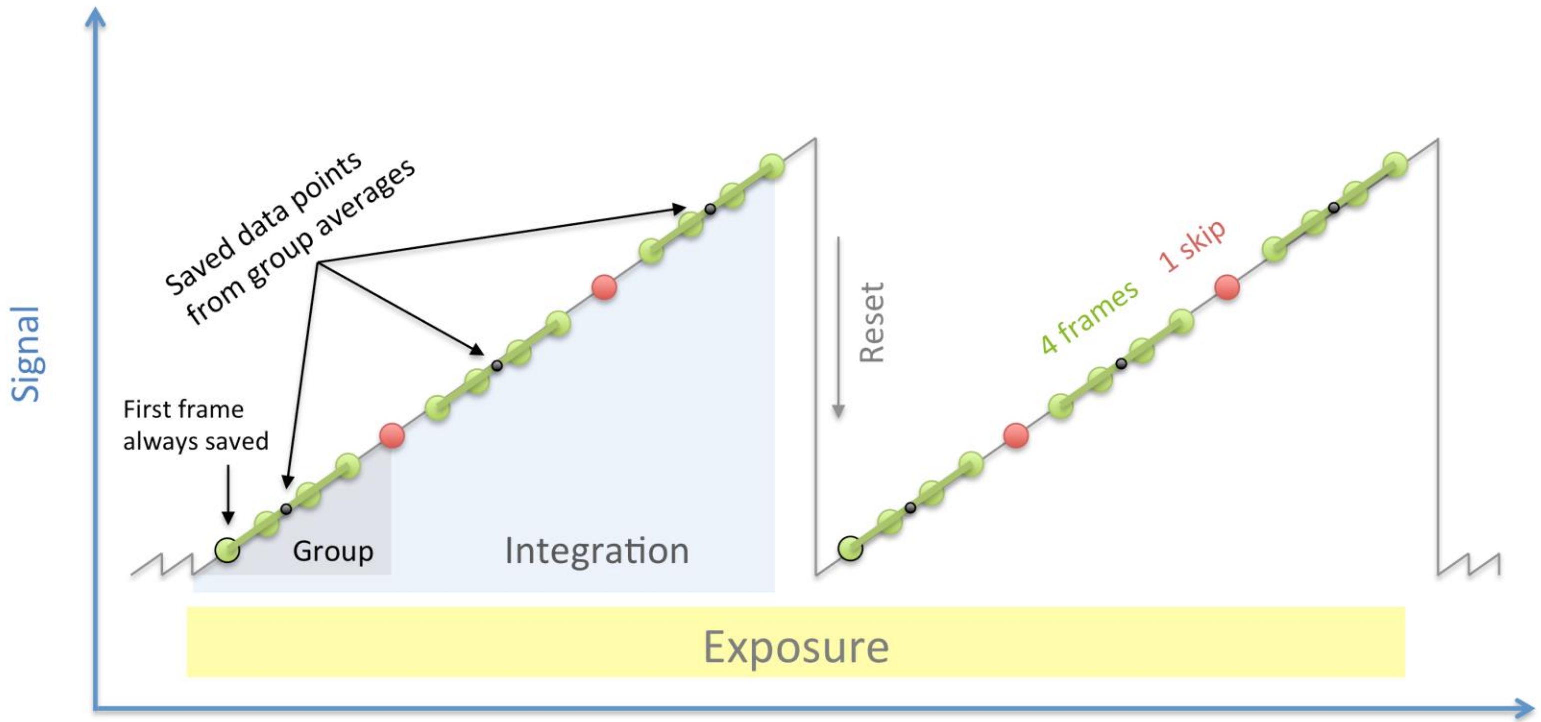


Back-up:

	$\sigma_\star$ [cm^2]	$M_{\rm max}$ [M$_\odot$]/Gyr
Sun	10^{-35}	10^{-21}
Earth	10^{-33}	10^{-26}
Moon	10^{-32}	10^{-27}
White Dwarf	10^{-39}	10^{-19}
Neutron Star	10^{-45}	10^{-15}

Garani et al arXiv: 1906.10145 [hep-ph]

Back-up:



