# DARK BARYONS

near a GeV

or, using the "neutron portal" for FUN & PROFIT

David McKeen TRIUMF

BLV c. 2020 July 8, 2020

work with Nelson, Reddy, Pospelov, Raj

see also Berezhiani; Fornal, Grinstein; Gardner; Cline, Cornell, Bringmann, ...

Plan

Discuss model where SM baryons mix with "dark baryons"

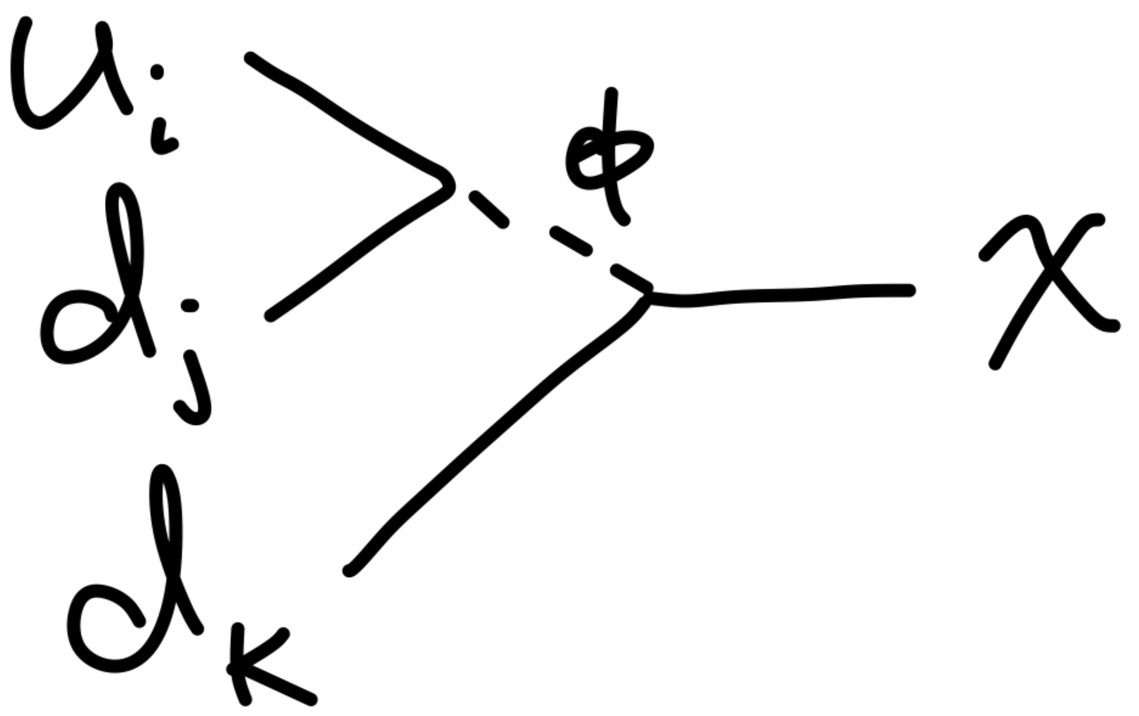
Describe baryogenesis in this framework

Focus on neutron mixing ("neutron portal")

Neutron star implications & atomic hydrogen decay

# The Model

$$\mathcal{L} \supset -g_{ij}\phi\, u_i^c d_j^c - y_k \phi^* d_k^c \chi - \left\{ \begin{matrix} m_\chi^{\Delta B=2}\chi\chi \\ m_\chi^{\Delta B=0}\chi^c\chi \end{matrix} \right\} + h.c.$$



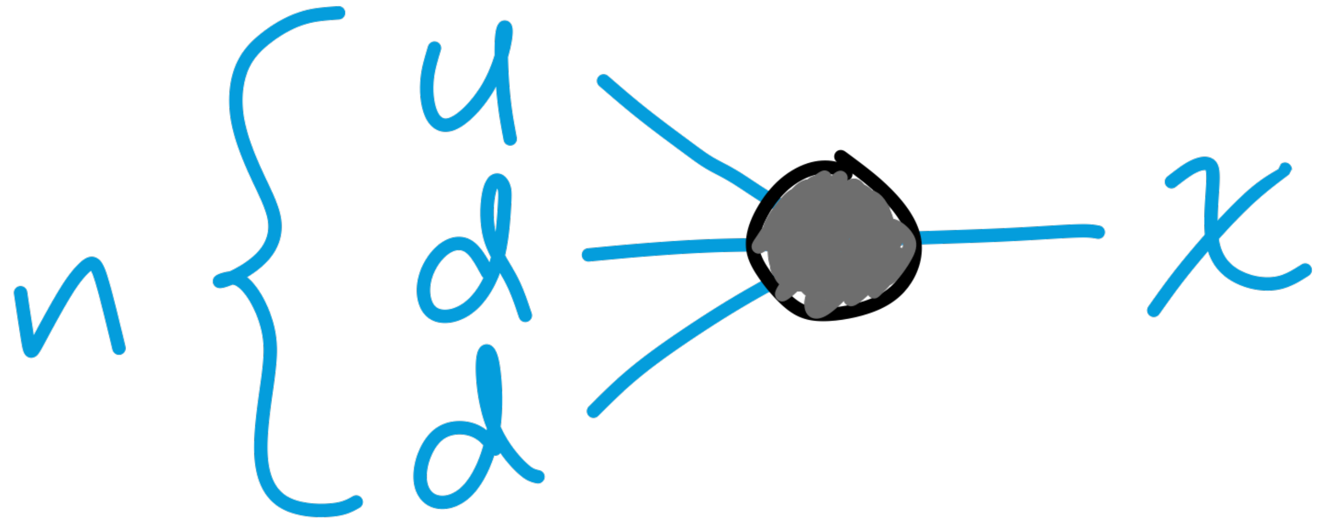

$$\mathcal{L}_{eff} \supset \underbrace{\frac{g_{ij}y_k}{m_\phi^2}}_{1/\Lambda^2} u_i^c d_j^c d_k^c \chi + h.c.$$

$m_\chi \sim \mathcal{O}(\mathrm{GeV})$ is interesting

N.B.

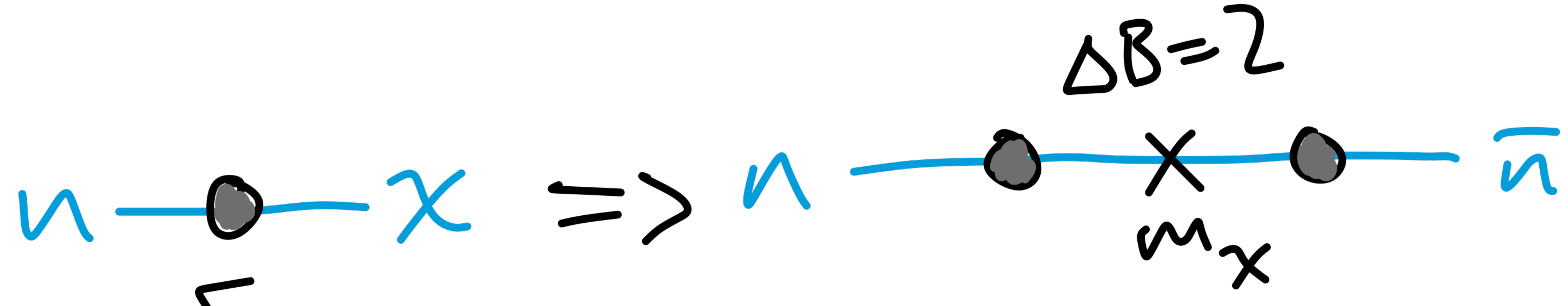
p & $^9$Be stability requires $m_\chi > 938.0$ MeV (Pfützner & Riisager)

# $n$-$\bar{n}$ oscillations and $\not{CP}$



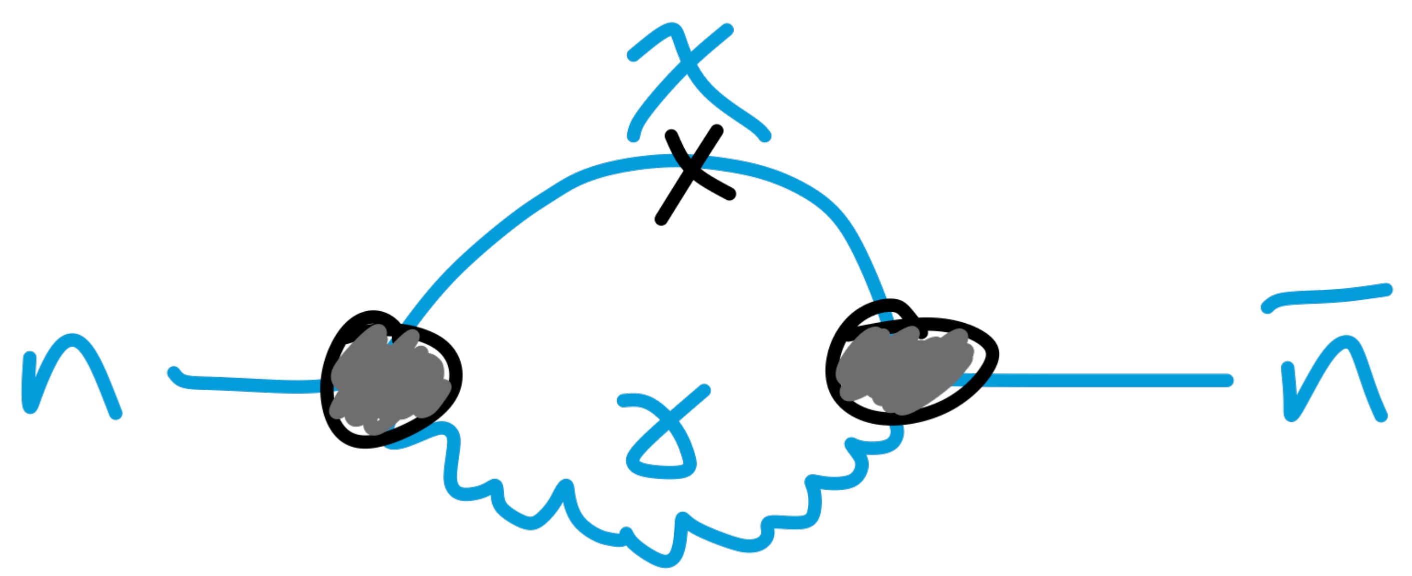

$$\mathcal{L}_{eff} \supset \frac{1}{\Lambda^2} u^c d^c d^c \chi + h.c. \Rightarrow \delta(\bar{n}\chi + \bar{\chi} n)$$

$$\delta \sim \frac{4\pi f_\pi^3}{\Lambda^2} \sim \frac{10^{-2}\,GeV^3}{\Lambda^2}$$

$\Rightarrow$ 


$\equiv M_{12}$ $\rightarrow$ $\not{CP}$

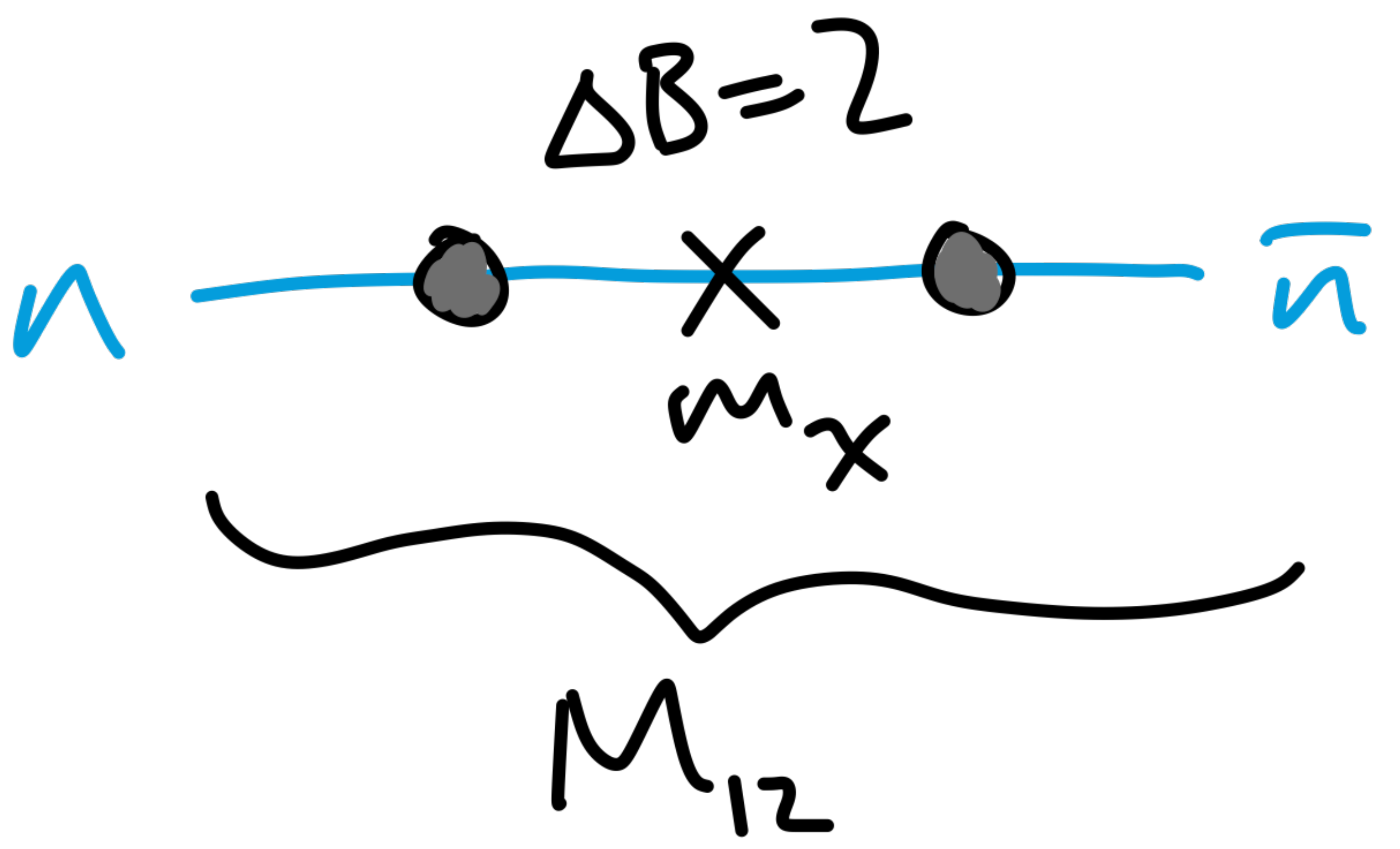
$$\theta = \frac{\delta}{\Delta m}$$

If $m_\chi < m_n$ 


$\equiv \Gamma_{12}$ $\rightarrow$ $\not{CP}$

[N.B. need $\geq 2$ $\chi$'s so $\arg(M_{12}^* \Gamma_{12}) \neq 0$]

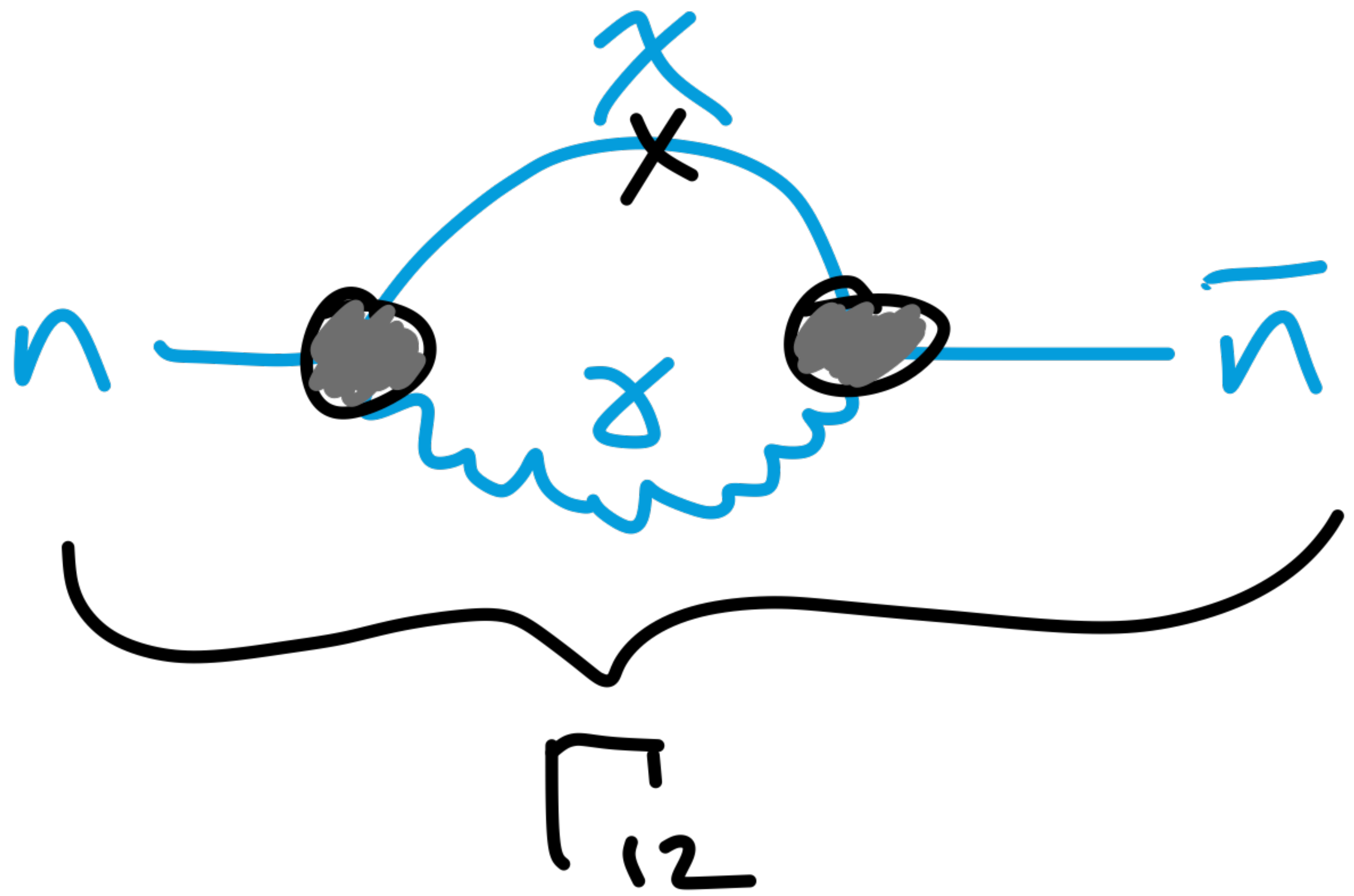
# $n-\bar{n}$ oscillations: how much $\not{CP}$?




