Neutron decay anomaly, Dark Matter & Neutron Stars

Mar Bastero Gil, Teresa Huertas & Daniel Santos

[ArXiv:2403.08666]

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Neutron decay anomaly, Dark Matter & Neutron Stars

- Neutron anomaly and dark decay channel: light scalar mediator
- DM abundance and Higgs physics
- Neutron Stars and DM
- Summary: parameter space

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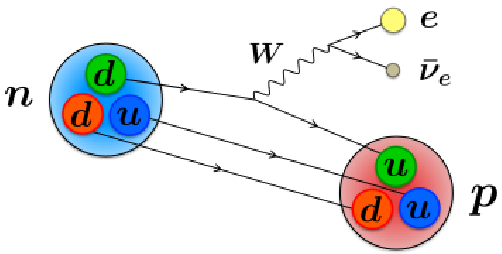
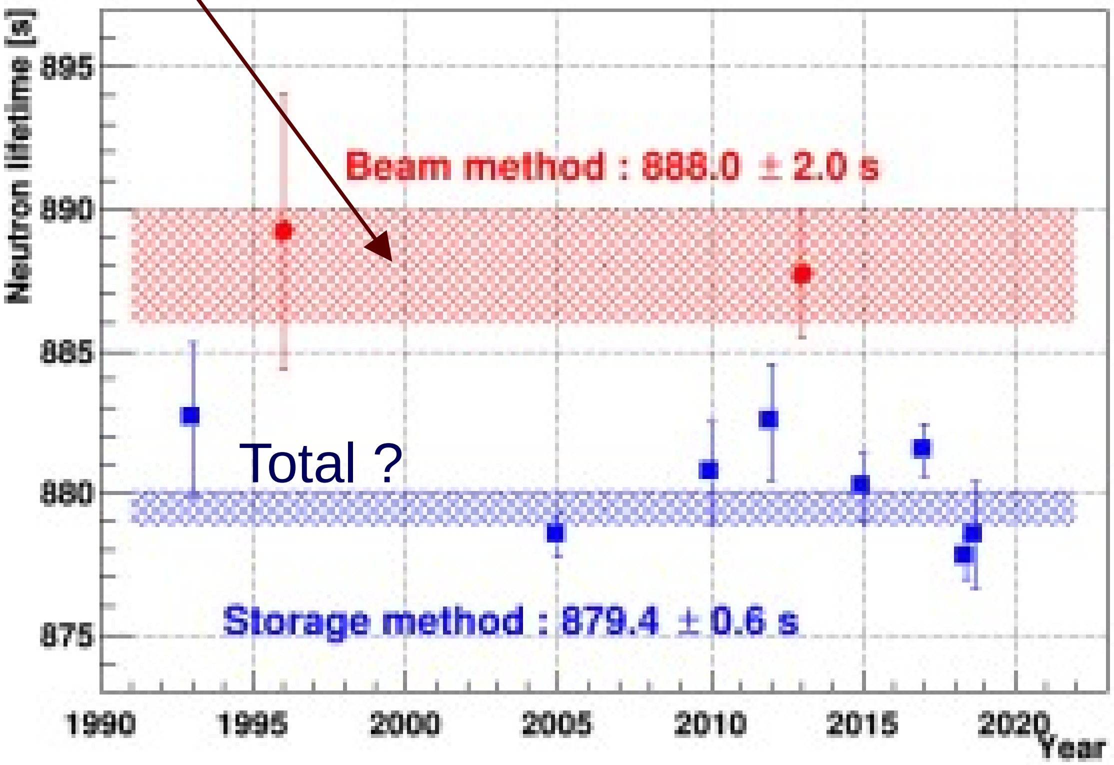
Neutron decay anomaly



Beta decay: $n \rightarrow p + e + \bar{\nu}_e$

~ 5σ difference



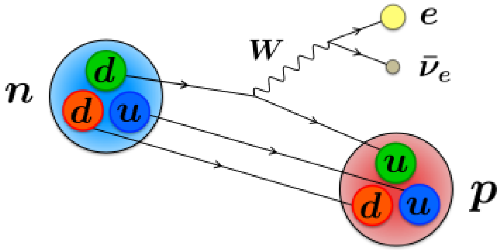
Total ?

New “dark” channel ?

Br(n → “dark”) ~ 1%

[N. Sumi et at, 2102.09758]

Neutron decay anomaly



Beta decay: $n \rightarrow p + e + \bar{\nu}_e$

New “dark” channel : **χ Dark Matter fermion**

$n \rightarrow \chi + \gamma$

$n \rightarrow \chi + e^{+} + e^{-}$

DM + “visible”

$n \rightarrow \chi + A$

$n \rightarrow \chi + \phi$

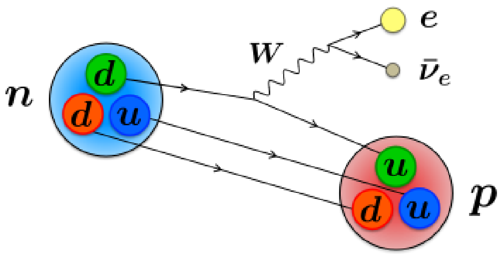
A=Dark photon

DM + “invisible”

ϕ= singlet scalar

[Grinstein & Fornal PRL 2018; Grinstein, Kouvaris & Nielsen PRL2019]

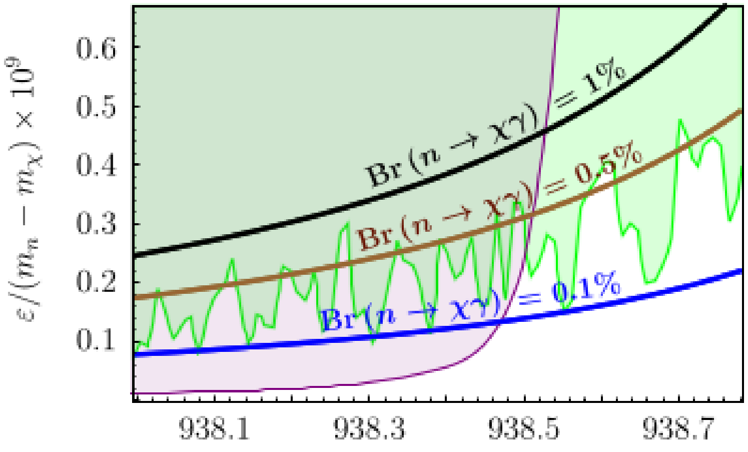
Neutron decay anomaly



Beta decay: $n \rightarrow p + e + \bar{\nu}_e$

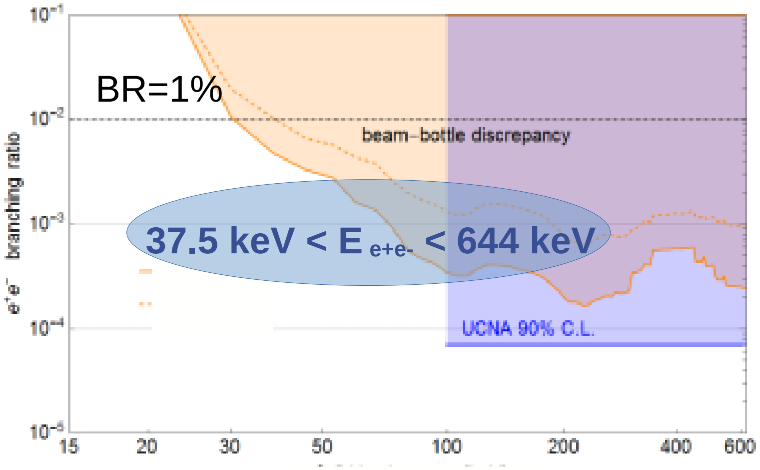
New “dark” channel : χ Dark Matter fermion + “visible”

