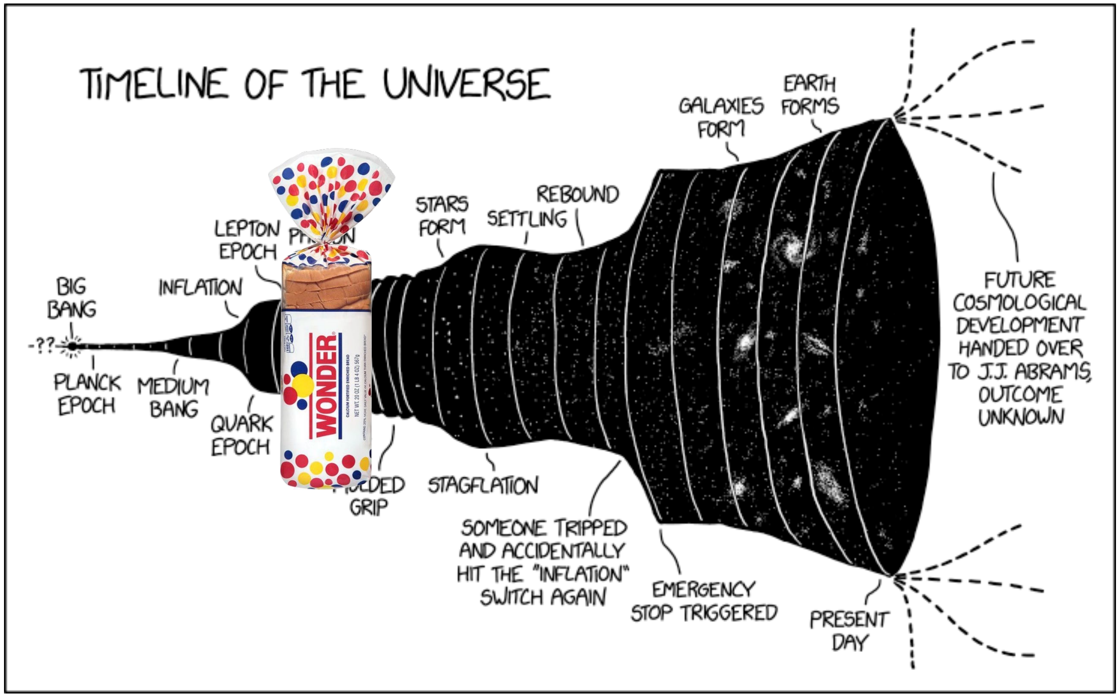
Baryon Number: Cosmic Wonder



Andrew Long
Rice University

@ BLV 2020, virtual
July 7, 2020

The mid-conference crisis:

Why do we study baryon- and lepton-number violation?

Our favorite theories predict it

SM … GUTs … RPV SUSY

… quantum gravity(?) …

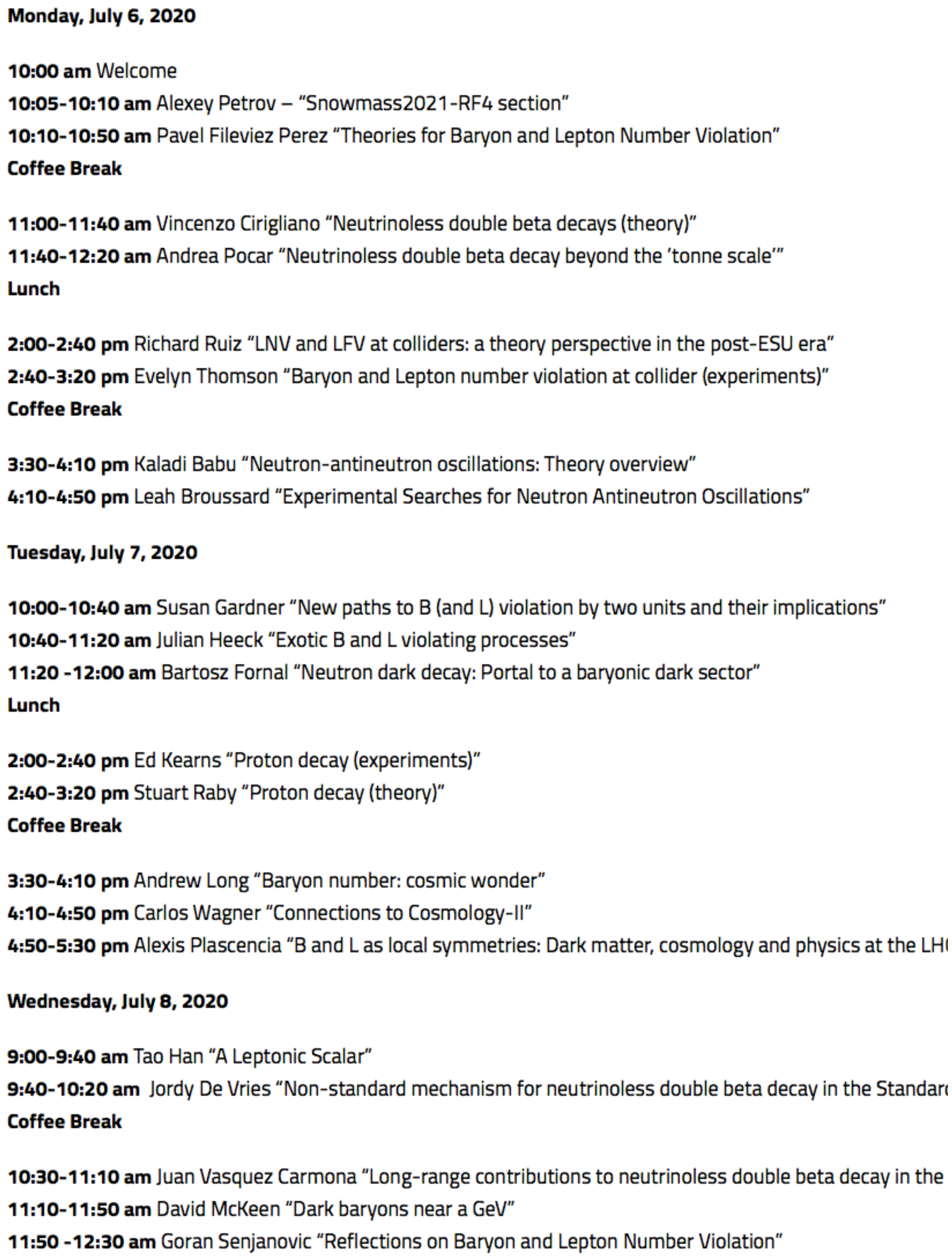
We can test for it

proton decay … $0\nu\beta\beta$ …

n-nbar oscillations … colliders …

Cosmology requires it

baryogenesis



Monday, July 6, 2020

10:00 am Welcome
10:05-10:10 am Alexey Petrov – "Snowmass2021-RF4 section"
10:10-10:50 am Pavel Fileviez Perez "Theories for Baryon and Lepton Number Violation"
Coffee Break

11:00-11:40 am Vincenzo Cirigliano "Neutrinoless double beta decays (theory)"
11:40-12:20 am Andrea Pocar "Neutrinoless double beta decay beyond the 'tonne scale'"
Lunch

2:00-2:40 pm Richard Ruiz "LNV and LFV at colliders: a theory perspective in the post-ESU era"
2:40-3:20 pm Evelyn Thomson "Baryon and Lepton number violation at collider (experiments)"
Coffee Break

3:30-4:10 pm Kaladi Babu "Neutron-antineutron oscillations: Theory overview"
4:10-4:50 pm Leah Broussard "Experimental Searches for Neutron Antineutron Oscillations"

Tuesday, July 7, 2020

10:00-10:40 am Susan Gardner "New paths to B (and L) violation by two units and their implications"
10:40-11:20 am Julian Heeck "Exotic B and L violating processes"
11:20 -12:00 am Bartosz Fornal "Neutron dark decay: Portal to a baryonic dark sector"
Lunch

2:00-2:40 pm Ed Kearns "Proton decay (experiments)"
2:40-3:20 pm Stuart Raby "Proton decay (theory)"
Coffee Break

3:30-4:10 pm Andrew Long "Baryon number: cosmic wonder"
4:10-4:50 pm Carlos Wagner "Connections to Cosmology-II"
4:50-5:30 pm Alexis Plascencia "B and L as local symmetries: Dark matter, cosmology and physics at the LH

Wednesday, July 8, 2020

9:00-9:40 am Tao Han "A Leptonic Scalar"
9:40-10:20 am Jordy De Vries "Non-standard mechanism for neutrinoless double beta decay in the Standar
Coffee Break

10:30-11:10 am Juan Vasquez Carmona "Long-range contributions to neutrinoless double beta decay in the
11:10-11:50 am David McKeen "Dark baryons near a GeV"
11:50 -12:30 am Goran Senjanovic "Reflections on Baryon and Lepton Number Violation"

outline

(1) review: intro to baryogenesis

- What's the cosmological evidence for B-violation?
- How does B-violation lead to baryogenesis?
- What's the role of SM B-violation?

