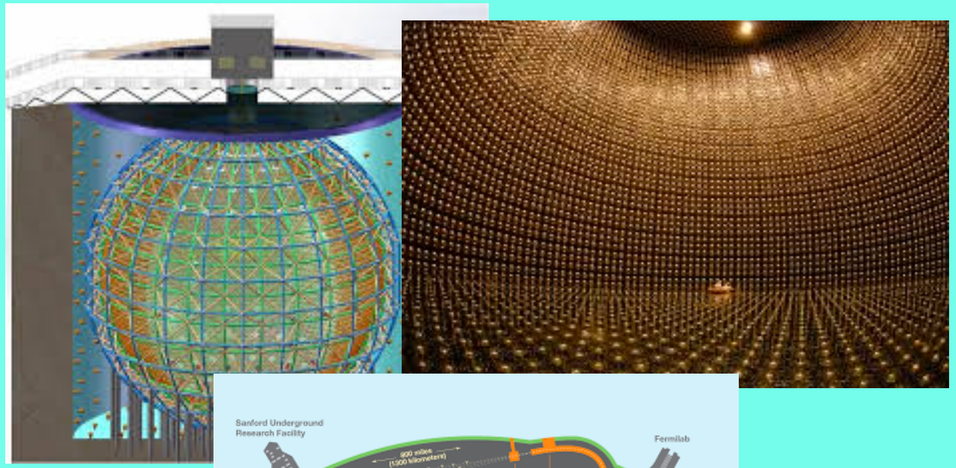
Confronting GUTs with Proton Decay and Gravitational Waves

Jessica Turner

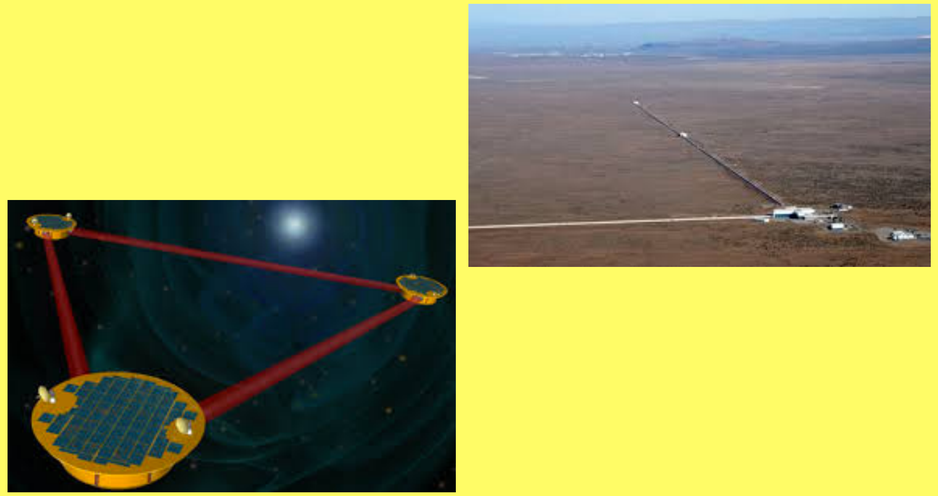
Institute of Particle Physics Phenomenology, Durham University

New observational windows om the high-scale origin of the matter-antimatter asymmetry, Kavli IPMU, 11th Jan 2022

Part I



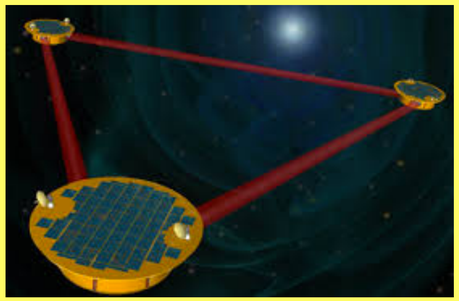
Proton Decay



Gravitational Waves

What is the nature of particles and forces at the GUT scale?

Part II



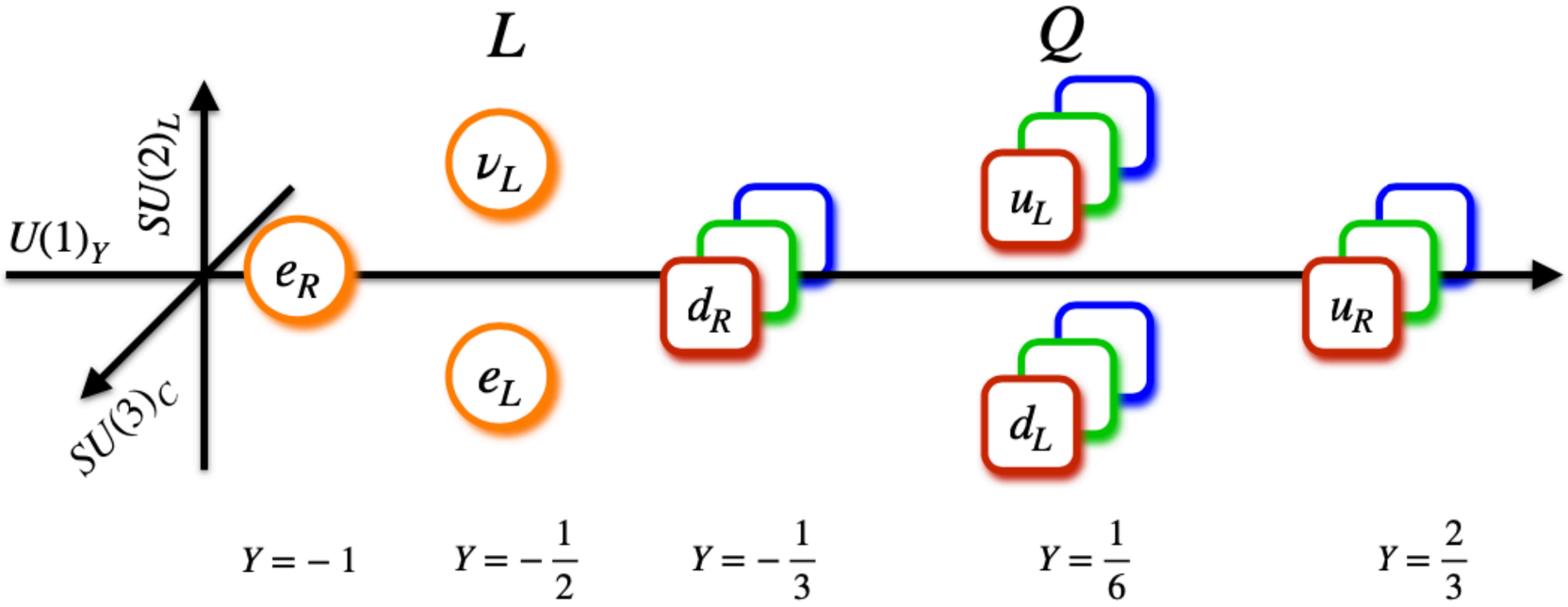
Gravitational Waves

What created the matter antimatter asymmetry?

Part I begins

The role of GUTs

- GUT unifies SM gauge interactions into a **single gauge group**
- SM fermionic multiplets into 1or 2 representations of the GUT representation
  $\Longrightarrow$ **reduces number of SM parameters**
- Many GUTs predict non-zero **neutrino masses**, dark matter candidate etc



GUT prediction I

- GUTs unify leptons and quarks into common multiplets.
- GUTs spontaneously broken to SM gauge group, heavy gauge boson integrated out $\Longrightarrow$ proton decay

Weinberg, 1979

$$\frac{\epsilon_{\alpha\beta}}{\Lambda_1^2}\left[(\overline{u_R^c}\gamma^\mu Q_\alpha)(\overline{d_R^c}\gamma_\mu L_\beta)+(\overline{u_R^c}\gamma^\mu Q_\alpha)(\overline{e_R^c}\gamma_\mu Q_\beta)\right]+\frac{\epsilon_{\alpha\beta}}{\Lambda_2^2}\left[(\overline{d_R^c}\gamma^\mu Q_\alpha)(\overline{u_R^c}\gamma_\mu L_\beta)+(\overline{d_R^c}\gamma^\mu Q_\alpha)(\overline{\nu_R^c}\gamma_\mu Q_\beta)\right],$$

$\mathrm{SU}(3)_C \times \mathrm{SU}(2)_L \times \mathrm{U}(1)_Y$ invariant but BNV

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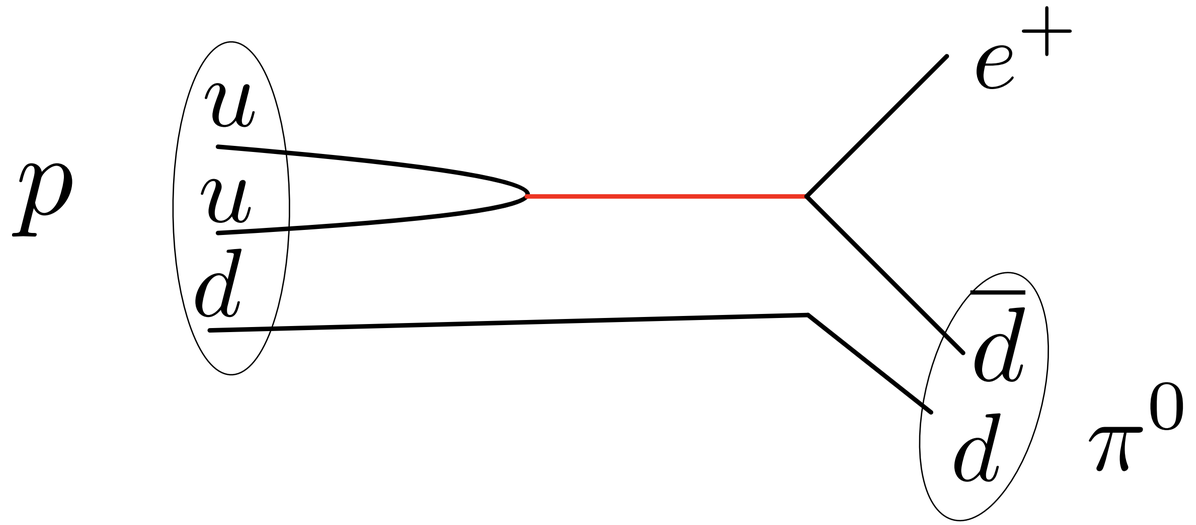
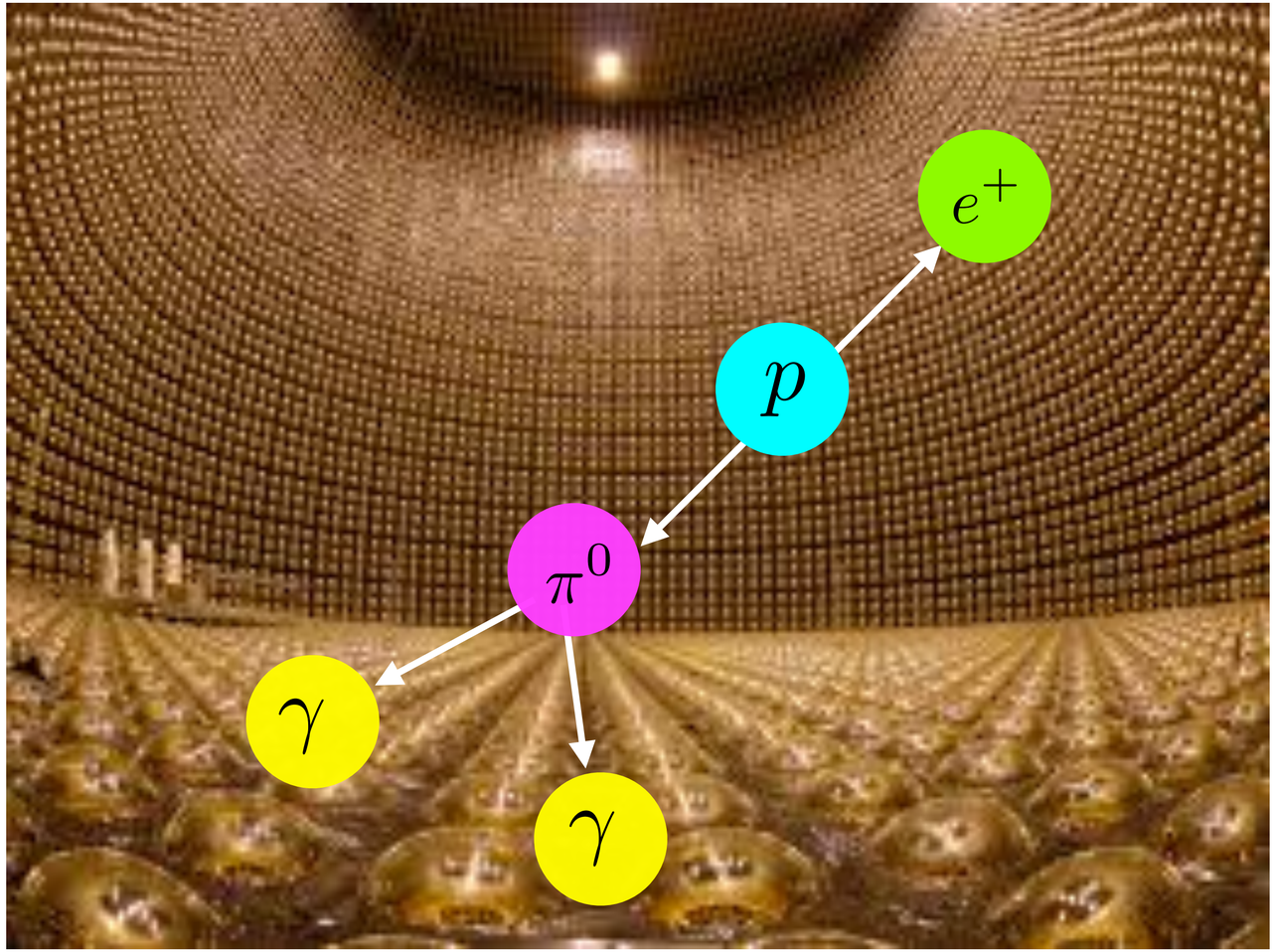


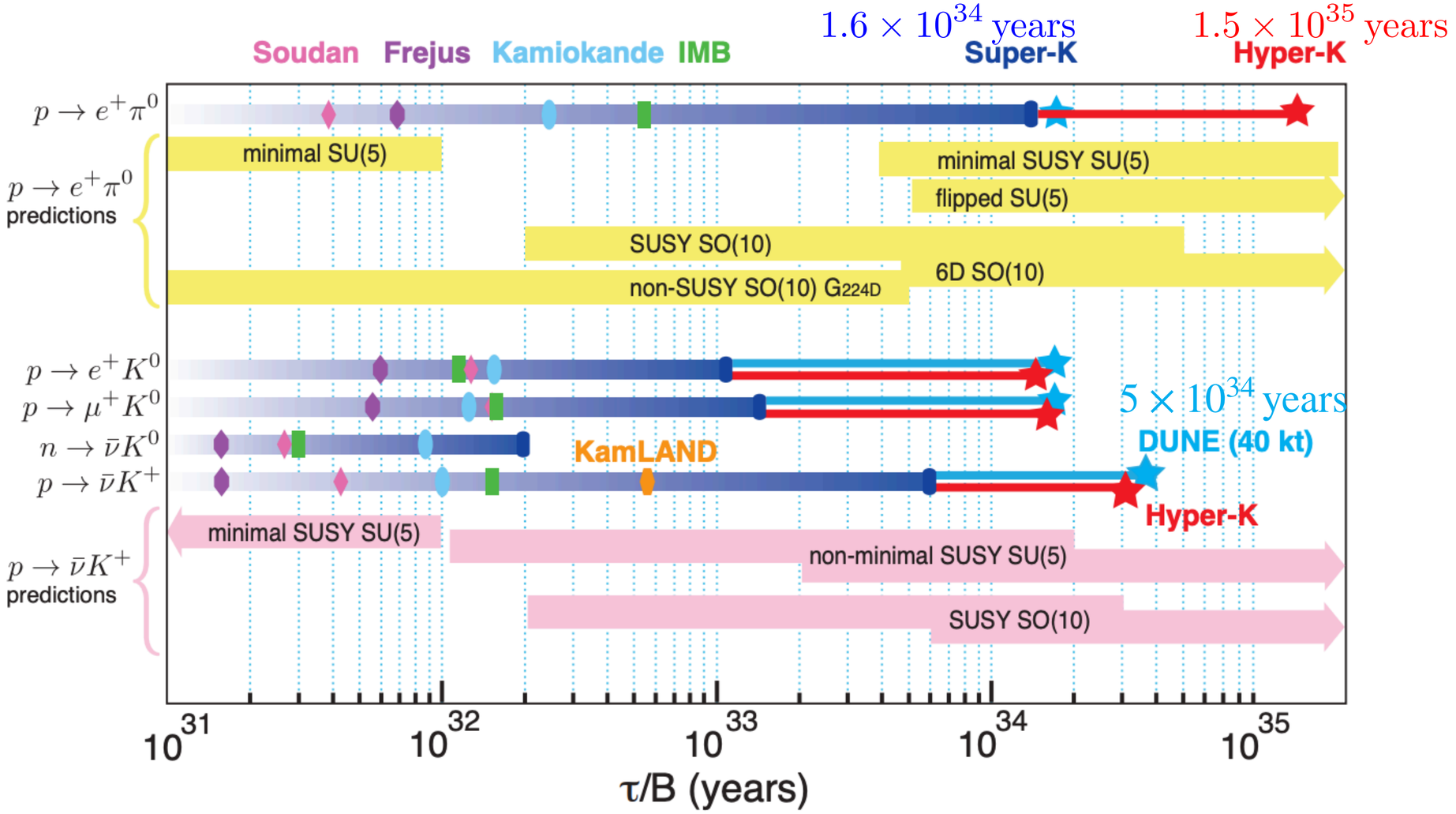
Limits (or even finding!) proton decay

Neutrino experiments are large vats of proton sitting around for a long time.

$$\tau_{\pi^0 e^+} > 1.6 \times 10^{34}\,\text{years}$$ **SK (1610.03597)**



Nucleon decay limits



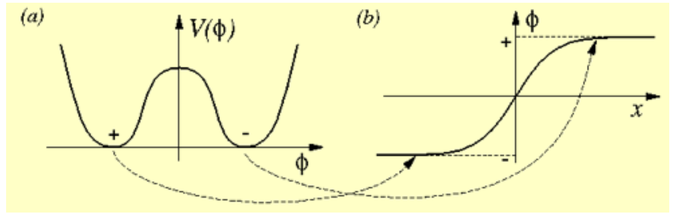
Water Cherenkov sensitive to $p \to e^+\pi^0$ LArTPC more sensitive to $p \to K^+\nu$

GUT prediction II

During SSB from $G_{GUT} \rightarrow \cdots \rightarrow G_{SM}$ topological defects may form.

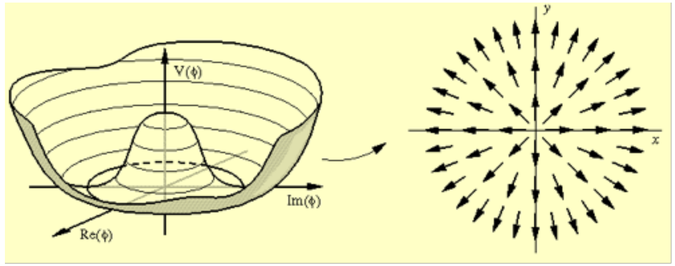
cambridge cosmic structures

Domain wall



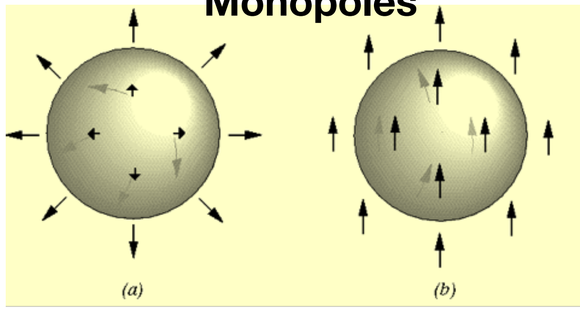
$\pi_0(\mathrm{G/H}) \neq 0$

Cosmic strings



$\pi_1(\mathrm{G/H}) \neq 0$

Monopoles



$\pi_2(\mathrm{G/H}) \neq 0$

GUT prediction II

During SSB from $G_{GUT} \rightarrow \cdots \rightarrow G_{SM}$ topological defects may form.

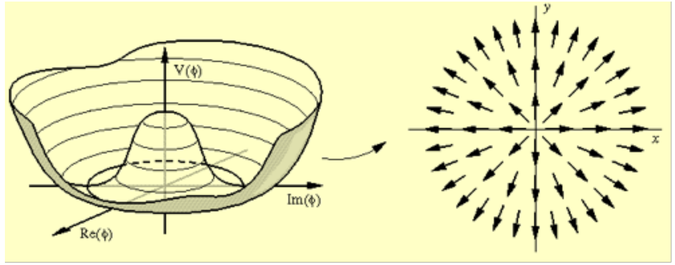
cambridge
cosmic structures

Domain wa

Inflation to dilute

$\pi_0(\mathrm{G/H}) \neq 0$

Cosmic strings



$\pi_1(\mathrm{G/H}) \neq 0$

nopoles

Inflation to dilute

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GUT prediction II

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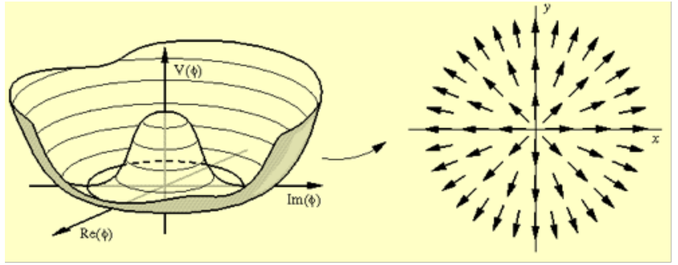


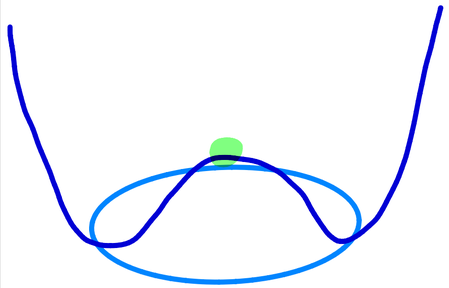
$\pi_1(\mathrm{G/H}) \neq 0$

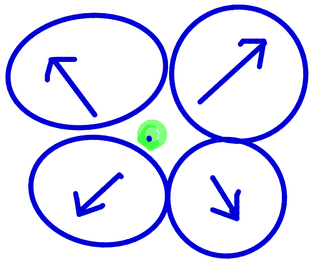
nopoles

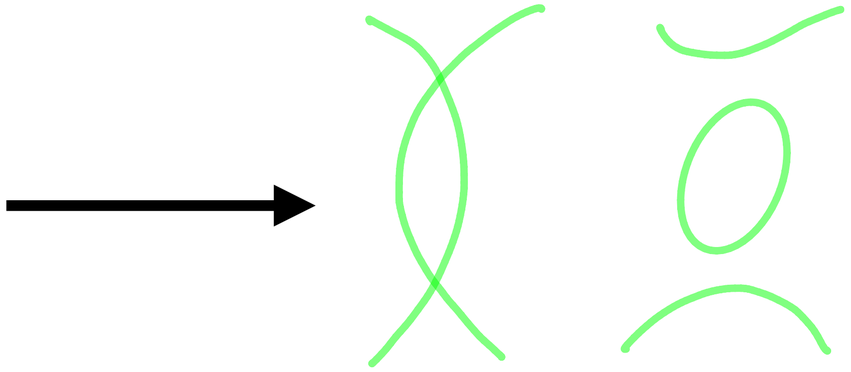
Inflation to dilute

$\pi_2(\mathrm{G/H}) \neq 0$

Cosmic strings induced via U(1) breaking are ubiquitously as GUT breaks to SM







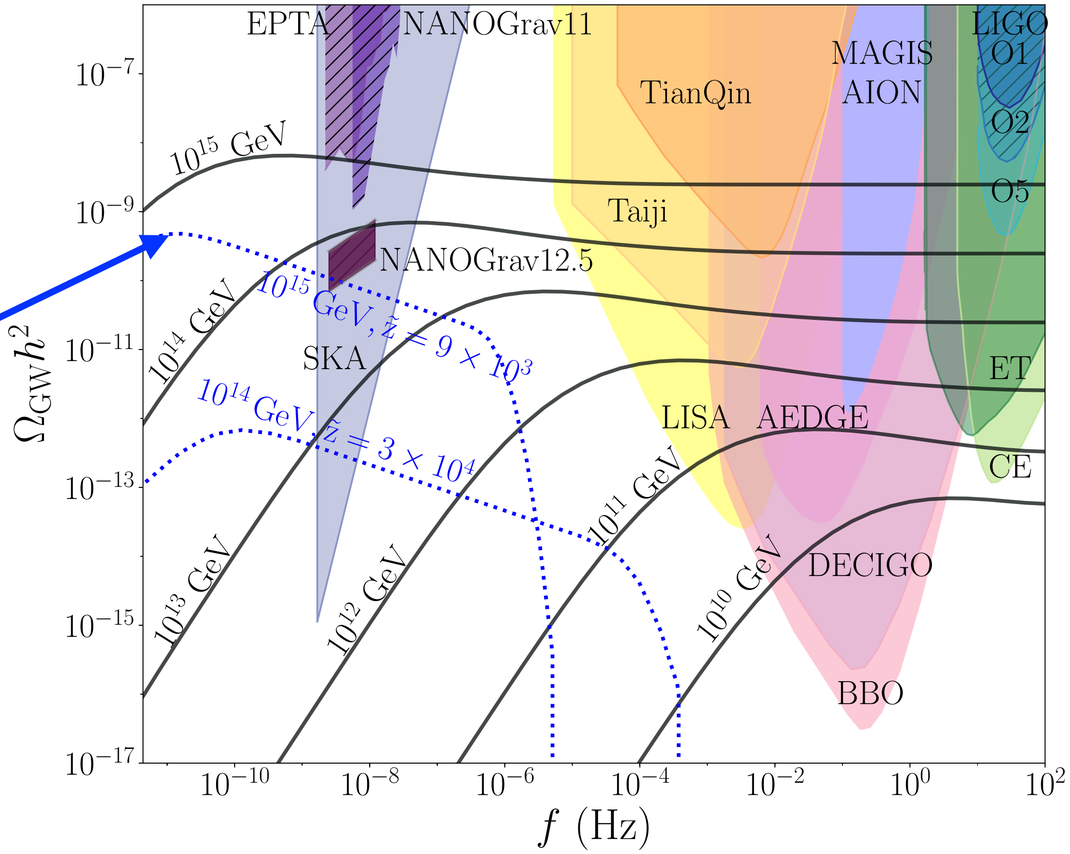
Kibble, & Nielsen, Ole

$$\frac{\rho_{\mathrm{string}}}{\rho_{\mathrm{tot}}} \propto G\mu \sim \left(\frac{\langle\phi\rangle}{M_{\mathrm{pl}}}\right)^2$$

$\mu \equiv$ string parameter

GUT prediction II

- Inflation occurs **before** string formation → string network gives “scaling” solution
- Inflation occurs **after** string formation → string network diluted and **no GW signal**
- Inflation occurs **during** string formation → partly diluted string network → **GW spectrum broken power law behaviour** (Cui, Lewicki, Morrissey) **1912.08832**



