How long does the H atom live? Constraining its decay to DM

David McKeen TRIUMF

based on 2003.02270
with Maxim Pospelov
(and work with Ann Nelson, Sanjay Reddy, ...)

Jozef Stefan Inst. Seminar
June 2, 2020

Dark Matter – required by many observations

must be: not too strongly interacting

cold (i.e. nonrelativistic)

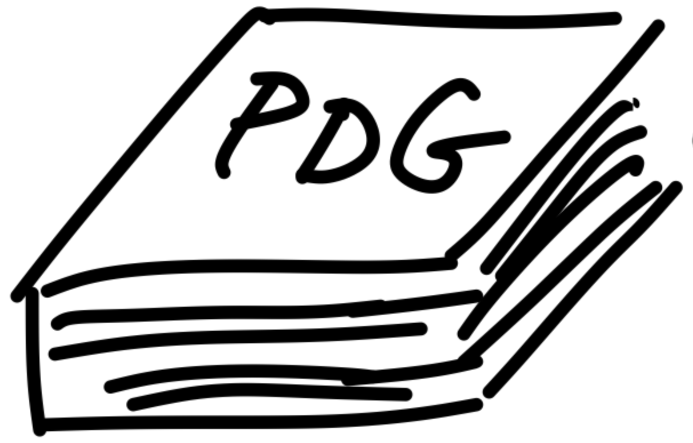
STABLE/LONG-LIVED

CMB: $e^{-t_u/\tau_x} > 0.95$ (<5% decayed)

$\Rightarrow \tau_x > 20\,\tau_u \simeq 3\times 10^{11}\,\mathrm{yr} \simeq 10^{19}\,\mathrm{s}$

Why should it live so long??

What makes particles stable?



almost all of these (very) unstable!

$\mu^{\pm} \sim 10^{-6}$ s

$\pi^{\pm}, K^{\pm} \sim 10^{-8}$ s

...

But: γ – massless so $E, \vec{p}$ conservation

$\nu_1 (\nu_3)$ – lightest fermion ($\vec{J}$ conservation)

$e^{\pm}$ – lightest charged particle (Q conservation)

p – why not $p \to \pi^0 e^+$? searched for extensively

(B conservation, at least approx.)

Why should DM be (nearly?) stable?

SUSY : R-parity

Ex. Dim. : KK parity

Sterile ν : } weak coupling (secretly a sym.?)

axion : }

Could it be stable for same reason normal matter (i.e. proton) is stable? (Approx?) Conservation of Baryon Number

Consider neutral fermion

χ with $B = 1$

First, do no harm...

$p \to \chi e^+ + \ldots$ forbidden if $m_p < m_\chi + m_e$

And make χ stable...

$\chi \to p e^- + \ldots$ forbidden if $m_\chi < m_p + m_e$

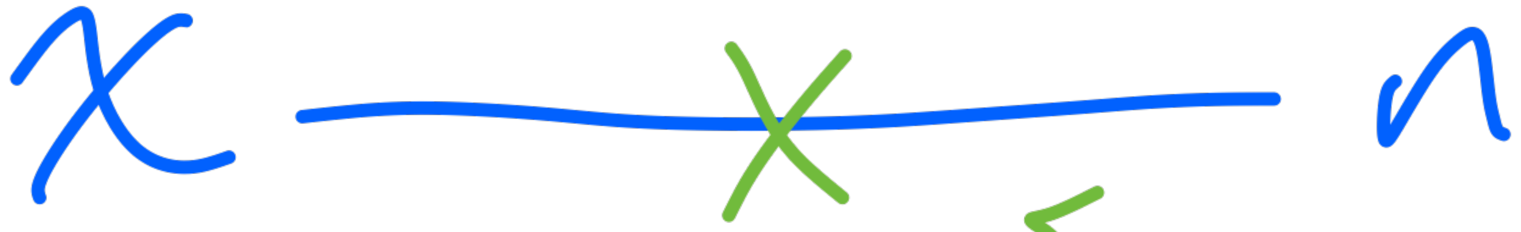
$$\Longrightarrow m_p - m_e < m_\chi < m_p + m_e$$

(^9Be stability tightens this slightly...)

Where would χ show up?

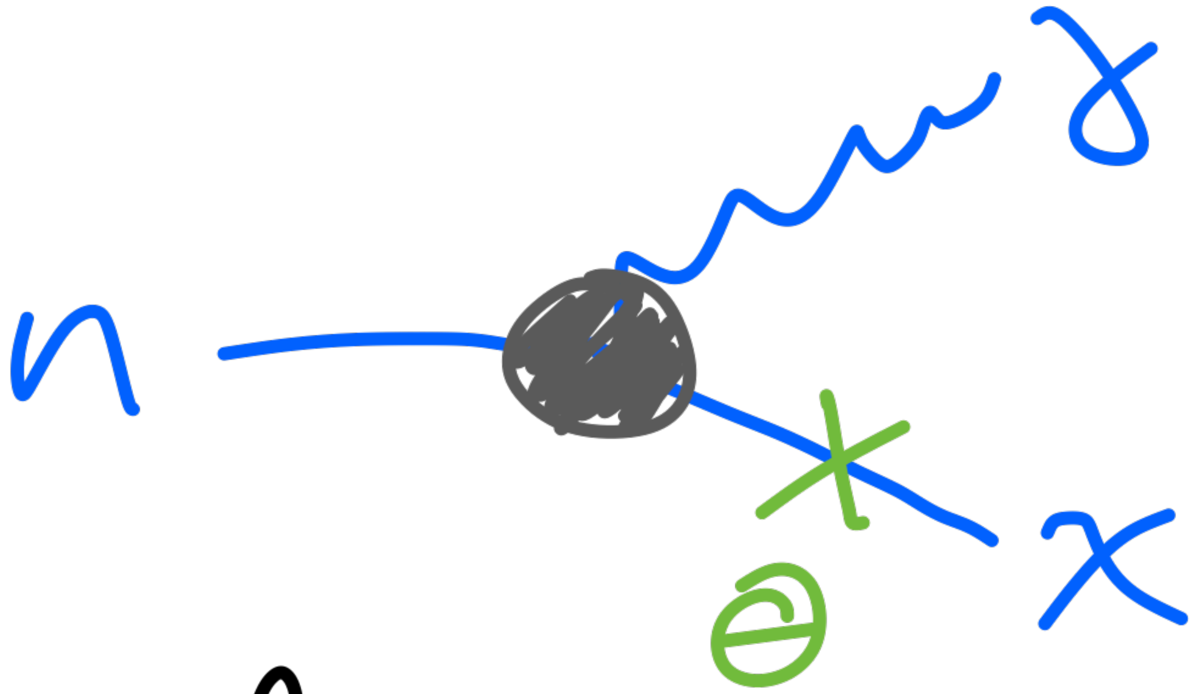
One must write $\mathcal{L}_{eff} \supset -\delta \bar{n} \chi + h.c.$

$\Rightarrow$



$\theta \sim \frac{\delta}{m_n - m_\chi}$

$\Rightarrow$



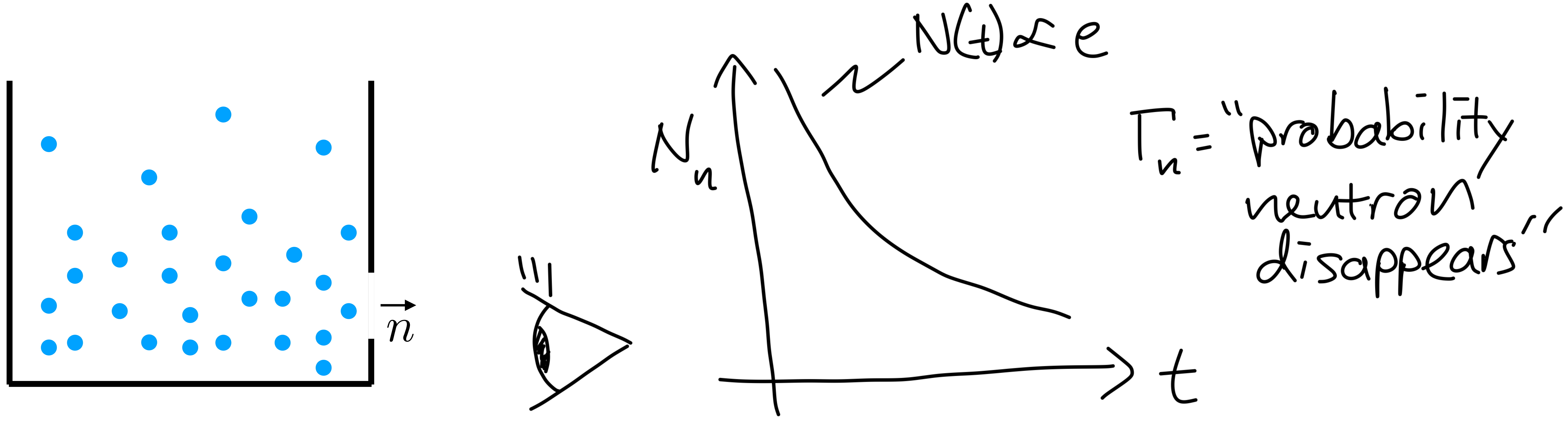
since $m_\chi < m_p + m_e < m_n$

A new neutron decay mode

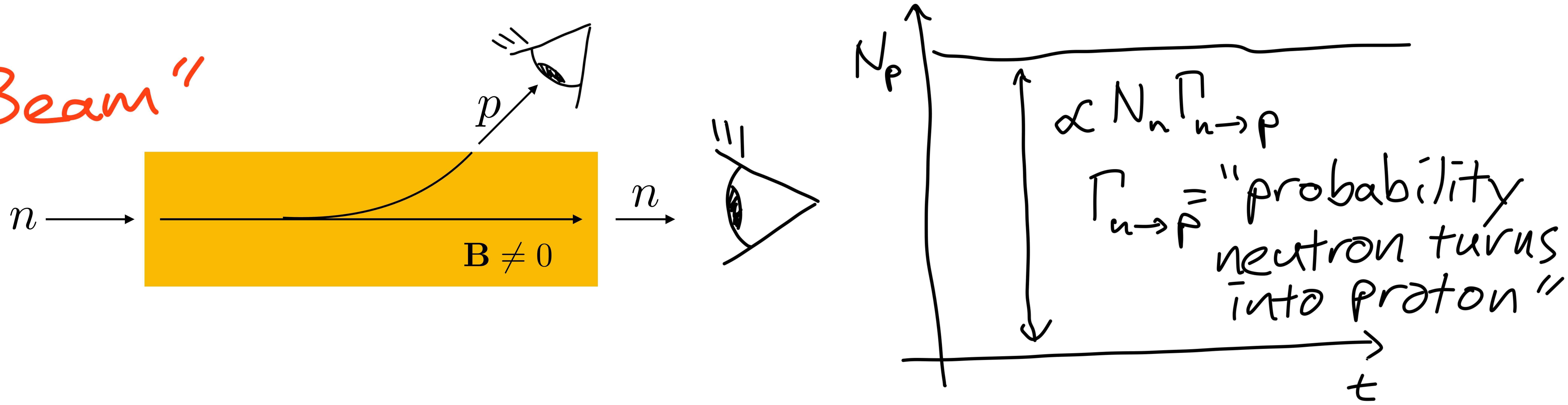
What do the data say?

