Neutron stars and dark matter

David McKeen

TRIUMF

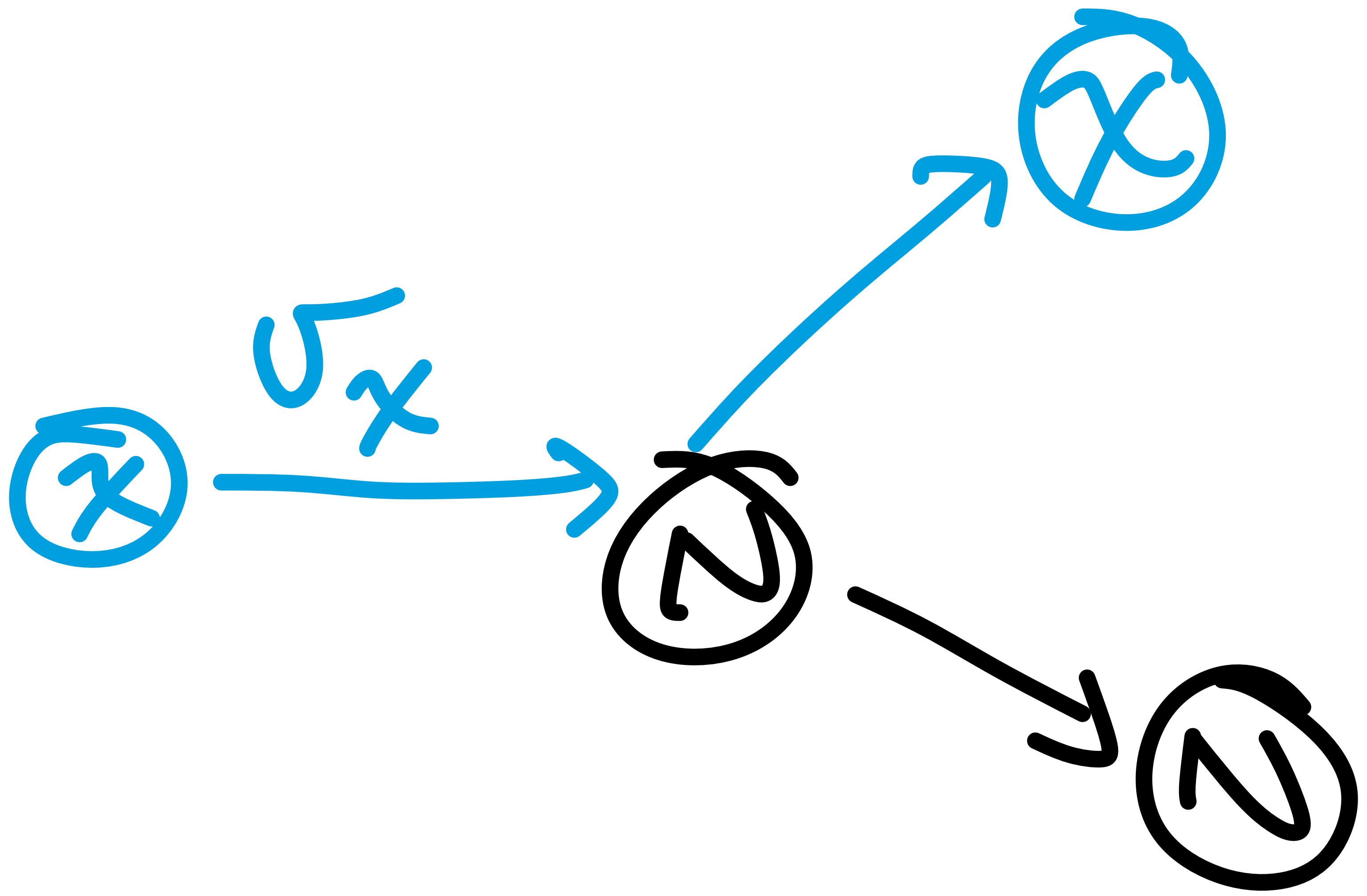
Based on work with **Coffey**, **Hostert**, **Morrissey**, **Pospelov**, **Raj**, **…**

Oklahoma State HEP Seminar
Jan. 19, 2023

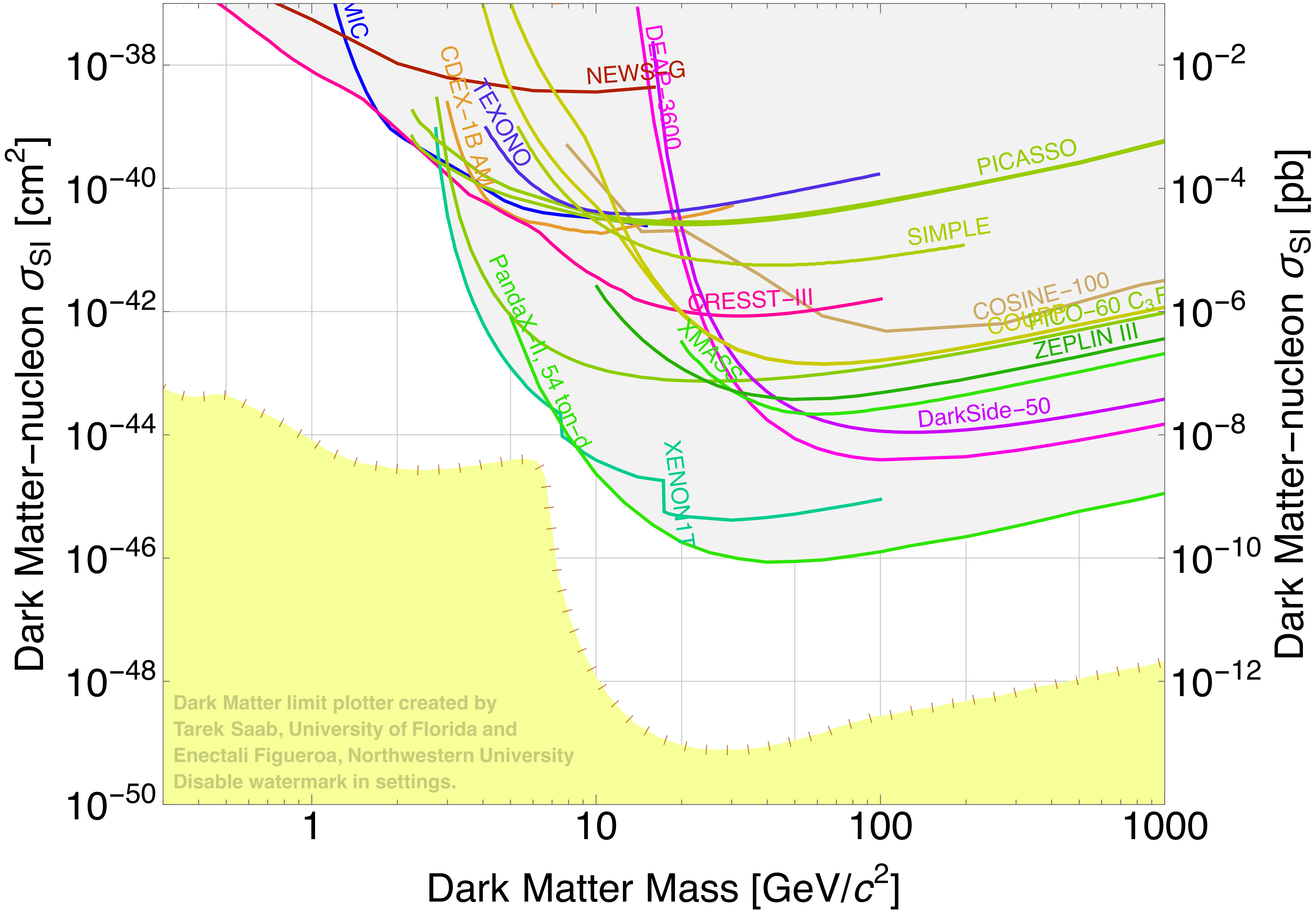
We live in a Dark Matter Halo

Image credit:
ESO/L Calçada

DM Direct Detection



$$E_{\text{recoil}} \leq \frac{2\mu_{\chi N}^2 v_\chi^2}{m_N} \sim \mathscr{O}(10 \text{ keV}) \text{ for } v_\chi \sim 10^{-3}c$$



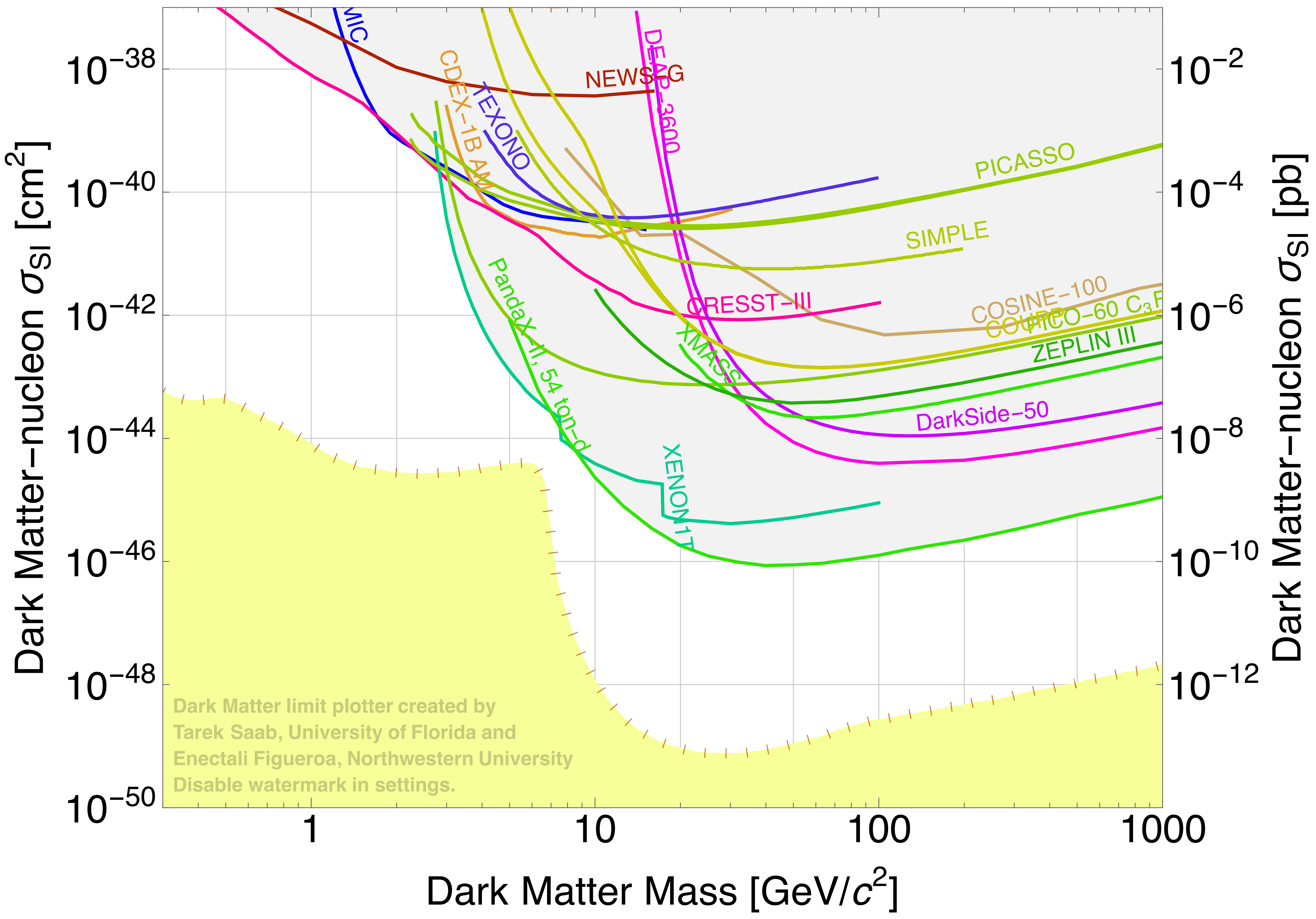
DM Direct Detection

Are there models DD has difficulty probing (but where DM still couples to SM)?

$$\mathscr{L}_{\text{eff}} = \frac{1}{\Lambda^2}\frac{m_q}{v}\bar{\chi}i\gamma^5\chi\bar{q}i\gamma^5 q$$

$$\sigma_{\text{SI}} \simeq \propto v_\chi^2$$

Can be very small for $v_\chi \sim 10^{-3}$



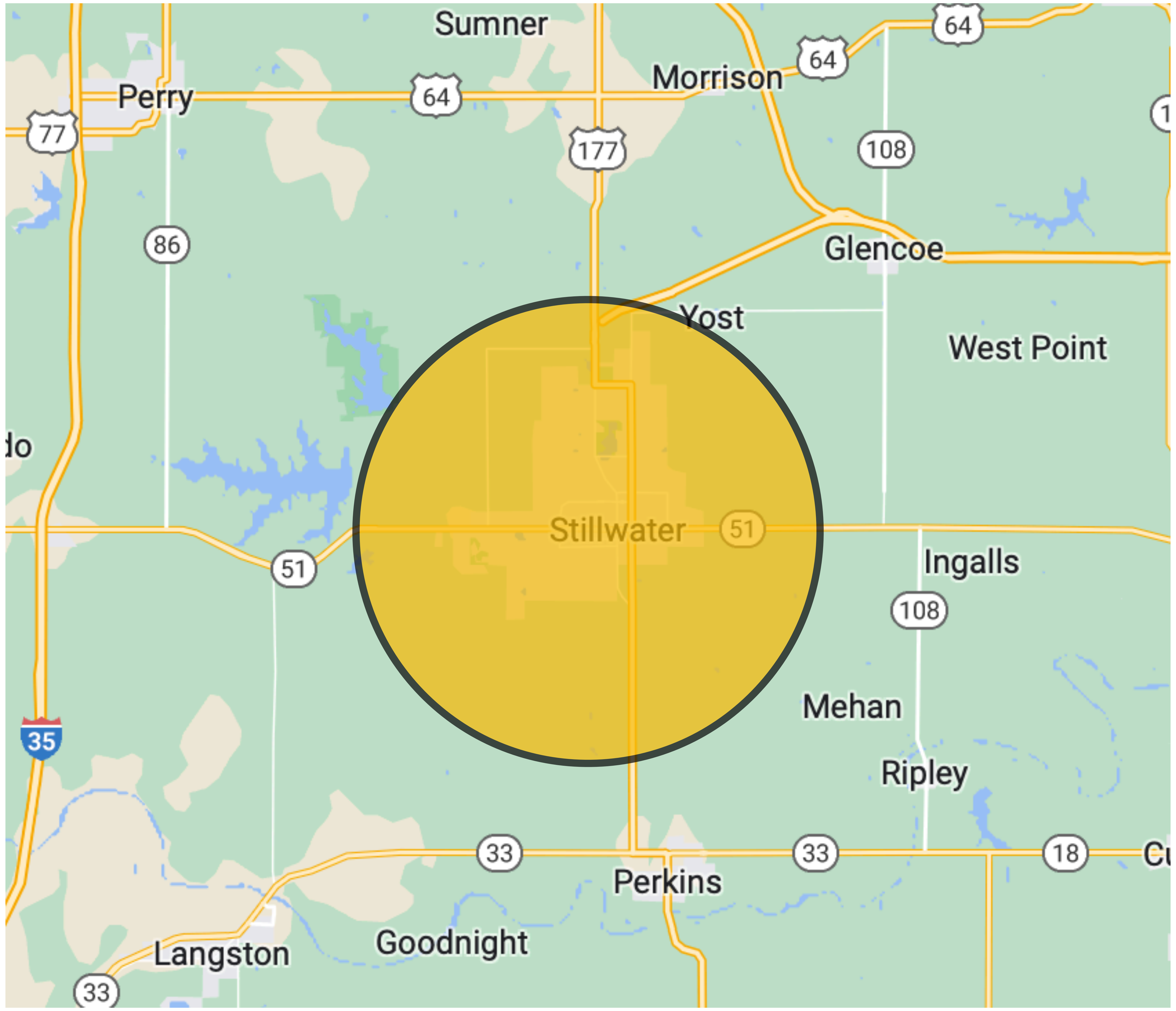
Neutron Stars

Can we really not do direct detection in this case? $\sigma_{\chi n} \propto v_\chi^2$ is tiny for $v_\chi \sim 10^{-3} c$ $\Rightarrow$ all we need to do is speed up the DM

$v_{\mathrm{esc}} = \sqrt{\dfrac{2GM}{R}} \sim 0.5c \sqrt{\dfrac{M}{M_\odot} \times \dfrac{10\ \mathrm{km}}{R}}$ $\Rightarrow$ put a sun's worth of stuff in a city's amount of space

⇒neutron star!