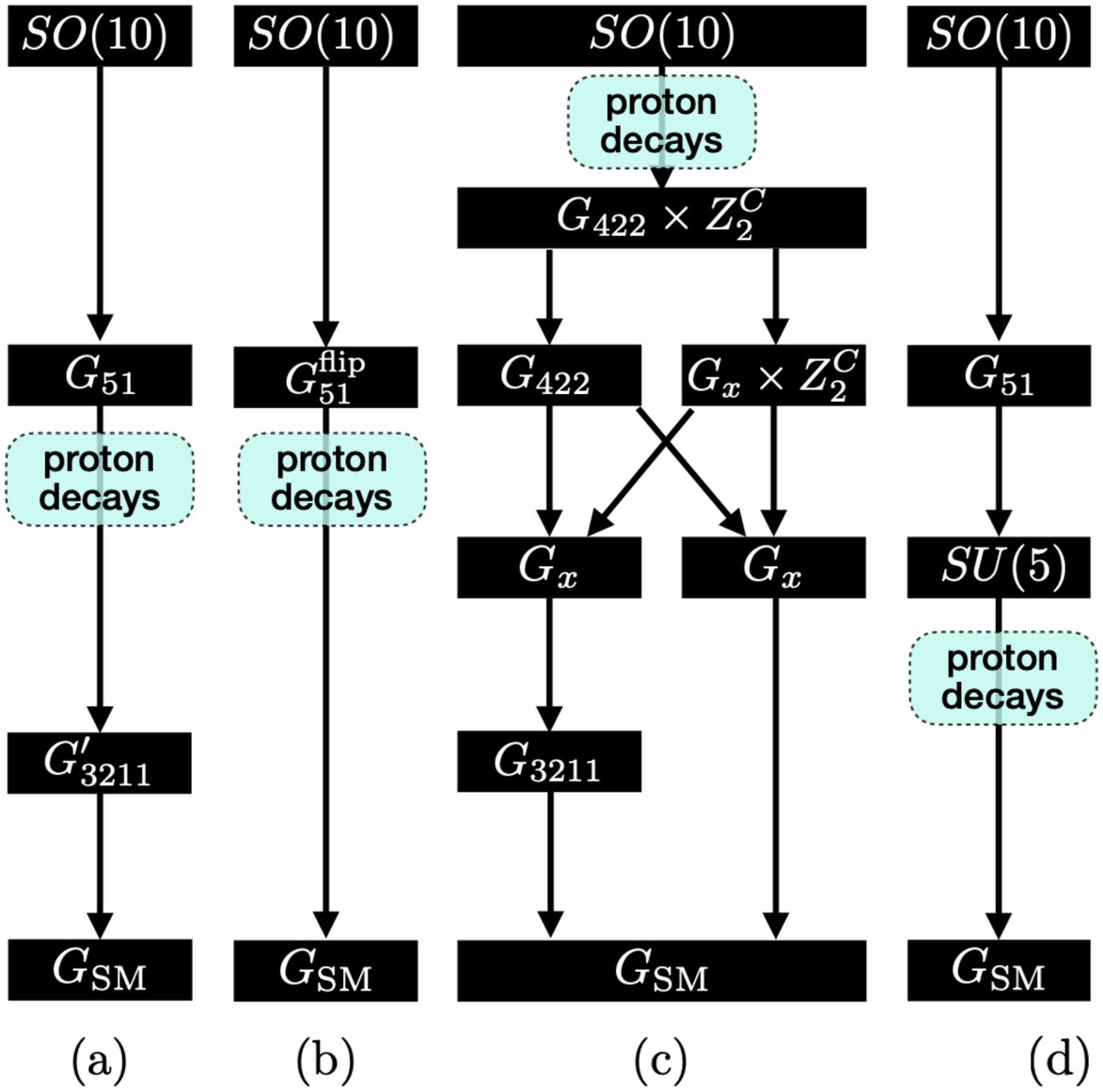
Diluted by inflation

$$\Lambda_{\rm cs} \equiv \sqrt{\mu}$$

$$\Lambda_{\rm cs} = 10^{14}\,{\rm GeV}$$

$$G\mu = 0.7 \times 10^{-10}$$

Proton decay in non-supersymmetric $\mathrm{SO}(10)$

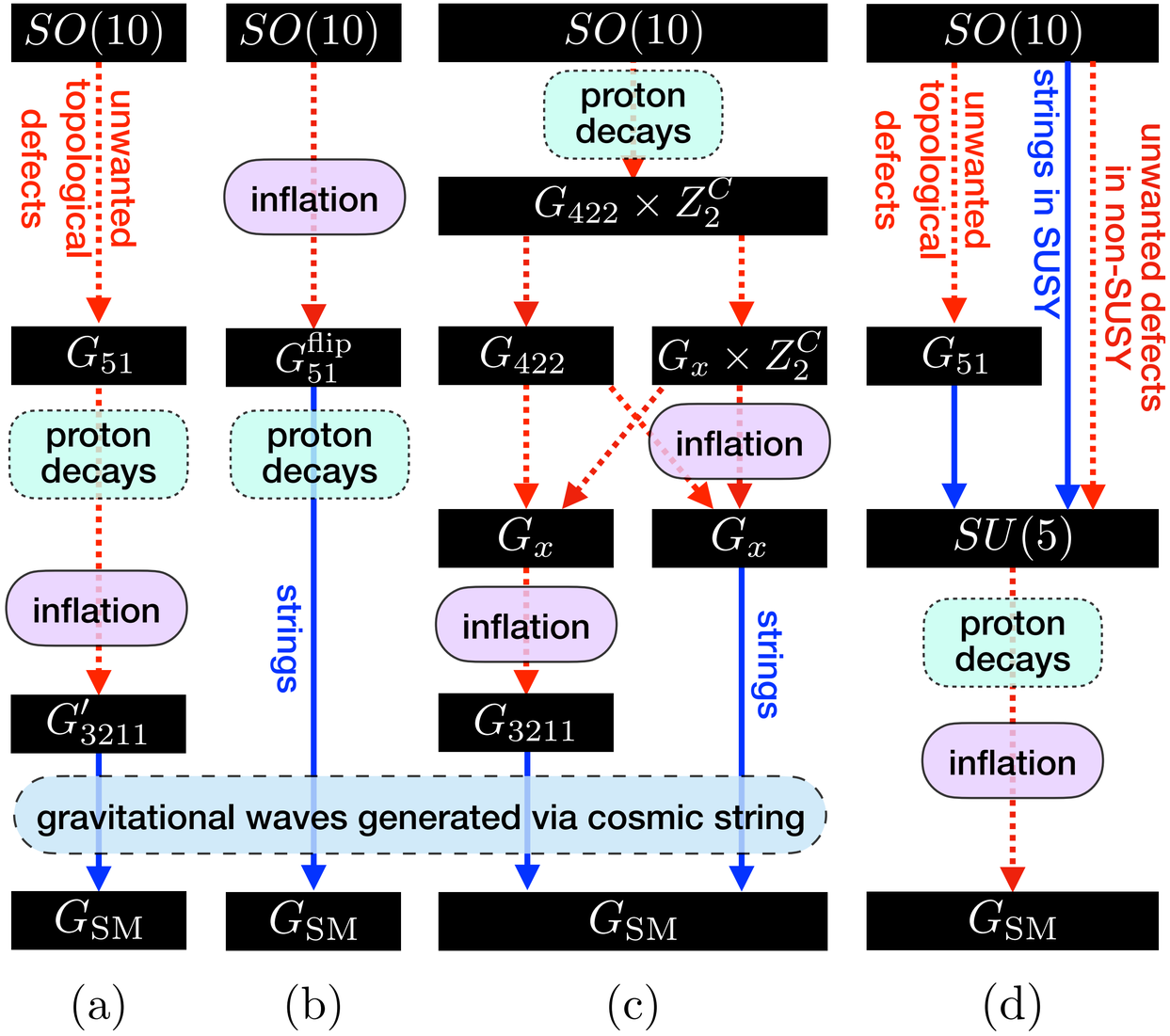


2005.13549 in collaboration with **Stephen King, Silvia Pascoli, and Ye-Ling Zhou** use PD and GWs to examine viable non-SUYS SO(10) GUT breaking chains.

$$
\begin{aligned}
G_{51} &= SU(5) \times U(1)_X \,, \\
G_{51}^{\rm flip} &= SU(5)_{\rm flip} \times U(1)_{\rm flip} \,, \\
G_{3211} &= SU(3)_C \times SU(2)_L \times U(1)_R \times U(1)_{B-L} \,, \\
G'_{3211} &= SU(3)_C \times SU(2)_L \times U(1)_Y \times U(1)_X \,, \\
G_{422} &= SU(4)_C \times SU(2)_L \times SU(2)_R \,. \\
G_x &= G_{3221} \text{ or } G_{421}
\end{aligned}
$$

Also work by Dror et al (**1908.03227**) Buchmuller et al (**1912.03695**)

Topological defects in non-supersymmetric $\mathrm{SO}(10)$



monopoles and domains walls are unwanted topological defects

$$G_x = G_{3221} \text{ or } G_{421}$$

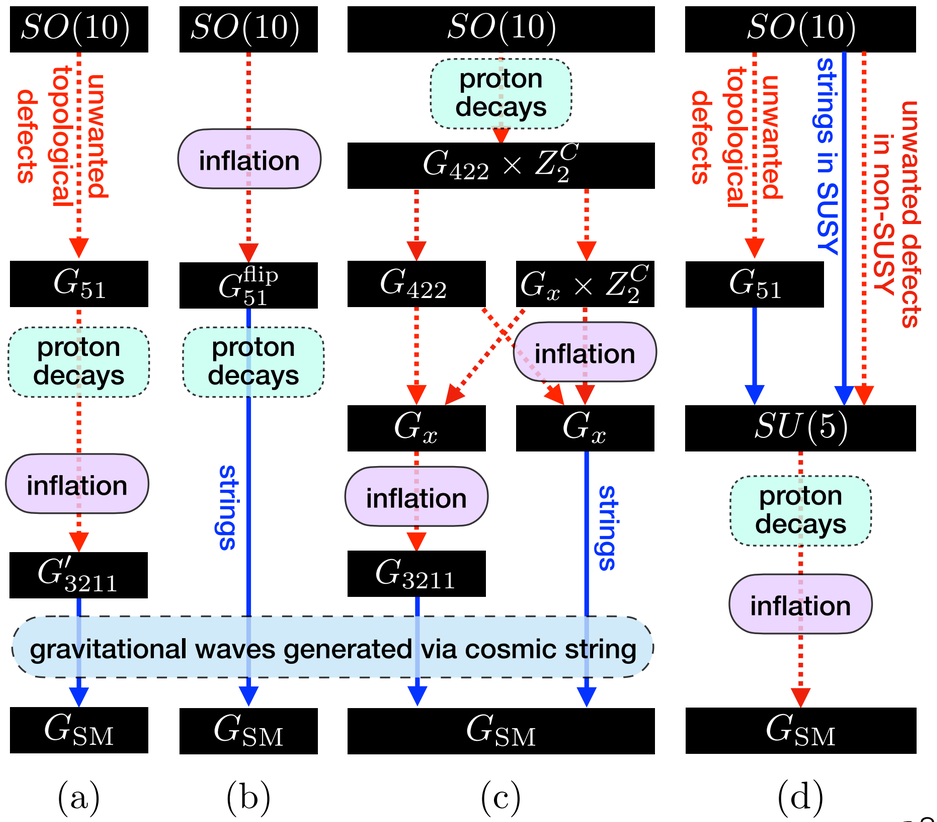
Assumed inflation at highest scale to remove unwanted defects and preserve cosmic strings

Jeannerot et al classified all GUT “breaking chains” **0308134**

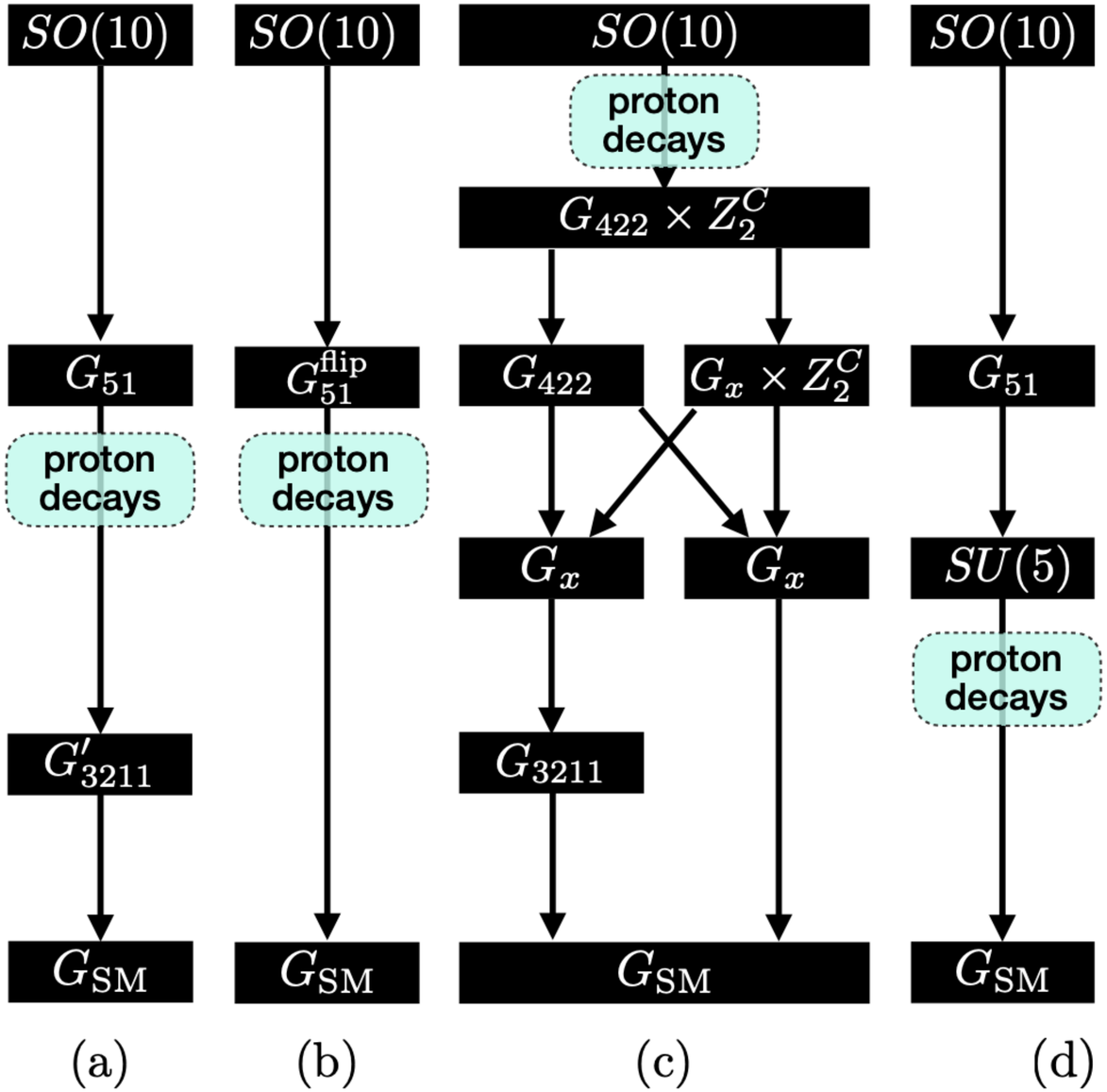
Proton decay and GWs as complementary windows

- Type (a) via SU(5) x U(1) predicts $\Lambda_{pd} > \Lambda_{cs}$
- Type (b) via flipped SU(5) x U(1) predicts $\Lambda_{pd} \sim \Lambda_{cs}$
- Type (c) via flipped SU(4) x $SU(2)_L$ x $SU(2)_R$ predicts $\Lambda_{pd} > \Lambda_{cs}$
- Type (d) via SU(5) no GWs predicted

Observables		**Proton decays**
		$p \to \pi^0 e^+$ observed $\Rightarrow$ non-SUSY contribution indicated
GWs	Observed	• types (a) and (c) favoured • types (b) and (d) excluded
	Marginal	• types (a) and (c) favoured • type (d) excluded • type (b) allowed if $p \to K^+\bar{\nu}$ not observed and $\Lambda_{pd} \sim \Lambda_{cs}$

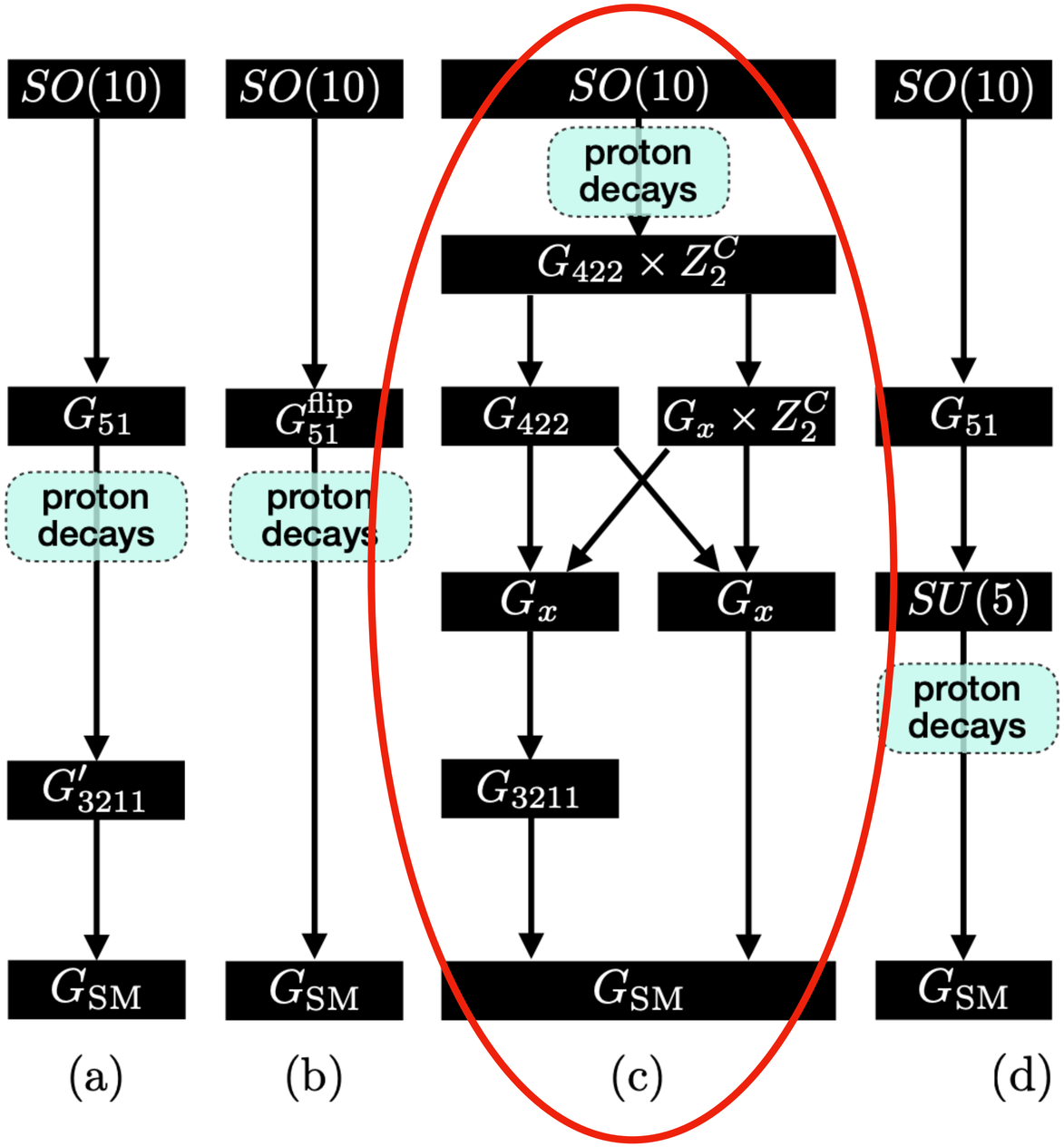


Proton decay and GWs as complementary windows



Further study in **2106.15634**

Proton decay and GWs as complementary windows



Further study in **2106.15634**

Non-SUSY $SO(10)$ with unification and GW signal only provided with Pati-Salam intermediate group

31 possible breaking chains

Proton decay and GWs as complementary windows

$SO(10)$	$\xrightarrow[\text{Higgs}]{\text{defect}}$	G_1	$\xrightarrow[\text{Higgs}]{\text{defect}}$	G_{SM}	Observable strings?
I1:	$\xrightarrow[\mathbf{45}]{\text{m}}$	G_{3221}	$\xrightarrow[\overline{\mathbf{126}}]{\text{s}}$		✓
I2:	$\xrightarrow[\mathbf{210}]{\text{m,s}}$	G_{3221}^C	$\xrightarrow[\overline{\mathbf{126}}]{\text{s,w}}$		✗
I3:	$\xrightarrow[\mathbf{45}]{\text{m}}$	G_{421}	$\xrightarrow[\overline{\mathbf{126}}]{\text{s}}$		✓
I4:	$\xrightarrow[\mathbf{210}]{\text{m}}$	G_{422}	$\xrightarrow[\overline{\mathbf{126}},\mathbf{45}]{\text{m}}$		✗
I5:	$\xrightarrow[\mathbf{54}]{\text{m,s}}$	G_{422}^C	$\xrightarrow[\overline{\mathbf{126}},\mathbf{45}]{\text{m,w}}$		✗
I6:	$\xrightarrow[\mathbf{210}]{\text{m}}$	G_{3211}	$\xrightarrow[\overline{\mathbf{126}}]{\text{s}}$		✓

$SO(10)$	$\xrightarrow[\text{Higgs}]{\text{defect}}$	G_3	$\xrightarrow[\text{Higgs}]{\text{defect}}$	G_2	$\xrightarrow[\text{Higgs}]{\text{defect}}$	G_1	$\xrightarrow[\text{Higgs}]{\text{defect}}$	G_{SM}	Observable strings?
III1:	$\xrightarrow[\mathbf{54}]{\text{m,s}}$	G_{422}^C	$\xrightarrow[\mathbf{210}]{\text{w}}$	G_{422}	$\xrightarrow[\mathbf{45}]{\text{m}}$	G_{421}	$\xrightarrow[\overline{\mathbf{126}}]{\text{s}}$		✓
III2:	$\xrightarrow[\mathbf{54}]{\text{m,s}}$	G_{422}^C	$\xrightarrow[\mathbf{210}]{\text{w}}$	G_{422}	$\xrightarrow[\mathbf{45}]{\text{m}}$	G_{3221}	$\xrightarrow[\overline{\mathbf{126}}]{\text{s}}$		✓
III3:	$\xrightarrow[\mathbf{54}]{\text{m,s}}$	G_{422}^C	$\xrightarrow[\mathbf{210}]{\text{w}}$	G_{422}	$\xrightarrow[\mathbf{210}]{\text{m}}$	G_{3211}	$\xrightarrow[\overline{\mathbf{126}}]{\text{s}}$		✓
III4:	$\xrightarrow[\mathbf{54}]{\text{m,s}}$	G_{422}^C	$\xrightarrow[\mathbf{210}]{\text{m}}$	G_{3221}^C	$\xrightarrow[\mathbf{45}]{\text{w}}$	G_{3221}	$\xrightarrow[\overline{\mathbf{126}}]{\text{s}}$		✓
III5:	$\xrightarrow[\mathbf{54}]{\text{m,s}}$	G_{422}^C	$\xrightarrow[\mathbf{210}]{\text{m}}$	G_{3221}^C	$\xrightarrow[\mathbf{45}]{\text{m,w}}$	G_{3211}	$\xrightarrow[\overline{\mathbf{126}}]{\text{s}}$		✓
III6:	$\xrightarrow[\mathbf{54}]{\text{m,s}}$	G_{422}^C	$\xrightarrow[\mathbf{45}]{\text{m,w}}$	G_{3221}	$\xrightarrow[\mathbf{45}]{\text{m}}$	G_{3211}	$\xrightarrow[\overline{\mathbf{126}}]{\text{s}}$		✓
III7:	$\xrightarrow[\mathbf{210}]{\text{m,s}}$	G_{3221}^C	$\xrightarrow[\mathbf{45}]{\text{w}}$	G_{3221}	$\xrightarrow[\mathbf{45}]{\text{m}}$	G_{3211}	$\xrightarrow[\overline{\mathbf{126}}]{\text{s}}$		✓
III8:	$\xrightarrow[\mathbf{210}]{\text{m}}$	G_{422}	$\xrightarrow[\mathbf{45}]{\text{m}}$	G_{3221}	$\xrightarrow[\mathbf{45}]{\text{m}}$	G_{3211}	$\xrightarrow[\overline{\mathbf{126}}]{\text{s}}$		✓
III9:	$\xrightarrow[\mathbf{54}]{\text{m,s}}$	G_{422}^C	$\xrightarrow[\mathbf{45}]{\text{m}}$	G_{421}	$\xrightarrow[\mathbf{45}]{\text{m}}$	G_{3211}	$\xrightarrow[\overline{\mathbf{126}}]{\text{s}}$		✓
III10:	$\xrightarrow[\mathbf{210}]{\text{m}}$	G_{422}	$\xrightarrow[\mathbf{45}]{\text{m}}$	G_{421}	$\xrightarrow[\mathbf{45}]{\text{m}}$	G_{3211}	$\xrightarrow[\overline{\mathbf{126}}]{\text{s}}$		✓

$SO(10)$	$\xrightarrow[\text{Higgs}]{\text{defect}}$	G_2	$\xrightarrow[\text{Higgs}]{\text{defect}}$	G_1	$\xrightarrow[\text{Higgs}]{\text{defect}}$	G_{SM}	Observable strings?
II1:	$\xrightarrow[\mathbf{210}]{\text{m}}$	G_{422}	$\xrightarrow[\mathbf{45}]{\text{m}}$	G_{3221}	$\xrightarrow[\overline{\mathbf{126}}]{\text{s}}$		✓
II2:	$\xrightarrow[\mathbf{54}]{\text{m,s}}$	G_{422}^C	$\xrightarrow[\mathbf{210}]{\text{m}}$	G_{3221}^C	$\xrightarrow[\overline{\mathbf{126}}]{\text{s,w}}$		✗
II3:	$\xrightarrow[\mathbf{54}]{\text{m,s}}$	G_{422}^C	$\xrightarrow[\mathbf{45}]{\text{m,w}}$	G_{3221}	$\xrightarrow[\overline{\mathbf{126}}]{\text{s}}$		✓
II4:	$\xrightarrow[\mathbf{210}]{\text{m,s}}$	G_{3221}^C	$\xrightarrow[\mathbf{45}]{\text{w}}$	G_{3221}	$\xrightarrow[\overline{\mathbf{126}}]{\text{s}}$		✓
II5:	$\xrightarrow[\mathbf{210}]{\text{m}}$	G_{422}	$\xrightarrow[\mathbf{45}]{\text{m}}$	G_{421}	$\xrightarrow[\overline{\mathbf{126}}]{\text{s}}$		✓
II6:	$\xrightarrow[\mathbf{54}]{\text{m,s}}$	G_{422}^C	$\xrightarrow[\mathbf{45}]{\text{m}}$	G_{421}	$\xrightarrow[\overline{\mathbf{126}}]{\text{s}}$		✓
II7:	$\xrightarrow[\mathbf{54}]{\text{m,s}}$	G_{422}^C	$\xrightarrow[\mathbf{210}]{\text{w}}$	G_{422}	$\xrightarrow[\overline{\mathbf{126}},\mathbf{45}]{\text{m}}$		✗
II8:	$\xrightarrow[\mathbf{45}]{\text{m}}$	G_{3221}	$\xrightarrow[\mathbf{45}]{\text{m}}$	G_{3211}	$\xrightarrow[\overline{\mathbf{126}}]{\text{s}}$		✓
II9:	$\xrightarrow[\mathbf{210}]{\text{m,s}}$	G_{3221}^C	$\xrightarrow[\mathbf{45}]{\text{m,w}}$	G_{3211}	$\xrightarrow[\overline{\mathbf{126}}]{\text{s}}$		✓
II10:	$\xrightarrow[\mathbf{210}]{\text{m}}$	G_{422}	$\xrightarrow[\mathbf{210}]{\text{m}}$	G_{3211}	$\xrightarrow[\overline{\mathbf{126}}]{\text{s}}$		✓
II11:	$\xrightarrow[\mathbf{54}]{\text{m,s}}$	G_{422}^C	$\xrightarrow[\mathbf{210}]{\text{m,w}}$	G_{3211}	$\xrightarrow[\overline{\mathbf{126}}]{\text{s}}$		✓
II12:	$\xrightarrow[\mathbf{45}]{\text{m}}$	G_{421}	$\xrightarrow[\mathbf{45}]{\text{m}}$	G_{3211}	$\xrightarrow[\overline{\mathbf{126}}]{\text{s}}$		✓