$n \rightarrow \chi + \gamma$



$m_\chi [MeV]$

$n \rightarrow \chi + e^+ + e^-$

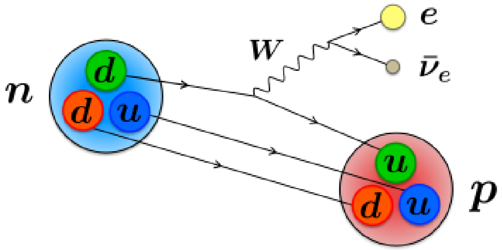


E_{e+e-} kinetic energy [keV]

[Zang et al. PRL121 ‘18]

[UCNA collab. PRC97 ‘18]
[PERKEOII collab. M. Klopf et al. PRL121 ‘19]

Neutron decay anomaly



Beta decay: $n \rightarrow p + e + \bar{\nu}_e$

New "dark" channel : χ Dark Matter fermion + "invisible"

$n \rightarrow \chi + A$

$n \rightarrow \chi + \phi$

- Compatible with NS physics
- Not enough DM abundance

(less than 10% of the total)

[Cline & Cornell JHEP07 '18]

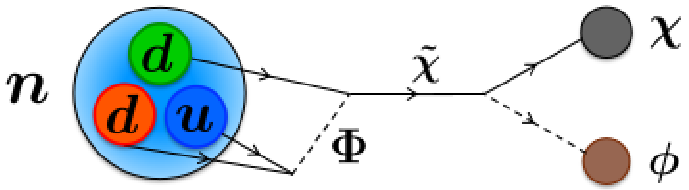
- Compatible with NS physics
- Light scalar mediator (Higgs portal)

Right DM abundance

[Grinstein, Kouvaris & Nielsen PRL2019]

Neutron decay anomaly

$n \rightarrow \chi + \phi$



χ Dark Matter fermion + ϕ singlet scalar

- **Masses:** $937.993\ \text{MeV} < m_\chi + m_\phi < 939.565\ \text{MeV}\ [m_n]$ [n decay and nuclei stability]

  $|m_\chi - m_\phi| < 938.783\ \text{MeV}\ [m_p + m_e]$ [DM stability]

- Light scalar mediator has to decay before **BBN**: $m_\phi > 2m_e$

  (constraint on effective no. of relativistic dof at BBN)

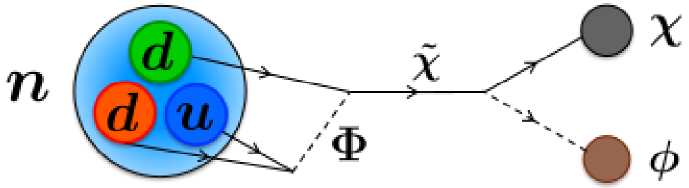
- This reintroduces the decay channel $n \rightarrow \chi + \phi \rightarrow \chi + e^{+} + e^{-}$

⇒ $2m_e < m_\phi < 2m_e + 0.0375\,\text{MeV}$, $m_\phi > 1.666\,\text{MeV}$ [UCNA & PERKEOII]

$m_\chi \sim O(1\,\text{GeV})$ $m_\phi \sim O(1\,\text{MeV})$

Particle Physics Model

$n \rightarrow \chi + \phi$



- Heavy scalar Φ = $(3,1)_{-1/3}$, $B_\Phi=-2/3$
- Light scalar ϕ (singlet), $B_\phi=0$
- Heavy fermion $\tilde{\chi}$
- DM fermion χ

$B_{\tilde{\chi}}=B_\chi=1$

Higgs

$$L=\cdots+\lambda_\phi \bar{\tilde{\chi}}\chi\phi+ g_\chi \bar{\chi}\chi\phi+ \underbrace{\mu H^{+\cdot} H\phi+ g_{\phi H}\phi^2 H^{+\cdot} H}$$

Parameter values

DM abundance:
Annihilation cross-section

Higgs physics: BR $_{\text{Higgs}\rightarrow\text{invisible}}$ ~ 12%

Singlet decay (**BBN**): $\tau_\phi<1$ s

$m_\phi > 2m_e$

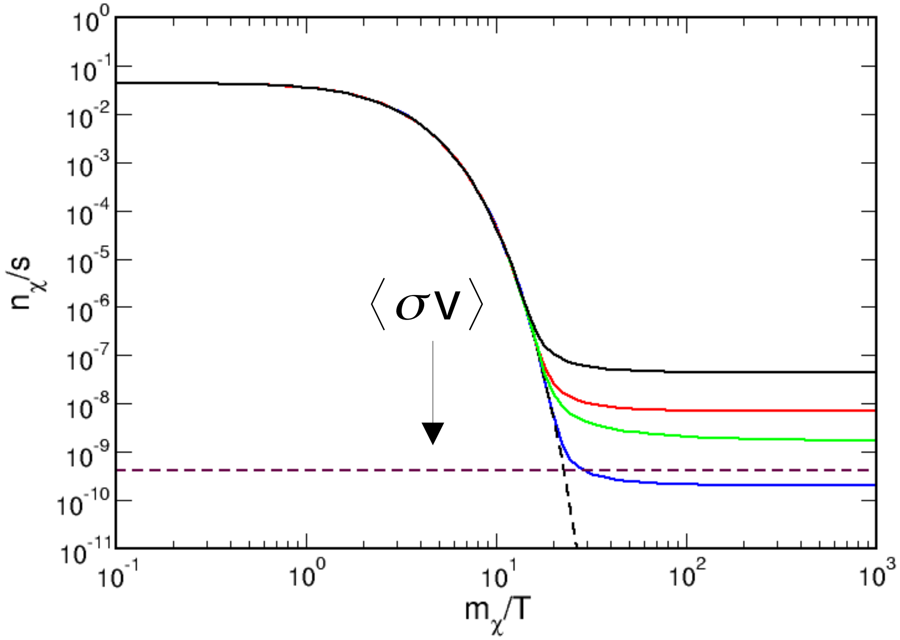
[Grinstein, Kouvaris & Nielsen PRL2019]

Dark Matter Abundance: “freeze-out” mechanism

- Boltzmann Eq: $$\frac{dn_\chi}{dt}+3Hn_\chi=-\langle\sigma v\rangle(n_{chi}^2-(n_\chi^{eq})^2)$$

- Standard freeze-out scenario: χ initially in equilibrium with ϕ,
  ϕ in equilibrium with SM through Higgs portal $g_{\phi H}\geq 10^{-7}$

- Annihilation cross-section $\chi\bar{\chi}\leftarrow\rightarrow\phi\phi$ $$\langle\sigma v\rangle\simeq\frac{3g_\chi^2}{32\pi m_\chi^2}\frac{T}{m_\chi}$$



- Today’s DM abundance:

(s₀= entropy density)

$$\Omega_{DM}=\frac{\rho_{DM}}{\rho_c}=\frac{s_0}{\rho_c}m_\chi\left(\frac{n_\chi}{s}\right)_{fo}$$

