Implications of Observable Baryon-Number Violation

Susan Gardner

Department of Physics and Astronomy
University of Kentucky
Lexington, KY

Based on work in collaboration with
Jeffrey Berryman (N3AS/UC Berkeley),
Xinshuai Yan (U. Kentucky/CCNU, Wuhan),
Mohammedreza Zakeri (U. Kentucky)

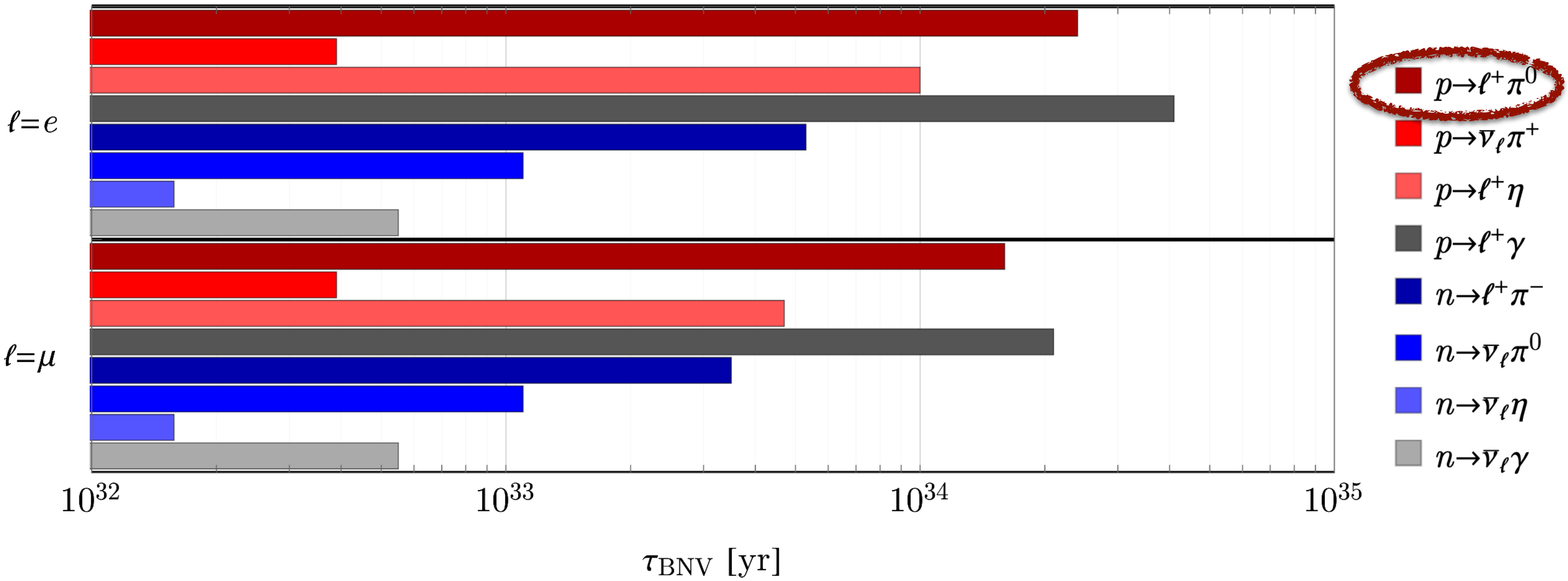
Talk on Tues.!

XV Conference on
Interconnections between
Particle Physics & Cosmology
PPC 2022
June 6-10, 2022 — St. Louis, MO

Research supported by the U.S. Dept. of Energy Office of Nuclear Physics
under DE-FG02-96ER40989

Limits on Nucleon ($|\Delta B| = 1$) Partial Lifetimes

90% C.L. upper limits to non-invisible final states



[compilation: Berryman, SG, & Zakeri, 2022]

Such processes may yet be seen*

We consider other possibilities & probes….

*Talks by Murgui, Fileviez Perez, Mehmood

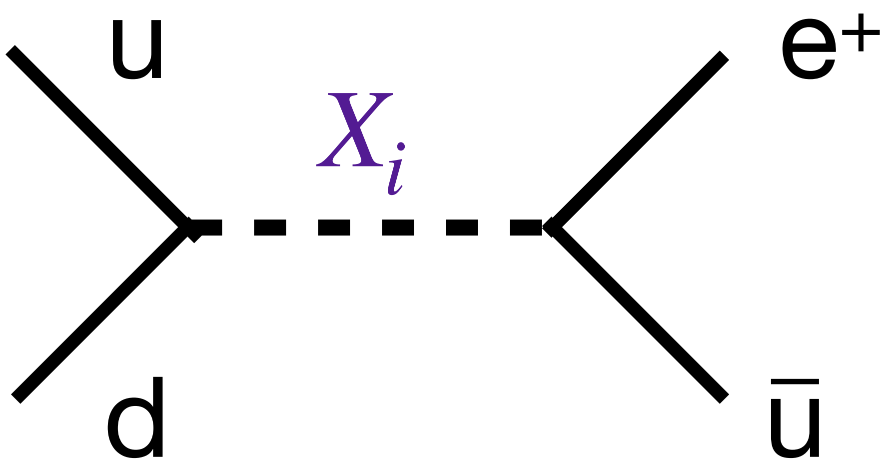
$|\Delta B| = 1$ vs. $|\Delta B| = 2$... Processes

Why their visibility can differ

Enter scalar X_i with SM quantum numbers:

$$X_i = (3,1,-1/3)$$

$SU(3) \times SU(2)_L \times U(1)_Y$



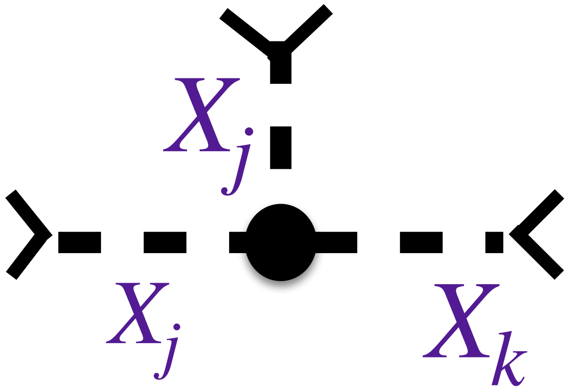
$p \to e^+\pi^0$

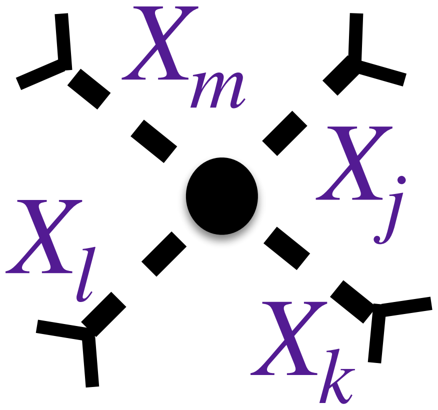
not observed

Distinct from

$n\bar{n}$ oscillations

[e.g., Marshak & Mohapatra, 1980;
Babu & Mohapatra, 2001 & 2012;
Arnold, Fornal, & Wise, 2013....]





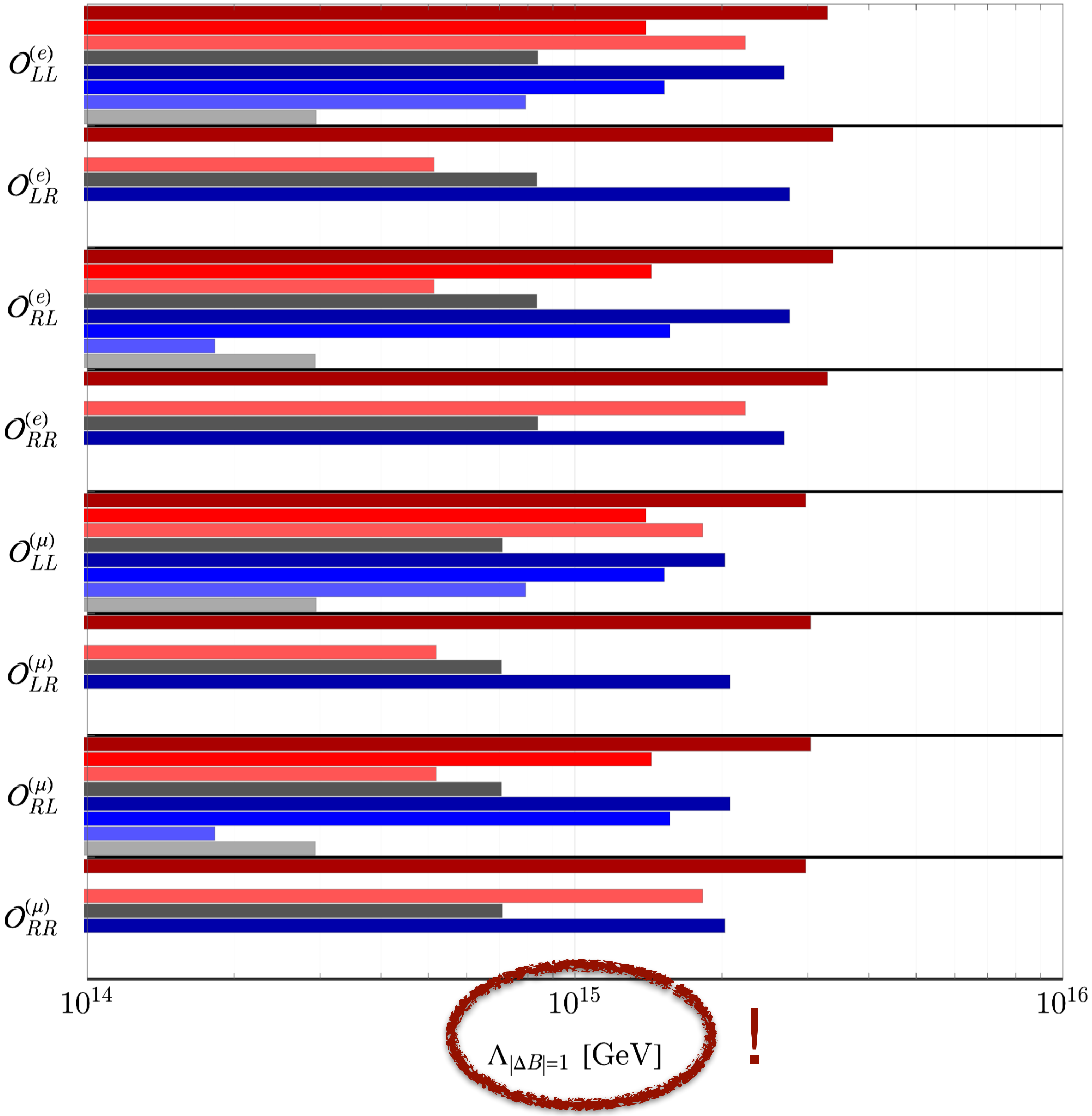
$nn \to \bar{\nu}\bar{\nu}$

independently constrained

Limits on $|\Delta B| = 1$ Decays

Mediated by mass dimension 6 operators in SMEFT

[Berryman, SG, & Zakeri, 2022]



$$\mathscr{L}^{(d=6)}_{|\Delta B|=1} \supset \sum_i \frac{c_i}{\Lambda^2_{|\Delta B|=1}} (qqq\ell)_i + \text{h.c.}$$

dim 6

But the origin of $|\Delta B| = 2$ processes can be distinct!

