Axion-like Particle Mediated Dark Matter and Neutron Star Properties in the QHD Model

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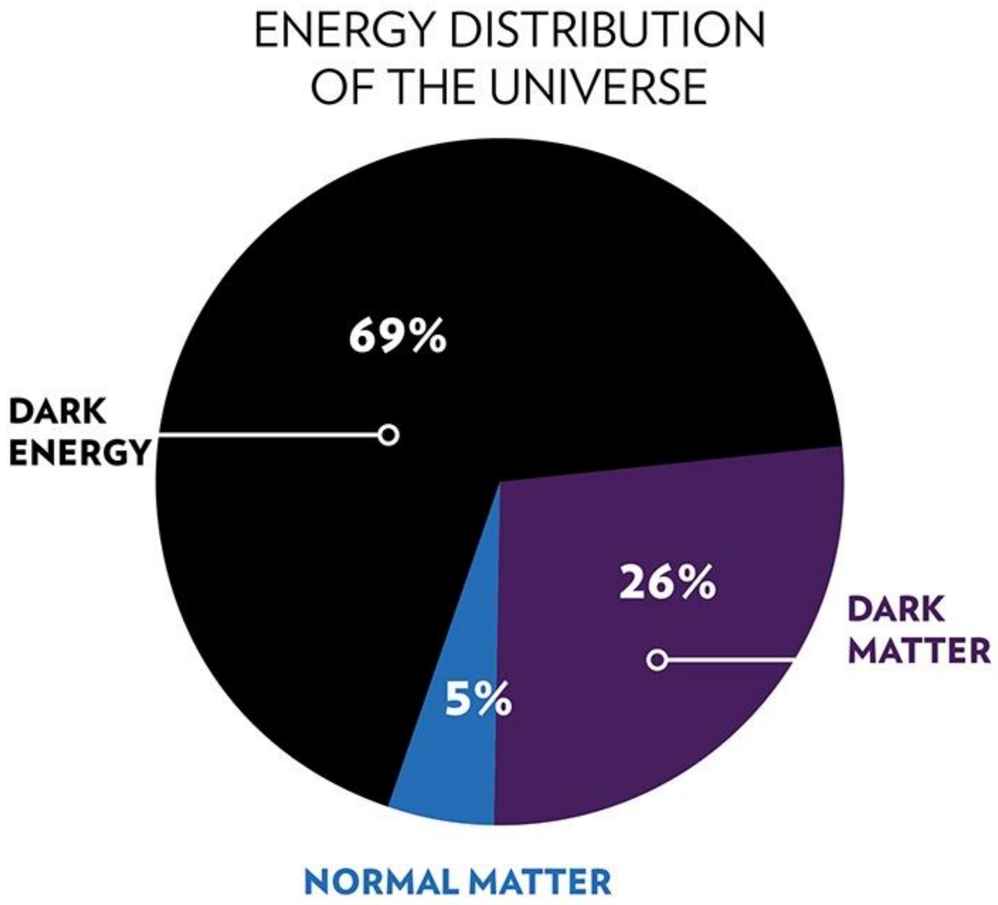
OUTLINE

- Dark matter
- Neutron star
- Quantum hadrodynamics and ALP-mediated DM model
- Results
- Conclusion

DARK MATTER

- We believed that **dark matter (DM)** are
    - Weak interaction with other particles
    - Massive
    - Uncharged
    - Stable
- DM cannot be detected by light
- DM feels ***gravitational force***
- The evidence of DM are rotation curve, bullet cluster, cosmic microwave background etc.



https://chandra.harvard.edu/graphics

DARK MATTER

- DM can be accumulated in the compact objects

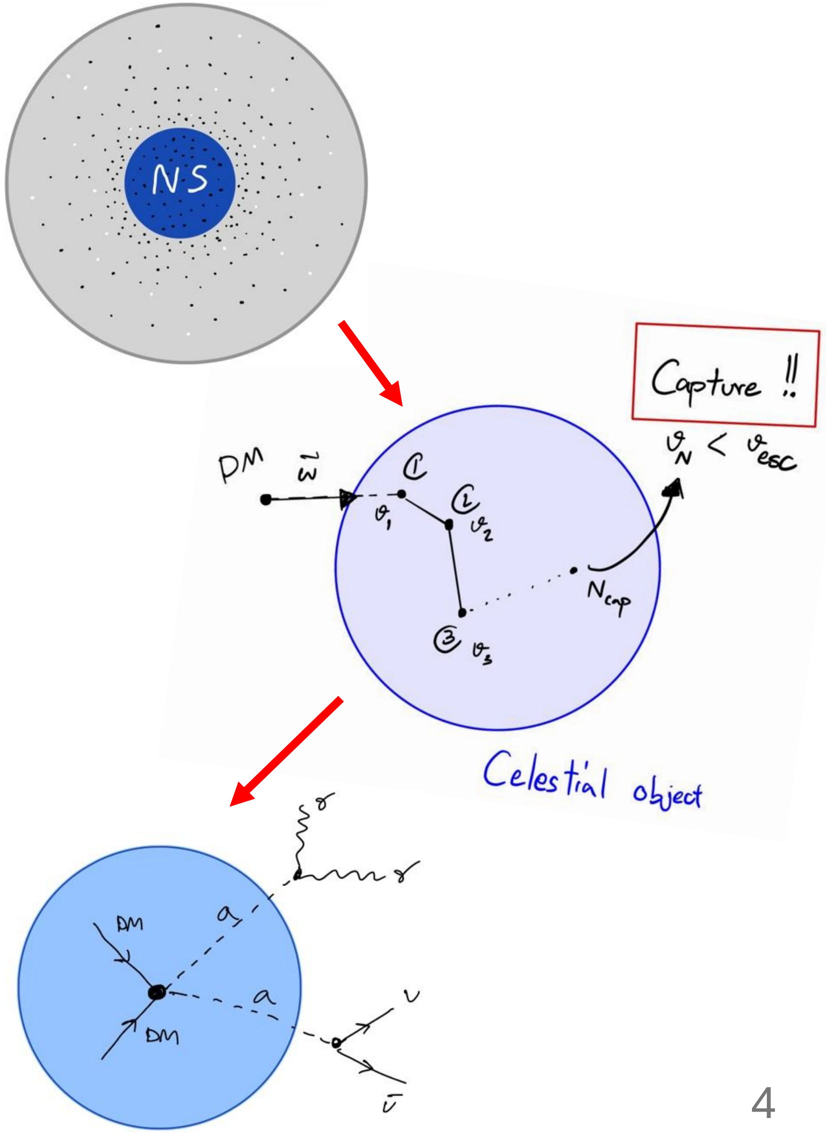
- We can study such objects by focusing on relevant frameworks