Neutron decay (lifetime)

"Bottle"

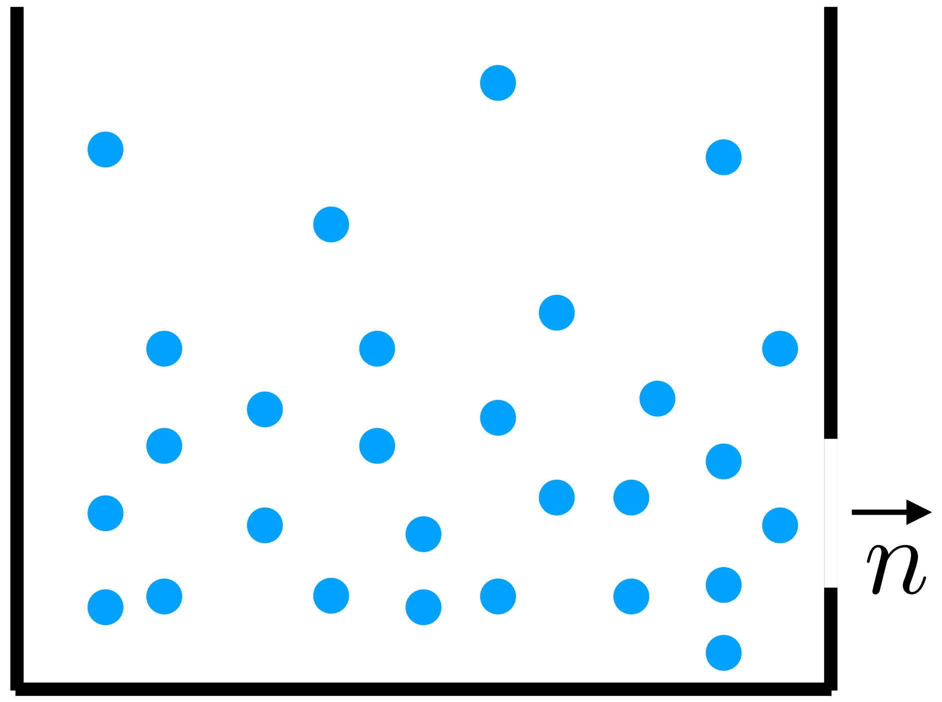


"Beam"

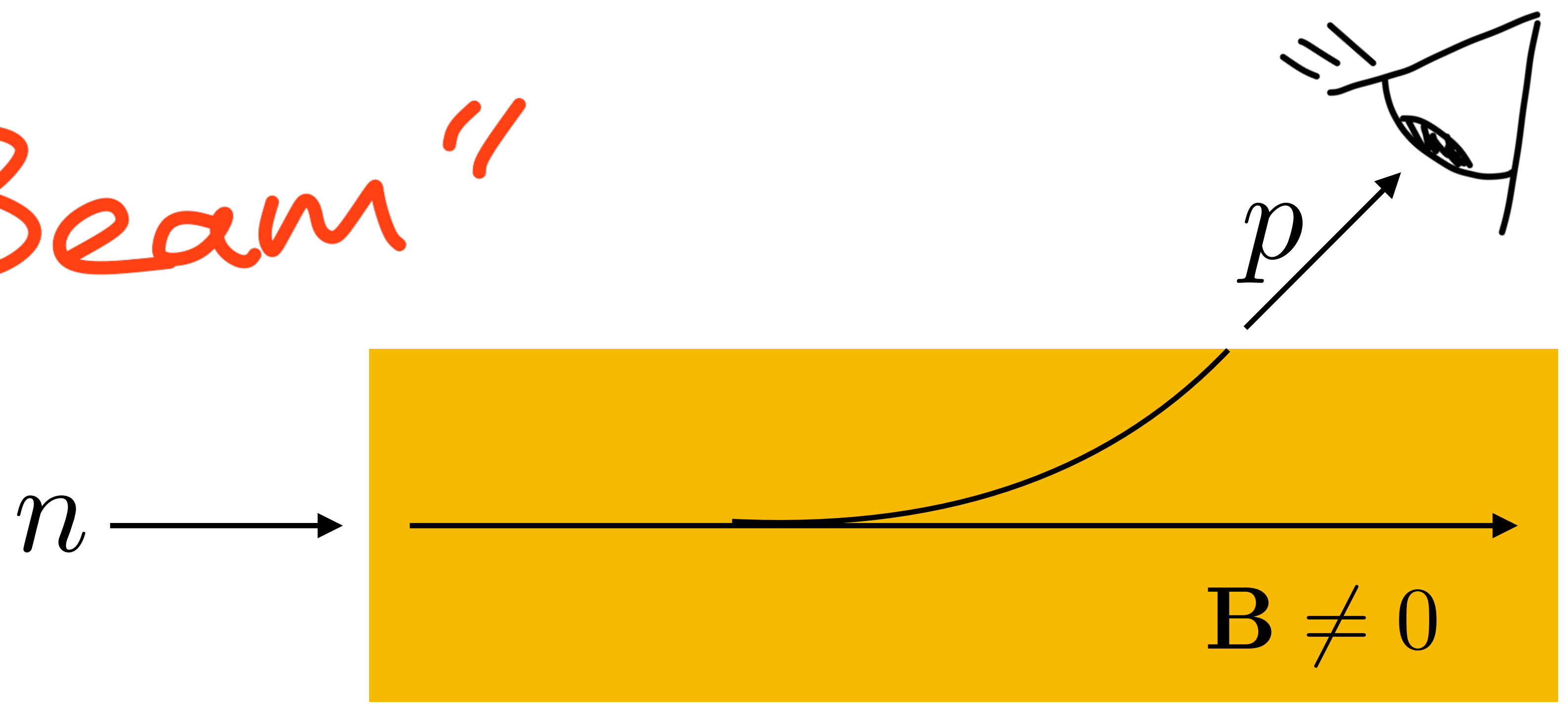


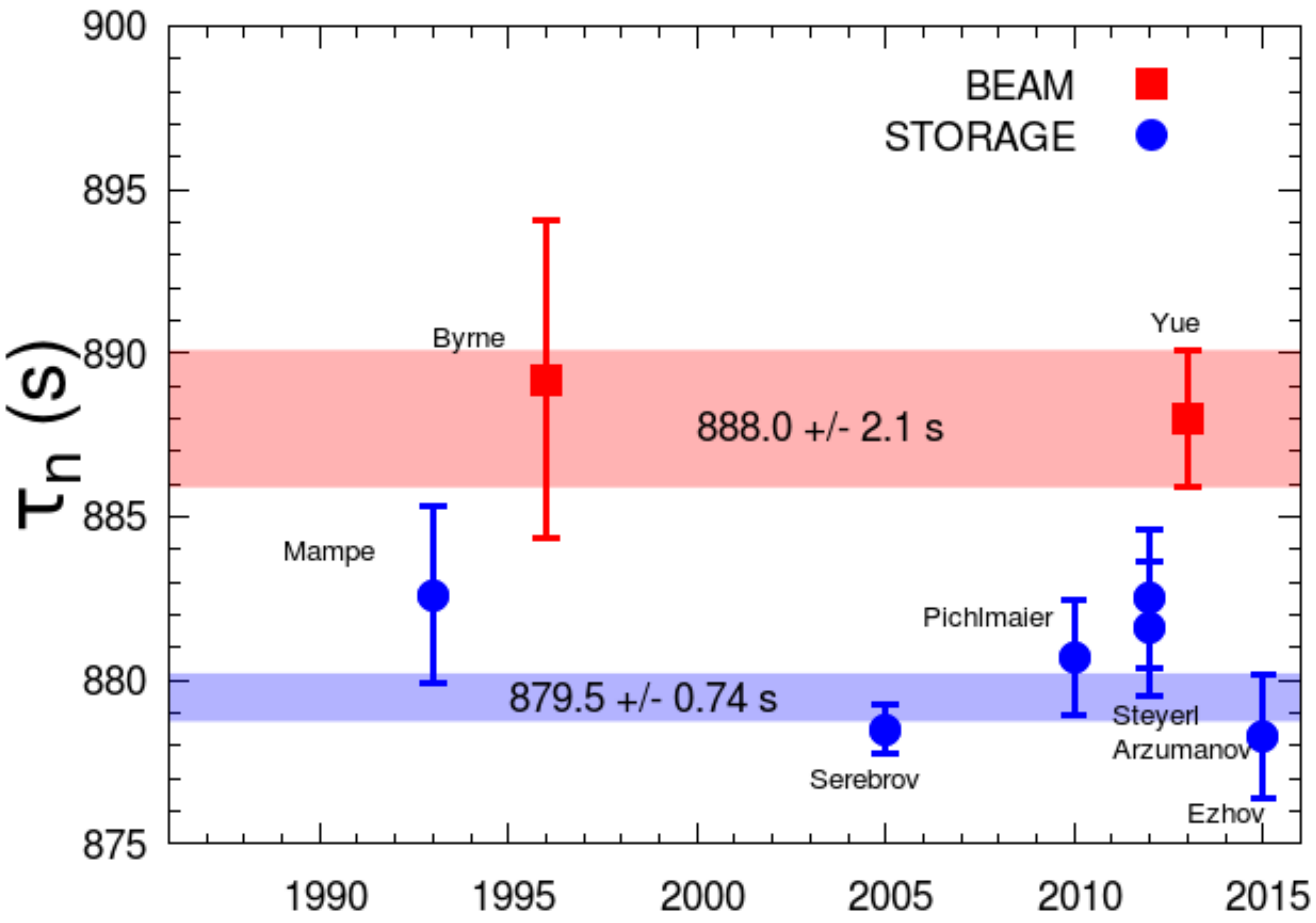
Neutron decay (lifetime)

"Bottle"



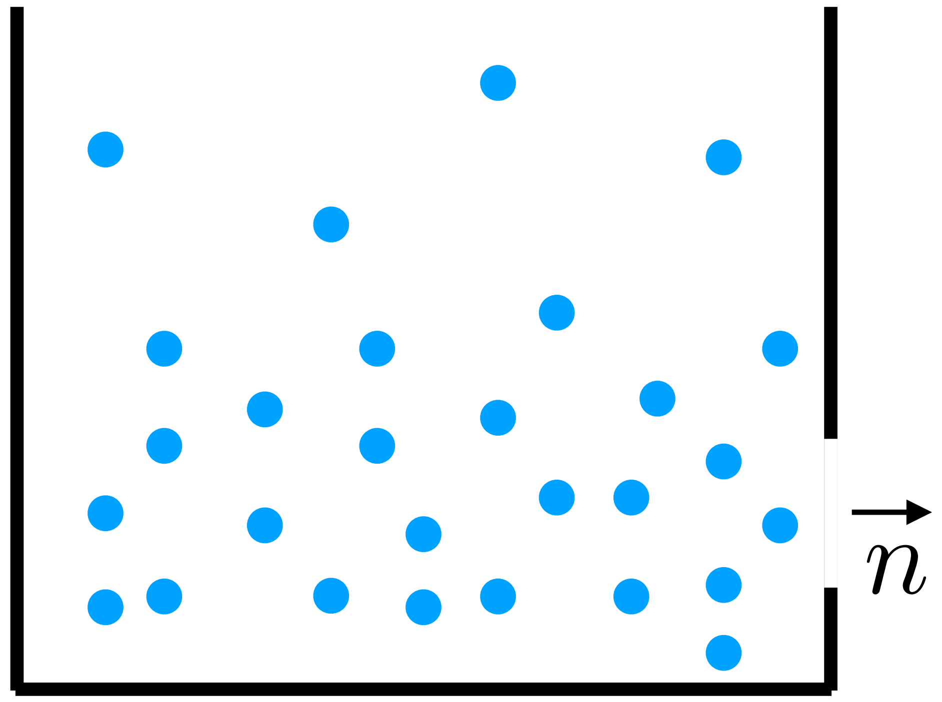
"Beam"