(2) overview: models of baryogenesis

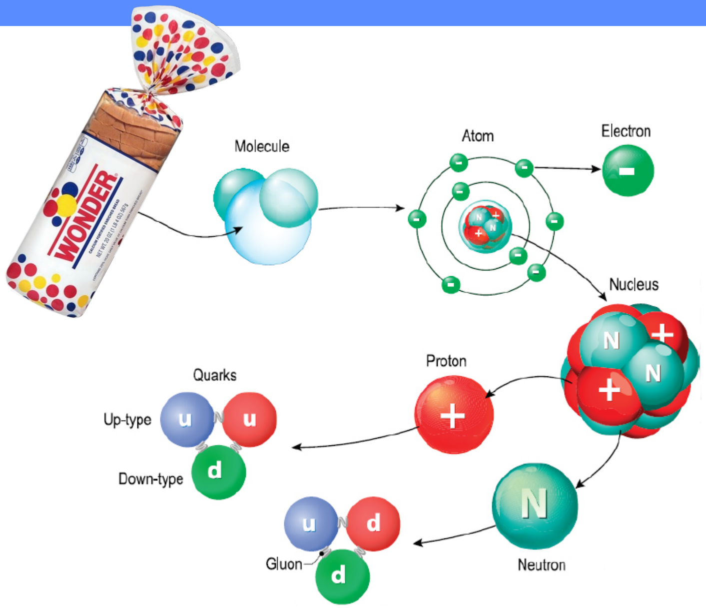
1. high-scale leptogenesis (FY)
2. low-scale leptogenesis (ARS)
3. CPV meson oscillations

(+ Carlos will talk about electroweak baryogenesis)

Cosmological evidence for B-violation

Our world is made up of matter
(rather than antimatter)

matter means baryons:
matter = nuclei + electrons
anti-matter = anti-nuclei + positrons



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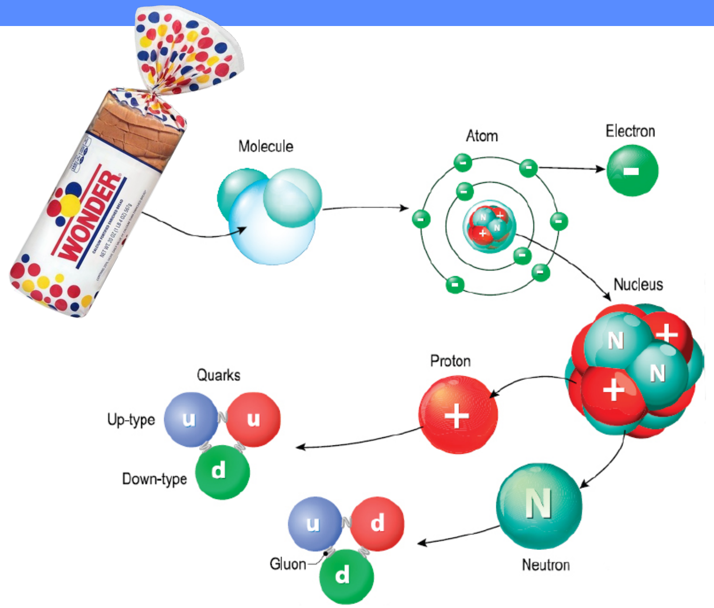

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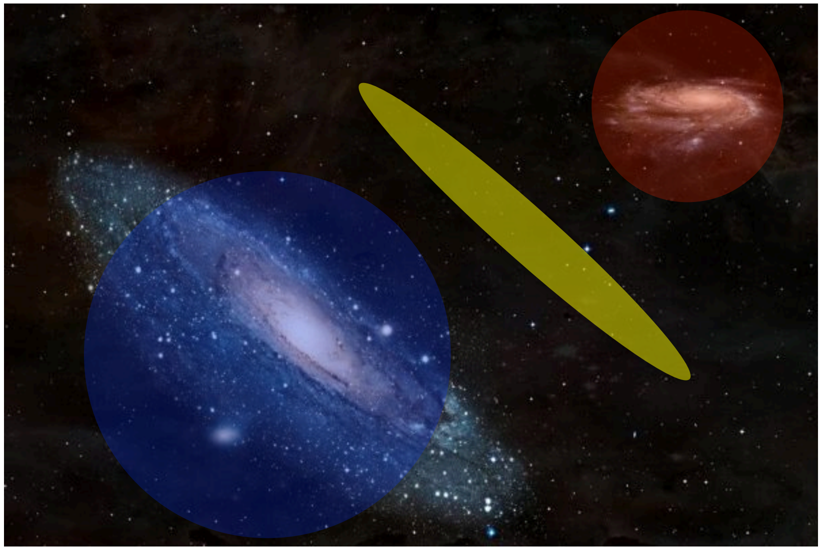


The entire observable universe (40 Gly) is made up of matter.

It's not a patchwork of matter & antimatter domains … e.g., no diffuse γ-rays at the interfaces

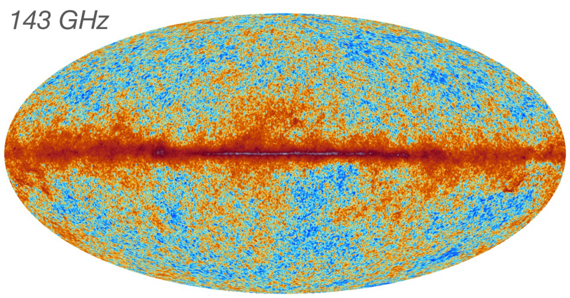
[Steigman (1976)]
[Cohen, De Rujula, & Glashow (1998)]
[Poulin et. al. (2018)]

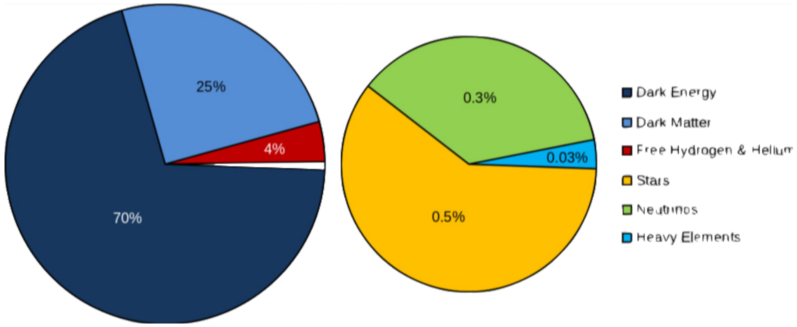
Cosmological evidence for B-violation

[*Planck* (2018)]

Cosmological observations allow us to measure the amount of matter in the visible universe.

sounds waves in the primordial baryon-photon plasma leave their imprint on the CMB anisotropies





$$\Omega_b h^2 \simeq 0.02230 \pm 0.00014$$

$$\Omega_b \simeq 5\% \text{ of energy budget}$$

$$\rho_b \simeq 4 \times 10^{-31}\ \text{g/cm}^3$$

$$n_b \simeq 3 \times 10^{-7}\,\text{cm}^{-3}$$

$$N_b \sim 10^{80}$$

units of baryon number in the observable universe

for cosmologists Ω_b is a free parameter that's fit to the data

for particle physicists this is a challenge!

Cosmological evidence for B-violation

A cosmic wonder

Why is there more matter than antimatter in the observable universe? How did the excess arise?

Baryogenesis

A dynamical event that took place in the early universe (t <~ 1 sec) during which the cosmological excess of matter over antimatter was created.

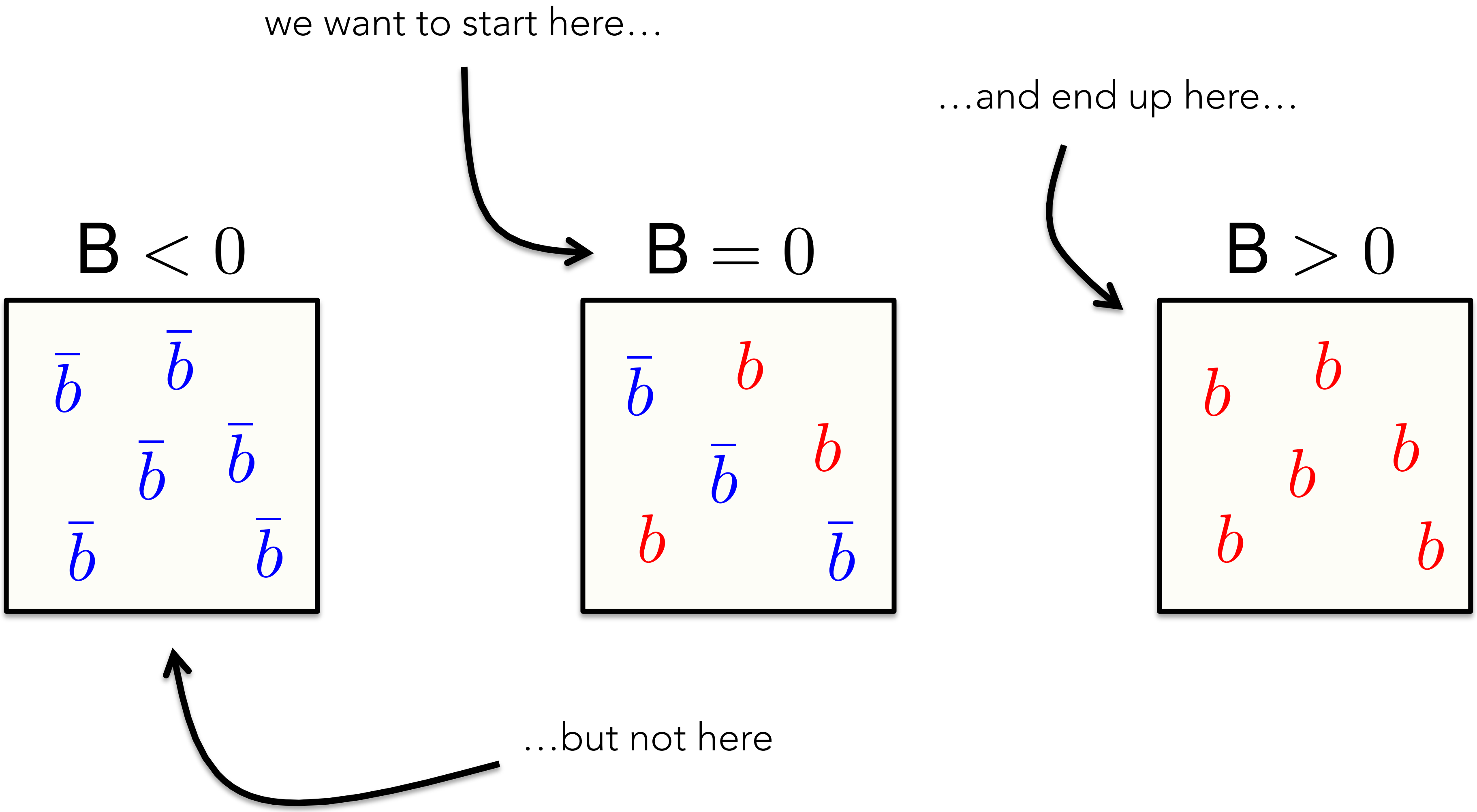
There is a lot that we don't know about baryogenesis!