- Annihilating DM: the study depend on the lifetime of mediator
  - **Lond-lived** mediator (looking for the signal from DM indirectly)

$$\frac{d\phi}{dE} = \frac{1}{8\pi} \frac{J}{m_{\rm DM}^2} \sum_i \frac{dN_i}{dE} \langle \sigma v \rangle_i$$

  - **Short-lived** mediator (study the effects of DM on another object)

- Non-annihilating DM: We can study the effects of DM on the properties of such object (neutron star)



NEUTRON STAR

- We can study NS by the considering the system of the spherically symmetric object, the metric tensor is given by

$$ds^2 = -e^{2\nu(r)}dt^2 + e^{2\lambda(r)}dr^2 + r^2(d\theta^2 + \sin^2\theta d\phi^2)$$

- We can solve the Einstein field equation by using this metric, the results are the Tolman-Oppenheimer-Volkoff (TOV) equations

$$\frac{dP}{dr} = -\frac{(4\pi r^3 P + M)\boxed{(\varepsilon + P)}}{r(r-2M)}$$

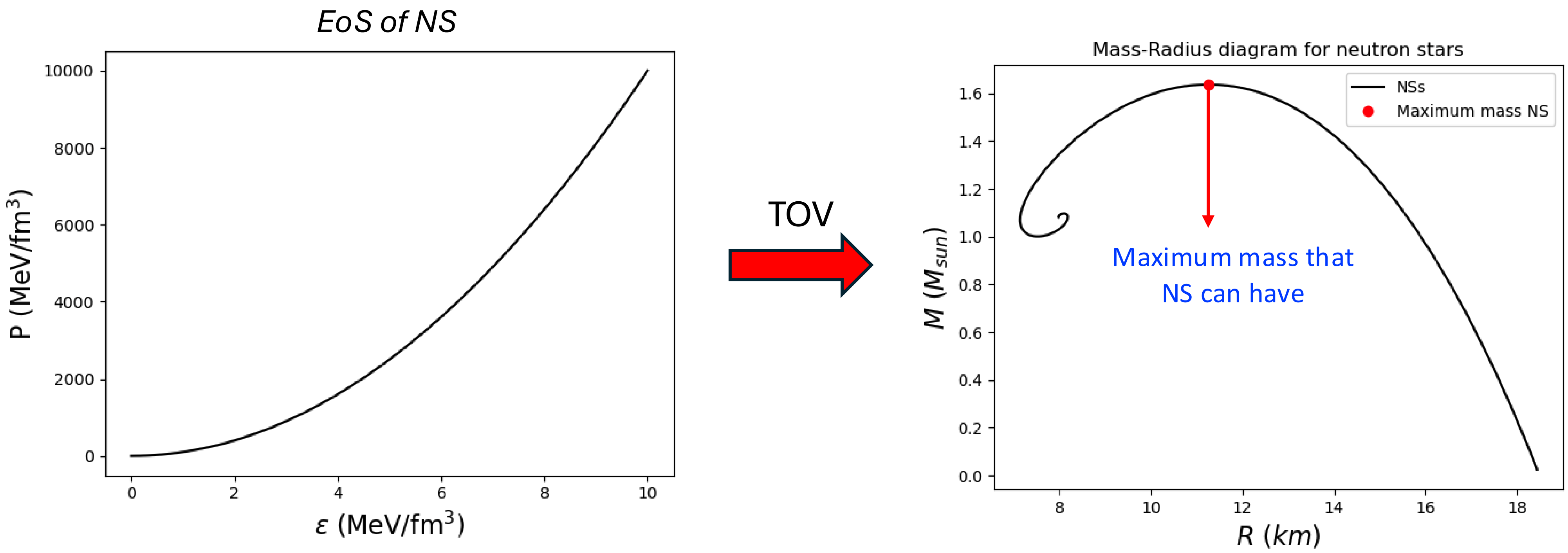
$$\frac{dM}{dr} = 4\pi r^2 \varepsilon$$