$SO(10)$	$\xrightarrow[\text{Higgs}]{\text{defect}}$	G_4	$\xrightarrow[\text{Higgs}]{\text{defect}}$	G_3	$\xrightarrow[\text{Higgs}]{\text{defect}}$	G_2	$\xrightarrow[\text{Higgs}]{\text{defect}}$	G_1	$\xrightarrow[\text{Higgs}]{\text{defect}}$	G_{SM}	Observable strings?
IV1:	$\xrightarrow[\mathbf{54}]{\text{m,s}}$	G_{422}^C	$\xrightarrow[\mathbf{210}]{\text{m}}$	G_{3221}^C	$\xrightarrow[\mathbf{45}]{\text{w}}$	G_{3221}	$\xrightarrow[\mathbf{45}]{\text{m}}$	G_{3211}	$\xrightarrow[\overline{\mathbf{126}}]{\text{s}}$		✓
IV2:	$\xrightarrow[\mathbf{54}]{\text{m,s}}$	G_{422}^C	$\xrightarrow[\mathbf{210}]{\text{w}}$	G_{422}	$\xrightarrow[\mathbf{45}]{\text{m}}$	G_{3221}	$\xrightarrow[\mathbf{45}]{\text{m}}$	G_{3211}	$\xrightarrow[\overline{\mathbf{126}}]{\text{s}}$		✓
IV3:	$\xrightarrow[\mathbf{54}]{\text{m,s}}$	G_{422}^C	$\xrightarrow[\mathbf{210}]{\text{w}}$	G_{422}	$\xrightarrow[\mathbf{45}]{\text{m}}$	G_{421}	$\xrightarrow[\mathbf{45}]{\text{m}}$	G_{3211}	$\xrightarrow[\overline{\mathbf{126}}]{\text{s}}$		✓

Proton decay and GWs as complementary windows

$SO(10)$	$\xrightarrow[\text{Higgs}]{\text{defect}}$	G_1	$\xrightarrow[\text{Higgs}]{\text{defect}}$	G_{SM}	Observable strings?
I1:	$\xrightarrow[\mathbf{45}]{\text{m}}$	G_{3221}	$\xrightarrow[\overline{\mathbf{126}}]{\text{s}}$		✓
I2:	$\xrightarrow[\mathbf{210}]{\text{m,s}}$	G^C_{3221}	$\xrightarrow[\overline{\mathbf{126}}]{\text{s,w}}$		✗
I3:	$\xrightarrow[\mathbf{45}]{\text{m}}$	G_{421}	$\xrightarrow[\overline{\mathbf{126}}]{\text{s}}$		✓
I4:	$\xrightarrow[\mathbf{210}]{\text{m}}$	G_{422}	$\xrightarrow[\overline{\mathbf{126}},\mathbf{45}]{\text{m}}$		✗
I5:	$\xrightarrow[\mathbf{54}]{\text{m,s}}$	G^C_{422}	$\xrightarrow[\overline{\mathbf{126}},\mathbf{45}]{\text{m,w}}$		✗
I6:	$\xrightarrow[\mathbf{210}]{\text{m}}$	G_{3211}	$\xrightarrow[\overline{\mathbf{126}}]{\text{s}}$		✓

Monopole

cosmic strings

Domain walls

$SO(10)$	$\xrightarrow[\text{Higgs}]{\text{defect}}$	G_2	$\xrightarrow[\text{Higgs}]{\text{defect}}$	G_1	$\xrightarrow[\text{Higgs}]{\text{defect}}$	G_{SM}	Observable strings?
II1:	$\xrightarrow[\mathbf{210}]{\text{m}}$	G_{422}	$\xrightarrow[\mathbf{45}]{\text{m}}$	G_{3221}	$\xrightarrow[\overline{\mathbf{126}}]{\text{s}}$		✓
II2:	$\xrightarrow[\mathbf{54}]{\text{m,s}}$	G^C_{422}	$\xrightarrow[\mathbf{210}]{\text{m}}$	G^C_{3221}	$\xrightarrow[\overline{\mathbf{126}}]{\text{s,w}}$		✗
II3:	$\xrightarrow[\mathbf{54}]{\text{m,s}}$	G^C_{422}	$\xrightarrow[\mathbf{45}]{\text{m,w}}$	G_{3221}	$\xrightarrow[\overline{\mathbf{126}}]{\text{s}}$		✓
II4:	$\xrightarrow[\mathbf{210}]{\text{m,s}}$	G^C_{3221}	$\xrightarrow[\mathbf{45}]{\text{w}}$	G_{3221}	$\xrightarrow[\overline{\mathbf{126}}]{\text{s}}$		✓
II5:	$\xrightarrow[\mathbf{210}]{\text{m}}$	G_{422}	$\xrightarrow[\mathbf{45}]{\text{m}}$	G_{421}	$\xrightarrow[\overline{\mathbf{126}}]{\text{s}}$		✓
II6:	$\xrightarrow[\mathbf{54}]{\text{m,s}}$	G^C_{422}	$\xrightarrow[\mathbf{45}]{\text{m}}$	G_{421}	$\xrightarrow[\overline{\mathbf{126}}]{\text{s}}$		✓
II7:	$\xrightarrow[\mathbf{54}]{\text{m,s}}$	G^C_{422}	$\xrightarrow[\mathbf{210}]{\text{w}}$	G_{422}	$\xrightarrow[\overline{\mathbf{126}},\mathbf{45}]{\text{m}}$		✗
II8:	$\xrightarrow[\mathbf{45}]{\text{m}}$	G_{3221}	$\xrightarrow[\mathbf{45}]{\text{m}}$	G_{3211}	$\xrightarrow[\overline{\mathbf{126}}]{\text{s}}$		✓
II9:	$\xrightarrow[\mathbf{210}]{\text{m,s}}$	G^C_{3221}	$\xrightarrow[\mathbf{45}]{\text{m,w}}$	G_{3211}	$\xrightarrow[\overline{\mathbf{126}}]{\text{s}}$		✓
II10:	$\xrightarrow[\mathbf{210}]{\text{m}}$	G_{422}	$\xrightarrow[\mathbf{210}]{\text{m}}$	G_{3211}	$\xrightarrow[\overline{\mathbf{126}}]{\text{s}}$		✓
II11:	$\xrightarrow[\mathbf{54}]{\text{m,s}}$	G^C_{422}	$\xrightarrow[\mathbf{210}]{\text{m,w}}$	G_{3211}	$\xrightarrow[\overline{\mathbf{126}}]{\text{s}}$		✓
II12:	$\xrightarrow[\mathbf{45}]{\text{m}}$	G_{421}	$\xrightarrow[\mathbf{45}]{\text{m}}$	G_{3211}	$\xrightarrow[\overline{\mathbf{126}}]{\text{s}}$		✓

$SO(10)$	$\xrightarrow[\text{Higgs}]{\text{defect}}$	G_3	$\xrightarrow[\text{Higgs}]{\text{defect}}$	G_2	$\xrightarrow[\text{Higgs}]{\text{defect}}$	G_1	$\xrightarrow[\text{Higgs}]{\text{defect}}$	G_{SM}	Observable strings?
III1:	$\xrightarrow[\mathbf{54}]{\text{m,s}}$	G^C_{422}	$\xrightarrow[\mathbf{210}]{\text{w}}$	G_{422}	$\xrightarrow[\mathbf{45}]{\text{m}}$	G_{421}	$\xrightarrow[\overline{\mathbf{126}}]{\text{s}}$		✓
III2:	$\xrightarrow[\mathbf{54}]{\text{m,s}}$	G^C_{422}	$\xrightarrow[\mathbf{210}]{\text{w}}$	G_{422}	$\xrightarrow[\mathbf{45}]{\text{m}}$	G_{3221}	$\xrightarrow[\overline{\mathbf{126}}]{\text{s}}$		✓
III3:	$\xrightarrow[\mathbf{54}]{\text{m,s}}$	G^C_{422}	$\xrightarrow[\mathbf{210}]{\text{w}}$	G_{422}	$\xrightarrow[\mathbf{210}]{\text{m}}$	G_{3211}	$\xrightarrow[\overline{\mathbf{126}}]{\text{s}}$		✓
III4:	$\xrightarrow[\mathbf{54}]{\text{m,s}}$	G^C_{422}	$\xrightarrow[\mathbf{210}]{\text{m}}$	G^C_{3221}	$\xrightarrow[\mathbf{45}]{\text{w}}$	G_{3221}	$\xrightarrow[\overline{\mathbf{126}}]{\text{s}}$		✓
III5:	$\xrightarrow[\mathbf{54}]{\text{m,s}}$	G^C_{422}	$\xrightarrow[\mathbf{210}]{\text{m}}$	G^C_{3221}	$\xrightarrow[\mathbf{45}]{\text{m,w}}$	G_{3211}	$\xrightarrow[\overline{\mathbf{126}}]{\text{s}}$		✓
III6:	$\xrightarrow[\mathbf{54}]{\text{m,s}}$	G^C_{422}	$\xrightarrow[\mathbf{45}]{\text{m,w}}$	G_{3221}	$\xrightarrow[\mathbf{45}]{\text{m}}$	G_{3211}	$\xrightarrow[\overline{\mathbf{126}}]{\text{s}}$		✓
III7:	$\xrightarrow[\mathbf{210}]{\text{m,s}}$	G^C_{3221}	$\xrightarrow[\mathbf{45}]{\text{w}}$	G_{3221}	$\xrightarrow[\mathbf{45}]{\text{m}}$	G_{3211}	$\xrightarrow[\overline{\mathbf{126}}]{\text{s}}$		✓
III8:	$\xrightarrow[\mathbf{210}]{\text{m}}$	G_{422}	$\xrightarrow[\mathbf{45}]{\text{m}}$	G_{3221}	$\xrightarrow[\mathbf{45}]{\text{m}}$	G_{3211}	$\xrightarrow[\overline{\mathbf{126}}]{\text{s}}$		✓
III9:	$\xrightarrow[\mathbf{54}]{\text{m,s}}$	G^C_{422}	$\xrightarrow[\mathbf{45}]{\text{m}}$	G_{421}	$\xrightarrow[\mathbf{45}]{\text{m}}$	G_{3211}	$\xrightarrow[\overline{\mathbf{126}}]{\text{s}}$		✓
III10:	$\xrightarrow[\mathbf{210}]{\text{m}}$	G_{422}	$\xrightarrow[\mathbf{45}]{\text{m}}$	G_{421}	$\xrightarrow[\mathbf{45}]{\text{m}}$	G_{3211}	$\xrightarrow[\overline{\mathbf{126}}]{\text{s}}$		✓

$SO(10)$	$\xrightarrow[\text{Higgs}]{\text{defect}}$	G_4	$\xrightarrow[\text{Higgs}]{\text{defect}}$	G_3	$\xrightarrow[\text{Higgs}]{\text{defect}}$	G_2	$\xrightarrow[\text{Higgs}]{\text{defect}}$	G_1	$\xrightarrow[\text{Higgs}]{\text{defect}}$	G_{SM}	Observable strings?
IV1:	$\xrightarrow[\mathbf{54}]{\text{m,s}}$	G^C_{422}	$\xrightarrow[\mathbf{210}]{\text{m}}$	G^C_{3221}	$\xrightarrow[\mathbf{45}]{\text{w}}$	G_{3221}	$\xrightarrow[\mathbf{45}]{\text{m}}$	G_{3211}	$\xrightarrow[\overline{\mathbf{126}}]{\text{s}}$		✓
IV2:	$\xrightarrow[\mathbf{54}]{\text{m,s}}$	G^C_{422}	$\xrightarrow[\mathbf{210}]{\text{w}}$	G_{422}	$\xrightarrow[\mathbf{45}]{\text{m}}$	G_{3221}	$\xrightarrow[\mathbf{45}]{\text{m}}$	G_{3211}	$\xrightarrow[\overline{\mathbf{126}}]{\text{s}}$		✓
IV3:	$\xrightarrow[\mathbf{54}]{\text{m,s}}$	G^C_{422}	$\xrightarrow[\mathbf{210}]{\text{w}}$	G_{422}	$\xrightarrow[\mathbf{45}]{\text{m}}$	G_{421}	$\xrightarrow[\mathbf{45}]{\text{m}}$	G_{3211}	$\xrightarrow[\overline{\mathbf{126}}]{\text{s}}$		✓

Proton decay and GWs as complementary windows

$SO(10)$	defect → Higgs	G_1	defect → Higgs	$G_{\rm SM}$	Observable strings?
I1:	$\xrightarrow[\mathbf{45}]{\text{m}}$	G_{3221}	$\xrightarrow[\overline{\mathbf{126}}]{\text{s}}$		✓
I2:	$\xrightarrow[\mathbf{210}]{\text{m,s}}$	G^C_{3221}	$\xrightarrow[\overline{\mathbf{126}}]{\text{s,w}}$		✗
I3:	$\xrightarrow[\mathbf{45}]{\text{m}}$	G_{421}	$\xrightarrow[\overline{\mathbf{126}}]{\text{s}}$		✓
I4:	$\xrightarrow[\mathbf{210}]{\text{m}}$	G_{422}	$\xrightarrow[\overline{\mathbf{126}},\mathbf{45}]{\text{m}}$		✗
I5:	$\xrightarrow[\mathbf{54}]{\text{m,s}}$	G^C_{422}	$\xrightarrow[\overline{\mathbf{126}},\mathbf{45}]{\text{m,w}}$		✗
I6:	$\xrightarrow[\mathbf{210}]{\text{m}}$	G_{3211}	$\xrightarrow[\overline{\mathbf{126}}]{\text{s}}$		✓

SO(10) **Higgs multiplets**

$SO(10)$	defect → Higgs	G_2	defect → Higgs	G_1	defect → Higgs	$G_{\rm SM}$	Observable strings?
II1:	$\xrightarrow[\mathbf{210}]{\text{m}}$	G_{422}	$\xrightarrow[\mathbf{45}]{\text{m}}$	G_{3221}	$\xrightarrow[\overline{\mathbf{126}}]{\text{s}}$		✓
II2:	$\xrightarrow[\mathbf{54}]{\text{m,s}}$	G^C_{422}	$\xrightarrow[\mathbf{210}]{\text{m}}$	G^C_{3221}	$\xrightarrow[\overline{\mathbf{126}}]{\text{s,w}}$		✗
II3:	$\xrightarrow[\mathbf{54}]{\text{m,s}}$	G^C_{422}	$\xrightarrow[\mathbf{45}]{\text{m,w}}$	G_{3221}	$\xrightarrow[\overline{\mathbf{126}}]{\text{s}}$		✓
II4:	$\xrightarrow[\mathbf{210}]{\text{m,s}}$	G^C_{3221}	$\xrightarrow[\mathbf{45}]{\text{w}}$	G_{3221}	$\xrightarrow[\overline{\mathbf{126}}]{\text{s}}$		✓
II5:	$\xrightarrow[\mathbf{210}]{\text{m}}$	G_{422}	$\xrightarrow[\mathbf{45}]{\text{m}}$	G_{421}	$\xrightarrow[\overline{\mathbf{126}}]{\text{s}}$		✓
II6:	$\xrightarrow[\mathbf{54}]{\text{m,s}}$	G^C_{422}	$\xrightarrow[\mathbf{45}]{\text{m}}$	G_{421}	$\xrightarrow[\overline{\mathbf{126}}]{\text{s}}$		✓
II7:	$\xrightarrow[\mathbf{54}]{\text{m,s}}$	G^C_{422}	$\xrightarrow[\mathbf{210}]{\text{w}}$	G_{422}	$\xrightarrow[\overline{\mathbf{126}},\mathbf{45}]{\text{m}}$		✗
II8:	$\xrightarrow[\mathbf{45}]{\text{m}}$	G_{3221}	$\xrightarrow[\mathbf{45}]{\text{m}}$	G_{3211}	$\xrightarrow[\overline{\mathbf{126}}]{\text{s}}$		✓
II9:	$\xrightarrow[\mathbf{210}]{\text{m,s}}$	G^C_{3221}	$\xrightarrow[\mathbf{45}]{\text{m,w}}$	G_{3211}	$\xrightarrow[\overline{\mathbf{126}}]{\text{s}}$		✓
II10:	$\xrightarrow[\mathbf{210}]{\text{m}}$	G_{422}	$\xrightarrow[\mathbf{210}]{\text{m}}$	G_{3211}	$\xrightarrow[\overline{\mathbf{126}}]{\text{s}}$		✓
II11:	$\xrightarrow[\mathbf{54}]{\text{m,s}}$	G^C_{422}	$\xrightarrow[\mathbf{210}]{\text{m,w}}$	G_{3211}	$\xrightarrow[\overline{\mathbf{126}}]{\text{s}}$		✓
II12:	$\xrightarrow[\mathbf{45}]{\text{m}}$	G_{421}	$\xrightarrow[\mathbf{45}]{\text{m}}$	G_{3211}	$\xrightarrow[\overline{\mathbf{126}}]{\text{s}}$		✓

$SO(10)$	defect → Higgs	G_3	defect → Higgs	G_2	defect → Higgs	G_1	defect → Higgs	$G_{\rm SM}$	Observable strings?
III1:	$\xrightarrow[\mathbf{54}]{\text{m,s}}$	G^C_{422}	$\xrightarrow[\mathbf{210}]{\text{w}}$	G_{422}	$\xrightarrow[\mathbf{45}]{\text{m}}$	G_{421}	$\xrightarrow[\overline{\mathbf{126}}]{\text{s}}$		✓
III2:	$\xrightarrow[\mathbf{54}]{\text{m,s}}$	G^C_{422}	$\xrightarrow[\mathbf{210}]{\text{w}}$	G_{422}	$\xrightarrow[\mathbf{45}]{\text{m}}$	G_{3221}	$\xrightarrow[\overline{\mathbf{126}}]{\text{s}}$		✓
III3:	$\xrightarrow[\mathbf{54}]{\text{m,s}}$	G^C_{422}	$\xrightarrow[\mathbf{210}]{\text{w}}$	G_{422}	$\xrightarrow[\mathbf{210}]{\text{m}}$	G_{3211}	$\xrightarrow[\overline{\mathbf{126}}]{\text{s}}$		✓
III4:	$\xrightarrow[\mathbf{54}]{\text{m,s}}$	G^C_{422}	$\xrightarrow[\mathbf{210}]{\text{m}}$	G^C_{3221}	$\xrightarrow[\mathbf{45}]{\text{w}}$	G_{3221}	$\xrightarrow[\overline{\mathbf{126}}]{\text{s}}$		✓
III5:	$\xrightarrow[\mathbf{54}]{\text{m,s}}$	G^C_{422}	$\xrightarrow[\mathbf{210}]{\text{m}}$	G^C_{3221}	$\xrightarrow[\mathbf{45}]{\text{m,w}}$	G_{3211}	$\xrightarrow[\overline{\mathbf{126}}]{\text{s}}$		✓
III6:	$\xrightarrow[\mathbf{54}]{\text{m,s}}$	G^C_{422}	$\xrightarrow[\mathbf{45}]{\text{m,w}}$	G_{3221}	$\xrightarrow[\mathbf{45}]{\text{m}}$	G_{3211}	$\xrightarrow[\overline{\mathbf{126}}]{\text{s}}$		✓
III7:	$\xrightarrow[\mathbf{210}]{\text{m,s}}$	G^C_{3221}	$\xrightarrow[\mathbf{45}]{\text{w}}$	G_{3221}	$\xrightarrow[\mathbf{45}]{\text{m}}$	G_{3211}	$\xrightarrow[\overline{\mathbf{126}}]{\text{s}}$		✓
III8:	$\xrightarrow[\mathbf{210}]{\text{m}}$	G_{422}	$\xrightarrow[\mathbf{45}]{\text{m}}$	G_{3221}	$\xrightarrow[\mathbf{45}]{\text{m}}$	G_{3211}	$\xrightarrow[\overline{\mathbf{126}}]{\text{s}}$		✓
III9:	$\xrightarrow[\mathbf{54}]{\text{m,s}}$	G^C_{422}	$\xrightarrow[\mathbf{45}]{\text{m}}$	G_{421}	$\xrightarrow[\mathbf{45}]{\text{m}}$	G_{3211}	$\xrightarrow[\overline{\mathbf{126}}]{\text{s}}$		✓
III10:	$\xrightarrow[\mathbf{210}]{\text{m}}$	G_{422}	$\xrightarrow[\mathbf{45}]{\text{m}}$	G_{421}	$\xrightarrow[\mathbf{45}]{\text{m}}$	G_{3211}	$\xrightarrow[\overline{\mathbf{126}}]{\text{s}}$		✓

$SO(10)$	defect → Higgs	G_4	defect → Higgs	G_3	defect → Higgs	G_2	defect → Higgs	G_1	defect → Higgs	$G_{\rm SM}$	Observable strings?
IV1:	$\xrightarrow[\mathbf{54}]{\text{m,s}}$	G^C_{422}	$\xrightarrow[\mathbf{210}]{\text{m}}$	G^C_{3221}	$\xrightarrow[\mathbf{45}]{\text{w}}$	G_{3221}	$\xrightarrow[\mathbf{45}]{\text{m}}$	G_{3211}	$\xrightarrow[\overline{\mathbf{126}}]{\text{s}}$		✓
IV2:	$\xrightarrow[\mathbf{54}]{\text{m,s}}$	G^C_{422}	$\xrightarrow[\mathbf{210}]{\text{w}}$	G_{422}	$\xrightarrow[\mathbf{45}]{\text{m}}$	G_{3221}	$\xrightarrow[\mathbf{45}]{\text{m}}$	G_{3211}	$\xrightarrow[\overline{\mathbf{126}}]{\text{s}}$		✓
IV3:	$\xrightarrow[\mathbf{54}]{\text{m,s}}$	G^C_{422}	$\xrightarrow[\mathbf{210}]{\text{w}}$	G_{422}	$\xrightarrow[\mathbf{45}]{\text{m}}$	G_{421}	$\xrightarrow[\mathbf{45}]{\text{m}}$	G_{3211}	$\xrightarrow[\overline{\mathbf{126}}]{\text{s}}$		✓

Proton decay and GWs as complementary windows

$SO(10)$	$\xrightarrow[\text{Higgs}]{\text{defect}}$	G_1	$\xrightarrow[\text{Higgs}]{\text{defect}}$	G_{SM}	Observable strings?
I1:	$\xrightarrow[\mathbf{45}]{\text{m}}$	G_{3221}	$\xrightarrow[\overline{\mathbf{126}}]{\text{s}}$		✓
I2:	$\xrightarrow[\mathbf{210}]{\text{m,s}}$	G_{3221}^C	$\xrightarrow[\overline{\mathbf{126}}]{\text{s,w}}$		✗
I3:	$\xrightarrow[\mathbf{45}]{\text{m}}$	G_{421}	$\xrightarrow[\overline{\mathbf{126}}]{\text{s}}$		✓
I4:	$\xrightarrow[\mathbf{210}]{\text{m}}$	G_{422}	$\xrightarrow[\overline{\mathbf{126}},\mathbf{45}]{\text{m}}$		✗
I5:	$\xrightarrow[\mathbf{54}]{\text{m,s}}$	G_{422}^C	$\xrightarrow[\overline{\mathbf{126}},\mathbf{45}]{\text{m,w}}$		✗
I6:	$\xrightarrow[\mathbf{210}]{\text{m}}$	G_{3211}	$\xrightarrow[\overline{\mathbf{126}}]{\text{s}}$		✓

