Confronting Astroparticle Physics with Colliders

A personal selection of recent developments in the field.

Julia Harz

6th September 2021

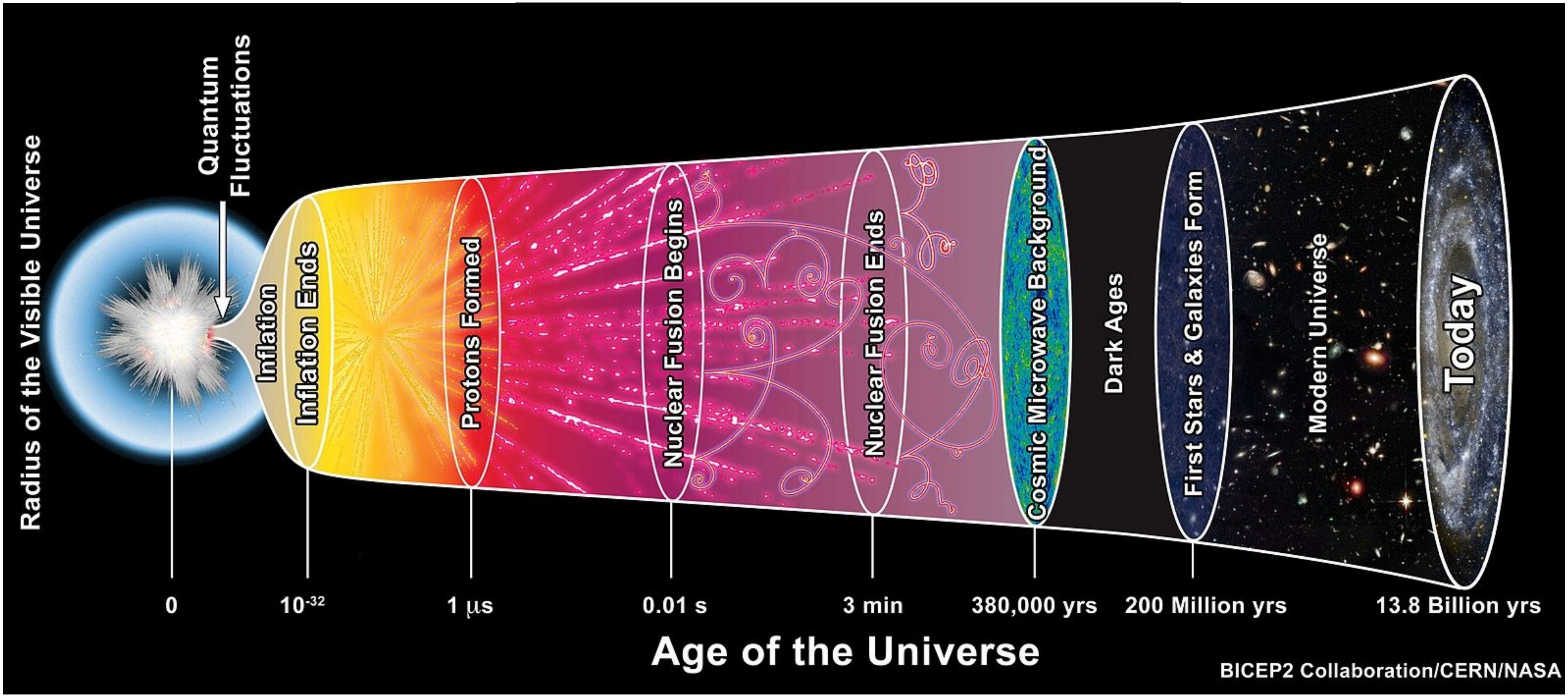
LFC21: Strong interactions from QCD to new strong dynamics at LHC and Future Colliders

Technische Universität München

Emmy Noether-Programm

DFG Deutsche Forschungsgemeinschaft

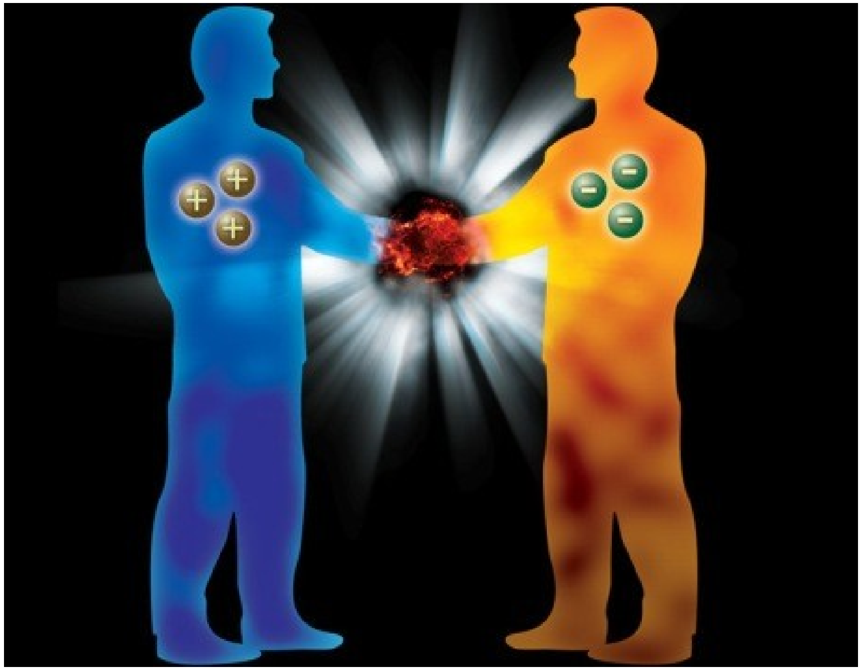
From the Big Bang to Today…



Why is there more matter than antimatter?

Our Universe consists mainly out of baryonic matter, quantified by the baryon-to-photon ratio:

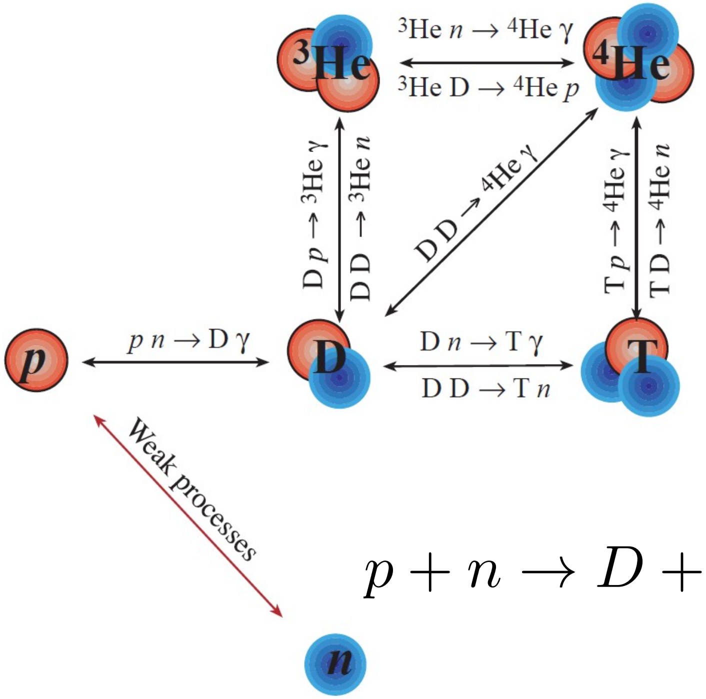
$$\eta_B = \frac{n_B}{n_\gamma} = \frac{n_b - n_{\bar{b}}}{n_\gamma}$$



$$\boxed{\eta_B^{\mathrm{obs}} = (6.09 \pm 0.06) \times 10^{-10}}$$

What created the asymmetry?

Big Bang Nucleosynthesis

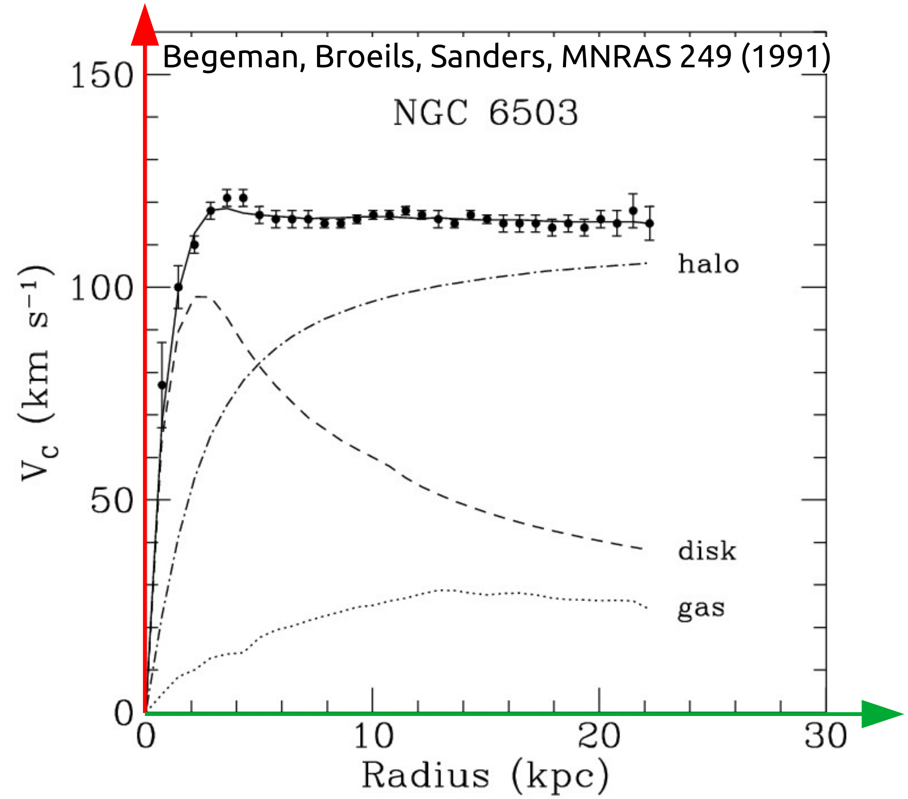


$$p + n \to D + \gamma$$

$$T_{\mathrm{nuc}}^D \approx \frac{B_D}{\log \eta_B^{-1}}$$

What is dark matter?

Rotation Curves of Spiral Galaxies



circular velocity from Newtonian gravity:

$$\mathrm{v}_c(r) = \sqrt{\frac{GM(r)}{r}}$$

expectation for r>R: $\mathrm{v}_c(r) \approx 1/\sqrt{r}$

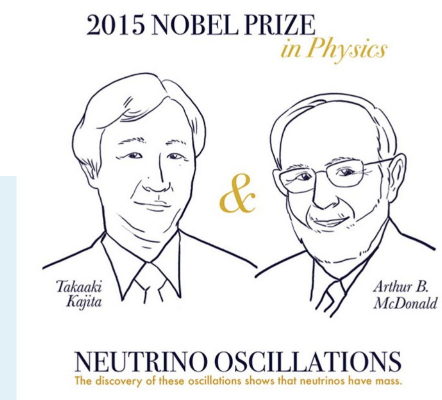
observation: $\mathrm{v}_c(r) \approx \mathrm{const}$

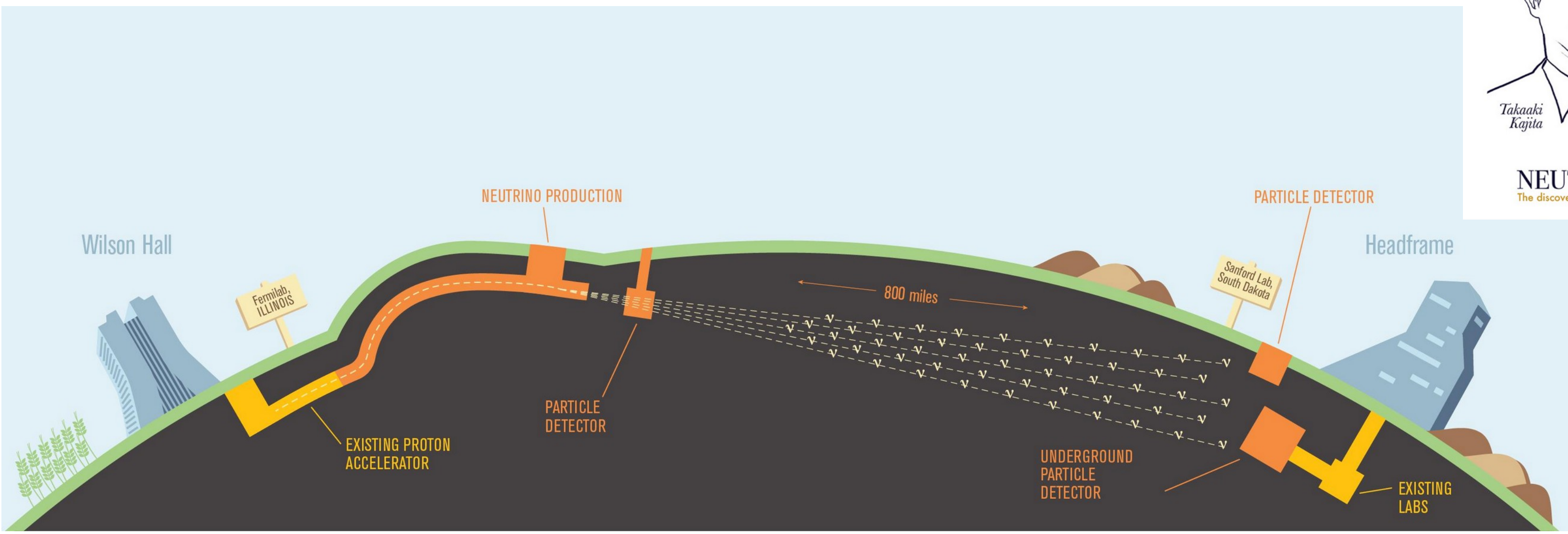
Different qualitative and quantitative evidence for the existence of Dark Matter!

$$\boxed{\Omega_{\mathrm{CDM}} h^2 = 0.120 \pm 0.001}$$

PLANCK 2018

What is the nature of neutrinos?





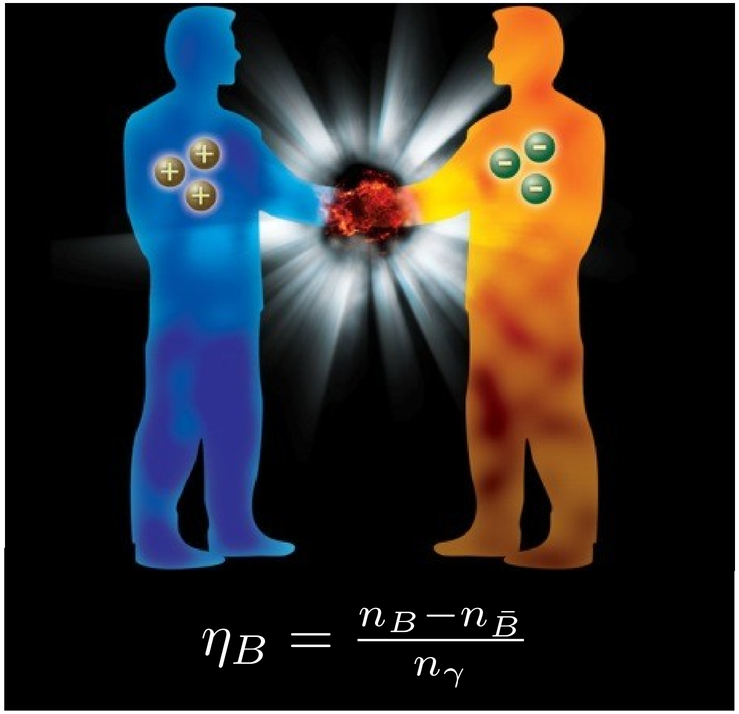
ν_e ν_μ

$$P(\nu_\alpha \to \nu_\beta) = \sin^2 2\theta \sin^2\left(\frac{\Delta m^2}{4E} L\right)$$

Neutrino **oscillations** require **massive** neutrinos, forbidden in the Standard Model.

How do neutrinos get their masses?

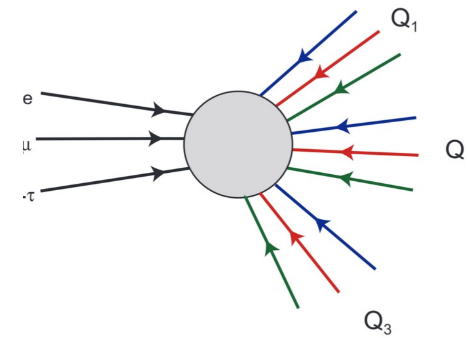
What nature do neutrinos have? Are they their own anti-particles?



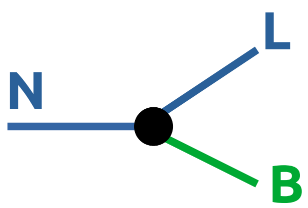
Baryon Asymmetry.

Why do we need new physics?

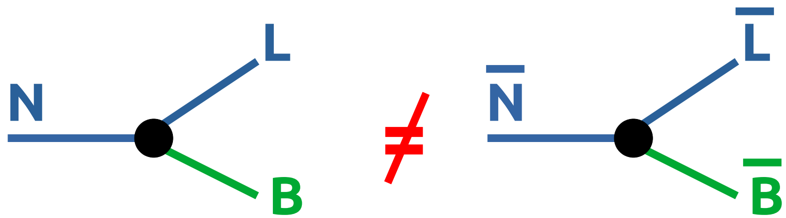
Theoretically, we know the conditions on interactions that have to be fulfilled (Sakharov conditions).



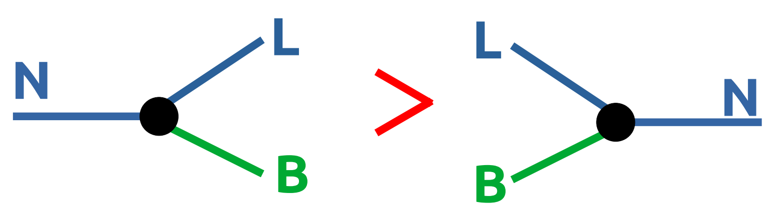
☐ baryon number violation



☐ C and CP violation



☐ departure from thermal equilibrium



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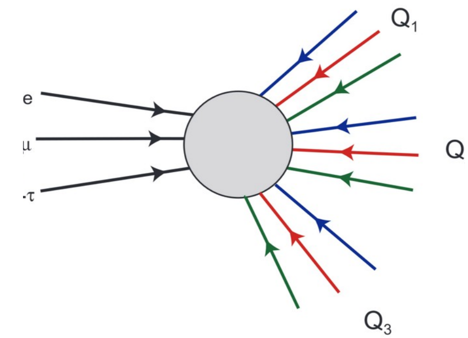
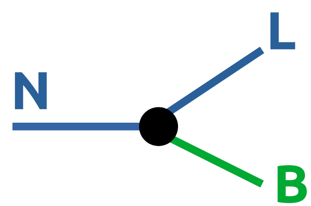
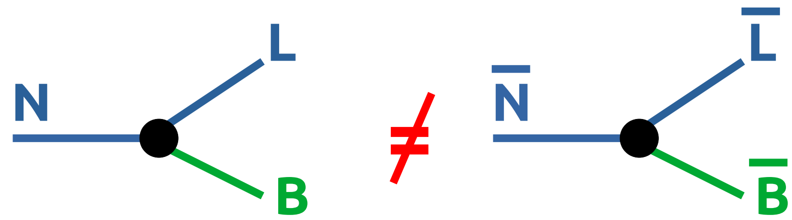


Standard Model?

✓ baryon number violation



✗ C and CP violation



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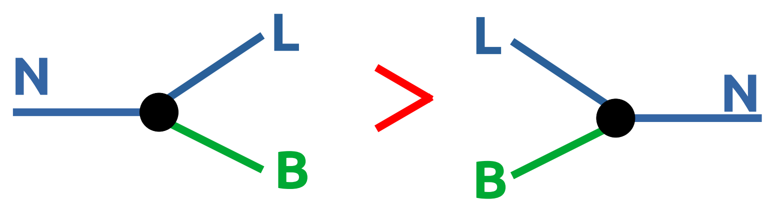
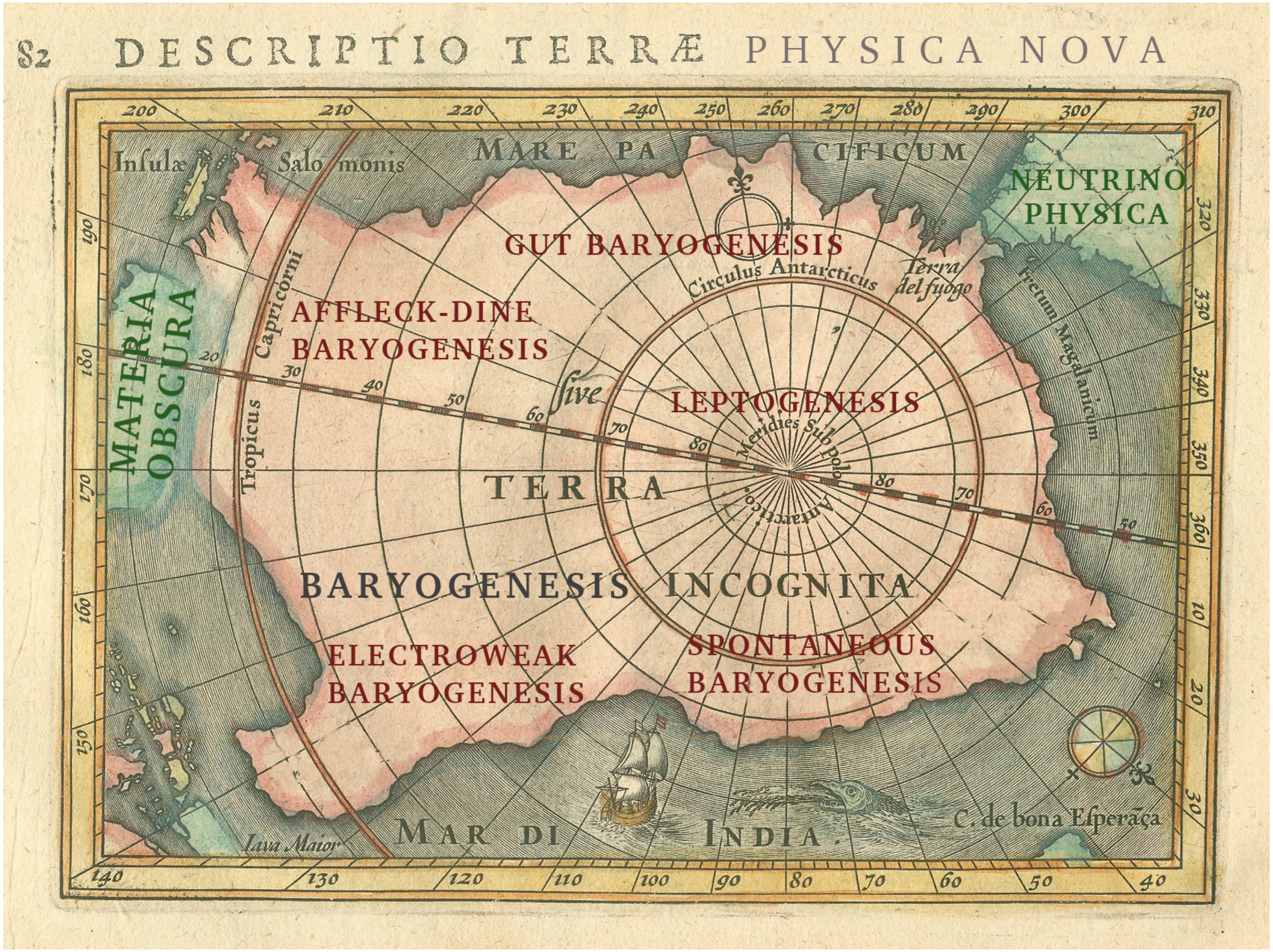


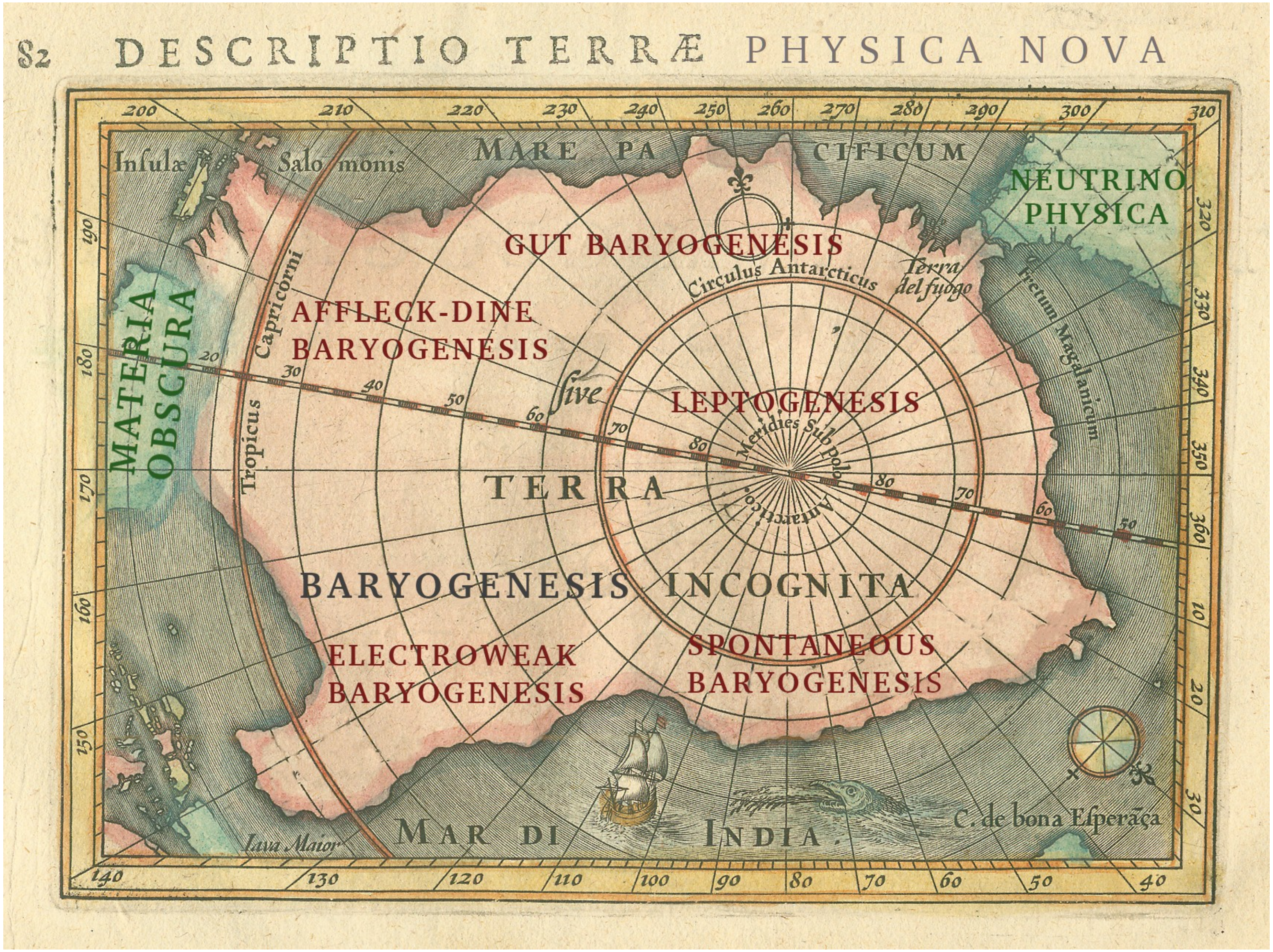
There has to be new physics in order to explain our own existence!