[Marshak & Mohapatra, 1980; Babu & Mohapatra, 2001 & 2012; Arnold, Fornal, & Wise, 2013....]

$$\mathscr{L}^{(d=9)}_{|\Delta B|=2} \supset \sum_i \frac{c_i}{\Lambda^5_{|\Delta B|=2}} (qqqqqq)_i + \text{h.c.}$$

dim 9

$n\bar{n}$ expt'l limit yields

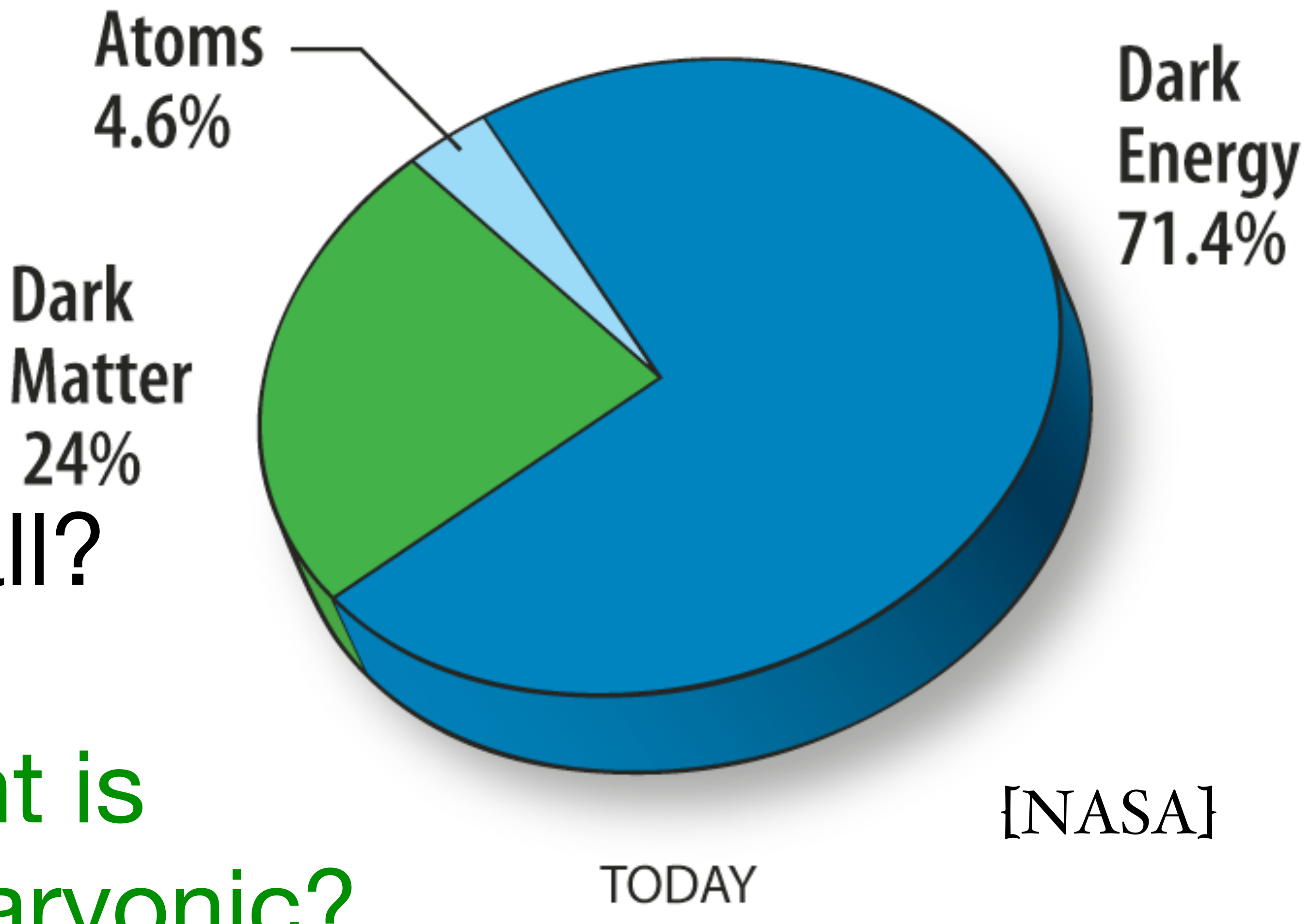
$$\Gamma_{|\Delta B|=2} \gtrsim 10^{5.5}\,\text{GeV}$$

Why Study Baryon Number Violation?

A key thread to interpreting *known* BSM physics!

SM BNV is invisible today!

Three ***essential*** questions:



[NASA]

How is it that the cosmic energy budget in ordinary matter is so small?

And how is it that its content is overwhelmingly (not *anti*-)baryonic?

How does the neutrino get its mass?

Their answers may be linked, and through observable BNV!

Baryon Number Violation (BNV)

Can be realized (& probed!) in different ways

- BNV can be **explicit**.

  $n\bar{n}$ oscillations ; $nn \to \nu\nu$; $e^- p \to e^+ \bar{p}$ ....

- BNV can be **apparent** (entrained with dark sectors). ★

  $n \to \chi\gamma; n \to \chi\chi\chi; nn \to \chi\chi$ ....

- BNV can be **spontaneous**.

  massive mediator of gauged B or $B - L$ or ....

Implications for origins of the BAU, neutrino mass....

Enter neutron stars — as a BNV laboratory!

Explicit BNV

Explicit BNV: $|\Delta B| = 2$ Processes

to explain the BAU

Need to explain BAU: enter $n\bar{n}$ oscillations! [Kuzmin, 1970]

Various explicit models: note, e.g., Q-L unification:

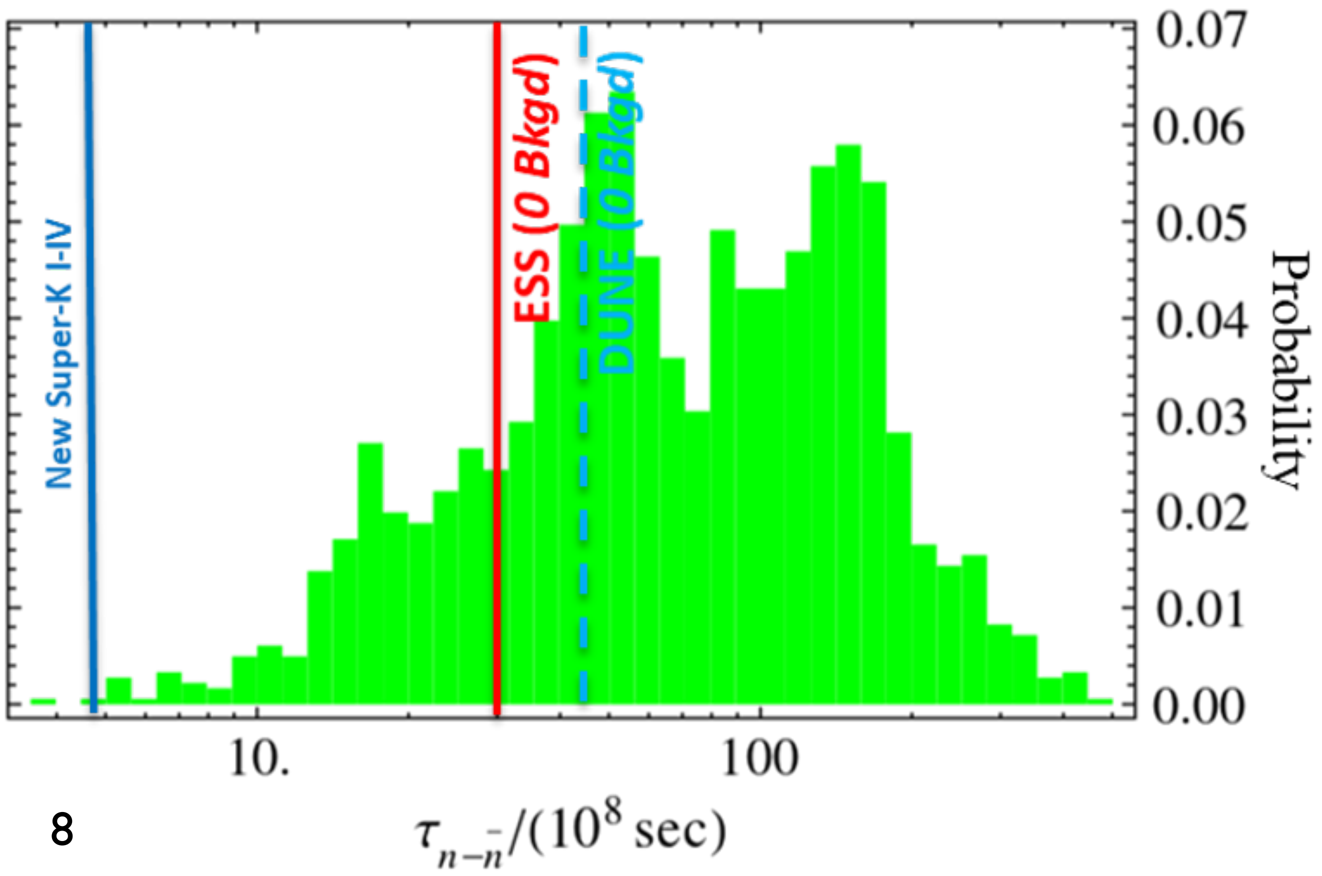
(Pati-Salam) $SU(2)_L \times SU(2)_R \times SU(4)_c$

[Mohapatra, Marshak, 1980]

The appearance of $n\bar{n}$ oscillations permits *post-sphaleron baryogenesis* [Babu, Mohapatra, Nasri, 2006]

Successful BAU:
Note upper limit on
$n\bar{n}$ oscillations!

[Babu, Dev, Mohapatra, 2009;
Babu et al., 2013]



On Neutrinoless Double Beta (0ν ββ) decay*

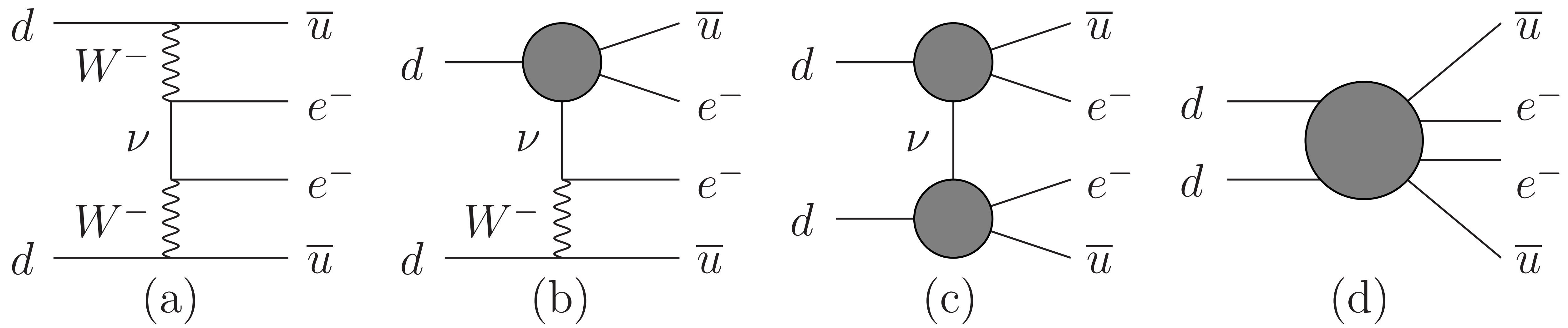
If observed, the ν has a Majorana mass

[Schechter & Valle, 1982]

0ν ββ mediated by a dimension 9 operator:

$\mathcal{O} \propto \bar{u}\bar{u}dd\bar{e}\bar{e}$ (or $\pi^- \pi^- \to e^- e^-$)

"mass mechanism"



"long range"

"short range"

[Bonnet, Hirsch, Ota, & Winter, 2013]

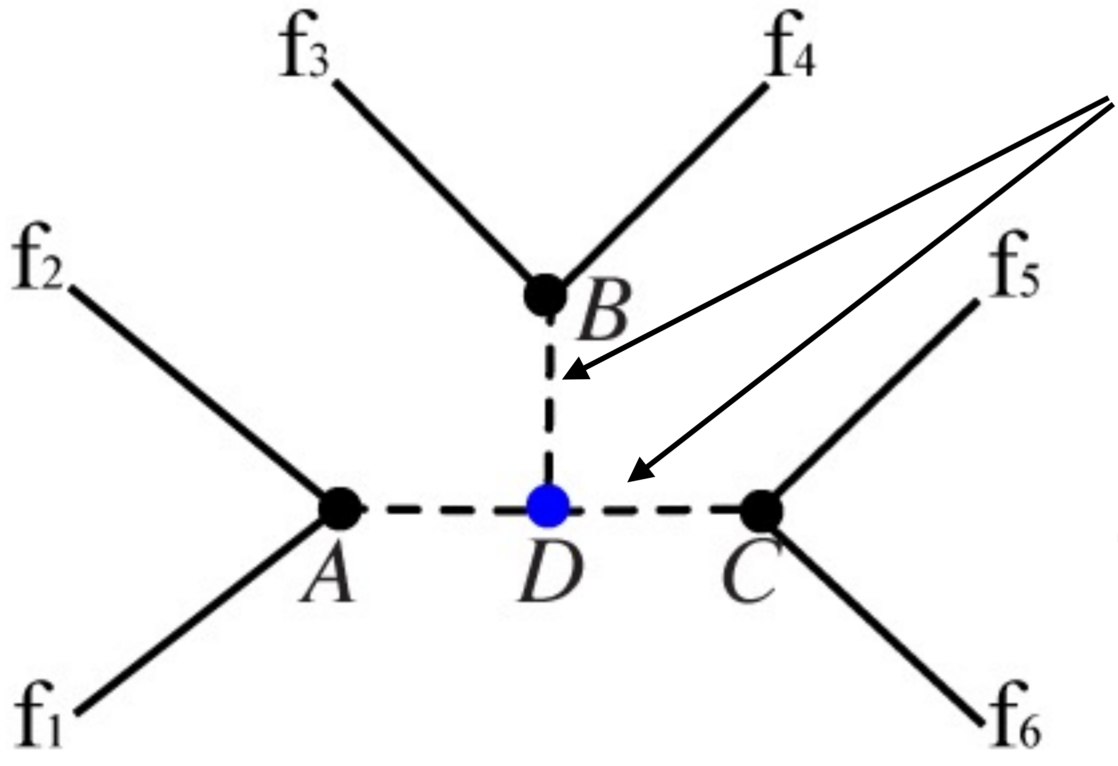
mediated by B-L breaking!