$$M_{12} = \frac{1}{\tau_{n\bar{n}}} = \frac{\delta^2 m_\chi}{m_n^2 - m_\chi^2} = \frac{1}{2}\theta^2 \Delta m$$

$$\left[\theta \lesssim 10^{-15}\sqrt{\frac{\text{MeV}}{\Delta m}\ \frac{10\ \text{yr}}{\tau_{n\bar{n}}}}\right.$$

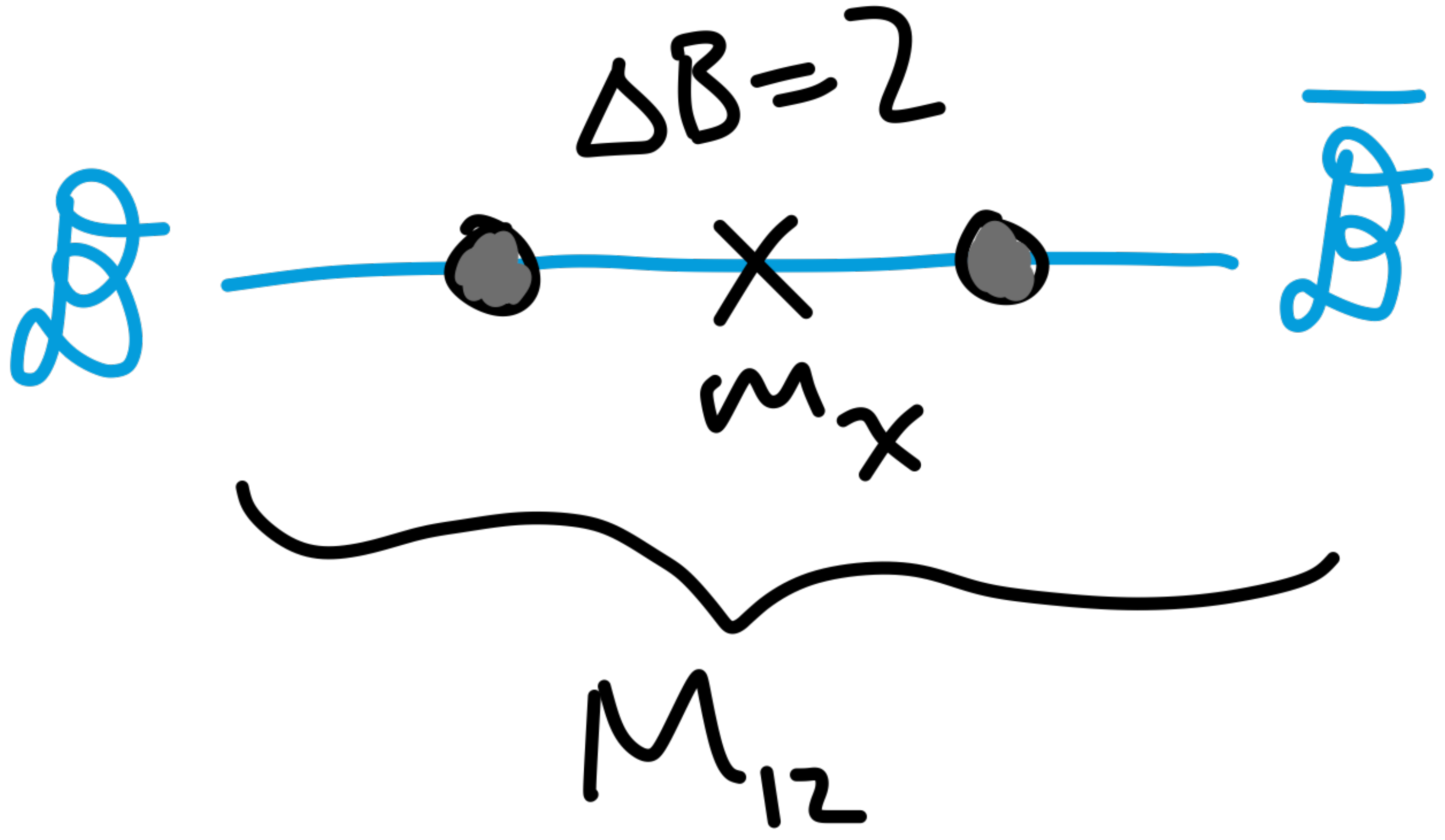
$$\left.\text{i.e. } \Lambda \gtrsim 10^{8}\ \text{GeV}\right]$$




$$\Gamma_{12} = \frac{m_n^2 \theta^2}{\pi}\ \frac{m_\chi \Delta m^3}{m_n^3}$$

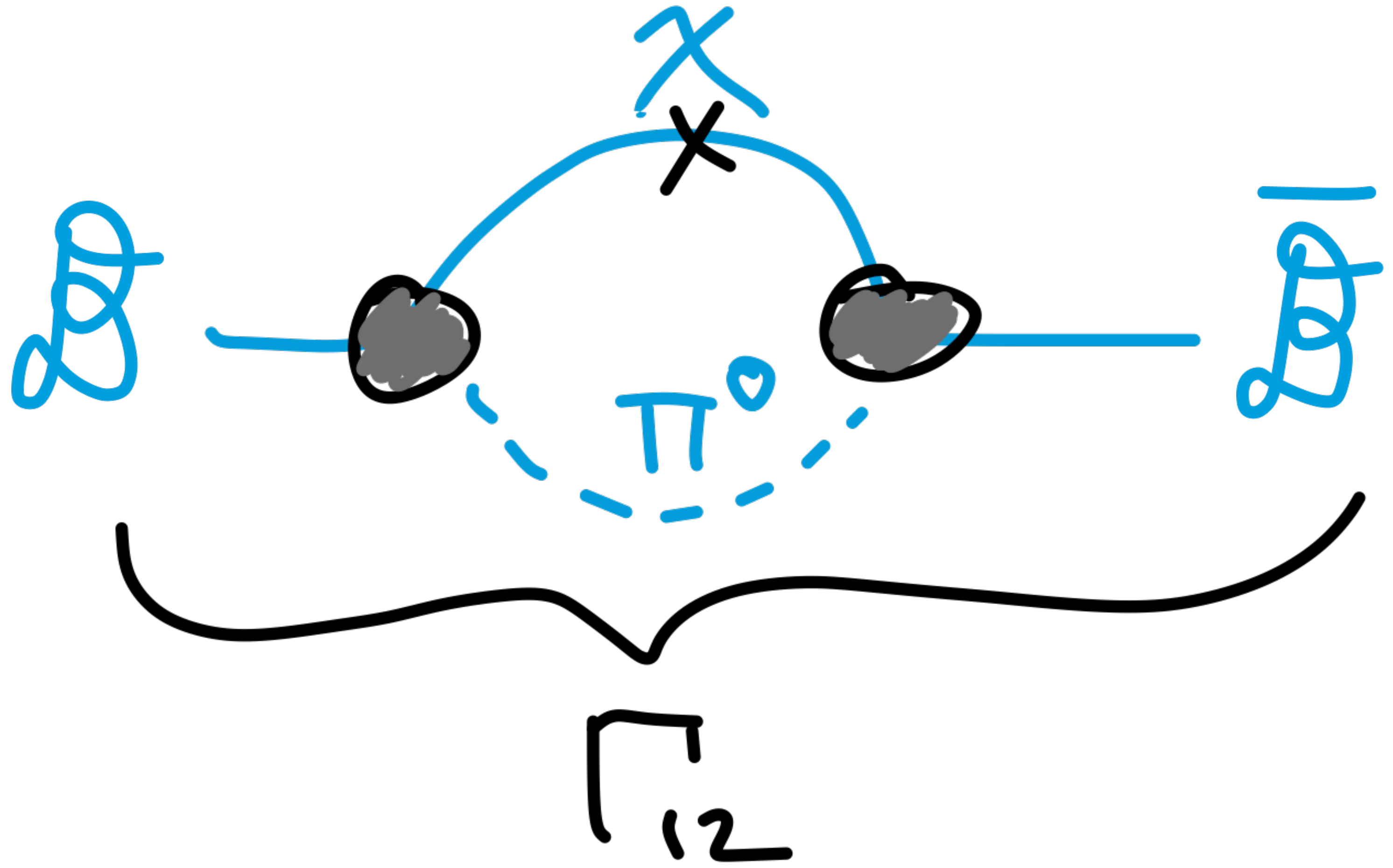
So $\not{CP} \propto \left|\frac{\Gamma_{12}}{M_{12}}\right| \sim 10^{-9}\left(\frac{\Delta m}{\text{MeV}}\right)^2$ TINY! But...

# Heavy flavor baryon oscillations: more $\not{CP}$ !




$M_{12} \propto \frac{1}{\Lambda^4}$ can be much bigger $\Lambda \sim \text{TeV}$ (Kuzmin)

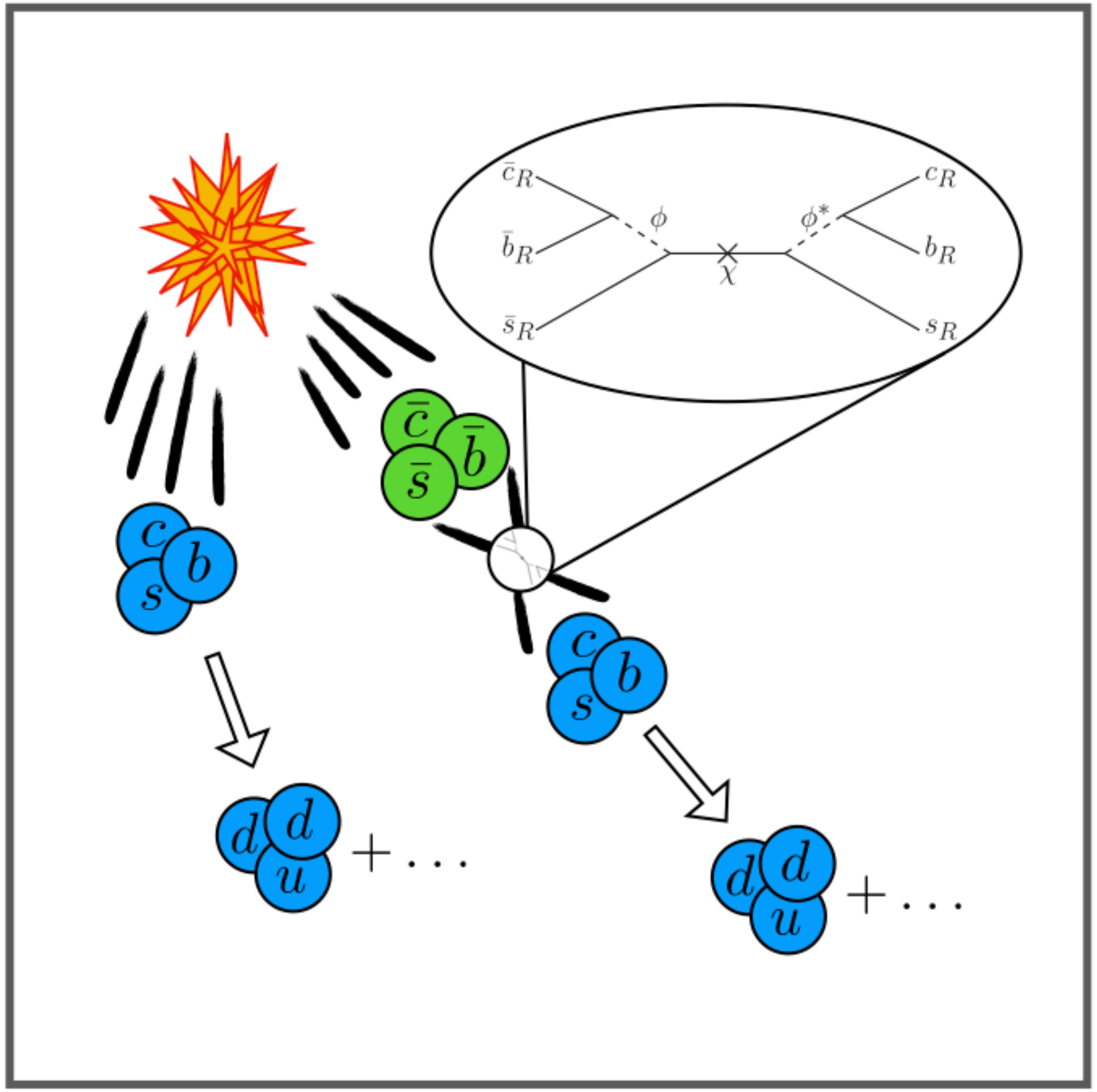
No dinucleon decay for, e.g. $\Delta s = 4$




$\Delta m \sim \mathcal{O}(100\,\text{MeV}) \Rightarrow \left|\frac{\Gamma_{12}}{M_{12}}\right|$ bigger!

Is this useful?

