University of Hawaii, Honolulu
6 September 2018

Climbing the particle physics and cosmological energy ladder with neutrinos

Pasquale Di Bari

(University of Southampton)

Plan

$\sim 10^{16}$ GeV — grand-unified models and leptogenesis

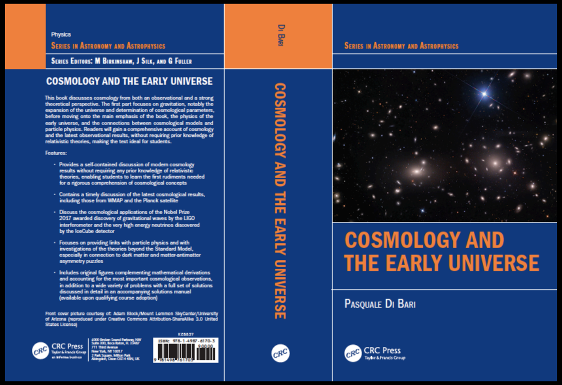
10^{2-13} GeV — matter-antimatter asymmetry (leptogenesis)

keV-PeV — right-handed neutrinos as dark matter and lab searc

meV-MeV — probing neutrino physics with standard cosmology

μeV — probing neutrino decays with 21 cm cosmology

Introduction: cosmology and the early universe, updates from *Planck* 2018

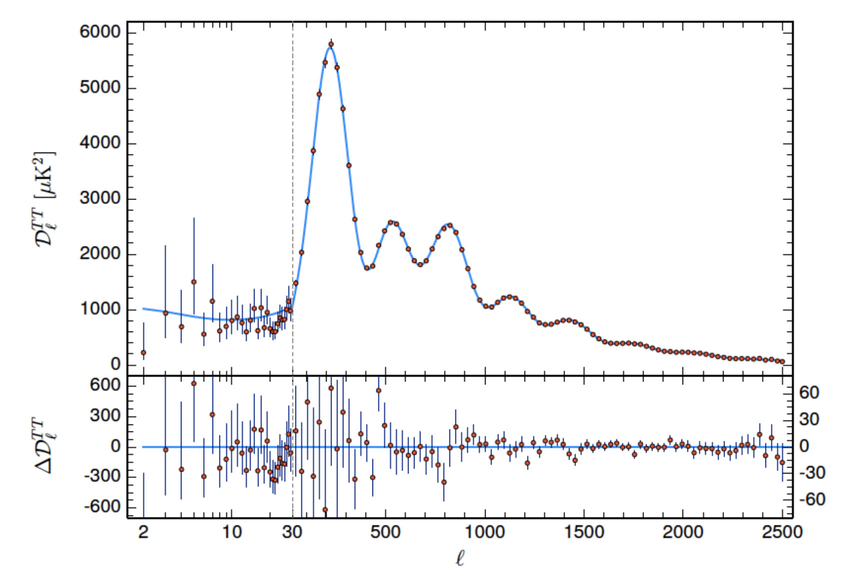


Cosmology and the early universe

ΛCDM model

It is a minimal flat cosmological model with only 6 parameters: baryon and cold dark matter abundances, angular size of sound horizon at recombination, reionization optical depth, amplitude and spectral index of primordial perturbations.

ΛCDM best fit to the *Planck* 2018 data (TT+TE+EE+low E+lensing)



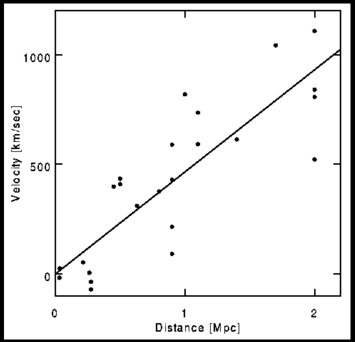
Parameter	TT,TE,EE+lowE+lensing 68% limits	TT,TE,EE+lowE+lensing+BAO 68% limits
$\Omega_b h^2$	0.02237 ± 0.00015	0.02242 ± 0.00014
$\Omega_c h^2$	0.1200 ± 0.0012	0.11933 ± 0.00091
$100\theta_{MC}$	1.04092 ± 0.00031	1.04101 ± 0.00029
τ	0.0544 ± 0.0073	0.0561 ± 0.0071
$\ln(10^{10}A_s)$	3.044 ± 0.014	3.047 ± 0.014
n_s	0.9649 ± 0.0042	0.9665 ± 0.0038

(Planck 2018 results, 1807.06209)

The *Planck* results are also in good agreement with BAO, SNe and galaxy lensing observations. The only significant (3.6σ) tension is with local measurement of the Hubble constant

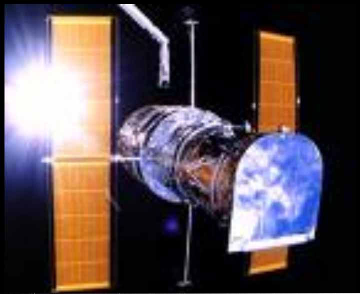
Hubble constant measurements

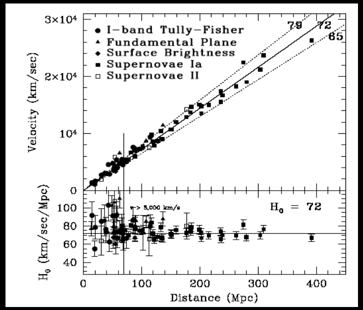
Edwin Hubble (1929)



$$H_0 \sim 500\, km\ s^{-1} Mpc^{-1}$$

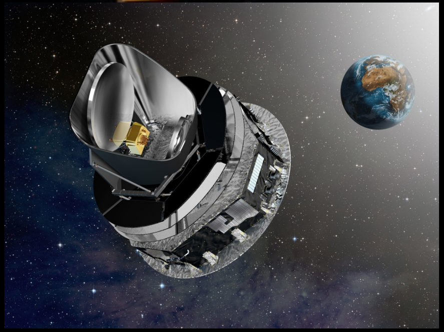
Hubble Space Telescope Key Project (2001)

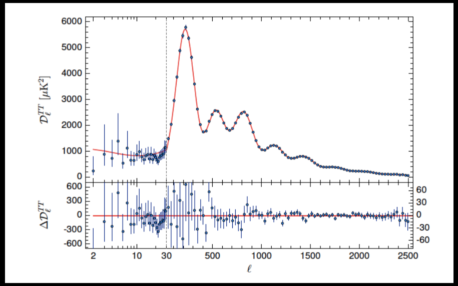




$$H_0 = (72 \pm 8)\, km\ s^{-1} Mpc^{-1}$$

Planck 2018 (ΛCDM)