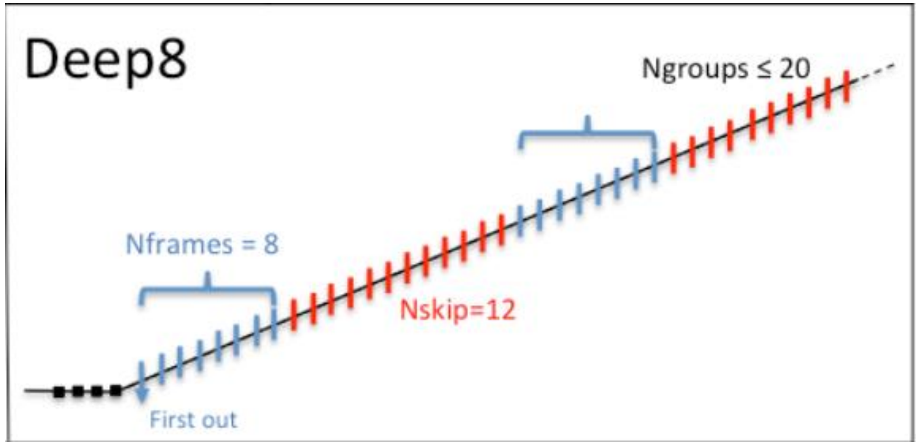
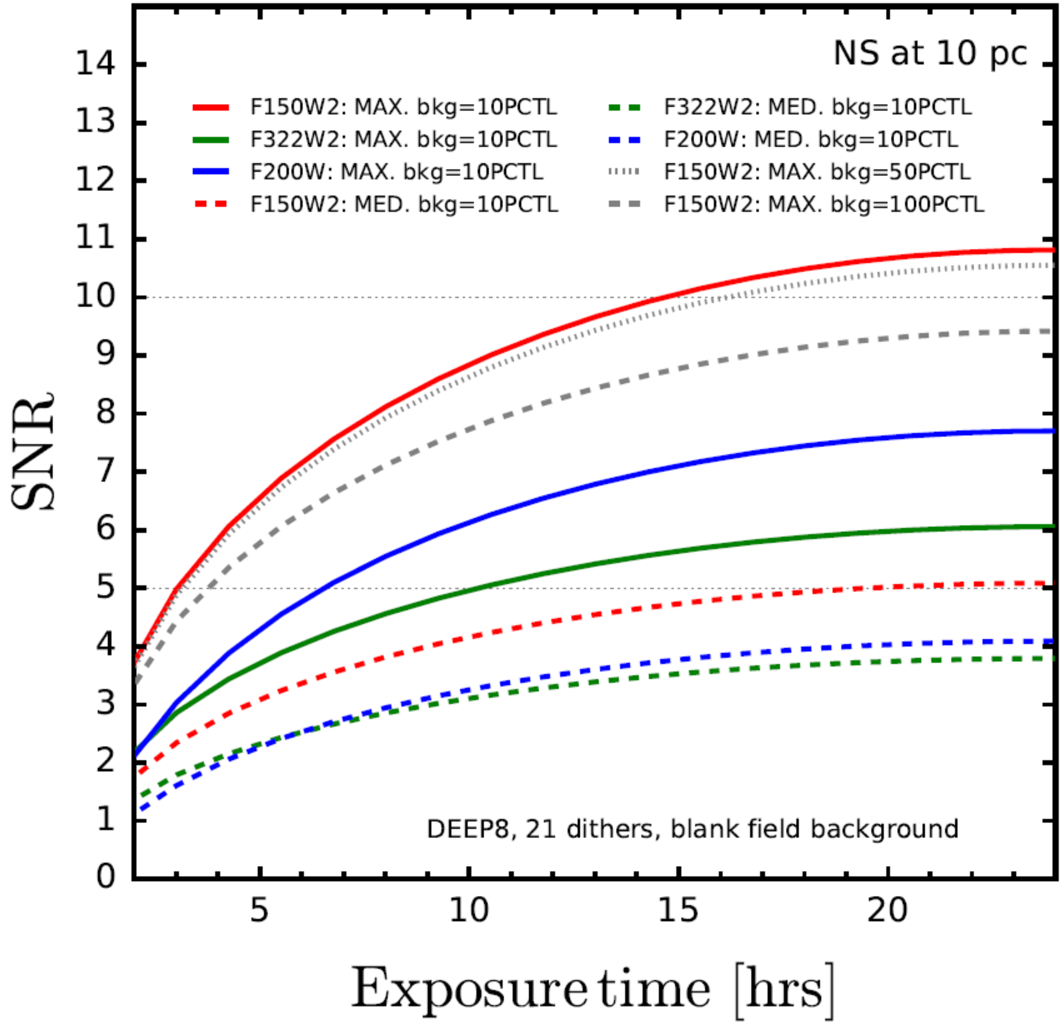


Table 1. Available NIRCam MULTIACCUM readout patterns

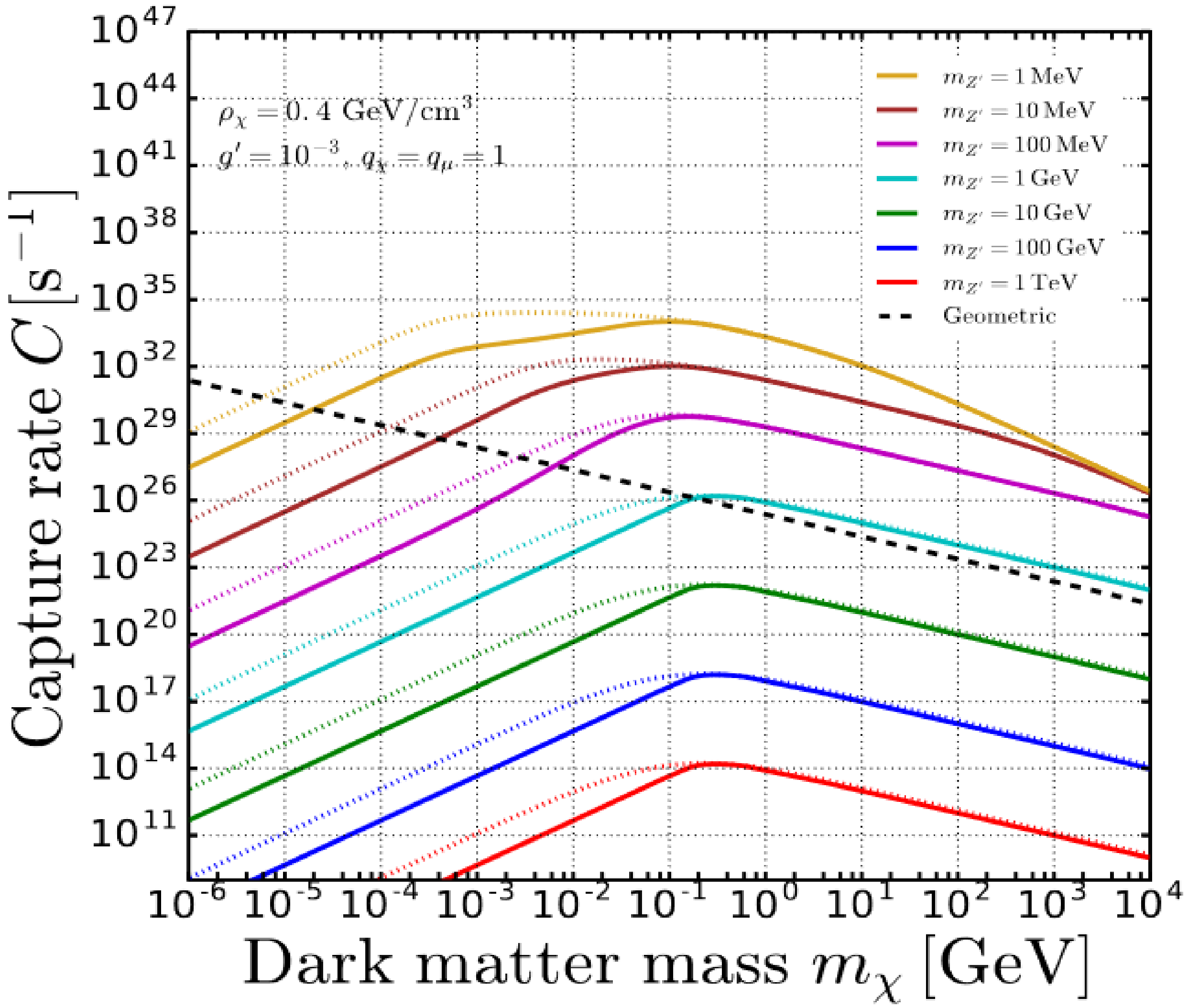
Readout pattern	Samples per group ($N_{samples} = N_{frames} + N_{skip}$)	Frames averaged in each group (N_{frames})
RAPID	1	1
BRIGHT1	2	1
BRIGHT2	2	2
SHALLOW2	5	2
SHALLOW4	5	4
MEDIUM2	10	2
MEDIUM8	10	8
DEEP2	20	2
DEEP8	20	8