(ρc= critical energy density)

$$\Omega_{DM}h^2=0.120 \rightarrow \boxed{g_\chi\simeq 0.053}$$

[Planck collab. A&A 2020]

Higgs Portal

After EW sym breaking

$$L=\cdots+\lambda_{\phi}\bar{\tilde{\chi}}\chi\phi+\ g_{\chi}\bar{\chi}\chi\phi+\mu H^{+\cdot}H\phi+\ g_{\phi H}\phi^{2}H^{+\cdot}H$$

- Singlet S + double Σ (Higgs)

$$V(S,\Sigma)=m_S^2S^2+m_\Sigma^2|\Sigma|^2+\lambda|\Sigma|^4+\frac{\lambda_S}{4}S^4+\frac{\lambda_{S\Sigma}}{2}S^2|\Sigma|^2+\frac{\mu_3}{3}S^3+\mu_1S|\Sigma|^2$$

$m_\chi \simeq 1\ \ \text{GeV} \rightarrow\ \langle s\rangle \ll v_{EW}$

[Kouvaris, Shoemaker & Tuominen PRD91 2015]

- Mixing: $\sigma^0=\cos\theta h+\sin\theta\phi \qquad s=\cos\theta\phi-\sin\theta h$
- **Invisible Higgs decay:** $\Gamma(h\rightarrow\phi\phi)\simeq\frac{\lambda_{S\Sigma}v_{EW}^2}{8\pi m_h} \qquad \Gamma(h\rightarrow\chi\chi)\simeq\frac{g_\chi^2\sin^2\theta}{8\pi}m_h$

Γ_h(invisible) < 14% Γ_h(visible) ➡ $\sin\theta\leq 0.194 \qquad \lambda_{S\Sigma}\simeq g_{\phi H}<5\,x\,10^{-3}$

$g_\chi\simeq 0.053$

- Singlet lifetime (**BBN**): $\tau_\phi=\frac{8\pi}{h_e^2\sin^2\theta m_\phi}\left(1-\frac{4m_e^2}{m_\phi^2}\right)^{-3/2}<1\ \ s$ ➡ $\sin\theta\geq 10^{-6}$
- **Trilinear coupling:** $2.6\,x\,10^{-4}\ \ \text{GeV}\leq\ \mu\simeq\frac{4m_h^2}{v_{EW}}\sin\theta\ \leq 49.4\ \ \text{GeV}$

Neutron Stars

- The DM-neutron interactions affect the Mass-Radius relation of Neutron Stars

Neutron Star : static, spherically symmetric compact object

- Tolman-Oppenheimer-Volkoff (TOV) equations:

EoS for nuclear matter

$$\left.\begin{array}{l} \dfrac{dP(r)}{dr} = -\dfrac{\rho(r)+P(r)}{r^2}\cdot\dfrac{M(r)+4\pi r^3 P(r)}{1-2GM/r} \\[2ex] \dfrac{dM(r)}{dr} = 4\pi r^2 \rho(r) \end{array}\right\} + \left\{\begin{array}{ll} E_n = a(n_n/n_0)^{\alpha} + b(n_n/n_0)^{\beta} & \text{Internal energy} \\ \rho_n = n_n(m_n + E_n) & \text{Energy density} \\ P_n = n_n^2 \dfrac{dE_n}{dn_n} & \text{Pressure} \end{array}\right.$$

Saturation density $n_0 = 0.16 \ \ \text{fm}^{-3}$

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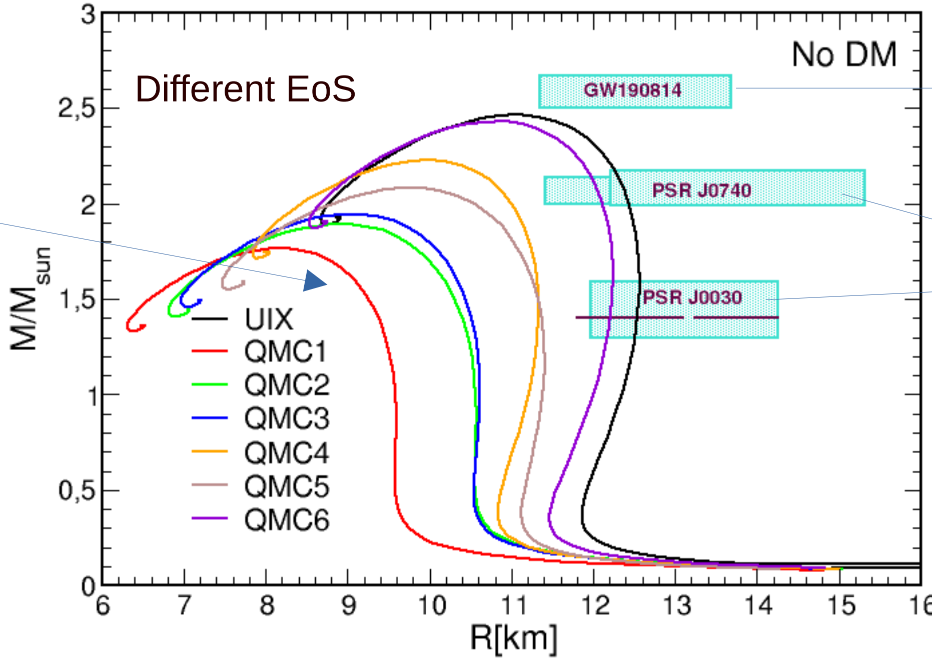
Different central values n_n

Eqs. Integrated until P(R)=0



LIGO-VIRGO

[2006.1261]

NICER data

[1912.0570, 2105.0698, 2105.0697]

Neutron Stars & Dark Matter

$m_\chi \simeq 1 \ \mathrm{GeV}$

- Adding DM :

$$\rho_T = \rho_n + \underbrace{\rho_\chi[k_F]}_{\text{Fermi gas}} + \underbrace{\frac{g_\chi^2}{2m_\phi^2} n_\chi^2}_{\text{DM self-interactions, singlet scalar exchange}} + \underbrace{\frac{|g_\chi g_n|}{2m_\phi^2} n_\chi n_n}_{\text{DM-neutron repulsive interaction}}$$

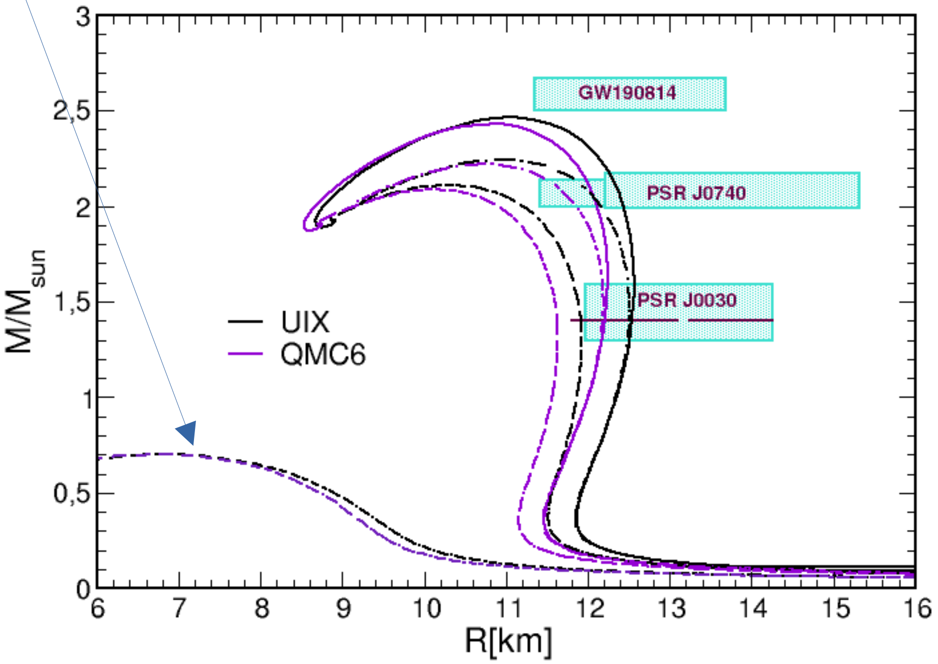
$$V = \frac{|g_\chi g_n|}{4\pi} \cdot \frac{e^{-m_\phi r}}{r}$$

$$g_n \simeq \frac{\mu \cdot \sigma_{\pi n}}{m_h^2} \simeq 2.4 \times 10^{-5} \frac{\mu}{\mathrm{GeV}}$$