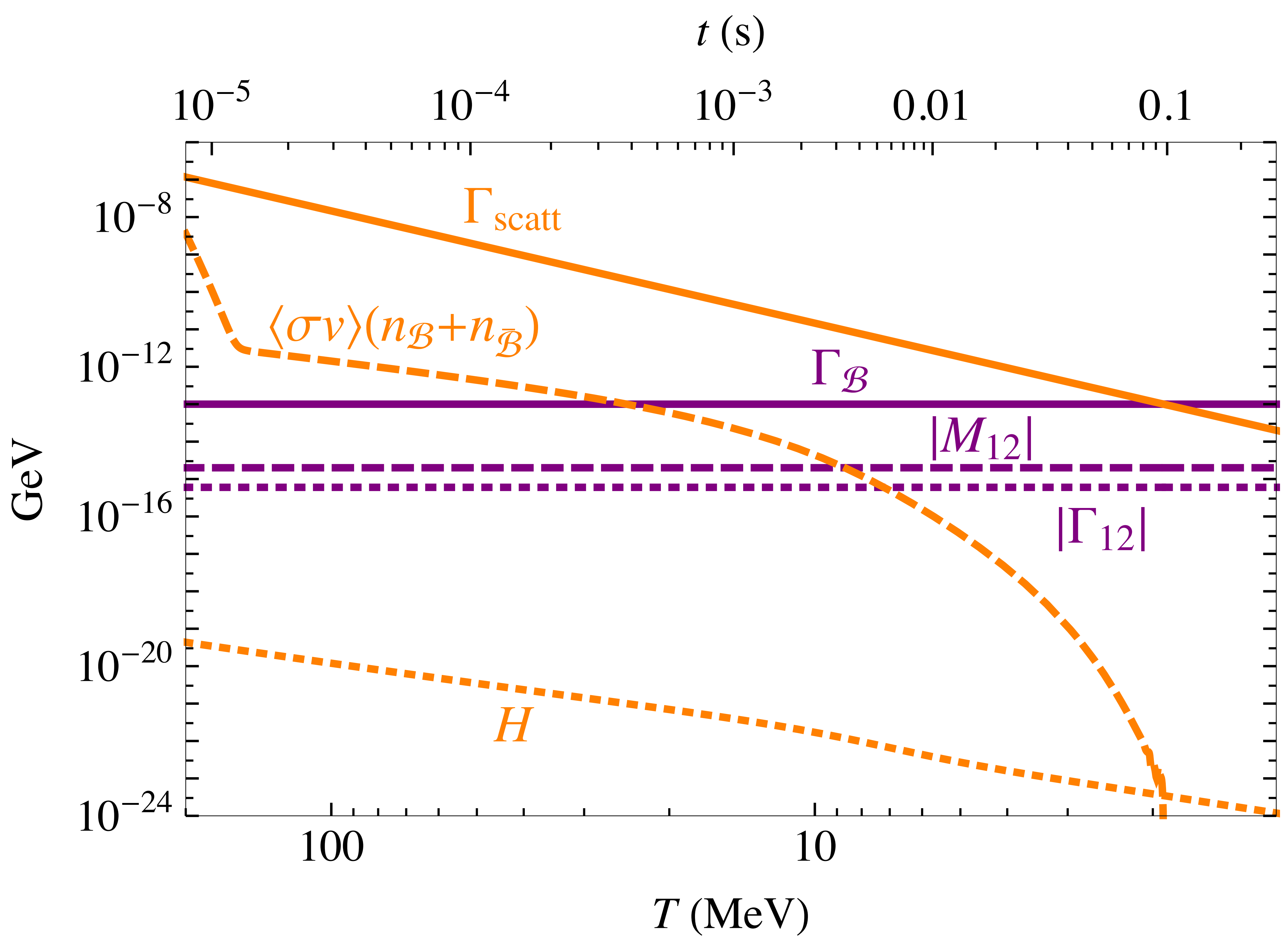
# Heavy flavor baryon oscillations: Baryogenesis

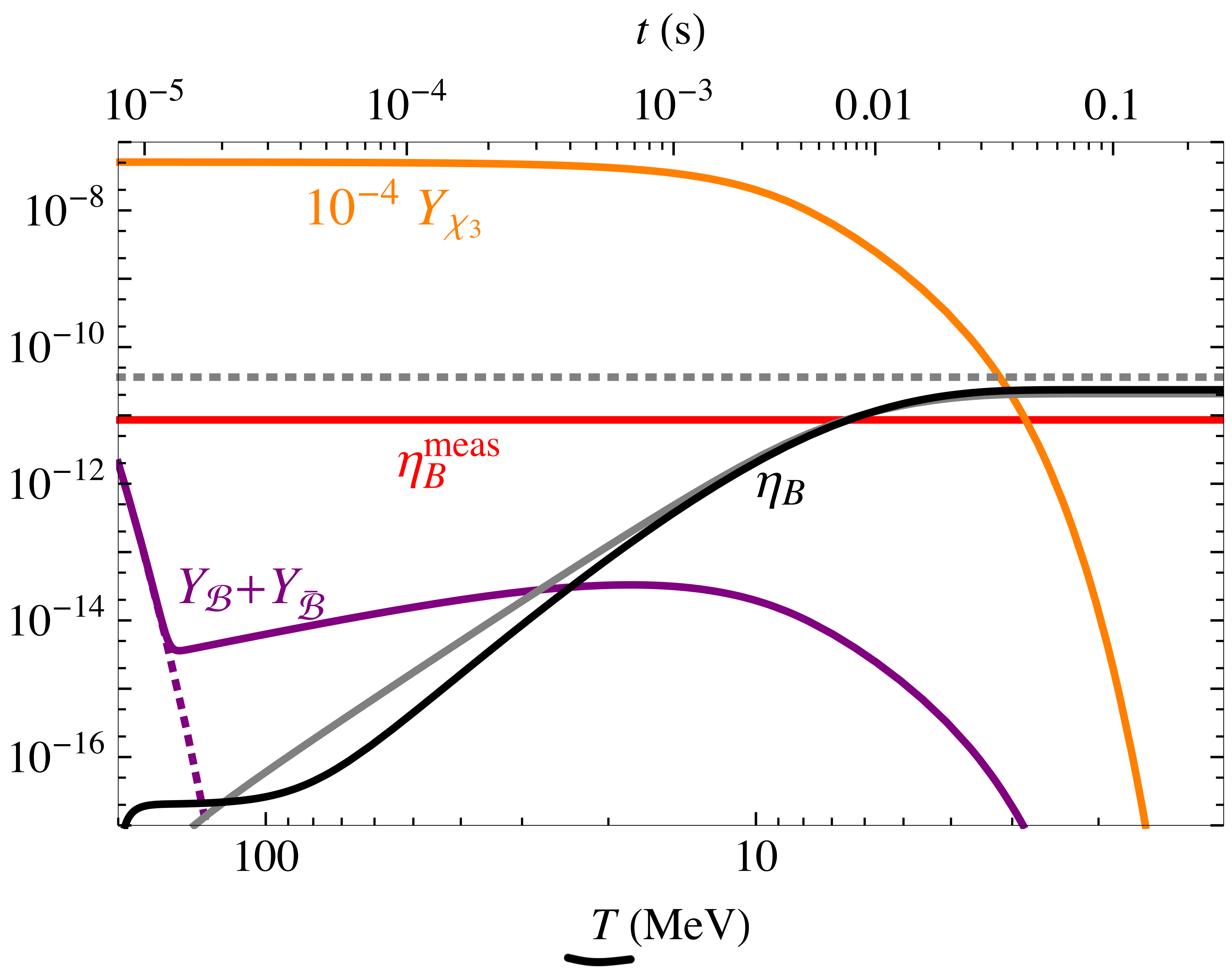



Similar to B meson oscillation baryogen. (A. Long talk) of Alonso-Alvaréz, Elor, Escudero, Nelson

Produce heavy baryons out of eq. (e.g. inflaton decay), CPV & $\Delta B=2$ biases decays to B

# Heavy flavor baryon oscillations: Baryogenesis




Decoherence important
⇒ action is ~10 MeV

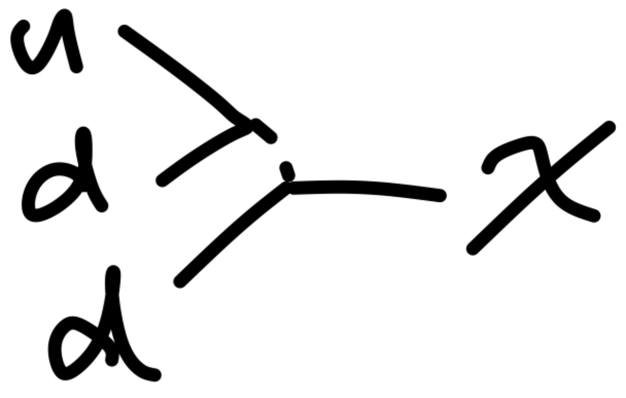
$\Omega_{cb}$-$\bar{\Omega}_{cb}$ system

$$\left[\begin{array}{c} m_{\mathcal{B}} = 7 \text{ GeV}, \ \Gamma_{\mathcal{B}} = 3 \times 10^{-12} \text{ GeV} \\ |M_{12}| = 3 \times 10^{-15} \text{ GeV}, \ |\Gamma_{12}/M_{12}| = 0.3 \\ m_{\chi_3} = 7.5 \text{ GeV}, \ \Gamma_{\chi_3} = 3 \times 10^{-23} \text{ GeV} \end{array}\right]$$

# Dirac Dark Baryons

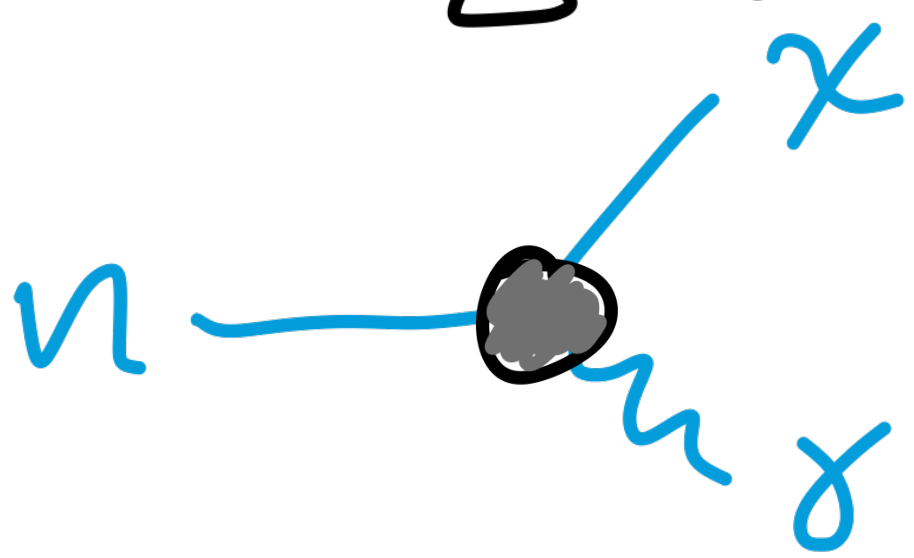
Low energy theory is

$$-\mathcal{L} \supset m_n \bar{n} n + m_\chi \bar{\chi}\chi + \delta(\bar{n}\chi + \bar{\chi} n)$$




No longer strong $n \to \bar{n}$, $nn \to \pi\pi$ bounds

$\theta = \frac{\delta}{\Delta m}$ can be much bigger. Useful?




$$Br_{n\to\chi\gamma} = 1\% \left(\frac{\theta}{5\times10^{-10}}\right)^2 \left(\frac{\Delta m}{\text{MeV}}\right)^3$$

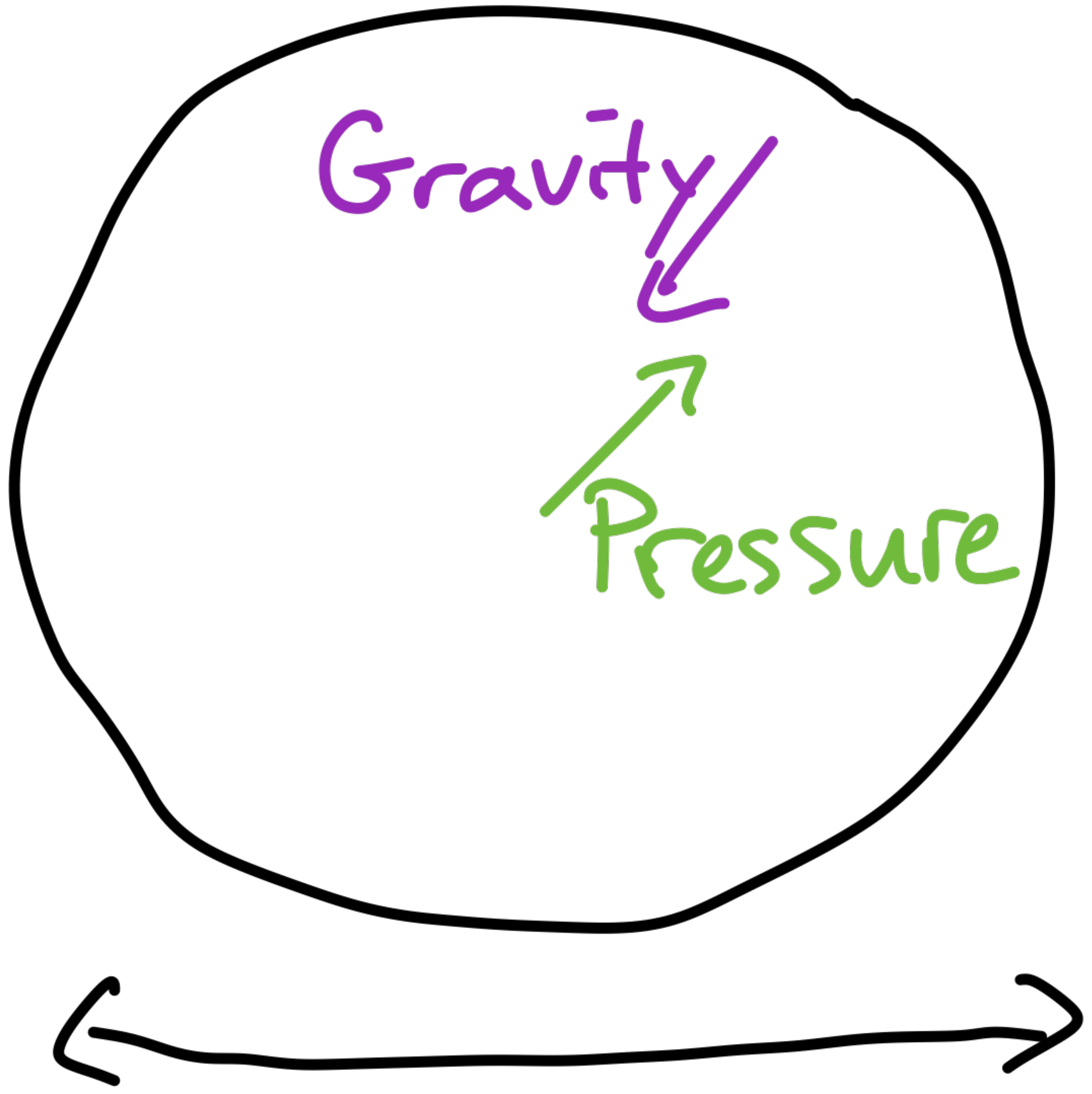
[direct search @ LANL]

n lifetime anomaly, $\chi$ as DM (stable if $m_\chi < m_e + m_p$)

(Fornal, Grinstein, Berezhiani, Cline, Cornell, ...)

Where else??