We can find M and R
if we know P and ε (EoS)

- This coupled equations described structure of a spherically symmetric body in the static equilibrium

NEUTRON STAR

- TOV equations can be solved neumerically by using the equation of state (EoS) of NS
- We can solve from the center, $r \to 0$, to the surface where the pressure is zero



- We have constraints on **mass-radius** of NS from the observations

NEUTRON STAR

- The **tidal deformability** quantifies the quadrupole deformation of a compact object in a binary system due to the tidal effect of its companion star

- The relation between the induced quadrupole moment tensor and the tidal field tensor is given by

tidal deformability

$$\underbrace{Q_{ij}}_{\text{quadrupole moment}} = -\lambda \mathcal{E}_{ij}$$

quadrupole moment

tidal field

- The tidal deformability can be calculated by the tidal Love number as

$$\lambda = \frac{2}{3} k_2 R^5$$

$$\Lambda = \frac{\lambda}{M^5} = \frac{2k_2}{3C^5}$$

Λ is dimensionless

$$k_2 = \frac{8C^5}{5}(1-2C^2)[2+2C(y-1)-y] \times \left\{2C(6-3y+3C(5y-8)) + 4C^3[13-11y+C(3y-2)+2C^2(1+y)] + 3(1-2C)^2[2-y+2C(y-1)]\log(1-2C)\right\}^{-1}$$

NEUTRON STAR

- The tidal Love number can be obtained by numerically solve this equation

Solve simulteneously with TOV

$$r y'(r) + y(r)^2 + y(r)F(r) + r^2 Q(r) = 0$$

$$F(r) = \left[1 + 4\pi r^2 \boxed{(P - \varepsilon)]}\right] \left(1 - \frac{2M}{r}\right)^{-1}$$

$$Q(r) = 4\pi \left[5\varepsilon + 9P + \frac{\varepsilon + P}{dp/d\varepsilon}\right] \left(1 - \frac{2M}{r}\right)^{-1} - \frac{6}{r^2}\left(1 - \frac{2M}{r}\right)^{-1} - \frac{4M^2}{r^4}\left(1 + \frac{4\pi r^3 P}{M}\right)^2 \left(1 - \frac{2M}{r}\right)^{-2}$$

- It represent how easily the bulk of the star is deformed under tidal effects, a higher value indicates a larger deformation

- Tidal deformability constraints, primarily derive from gravitational wave events of the binary system of NS

GW170817

$$(\Lambda_{1.4} = 190^{+390}_{-120})$$

GW190814

$$(\Lambda_{1.4} = 616^{+273}_{-158})$$

QHD AND ALP-MEDIATED DM MODEL

- The stellar mass, radius, and the dimensionless tidal deformability, strongly depend on the **EoS of a NS**

- Quantum hadrodynamics (QHD) is a theoretical framework for modeling the nuclear interactions inside NS

- The simplest version of QHD has described the nucleon-nucleon interaction by $\sigma - \omega$ model

- The scalar meson, σ is responsible for the attractive force and a vector meson, ω is responsible for for the repulsive force

$$\mathcal{L}_{HAD} = \bar{\psi}\left[\gamma^{\mu}\left(i\partial_{\mu} - g_{\omega}\omega_{\mu}\right) - (M + g_{\sigma}\sigma)\right]\psi + \frac{1}{2}\left(\partial_{\mu}\sigma\partial^{\mu}\sigma - m_{\sigma}^{2}\sigma^{2}\right) + \frac{1}{2}m_{\omega}^{2}\omega_{\mu}\omega^{\mu}$$

- We considering additional interactions, such as the exchange of the isovector meson, ρ between nucleons and nonlinear interaction terms

QHD AND ALP-MEDIATED DM MODEL

- The QHD Lagrangian in this model is given by

$$\mathcal{L}_{HAD} = \bar{\psi}\left[\gamma^\mu\left(i\partial_\mu - g_\omega\omega_\mu - g_\rho\vec{\tau}\cdot\vec{b}\right) - (M + g_\sigma\sigma)\right]\psi + \frac{1}{2}\left(\partial_\mu\sigma\partial^\mu\sigma - m_\sigma^2\sigma^2\right) - \frac{1}{3}A\sigma^3 - \frac{1}{4}B\sigma^4 - \frac{1}{4}\Omega_{\mu\nu}\Omega^{\mu\nu} + \frac{1}{2}m_\omega^2\omega_\mu\omega^\mu - \frac{1}{4}R_{\mu\nu}R^{\mu\nu} + \frac{1}{2}m_\rho^2\vec{b}_\mu\vec{b}^\mu$$