Terra baryogenesis incognita



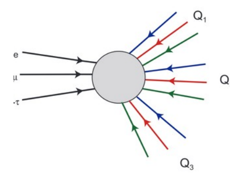
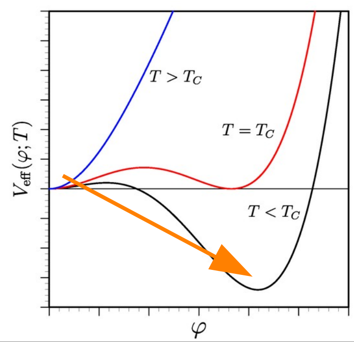
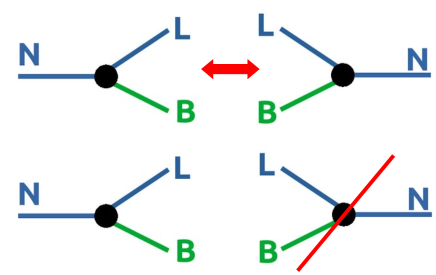
Which mechanism is realised in nature?

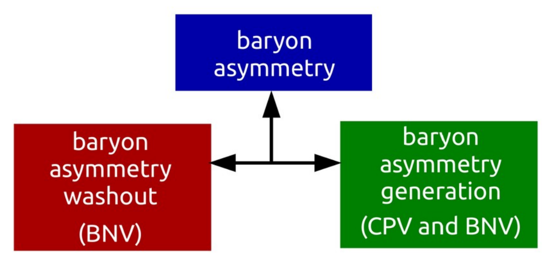
Terra baryogenesis incognita



What can colliders tell us?

Theoretical strategies for baryogenesis

Sakharov condition	realisation I	realisation II
1. C and CP violation	+ a new source of CPV	
2. B violation	**SM sphalerons** active above T_{EW} > 175 GeV  $\Delta B = \Delta L = 3$ B+L violation, B-L conservation	**new B-L violating source** • baryogenesis • leptogenesis
3. Out of equilibrium	**Strong first order phase transition**  	**Out-of-equilibrium decay** $T > m_N$ $T < m_N$ 

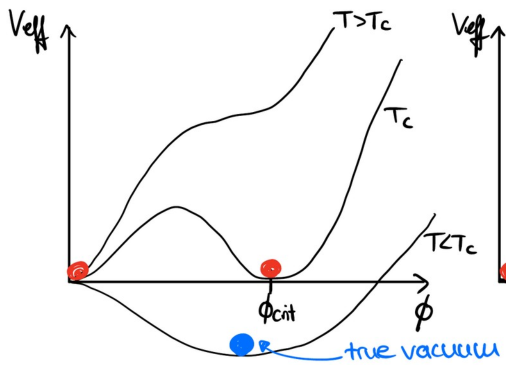


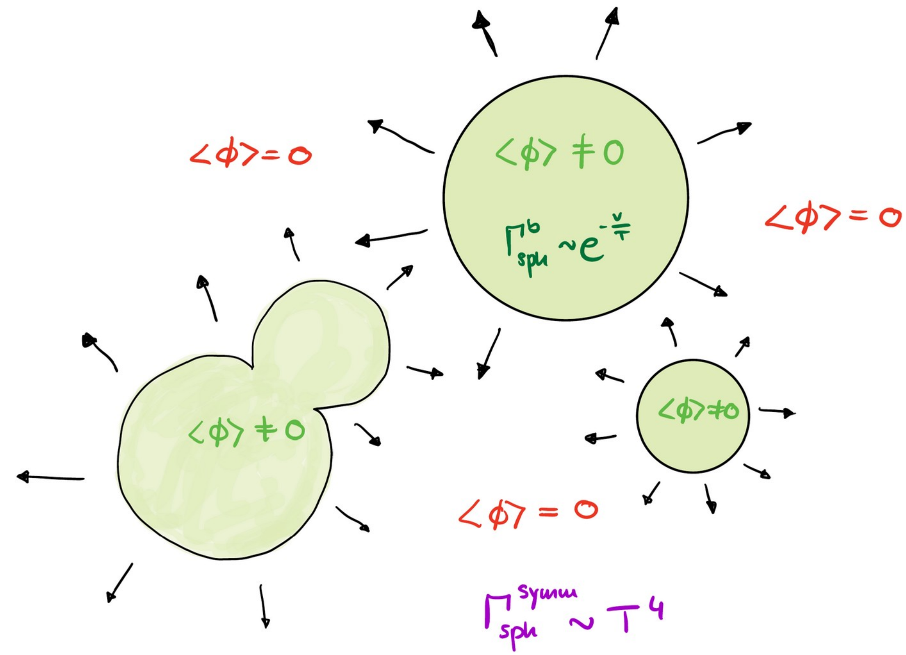
Experimental strategies

- Search for physics leading to out-of-equilibrium condition (strong first order phase transition / heavy particle decay)
- Search for a new source of CPV
- Search for a baryon or lepton violating source
- Search for new degrees of freedoms from specific UV model

The Higgs discovery – a first guidance

The 125 GeV Higgs excludes a strong first order phase transition (SFOPT) within the SM!





Even with a new CP source, electroweak BG not possible within the SM!

→ **new d.o.f. altering the potential leading to a SFOPT**

→ **out-of-equilibrium decays from heavy new particles**

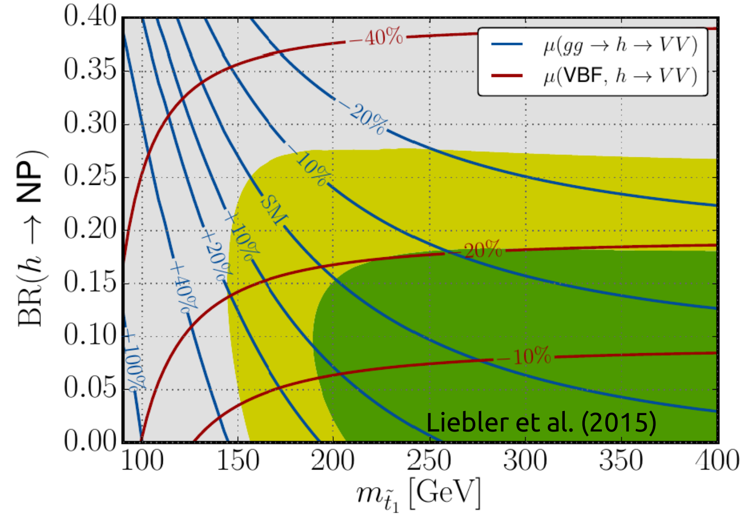
Probing a strong first order phase transition

Electroweak baryogenesis beyond the SM

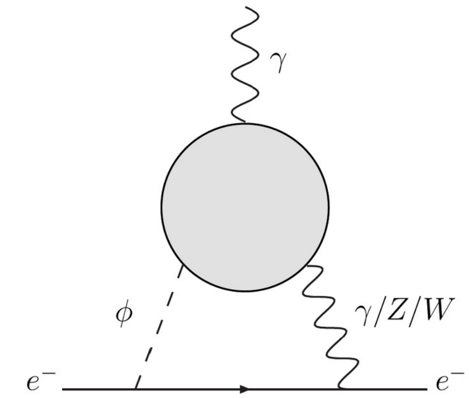
Are there new degrees of freedom that modify the scalar potential and lead to a SFOPT for successful baryogenesis?

- **Prime example: MSSM with a light stop**
  - Lattice calculations set limit of <155 GeV
  - **Is the necessary light stop conclusively excluded by the LHC?**

Delphine et al. (1996), Carena et al. (1996, 1998, 2003, 2009), Espinosa et al. (1996), Huber et al. (1999), Profumo (2007), Curtin (2012), Liebler (2015) and more….



- **General extended scalar sectors, e.g.**
  - 2HDM with extra bottom Yukawa coupling Modak et al. (2020)
  - B-LSSM (B-L symmetric MSSM) Yang et al. (2019)
  - New gauge singlets and vector-like leptons Bell et al. (2019)



General difficulties:

- Constraints from EDMs
- **Collider constraints on Higgs physics set stringent constraints**

Probing a first order phase transition

Higgs potential with higher dimensional operators:

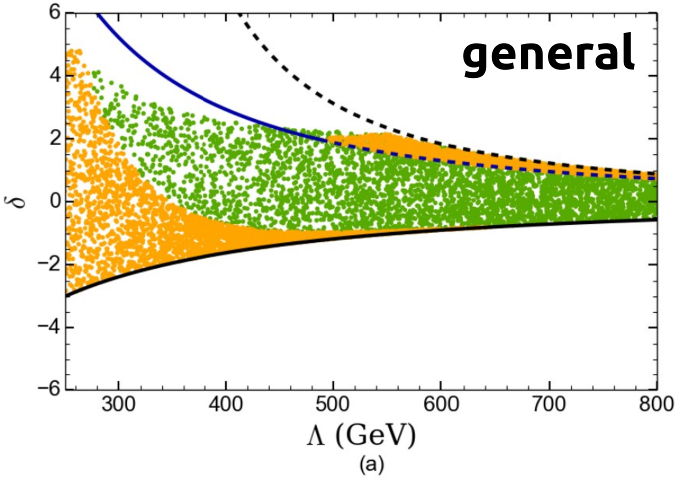
$$V(\phi,0) = \frac{m^2}{2}(\phi^\dagger\phi) + \frac{\lambda}{4}(\phi^\dagger\phi)^4 + \sum_{n=1}^{\infty}\frac{c_{2n+4}}{2^{(n+2)}\Lambda^{2n}}\left(\phi^\dagger\phi\right)^{n+2}$$

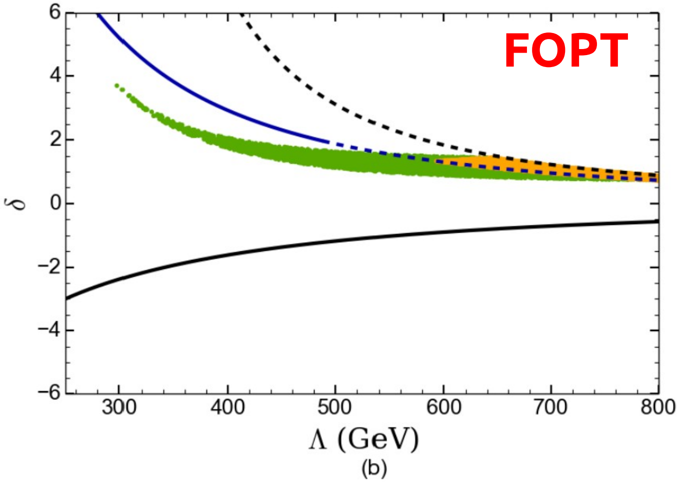
Correction to triple Higgs coupling:

$$\delta = \frac{\lambda_3}{\lambda_3^{SM}} - 1 = \frac{8v^2}{3m_h^2}\sum_{n=1}^{\infty}\frac{n(n+1)(n+2)c_{2n+4}v^{2n}}{2^{n+2}\Lambda^{2n}}$$

Larger triple Higgs coupling associated with FOPT, smaller with SOPT:

$(\phi\phi^\dagger)^4$

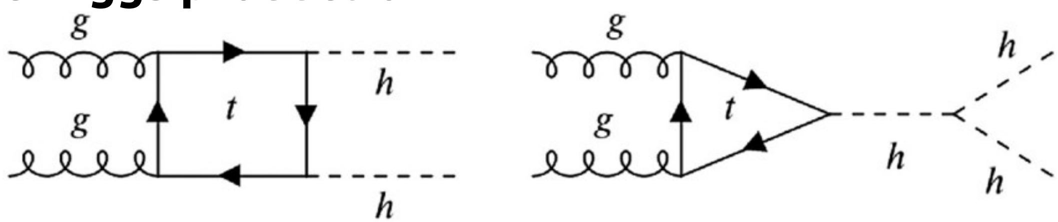


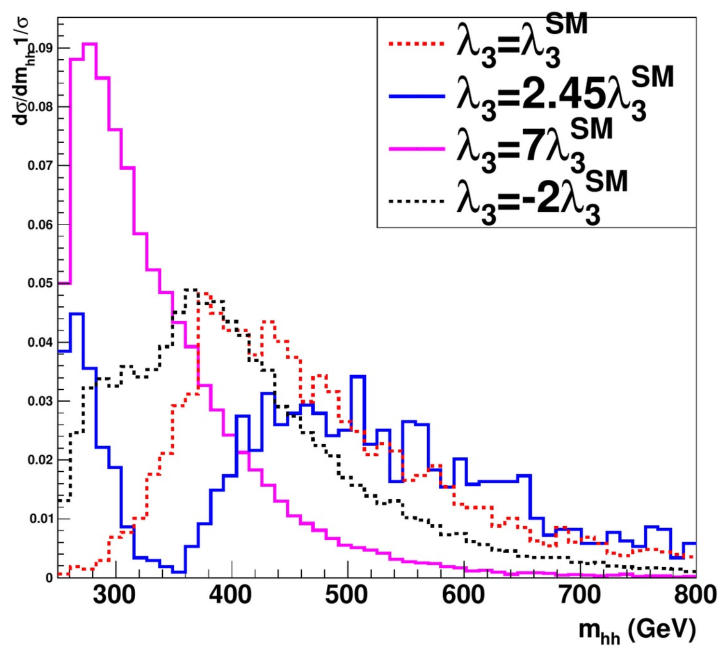


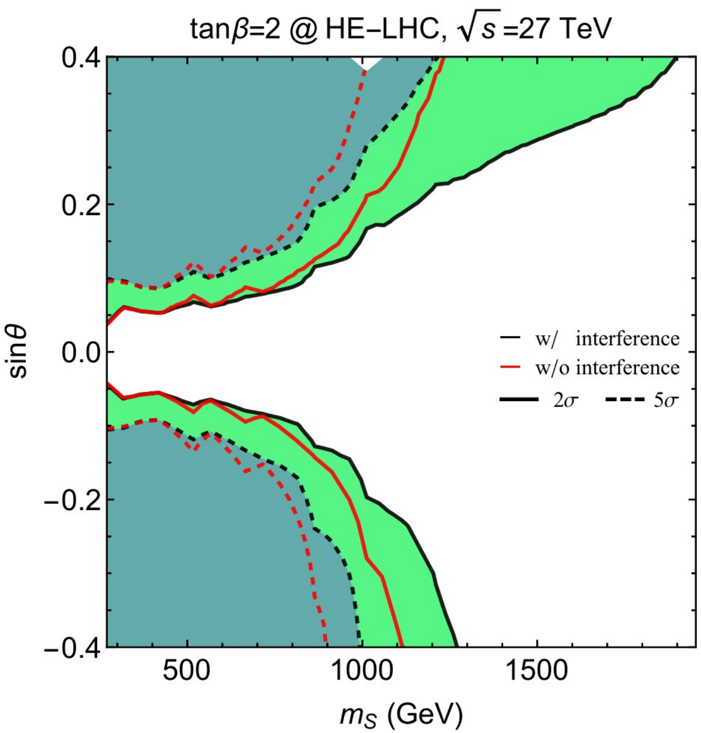
Huang et al. (2015)

Probing a first order phase transition

Collider probe: Double Higgs production







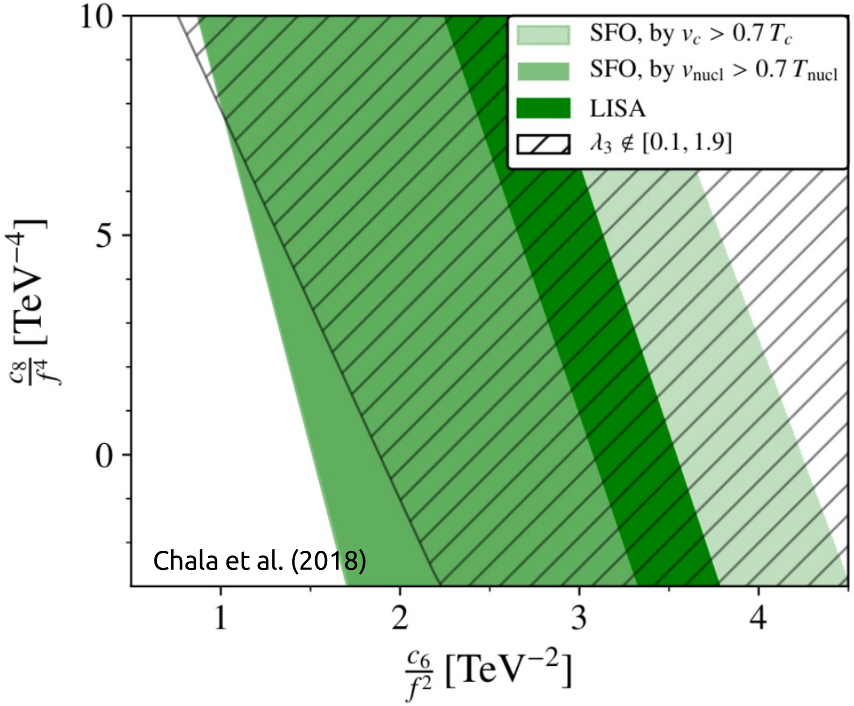
$$V(s,\phi) = -\mu^2\phi^\dagger\phi - \frac{1}{2}\mu_s^2 s^2 + \lambda(\phi^\dagger\phi)^2 + \frac{\lambda_s}{4}s^4 + \frac{\lambda_{s\phi}}{2}s^2\phi^\dagger\phi.$$

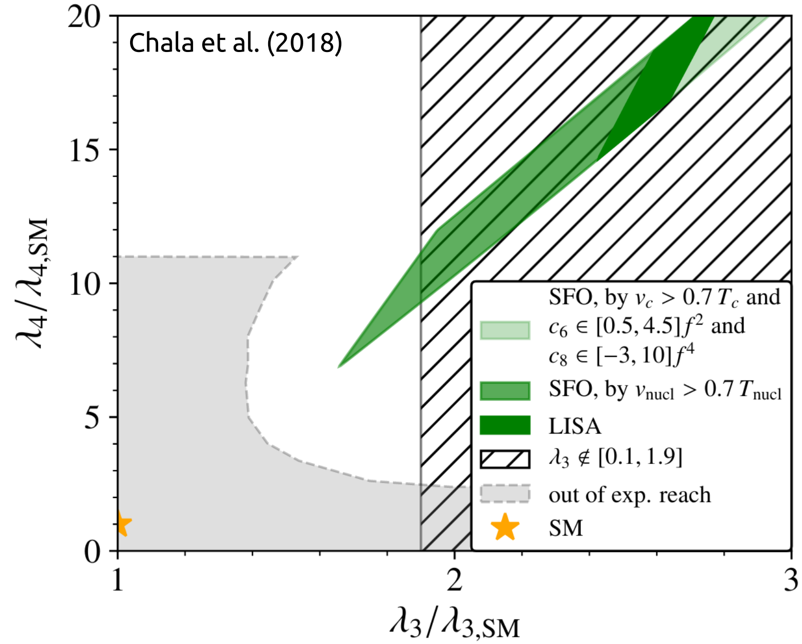
Huang et al. (2015)

Carena et al. (2018)

Probing a first order phase transition

$$L = L_{\rm SM} + \frac{c_6}{f^2}(\phi^\dagger\phi)^3 + \frac{c_8}{f^4}(\phi^\dagger\phi)^4$$





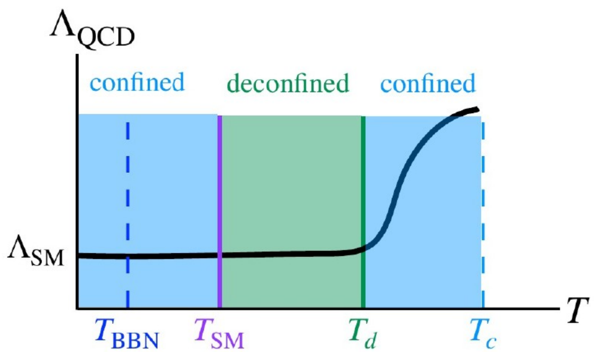
$$\frac{\lambda_3}{\lambda_{3,\rm SM}} = 1 + \frac{v^2}{m_h^2}\left(2c_6\frac{v^2}{f^2} + 4c_8\frac{v^4}{f^4}\right)$$

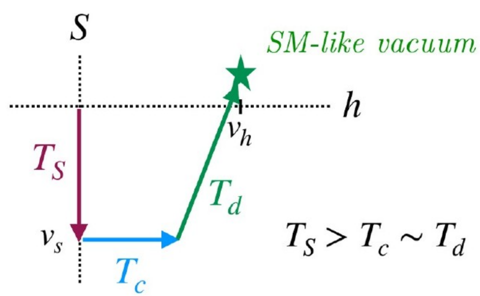
Exciting interplay of LHC and LISA!

$$\frac{\lambda_4}{\lambda_{4,\rm SM}} = 1 + 4\frac{v^2}{m_h^2}\left(3c_6\frac{v^2}{f^2} + 8c_8\frac{v^4}{f^4}\right)$$

QCD baryogenesis

If # of massless fermions > 3, QCD confinement proceeds via SFOFT Pisarski (1984)

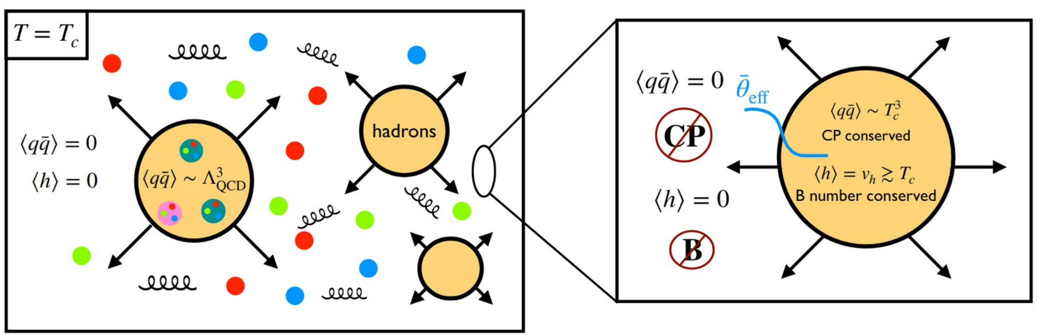




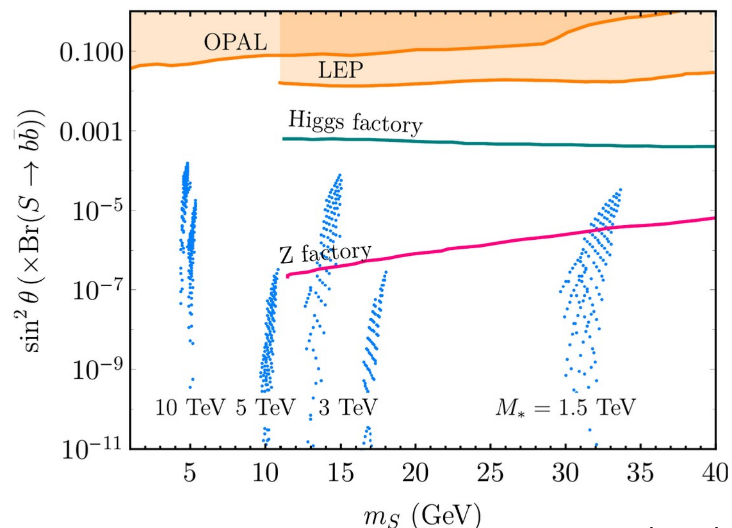
$$-\frac{1}{4}\left(\frac{1}{g_{s0}^2}+\frac{S}{M_*}\right)G^a_{\mu\nu}G^{\mu\nu}_a$$

If QCD confines when the Higgs vev is zero (fermions massless), phase transition is first order.

