Neutrinos

and the

Baryon Asymmetry of the Universe

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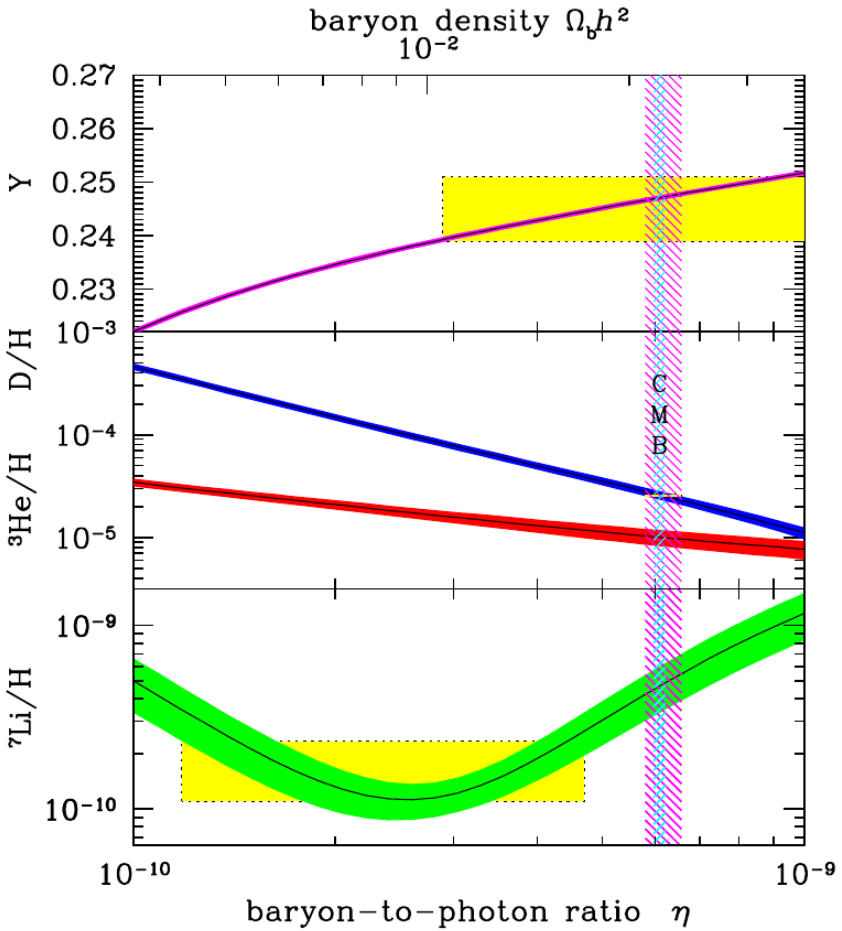
based partly on
1507.06215, 1709.00414
in collaboration with
A. Abada, G. Arcadi,
and M. Lucente

The observed baryon asymmetry of the Universe



[Particle Data Group]

- tiny matter-antimatter asymmetry in the early universe
- as particles and anti-particles annihilate, tiny asymmetry results in matter dominated Universe
- Sakharov conditions for dynamical generation
  [Sakharov '67]
  - violation of B (or L)
  - violation of C and CP
  - departure from thermal equilibrium

Baryogenesis meets particle physics

electroweak baryogenesis
(1st order phase EW PT)

thermal leptogenesis
(N_R decay)

ARS leptogenesis
(N_R oscillations)

GUT baryogenesis
(X decay)

Baryogenesis / Leptogenesis

SM sphalerons, violate $B+L$

$\longleftarrow$

gravitational
(SM gravitiational anomaly, $R\tilde{R}$)

non-thermal leptogenesis
(N_R decay)

Affleck-Dine
($B-L$ charged scalar)

through magnetogenesis
(helical magnetic fields)

and more ...

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Outline

- (Standard) thermal leptogenesis
  - overview
  - implications for the neutrino sector
- Leptogenesis through neutrino oscillations (ARS)
  - overview
  - neutrino mass models
- Neutrino observables from ARS
  - active-sterile mixing
  - tests at colliders
  - neutrinoless double beta decay

(Standard) thermal leptogenesis

[Fukugita, Yanagida '86]

- right-handed Majorana neutrinos with $\Delta L = 2$ process

$$LH \overset{h_\nu}{\to} N \to \bar{N} \overset{h_\nu}{\to} \bar{H}\bar{L}$$

- thermal initial conditions

$$\frac{n^{\text{eq}}_{N,\bar{N}}}{n_\gamma} = \begin{cases} 1 & \text{for } T > M_N \\ \frac{\pi^2}{\zeta(3)} \left(\frac{m_N}{2\pi T}\right)^{3/2} e^{-M_N/T} & \text{for } T < M_N \end{cases}$$

- if $\Gamma_N \lesssim H|_{T=M_N}$, abundance cannot track rapidly falling thermal abundance $\to$ departure from thermal equilibrium:

$$\Gamma_N \lesssim H|_{T=M_N} \quad \to \quad (h_\nu^\dagger h_\nu) M_N \lesssim M_N^2/M_P$$

- CP violation ϵ in N-decays $\quad \to \quad n_{\Delta L}/s \sim \epsilon\, T_{\text{RH}}/M_N$
- conversion to baryon asymmetry through sphaleron processes

(Standard) thermal leptogenesis

The two key parameters of thermal leptogenesis are closely tied to neutrino physics:

$$\not{CP} : \epsilon = \frac{\Gamma_{N\to LH} - \Gamma^{\rm CP}_{N\to \bar{L}\bar{H}}}{\Gamma_{N\to LH} + \Gamma^{\rm CP}_{N\to \bar{L}\bar{H}}} \qquad \text{wash-out} : \widetilde{m}_1 \sim \frac{(h_\nu^\dagger h_\nu) v^2}{M_N}$$

Type - I seesaw mechanism:

$$m_\nu = \frac{1}{2}(h_\nu^T M_N^{-1} h_\nu) v^2 \sim \widetilde{m}_1 \,, \quad \epsilon \lesssim 0.1 \frac{m_\nu M_N}{v^2}$$