JWST documentation

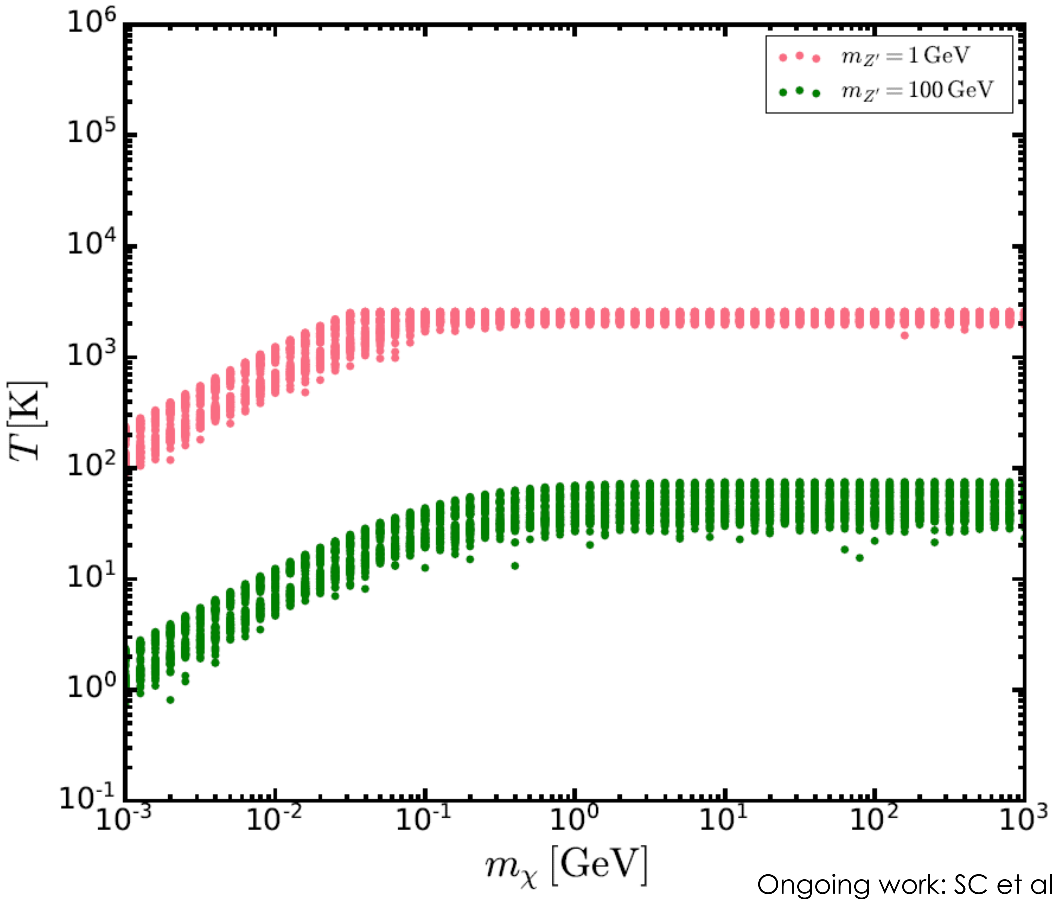
Back-up:


NS at 10 pc
F150W2: MAX. bkg=10PCTL
F322W2: MAX. bkg=10PCTL
F200W: MAX. bkg=10PCTL
F150W2: MED. bkg=10PCTL
F322W2: MED. bkg=10PCTL
F200W: MED. bkg=10PCTL
F150W2: MAX. bkg=50PCTL
F150W2: MAX. bkg=100PCTL
DEEP8, 21 dithers, blank field background
SNR
Exposure time [hrs]
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
5
10
15
20

(I) Dark Matter Probe for $U(1)_{L_\mu - L_\tau}$ model:

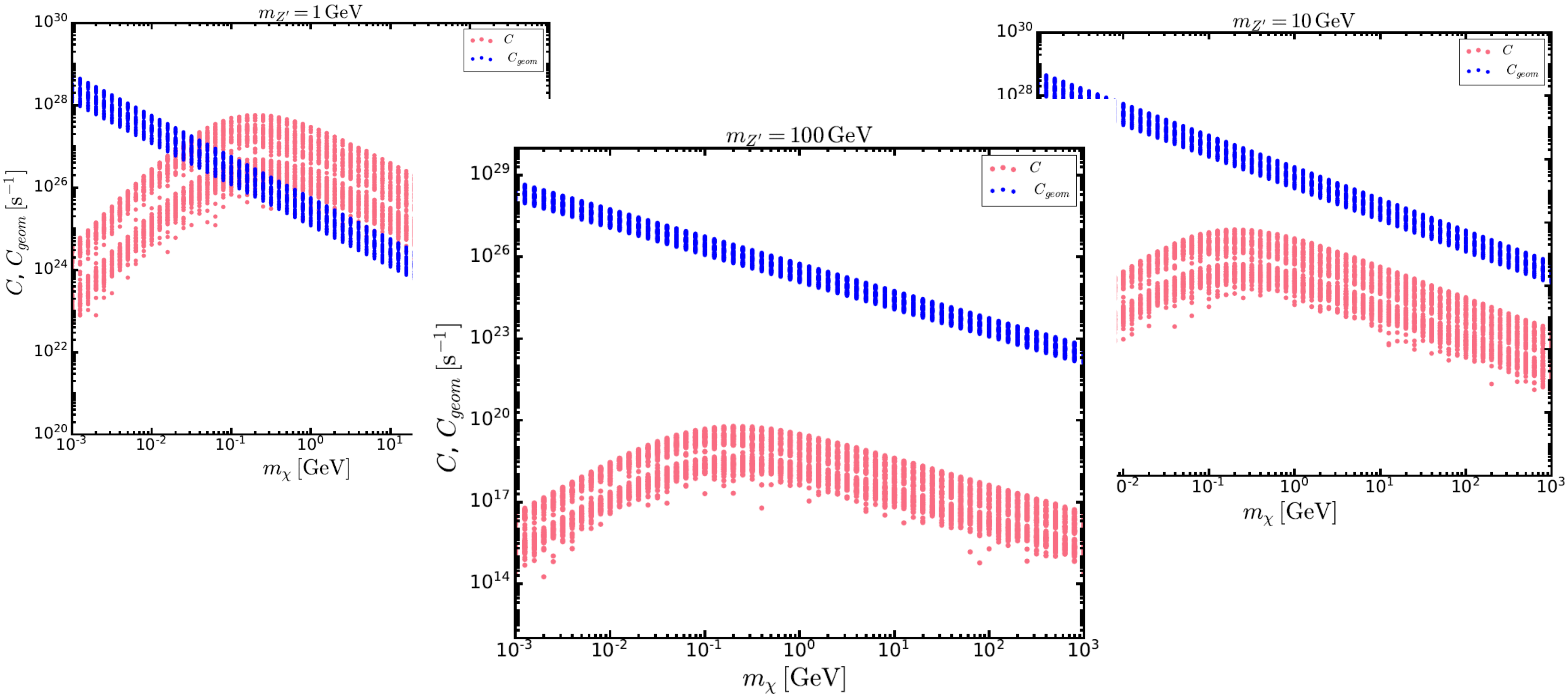


Garani and Heeck 2019



Ongoing work: SC et al

Back-up:



$m_{Z'} = 1\,\mathrm{GeV}$
$m_{Z'} = 100\,\mathrm{GeV}$
$m_{Z'} = 10\,\mathrm{GeV}$
C
C_{geom}
$C,\ C_{geom}\ [\mathrm{s}^{-1}]$
m_χ [GeV]

(II) Maximum temperatures and detectability:

- Observed quantity: Flux from old, isolated neutron star, i.e. its surface temperature, assuming a blackbody spectrum

$$T_{surface}^{observed} \propto \text{astrophysics} \times \text{Nuclear EoS} \times \text{particle physics}$$

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$$T_{kin}^{\infty} \simeq 1787K \left(\frac{\alpha_{kin}}{0.08} \left(\frac{\rho_{DM}}{0.42\ GeV/cm^3} \right) \frac{220\ km/s}{v_*} Erf \left(\frac{270\ km/s}{v_d} \frac{v_*}{220\ km/s} \right) \right)^{1/4}$$

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where $\alpha_{KA} = \frac{\gamma(\gamma^2-1)}{\gamma^4}$

($M = 1.5\ M_{\odot}, R = 10\ km$ for $\alpha_{KA} = 0.33$)

Neutron Star as Dark Matter Probes

An account of uncertainties:

$$T_{kin} = T_{max} min\left[1, \left(\frac{C}{C_{geom}}\right)^{1/4}\right]\left(\frac{\rho_\chi}{0.4\ GeV cm^{-3}}\right)^{1/4}$$

$$T_{max} = \left(\frac{\rho_\chi}{4\sigma_{SB}}\frac{\gamma-1}{1-v_{esc}^2}\langle v_0\rangle\sqrt{\frac{3}{8\pi}}\frac{v_{esc}^2}{v_* v_d}Erf\left(\sqrt{\frac{3}{2}}\frac{v_*}{v_d}\right)\right)^{1/4}$$

$\simeq 1700\ K$ for standard values

The magnitude of heating depends on astrophysical and particle physics parameters through:

$$C = \int_0^{R_*} dr\ 4\pi r^2\ n_\mu(r)\int du_\chi\left(\frac{\rho_\chi}{m_\chi}\right)f_{v_*}(u_\chi)\left(u_\chi^2 + v_{esc}^2(r)\right)\zeta(r)\int_{E_R^{min}}^{E_R^{max}} dE_R\frac{d\sigma}{dE_R}$$

$\zeta(r) = \min(1, \delta p(r)/p_F(r))$ takes Pauli blocking into account where $\delta p(r) \simeq \sqrt{2} m_{red} v_{esc}(r)$ and $p_F(r) = \sqrt{2 m_\mu \mu_\mu(r)}$

$$\frac{d\sigma}{dE_R} = \frac{(g')^4 q_\chi^2 q_\mu^2}{2\pi}\frac{m_\mu}{\left(u_\chi^2 + v_{esc}^2(r)\right)(2m_\mu E_R + m_{Z'}^2)}$$

$$C_{geom} = \pi R_*^2\left(\frac{\rho_\chi}{m_\chi}\right)\langle v\rangle_0\left(1 + \frac{3}{2}\frac{v_{esc}^2(R_*)}{v_d^2}\right)\xi(v_*, v_d)$$

$NS\ velocity$: v_*

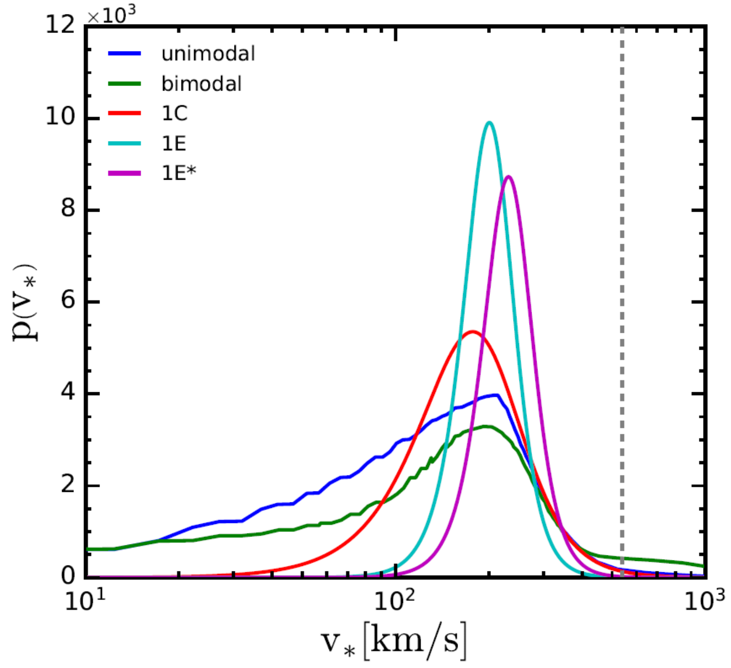
$DM\ density\ and\ dispersion\ velocity$: ρ_{DM}, v_d