When did baryogenesis occur?
What's the relevant energy scale?
What particles & interactions were involved?
What other relics may have been produced at the same time?

How does B-violation lead to baryogenesis?

[Sakharov (1967)]
[Yoshimura (1978)]
[Dimopoulos & Susskind (1978)]
[Kolb & Wolfram (1979)]

Three ingredients for successful baryogenesis



we want to start here…

…and end up here…

$B < 0$

$B = 0$

$B > 0$

…but not here

How does B-violation lead to baryogenesis?

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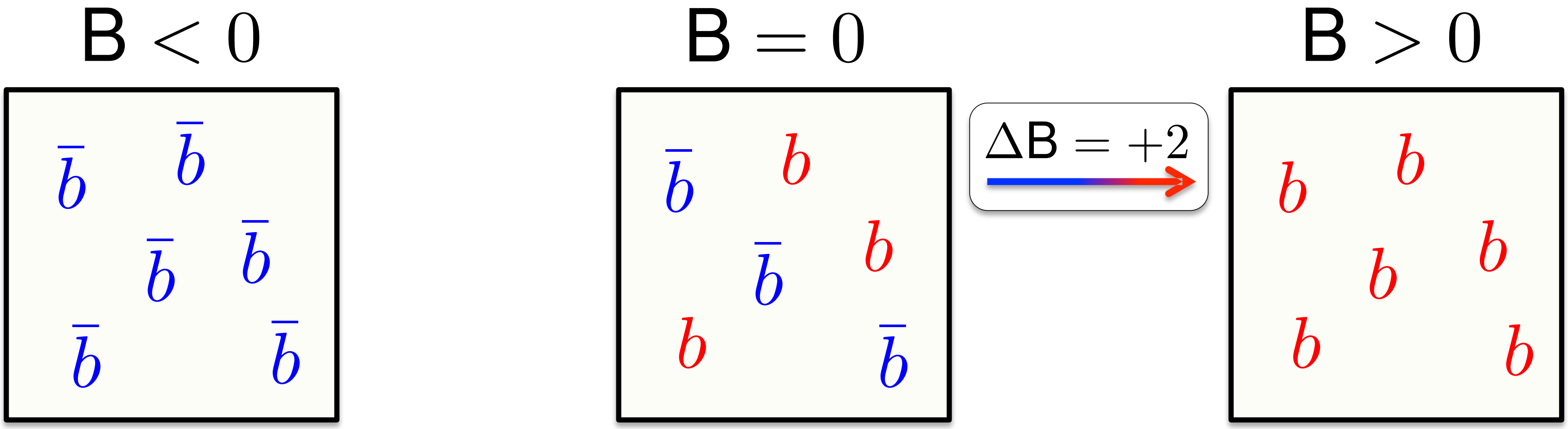
Three ingredients for successful baryogenesis

(1) A process that changes B



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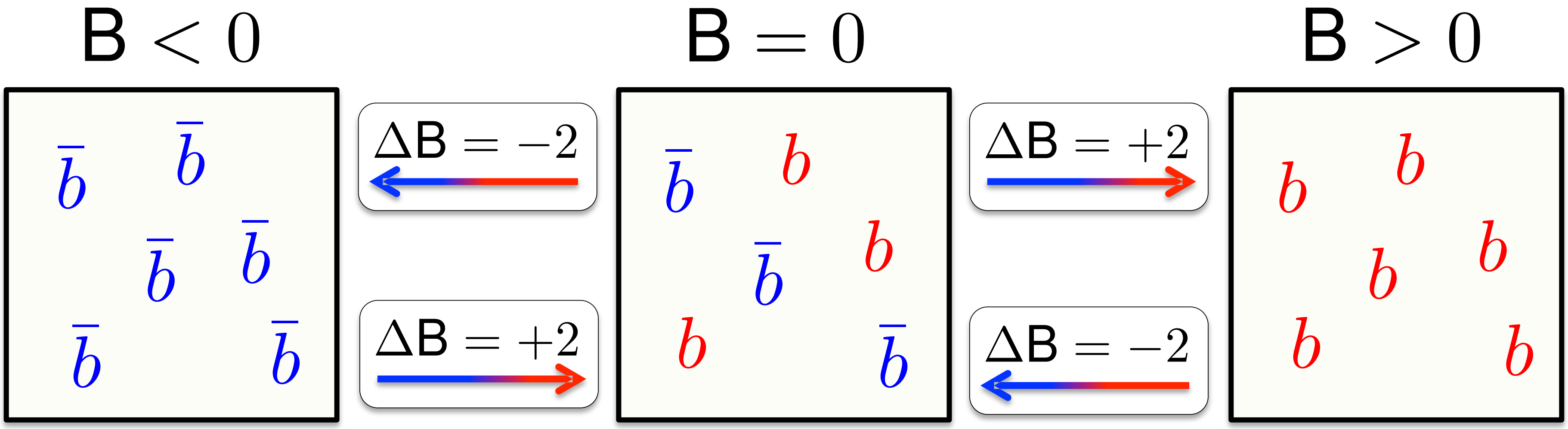

$\mathrm{B} < 0$

$\bar{b}$ $\bar{b}$ $\bar{b}$ $\bar{b}$ $\bar{b}$ $\bar{b}$

$\Delta\mathrm{B} = -2$

$\Delta\mathrm{B} = +2$

$\mathrm{B} = 0$

$\bar{b}$ b $\bar{b}$ b b $\bar{b}$

$\Delta\mathrm{B} = +2$

$\Delta\mathrm{B} = -2$

$\mathrm{B} > 0$

b b b b b b

unitarity requires these other processes as well

How does B-violation lead to baryogenesis?

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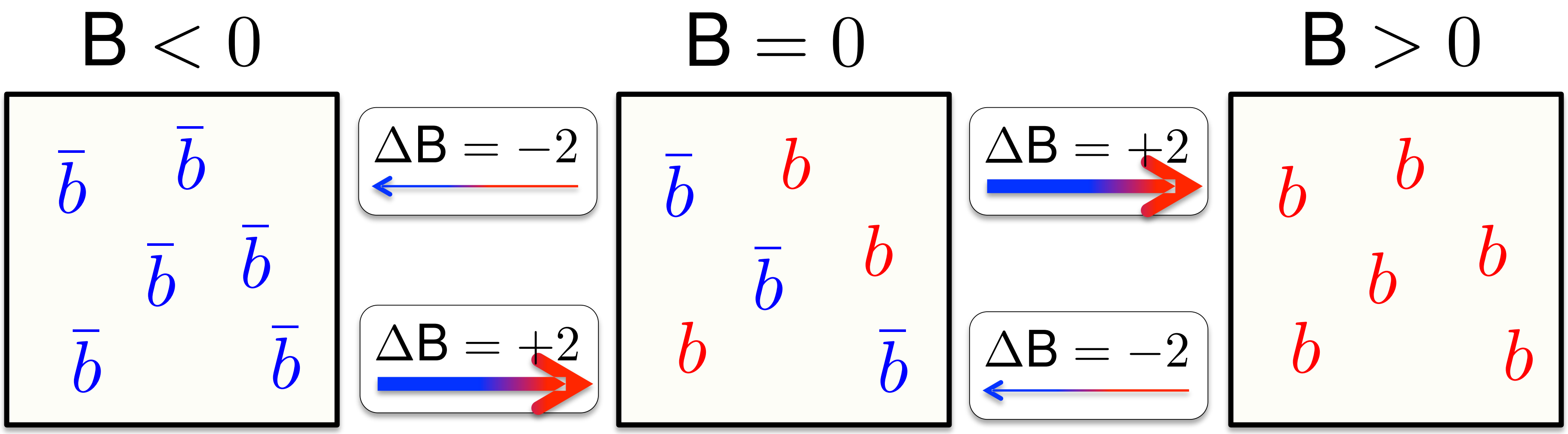
Three ingredients for successful baryogenesis

(1) A process that changes B
(2) A bias (C & CP-violation) favoring ΔB>0



How does B-violation lead to baryogenesis?

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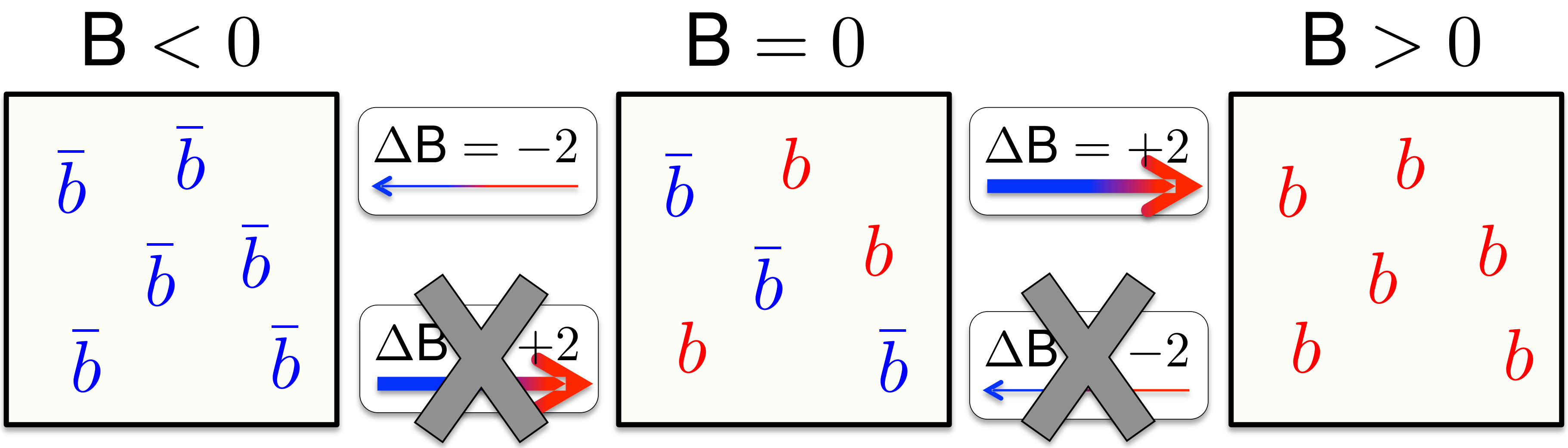
Three ingredients for successful baryogenesis

(1) A process that changes B
(2) A bias (C & CP-violation) favoring ΔB>0
(3) A departure from thermal equilibrium



take away: baryogenesis requires baryon-number violation

How does B-violation lead to baryogenesis?