Trilinear coupling
Singlet scalar-Higgs

- Too “soft” EoS, less massive star : $g_\chi = g_n = 0$

[Baym et al. PRL121 2018]



Neutron Stars & Dark Matter

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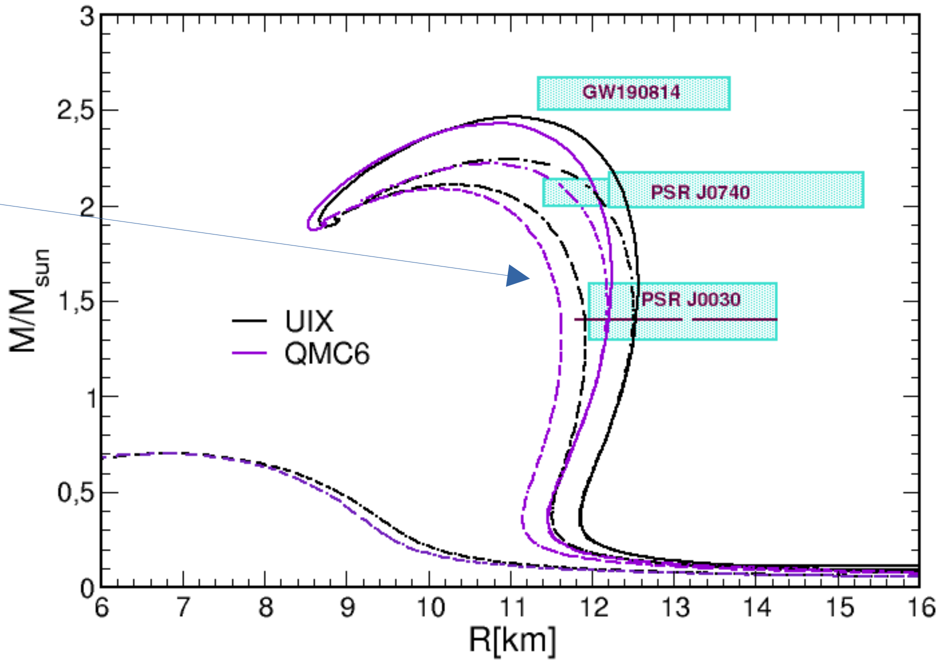
$m_\chi \simeq 1$ GeV

- Too “soft” EoS, less massive star : $g_\chi = g_n = 0$

[Baym et al. PRL121 2018]

- With DM self-interactions:

$$z_\chi = \frac{m_\phi}{g_\chi} = 50\,\mathrm{MeV} \quad g_n = 0$$



Neutron Stars & Dark Matter

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$$\boxed{m_\chi\simeq1\ \ \text{GeV}}$$

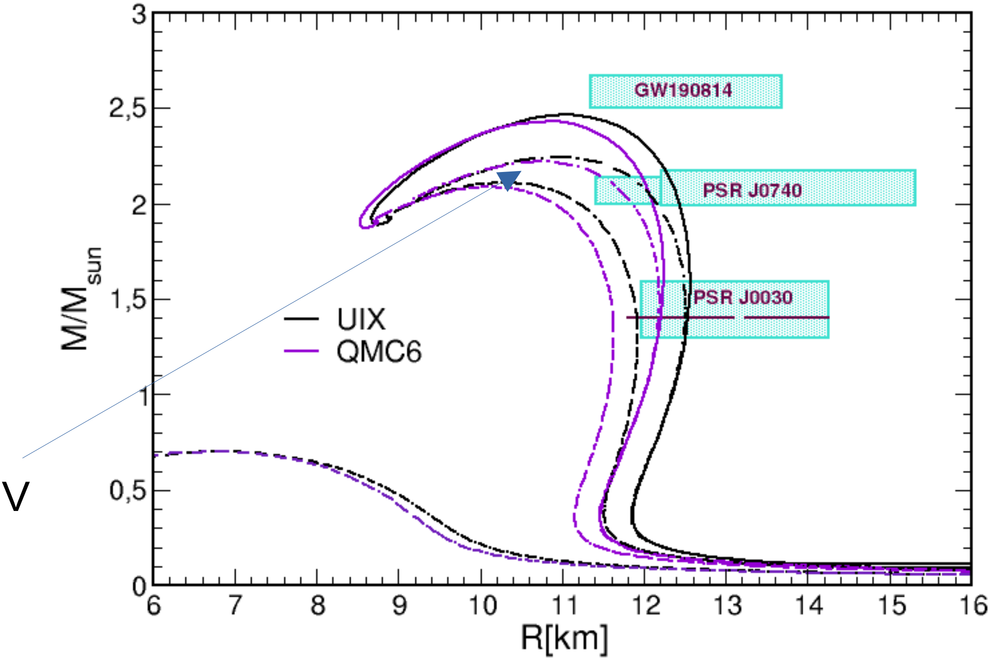
- Too “soft” EoS, less massive star : $g_\chi=g_n=0$ [Baym et al. PRL121 2018]

- With DM self-interactions:

$$z_\chi=\frac{m_\phi}{g_\chi}=50\,\text{MeV}\quad g_n=0$$

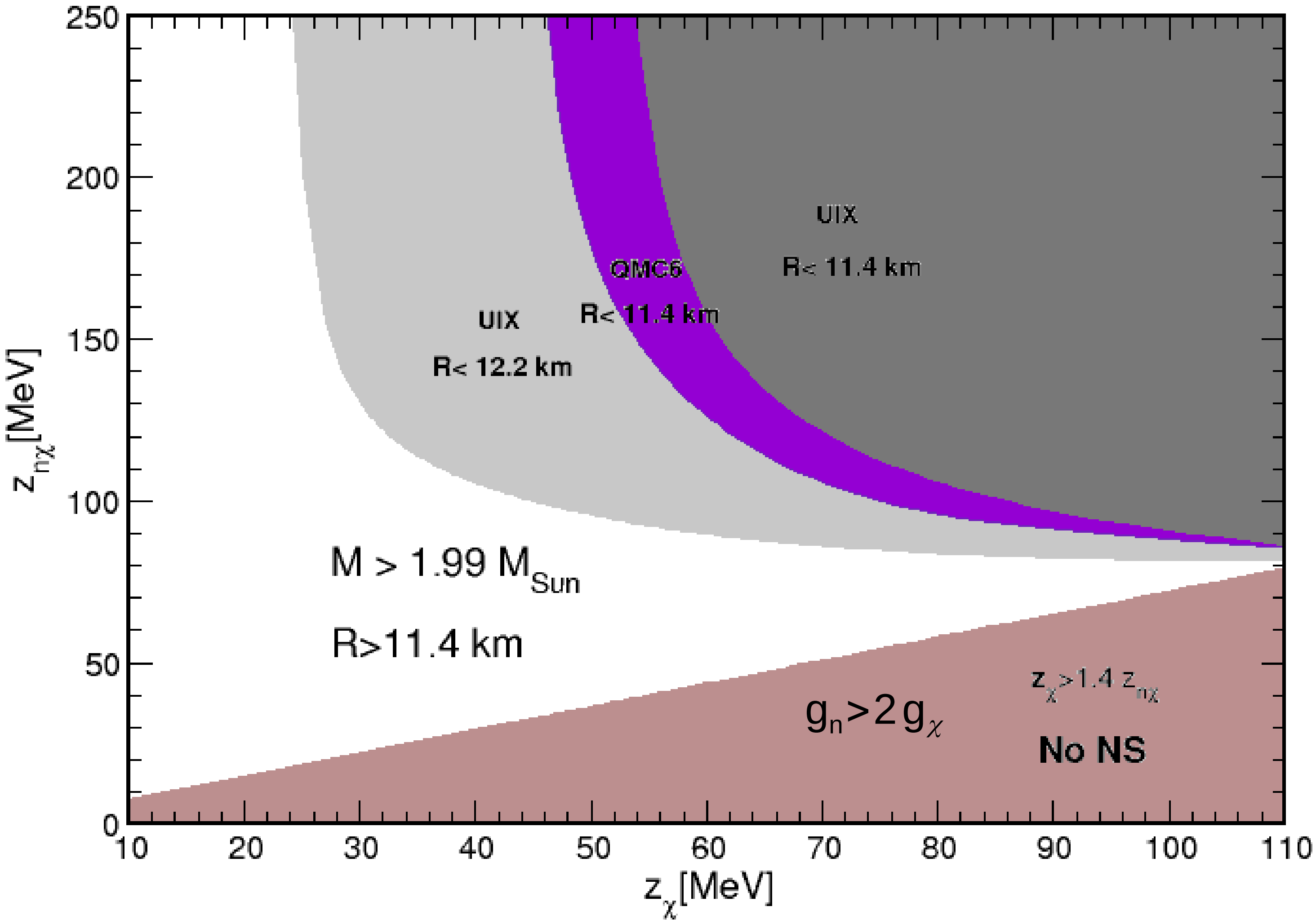
- With DM SI & repulsive DM-neutron interactions:

$$z_\chi=\frac{m_\phi}{g_\chi}=50\,\text{MeV}\quad z_{n\chi}=\frac{m_\phi}{\sqrt{g_n g_\chi}}=100\ \ \text{MeV}$$



Neutron Stars & Dark Matter

Parameter space (EoS dependent) $m_\chi \simeq 1$ GeV

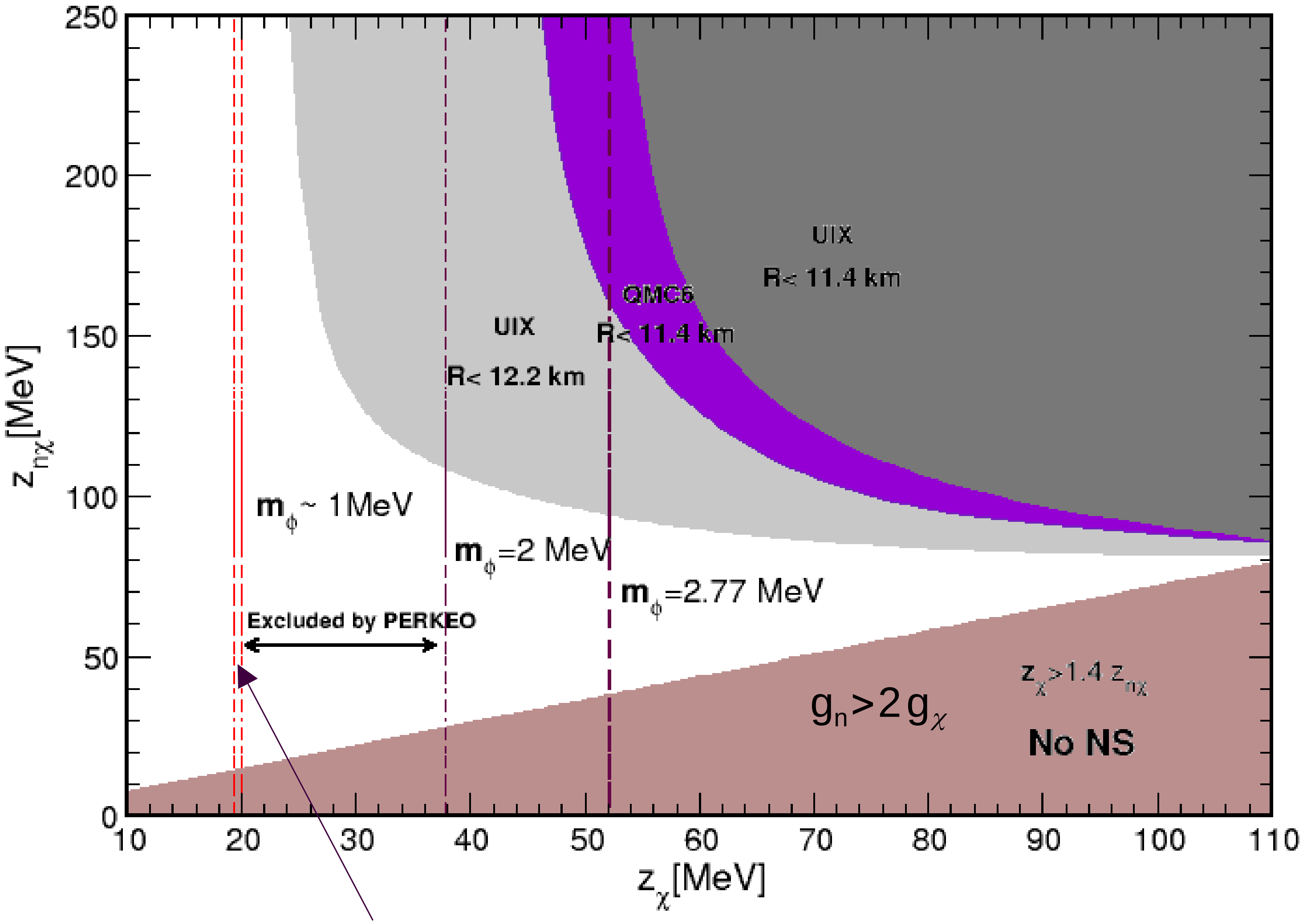


$$z_\chi = \frac{m_\phi}{g_\chi} \quad z_{n\chi} = \frac{m_\phi}{\sqrt{g_n g_\chi}}$$

