Lepton Flavored Dark Matter: Two Scenarios

Shiuli Chatterjee
CHEP, Indian Institute of Science

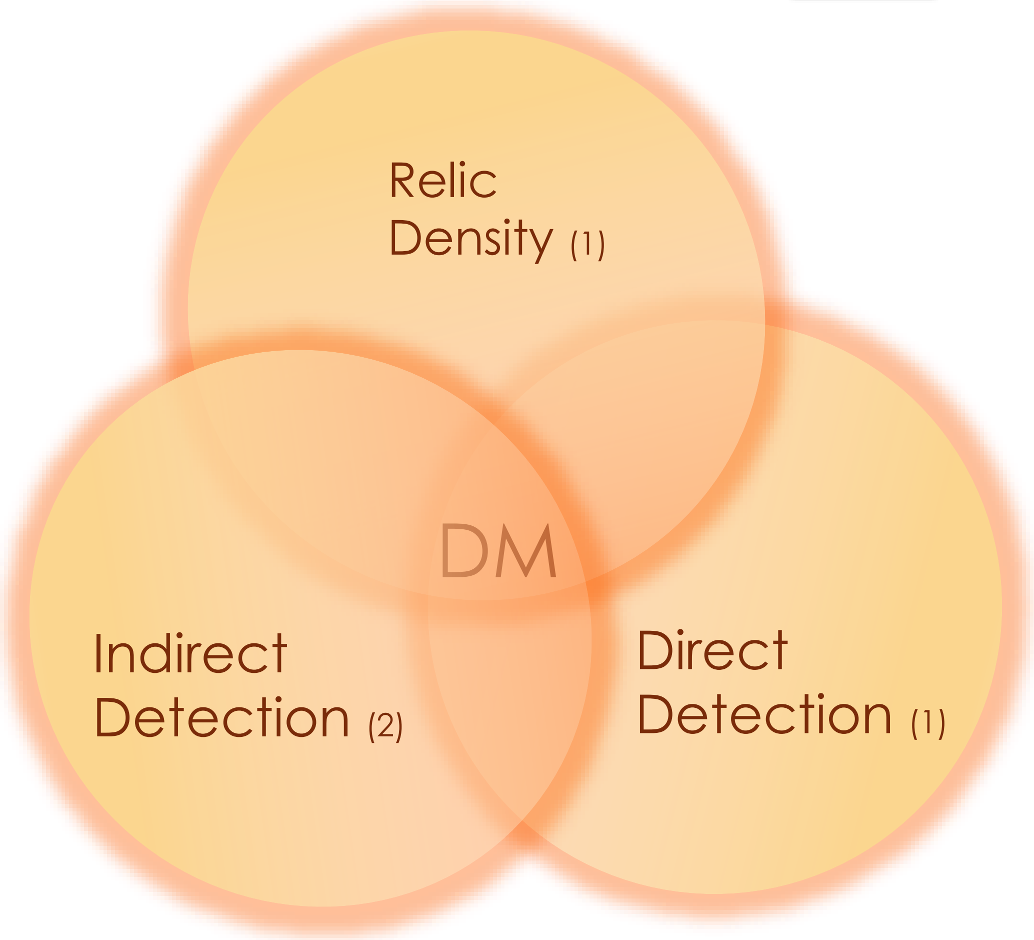
based on

- "Freezing-in with Lepton Flavored Fermions"
  Giancarlo D'Ambrosio, SC, Ranjan Laha and Sudhir K. Vempati (**SciPost Phys. 11, 006 (2021)**)
- "Neutron Stars as Reliable Probes of Particle Dark Matter"
  SC, Raghuveer Garani, Rajeev K. Jain, Brijesh Kanodia, Sudhir K. Vempati (in preparation)

State of the Universe seminar, TIFR
December 14th, 2021

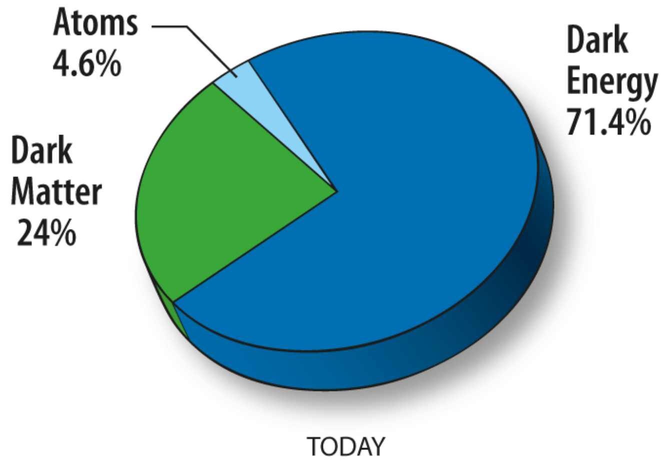
Overview:

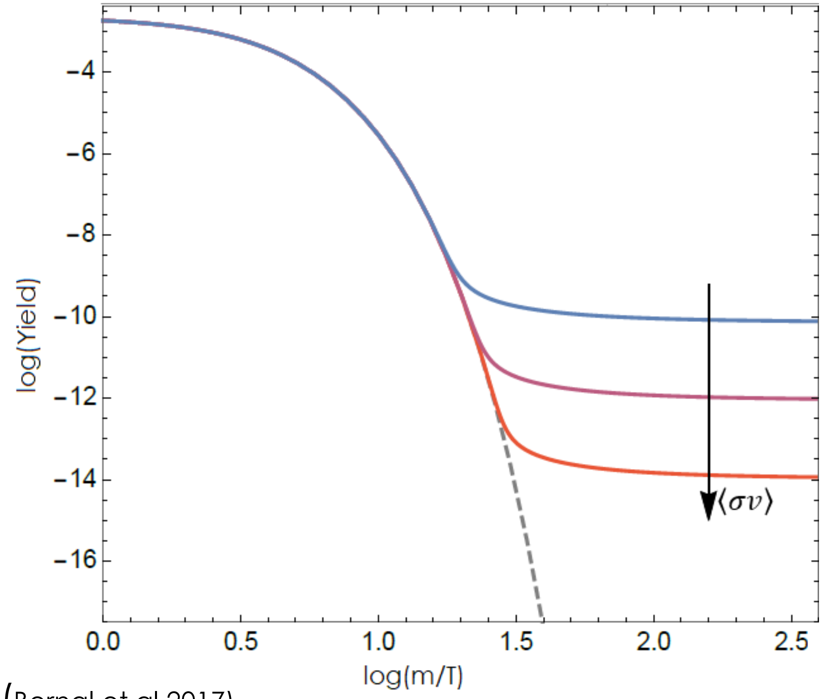
- A freeze-in model for lepton flavored dark matter
  - Minimal Flavor Violation in lepton sector
  - Stability
  - Detection
- Neutron Star as Dark Matter Probes
  - Kinetic heating
  - Uncertainties
  - Results
- Summary



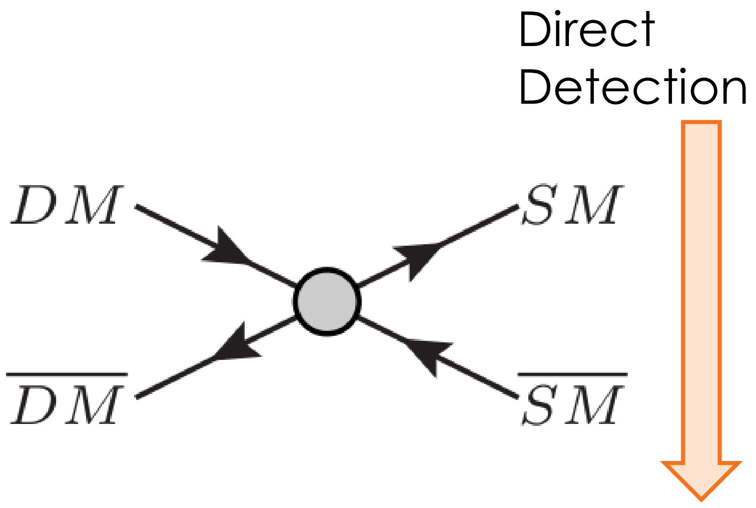
Dark Matter & Production

- Dark matter constitutes ~1/4th of total energy density
- DM particle must
  - Be stable on cosmological scales
  - Reproduce relic density: $\Omega h^2 = 0.12$
- Production mechanism: Freeze-out





(Bernal et al 2017)