# Neutron Stars

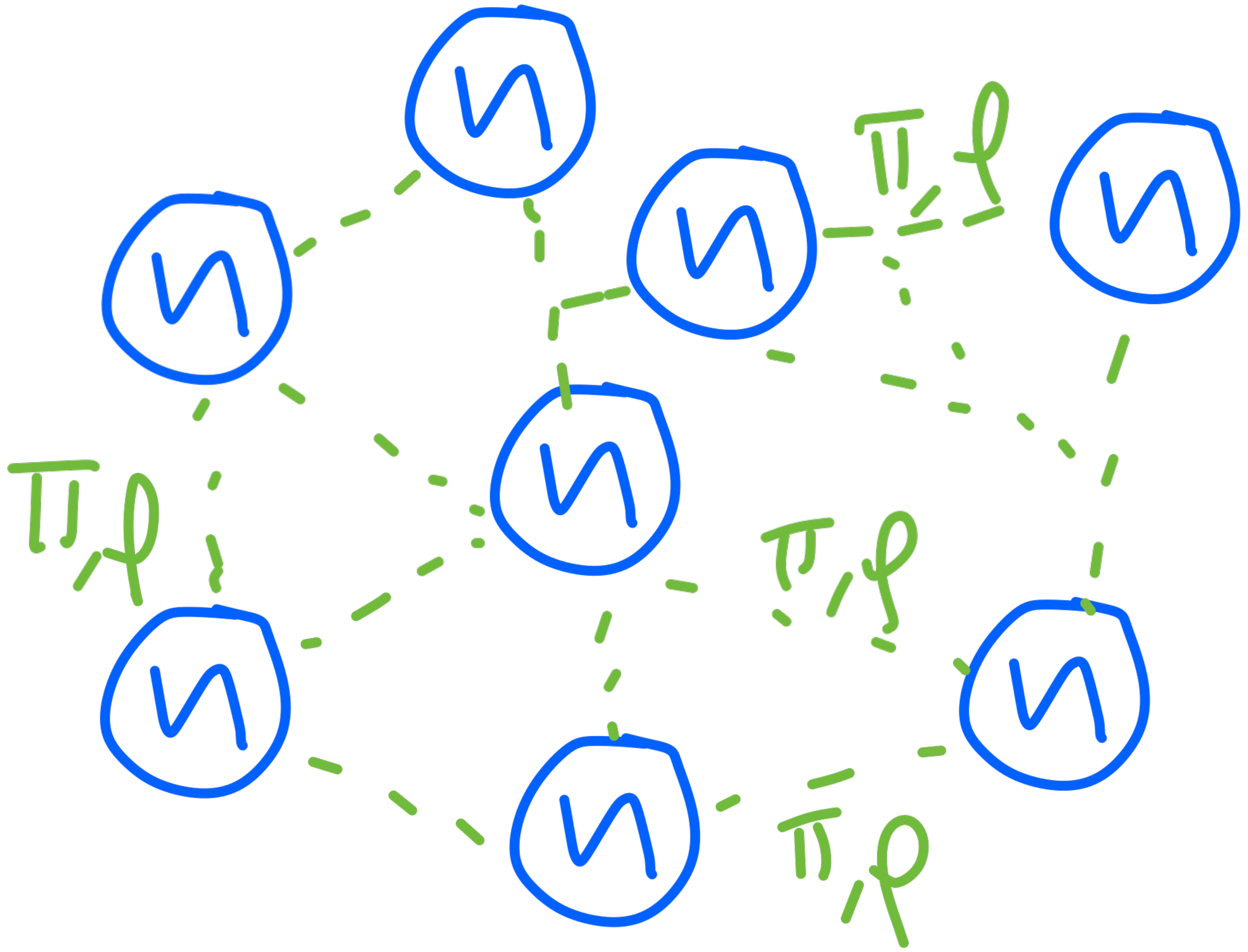



$\mathcal{O}(20\,\text{km})$

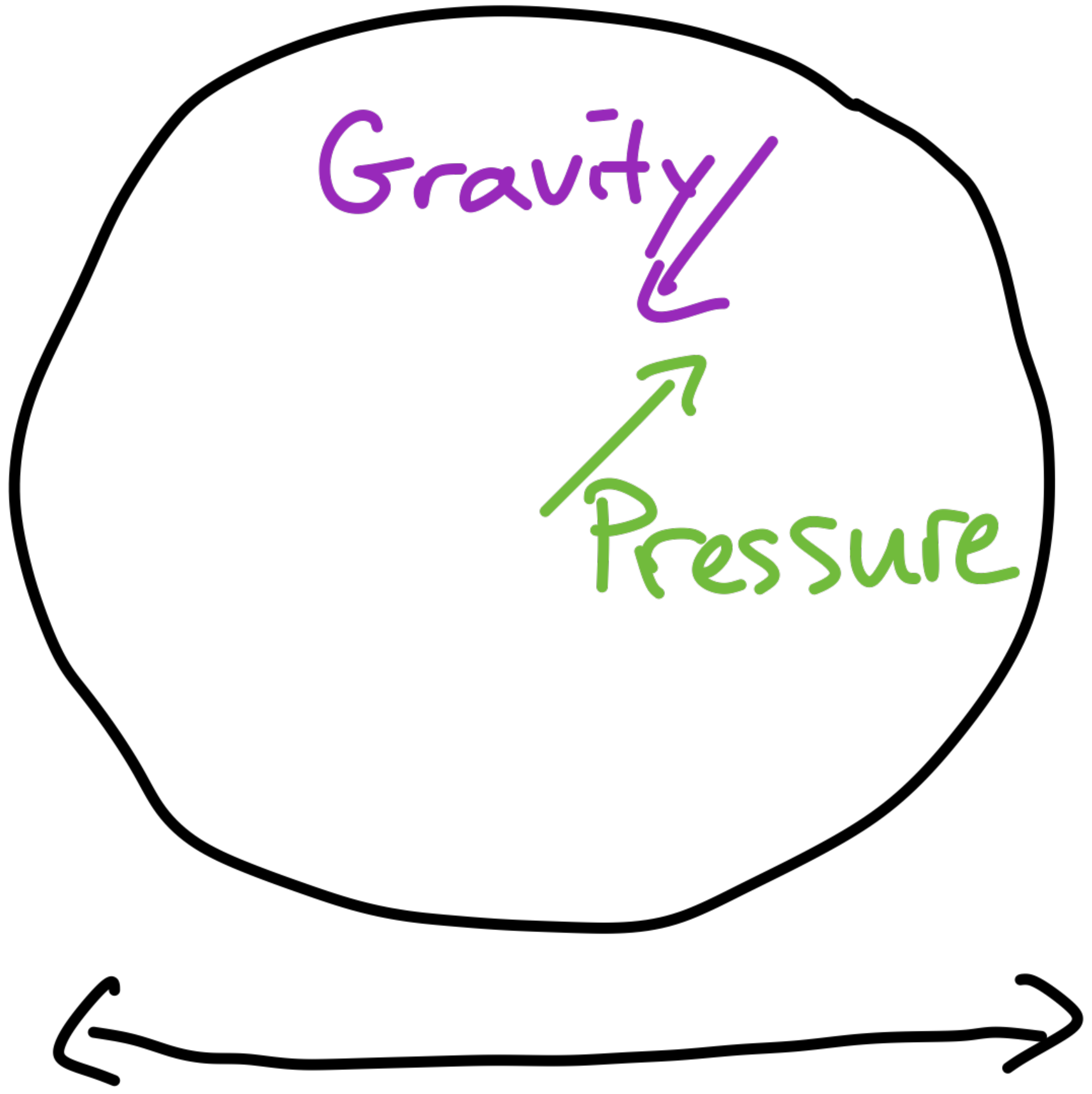
$M \sim M_\odot \sim 10^{57}\,\text{GeV}$

TOV eq: $\frac{dp}{dr} = -\frac{G\varepsilon(r)M(r)}{r^2} \times \overbrace{(GR)}^{\gtrsim 1}$

E.o.S.: $p(r) = f[\varepsilon(r)]$



# Neutron Stars

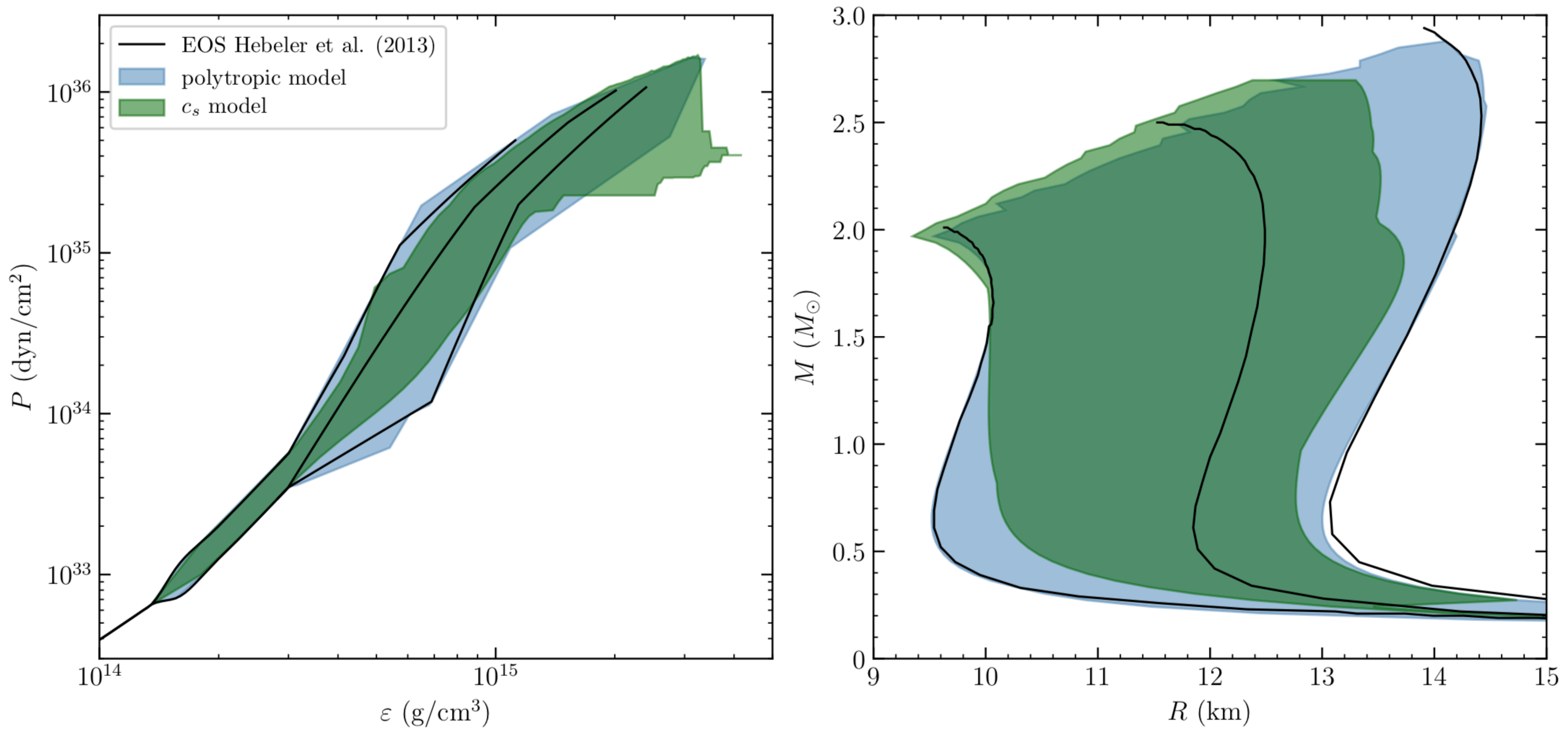



$\mathcal{O}(20\,\mathrm{km})$

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

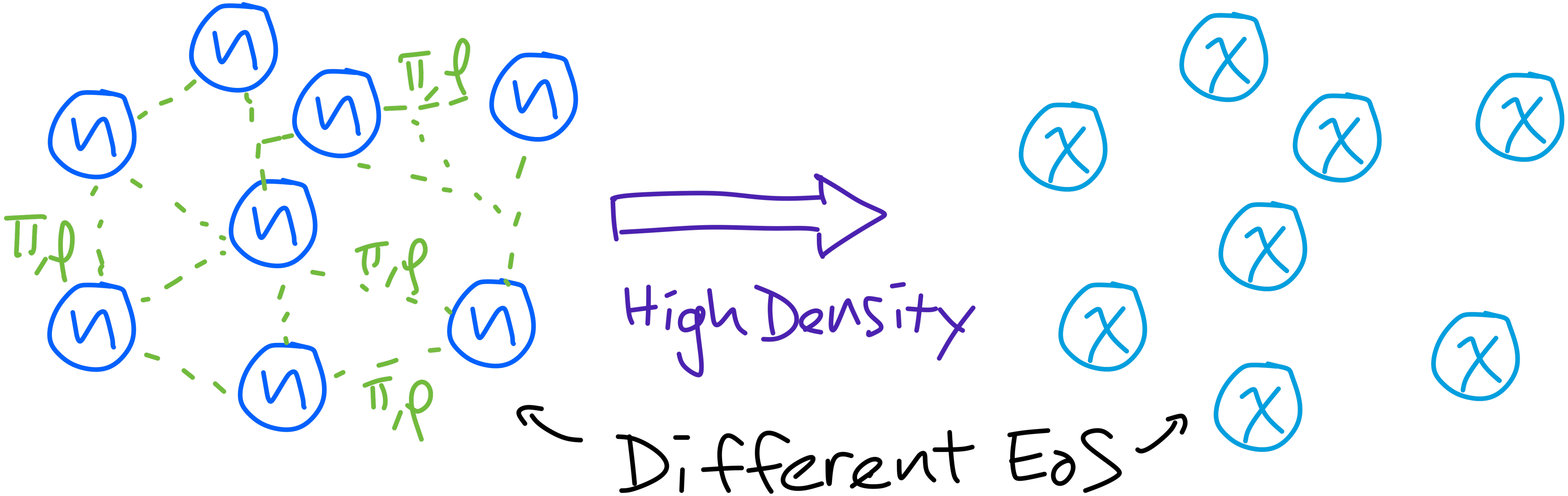
TOV eq: $$\frac{dp}{dr} = -\frac{G\,\varepsilon(r)\,M(r)}{r^2} \times \overbrace{(GR)}^{\gtrsim 1}$$

