# Nu cosmologies and signals

**Jeff Dror**

2004.09511 **JD**, David Dunsky, Lawrence Hall, Keisuke Harigaya
1908.03227 **JD**, Takashi Hiramatsu, Kazunori Kohri, Hitoshi Murayama, Graham White

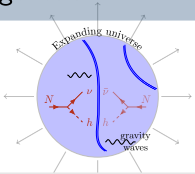
# Outline

## Left-right cosmology

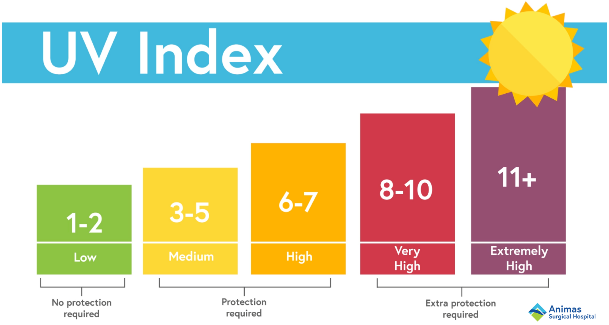
- UV perspective on new physics
- Overview of left-right ("LR") theories
- Cosmologies of right-handed neutrino dark matter
- Freeze-out and dilution
  - Mechanism
  - Parameter space
- Freeze-in


## Leptogenesis

- Overview of See-saw+leptogenesis
- The need for a restored symmetry
- Remnants from phase transitions
- Cosmic string detection
- Detecting (high-scale!) leptogenesis



# Physics in the ultraviolet (high energies)



# Hints of new physics

strong
CP

neutrino
masses

heirarchy
problem

GUT
scale

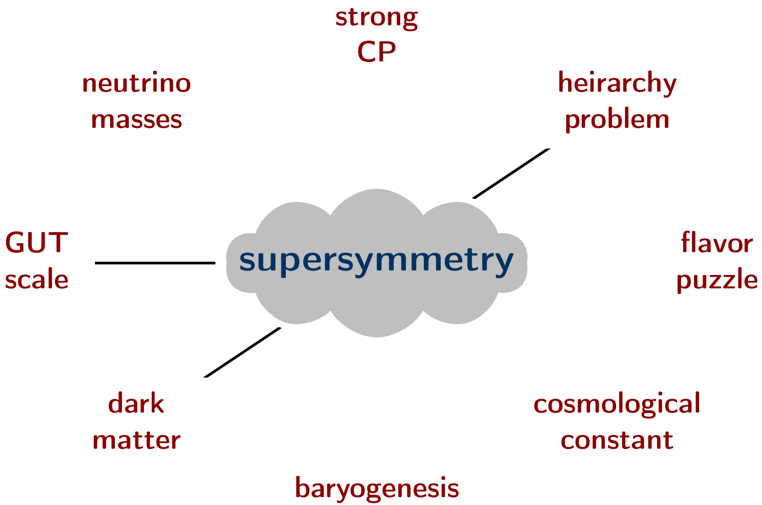
flavor
puzzle

dark
matter

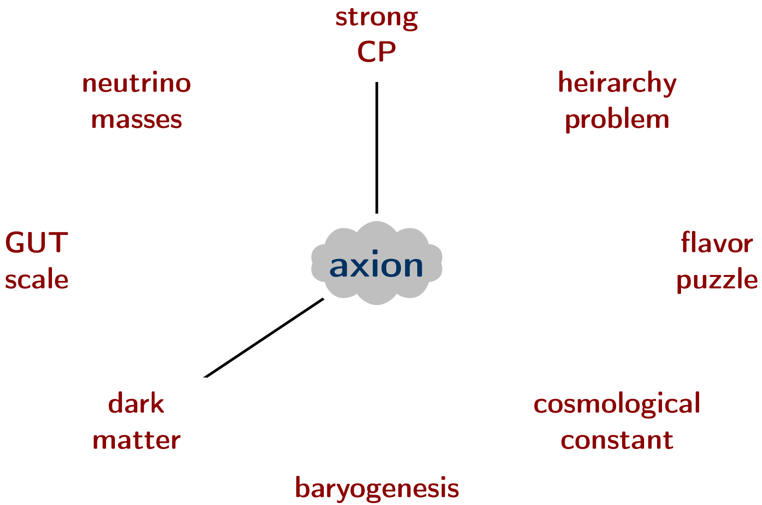
cosmological
constant

baryogenesis

# Hints of new physics



# Hints of new physics



strong
CP

neutrino
masses

heirarchy
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GUT
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Froggatt-Nielsen

