Topics in Leptogenesis

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Lecture 1

University College London

- Baryon Asymmetry
- Big Bang Nucleosynthesis
- Cosmic Microwave Background
- Sakharov Conditions
- Sphalerons

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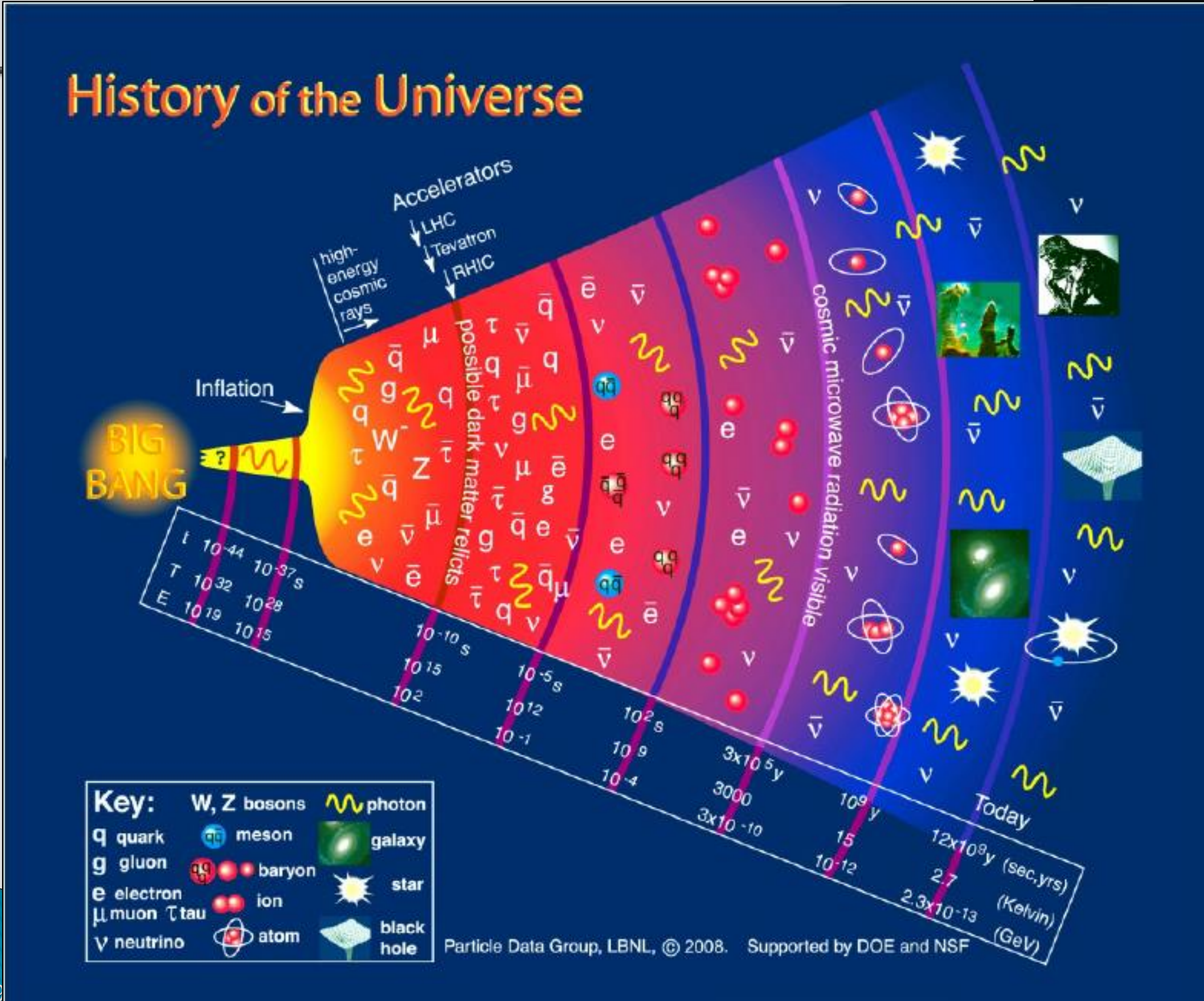
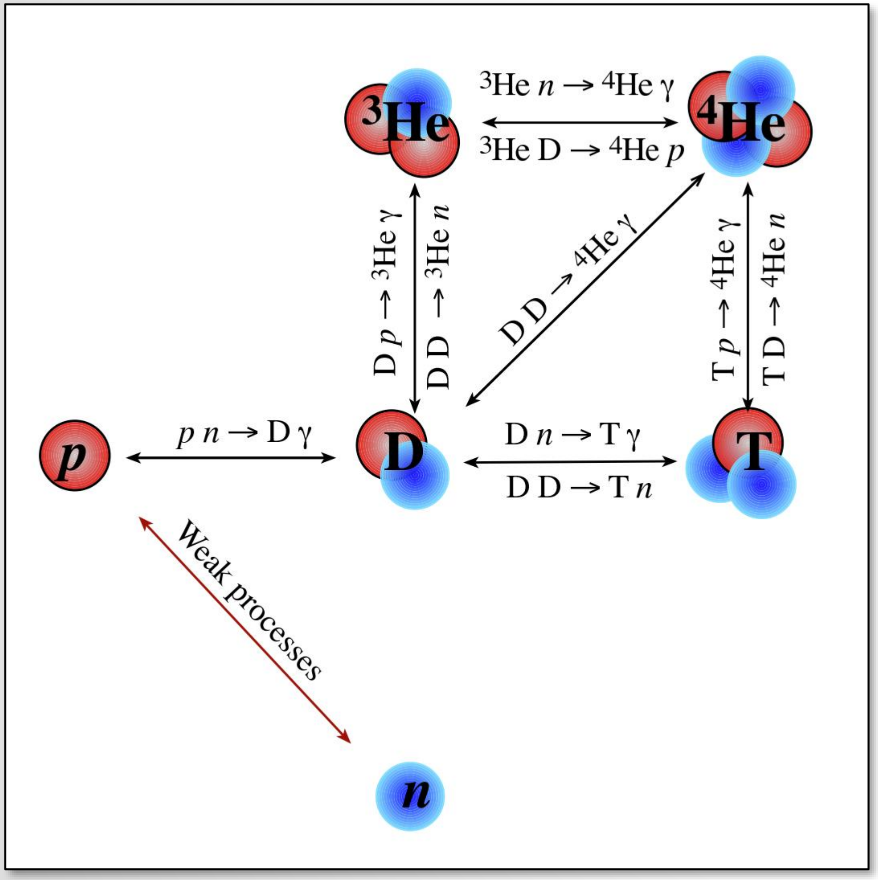
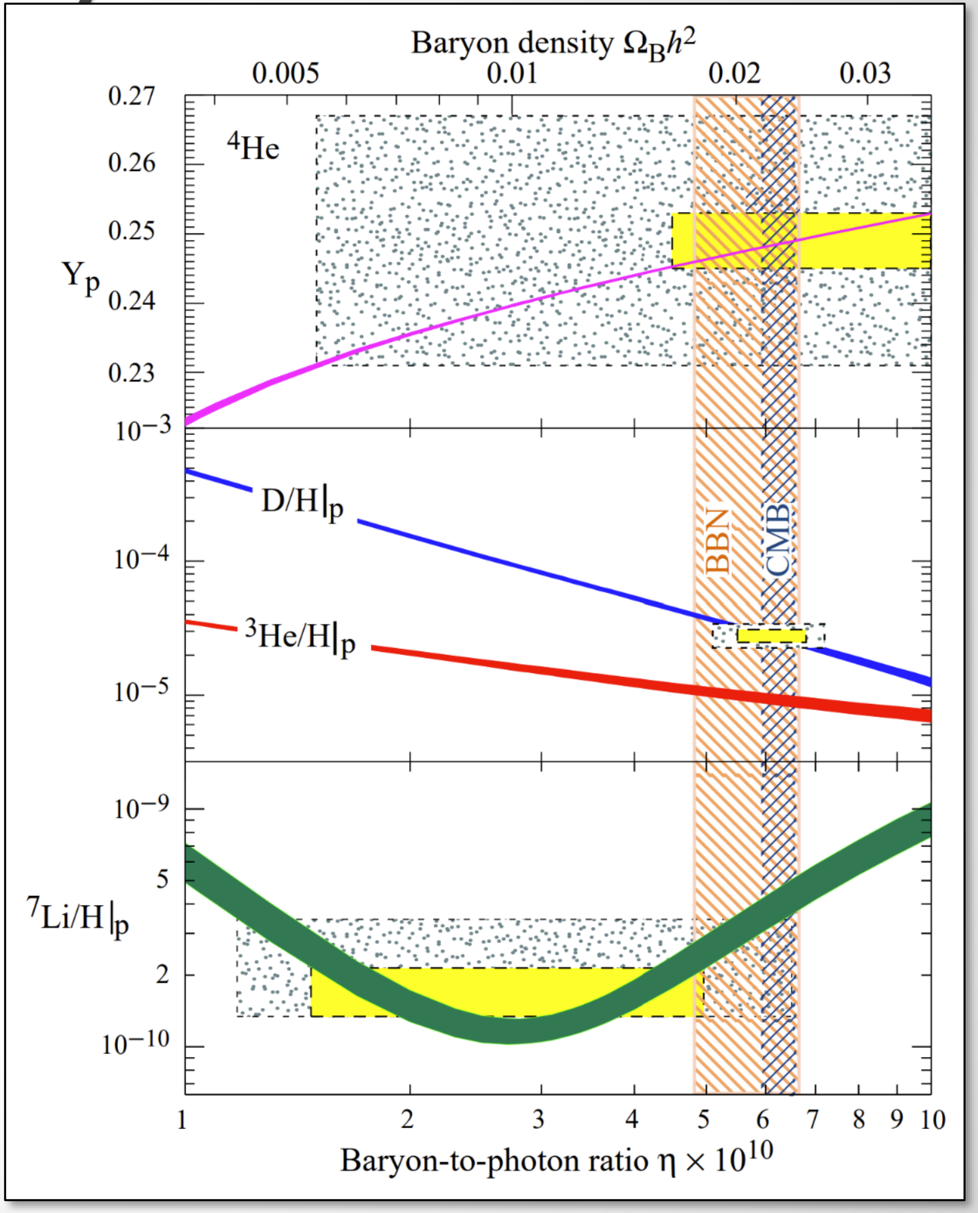
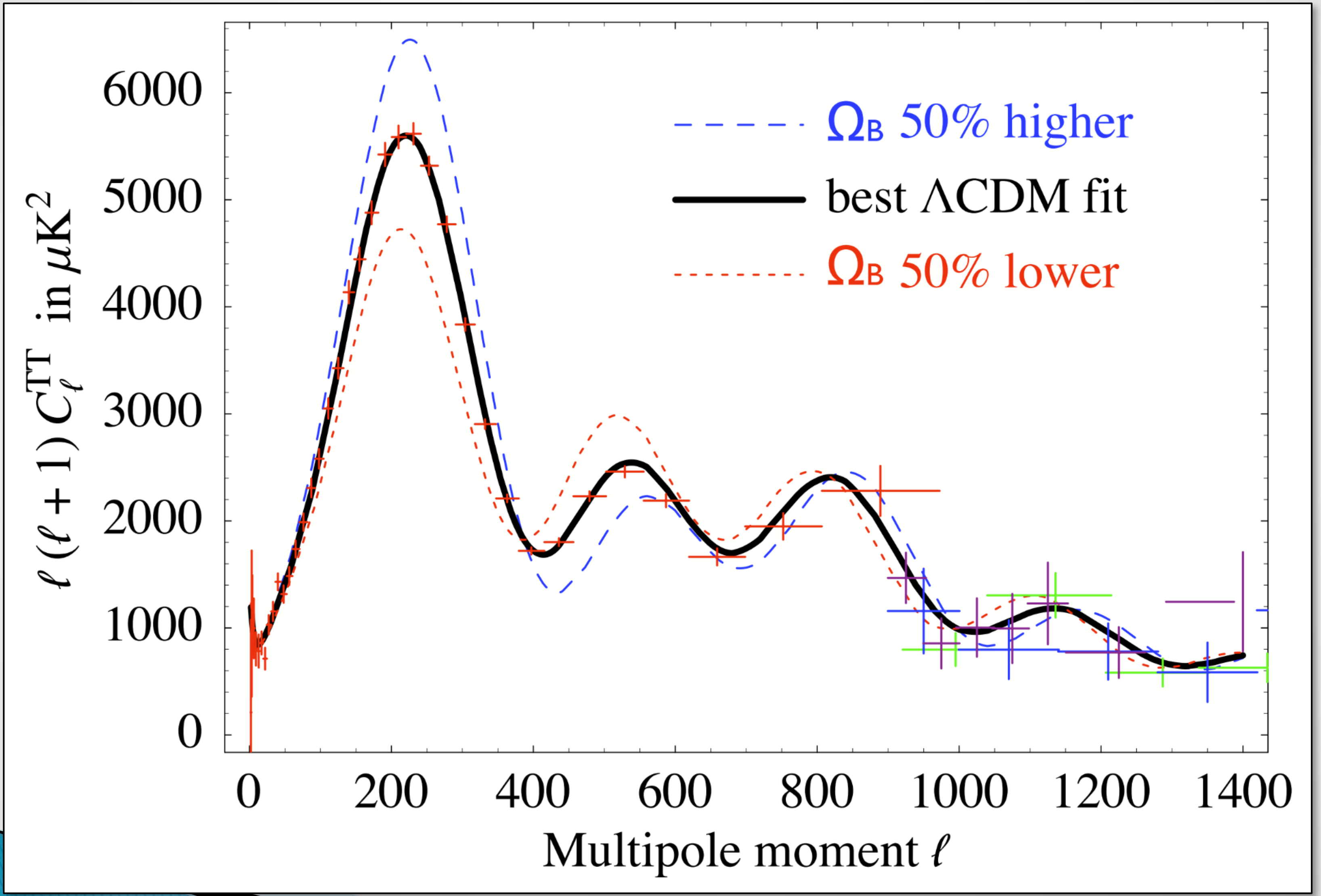