If unwanted defect created in final SSB ⟹ no GW else GW

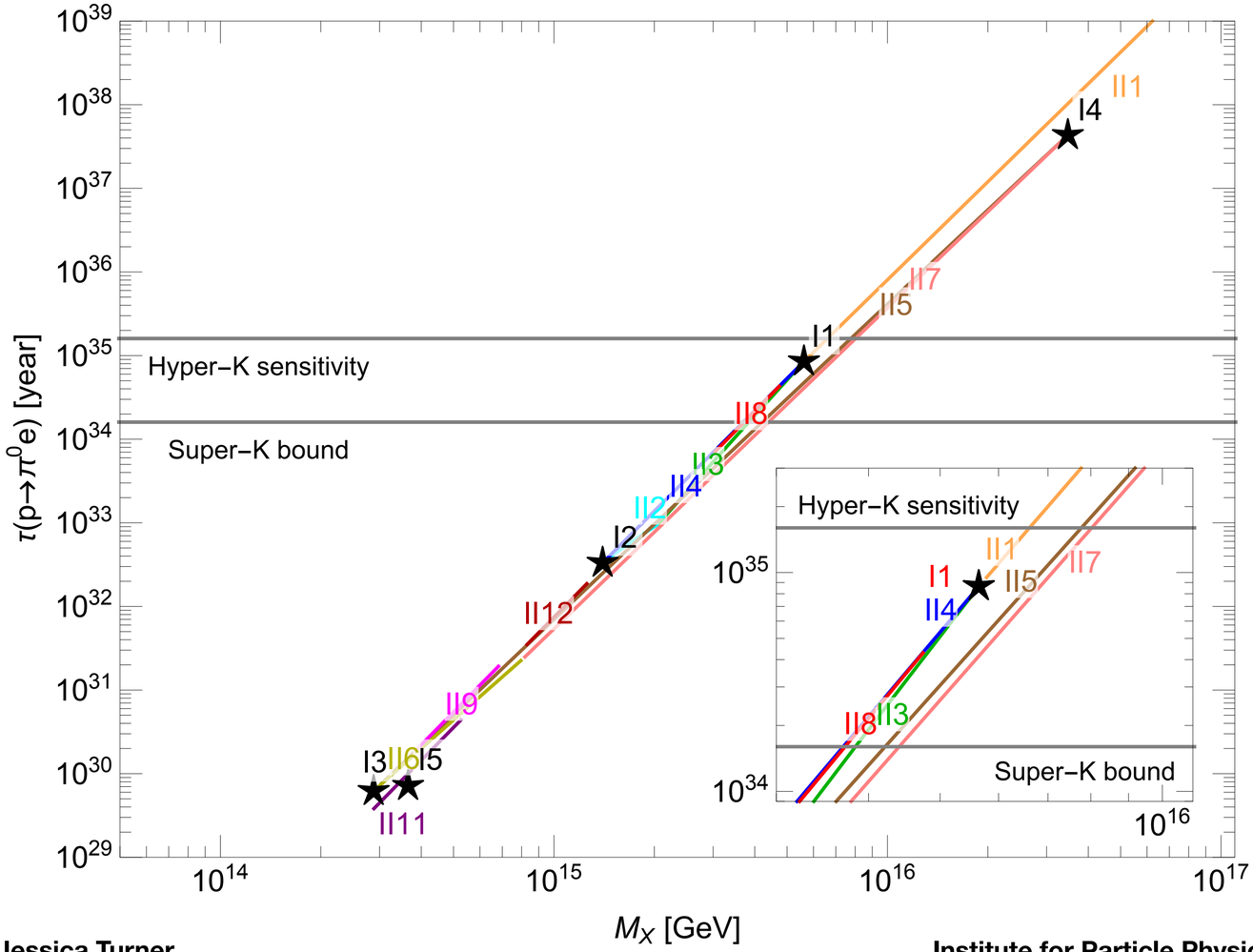
$SO(10)$	$\xrightarrow[\text{Higgs}]{\text{defect}}$	G_3	$\xrightarrow[\text{Higgs}]{\text{defect}}$	G_2	$\xrightarrow[\text{Higgs}]{\text{defect}}$	G_1	$\xrightarrow[\text{Higgs}]{\text{defect}}$	G_{SM}	Observable strings?
III1:	$\xrightarrow[\mathbf{54}]{\text{m,s}}$	G_{422}^C	$\xrightarrow[\mathbf{210}]{\text{w}}$	G_{422}	$\xrightarrow[\mathbf{45}]{\text{m}}$	G_{421}	$\xrightarrow[\overline{\mathbf{126}}]{\text{s}}$		✓
III2:	$\xrightarrow[\mathbf{54}]{\text{m,s}}$	G_{422}^C	$\xrightarrow[\mathbf{210}]{\text{w}}$	G_{422}	$\xrightarrow[\mathbf{45}]{\text{m}}$	G_{3221}	$\xrightarrow[\overline{\mathbf{126}}]{\text{s}}$		✓
III3:	$\xrightarrow[\mathbf{54}]{\text{m,s}}$	G_{422}^C	$\xrightarrow[\mathbf{210}]{\text{w}}$	G_{422}	$\xrightarrow[\mathbf{210}]{\text{m}}$	G_{3211}	$\xrightarrow[\overline{\mathbf{126}}]{\text{s}}$		✓
III4:	$\xrightarrow[\mathbf{54}]{\text{m,s}}$	G_{422}^C	$\xrightarrow[\mathbf{210}]{\text{m}}$	G_{3221}^C	$\xrightarrow[\mathbf{45}]{\text{w}}$	G_{3221}	$\xrightarrow[\overline{\mathbf{126}}]{\text{s}}$		✓
III5:	$\xrightarrow[\mathbf{54}]{\text{m,s}}$	G_{422}^C	$\xrightarrow[\mathbf{210}]{\text{m}}$	G_{3221}^C	$\xrightarrow[\mathbf{45}]{\text{m,w}}$	G_{3211}	$\xrightarrow[\overline{\mathbf{126}}]{\text{s}}$		✓
III6:	$\xrightarrow[\mathbf{54}]{\text{m,s}}$	G_{422}^C	$\xrightarrow[\mathbf{45}]{\text{m,w}}$	G_{3221}	$\xrightarrow[\mathbf{45}]{\text{m}}$	G_{3211}	$\xrightarrow[\overline{\mathbf{126}}]{\text{s}}$		✓
III7:	$\xrightarrow[\mathbf{210}]{\text{m,s}}$	G_{3221}^C	$\xrightarrow[\mathbf{45}]{\text{w}}$	G_{3221}	$\xrightarrow[\mathbf{45}]{\text{m}}$	G_{3211}	$\xrightarrow[\overline{\mathbf{126}}]{\text{s}}$		✓
III8:	$\xrightarrow[\mathbf{210}]{\text{m}}$	G_{422}	$\xrightarrow[\mathbf{45}]{\text{m}}$	G_{3221}	$\xrightarrow[\mathbf{45}]{\text{m}}$	G_{3211}	$\xrightarrow[\overline{\mathbf{126}}]{\text{s}}$		✓
III9:	$\xrightarrow[\mathbf{54}]{\text{m,s}}$	G_{422}^C	$\xrightarrow[\mathbf{45}]{\text{m}}$	G_{421}	$\xrightarrow[\mathbf{45}]{\text{m}}$	G_{3211}	$\xrightarrow[\overline{\mathbf{126}}]{\text{s}}$		✓
III10:	$\xrightarrow[\mathbf{210}]{\text{m}}$	G_{422}	$\xrightarrow[\mathbf{45}]{\text{m}}$	G_{421}	$\xrightarrow[\mathbf{45}]{\text{m}}$	G_{3211}	$\xrightarrow[\overline{\mathbf{126}}]{\text{s}}$		✓

$SO(10)$	$\xrightarrow[\text{Higgs}]{\text{defect}}$	G_2	$\xrightarrow[\text{Higgs}]{\text{defect}}$	G_1	$\xrightarrow[\text{Higgs}]{\text{defect}}$	G_{SM}	Observable strings?
II1:	$\xrightarrow[\mathbf{210}]{\text{m}}$	G_{422}	$\xrightarrow[\mathbf{45}]{\text{m}}$	G_{3221}	$\xrightarrow[\overline{\mathbf{126}}]{\text{s}}$		✓
II2:	$\xrightarrow[\mathbf{54}]{\text{m,s}}$	G_{422}^C	$\xrightarrow[\mathbf{210}]{\text{m}}$	G_{3221}^C	$\xrightarrow[\overline{\mathbf{126}}]{\text{s,w}}$		✗
II3:	$\xrightarrow[\mathbf{54}]{\text{m,s}}$	G_{422}^C	$\xrightarrow[\mathbf{45}]{\text{m,w}}$	G_{3221}	$\xrightarrow[\overline{\mathbf{126}}]{\text{s}}$		✓
II4:	$\xrightarrow[\mathbf{210}]{\text{m,s}}$	G_{3221}^C	$\xrightarrow[\mathbf{45}]{\text{w}}$	G_{3221}	$\xrightarrow[\overline{\mathbf{126}}]{\text{s}}$		✓
II5:	$\xrightarrow[\mathbf{210}]{\text{m}}$	G_{422}	$\xrightarrow[\mathbf{45}]{\text{m}}$	G_{421}	$\xrightarrow[\overline{\mathbf{126}}]{\text{s}}$		✓
II6:	$\xrightarrow[\mathbf{54}]{\text{m,s}}$	G_{422}^C	$\xrightarrow[\mathbf{45}]{\text{m}}$	G_{421}	$\xrightarrow[\overline{\mathbf{126}}]{\text{s}}$		✓
II7:	$\xrightarrow[\mathbf{54}]{\text{m,s}}$	G_{422}^C	$\xrightarrow[\mathbf{210}]{\text{w}}$	G_{422}	$\xrightarrow[\overline{\mathbf{126}},\mathbf{45}]{\text{m}}$		✗
II8:	$\xrightarrow[\mathbf{45}]{\text{m}}$	G_{3221}	$\xrightarrow[\mathbf{45}]{\text{m}}$	G_{3211}	$\xrightarrow[\overline{\mathbf{126}}]{\text{s}}$		✓
II9:	$\xrightarrow[\mathbf{210}]{\text{m,s}}$	G_{3221}^C	$\xrightarrow[\mathbf{45}]{\text{m,w}}$	G_{3211}	$\xrightarrow[\overline{\mathbf{126}}]{\text{s}}$		✓
II10:	$\xrightarrow[\mathbf{210}]{\text{m}}$	G_{422}	$\xrightarrow[\mathbf{210}]{\text{m}}$	G_{3211}	$\xrightarrow[\overline{\mathbf{126}}]{\text{s}}$		✓
II11:	$\xrightarrow[\mathbf{54}]{\text{m,s}}$	G_{422}^C	$\xrightarrow[\mathbf{210}]{\text{m,w}}$	G_{3211}	$\xrightarrow[\overline{\mathbf{126}}]{\text{s}}$		✓
II12:	$\xrightarrow[\mathbf{45}]{\text{m}}$	G_{421}	$\xrightarrow[\mathbf{45}]{\text{m}}$	G_{3211}	$\xrightarrow[\overline{\mathbf{126}}]{\text{s}}$		✓

$SO(10)$	$\xrightarrow[\text{Higgs}]{\text{defect}}$	G_4	$\xrightarrow[\text{Higgs}]{\text{defect}}$	G_3	$\xrightarrow[\text{Higgs}]{\text{defect}}$	G_2	$\xrightarrow[\text{Higgs}]{\text{defect}}$	G_1	$\xrightarrow[\text{Higgs}]{\text{defect}}$	G_{SM}	Observable strings?
IV1:	$\xrightarrow[\mathbf{54}]{\text{m,s}}$	G_{422}^C	$\xrightarrow[\mathbf{210}]{\text{m}}$	G_{3221}^C	$\xrightarrow[\mathbf{45}]{\text{w}}$	G_{3221}	$\xrightarrow[\mathbf{45}]{\text{m}}$	G_{3211}	$\xrightarrow[\overline{\mathbf{126}}]{\text{s}}$		✓
IV2:	$\xrightarrow[\mathbf{54}]{\text{m,s}}$	G_{422}^C	$\xrightarrow[\mathbf{210}]{\text{w}}$	G_{422}	$\xrightarrow[\mathbf{45}]{\text{m}}$	G_{3221}	$\xrightarrow[\mathbf{45}]{\text{m}}$	G_{3211}	$\xrightarrow[\overline{\mathbf{126}}]{\text{s}}$		✓
IV3:	$\xrightarrow[\mathbf{54}]{\text{m,s}}$	G_{422}^C	$\xrightarrow[\mathbf{210}]{\text{w}}$	G_{422}	$\xrightarrow[\mathbf{45}]{\text{m}}$	G_{421}	$\xrightarrow[\mathbf{45}]{\text{m}}$	G_{3211}	$\xrightarrow[\overline{\mathbf{126}}]{\text{s}}$		✓

Proton decay and GWs as complementary windows

- Assume minimal survival hypothesis
- Perform two-loop RGE analysis to determine GUT scale (i.e. proton decay rate) in terms intermediate breaking scales (due to unification).



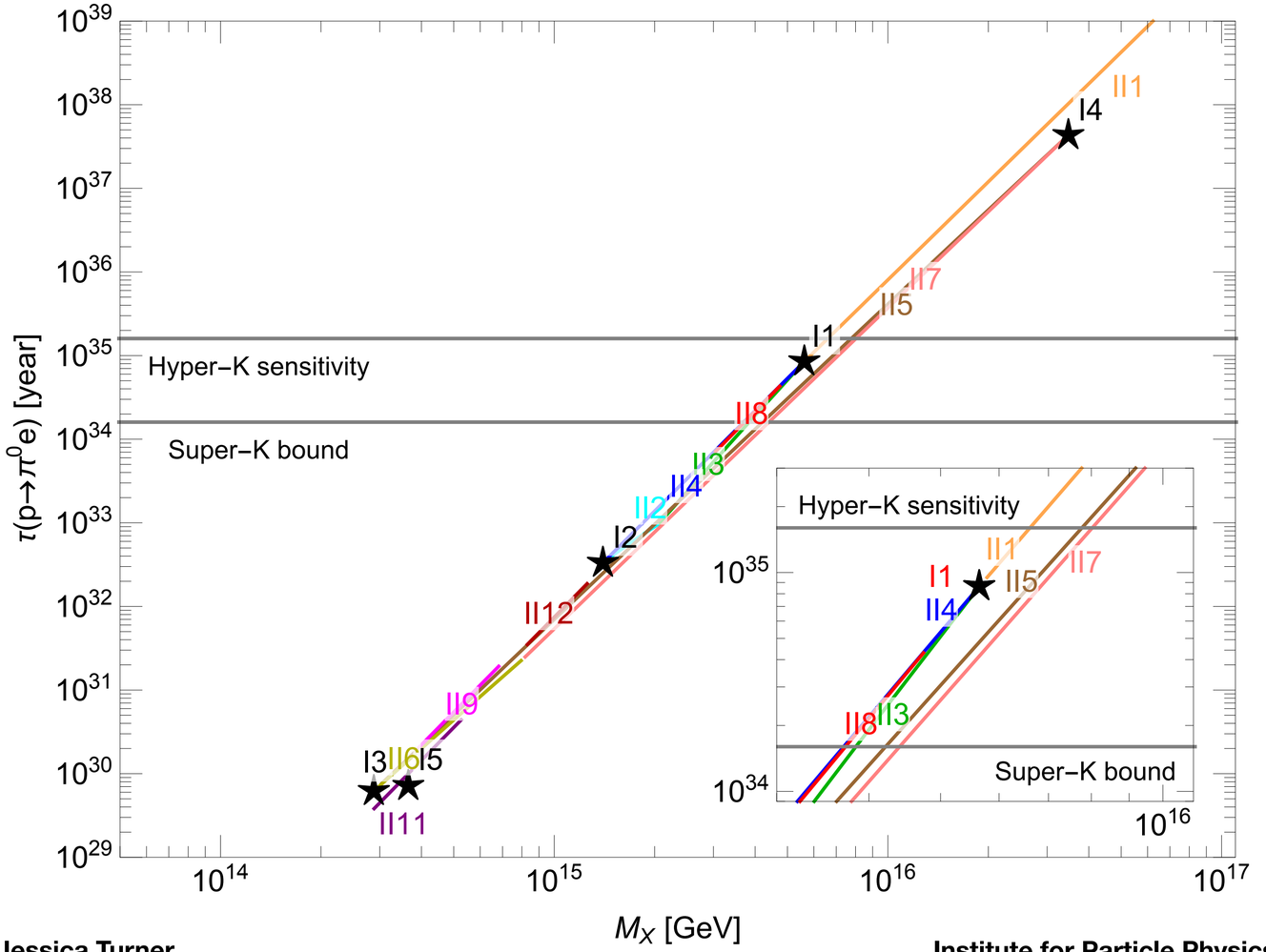
Breaking chains allowed by Super-K:
I1, I4, II1, 3, 4, 5, 7, 8

$$\mathrm{I1}: \mathrm{SO}(10) \xrightarrow{M_X} G_{3221} \xrightarrow{M_1} G_{SM}$$

$$\mathrm{II1}: \mathrm{SO}(10) \xrightarrow{M_X} G_{422} \xrightarrow{M_2} G_{3221} \xrightarrow{M_1} G_{SM}$$

Proton decay and GWs as complementary windows

- Assume minimal survival hypothesis
- Perform two-loop RGE analysis to determine GUT scale (i.e. proton decay rate) in terms intermediate breaking scales (see backup details)



Breaking chains allowed by Super-K:
I1, I4, II1, 3, 4, 5, 7, 8

$$\text{I1} : \text{SO}(10) \xrightarrow{M_X} G_{3221} \xrightarrow{M_1} G_{SM}$$

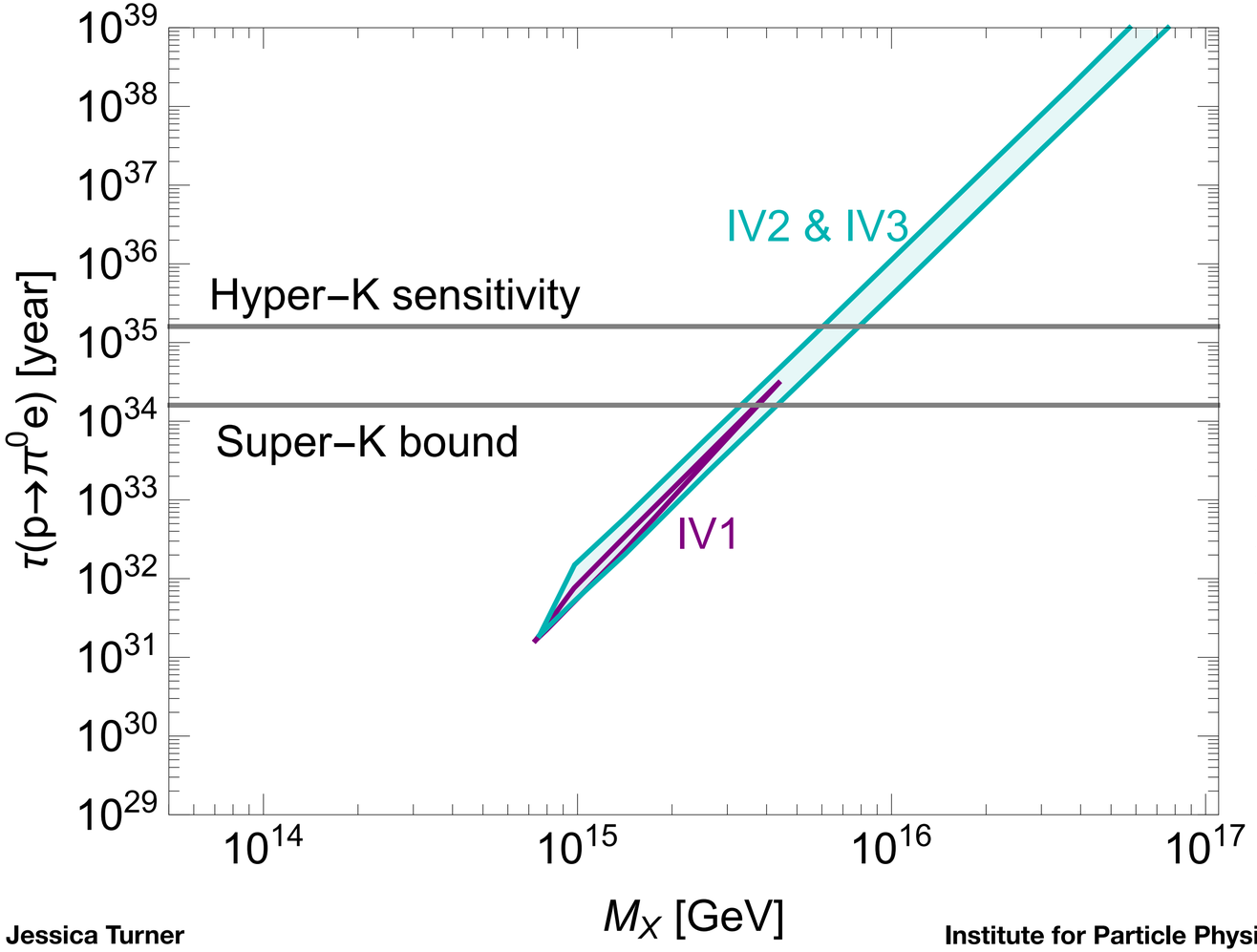
$$\text{II1} : \text{SO}(10) \xrightarrow{M_X} G_{422} \xrightarrow{M_2} G_{3221} \xrightarrow{M_1} G_{SM}$$

Parametrises PD/GUT scale

Parametrises GW scale

Proton decay and GWs as complementary windows

- Assume minimal survival hypothesis
- Perform two-loop RGE analysis to determine GUT scale (i.e. proton decay rate) in terms intermediate breaking scales (see backup details)



Breaking chains allowed by Super-K:
IV2 & IV3

$$\text{IV2}: \text{SO}(10) \xrightarrow{M_X} G_{422}^C \xrightarrow{M_4} G_{422} \xrightarrow{M_3} G_{3221} \xrightarrow{M_2} G_{3211} \xrightarrow{M_1} G_{SM}$$

$$\text{IV3}: \text{SO}(10) \xrightarrow{M_X} G_{422}^C \xrightarrow{M_4} G_{422} \xrightarrow{M_3} G_{421} \xrightarrow{M_2} G_{3211} \xrightarrow{M_1} G_{SM}$$

Regions due to more free parameters

Proton decay and GWs as complementary windows

- RGE provide information on GUT but also intermediate scale breaking.
- For **type (c) chains** an observable **GW signal** is produced in the **final SSB**.
- We assume Nambu-Goto string $\Longrightarrow$ gravitational radiation primary emission.
- Determine M_1 we can determine when cosmic string formed $\Longrightarrow$ string tension

$$\mu \approx 2\pi v^2$$

$$v = |\langle \phi \rangle|$$

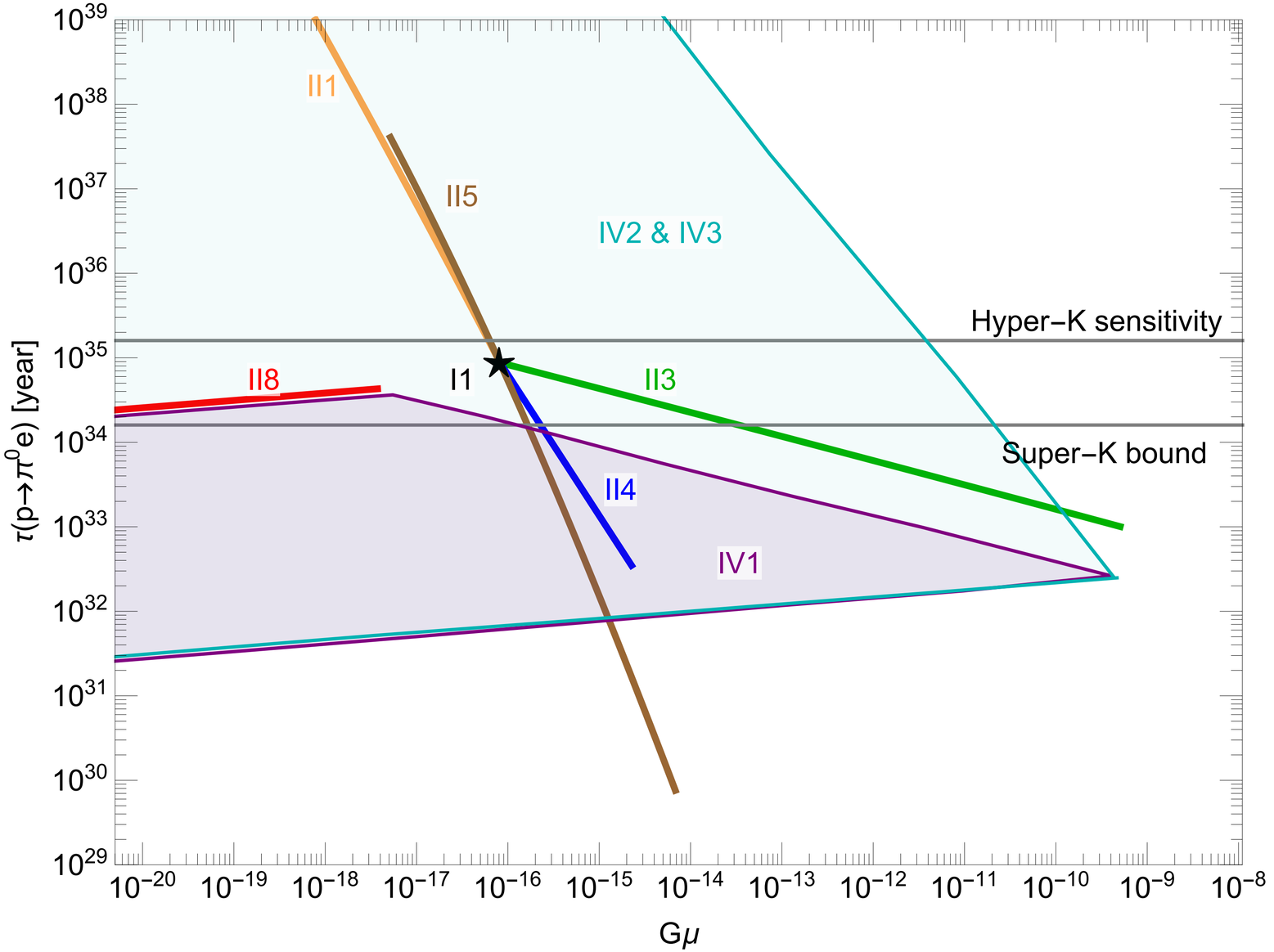
vev of Higgs that breaks U(1) gauge symmetry

$$M_1^2 = M_{Z'}^2 = 4\pi\alpha v^2 \implies G\mu = \frac{M_1^2}{2\alpha M_{PL}^2}$$

α of U(1) that get broken

RGE correlates M_1 with M_X and therefore $G\mu$ can be correlated with $\tau(p \to e^+\pi^0)$

Proton decay and GWs as complementary windows



Summary

- non-SUSY $SO(10)$ Pati Salam type provide unification: **31 breaking chains**
- Two-loop RGE, **17 not excluded** by Super-K lower bound PD.

Chain	$G\mu$ after Hyper-K (no proton decay)
I1	excluded
II1:	$G\mu \lesssim 1.5 \times 10^{-17}$
II3:	excluded
II4:	excluded
II5:	$G\mu \simeq 5.1 \times 10^{-18} - 6.3 \times 10^{-17}$
II8:	excluded
III1:	$G\mu \simeq 1.3 \times 10^{-18} - 1.6 \times 10^{-15}$
III2:	$G\mu \lesssim 5.0 \times 10^{-12}$
III3:	$G\mu \lesssim 6.2 \times 10^{-14}$
III4:	excluded
III6:	excluded
III7:	excluded
III8:	excluded
III10:	$G\mu \lesssim 1.1 \times 10^{-21}$
IV1:	excluded
IV2:	$G\mu \lesssim 9.4 \times 10^{-13}$
IV3:	$G\mu \lesssim 9.4 \times 10^{-13}$

Testable by LIGO, DECIGO, AEDGE, C, ET, MAGIS..

If HyperK **does not** observe PD, 9 chains excluded

8 survivors! If we observe GW signal from cosmic string **larger upper bounds** (see table) we can exclude those breaking chains

If we observe PD, M_1 determined and so is GW signal. Correlations matters!

Summary

- Proton decay is a smoking gun of GUTs and the next generation of neutrino oscillation experiments will probe the ultrahigh GUT scale determination of the proton lifetime.

- Topological defects are prodigiously produced during GUT symmetry breaking. The undesirable kind are monopoles and domain walls which, if existent, must have been inflated away. As defects cosmic strings are “well behaved” and can generate GW.

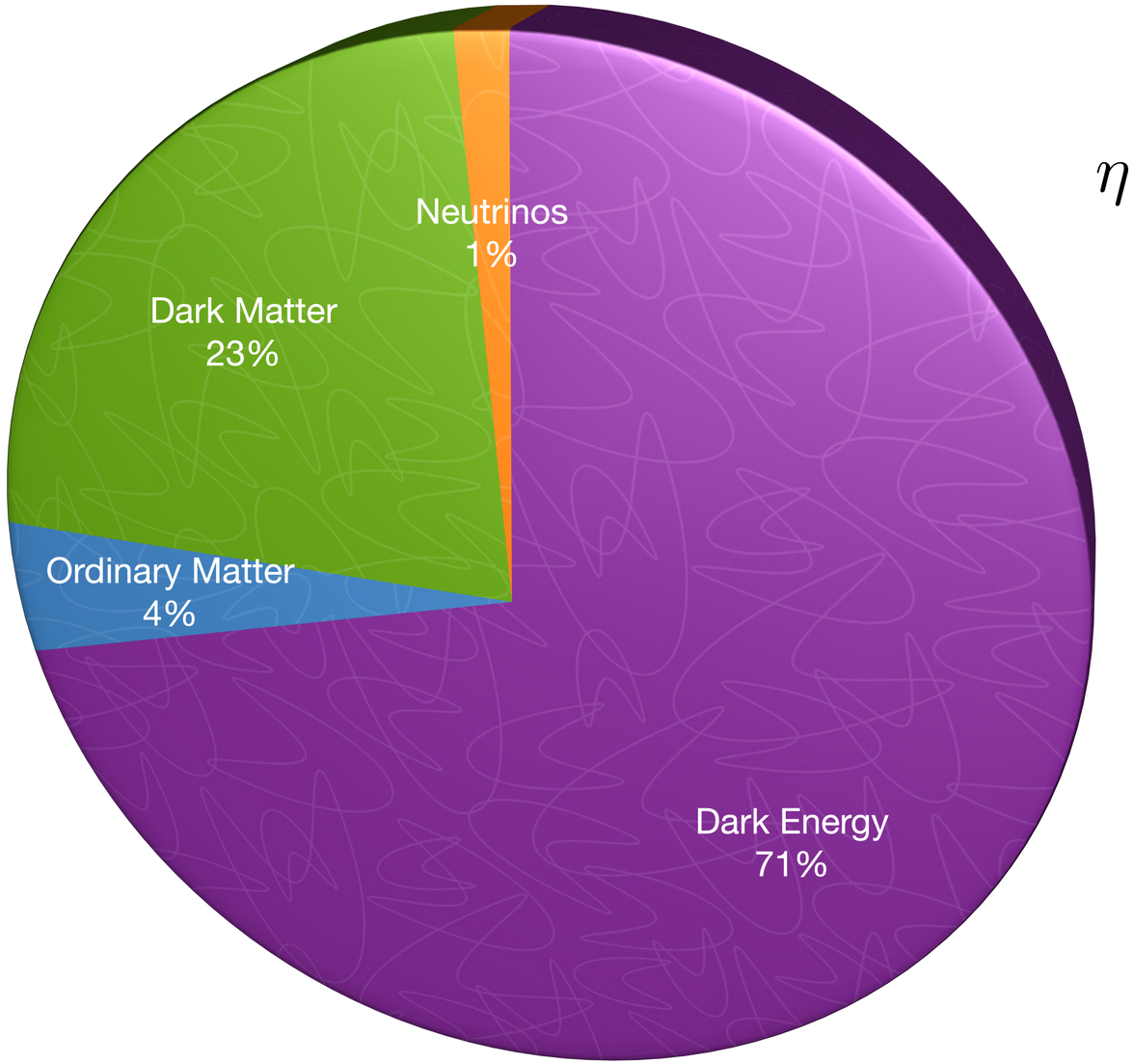
- The presence/absence and nature is determined by the inflationary scale.