flavor
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cosmological
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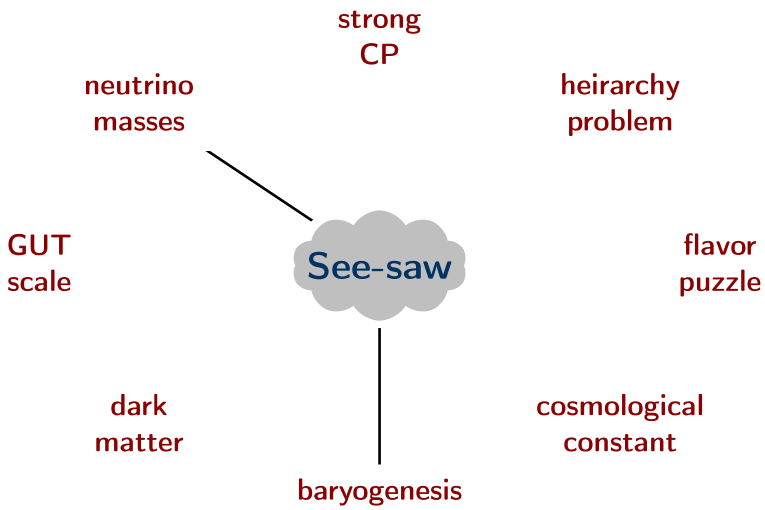
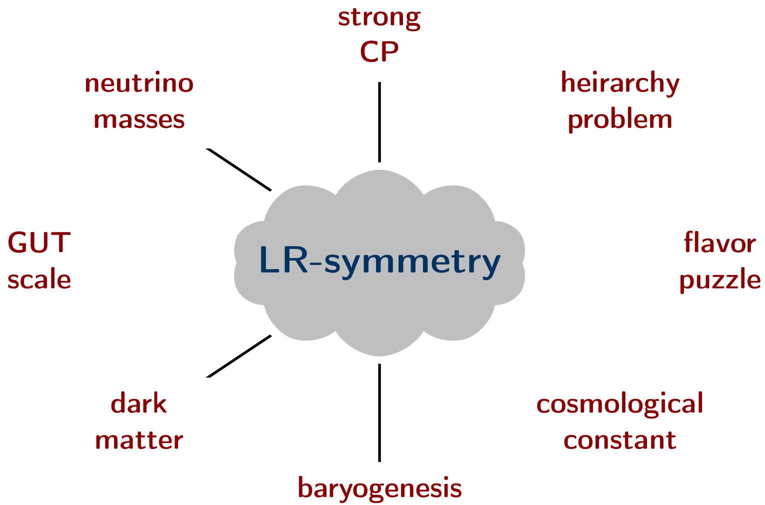
baryogenesis

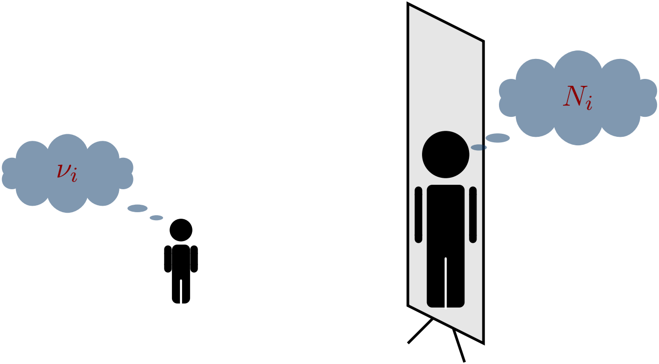
# Hints of new physics



# Hints of new physics



# LR theories



# LR symmetry

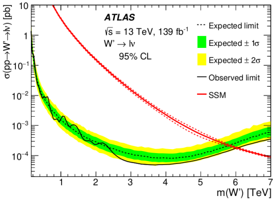
- Left-right theories create:

**Symmetry between left and right-chiral particles in the UV**

- Extend gauge group from Standard Model to

$$SU(3)_C \times SU(2)_L \times SU(2)_R \times U(1)_{B-L}$$

- Can only be a broken symmetry
- New gauge bosons $Z_R, W_R^{\pm}$
- New neutral leptons, $N_i$
- Scale of symmetry breaking, $v_R \gg v$




[1906.05609 - ATLAS]

- Right-handed neutrinos can be much lighter then gauge sector
- Will be ignorant to SU(2)$_R$-symmetry breaking sector

# Neutral leptons

- Standard Model + 3 right-handed neutrinos ($N_i$)

$$-\mathcal{L} \supset y_{ij}(\ell_i N_j)H_L + \qquad\qquad y''_{ij} M_R (N_i N_j) + \text{h.c.}$$

# Neutral leptons

- Standard Model + 3 right-handed neutrinos ($N_i$)

$$-\mathcal{L} \supset y_{ij}(\ell_i N_j)H_L + \frac{y'_{ij}}{\Lambda}(\ell_i \ell_j)H_L^2 + y''_{ij} M_R (N_i N_j) + \text{h.c.}$$

→ choose $y'_{ij} \propto \delta_{ij}$

# Neutral leptons

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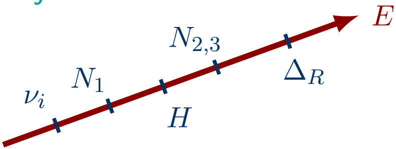
→ choose $y'_{ij} \propto \delta_{ij}$

- Simple left-right symmetric models have relation between $y'_{ij}$ and $y''_{ij}$,

$$-\mathcal{L} \supset y_{ij}\,(\ell_i\, N_j)\, H_L + \frac{c\, y'_{ij}}{v_R}\,(\ell_i\, \ell_j)\, H_L^2 + y'_{ij}\, v_R\, (N_i\, N_j)$$

- Residual left-right symmetry
- $M_R = v_R$, $\Lambda = v_R/c$
- $c$ - free parameter ($c \gtrsim 1 \Rightarrow$ fine-tuning)



# Neutrino masses

- Neutral lepton masses

$$\begin{pmatrix} \nu_i & N_i \end{pmatrix} \begin{pmatrix} cM_{ij}\, v^2/v_R^2 & y_{ij}v \\ y_{ji}v & M_{ij} \end{pmatrix} \begin{pmatrix} \nu_j \\ N_j \end{pmatrix}$$

- Physical neutrino masses:

$$m_{ij} = \underbrace{\delta_{ij} m_{\nu,i}^{(5)}}_{\text{additional dim-5 term}} - \underbrace{m_{\nu,ij}^{ss,N}}_{\text{usual see-saw}}$$

additional dim-5 term — usual see-saw

- Either term may dominate (and can cancel with fine-tuning)
- Heavy states are natural dark matter candidate - "$N_i$"
- Need to answer...

stable? cosmology? Mass?