E.o.S.: $p(r) = f[\varepsilon(r)]$



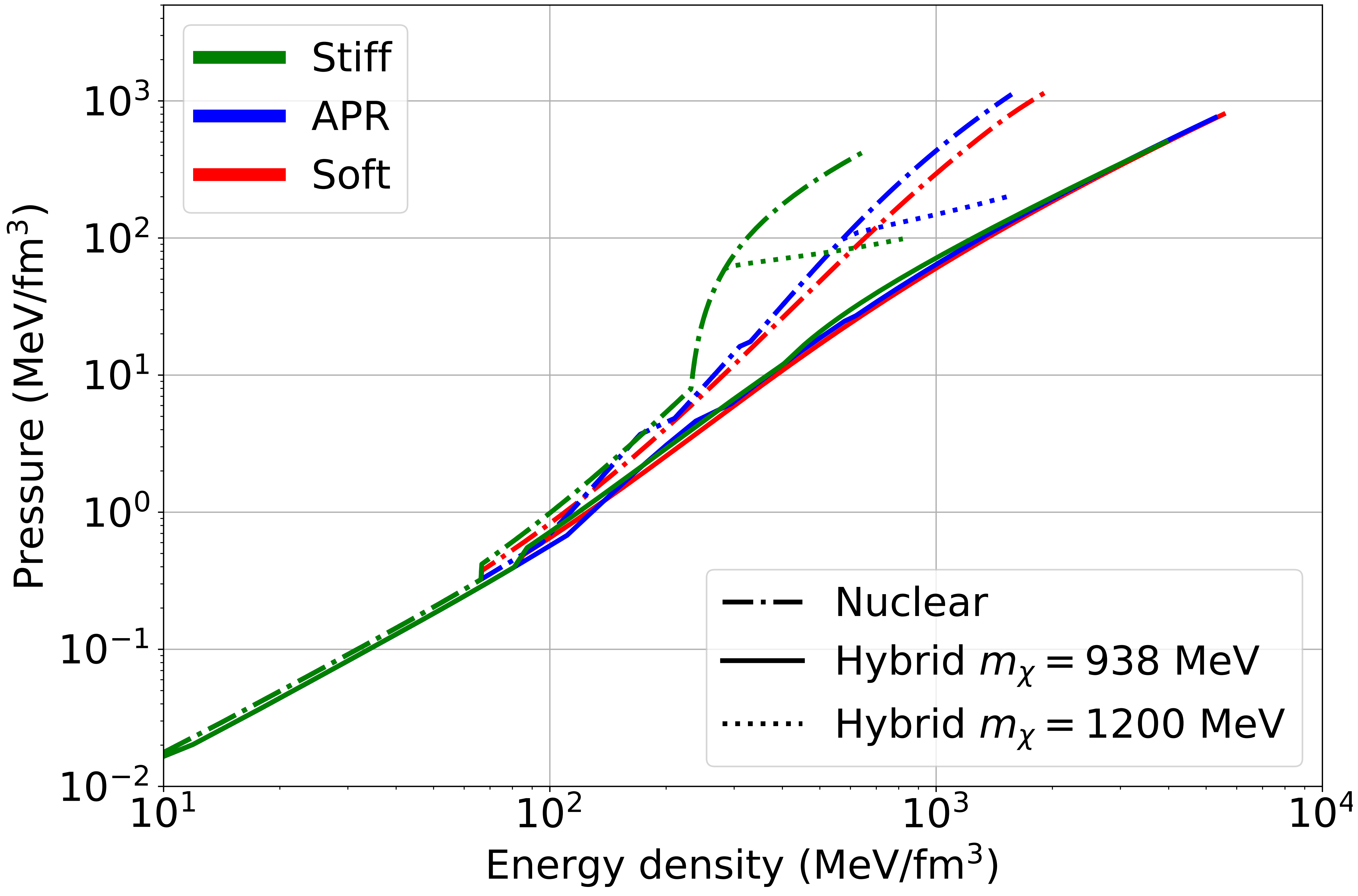

Greif, Raaijmakers, Hebeler, Schwenk, & Watts arXiv:1812.08188

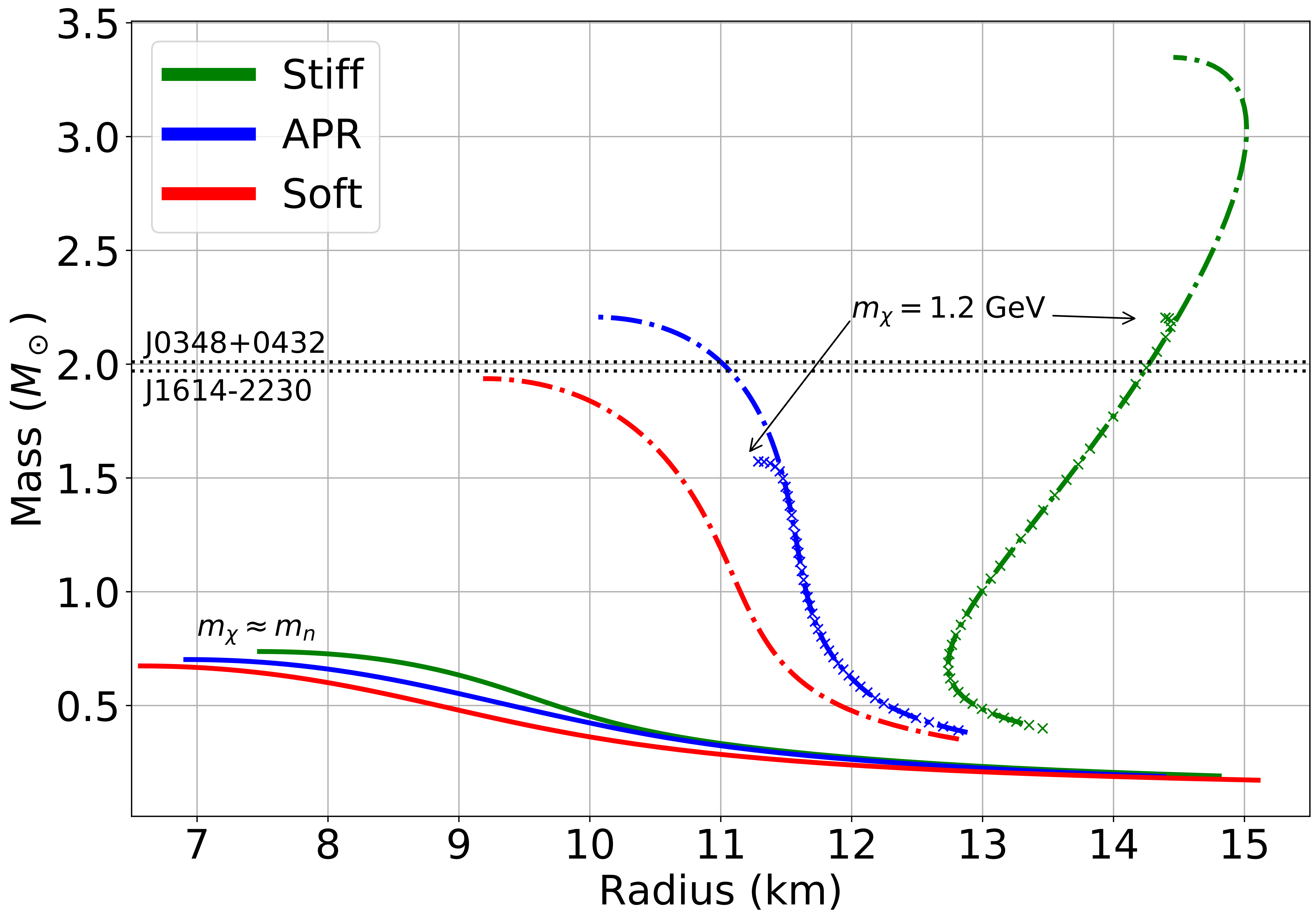
# Neutron Stars & Dark Baryons



# Neutron Stars & Dark Baryons

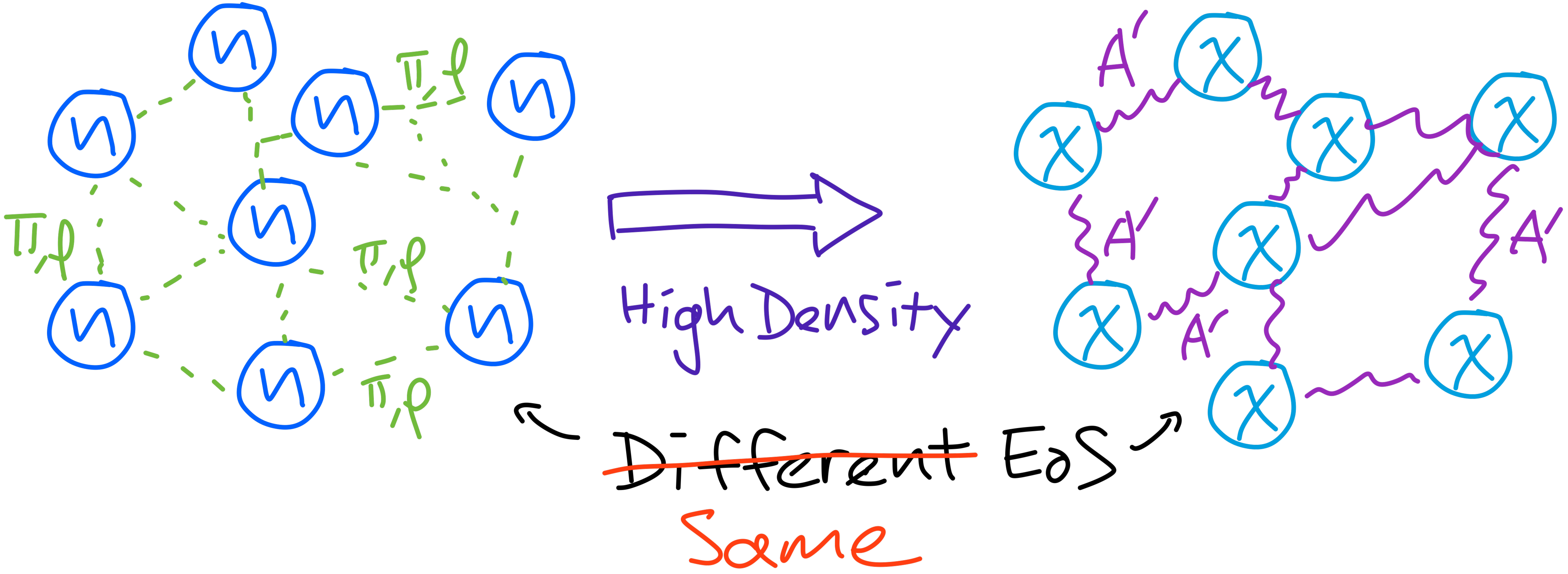
DM, Nelson, Reddy, & Zhou, PRL **121**, 061802; Baym *et al.*, Motta *et al.*



# Neutron Stars & Dark Baryons

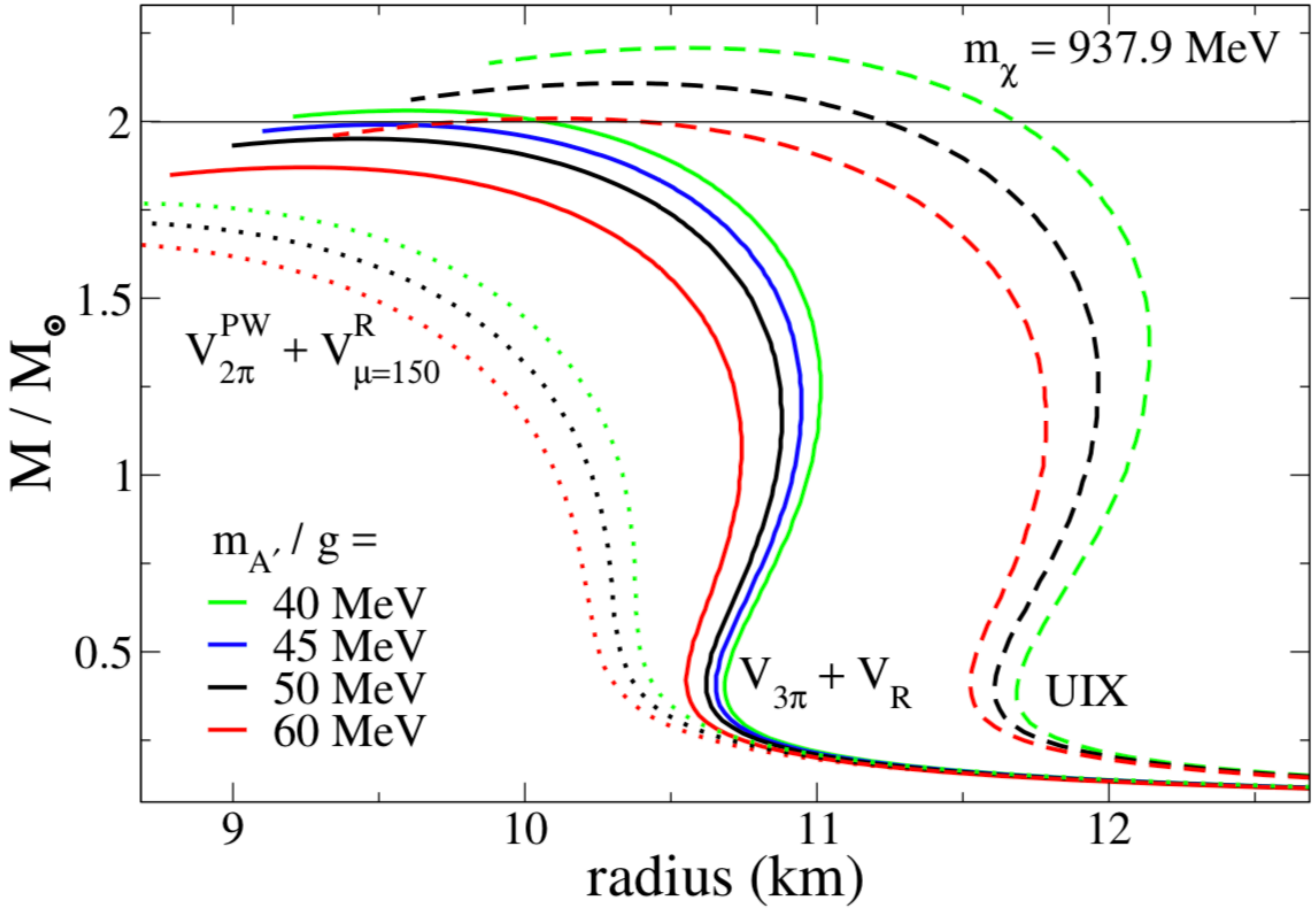
## A way out?



# Neutron Stars & Dark Baryons

A way out?

Cline & Cornell, JHEP **1807** 081

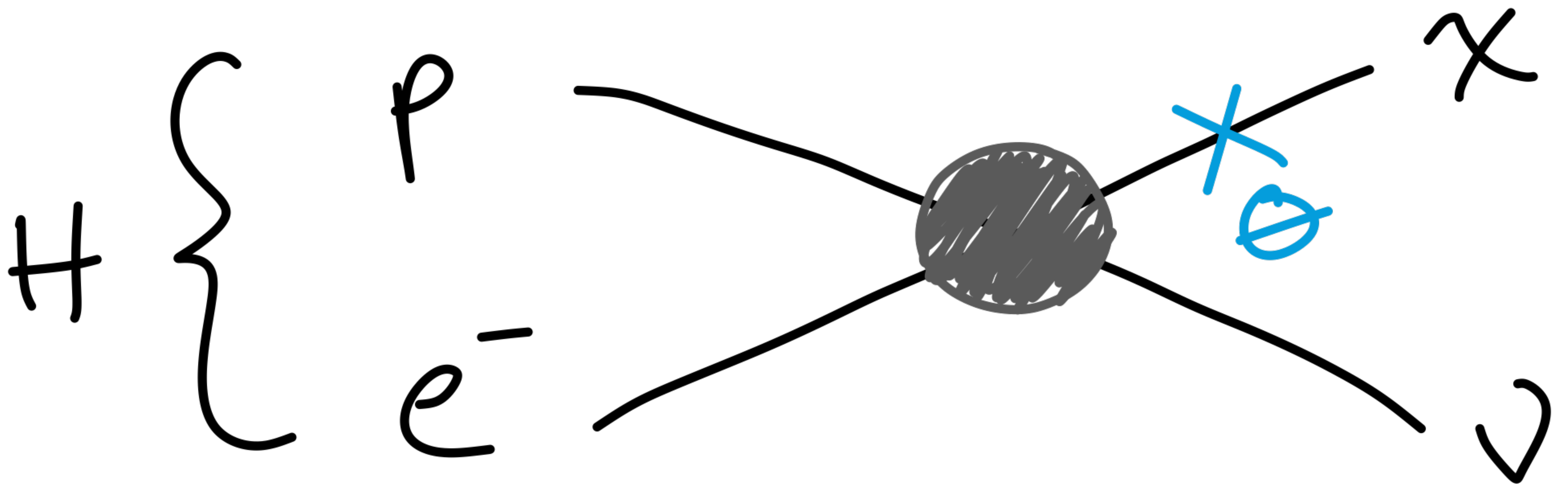



Exotic neutron decay invisible:

$n \to \chi A'$

# Anywhere else? Hydrogen decay!

If $m_\chi < m_p + m_e = m_H$ (+13.6eV), i.e. where $\chi$ is stable

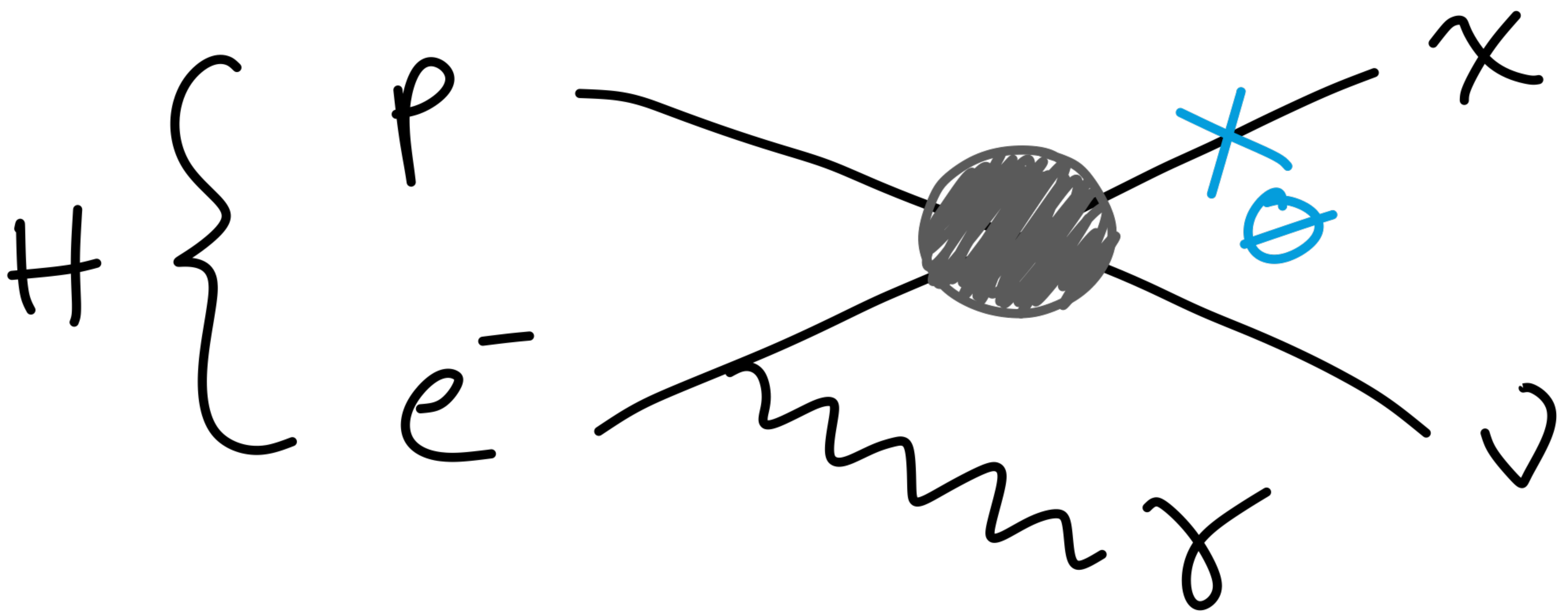



Leading mode

$$\tau_H \sim 10^{27}\,s \left(\frac{10^{-9}}{\theta}\right)^2 \left(\frac{m_e}{Q}\right)^2$$

Invisible - hard to test...

and...




$$Br_\gamma = \underbrace{\frac{\alpha}{12\pi}}_{2\times10^{-4}} \left(\frac{Q}{m_e}\right)^2$$