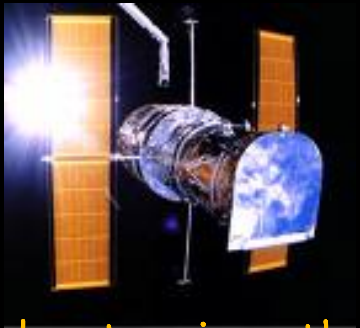




$$H_0 = (67.4 \pm 0.5)\, km\ s^{-1} Mpc^{-1}$$

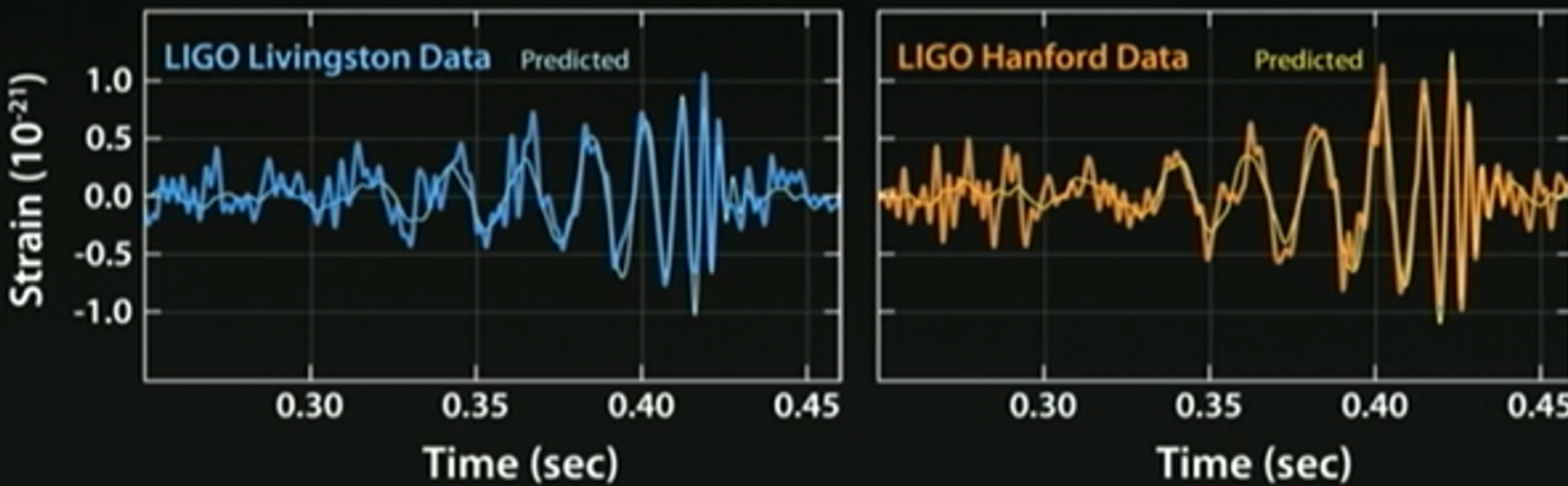
3.6σ tension

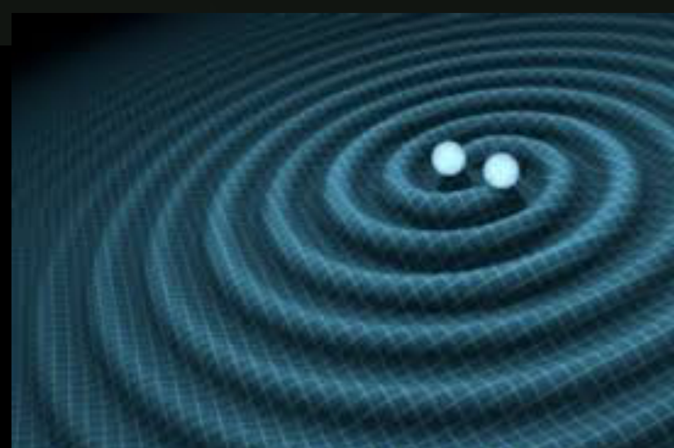
Hubble Space Telescope , Riess et al. (2018)



$$H_0 = (73.48 \pm 1.66)\, \mathrm{km\, s^{-1}\, Mpc^{-1}}$$

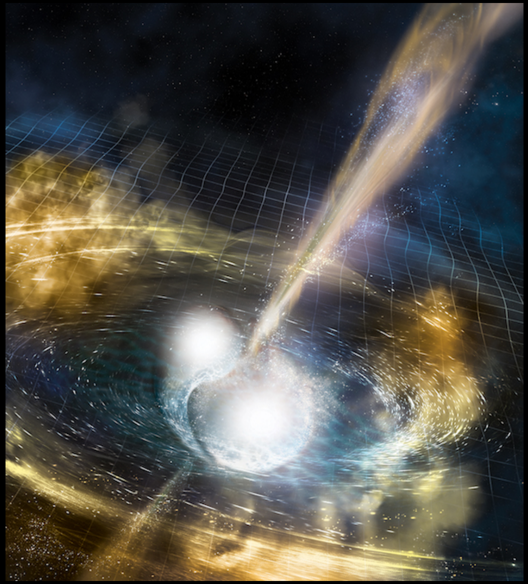
Simple model extensions that can solve the tension are not favoured by *Planck* data


LIGO Livingston Data
Predicted
LIGO Hanford Data
Predicted
Strain (10⁻²¹)
1.0
0.5
0.0
-0.5
-1.0
0.30
0.35
0.40
0.45
Time (sec)
0.30
0.35
0.40
0.45
Time (sec)



GW170817: The first observation of gravitational waves from from a binary neutron star inspiral

(almost) coincident detection of GW's and light: one can measure distance from GW's "sound" and redshift from light: STANDARD SIREN!



A GRAVITATIONAL-WAVE STANDARD SIREN MEASUREMENT OF THE HUBBLE CONSTANT

THE LIGO SCIENTIFIC COLLABORATION AND THE VIRGO COLLABORATION, THE 1M2H COLLABORATION, THE DARK ENERGY CAMERA GW-EM COLLABORATION AND THE DES COLLABORATION, THE DLT40 COLLABORATION, THE LAS CUMBRES OBSERVATORY COLLABORATION, THE VINROUGE COLLABORATION, THE MASTER COLLABORATION, et al.

arXiv:1710.05835

$$H_0 = 70^{+12}_{-8}\ km\ s^{-1}\ Mpc^{-1}$$

~100 more detections of standard sirens should reduce the error below 1 km s^{-1} Mpc^{-1} and solve the current tension between Planck and HST measurements

Lemaitre models

Admixture of 3 fluids: matter (M) + radiation (R) + Λ-like fluid (Λ) :

$$p = p_M + p_R + p_\Lambda, \quad \varepsilon = \varepsilon_M + \varepsilon_R + \varepsilon_\Lambda$$

with equations of state: $p_M = 0,\ p_R = \frac{1}{3}\varepsilon_R,\ p_\Lambda = -\varepsilon_\Lambda$

from the fluid equation: $\varepsilon_M = \frac{\varepsilon_{M,0}}{a^3},\ \varepsilon_R = \frac{\varepsilon_{R,0}}{a^4},\ \varepsilon_\Lambda = \varepsilon_{\Lambda,0}$

density parameters: $\Omega_0 = \frac{\varepsilon_0}{\varepsilon_{c0}},\ \Omega_{X,0} = \frac{\varepsilon_{X,0}}{\varepsilon_{c0}} \quad (X = M, R, \Lambda)$