# A dissapearing dark matter candidate

**Does there exist a range of parameters leading to cold $N_1$ with $\Omega_{N_1} = \Omega_{\rm DM}$?**

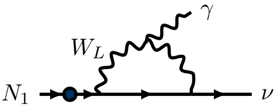
- Will **not** consider matter content beyond minimal LR theory
- Free*(ish)* parameters:

| | |
|---|---|
| Right-handed symmetry breaking scale | $v_R$ |
| Mass of right-handed neutrinos | $M_i$ |
| Mixing matrix between neutrinos | $y_{ij}$ |
| Interpolation parameter between LR theories | $c$ |

- Constraints:
  - Stability of $N_1$
  - Observed neutrino masses

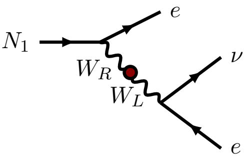
# Stability

- Dominant decay processes:



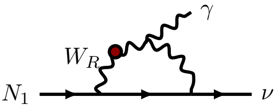

$$\Gamma_{N_1\to\nu\gamma} \sim \frac{\alpha}{(4\pi)^4}\frac{M_1^5}{v^4}\sin^2 2\theta_1$$

**small** $\theta_1,\ M_1$




$$\Gamma_{N_1\to\ell^+\ell^-\nu} \sim \frac{1}{(4\pi)^3}\frac{M_1^5}{v_R^4}\times \text{mixing}$$

**large** $v_R$




$$\Gamma_{N_1\to\nu\gamma,\text{mix}} \sim \frac{\alpha}{(4\pi)^4}\frac{m_\tau^2 M_1^3}{v_R^4}\times \text{mixing}$$

- $W_R - W_L$ mixing can be $\mathcal{O}(1)$ or 1-loop suppressed

# $N_1$ relic density

- Assuming $N_1$ is sufficiently stable can it get the right relic density?
- Options:

  **Freeze-out**

  **Dodelson-Widrow**

  **Freeze-in**

  **Freeze-out+dilution**

# $N_1$ relic density

- Assuming $N_1$ is sufficiently stable can it get the right relic density?
- Options:

**Freeze-out** — Stability $\Rightarrow$ couplings too small

**Dodelson-Widrow**

$$\langle \sigma v \rangle \sim \frac{g^2 s_\theta^2}{m_W^2} \sim \frac{1}{(10\ \mathrm{TeV})^2}$$

But need $s_\theta \ll 1$

**Freeze-in**

**Freeze-out+dilution**

# $N_1$ relic density

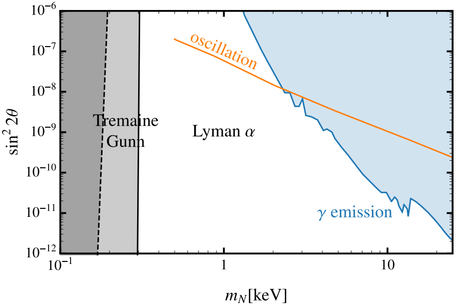
- Assuming $N_1$ is sufficiently stable can it get the right relic density?
- Options:

**Freeze-out** ✗

**Dodelson-Widrow** Ruled out by x-ray bounds

**Freeze-in**

**Freeze-out+dilution**




[data from - 1602.04816]

# $N_1$ relic density

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- Options:

| | |
|---|---|
| **Freeze-out** | ✗ |
| **Dodelson-Widrow** | ✗ |
| **Freeze-in** | Subject of this work |
| **Freeze-out+dilution** | |

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# $N_1$ relic density

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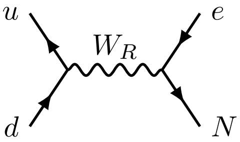
| Freeze-in | ✓ |
| Freeze-out+dilution | ✓ |

[Asaka, Shaposhnikov, Kusenko - hep-ph/0602150]
[Gelmini, Osoba, Palomares-Ruiz, Pascoli - 0803.2735]
[Bezrukov, Hettmansperger, Lindner - 0912.4415]
[Nemevsek, Senjanovic, Zhang - 1205.0844]
[Patwardhan, Fuller, Kishimoto, Kusenko - 1507.01977]

# Initial temperature of the universe

- Type of cosmology depends on $T_{\rm RH}^{\rm inf}$




$$T_{\rm therm} \sim 10^8 \text{ GeV} \left(\frac{v_R}{10^{10} \text{ GeV}}\right)^{4/3}$$

**$\mathbf{T}_{\rm RH}^{\rm inf} \gtrsim \mathbf{T}_{\rm therm}$**

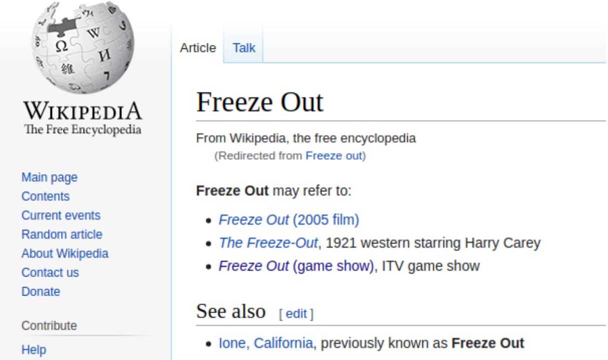
- $N_1$ can freeze-out while relativistic
- Decays of $N_{2,3}$ dilute $N_1$
- Abundance is UV insensitive

**$\mathbf{T}_{\rm RH}^{\rm inf} \ll \mathbf{T}_{\rm therm}$**

- $N_1$ will not come into thermal contact with bath
- $N_1$ produced through bath interactions

Unique options within this minimal framework!