Berezhiani; DM & Pospelov

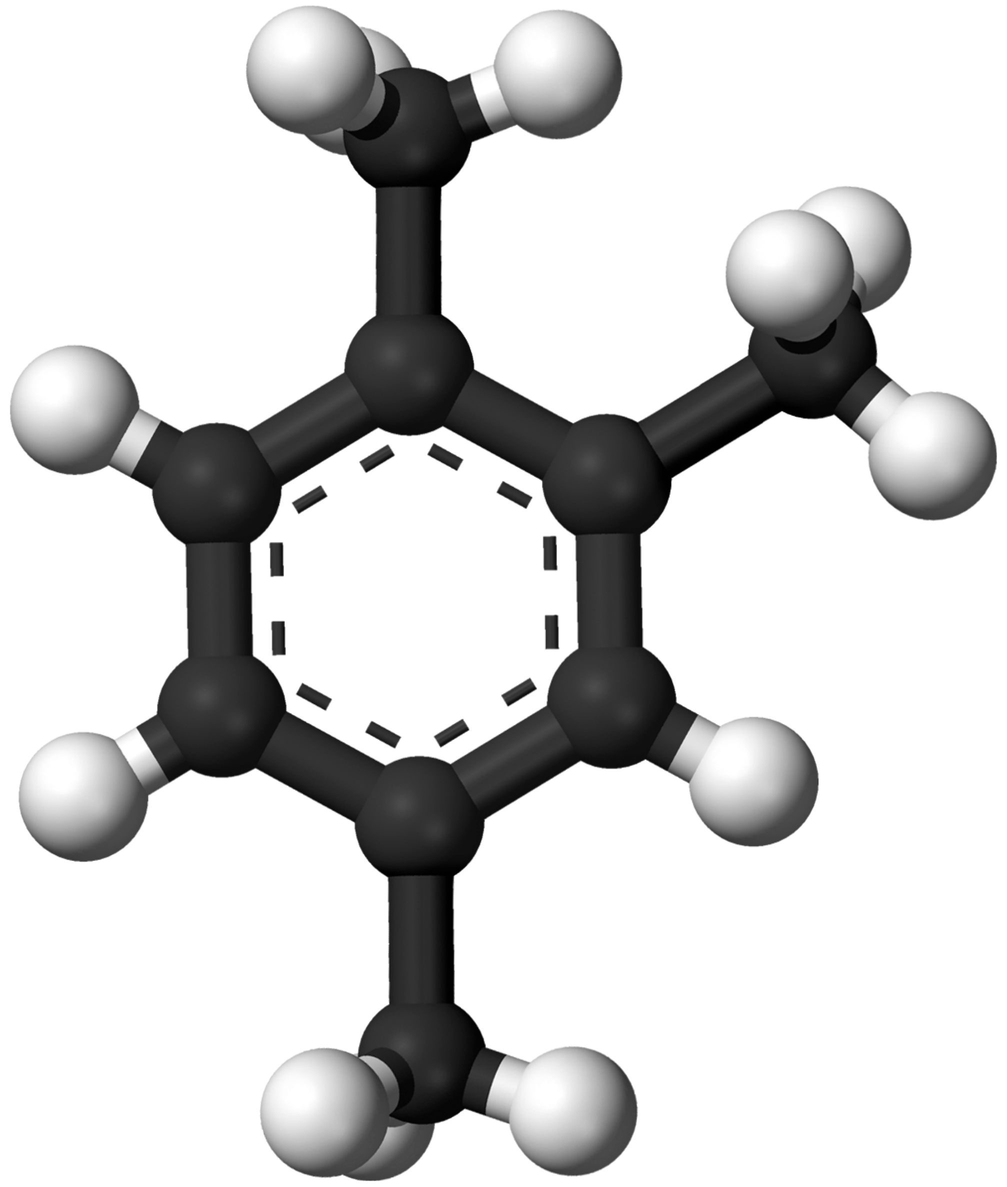
Need: lots of H

sensitivity to $\mathcal{O}$(100 keV $\gamma$s)

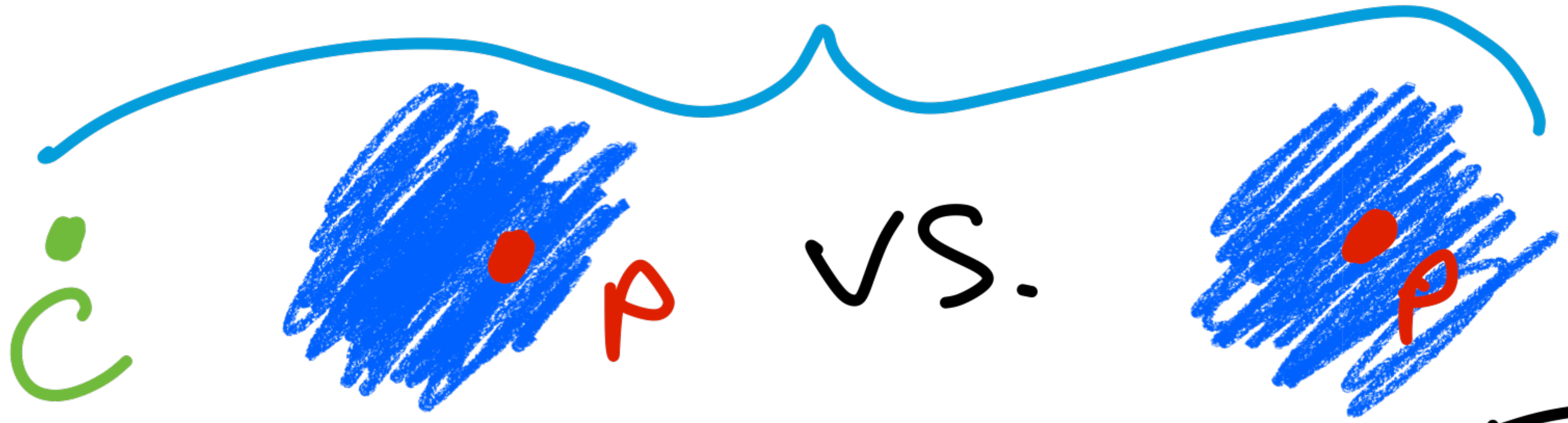
e.g. Borexino

$\mathcal{O}$(100 t) pseudocumene

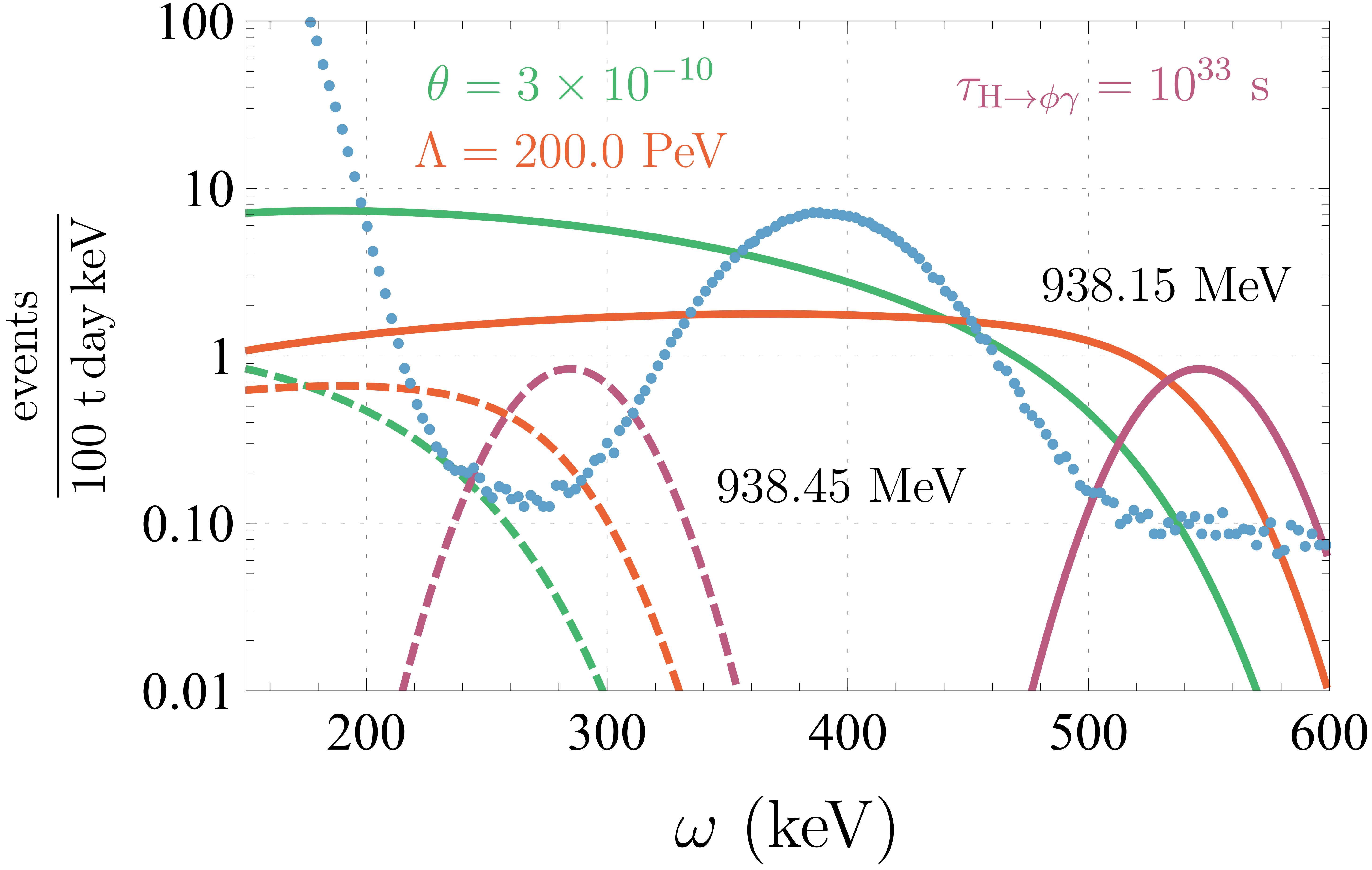
$C_6H_3(CH_3)_3$ – 10% H



Rate: $$\frac{4\times10^4}{100\,t\,\text{day}}\left(\frac{\theta}{10^{-9}}\right)^2\left(\frac{Q}{m_e}\right)^4\left(\frac{|\psi_{mol}(0)/\psi_H(0)|^2}{0.5}\right)$$



# Spectrum @ BOREXINO



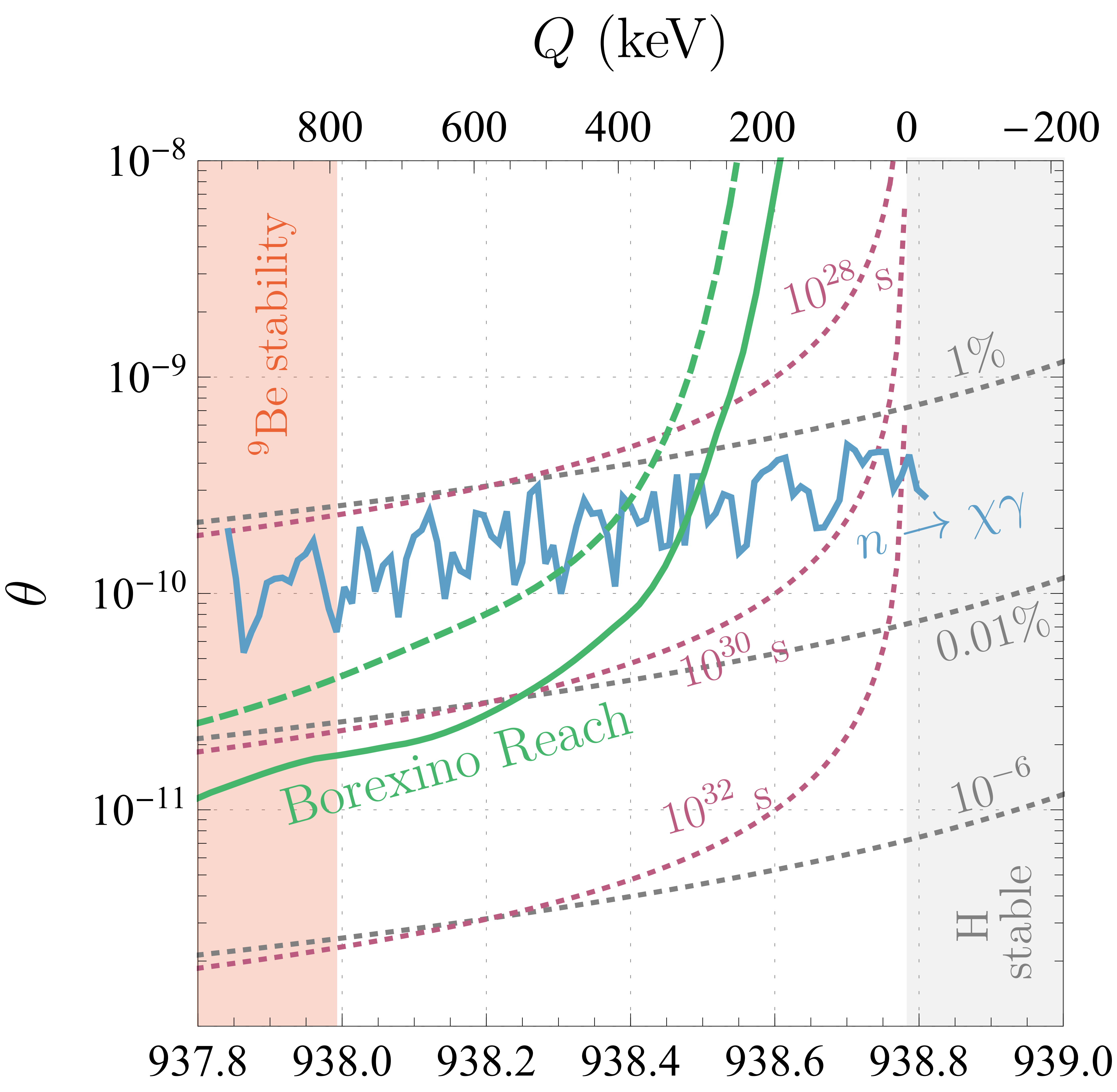

Blue: data from 1509.01223 (search for $e^- \to \gamma\nu$, test of Q cons.)