Neutron Stars



End stage of life of relatively massive stars after using up fuel

$$M \sim 1 - 2M_{\odot}, R \sim 10 \text{ km}$$

Highly degenerate

Densities of order nuclear density

Coffey, DM, Morrissey, Raj 2207.02221

Model Number 1

Axion(-like) Particles

Introduce DM and a complex scalar field

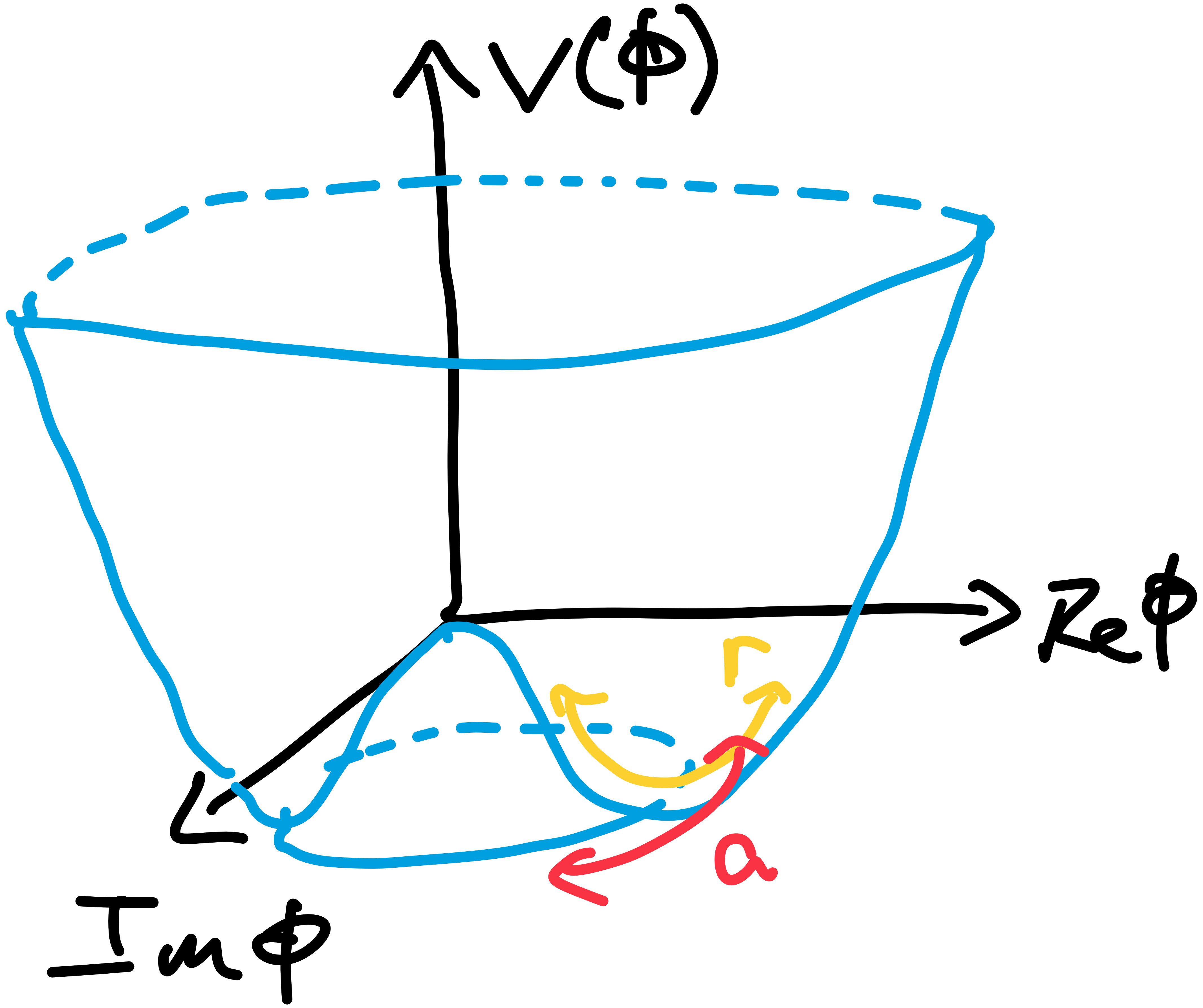
$$\mathscr{L} \supset -g_\chi \phi \bar{\chi}_R \chi_L + \mathrm{h.c.}$$

Scalar field develops vev

$$\phi = \frac{f}{\sqrt{2}}\left(1+\frac{r}{f}\right)e^{ia/f} \Rightarrow \mathscr{L} \supset m_\chi \frac{a}{f}\bar{\chi} i\gamma^5 \chi$$

Coupled to SM through e.g. vector-like quarks

$$\mathscr{L} \supset -y_Q \phi \bar{Q}_R Q_L + \mathrm{h.c.} \Rightarrow \frac{\alpha_s}{4\pi}\frac{N_Q}{2}\frac{a}{f}G\tilde{G}$$



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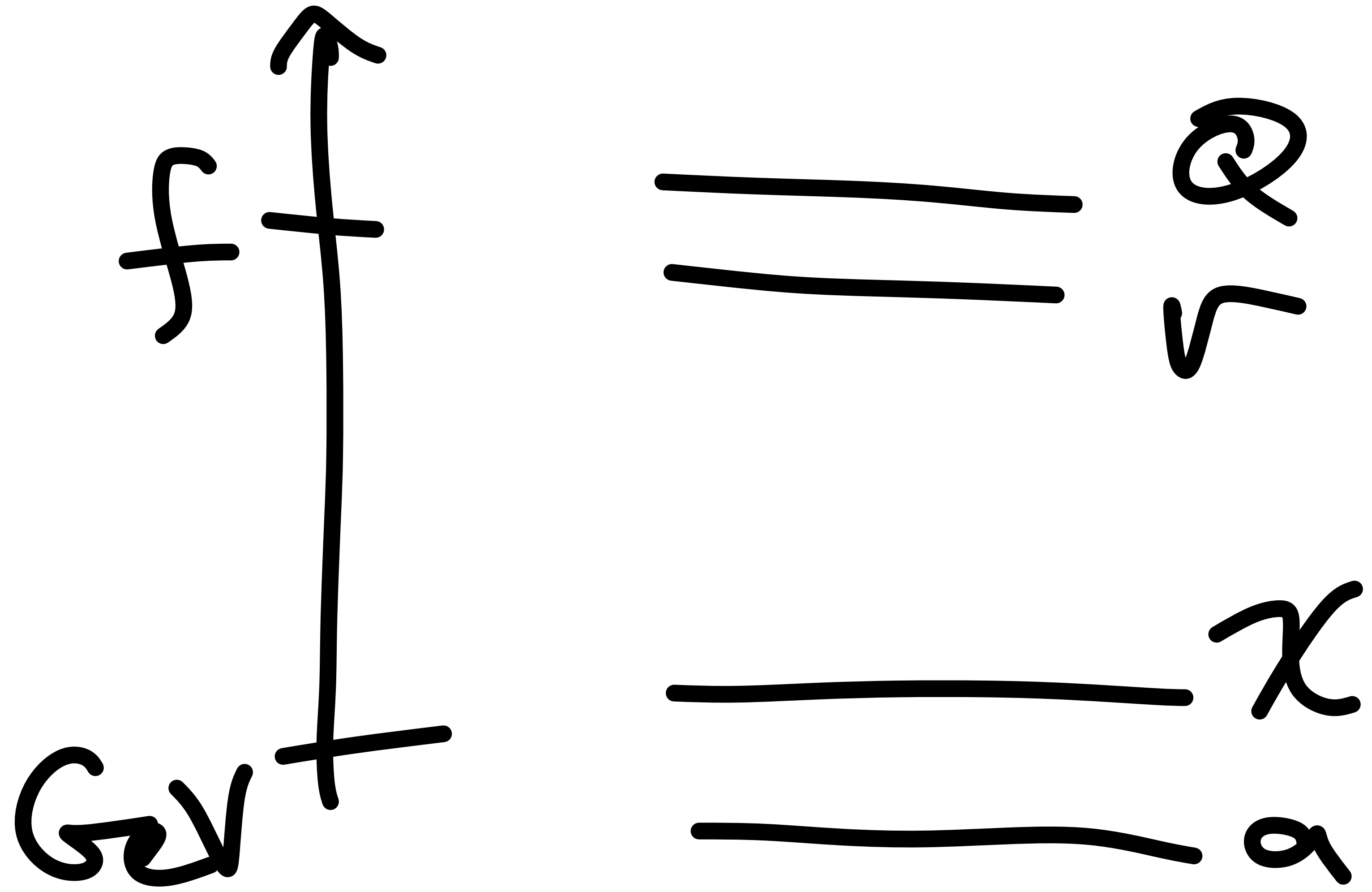
Spectrum



a is naturally "light" (GeV or lower here)

Axion(-like) Particles

Introduce DM and a complex scalar field

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Scalar field develops vev

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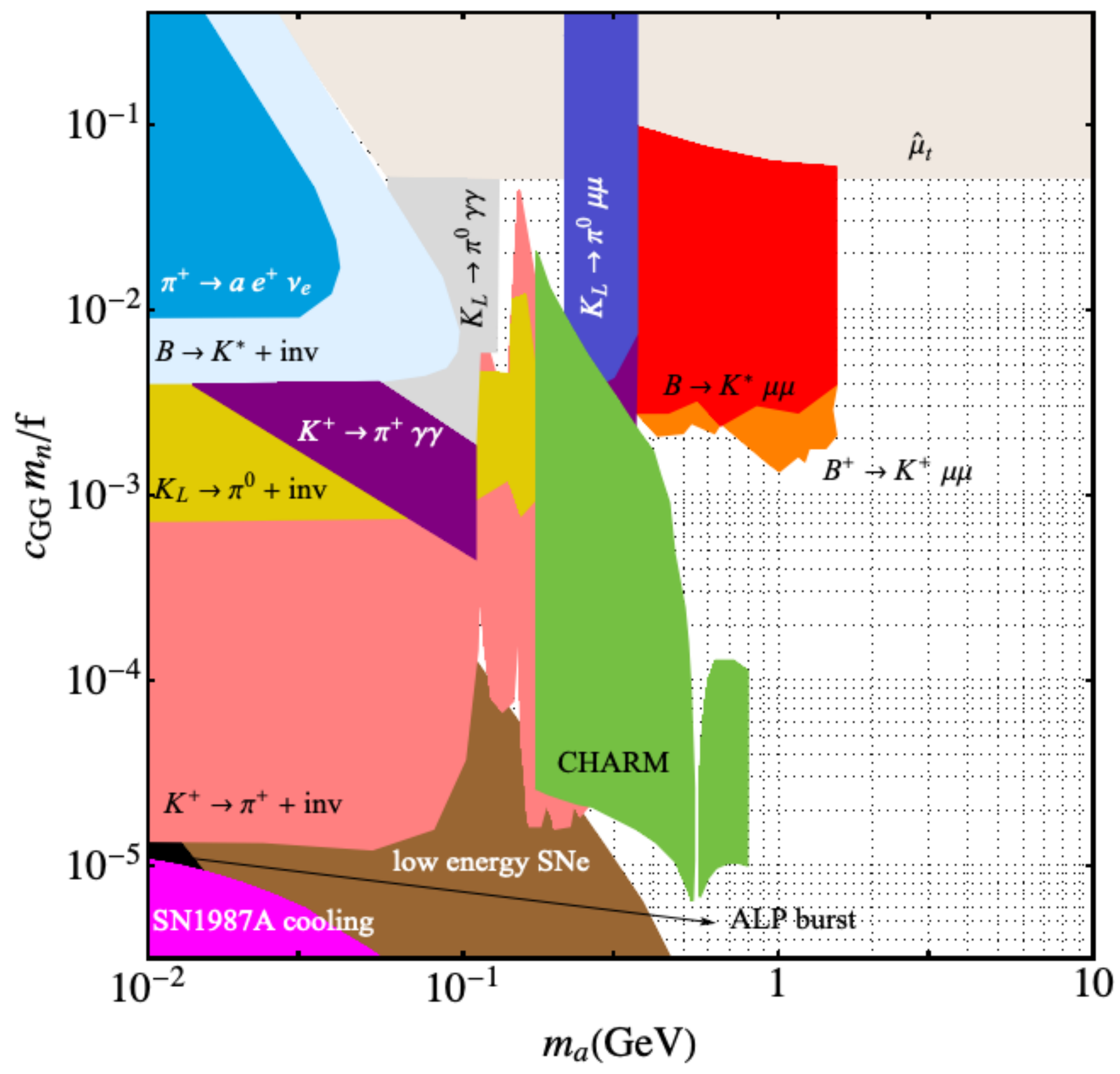
Coupled to SM through e.g. vector-like quarks

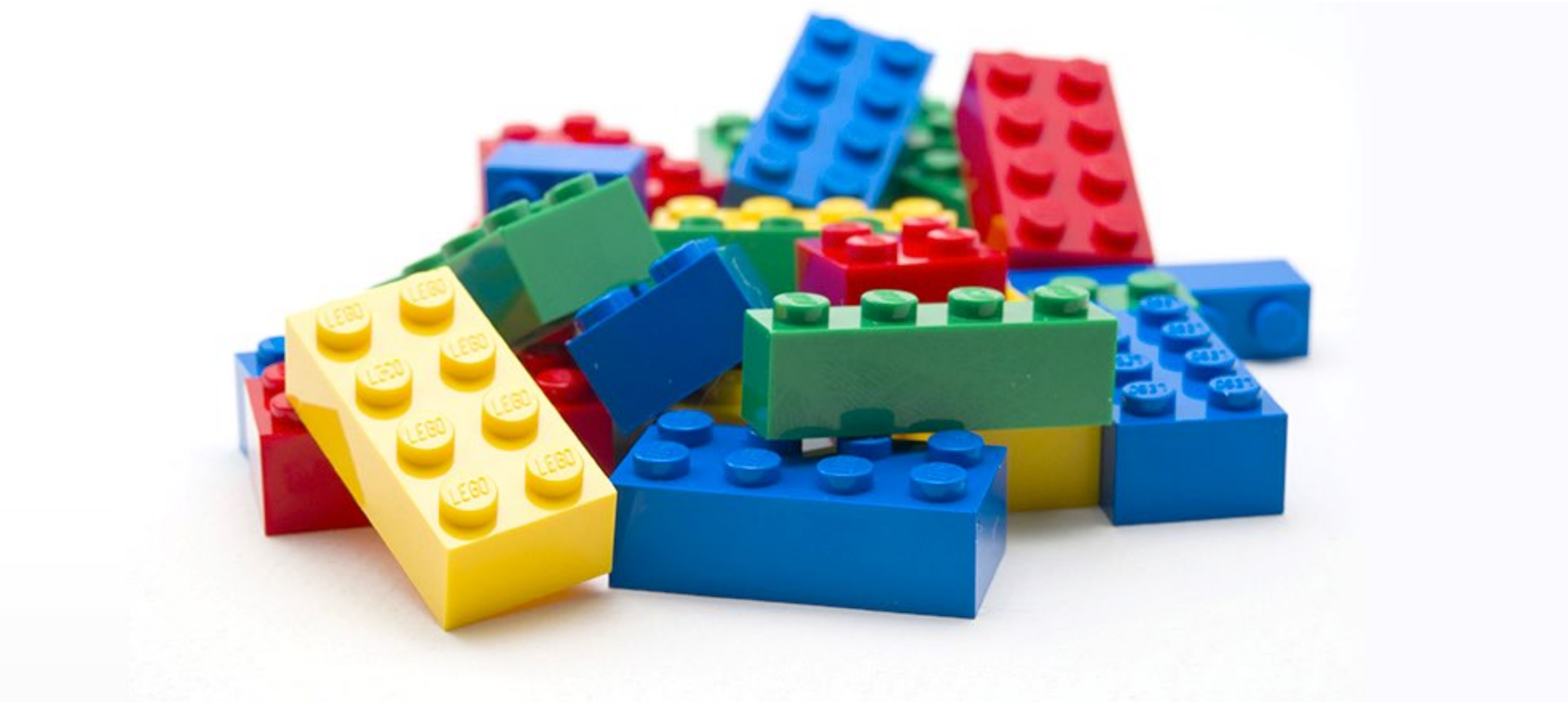
$$\mathscr{L} \supset -y_Q \phi \bar{Q}_R Q_L + \mathrm{h.c.} \Rightarrow \underset{\hookrightarrow C_{GG}}{\frac{\alpha_s}{4\pi} \frac{N_Q}{2}} \frac{a}{f} G\tilde{G}$$



See e.g. Bauer et al. 2012.12272

Coffey, DM, Morrissey, Raj 2207.02221

Model Number 2



2HDM+a

PHYSICAL REVIEW D **90,** 055021 (2014)

Renormalizable model for the Galactic Center gamma-ray excess from dark matter annihilation

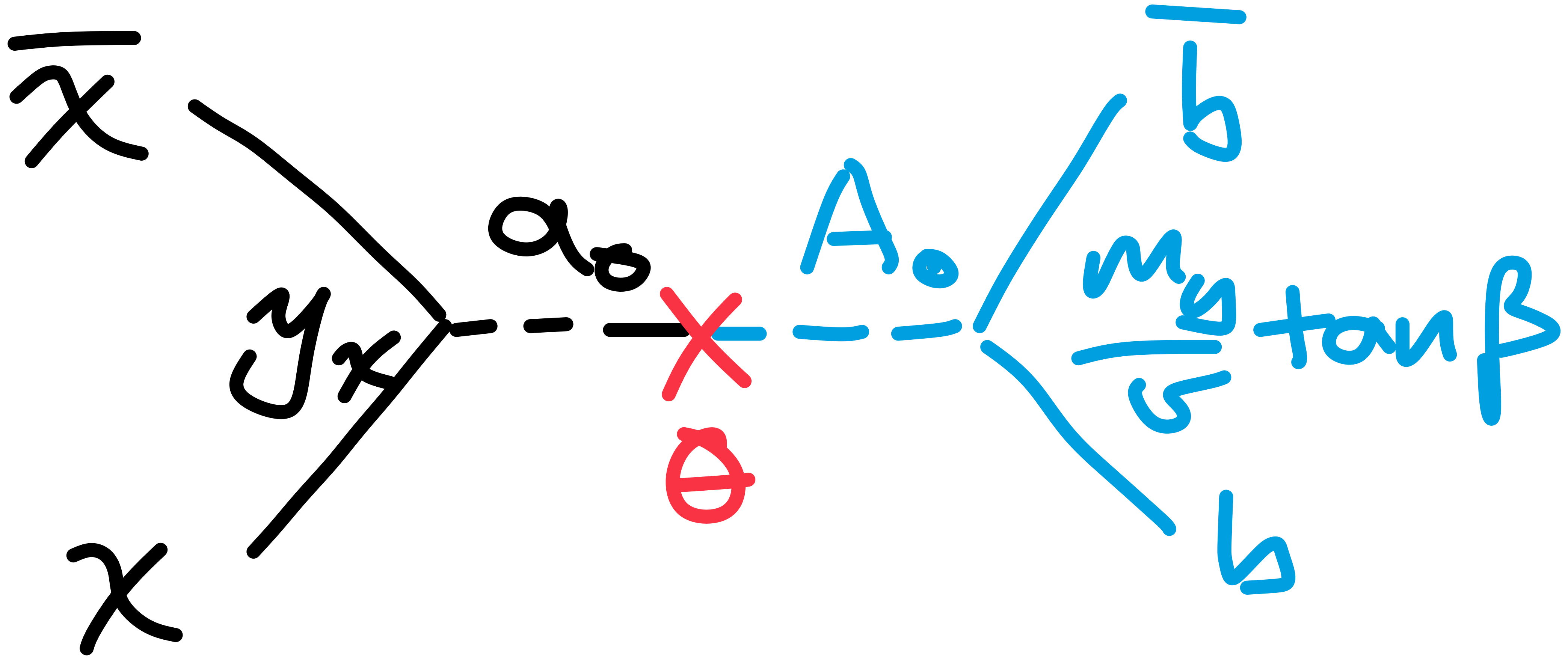
Seyda Ipek, David McKeen, and Ann E. Nelson
Department of Physics, University of Washington, Seattle, Washington 98195, USA
(Received 15 July 2014; published 22 September 2014)

$$\mathscr{L} \supset -y_\chi a_0 \bar{\chi} i\gamma^5 \chi - (i\mu_{a12} a_0 H_1^\dagger H_2 + \mathrm{h.c.}) - \frac{1}{2} m_{a_0}^2 a_0^2$$