[Sakharov (1967)]
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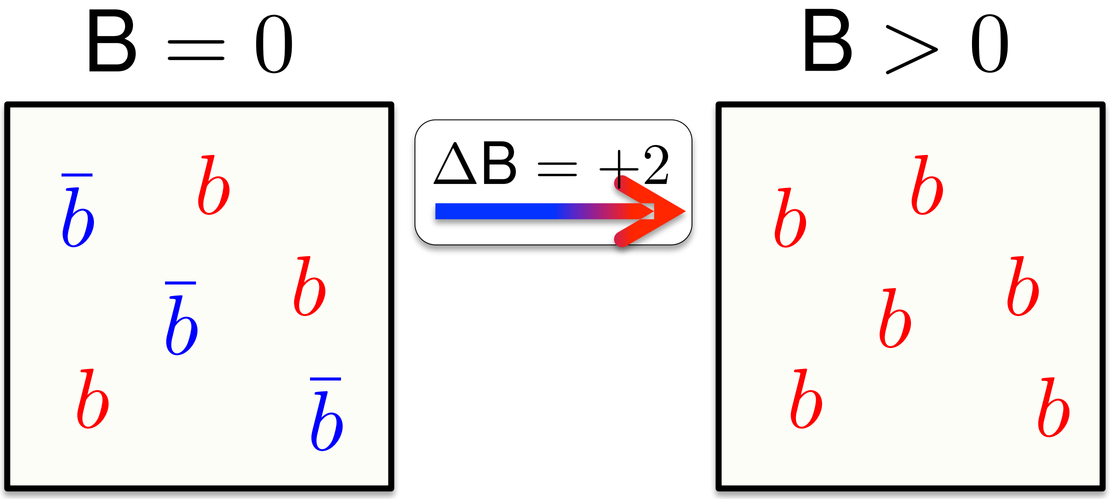
Three ingredients for successful baryogenesis

(1) A process that changes B
(2) A bias (CP-violation) favoring $\Delta B > 0$
(3) A departure from thermal equilibrium



take away: baryogenesis needs baryon-number violation

Where does B-violation come from?

Beyond the Standard Model?

$$\Delta\mathscr{L} = \frac{LHLH}{\Lambda} \quad \left(\Delta\mathsf{B} = 0,\ \Delta\mathsf{L} = 2\right)$$

$$\Delta\mathscr{L} = \frac{QQQL}{\Lambda^2} \quad \left(\Delta\mathsf{B} = 1,\ \Delta\mathsf{L} = 1\right)$$

Within the Standard Model?

$$\partial_\mu j^\mu_{\mathsf{B}} = \partial_\mu j^\mu_{\mathsf{L}} = 3 \times \left(\frac{g^2}{32\pi^2} W^a_{\mu\nu}\widetilde{W}^{a\mu\nu} - \frac{g'^2}{32\pi^2} Y_{\mu\nu}\tilde{Y}^{\mu\nu}\right)$$

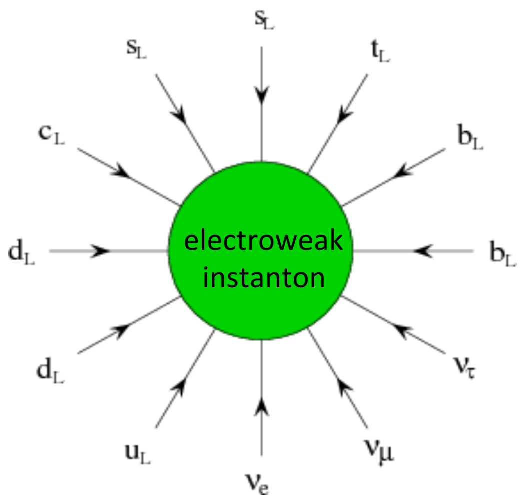
Standard Model baryon-number violation

[‘t Hooft (1976)]

The chiral EW interactions lead to anomalies in B and L

$$\partial_\mu j^\mu_{\mathrm{B}} = \partial_\mu j^\mu_{\mathrm{L}} = 3 \times \left(\underline{\frac{g^2}{32\pi^2} W^a_{\mu\nu}\widetilde{W}^{a\mu\nu}} - \frac{g'^2}{32\pi^2} Y_{\mu\nu}\tilde{Y}^{\mu\nu} \right)$$

Large quantum fluctuations of W_μ^a (aka electroweak instanton) induce reactions among the quarks and leptons that violate baryon number



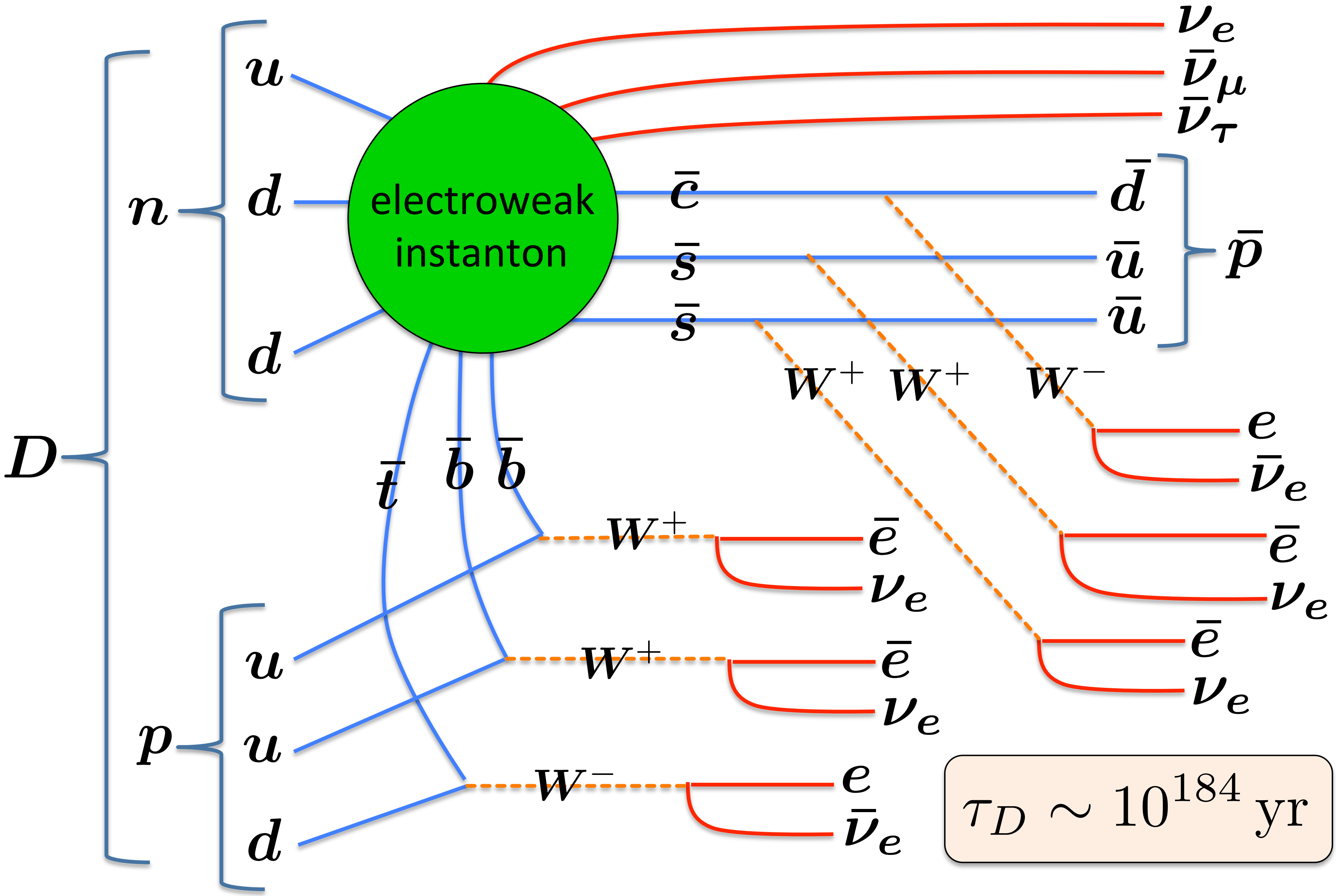
$$\langle W\widetilde{W}\rangle = \text{quantum}$$

$$\Delta\mathrm{B} = \Delta\mathrm{L} = \pm 3$$

The Standard Model predicts
catastrophic nuclear decay!

$$D \to \bar{p} + 4e^{+} + 2e^{-} + 4\nu_e + 3\bar{\nu}_e + \bar{\nu}_\mu + \bar{\nu}_\tau$$

$$\Gamma \sim G_F^{12}\, m_D^{25}\, V_{td}^2\, V_{ub}^4\, V_{cd}^2\, V_{us}^4\, e^{-16\pi^2/g^2}$$



$$\tau_D \sim 10^{184}\ \mathrm{yr}$$

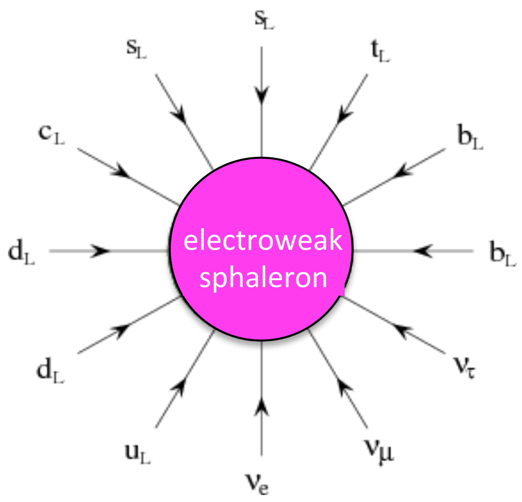
Standard Model baryon-number violation

[Klinkhamer & Manton (1984); Kuzmin, Rubakov, & Shaposhnikov (1985)]