*Talk by Cirigliano

Context: 0ν ββ Decay in Nuclei

Can be mediated by "short-" or "long"-range mechanisms

The "short-range" mechanism involves new B-L violating dynamics; e.g.,



S or V that carries B or L

For choices of fermions f_i this decay topology can yield $n\text{-}\bar{n}$ or 0ν ββ decay

[Bonnet, Hirsch, Ota, & Winter, 2013; Berezhiani, 2013]

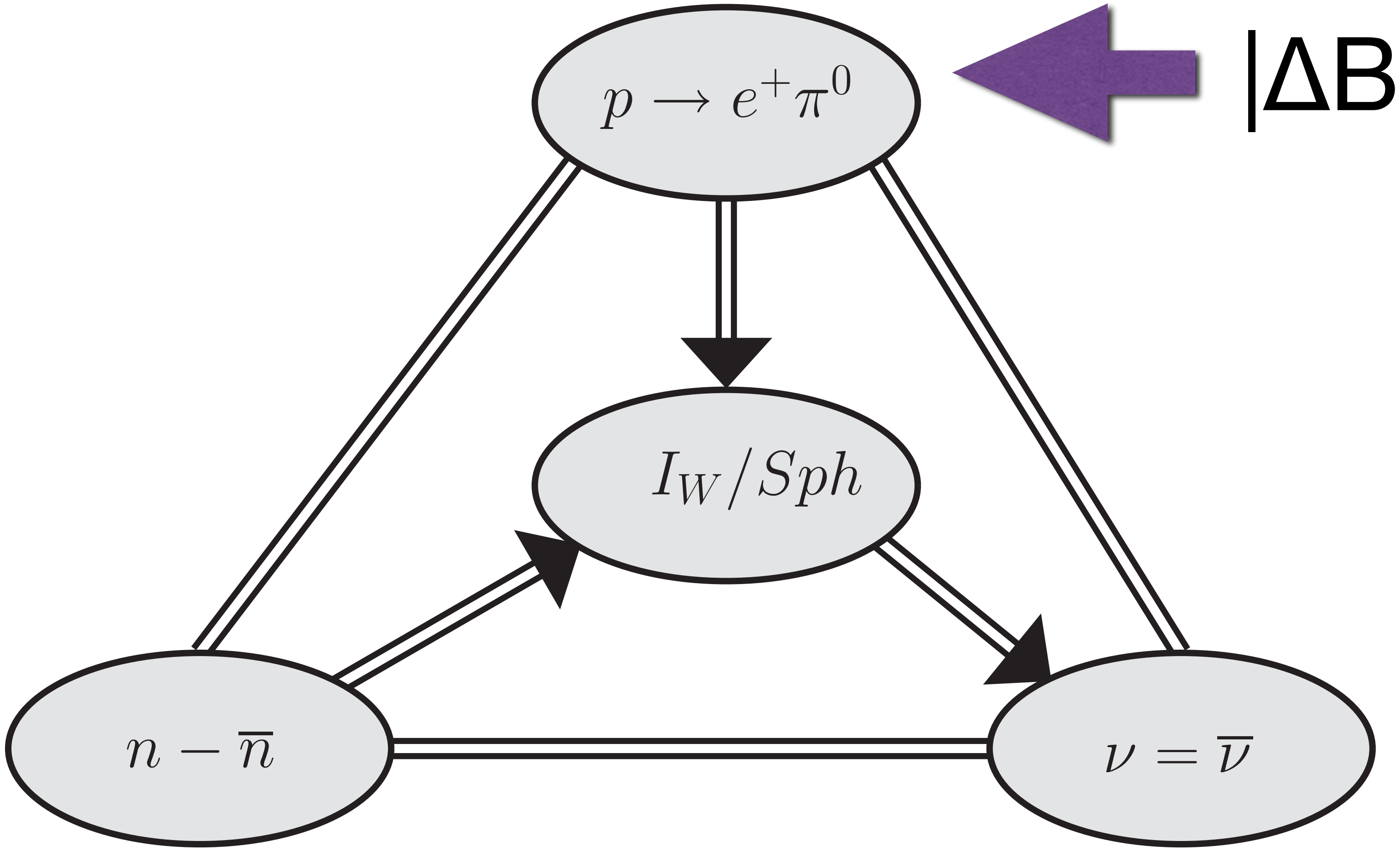
The possibilities can be related in a data-driven way

[SG & Xinshuai Yan, 2019]

Cf. connection via $|\Delta B|=1$ process
[Babu & Mohapatra, 2015]

Explicit BNV (& LNV)

patterns of observed violation
implies a Majorana neutrino



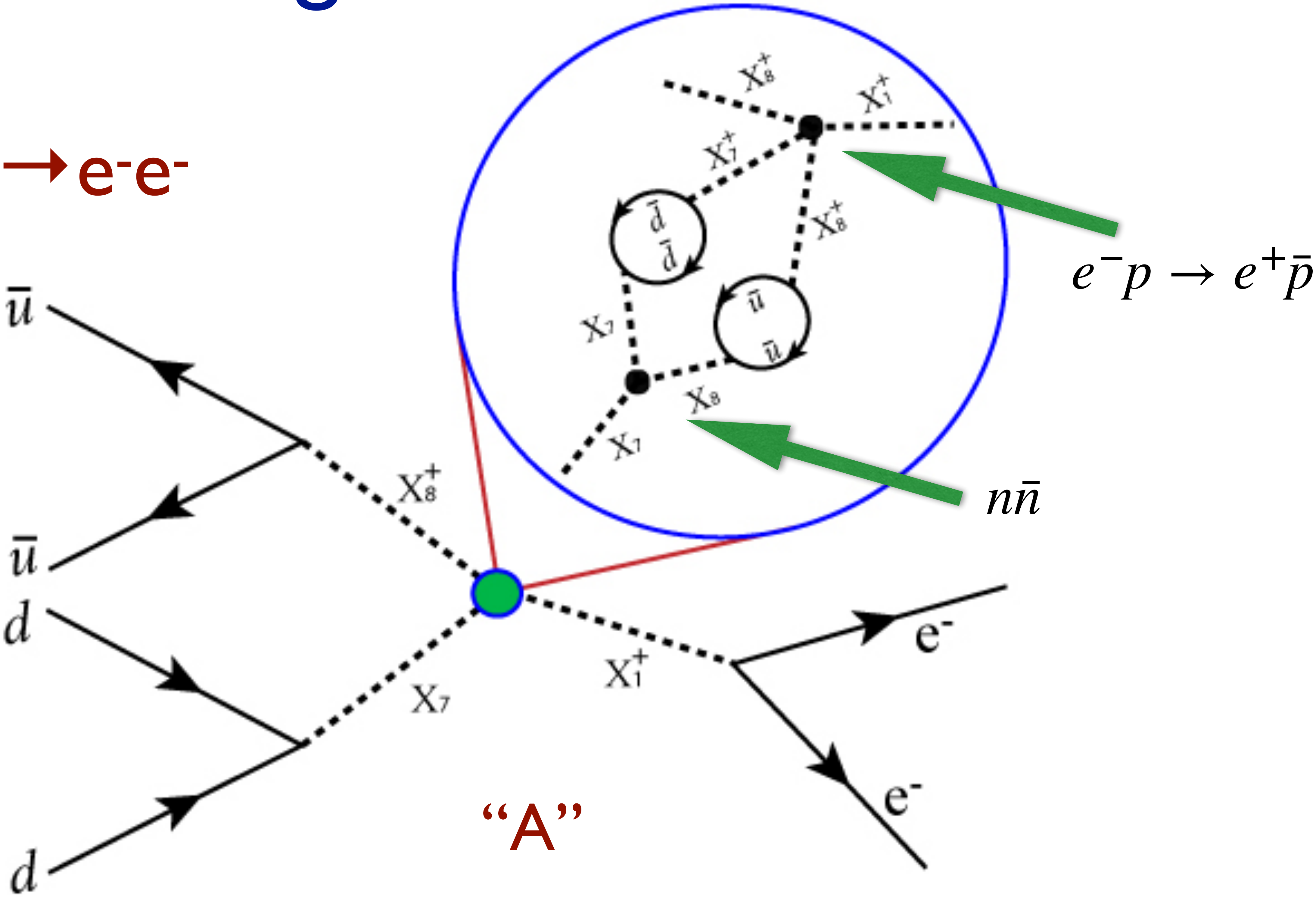
|ΔB|=1

“B-L” Triangle

[Babu & Mohapatra, 2015]

Connecting $|\Delta B|=2$ to $|\Delta L|=2$…

$\pi^-\pi^- \rightarrow e^-e^-$



$e^-p \rightarrow e^+\bar{p}$

$n\bar{n}$

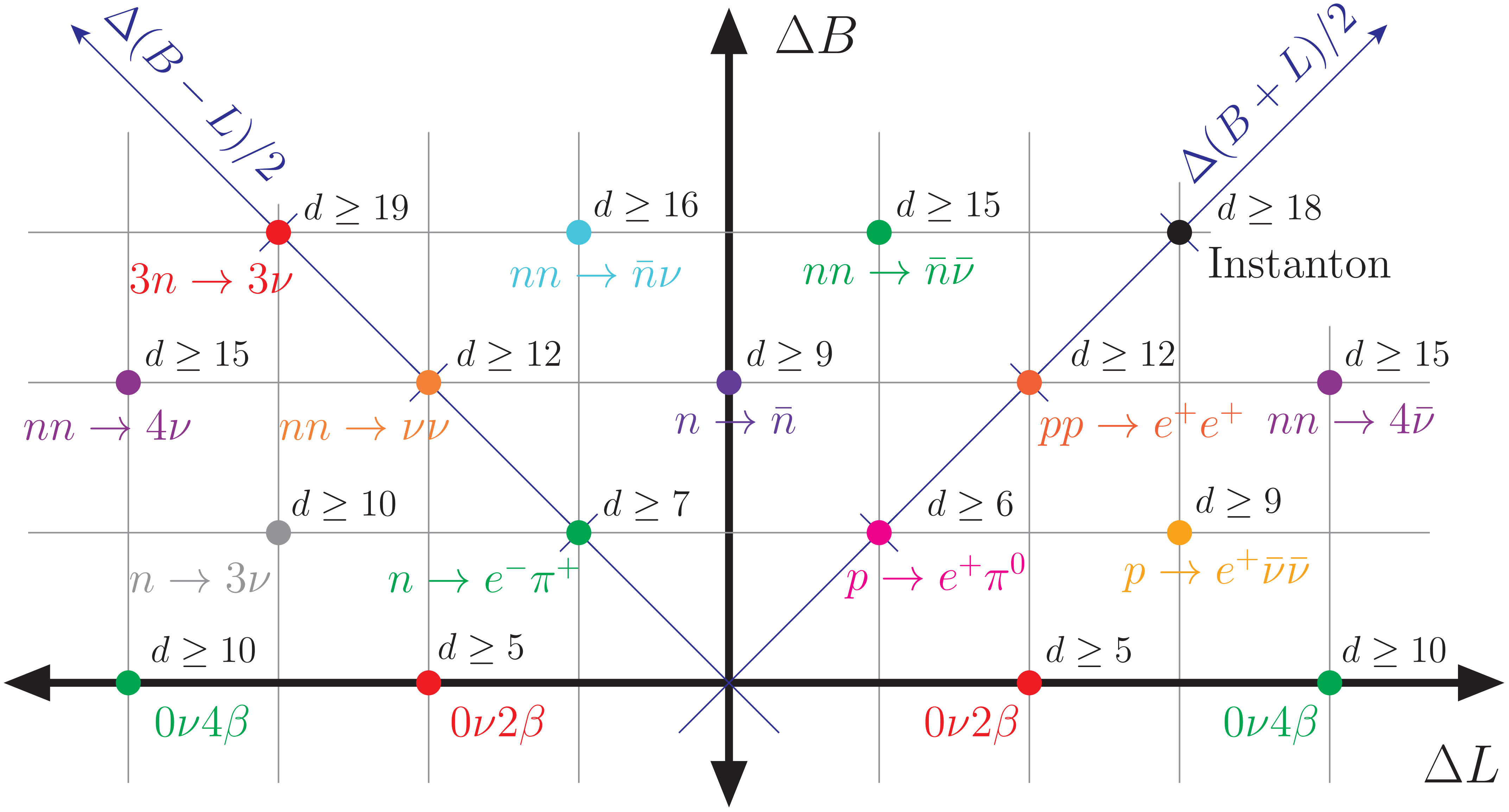
“A”