2.25HDM

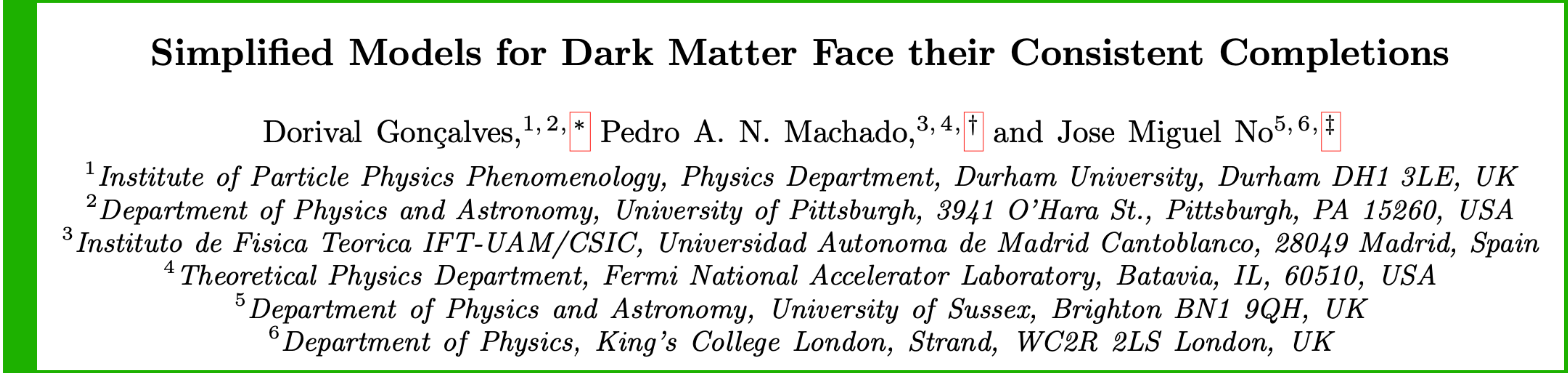
$$\tan 2\theta = -\frac{2\mu_{a12} v}{m_A^2 - m_a^2}$$

$$\langle \sigma v_{\rm rel} \rangle = 3 \times 10^{-26}\ \frac{\mathrm{cm}^3}{\mathrm{s}} \left(\frac{y_\chi \sin 2\theta \tan\beta}{2.4} \right)^2 .$$



$\sigma_{\rm SI} \propto v_\chi^2$ is “small”

Motivation for 2.25HDM



Simplified Models for Dark Matter Face their Consistent Completions

Dorival Gonçalves,[1, 2, *] Pedro A. N. Machado,[3, 4, †] and Jose Miguel No[5, 6, ‡]
[1] Institute of Particle Physics Phenomenology, Physics Department, Durham University, Durham DH1 3LE, UK
[2] Department of Physics and Astronomy, University of Pittsburgh, 3941 O'Hara St., Pittsburgh, PA 15260, USA
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[4] Theoretical Physics Department, Fermi National Accelerator Laboratory, Batavia, IL, 60510, USA
[5] Department of Physics and Astronomy, University of Sussex, Brighton BN1 9QH, UK
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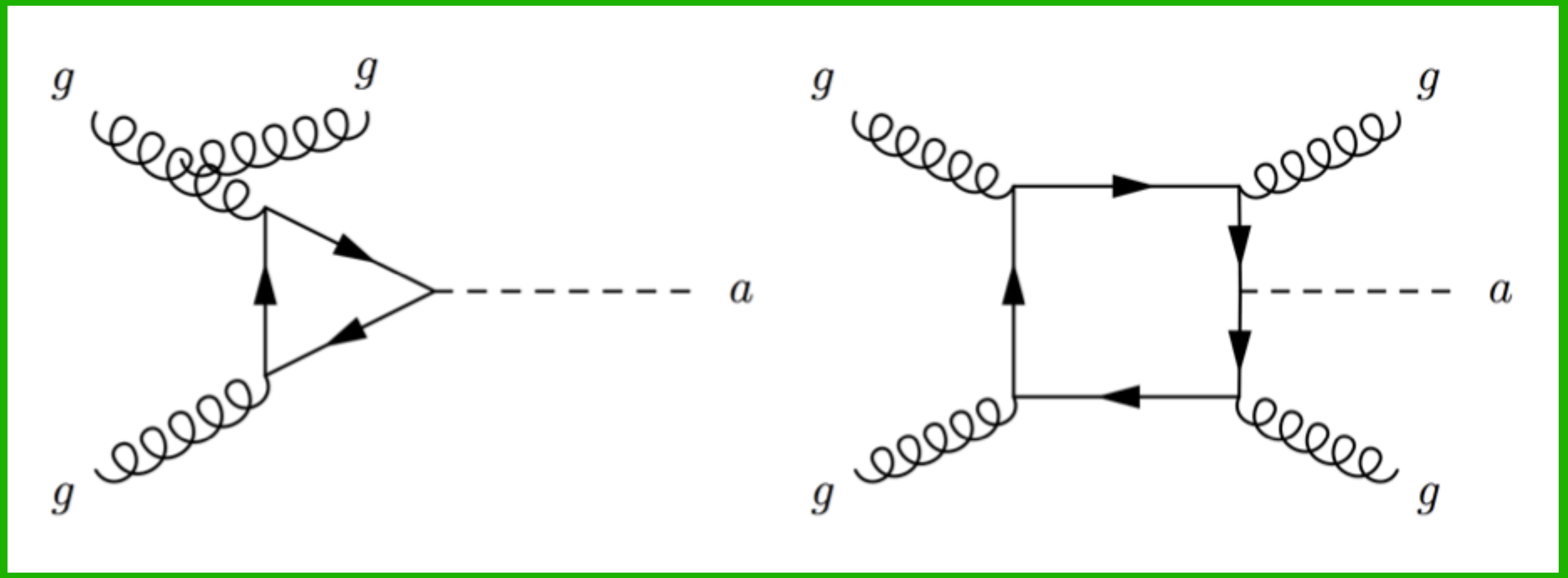
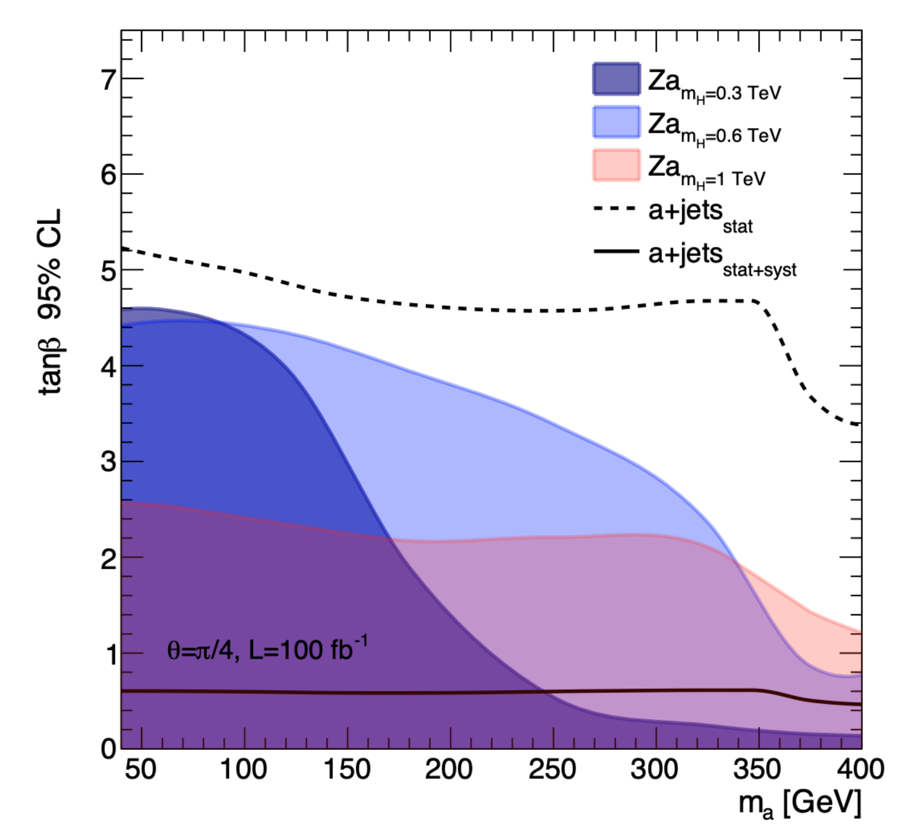
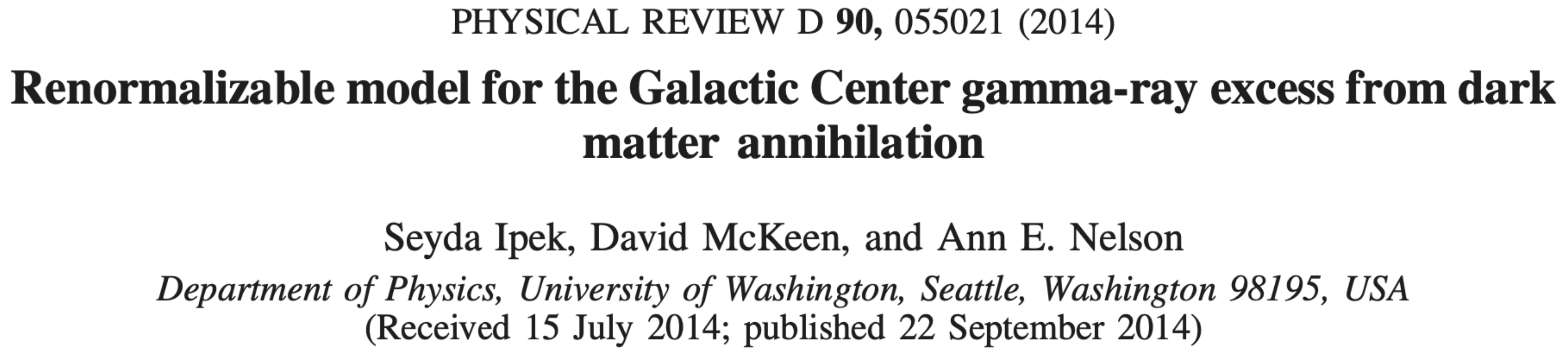




2HDM+a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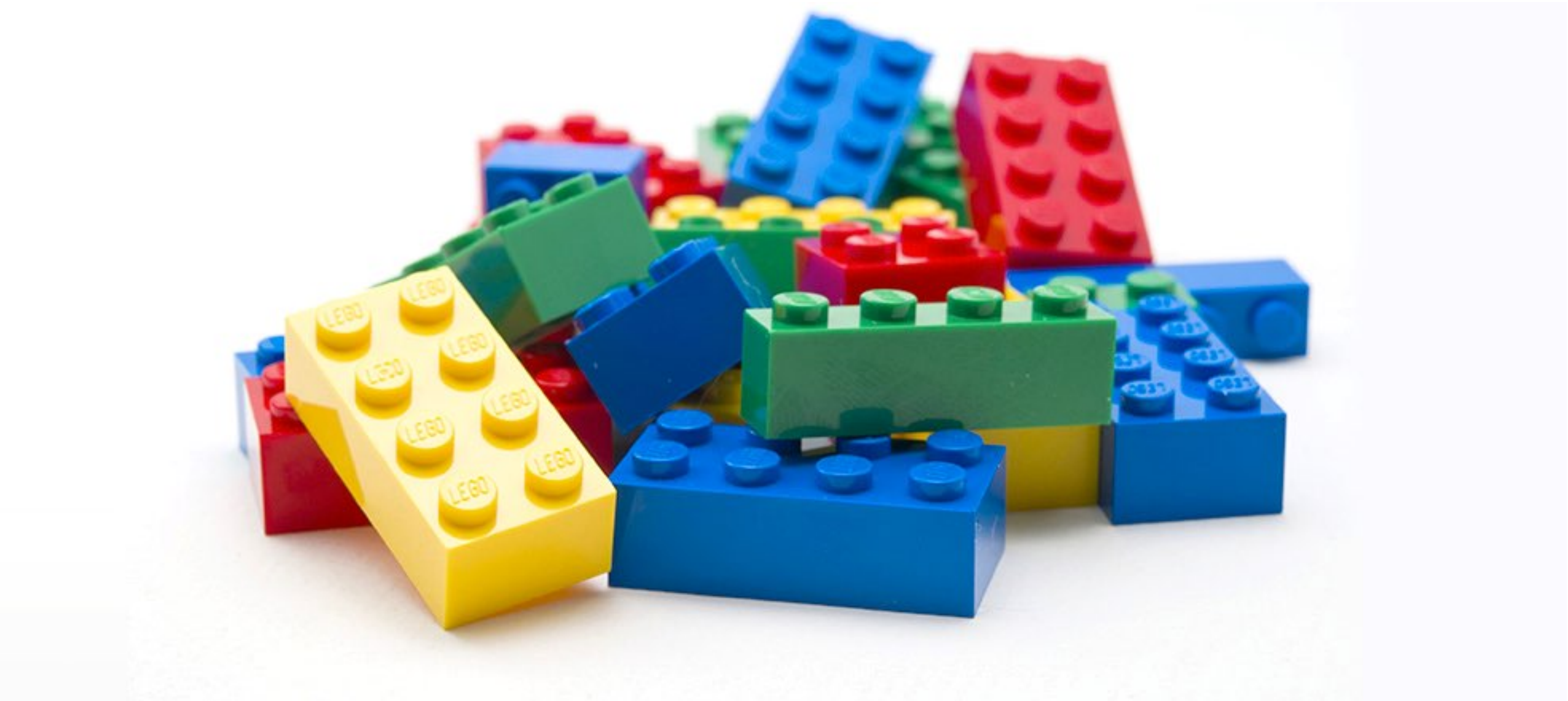


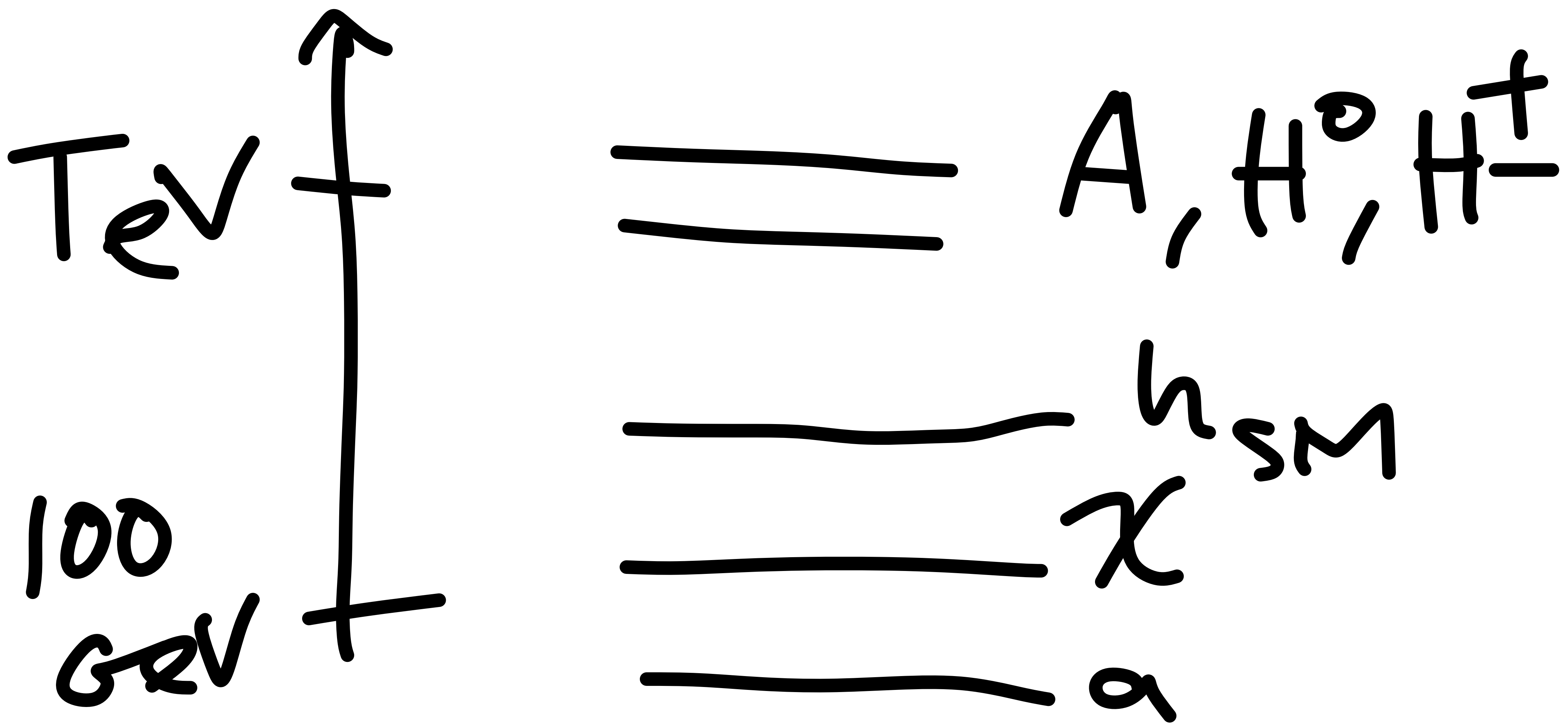
$$\mathscr{L} \supset -y_\chi a_0 \bar{\chi} i\gamma^5 \chi - (i\mu_{a12} a_0 H_1^\dagger H_2 + \mathrm{h.c.}) - \frac{1}{2} m_{a_0}^2 a_0^2$$

2.25HDM

$$\tan 2\theta = -\frac{2\mu_{a12} v}{m_A^2 - m_a^2}$$

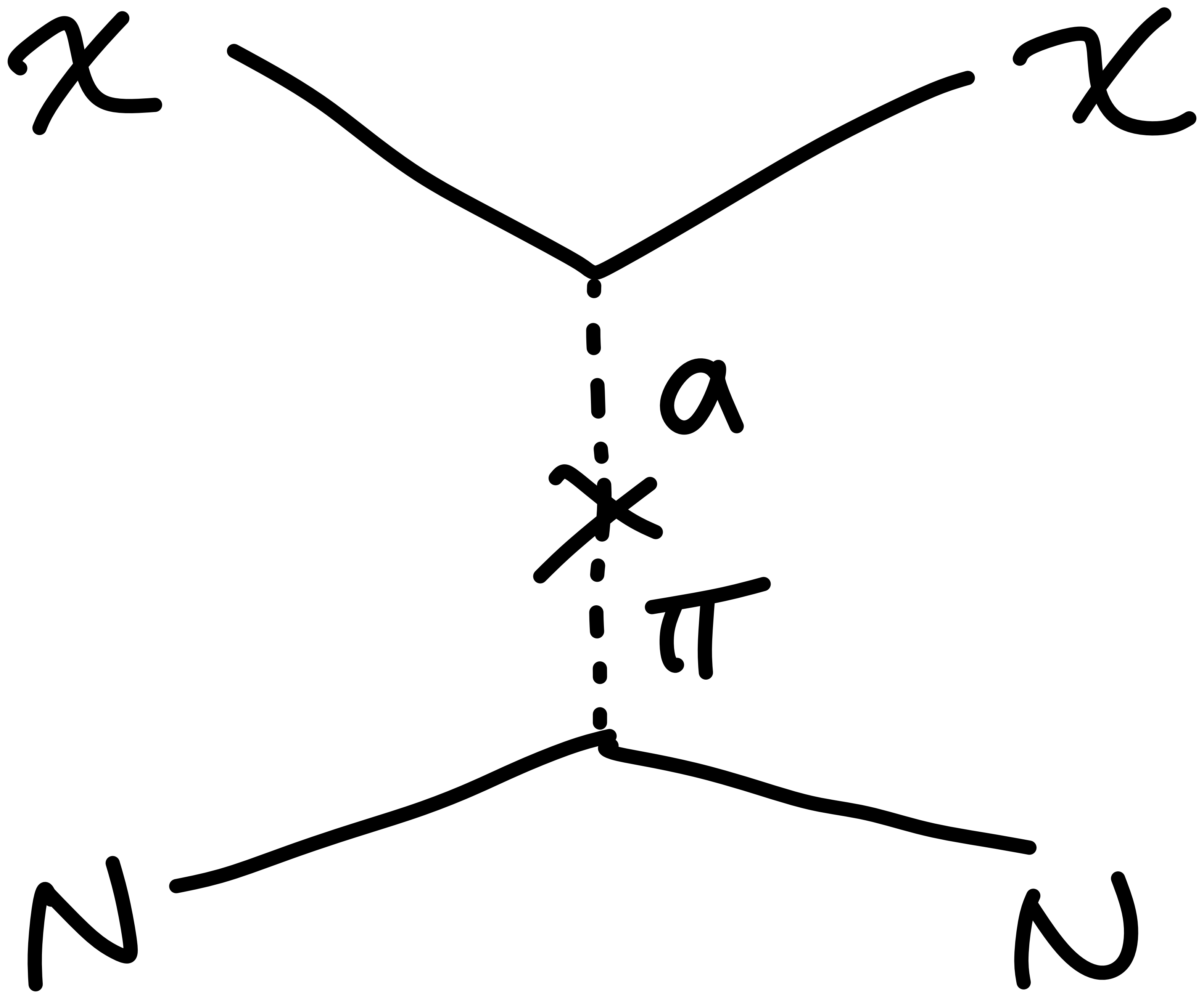
a is "comfortable" at the $\mathcal{O}(10\ \mathrm{GeV})$ scale