The chiral EW interactions lead to anomalies in B and L

$$\partial_\mu j^\mu_{\mathsf{B}} = \partial_\mu j^\mu_{\mathsf{L}} = 3 \times \left(\underline{\frac{g^2}{32\pi^2} W^a_{\mu\nu} \widetilde{W}^{a\mu\nu}} - \frac{g'^2}{32\pi^2} Y_{\mu\nu} \tilde{Y}^{\mu\nu} \right)$$

At high temperature large thermal fluctuations of $W_\mu{}^a$ (aka electroweak sphaleron) mediate unsuppressed baryon-number violation



$$\langle W\widetilde{W} \rangle = \text{thermal}$$

$$\Delta \mathsf{B} = \Delta \mathsf{L} = \pm 3$$

$$\text{at } \; T > 100 \text{ GeV}$$

$$\Gamma_{\mathsf{B}} \sim \alpha_{\mathrm{W}}^5 T$$

take away message:

SM B-number violation plays an important role in many models of baryogenesis

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(+ Carlos will talk about electroweak baryogenesis)

1. High-Scale Leptogenesis (FY)

High-Scale (FY) Leptogenesis

[Fukugita & Yanagida (1986)]

The Model

SM + heavy Majorana neutrinos N_i

$$\Delta\mathscr{L} = -\frac{1}{2} m_N^{ij} N_i N_j - \lambda_N^{ij} L_i H N_j \qquad \begin{pmatrix} m_{N_1} \sim 10^{10}\ \mathrm{GeV} \\ m_{N_{2,3}} \gg m_{N_1} \\ \lambda_N \sim 0.01 \end{pmatrix}$$

High-Scale (FY) Leptogenesis

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Baryogenesis

① initially N's are thermalized at temp. $T > m_N$

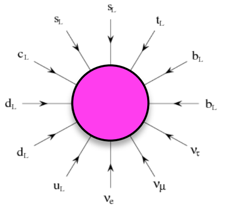
$$N \leftrightarrow LH$$
$$N \leftrightarrow \bar{L}\bar{H}$$

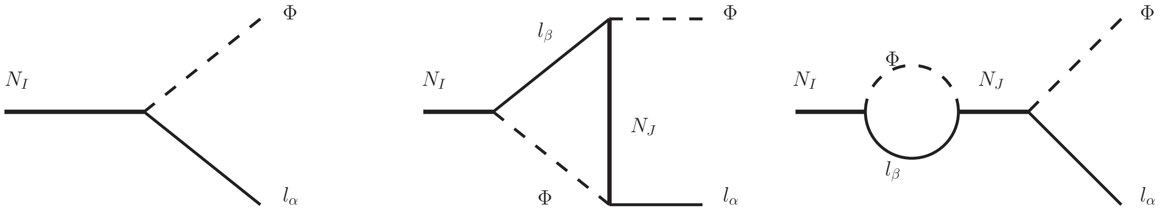
② as plasma cools to $T = m_N$, N's go OOE and decay

③ N decays violate L-number & CP, creating a lepton asymmetry

$$N \rightarrow LH$$
$$N \Rightarrow \bar{L}\bar{H}$$

④ EW sphalerons convert L into B-number



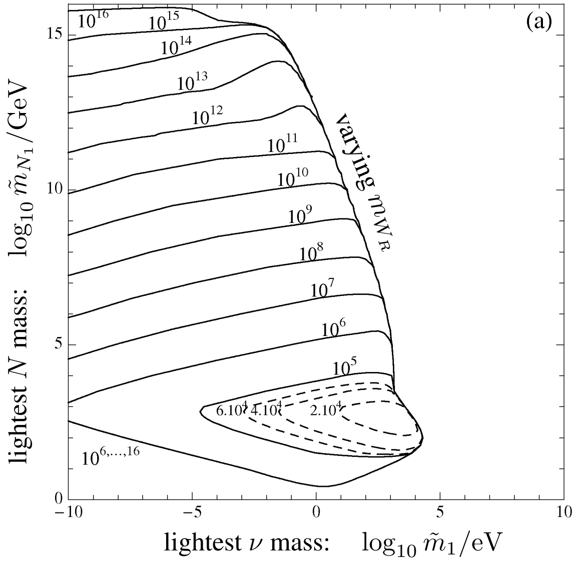


High-Scale (FY) Leptogenesis

Phenomenology

Energy Frontier:

- N's cannot be accessed at colliders
- But if we see evidence of L-number violation at the TeV-scale, this could be used to "falsify" high-scale leptogenesis [caveat: flavor].


[Frere, Hambye, & Vertongen (2008)]

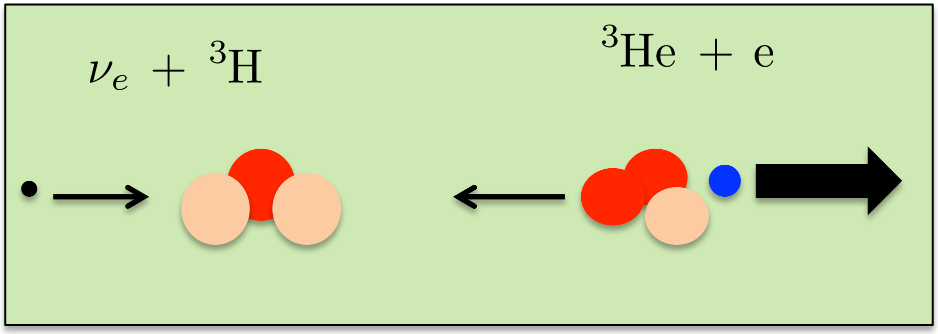
Intensity Frontier:

- low-energy probes of CP-violation (δ_{CP}), have model-dependent connections with leptogenesis at high energies [Moffat, Pascoli, Petcov, & Turner (2018)]
- light ν's are Majorana: 0νββ possible [Schechter & Valle (1982)]
  relic ν capture on ^{3}H [AL, Lunardini, Sabancilar (2014)]

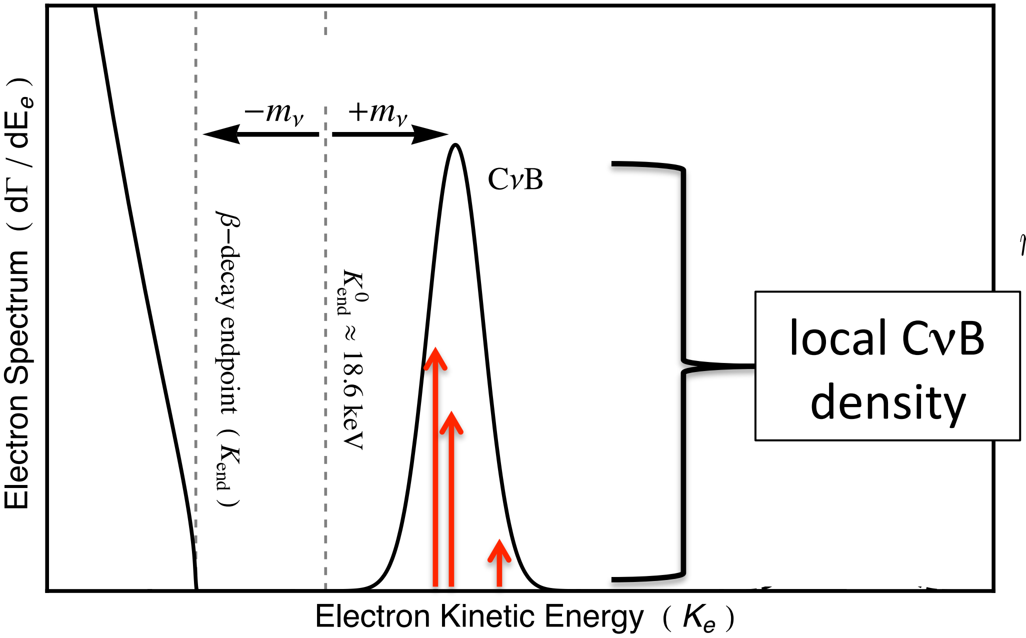
[Weinberg (1962)]
[Irvine & Humphreys (1963)]
[Holschuh (2992)]
[PTOLEMY]

[AL, Lunardini, Sabancilar (2014)]

Neutrino-Capture Beta Decay (NCB)



$$K_{\mathrm{e},\mathrm{C}\nu\mathrm{B}} = M({}^3\mathrm{H}) - M({}^3\mathrm{He}) - M(e) + M(\nu) - E_{\mathrm{recoil}}$$



Dirac Neutrinos

$n_{C\nu B} \simeq 336\ \mathrm{cm}^{-3} = 3$ families ×

	ν	$\bar{\nu}$
$p \cdot S > 0$	$0\ \mathrm{cm}^{-3}$	$56\ \mathrm{cm}^{-3}$
$p \cdot S < 0$	$56\ \mathrm{cm}^{-3}$	$0\ \mathrm{cm}^{-3}$

$\Gamma^{\mathrm{Dir.}}_{C\nu B} \simeq 4\,\mathrm{yr}^{-1}$

detectable

Majorana Neutrinos

$n_{C\nu B} \simeq 336\ \mathrm{cm}^{-3} = 3$ families ×

	ν
$p \cdot S > 0$	$56\ \mathrm{cm}^{-3}$
$p \cdot S < 0$	$56\ \mathrm{cm}^{-3}$

$\Gamma^{\mathrm{Maj.}}_{C\nu B} \simeq 8\,\mathrm{yr}^{-1}$

rates for 100g tritum target

Dirac Neutrinos

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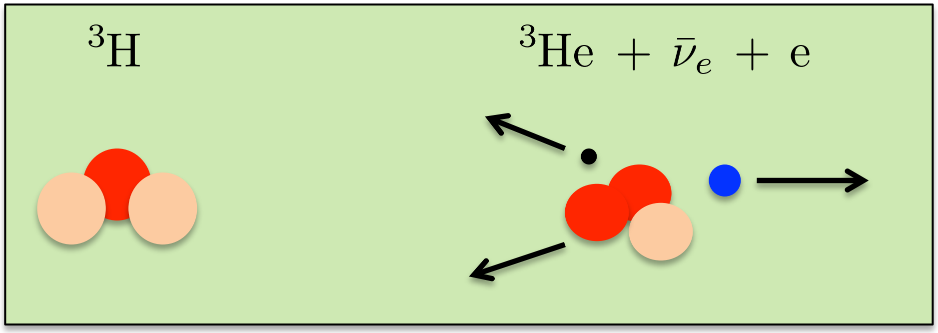
$$\Gamma^{\mathrm{Maj.}}_{\mathrm{C}\nu\mathrm{B}} \simeq 8\,\mathrm{yr}^{-1}$$