History of the Universe
Accelerators
LHC
Tevatron
RHIC
high-energy cosmic rays
Inflation
BIG BANG
possible dark matter relicts
cosmic microwave radiation visible
t 10^-44 10^-37 s
T 10^32 10^28
E 10^19 10^15
10^-10 s
10^15
10^2
10^-5 s
10^12
10^-1
10^2 s
10^9
10^-4
3x10^5 y
3000
3x10^-10
10^9 y
15
10^-12
Today
12x10^9 y (sec,yrs)
2.7 (Kelvin)
2.3x10^-13 (GeV)
Key:
q quark
g gluon
e electron
μ muon τ tau
ν neutrino
W, Z bosons
meson
baryon
ion
atom
photon
galaxy
star
black hole
Particle Data Group, LBNL, © 2008. Supported by DOE and NSF

Big Bang Nucleosynthesis





Cosmic Microwave Bckg.



Lecture 2

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- Seesaw and Leptogenesis
- CP Asymmetry
- Out-of-equilibrium Decays and Inverse Decays
- Boltzmann Equations
- Fast Sphaleron and SM Interactions

Baryon Asymmetry

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- Dynamic generation of baryon asymmetry requires (Sakharov '66)
  - Baryon number violation
  - C and CP Violation
  - Out-of-equilibrium dynamics
- Standard Model
  - Baryon number violated at quantum level (Sphalerons)
  - C and CP violated but effect too small

$$\frac{\mathrm{Im}\,\det\left(m_u m_u^+ m_d m_d^+\right)}{v^{12}} = J\,\frac{m_t^4 m_c^2 m_b^4 m_s^2}{v^{12}} \approx 10^{-19}$$

  - Electroweak phase transition out-of-equilibrium if first order but requires

$$m_h < 60 \ - 80\ \mathrm{GeV}$$

Sphalerons

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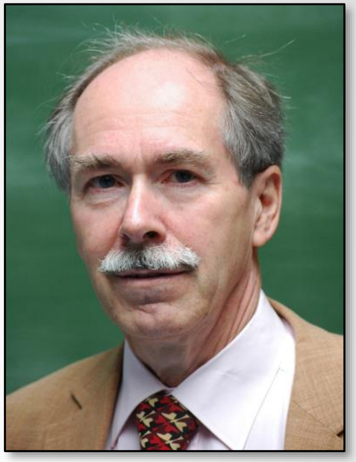
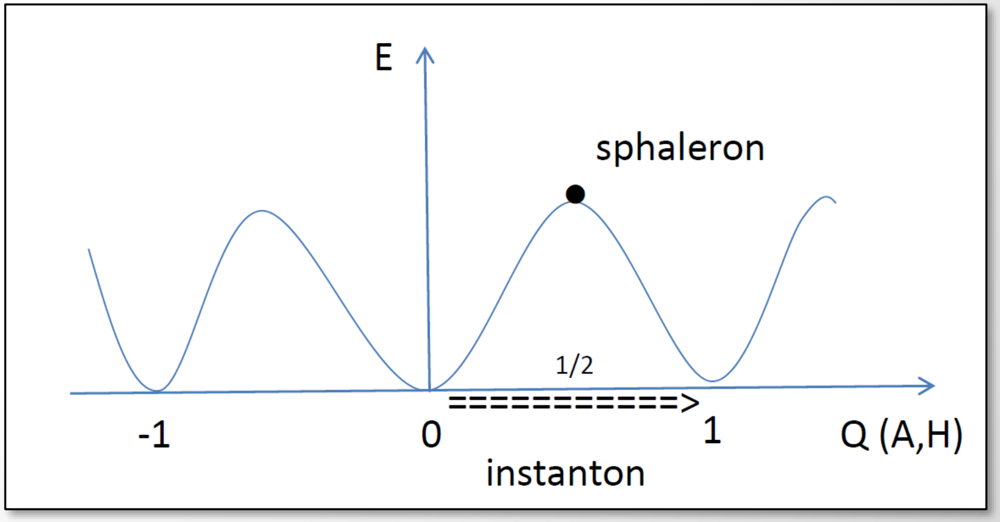


- Baryon and Lepton numbers accidental, classical symmetries in the Standard Model
- Violated at the quantum level (t' Hooft '76)

$$\partial_\mu J_B^\mu = \partial_\mu J_L^\mu = \frac{g^2}{32\pi^2} F_{\mu\nu}\tilde{F}^{\mu\nu}$$

  - $B + L$ violated
  - $B - L$ remains conserved
- Sphaleron transitions in equilibrium $\frac{\Gamma_{Sph}}{H} > 1$ for

$$\Lambda_{EW} \approx 10^2\text{GeV} < T < 10^{12}\text{ GeV}$$



Leptogenesis

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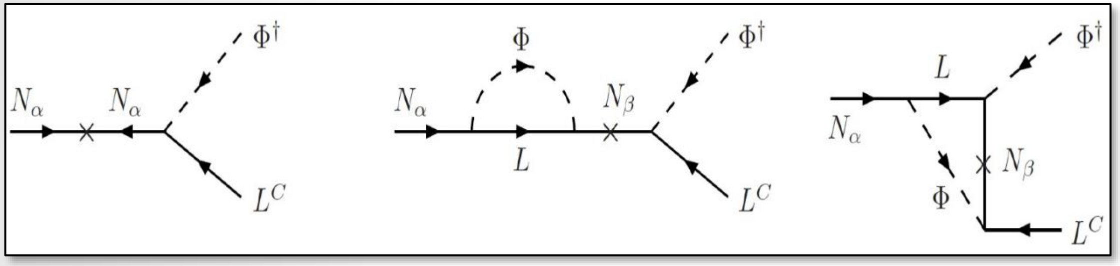
- Decays of heavy Majorana neutrinos violating L and CP (Fukugita, Yanagida ‘86)

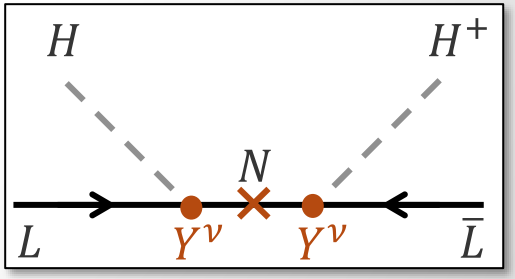


  - CP asymmetry

$$\epsilon_1 = \frac{\Gamma(N_1 \to LH^+) - \Gamma(N_1 \to \bar{L}H)}{\Gamma(N_1 \to LH^+) + \Gamma(N_1 \to \bar{L}H)} \approx \frac{3}{8\pi} \frac{\mathrm{Im}\left[(Y_\nu Y_\nu^+)^2_{1k}\right]}{(Y_\nu Y_\nu^+)_{11}} \frac{M_1}{M_k}$$

- Competition with washout processes eradicating L asymmetry

$$M_N \gtrsim 10^8 \left(\frac{\eta_B}{5 \times 10^{-11}}\right) \left(\frac{0.06\mathrm{eV}}{m_3}\right) \mathrm{GeV}$$