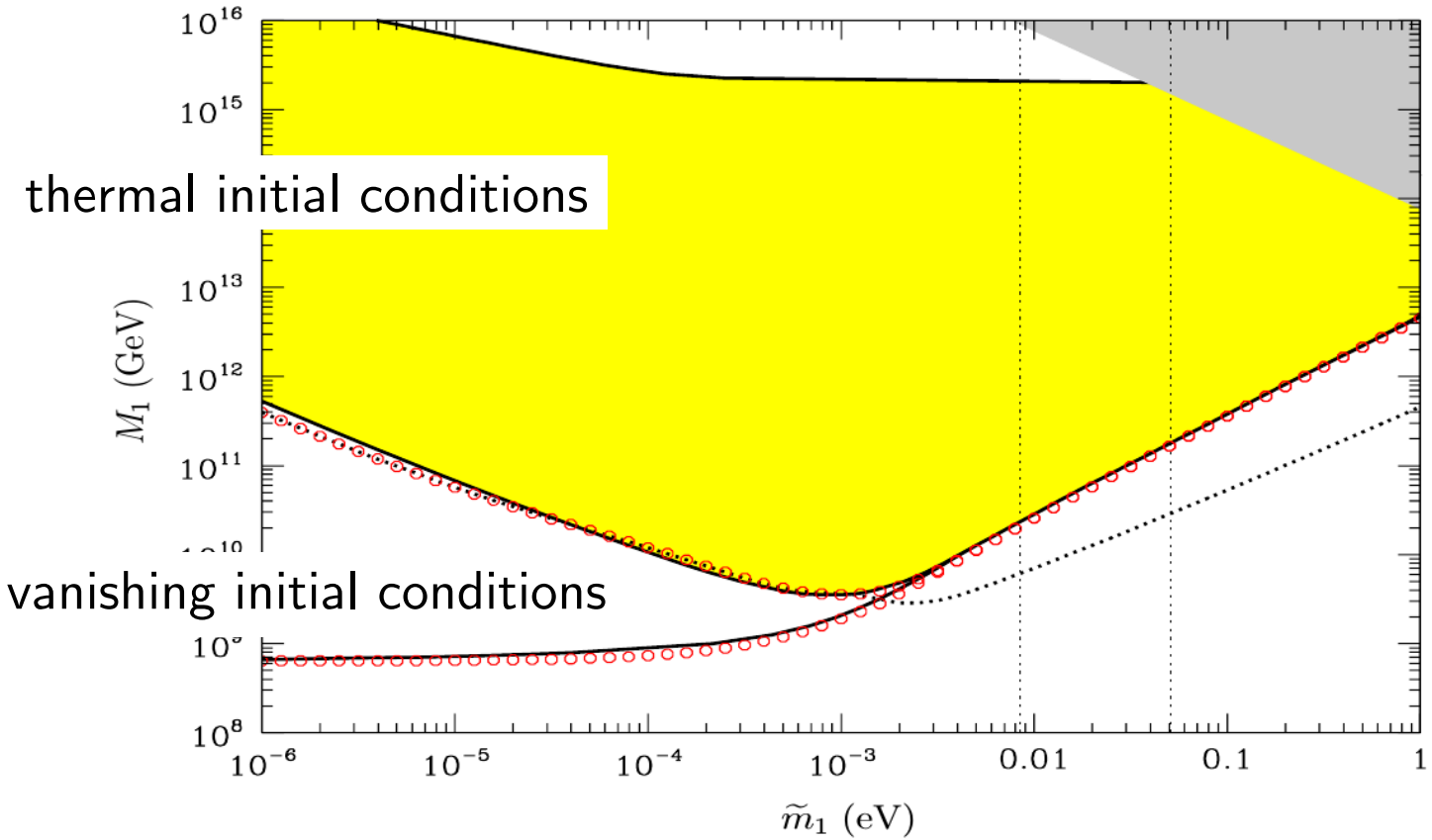
$\rightarrow$ lower bound: $T_{\rm RH} > M_N > 10^8$ GeV [Davidson,Ibarra '02]
A typical example ($\sim$ GUT scale leptogenesis):

$$M_N \sim 10^{13} \text{ GeV} \,, \quad \tilde{m}_1 \sim 0.01 \text{ eV} \,, \quad h_\nu \sim 0.1 \,, \quad \epsilon \sim 10^{-3}$$

Neutrino mass generation + cosmic history
$\rightarrow$ viable high-scale leptogenesis mechanism

(Standard) thermal leptogenesis

[Buchmüller, Di Bari, Plümacher '04]



Beautiful - but very hard to test!

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Leptogenesis through neutrino oscillations

[Akhmedov, Rubakov, Smirnov '98]

- nearly degenerate right-handed Majorana neutrinos N with $M_N \sim$ MeV - GeV and weak coupling to SM, $h_\nu \sim 10^{-7\pm2}$
- starting from a vanishing initial abundance, Ns are thermally produced but do not reach full thermal equilibrium before the EW phase transition ($=$ sphaleron freeze-out)
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- N_R oscillations create a CP violating background for the active neutrinos
- defining a generalized lepton number $\mathcal{L}$ under which also the Ns are charged, both the active and sterile sector develop a $\Delta\mathcal{L}$ of equal magnitude but opposite sign (for $M_N \gg T$)
- Sphaleron processes only pick up the $\Delta\mathcal{L} = \Delta L$ of the active sector, leading to a net baryon asymmetry

low-scale leptogenesis mechanism $\rightarrow$ experimentally accessible !

Boltzmann equations

Kinetic equations for neutrino density matrix ρ_{AB}, $\quad A, B \in \{N, \bar{N}, \nu, \bar{\nu}\}$

$$i\frac{d\rho}{dt} = [H, \rho] - \frac{i}{2}\{\Gamma, \rho\} + \frac{i}{2}\{\Gamma^p, I - \rho\} \qquad \text{[Sigl, Raffelt '93]}$$

Assuming $M_N \gg m_\nu$: active-sterile oscillations suppressed,
kinetic equilibrium: $\rho_{NN}(T,k) = R_N(T)\rho^{\mathsf{eq}}_{NN}(T,k)$,
thermal equilibrium for active ν: $\rho_{\nu,\bar{\nu}} \sim \rho_{\mathsf{eq}}(T,k)\exp\left[\pm\mathsf{diag}(\mu_{L_\alpha})\right]$:

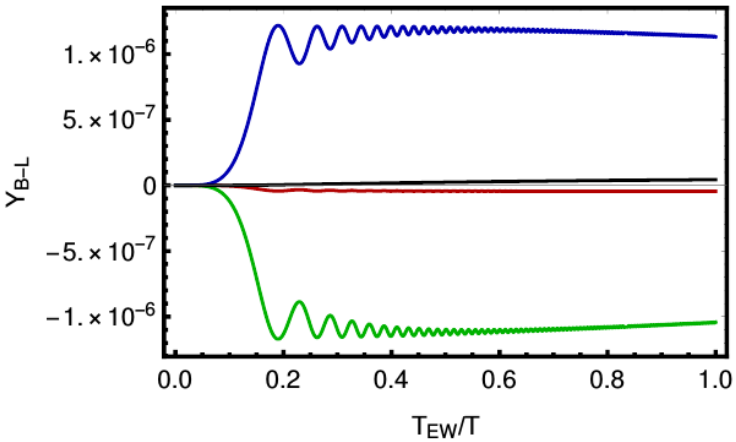
$$\begin{aligned}
\frac{dR_N}{dt} =& -i\left[\langle H\rangle, R_N\right] - \frac{1}{2}\langle\gamma^{(0)}\rangle\left\{F^\dagger F, R_N - I\right\} - \frac{1}{2}\langle\gamma^{(1b)}\rangle\left\{F^\dagger\mu_L F, R_N\right\} \\
&+ \langle\gamma^{(1a)}\rangle F^\dagger\mu_L F\,, \\
\frac{d\mu_{\Delta\alpha}}{dt} =& -\frac{9\,\zeta(3)}{2N_D\,\pi^2}\Big\{\langle\gamma^{(0)}\rangle\left(FR_NF^\dagger - F^*R_{\bar{N}}F^T\right) - 2\langle\gamma^{(1a)}\rangle\mu_L FF^\dagger + \\
&+ \langle\gamma^{(1b)}\rangle\mu_L\left(FR_NF^\dagger + F^*R_{\bar{N}}F^T\right)\Big\}_{\alpha\alpha}\,, \qquad \text{[Asaka, Shaposhnikov '05]}
\end{aligned}$$