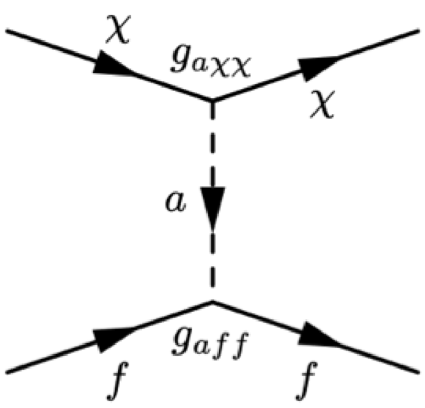
m_σ (MeV)	g_σ	m_ω (MeV)	g_ω
508.194	10.217	782.501	12.868

m_ρ	g_ρ	A (fm^{-1})	B
763.000	4.474	-10.431	-28.885

Parameters of the NL3 model

- For DM part, we study the axion-like particle (ALP)-mediated DM model

$$\mathcal{L}_{DM} = \bar{\chi}(i\gamma^\mu\partial_\mu - m_\chi)\chi + \frac{1}{2}\partial_\mu a\partial^\mu a - \frac{1}{2}m_a^2 a^2 + \sum_f \frac{m_\chi}{f_a}C_\chi\bar{\chi}i\gamma^5\chi a + \sum_f \frac{m_f}{f_a}C_f\bar{\psi}i\gamma^5\psi a$$



scattering

QHD AND ALP-MEDIATED DM MODEL

- The total Lagrangian of QHD-ALP-DM system is $\mathcal{L} = \mathcal{L}_{HAD} + \mathcal{L}_{DM}$

- The equation of state can be calculated by

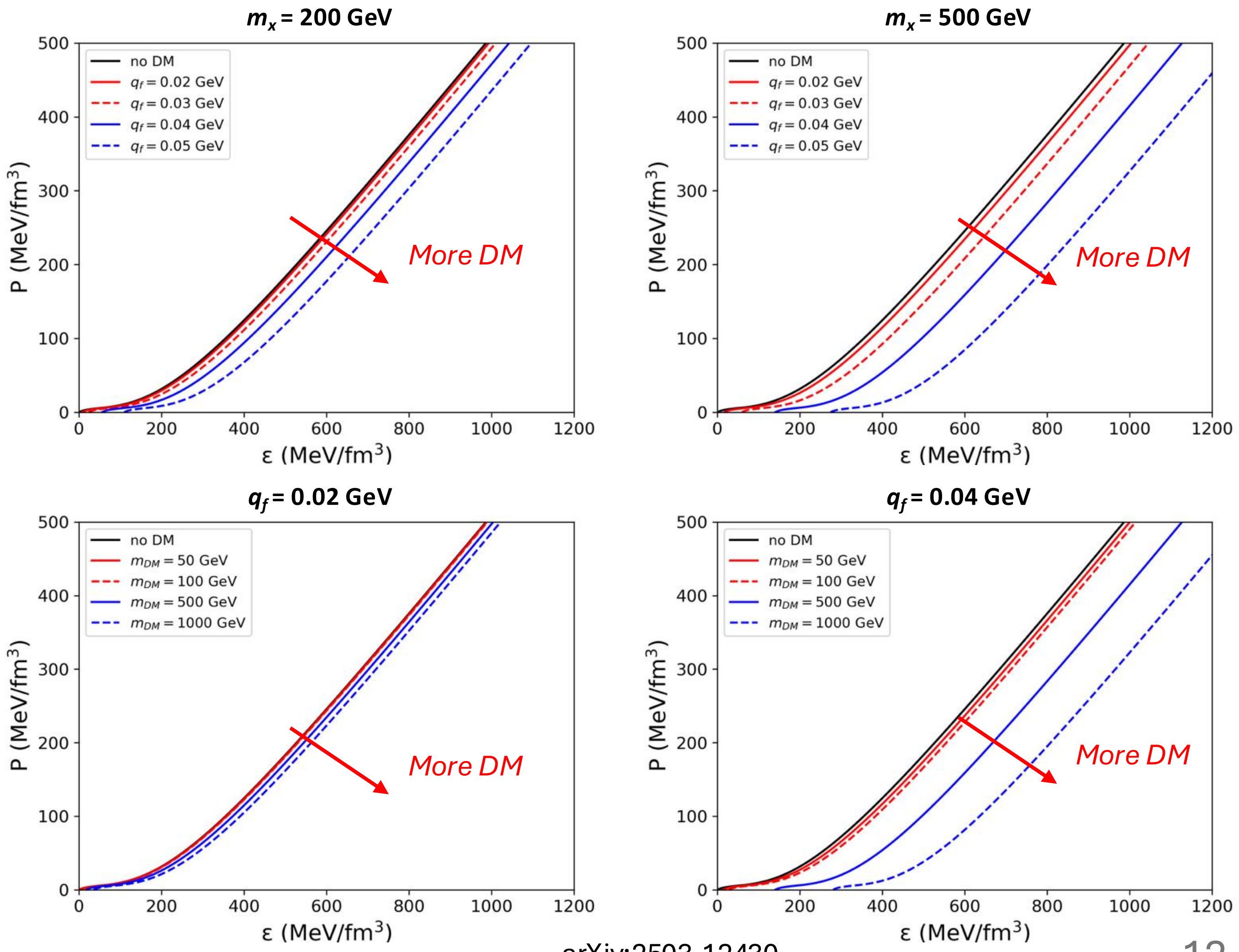
$$\varepsilon = \frac{\gamma}{2\pi^2}\int_0^{k_f} dk\; k^2\sqrt{k^2+\tilde{m}^2} + \frac{\gamma_\chi}{2\pi^2}\int_0^{q_f} dq\; q^2\sqrt{q^2+\tilde{m}_\chi^2} + g_\omega\omega_0\rho + g_\rho b_0\rho_3$$
$$+\frac{1}{2}m_\sigma^2\sigma_0^2 + \frac{1}{3}A\sigma_0^3 + \frac{1}{4}B\sigma_0^4 - \frac{1}{2}m_\omega^2\omega_0^2 - \frac{1}{2}m_\rho^2 b_0^2 + \frac{1}{2}m_a^2 a_0^2.$$
$$P = \frac{\gamma}{6\pi^2}\int_0^{k_f} dk\frac{k^4}{\sqrt{k^2+\tilde{m}^2}} + \frac{\gamma_\chi}{6\pi^2}\int_0^{q_f} dq\frac{q^4}{\sqrt{q^2+\tilde{m}_\chi^2}}$$
$$-\frac{1}{2}m_\sigma^2\sigma_0^2 - \frac{1}{3}A\sigma_0^3 - \frac{1}{4}B\sigma_0^4 + \frac{1}{2}m_\omega^2\omega_0^2 + \frac{1}{2}m_\rho^2 b_0^2 - \frac{1}{2}m_a^2 a_0^2$$