- Non-observation is useful and can exclude many GUT breaking chains. Naturally observation would be more exciting in which case correlation between terrestrial and cosmological observables is key.

Part I ends

Part II begins

Matter-antimatter asymmetry

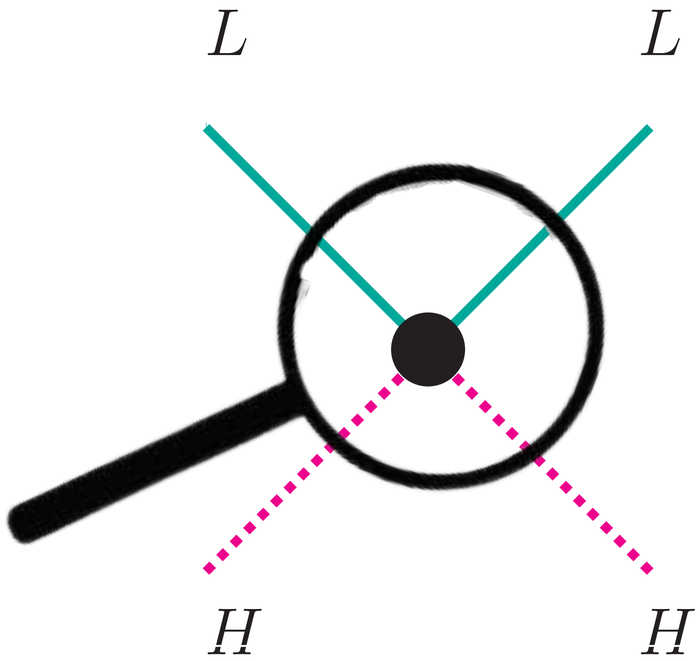


$$\eta = \frac{n_B}{n_\gamma} \sim 6 \times 10^{-10}$$

Possible connection to neutrino masses

Standard Model is an effective theory which contains non-renormalisable operators

$$\mathcal{L} \supset -Y_{ij}\frac{L^i H L^j H}{2M} + \mathcal{O}\left(\frac{1}{M^2}\right) + \text{h.c}$$



Possible connection to neutrino masses

After SSB a Majorana mass is produced for the active neutrinos **Weinberg, 1979**

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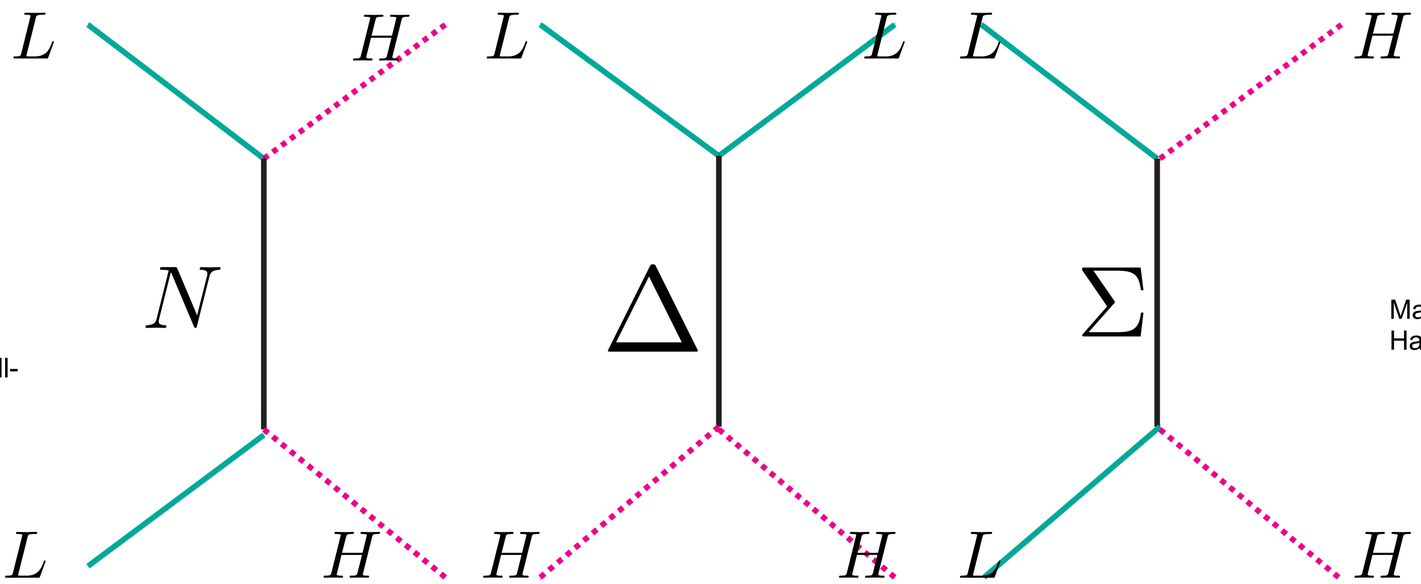

Minkowski, Yanagida, Glashow, Gell-Mann, Ramond, Slansky, Mohapatra, Senjanovic

Magg, Wetterich, Lazarides, Shafi. Mohapatra, Senjanovic, Schecter, Valle

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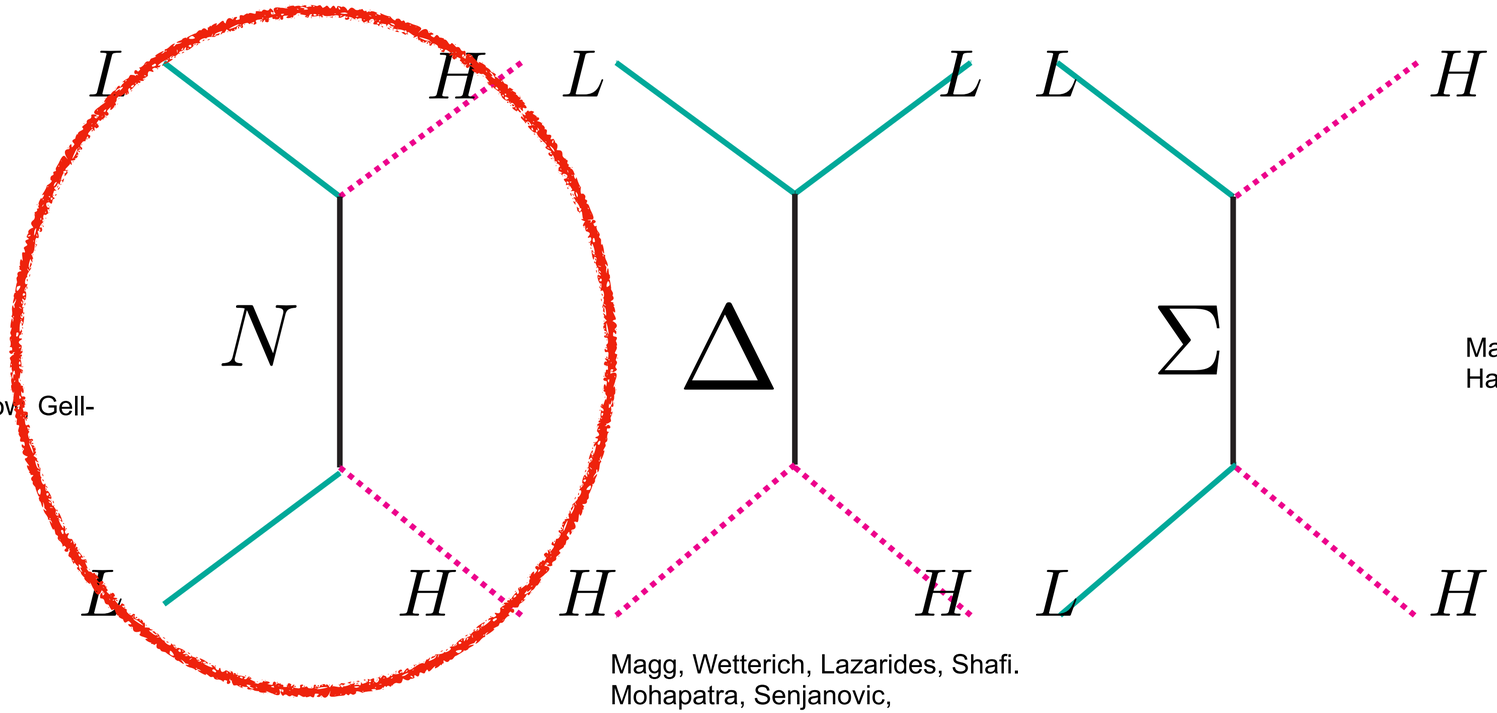

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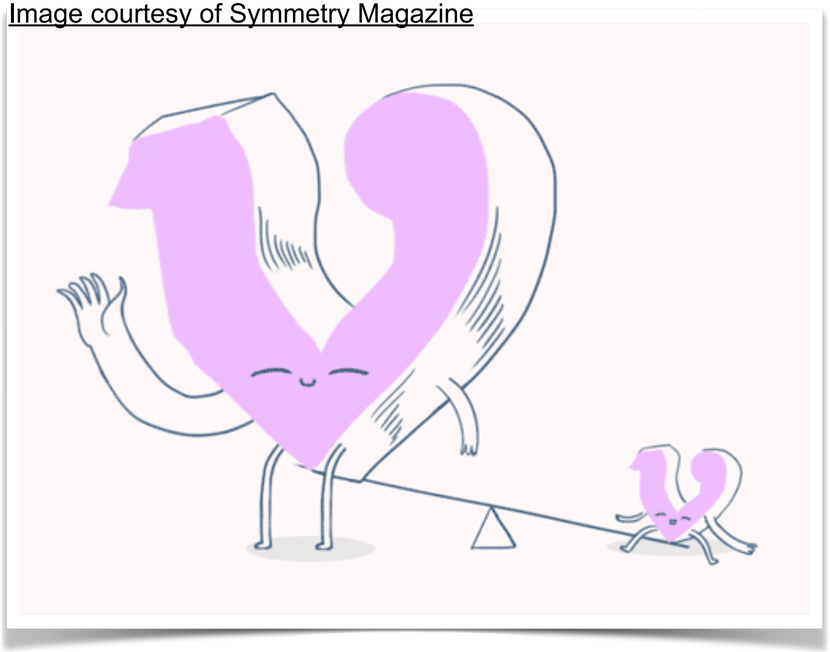
Possible connection to neutrino masses

$$\mathcal{L} \supset -\overline{L_\alpha} Y_{\alpha i} N_i \tilde{H} - \frac{1}{2}\overline{N_i^C} M_{N_i} N_i + \text{h.c.}$$

After diagonalising the mass matrix $$m_\nu \approx \frac{m_D m_D^T}{M_N} = \frac{Y^2 v^2}{M_N}$$

Image courtesy of Symmetry Magazine



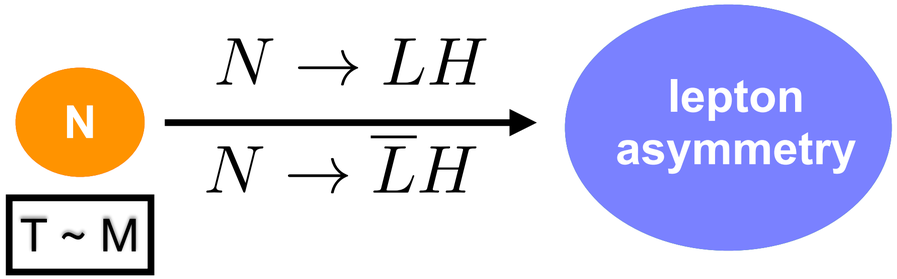
Sakharov's Conditions

- ☑ Baryon number violation
- ☑ C & CP-violation
- ☑ Departure from thermal equilibrium

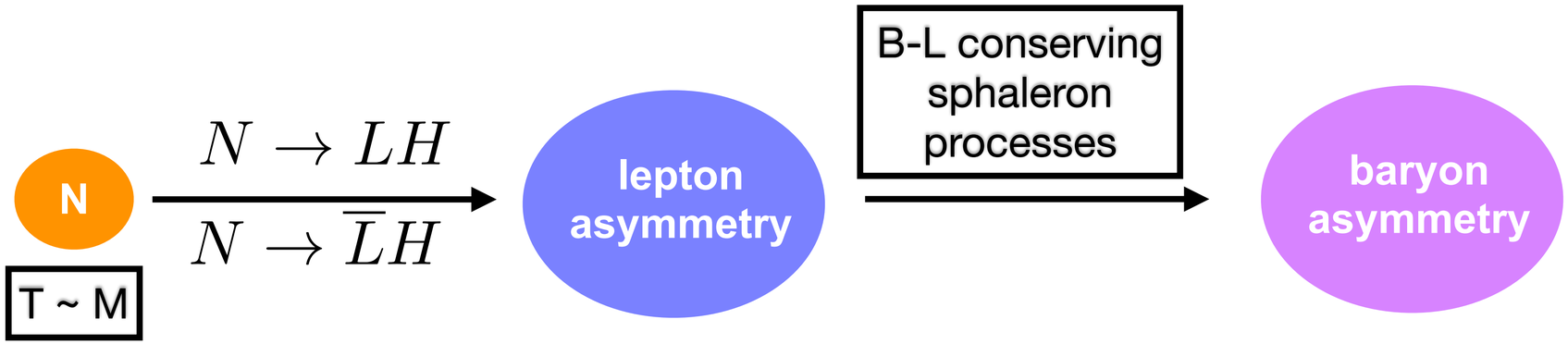
Thermal leptogenesis

Fukugita, Yanagida

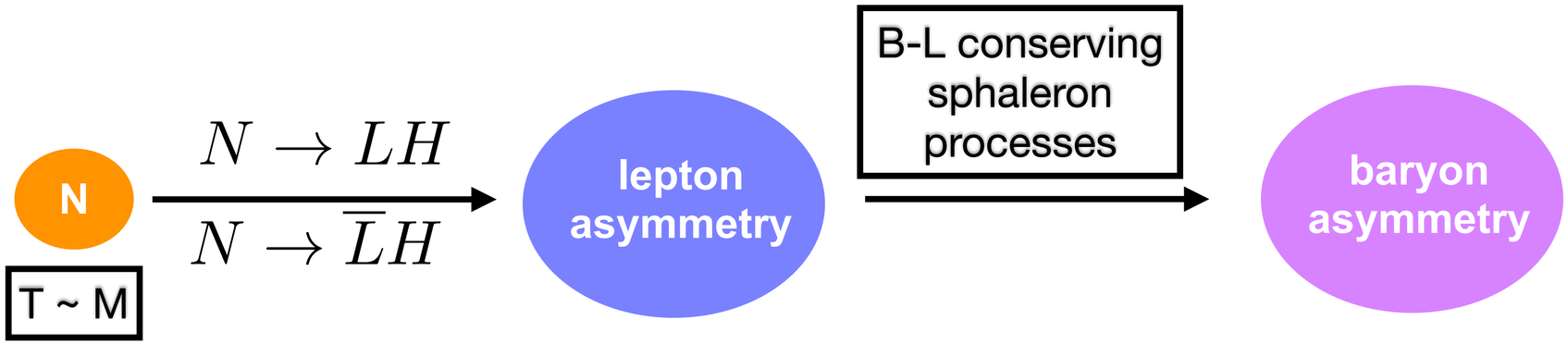
Thermal leptogenesis



Thermal leptogenesis

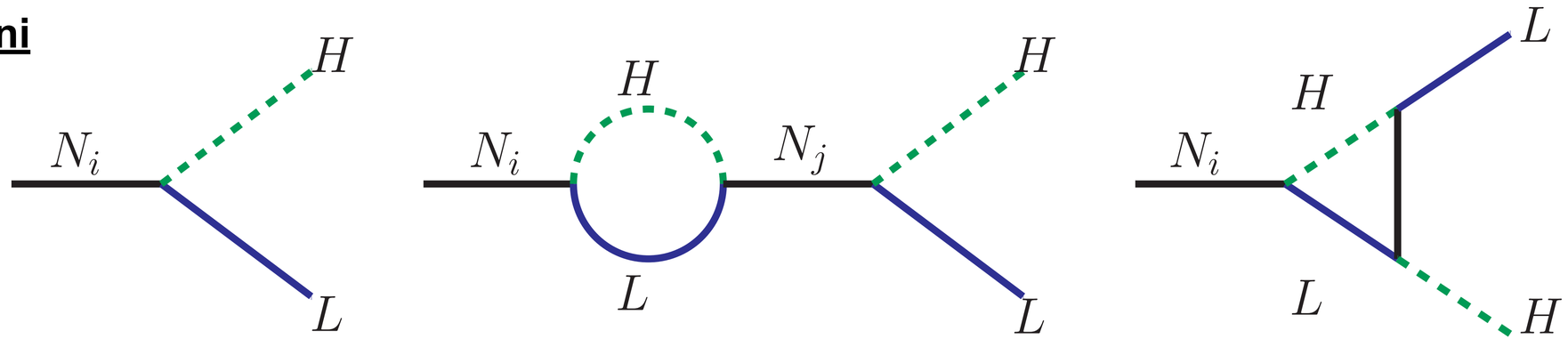


Thermal leptogenesis



Decay asymmetry from interference between tree and loop level diagrams

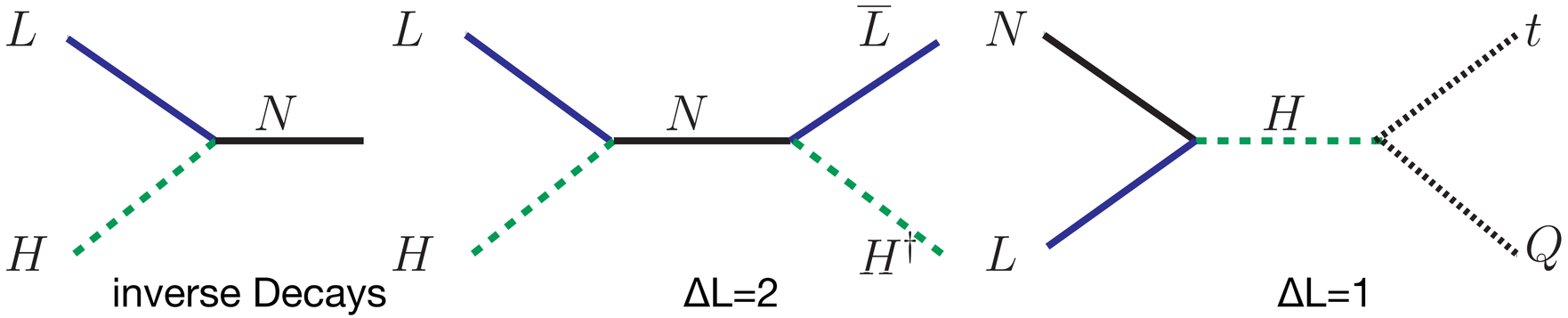
Covi, Roulet, Vissani

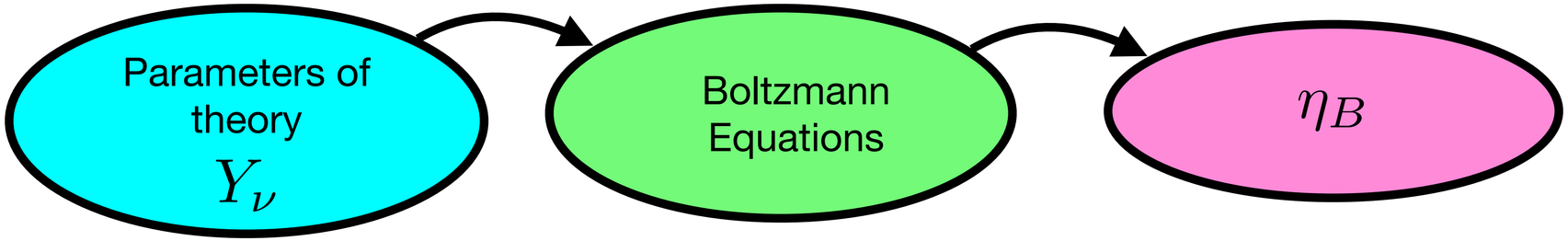


$$\epsilon_i = \frac{\Gamma_i - \overline{\Gamma_i}}{\Gamma_i + \overline{\Gamma_i}}$$

Thermal leptogenesis

Washout and scattering processes





$$\frac{dn_{N_i}}{dz} = -\,D_i(n_{N_i} - n_{N_i}^{\rm eq}),$$

source sink

$$\frac{dn_{B-L}}{dz} = \sum_{i=1}^{3}\left(\epsilon^{(i)} D_i(n_{N_i} - n_{N_i}^{\rm eq}) - W_i n_{B-L}\right).$$

Primordial Black holes induced leptogenesis

Work in collaboration with Yuber Perez Gonzalez: **2010.03565**

Astrophysical BHs require $M > 3M_\odot$

For smaller BH mass require large perturbations in the early Universe : **bubble collision, collapse of density perturbations…**

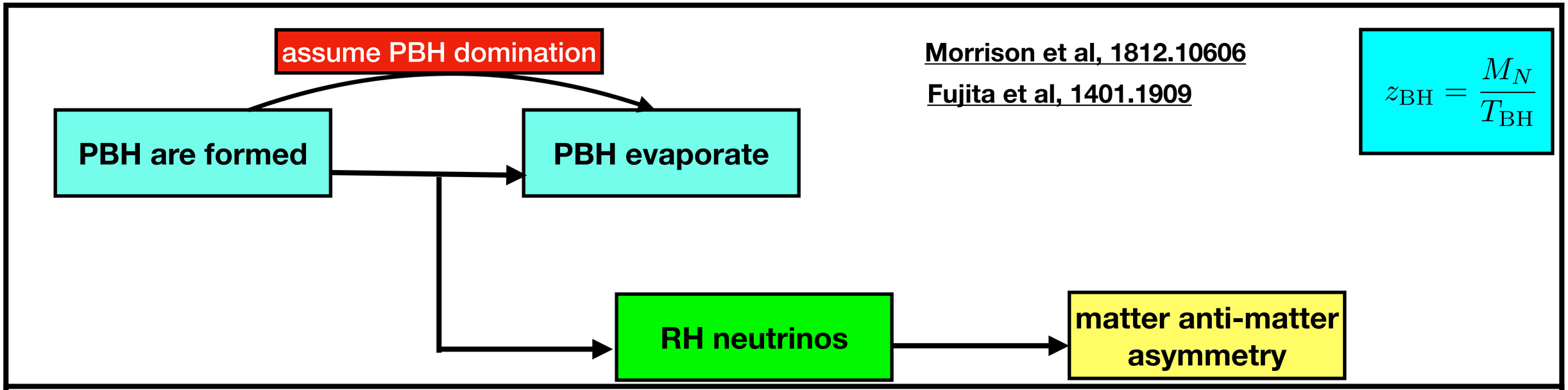
Carr et al (0912.5297)

PBHs evaporate by emitting thermal spectrum of particles **Hawking, 1975**

$$\frac{dM}{dt} = -\sum_a \frac{g_a}{2\pi^2} \int_0^\infty \frac{\sigma_{\rm abs}^{s_a}(GMp)\, p^3\, dp}{\exp[E_a(p)/T_{\rm BH}] - (-1)^{2s_a}} \qquad T_{\rm BH} = \frac{1}{8\pi GM} \approx 1.06 \left(\frac{10^{13}\ {\rm g}}{M}\right)\ {\rm GeV}\,.$$

PBHs are totally indiscriminate in their particle production: just need T_{BH} to be close to particle mass

Primordial Black holes induced leptogenesis



Morrison et al, 1812.10606

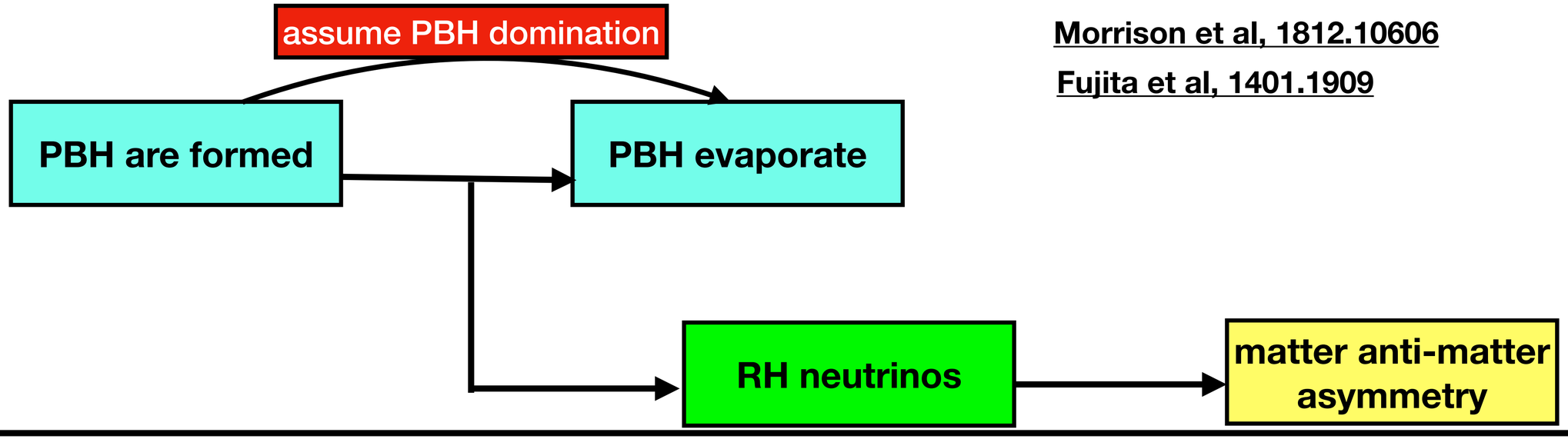
Fujita et al, 1401.1909

$$z_{\rm BH} = \frac{M_N}{T_{\rm BH}}$$

$$aH\frac{dn_{N_1}}{da} = -(n_{N_1} - n_{N_1}^{\rm eq})\Gamma_{N_1}^{T} + n_{\rm BH}\widetilde{\Gamma}_{N_1}^{\rm BH}\,,$$

$$aH\frac{dn_{\alpha\beta}^{\rm B-L}}{da} = \epsilon_{\alpha\beta}^{(1)}\left[\left(n_{N_1} - n_{N_1}^{\rm eq}\right)\Gamma_{N_1}^{T} + n_{\rm BH}\widetilde{\Gamma}_{N_1}^{\rm BH}\right] - \mathcal{W}_{\alpha\beta}$$

Primordial Black holes induced leptogenesis



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contribution to RHN population from thermal plasma