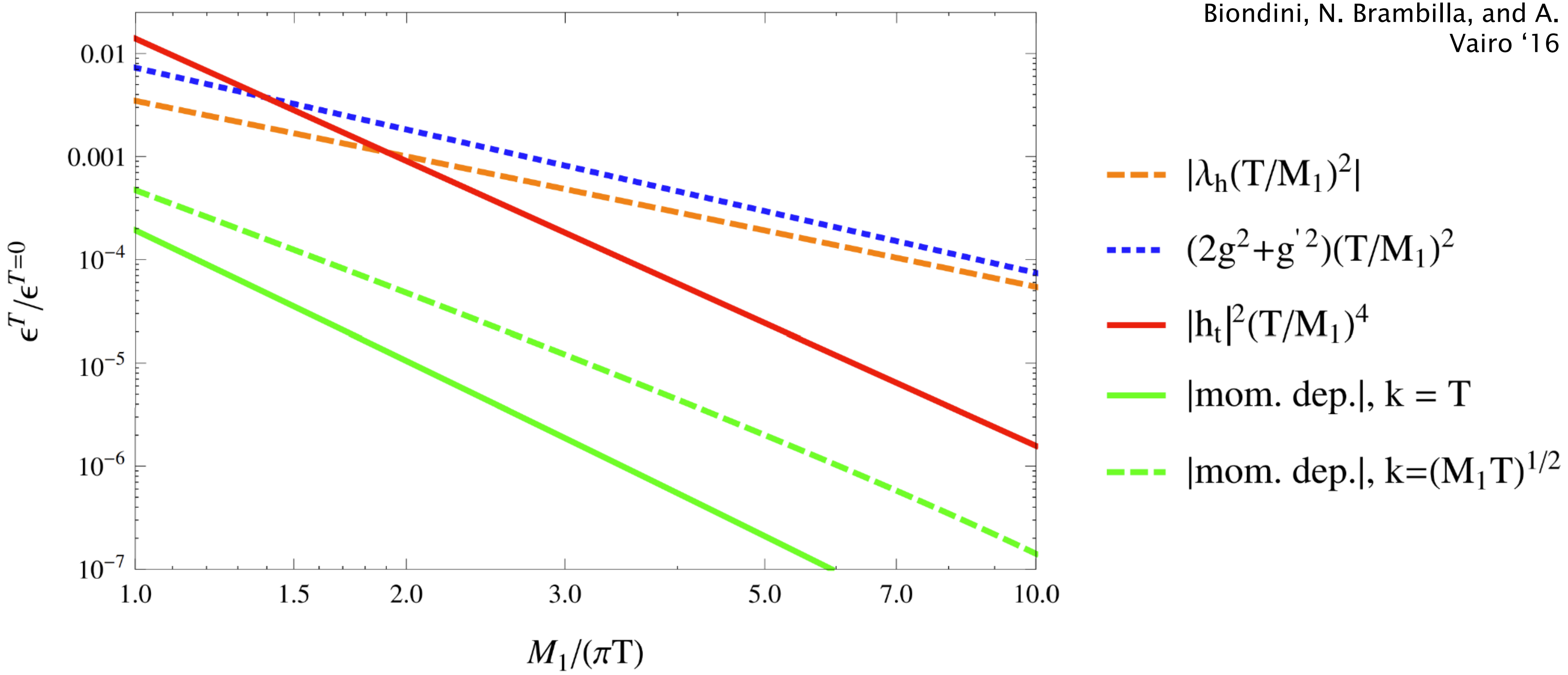


- Conversion to baryon asymmetry via sphaleron processes

$$\eta_B \approx \eta_L$$

Leptogenesis

- Finite Temperature Effects (Giudice, Notari, Raidal, Riotto, Strumia '04)
  - Corrections to sterile neutrino production rate, CP asymmetry and washout rates



Biondini, N. Brambilla, and A. Vairo '16

Leptogenesis

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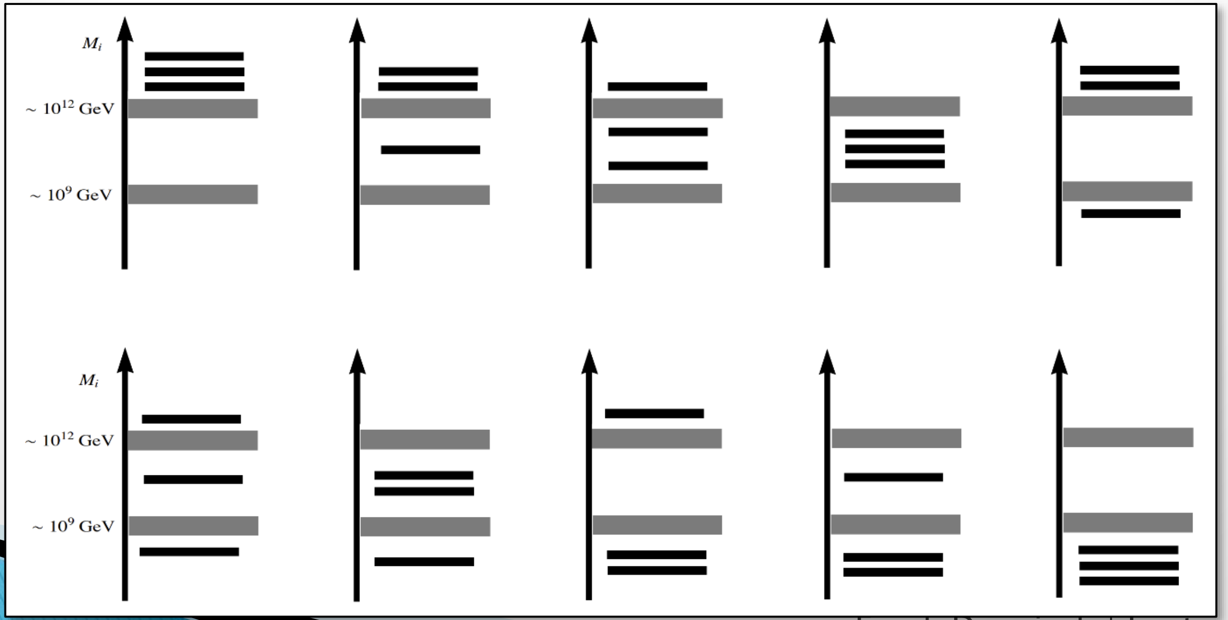
- Flavour Effects (Pilaftsis '04, Endoh, Morozumi, Xiong '04, Barbieri, Creminelli, Strumia, Tetradis '00)
  - Charged leptons not all equilibrated below 10^{12} GeV
  - Flavour composition of N_1, N_2, N_3 decays
    - Usual assumption: $m_{N_1} \ll m_{N_2} \ll m_{N_3}$ and N_1 decays washing out $N_{2,3}$ asymmetries not always applicable
  - Flavour-covariant formalism as consistent quantum statistical framework beyond classical Boltzmann (Dev, Millington, Teresi '14)



Dev, FPCP18

Leptogenesis – Resonant

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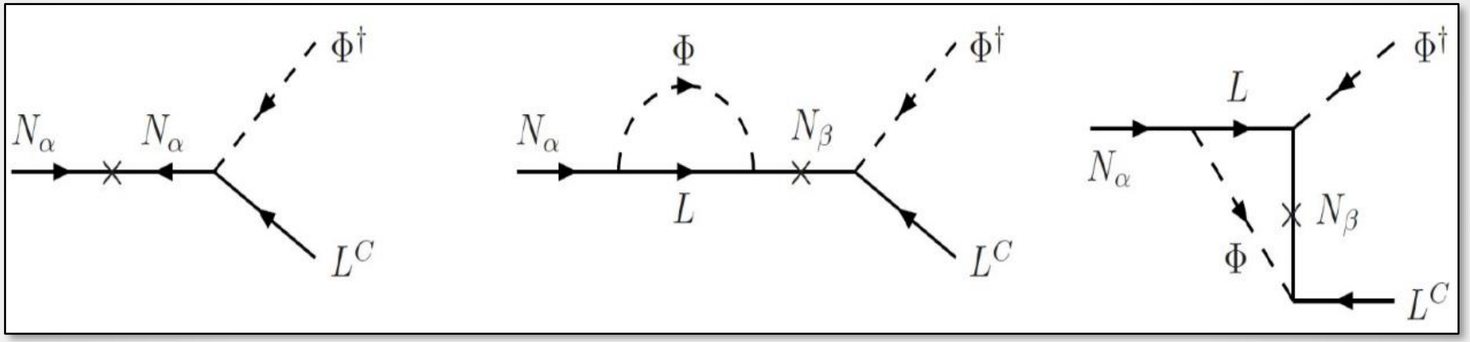
- Dominance of self-energy loop for small mass difference between heavy neutrinos (Pilaftsis '97)



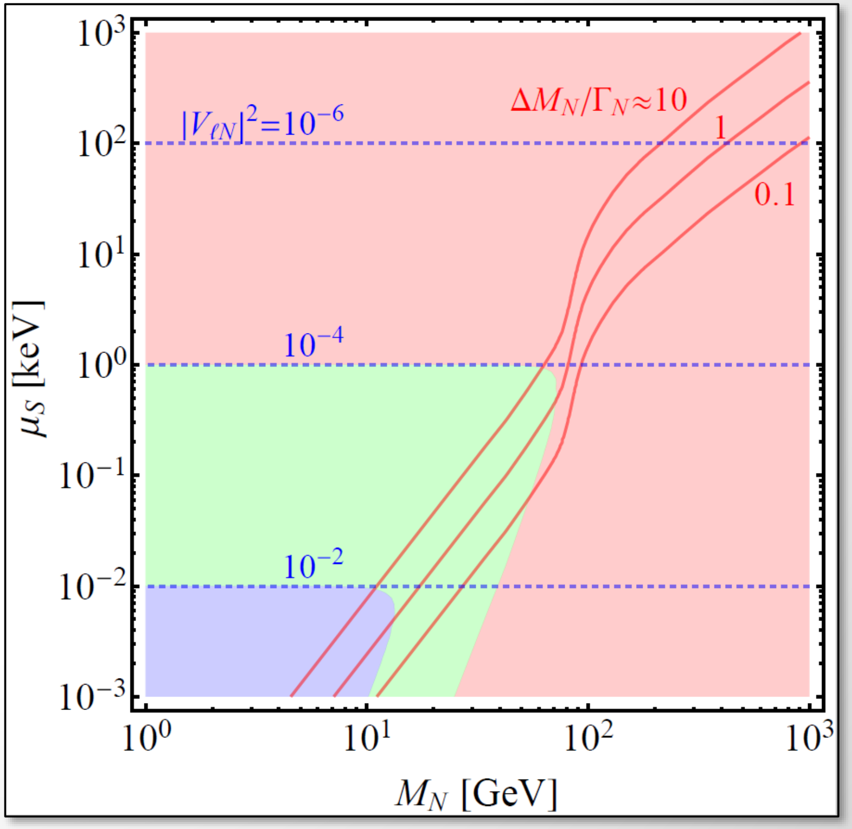
  - CP asymmetry can be $O(1)$ for $\Delta M_N \approx \Gamma_N$
  - Viable leptogenesis for neutrino masses as light as $M_N \approx 100\ \mathrm{GeV}$