- We will focus on study on DM parameters of ALP-mediated DM model
    - DM mass: $\boldsymbol{q_f}$
    - DM fermi momentum: $\boldsymbol{m_x}$

RESULTS

Equation of state

- The effects of q_f is <u>more pronouced in higher values of m_x</u>
- <u>Increasing the DM content</u> softens the EoS, implying a <u>reduction in pressure support</u> and shifting the EoS to higher energy densities
- Reducing pressure result in a smaller radius

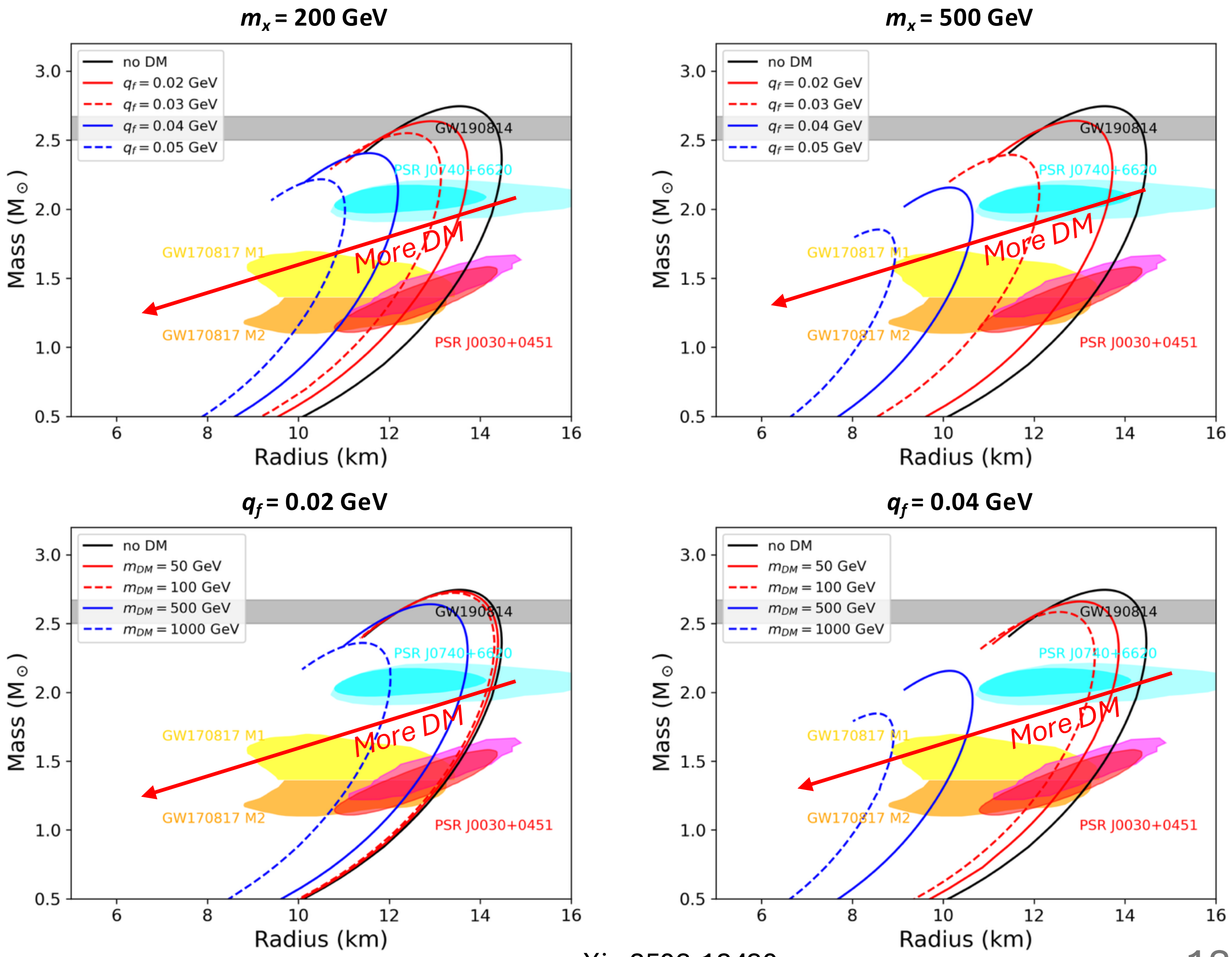


arXiv:2503.12430

RESULTS

Mass-radius relation

- Increasing either m_x or q_f reduces both the maximum mass and radius of NS
- The results satisfy one or all of the constraints from the observations
- It is worth noting that the results for a small amount of DM can meet all of the observational constraints