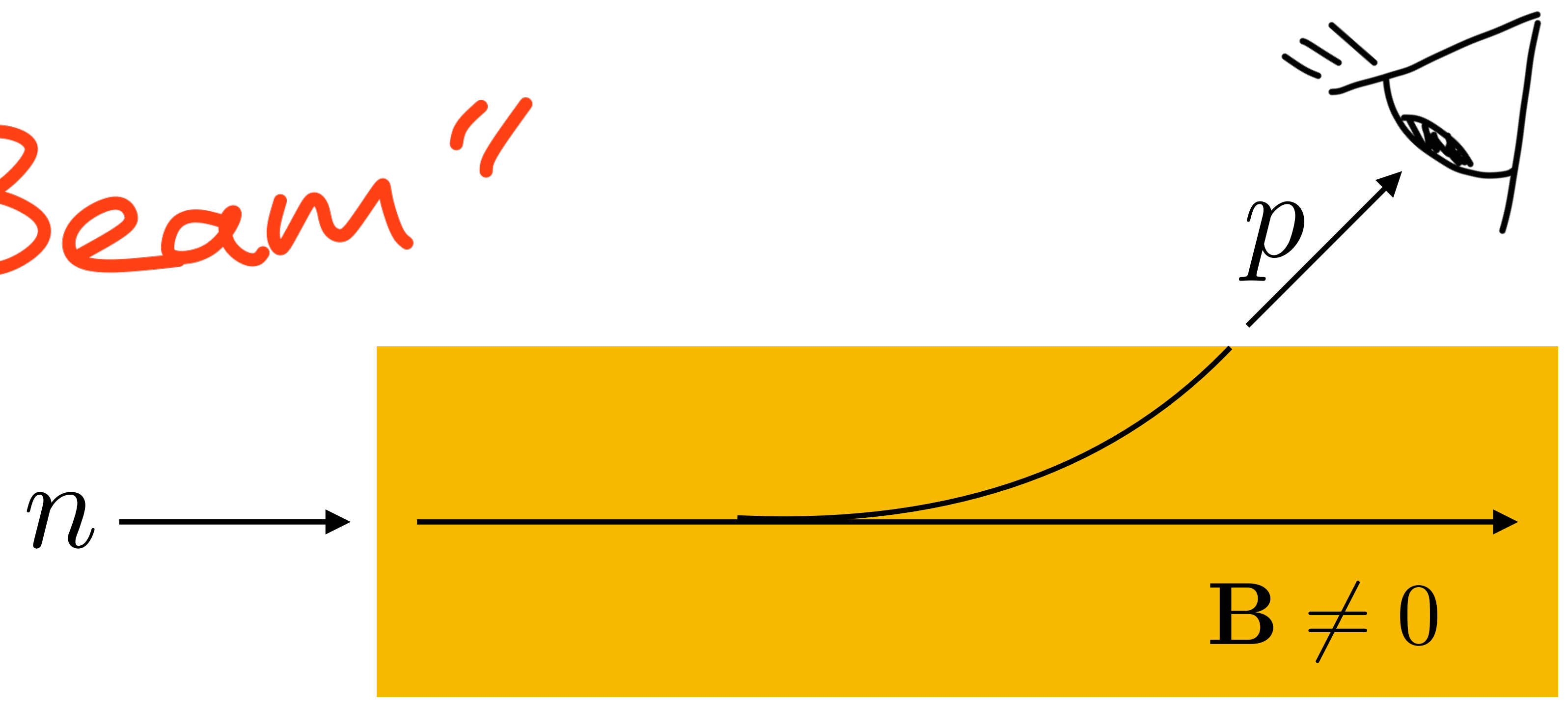


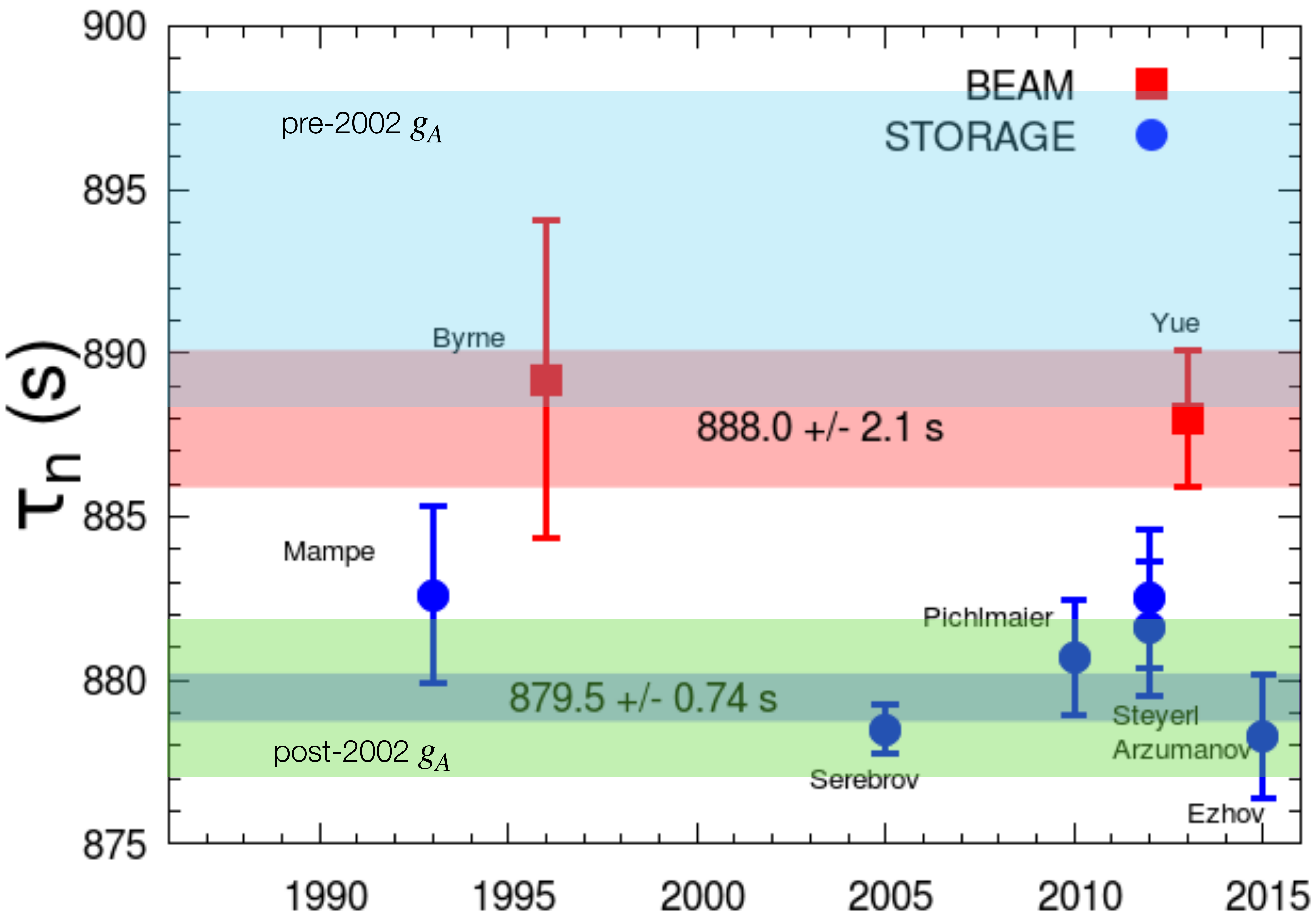
Neutron decay (lifetime)

"Bottle"



"Beam"





Czarnecki, Marciano, Sirlin PRL 120 202002

$\Gamma_{n\to p} \propto 1 + 3g_A^2 \propto \frac{1}{\tau_n}$ in standard model

Neutron decay (lifetime)

$$\tau_{bot} = \underbrace{\frac{1}{\Gamma_{n\to p} + \delta\Gamma}}_{(879.5\pm0.7)s} < \tau_{beam} = \underbrace{\frac{1}{\Gamma_{n\to p}}}_{(888.0\pm2.0)s}$$

Putting some numbers together

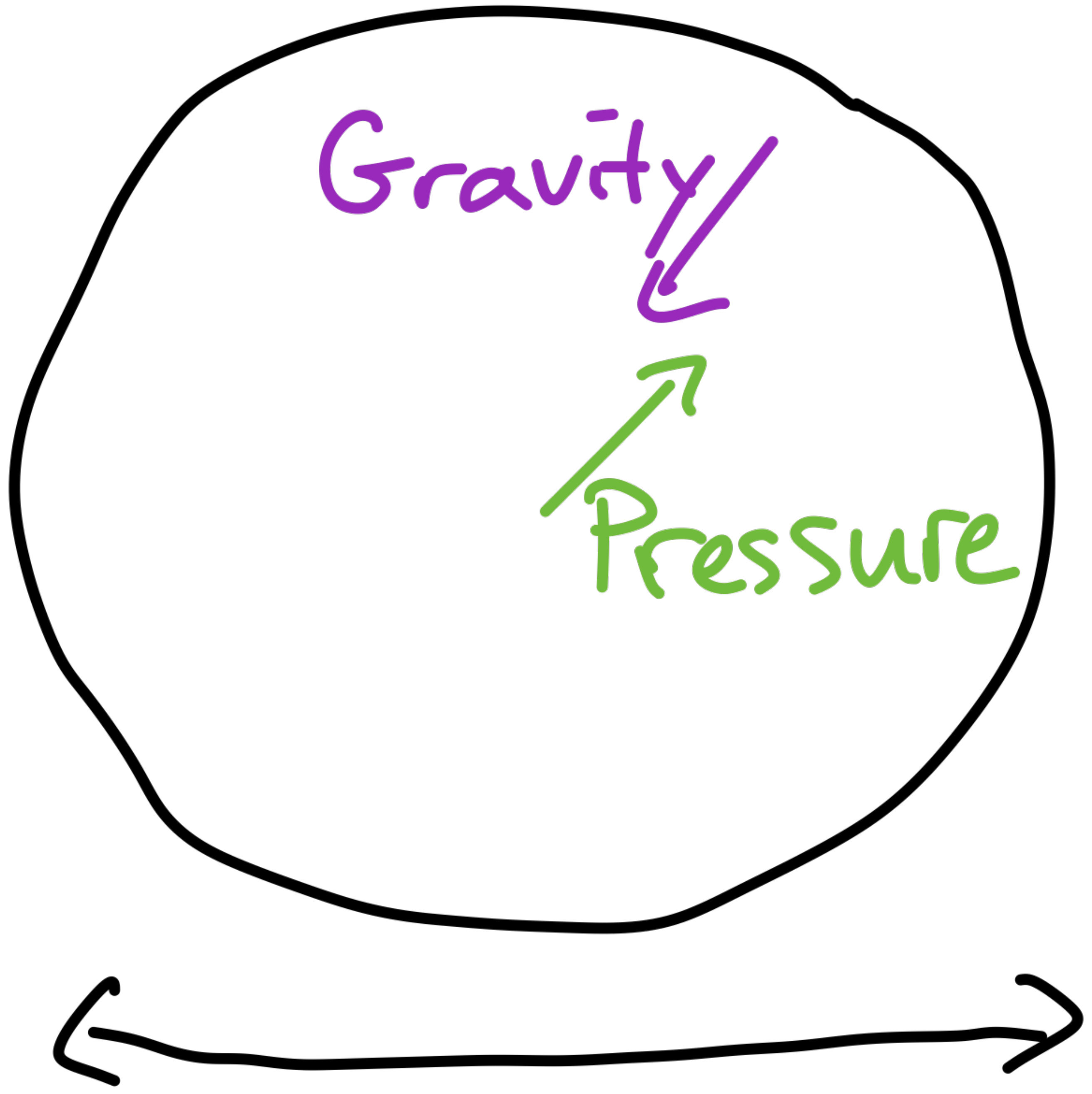
$$\frac{\delta\Gamma}{\Gamma_{n\to p}+\delta\Gamma} = 1 - \frac{\tau_{bot}}{\tau_{beam}} \simeq 1\%$$