Introduce scalar field S that perturbs the Higgs potential such that $T_c < T_{EW}$



Baryogenesis via FOPT during QCD confinement, axion as a CP source, sphalerons must be suppressed in confined phase $v_h / T_c > 1$



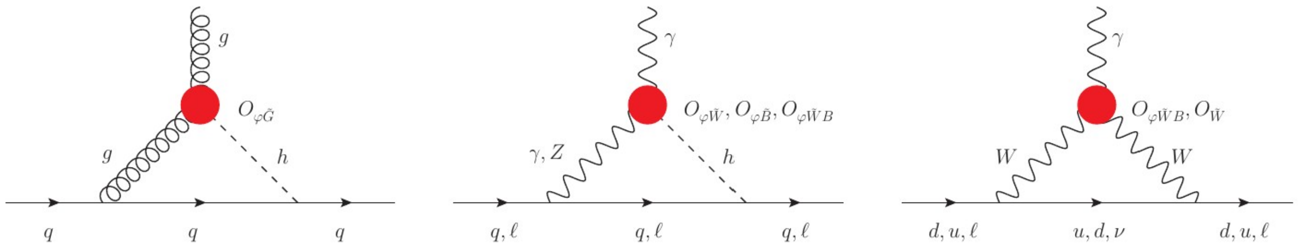
Testable light states predicted.

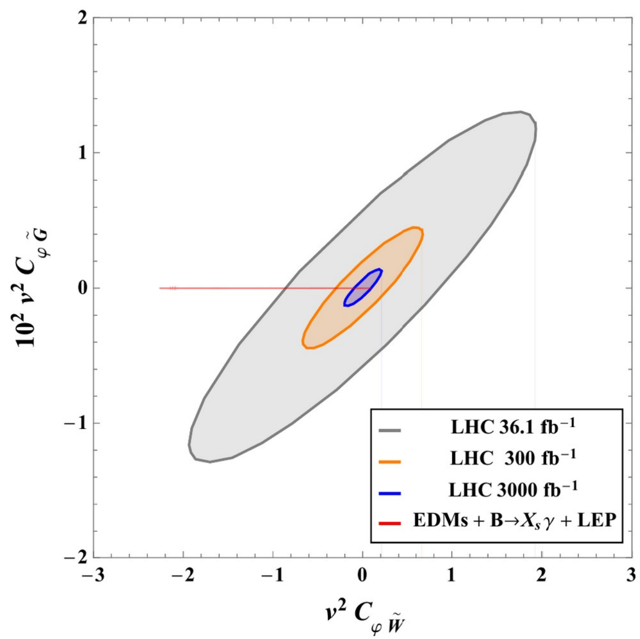
Ipek et al. (2019)
Croon et al. (2020)

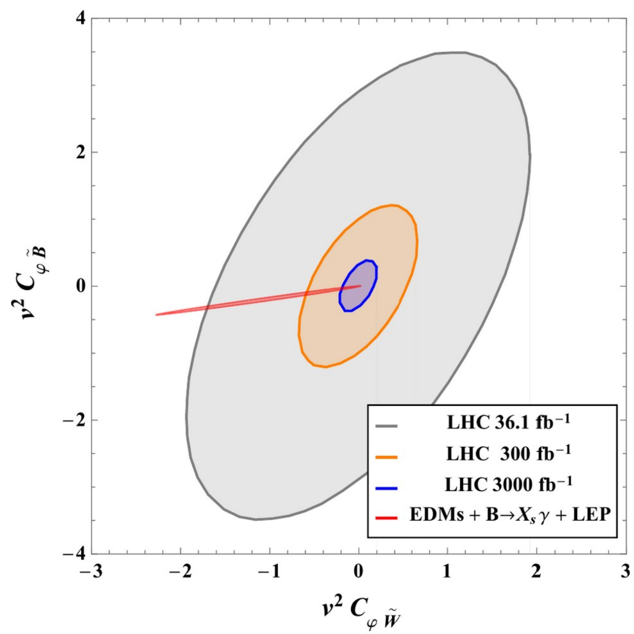
Probing CP Violation

Probing CPV

Possible 6-dim operators in universal theories:







EDMs enforce strong correlations that can be tested at colliders.

Cirigliano et al. (2019)

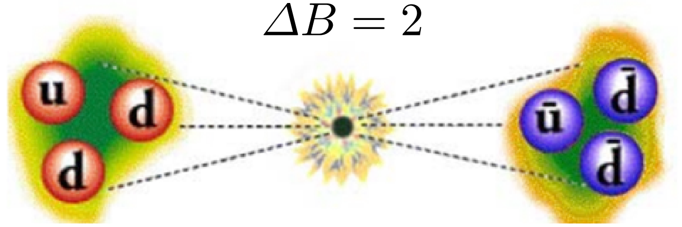
Probing B-L number violation

Probing baryon number violation

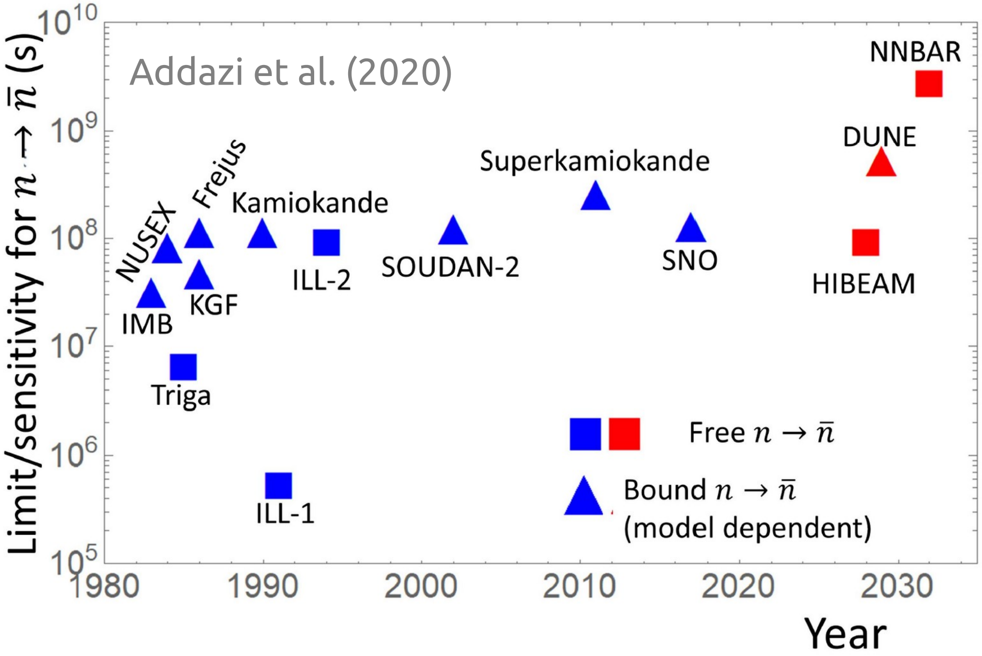
Probing baryon number violation (BNV)

- **ΔB = 1:** highly constrained by limits from **proton decay**
- **ΔB = 2:** excellent future prospects from **nnbar oscillations!**

$\Delta B = 2$



$$\frac{1}{\Lambda_{\rm NP}^5} uddudd$$



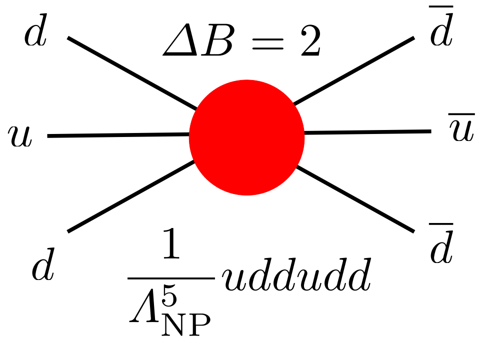
HIBEAM/NNBAR program and DUNE will reach unprecedented sensitivity in the **search for baryon number violation**:

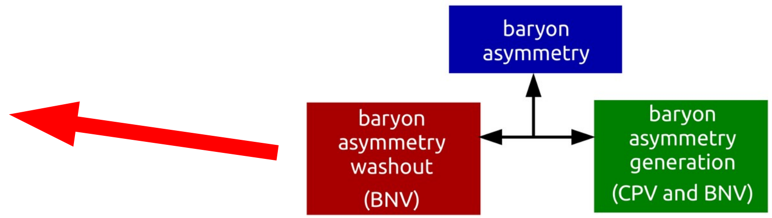
Future sensitivity: $\tau_{n\bar{n}} \geq 10^{10} s$

Naive estimate: $\tau_{n\bar{n}} \approx \frac{\Lambda_{\rm NP}^5}{\Lambda_{\rm QCD}^6}$

$$\boxed{\Lambda_{\rm NP} > 10^6 \,\mathrm{GeV}}$$

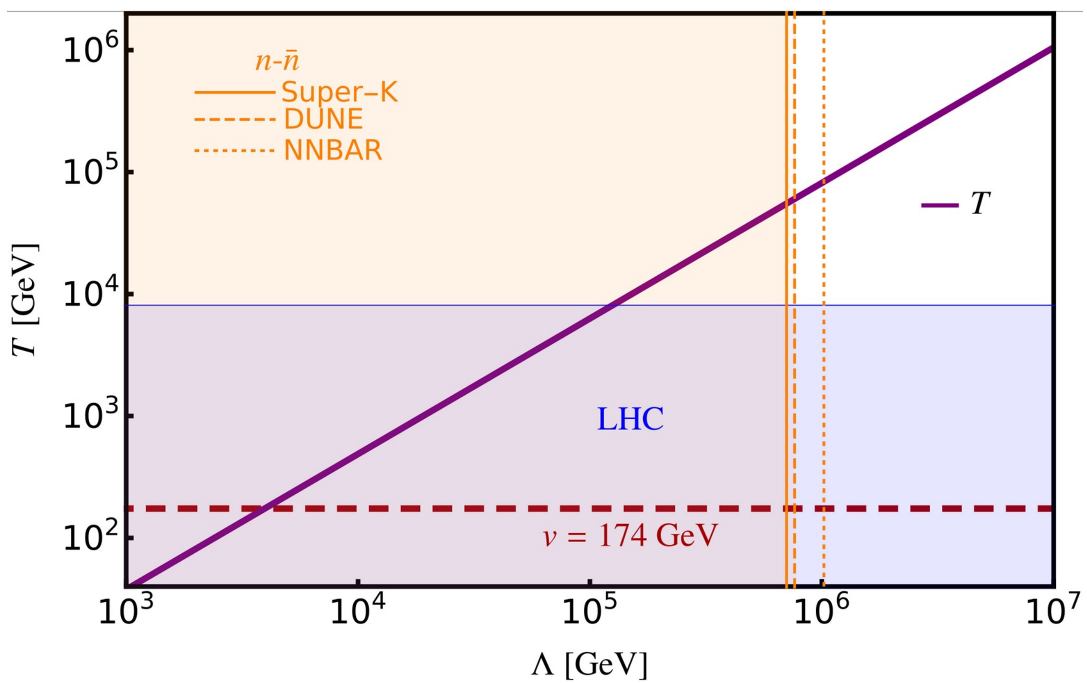
Implications of observation of $n\bar{n}$ oscillations





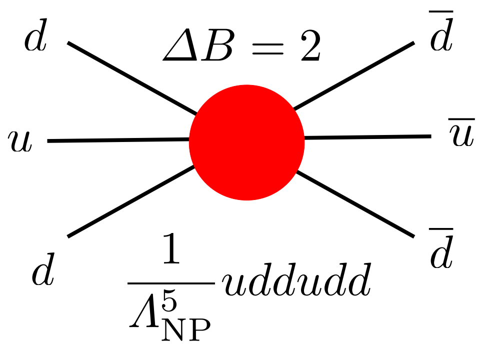
Large washout, if $\frac{\Gamma_W}{H} > 1$.

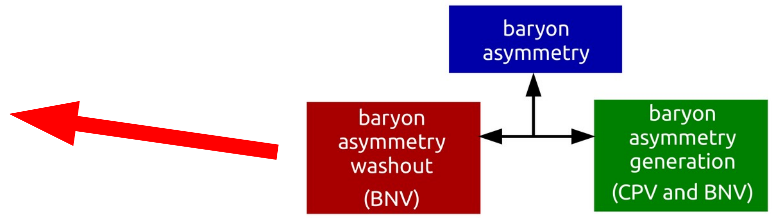
$$\frac{\Gamma_W}{H} = c' \frac{M_{\rm Pl}}{\Lambda_{\rm NP}} \left(\frac{T}{\Lambda_{\rm NP}}\right)^9 \gtrsim 1$$



Fridell, JH, Hati (2021)

Implications of observation of $n\bar{n}$ oscillations





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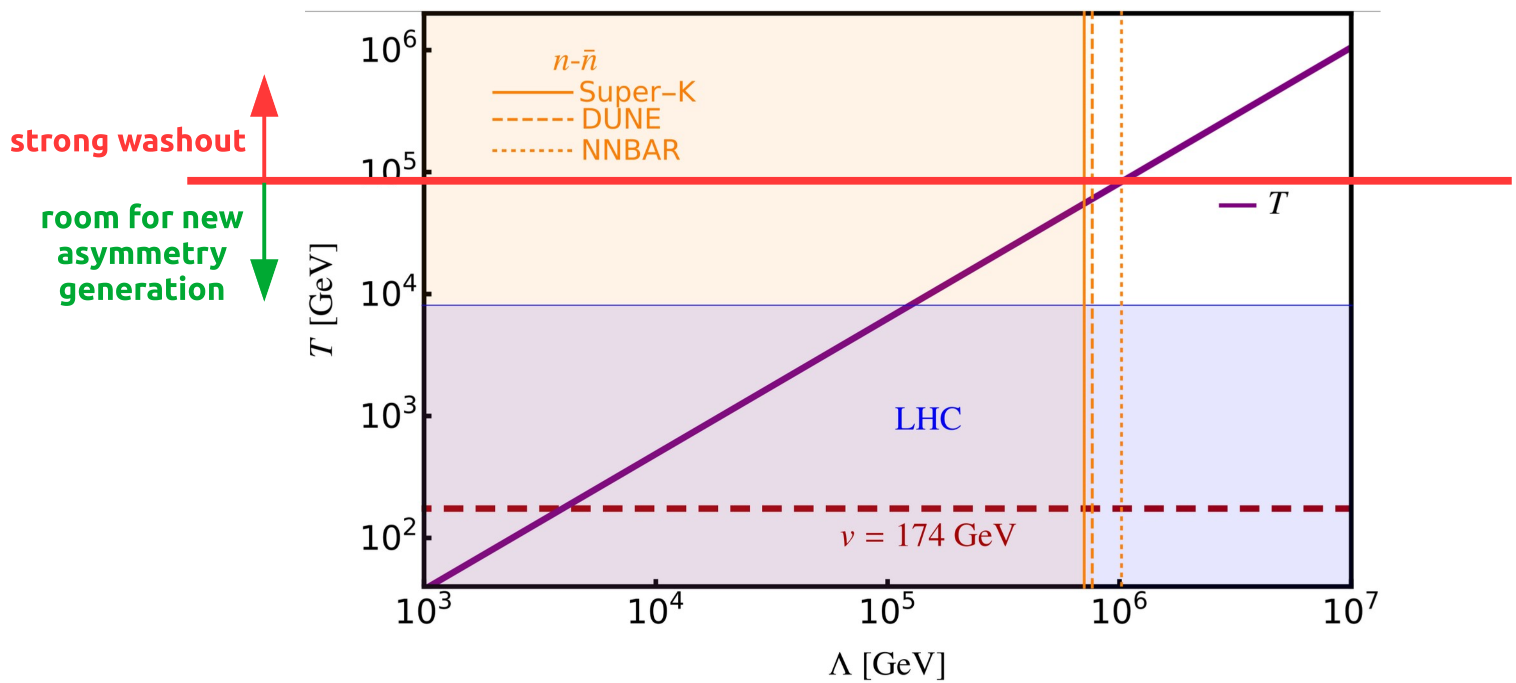
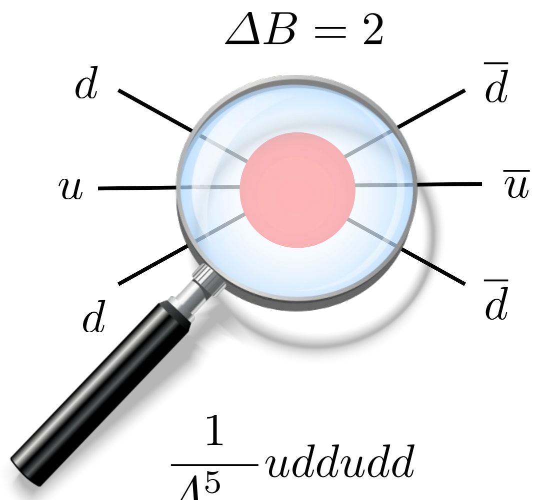


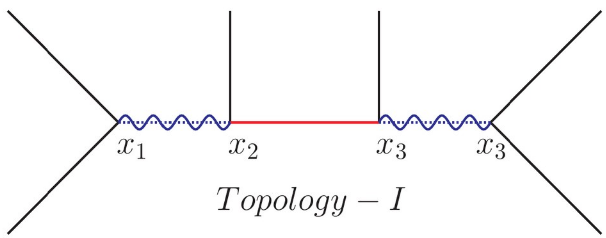
Without CPV in the effective operator, observation of nnbar oscillations would imply a strong asymmetry washout until a scale reachable at future colliders!

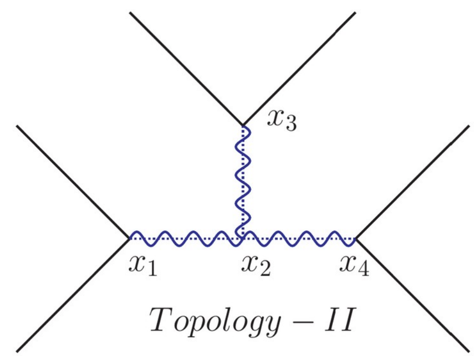
Fridell, JH, Hati (2021)

Possible UV topologies



$$\frac{1}{\Lambda_{\rm NP}^5} uddudd$$





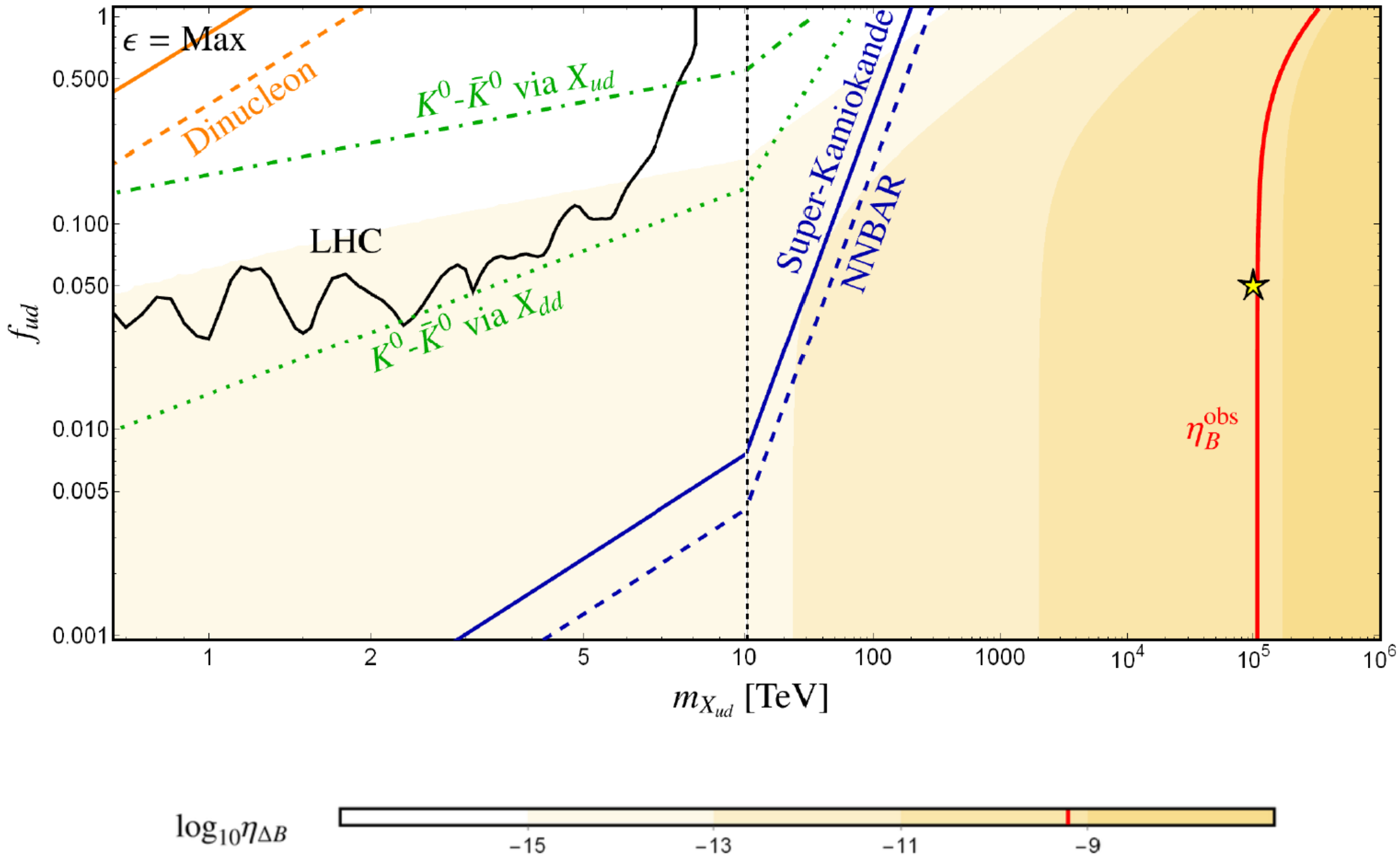
Grojean et al. (2019)

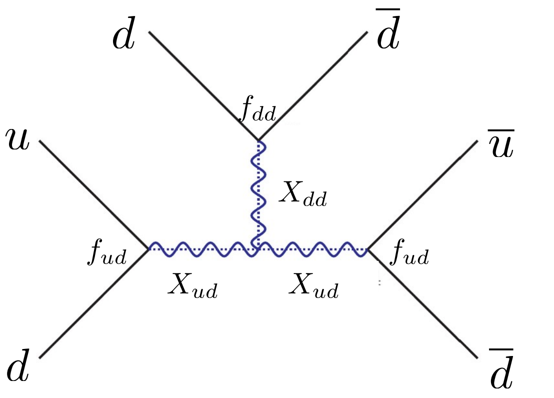
- Left-right symmetric model
- SO(10) GUT
- Post-sphaleron baryogenesis

Mohapatra et al. (1980)
Babu et al. (2006)
Baldes et al. (2011)
Babu et al. (2012)
Herrmann (2014)

Now: Confronting simplified model including CP source and different hierarchies with current and future experiments