Leptogenesis – Resonant

- Seesaw I mechanism with TeV scale heavy neutrinos
  - Standard Seesaw with small Yukawa couplings $Y_\nu \approx 10^{-6}\sqrt{M_N/\mathrm{TeV}}$
  - "Bent" Seesaw I mechanisms (e.g. Inverse Seesaw)
    - Decouple Λ_{LNV} from heavy neutrino mass
    - Example

$$\begin{pmatrix} 0 & Y_\nu\langle H\rangle & 0 \\ Y_\nu\langle H\rangle & \mu & M \\ 0 & M & \mu \end{pmatrix}$$

    - LNV in $0\nu\beta\beta$ suppressed by $\frac{\Delta m_N}{m_N}$
    - LNV in resonant N production suppressed by $\frac{\Delta m_N}{\Gamma_N} \approx \frac{\mu}{\Gamma_N}$



Leptogenesis – Oscillations

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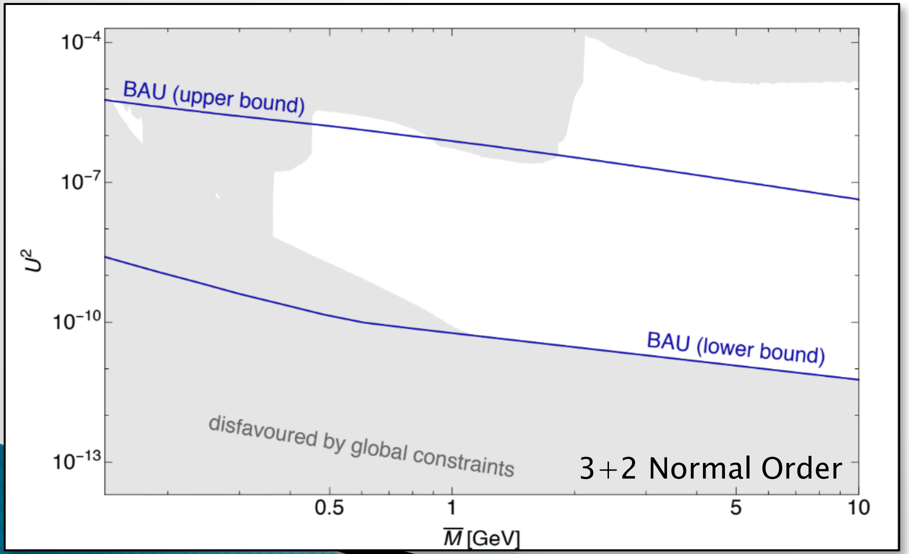
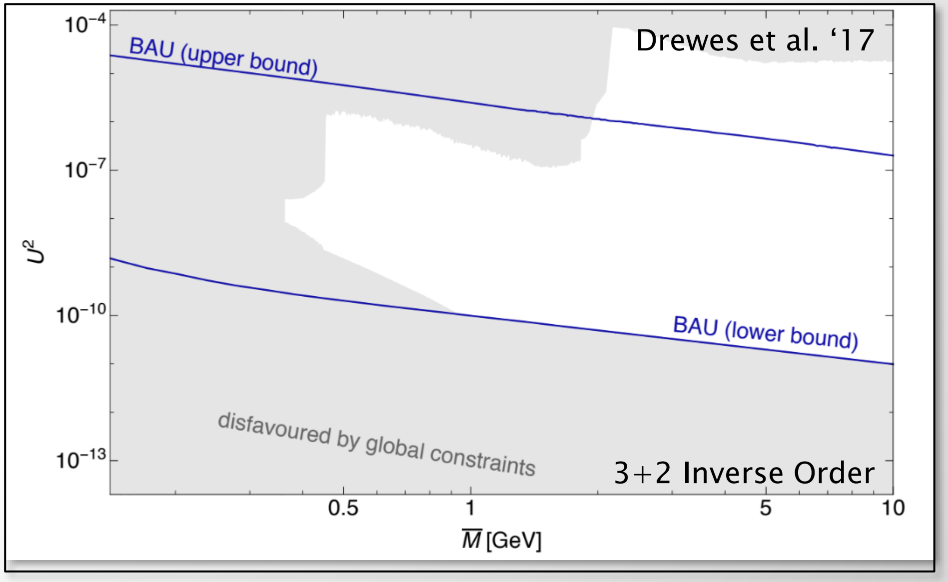
- Sterile neutrinos with small hierarchical Yukawa couplings
  (Akhmedov, Rubakov, Smirnov '98)
  - One neutrino not in equilibrium before critical sphaleron T
  - CP and flavor violating oscillations between sterile neutrinos generate asymmetry
  - Viable mechanism for $m_N \approx 1 - 100\ \mathrm{GeV}$
  - Does not rely on Majorana nature of sterile neutrinos





Dirac vs Majorana

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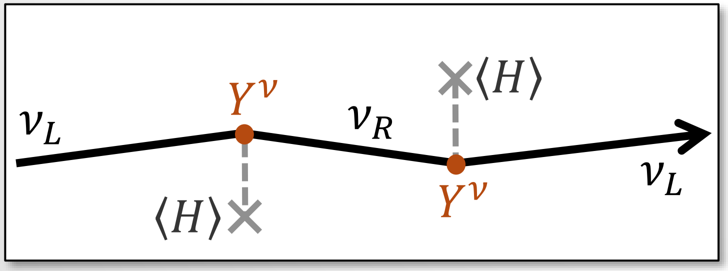
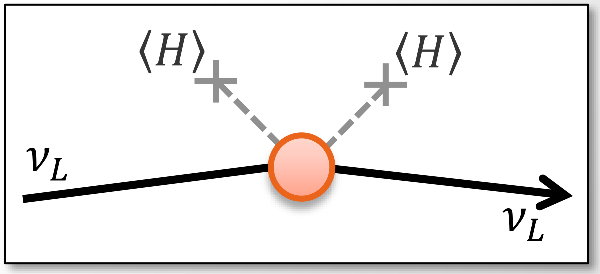
- Origin of neutrino masses beyond the Standard Model
- Two possibilities to define neutrino mass

Dirac mass analogous to other fermions but with ${}^{m_\nu}/_{\Lambda_{EW}} \approx 10^{-12}$ couplings to Higgs

Majorana mass, using only a left-handed neutrino
→ Lepton Number Violation





Neutrino Oscillations

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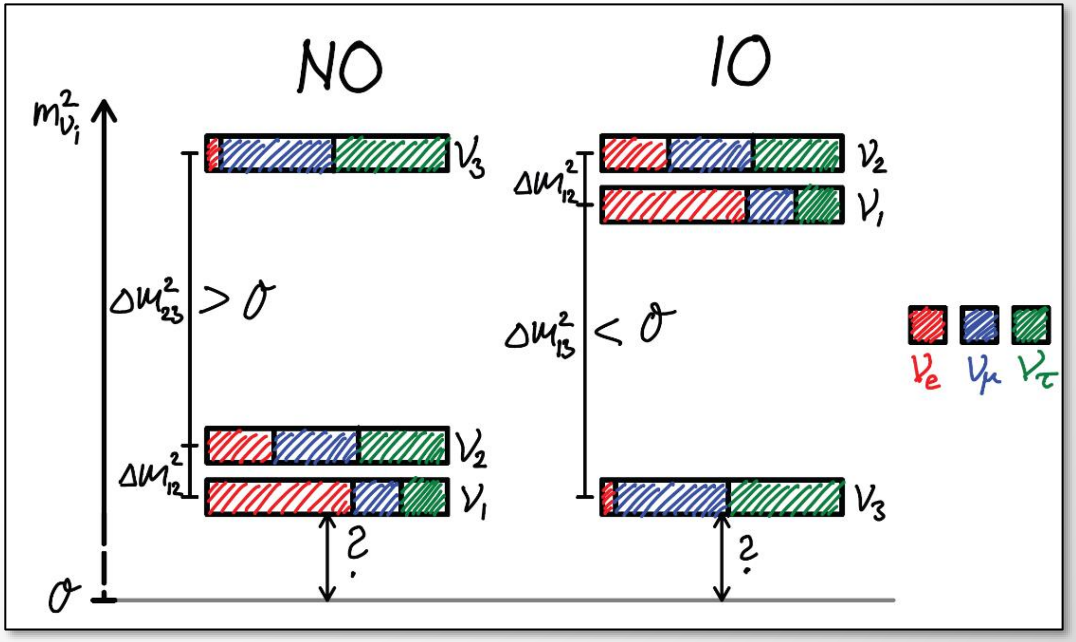
- Three Flavour Mixing

$$U_{\mathrm{PMNS}} = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta_{CP}} \\ -s_{12}c_{23} - c_{12}s_{13}s_{23}e^{i\delta_{CP}} & c_{12}c_{23} - s_{12}s_{13}s_{23}e^{i\delta_{CP}} & c_{13}s_{23} \\ s_{12}s_{23} - c_{12}s_{13}c_{23}e^{i\delta_{CP}} & -c_{12}s_{23} - s_{12}s_{13}c_{23}e^{i\delta_{CP}} & c_{13}c_{23} \end{pmatrix}$$

- Three mixing angles
  - Solar θ_{12}
  - Atmospheric θ_{23}
  - Reactor θ_{13}
- Two mass splittings
  - Δm_{12}^2, Δm_{13}^2
- CP-phase δ_{CP}



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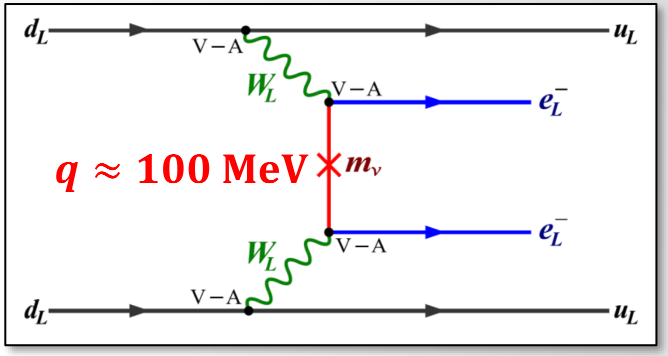
$0\nu\beta\beta$