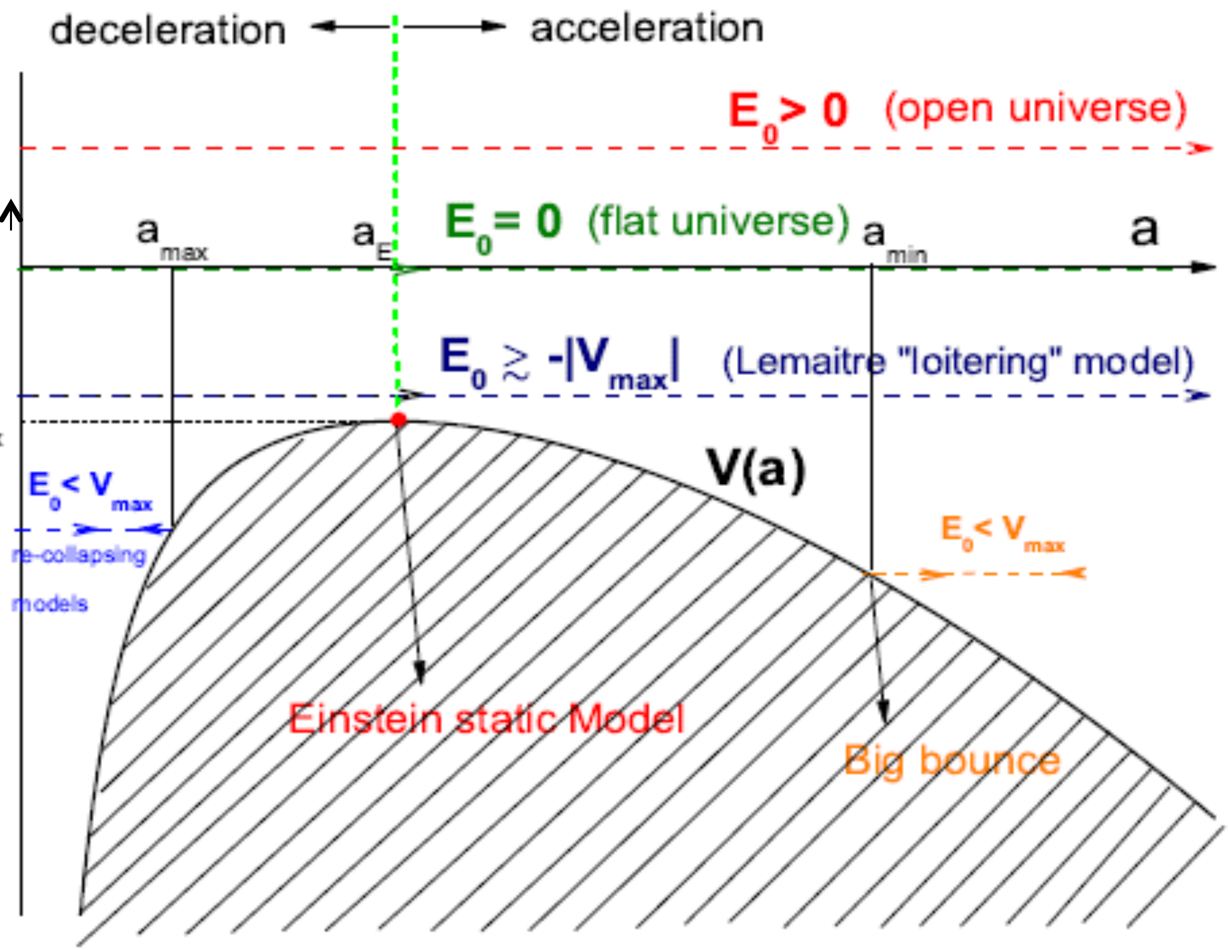
Friedmann equation

$$\left(\frac{\dot{a}}{a}\right)^2 \equiv H^2 = \frac{8\pi G}{3}\varepsilon + \frac{H_0^2(1-\Omega_0)}{a^2} \Leftrightarrow \frac{\dot{a}^2}{H_0^2} + V(a) = 1 - \Omega_0 \equiv \Omega_{k0}$$

$$\Rightarrow V(a) \equiv -\frac{8\pi G}{3}\varepsilon a^2 = -a^2\left(\frac{\Omega_{R,0}}{a^4} + \frac{\Omega_{M,0}}{a^3} + \Omega_{\Lambda,0}\right)$$

effective potential

Classification of Lemaitre models

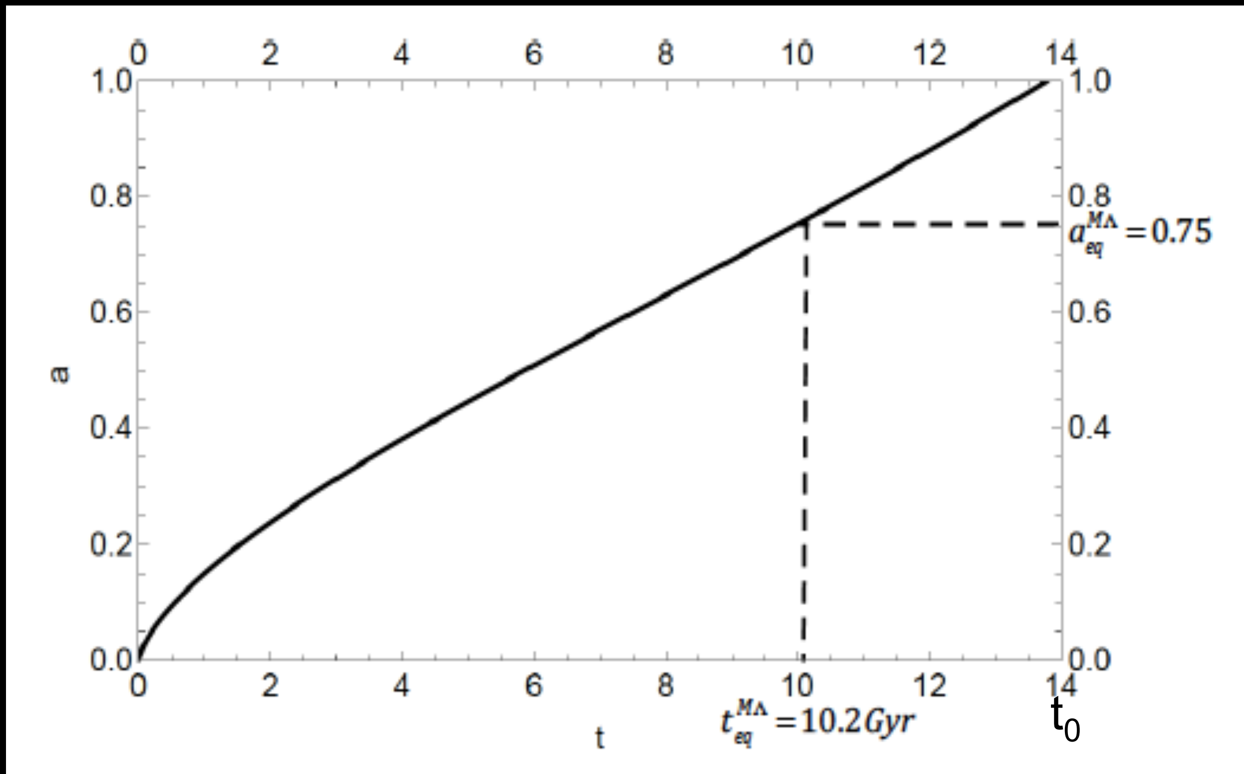


$$E(a) \equiv \frac{\dot{a}^2}{H_0^2} + V(a) = E_0$$

From Planck 2018 (68% CL,TT,TE,EE+lowE+lensing+BAO):

$$\Omega_{k0} = 0.0007 \pm 0.0019, \quad \Omega_{M0} = 0.3111 \pm 0.0056, \quad \Omega_{\Lambda 0} = 0.6889 \pm 0.0056$$

Expansion in the ΛCDM model



$$\Omega_{\Lambda 0} = 0.69$$

$$\Omega_{M0} = 0.31$$

$$H_0^{-1} = 14.4Gyr$$

$$t_0 = \frac{2H_0^{-1}}{3\sqrt{\Omega_{\Lambda 0}}} \ln\left[\frac{1+\sqrt{\Omega_{\Lambda 0}}}{\sqrt{1-\Omega_{\Lambda 0}}}\right] \simeq 13.8Gyr$$

Plan

- ~10^{16} GeV — grand-unified models and leptogenesis
- $10^{2\text{-}13}$ GeV — matter-antimatter asymmetry (leptogenesis)
- keV-PeV — right-handed neutrinos as dark matter (and at colli
- meV-MeV — probing neutrino physics with standard cosmology
- μeV — probing neutrino decays with 21 cm cosmology