# Freeze-out + dilution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## Freeze Out

From Wikipedia, the free encyclopedia
(Redirected from Freeze out)

**Freeze Out** may refer to:

- *Freeze Out* (2005 film)
- *The Freeze-Out*, 1921 western starring Harry Carey
- *Freeze Out* (game show), ITV game show

### See also [ edit ]

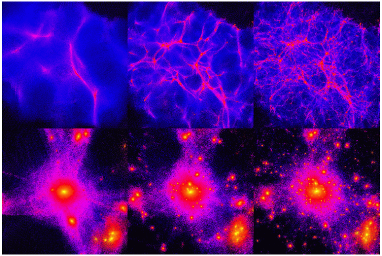
- Ione, California, previously known as **Freeze Out**

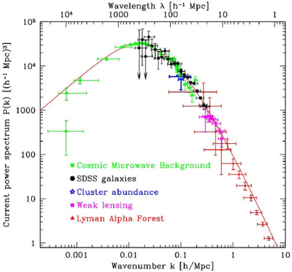
- Particles that decouple before $T \sim m$ have a "thermal abundance"

$$n \sim T^3 \qquad \text{(e.g., } \nu\text{)}$$

- If particle has mass, $m$: $\dfrac{\rho}{s} \sim \dfrac{mn}{s} \sim \dfrac{m}{g_\star}$ ⟵ should be $\sim$ eV to be dark matter

- Would wipe out small scale structure

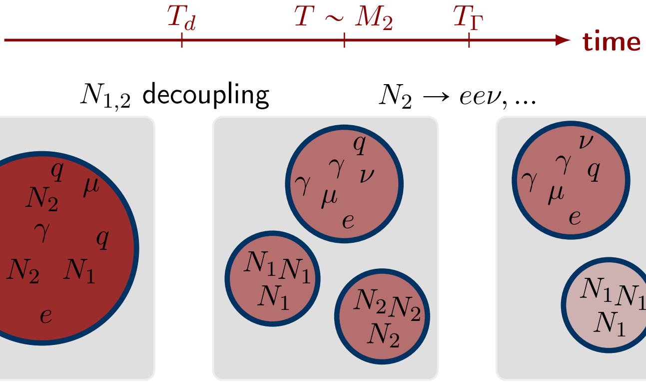





[ - burro.case.edu/Academics/Astr222/Cosmo/Structure/darkmatter.html]
[ - ned.ipac.caltech.edu/level5/Sept11/Norman/Norman2.html]

# High scale reheating

- To be viable candidate, dark matter needs to be cooled
- Simple mechamism - decays to Standard Model bath after decoupling



# Quantitative

- $N_2$ decays after $N_1$ decouples from the SM
- Energy density is diluted by entropy ratio,

$$\Omega \simeq \Omega_{\mathrm{DM}} \left( \frac{M_1}{10\ \mathrm{eV}} \right) \frac{(sa^3)_i}{(sa^3)_f}$$

- Entropy ratio can be computing using thermodynamics,

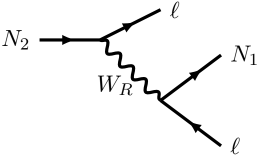
$$\frac{(sa^3)_f}{(sa^3)_i} \simeq \left( 1 + (1.4/A)^{2/3} \right)^{3/4}$$

- $A \equiv \Gamma M_{\mathrm{pl}} / M_2^2$
- Since $n \sim T'^3$, Smaller $\Omega \Rightarrow$ colder DM
- $A > 1 \Rightarrow \Gamma \lesssim M_2^2 / M_{\mathrm{pl}}$

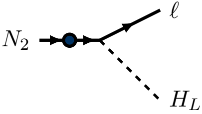
[Asaka, Shaposhnikov, Kusenko - hep-ph/0602150]

# $N_2$ decays

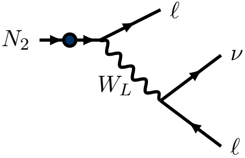
- This second reheating occurs from $N_2$ decay
- Dominant processes are close analogs to $N_1$




$$\Gamma_{N_2 \to N_1 \ell^+ \ell^-} + \ldots \sim \frac{1}{(4\pi)^3} \frac{M_2^5}{v_R^4}$$



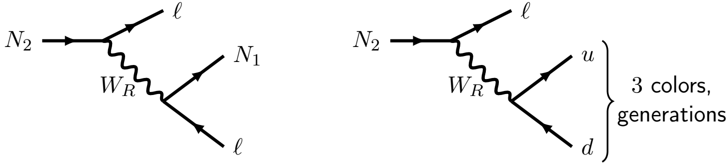

$$\Gamma_{N_2 \to \ell H_L} + \ldots \sim \frac{1}{(4\pi)} |y_{2i}|^2 M_2$$




$$\Gamma_{N_2 \to \nu \ell^+ \ell^-} + \ldots \sim \frac{1}{(4\pi)^3} \frac{M_2^3}{v^2} |y_{2i}|^2$$