$NS\ EoS\ dependent$: $n_\mu(r), \mu_\mu(r), v_{esc}(r)$

Baryakhtar et al arXiv:1704.01577 [hep:ph]

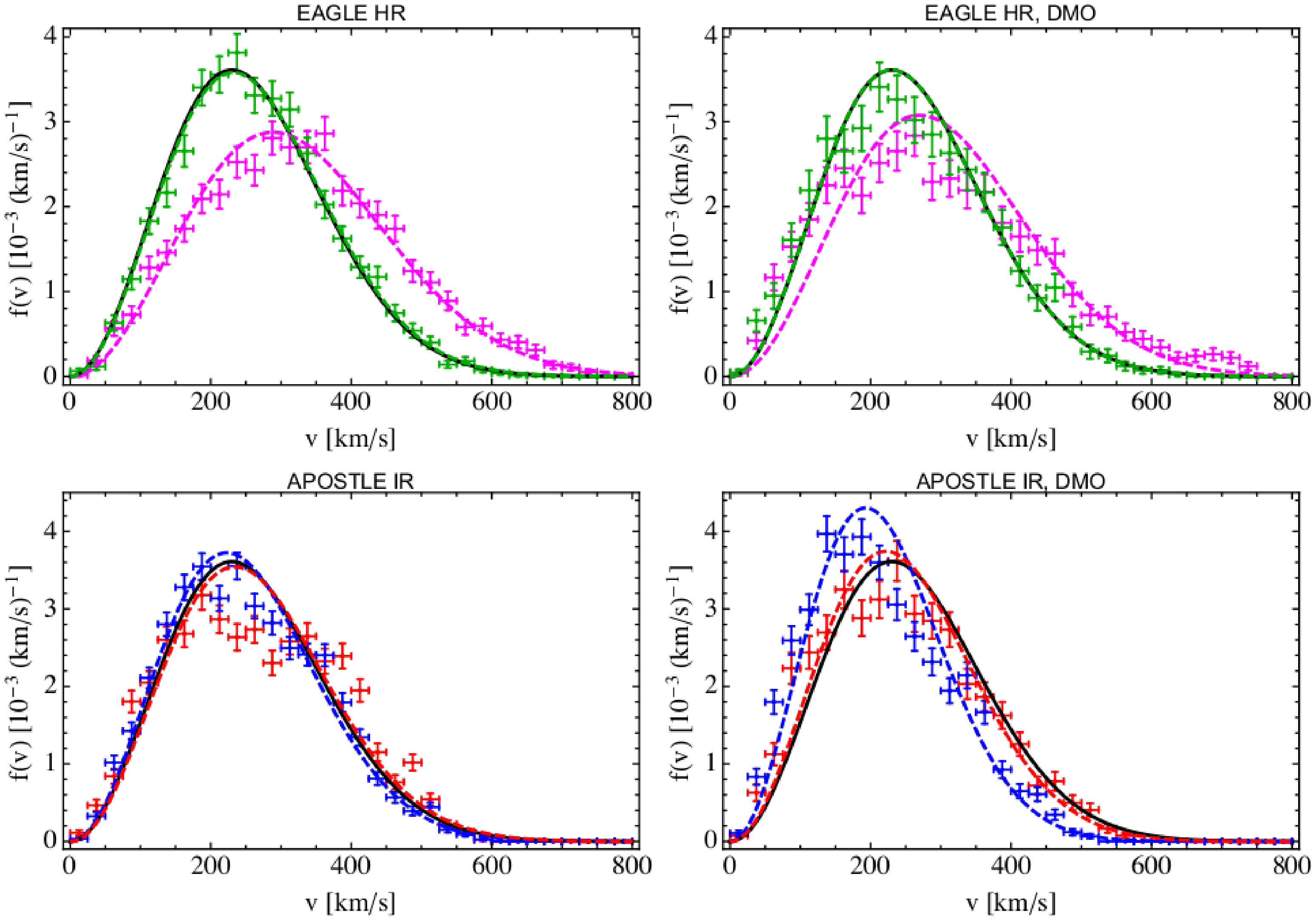
Neutron Star as Dark Matter Probes

NS velocity: v_*



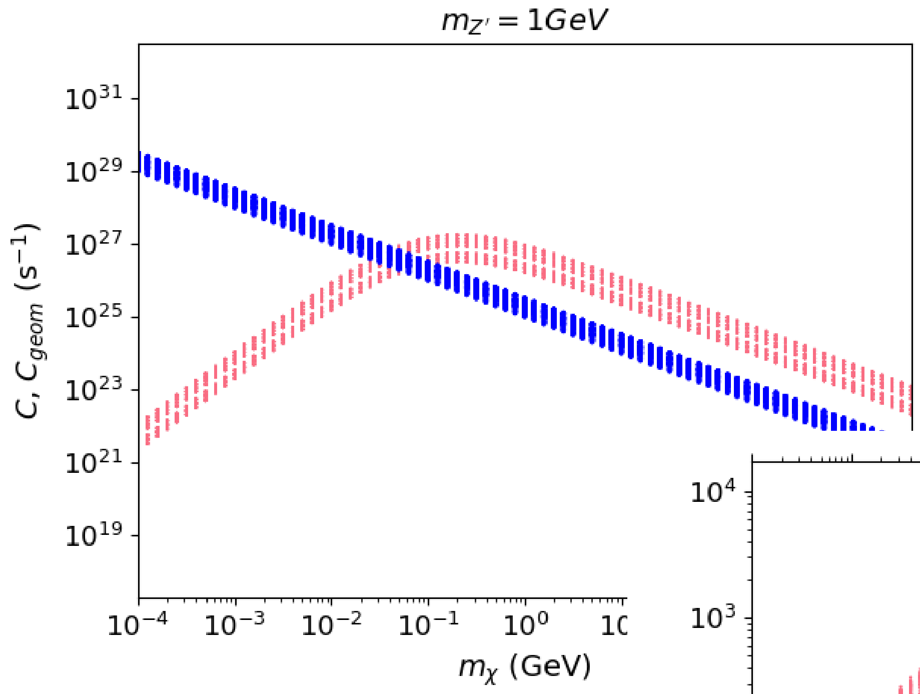
arXiv:0910.3684v1 [astro-ph.GA]