Introduction: cosmology and the early universe, updates from *Planck* 2018

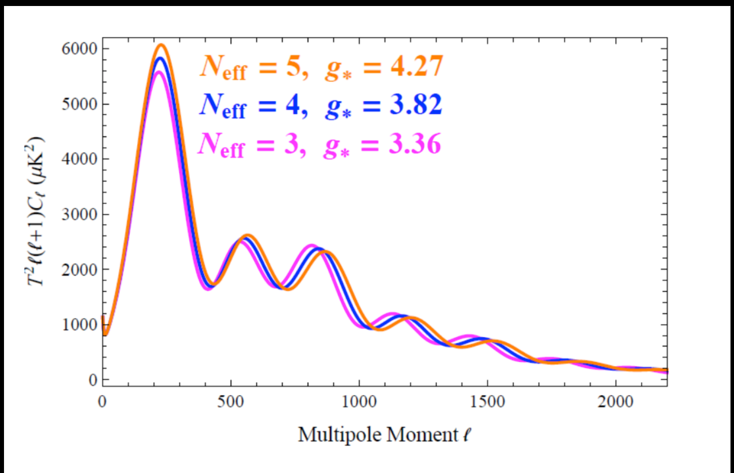
Effective number of neutrinos at recombination

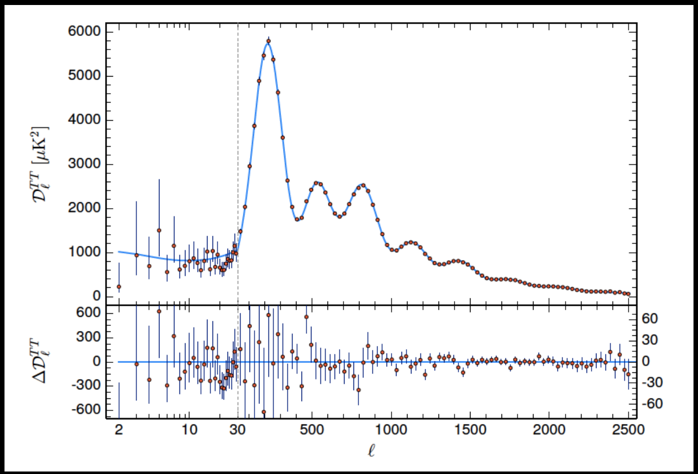
$$\Omega_{R0} = \Omega_{\gamma 0} + \Omega_{\nu 0} = g_{R0} \frac{\pi^2}{30} \frac{T_0^4}{\varepsilon_{c0}} \simeq 0.27 g_{R0} \times 10^{-4}$$

Number of u.r. degrees of freedom

$$g_{R0} = 2 + N_\nu^{rec} \frac{7}{4} \left(\frac{T_{\nu 0}}{T_0} \right)^4 \simeq 3.36 + \frac{7}{4} (N_\nu^{rec} - 3) \left(\frac{T_{\nu 0}}{T_0} \right)^4$$

Effective number of neutrino species at recombination





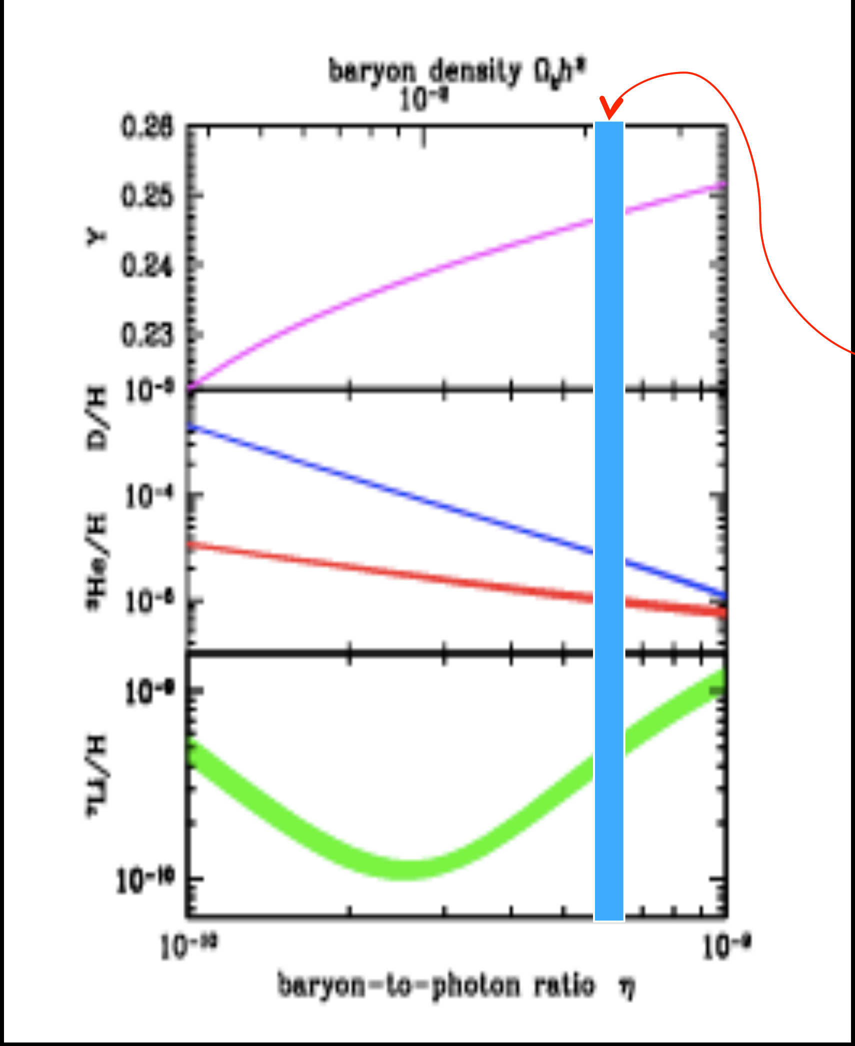
(Planck 2018, 1807.06209)

TT+TE+EE+lensing+BAO → $N_\nu^{rec} = 2.99^{+0.34}_{-0.33}$ (95% C.L.)

This proves the presence of neutrinos at recombination and also places a stringent upper bound on the amount of dark radiation ⇒ strong constraints on BSM models (more precisely the SM expectation is $N_\nu^{rec} = 3.04$)

Big Bang nucleosynthesis+CMB

(PDB hep-ph/0108182)



(Cyburt, Field, Olive, Yeh 1505.01076)

$$\eta_{B0} \simeq 273.5\,\Omega_{B0} h^2 \times 10^{-10}$$

$$\Rightarrow \eta_{B0}^{(CMB)} = (6.08 \pm 0.06) \times 10^{-10}$$

Using this measurement of η_{B0} from CMB from ^{4}He abundance (Y) one finds:

$$N_\nu(t_f = 1s) = 2.9 \pm 0.2$$

And from Deuterium abundance:

$$N_\nu(t_{nuc} \simeq 300s) = 2.8 \pm 0.3$$

This shows that $T_{RH} \gg T_\nu^{dec} \sim 1$ MeV and again NO EXTRA RADIATION

Active-sterile neutrino mixing in the early universe

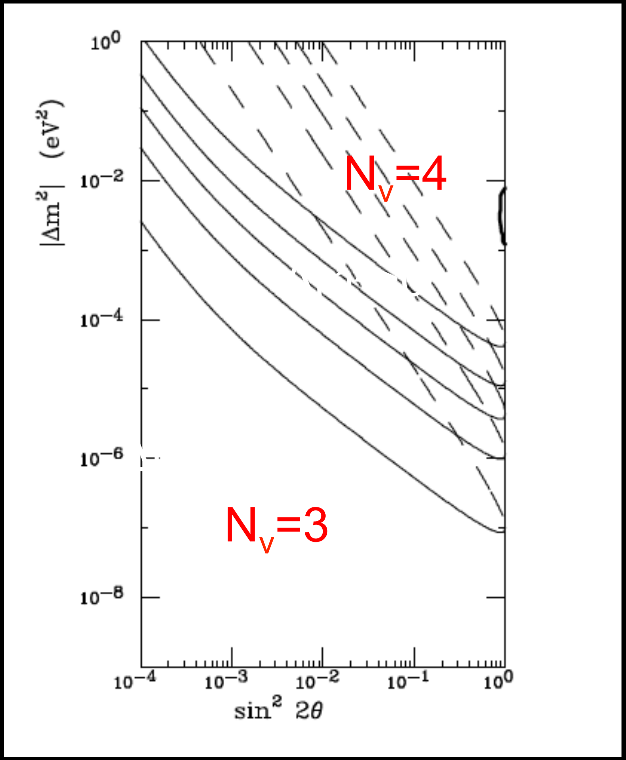
(Barbieri,Dolgov '90; Enqvist, Kainulainen, Maalampi '90; Cline '92; PDB, Lipari, Lusignoli '98; PDB 2001)