# $N_2$ decays

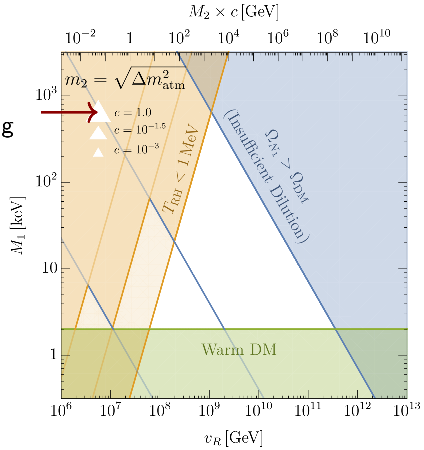
- If $v_R$ is small dominant decays to




- $\mathrm{Br}_{N_1 \ell^+ \ell^-} = 10\%$
- Two effects
  1. Dilutes pre-existing $N_1$ population
  2. Produces additional component of hot $N_1$
- Mixed dark matter predicted in this range of parameter space
- Predicts $\Delta N_{\text{eff}} \simeq 0.1$
- Mild tension with CMB data

○ $N_1$ parameter space [2004.09511 - **JD**, Dunsky, Hall, Harigaya]

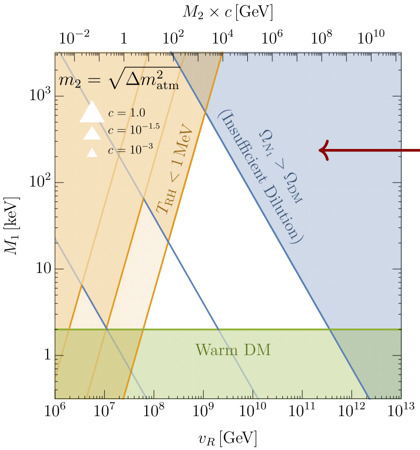
$c$ determined by symmetry breaking




$\Omega_{N_1} = \Omega_{\rm DM}$

# Parameter space

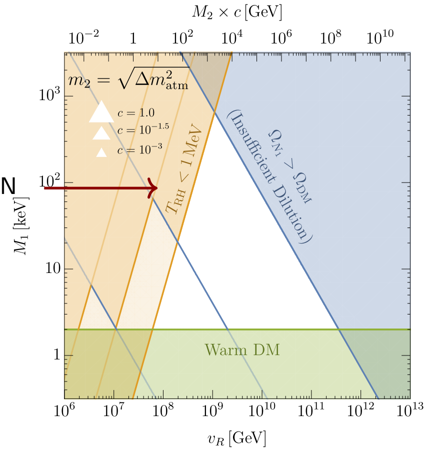
- $N_1$ parameter space [2004.09511 - **JD**, Dunsky, Hall, Harigaya]




Large enough dilution factor

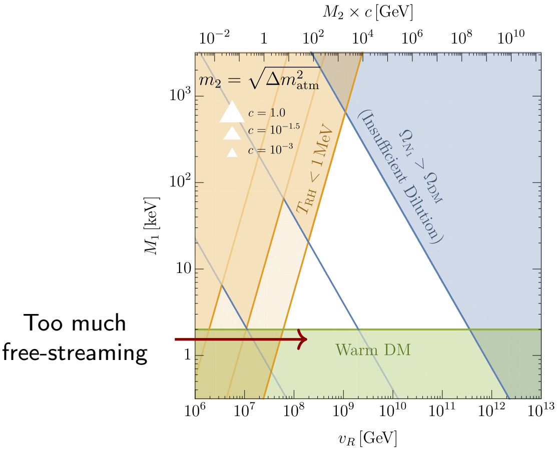
- $N_1$ parameter space [2004.09511 - **JD**, Dunsky, Hall, Harigaya]

Decay after BBN




[1908.10189 - Hasegawa, Hiroshima, Kohri, Hansen, Tram, Hannestad]

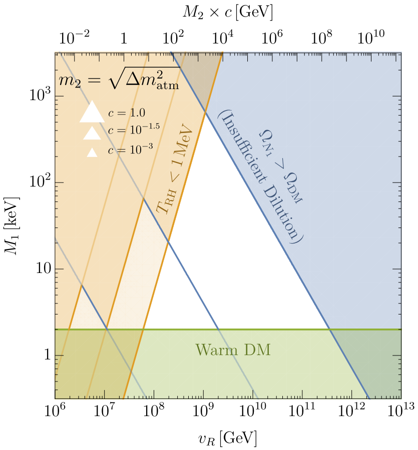
○ $N_1$ parameter space [2004.09511 - **JD**, Dunsky, Hall, Harigaya]




[1702.03314 - Yeche, Palanque-Delabrouille, Baur, du Mas des BourBoux]

# Parameter space

- $N_1$ parameter space

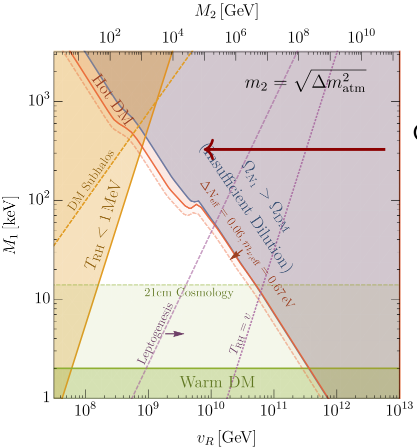



- Parameter space has sharp upper and lower bounds for all $c$

# Future probes

- $N_1$ parameter space

[2004.09511 - **JD**, Dunsky, Hall, Harigaya]

