ULYSSES Tutorial

YETI 2024 - The 3 Neutrino Problem

Durham, 31st of July 2024

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1. Navigate to the tutorial on the Jupyter notebook: https://yeti-2425.notebooks.danielmaitre.phyip3.dur.ac.uk/ enter username & password

2. Click on the ipynb file!

3. Run notebook as it is

4. Play around with widgets and write some code (if you like!)

5. ULYSSES manual may be useful: https://arxiv.org/abs/2007.09150

The aim of this tutorial is to give you an idea of what ULYSSES is all about. No matter how complicated baryogenesis mechanisms are they always boil down to the same thing: solve a Boltzmann Eq for a given theory input parameter, see if you can match the observed baryon asymmetry!

ULYSSES has different “models” of Boltzmann equations.
1BE1F = track decays & washout of lightest RHN in one flavour regime
1BE3F = track decays & washout of lightest RHN in three flavour regime
2RES = track decays & washout of N1 and N2 in resonant regime $\Delta M \ll \Gamma_N$
3DME = track decays, washout and oscillations of 3RHNs using the density matrix formalism

Define models we will explore and default values for Casas-Ibarra parameters we will be exploring

In [19]:
```
#  provide shorthand names for the BE "models"

#  1BE1F = 1RHN is decaying anf BE are in the one flavour regime
#  2BE2F = 1RHN is decaying anf BE are in the two flavour regime
#  2RES  = 2 RHN neutrinos in the resonant regime etc
d_model = widgets.Dropdown(
    options=['1BE1F','1BE2F','1BE3F', '2BE2F','2BE3F','1DME','2DME','3DME','2RES'],
    value='1BE1F',
    description='Model:',
)
```

Now we have a model, we can define some input parameters from the Casas-Ibarra parametrisation. We will fix some of them and allow others to vary

Parameter	Unit	Code input example	
δ	[°]	delta	270
α_{21}	[°]	a21	0
α_{31}	[°]	a31	0
θ_{23}	[°]	t23	48.7
θ_{12}	[°]	t12	33.63
θ_{13}	[°]	t13	8.52
x_1	[°]	x1	45
y_1	[°]	y1	45
x	[°]	x2	45
y_2	[°]	y2	45
x	[°]	x3	45
y_3	[°]	y3	45
$\log_{10}(m_{1/3})$	[eV]	m	-0.606206
$\log_{10}(M_1)$	[GeV]	M1	11
$\log_{10}(M_2)$	[GeV]	M2	12
$\log_{10}(M_3)$	[GeV]	M3	15

```
]: def on_value_change(change):
       # Create a StringIO buffer to capture print statements
       f = io.StringIO()
       with contextlib.redirect_stdout(f):
           L = uls.selectModel(d_model.value)
           p = {'m': s_m.value, 'M1': 14, 'M2': 15, 'M3': 16, 'x1': s_x1.value, 'y1': s_y1.value, 'x2': s_x2.value, 'y2
```