Implications of observation of $n\bar{n}$ oscillations



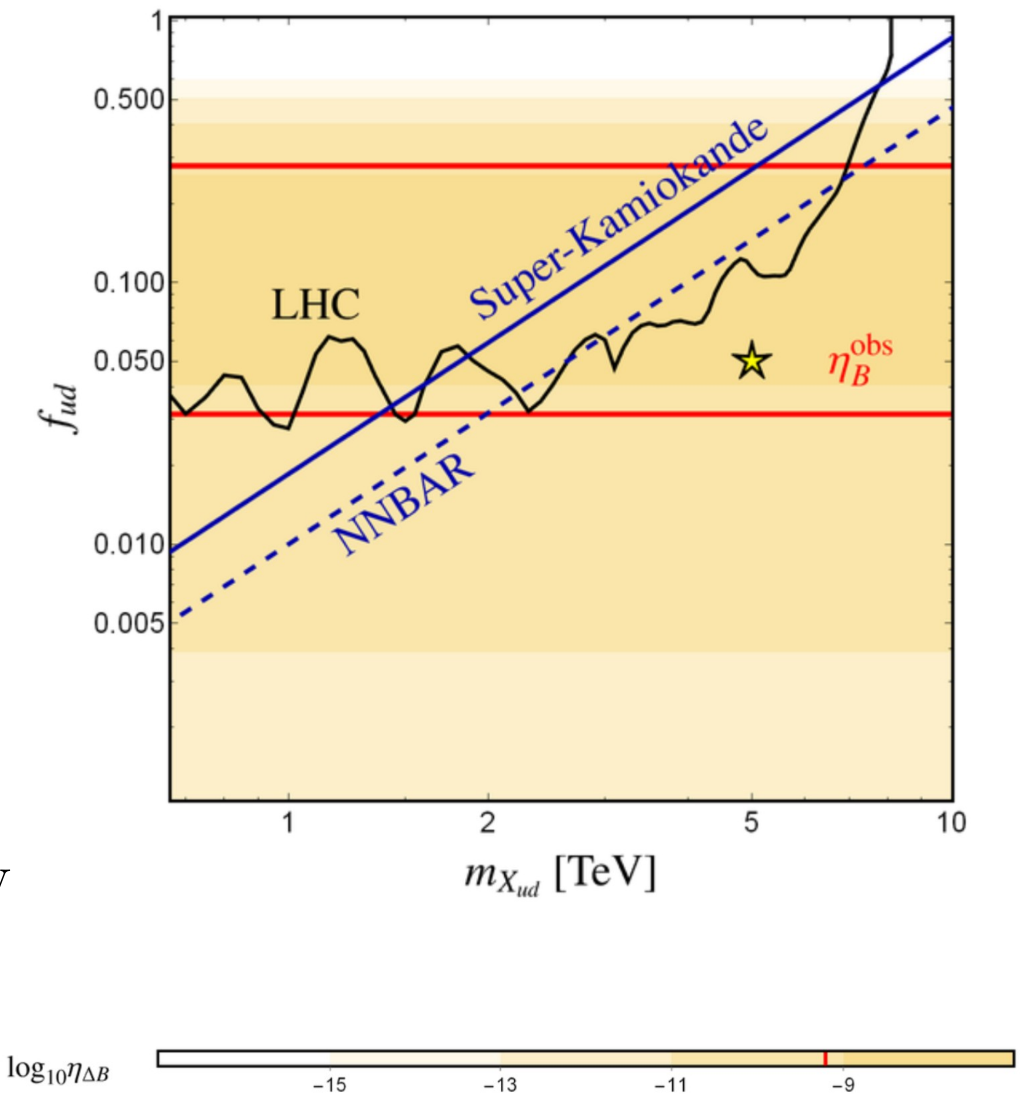


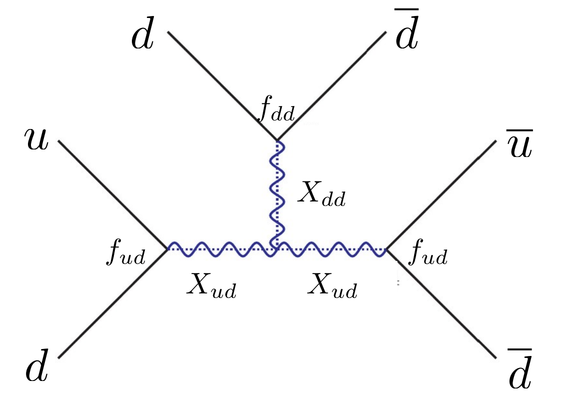
$$m_{X_{dd}} = 3m_{X_{ud}}$$
$$f_{ud} = f_{dd}$$

$$C_1 \approx \frac{\left(f_{11}^{ud}\right)^2 f_{11}^{dd}}{m_{X_{dd}} m_{X_{ud}}^4}$$

Fridell, JH, Hati (2021)

Implications of observation of $n\bar{n}$ oscillations





$$m_{X_{dd}} = 10^{13}\ \mathrm{GeV}$$
$$f_{ud} = f_{dd}$$

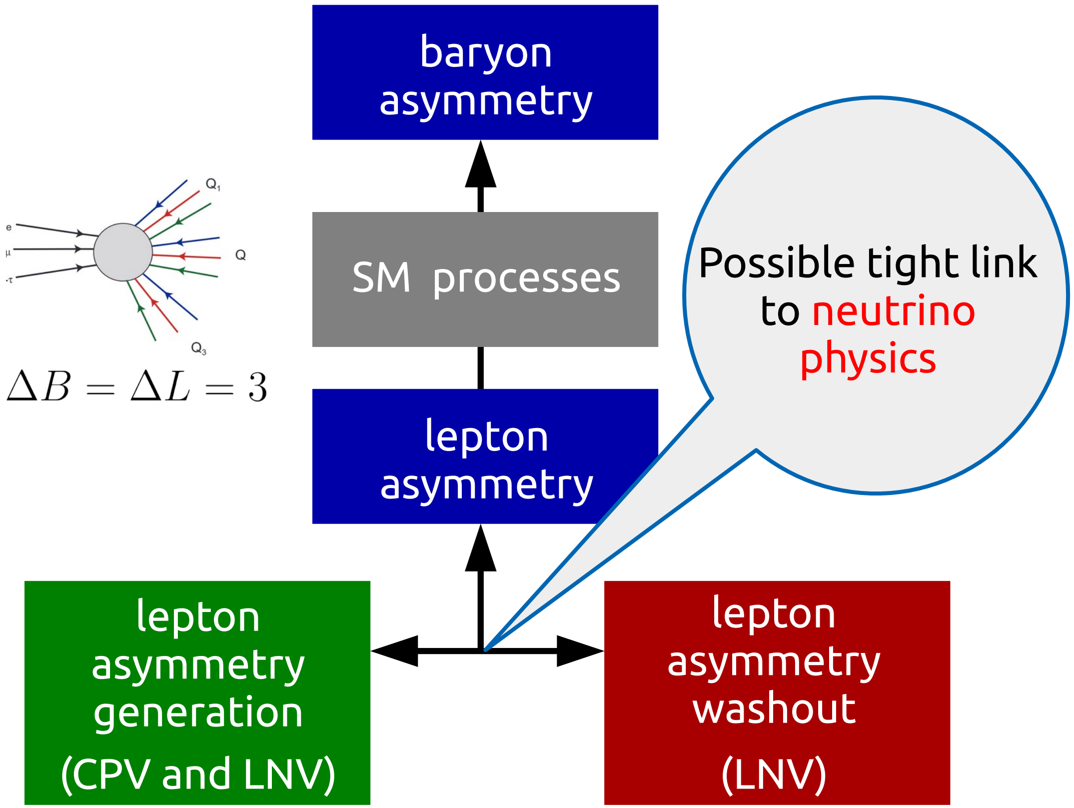
$$C_1 \approx \frac{\left(f_{11}^{ud}\right)^2 f_{11}^{dd}}{m_{X_{dd}} m_{X_{ud}}^4}$$

Fridell, JH, Hati (2021)

Probing lepton number violation

Leptogenesis

The generation of a baryon asymmetry – baryogenesis – can be created by a lepton asymmetry – leptogenesis:



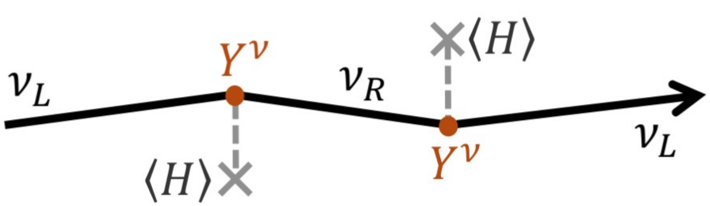
In turn, lepton number violation (LNV) can destroy a lepton asymmetry, and thus even a baryon asymmetry!

Lepton Number Violation and the nature of neutrinos

Dirac mass

$$y_\nu L \epsilon H \overline{\nu}_R \supset m_D \nu_L \overline{\nu}_R$$

→ lepton number no accidental symmetry anymore



Majorana mass

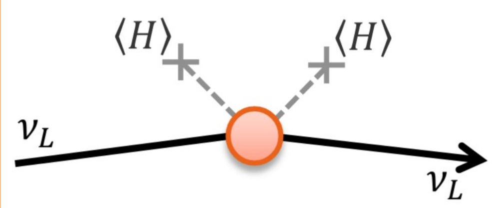
$$m_M \overline{\nu}_R \nu_R^c$$

→ higher dimensional operator

$$m_M \overline{\nu}_L \nu_L^c \qquad LLHH$$

not at tree-level within the SM possible

→ Lepton number violation (LNV)

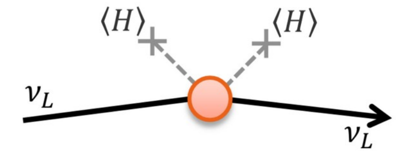


Leptogenesis & the neutrino mass mechanism

The origin of neutrino masses lies beyond the standard model

$$\mathrm{L} = \overline{N}_k\, i\partial\!\!\!/\, N_k - \left(\tfrac{1}{2} M_k\, \bar{N}_k^c N_k + \lambda_{\alpha k}\, \bar{\ell}_\alpha \phi^c N_k + \mathrm{h.c.}\right)$$

$$\mathrm{M}_\nu \approx -\frac{v^2}{2} \lambda M_N^{-1} \lambda^T$$



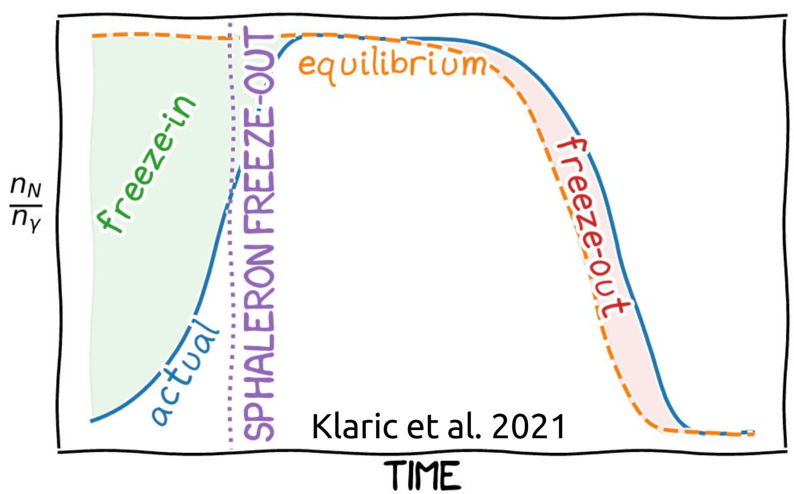
- Majorana neutrino mass
- Higher dimensional operator
- Lepton number violation (LNV)

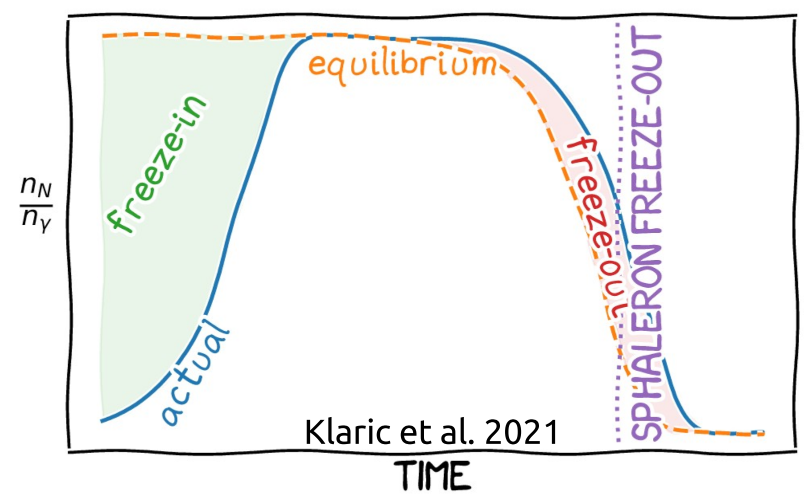
$$\mathrm{M}_\nu \simeq 0.3 \left(\frac{\mathrm{GeV}}{M_N}\right)\left(\frac{\lambda^2}{10^{-14}}\right) \mathrm{eV}$$

Leptogenesis via oscillations

$$\mathrm{M}_\nu \simeq 0.3 \left(\frac{10^8\,\mathrm{GeV}}{M_N}\right)\left(\frac{\lambda^2}{10^{-6}}\right) \mathrm{eV}$$

High-scale Leptogenesis





Combined analysis of both regimes and comparison with existing literature (Klaric et al. 2021)

Probing high-scale leptogenesis

Ways out to overcome the problem of **small neutrino masses** and **washout** in models with leptogenesis from out-of-equilibrium decays

- almost degenerate particles (resonant Leptogenesis)
- late decays
- massive decay (annihilation) products

Racker (2016)

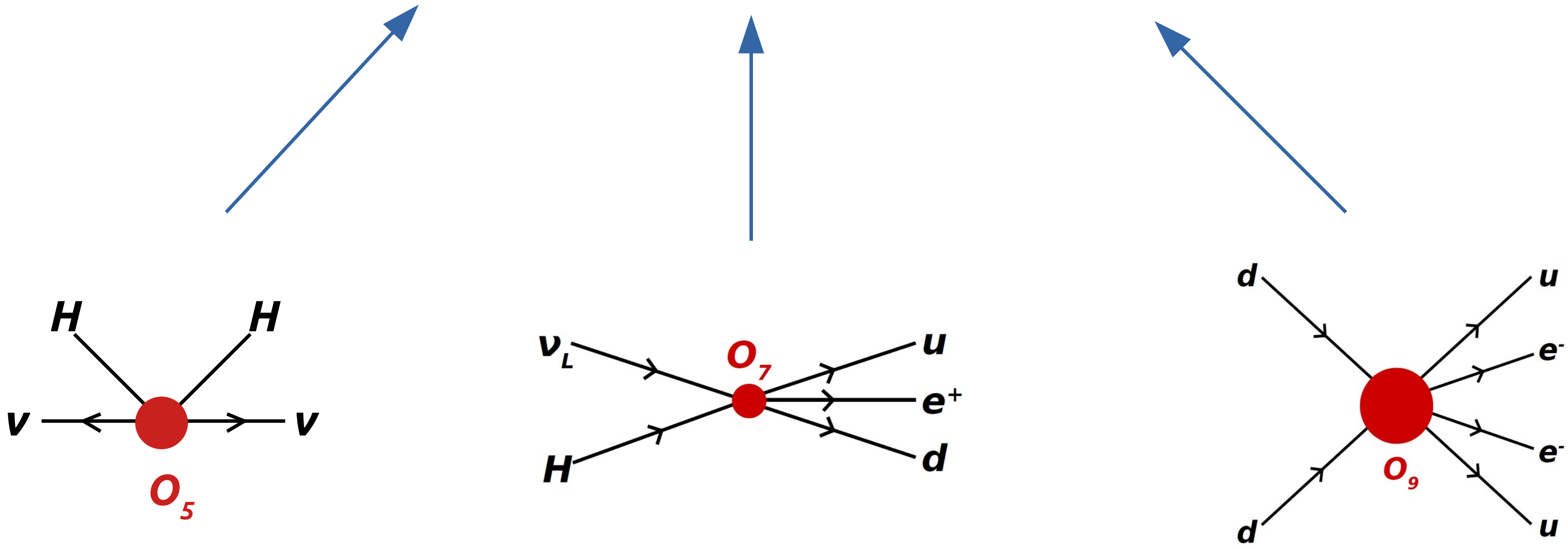
Plethora of examples:

- Extension of seesaw type-I by **new scalars** with same quantum numbers as SM fermions → e.g. long-lived scalars, R-hadrons, heavy sterile neutrinos e.g. Fong et al. (2013)
- **Z' models** → same-sign di-lepton final states e.g. Chun (2005)
- **Left-right symmetric models** → falsification by low mass W_R e.g. Dev. et al. (2015)
- **Soft leptogenesis** → type-I: charged LFV e.g. Adhikari et al. (2015)
  → type-II: same-sign di-lepton resonance, same-sign tetra-leptons e.g. Chun et al. (2006)

Lepton Number Violation (LNV)

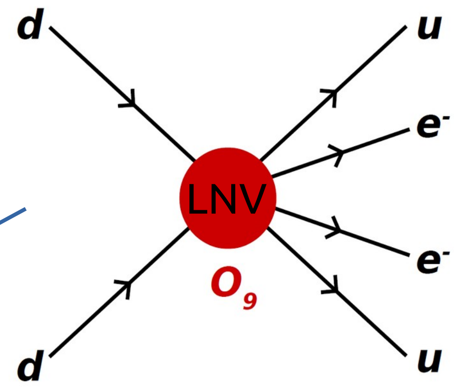
LNV occurs only at odd mass dimension beyond dim-4:

$$\mathcal{L} = \mathcal{L}_{SM} + \frac{1}{\Lambda_1}\mathcal{O}_1^{(5)} + \sum_i \frac{1}{\Lambda_i^3}\mathcal{O}_i^{(7)} + \sum_i \frac{1}{\Lambda_i^5}\mathcal{O}_i^{(9)} + \cdots$$

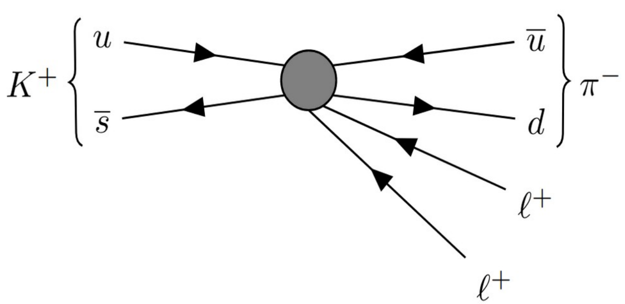


See surveys of all LNV operators up to dim-11 e.g. in
Babu, Leung (2001), Gouvea, Jenkins (2008), Graf, JH, Deppisch, Huang (2018)

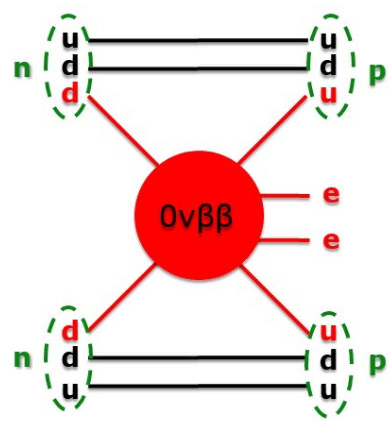
Probing LNV interactions



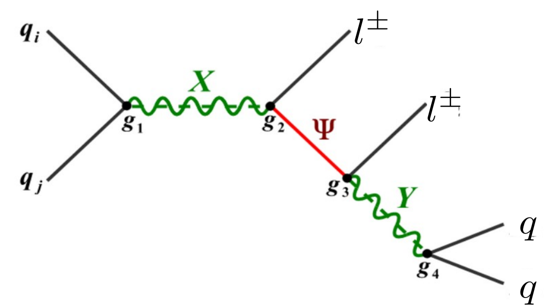
rare meson decays



neutrinoless double beta decay

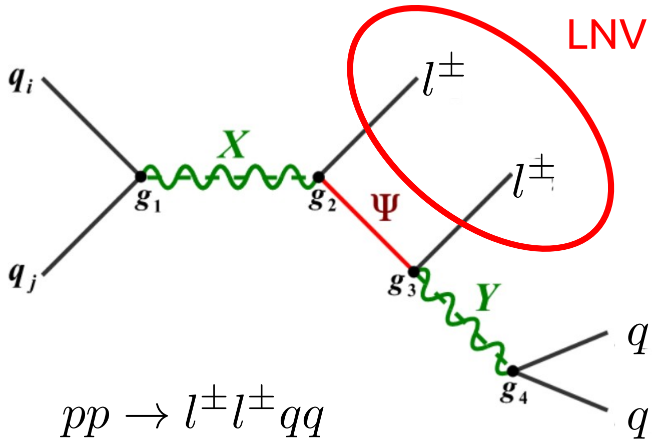


colliders



Probing LNV interactions at the LHC

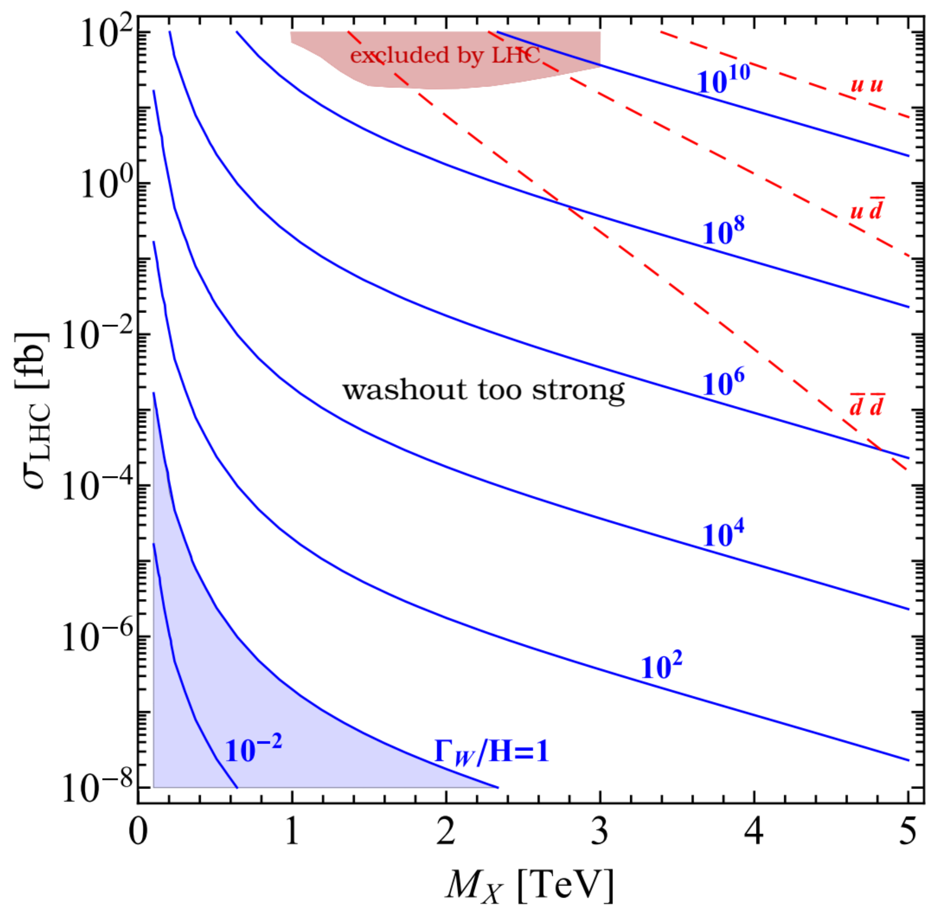
Washout processes could be observable at the LHC



$$\log_{10}\frac{\Gamma_W}{H} > 6.9 + 0.6\left(\frac{M_X}{\mathrm{TeV}} - 1\right) + \log_{10}\frac{\sigma_{\mathrm{LHC}}}{\mathrm{fb}}$$

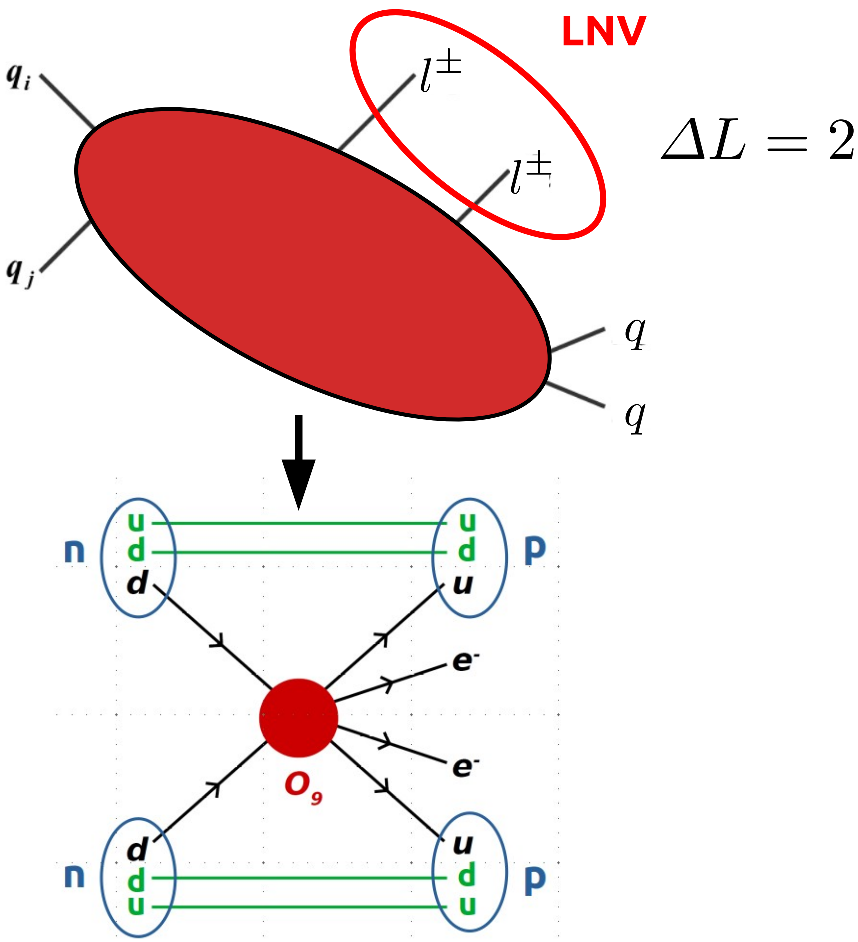
Observation of any washout process at LHC would falsify high scale baryogenesis!