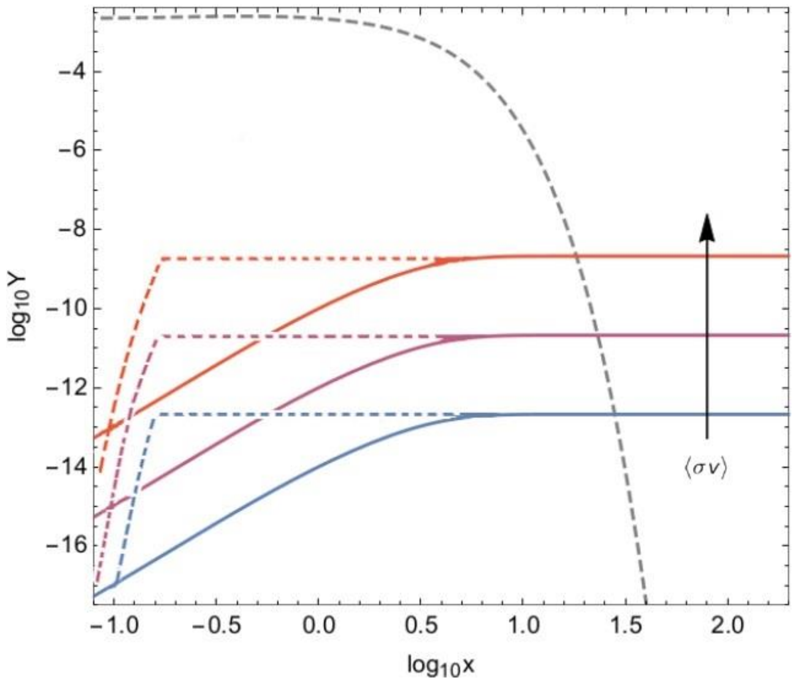


WIMP "miracle":

A Weakly Interacting Massive Particle with
$\alpha \sim 0.01$
$m_\chi \sim 100\ GeV$
$\sigma \sim \frac{\alpha^2}{m_\chi^2}$
reproduces the observed relic density

Freeze-in & Lepton Flavored Dark Matter

- Freeze-in mechanism
  - Non-thermalized: **small couplings**
  - $SM(SM) \longrightarrow DM, DM$
  - $\Omega h^2 \propto \langle \sigma v \rangle$



  - Small couplings make **detection** difficult

Electron Yukawa

is a *small* parameter in the SM

Lepton Flavored Dark Matter

Minimal model with fermionic dark matter under

Minimal Flavor Violation

leads to photon mediated direct detection process

Light mediator

Minimal Flavor Violation: Quark sector

- Consider the quark sector of the Standard Model

$$\mathcal{L}_{SM} \supset i\bar{Q}\not{D}Q + i\bar{u}_R\not{D}u_R + i\bar{d}_R\not{D}d_R - \bar{Q}Y_u u_R\tilde{H} - \bar{Q}Y_d d_R H$$

$$Q \sim \begin{pmatrix} (u,d) \\ (c,s) \\ (t,b) \end{pmatrix}_L, \qquad u_R \sim \begin{pmatrix} u_R \\ c_R \\ t_R \end{pmatrix}, \qquad d_R \sim \begin{pmatrix} d_R \\ s_R \\ b_R \end{pmatrix}$$

- All but the Yukawa term are symmetric under a large Global symmetry

$$Q \to U_Q Q\,, \qquad u_R \to U_{u_R} u_R, \qquad d_R \to U_{d_R} d_R$$

$$G_{LF} \sim SU(3)_Q \otimes SU(3)_{u_R} \otimes SU(3)_{d_R}$$

$$Q \sim (3,1,1),\ u_R \sim (1,3,1), d_R \sim (1,1,3)$$

- MFV hypothesis demands that the SM Yukawa matrices be the only sources of flavor breaking. Treats Yukawas as spurions transforming non-trivially under flavor:

$$\bar{Q}Y_u u_R\tilde{H} \Rightarrow Y_u \sim (3, \bar{3}, 1),\ \bar{Q}Y_d d_R H \Rightarrow Y_d \sim (3,1,\bar{3})$$

- Models are constructed by adding flavored particles and constructing operators invariant under G_{LF}

Minimal Flavor Violation: Stability Analysis

Denote the irreducible representation of a SM singlet DM χ under G_{LF}

$$\chi \sim \left(n_Q, m_Q\right)_Q \times (n_u, m_u)_{u_R} \times (n_d, m_d)_{d_R}$$

And write the most general decay operator

$$\mathcal{O}_{decay} = \chi_{L,R}\, \underbrace{Q \ldots}_{A}\, \underbrace{\bar{Q} \ldots}_{B}\, \underbrace{u_R \ldots}_{C}\, \underbrace{\bar{u}_R \ldots}_{D}\, \underbrace{d_R \ldots}_{E}\, \underbrace{\bar{d}_R \ldots}_{F}\, \underbrace{Y_u \ldots}_{G}\, \underbrace{Y_u^\dagger \ldots}_{H}\, \underbrace{Y_d \ldots}_{I}\, \underbrace{Y_d^\dagger \ldots}_{J}\, \mathcal{O}_{weak}$$

Condition for $\mathcal{O}_{decay}$ to be allowed:

MFV:

$$SU(3)_Q: \left(A - B + G - H + I - J + n_Q - m_Q\right) mod\ 3 = 0$$

$$SU(3)_d: (C - D - G + H + n_u - m_u)\ mod\ 3 = 0$$

$$SU(3)_u: (E - F - I + J + n_d - m_d)\ mod\ 3 = 0$$

SM color:

$$SU(3)_c: (A - B + C - D + E - F)\ mod\ 3 = 0$$

$Q \sim (3,1,1)$,
$u_R \sim (1,3,1)$,
$d_R \sim (1,1,3)$,
$Y_u \sim (3, \bar{3}, 1)$,
$Y_d \sim (3,1,\bar{3})$

$3 \otimes \bar{3} \Rightarrow 1$
$3 \otimes 3 \otimes 3 \Rightarrow 1$
$\bar{3} \otimes \bar{3} \otimes \bar{3} \Rightarrow 1$
$(n_3 - n_{\bar{3}})\ mod\ 3 = 0$

Stability $\Longrightarrow \left(n_Q - m_Q + n_u - m_u + n_d - m_d\right) mod\ 3 \neq 0$

Allowed $\Longrightarrow \left(n_Q - m_Q + n_u - m_u + n_d - m_d\right) mod\ 3 = 0$

Batell et al (2011)

Minimal Flavor Violation: Lepton Sector

- Consider the lepton sector of the Standard Model

$$\mathcal{L}_{SM} \supset i\bar{L}\not{D}L + i\bar{e}_R\not{D}e_R - \bar{L}Y_l e_R H$$

$$L \sim \begin{pmatrix} l_e \\ l_\mu \\ l_\tau \end{pmatrix}, \qquad e_R \sim \begin{pmatrix} e_R \\ \mu_R \\ \tau_R \end{pmatrix}$$

- All but the Yukawa term are symmetric under a large Global symmetry

$$G_{LF} \sim SU(3)_L \otimes SU(3)_{e_R}$$

$$L \sim (3,1),\ e_R \sim (1,3)$$

- MFV hypothesis demands that the SM Yukawa matrices be the only sources of flavor breaking. Treats Yukawas as spurions transforming non-trivially under flavor:

$$\bar{L}Y_l e_R H \ \Rightarrow Y_l \sim (3, \bar{3})$$

- Models are constructed by adding flavored particles and constructing operators invariant under G_{LF}

Minimal Flavor Violation: Stability Analysis

Denote the irreducible representation of a SM singlet DM χ under G_{LF}

$$\chi \sim (n_L, m_L)_L \times (n_e, m_e)_{e_R}$$

And write the most general decay operator

$$\mathcal{O}_{decay} = \chi_{L,R} \underbrace{L \ldots}_{A} \underbrace{\bar{L} \ldots}_{B} \underbrace{e_R \ldots}_{C} \underbrace{\bar{e}_R \ldots}_{D} \underbrace{Y_l \ldots}_{E} \underbrace{Y_l^\dagger \ldots}_{F} \mathcal{O}_{weak}$$

Condition for $\mathcal{O}_{decay}$ to be allowed:

$$SU(3)_L: (A - B + E - F + n_L - m_L) \bmod 3 = 0$$
$$SU(3)_R: (C - D - E + F + n_E - m_E) \bmod 3 = 0$$
$$\Rightarrow (A - B + C - D + n_L - m_L + n_E - m_E) \bmod 3 = 0$$

$$3 \otimes \bar{3} \Rightarrow 1$$
$$3 \otimes 3 \otimes 3 \Rightarrow 1$$
$$\bar{3} \otimes \bar{3} \otimes \bar{3} \Rightarrow 1$$
$$(n_3 - n_{\bar{3}}) \bmod 3 = 0$$