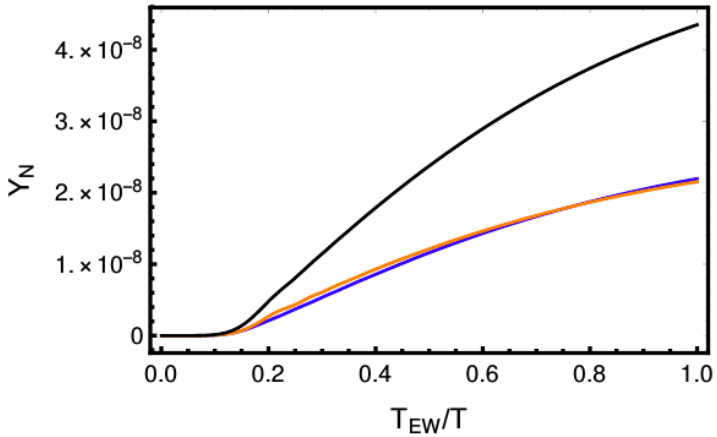
w. F = Yukawa coupling in mass basis, H = eff. Hamiltonian, $\langle\cdot\rangle$ = thermal average

Benchmark solutions

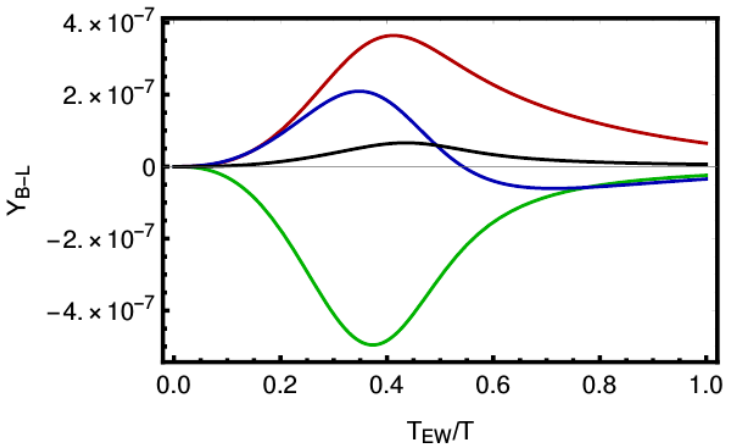
[Abada, Arcadi, VD, Lucente '15, '17]

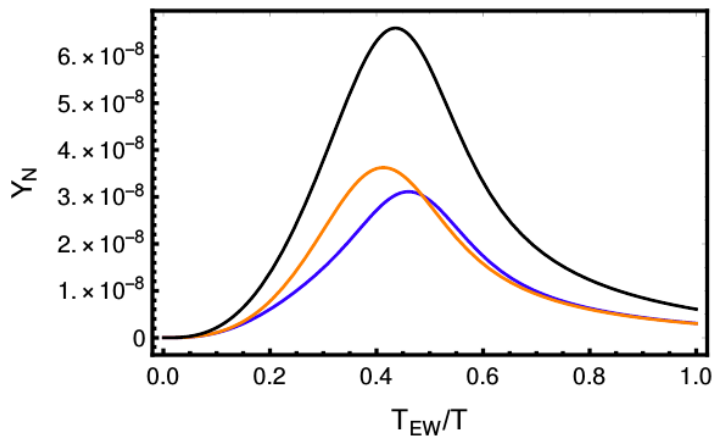
weak washout regime, $|F| \lesssim 10^{-7}$ (analytical solutions available)





intermediate/strong washout regime, $|F| \sim 10^{-6}$ (perturbative expansion)





Neutrino mass models for ARS leptogenesis

Inverse Seesaw [Wyler, Wolfenstein '83; Mohapatra, Valle '86]

(schematically for 'active', 'RH', 'sterile')

$$M_\nu = \underbrace{\begin{pmatrix} 0 & \frac{1}{\sqrt{2}} h_\nu v & 0 \\ \frac{1}{\sqrt{2}} h_\nu v & 0 & \Lambda \\ 0 & \Lambda & 0 \end{pmatrix}}_{\text{L conserving}} + \xi \underbrace{\begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & \Lambda \end{pmatrix}}_{\Delta L=2}$$

$$\Rightarrow \quad m_\nu \simeq \frac{\xi (h_\nu v)^2}{2\Lambda}\,, \qquad \Delta m^2 = M_{N_2}^2 - M_{N_1}^2 \simeq 2\xi\Lambda^2$$

Linear Seesaw [Barr '04; Malinsky, Romao, Valle '05]

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Linear Seesaw [Barr '04; Malinsky, Romao, Valle '05] plus Inverse Seesaw

$$M_\nu = \underbrace{\begin{pmatrix} 0 & \frac{1}{\sqrt{2}} h_\nu v & 0 \\ \frac{1}{\sqrt{2}} h_\nu v & 0 & \Lambda \\ 0 & \Lambda & 0 \end{pmatrix}}_{\text{L conserving}} + \epsilon \underbrace{\begin{pmatrix} 0 & 0 & \frac{1}{\sqrt{2}} h'_\nu v \\ 0 & 0 & 0 \\ \frac{1}{\sqrt{2}} h'_\nu v & 0 & \frac{\xi}{\epsilon}\Lambda \end{pmatrix}}_{\Delta L=2}$$

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Strategy

[Abada, Arcadi, VD, Lucente '15,'17]

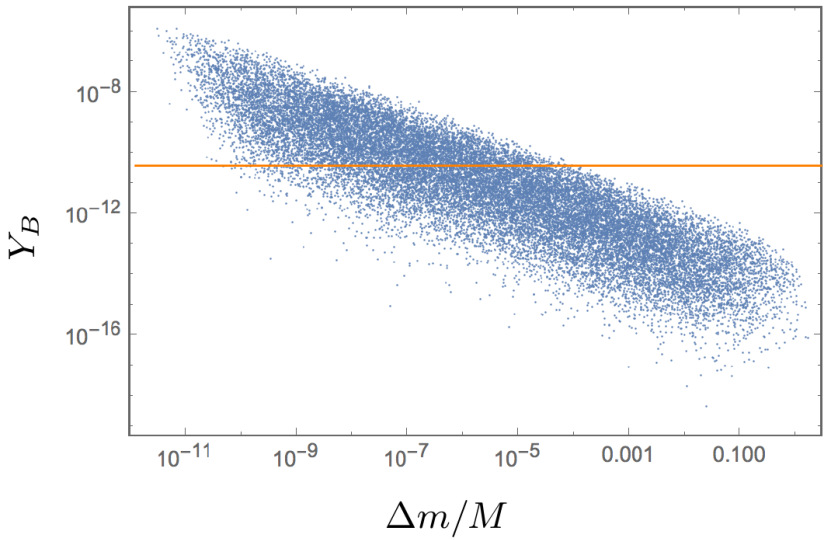
- Generate data points which respect all constraints on active neutrino masses/mixings as well as laboratory constraints on sterile neutrinos
  $\Rightarrow$ minimial models: LISS(1,1), ISS(2,2), ISS(2,3) [Abada, Lucente '14]