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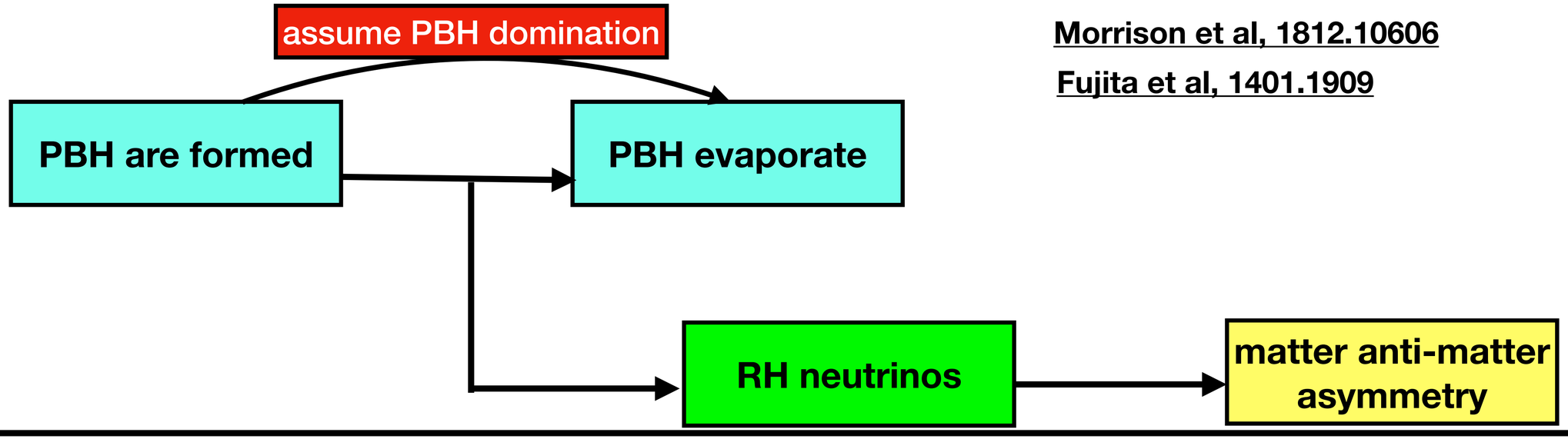

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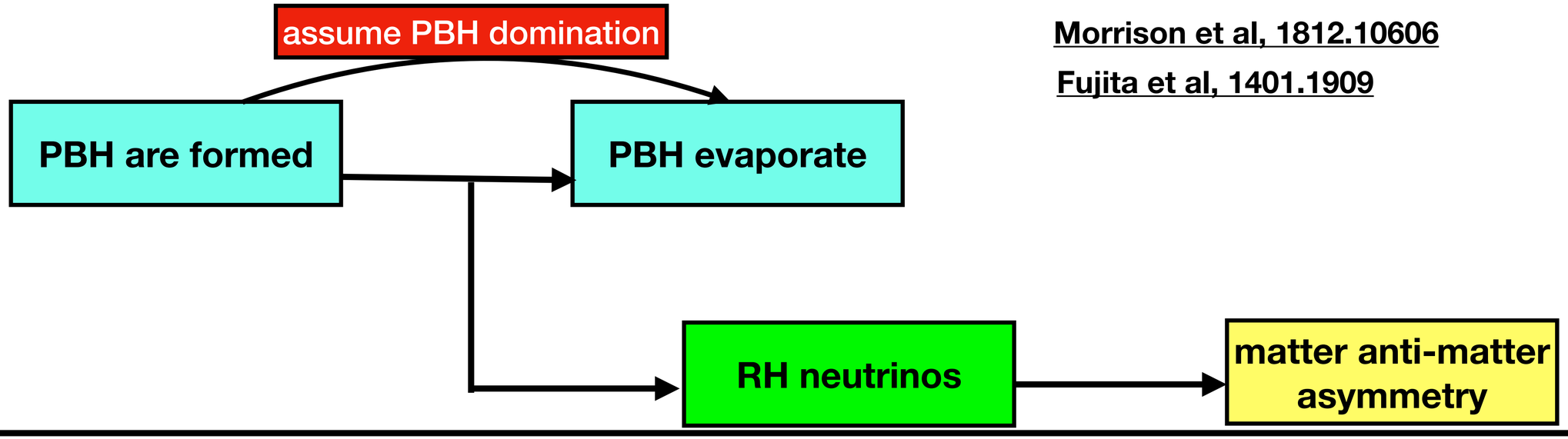
Primordial Black holes induced leptogenesis



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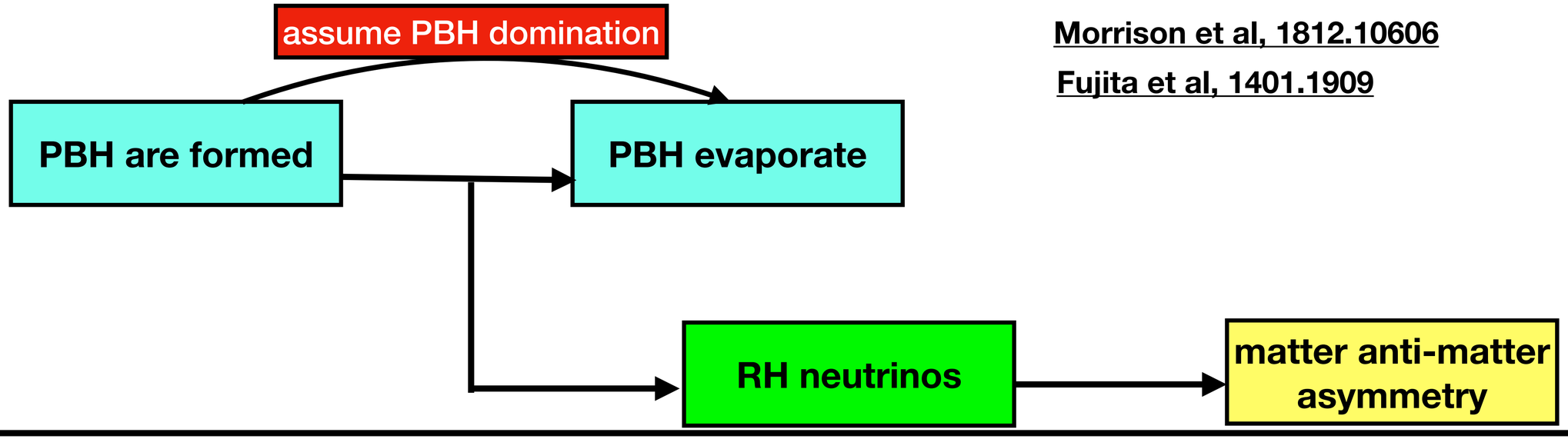

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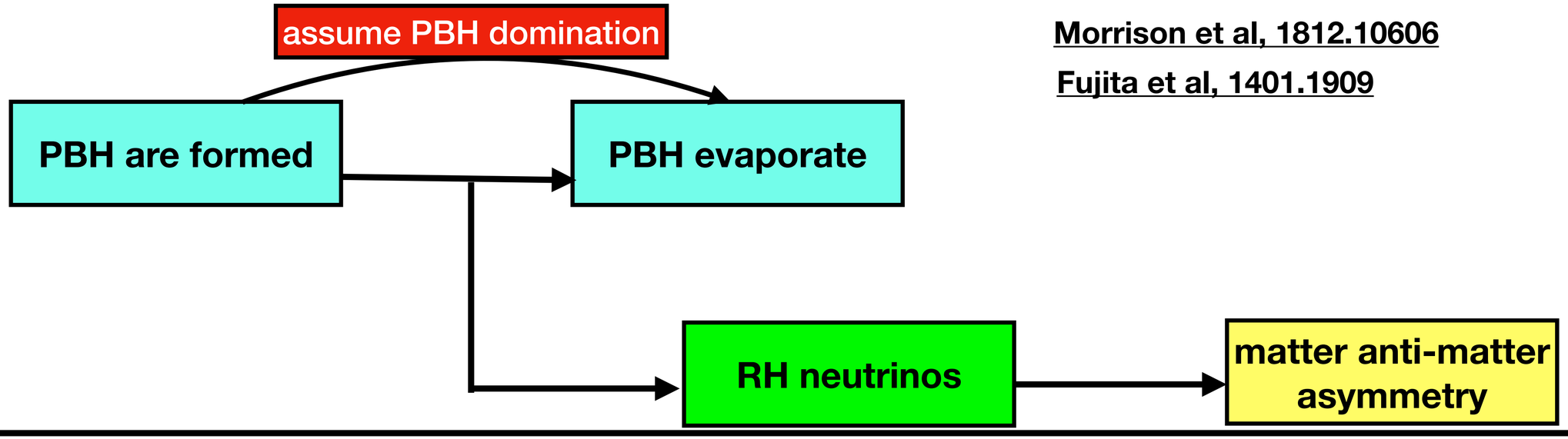
thermal averaged decay of RHN from PBH evaporation (function of z_{BH})

Primordial Black holes induced leptogenesis



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contribution to RHN population from PBH evaporation

lepton asymmetry production from RHN decays and inverse decays

Washout effects only sensitive to neutrino parameters

$$aH\frac{dn_{\alpha\beta}^{\rm B-L}}{da} = \epsilon_{\alpha\beta}^{(1)}\left[\left(n_{N_1} - n_{N_1}^{\rm eq}\right)\Gamma_{N_1}^{T} + n_{\rm BH}\widetilde{\Gamma}_{N_1}^{\rm BH}\right] - \mathcal{W}_{\alpha\beta}$$

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Primordial Black holes induced leptogenesis

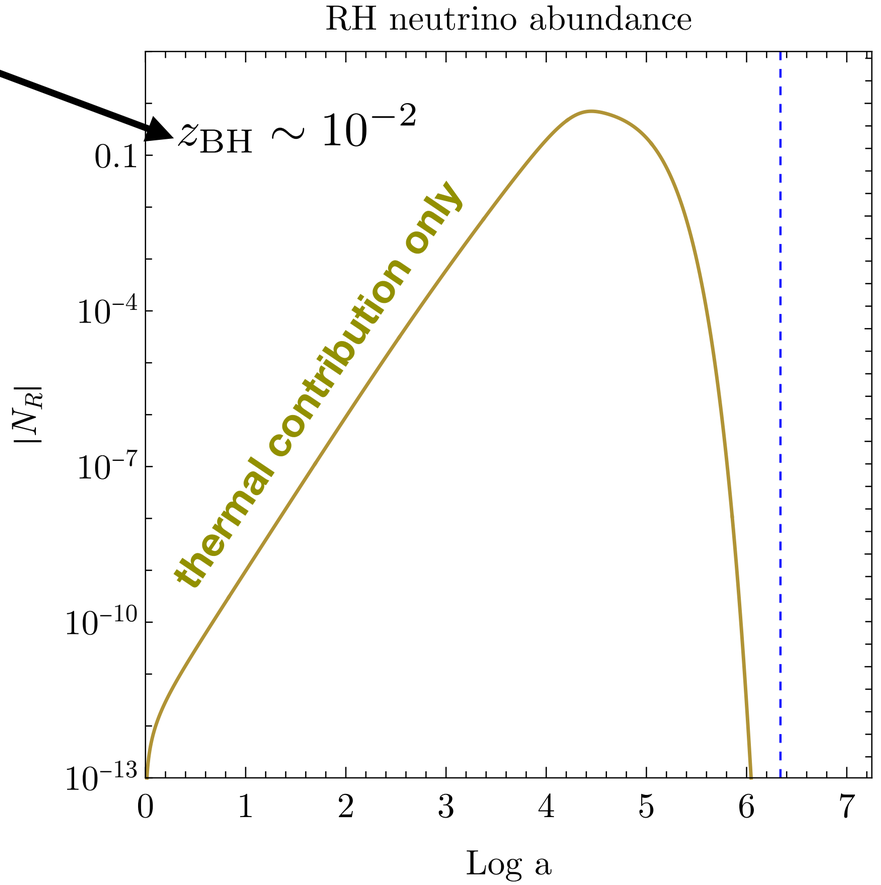
A. PBH evaporate **before/during** RHNs are thermally produced from plasma → PBH evaporation creates an initial condition which gets erased by fast interactions in the plasma

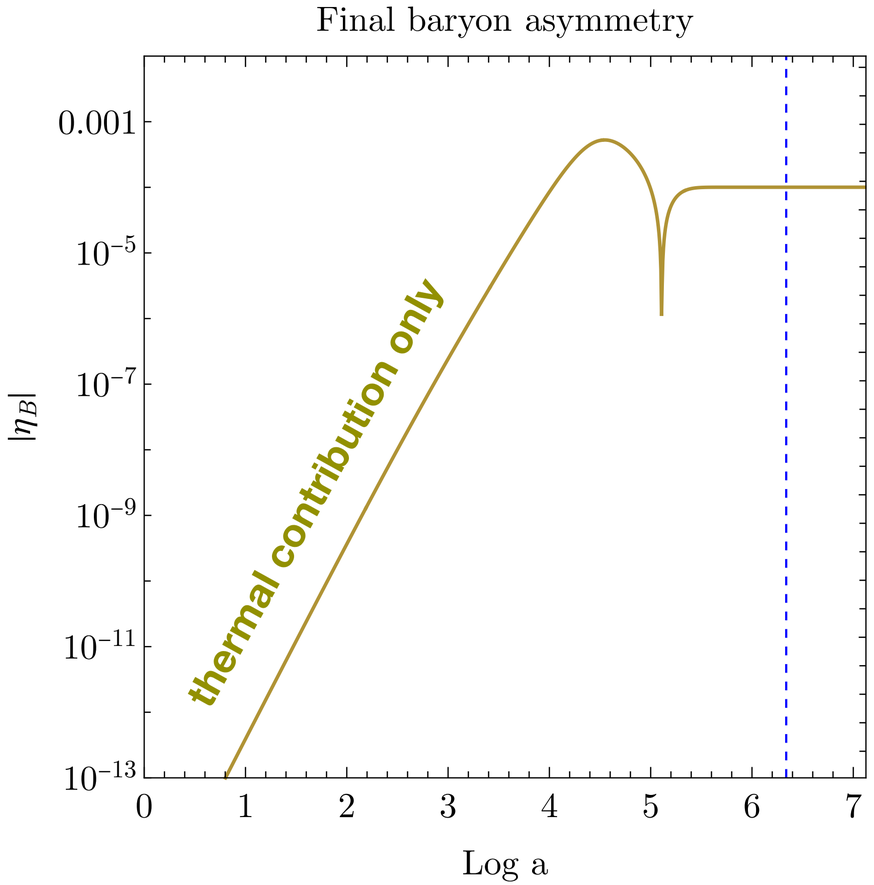
B. PBH evaporation happens **shortly after** thermal leptogenesis

$$M_i = 1.7\,\mathrm{g} \quad \beta_i = 10^{-3} \quad M_N = 10^{11}\,\mathrm{GeV}$$

temperature of PBH can exceed RHN mass athermal not suppressed

$$z_{\rm BH} = \frac{M_N}{T_{\rm BH}}$$





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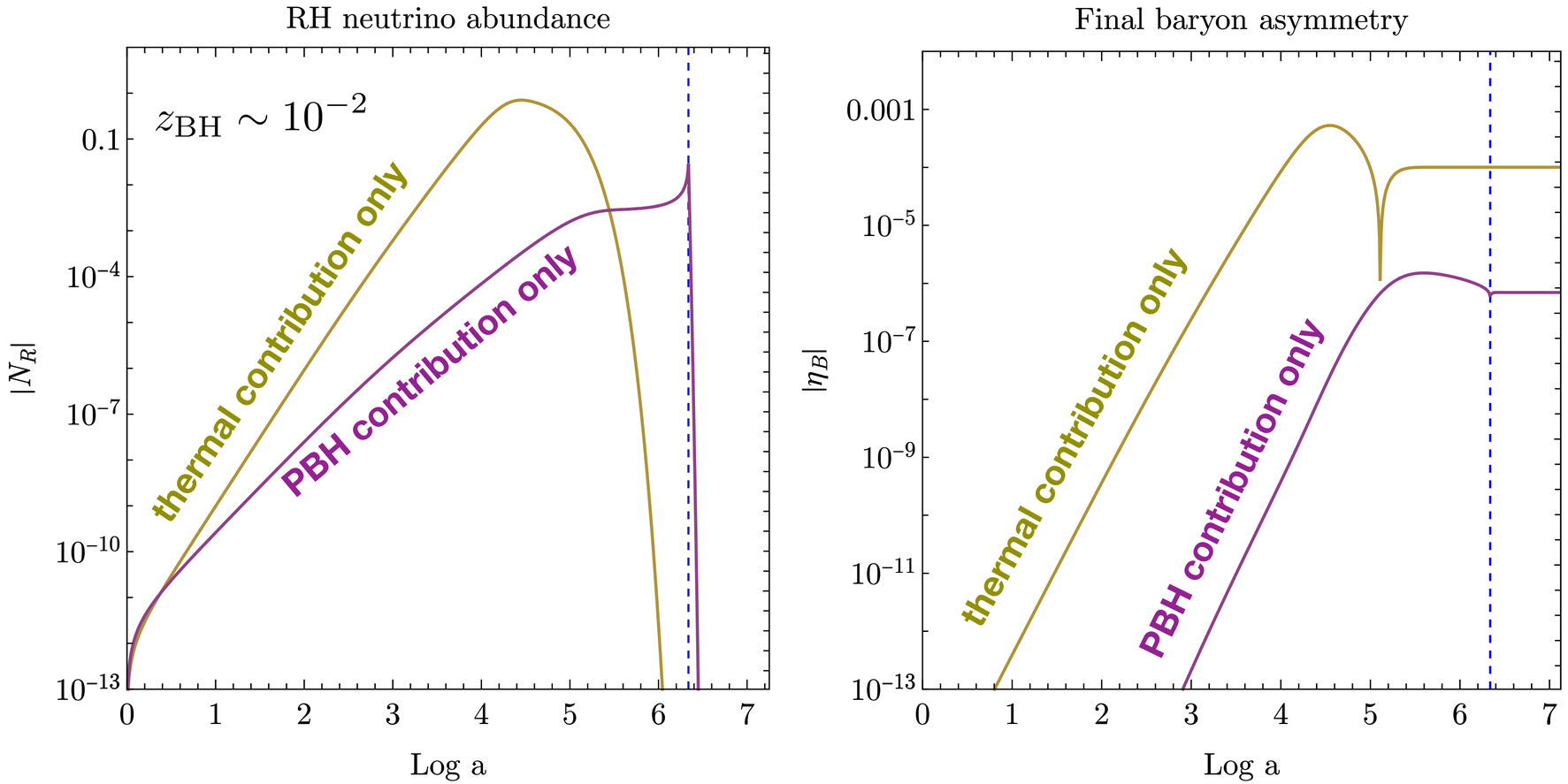

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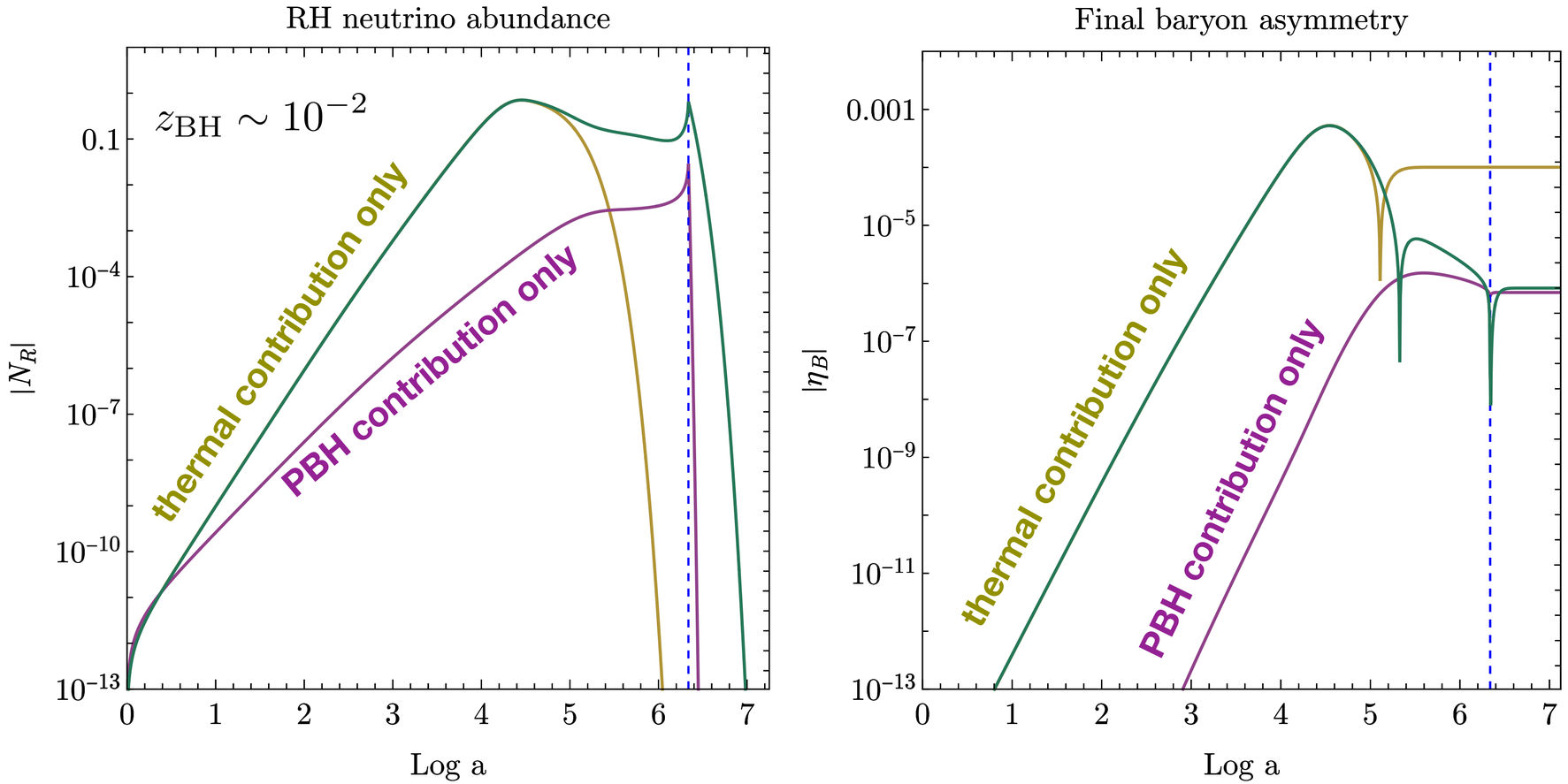

Primordial Black holes induced leptogenesis

D. PBH evaporation occurs **way after** thermal leptogenesis era

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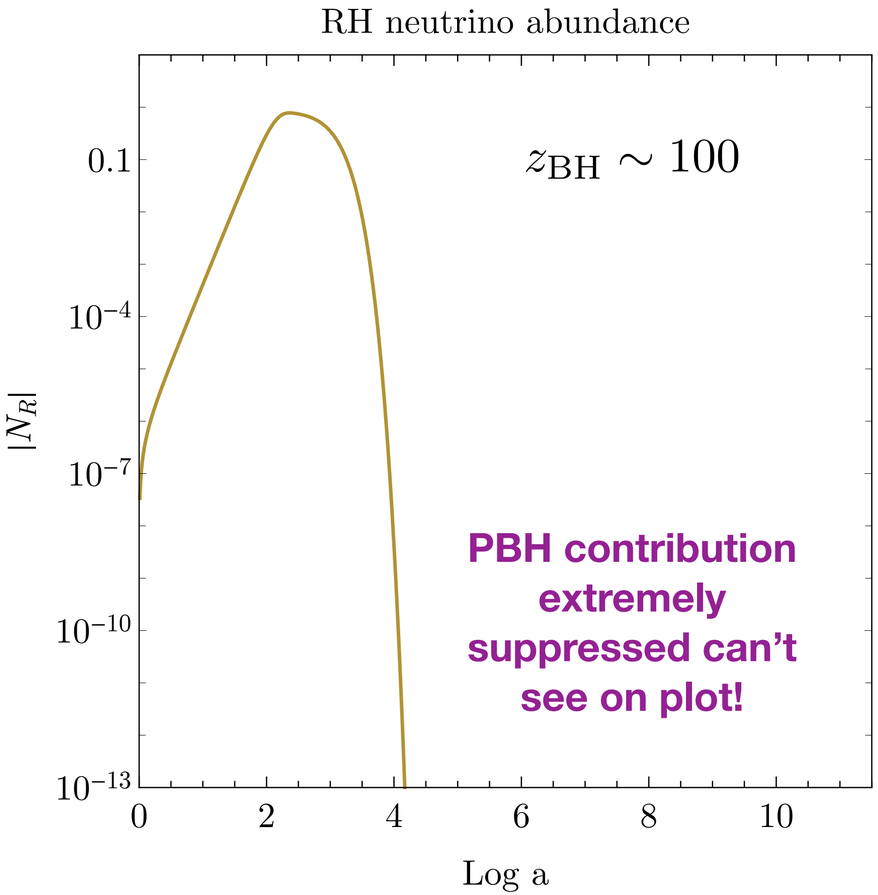