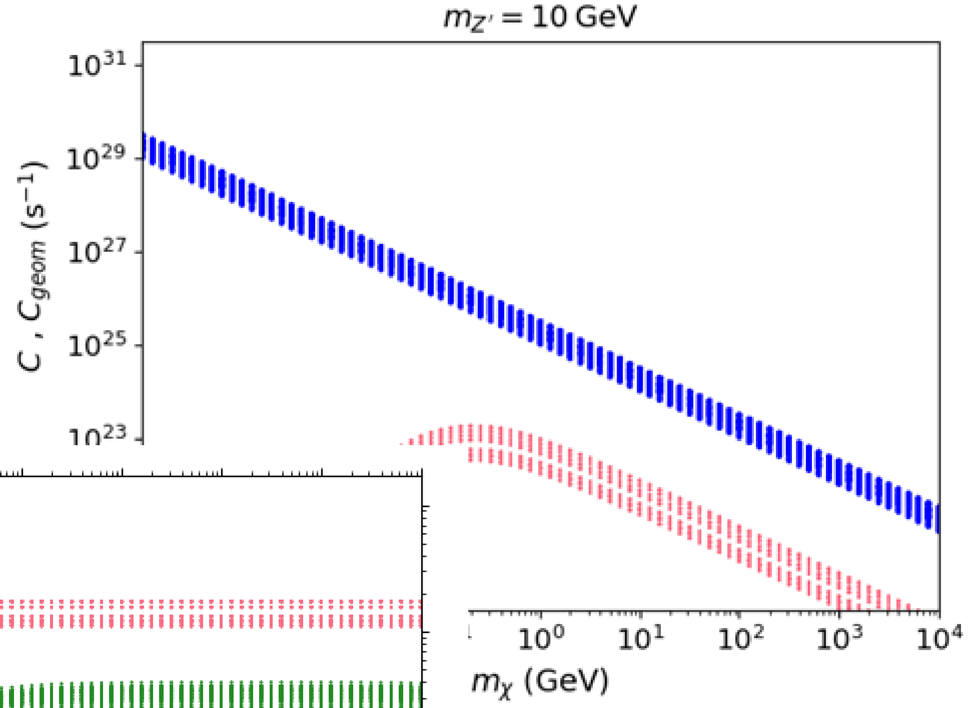
DM density & dispersion velocity: ρ_{DM}, v_d

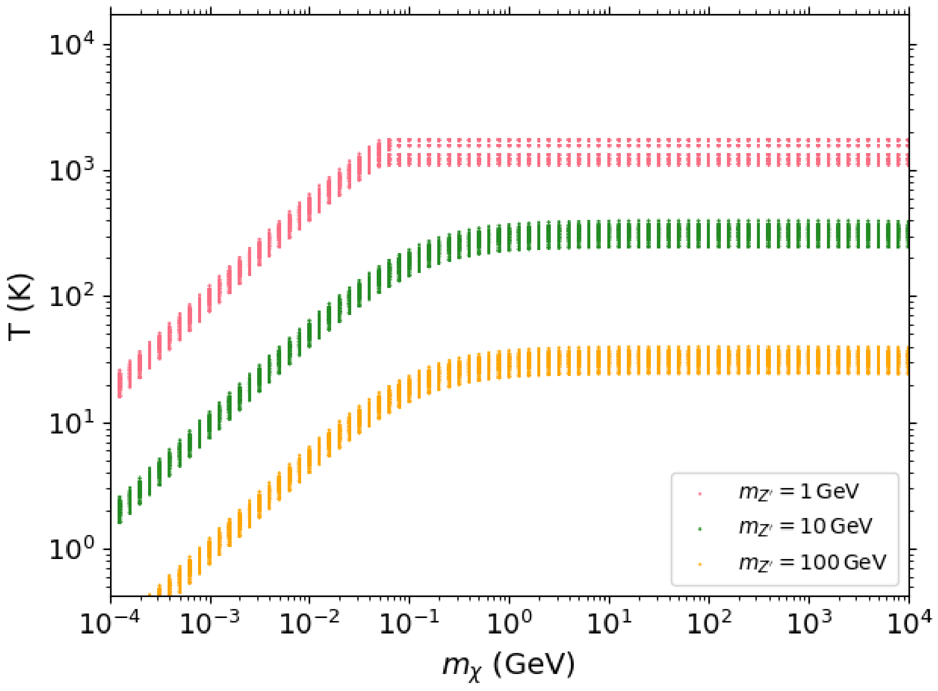


arXiv:1601.04707v2 [astro-ph.CO]