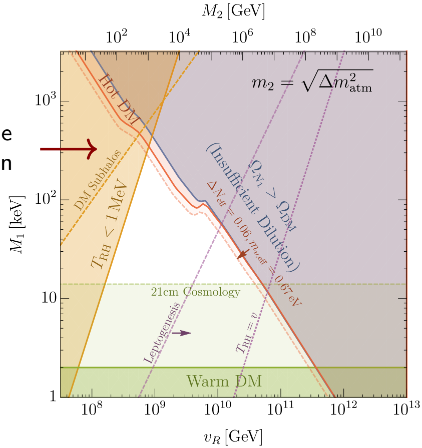



CMB-IV will improve hot DM bound

- $N_1$ parameter space

[2004.09511 - **JD**, Dunsky, Hall, Harigaya]

Pulsar timing can probe early matter domination

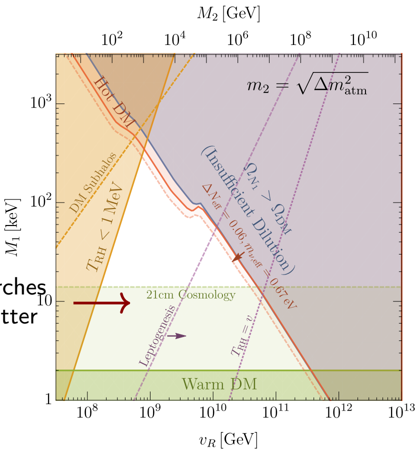


# Future probes

○ $N_1$ parameter space

[2004.09511 - **JD**, Dunsky, Hall, Harigaya]

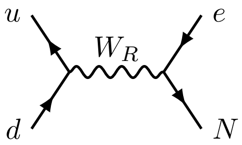
21 cm surveys searches for warm dark matter



# Freeze-in

# Freeze-in

- If $N_1$ is never thermalized there is more freedom
- $N_1$ still populated by non-renormalizable interactions



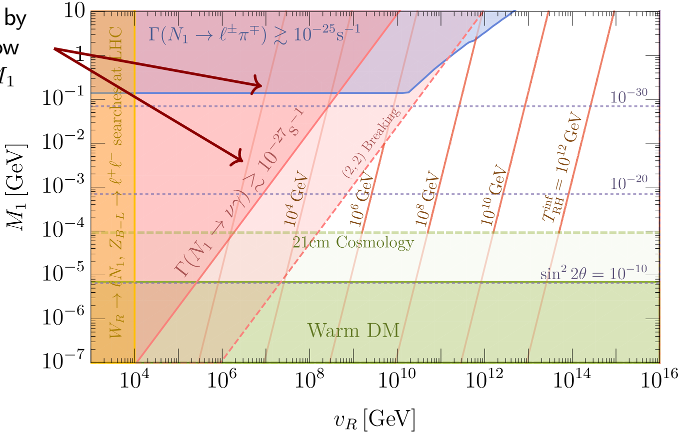

- Abundance sensitive to $T_{\rm RH}^{\rm inf}$
- "UV-freeze in"

$$\Omega \simeq \Omega_{\rm DM} \left(\frac{M_1}{150\ \text{keV}}\right) \left(\frac{10^{10}\ \text{GeV}}{v_R}\right)^4 \left(\frac{T_{\rm RH}^{\rm inf}}{10^7\ \text{GeV}}\right)^3$$

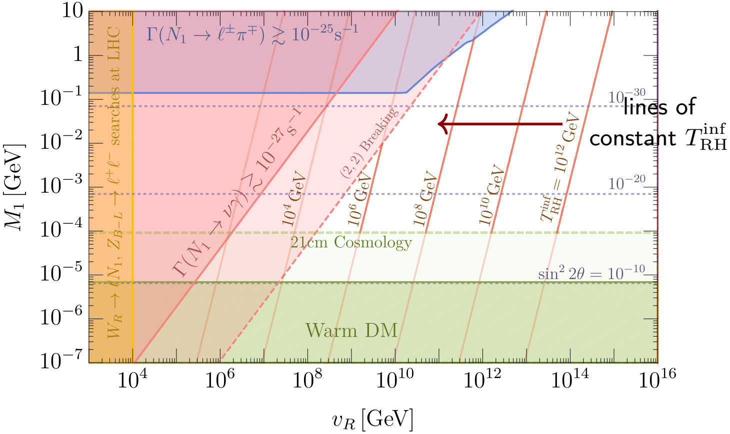
- Neglect dilution

○ $N_1$ parameter space (every point has observed relic density)

Constrained by decays at low $v_R$/large $M_1$

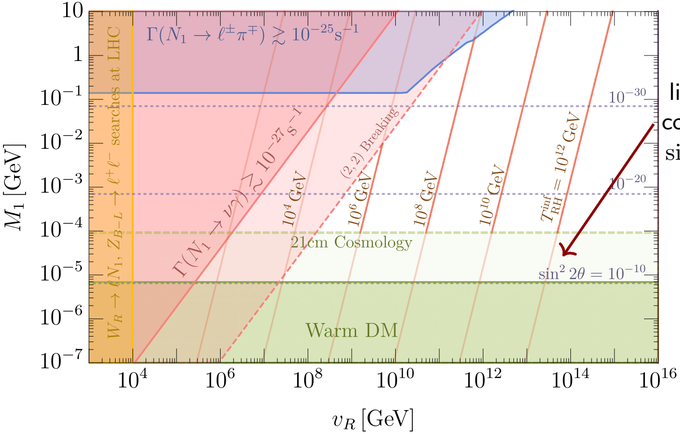


- $N_1$ parameter space (every point has observed relic density)