Assume χ has lepton number q_{LN} and demand for lepton number conservation

$$(A - B + C - D + q_{LN}) = 0$$

Stability $\Rightarrow (n_L - m_L + n_E - m_E - q_{LN}) \bmod 3 \neq 0$

Batell et al (2011)
Chen et al (2016)

Lepton flavored DM under MFV

$$(n_L - m_L + n_E - m_E - q_{LN})\ mod\ 3 \neq 0$$

MFV + Lepton number conservation ⇒ DM representation automatically stable ***up to all orders***

χ_L	χ_R	q_{LN}	***MFV***	***LNC***	***Stable***	***Operators***
(3,1)	(1,3)	−1	✔	✔	✔	$(\bar{\chi}_L \sigma_{\mu\nu} Y_l \chi_R) B^{\mu\nu}, (\bar{\chi}_L \sigma_{\mu\nu} Y_l \gamma_5 \chi_R) B^{\mu\nu}, (\bar{\chi}_L Y_l \chi_R) H^\dagger H$
(3,1)	(3,1)	−1	✔	✔	✔	$(\bar{\chi}_L \sigma_{\mu\nu} \chi_R) B^{\mu\nu}, (\bar{\chi}_L \sigma_{\mu\nu} \gamma_5 \chi_R) B^{\mu\nu}, (\bar{\chi}_L \chi_R) H^\dagger H$
(8,1)	(1,8)	−1,1	✔	✔	✔	$(\bar{\chi}_L \sigma_{\mu\nu} Y_l Y_l^\dagger \chi_R) B^{\mu\nu}, (\bar{\chi}_L \sigma_{\mu\nu} Y_l Y_l^\dagger \gamma_5 \chi_R) B^{\mu\nu}, (\bar{\chi}_L Y_l Y_l^\dagger \chi_R) H^\dagger H$

Introduce a chiral, fermionic DM transforming nontrivially under flavor group:

$$\chi_L \sim (3,1)_{G_{LF}} \sim (\chi_1, \chi_2, \chi_3)_L, \qquad \chi_R \sim (1,3)_{G_{LF}} \sim (\chi_1, \chi_2, \chi_3)_R, \text{ where } \quad G_{LF} \sim SU(3)_L \otimes SU(3)_{e_R}$$

$$\mathcal{L}_{int} \supset \underbrace{\frac{1}{2\Lambda_{MFV}} (\bar{\chi}_L \sigma_{\mu\nu} Y_l \chi_R) B^{\mu\nu}}_{\text{Magnetic dipole moment } (MDM)} + \underbrace{\frac{i}{2\Lambda_{MFV}} (\bar{\chi}_L \sigma_{\mu\nu} \gamma_5 Y_l \chi_R) B^{\mu\nu}}_{\text{Electric dipole moment } (EDM)} + \underbrace{\frac{1}{2\Lambda_{MFV}} (\bar{\chi}_L Y_l \chi_R) H^\dagger H}_{\text{H-mediated}}$$

and the masses of the DM partners get related by:

$$m_\chi (\bar{\chi}_L Y_l \chi_R) \Longrightarrow m_{\chi_1} : m_{\chi_2} : m_{\chi_3} = m_e : m_\mu : m_\tau$$

Lepton Flavored DM: Freeze-in

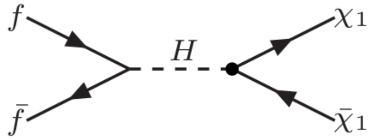
$\chi_L \sim (3,1)_{G_{LF}} \sim (\chi_1, \chi_2, \chi_3)_L, \quad \chi_R \sim (1,3)_{G_{LF}} \sim (\chi_1, \chi_2, \chi_3)_R,$ where $G_{LF} \sim SU(3)_L \otimes SU(3)_{e_R}$

$$\mathcal{L}_{int} \supset \underbrace{\frac{1}{2\Lambda_{MFV}}(\bar{\chi}_L \sigma_{\mu\nu} Y_l \chi_R) B^{\mu\nu}}_{\text{Magnetic dipole moment }(MDM)} + \underbrace{\frac{i}{2\Lambda_{MFV}}(\bar{\chi}_L \sigma_{\mu\nu} \gamma_5 Y_l \chi_R) B^{\mu\nu}}_{\text{Electric dipole moment }(EDM)} + \underbrace{\frac{1}{2\Lambda_{MFV}}(\bar{\chi}_L Y_l \chi_R) H^\dagger H}_{\text{H-mediated}}$$

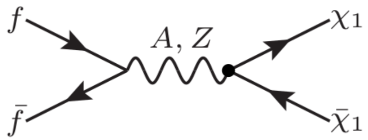
and the masses of the DM partners get related by:

$$m_\chi(\bar{\chi}_L Y_l \chi_R) \Longrightarrow m_{\chi_1} : m_{\chi_2} : m_{\chi_3} = m_e : m_\mu : m_\tau$$

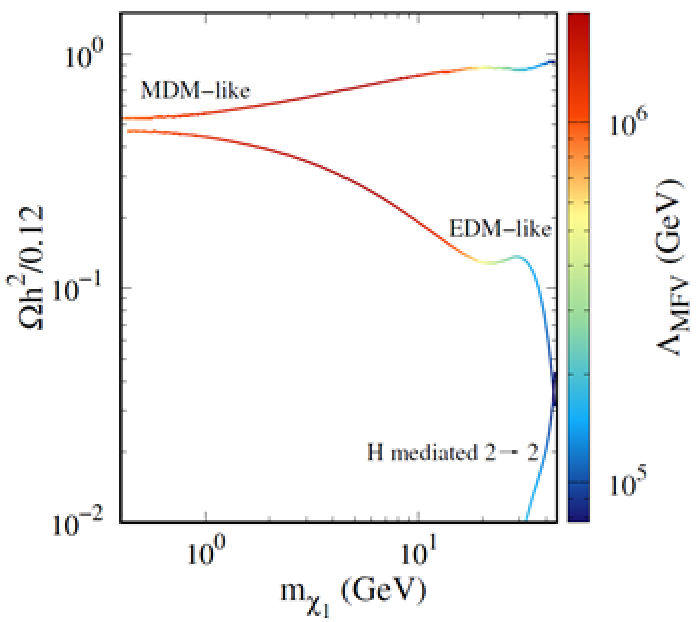
- Higgs mediated term ⇒ IR freeze-in



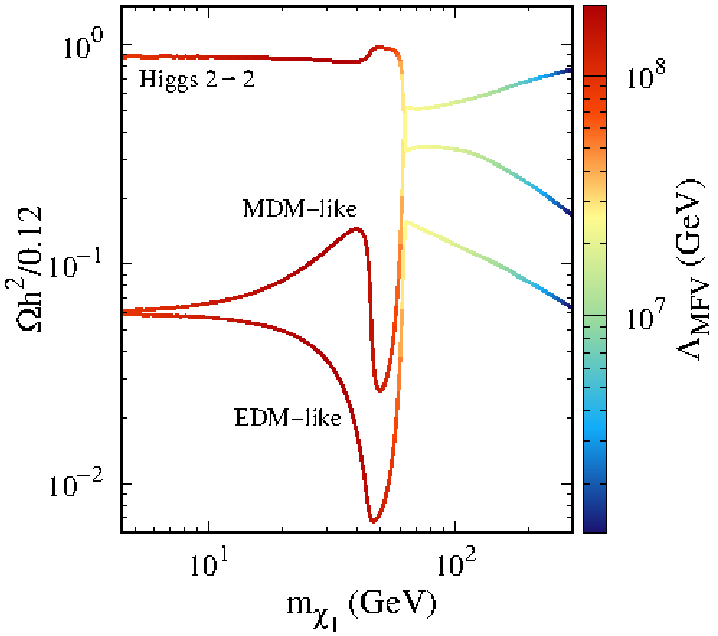
- Dipole moment like terms ⇒ UV freeze-in (sensitive to reheating temperature)



$T_{RH} = 5\ GeV$:



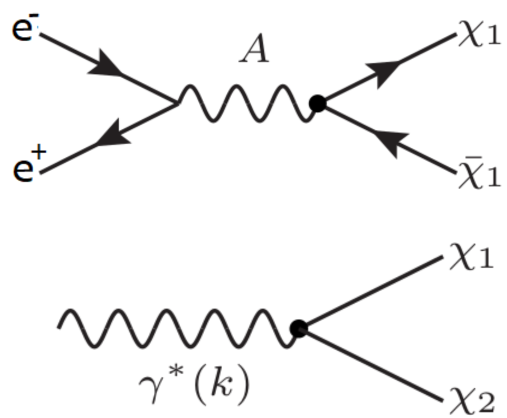
$T_{RH} = 50\ GeV$:

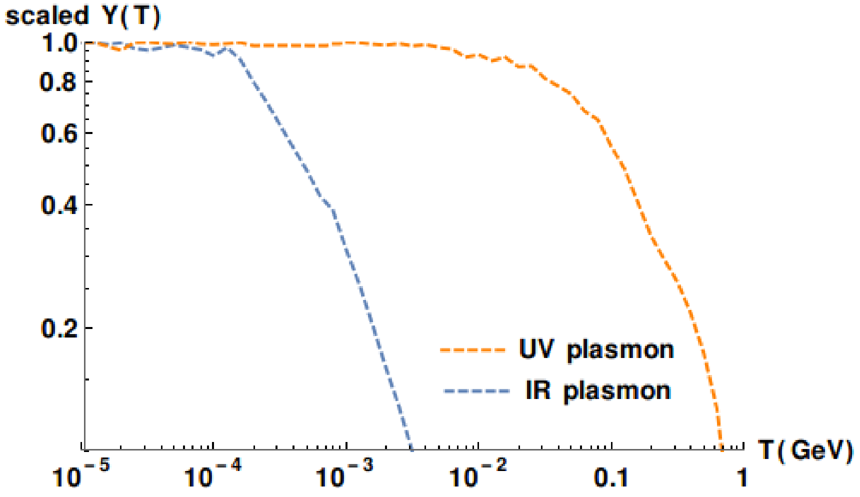


Plasmons: A brief digression

- An additional production channel was identified for freeze-in mechanism (Dvorkin et al 2019).
- Decay of photons that acquire an in-medium plasma mass. This was already known in the SN cooling process.
- These plasmon decays were shown to be a dominant channel for DM production for sub-MeV DM masses (lighter than the electron).
- Thus including this channel was shown to lead to significant reduction in the predicted signal strength for DM searches.
- In UV freeze-in the plasmon production is also maximum at largest temperature and there is no competition between the $2 \longrightarrow 2$ process and the decay process

$$\underbrace{\frac{1}{2\Lambda_{MFV}}(\bar{\chi}_L \sigma_{\mu\nu} Y_l \chi_R) B^{\mu\nu}}_{\text{Magnetic dipole moment }(MDM)}, \underbrace{\frac{i}{2\Lambda_{MFV}}(\bar{\chi}_L \sigma_{\mu\nu} \gamma_5 Y_l \chi_R) B^{\mu\nu}}_{\text{Electric dipole moment }(EDM)}$$





(Chang et al 2019)

Lepton Flavored DM: Direct Detection

$\chi_L \sim (3,1)_{G_{LF}} \sim (\chi_1, \chi_2, \chi_3)_L$, $\chi_R \sim (1,3)_{G_{LF}} \sim (\chi_1, \chi_2, \chi_3)_R$, where $G_{LF} \sim SU(3)_L \otimes SU(3)_{e_R}$

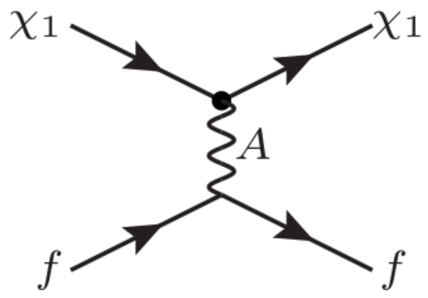
$$\mathcal{L}_{int} \supset \underbrace{\frac{1}{2\Lambda_{MFV}}(\bar{\chi}_L \sigma_{\mu\nu} Y_l \chi_R) B^{\mu\nu}}_{\text{Magnetic dipole moment }(MDM)} + \underbrace{\frac{i}{2\Lambda_{MFV}}(\bar{\chi}_L \sigma_{\mu\nu} \gamma_5 Y_l \chi_R) B^{\mu\nu}}_{\text{Electric dipole moment }(EDM)} + \underbrace{\frac{1}{2\Lambda_{MFV}}(\bar{\chi}_L Y_l \chi_R) H^\dagger H}_{\text{H-mediated}}$$

and the masses of the DM partners get related by:

$$m_\chi(\bar{\chi}_L Y_l \chi_R) \Longrightarrow m_{\chi_1} : m_{\chi_2} : m_{\chi_3} = m_e : m_\mu : m_\tau$$

For direct detection:

$$\frac{dR}{dE_R} = \frac{1}{m_N} \frac{\rho_{DM}}{m_{\chi_1}} \int_{v_{min}(E_R)}^{v_{esc}} dv\, f_\odot(v) \frac{d\sigma_N}{dE_R}(v, E_R)\, v$$

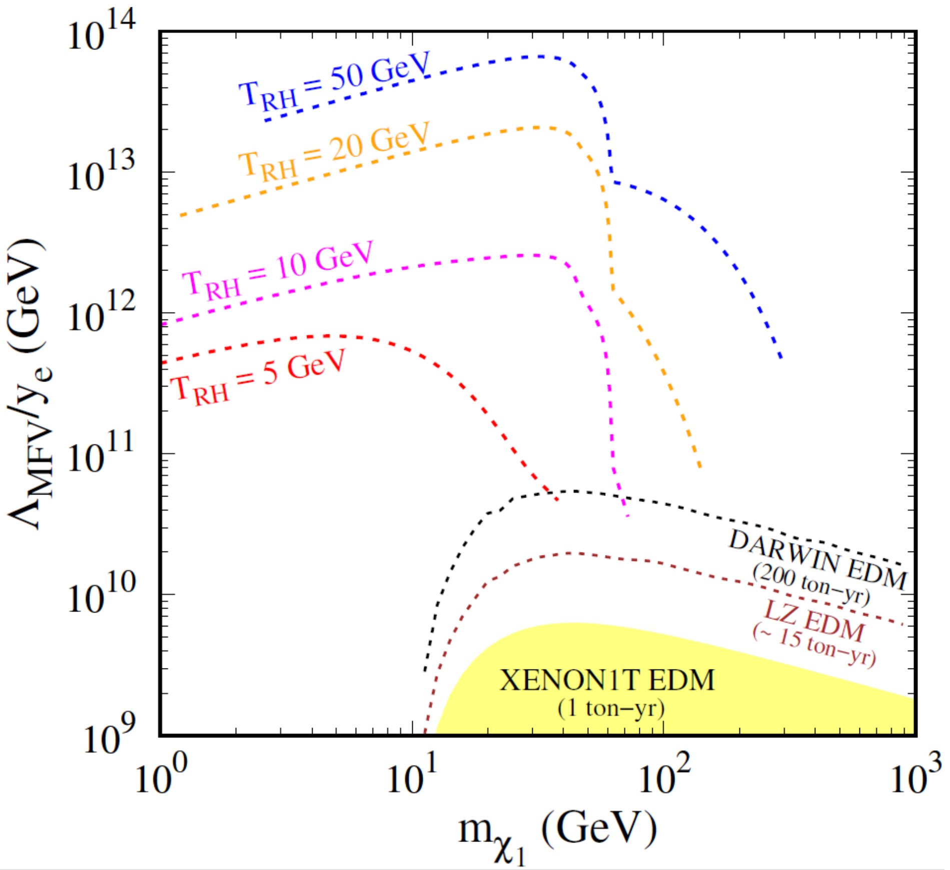


$$\frac{d\sigma_N}{dE_R} = Z^2 \alpha^2 c_W^2 y_e^2 \frac{1}{\Lambda_{MFV}^2} \frac{1}{v^2 E_R} |F(E_R)|^2, \text{for EDM},$$

$$\frac{d\sigma_N}{dE_R} = Z^2 \alpha^2 c_W^2 y_e^2 \frac{1}{\Lambda_{MFV}^2} \left(\frac{1}{E_R} + \frac{1}{2 m_N v^2} - \frac{1}{m_{\chi_1} v^2} \right) |F(E_R)|^2, \text{for MDM dipole} - \text{charge}.$$

Results: $G_{LF} \sim SU(3)_L \otimes SU(3)_{e_R}$ $\chi_L \sim (3,1), \chi_R \sim (1,3)$