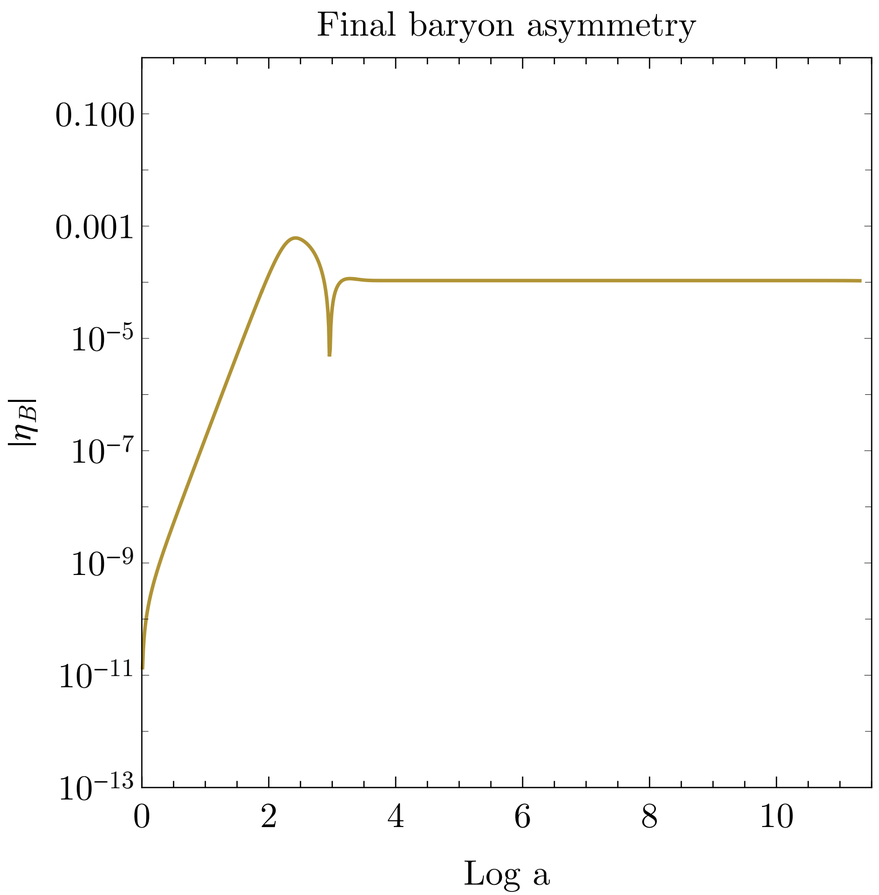

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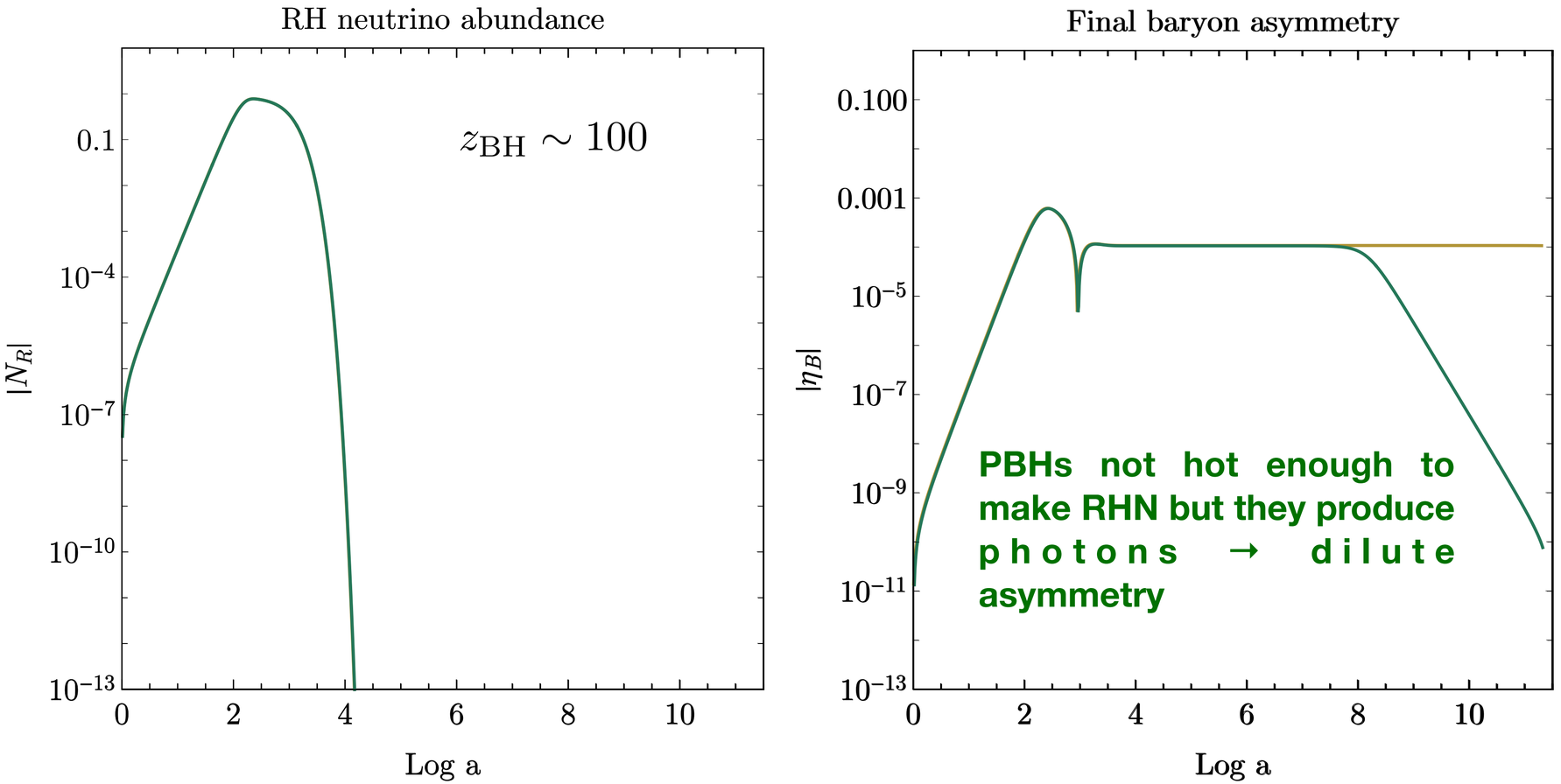
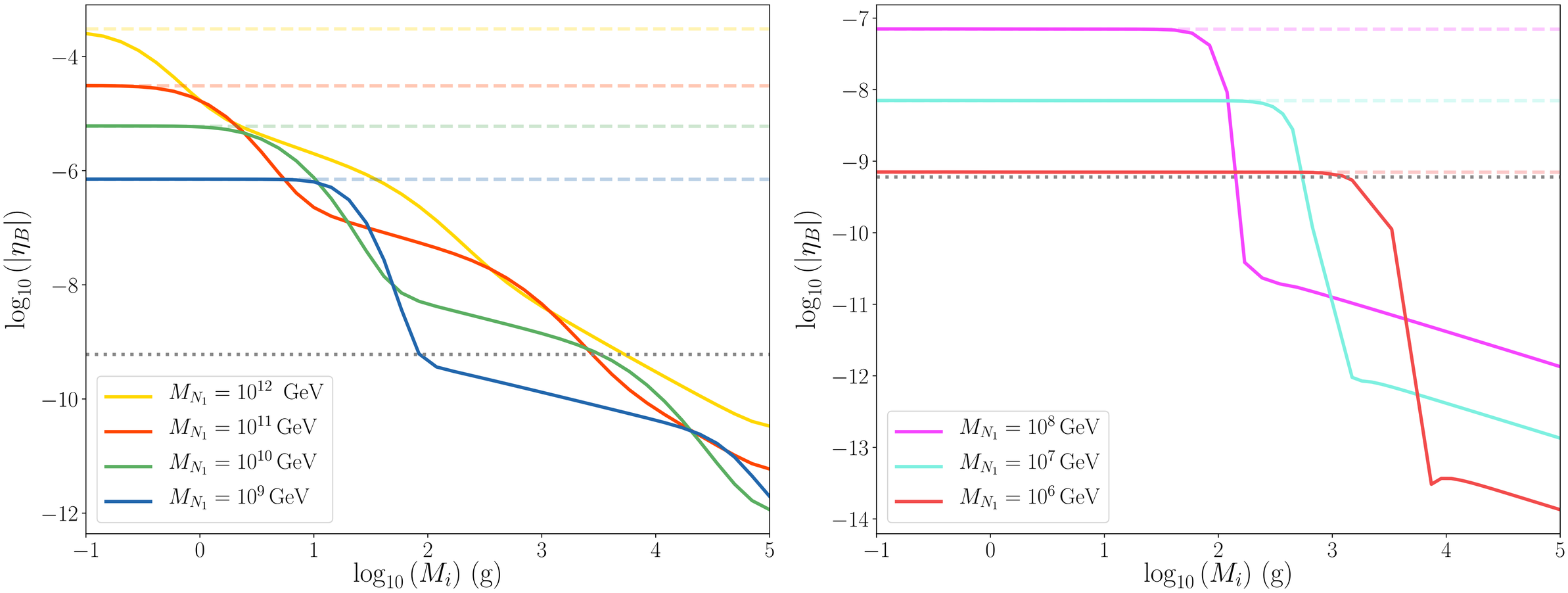


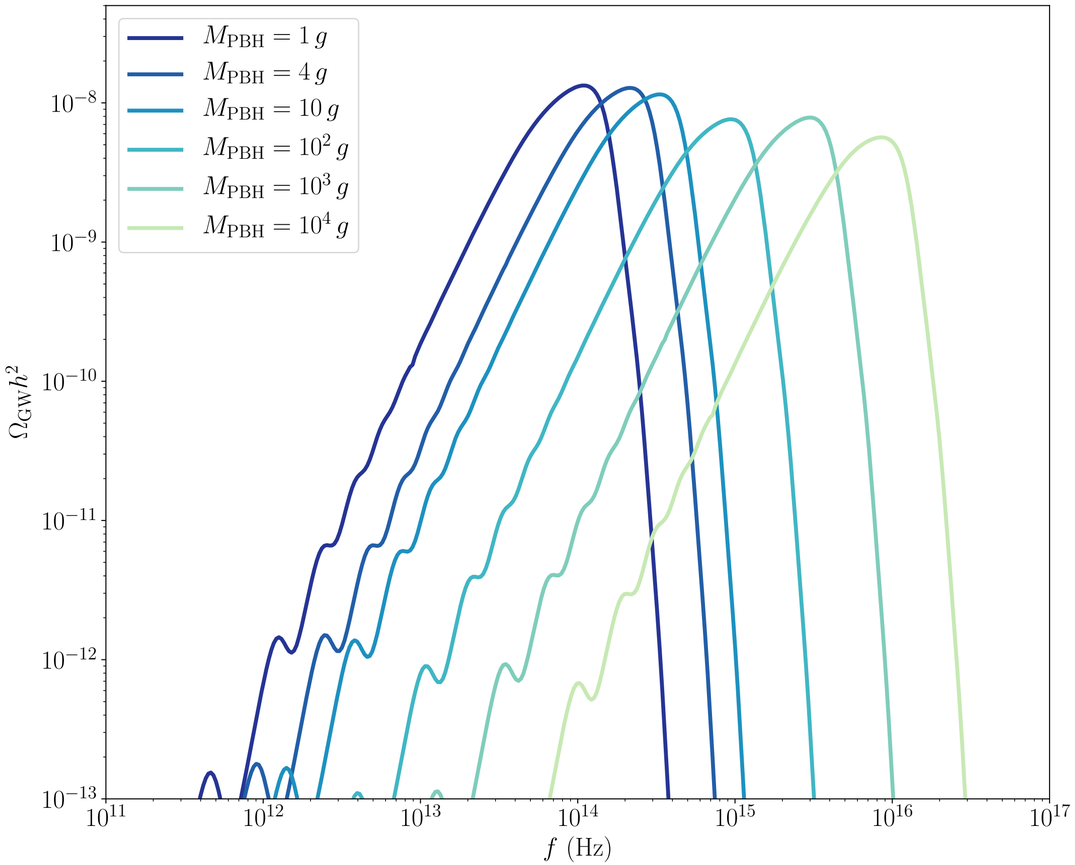
Thermal leptogenesis and primordial black holes

$\beta' = 10^{-3}$



Chose Yukawa matrix for maximal baryon asymmetry

Thermal leptogenesis and primordial black holes



Smaller PBH evaporate earlier and experience more redshift

GW spectrum produced **directly** from PBHs very high frequency.

Interesting proposal to detect GHz GWs via microwave cavity Berlin et al (2112.11465)

We could potentially observe GWs from curvature perturbations: PBH's $\approx 10 - 1000\,\mathrm{kg}$ GW detectable by LIGO & DECIGO (Papanikolaou et al, **2010.11573**, Domenech et al **2012.08151**)

Thermal leptogenesis and primordial black holes

- Leptogenesis is one of the leading explanations of the matter anti-matter asymmetry. Added bonus is that light neutrino masses are also explained.
- It is entirely feasible the Universe underwent some non-standard cosmology such as PBH domination
- Due to the democratic nature of PBH, all particle degrees of freedoms are produced if the PBH is sufficiently hot.
- Non-trivial interplay between leptogenesis era and PBH evaporation. PBHs heavier than $\mathcal{O}(1)\,\mathrm{kg}$ dilute baryon asymmetry of intermediate-scale leptogenesis.
- While thermal leptogenesis is a very scale mechanism and therefore difficult to test, future probes of GWs could falsify the certain regimes of leptogenesis.

Arigato gozaimasu!

RGE

Beta function coefficients 1 and 2-loop respectively

$$b_i = -\frac{11}{3}C_2(H_i) + \frac{2}{3}\sum_F T(F_i) + \frac{1}{3}\sum_S T(S_i)\,,$$

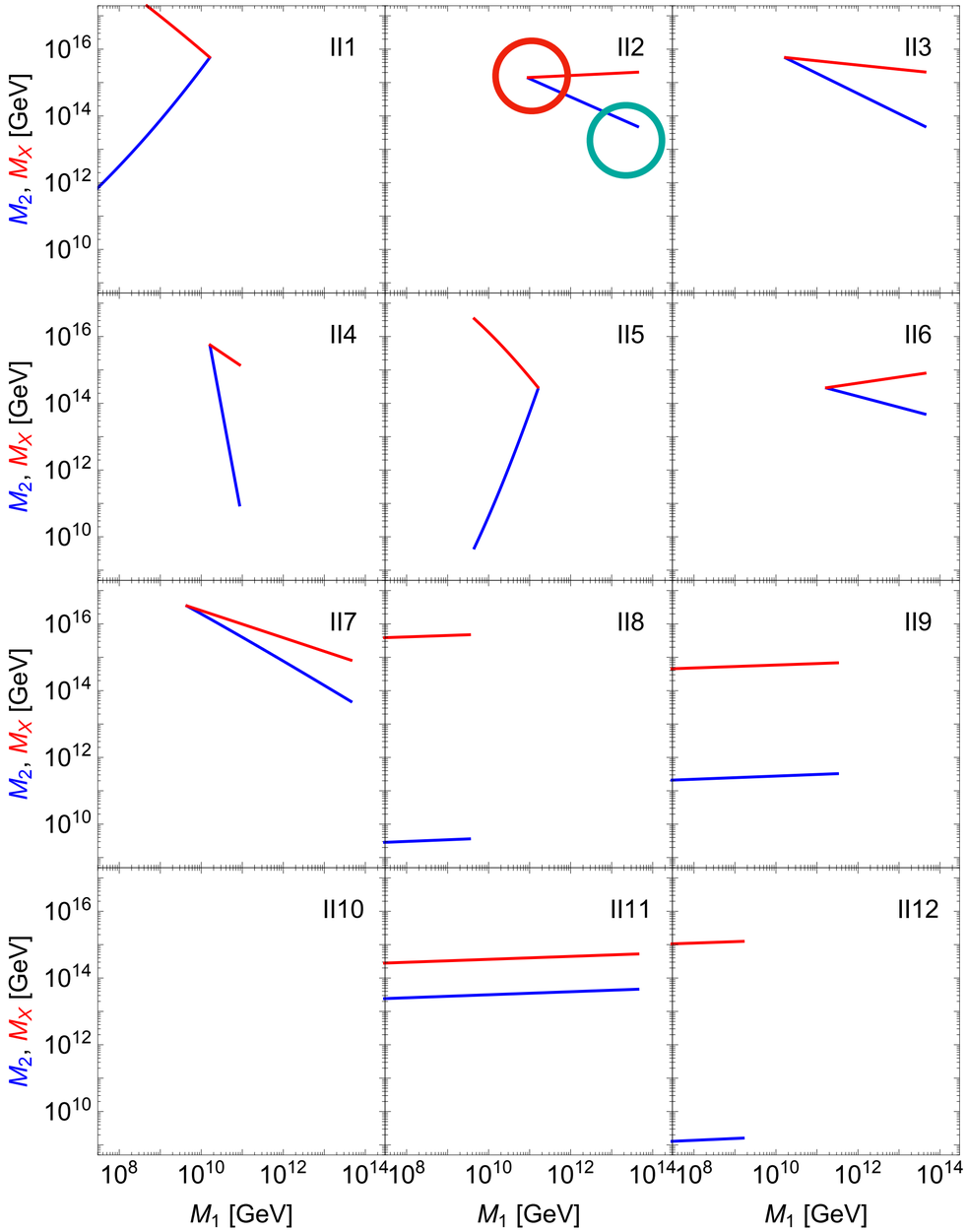
$$b_{ij} = -\frac{34}{3}[C_2(H_i)]^2\delta_{ij} + \sum_F T(F_i)[2C_2(F_j) + \frac{10}{3}C_2(H_i)\delta_{ij}] + \sum_S T(S_i)[4C_2(S_j) + \frac{2}{3}C_2(H_i)\delta_{ij}]\,,$$

Two-loop RGE equation

$$\alpha_i(\mu)^{-1} = \alpha_i(\mu_0)^{-1} - \frac{b_i}{2\pi}\log\frac{\mu}{\mu_0} + \sum_j \frac{b_{ij}}{4\pi b_i}\log\left(1 - b_j\alpha_j(\mu_0)\log\frac{\mu}{\mu_0}\right)\,,$$

Matching condition

$$H_i \to H_j\,, \quad \frac{1}{\alpha_{H_i}(M_I)} - \frac{C_2(H_i)}{12\pi} = \frac{1}{\alpha_{H_j}(M_I)} - \frac{C_2(H_j)}{12\pi}\,.$$



$$\text{II2} : SO(10) \xrightarrow{M_X} G^C_{422} \xrightarrow{M_2} G^C_{3221} \xrightarrow{M_1} G_{\rm SM}$$

Intersection of M2 and Mx reduces II2 to I2

$$\text{I2} : SO(10) \to G^C_{3221} \to G_{\rm SM}$$

$$M_X \equiv M_2$$

At right side blue curve

$$M_2 \equiv M_1$$

II2 becomes I5

$$\text{I5} : SO(10) \to G^C_{422} \to G_{\rm SM}$$

$$\epsilon^{ijk}\epsilon_{\alpha\beta}\Big(\frac{1}{\Lambda_1^2}(\overline{u_R^{jc}}\gamma^\mu Q_\alpha^k)(\overline{d_R^{ic}}\gamma_\mu L_\beta)+\frac{1}{\Lambda_1^2}(\overline{u_R^{jc}}\gamma^\mu Q_\alpha^k)(\overline{e_R^{c}}\gamma_\mu Q_\beta^i)$$
$$+\frac{1}{\Lambda_2^2}(\overline{d_R^{jc}}\gamma^\mu Q_\alpha^k)(\overline{u_R^{ic}}\gamma_\mu L_\beta)+\frac{1}{\Lambda_2^2}(\overline{d_R^{jc}}\gamma^\mu Q_\alpha^k)(\overline{\nu_R^{c}}\gamma_\mu Q_\beta^i)+\text{h.c.}\Big)\,,$$

$$\Lambda_1=\Lambda_2\simeq\left(g_X M_X\right)/2$$

$$\Gamma(p\to\pi^0+e^+)=\frac{m_p}{32\pi}\left(1-\frac{m_{\pi^0}^2}{m_p^2}\right)^2 A_L^2\times\Big[A_{SL}\Lambda_1^{-2}(1+|V_{ud}|^2)\left|\langle\pi^0\left|(ud)_R u_L|p\right\rangle\right|^2$$
$$+A_{SR}(\Lambda_1^{-2}+|V_{ud}|^2\Lambda_2^{-2})\left|\langle\pi^0|(ud)_L u_L|p\rangle\right|^2\Big]\,,$$

$$A_{SL(R)}=\prod_{A}^{M_Z\leqslant M_A\leqslant M_X}\prod_i\left[\frac{\alpha_i(M_{A+1})}{\alpha_i(M_A)}\right]^{\frac{\gamma_{iL(R)}}{b_i}}\,,$$

Example of correlation of string parameter with lowest intermediate scale / GW scale M1

$$G_{3211} \to G_{\rm SM}$$

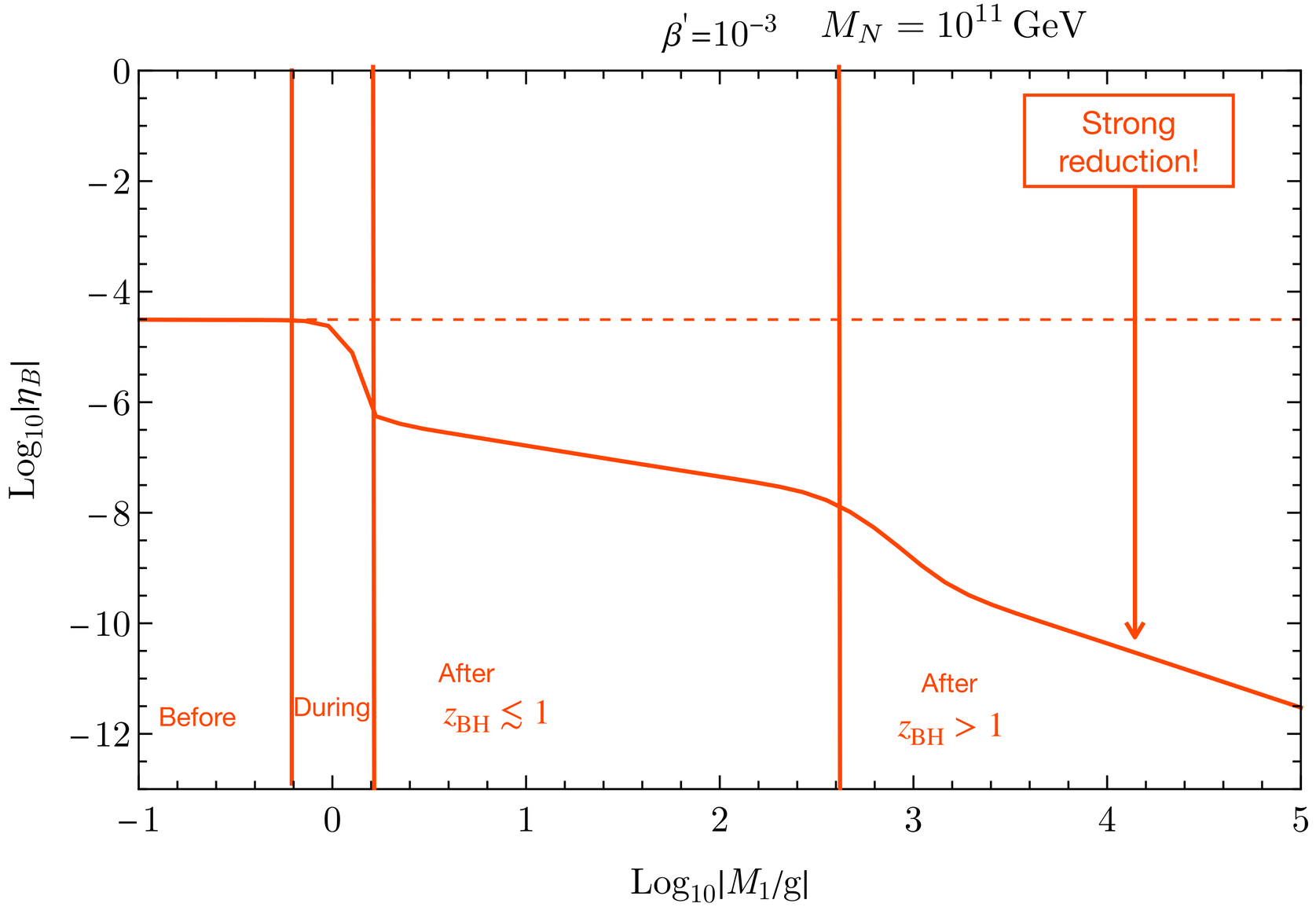
$$U(1)_R \times U(1)_X \overset{M_1}{\to} U(1)_Y$$

$$M_1^2 \simeq 4\pi(\alpha_{1R}(M_1) + \alpha_{1X}(M_1))v^2$$

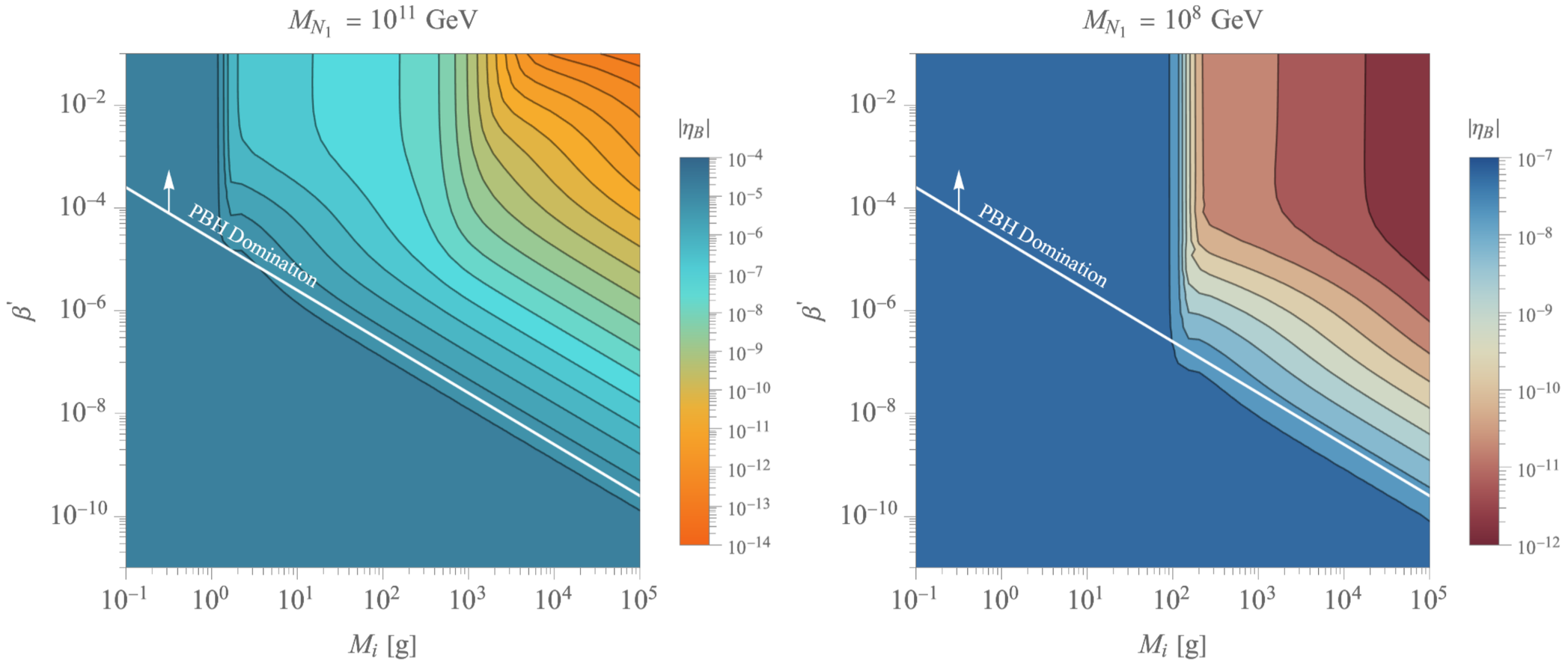
$$G\mu \simeq \frac{1}{2(\alpha_{1R}(M_1) + \alpha_{1X}(M_1))} \frac{M_1^2}{M_{\rm pl}^2}$$

Gauge boson mass squared

Primordial Black holes induced leptogenesis



Thermal leptogenesis and primordial black holes



Dilution effect present as long as there is PBH domination

System of equations

$$\frac{dM}{dt} = -\sum_a \frac{g_a}{2\pi^2} \int_0^\infty \frac{\sigma_{\rm abs}^{s_a}(GMp)\, p^3\, dp}{\exp[E_a(p)/T_{\rm BH}] - (-1)^{2s_a}}$$

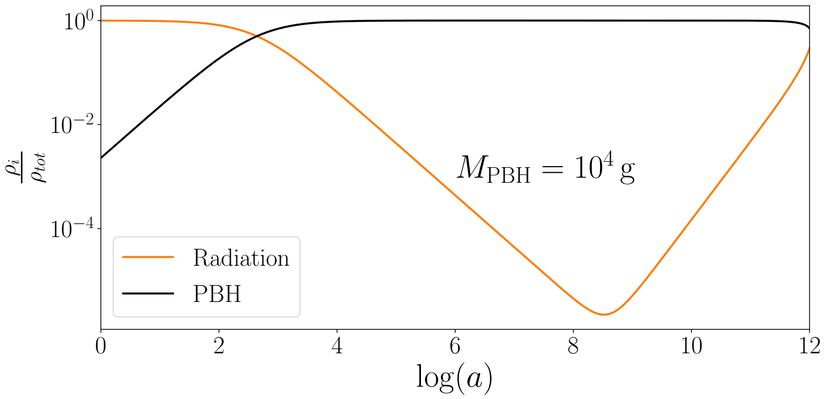
$$= -\kappa\, \varepsilon(M) \left(\frac{1\ {\rm g}}{M}\right)^2$$