(Fornal & Grinstein, Berezhiani)

$\Theta \sim 10^{-9} \Rightarrow Br_{n\to x\gamma} \simeq 1\%$ solves "neutron lifetime anomaly"

(Direct search @ LANL $Br_{n\to\gamma x} \lesssim 0.1\%$)

Neutron Stars

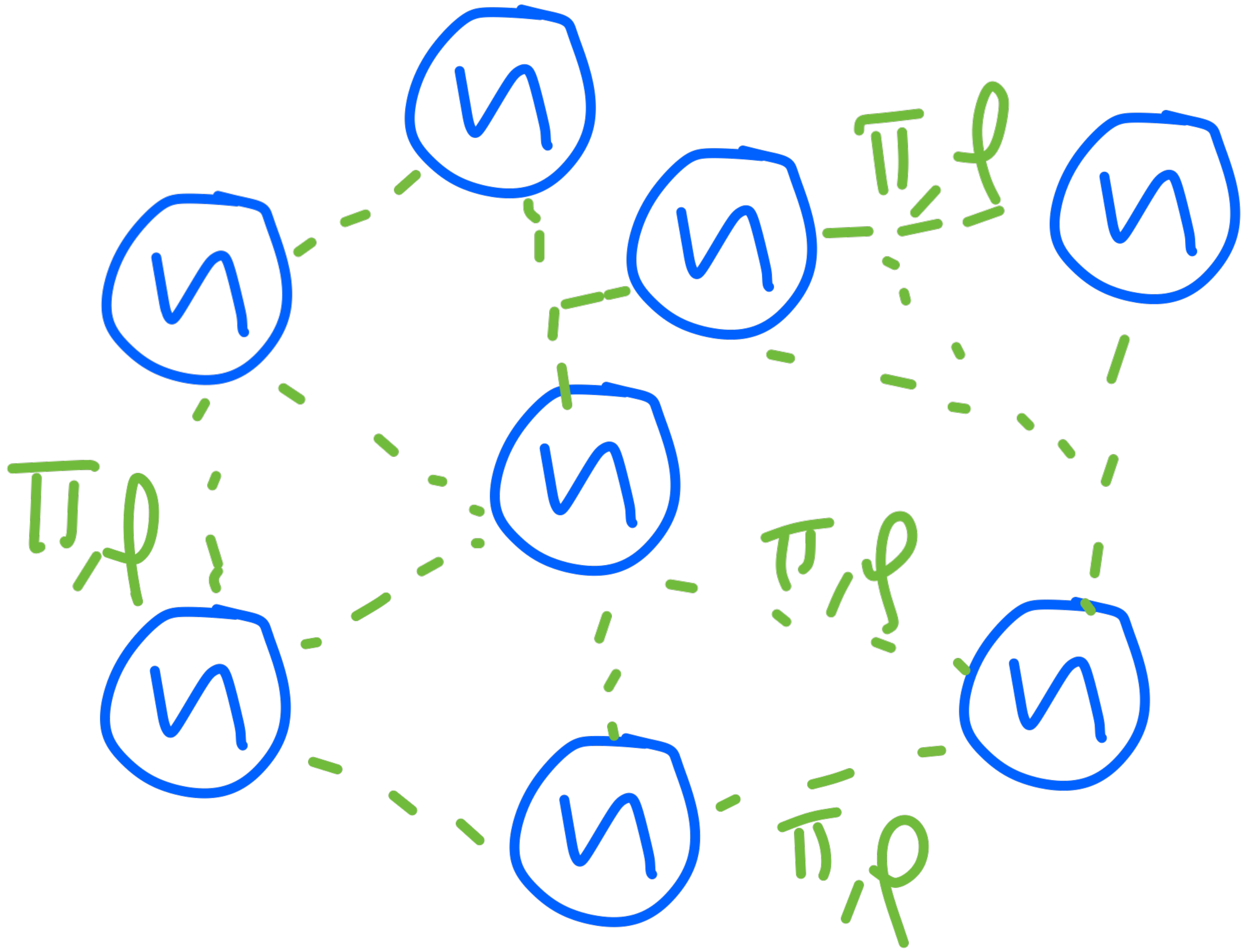


$\mathcal{O}(20\,\text{km})$

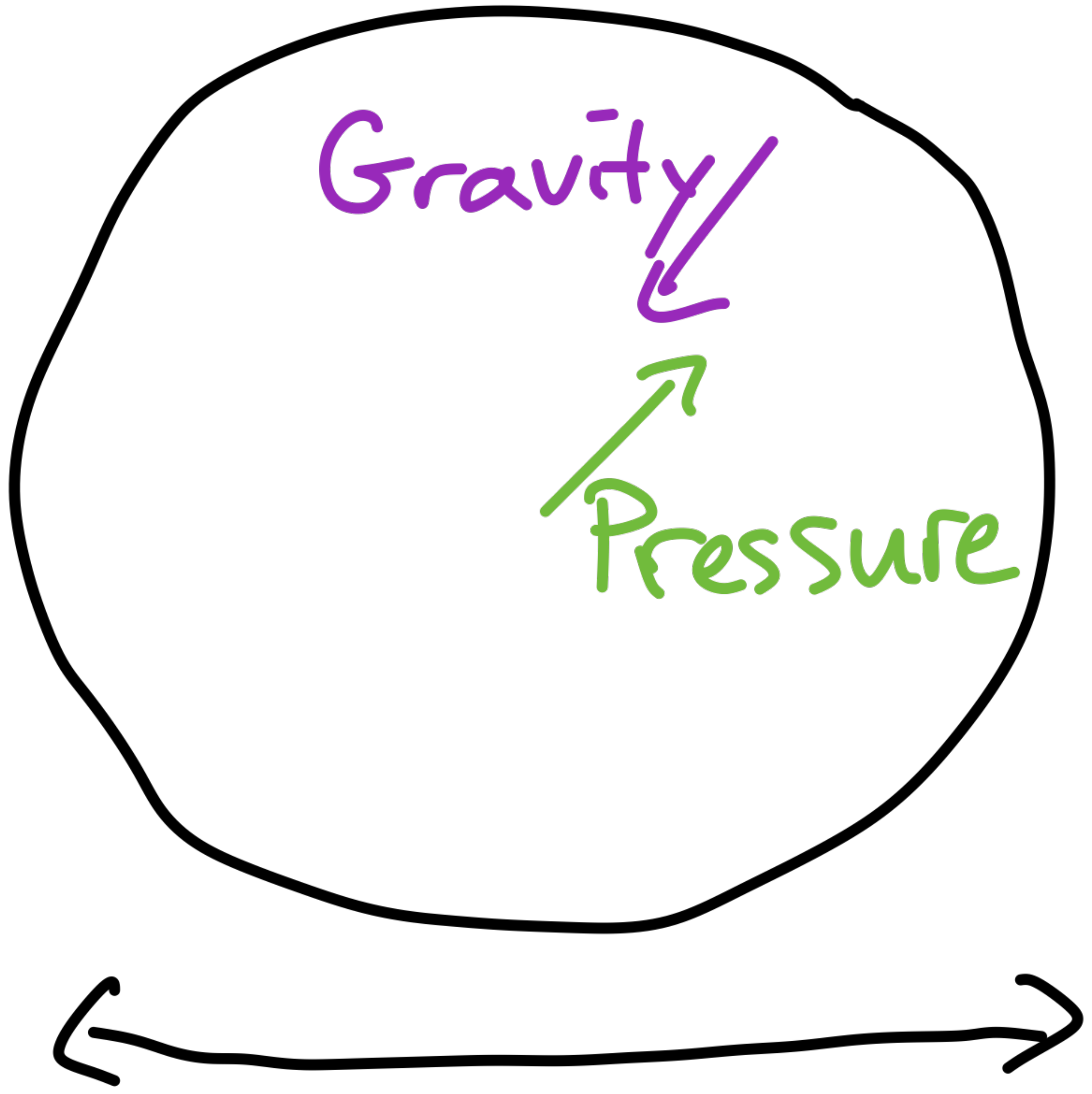
$M \sim M_\odot \sim 10^{57}\,\text{GeV}$