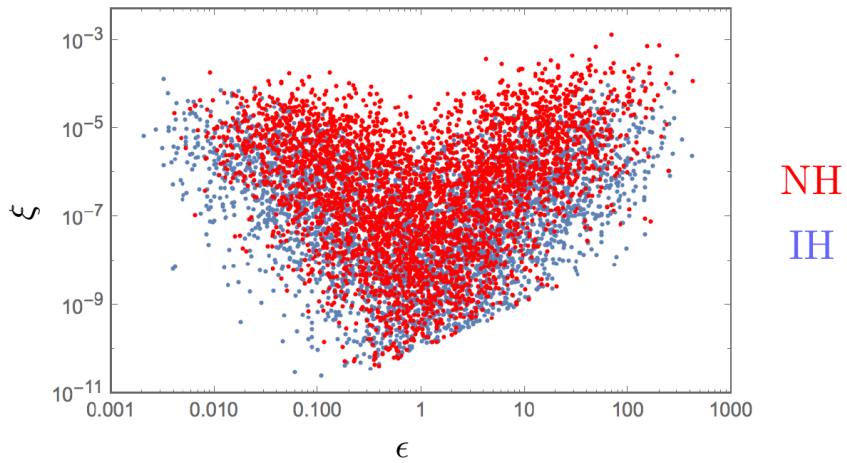
- Calculate baryon asymmetry by solving Boltzmann equations
  - analytically in the weak washout regime
  - perturbative numerical procedure otherwise

- $\Rightarrow$ requirements for successful leptogenesis:
  constraints on masses, Yukawa couplings, mixing angles...

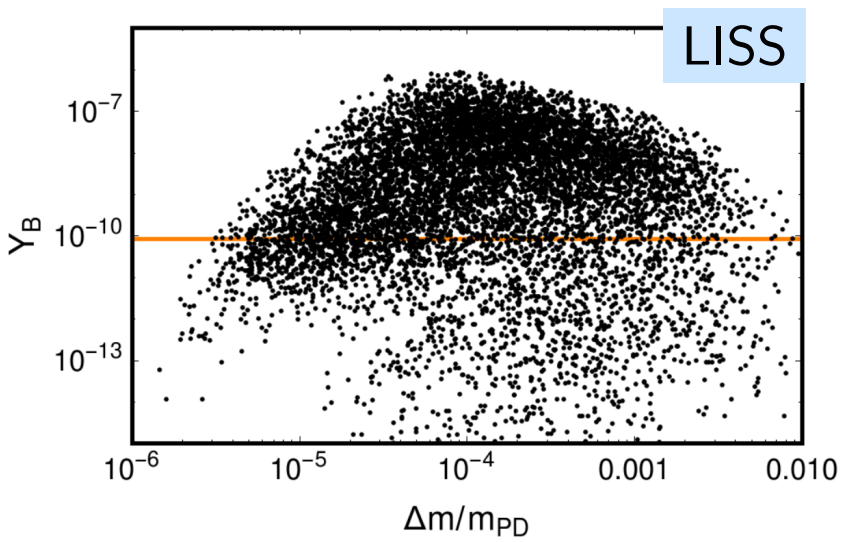
Neutrino mass models for ARS leptogenesis

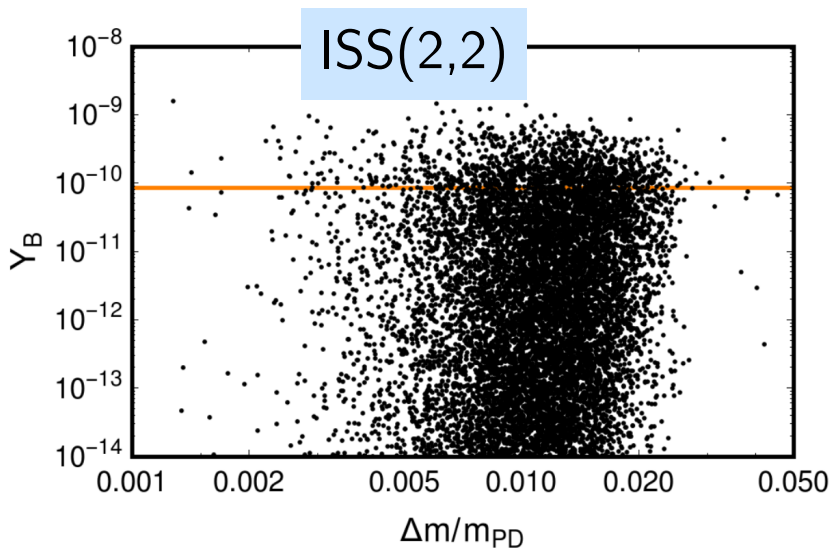
weak washout regime, LISS model (2 additional N_R's):





intermediate/strong washout regime:

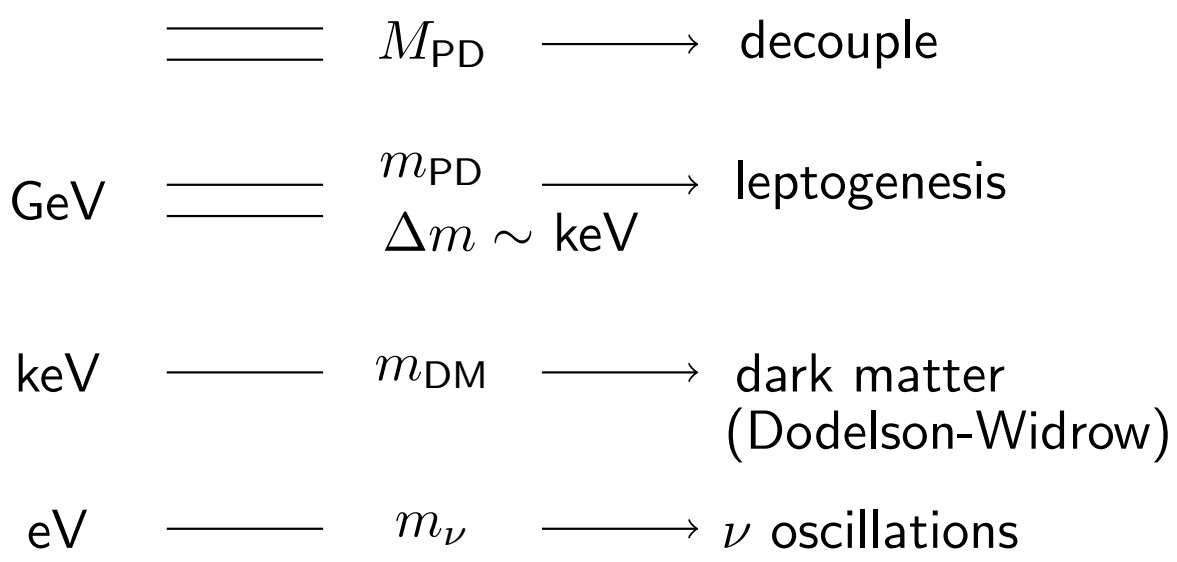




Why consider specific mass models?