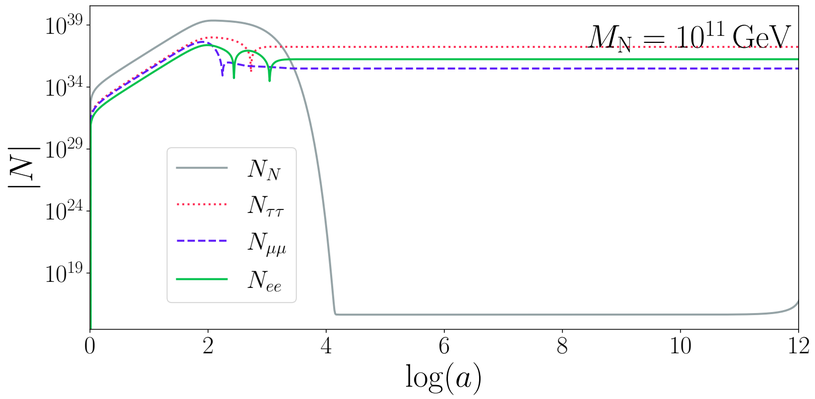
$$\varepsilon(M) = \varepsilon_{\rm SM}(M) + \varepsilon_N(M)$$

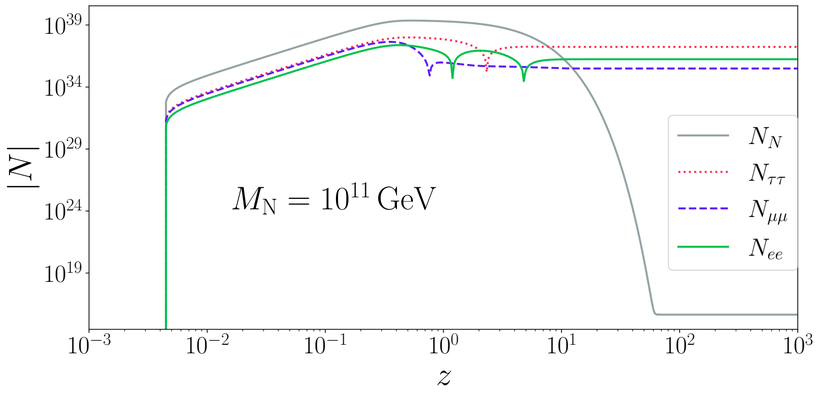
$$\varepsilon_N(M) \approx 2\, n_{N_i}\, f_{1/2}^0 \sum_{i=1}^{n_{N_i}} \exp\left[-\frac{8\pi G M M_{N_i}}{4.53}\right]$$

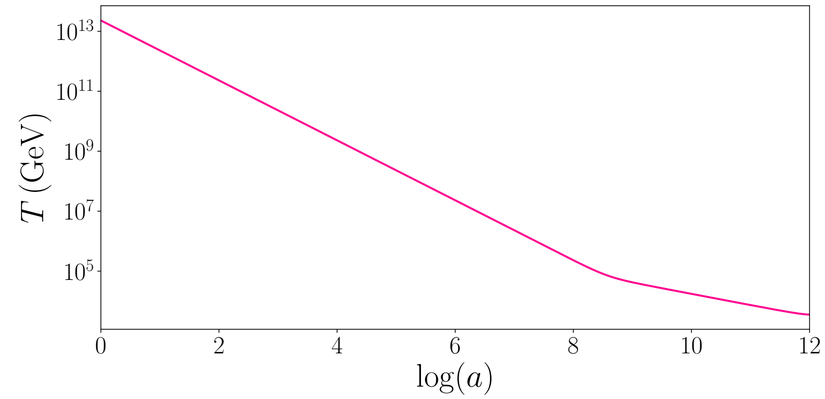
System of equations

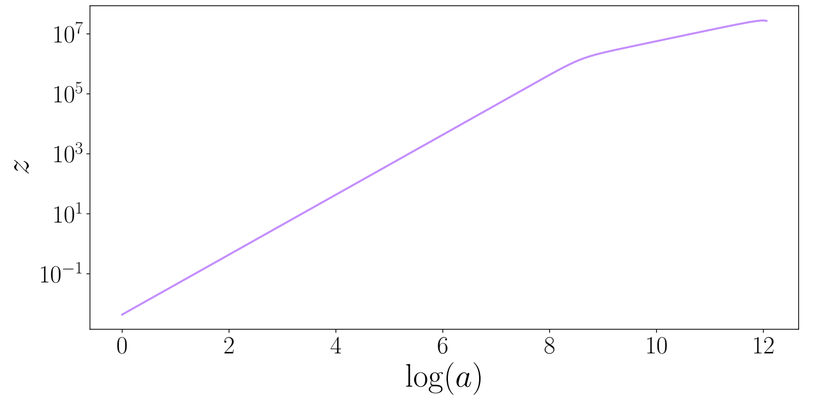
$$dM \qquad \sum_a g_a \int^{\infty} \qquad \sigma^{s_a}_{\rm abs}(GMp)\, p^3\, dp$$

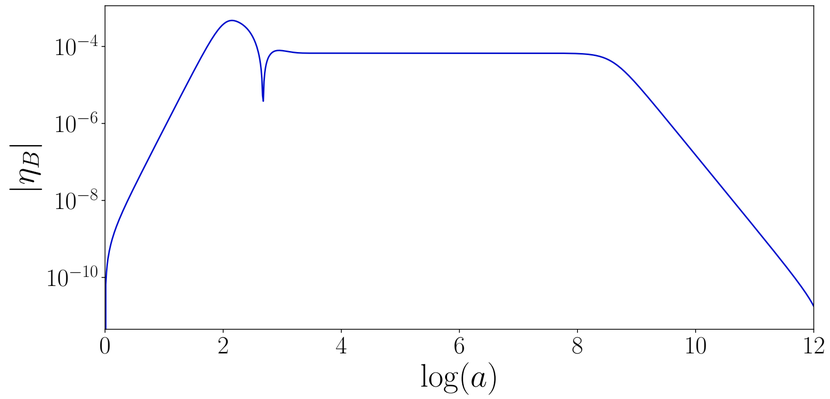




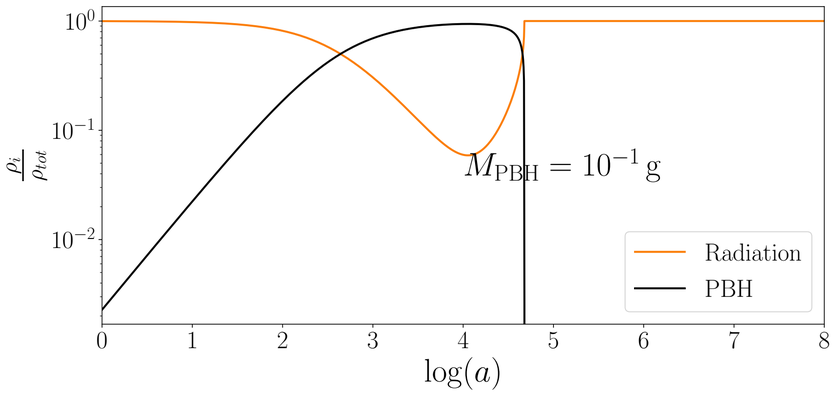


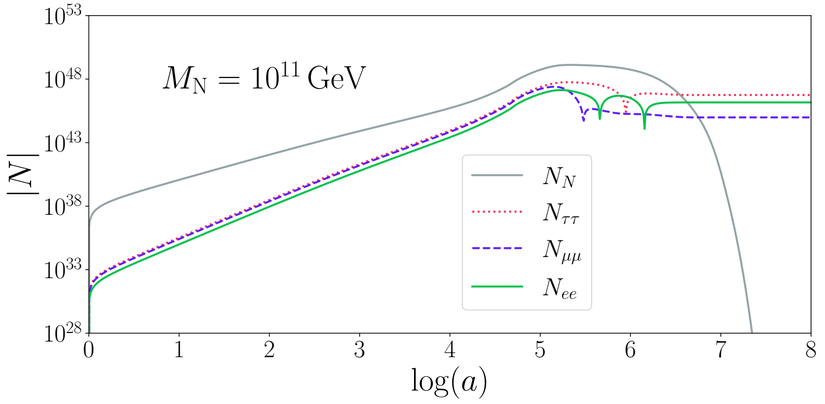


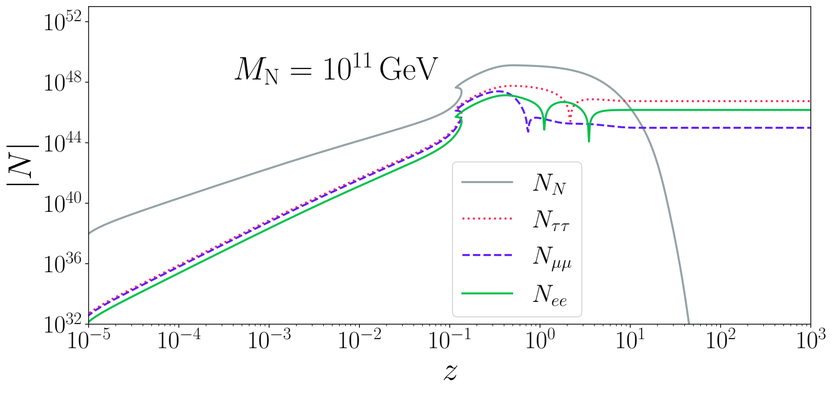


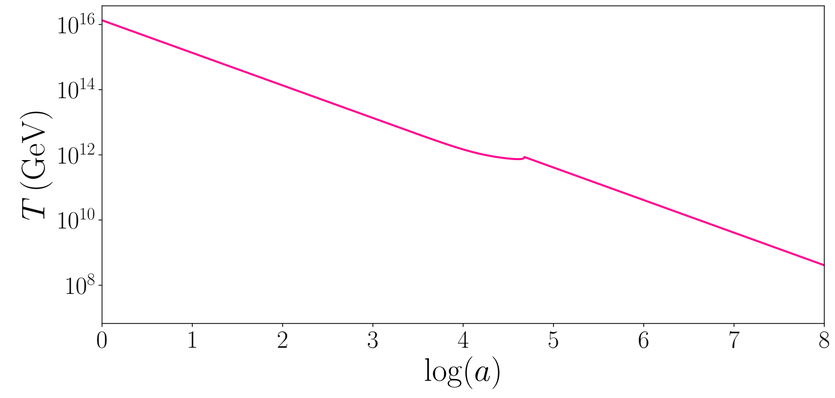


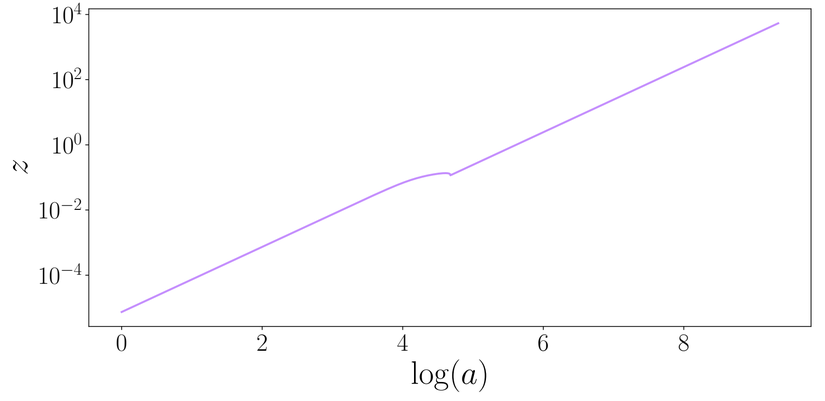
$$aH\frac{d\eta_{\alpha\beta}}{da} = \epsilon^{(1)}_{\alpha\beta}\left[(n^{\rm TH}_{N_1} - n^{\rm eq}_{N_1})\Gamma^{T}_{N_1} + n^{\rm BH}_{N_1}\Gamma^{\rm BH}_{N_1}\right] + \mathcal{W}_{\alpha\beta}$$

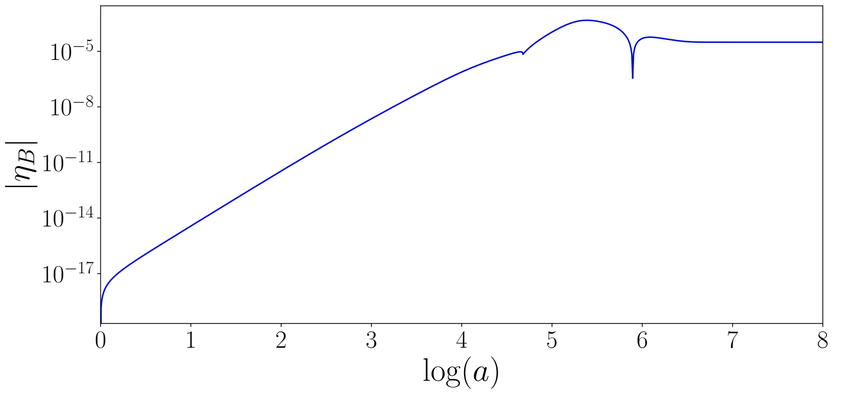

$\frac{\rho_i}{\rho_{tot}}$
$M_{\rm PBH} = 10^{-1}\,{\rm g}$
Radiation
PBH
$\log(a)$

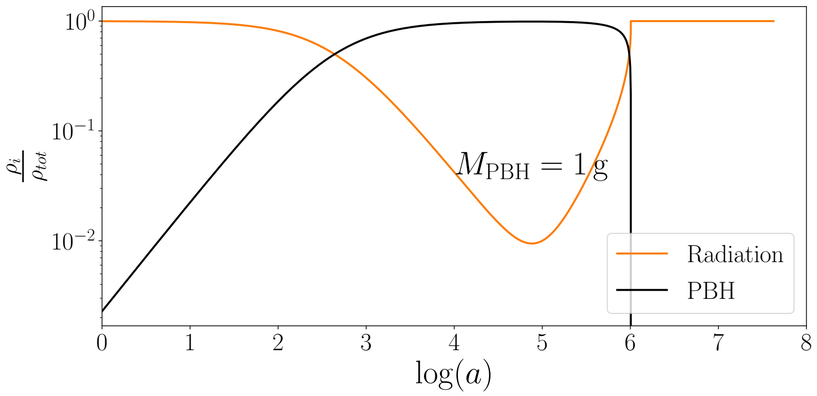

$M_{\rm N} = 10^{11}\,{\rm GeV}$
$|N|$
N_N
$N_{\tau\tau}$
$N_{\mu\mu}$
N_{ee}
$\log(a)$

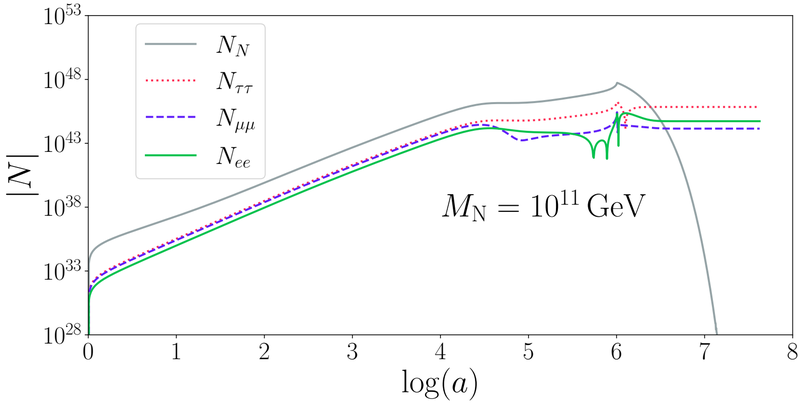

$M_{\rm N} = 10^{11}\,{\rm GeV}$
$|N|$
N_N
$N_{\tau\tau}$
$N_{\mu\mu}$
N_{ee}
z

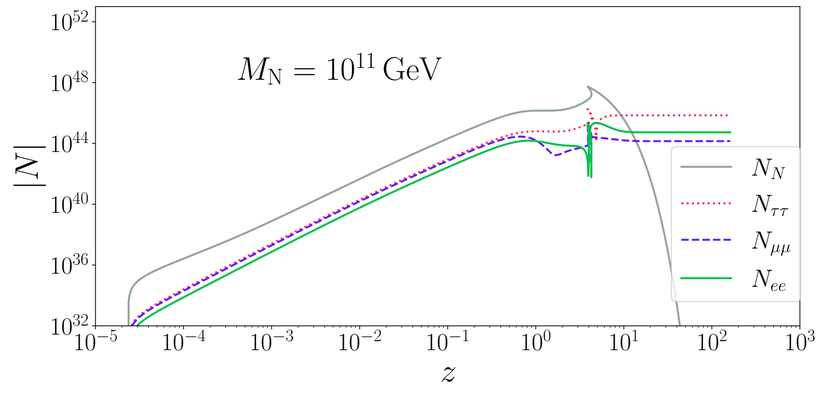

$T\,({\rm GeV})$
$\log(a)$

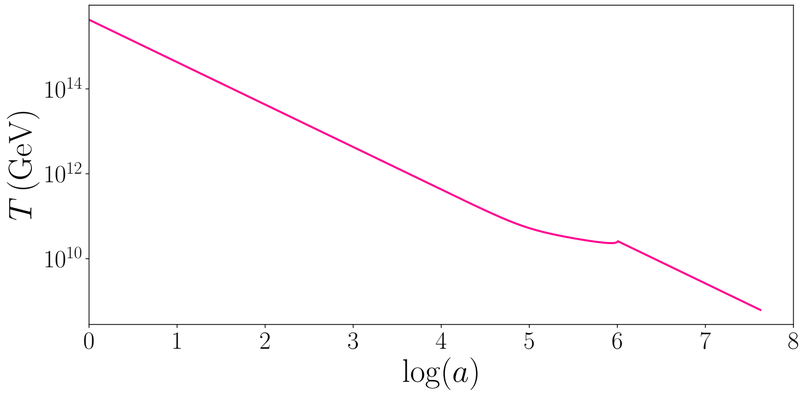

z
$\log(a)$

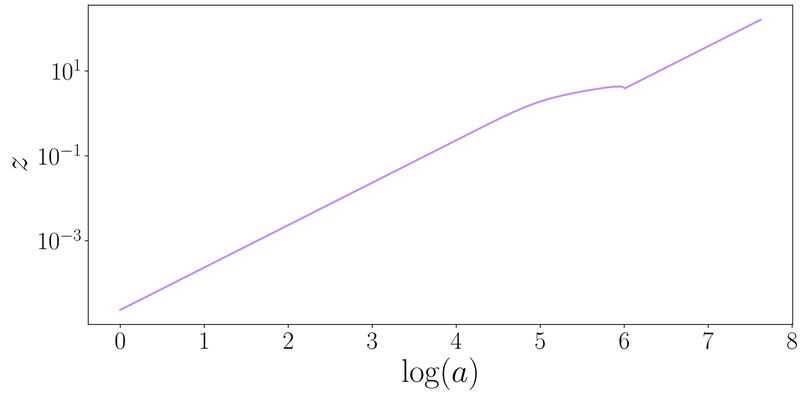

$|\eta_B|$
$\log(a)$

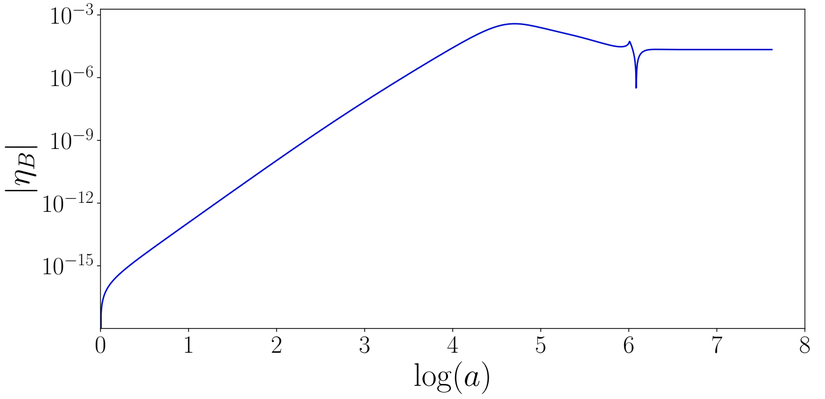

$\frac{\rho_i}{\rho_{tot}}$
$M_{\rm PBH} = 1\,{\rm g}$
Radiation
PBH
$\log(a)$

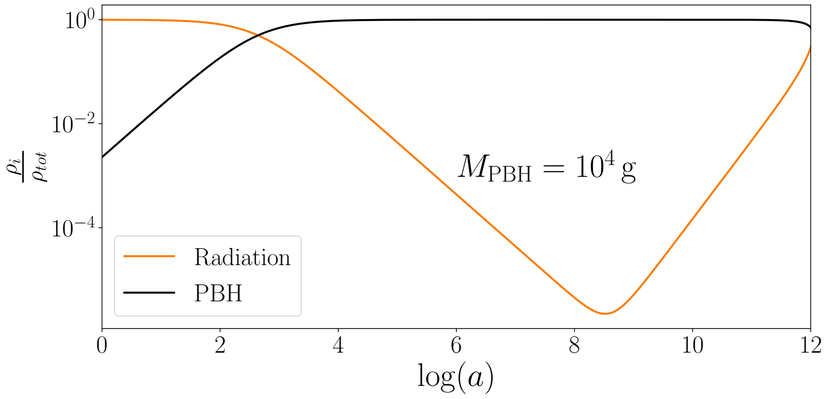

$|N|$
N_N
$N_{\tau\tau}$
$N_{\mu\mu}$
N_{ee}
$M_{\rm N} = 10^{11}\,{\rm GeV}$
$\log(a)$

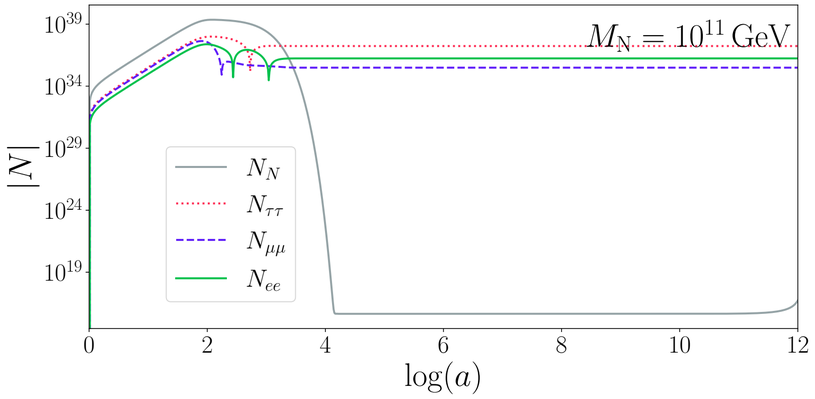

$|N|$
$M_{\rm N} = 10^{11}\,{\rm GeV}$
N_N
$N_{\tau\tau}$
$N_{\mu\mu}$
N_{ee}
z

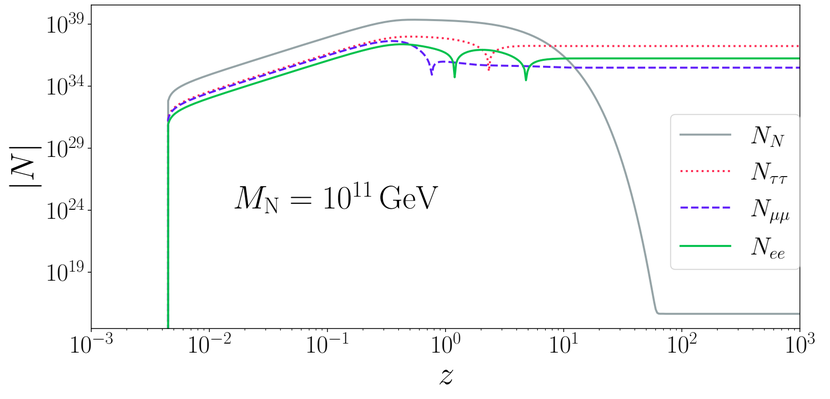

$T\,({\rm GeV})$
$\log(a)$

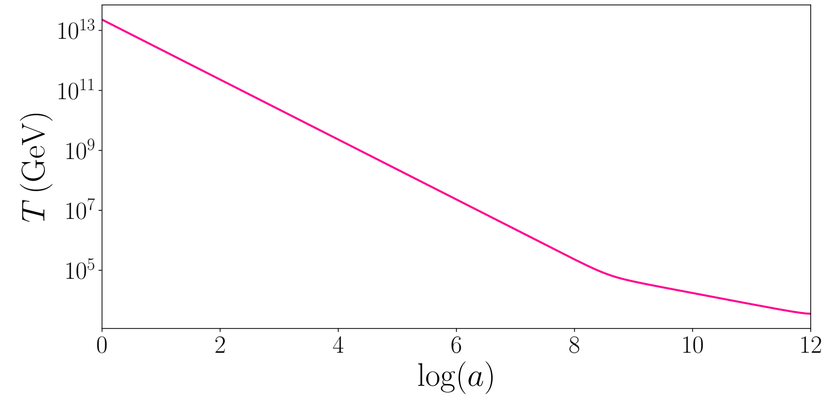

z
$\log(a)$

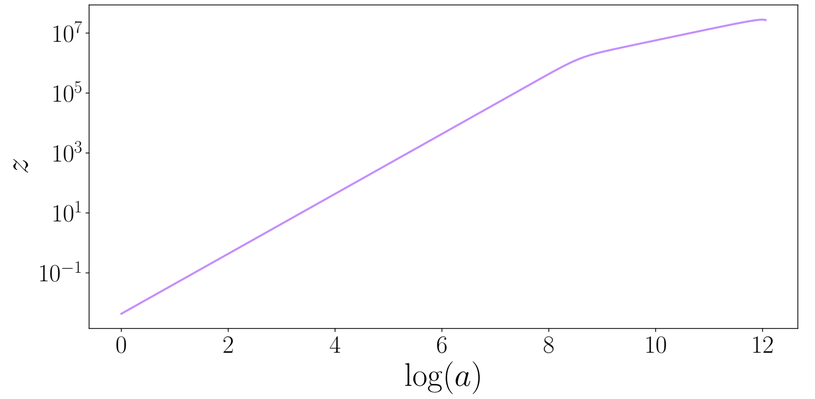

$|\eta_B|$
$\log(a)$

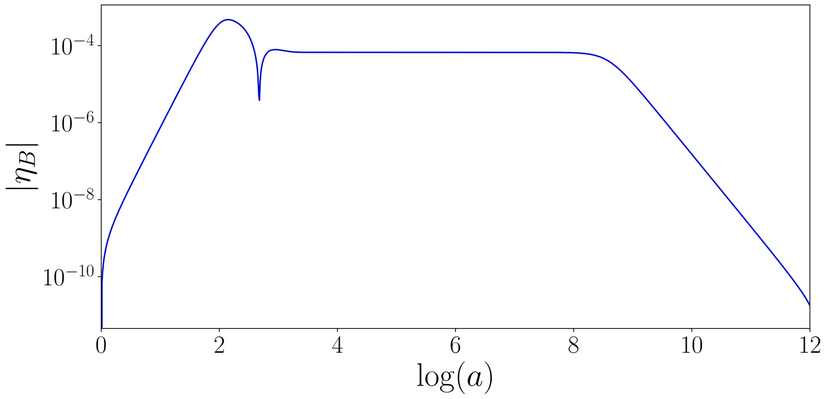

$\frac{\rho_i}{\rho_{tot}}$
$M_{\rm PBH} = 10^4\,{\rm g}$
Radiation
PBH
log(a)


$M_{\rm N} = 10^{11}\,{\rm GeV}$
$|N|$
N_N
$N_{\tau\tau}$
$N_{\mu\mu}$
N_{ee}
log(a)


$M_{\rm N} = 10^{11}\,{\rm GeV}$
$|N|$
N_N
$N_{\tau\tau}$
$N_{\mu\mu}$
N_{ee}
z


$T\,({\rm GeV})$
log(a)


z
log(a)


$|\eta_B|$
log(a)