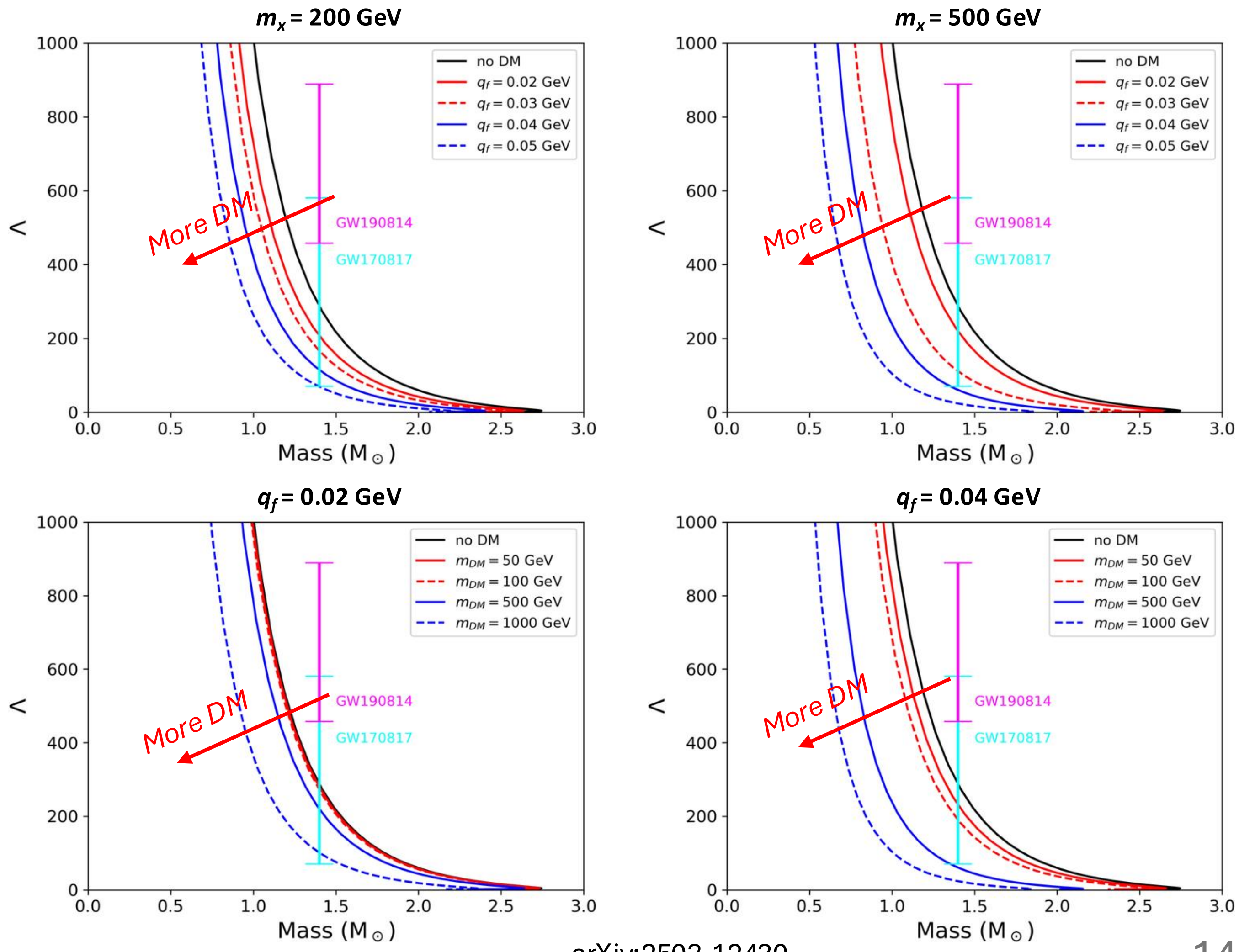


arXiv:2503.12430

RESULTS

Tidal deformability –mass relation

- The results are shown with the constraints from GW events of binary NS with <u>1.4 solar masses</u>
- Most of the results can meet the constraint from GW170817
- Notice that none of the results can satisfy the constraint from GW190814



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CONCLUSION

- In this work, we have studied the effects of the ALP-mediated DM model on the EoS of NS.
- We show that increasing DM content shifts the energy density to higher values.
- This is because the presence of DM inside NS modifies their internal structure by introducing additional degrees of freedom that soften the overall pressure support
- Since DM does not participate in standard nuclear interactions, its inclusion dilutes the hadronic pressure, lowering both the maximum mass and radius of the NS
- As a result, NS with significant DM content become more compact and less deformable under tidal forces

THANK YOU

BACK UP

EFFECT OF DM ON EOS

- The differential flux is given by

$$E^2 \frac{d\Phi}{dE} = \frac{\Gamma_{\rm ann}}{4\pi D^2} \times E^2 \frac{dN}{dE} \times {\rm BR}(a \to {\rm SM}) \times P_{\rm surv}$$