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

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



Neutron Stars

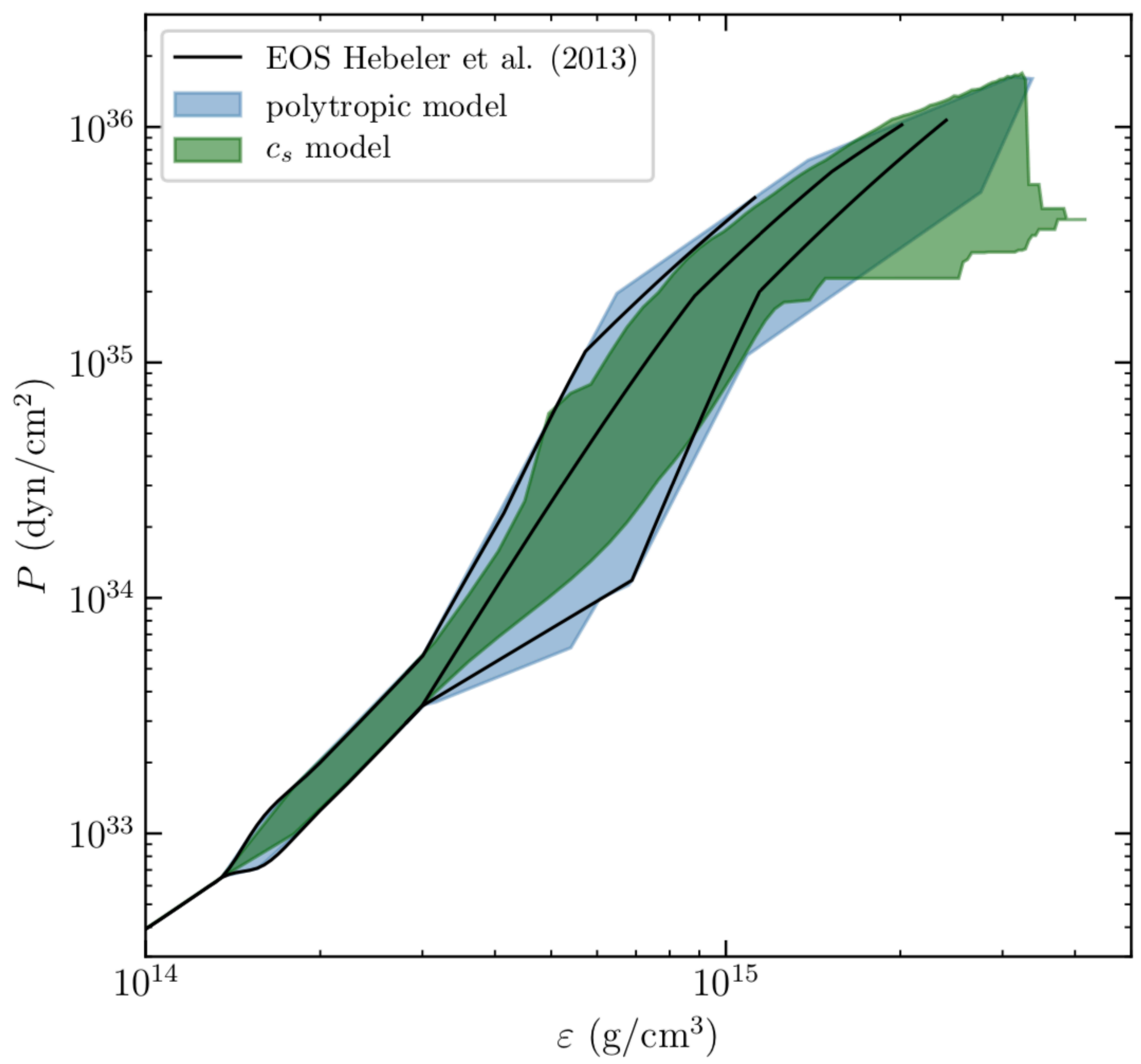


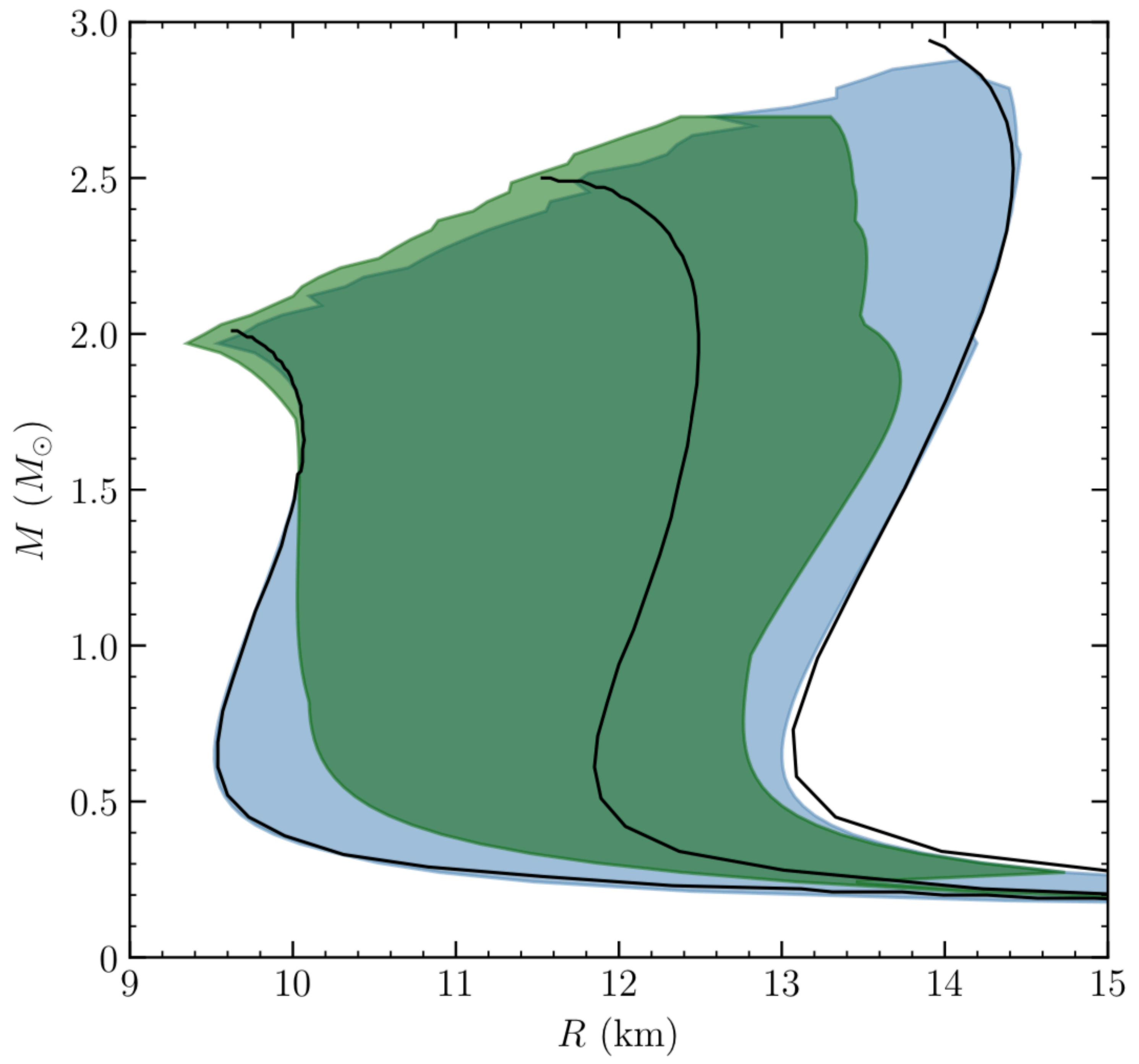
$\mathcal{O}(20\,\mathrm{km})$

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

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

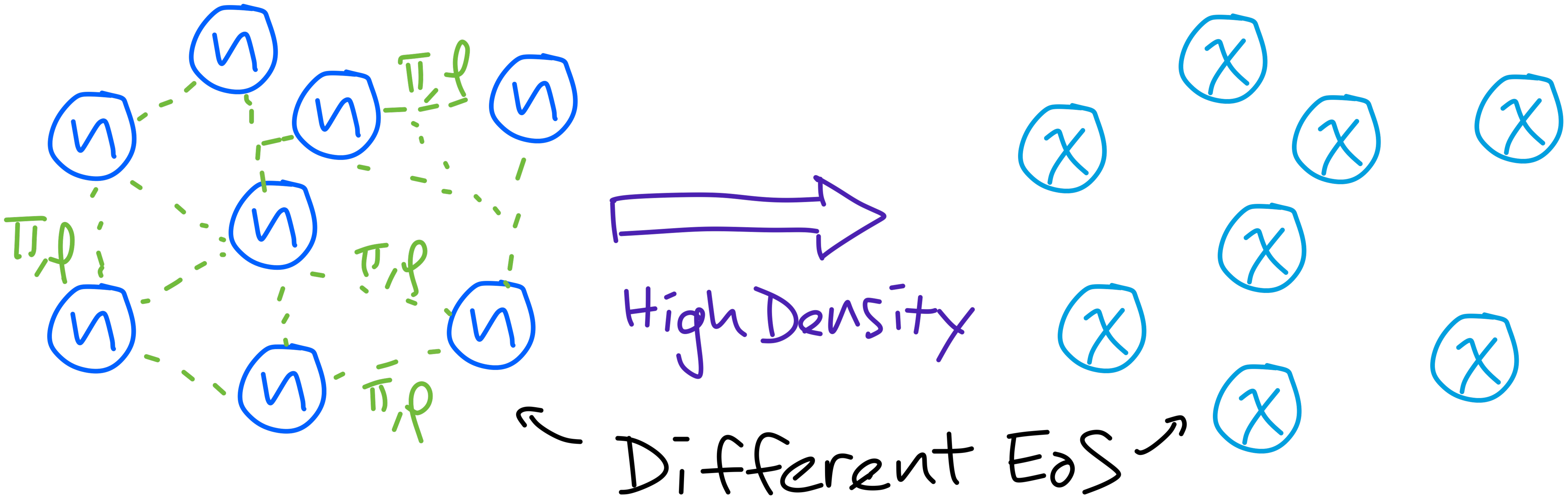
E.o.S.: $p(r) = f[\varepsilon(r)]$





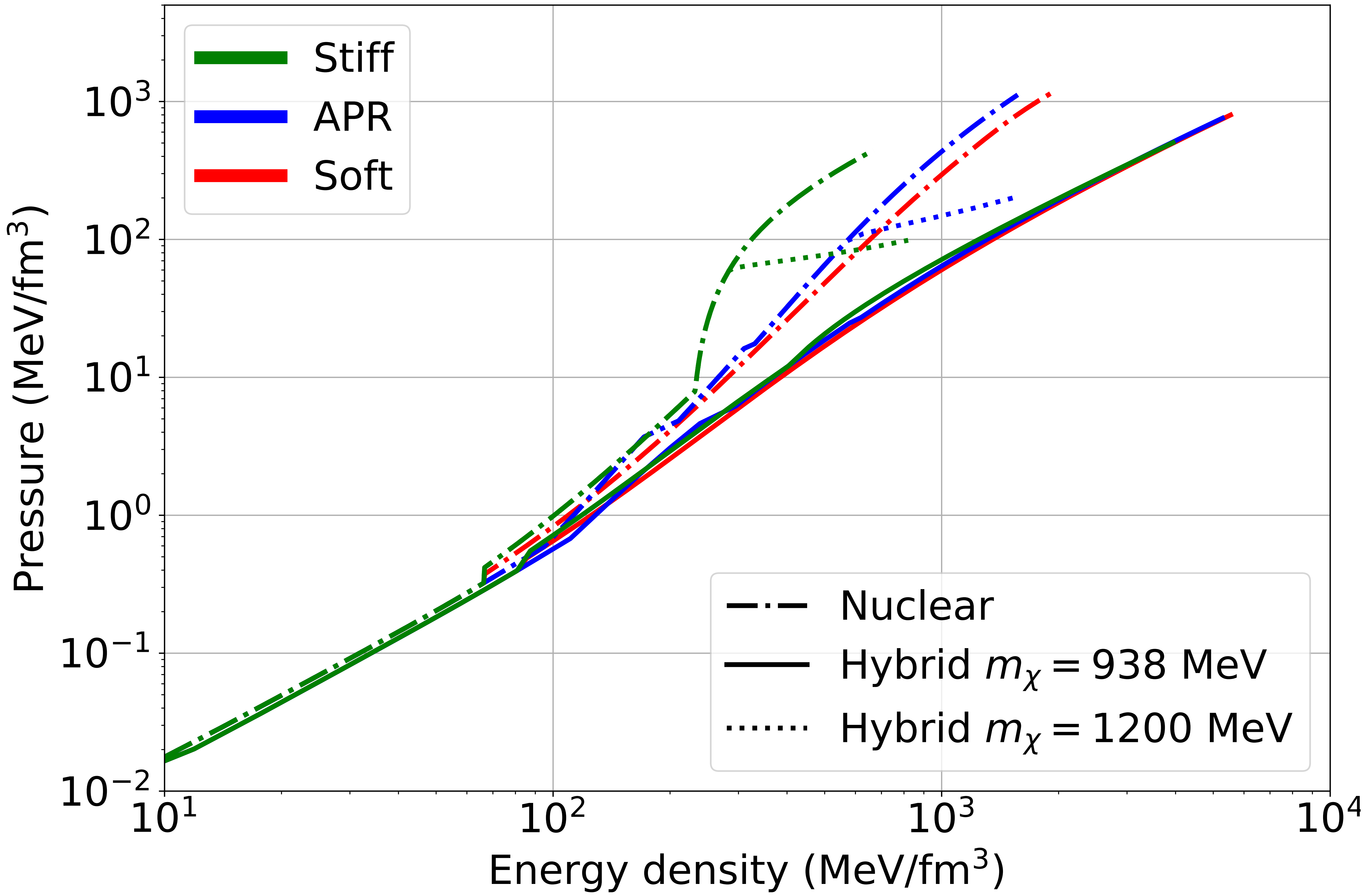
Greif, Raaijmakers,
Hebeler, Schwenk, &
Watts arXiv:1812.08188