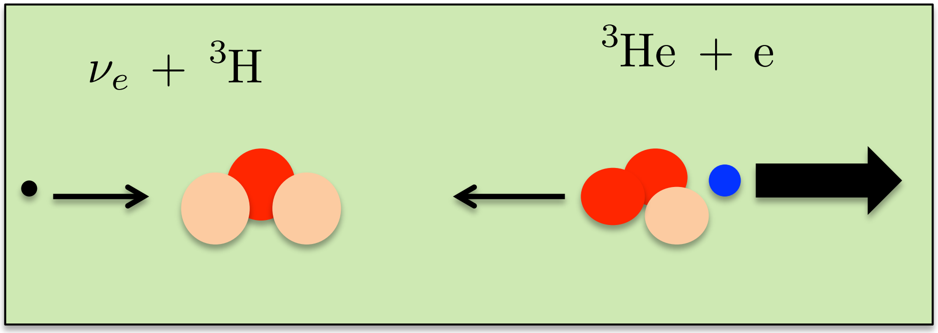
ν-Capture on tritium ^{3}H

Beta Decay

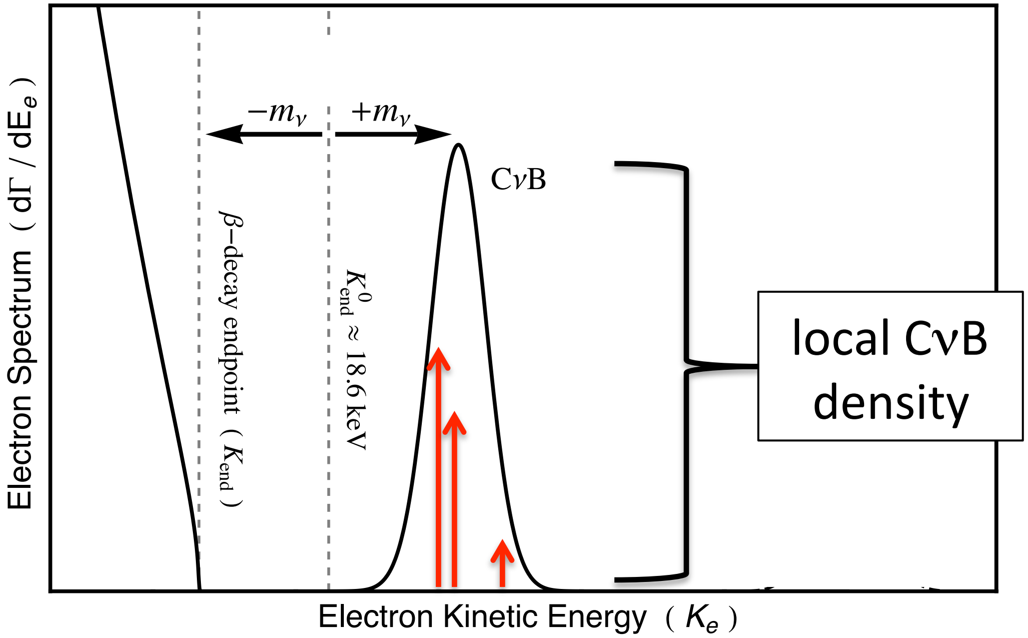


$$K_{e,\max} = M(^3\mathrm{H}) - M(^3\mathrm{He}) - M(e) - M(\nu) - E_{\mathrm{recoil}}$$

Neutrino-Capture Beta Decay (NCB)



$$K_{e,C\nu B} = M(^3\mathrm{H}) - M(^3\mathrm{He}) - M(e) + M(\nu) - E_{\mathrm{recoil}}$$



Weinberg (1962)
Irvine & Humphreys (1983)
Holzschuh (1992)

High-Scale (FY) Leptogenesis

The Model

SM + heavy Majorana neutrinos N_i

$$\Delta\mathscr{L} = -\frac{1}{2} m_N^{ij} N_i N_j - \lambda_N^{ij} L_i H N_j \qquad \begin{pmatrix} m_{N_1} \sim 10^{10}\ \mathrm{GeV} \\ m_{N_{2,3}} \gg m_{N_1} \\ \lambda_N \sim 0.01 \end{pmatrix}$$

Summary

PRO

embed N into a GUT
light ν masses (seesaw)
light ν's are Majorana
favors high-scale inflation
"minimal" / "simple"

CON

hard to reheat so high
high-scale new physics
hard to test

2. Low-Scale Leptogenesis (ARS)

Low-Scale (ARS) Leptogenesis

[Akhmedov, Rubakov, & Smirnov (1998)]
review: (Drewes et. al. [1711.02862])

The Model

SM + 2 (or 3) GeV-scale Majorana neutrinos N_i

$$\Delta\mathscr{L} = -\frac{1}{2}m_N^{ij}N_iN_j - \lambda_N^{ij}L_iHN_j \quad \begin{pmatrix} m_{N_1} \sim 1\ \mathrm{GeV} \\ \Delta m_{12}/m_{N_1} \sim 10^{-3} \\ \lambda_N \sim 10^{-7} \end{pmatrix}$$

Low-Scale (ARS) Leptogenesis

[Akhmedov, Rubakov, & Smirnov (1998)]
review: (Drewes et. al. [1711.02862])

The Model

SM + 2 (or 3) GeV-scale Majorana neutrinos N_i

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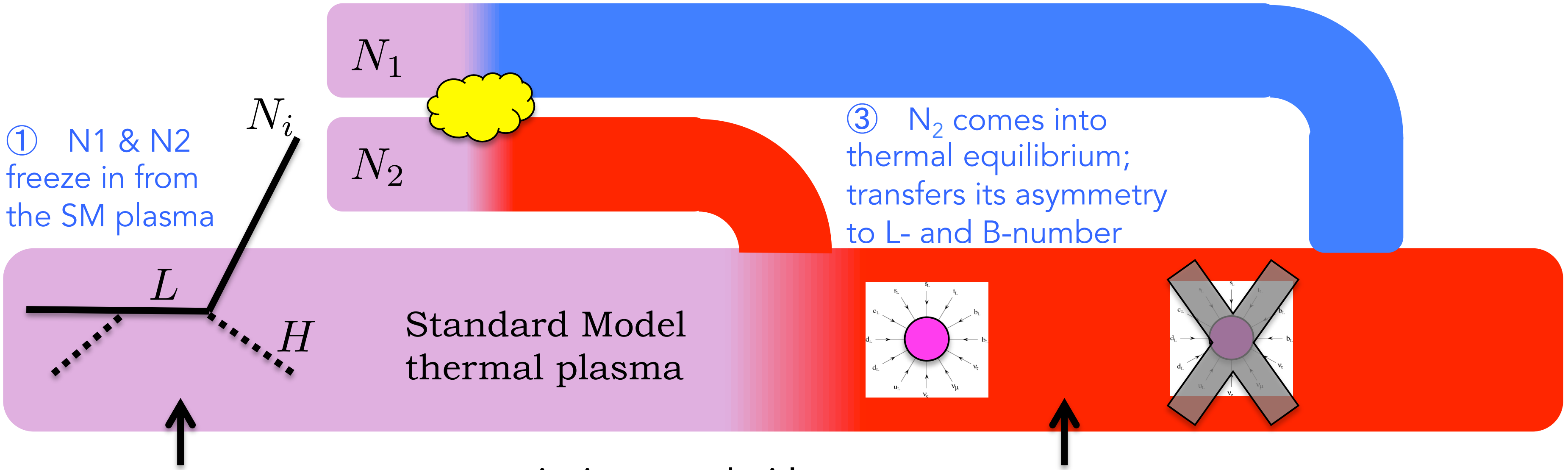
Baryogenesis



① N1 & N2 freeze in from the SM plasma

② CPV oscillations create equal & opposite asymmetries in N_1 and N_2

③ N_2 comes into thermal equilibrium; transfers its asymmetry to L- and B-number

④ EW sphalerons go out of equilibrium before N_1 thermalizes

Standard Model thermal plasma

$T \sim 100$ TeV

time increases to the right

$T \sim 100$ GeV

Low-Scale (ARS) Leptogenesis

[Drewes, Garbrecht, Gueter, & Klaric (2017)]