Gamma-ray fluxes

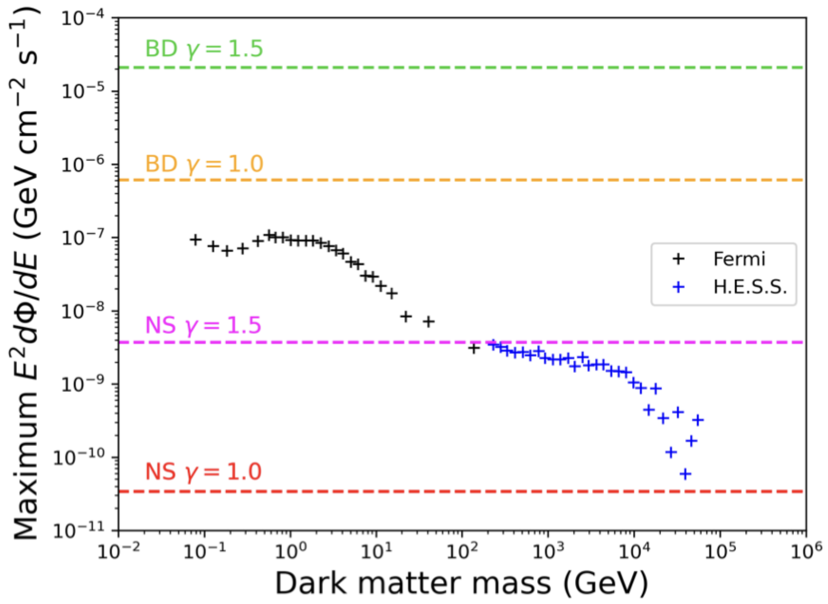
Annihilation rate of DM inside the object
This proportional to the capture rate

Number distribution

Branching ratio of the mediator the final state

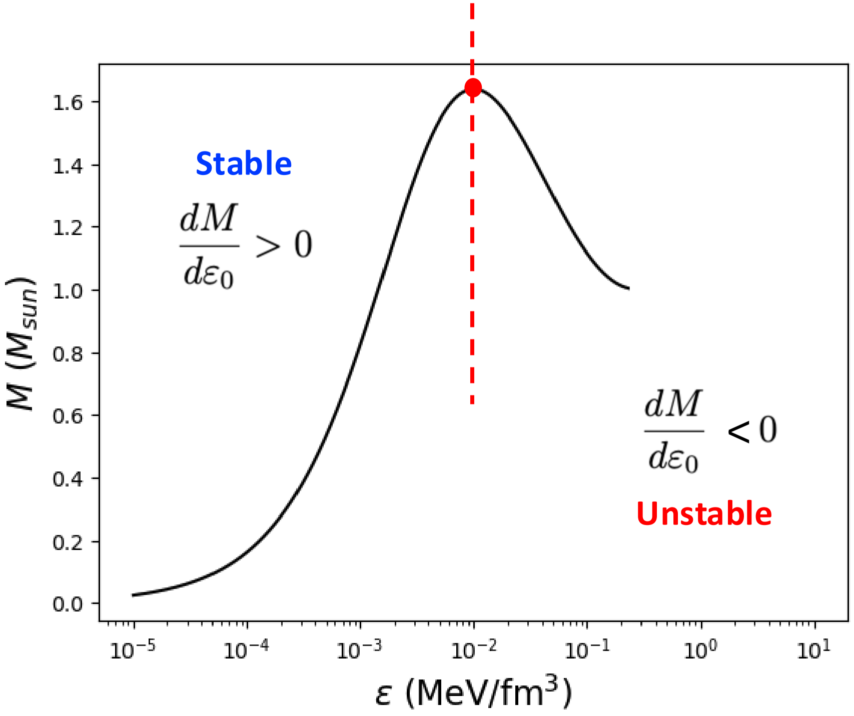
Survival probability of the mediator

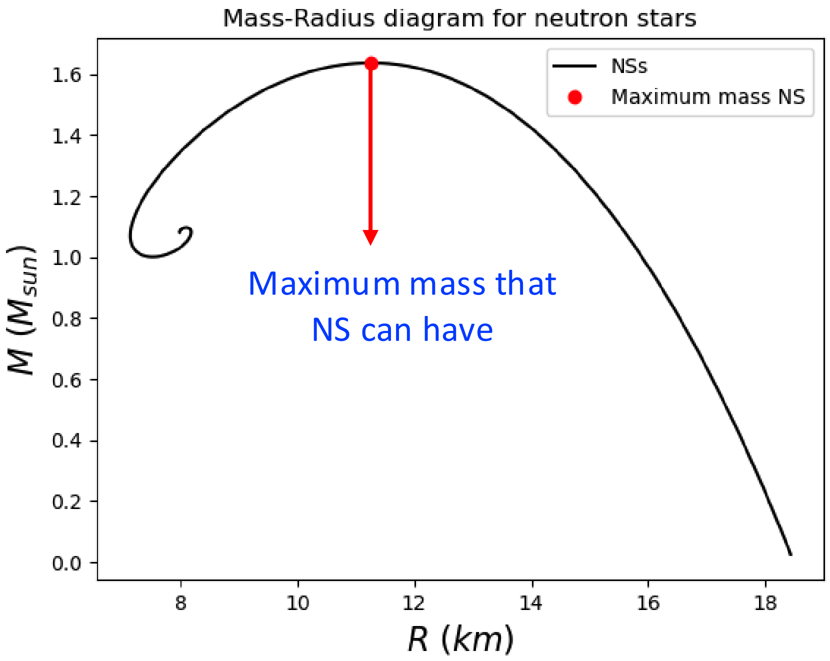
maximally optimistic limit
$P_{surv} = 1$ *and* $BR = 1$