“Everything not forbidden is compulsory” [M. Gell-Mann, after T.H. White]

[SG & Xinshuai Yan, 2019]

Still Broader Possibilities

Different channels connected by vector addition



[Heeck & Takhistov, 2020]

[Note also Berryman, SG, Zakeri, 2022]

Modeling |ΔB|=2 Processes

Enter minimal scalar models without proton decay

[Arnold, Fornal, and Wise, 2013; Dev & Mohapatra, 2015; SG & Yan, 2019, 2020; Murgui & Wise, 2021]

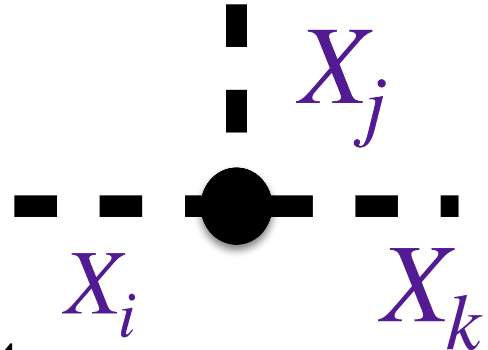
Already used for $n \to \bar{n}$ oscillation without p decay

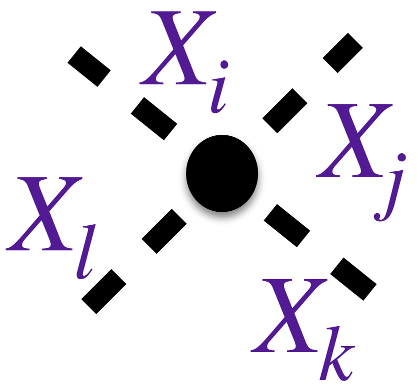
[Arnold, Fornal, Wise, 2013]

Add new scalars X_i that do not give N decay at tree level

Also choose X_i that respect SM gauge symmetry and also under interactions $X_iX_jX_k$ or $X_iX_jX_kX_l$ — cf. "hidden sector" searches: possible masses are limited by experiment

With this a much richer set of B and L violating processes emerge!





Scalars without Proton Decay

That also carry B or L charge

Scalar-fermion couplings

$Q_{em} = T_3 + Y$

Scalar	SM Representation	B	L	Operator(s)	$[g_i^{ab}?]$
X_1	$(1,1,2)$	0	-2	$Xe^a e^b$	[S]
X_2	$(1,1,1)$	0	-2	$XL^a L^b$	[A]
X_3	$(1,3,1)$	0	-2	$XL^a L^b$	[S]
X_4	$(\bar{6},3,-1/3)$	-2/3	0	$XQ^a Q^b$	[S]
X_5	$(\bar{6},1,-1/3)$	-2/3	0	$XQ^a Q^b, Xu^a d^b$	[A,–]
X_6	$(3,1,2/3)$	-2/3	0	$Xd^a d^b$	[A]
X_7	$(\bar{6},1,2/3)$	-2/3	0	$Xd^a d^b$	[S]
X_8	$(\bar{6},1,-4/3)$	-2/3	0	$Xu^a u^b$	[S]
X_9	$(3,2,7/6)$	1/3	-1	$X\bar{Q}^a e^b, XL^a \bar{u}^b$	[–,–]

Note SU(3) rep'ns

$SU(3)\times SU(2)_L\times U(1)_Y$

chiral

[?: a⟷b symmetry]

cf. n dark decay: $(3,1,-1/3)$

Phenomenology of New Scalars

Constraints from many sources — Focus on first generation

i) n-$\bar{n}$ (But some models do not produce it)

ii) Collider constraints

CMS: $\ell^+\ell^+$ search; cannot look at invariant masses below 8 GeV

[CMS 2012, 2014, 2016]

iii) $(g-2)_e$ [Babu & Macesanu, 2003]

[superseded by Møller expt, save for light masses] [SG & Xinshuai Yan, 2020]

Use latest exp't! [Hanneke, Fogwell, Gabrielse, 2008]

Limit: $M_1/g_1^{11} \geq 80$ GeV

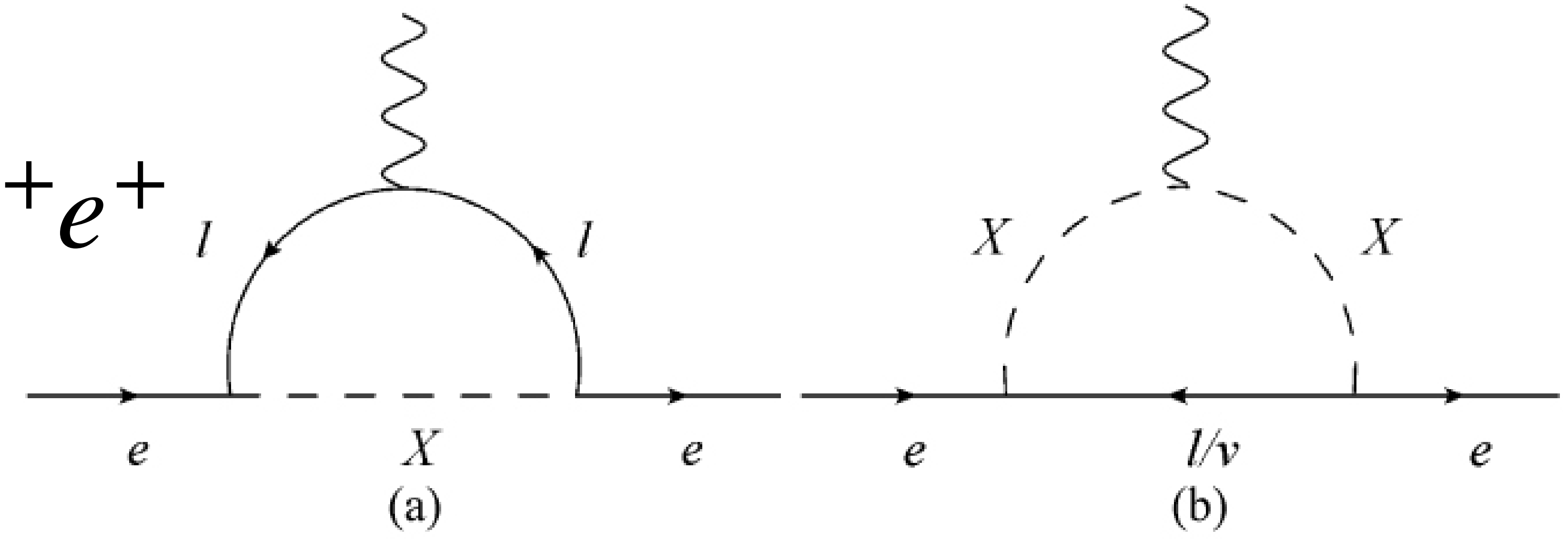
$M_{X_{1,3}}/g^{11}_{1,3} \geq 2.7\,\mathrm{TeV}$ @ 90 % CL [E158] (if "heavy")

iii) Nuclear stability

SuperK $^{16}\mathrm{O}$: $pp \to e^+e^+$

[Bramante, Kumar, & Learned, 2015]

But note short-distance repulsion!



(a) (b)

iv) $H\bar{H}$ annihilation

[Grossman, Ng, & Ray, 2018]

But beware galactic magnetic fields!

Few GeV mass window possible

Patterns of |ΔB|=2 Violation

Discovery implications for 0ν ββ decay

Model	$n\bar{n}$?	$e^- n \to e^- \bar{n}$?	$e^- p \to \bar{\nu}_X \bar{n}$?	$e^- p \to e^+ \bar{p}$?	$0\nu\beta\beta$?
M3	Y	N	N	Y	Y [A]
M2	Y	Y	Y	Y	Y [B]
M1	Y	Y	Y	N	? [D]
–	N	N	Y	Y	? [C?]

Patterns of observation can distinguish the possibilities.

$n\bar{n}$ limits are severe! $\tau_{n\bar{n}} > 2.7 \times 10^8\,\mathrm{s}$ @ 90 % CL

[SuperK: Abe et al., 2015]

Note "XXXX" processes can be studied at low E, high intensity e^- facilities: e.g., Ariel @ TRIUMF ($E = 15\,\mathrm{MeV}$)

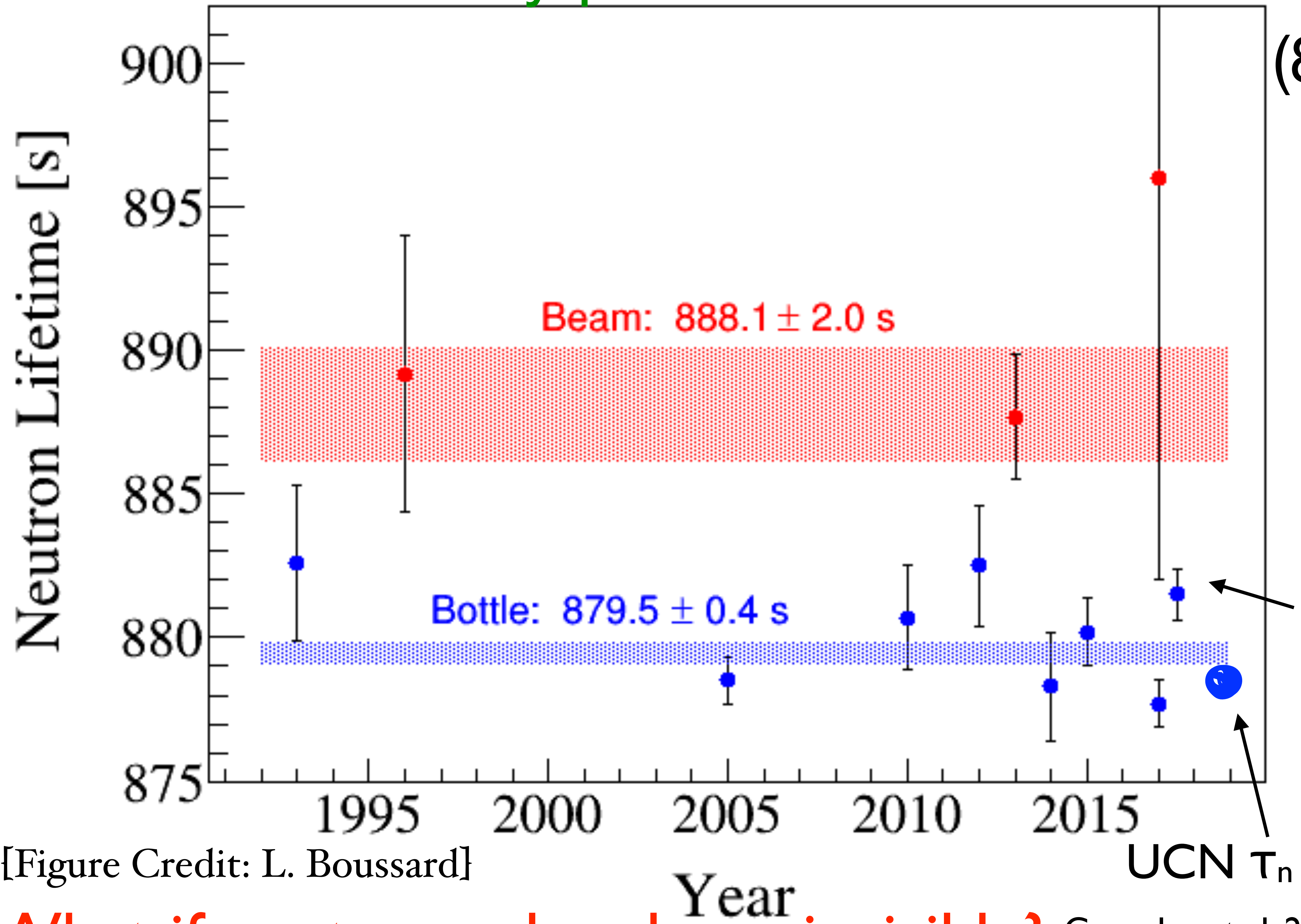
Low E: prompt annihilation of $\bar{N}$; low background!!