- fewer parameters / more predictive
- small parameters are symmetry protected
  $\rightarrow$ directions for further model building
- distinguish model independent from model-dependent features
- but do not cover entire ARS parameter space

An example: dark matter in the ISS(2,3)



with

$$\frac{m_{\mathrm{DM}}}{m_{\mathrm{PD}}} \simeq \frac{\Delta m}{m_{\mathrm{PD}}} \simeq 10^{-3} \left(\frac{10^{-5}}{|F|}\right) \left(\frac{m_{\mathrm{PD}}}{\mathrm{GeV}}\right)^{1/2} \left(\frac{m_\nu}{0.05\ \mathrm{eV}}\right)^{1/2}$$

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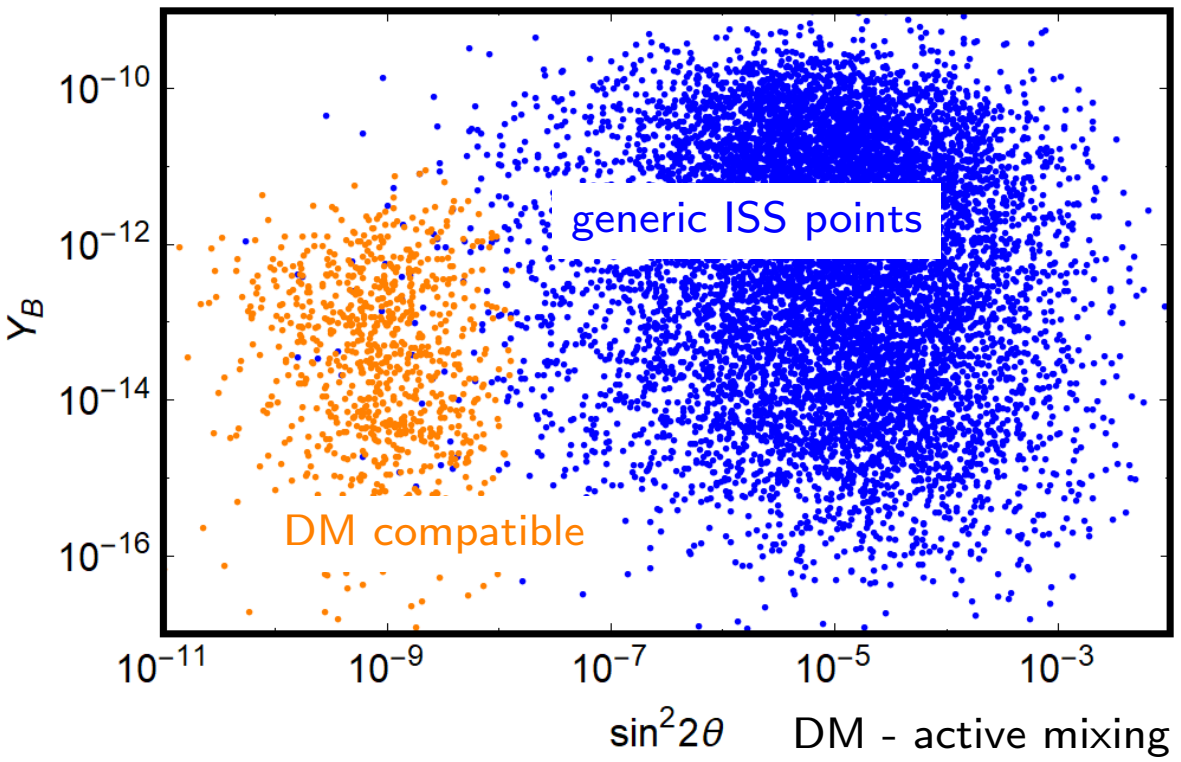
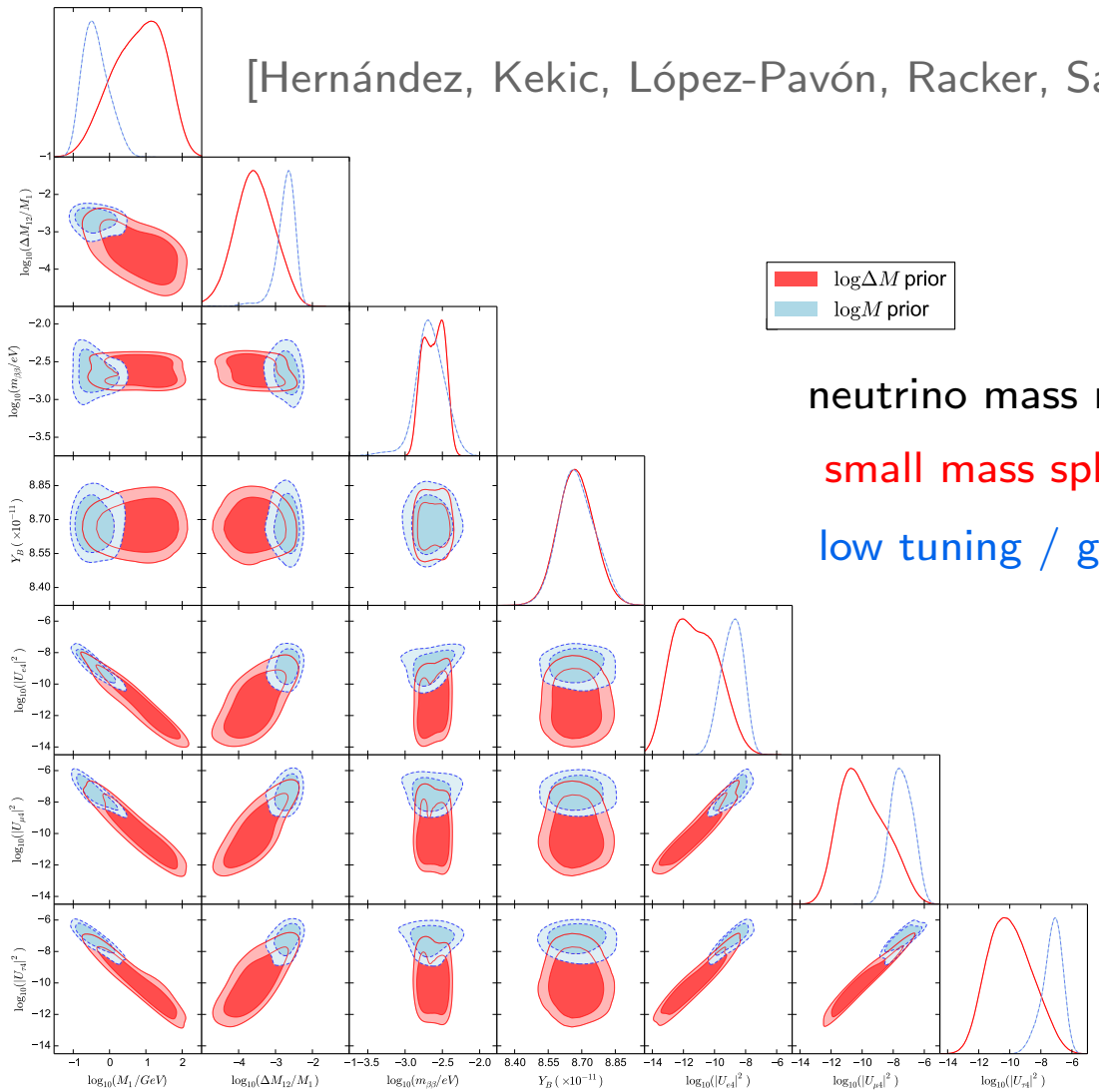