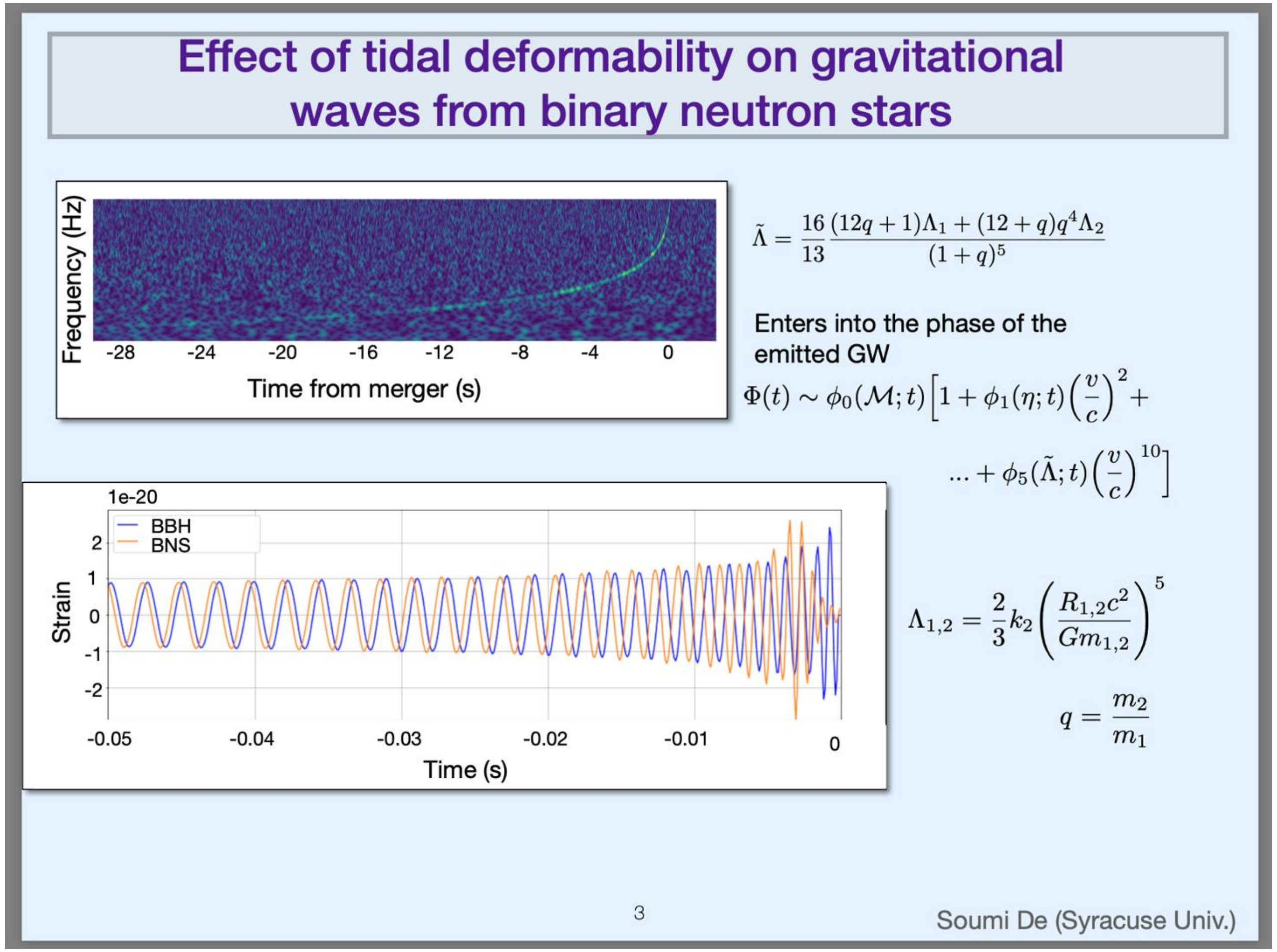
STABLE STAR CONDITION

- TOV equations can be solved neumerically by using the equation of state (EoS) of NS





TIDAL DEFORMABILITY



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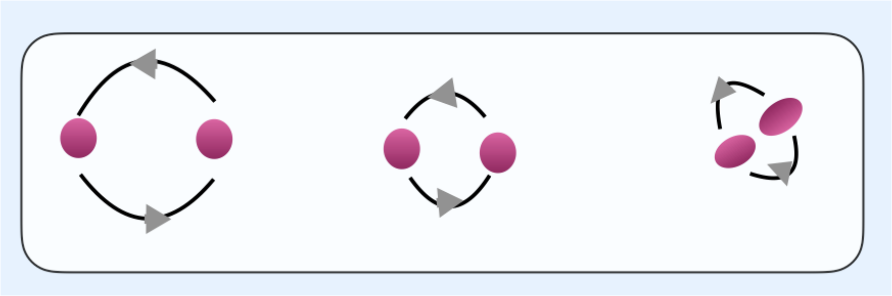

Neutron stars in binaries are deformed by the gravitational field of their companion towards the end of the inspiral

Tidal effects on GW signal can constrain dense matter equation of state