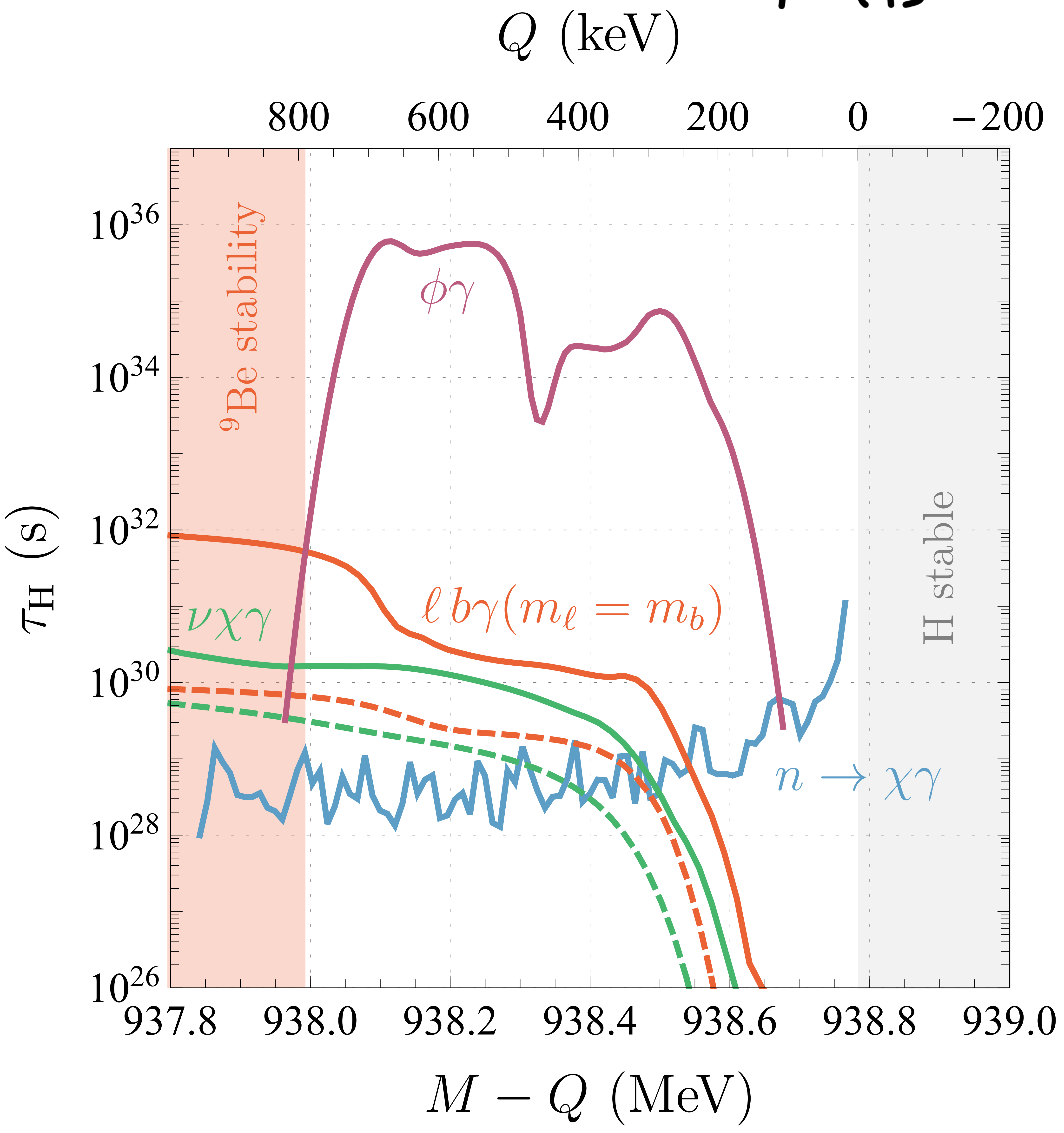
Green: $\chi \xrightarrow{\theta} n$

Purple: $\mathcal{L} \supset y \bar{e}^c p \phi$

Red: $\mathcal{L} \supset \frac{1}{\Lambda^2} \bar{\chi} e \bar{b} p$

# Fit Results - can probe $\tau_H \sim 10^{30}$s in this model



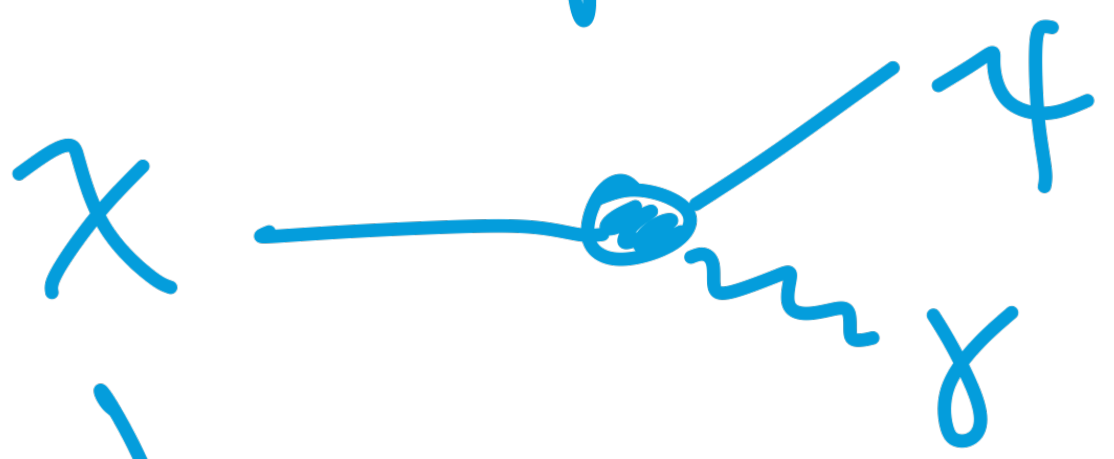




DM & Pospelov

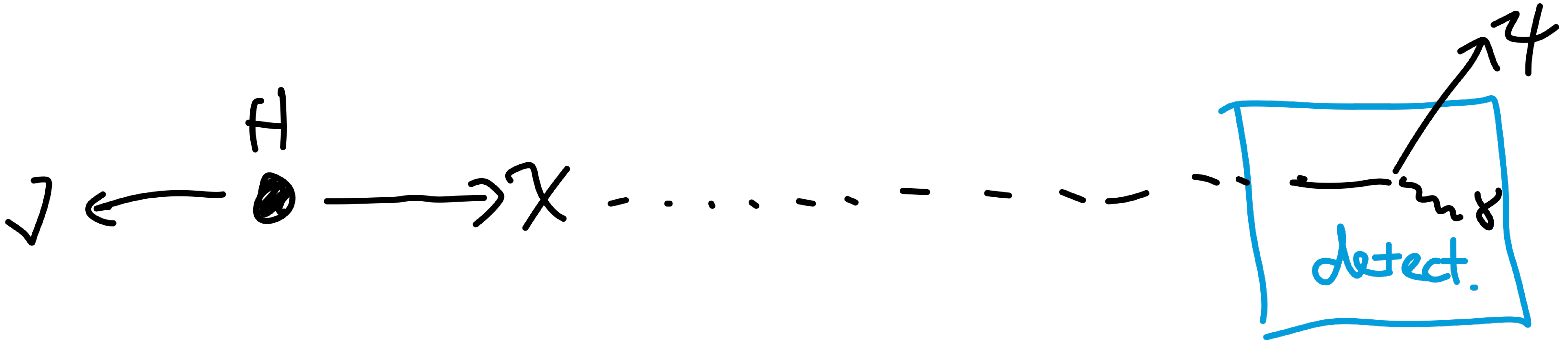
# Other sources of dark baryons

Lots of H on Earth & in Sun!

Consider: $\chi$ has transition dipole to another dark baryon:



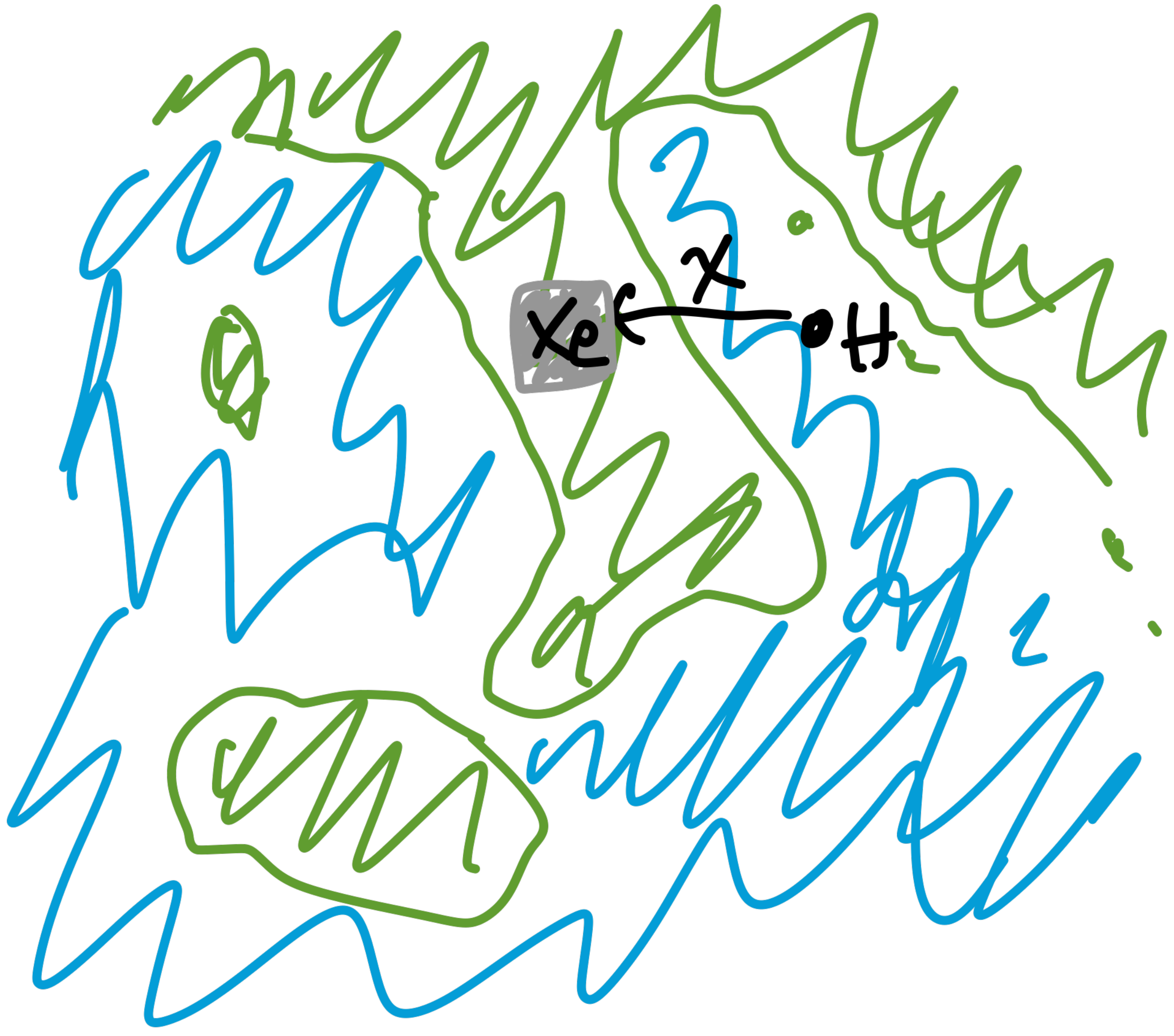

(NS ⇒ nontrivial interactions)



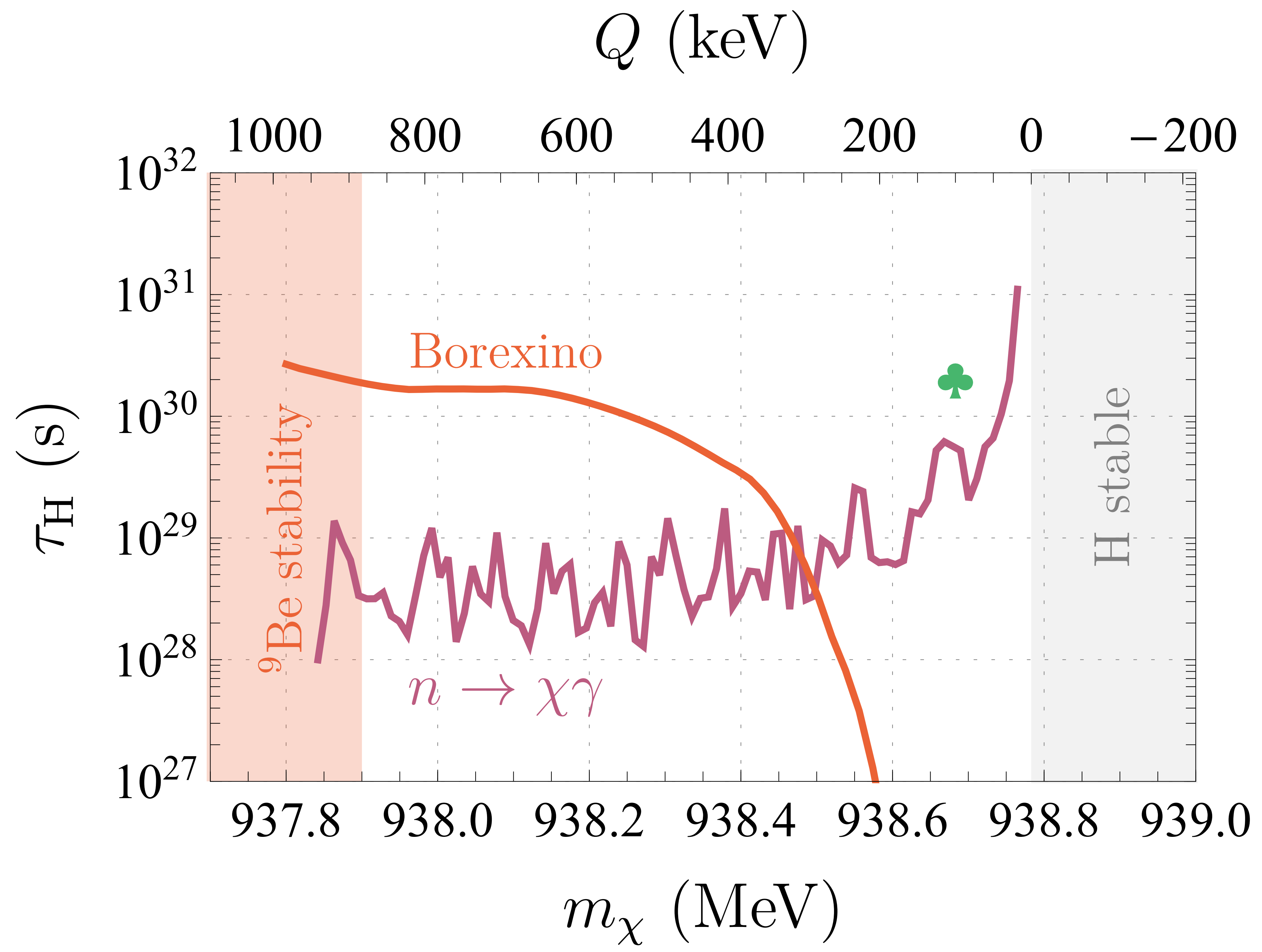

can see $\chi$ decay

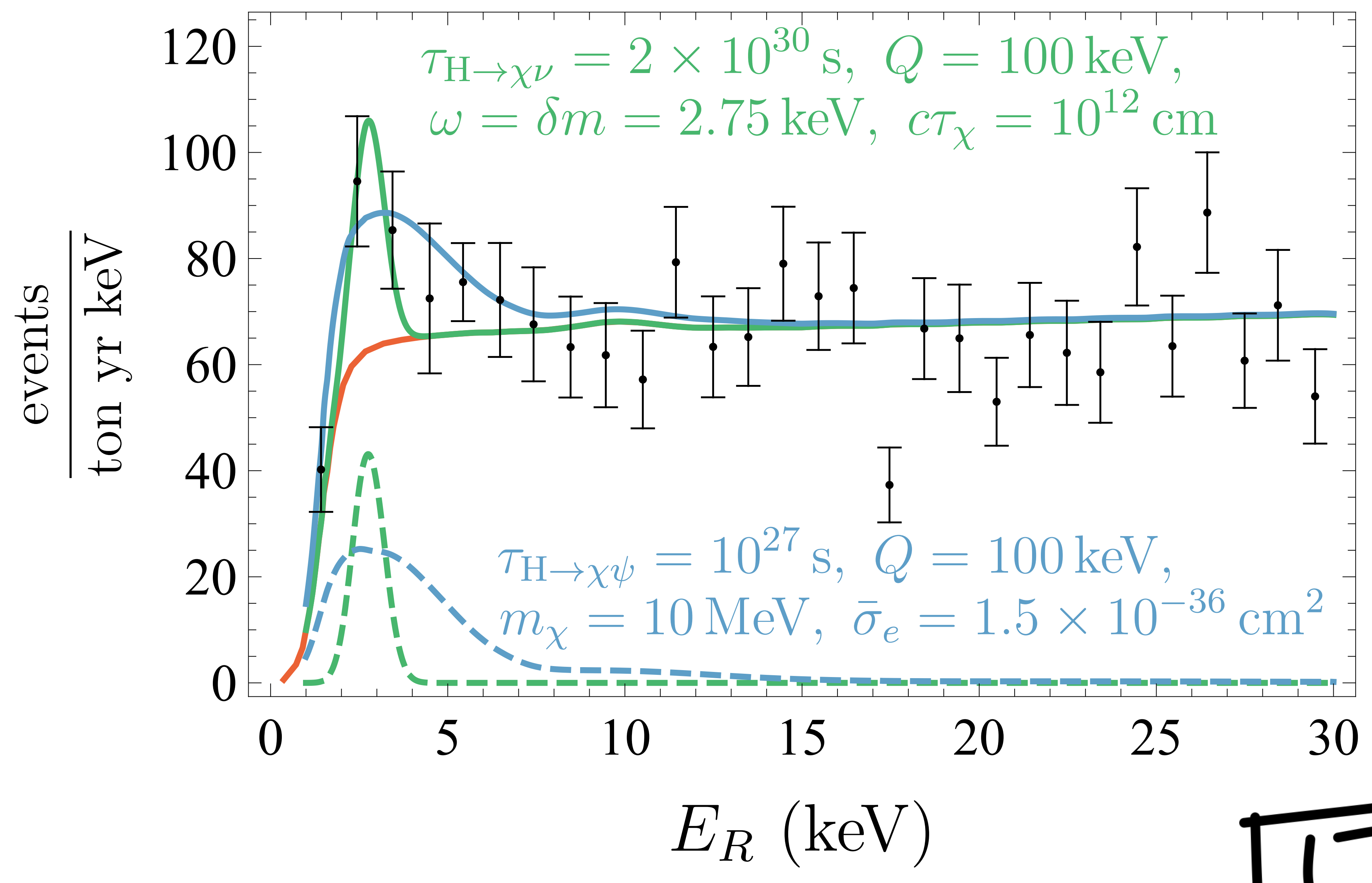
DM, Pospelov, Raj

# Application: XENON1T




can fit recent excess in this setup




DM, Pospelov, Raj

# Wrap Up

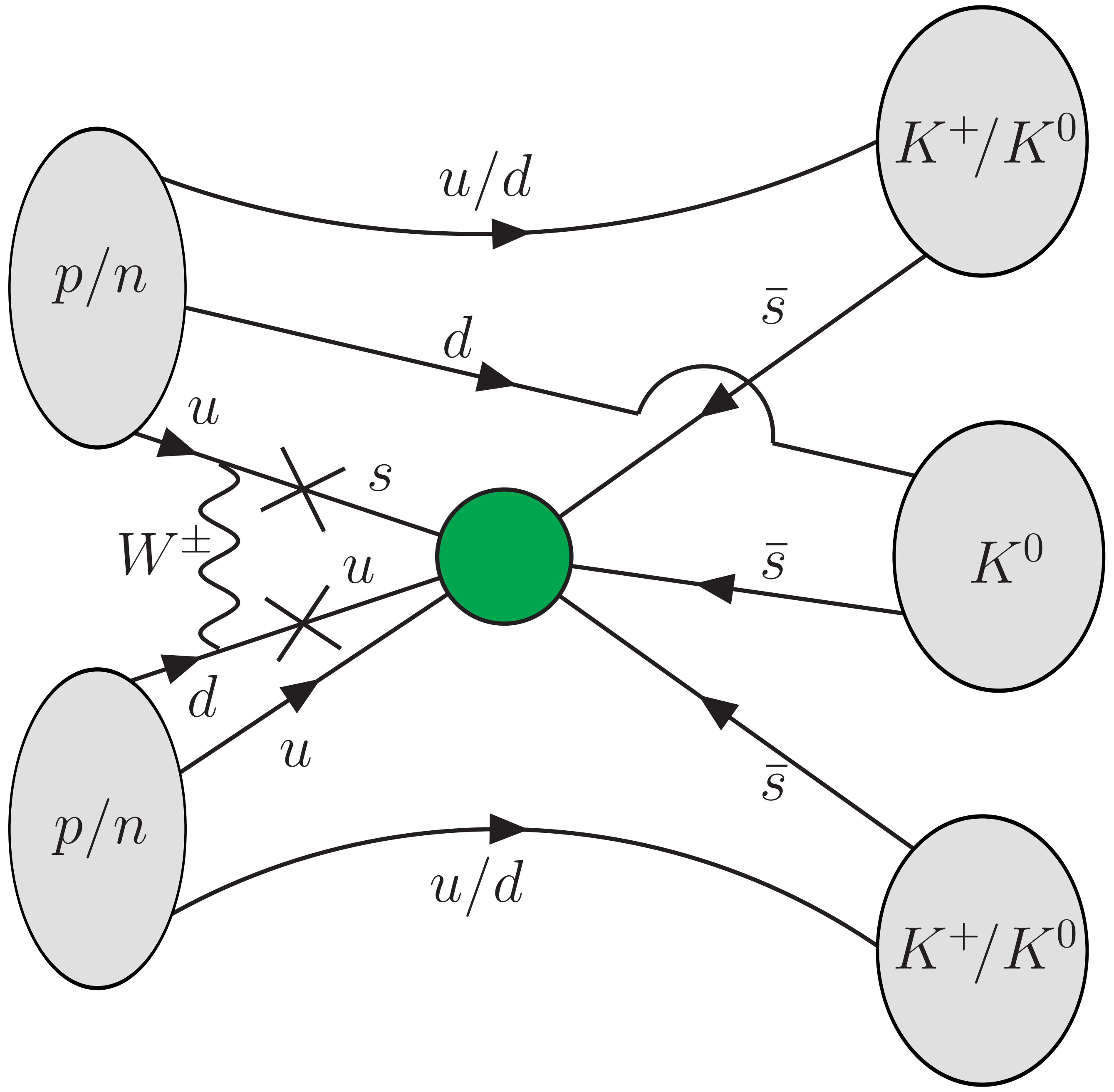
Dark baryons offer interesting way to adress some problems – baryogenesis n lifetime anomaly, & dark matter