Spectrum

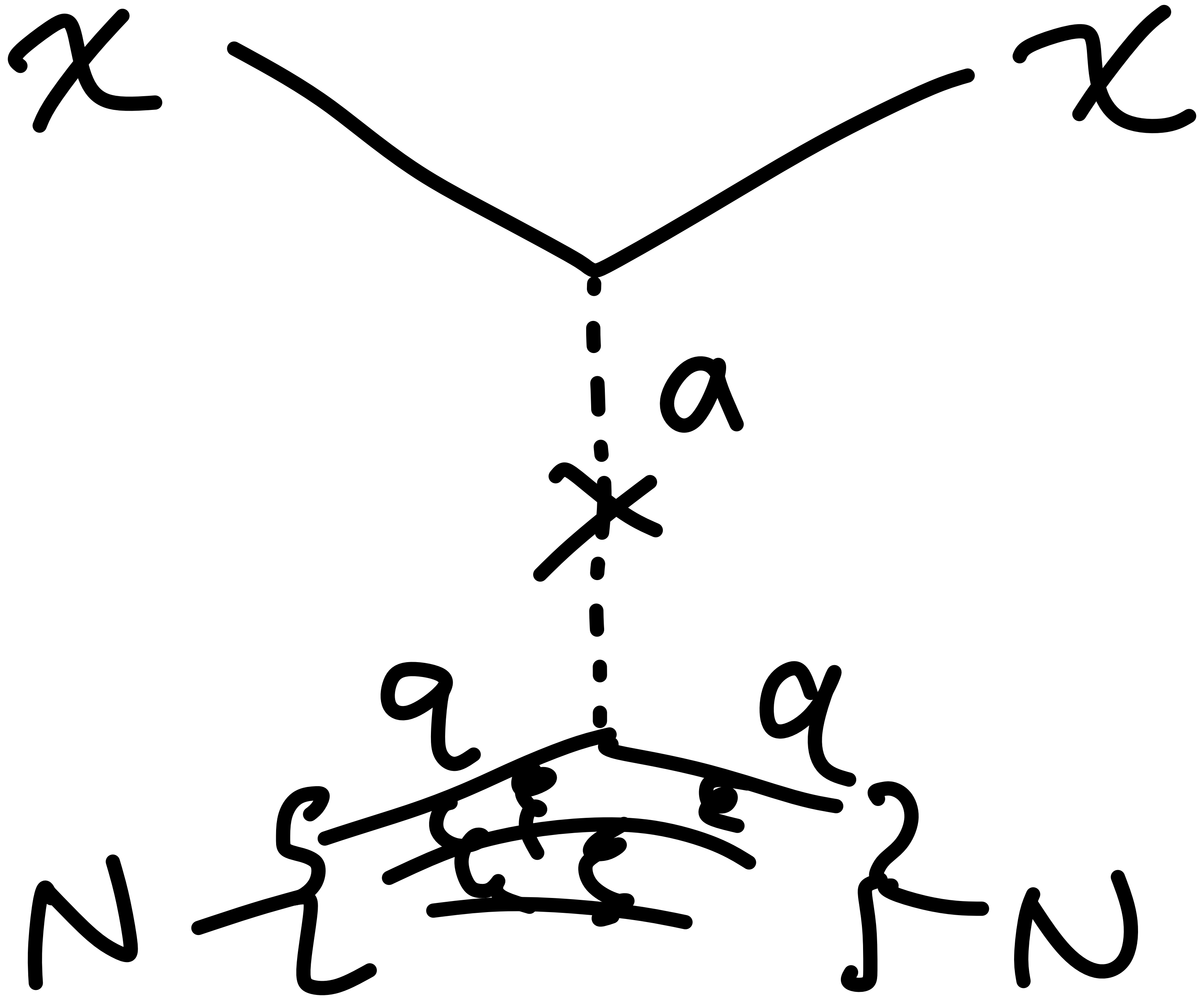


Scattering on Nucleons

ALP model



2HDM+a model



Velocity (and spin) dependent

Scattering on Nucleons

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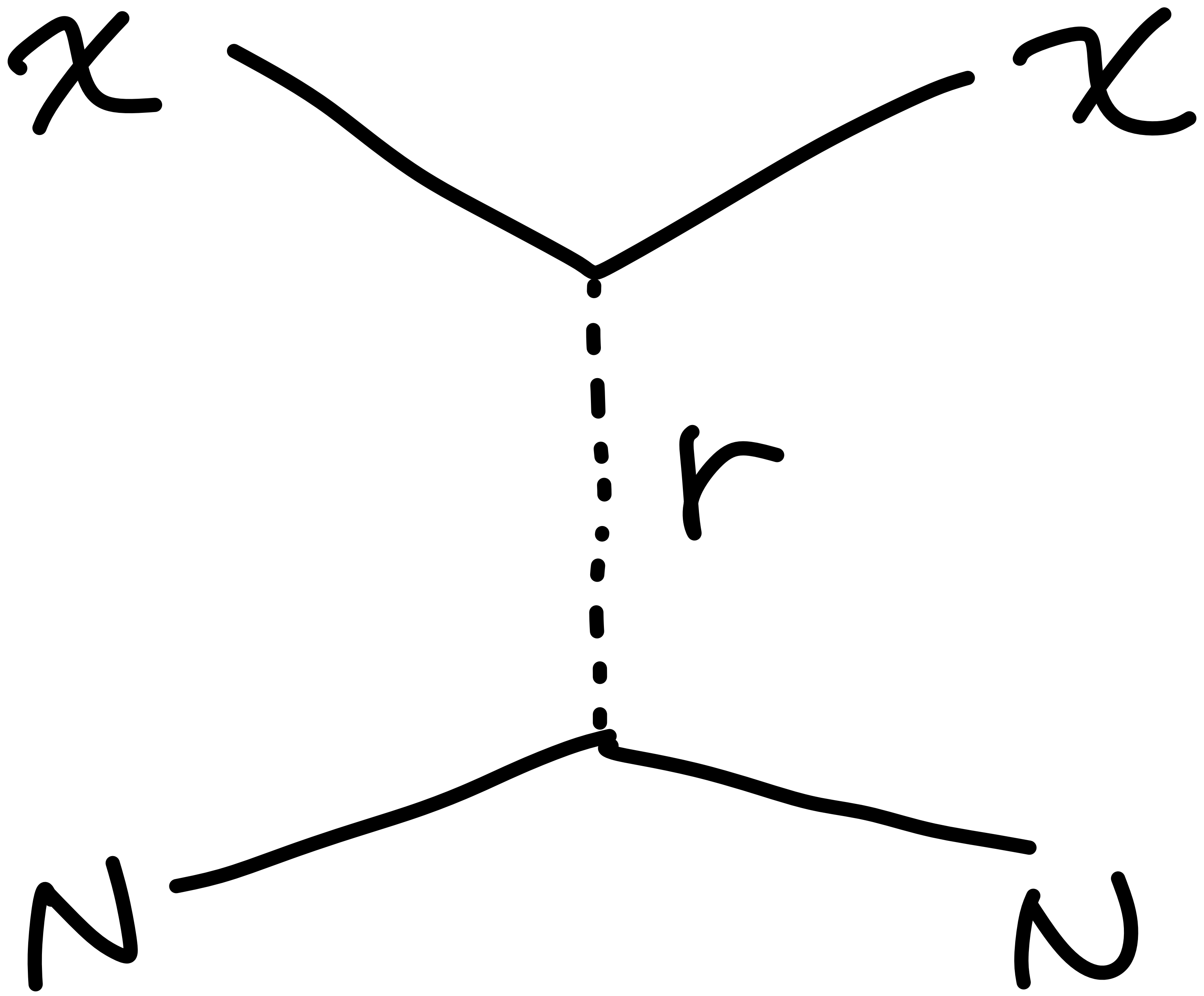

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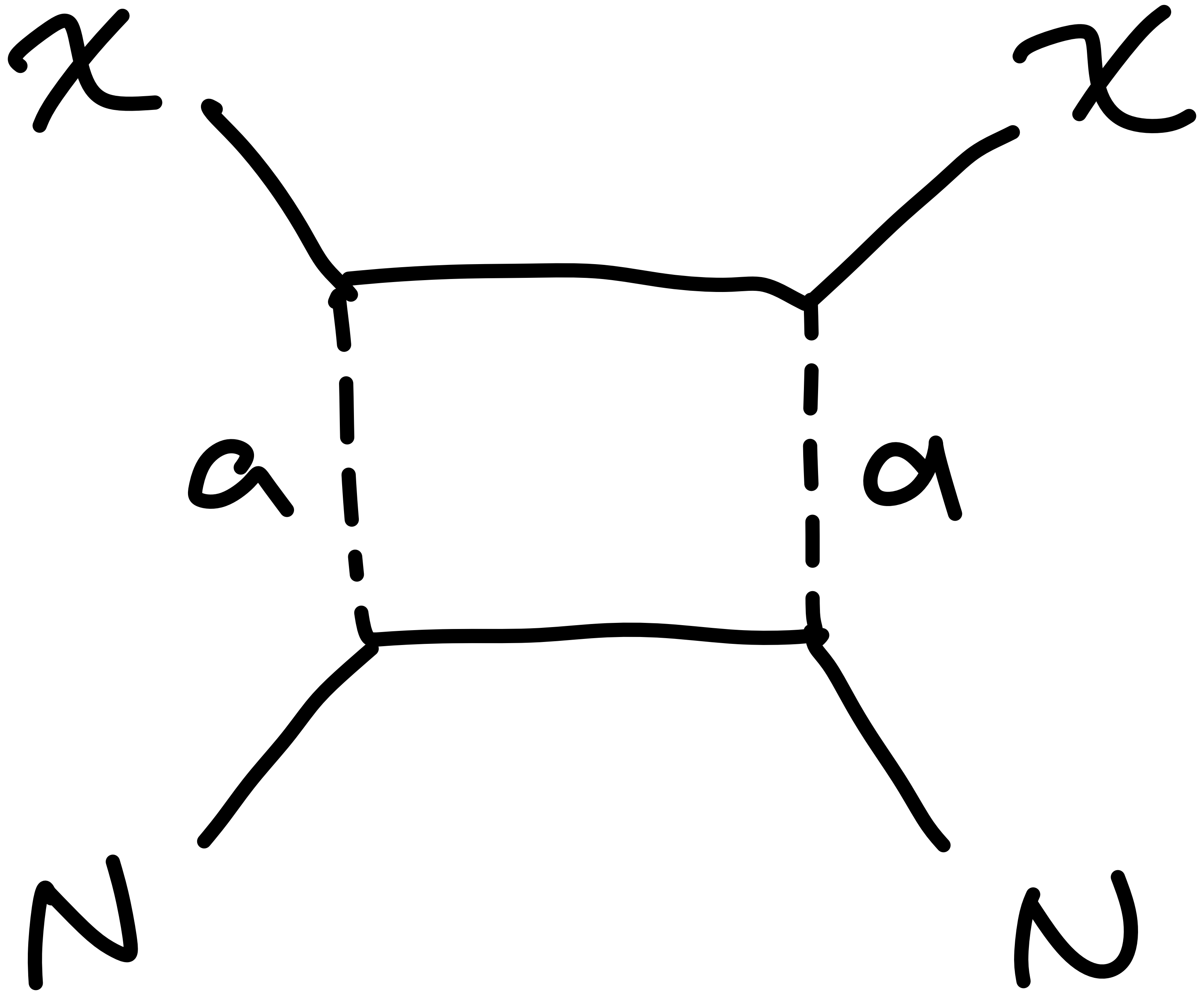
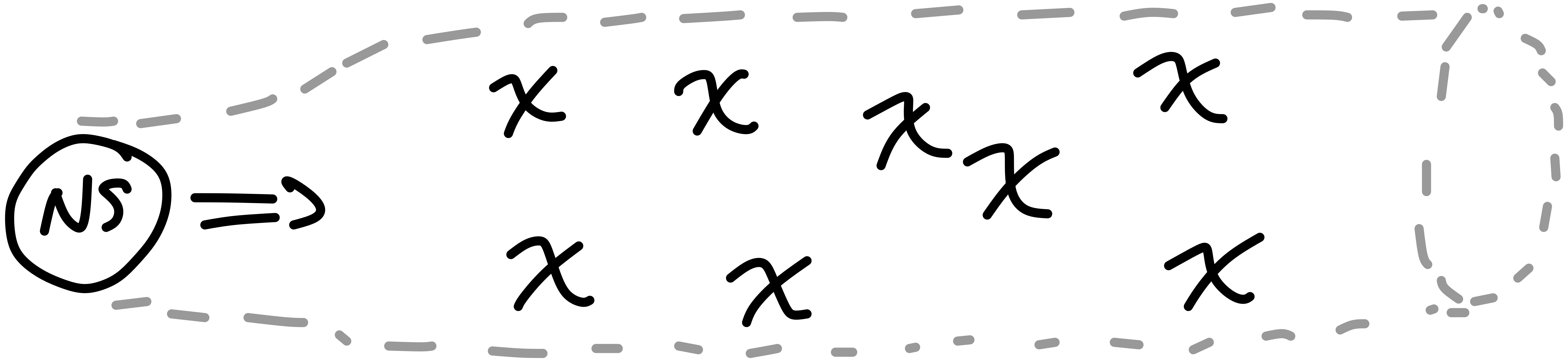


Velocity (and spin) independent

Neutron Stars

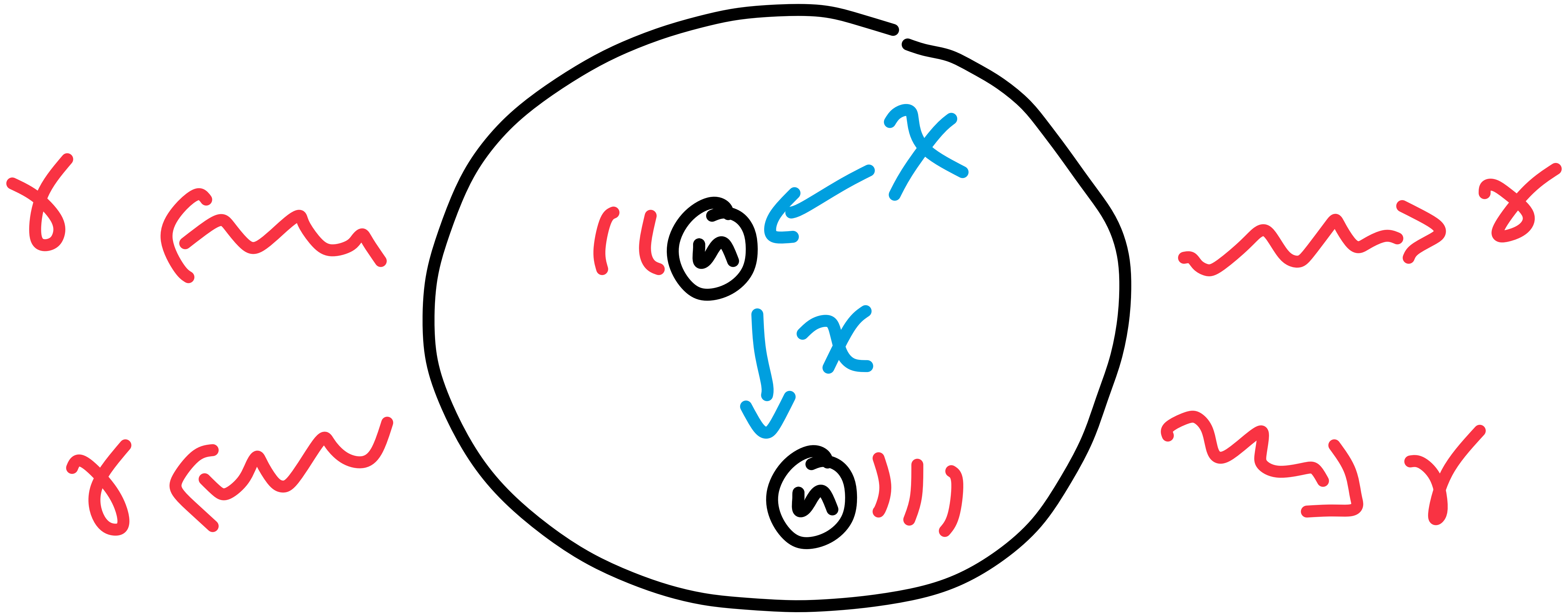


Mass of DM a NS star passes through per unit time

$$\dot{M} = \rho_\chi v_\chi \pi R_{\rm NS}^2 \times \frac{(v_{\rm esc}/v_\chi)^2}{\sqrt{1 - v_{\rm esc}^2}} \sim 10^{25} \frac{\rm GeV}{\rm s} \Rightarrow T_{\rm NS} \sim 1500 \text{ K}$$

See Baryakhtar, Bramante, Li, Linden, Raj PRL **119**, 131801 (2017)