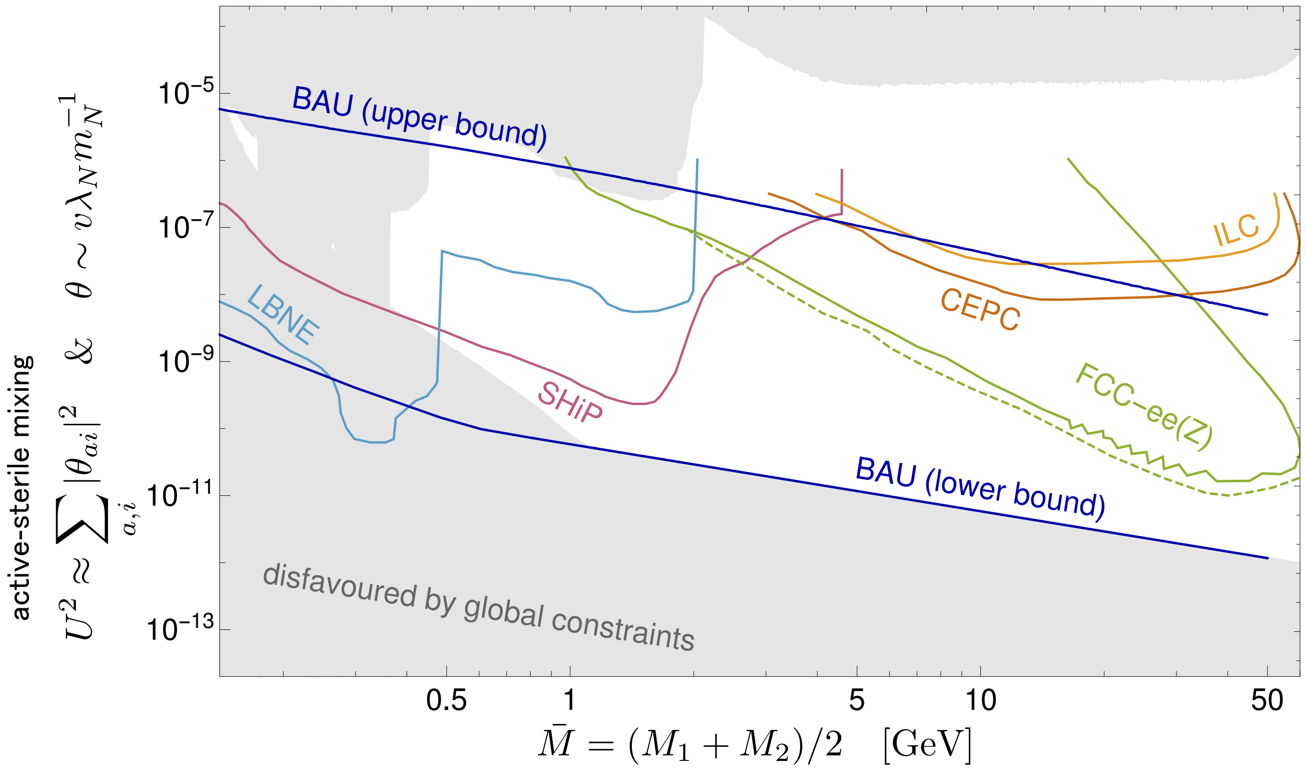
Phenomenology

Intensity Frontier:

Light ν's are Majorana: 0νββ, etc

Energy Frontier:

Long-lived particle searches @ collider or beam dump …



beam + target
→ mesons
→ rare decay to N
→ N decays to visible

E.g.,
N → νe^+e^-
N → $\nu\pi^0$
N → $e^-\pi^+$

Low-Scale (ARS) Leptogenesis

[Drewes, Garbrecht, Gueter, & Klaric (2017)]
[many thanks to Marco Drewes for making the plot]

Phenomenology

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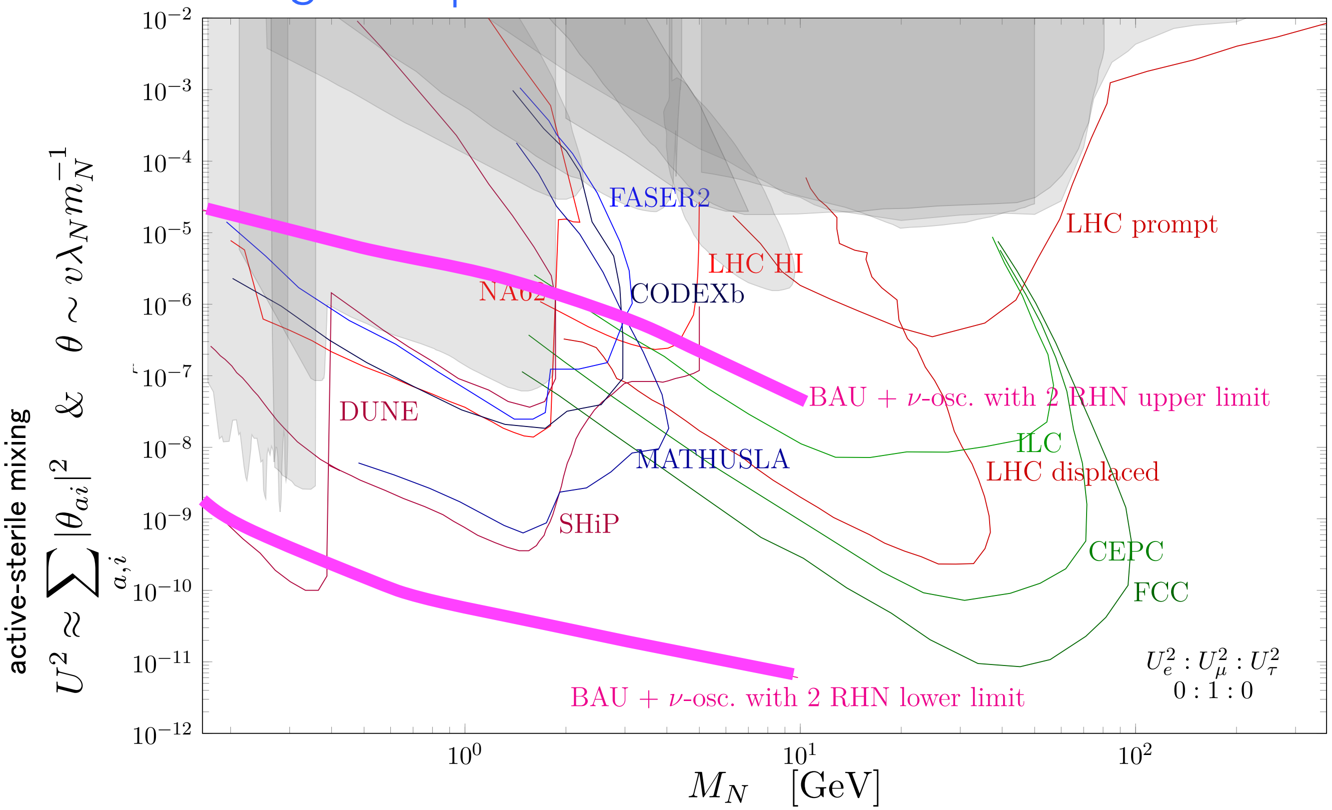
Energy Frontier:

Long-lived particle searches @ collider or beam dump …



E.g.,
beam + target
→ mesons
→ rare decay to N
→ N decays to visible
(e.g, $\nu e^+ e^-$, $\nu\pi^0$, $e^-\pi^+$)

Low-Scale (ARS) Leptogenesis

The Model

SM + 2 (or 3) GeV-scale Majorana neutrinos N_i

$$\Delta\mathscr{L} = -\frac{1}{2} m_N^{ij} N_i N_j - \lambda_N^{ij} L_i H N_j \quad \begin{pmatrix} m_{N_1} \sim 1\ \mathrm{GeV} \\ \Delta m_{12}/m_{N_1} \sim 10^{-3} \\ \lambda_N \sim 10^{-7} \end{pmatrix}$$

Summary

PRO

very testable

light ν masses (seesaw)

light ν's are Majorana

predicts 0νββ

new physics is GeV-scale

allows keV-sterile DM

CON

lose GUT motivation for N

hard to measure Δm (2HNL)

3. CP-Violating Meson Oscillations

CP-violating meson oscillations

[Elor, Escudero, & Nelson (2018)], [Nelson & Xiao (2019)] & [Alonso-Alvarez, Elor, Nelson, & Xiao (2019)]
see also: [McKeen & Nelson (2015)]
see also: [Ghalsasi, McKeen, & Nelson (2015)]
see also: [Aitken, McKeen, Nelson, & Neder (2017)]

The Model

SM + TeV-scale inflaton/moduli + GeV-scale B-number-charged dark sector

$$\Delta\mathscr{L} = -\lambda_\Phi \Phi \bar{b} b - y_{ub}\, Y^* \bar{u} b^c - y_{\psi s}\, Y \bar{\psi} s^c - \lambda\, \bar{\psi}\phi\xi \qquad \begin{pmatrix} m_\Phi \sim 50\ \mathrm{GeV} \\ m_Y \sim \mathrm{TeV} \\ m_\psi \sim 4\ \mathrm{GeV} \\ m_\phi \sim 1.2\ \mathrm{GeV} \\ m_\xi \sim 0.3\ \mathrm{GeV} \\ \mathrm{BR}_{B^0 \to \mathcal{B}+X} \sim 10^{-3} \end{pmatrix}$$

Field	Spin	Q_{EM}	Baryon no.	$\mathbb{Z}_2$	Mass
Φ	0	0	0	$+1$	$11 - 100\,\mathrm{GeV}$
Y	0	$-1/3$	$-2/3$	$+1$	$\mathcal{O}(\mathrm{TeV})$
ψ	$1/2$	0	-1	$+1$	$\mathcal{O}(\mathrm{GeV})$
ξ	$1/2$	0	0	-1	$\mathcal{O}(\mathrm{GeV})$
ϕ	0	0	-1	-1	$\mathcal{O}(\mathrm{GeV})$

CP-violating meson oscillations

[Elor, Escudero, & Nelson (2018)], [Nelson & Xiao (2019)] & [Alonso-Alvarez, Elor, Nelson, & Xiao (2019)]