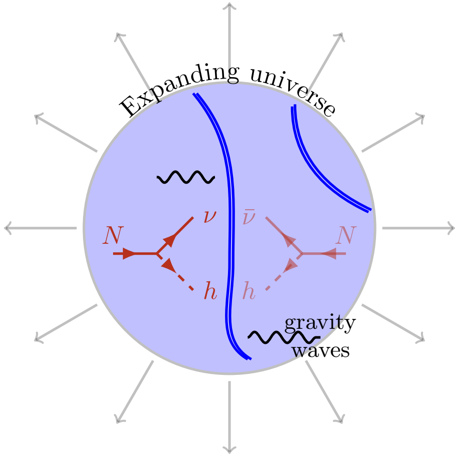
# Parameter space

- $N_1$ parameter space (every point has observed relic density)




lines of constant $\sin^2 2\theta_1$

# Leptogenesis

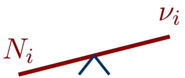


# See-saw mechanism

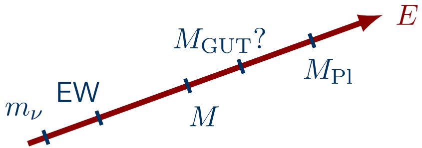
- See-saw mechanism: simplest natural mechanism to generate $m_\nu \sim 0.1\text{eV}$

$$\mathcal{L} \supset y_{ij} H \ell_i N_j + M_{ij} N_i N_j$$

$$\Rightarrow m_\nu \sim y^2 v^2 / M$$




- Perturbativity $(y \lesssim 1) \Rightarrow M \lesssim 10^{15}$ GeV
- Why is $M \neq M_{\text{pl}} \sim 10^{19}$ GeV?
- Naturalness **requires** symmetry to forbid $N_i$ mass



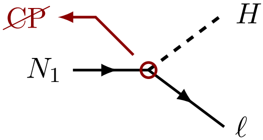
# Leptogenesis

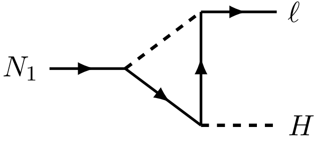
- See-saw can also explain baryon asymmetry in the unvierse
- $N_i$ decay late into the Standard Model
- Yukawa couplings can have phases
- $N_i$ have majorana masses

**Out of equilibrium** ✓

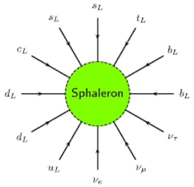
**CP violation** ✓

**$L$ violation** ✓



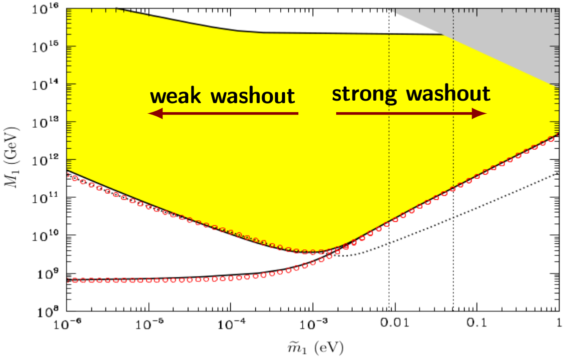




- Inverse decays partly wash-out asymmetry
  - Restricts viable range
- Sphelarons convert lepton → baryon



- Range of masses parameterized by $M_1$ and $\tilde{m}_1 \sim m_\nu$
- Varying over parameters gives parameter space

[hep-ph/0401240 - Buchmuller, Di Bari, Plumacher]




$$2 \times 10^9 \text{ GeV} \lesssim M_1 \lesssim 10^{15} \text{ GeV}$$

# Symmetries

- Appears to be some symmetry breaking well below GUT scale
- Symmetries that **protect $N$ mass**, **anomaly free**, **max rank 5**:

$$\begin{aligned} G_{\text{disc}} &= G_{\text{SM}} \times \mathbb{Z}_N \\ G_{B-L} &= G_{\text{SM}} \times U(1)_{B-L} \\ G_{LR} &= SU(3)_C \times SU(2)_L \times SU(2)_R \times U(1)_{B-L} \\ G_{421} &= SU(4)_{\text{PS}} \times SU(2)_L \times U(1)_Y \\ G_{\text{flip}} &= SU(5) \times U(1) \end{aligned}$$

exhaustive list

- $T_{\text{RH}}^{\text{inf}} \gtrsim M$ to have leptogenesis
  $\Rightarrow$ **phase transition in early universe**
- Can you see this phase transition?

# Symmetry breaking

- Broken symmetries in early universe leave remnants
- Possibilities are:

**1st order transition**

bubble collisions & turbulence

**Gravity waves centered at**

$$f \sim \frac{T_*}{10^6\ \mathrm{GeV}} \mathrm{Hz}$$

↑ too high

**Early matter domination**

Produces small scale structure

**Ultralight clumps PBHs?**

↑ too light

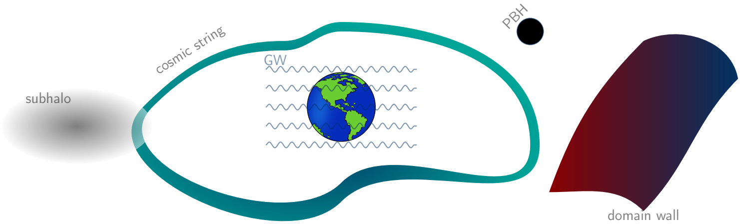
**Topological defects**

domain walls
cosmic strings
monopoles
texture

**Can emit gravity waves**

↑ promising

# Cosmic remnants



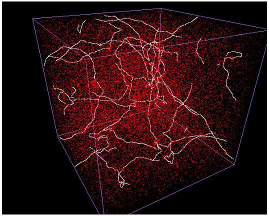
- Type of defects depend on broken symmetry
  - Different **Higgs** + **gauge groups** $\Rightarrow$ different **defects**
  - Determined by "homotopy theory"