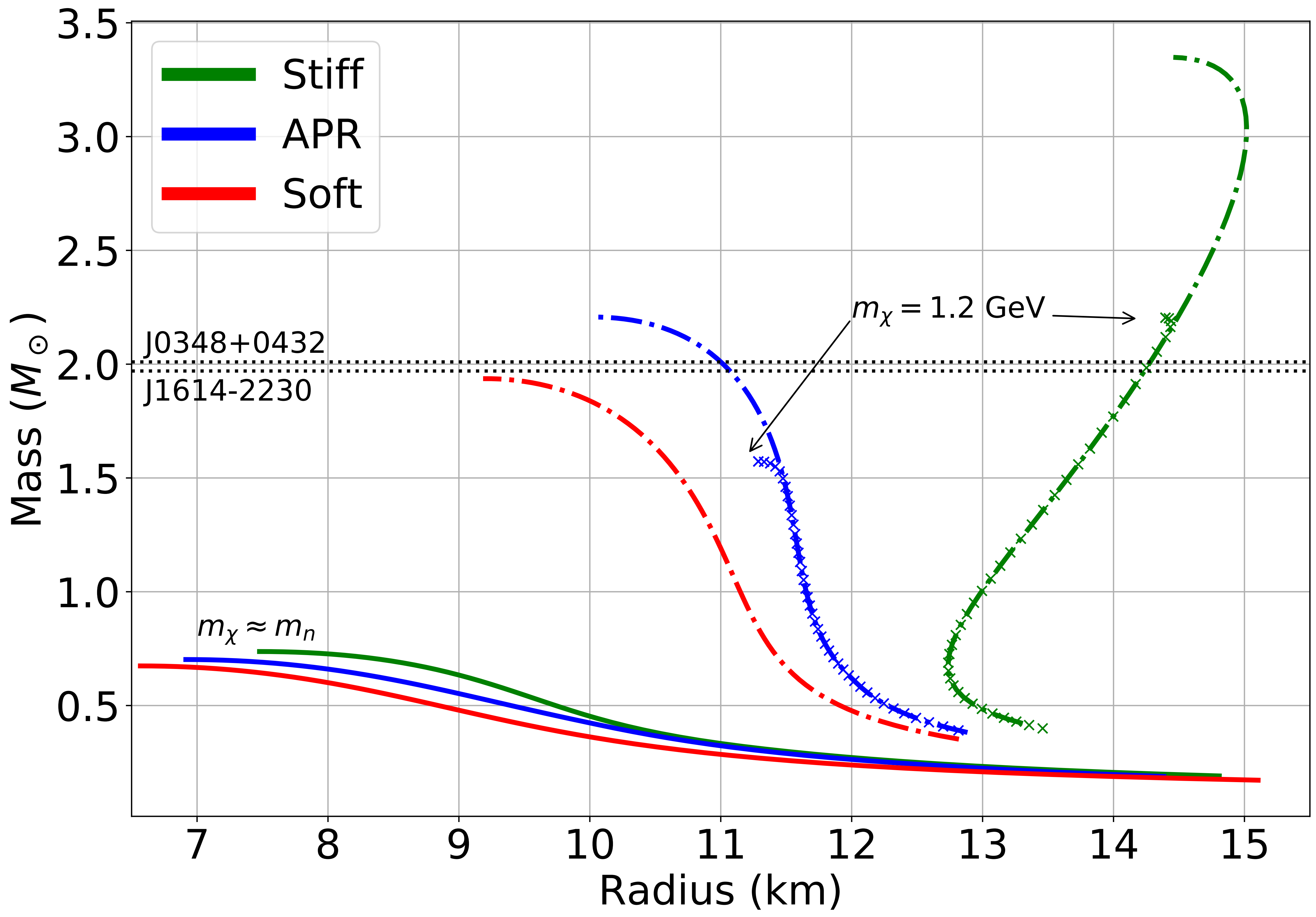
Neutron Stars & Dark Baryons



Neutron Stars & Dark Baryons

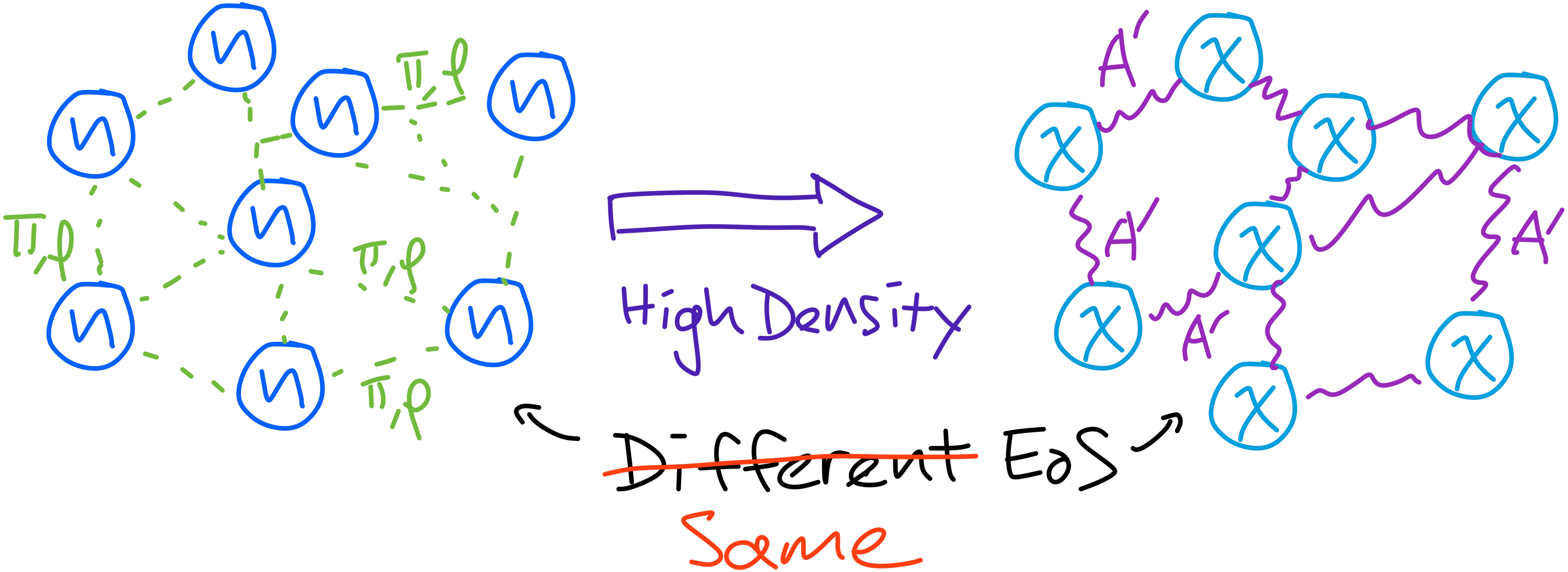
DM, Nelson, Reddy, & Zhou, PRL **121**, 061802; Baym *et al.*, Motta *et al.*





Neutron Stars & Dark Baryons

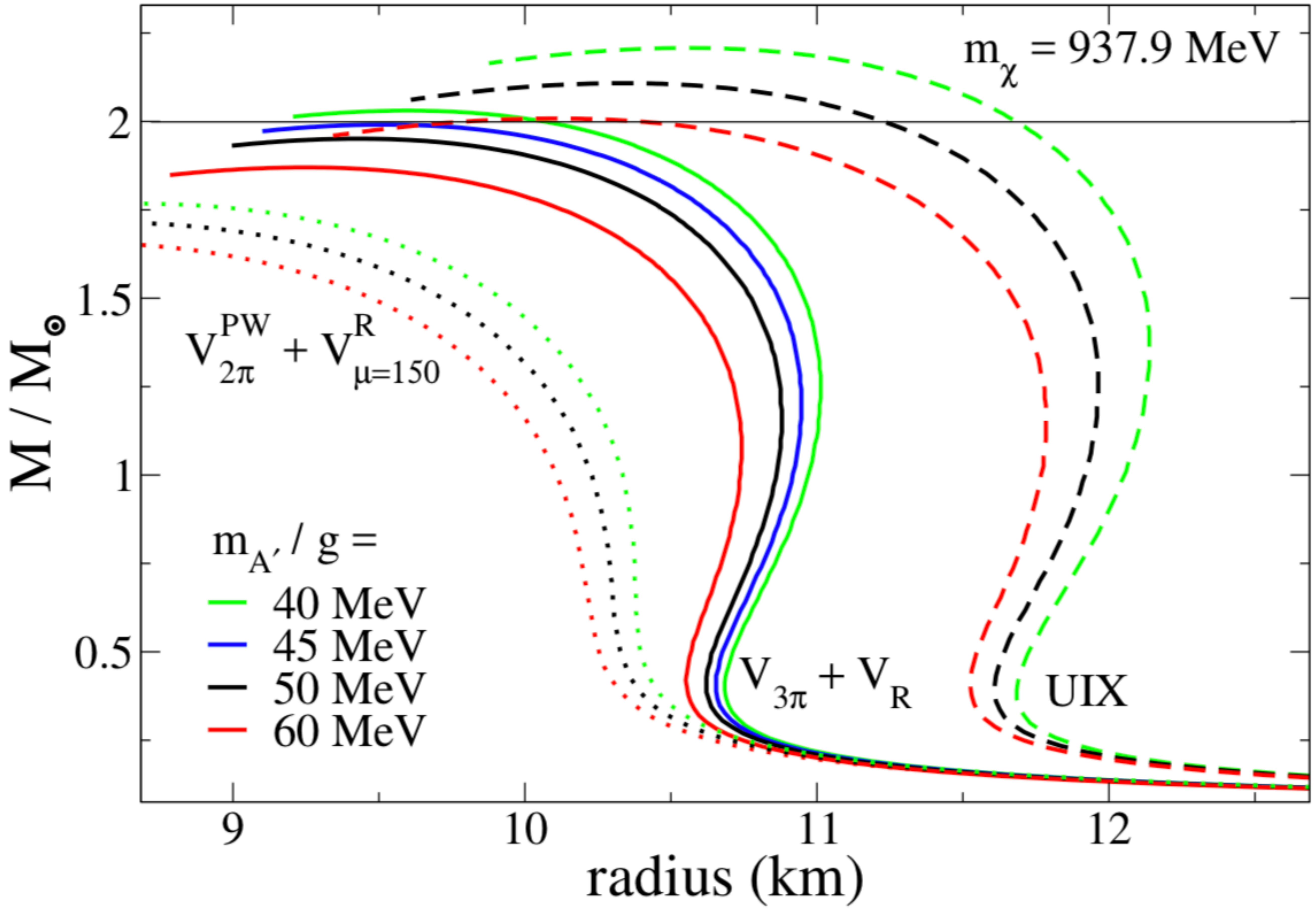
A way out?