The Model

SM + TeV-scale inflaton/moduli + GeV-scale B-number-charged dark sector

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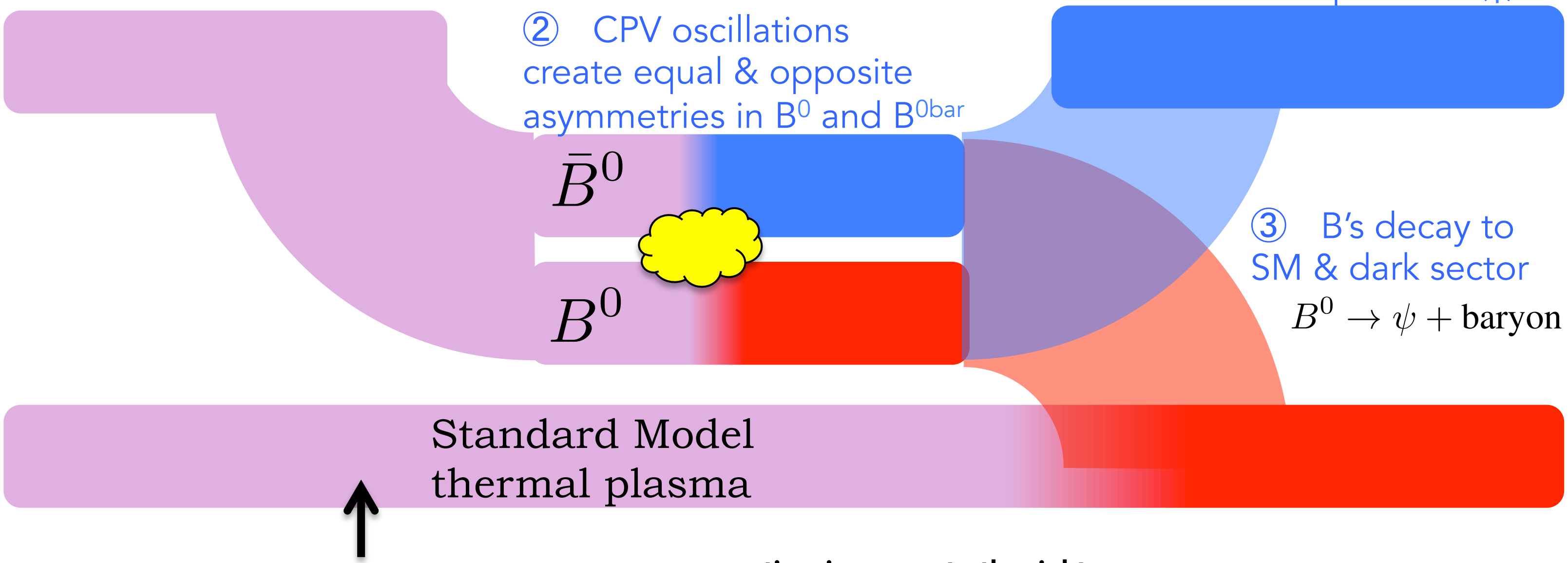
Baryogenesis



① inflaton or moduli field decays to q & q^{bar} → B mesons

② CPV oscillations create equal & opposite asymmetries in B^0 and B^{0bar}

$\bar{B}^0$

B^0

④ asymmetry stored in dark sector particles (ϕ)

③ B's decay to SM & dark sector

$B^0 \to \psi + \text{baryon} + X$

Standard Model thermal plasma

$T \sim 100$ MeV

time increases to the right

CP-violating meson oscillations

[Elor, Escudero, & Nelson (2018)], [Nelson & Xiao (2019)] & [Alonso-Alvarez, Elor, Nelson, & Xiao (2019)]

Phenomenology

Energy Frontier:

- LHC search for colored scalar mediator (Y)

  QCD → YY → 4-jet (ubub) or 2-jet (sψsψ) + MET; allows m_Y >~ TeV

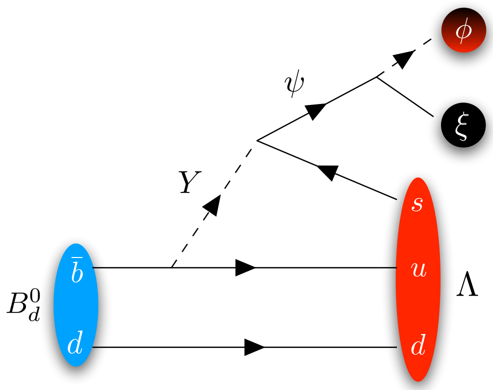
- exotic B-meson decay [LHCb, Belle-II]

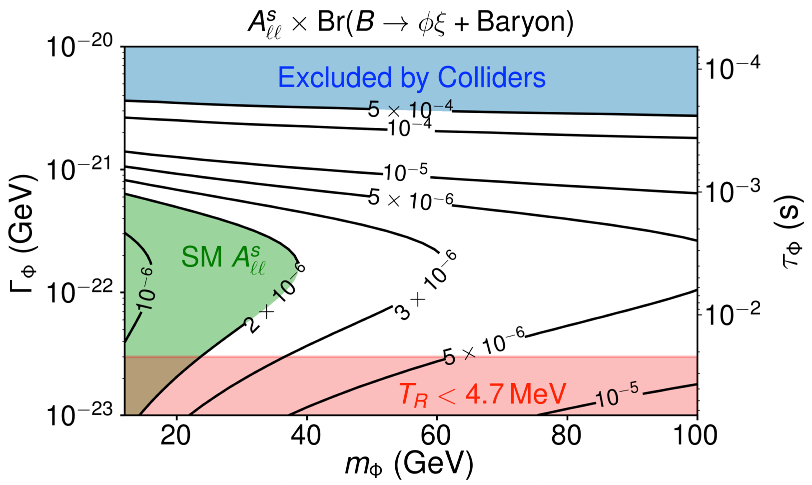
  B^0 & B^{+-} → baryon + mesons + missing energy

  (the same goes for for b-flavored baryons, e.g. Λ^0 -> K^+ + π^- + MET)

- use B-meson oscillations to search for CP-violation [LHCb, Belle-II]

  semileptonic charge asymmetry (e.g., B^0 -> D^- μ^+ ν_μ X)





(inflaton / moduli field)

$$a_{\rm sl}^q \equiv \frac{\Gamma(\bar{B}_q^0 \to f) - \Gamma(B_q^0 \to \bar{f})}{\Gamma(\bar{B}_q^0 \to f) + \Gamma(B_q^0 \to \bar{f})}$$

$$\begin{aligned} a_{\rm sl}^{s,\rm SM} &= (2.22 \pm 0.27) \times 10^{-5} \\ a_{\rm sl}^{s,\rm exp} &= (-60 \pm 280) \times 10^{-5} \\ a_{\rm sl}^{s,\rm need} &\sim (1 - 100) \times 10^{-5} \end{aligned}$$

$$\begin{aligned} a_{\rm sl}^{d,\rm SM} &= (47 \pm 6.0) \times 10^{-5} \\ a_{\rm sl}^{d,\rm exp} &= (-210 \pm 170) \times 10^{-5} \\ a_{\rm sl}^{d,\rm need} &\sim (1 - 100) \times 10^{-5} \end{aligned}$$

CP-violating meson oscillations

[Elor, Escudero, & Nelson (2018)], [Nelson & Xiao (2019)] & [Alonso-Alvarez, Elor, Nelson, & Xiao (2019)]

Phenomenology

Intensity Frontier:

- Proton decay (& invisible n decay) forbidden by kinematics.
- n-nbar oscillations forbidden by B-conservation.
- $0\nu\beta\beta$ forbidden by L-conservation.

Cosmic Frontier:

- inflation:
  low-scale inflation presents a model building challenge

- dark matter direct detection:
  DM-nucleon scattering via ψ & b-quark [suppressed]

CP-violating meson oscillations

[Elor, Escudero, & Nelson (2018)], [Nelson & Xiao (2019)] & [Alonso-Alvarez, Elor, Nelson, & Xiao (2019)]

The Model

SM + TeV-scale inflaton/moduli + GeV-scale B-number-charged dark sector

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$$\begin{pmatrix} m_\Phi \sim 50\ \text{GeV} \\ m_Y \sim\ \text{TeV} \\ m_\psi \sim 4\ \text{GeV} \\ m_\phi \sim 1.2\ \text{GeV} \\ m_\xi \sim 0.3\ \text{GeV} \\ \text{BR}_{B^0 \to \mathcal{B}+X} \sim 10^{-3} \end{pmatrix}$$

Summary

PRO

very testable

CPV is testable (a_{sl})

probed by LHC, Belle-II, etc

solves both DM & BAU

CON

“baroque”

requires low-T reheating

overproduce symmetric DM

Summary

Summary

Cosmological baryon-number violation

- My motivation for studying BLV: the Universe is made of baryons, and explaining this requires B-number violation.

- Compare / contrast with other cosmological relics:

	Step #1 did we detect it?	Step #2 understand production?
primordial photons:	**YES!** (it's the CMB)	**YES!** (recombination)
primordial neutrinos:	**YES!** (via the CMB)	**YES!** (ν decoupling via weak int)
primordial grav. waves:	**NO!**	**NO!**
dark matter:	**NO!**	**NO!**
baryon asymmetry:	**YES!** (we are the B-asym)	**NO!**

The baryon asymmetry is the only cosmological relic that we've discovered, but still don't understand how it was produced in the early universe.

Summary

Models of baryogenesis

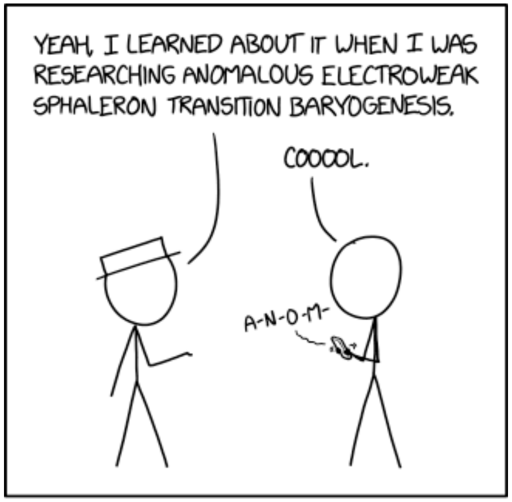
- in general: building a *compelling* model is “easy”
  … building a *testable* model is “hard”
  … building a *compelling & testable* model is “very hard”

When a good model comes along, it is worth exploring closely.

① High-Scale (FY) Leptogenesis
probes of Majorana nu: $0\nu\beta\beta$, ^{3}H capture
falsify high-scale LG with colliders

② Low-Scale (ARS) Leptogenesis
brings HNL within reach of colliders;
LLP search @ beam dump, LHC, future collider

③ CPV B-meson Oscillations
rare B-meson decay; semileptonic charge asym;
asymmetric DM



MY HOBBY: COLLECTING REALLY SATISFYING-SOUNDING FIVE-WORD TECHNICAL PHRASES.