- Half-life

$$T_{1/2}^{-1} = |m_{\beta\beta}|^2 G^{0\nu} \left|M^{0\nu}\right|^2$$

- Particle Physics

$$\mathcal{A}_{\mu\nu}^{lep} = \frac{1}{4}\sum_{i=1}^{3} U_{ei}^2\, \gamma_\mu(1+\gamma_5)\frac{\not{q} + m_{\nu_i}}{q^2 - m_{\nu_i}^2}\gamma_\nu(1-\gamma_5) \approx \frac{\gamma_\mu(1+\gamma_5)\gamma_\nu}{4q^2}\sum_{i=1}^{3} U_{ei}^2\, m_{\nu_i}$$

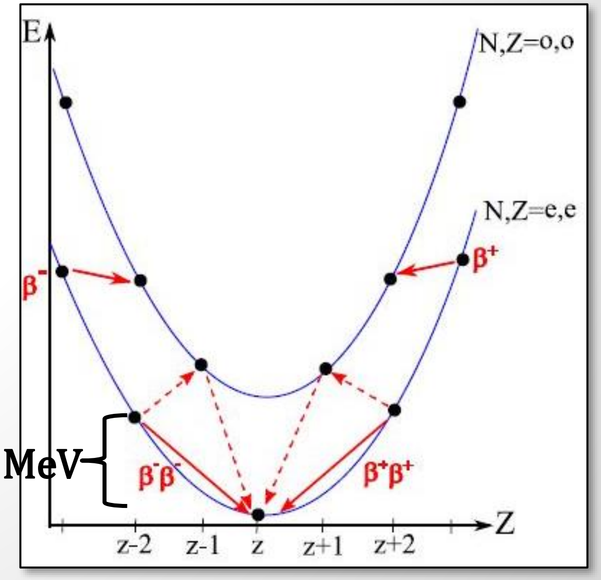
→ $m_{\beta\beta}$

- Atomic Physics
  - Leptonic phase space $G^{0\nu}$
- Nuclear Physics
  - Nuclear transition matrix element $M^{0\nu}$

$$T_{1/2}^{-1} \propto \frac{|m_{\beta\beta}|^2}{q^4} G_F^4 Q^5$$

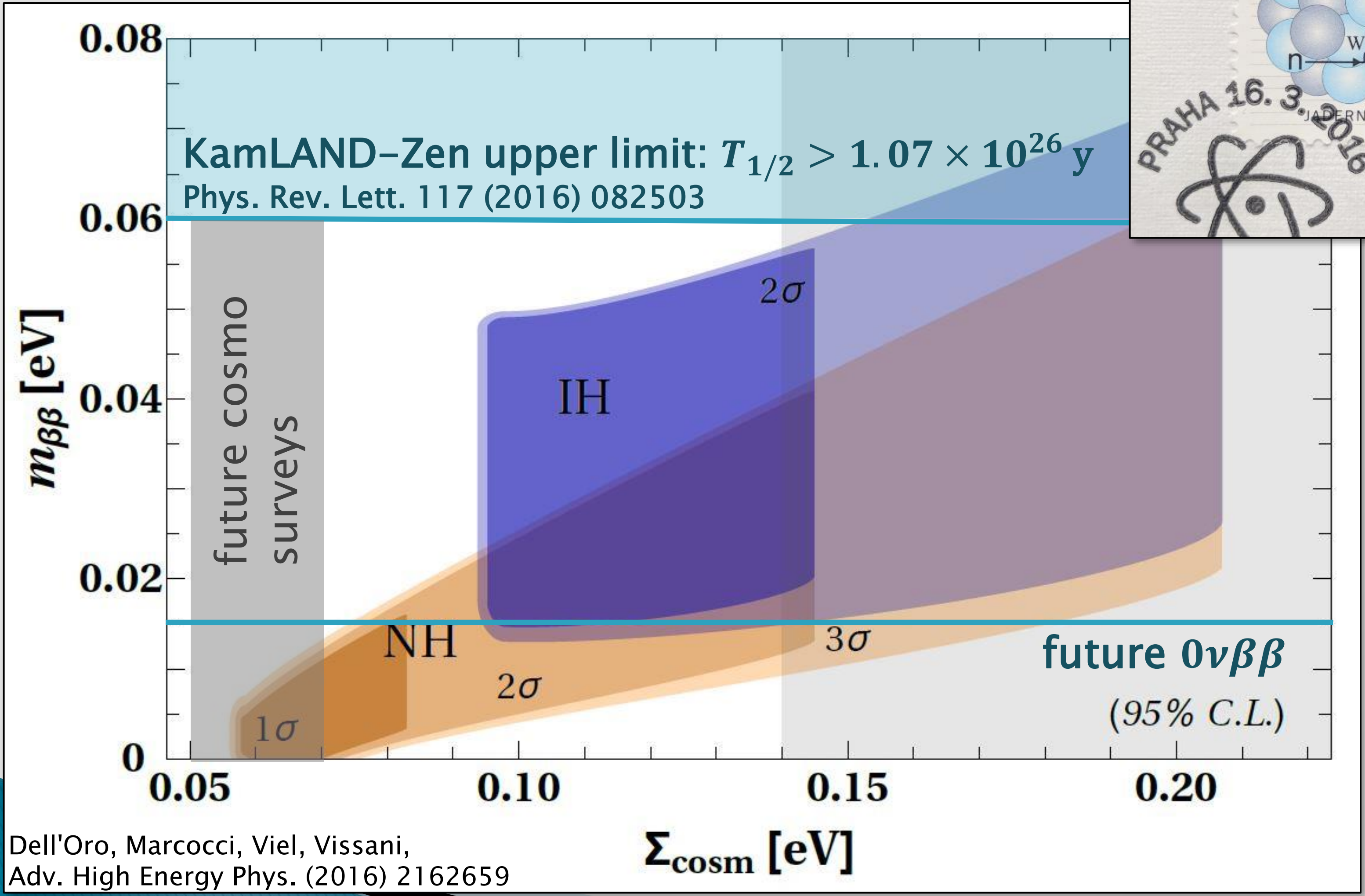
$$\frac{10^{25}\text{yr}}{T_{1/2}} \approx \left(\frac{|m_{\beta\beta}|}{eV}\right)^2$$