In vacuum (i=1,2,3):

$$\Delta m^2 = m_4^2 - m_i^2$$

$$|\nu_\alpha\rangle = \cos\theta_{i4}\,|\nu_i\rangle + \sin\theta_{i4}\,|\nu_4\rangle$$

$$|\nu_s\rangle = \cos\theta_{i4}\,|\nu_4\rangle - \sin\theta_{i4}\,|\nu_i\rangle$$



Medium effects :

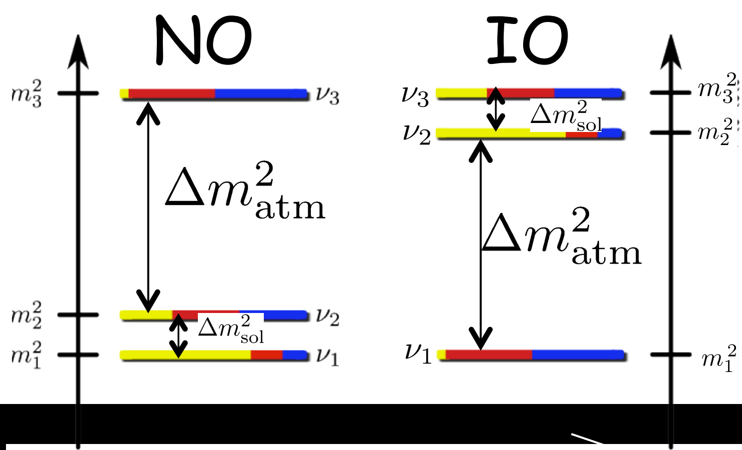
$$\sin^2 2\theta^m_{4i} = \frac{\sin^2_{4i}}{\sin^2_{4i} + (\cos^2_{4i} - v_\alpha + v_s)^2}$$

$$v_{\alpha,s} = \frac{2p}{\Delta m^2_{4i}} V_{\alpha,s}$$

effective potentials

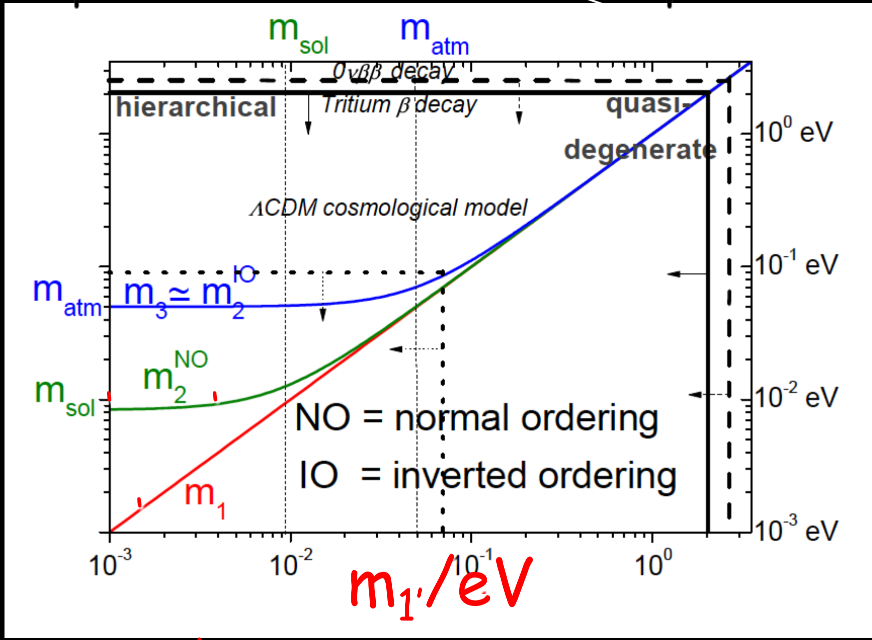
Solution to short-baseline neutrino anomalies (e.g. LSND and MiniBoone) always corresponds to the region where the sterile neutrino gets fully thermalised with some caveats: large initial lepton asymmetry sterile neutrino self-interactions, low reheat temperature, etc. etc.

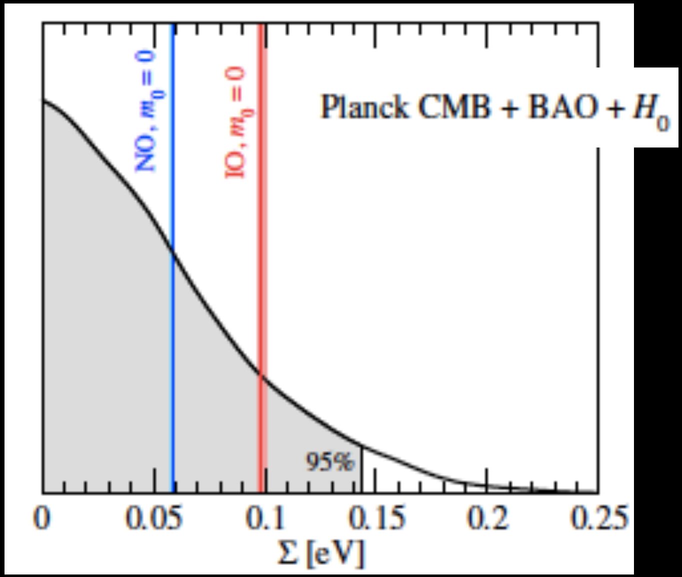
Neutrino masses: $m_{1'} < m_{2'} < m_{3'}$



$$m_{atm} \equiv \sqrt{\Delta m^2_{atm} + \Delta m^2_{sol}} \simeq 0.05\,\text{eV}$$

$$m_{sol} \equiv \sqrt{\Delta m^2_{sol}} \simeq 0.009\,\text{eV}$$





(Hannestad,Schwetz,1606.04691)

$Planck2015 \Rightarrow \Sigma_i m_i \leq 0.23\text{ eV} \Rightarrow m_{1'}^{NO(IO)} \leq 0.071\ (0.066)\text{ eV}$

$\Sigma_i m_i \leq 0.14\text{ eV} \Rightarrow m_{1'}^{NO(IO)} \leq 0.038\ (0.027)\text{ eV}$

Any cosmological role for neutrino masses?

- Neutrinos do not seem to play any role in structure formation,
- In fact neutrino masses are even detrimental contributing to unwanted hot dark matter and for this reason from cosmology (combining CMB + BAO) one obtains an upper bound on the sum of neutrino masses:

But we know that neutrino are massive from neutrino mixing experiments:

$$0.06 \text{ eV} \le \sum_i m_i \le 0.23 \text{ eV} \quad (95\% \, C.L.)$$

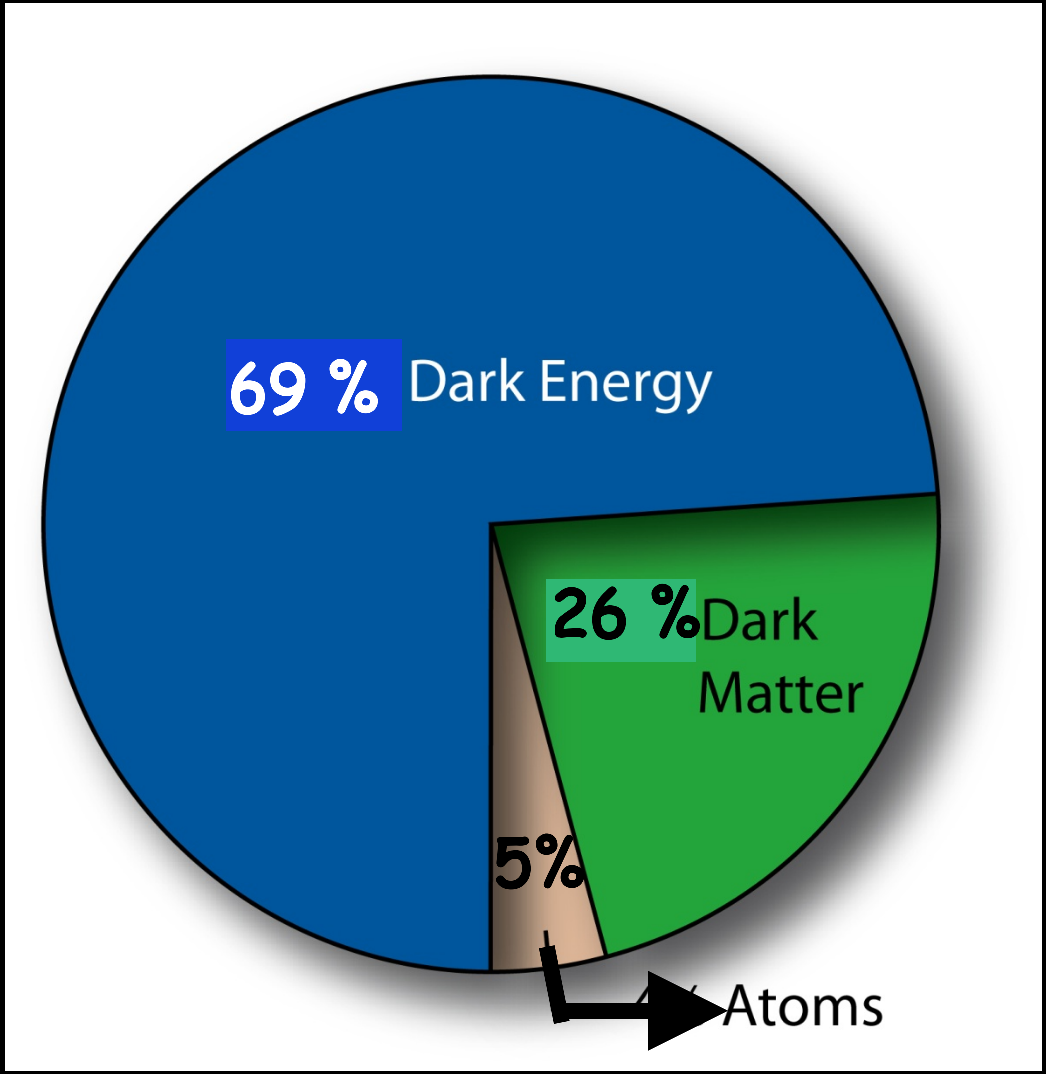
The window is narrowing: fascinating test in next years!

$$\Omega_{stars,0}/3 \le \Omega_{\nu 0} \simeq \frac{\sum_i m_i}{45 \, eV} \le \Omega_{stars,0} \simeq 0.004$$

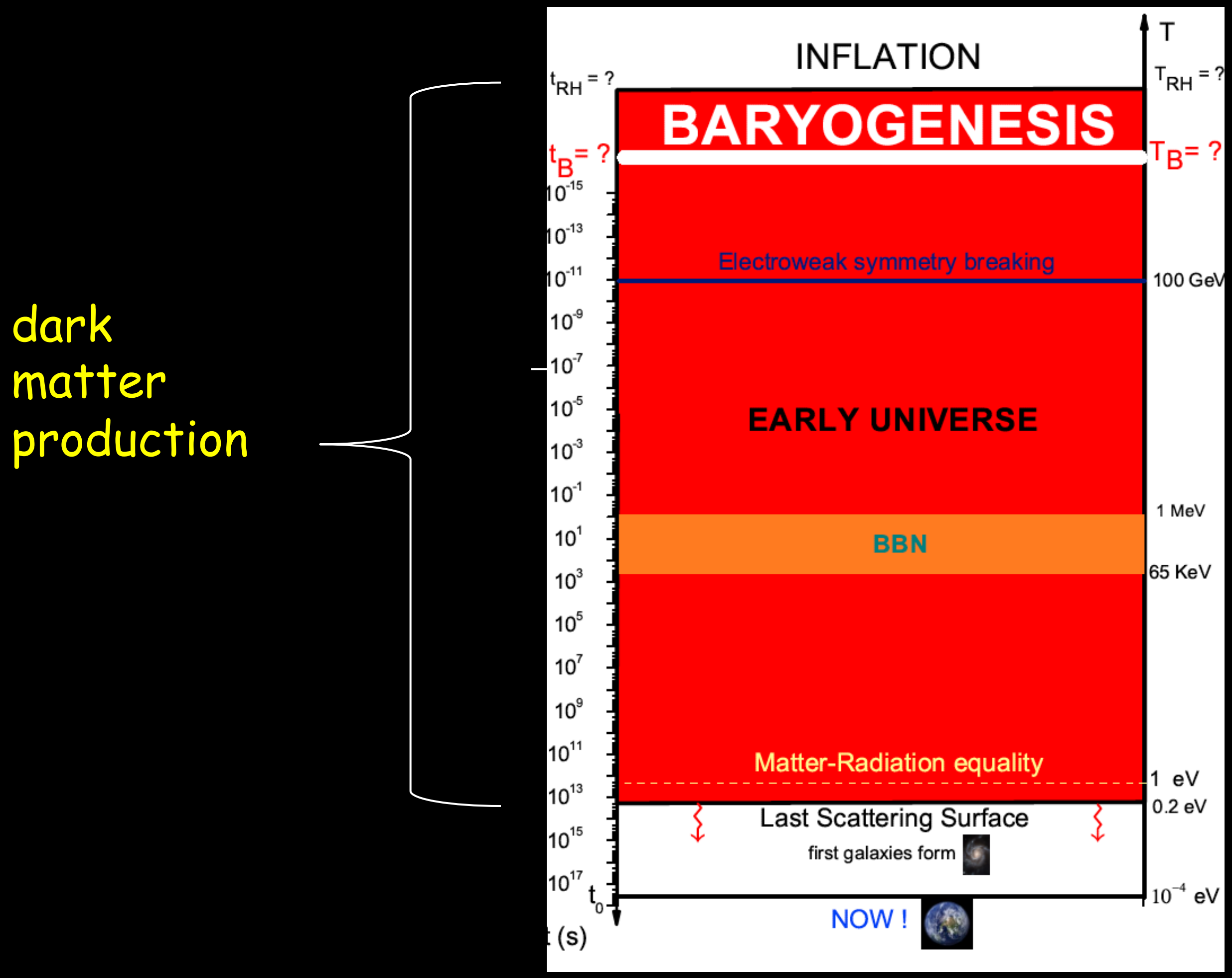
Neutrino masses contribution to matter today is comparable to that of stars !