[SG & Xinshuai Yan, 2018, 2019,...]

Apparent BNV

The Neutron Lifetime Puzzle

A darkly provocative result?



(8.6 s, (>)4σ)

Count **protons** that appear

Serebrov

Count **neutrons** that persist

UCN τ_n

Gonzalez et al.,2021

[Figure Credit: L. Boussard]

What if neutrons also decay invisibly?

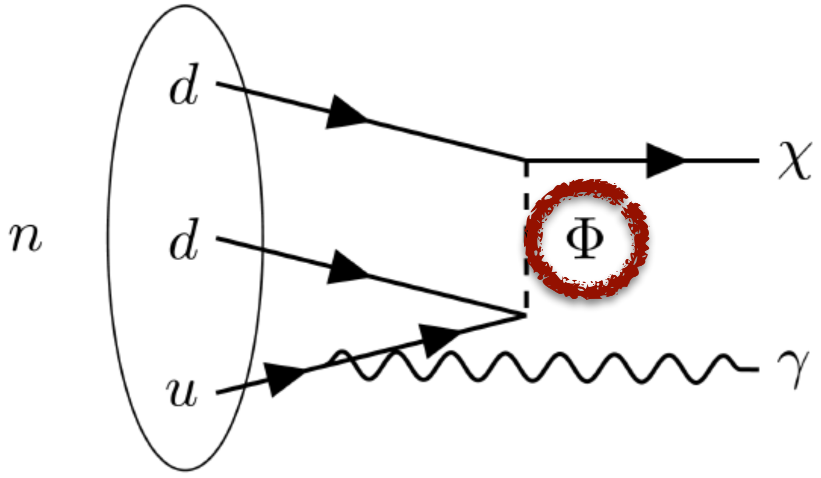
[Recall early suggestion: Z. Berezhiani & “mirror neutrons” & 2019; note Broussard et al., 2022!]

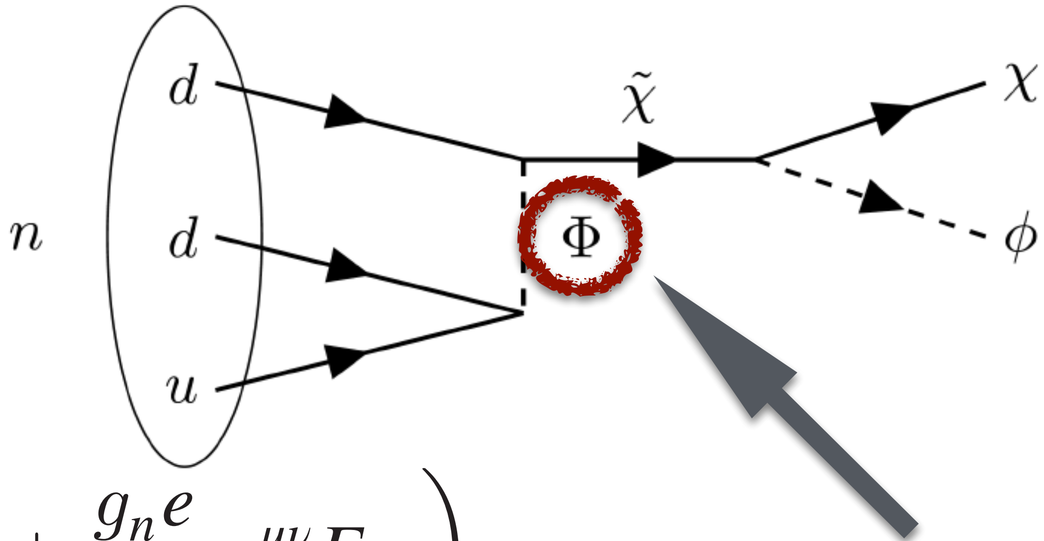
Neutron Dark Decays

Modeled to solve the neutron lifetime puzzle

[Fornal & Grinstein, 2018]

★ Enter $n \to \chi\gamma$; also $n \to \chi(\phi \to e^+e^-)$





$\phi \to e^+e^-$

B-carrying scalar!

At low E:

$$\mathcal{L}_1^{\text{eff}} = \bar{n}\left(i\partial\!\!\!/ - m_n + \frac{g_n e}{2m_n}\sigma^{\mu\nu}F_{\mu\nu}\right)n + \bar{\chi}(i\partial\!\!\!/ - m_\chi)\chi + \varepsilon(\bar{n}\chi + \bar{\chi}n)$$

Select χ mass window to avoid **proton decay** ($|\Delta B| = 1$)

& nuclear constraints: $937.900\,\text{MeV} < m_\chi < 938.783\,\text{MeV}$

Thus $\tau_n^{\text{beam}} = \tau_n^{\text{bottle}}$ / Br(n→p + anything)

Many constraints! But $\Gamma_{n\,\text{dark}} \gg \Gamma_{|\Delta B|=1}$ still possible!

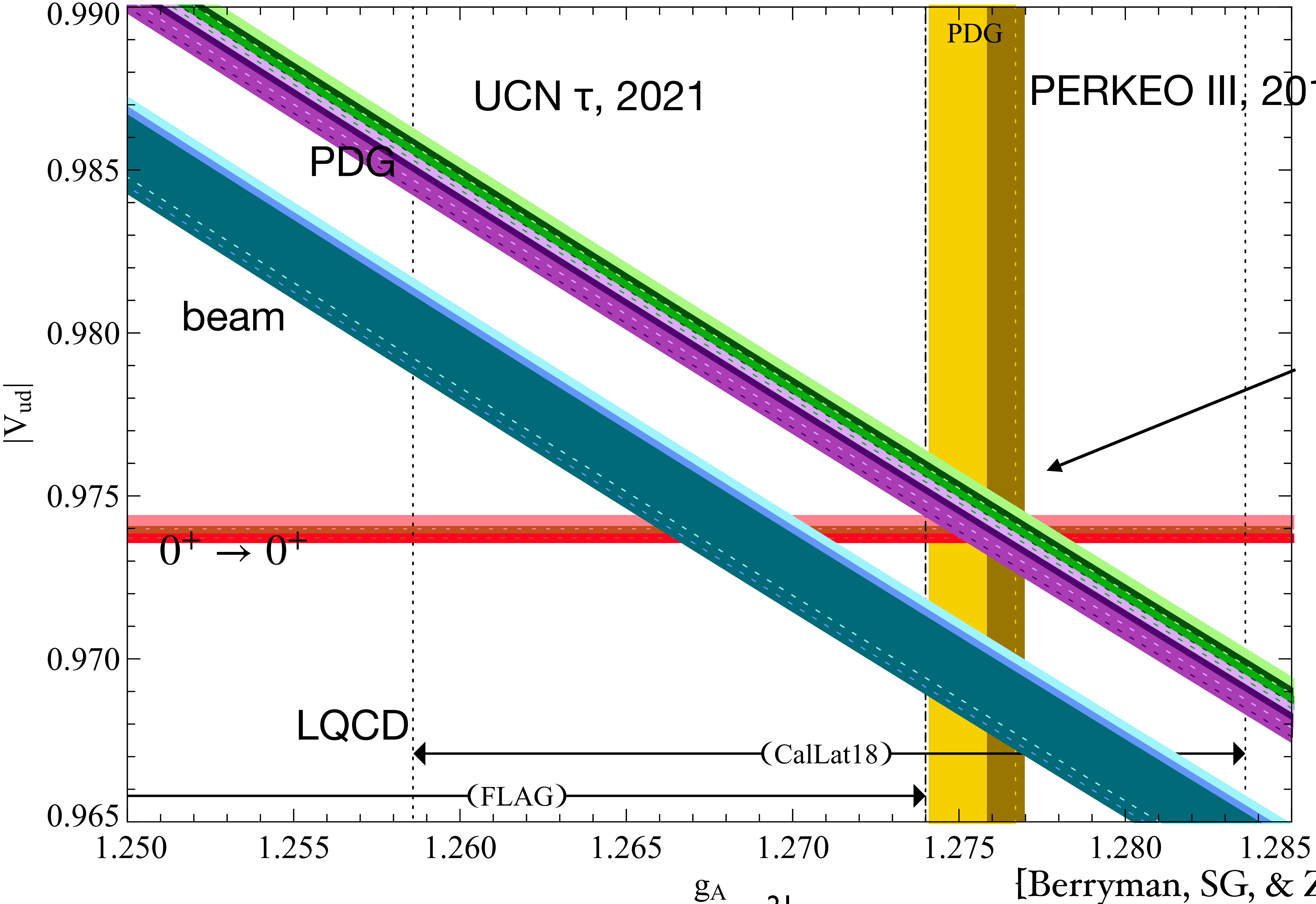
[Note also Strumia, 2022]

β Decay in the SM

[Czarnecki, Marciano, Sirlin, 2018]

Constrains n dark decays

$$|V_{ud}|^2 \tau_n (1 + 3g_A^2) = \frac{2\pi^3}{G_F^2 m_e^5 (1 + \delta_{\mathrm{RC}}) f}$$



cf. new CDF II W mass?

SM!

[Berryman, SG, & Zakeri, 2022]

Neutron Stars to Limit BNV*

Assumptions for a model-independent analysis

$$\Gamma_{\mathrm{BNV}} << \Gamma_{\mathrm{weak}}$$

SM processes continue to control the EOS, as the star adjusts to the presence of BNV

This can occur if any new final-state particles either annihilate or decay to particles already present in the star (plus ν's & γ's)

Outcome: inclusive limit on all BNV processes that **can occur** in the star!

*Talk by Zakeri

Neutron Stars to Limit BNV

Use pulsar binary period decay rate…

- Double pulsar (PSR J0737-3039A/B)
- Hulse-Taylor binary (PSR B1913+16)
- White Dwarf-Neutron Star (PSR J1713+0747)

Name	**J0737−3039A/B**	**B1913+16**	**J1713+0747**
P_b (days)	$0.1022515592973(10)$	$0.322997448918(3)$	$67.8251299228(5)$
$\dot{P}_b^{\mathrm{int}}$ $(\times 10^{-12})$	$-1.247752(79)$	$-2.398(4)$	$0.03(15)$
$\dot{P}_b^{\mathrm{GR}}$ $(\times 10^{-12})$	$-1.247827(+6,-7)$	$-2.40263(5)$	$-6.3(6) \times 10^{-6}$
$(\frac{\dot{P}_b}{P_b})^{\dot{\mathrm{E}}}_{2\sigma}$ (yr^{-1})	8.3×10^{-13}	1.4×10^{-11}	1.8×10^{-12}
$(\frac{\dot{P}_b}{P_b})^{\dot{\Omega}}$ (yr^{-1})	$1.04(7) \times 10^{-13}$	$\lesssim 2.5 \times 10^{-13}$	$\approx 8 \times 10^{-14}$
$(\frac{\dot{P}_b}{P_b})^{\mathrm{BNV}}_{2\sigma}$ (yr^{-1})	7.3×10^{-13}	1.4×10^{-11}	1.8×10^{-12}
$\lvert\frac{\dot{B}}{B}\rvert_{2\sigma}$ (yr^{-1})	3.7×10^{-13}	7×10^{-12}	1.1×10^{-12}

$$\dot{B} = f \times B \times \Gamma_{\mathrm{BNV}} \qquad \Gamma_{\mathrm{BNV}} < 4 \times 10^{-13}\,\mathrm{yr}^{-1}\ [95\,\%\,\mathrm{CL}]$$

f: fraction participating

n; inclusive

Neutron Stars to Limit BNV

Use pulsar spin down rate…

- Pulsar-white dwarf binary PSR J0348+0432
- $M_p = 2.01 \pm 0.04\, M_\odot$ (!)
- Assuming BNV is from a decay (note EOS choice)

$$\Gamma_n < 1.7 \times 10^{-9}\,\mathrm{yr}^{-1}$$
$$\Gamma_\Lambda < 2.8 \times 10^{-7}\,\mathrm{yr}^{-1}$$
$$\Gamma_{\Sigma^-} < 6.5 \times 10^{-5}\,\mathrm{yr}^{-1}$$

Much more severe than exclusive Λ dark decay limits from neutrino burst duration in SN 1987A!