$Q \approx 2{-}4$ MeV



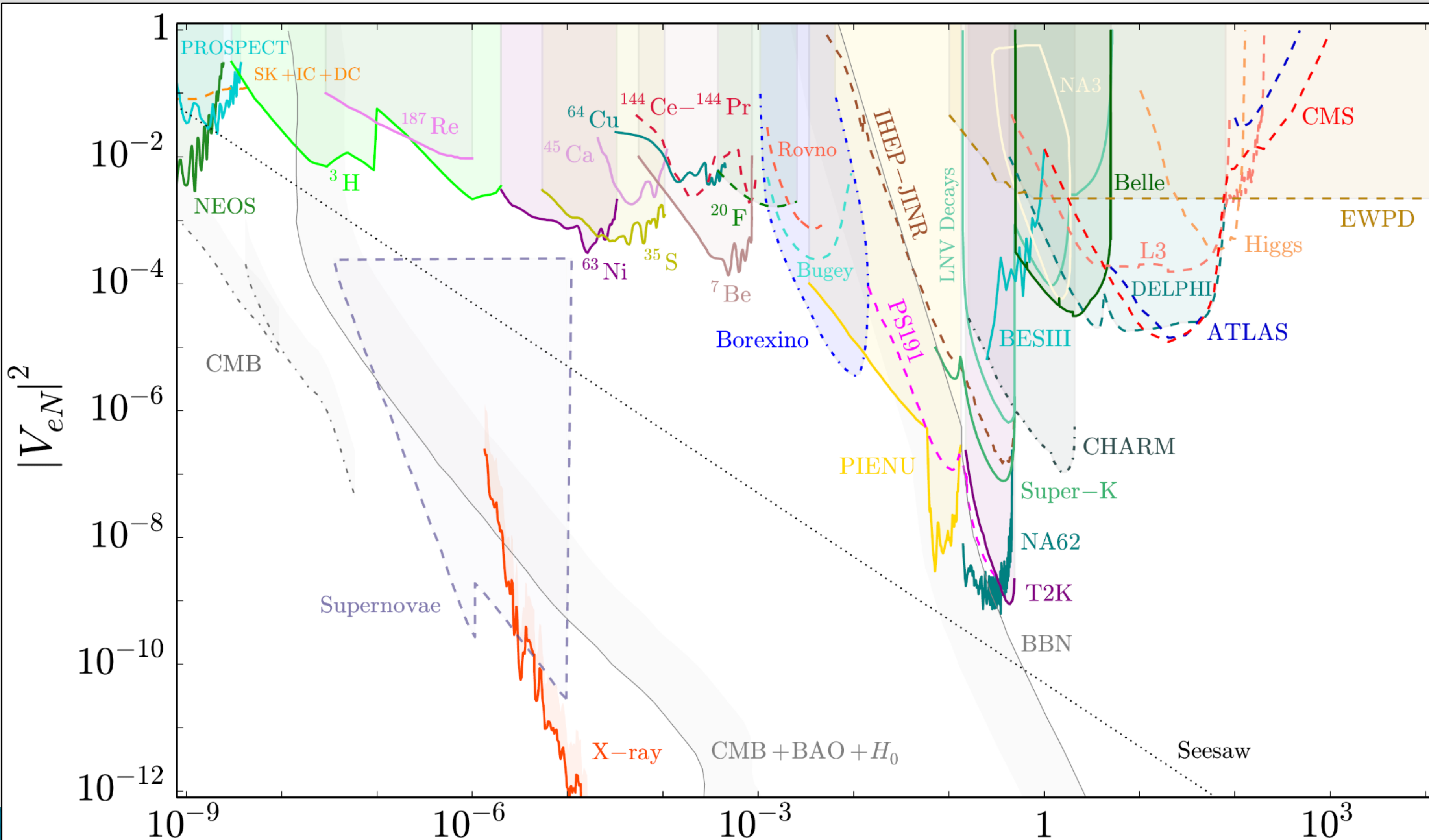
$0\nu\beta\beta$

- Effective $0\nu\beta\beta$ Mass



Dell'Oro, Marcocci, Viel, Vissani,
Adv. High Energy Phys. (2016) 2162659

Direct Searches



Bolton, FFD, Dev Moriond 2022

Direct search limits: sterile-neutrino.org

Direct Searches

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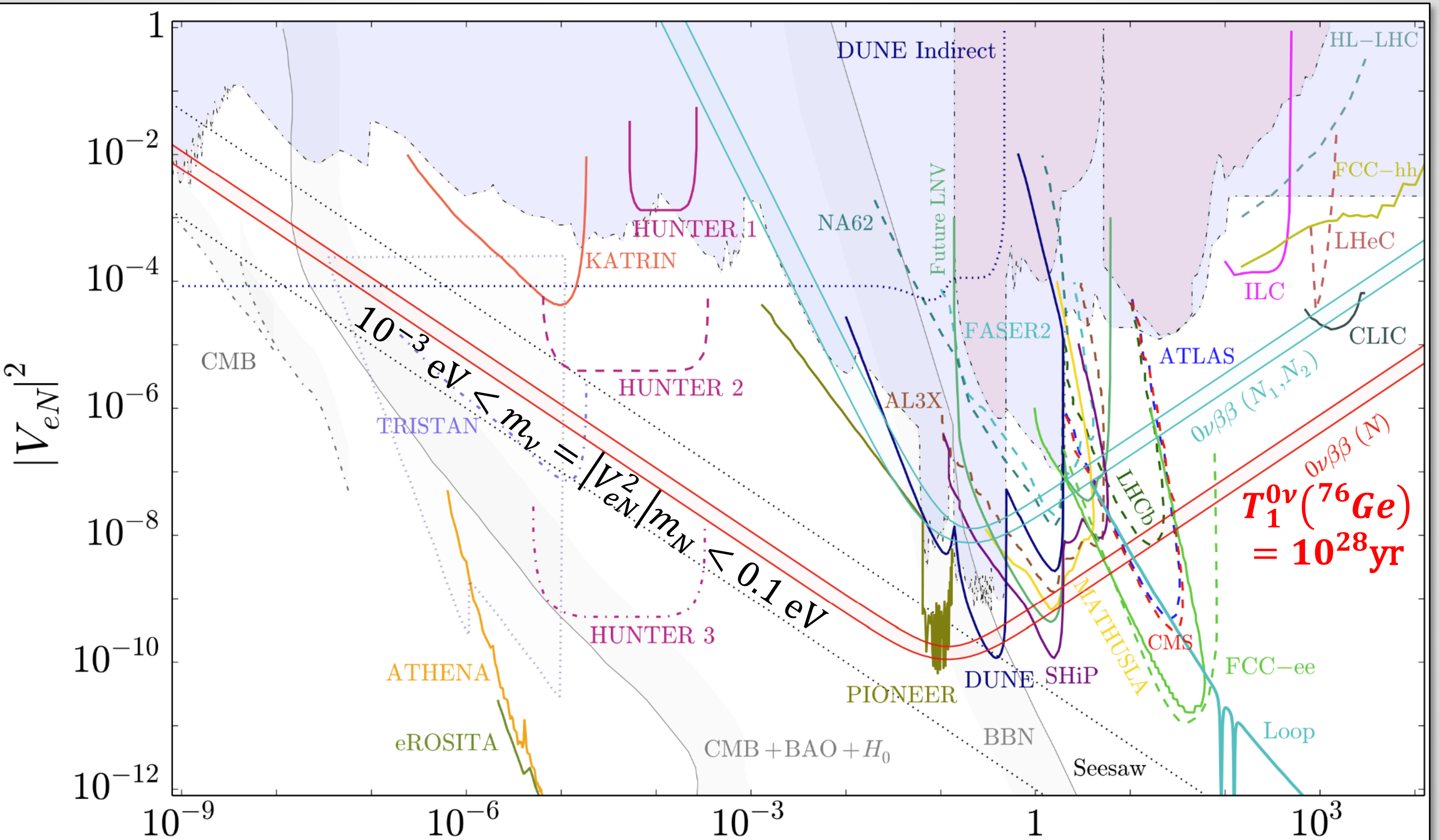

Bolton, FFD, Dev Moriond 2022

Direct search limits: sterile-neutrino.org

Direct Searches and $0\nu\beta\beta$

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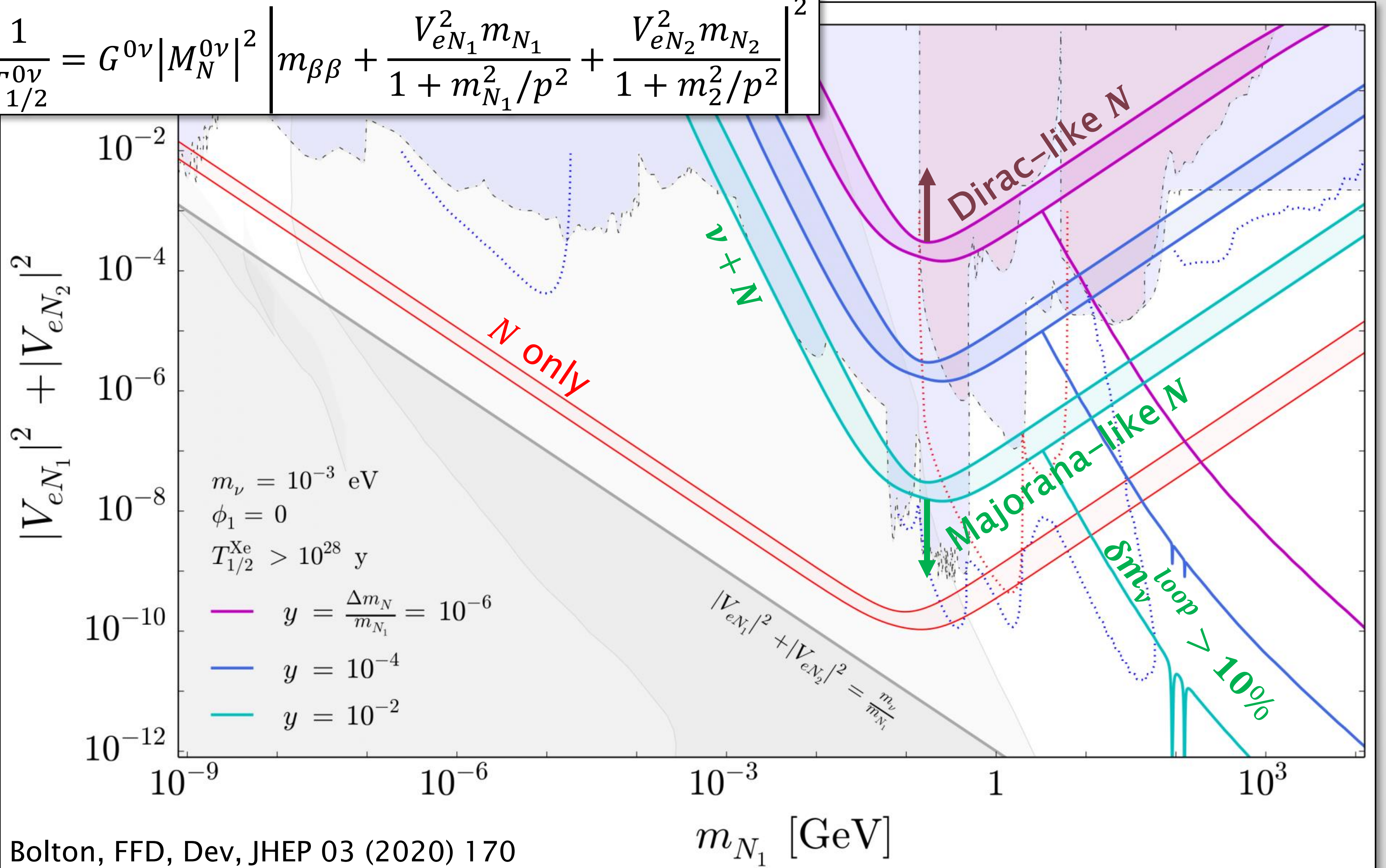
$$\frac{1}{T_{1/2}^{0\nu}} = G^{0\nu}\left|M_N^{0\nu}\right|^2 \left| m_{\beta\beta} + \frac{V_{eN_1}^2 m_{N_1}}{1+m_{N_1}^2/p^2} + \frac{V_{eN_2}^2 m_{N_2}}{1+m_2^2/p^2}\right|^2$$

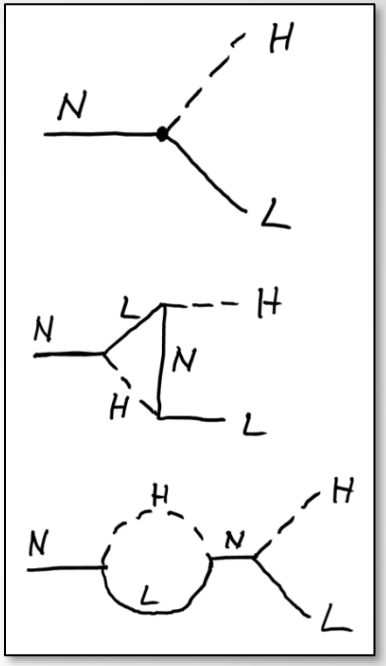


Bolton, FFD, Dev, JHEP 03 (2020) 170

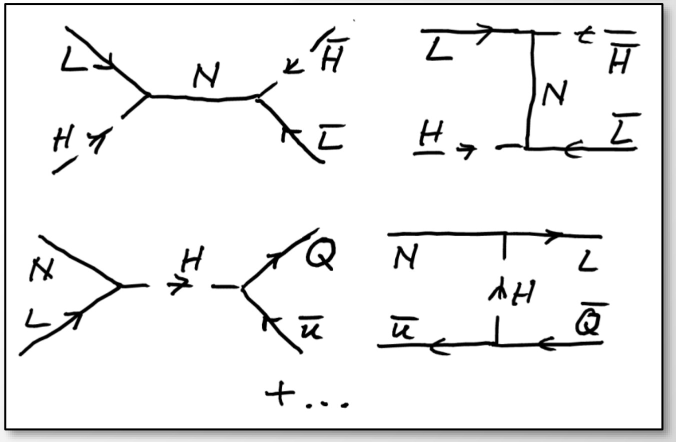
Baryon Asymmetry
Generation and Washout

- Classic Example: High-Scale Leptogenesis
  - Generation via heavy neutrino decays
  - Competition with LNV washout processes
  - Conversion to baryon asymmetry
    - EW sphaleron processes at $T \approx 100\,\mathrm{GeV}$
    - Observed asymmetry

$$\eta_B \equiv \frac{n_B - n_{\bar{B}}}{n_\gamma} = (6.20 \pm 0.15) \times 10^{-10}$$