Neutron Stars & Dark Baryons

A way out?

Cline & Cornell, JHEP **1807** 081

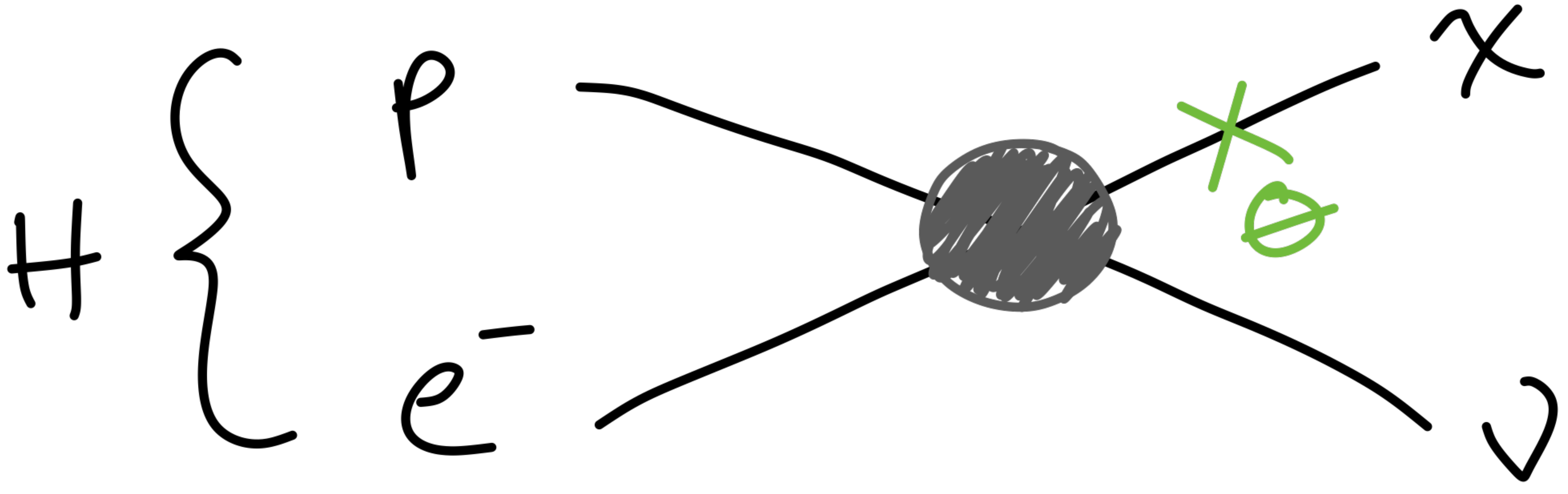


Exotic neutron decay invisible:

$n \to \chi A'$

Where else? Hydrogen decay!

Recall $m_\chi < m_p + m_e = m_H$ (+13.6 eV)

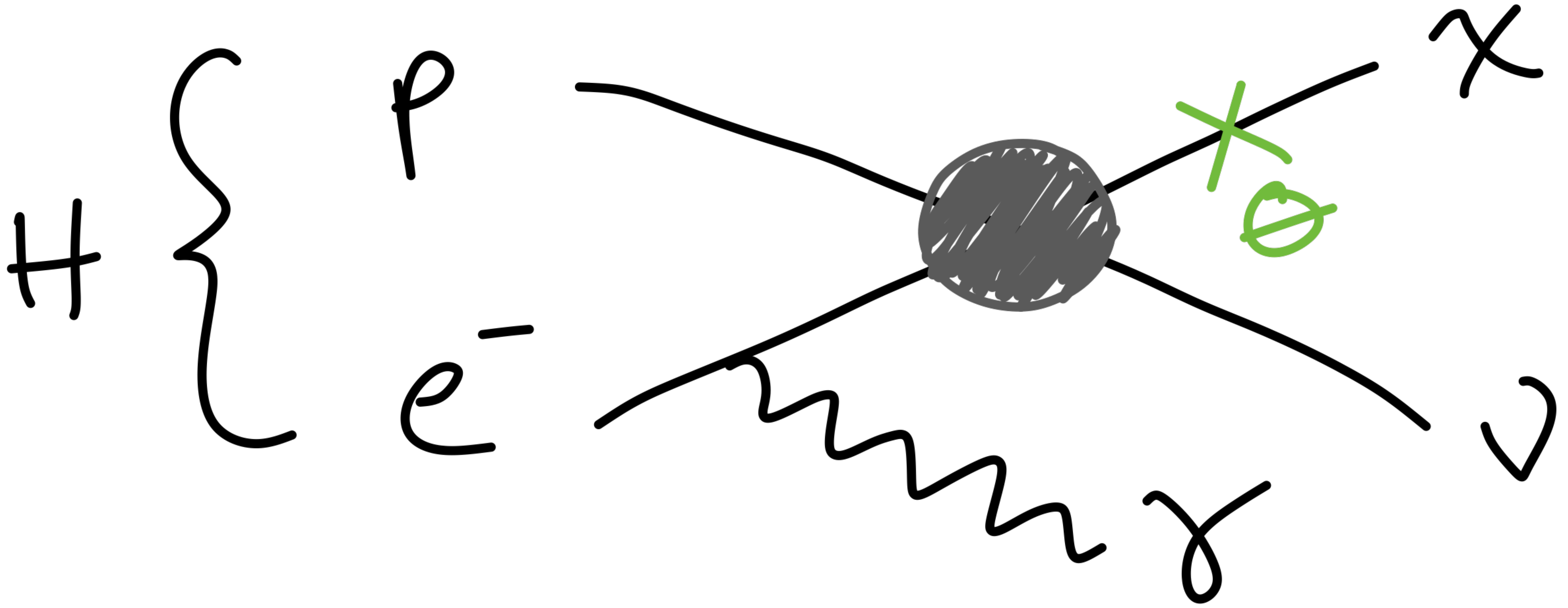


Leading mode

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

Invisible - hard to test...

and...