ISS + ARS leptogenesis too constraining on mixing angles

Complementary approach: bayesian analysis

[Hernández, Kekic, López-Pavón, Racker, Salvado, '16]



neutrino mass model:

small mass splitting

low tuning / generic

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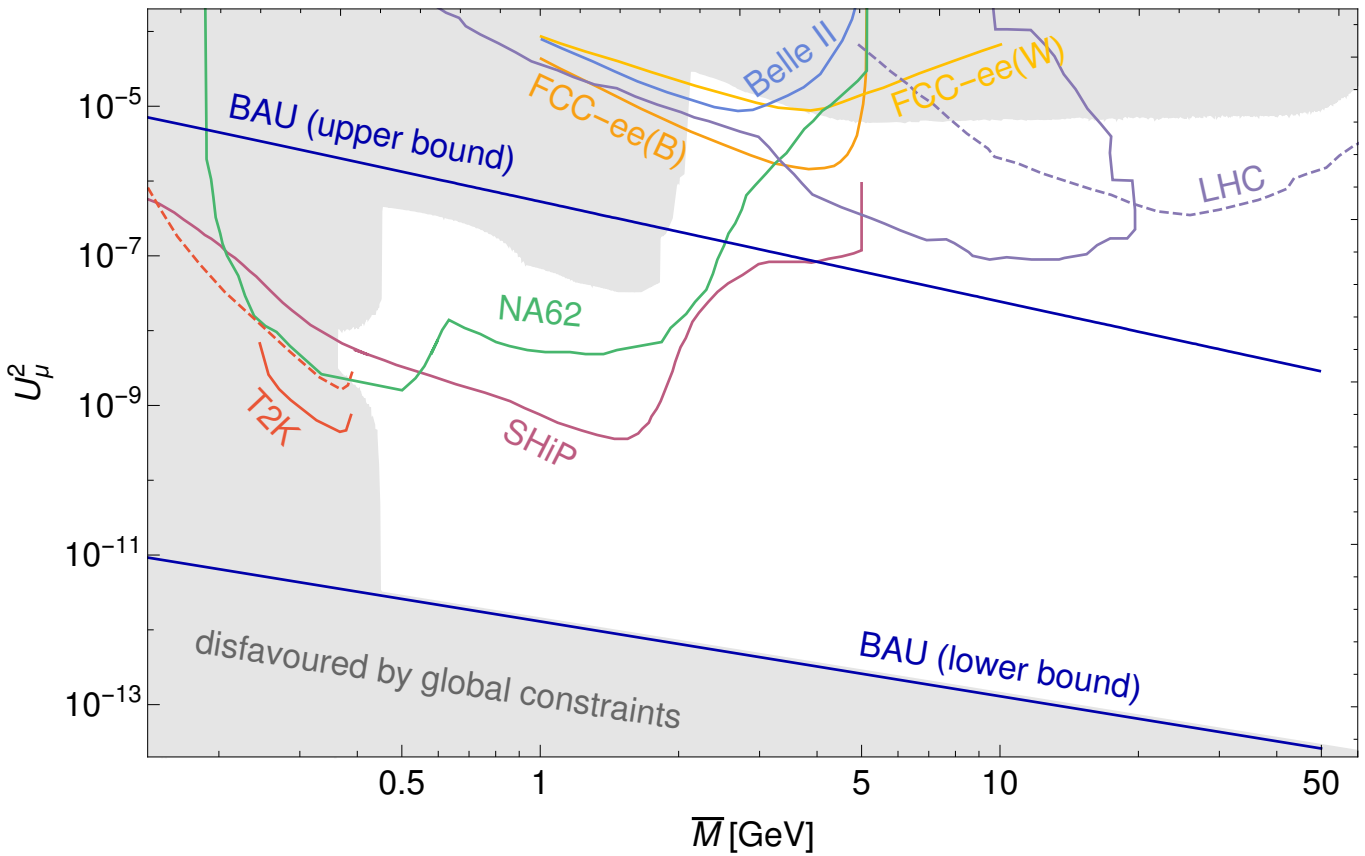
Active sterile mixing

Minimimal type-I seesaw [Drewes, Garbrecht, Gueter, Klaric '16]



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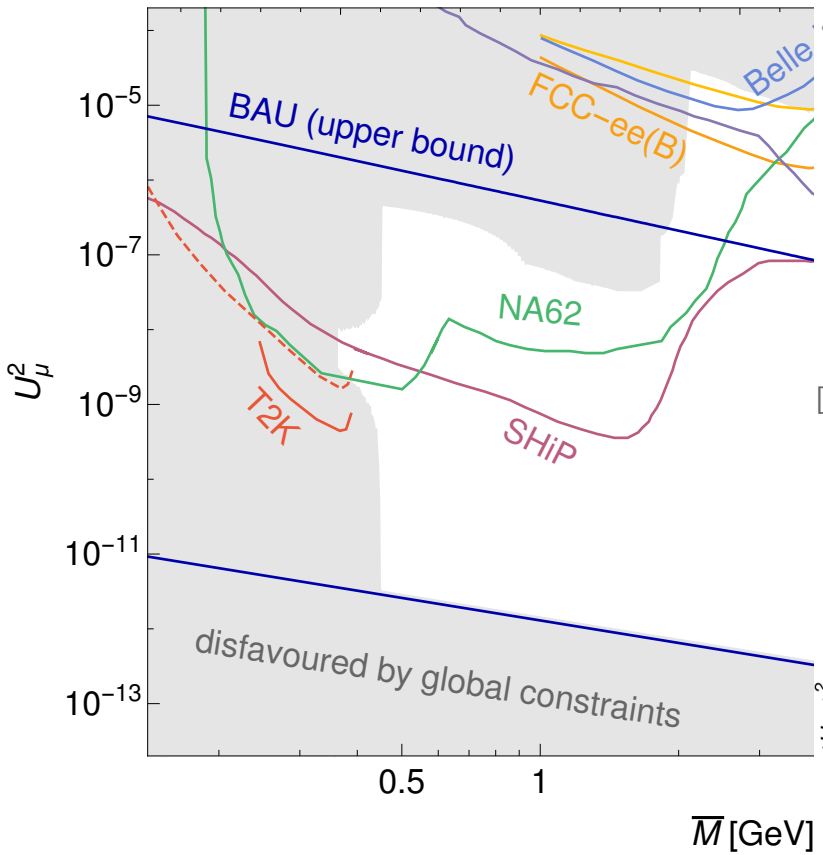
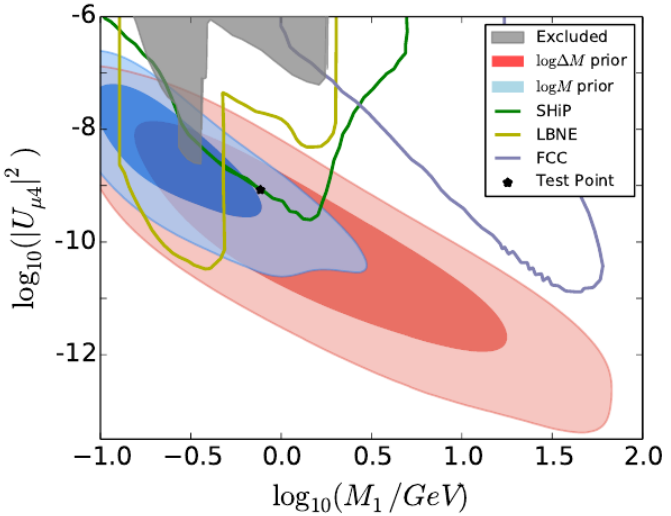
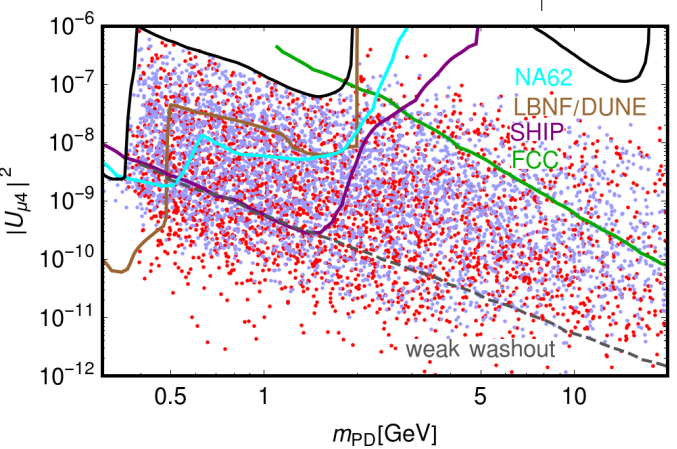