Important constraints come from neutron stars & atomic H decay

Novel signatures at ton-scale direct detection exp'ts => further work ongoing (CMB, BBN, neutron stars)

# Backup: (Indirect) Dinucleon Decay

There is still contribution to dinucleon decay in presence of weak interactions

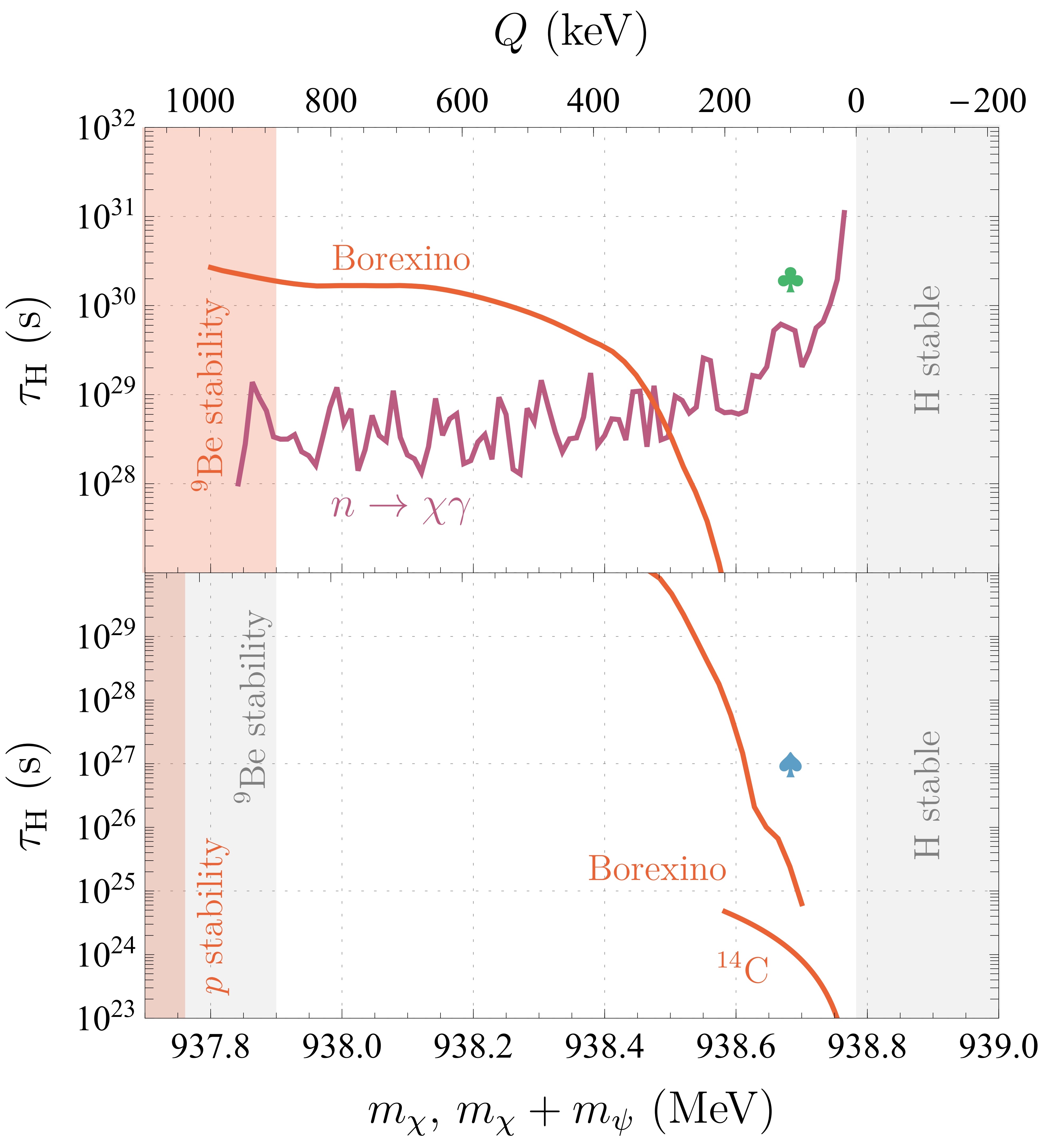


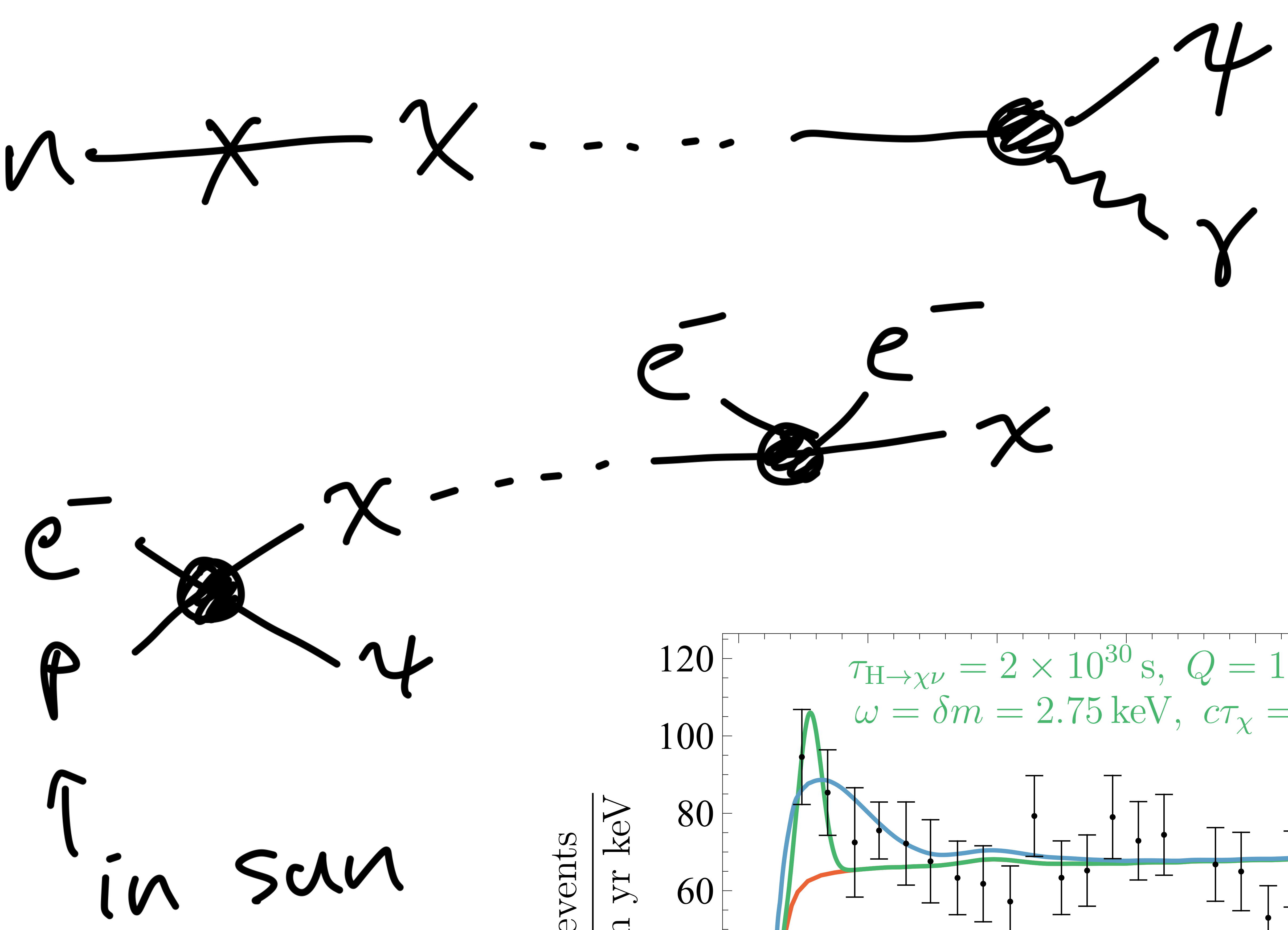

| Operator | $\mathcal{B}$ | Weak Insertions Required | Measured $\Gamma$ (GeV) [19] | Limits on $\delta_{\mathcal{BB}} = M_{12}$ (GeV) Dinucleon decay | Collider |
|---|---|---|---|---|---|
| $(udd)^2$ | $n$ | None | $(7.477 \pm 0.009) \times 10^{-28}$ | $10^{-33}$ | $10^{-17}$ |
| $(uds)^2$ | $\Lambda$ | None | $(2.501 \pm 0.019) \times 10^{-15}$ | $10^{-30}$ | $10^{-17}$ |
| $(uds)^2$ | $\Sigma^0$ | None | $(8.9 \pm 0.8) \times 10^{-6}$ | $10^{-30}$ | $10^{-17}$ |
| $(uss)^2$ | $\Xi^0$ | One | $(2.27 \pm 0.07) \times 10^{-15}$ | $10^{-22}$ | $10^{-17}$ |
| $(ddc)^2$ | $\Sigma_c^0$ | Two | $(1.83^{+0.11}_{-0.19}) \times 10^{-3}$ | $10^{-17}$ | $10^{-16}$ |
| $(dsc)^2$ | $\Xi_c^0$ | Two | $(5.87^{+0.58}_{-0.61}) \times 10^{-12}$ | $10^{-16}$ | $10^{-15}$ |
| $(ssc)^2$ | $\Omega_c^0$ | Two | $(9.5 \pm 1.2) \times 10^{-12}$ | $10^{-14}$ | $10^{-15}$ |
| $(udb)^2$ | $\Lambda_b^0$ | Two | $(4.490 \pm 0.031) \times 10^{-13}$ | $10^{-13}$ | $10^{-17}$ |
| $(udb)^2$ | $\Sigma_b^{0*}$ | Two | $\sim 10^{-3*}$ | $10^{-13}$ | $10^{-17}$ |
| $(usb)^2$ | $\Xi_b^0$ | Two | $(4.496 \pm 0.095) \times 10^{-13}$ | $10^{-10}$ | $10^{-17}$ |
| $(dcb)^2$ | $\Xi_{cb}^{0\dagger}$ | Two | $\sim 10^{-12\dagger}$ | $10^{-17}$ | $10^{-15}$ |
| $(scb)^2$ | $\Omega_{cb}^{0\dagger}$ | Two | $\sim 10^{-12\dagger}$ | $10^{-14}$ | $10^{-15}$ |
| $(ubb)^2$ | $\Xi_{bb}^{0\ddagger}$ | Four | $\sim 10^{-13\ddagger}$ | $>1$ | $10^{-17}$ |
| $(cbb)^2$ | $\Omega_{cbb}^{0\dagger}$ | Four | $\sim 10^{-12\dagger}$ | $>1$ | $10^{-15}$ |

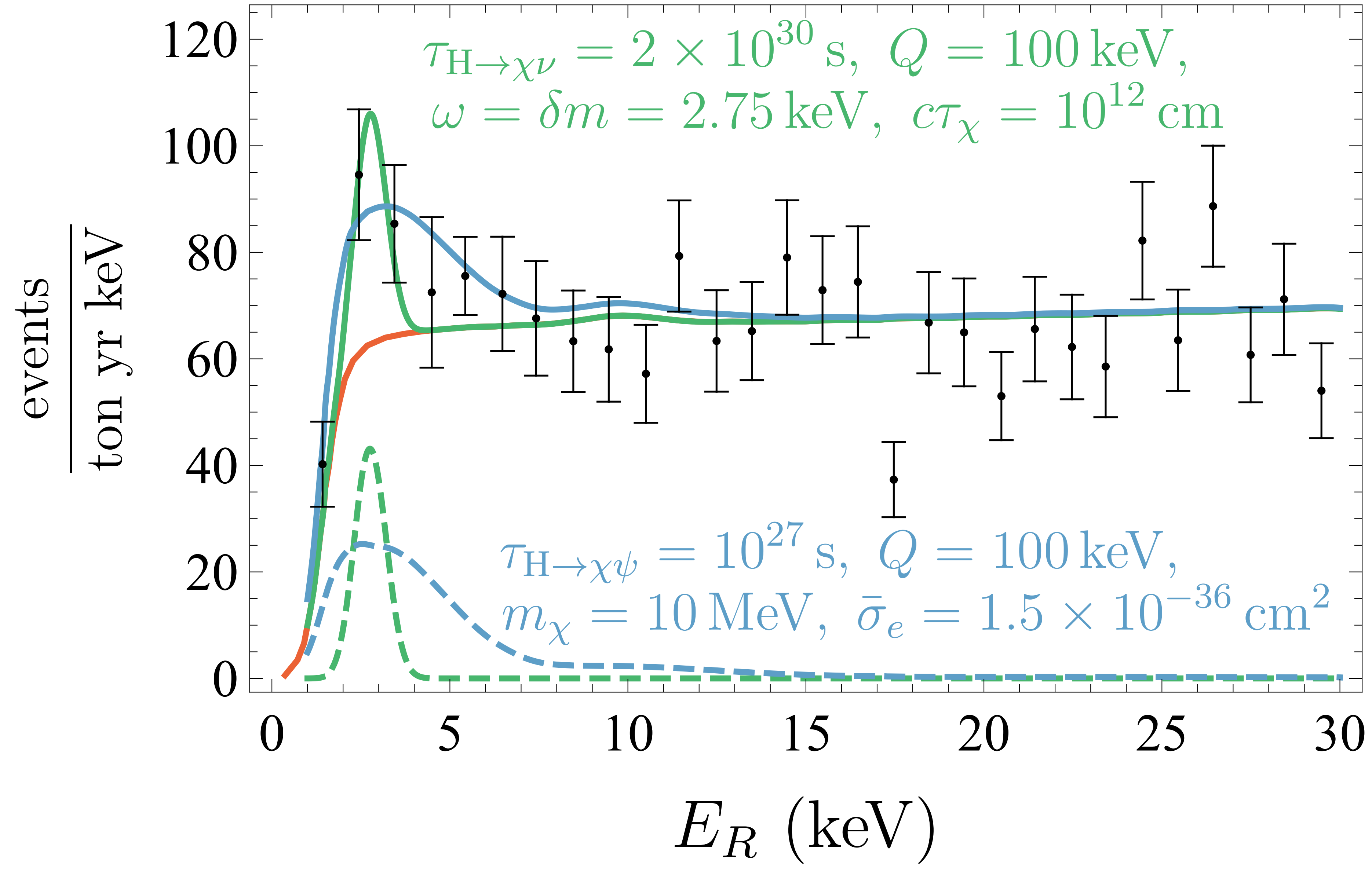
Naive estimate of suppression (proper treatment involves matching onto chiral perturbation theory)

$$\frac{1}{4\pi^2}\frac{G_F}{\sqrt{2}}|V_{us}^*||V_{ud}|m_u m_s \log\left(\frac{m_W^2}{\Lambda_{\rm IR}^2}\right) \sim 10^{-10}$$

# Backup: XENON1T




DM, Pospelov, Raj