[Alonso-Alvarez et al., 2021 [2111.12712]]

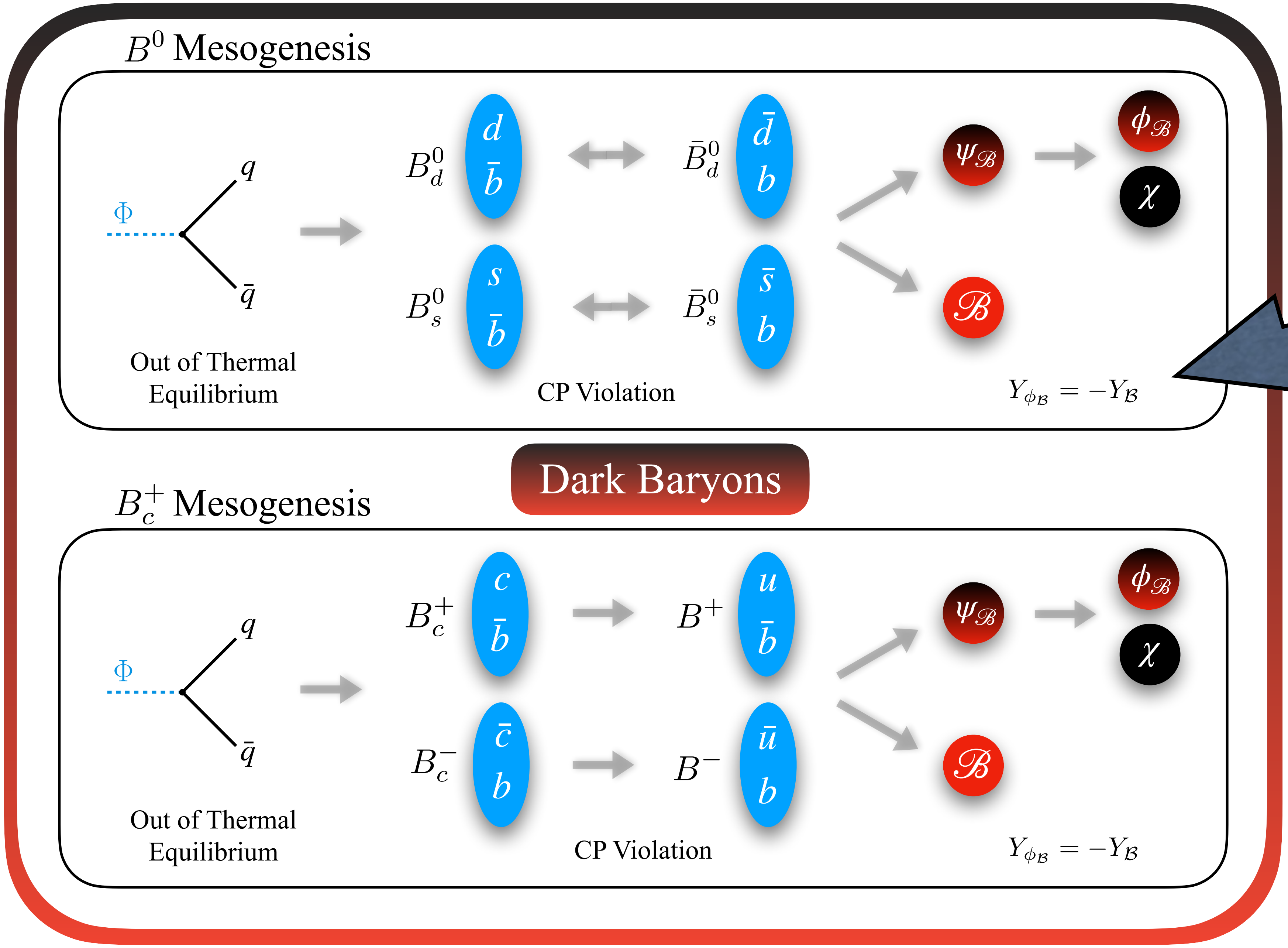
Comparative analysis ongoing

Broader Impacts

“Mesogenesis”

New dark sector fermion ψ_B with $B = -1$….

[Elor, Escudero, Nelson, 2019; Elor & McGehee, 2021;…]



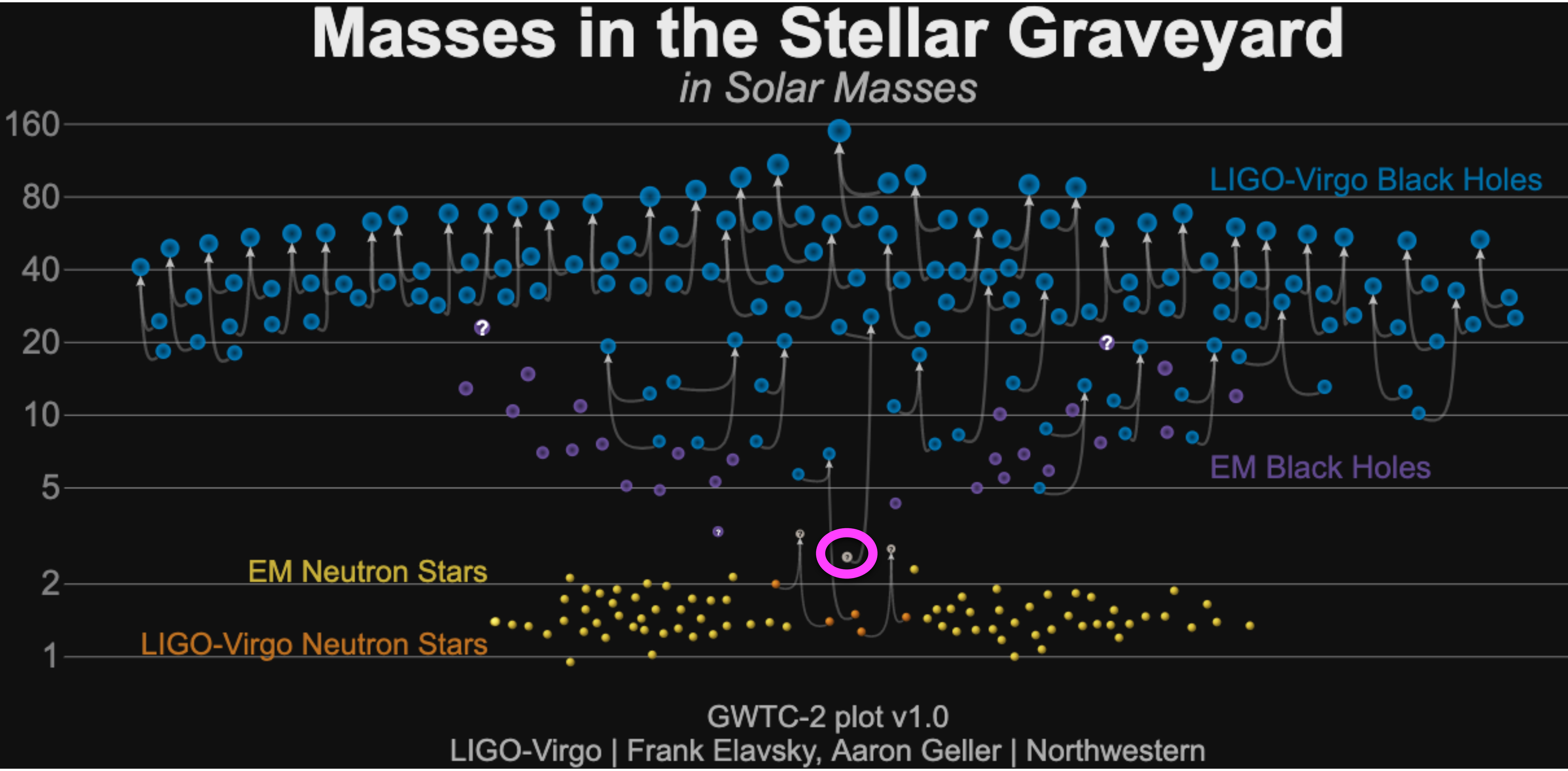
Note!

Different variants!

Spontaneous BNV

A Surprise: GW190814

A $2.6M_\odot$ object — neutron star or black hole?



https://ligo.northwestern.edu/media/mass-plot/index.html

New Short-Range Force?*

E.g., a $U(1)_\mathrm{B}$ gauge boson $B\ldots$

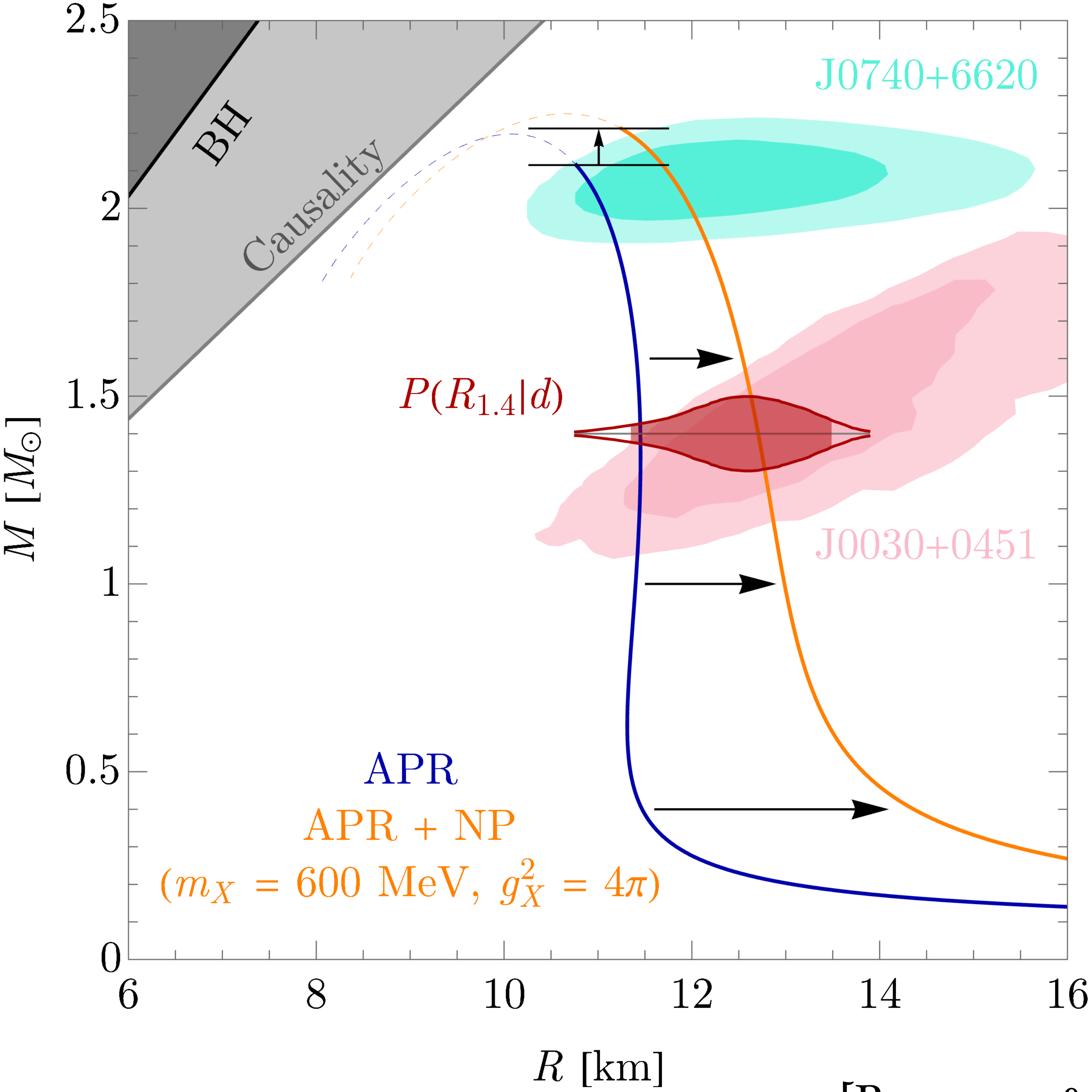
- Can be heavy ($\gtrsim 600\,\mathrm{MeV}$) and not so weakly coupled with little impact on NN phenomenology
- Generates a repulsive force between neutrons
- Need to work within non-relativistic many-body physics for connection to NN physics
- Can modify neutron star properties to yield a larger maximum neutron star mass