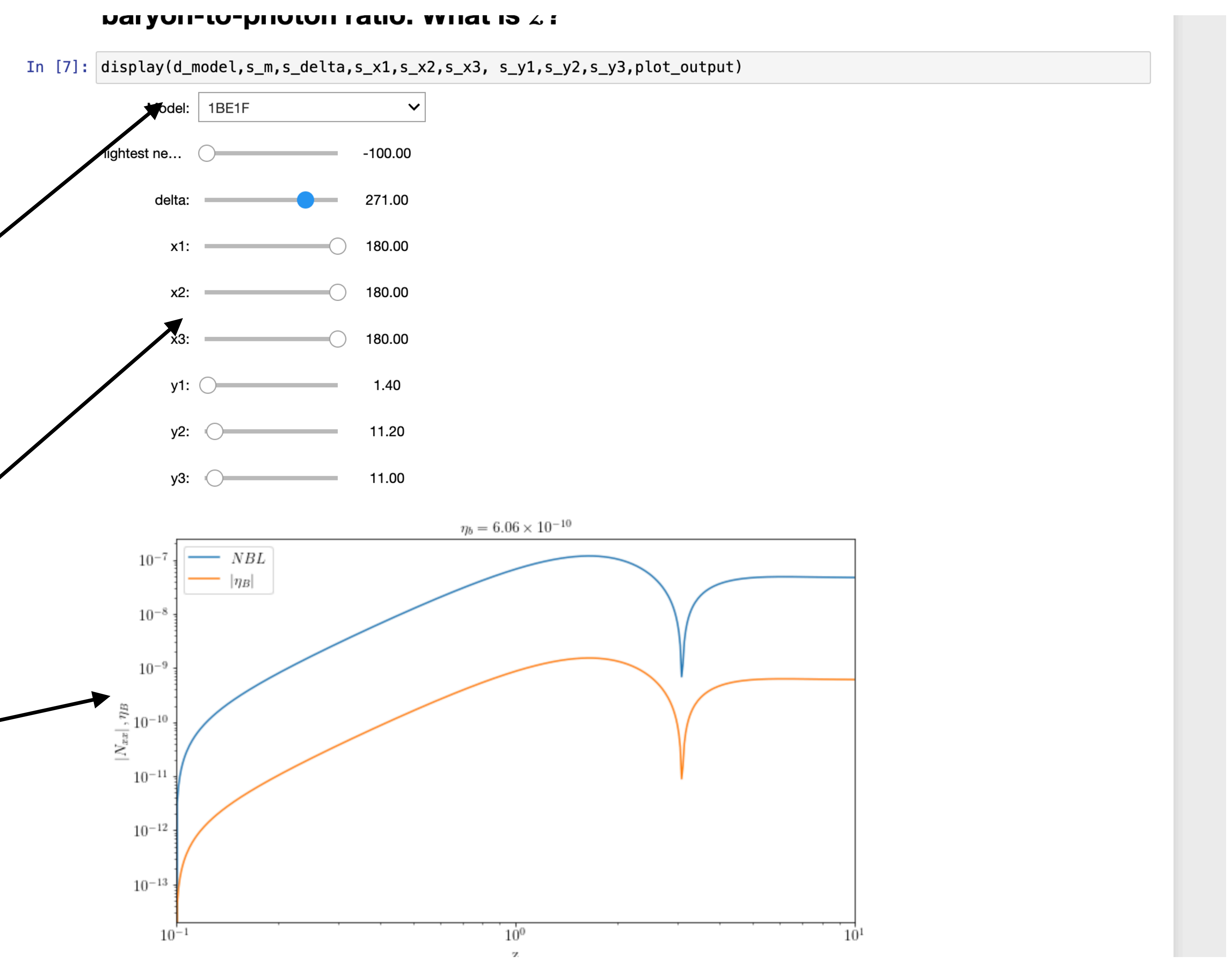
Lightest RHN mass

$M_1 = 10^{14}$ GeV

Second lightest RHN mass

$M_1 = 10^{15}$ GeV

We will vary the remainder for different models



Select a model

Vary input parameters

Look at how solution changes

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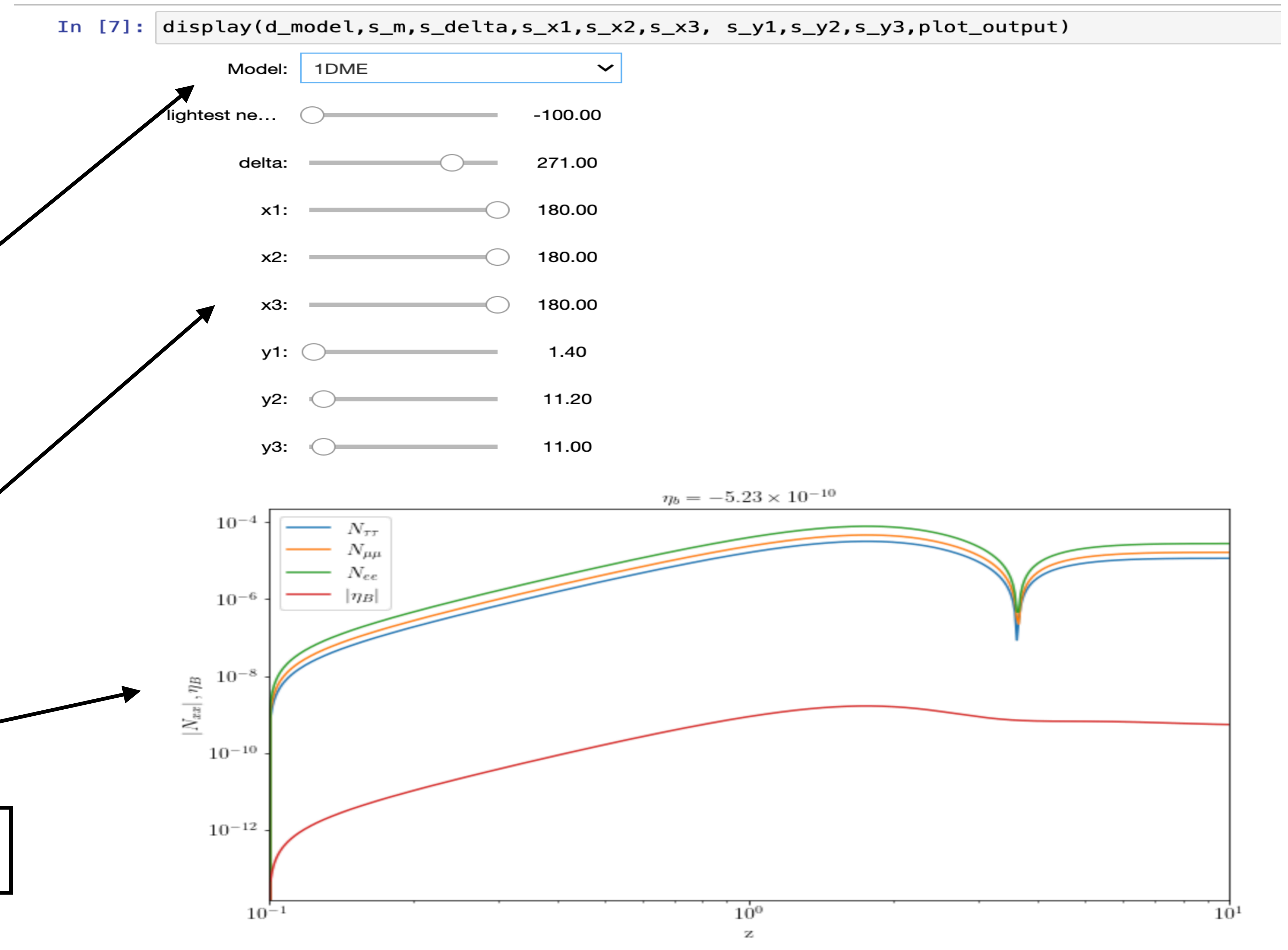


Select a model

Vary input parameters

Look at how solution changes

Try different models and varying the input parameters

Note that the inputs for angles are in 1 degree increments and for the lightest active neutrino mass m1 in 0.1 (of the appropriate units) so changing the widgets by large amounts might take some time: the solution to the BEs (which can be complicated for example 3DME) needs to be recalculated. So the final plot might take some time to “settle down”

Task 1: Explore what happens when you change the parameters on the toggles.

Task 2: Change the model from 1BE1F to 1DME, what is being plotted, what is the difference?

Task 3: Change the masses of the right-handed neutrinos, what happens as you make the masses more degenerate with each other?

Task 4: Make all the complex phases equal to 0. What happens to the lepton asymmetry? Explain