Neutron Stars & Dark Matter

Parameter space (EoS dependent) $m_\chi \simeq 1$ GeV

Dark Matter Abundance: $g_\chi \simeq 0.053$



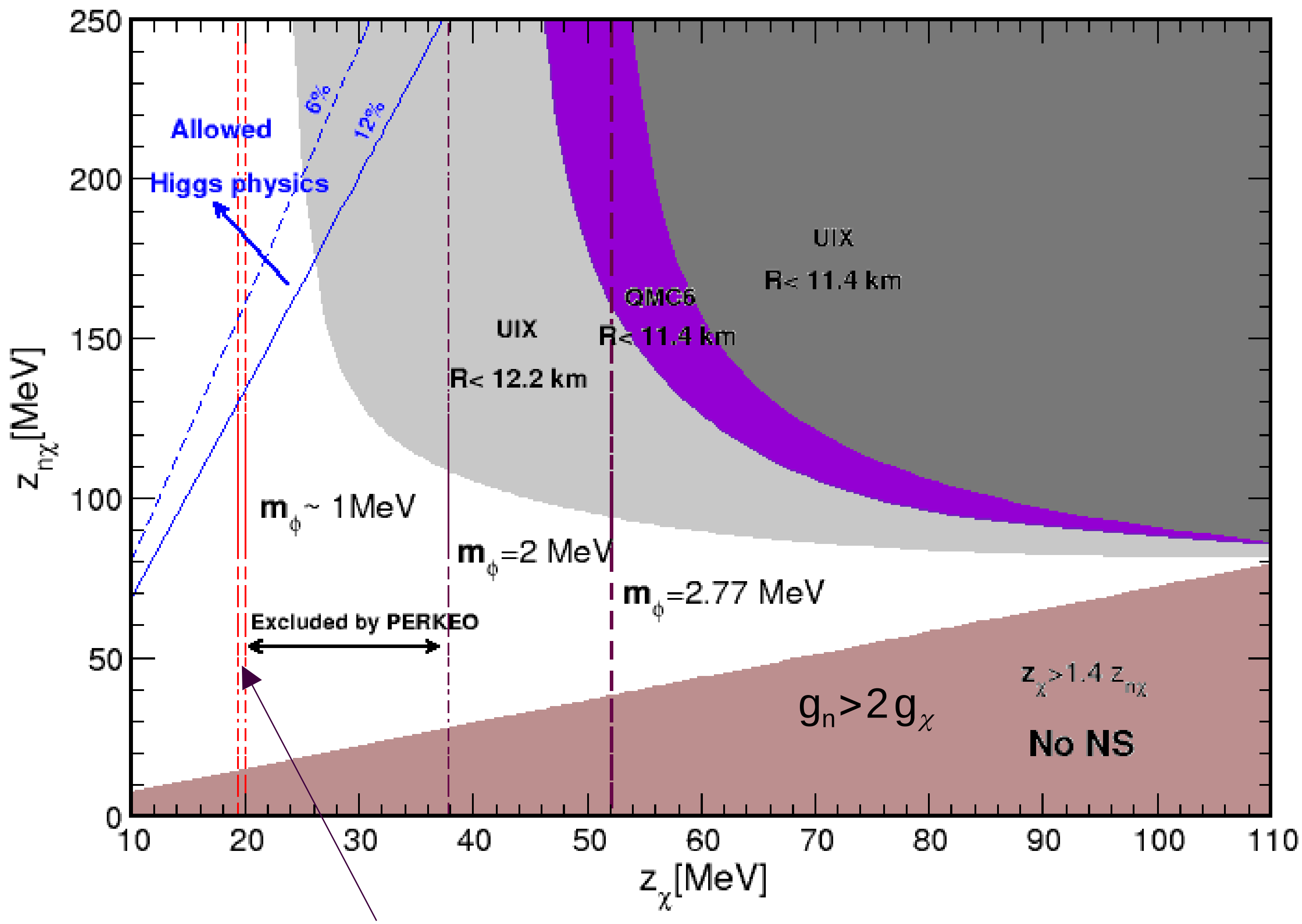
$2m_e \leq m_\phi < 2m_e + 37.5\,\text{keV}$

$$z_\chi = \frac{m_\phi}{g_\chi} \qquad z_{n\chi} = \frac{m_\phi}{\sqrt{g_n g_\chi}}$$

Neutron Stars & Dark Matter

Parameter space (EoS dependent) $m_\chi \simeq 1 \;\; \mathrm{GeV}$

Higgs physics: $2.6\,\mathrm{x}\,10^{-4} \;\; \mathrm{GeV} \le |\mu| \le 49.4\,\mathrm{GeV}$ Dark Matter Abundance: $g_\chi \simeq 0.053$



$2m_e \le m_\phi < 2m_e + 37.5\,\mathrm{keV}$

$z_\chi = \dfrac{m_\phi}{g_\chi} \qquad z_{n\chi} = \dfrac{m_\phi}{\sqrt{g_n g_\chi}}$

Neutron Stars & Dark Matter

Parameter space (EoS dependent) $m_\chi \simeq 1 \ \text{GeV}$

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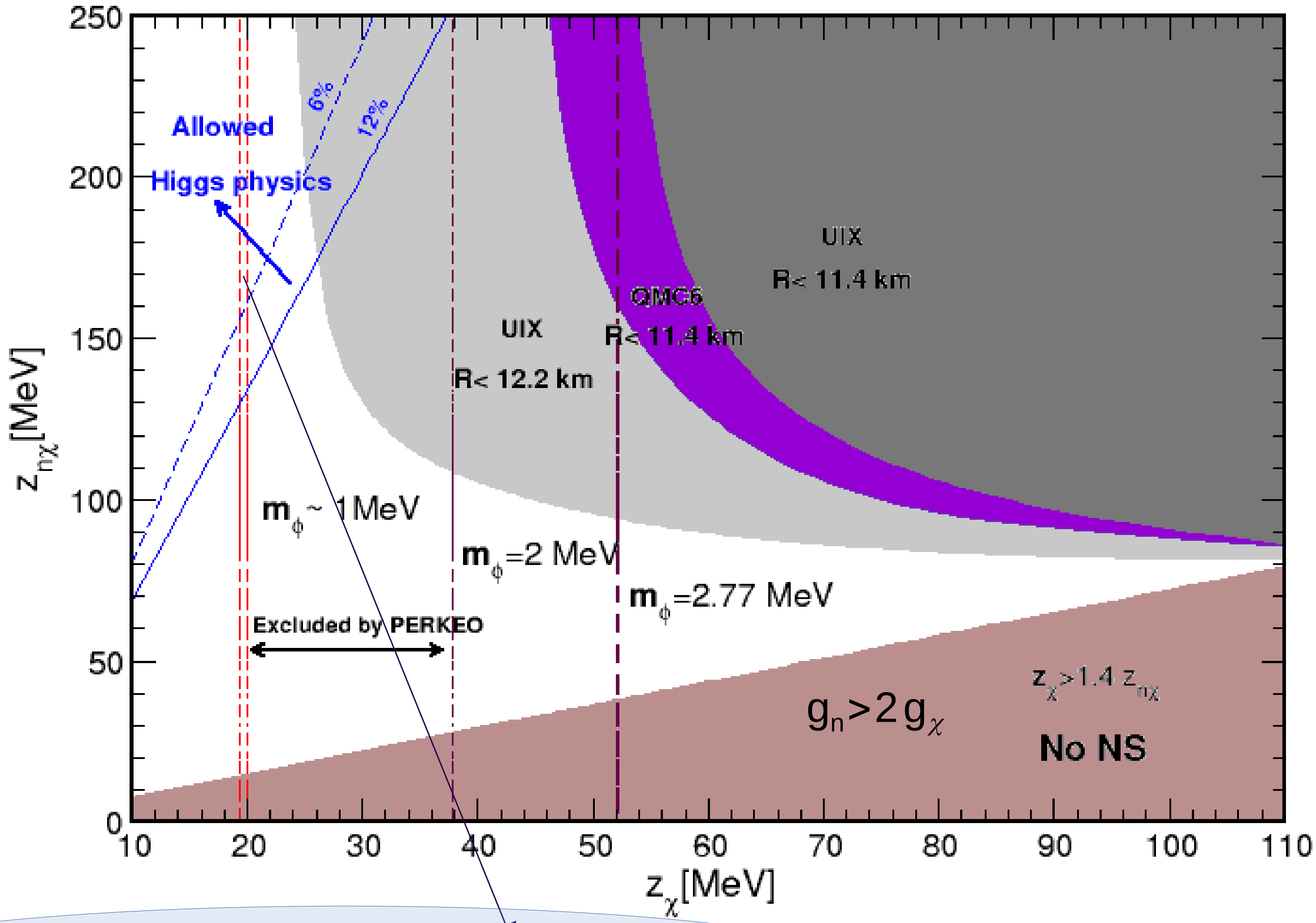