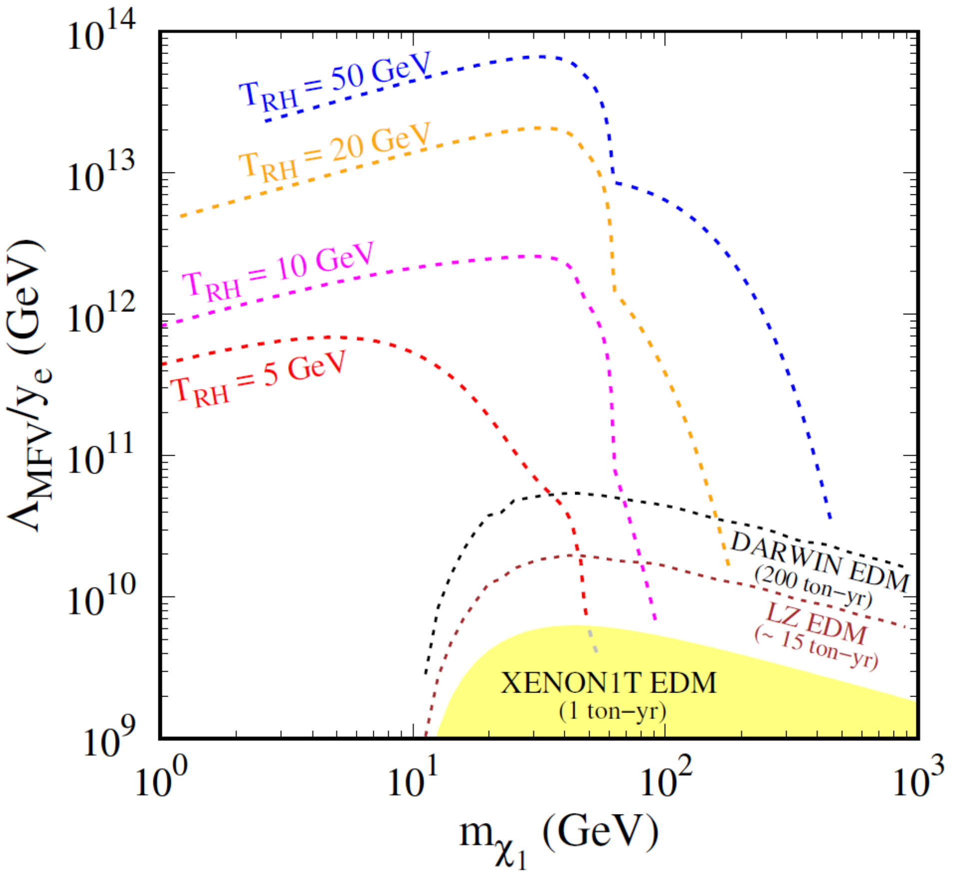
- Conditions:
  - $\Lambda_{MFV} > T_{RH}$
  - $m_{\chi_1}, m_{\chi_2}, m_{\chi_3} < \Lambda_{MFV}$
  - The lightest DM partner χ_1 also has the smallest coupling, form the complete relic abundance ($m_{\chi_2} \gg T_{RH}$)
- Future direct detection experiments will probe parts of the parameter space



Results: $G_{LF} \sim SU(2)_L \otimes SU(2)_{e_R}$

$\chi_L \sim (2,1), \chi_R \sim (1,2)$

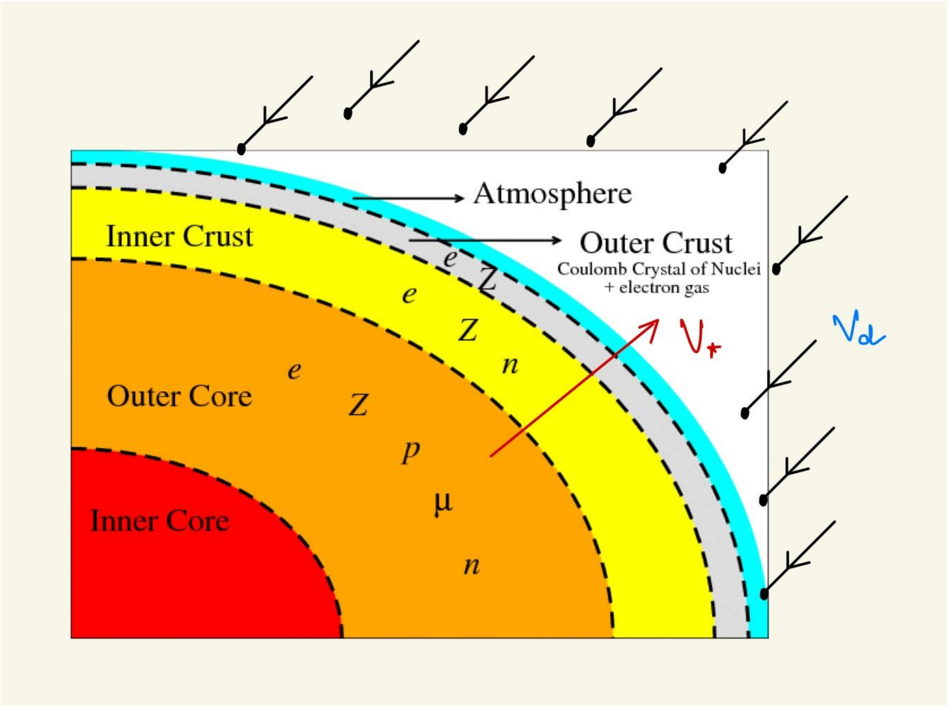
- Conditions:
  - $\Lambda_{MFV} > T_{RH}$
  - $m_{\chi_1}, m_{\chi_2} < \Lambda_{MFV}$
  - The lightest DM partner χ_1 also has the smallest coupling, and forms the complete relic abundance ($m_{\chi_2} \gg T_{RH}$)
- XENON1T already rules out parts of the parameter space with future experiments probing it more extensively.



Summary

- We consider lepton flavored dark matter particles in the paradigm of Minimal Flavor Violation to motivate a small coupling for freeze-in production of dark matter
- Lepton number conservation in conjunction with MFV leads to stability at cosmological scales
- We show with the example of a model that such a stable particle can reproduce the observed relic density through freeze-in
- And we get viable freeze-in models that can be probed in present/ future direct detection experiments