Task 5 & 6

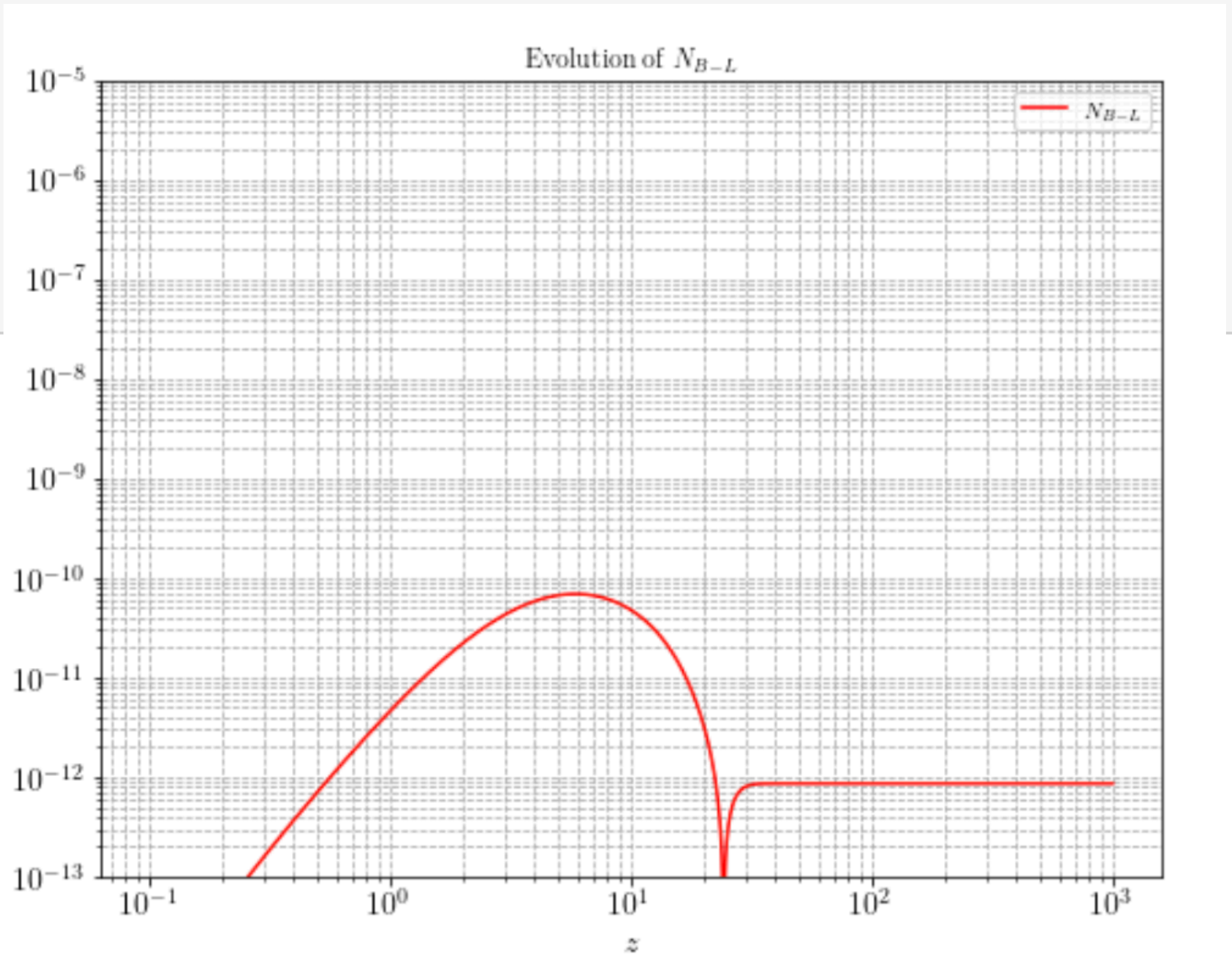
Here we have the Boltzmann equation for 1BE1F, simplest BE around.

Here is a point in the Casas-Ibarra Parameter space.

```
In [18]: # set up a point in the model parameter space i.e. the inputs for the Casas Ibarra
p = {
    'm': -100,
    'M1': 12,
    'M2': 13,
    'M3': 15,
    'x1': 180,
    'y1': 1.0,
    'x2': 180,
    'y2': 1,
    'x3': 180,
    'y3': 1,
    'delta': 270,
    'a21': 0,
    'a31': 0,
    't23': 49.7,
    't12': 33.82,
    't13': 8.61
}
```