Not excluded mass range: $2m_e \leq m_\phi \leq 2m_e + 37.5 \ \text{keV}$

$$z_\chi = \frac{m_\phi}{g_\chi} \qquad z_{n\chi} = \frac{m_\phi}{\sqrt{g_n g_\chi}}$$

Summary

- **Neutron decay anomaly:** new “dark” decay channel? $n \rightarrow \chi + \phi$

$$937.993\ \text{MeV} < m_\chi + m_\phi < m_n \qquad m_\chi \sim 1\,\text{GeV}, \qquad m_\phi \sim O(\text{MeV})$$

- The fermion χ is a good candidate for Dark Matter: **standard “freeze-out”** mechanism

$$\Omega_{DM} h^2 = 0.120 \Rightarrow g_\chi \simeq 0.053$$

(coupling fermion-scalar)

- The light scalar $m_\phi > 2m_e$ decays before **BBN**, and it does not contribute to the relativistic no. of dof at the time of BBN

- **Scalar-Higgs coupling:** Limits on the invisible Higgs decay set an upper limit on the mixing ϕ-Higgs, and the couplings scalar-Higgs

- **Neutron stars:** less massive neutron stars when DM is present, but the scalar-Higgs coupling would induce an effective **repulsive interaction** neutron-DM that may compensate that effect.

$$M_{NS} \sim 2 M_{sun}\ , R < 11.4\ \text{km} \Rightarrow m_\phi < 2.77\ \text{MeV}$$

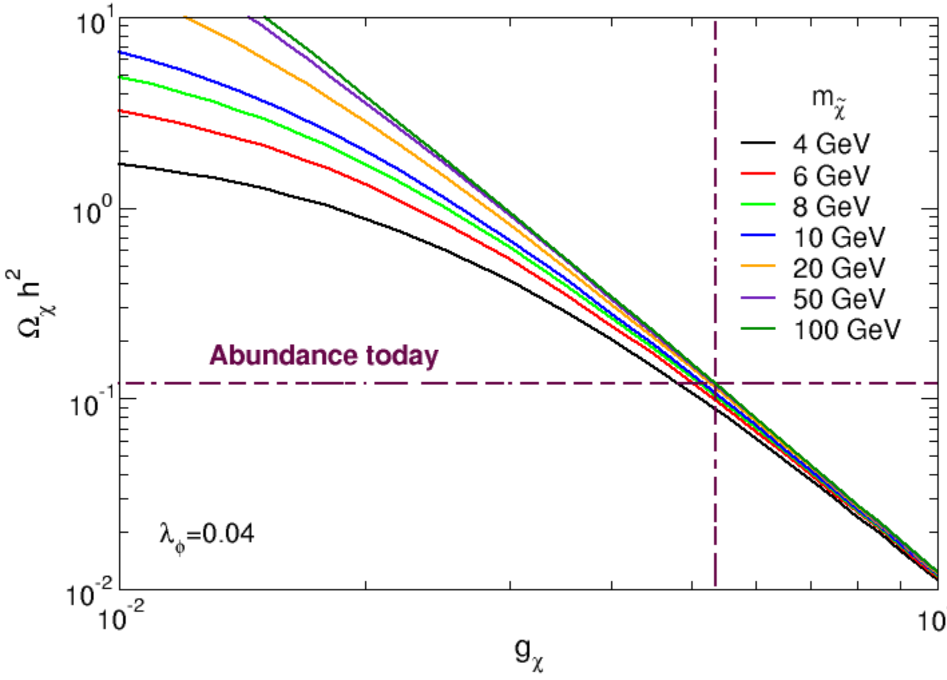
- **All constraints together:** $2m_e \le m_\phi \le \underbrace{2m_e + 37.5\ \text{keV}}$

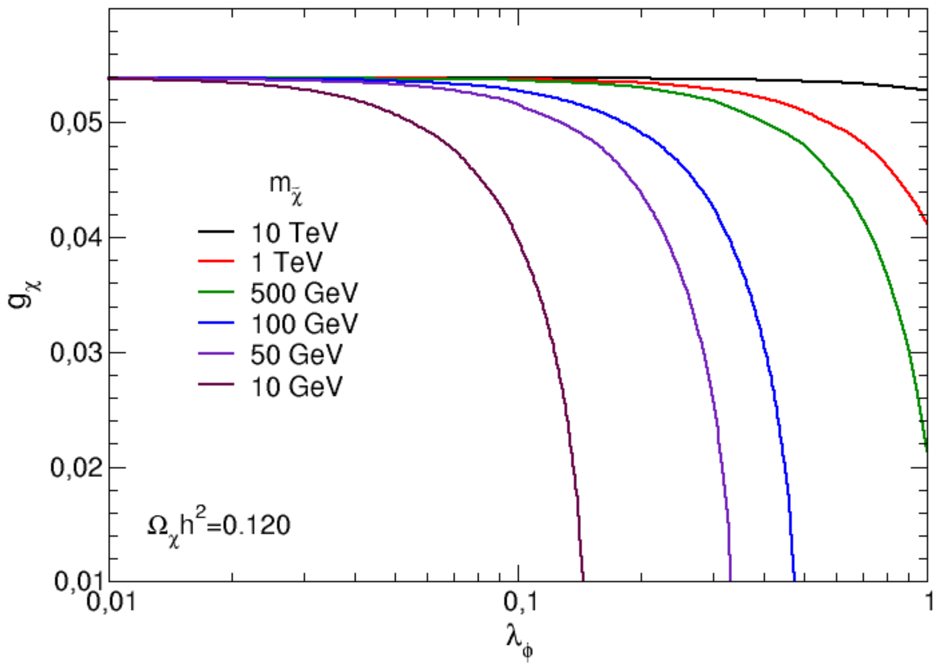
Experimental threshold [PERKEOII]