We will see however that neutrino masses might have played an even more important cosmological role than structure formation: origin of matter itself

Matter-energy budget at present



Cosmological puzzles



It is reasonable to think that the same extension of the SM necessary to explain neutrino masses and mixing might also address the cosmological puzzles:

- Leptogenesis,
- RH neutrino as Dark matter

Plan

- $\sim 10^{16}$ GeV — grand-unified models and leptogenesis
- 10^{2-13} GeV — matter-antimatter asymmetry (leptogenesis)
- keV-PeV — right-handed neutrinos as dark matter (and at colli
- meV-MeV — probing neutrino physics with standard cosmology
- μeV — probing neutrino decays with 21 cm cosmology

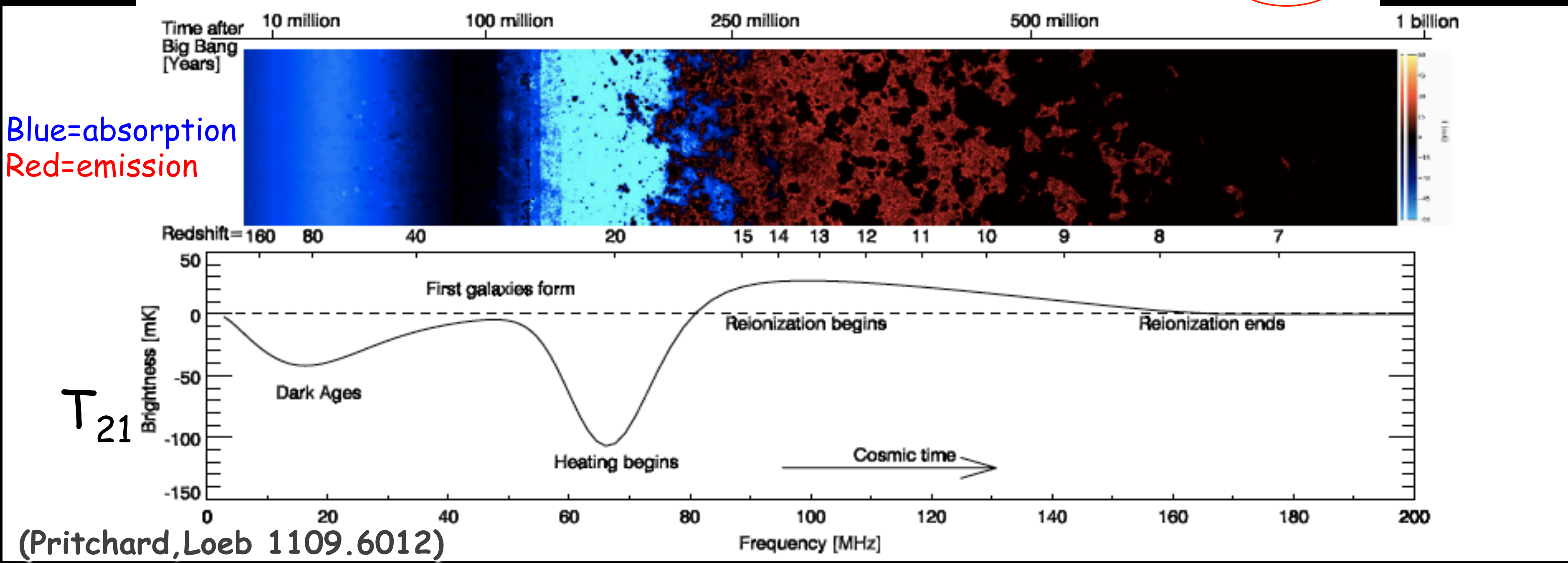
Introduction: cosmology and the early universe, updates from *Planck* 2018

21 cm cosmology (global signal)

- 21 cm line (emission or absorption) is produced by hyperfine transitions between the two energy levels of 1s ground state of Hydrogen atoms. The energy splitting between the two level is $E_{21}=5.87\times\mu eV$
- It is a powerful investigative astrophysical tool allowing to map Hydrogen gas intervening between a source and the observer. In the case of the global cosmological signal the source is the primordial radiation itself interacting with Hydrogen gas at all redshifts below $z_{rec}\simeq 1100$.
- The 21cm brightness temperature parametrises the brightness contrast :

$$T_{21}(z) \simeq 23\,\mathrm{mK}\,(1+\delta_B)\,x_{H_I}(z)\left(\frac{\Omega_B h^2}{0.02}\right)\left[\left(\frac{0.15}{\Omega_m h^2}\right)\left(\frac{1+z}{10}\right)\right]^{1/2}\left[1-\frac{T_\gamma(z)}{T_S(z)}\right],$$

spin temperature

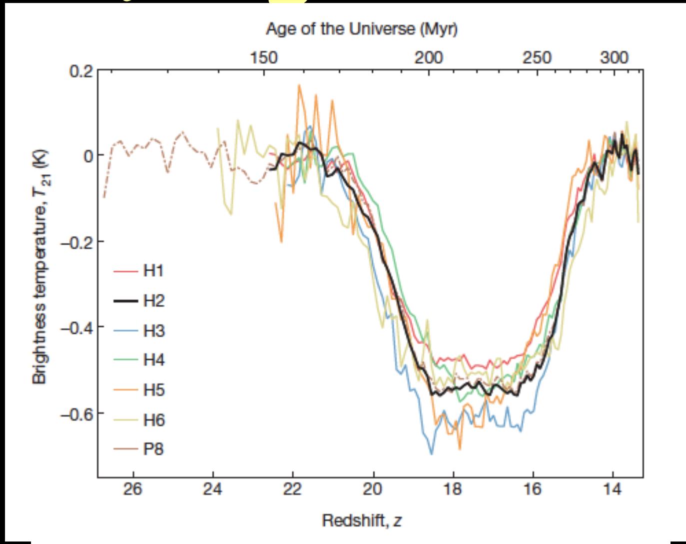


(Pritchard, Loeb 1109.6012)

EDGES (anomalous) signal

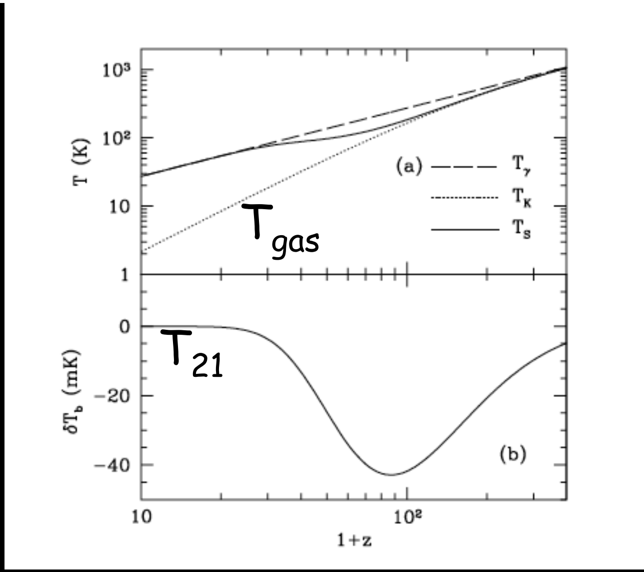
Bowman et al., Nature 555 (2018) 7694, 67-70

- EDGES measured a 21 cm (global) signal at a frequency ~ 70MHz corresponding to a redshift $z_E \simeq 17.2$
- It finds an absorption signal that is double compared to the expected one in a cosmological standard model.