- Other possible scenarios
  - For us only important:
    $(B - L)$ asymmetry generated
    above LHC scale



Baryon Asymmetry Generation and Washout

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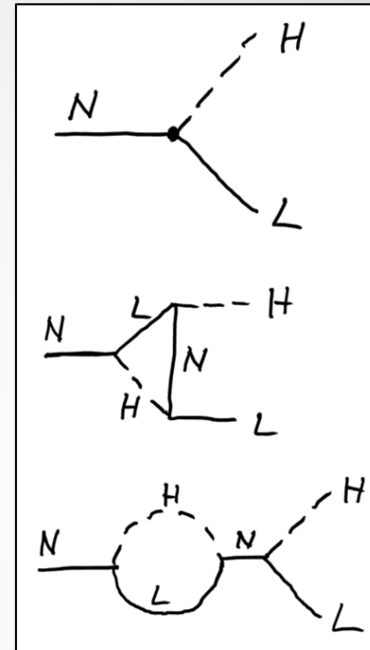
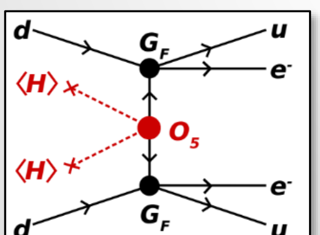
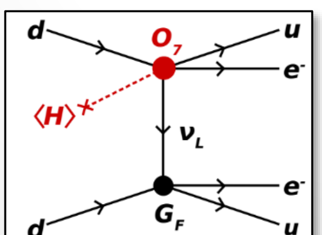
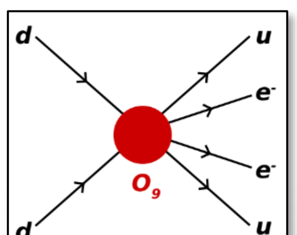
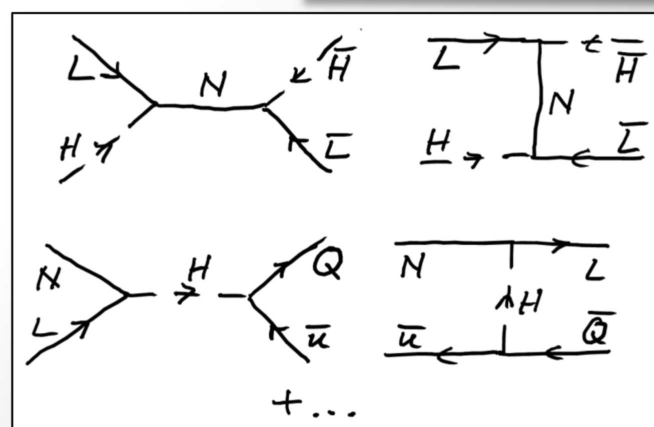


- What if we observe lepton number violating processes in $0\nu\beta\beta$?









Washout via $0\nu\beta\beta$ operators

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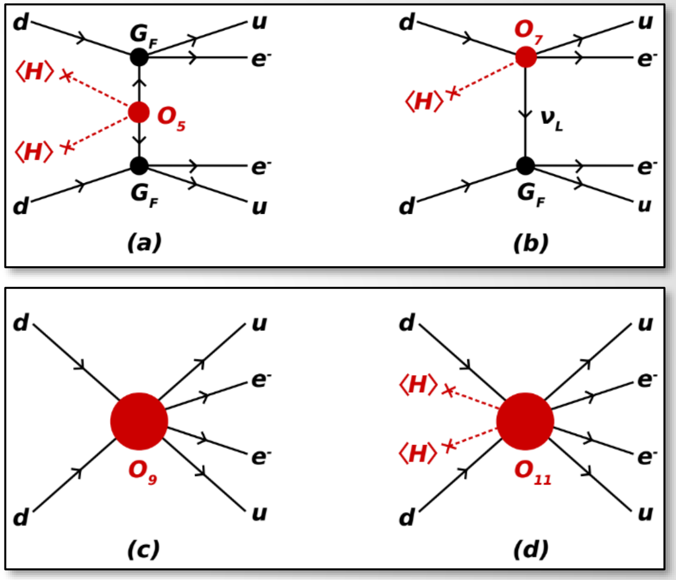
- Analogous analysis using LNV effective operators of mass dimensions 5, 7, 9, 11
  - 129 Operators (Babu, Leung '01, de Gouvea, Jenkins '08)
  - Examples

$$\mathcal{O}_5 = (L^i L^j) H^k H^l \epsilon_{ik}\epsilon_{jl},$$
$$\mathcal{O}_7 = (L^i d^c)(\bar{e^c}\bar{u^c}) H^j \epsilon_{ij},$$
$$\mathcal{O}_9 = (L^i L^j)(\bar{Q}_i \bar{u^c})(\bar{Q}_j \bar{u^c}),$$
$$\mathcal{O}_{11} = (L^i L^j)(Q_k d^c)(Q_l d^c) H_m \bar{H}_i \epsilon_{jk}\epsilon_{lm},$$

  - Matching to $0\nu\beta\beta$ operators

$$m_e \epsilon_5 = \frac{g^2 v^2}{\Lambda_5}, \quad \frac{G_F \epsilon_7}{\sqrt{2}} = \frac{g^3 v}{2\Lambda_7^3}, \quad \frac{G_F^2 \epsilon_{\{9,11\}}}{2 m_p} = \{\frac{g^4}{\Lambda_9^5}, \frac{g^6 v^2}{\Lambda_{11}^7}\}.$$

$$T_{1/2} = 2.1 \times 10^{25}\ \mathrm{y} \cdot \left(\Lambda_D / \Lambda_D^0\right)^{2d-8}$$



$\mathcal{O}_D$	λ_D^0 [GeV]	Λ_D^0 [GeV]
$\mathcal{O}_5$	9.2×10^{10}	9.1×10^{13}
$\mathcal{O}_7$	1.2×10^{2}	2.6×10^{4}
$\mathcal{O}_9$	4.3×10^{1}	2.1×10^{3}
$\mathcal{O}_{11}$	7.8×10^{1}	1.0×10^{3}

Washout via $0\nu\beta\beta$ operators

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- Boltzmann equation including washout of D-dim effective operator

$$n_\gamma H T \frac{d\eta_L}{dT} = c_D \frac{T^{2D-4}}{\Lambda_D^{2D-8}} \eta_L$$

  - $c_{\{5,7,9,11\}} = \{\frac{8}{\pi^5}, \frac{27}{2\pi^7}, \frac{3.2\times10^4}{\pi^9}, \frac{3.9\times10^5}{\pi^{13}}\}$

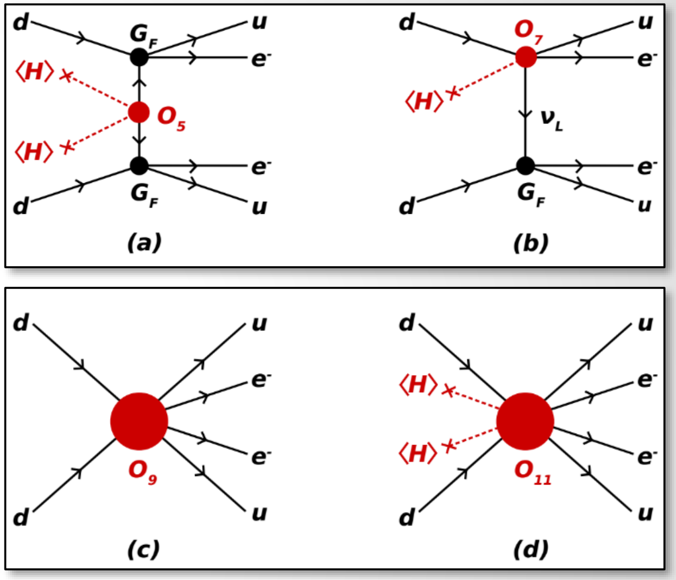
- Effective washout if

$$\frac{\Gamma_W}{H} \equiv \frac{c_D}{n_\gamma H} \frac{T^{2D-4}}{\Lambda_D^{2D-8}} = c'_D \frac{\Lambda_{\rm Pl}}{\Lambda_D} \left(\frac{T}{\Lambda_D}\right)^{2D-9} \gtrsim 1$$

$$\Lambda_D \left(\frac{\Lambda_D}{c'_D \Lambda_{\rm Pl}}\right)^{\frac{1}{2D-9}} \equiv \lambda_D \lesssim T \lesssim \Lambda_D$$

- Better: Solve Boltzmann such that initial asymmetry is washed out at the EW scale

$$\hat{\lambda}_D \approx \left[(2D-9) \ln\left(\frac{10^{-2}}{\eta_B^{\rm obs}}\right) \lambda_D^{2D-9} + v^{2D-9}\right]^{\frac{1}{2D-9}},$$



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$\mathcal{O}_{11}$	7.8×10^{1}	1.0×10^{3}