Neutron Stars



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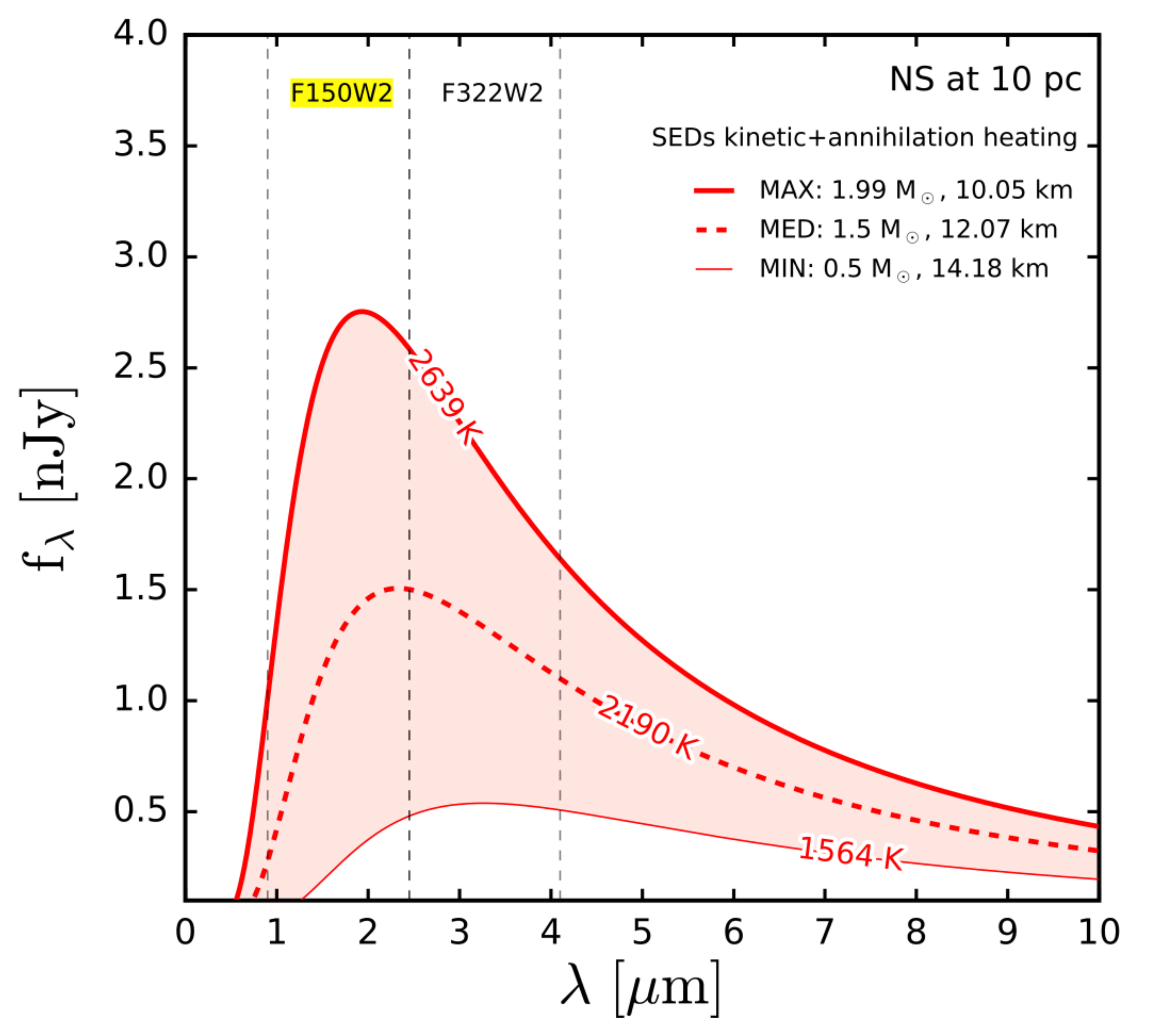
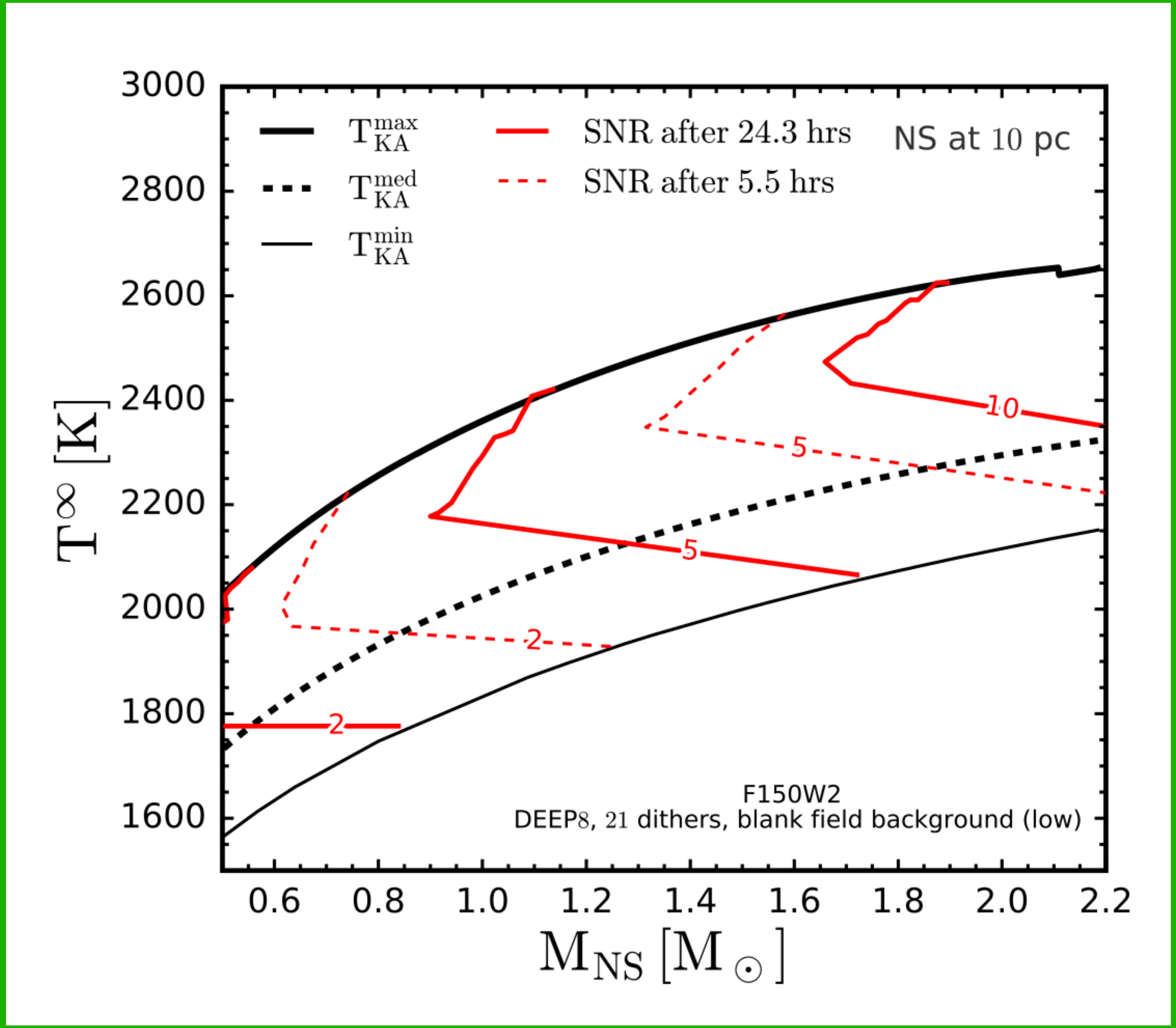
Neutron Stars

L

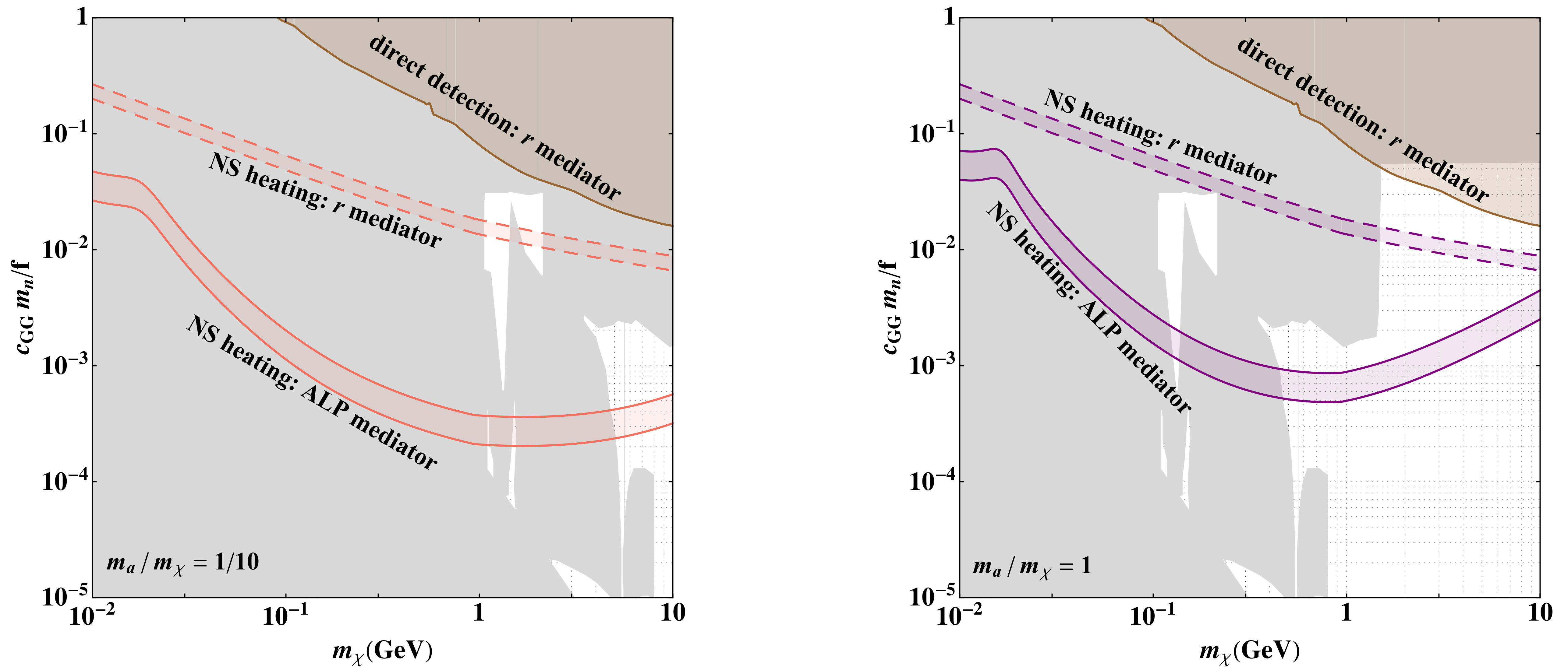




Garani et al. 2205.05048

Neutron Stars

ALP model

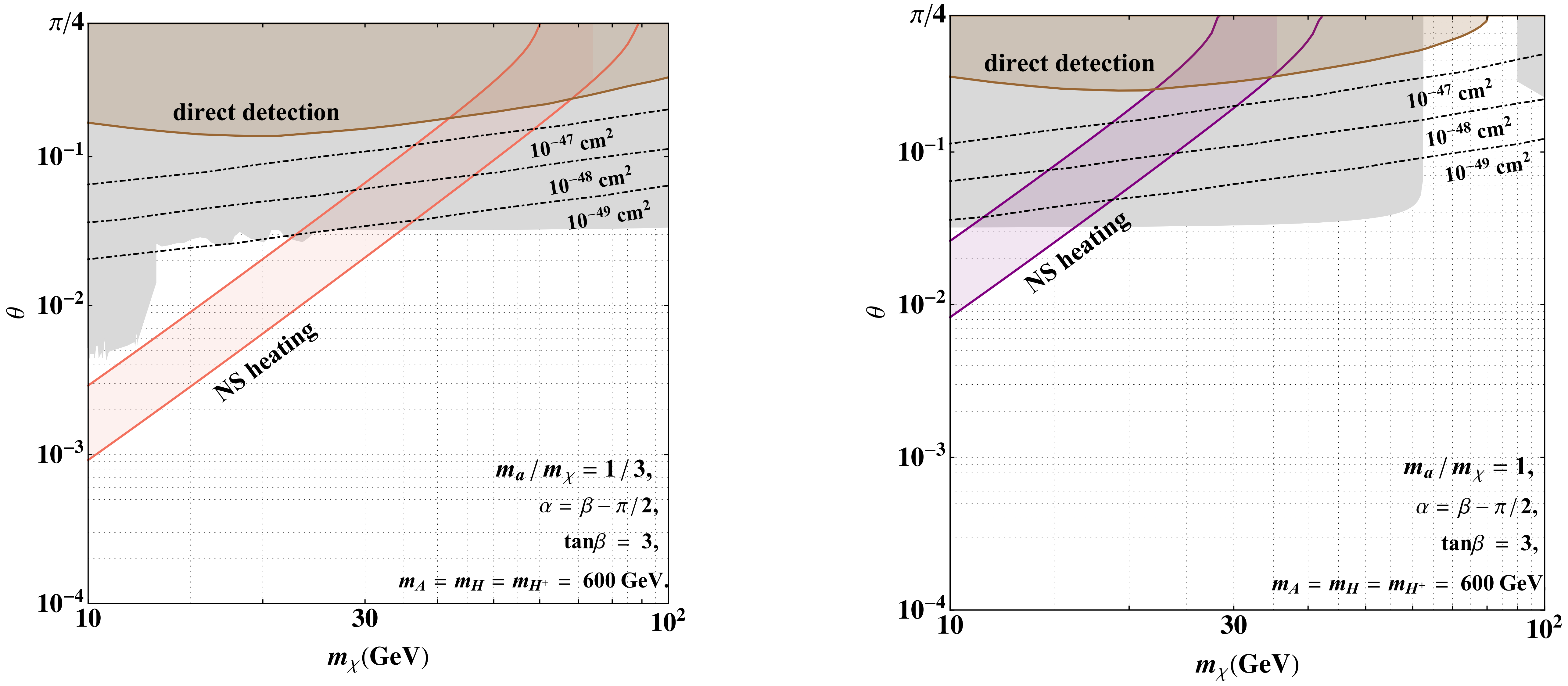


Observing NS with

$L_{\rm max}$ varying

$1.5\, M_\odot < M_{\rm NS} < 2.1\, M_\odot$

2HDM+a model

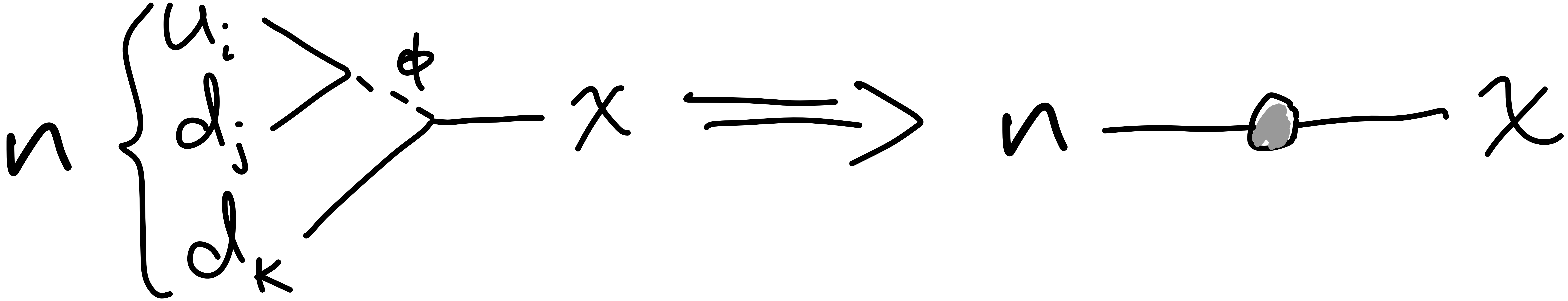


Changing gears…are there other DM models where neutron stars play an important role?

(DM & Nelson)

“Neutron portal”

$$\mathscr{L} \supset - g\phi u^c d^c - y\phi^* d^c\chi - \underbrace{m_\chi\bar{\chi}\chi}_{\Delta B=0} + \mathrm{h.c.} \to \frac{gy}{m_\phi^2} u^c d^c d^c \chi + \mathrm{h.c.} \to \underbrace{\frac{4\pi f_\pi^3}{\Lambda^2}}_{\varepsilon}\bar{n}\chi + \mathrm{h.c.}$$



$m_\chi \sim \mathscr{O}(\mathrm{GeV})$ is interesting: χ is a “dark baryon” or “dark neutron”

(DM & Nelson)

Neutron portal dark matter?

$$\mathscr{L} \supset -g\phi u^c d^c - y\phi^* d^c\chi - \underbrace{m_\chi\bar{\chi}\chi}_{\Delta B = 0} + \mathrm{h.c.} \to \frac{gy}{m_\phi^2} u^c d^c d^c \chi + \mathrm{h.c.} \to \underbrace{\frac{4\pi f_\pi^3}{\Lambda^2}}_{\varepsilon} \bar{n}\chi + \mathrm{h.c.}$$

If $m_p - m_e < m_\chi < m_p + m_e$,

$p \to \chi e^+ + \ldots$ and $\chi \to p e^- + \ldots$

don't occur (Pfütner & Riisager: ${}^9\mathrm{Be}$ stability $\Rightarrow m_\chi > 938.0\ \mathrm{MeV}$)

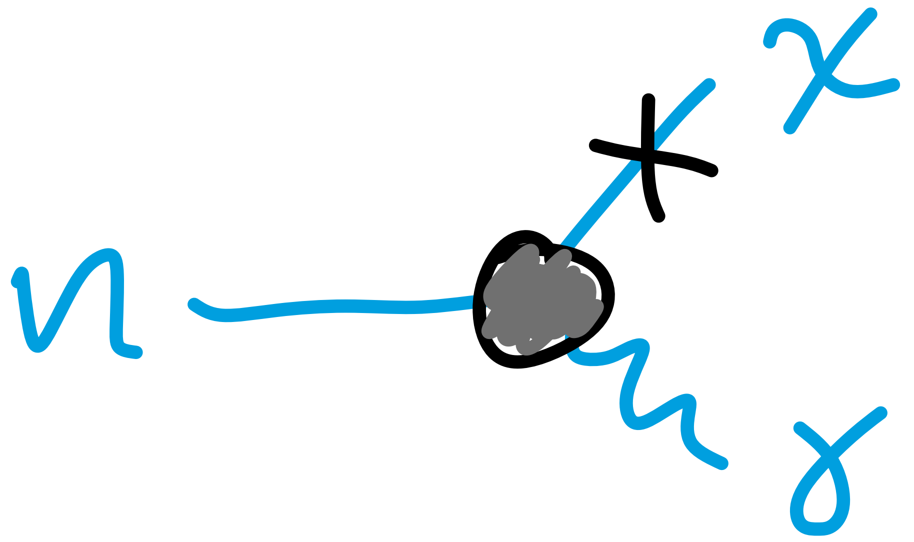
$\Rightarrow \chi$ is DM candidate (matter & dark matter stable for same reason)

Where else does it show up?