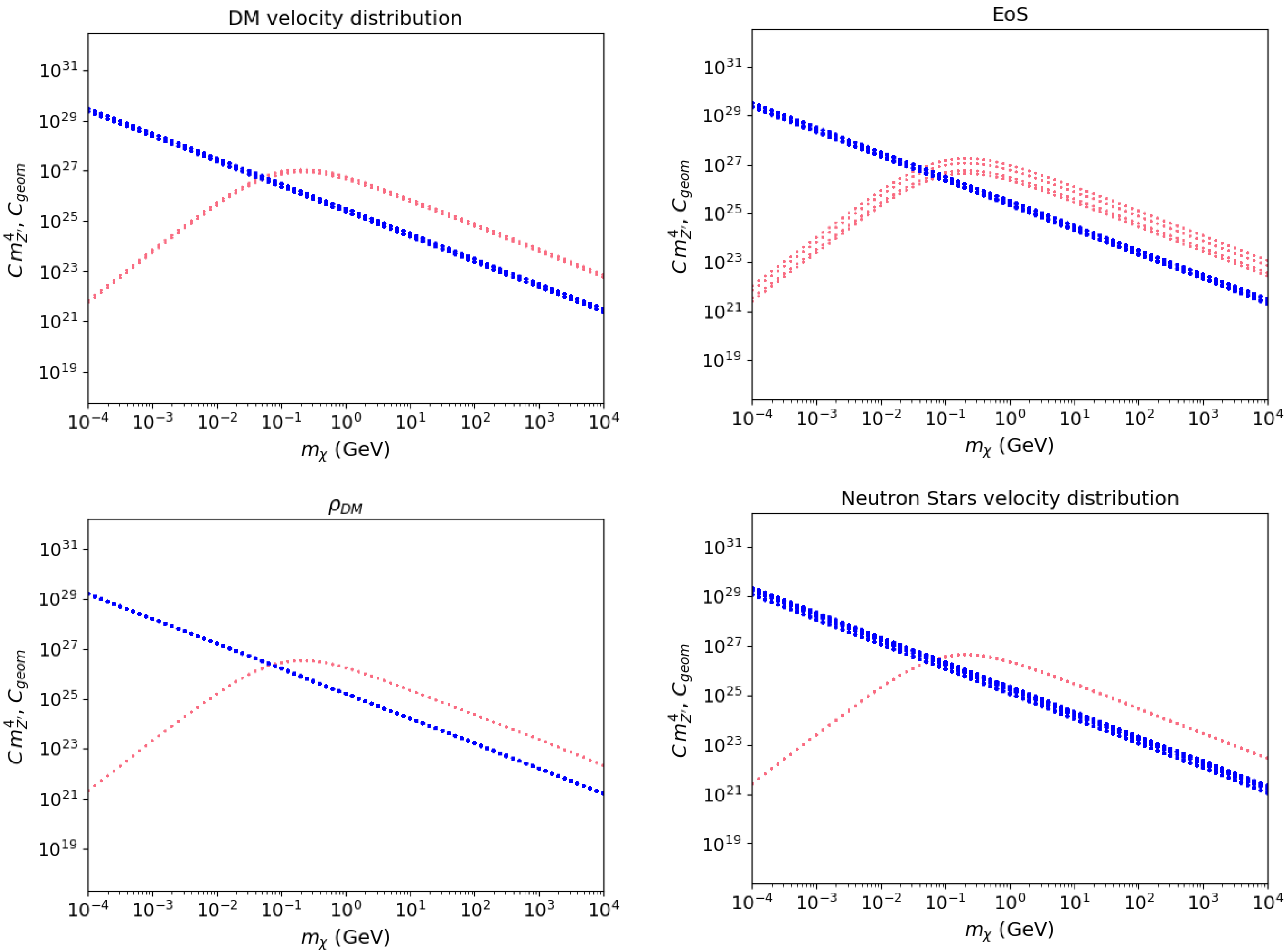
Neutron Star as Dark Matter Probes





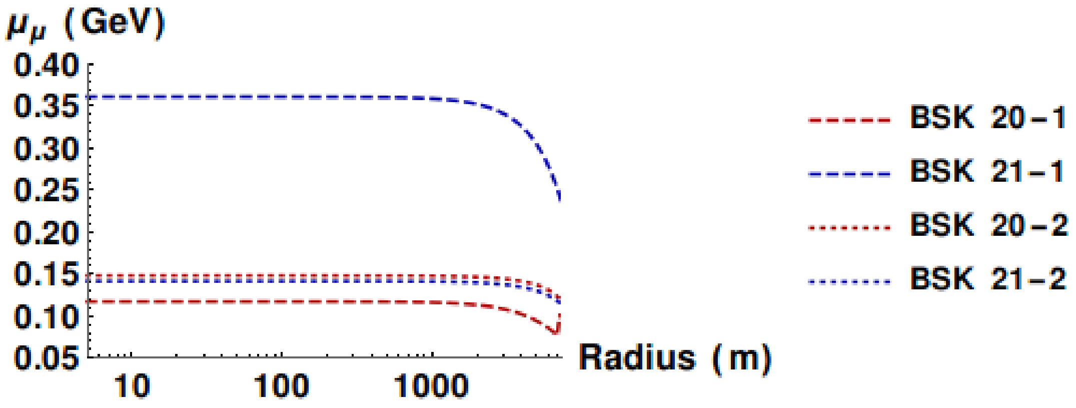


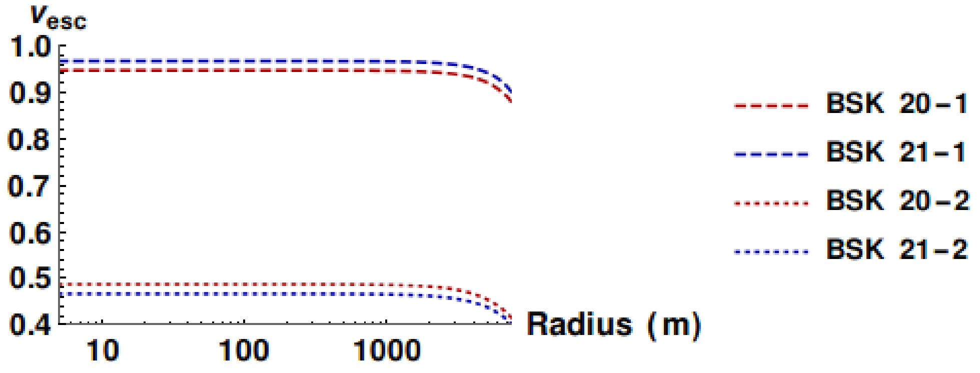
Dispersion velocity v_d (km/s)	**Energy density at solar radius ρ_{DM} (GeV/cm^3)**
235.8	0.41
356.6	0.54

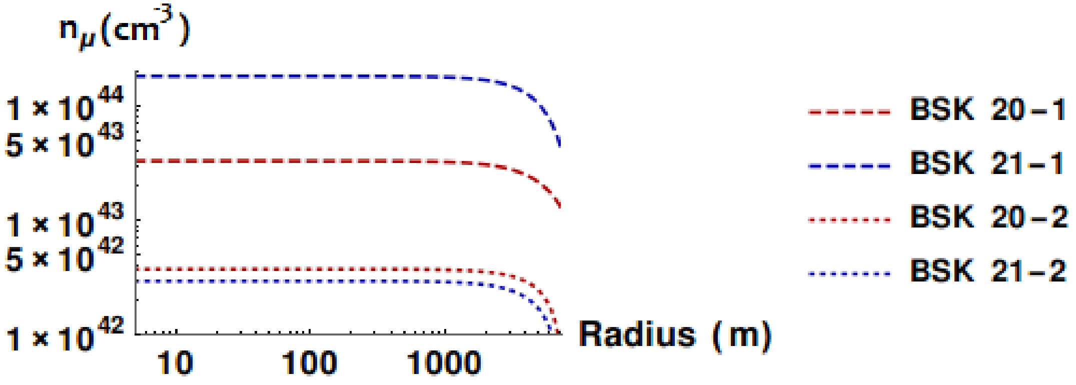


DM velocity distribution
EoS
ρ_DM
Neutron Stars velocity distribution
C m^4_Z', C_geom
m_χ (GeV)
10^31
10^29
10^27
10^25
10^23
10^21
10^19
10^-4
10^-3
10^-2
10^-1
10^0
10^1
10^2
10^3
10^4