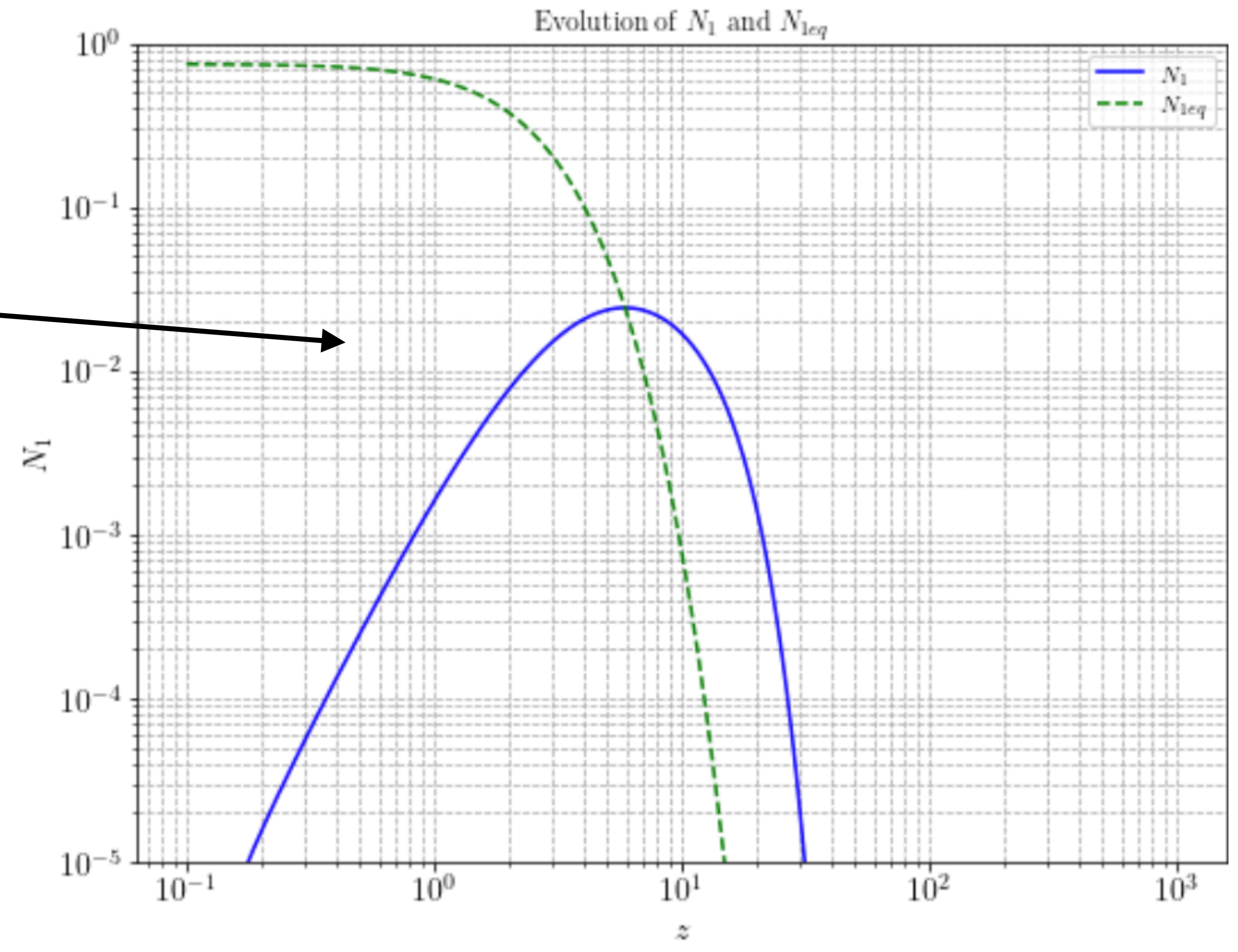
Understand how the ODE is solved and how the solutions are stored

I have plotted the lepton asymmetry (N_{B-L}) number density in red.



Is this for weak or strong washout?
What is the value of etaB?

Can you plot the number density of N1 on the same plot as the N1 equilibrium number ?



How does the behaviour of N1(z) change for strong and weak washout?
Change the point above and see if you can achieve strong washout.

Explain the difference between strong and weak washout

Task 7 (optional)

Next task is to pick a model, say 1BE2F (1RHN decaying in the two flavour regime) and **fix all but one** Casas-Ibarra Parameter fixed

For example this point “p” all parameters fixed apart from δ

Now call this model and allow delta to vary!

Plot $\eta_B \times 10^{10}$ as a function of δ

```python
# Define the fixed parameters with a21 = 180 and a31 = 0
p = {
    'm': 1.69897,
    'M1': 12.4502,
    'M2': 12.9,
    'M3': 13.4997,
    'x1': 90,
    'y1': 10,
    'x2': 18,
    'y2': 0,
    'x3': 180,
    'y3': 3,
    'delta': 0,  # This will be varied
    'a21': 180,
    'a31': 0,
    't23': 49.7,
    't12': 33.82,
    't13': 8.61
}
```