| | $H = G_{\rm SM}$ | | $H = G_{\rm SM} \times \mathbb{Z}_2$ | |
|---|---|---|---|---|
| $G$ | **defects** | **Higgs** | **defects** | **Higgs** |
| $G_{\rm disc}$ | domain wall* | $B-L=1$ | domain wall* | $B-L=2$ |
| $G_{B-L}$ | abelian string* | $B-L=1$ | $\mathbb{Z}_2$ string† | $B-L=2$ |
| $G_{LR}$ | texture* | $(\mathbf{1},\mathbf{1},\mathbf{2},\frac{1}{2})$ | $\mathbb{Z}_2$ string | $(\mathbf{1},\mathbf{1},\mathbf{3},1)$ |
| $G_{421}$ | none | $(\mathbf{10},\mathbf{1},2)$ | $\mathbb{Z}_2$ string | $(\mathbf{15},\mathbf{1},2)$ |
| $G_{\rm flip}$ | none | $(\mathbf{10},1)$ | $\mathbb{Z}_2$ string | $(\mathbf{50},2)$ |

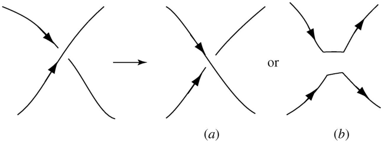
- Cosmic strings are a common prediction

# Cosmic strings and GW

- Naively: $\rho_s \propto a^{-2}$, reality: $\rho_s \propto a^{-4}$ "scaling solution"
- Strings intercommute each other
- Loops form which radiate energy and dissapear



[ - Ringeval, Bouchet]




[ - Copeland, Kibble]

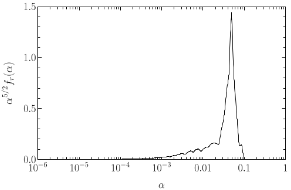
- Kinks in strings emit into heavy particles
- Coherent motion into gravitational waves
- Gravitational waves dominate?
  [Matsunami, Pogosian, Saurabh, Vachaspati - 1903.05102]

# Production of gravitational waves

- Semi-analytic way to estimate gravitational wave production
- Energy dissapation depends on loop size
  - **Large** loops: lose energy through particle emission
  - **Small** loops: relavistic motion and lose energy to redshifting
- Initial length some fraction of universe

$$l(t) = \alpha t_i - \Gamma G\mu(t - t_i)$$

- From simulations ($\mu \sim v^2$):
  - fraction $\sim 0.1$ into large loops
  - initial size parameter: $\alpha \sim 0.1$

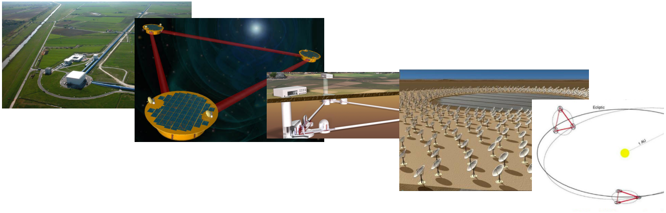


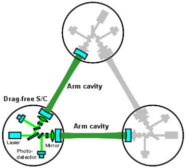

[Blanco-Pillado, Olum, Shlaer - 1309.6637]

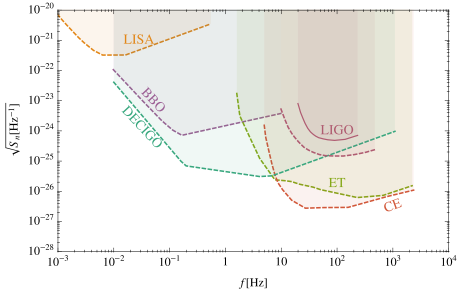
- Can now compute GW spectrum

$$\Omega_{\rm GW} \propto \sqrt{G\mu}$$

# Future is bright in GW



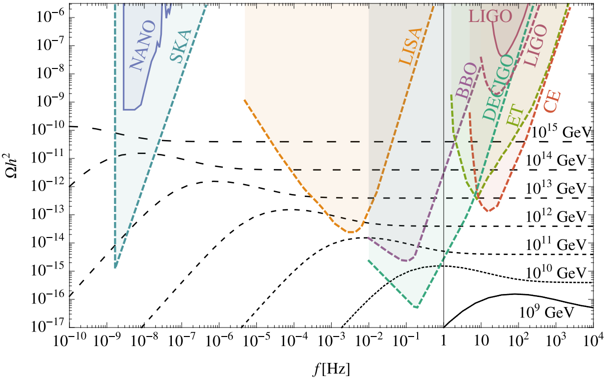




$$\mathrm{SNR}^2 \propto \frac{1}{S_n}$$

# Projected constraints

- Reach and signals from cosmic strings




- Probe all of range relevant for leptogenesis!

# Conclusions

- Explored new implications of two well motivated frameworks
- In (minimal) left-right theories:
  - Explored the full cosmology leading to dark matter
    - Freeze-out and dilution
      - bounded parameter space
      - can be probed in near future
    - Freeze-in
      - More flexibility
    - Can get observed relic density in either case
- See-saw mechanism
  - Natural theory requires:
    1. $10^9 \text{ GeV} \lesssim M_1 \lesssim 10^{15} \text{ GeV}$
    2. Symmetry to protect right-handed neutrinos
    3. Symmetry to be broken in early universe
  - Explored prospects to find broken symmetry
  - Focused on cosmic strings