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

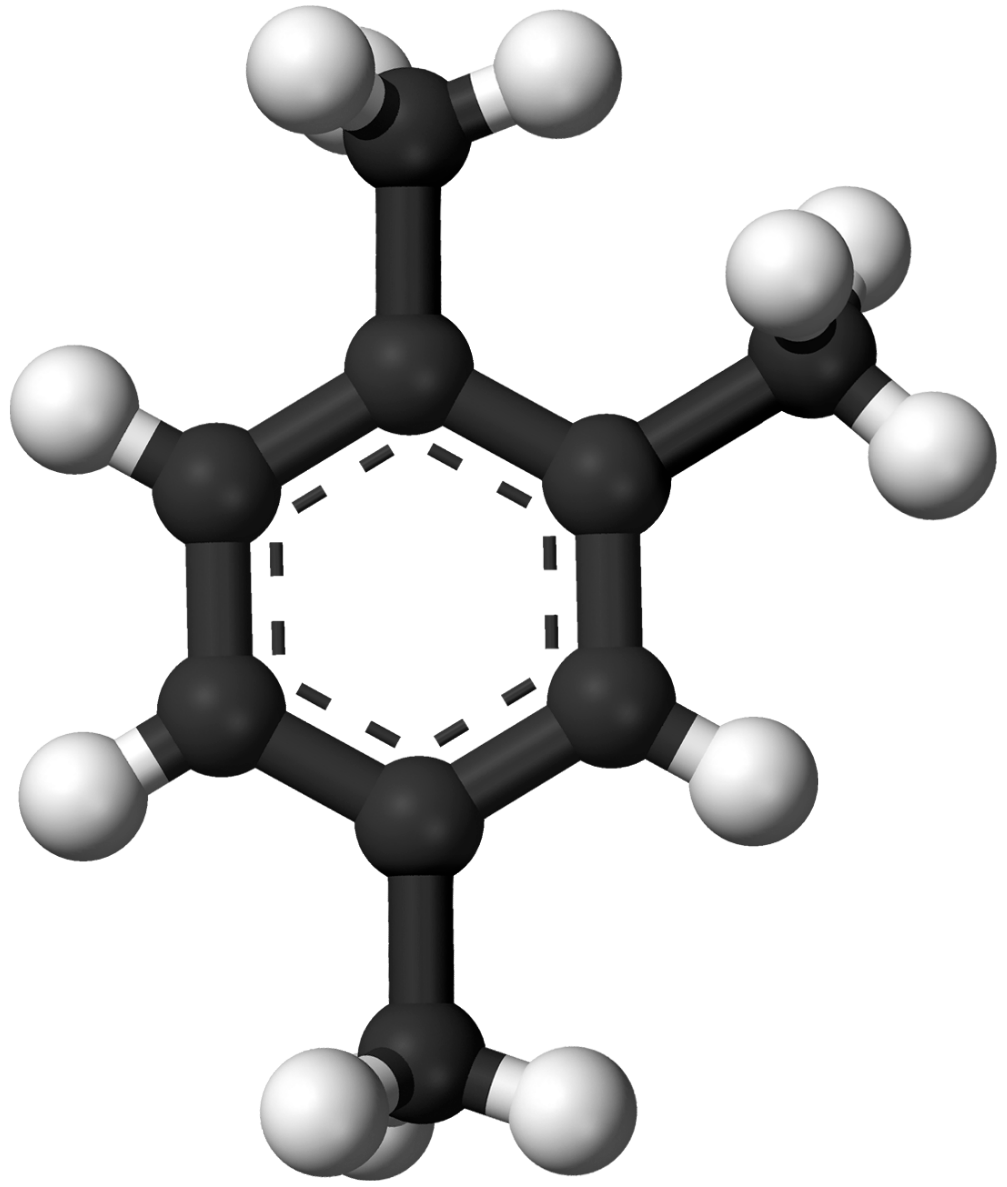
Need: lots of H

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

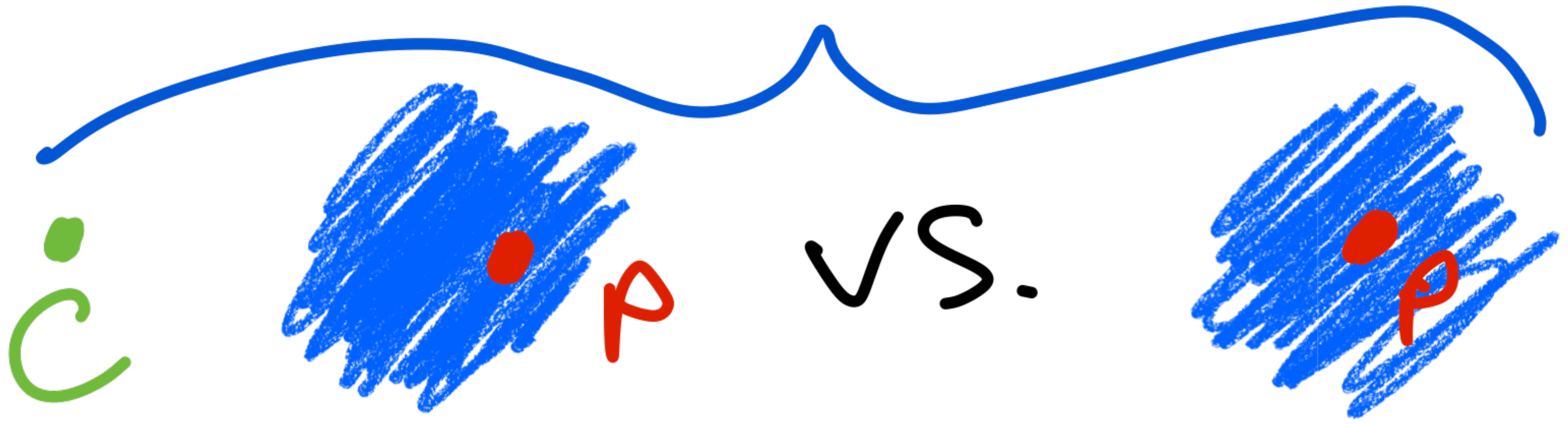
e.g. Borexino

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

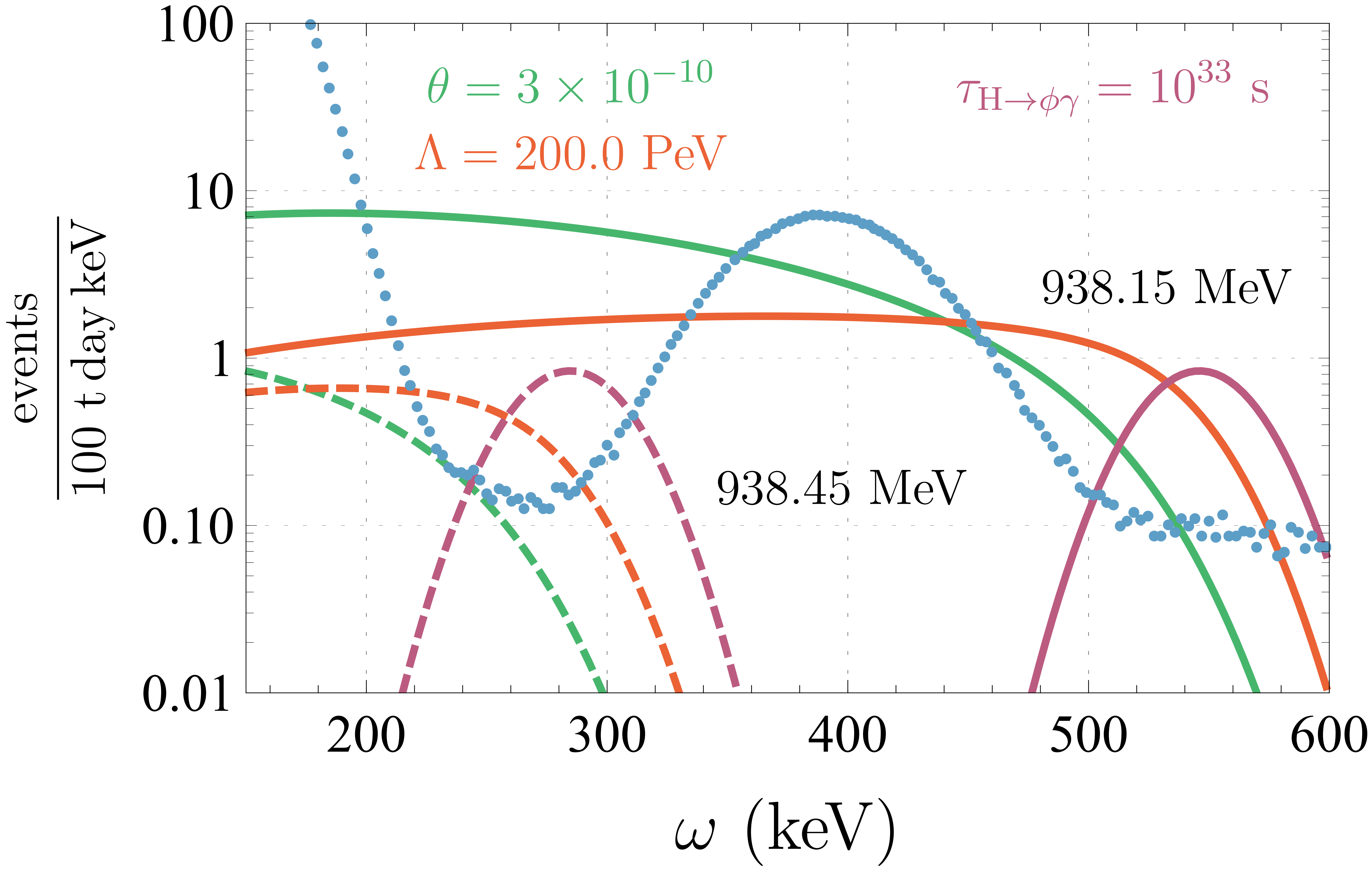
$C_6H_3(CH_3)_3$ – 10% H



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



Spectrum @ BOREXINO



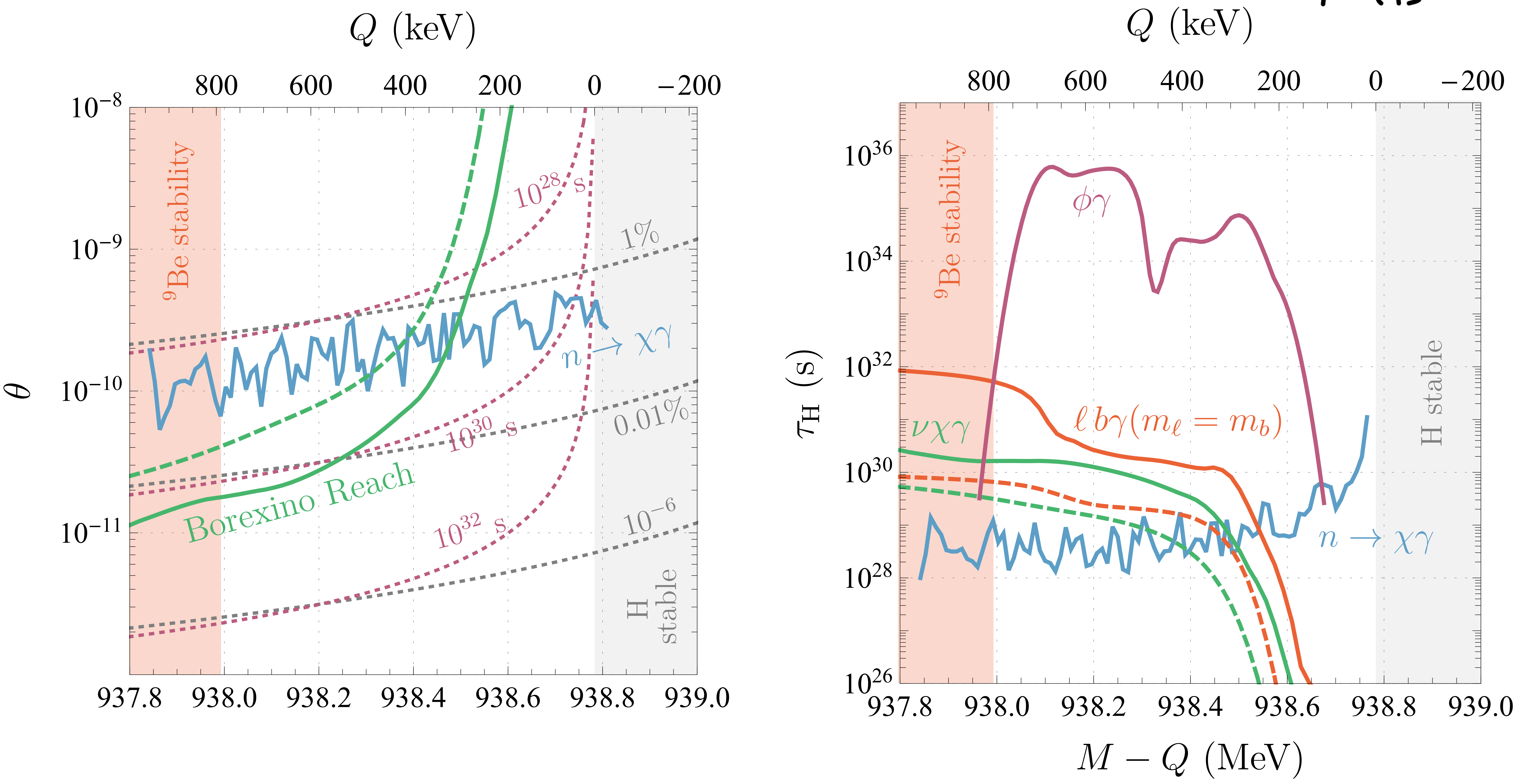
Blue: data from 1509.01223 (search for $e^- \to \gamma\nu$, test of Q cons.)

Green: $\chi \overset{\theta}{\times} n$

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

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

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



Wrap Up

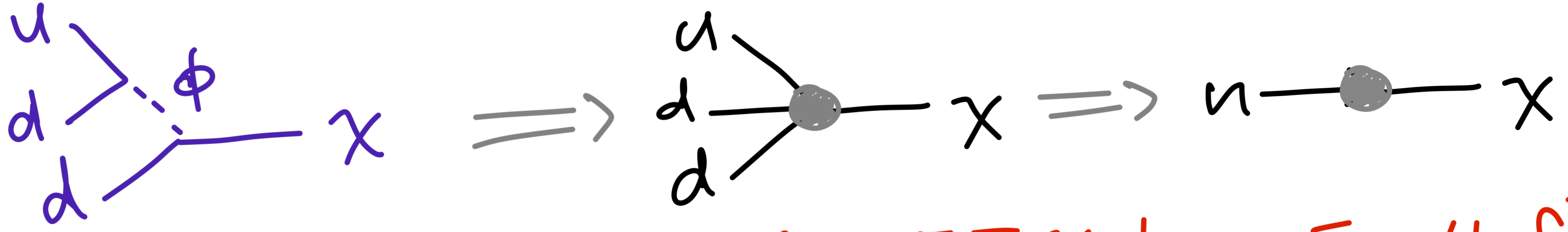
There are scenarios where p stable but H not – n lifetime anomaly is a motivation

In n-mixing model, dominant H decay mode fully invisible but radiative mode w/ $\mathcal{O}(10^{-4})$ branching can be seen at e.g. BOREXINO

Current data sensitive to $\tau_H \sim 10^{30}$ s or longer (model-dep.) – future prospects?

Back Up

A UV completion: $\mathcal{L} \supset g\phi^* u^c d^c + y\phi d^c \chi + h.c.$



$\mathcal{L} \supset \frac{gy}{m_\phi^2} u^c d^c d^c \chi + h.c. \Rightarrow \mathcal{L} \supset -\delta \bar{n} \chi + h.c., \quad \delta \sim 4\pi f_\pi^3 \times \frac{gy}{m_\phi^2}$

If χ majorana, $n \leftrightarrow \bar{n}$ limits $\delta \lesssim 10^{-33}$ GeV

For $\theta \sim 10^{-9}$, need $\delta \sim 10^{-12}\,\mathrm{GeV} \left(\frac{m_n - m_\chi}{\mathrm{MeV}}\right)^{-1}$

Such models have baryogenesis implications (see work with Nelson)