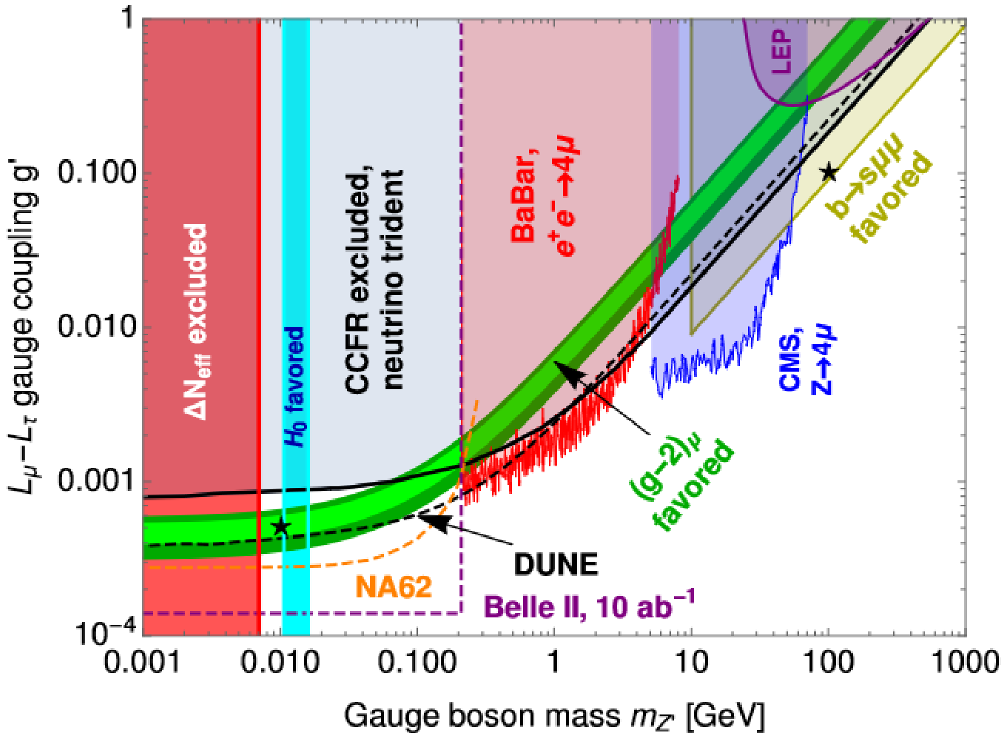
Back-up: EoS NS



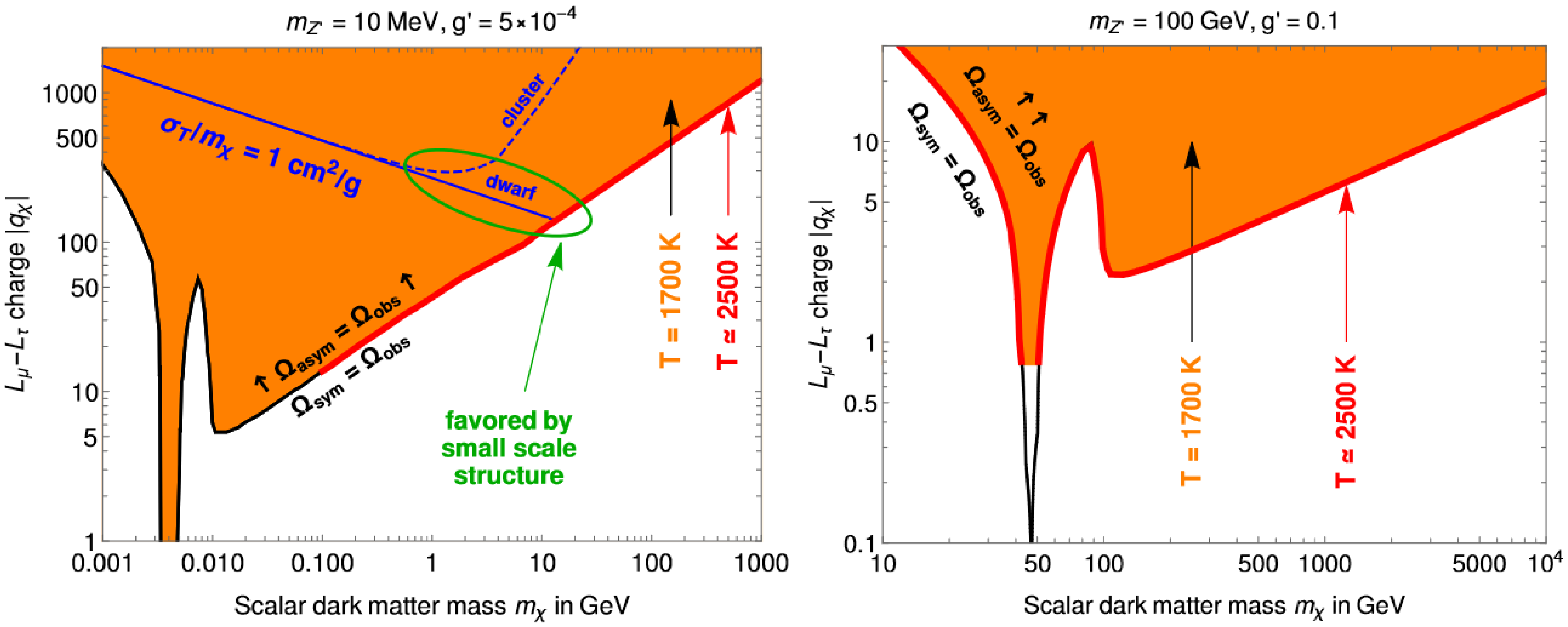




$$C = \int_0^{R_*} dr\, 4\pi r^2\, n_\mu(r) \int du_\chi \left(\frac{\rho_\chi}{m_\chi}\right) f_{v_*}(u_\chi) \left(u_\chi^2 + v_{esc}^2(r)\right) \zeta(r) \int_{E_R^{min}}^{E_R^{max}} dE_R \frac{d\sigma}{dE_R}$$



Garani et al arXiv:1906.10145



Garani et al arXiv:1906.10145