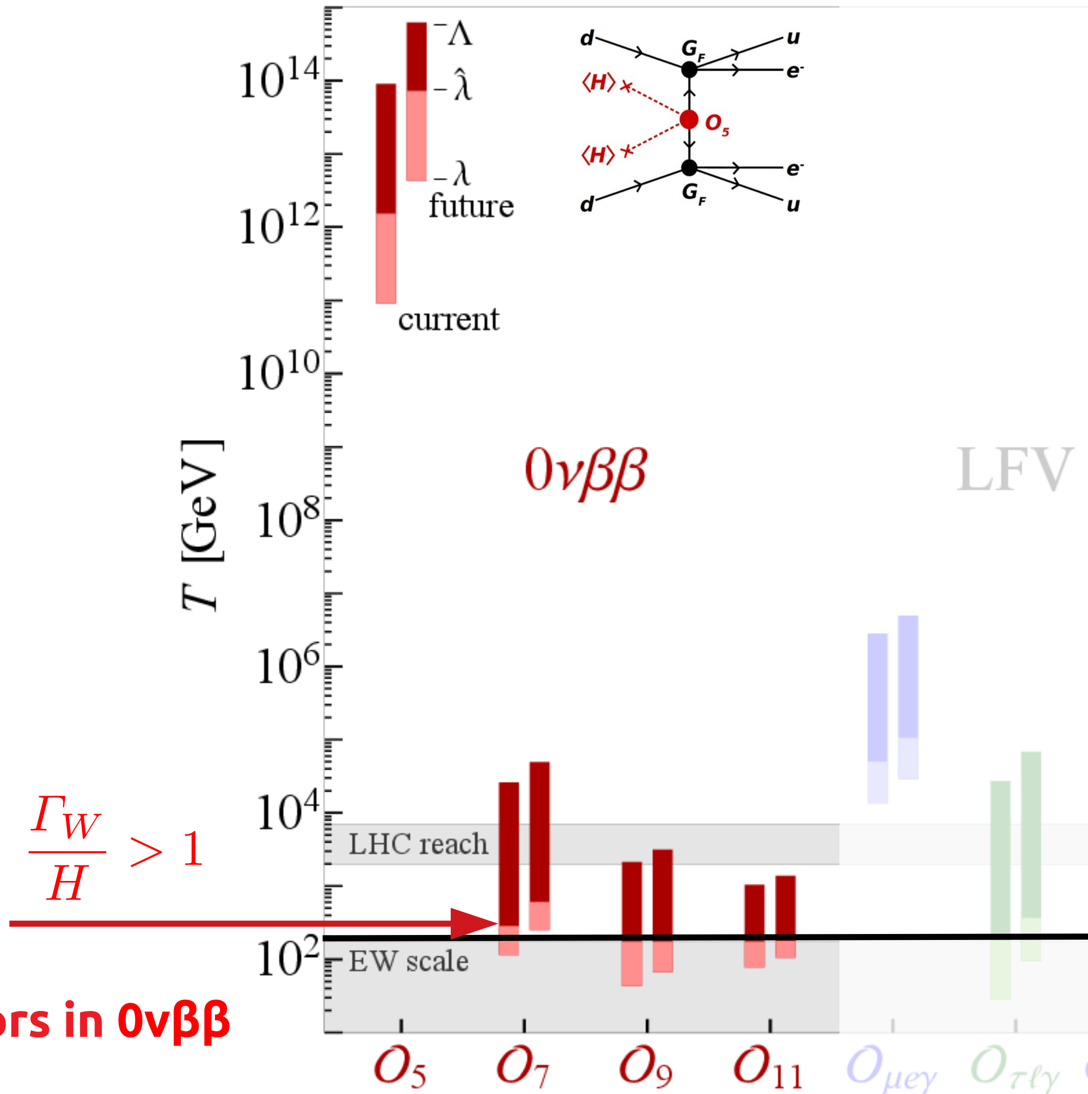
(scale of asymmetry generation *above* M_X)

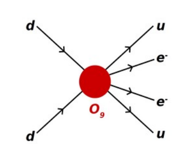


Deppisch, JH, Hirsch, Phys. Rev. Lett. (2014)
Deppisch, JH, Hirsch, Päs, Int. J. Mod. Phys. A (2015)

Probing high-scale leptogenesis with 0νββ decay







Observation of higher dimensional operators in 0νββ decay excludes high-scale baryogenesis!

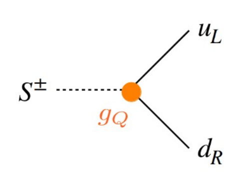
Deppisch, Graf, JH, Huang (2018)
Deppisch, JH, Huang, Hirsch, Päs (2015)

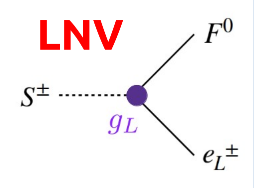
A simplified model study of TeV scale LNV

UV realization of dim-9 operator:

$$\tilde{\mathcal{L}} \supset g_Q \overline{Q} S d_R + g_L \overline{L}(i\tau^2) S^* F - m_S^2 S^\dagger S - \frac{m_F}{2} \overline{F^c} F + \lambda_{HS}(S^\dagger H)^2 + \text{h.c.}$$

TeV-scale LNV "washout" interactions



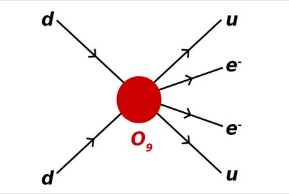


$$\Lambda = (m_S^4 m_F)^{1/5}$$

$$C_1 = g_L^2 g_Q^2$$

Integrating out heavy d.o.f. leads to dim-9 LNV operator:

$$L_{LNV}^{eff} = \frac{C_1}{\Lambda^5} \bar{Q}\tau^+ d \bar{Q}\tau^+ d \bar{L} L^C + \text{h.c.}$$



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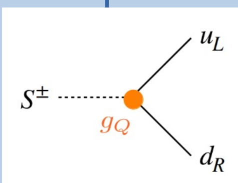

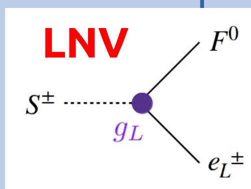

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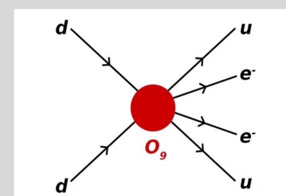
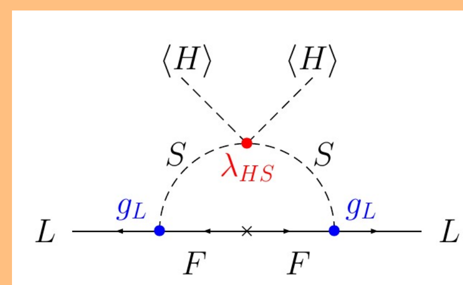


Contribution to neutrino mass dependent on size of λ_{HS}:

$$m_\nu \sim \frac{\lambda_{HS} g_L^2 \langle H\rangle^2}{\Lambda}$$



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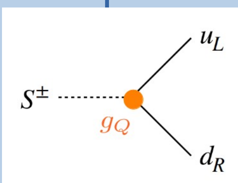

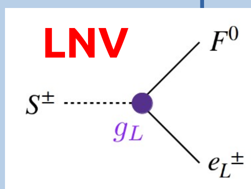

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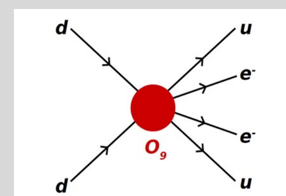

Right-handed neutrino interactions ("standard thermal LG"):

$$\mathcal{L} \supset y_\nu \bar{L} H N - \frac{m_N}{2} \bar{N}^c N + \text{h.c.}$$

high-scale source of lepton asymmetry

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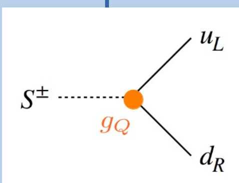

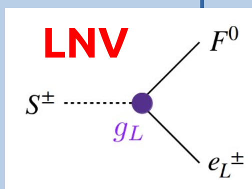

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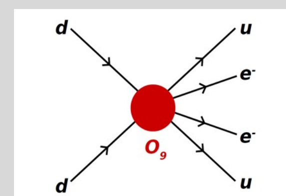

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high-scale source of lepton asymmetry

Can TeV-scale LNV destroy the lepton asymmetry from standard thermal LG?

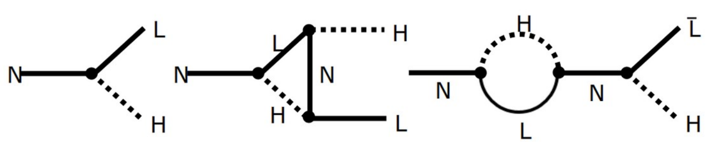
Implications for Leptogenesis

$$\frac{dY_N}{dz} = -\left(D+S\right)\left(Y_N - Y_N^{\text{eq}}\right)$$

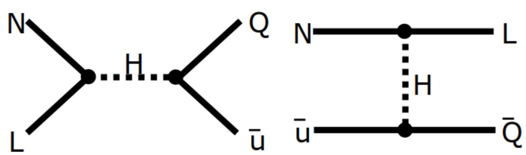
$$\frac{dY_{B-L}}{dz} = -\epsilon\, D\left(Y_N - Y_N^{\text{eq}}\right) - W\, Y_{B-L}$$

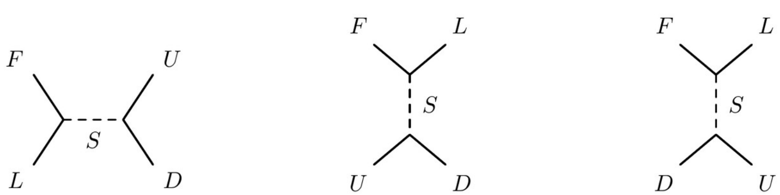
$\Delta L = 1$

source of CP violation



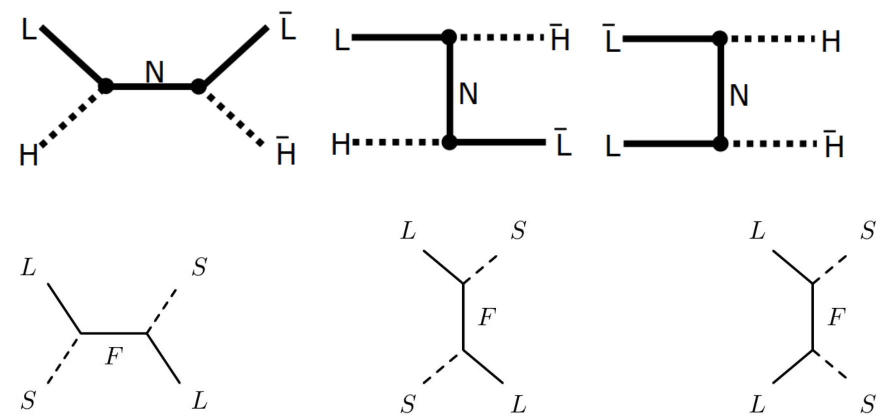
scattering processes





washout processes

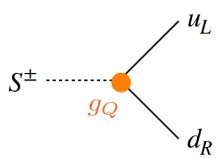
$\Delta L = 2$

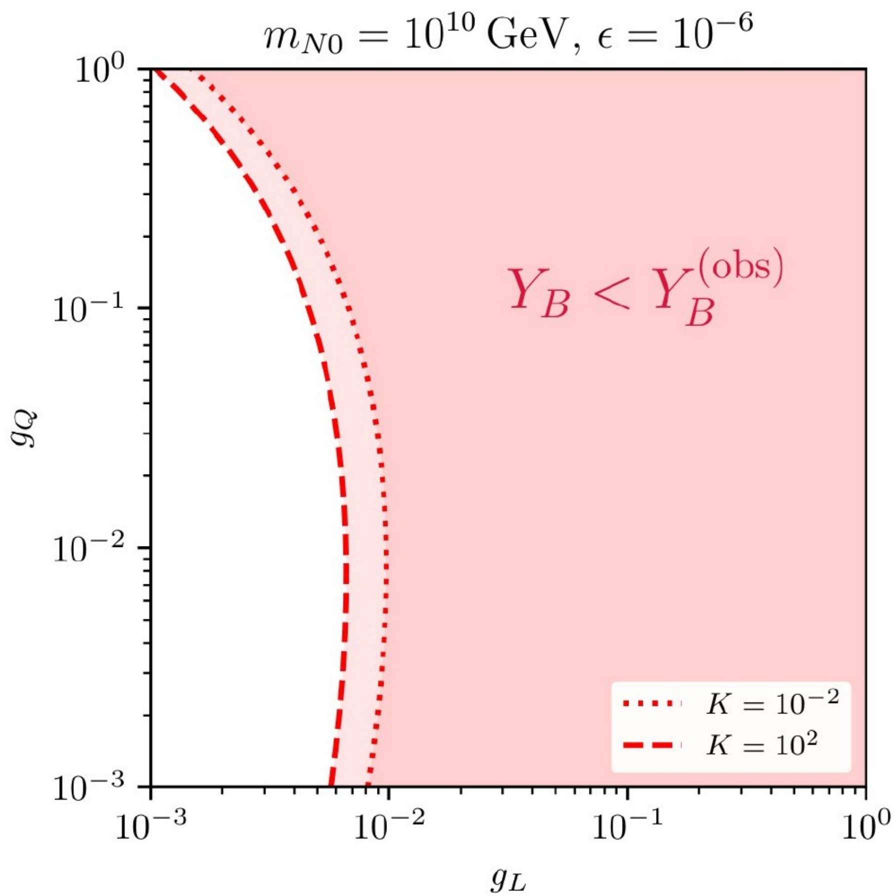


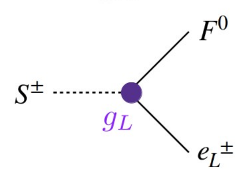
washout processes

JH, Ramsey-Musolf, Shen, Urrutia-Quiroga (2021)

Implications for Leptogenesis





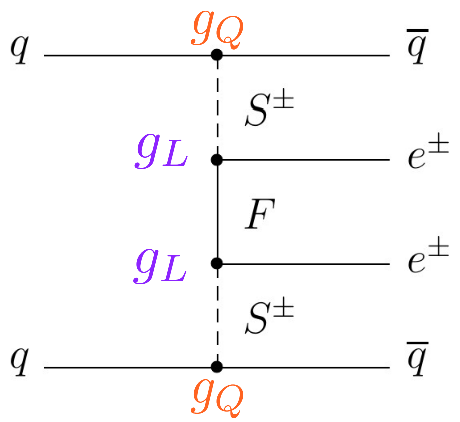


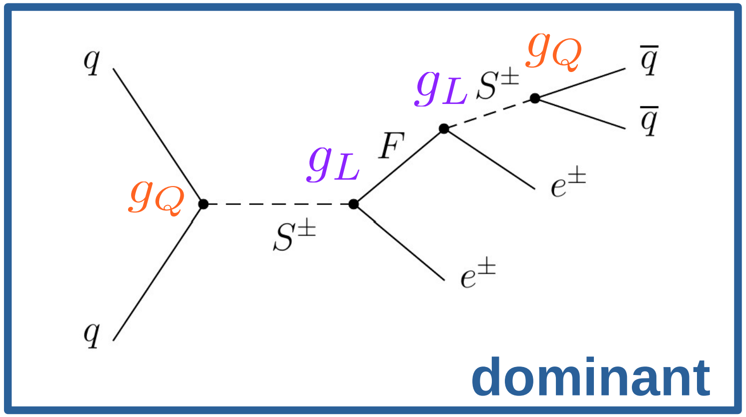
Washout-parameter:

$$K = \frac{\Gamma_N}{H(z=1)}$$

JH, Ramsey-Musolf, Shen, Urrutia-Quiroga (2021)

Reach at colliders





Case	Mass hierarchy	Process
C1	$m_S < m_F$	$pp \to e^\pm F, \quad F \to e^\pm S^\mp, \quad S^\mp \to jj$
C2	$m_S = m_F$	$pp \to e^\pm F, \quad F \to e^\pm jj$
C3	$m_S > m_F$	$pp \to S^\pm, \quad S^\pm \to e^\pm F, \quad F \to e^\pm jj$

Signal generation: Madgraph + Pythia 8 + Delphes

Background:

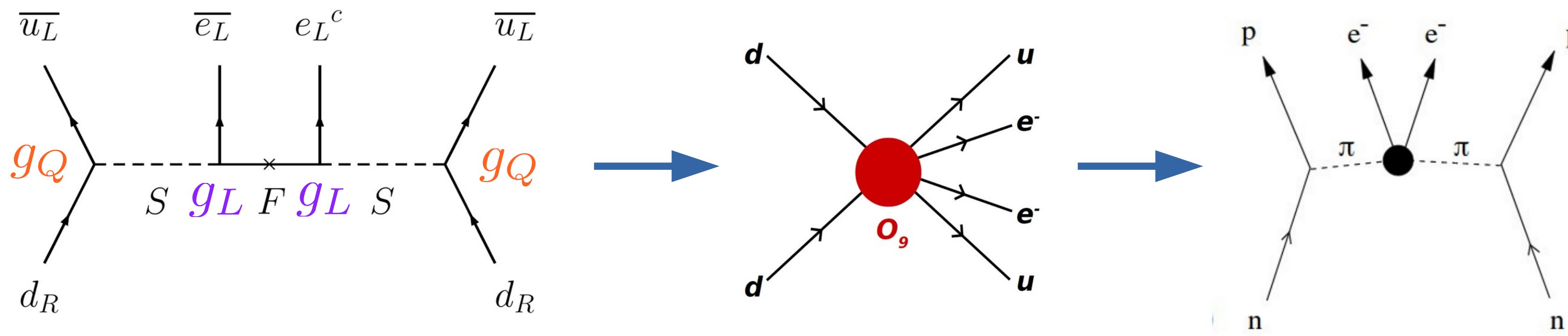
- SM processes with same-sign leptons (e.g. jjWW)
- Charge misidentification
- Jet-fake leptons from heavy flavour decays

S/B discrimination:

neural network

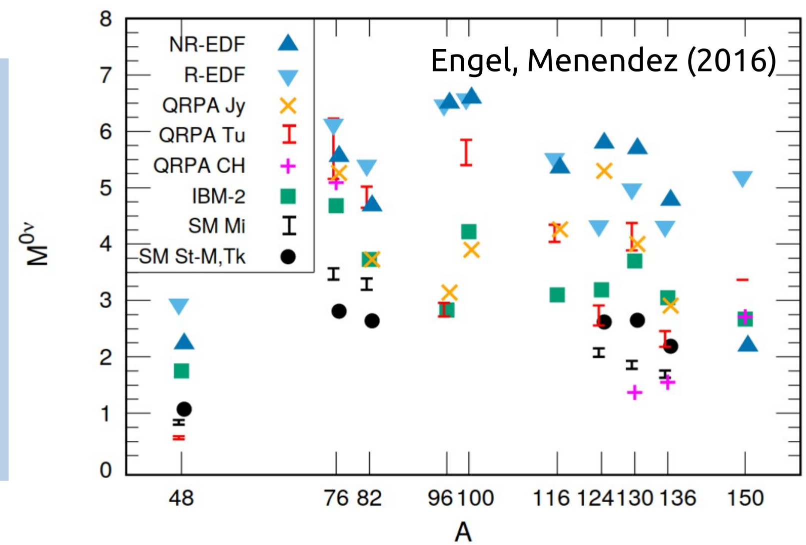
JH, Ramsey-Musolf, Shen, Urrutia-Quiroga (2021)

Reach at 0νββ decay experiments



$$\frac{C_{\rm eff}}{2\Lambda^5}\left(\bar q_L\tau^+q_R\ \bar q_L\tau^+q_R+\bar q_R\tau^+q_L\ \bar q_R\tau^+q_L\right)\bar e_L e_R^c+\text{h.c.}$$

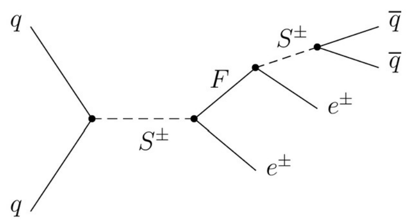
$$\frac{C_{\rm eff}\Lambda_H^2F_\pi^2}{2\Lambda^5}\pi^-\pi^-\bar e_L e_R^c+\text{h.c.}$$

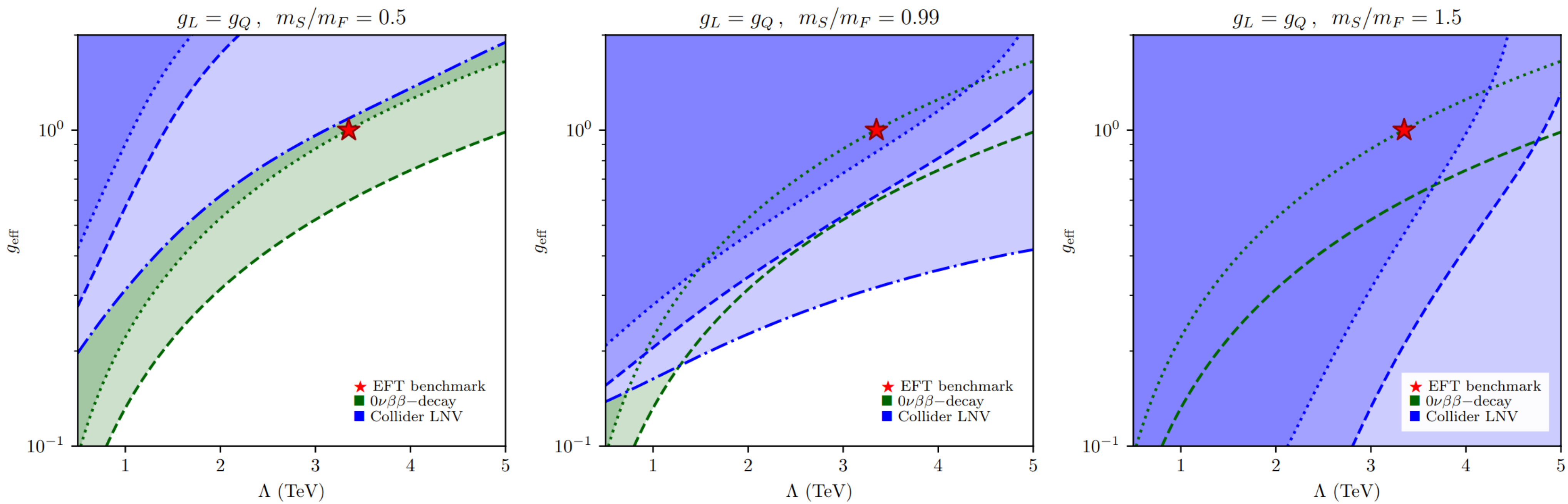


$$\frac{1}{T_{1/2}}=|M_0|^2\left[G_{0\nu}\times(1\,\text{TeV})^2\right]\left(\frac{\Lambda_H}{\text{TeV}}\right)^4\left(\frac{1}{144}\right)\times\left(\frac{v}{\text{TeV}}\right)^8\left(\frac{1}{\cos\theta_C}\right)^4\left[\frac{C_{\rm eff}^2}{(\Lambda/\text{TeV})^{10}}\right]$$

JH, Ramsey-Musolf, Shen, Urrutia-Quiroga (2021)