[Hernández, Kekic, López-Pavón, Racker, Salvado, '16]

[Abada, Arcadi, VD, Lucente '17]



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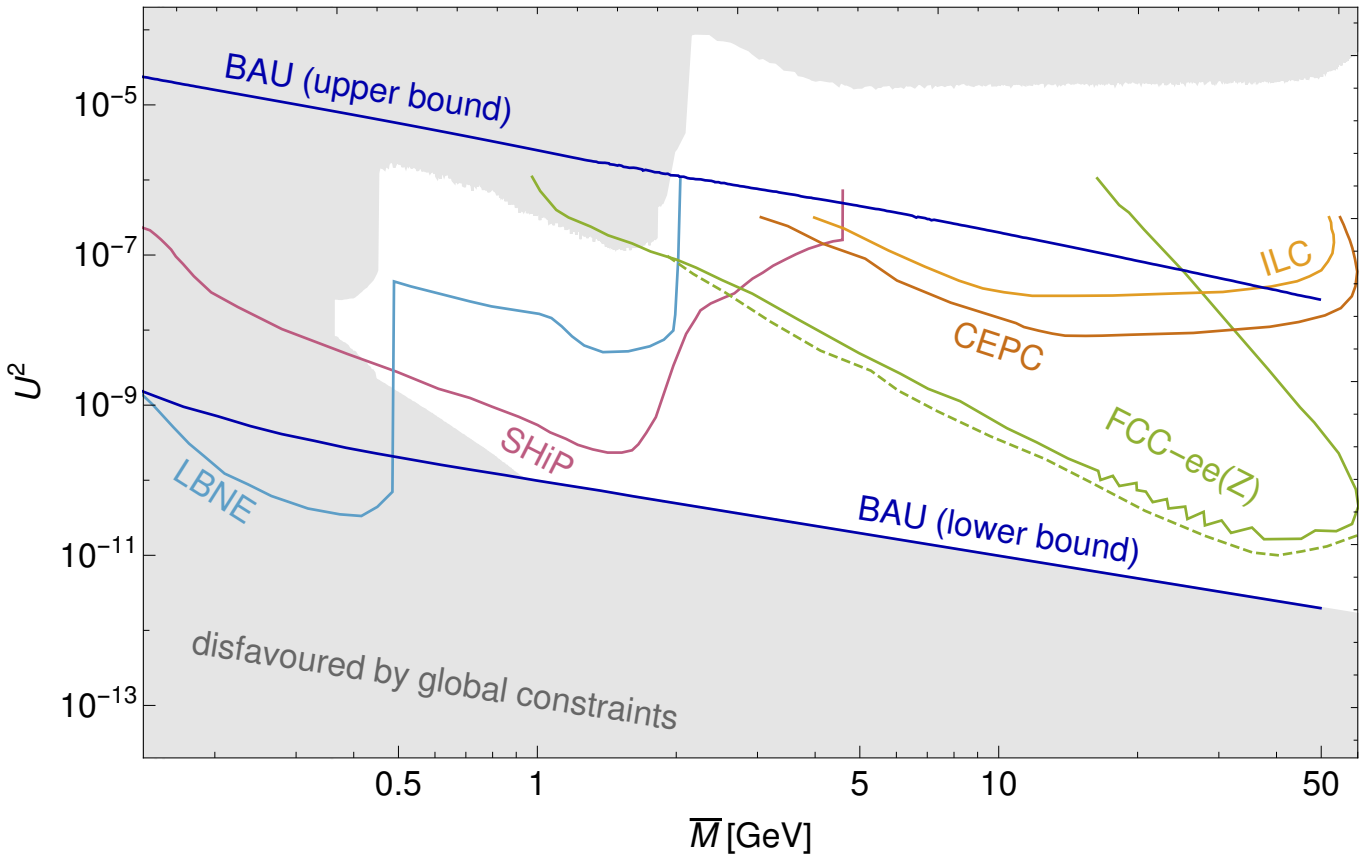
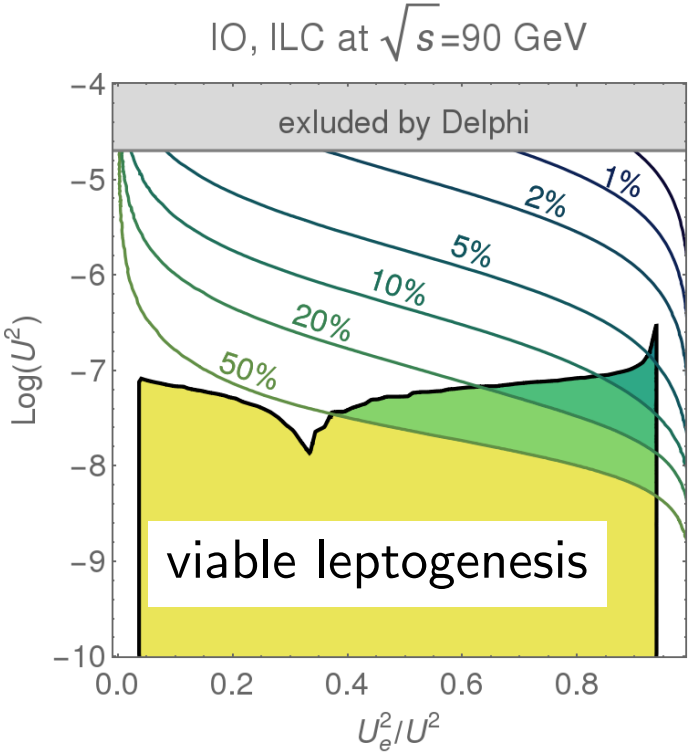


A significant part of the relevant parameter space can be probed!