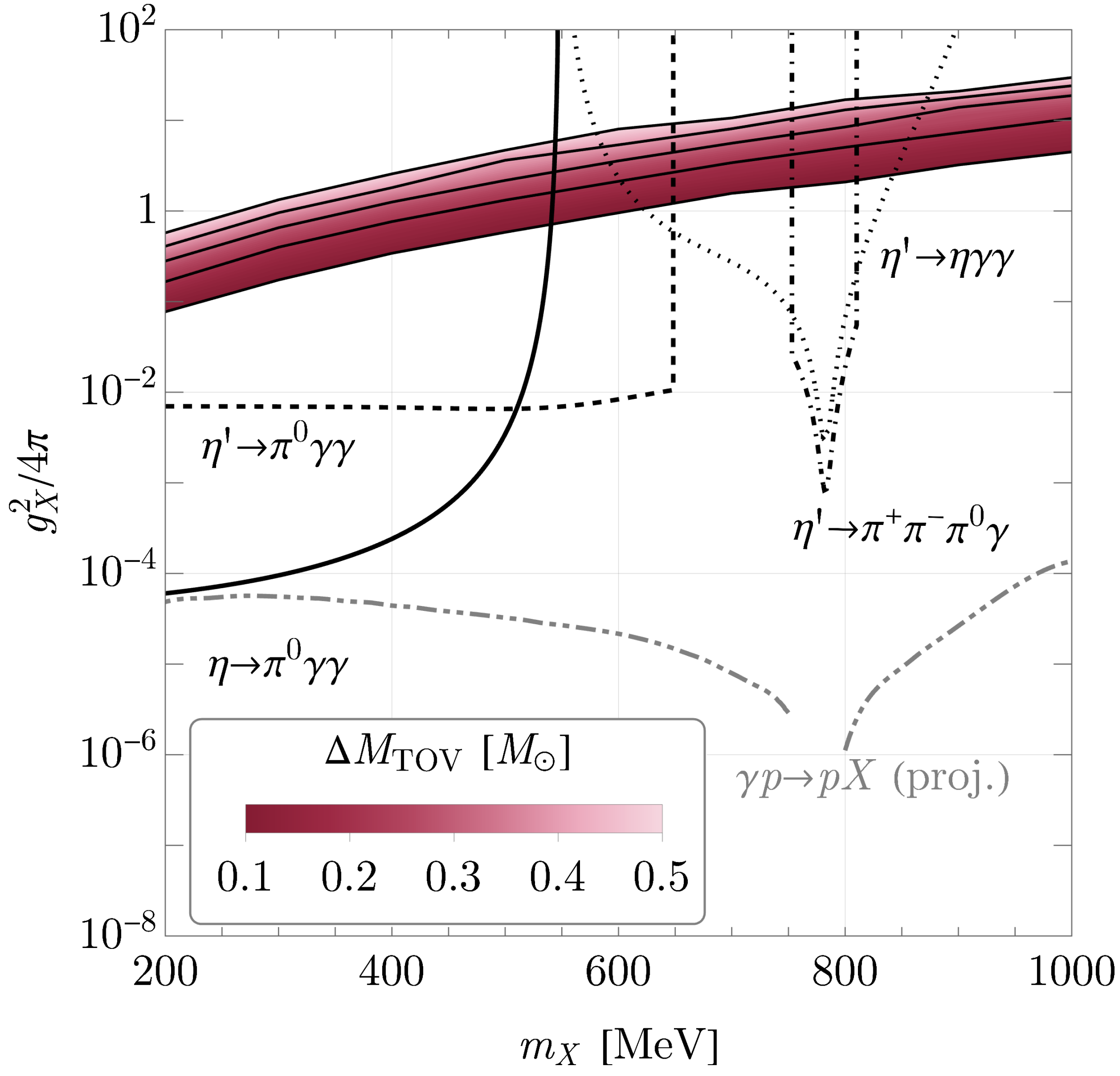
*Talk by Kim; note "vector portal" models

[Berryman & SG, 2021]

Neutron Star Structure

with gauged $U(1)_{\mathrm{B}_1}$





Test with rare eta decays!

[Berryman & SG, 2021; Berryman, SG, & Zakeri, 2022]

Summary

—New, possible avenues for B (& L) NV (by 2 units & more) have been largely overlooked

—These studies may provide new insights into the nature of the neutrino mass

—Light hidden sectors that could help mediate rare processes associated with dim ≥ 9 BNV operators are potentially discoverable in low E accelerator experiments

—Neutron stars contain $\sim 10^{57}$ baryons; energy loss constraints limit BNV rates under weak assumptions…(& more under development)

—Spontaneous BNV can modify the structure of neutron stars, making them heavier and “fatter”

Collaborators
— Baryon Number Violation —

Jeff Berryman

M. Zakeri (Zaki)

Xinshuai Yan

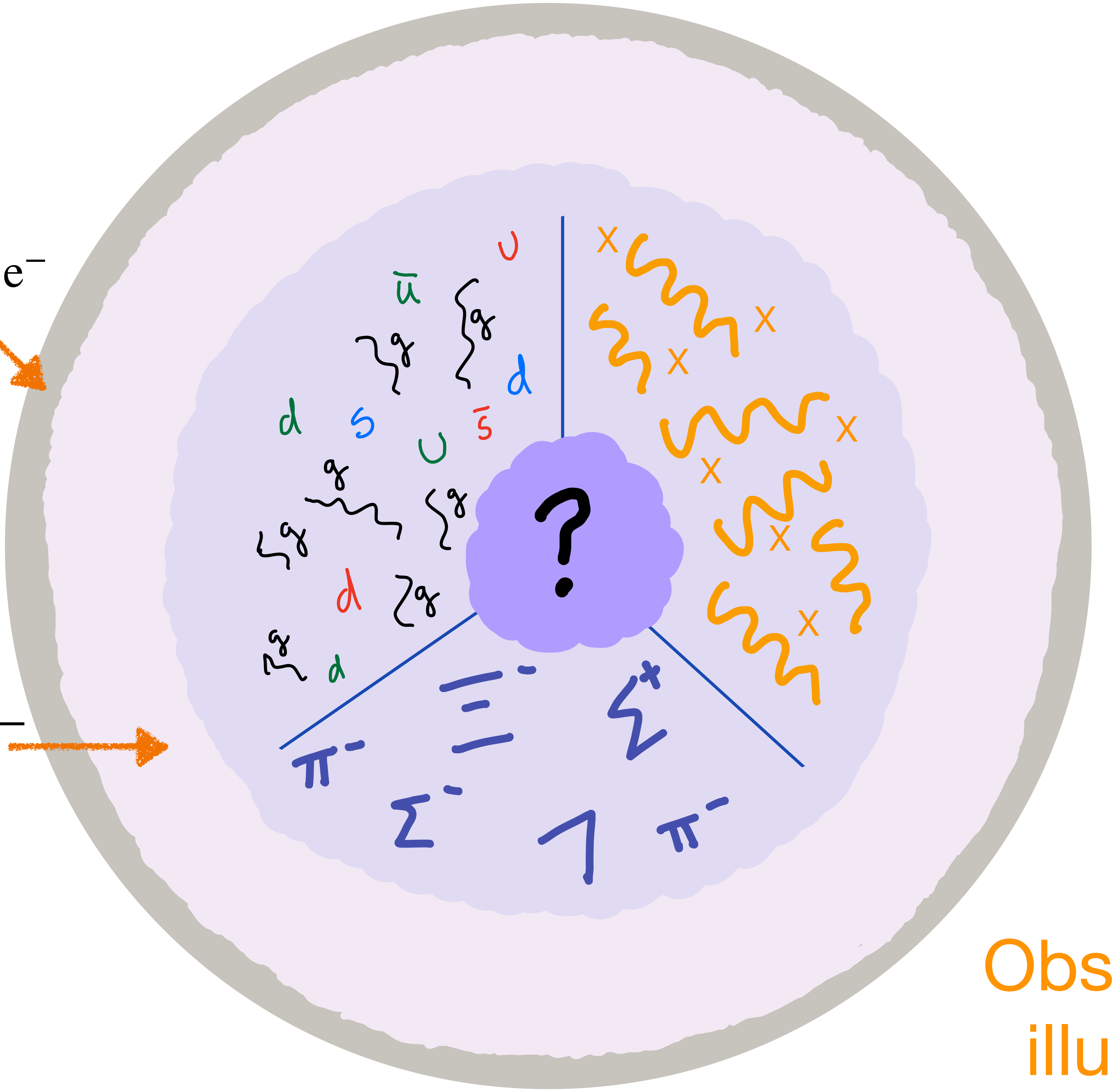
Backup Slides

Neutron Star Schematic

The interior is not well-understood

Nuclei + e^-

n, p, e^-, μ^-



Critical phenomena in **cold** QCD?

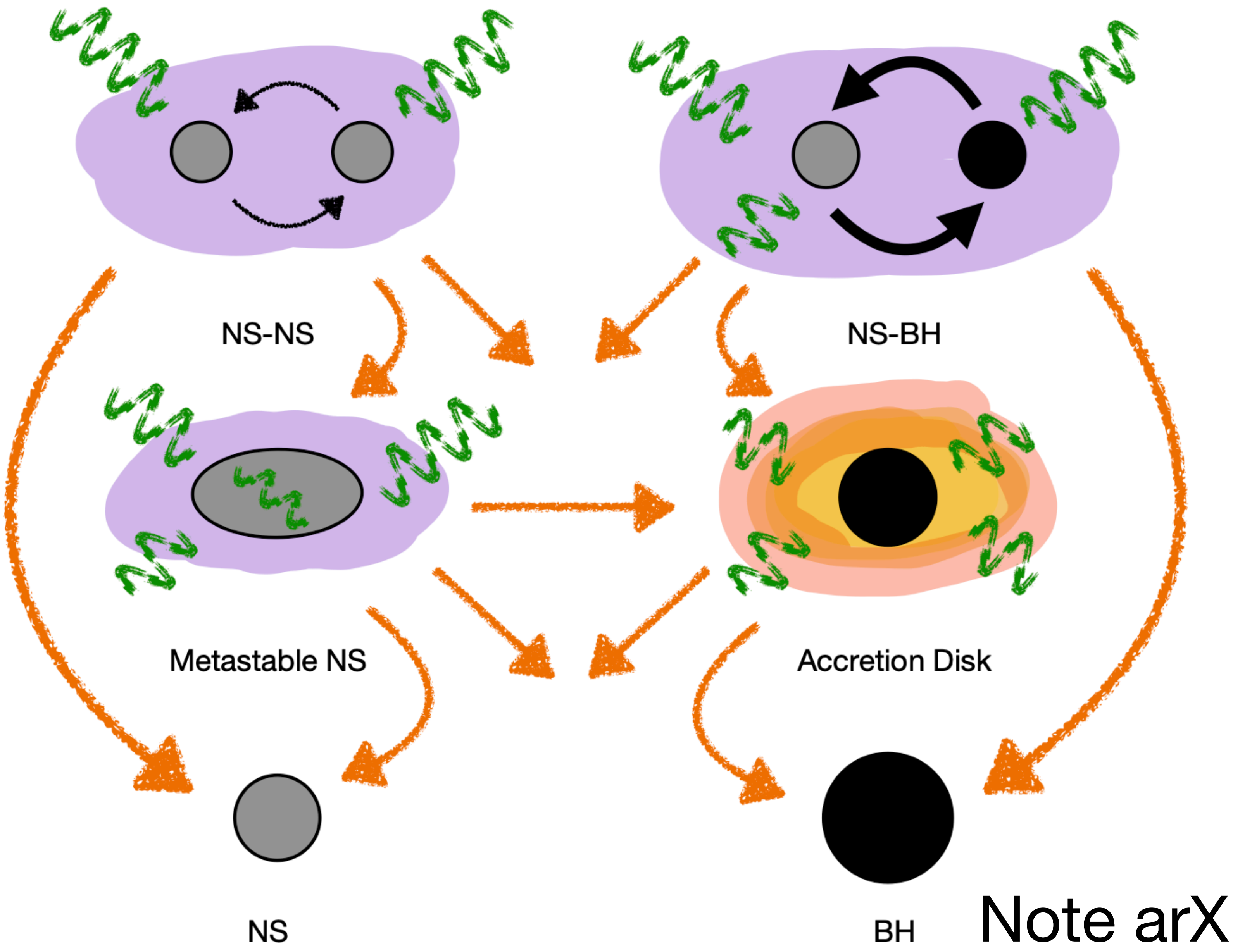
Observational studies illuminate structure & dynamics….