Falsifying Baryogenesis

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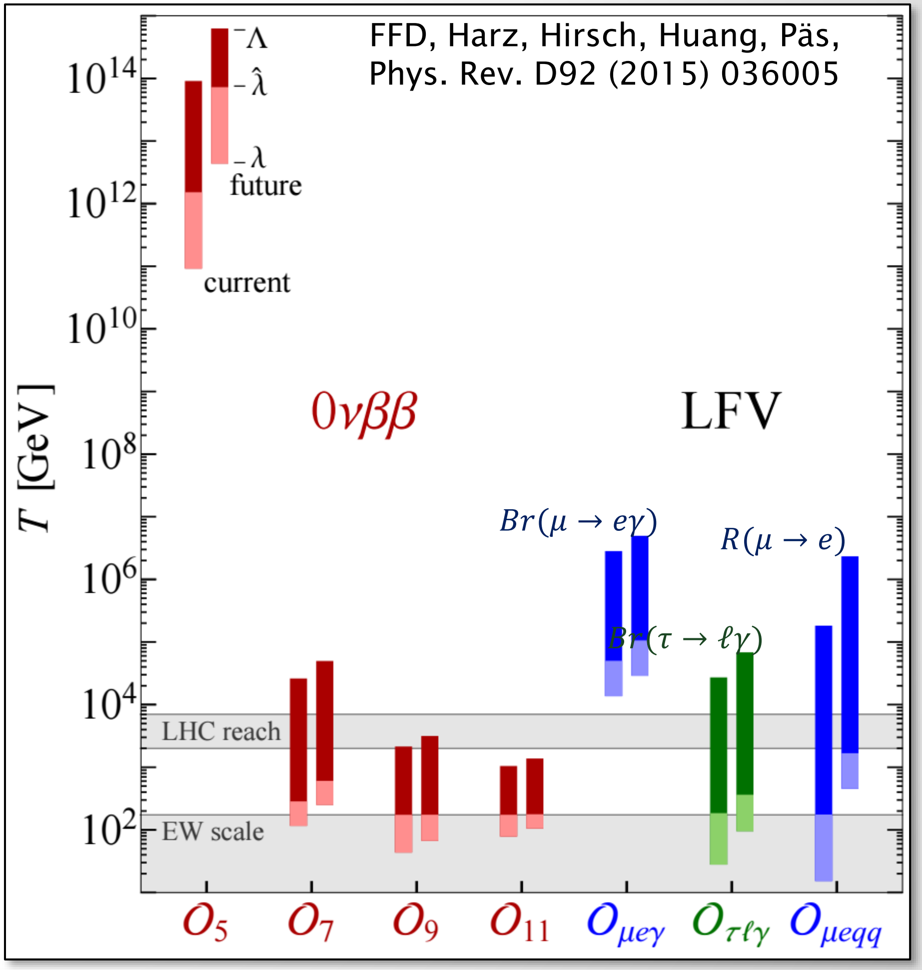
- Temperature ranges of strong equilibration
  - **Assumes observation of corresponding process!**
- Observation of LNV
  - gives information at what temperatures operators are in equilibrium
  - **can falsify high-scale baryogenesis scenarios**
    FFD, Harz, Hirsch, Phys.Rev.Lett. 112 (2014) 221601, FFD, Harz, Hirsch, Huang, Päs, Phys.Rev.D 92 (2015) 3, 036005



Falsifying Baryogenesis

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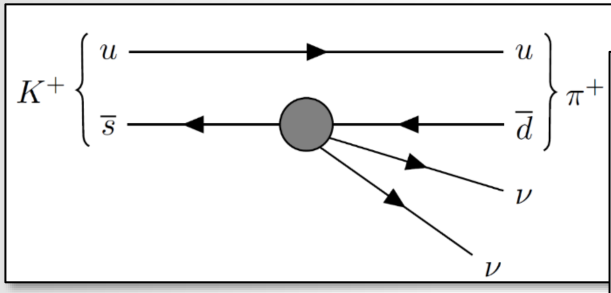
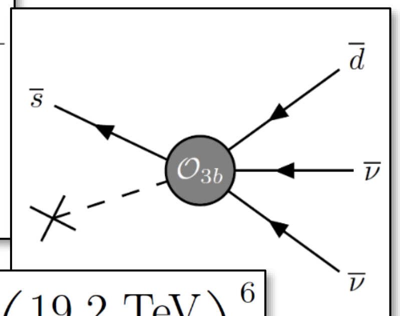
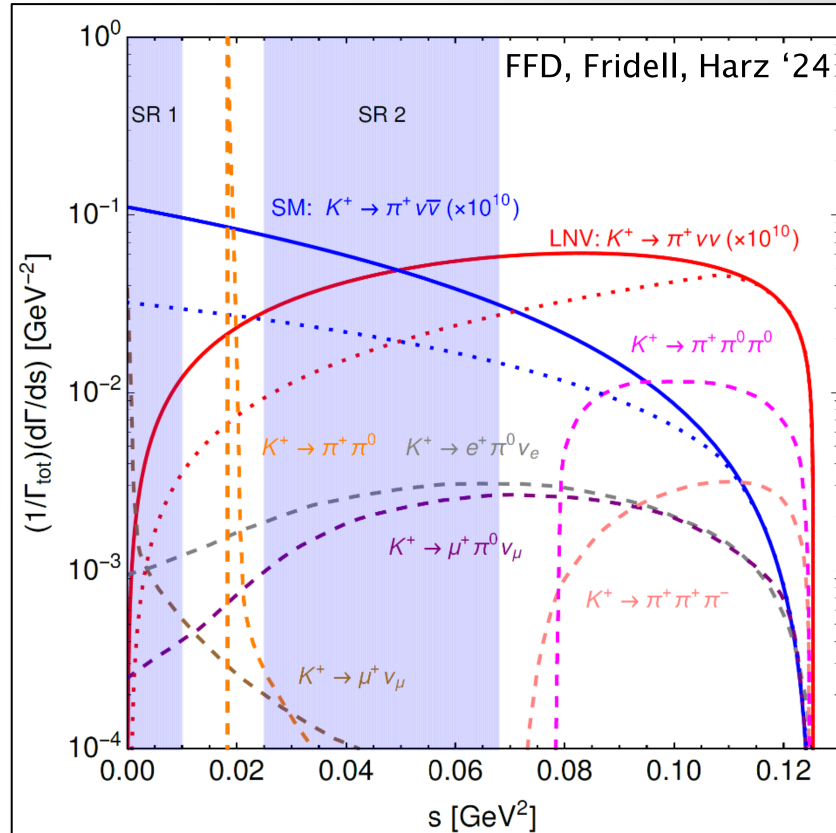
- Using other LNV observables, e.g., LNV Meson Decays





$$\mathrm{BR}_{\mathrm{LNV}}(K^+ \to \pi^+ \nu_i \nu_j) = 10^{-10} \left(\frac{19.2\ \mathrm{TeV}}{\Lambda_{ijsd}} \right)^6$$



  - LNV not directly visible but different kinematic spectrum
  - Discovery at NA62 within 1.7σ of SM expectation

- Survey of operators and processes (Fridell, Graf, Harz, Hati '24)

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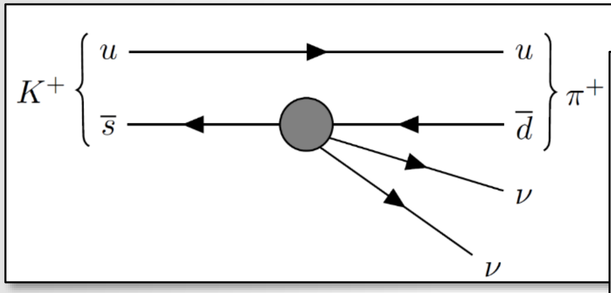
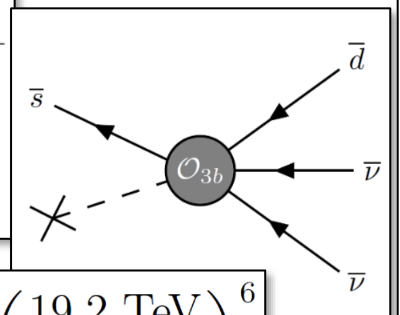
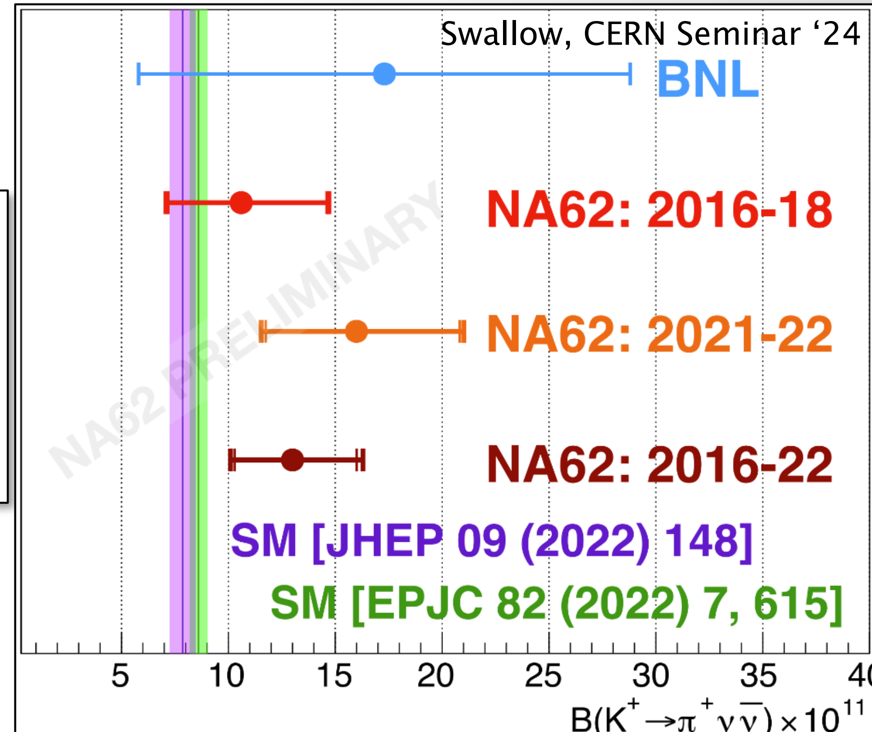
Falsifying Baryogenesis

- Using other LNV observables, e.g., LNV Meson Decays





$$\mathrm{BR}_{\mathrm{LNV}}(K^+ \to \pi^+ \nu_i \nu_j) = 10^{-10} \left(\frac{19.2\ \mathrm{TeV}}{\Lambda_{ijsd}} \right)^6$$



$$\mathcal{B}_{16-22}(K^+ \to \pi^+ \nu \bar{\nu}) = \left(13.0^{+3.3}_{-2.9}\right) \times 10^{-11}$$

  - LNV not directly visible but different kinematic spectrum
  - Discovery at NA62 within 1.7σ of SM expectation
- Survey of operators and processes (Fridell, Graf, Harz, Hati '24)

Conclusion

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- **Addressing two issues of the SM in Seesaw model**
  - Majorana neutrino mass models
  - Baryogenesis via Leptogenesis
- **High-scale leptogenesis as natural consequence**

$$M_N \gtrsim 10^8 \left(\frac{\eta_B}{5\times 10^{-11}}\right)\left(\frac{0.06\text{eV}}{m_3}\right) \text{GeV}$$

- **Embarrassment of riches**
  - Viable solutions over broad parameter space $1\,\text{GeV} < m_N < \Lambda_{GUT}$
- **Many extensions and embeddings**
  - E.g., Type-II and III Seesaw, Gauge extensions ($U(1)_{B-L}$, Left-Right symmetry, $SO(10)$), Supersymmetry
- **Bottom-up approach**
  - Experimental data → Constrained model-landscape
- **Important information for model selection, e.g.,**
  - Observation of $0\nu\beta\beta$
  - Observation of LNV @ LHC