Neutron portal dark matter?

$$\mathscr{L} \supset -g\phi u^c d^c - y\phi^* d^c \chi - \underbrace{m_\chi \bar{\chi}\chi}_{\Delta B = 0} + \text{h.c.} \rightarrow \frac{gy}{m_\phi^2} u^c d^c d^c \chi + \text{h.c.} \rightarrow \underbrace{\frac{4\pi f_\pi^3}{\Lambda^2}}_{\varepsilon} \bar{n}\chi + \text{h.c.}$$

If $m_\chi < m_n$

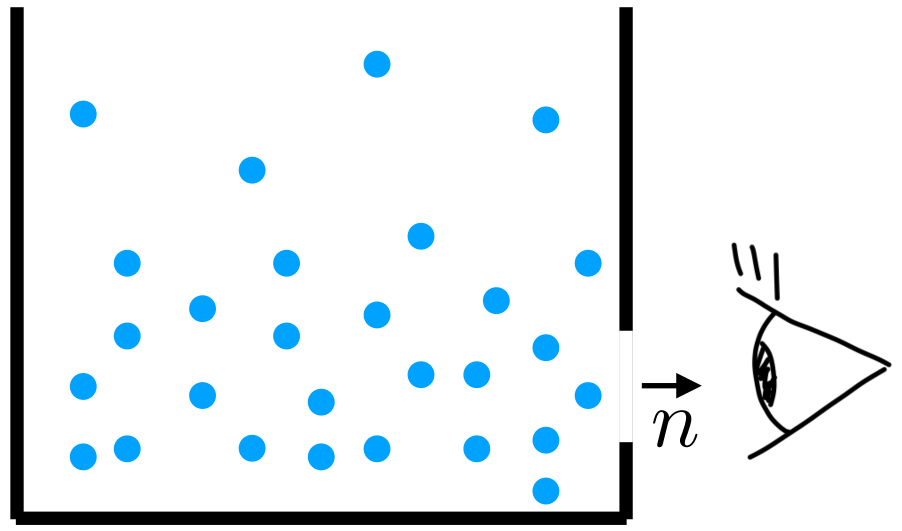


with mixing angle $\theta \equiv \dfrac{\epsilon}{m_n - m_\chi}$

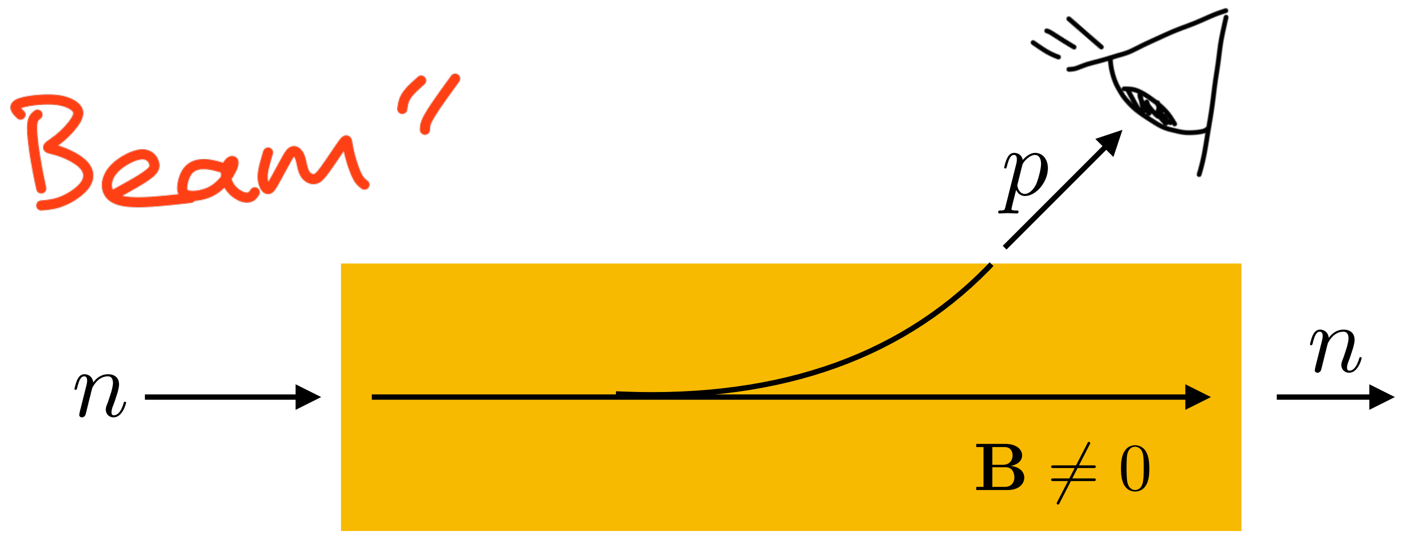
gives $\mathrm{Br}_{n \to \chi\gamma} = 1\,\% \left(\dfrac{\theta}{5 \times 10^{-10}}\right)^2 \left(\dfrac{\Delta m}{\mathrm{MeV}}\right)^3$

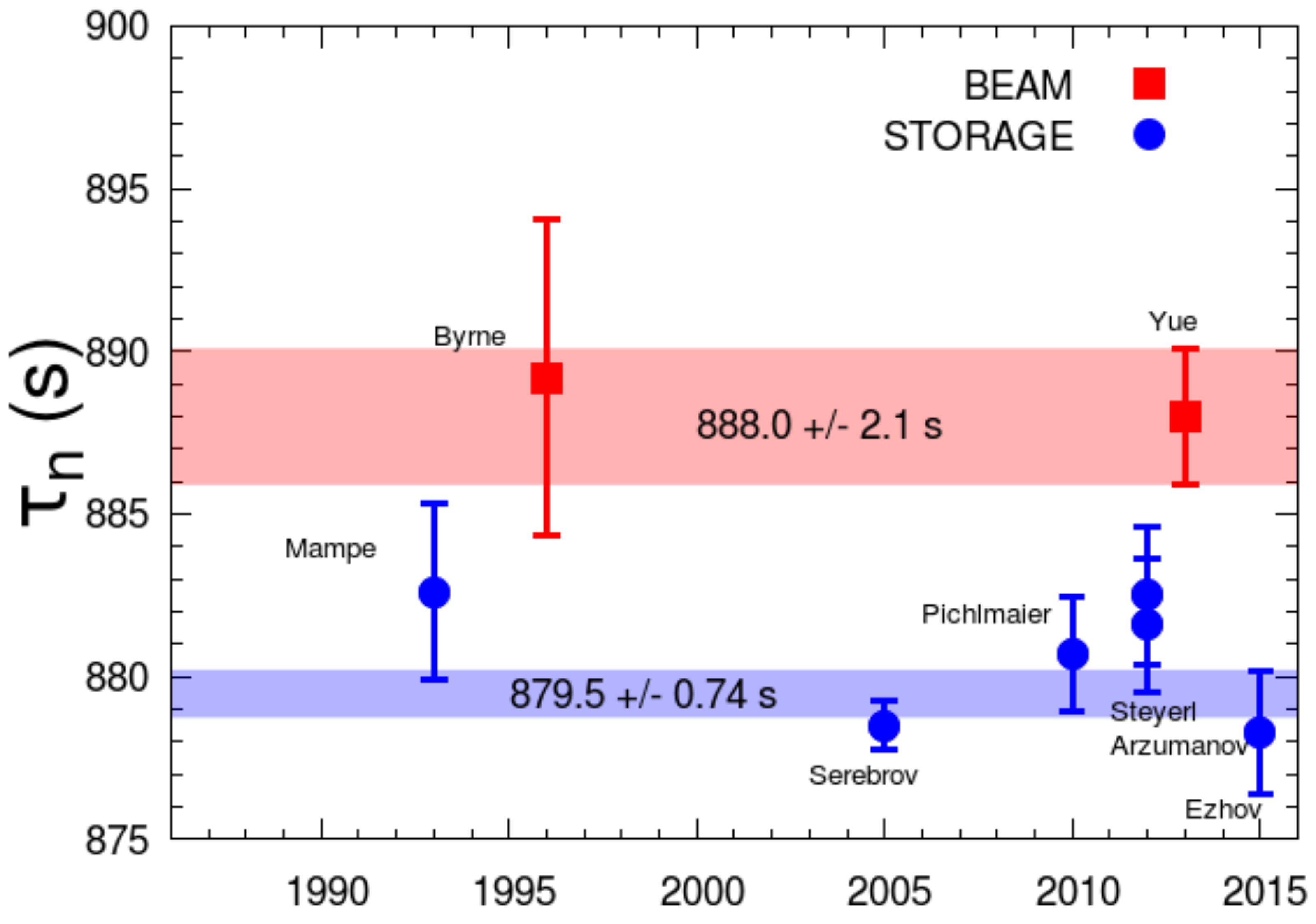
Neutron decay modes

"Bottle"



"Beam"





1% unseen branching

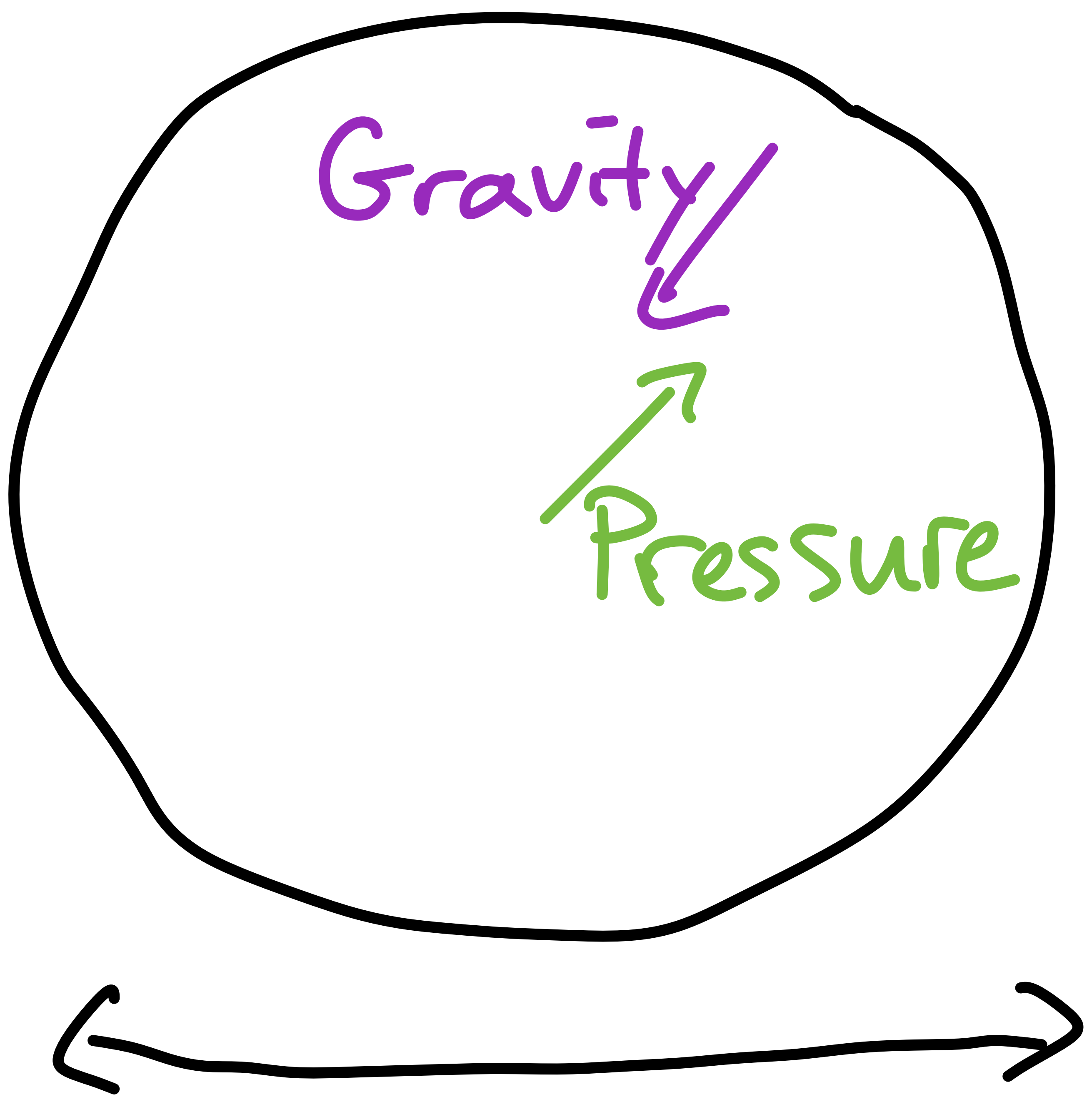
(Berezhiani; Fornal & Grinstein)

$$\text{gives } \mathrm{Br}_{n\to\chi\gamma} = 1\,\% \left(\frac{\theta}{5\times 10^{-10}}\right)^2 \left(\frac{\Delta m}{\mathrm{MeV}}\right)^3$$

(Note: $\theta \lesssim 10^{-20}$ if χ Majorana)

Where else can it appear?

Neutron stars

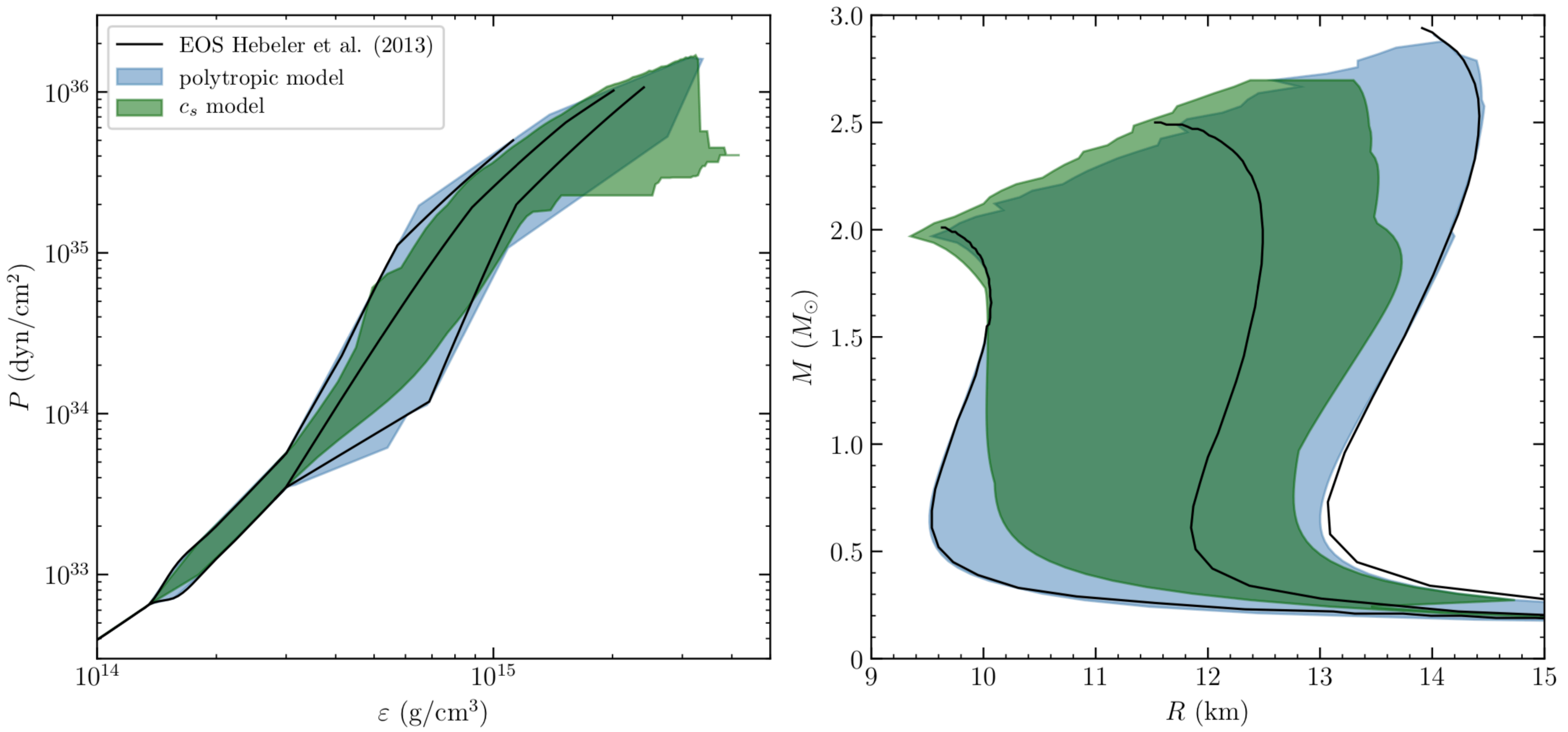


$\mathcal{O}(20\,\mathrm{km})$

$M \sim M_{\odot} \sim 10^{57}\,\mathrm{GeV}$

TOV equation: $\frac{dp}{dr} = -\frac{G\epsilon(r)M(r)}{r^2} \times (\mathrm{GR})$