{Berryman, SG, & Zakeri, 2022; after Baym & Pethick, 1975}

Dark Matter: Cosmic Probes

CF3

Extreme Astrophysical Environments



Note arXiv:2201.02637

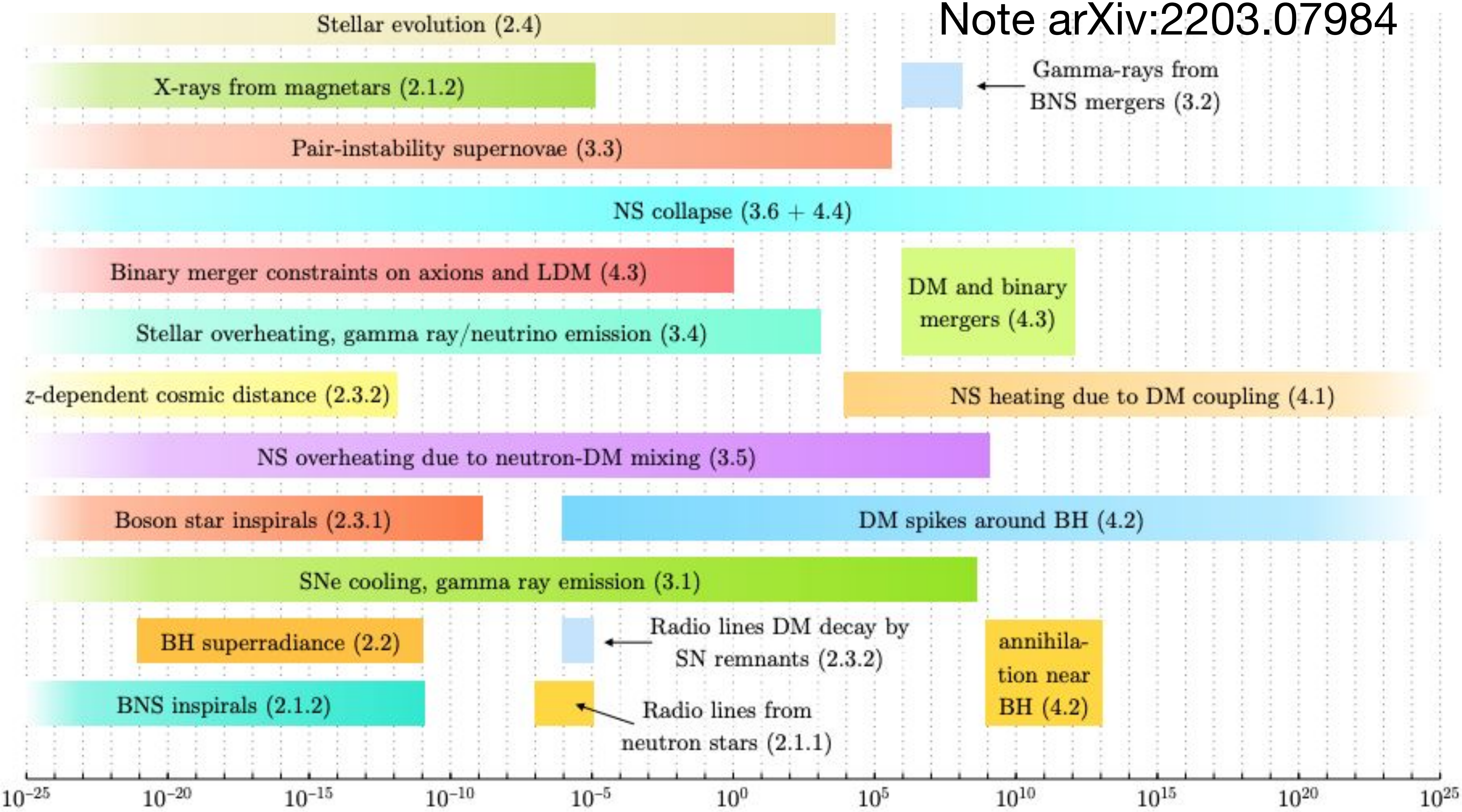
Outcomes sensitive to dynamical details….

Dark Matter: Cosmic Probes

Extreme Astrophysical Environments

CF3

Note arXiv:2203.07984

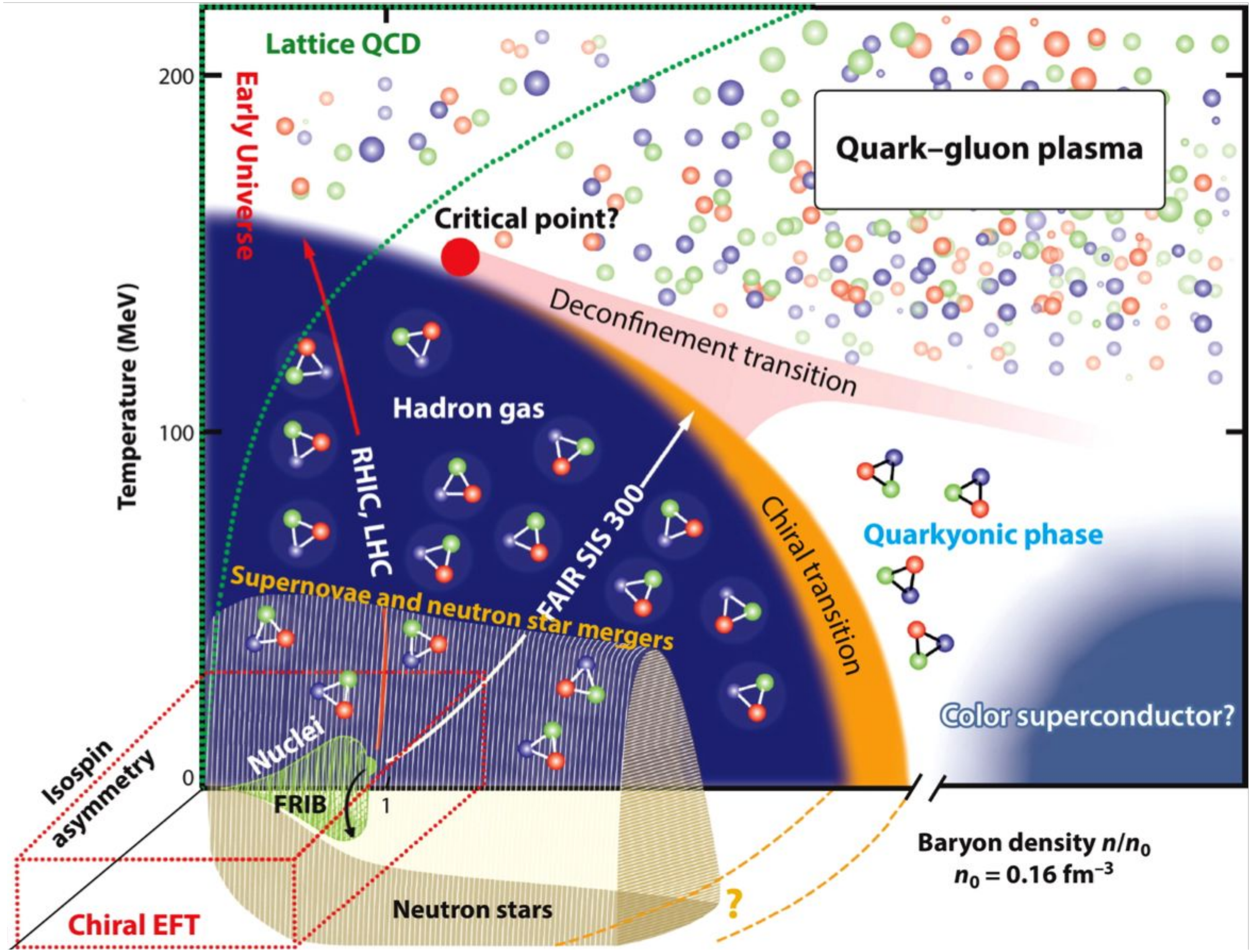


DM mass in eV

10^{-25} eV RPF Interface (e.g.): rare decays, BNV, dark sector probes…. 10^{25} eV

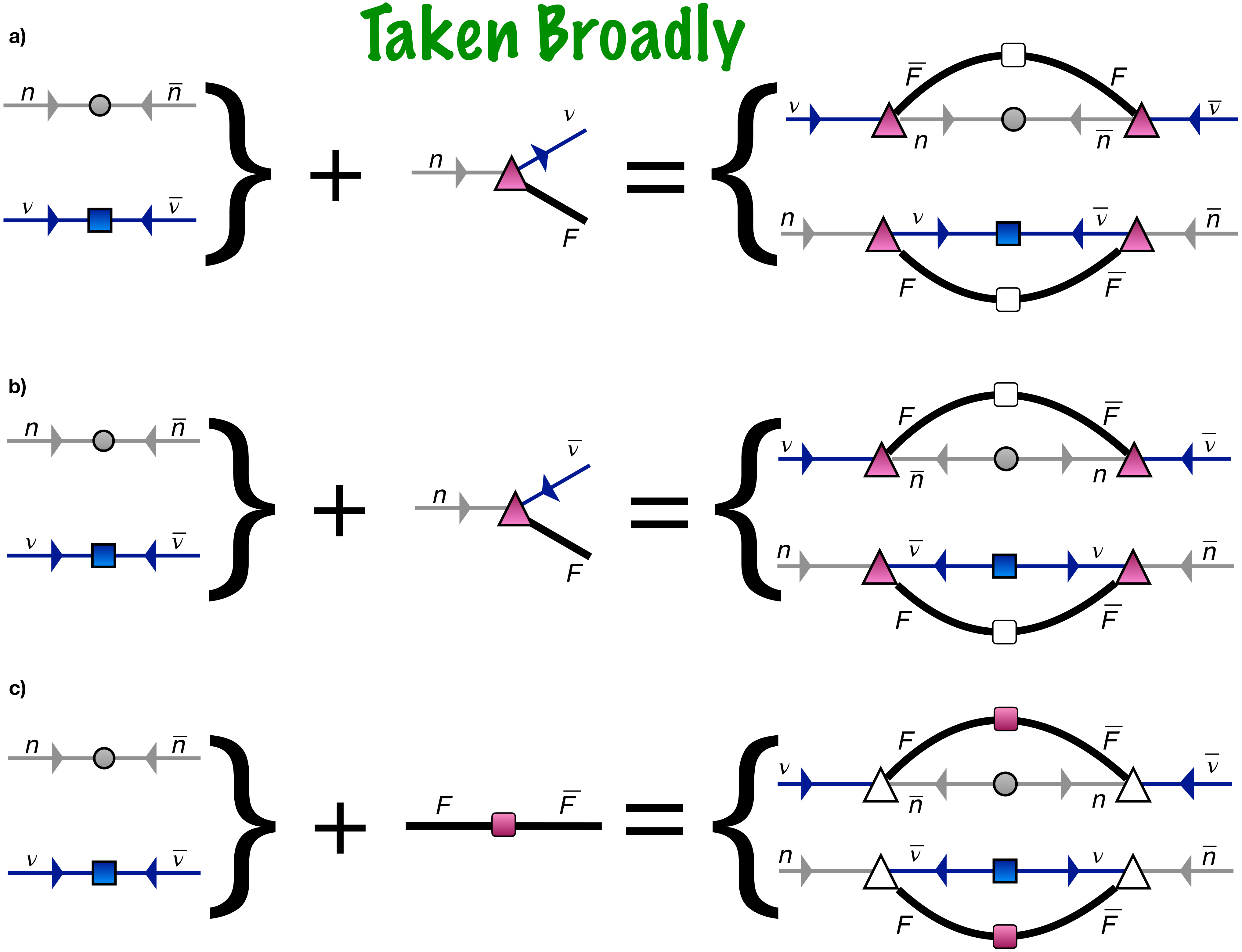
Broader Complementarities

heavy-ion collisions



Connecting Majorana Masses

Taken Broadly



[Berryman, SG, & Zakeri, 2022]