Next step: Testing leptogenesis at future colliders



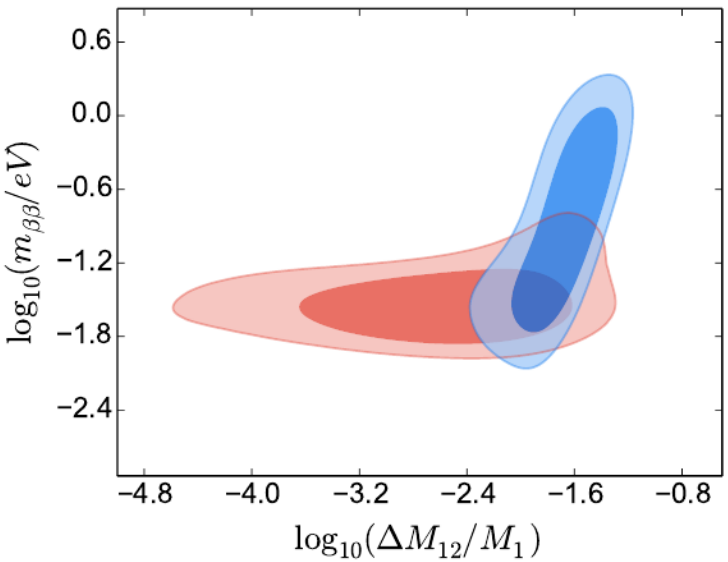
[Antusch, Cazzato, Drewes, Fischer, Garbrecht, Gueter, Klaric '17]

- minimal type-I seesaw
- compare parameter space for neutrino mass generation, leptogenesis and collider searches
- How well can we hope to measure parameters?

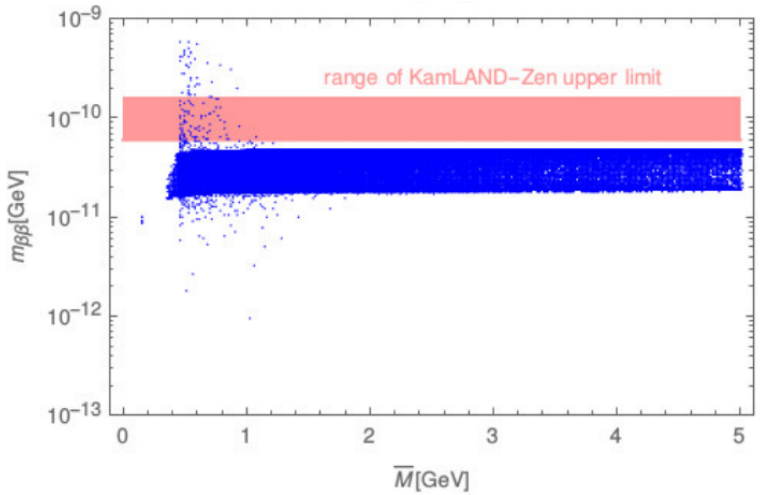
Valuable information contained in multidimensional parameter space

Neutrinoless double beta decay (IH)

[Hernández, Kekic, López-Pavón, Racker, Salvado, '16]



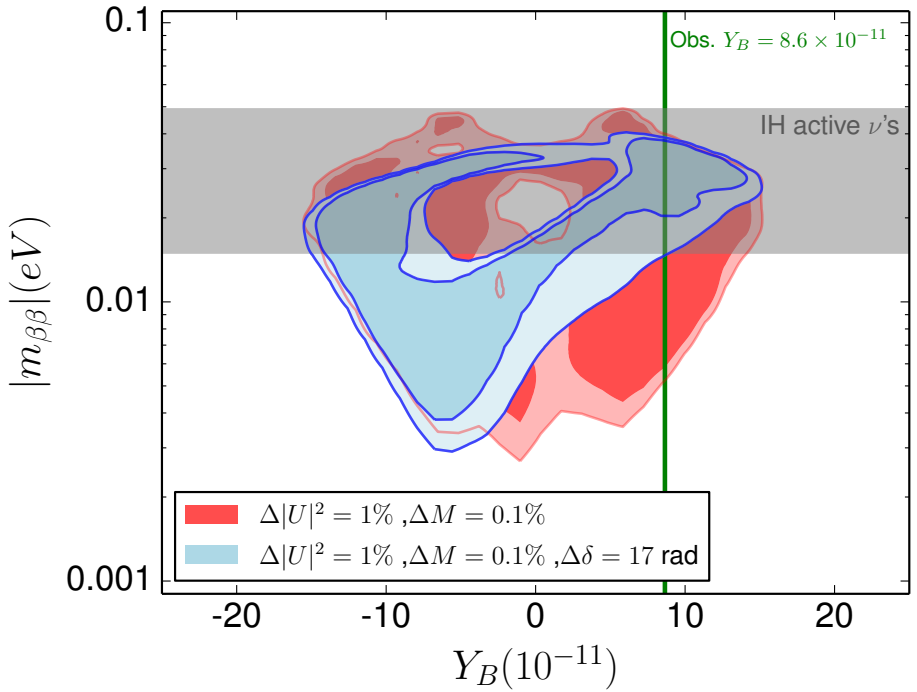
[Drewes, Eijima '16]



enhancement possible, in particular for large mass splitting

Next step: from discovery to testability

[Hernández, Kekic, López-Pavon, Racker, Salvado '16]



- hypothetical measurement of masses and mixings by SHIP (and δ_{CP} by DUNE) for IH parameter point
- correlation in Y_B vs $m_{\beta\beta}$ plane

proof of principle of predictivity

Things I did not discuss

- violation of total lepton number [Hambye, Teresi '16/'17; Eijima, Shaposhnikov '17; Ghiglieri, Laine '17]
- More than two right-handed neutrinos [Drewes, Garbrecht '12]; Hernández, Kekic, López-Pavón, Racker, Rius '15]
- testing CP violation
- many technical improvements in the theoretical computations over the past few years
- dark matter (νMSSM and ISS(2,3))
- ...

Conclusion

- observed matter-antimatter asymmetry requires BSM physics
- leptogenesis through neutrino oscillations provides a testable mechanism
  - oscillations of GeV right-handed neutrinos before EW phase transition
  - nonzero lepton number in the active sector
  - transmitted to baryons through sphaleron processes
- Generic predictions (mass range, sizeable active sterile mixing) but also sensitivity to underlying neutrino mass model
  - symmetry inspired vs minimal tuning
  - strong washout vs weak washout
  - minimal particle content vs minimal parameters
  - individual mixing elements experimentally accessible

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