Combined reach of LHC & 0νββ decay experiments



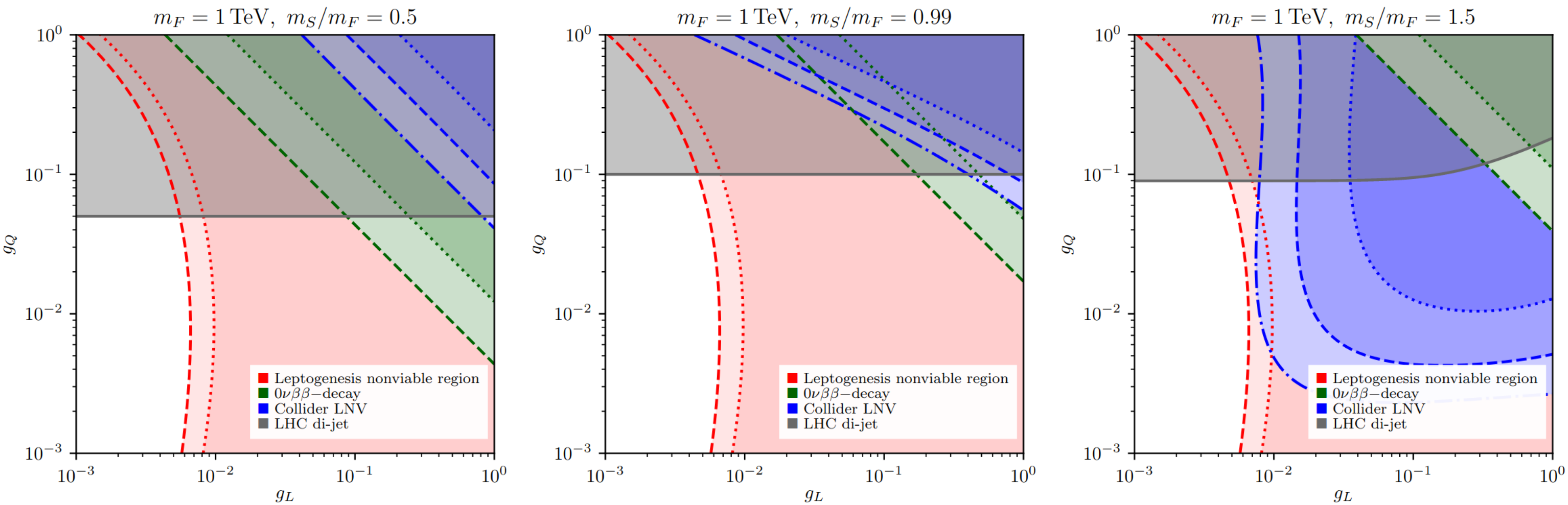


$$\Lambda = (m_S^4 m_F)^{1/5}$$

$$g_{\text{eff}} = g_L = g_Q$$

JH, Ramsey-Musolf, Shen, Urrutia-Quiroga (2021)

Combined results: Leptogenesis, LHC & 0νββ decay

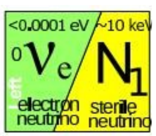


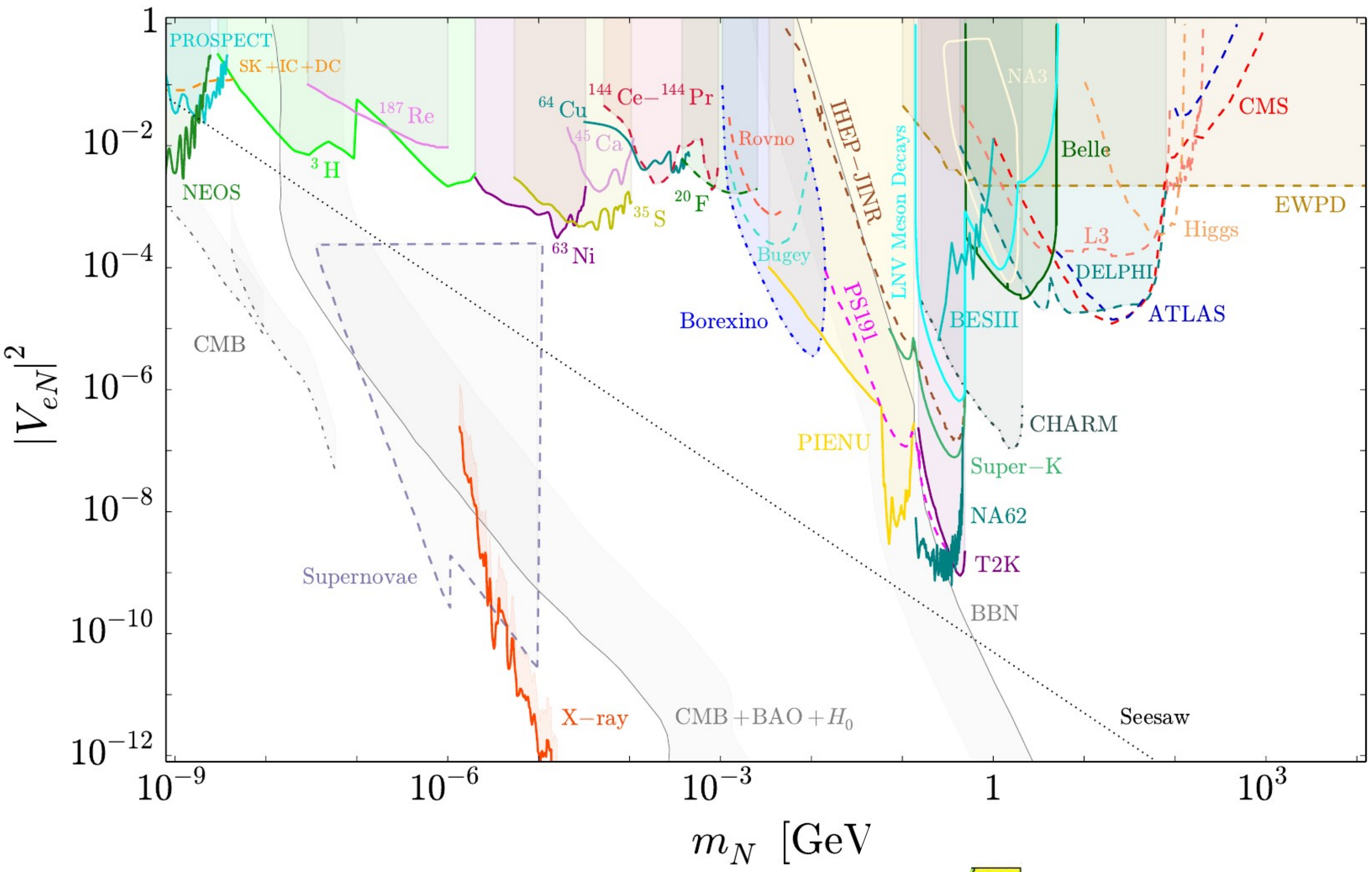
Comprehensive analysis confirms EFT results and demonstrates interesting interplay between collider and 0νββ reach.

JH, Ramsey-Musolf, Shen, Urrutia-Quiroga (2021)

General constraints on right-handed neutrinos

mixing of sterile to active neutrino



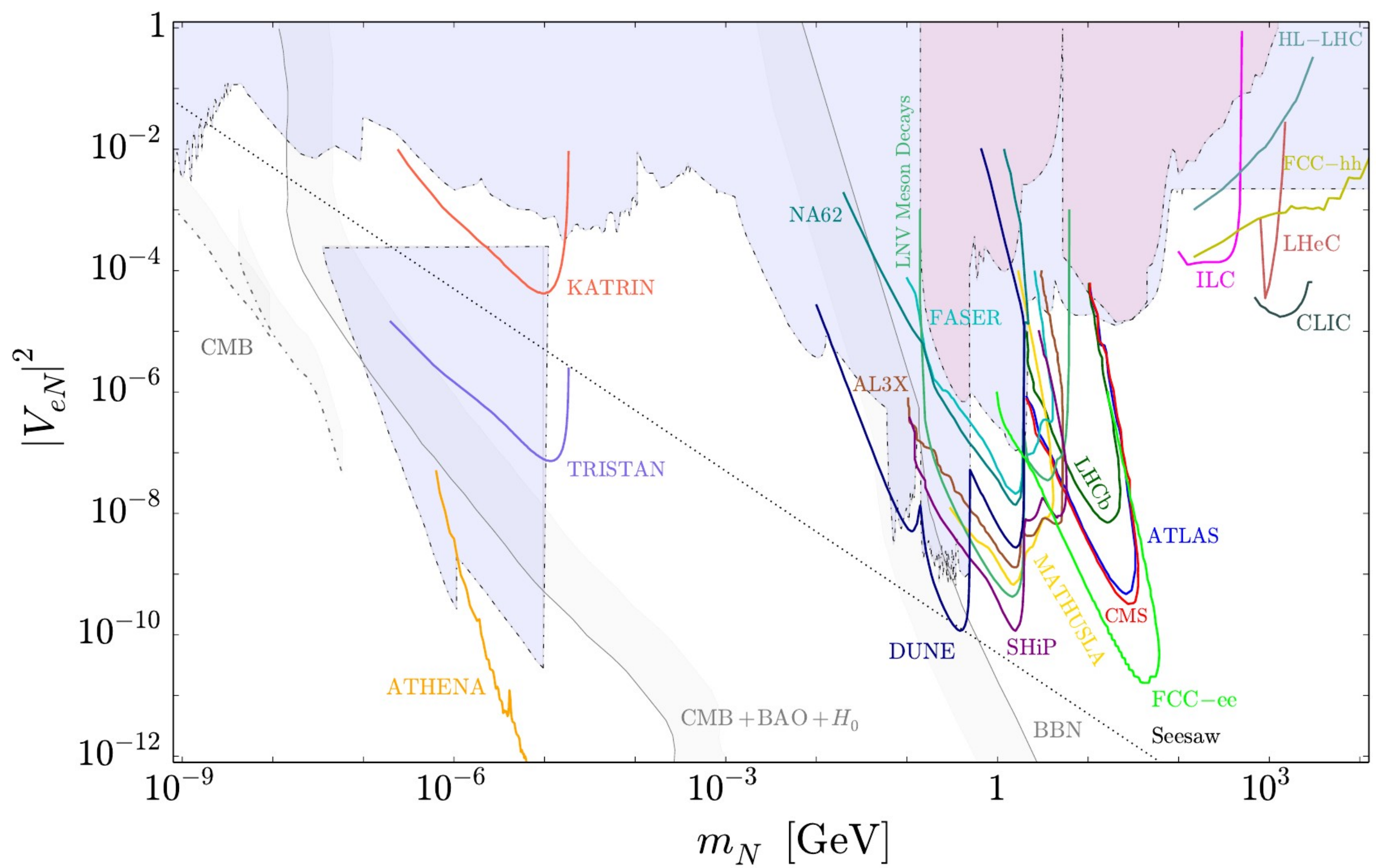


mass of sterile neutrino

Bolton, Deppisch, Dev (2019)
Atre, Han, Pascoli, Zhang (2009)

General constraints on right-handed neutrinos

mixing of sterile to active neutrino



mass of sterile neutrino

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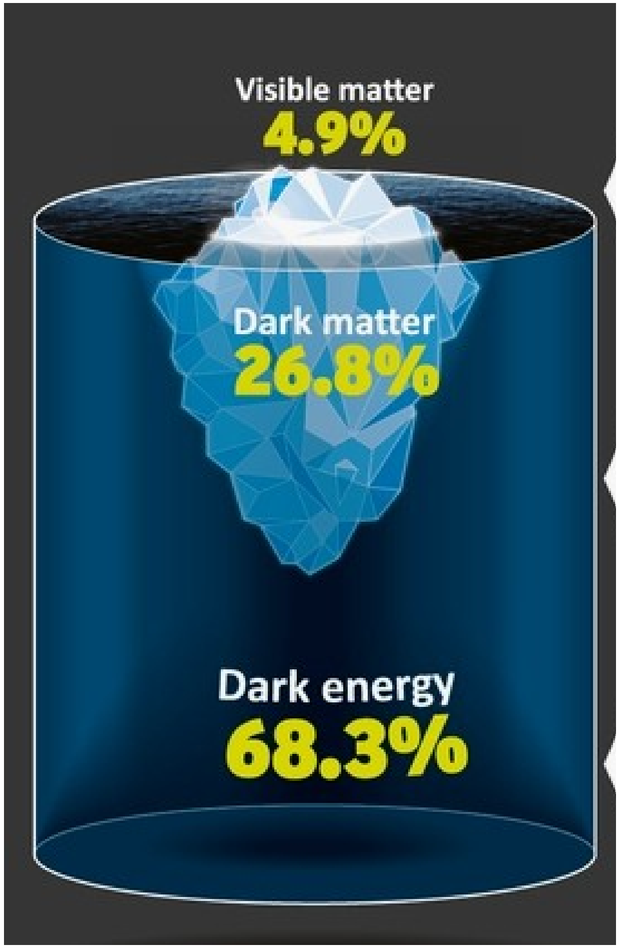

What is dark matter?

What is the status of the WIMP?

Weakly **i**nteracting **m**assive **p**article – **WIMP** – a failed miracle?

Berkeley News | Research | People | Campus & community

RESEARCH, SCIENCE & ENVIRONMENT

MACHOs are dead. WIMPs are a no-show. Say hello to SIMPs.

By Robert Sanders, Media relations | DECEMBER 4, 2017

nature

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NEWS · 02 OCTOBER 2020

Last chance for WIMPs: physicists launch all-out hunt for dark-matter candidate

Researchers have spent decades searching for the elusive particles – a final generation of detectors should leave them no place to hide.

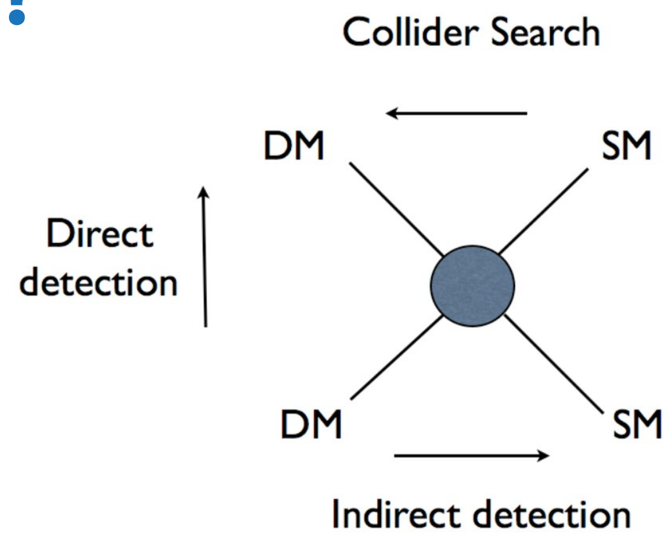
Forbes

Feb 22, 2019, 02:00am EST | 57.866 views

The 'WIMP Miracle' Hope For Dark Matter Is Dead

Ethan Siegel Senior Contributor
Starts With A Bang Contributor Group
Science
The Universe is out there, waiting for you to discover it.

What is the status of the WIMP?



- **no observations** at the LHC, direct or indirect detection so far that supports the *minimal* WIMP model

- **Reasons** could be manifold

(1) more **complex WIMP** models can evade bounds

(2) “exceptions” in the **DM abundance calculation** that were previously not considered

(3) **another DM generation mechanism**, e.g. freeze-in instead of freeze-out

(4) a much **lighter** or **heavier** DM candidate

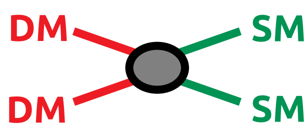
(5) completely **different type** of DM (PBHs, axions, etc.)

(6) …

Calculation of the relic abundance

Relic abundance

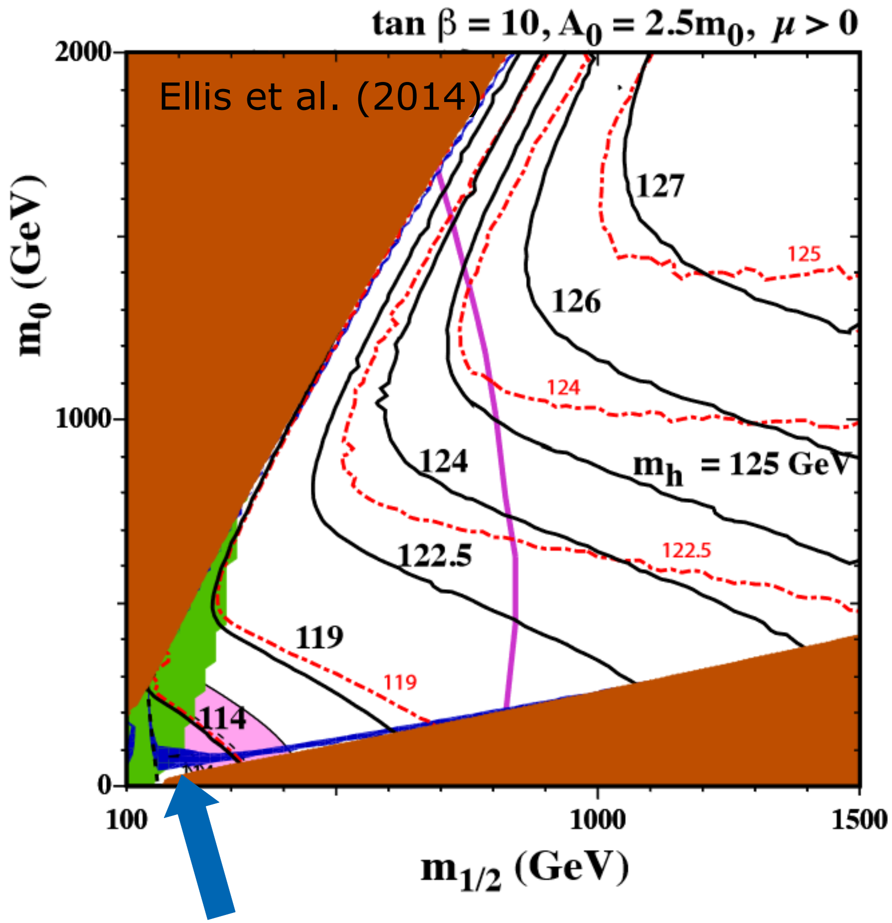
$$\Omega_\chi h^2 \propto \frac{1}{\langle \sigma_{\rm eff} v \rangle}$$



particle physics

co-annihilation

If another new particle is degenerate in mass to the DM particle, coannihilation can occur.

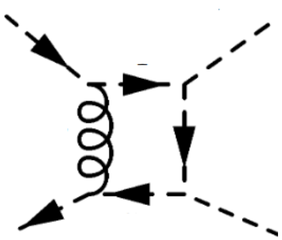


Relic abundance constraints the parameter space to a **small strip**

Towards new standards for the DM abundance

$$\Omega_\chi h^2 \propto \frac{1}{\langle \sigma_{\text{eff}} v \rangle}$$

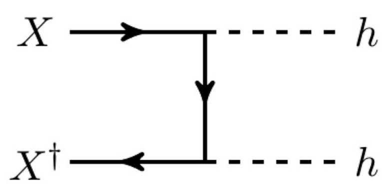
Higher order corrections



$$\sigma_{\text{eff}} v_{\text{rel}} = \sigma^{\text{NLO}} v_{\text{rel}}$$

can lead to sizeable corrections to the DM abundance

Born level annihilation

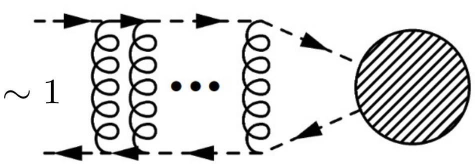


$$\sigma_{\text{eff}} v_{\text{rel}} = \sigma^{\text{tree}} v_{\text{rel}}$$

DM codes include *only* tree level

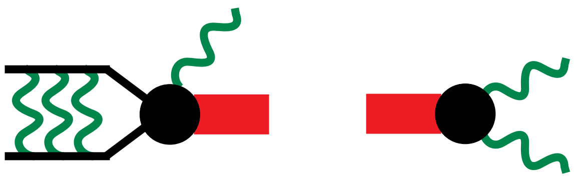
Sommerfeld enhancement

$$\left(\frac{\alpha}{v_{\text{rel}}}\right)^n \sim 1$$



$$\sigma_{\text{eff}} v_{\text{rel}} = \sigma^{\text{tree}} v_{\text{rel}} \times S_0$$

Bound state formation

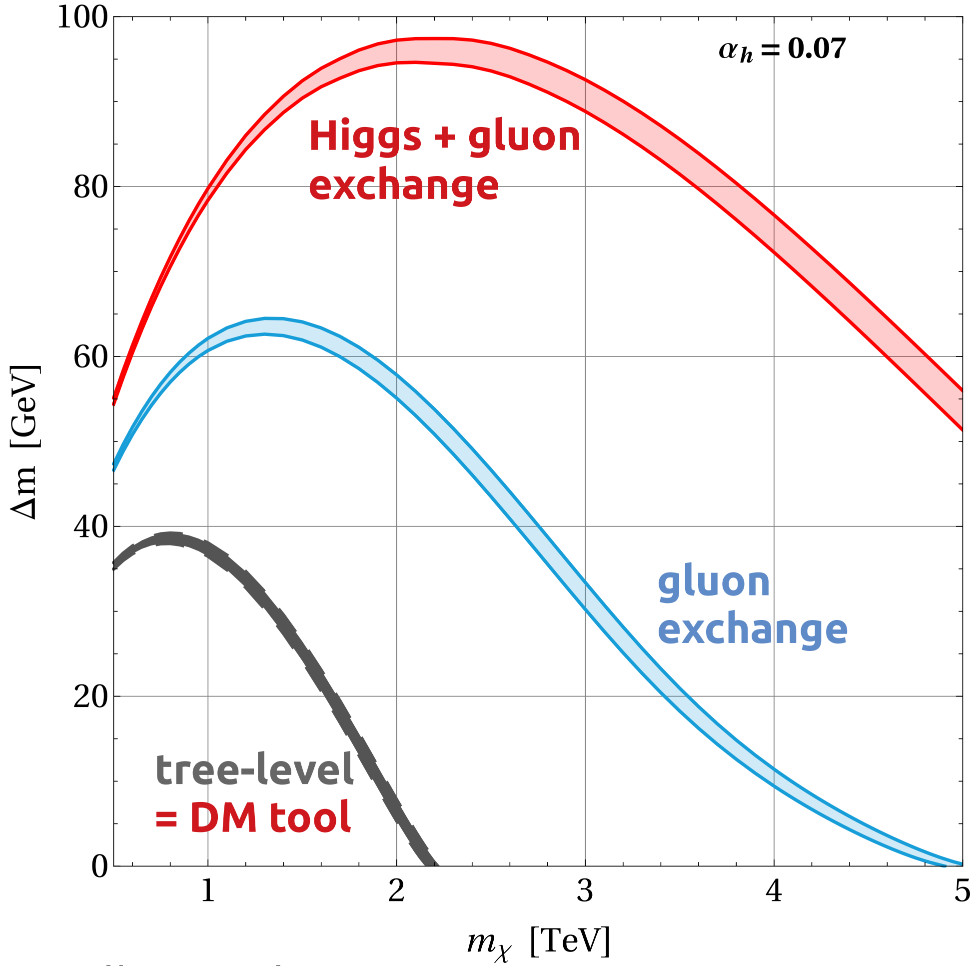


$$\langle \sigma_{\text{eff}} v_{\text{rel}} \rangle = \langle \sigma_{\text{ann}} v_{\text{rel}} \rangle + \langle \sigma_{\text{BSF}} v_{\text{rel}} \rangle_{\text{eff}}$$

bound state formation and **subsequent decay** open up a new **effective DM annihilation** channel

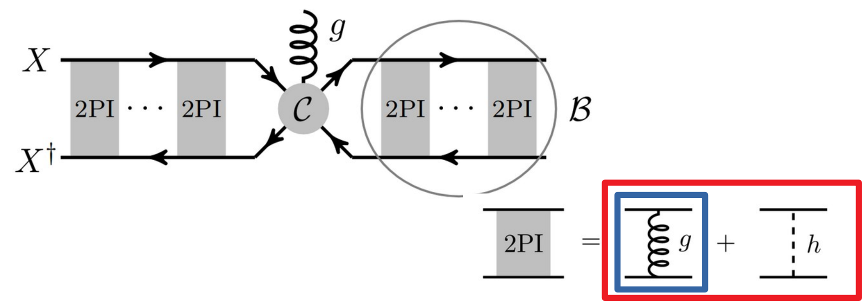
Example: Bound state formation

The formation and subsequent decay of an unstable bound state impacts significantly the prediction of the dark matter abundance.



$$\Omega_\chi h^2 \propto \frac{1}{\langle \sigma_{\mathrm{eff}} v \rangle}$$

bound state formation and decay



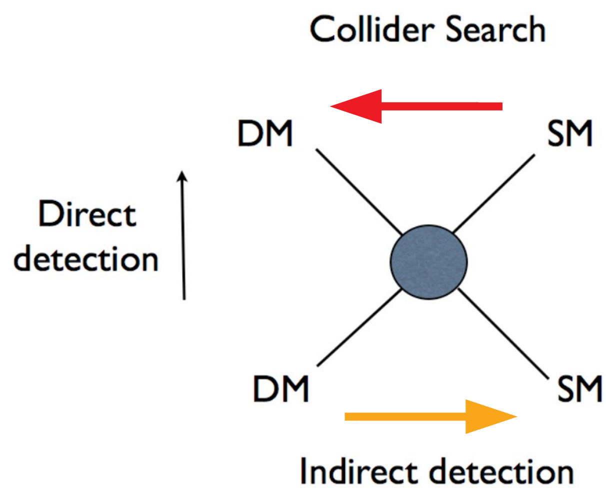
$$\langle \sigma_{\mathrm{eff}} v_{\mathrm{rel}} \rangle = \langle \sigma_{\mathrm{ann}} v_{\mathrm{rel}} \rangle + \langle \sigma_{\mathrm{BSF}} v_{\mathrm{rel}} \rangle_{\mathrm{eff}}$$

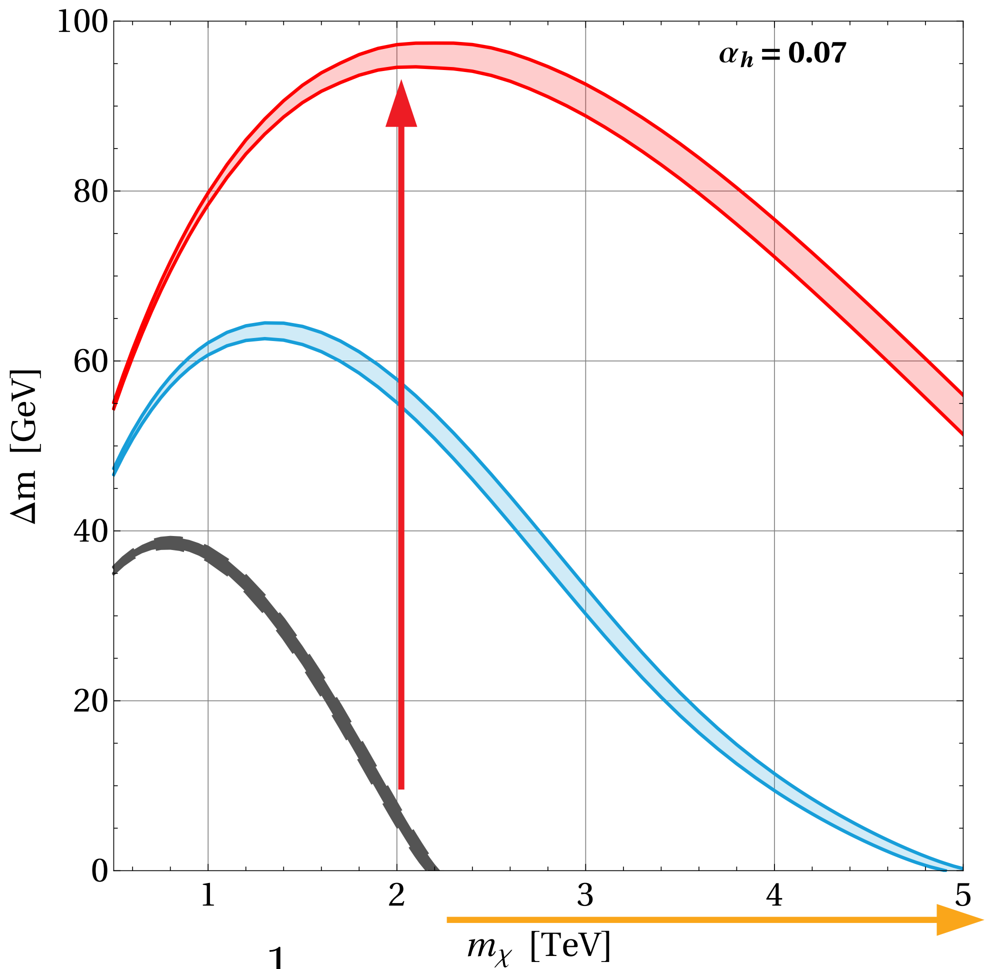
→ **demonstrated significant impact of BSF in non-abelian theories**

→ **Higgs can alter the result significantly, but was previously neglected!**

JH, Petraki, JHEP 1904 (2019) 130

Why relevant?