Backup slides

Dark Matter Abundance: “freeze-out” mechanism

- Annihilation cross-section: dependence on λ_ϕ, $m_{\tilde{\chi}}$

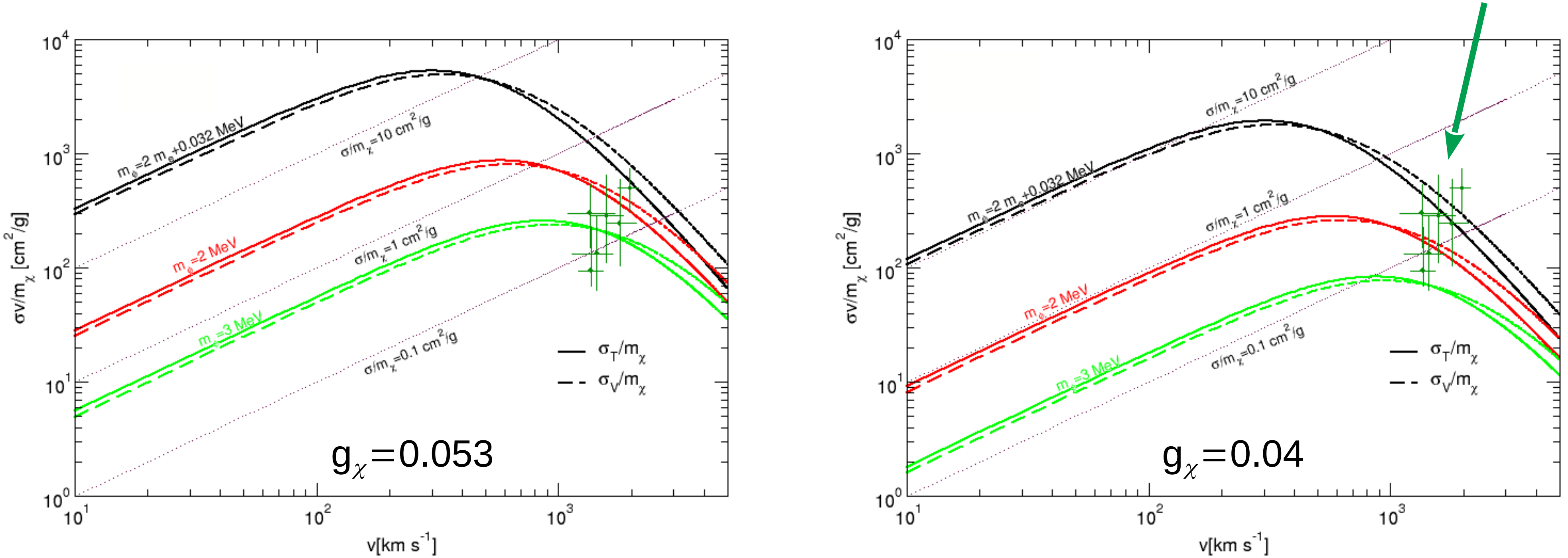




$$g_\chi \sim 0.04\,, \quad \lambda_\phi \geq 0.1\,, \quad m_{\tilde{\chi}} \leq 1 \ \text{TeV}$$

Self-Interacting Dark Matter and small scale structure

- Velocity dependent “transfer” σ_T and “viscosity σ_V cross-sections



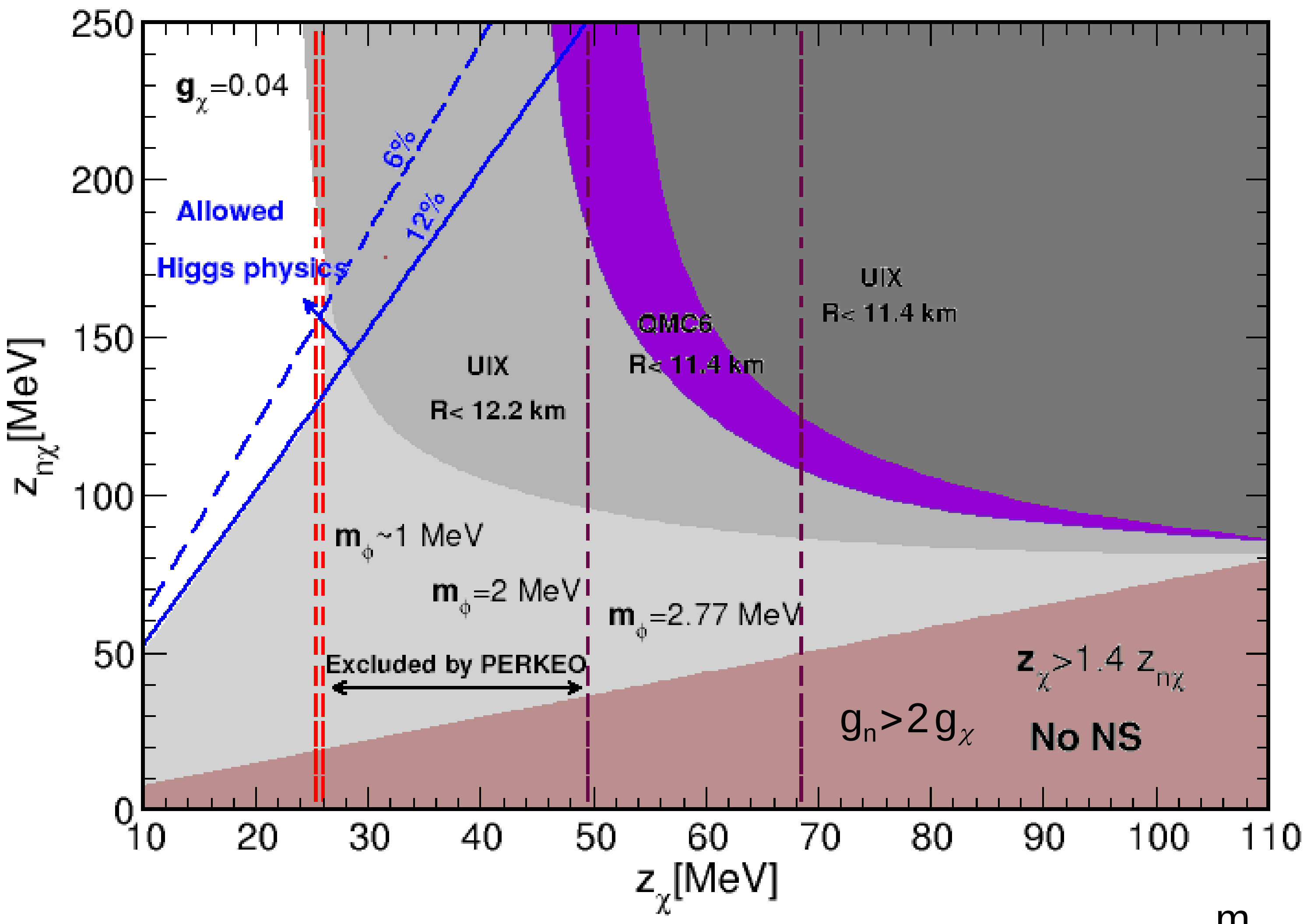
[Kaplingat, Tulin, Yu, 1508.0339]

- σ/m < 1 cm^2/g , v~ 1000-4000 km/s [Clusters]
- σ/m ~ 10 cm^2/g , v~ 30 km/s [dwarf galaxies]

Neutron Stars & Dark Matter

Parameter space (EoS dependent) $m \simeq 1$ GeV

Higgs physics: 2.6×10^{-4} GeV $\leq |\mu| \leq 49.4$ GeV Dark Matter Abundance: $g_\chi \simeq 0.04$



$$z_\chi = \frac{m_\phi}{g_\chi} \qquad z_{n\chi} = \frac{m_\phi}{\sqrt{g_n g_\chi}}$$