Neutron Star as Dark Matter Probes

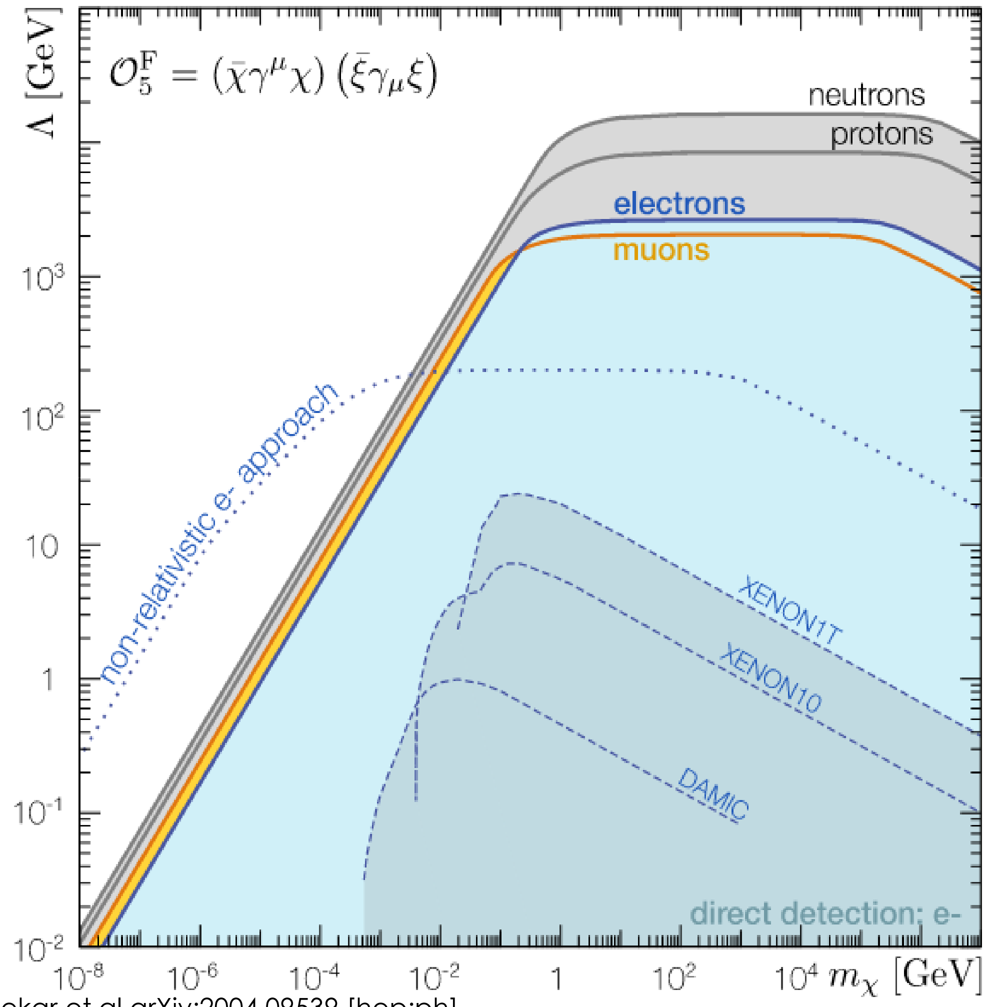


- For any astrophysical object existing in a DM-rich environment, DM particles can scatter with the constituents, get "captured" and deposit kinetic energy.
- Neutron Stars are one of the most compact astrophysical objects known to us ⟶ efficient capture.
- Assuming the NS is made up of n, p, e and μ: laboratory to probe flavored DM, especially muon.
- Old neutron stars are expected to have energies of $O(100)\ K$.
- This leads to a heating and can bring up the temperatures to $O(1000)\ K \sim O(\mu m)$.
- Detection at near future IR telescopes like the James Webb Space Telescope.

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]
Dasgupta et al arXiv: 2006.10773 [hep-ph]

Neutron Star as Dark Matter Probes

- Assuming the NS is made up of n, p, e and μ: laboratory to probe flavored DM, especially muon.
- Although there is only $1\,\mu$ per $100\,n$ in a typical neutron star, it still leads to high absolute number densities of muons $O(10^{44}/cm^3)$ making it a rare and interesting probe for DM interacting with the muons
- For concreteness we consider a $U(1)_{L_\mu - L_\tau}$ model with fermionic DM.
- Kinetic heating occurs through elastic scattering process
$$\chi\mu \to \chi\mu$$
- Same parameter space as DD, but complementary:
  - DD is limited by threshold recoil energy, while kinetic heating is dictated by chemical potential etc.
  - DM relative velocities are different $v_{DM}^{DD} \sim 10^{-3}, v_{DM}^{NS} \sim 0.2$



Joglekar et al arXiv:2004.09539 [hep:ph]

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_*

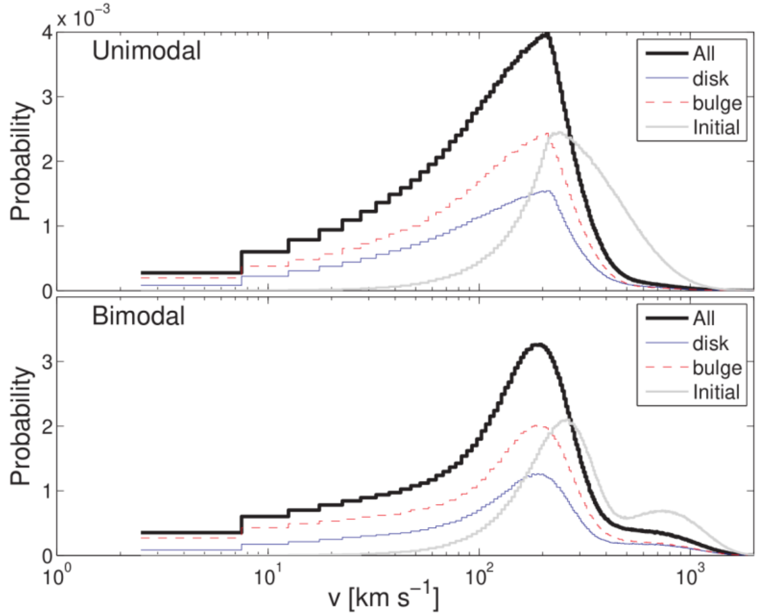
$DM\ density\ and\ dispersion\ velocity$: ρ_{DM}, v_d

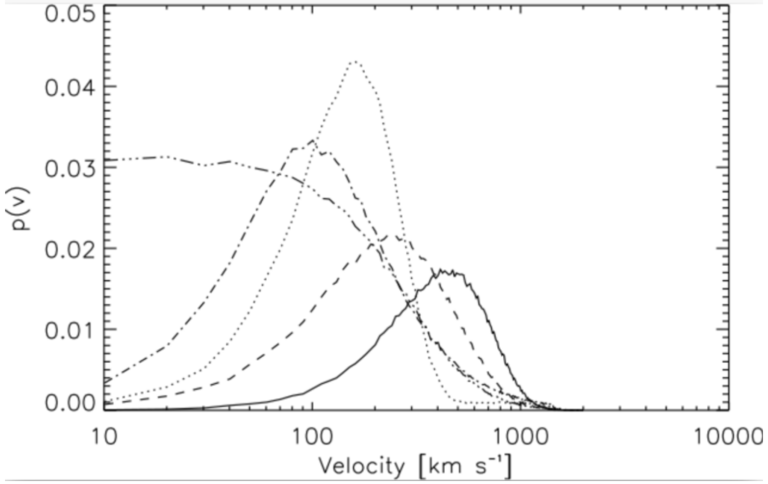
$NS\ EoS\ dependent$: $n_\mu(r), \mu_\mu(r), v_{esc}(r)$

Baryakhtar et al arXiv:1704.01577 [hep:ph]

Neutron Star as Dark Matter Probes

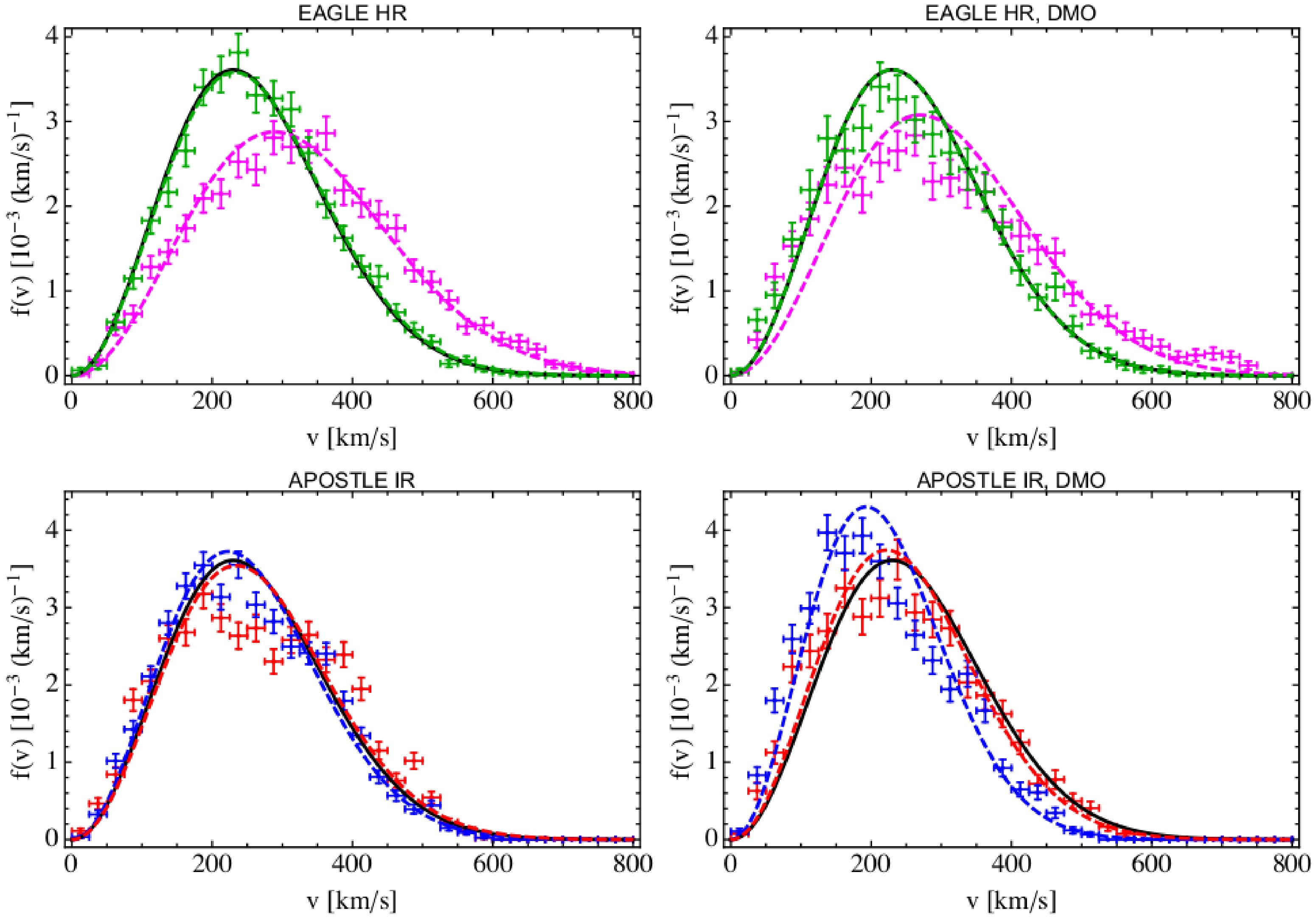
$NS\ velocity$: v_*





arXiv:0910.3684v1 [astro-ph.GA]