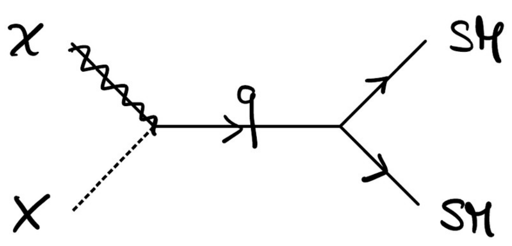
$$\Omega_\chi h^2 \propto \frac{1}{\langle \sigma_{\rm eff} v \rangle}$$

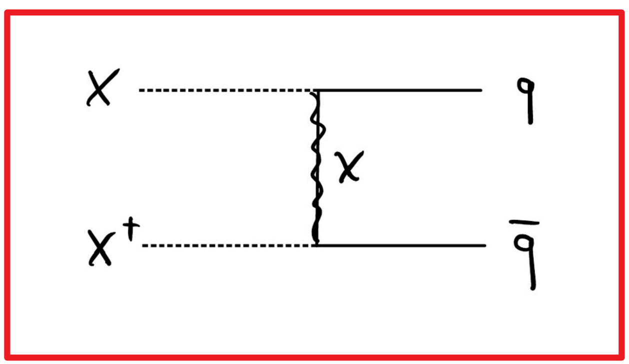
- increased predicted mass splitting
  → **multi-/mono-jet searches**
- DM expected in **multi-TeV regime**
  → **future indirect detection experiments**
- setting a **new standard**

Example: t-channel simplified model

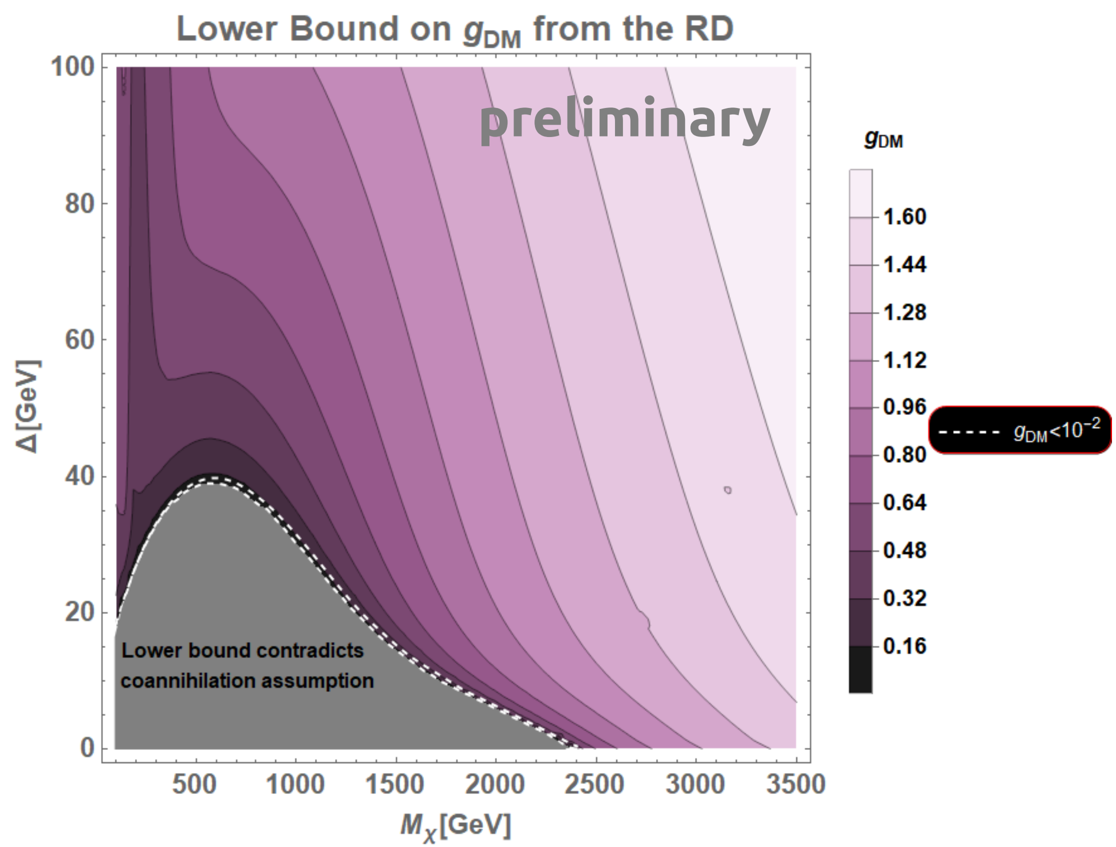
How do results change when including non-perturbative effects?

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \mathcal{L}_{\rm kin,BSM} + g_{\rm DM}\bar{\chi}u_R X^\dagger + h.c.$$





subject to non-perturbative effects



Becker, Copello, Harz, Mohan, Sengupta, in preparation

Example: t-channel simplified model

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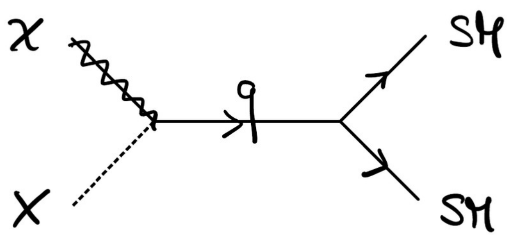
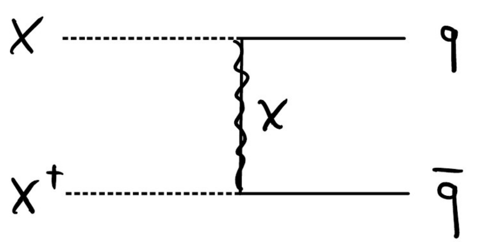
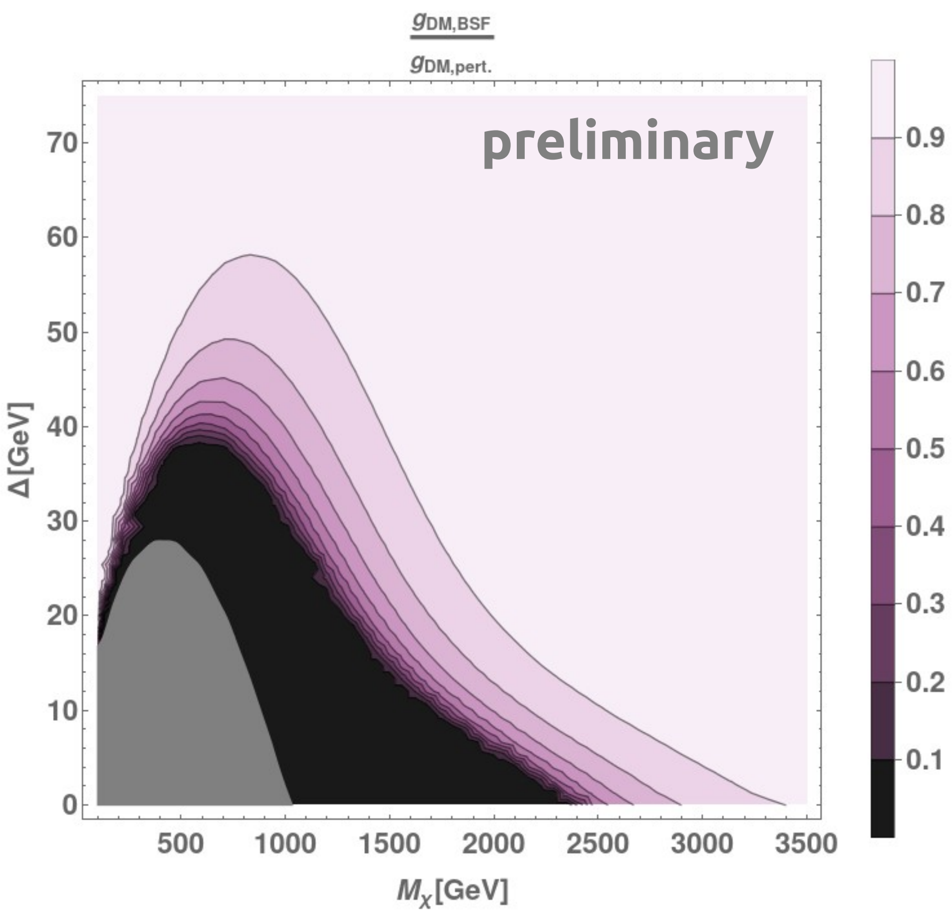




subject to non-perturbative effects



Becker, Copello, Harz, Mohan, Sengupta, in preparation

Example: t-channel simplified model

How do results change when including non-perturbative effects?

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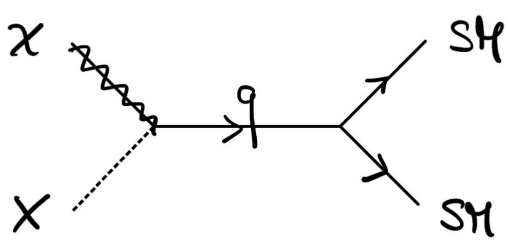
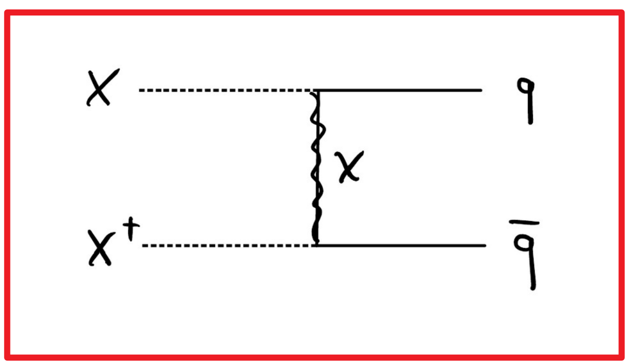
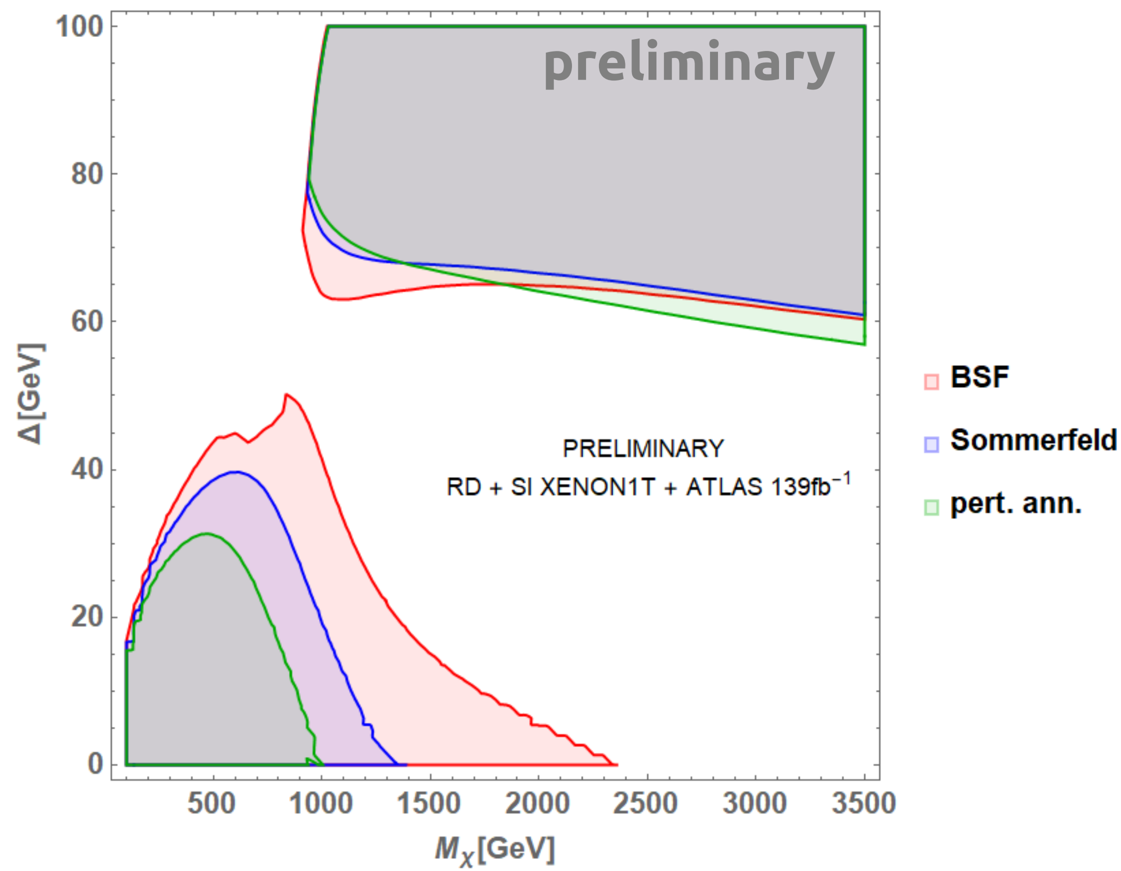


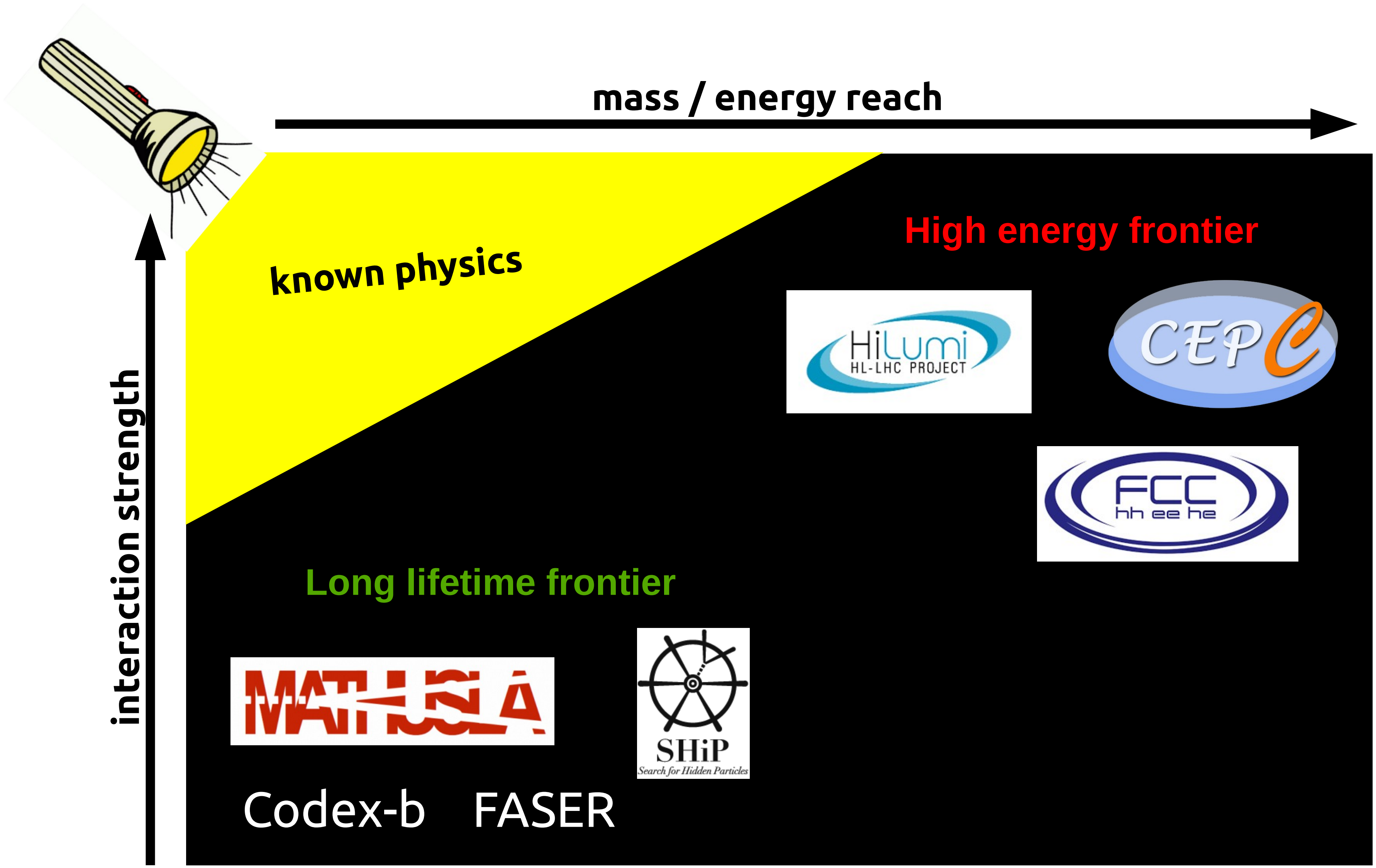


subject to non-perturbative effects



Becker, Copello, Harz, Mohan, Sengupta, in preparation

Why have we not seen DM yet?



Is DM feebly interacting?

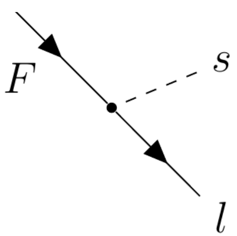
The freeze-in mechanism

Freeze-in
DM = FIMP

(1) DM *not* in thermal equilibrium with SM bath

DM is feebly interacting with the SM bath; abundance negligible

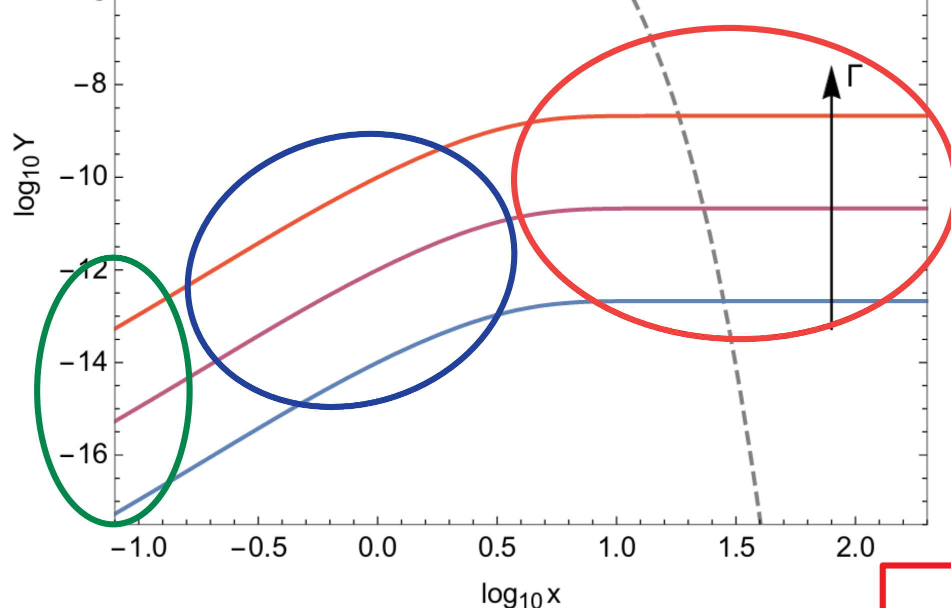
$$\lambda \sim \mathcal{O}(10^{-7})$$



(2) DM production

DM gets produced via decay of a heavier particle Y that is in equilibrium with the SM bath

$$Y \to \mathrm{SM}\ \chi$$



$$x = m_Y/T$$

cooling down

(3) Freeze-in

when T falls below mass of parent particle Y, production gets Boltzmann suppressed

$$n_Y \approx \exp(-m_Y/T)$$

$$\boxed{\Omega_\chi h^2 \sim 4.48 \times 10^8 \frac{g_Y}{g_*^S \sqrt{g_*}} \frac{m_\chi}{\mathrm{GeV}} \frac{M_{\mathrm{Pl}} \Gamma_Y}{m_Y^2}}$$