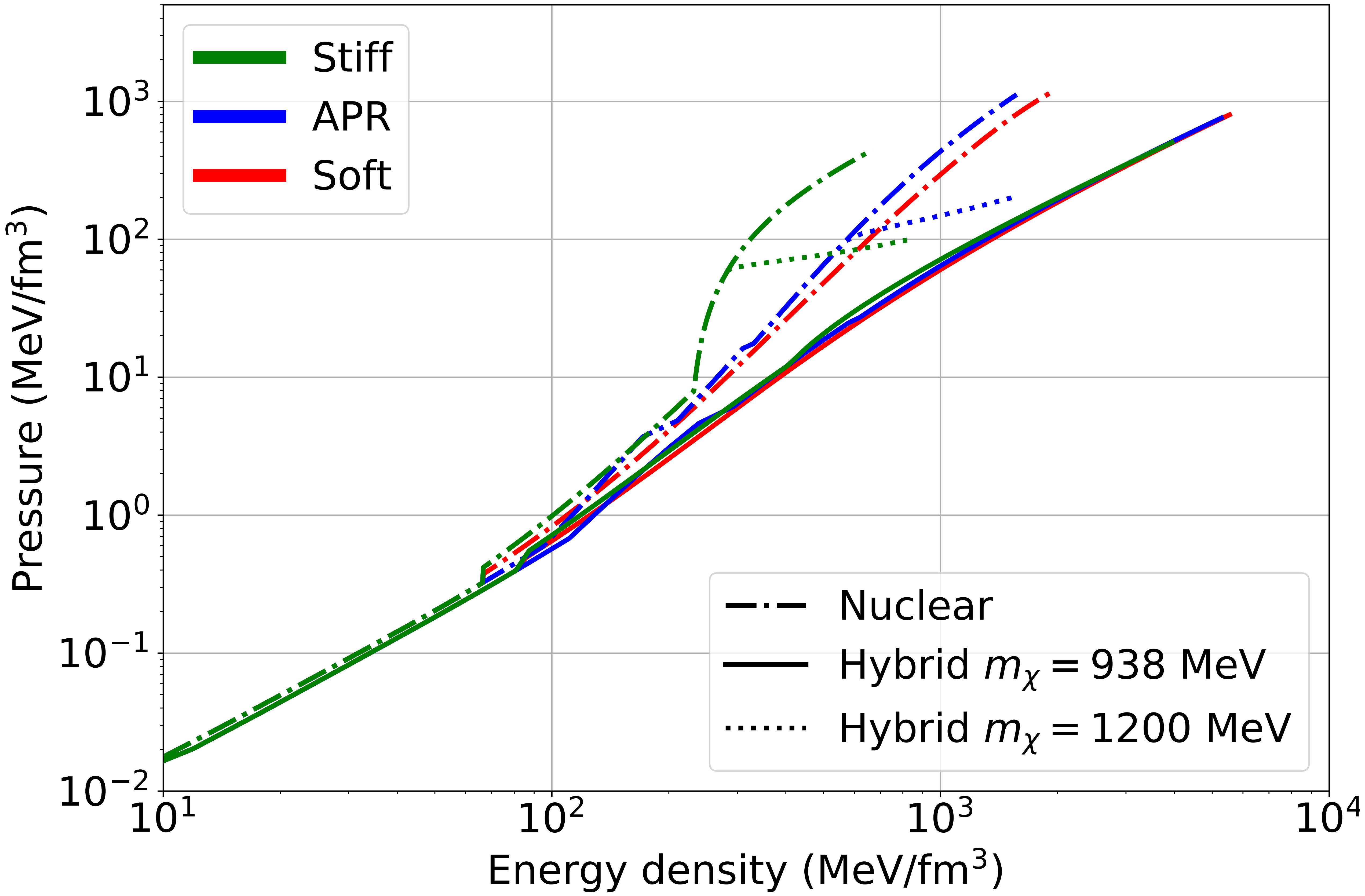
EoS: $p(r) = f[\epsilon(r)]$

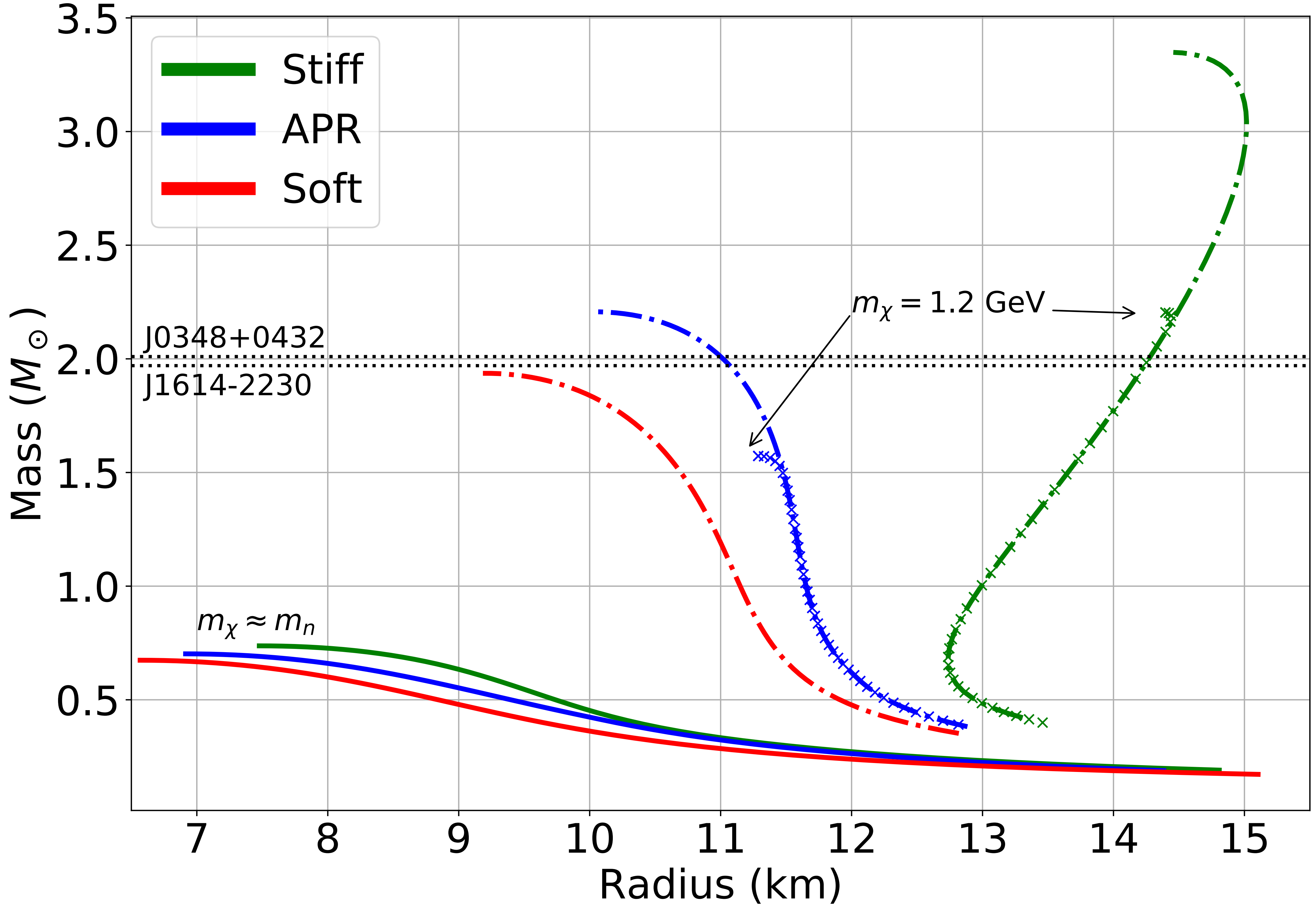


Greif, Raaijmakers, Hebeler, Schwenk, & Watts arXiv:1812.08188

Neutron stars & dark baryons

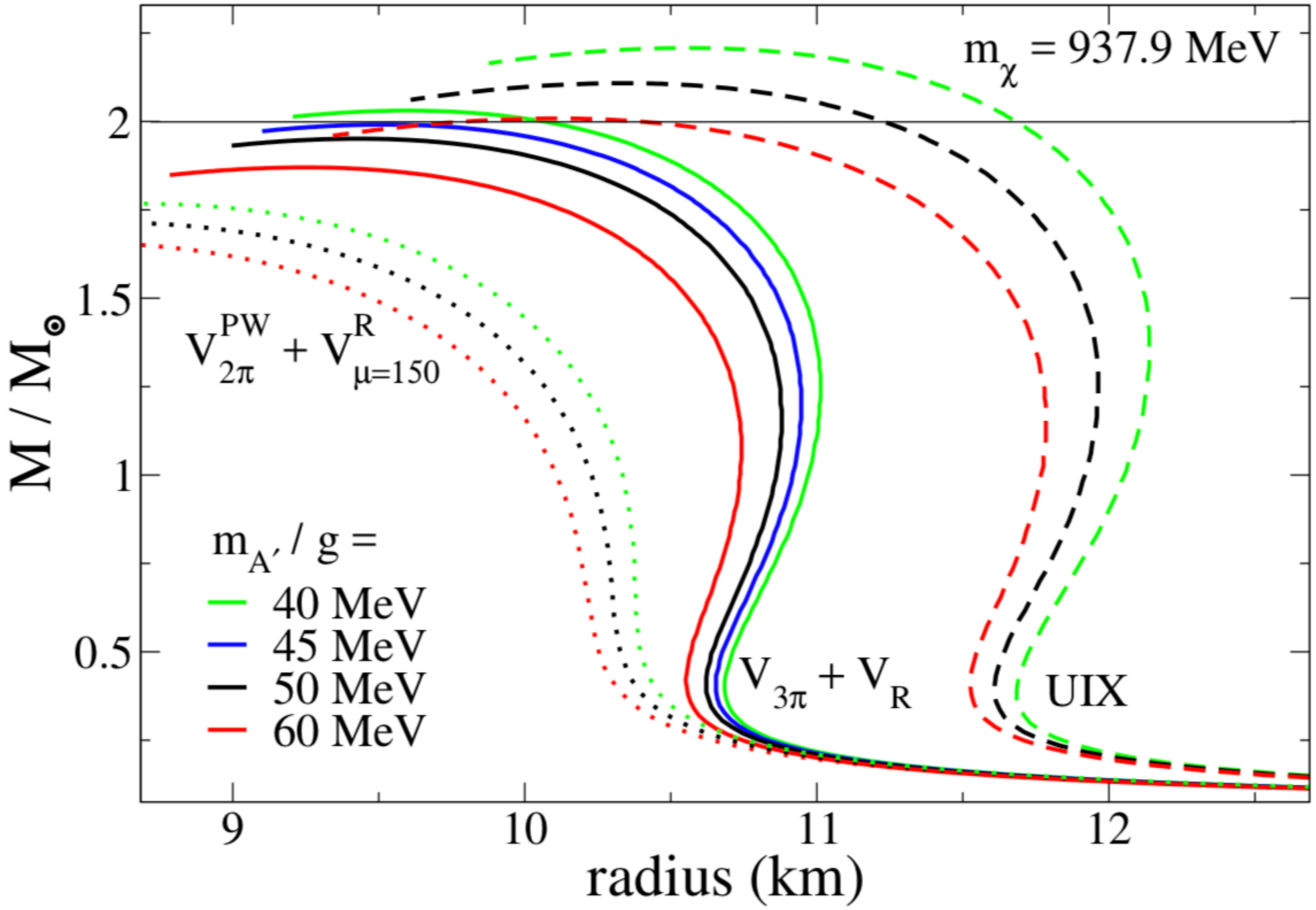
DM, Nelson, Reddy, & Zhou, PRL **121**, 061802; Baym *et al.*, Motta *et al.*,
Mohapatra, Nussinov, *et al.*





Neutron stars & dark baryons: a way out?

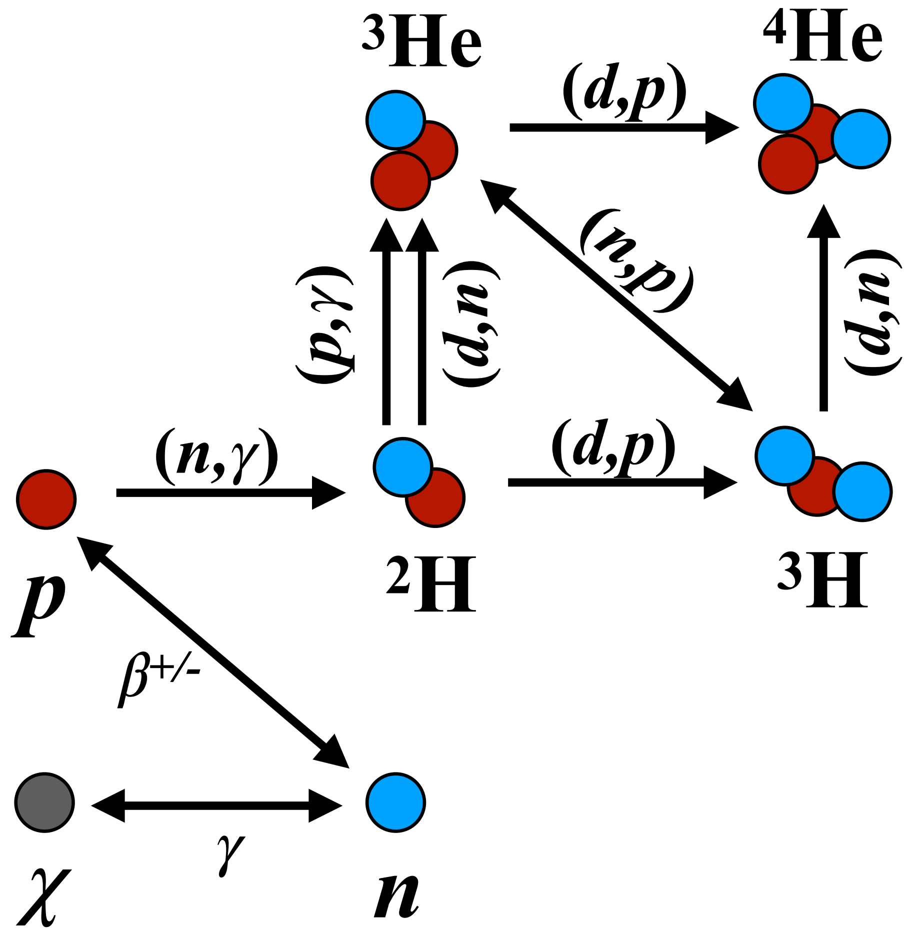
Cline & Cornell, JHEP **1807** 081

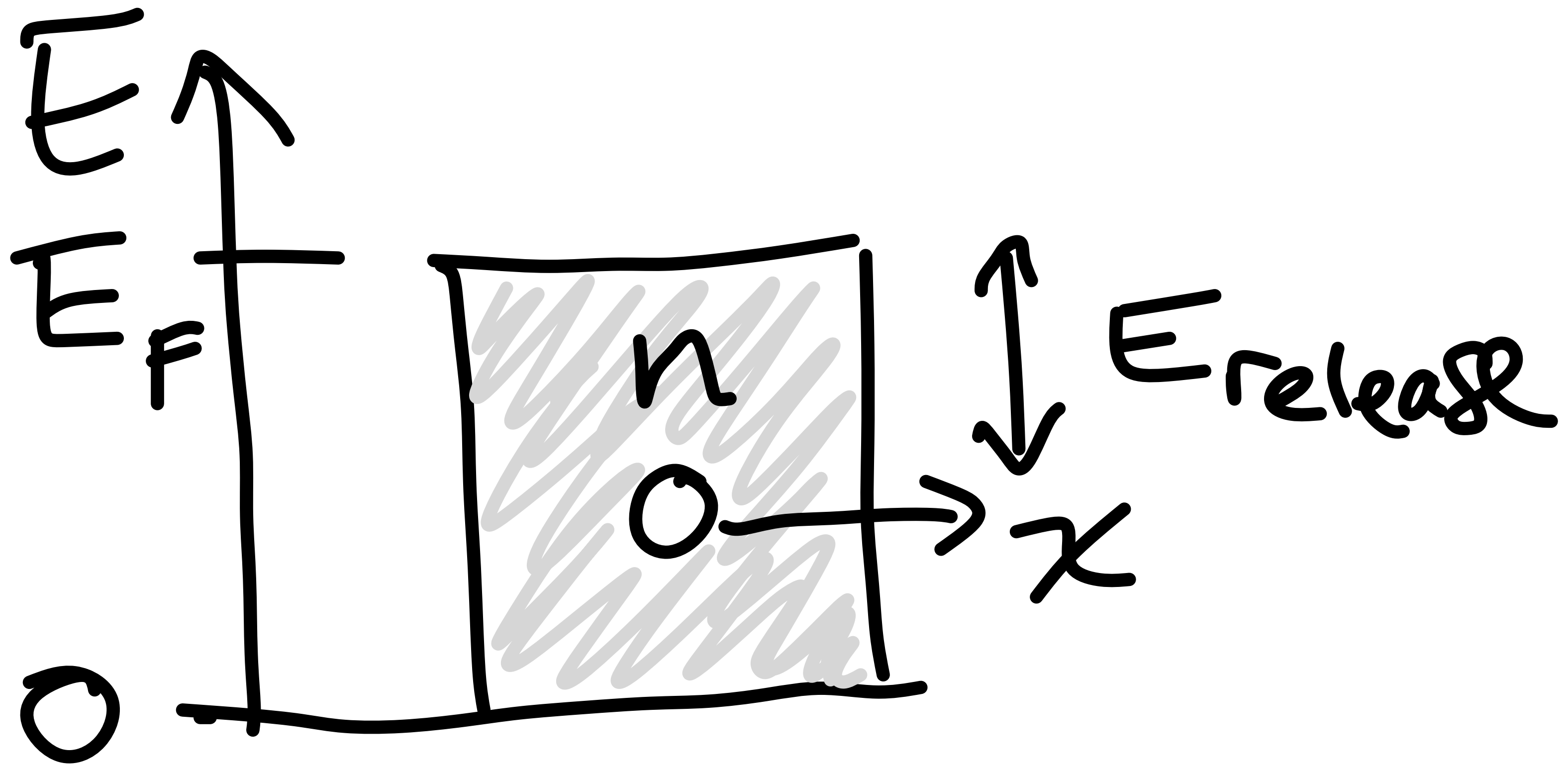


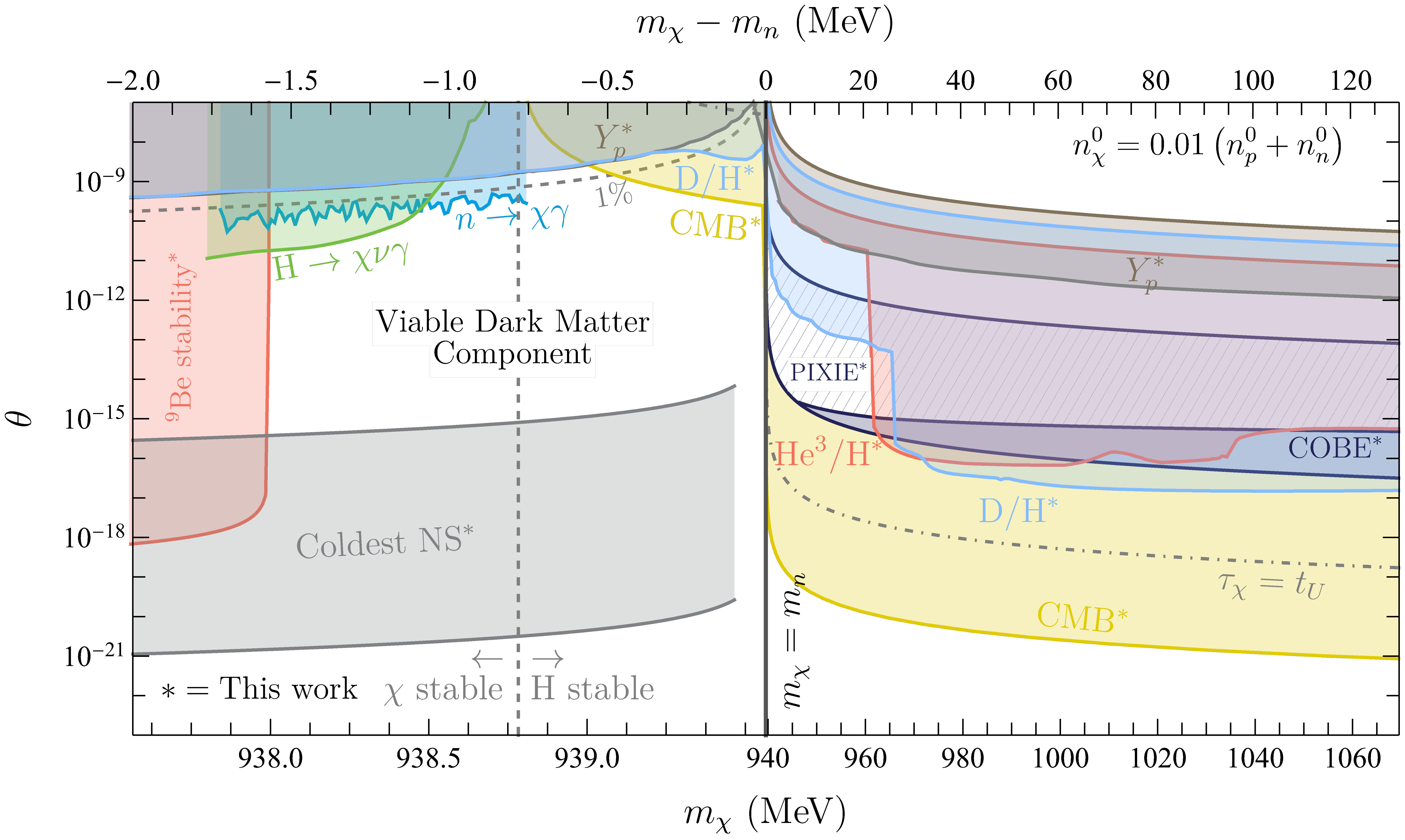
Exotic neutron decay invisible:

$n \to \chi A'$

Cosmological/Astrophysical Implications

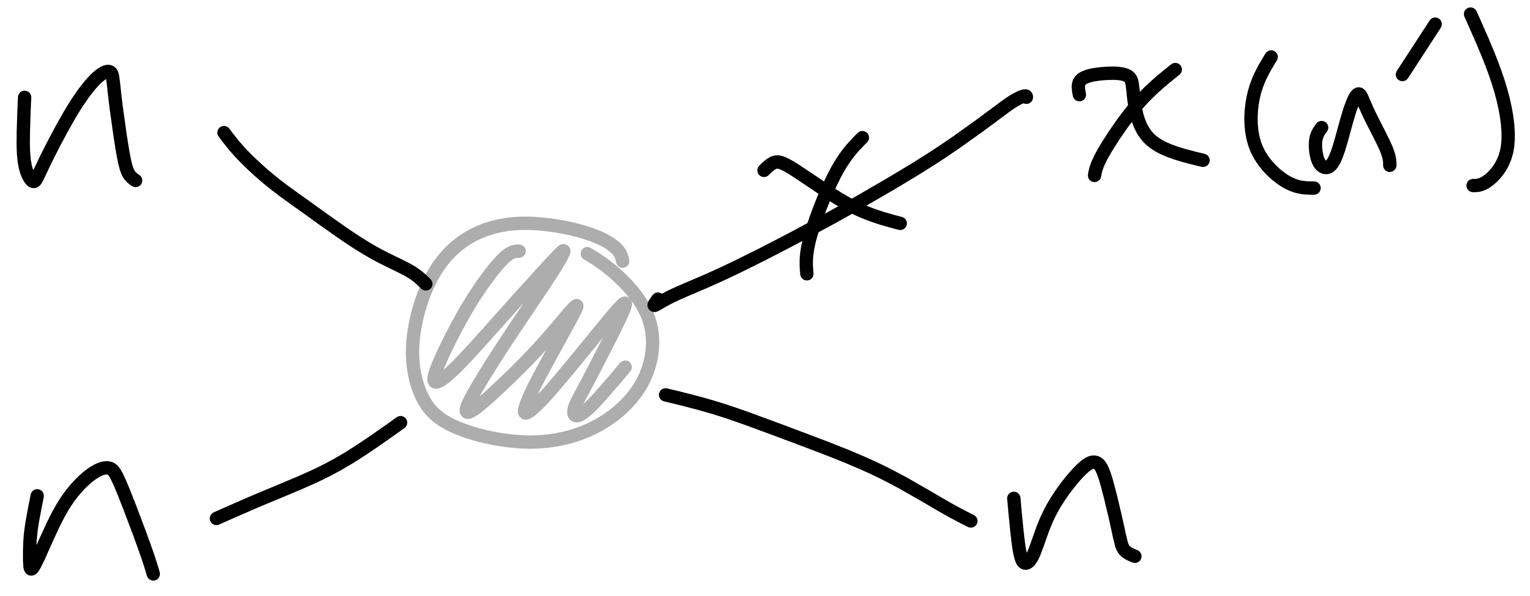


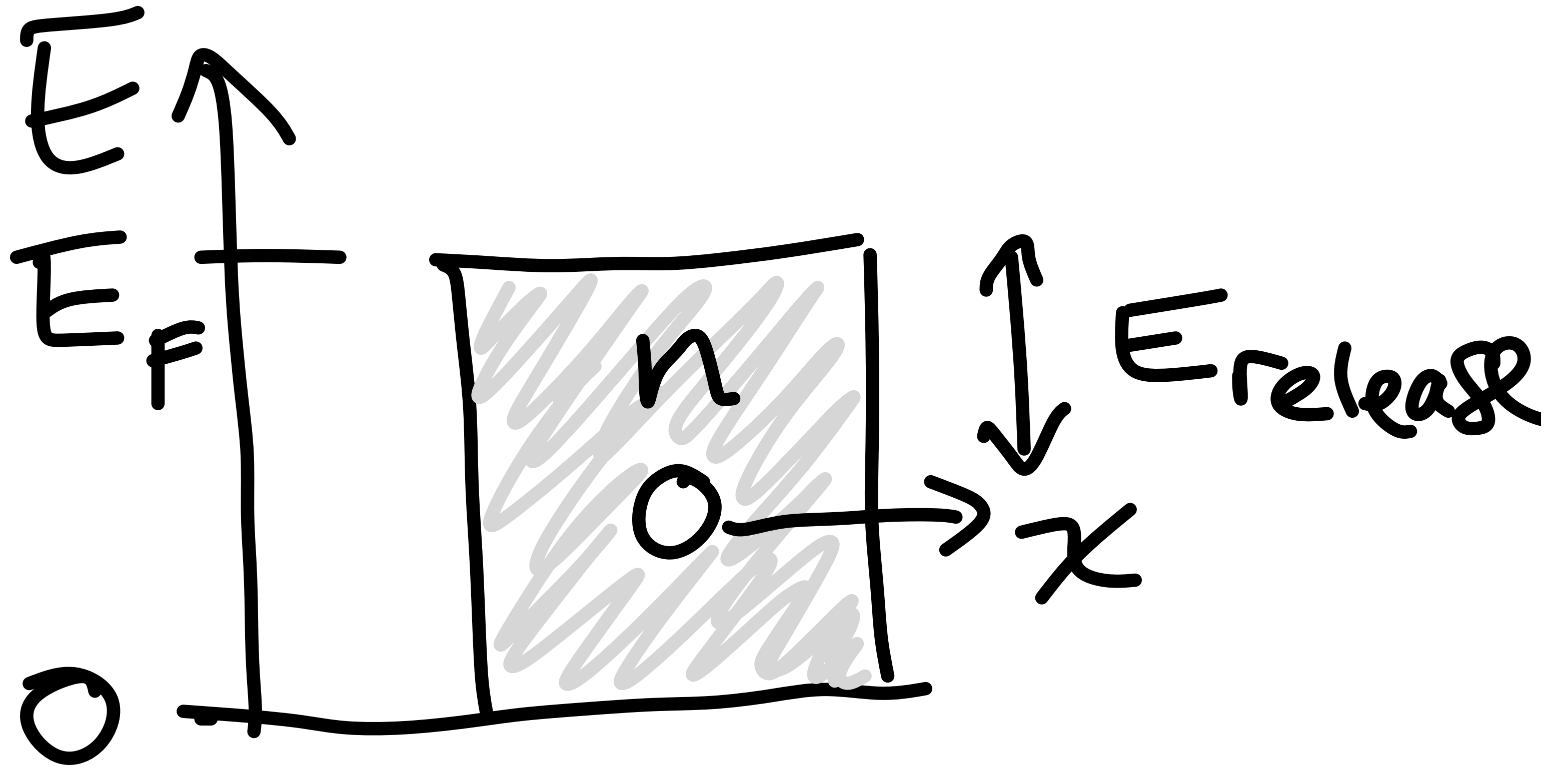




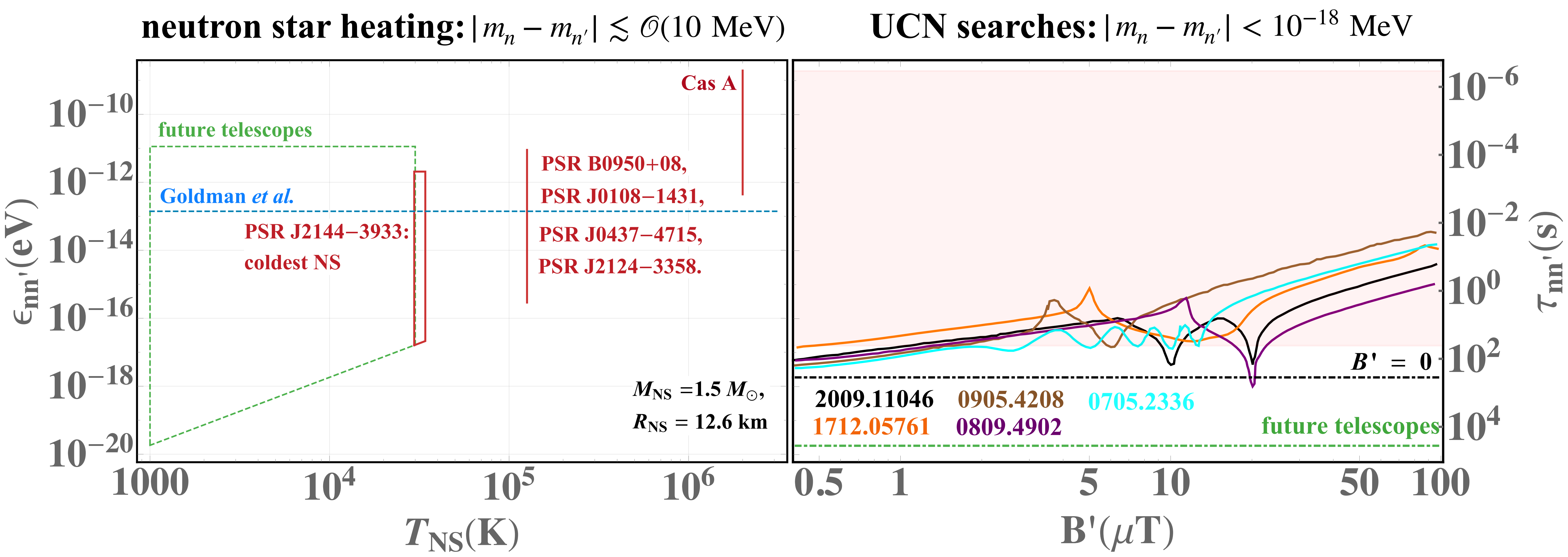
DM, Pospelov, Raj 2012.09865 (PRD)

Cosmological/Astrophysical Implications



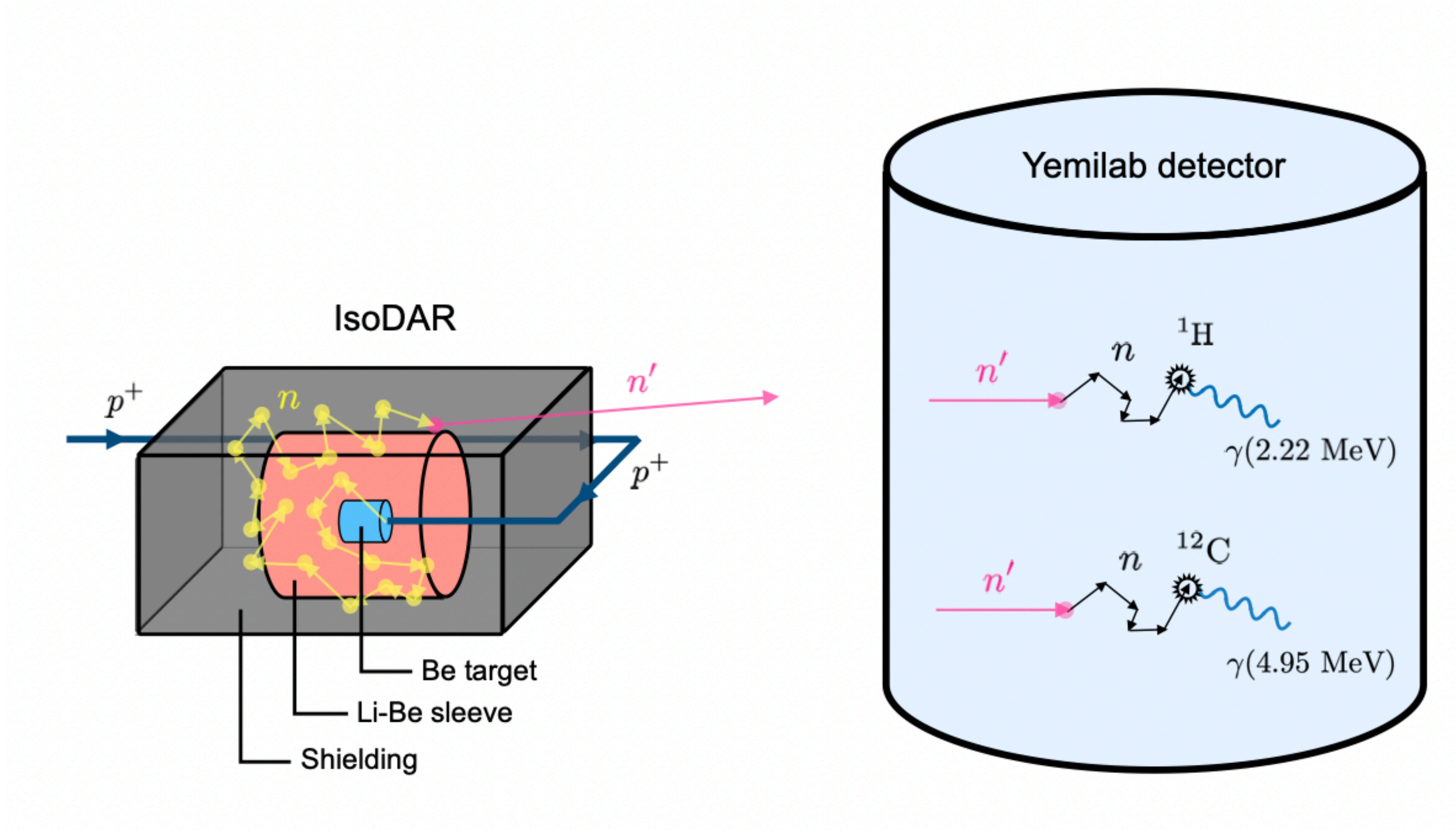


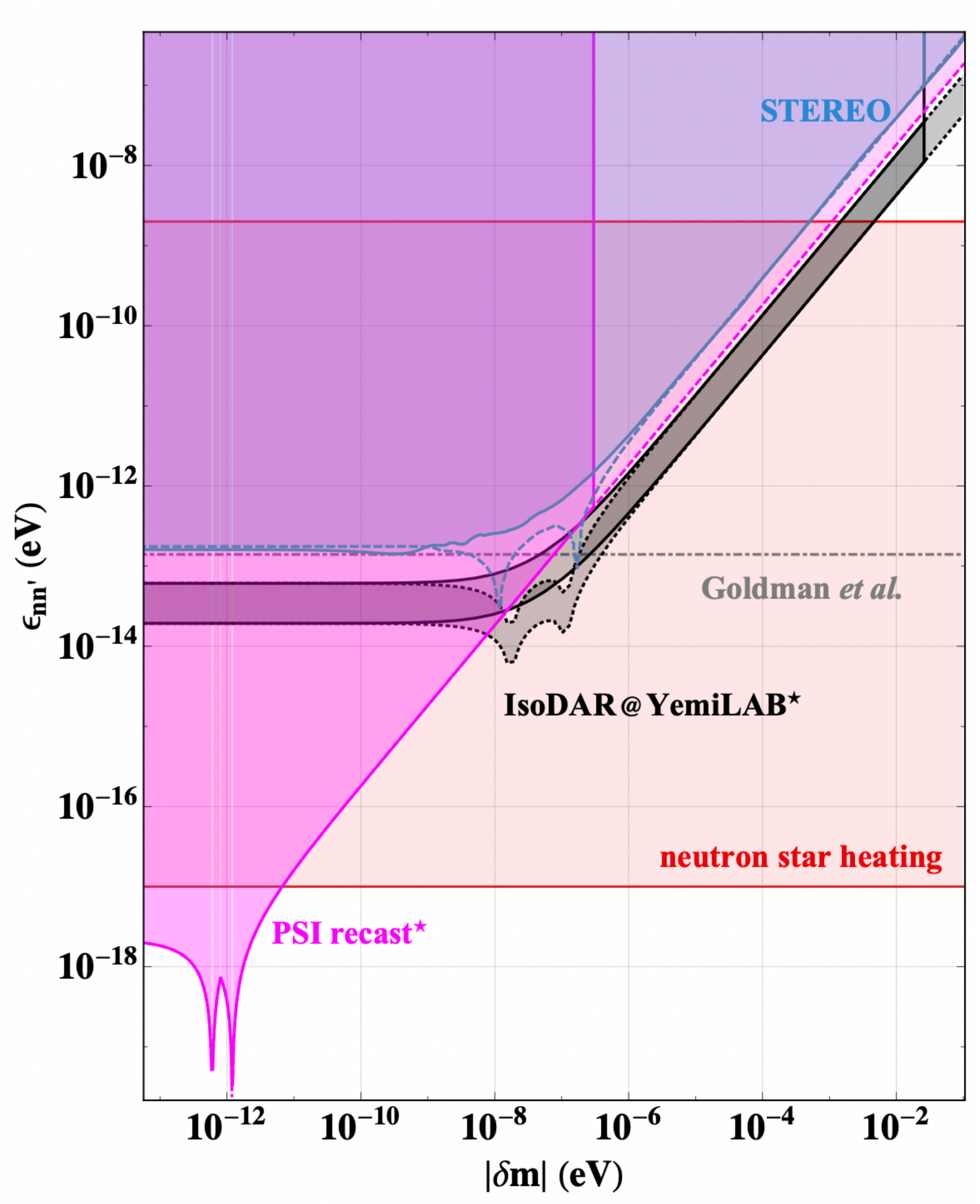
$n \rightarrow n'$



DM, Pospelov, Raj 2105.09951 (PRL)

Neutrons Through Walls





Hostert, DM, Pospelov, & Raj (2201.02603)

Wrap up

Neutron stars offer a good opportunity to look for dark matter that has velocity-suppressed scattering on nucleons

We considered two realistic benchmark scenarios where DM interacts with SM through pseudoscalar exchange: ALP & 2HDM+a mediation

Observation of NS with $T_{\rm NS} \lesssim 1500\ {\rm K}$ could set leading constraint on these models even compared to terrestrial probes

Also looked at neutron portal and its effects on heating neutron stars, compared to terrestrial probes

Still lots to do!