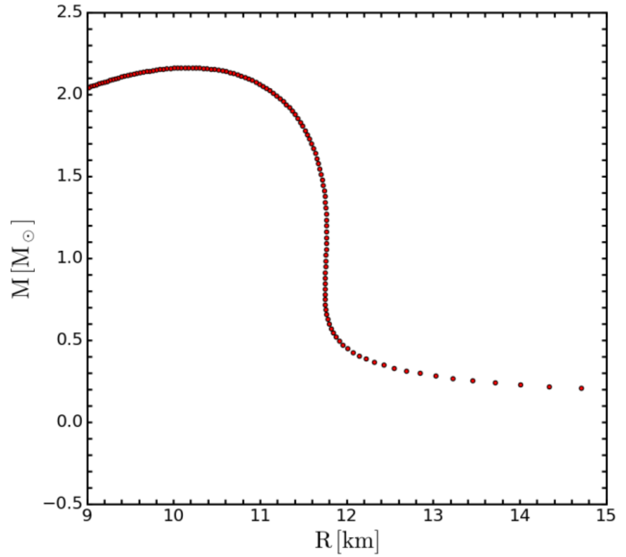
$DM\ density\ \&\ dispersion\ velocity$: ρ_{DM}, v_d



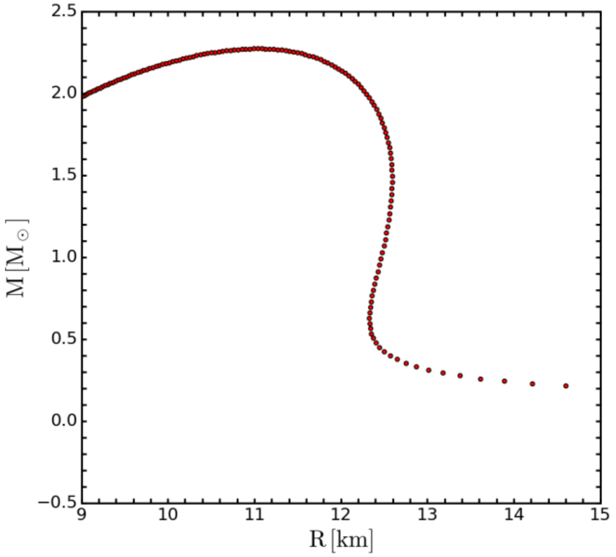
arXiv:1601.04707v2 [astro-ph.CO]

Neutron Star as Dark Matter Probes

BSK-21:



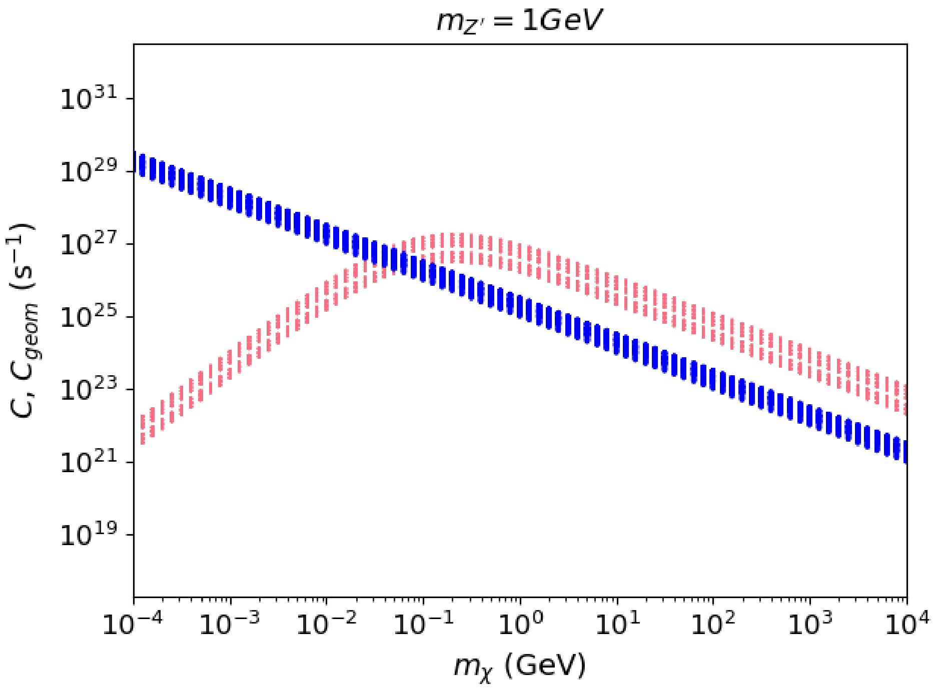
BSK-20:

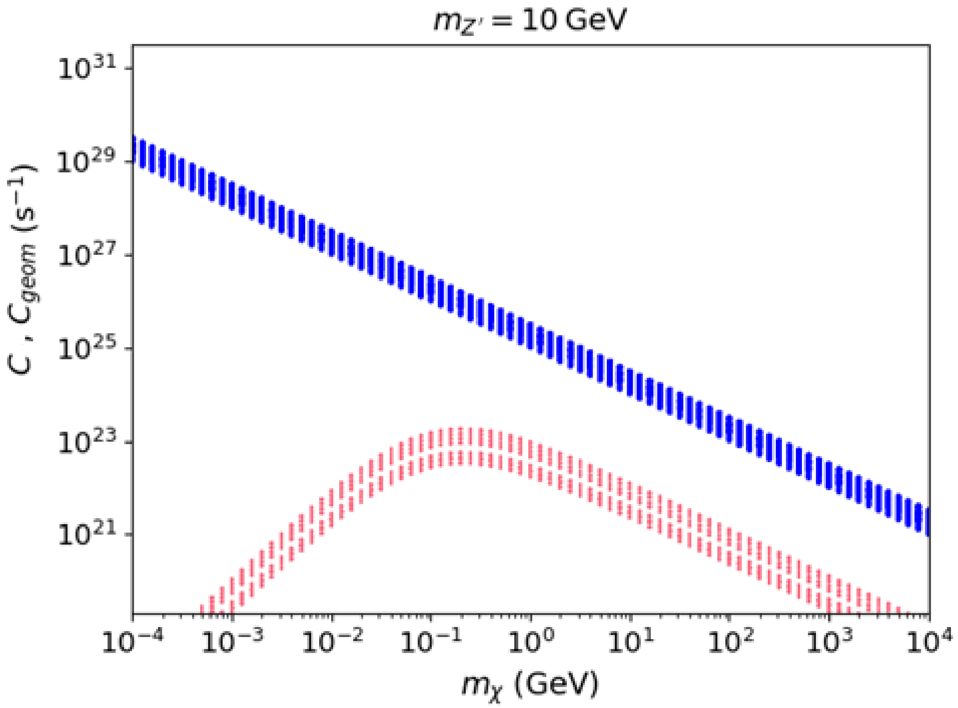


Benchmark NS models considered:

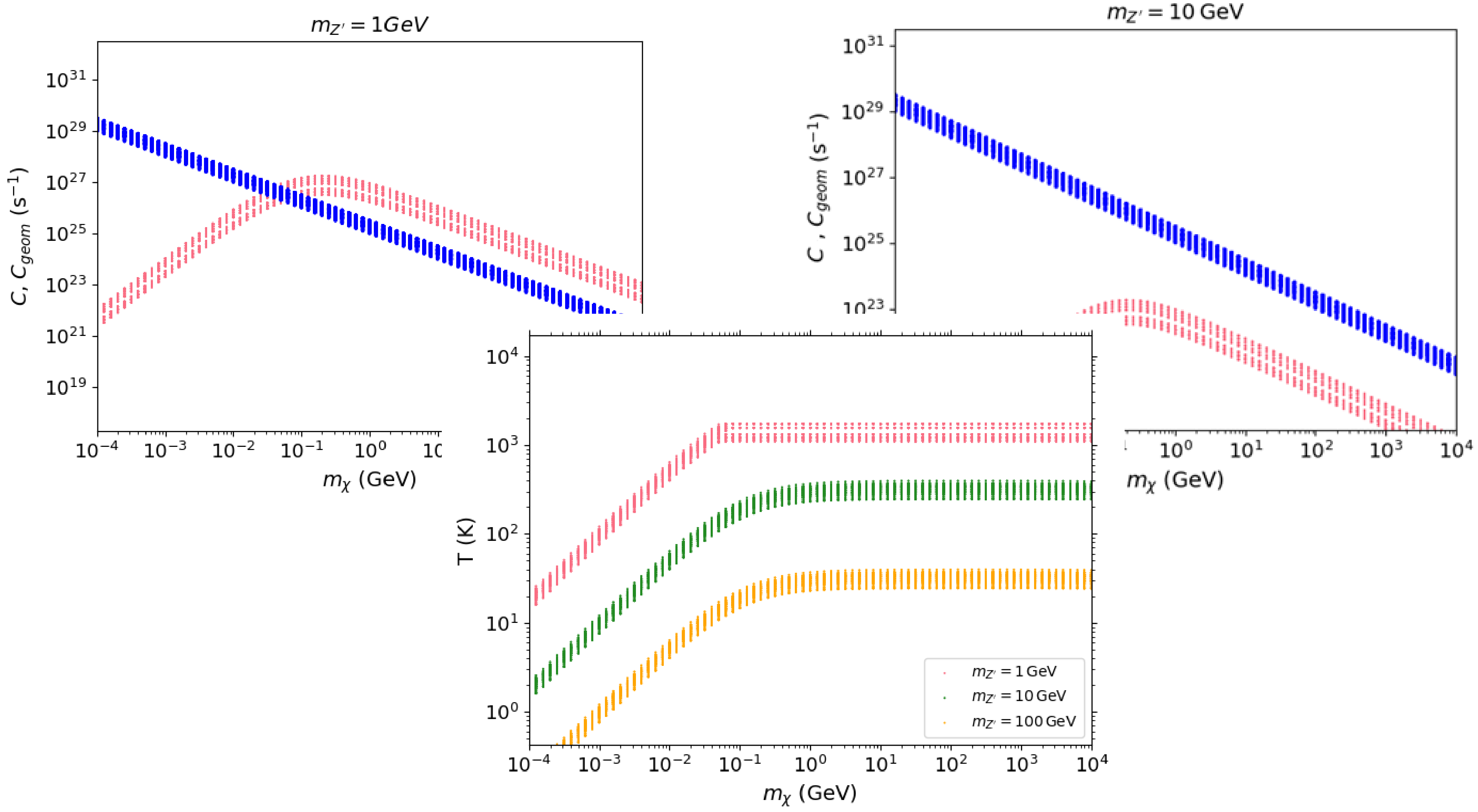
Model	A BSK-20-1	B BSK-20-2	C BSK 21-1	D BSK 21-2
Radius $R_\star$ [km]	11.6	10.7	12.5	12.0
Mass $M_\star$ [M$_\odot$]	1.52	2.12	1.54	2.11
Number of free particles normalized to BSK-20-1				
Core chemical potential [GeV]				
μ_n	0.27	0.81	0.24	0.51
μ_p	0.098	0.60	0.38	0.25
μ_μ	0.065	0.11	0.095	0.16

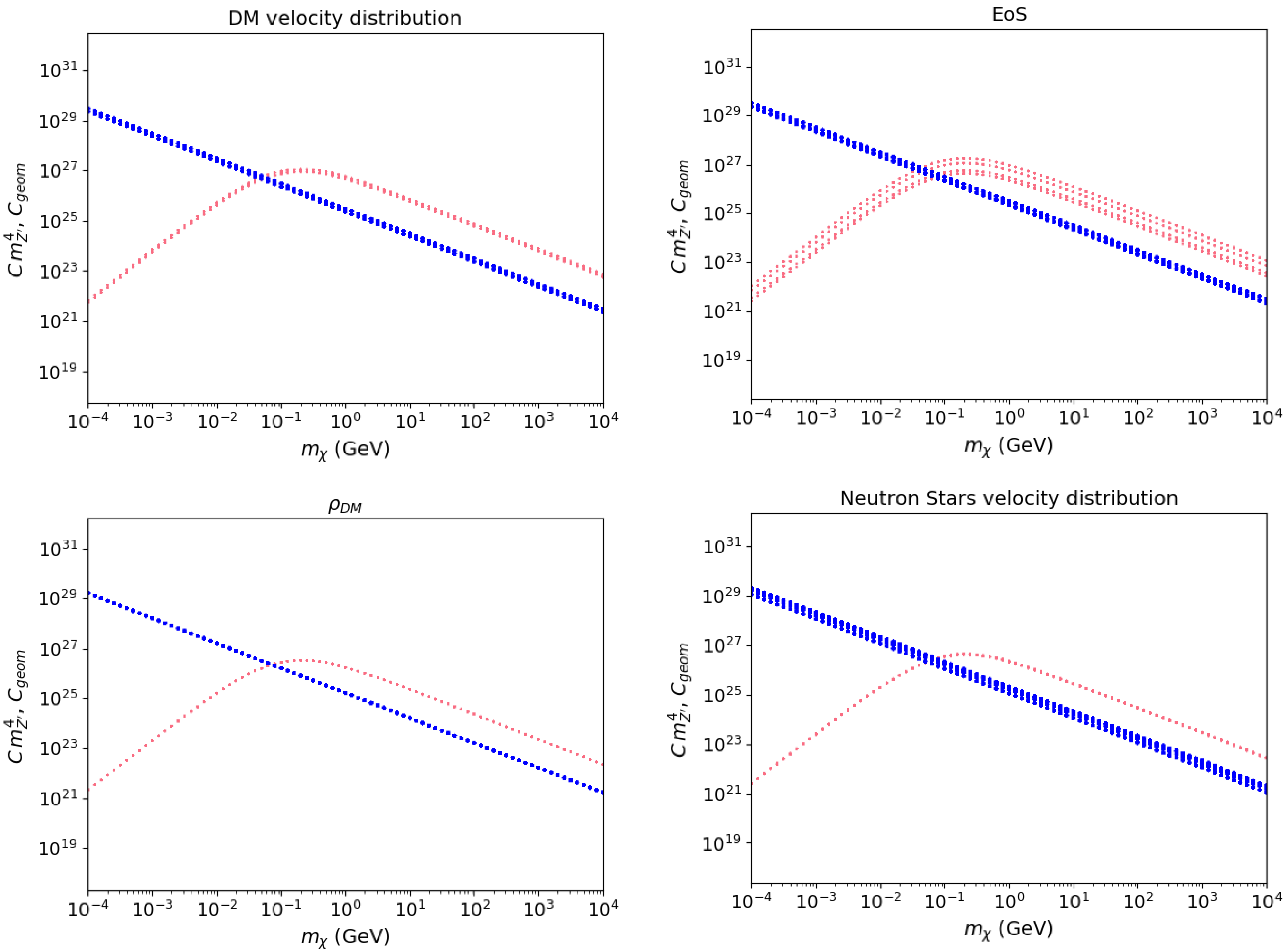
Neutron Star as Dark Matter Probes





Neutron Star as Dark Matter Probes




DM velocity distribution
EoS
ρDM
Neutron Stars velocity distribution
$C\,m_{Z'}^4$, 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}

Summary

- We have studied flavored DM phenomenology in stability conditions, relic density production, direct detection and indirect detection.
- We have systematically found representations of lepton flavored DM that are automatically stable in a MFV paradigm under lepton number conservation.
- Such lepton flavored DM can be probed at future direct detection experiments.
- We have studied the robustness of using old neutron stars as probes of DM and shown that astrophysical uncertainties cumulatively lead to $O(1)$ variation in the NS surface temperature from kinetic heating via DM.

Thank you!