LHC friendly freeze-in models

We consider an extension of the SM by a Z_2-odd real scalar singlet s (DM) and a Z_2-odd vector-like SU(2) singlet fermion F (parent)

$$\boxed{\begin{aligned}\mathcal{L} = \mathcal{L}_{\rm SM} + \partial_\mu s\, \partial^\mu s - \frac{\mu_s^2}{2} s^2 + \cancel{\frac{\lambda_s}{4}} s^4 + \cancel{\lambda_{sh}} s^2 \left(H^\dagger H\right) \\ + \bar{F}\left(iD\right)F - m_F \bar{F} F - \sum_f y_s^f \left(s\bar{F}\left(\frac{1+\gamma^5}{2}\right) f + \text{h.c.}\right)\end{aligned}}$$

$$\mathrm{y}_\chi Y_F X_{SM} \chi_s$$

with $F = \{e, \mu, \tau\}$ **(1,1,-1)** heavy lepton

$\{u, c, t\}$ **(3,1,-2/3)** heavy up-type quark

$\{d, s, b\}$ **(3,1,1/3)** heavy down-type quark

with $\mu_s^2 = m_s^2 + \lambda_{sh} v^2$

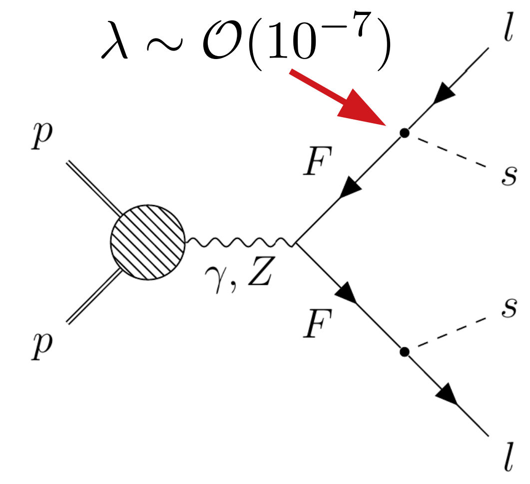
Free parameters: $m_s, m_F, \{y_s^f\}$

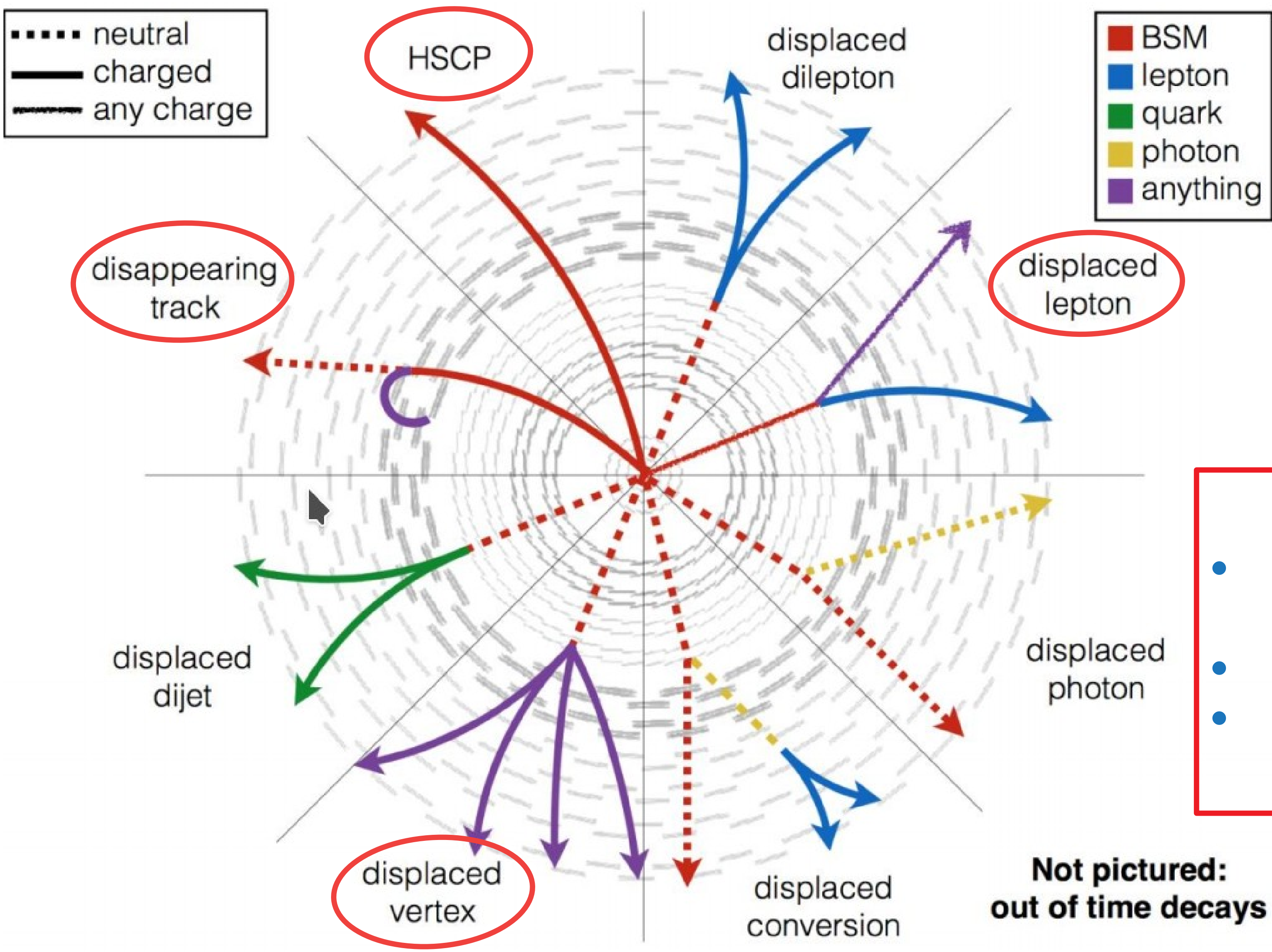
two separate studies:

- heavy lepton & heavy up-type quark
- only 1st and 2nd generation

Belanger, JH et al. (2018)

Collider constraints





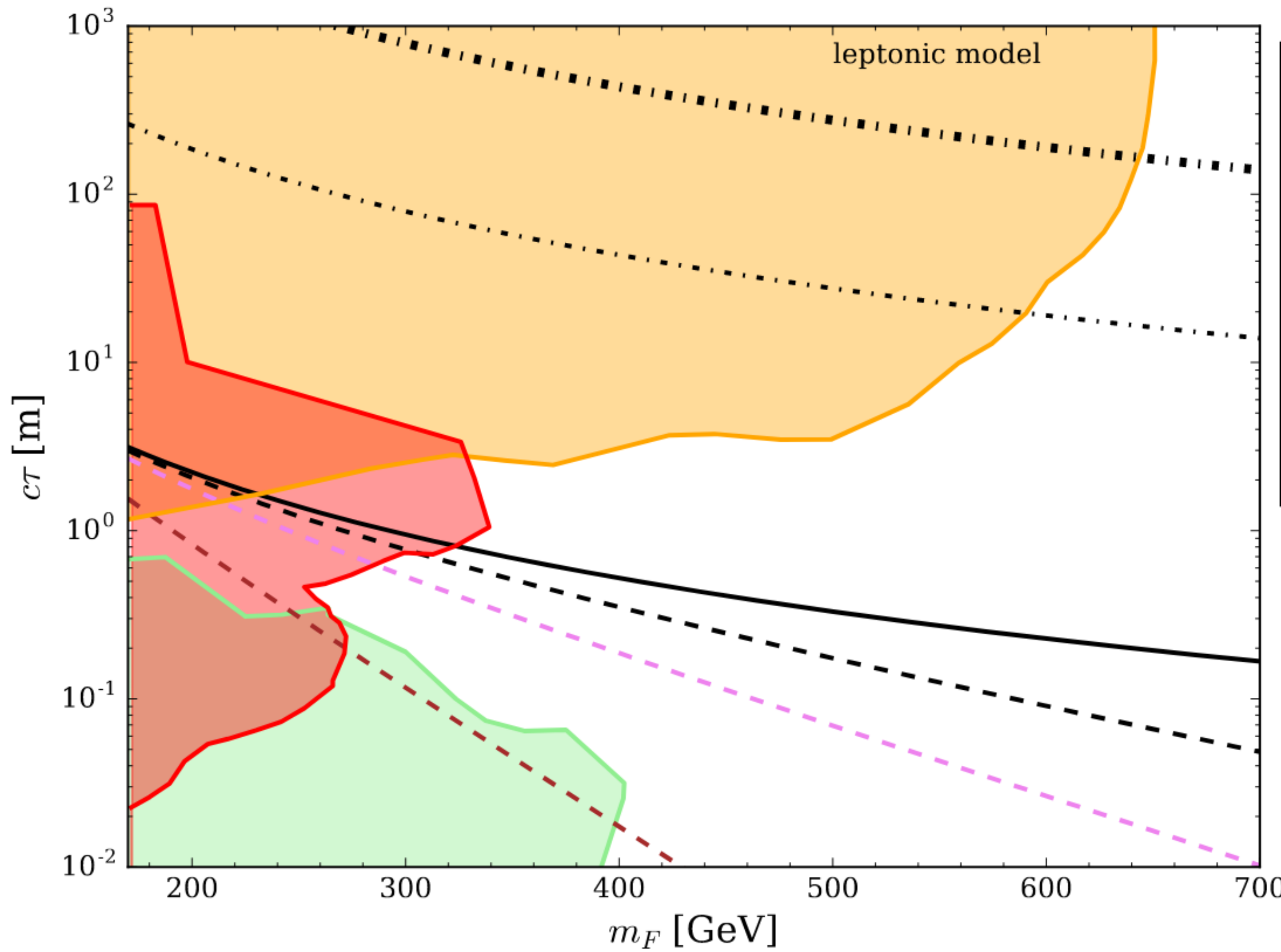
Not pictured: out of time decays

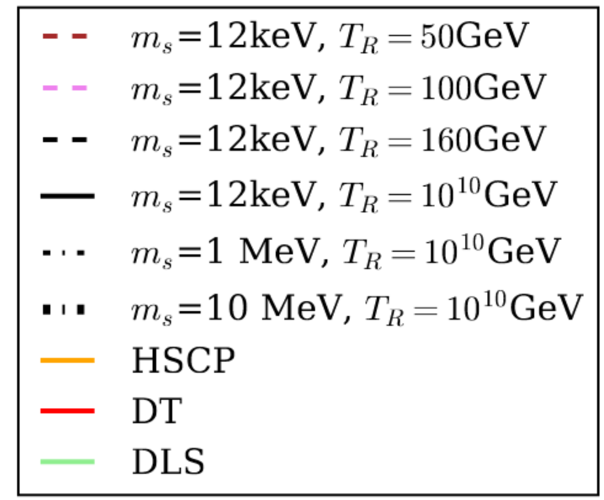
Long-lived particles (LLPs)

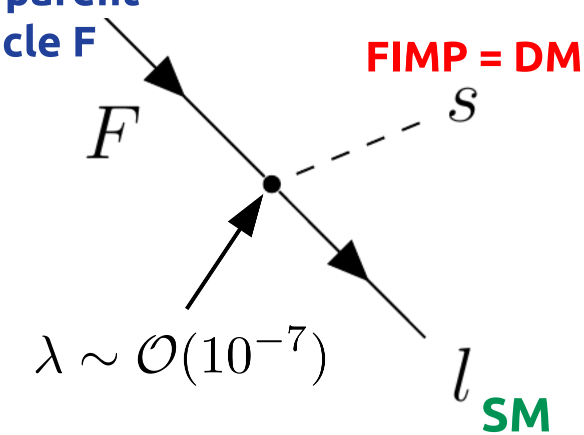
- Large mass hierarchies / off-shell mediator
- Compressed spectra
- *Small couplings / small rates*

Review: "*Searching for long-lived particles beyond the Standard Model at the Large Hadron Collider*"

Results for the leptonic model





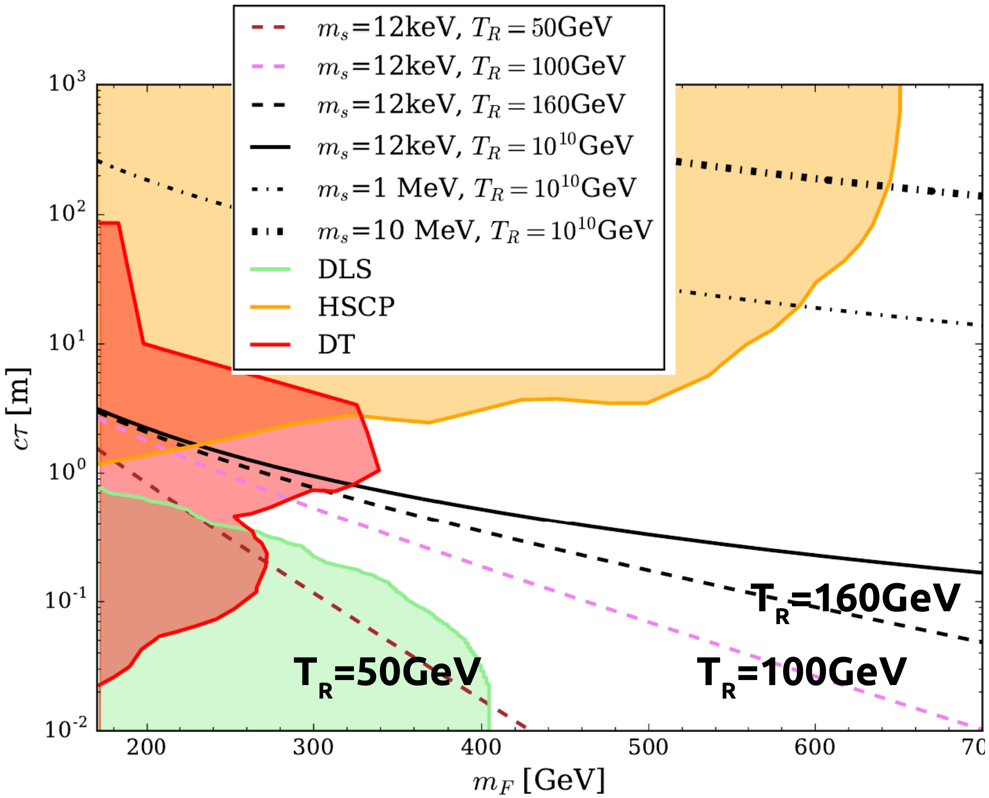


Belanger, JH et al. (2018)

Probing freeze-in dark matter and baryogenesis

Assuming that DM is mostly generated by decays of the parent F, we can relate the **relic abundance** with the parent particle life time

$$c\tau \approx 4.5 \text{ m } \xi g_F \left(\frac{0.12}{\Omega_s h^2}\right)\left(\frac{m_s}{100\text{keV}}\right)\left(\frac{200\text{GeV}}{m_F}\right)^2\left(\frac{102}{g_*(m_F/3)}\right)^{3/2}\left[\frac{\int_{m_F/T_R}^{m_F/T_0} dx\ x^3 K_1(x)}{3\pi/2}\right]$$



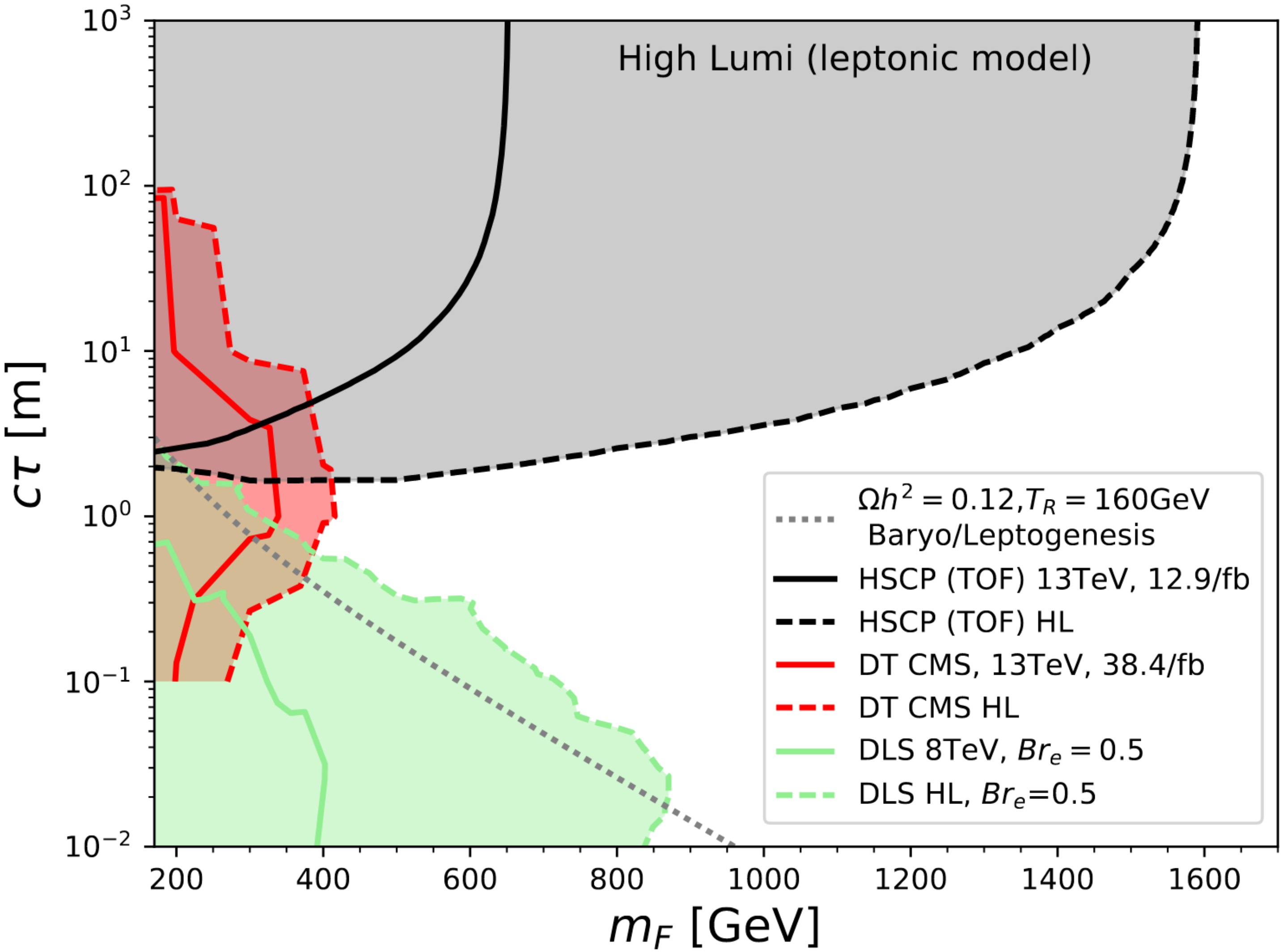
- m_s=12keV is the **smallest possible mass** from Lyman-α constraints
  m_s > 12 keV would imply even smaller T_R
- If s made up **not all of the DM**, a smaller T_R would be implied

→ **most conservative choice**

Possibility to falsify baryogenesis / leptogenesis models that rely on effective sphaleron interactions.

Belanger, JH et al. (2018)

Future prospects



Belanger, JH et al. (2018)

Freeze-in extensions

Neutrino portal:

Light sterile neutrino production via Dodelson-Widrow mechanism ruled out by x-ray and Lyman-α
→ sterile neutrino freeze-in

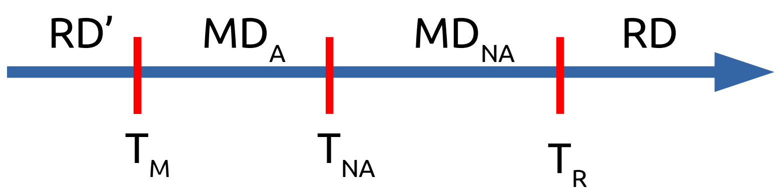
$$\mathcal{L} \supset y\, \bar{L}\, \tilde{\Phi}^\dagger\, \nu_{\rm R} + m\, \bar{\nu}_{\rm R}^c\, \nu_{\rm R} + s\, \bar{\nu}_{\rm R}^c\, (y_S + i\, y_P)\, \nu_{\rm R} + {\rm h.c.} + V(\Phi, s)$$

$$\frac{\Omega_{\nu_{\rm R}} h^2}{0.12} \simeq \left(\frac{y}{10^{-8}}\right)^3 \frac{\langle s \rangle}{m_{\rm s}}$$

Kusenko (2006)
Petraki, Kusenko (2007)

Sterile Neutrino DM from freeze-in, Shakya (2015)
Dark Matter from Freeze-In via the Neutrino Portal, Becker (2018)
The Dark Side of the Littlest Seesaw, Chianese, King (2018)

Probing an altered cosmological history:

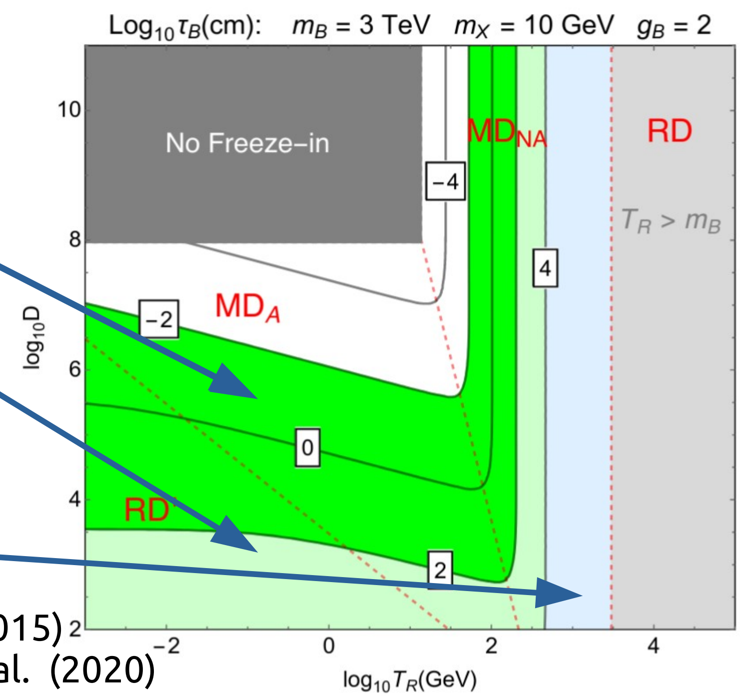


$$D \approx \frac{T_M}{T_R}$$

displaced vertices
$10^{-2}\text{cm} < \tau < 10^{2}\text{cm}$

displaced jets / leptons
$10^{2}\text{cm} < \tau < 10^{4}\text{cm}$

stopped particle decay
$\tau > 10^{4}\text{cm}$



Freeze-In Dark Matter with Displaced Signatures at Colliders, Co et al. (2015)
Neutrino Portal to FIMP Dark Matter with an Early Matter Era, Cosme et al. (2020)

Strongly interacting DM

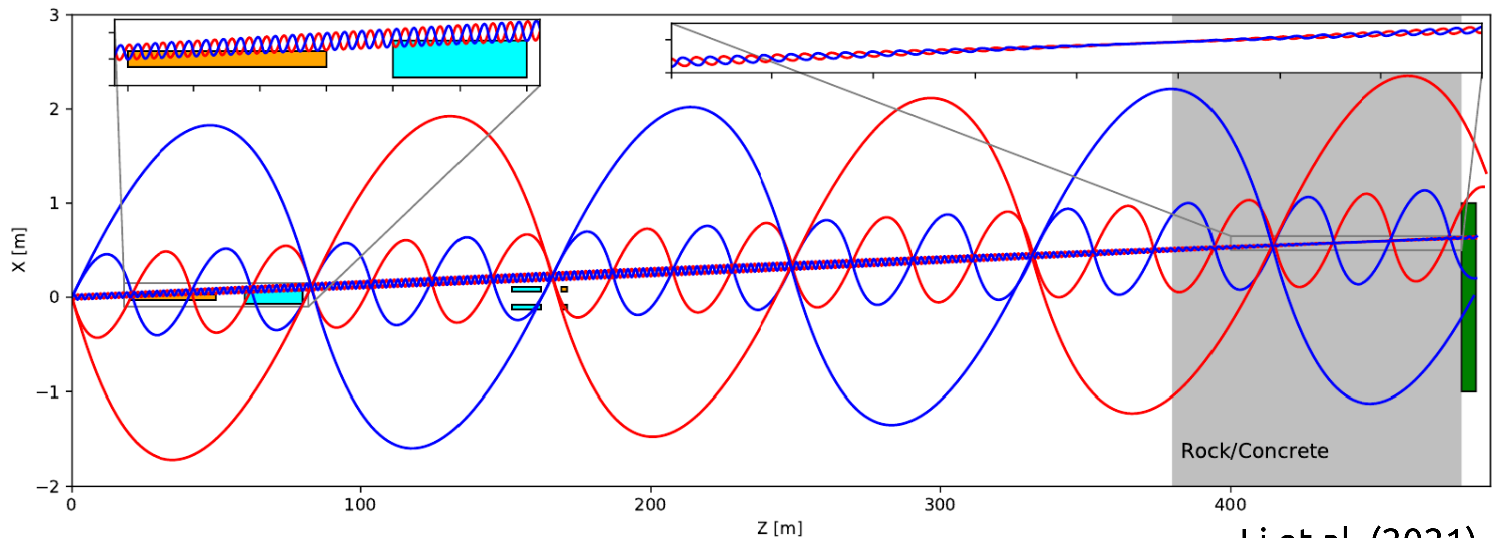
Unitary bound sets a limit on the maximal DM mass… ways out?

Composite DM – QCD-like dark sector

- Could we have a rich strongly interacting dark sector similarly to the SM?
- Depending on Λ_{QCD} and the constituent masses, we could get darkonium, dark mesons or quirks

–> Rich new signals: emerging jets, oscillating quirk signals, dark showers, etc….

Schwaller et al. (2015), Cohen et al. (2017), Cohen et al. (2020)
Kribs et al. (2010), Knapen et al. (2017), Evans et al. (2019)
Geller et al. (2018), Smirnov, Beacom (2019), Contino et al. (2019), Gross et al. (2019)



Li et al. (2021)

→ **Quirk signals at Faser?**

No time to discuss…

axions, axionlike particles, PBHs, ….

Conclusions

?

Conclusions

- **Astroparticle physics connects the early universe cosmology with elementary particle physics**
- **Still many open questions: dark matter, baryon asymmetry, neutrinos,...**
- **Many ideas and great prospects for future collider searches to contribute in a complementary way to the common quest**
- **Bright experimental future ahead at all frontiers**
- **Nature has to give us a hint via the experiments**

Conclusions

Codex-b
FASER
SHiP Search for Hidden Particles
MATHUSLA
lifetime frontier

HiLumi HL-LHC PROJECT
ATLAS EXPERIMENT
CEPC
FCC hh ee he
future colliders

LISA
Euclid consortium
CMB-S4 Next Generation CMB Experiment
cosmology

ORCA KM3NeT
annie
DUNE DEEP UNDERGROUND NEUTRINO EXPERIMENT
ICECUBE SOUTH POLE NEUTRINO OBSERVATORY
PROJECT 8
BOREXINO GRAN SASSO
Hyper-K
JUNO
neutrino experiments

NA64
NA62
MEG II Mu - E - Gamma collaboration
rare decays

Xe XENON Dark Matter Project
LZ
DARWIN
H.E.S.S.
sensei
cta
dark matter

Thank you for your attention!