The spin temperature is related to the gas temperature:

$$\left(1 - \frac{T_\gamma}{T_S}\right) \simeq \frac{x_c + x_\alpha}{1 + x_c + x_\alpha}\left(1 - \frac{T_\gamma}{T_{\rm gas}}\right)$$

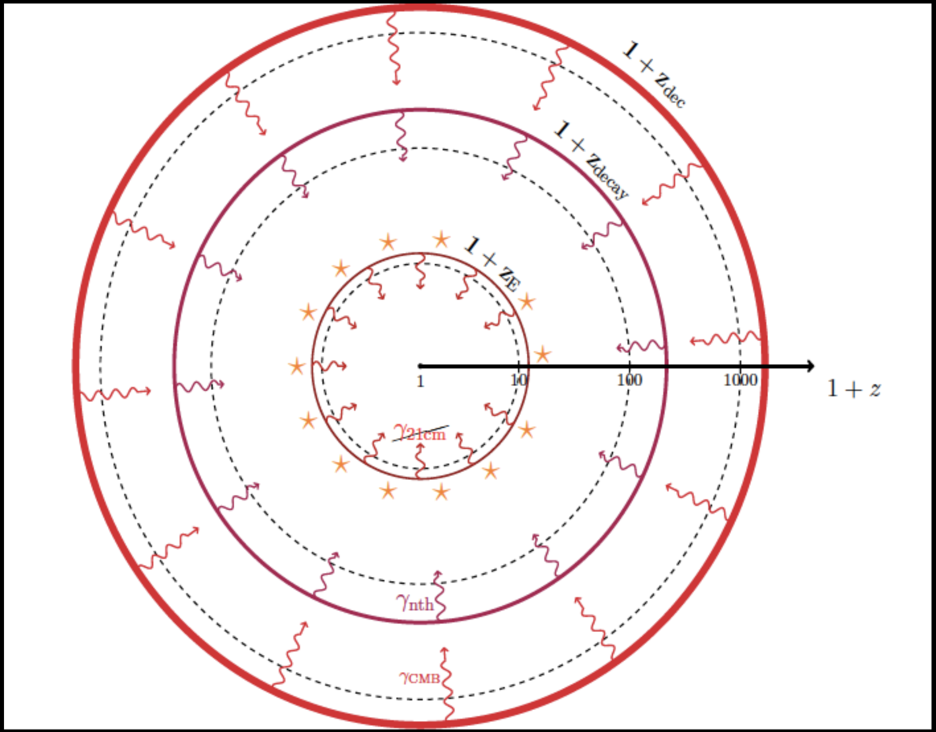


A doubled signal can be explained either in terms of a colder gas (earlier decoupling? Interaction with dark matter component?) or due to the presence of an additional non-thermal background that increases T_γ

EDGES anomaly and radiative neutrino decays into sterile neutrinos

(Chianese, PDB, Farrag, Samanta, arXiv 1805.11717)

- We have considered the possibility that $\nu_i \to \nu_s + \gamma$ with $m_i - m_s = E_{21}\, z_{decay}/z_E$
- Active neutrinos have to decay non-relativistically since otherwise we would detect a non-thermal photon background in microwaves that we do not observe. This condition requires quasi-degenerate neutrinos: $m_i - m_s \ll m_i$
- Active-to-active neutrino decays are ruled out by the upper bound on neutrino masses but also because they would imply too large neutrino magnetic moments



Probing radiative neutrino decays into sterile neutrinos

(Chianese, PDB, Farrag, Samanta, arXiv 1805.11717)

- The specific intensity produced by the decays is found to be

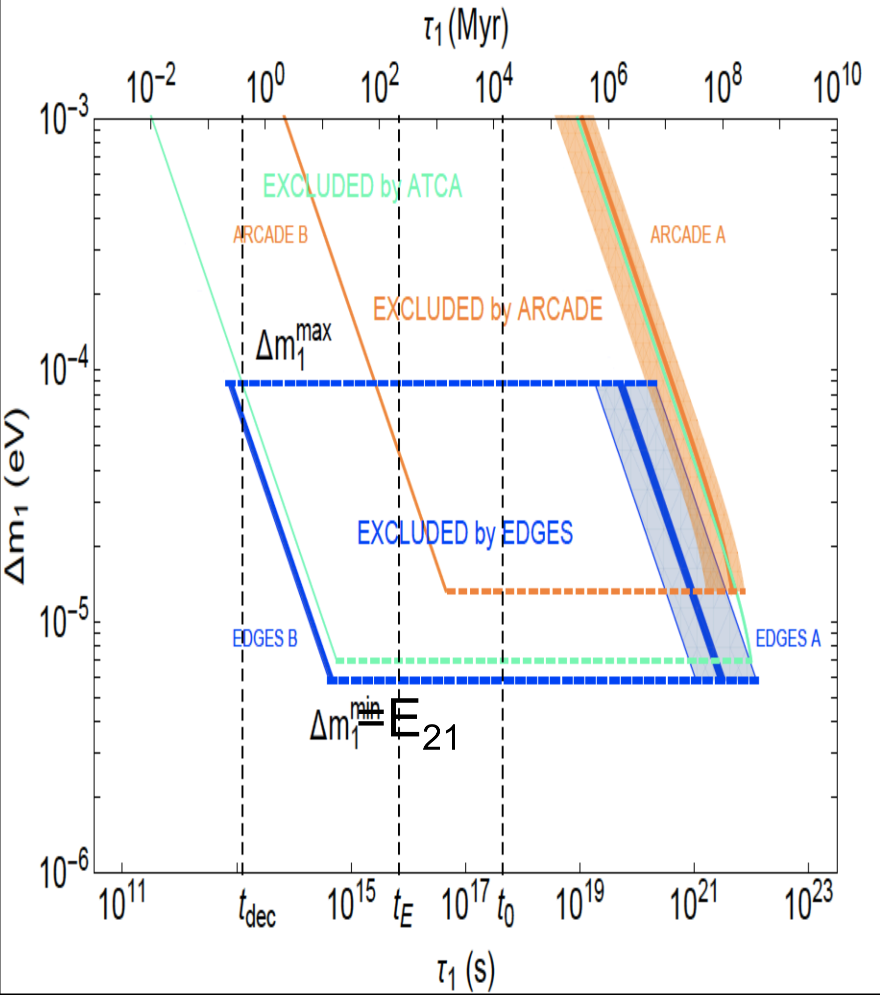
$$I_{\rm nth}(E_{21}, z_E) = \frac{1}{4\pi}\frac{d\varepsilon_{\gamma_{\rm nth}}}{dE} = \frac{n^{\infty}_{\nu_1}(z_E)}{4\pi}\left(\frac{E_{21}}{\Delta m_1}\right)^{3/2}\frac{e^{-\frac{t_E}{\tau_1}\left(\frac{E_{21}}{\Delta m_1}\right)^{3/2}}}{H_E\,\tau_1}$$

- The EDGES signal is explained imposing

$$R \equiv \frac{I_{\rm nth}(E_{21}, z_E)}{I_{CMB}(E_{21}, z_E)} = \frac{T_{\gamma_{\rm nth}}(E_{21}, z_E)}{T_{CMB}(z_E)} = R_E \equiv 1.15^{+2.15}_{-0.8}$$

or alternatively one can always interpret the EDGES results as an upper bound $R < R_E$ resulting in an excluded region

- Intriguingly the same mechanism can also explain the ARCADE excess in the radio background and the two allowed regions marginally overlap!



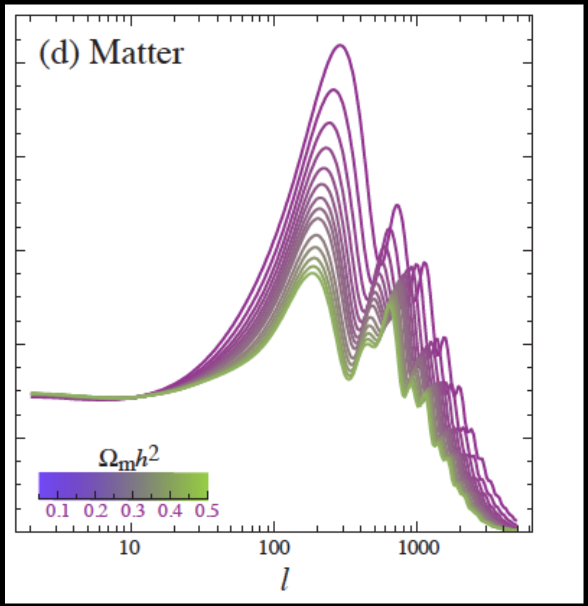
Plan

- $\sim 10^{16}$ GeV — grand-unified models and leptogenesis
- $10^{2\text{-}13}$ GeV — matter-antimatter asymmetry (leptogenesis)
- keV-PeV — right-handed neutrinos as dark matter (and at colli
- meV-MeV — probing neutrino physics with standard cosmology
- μeV — probing neutrino decays with 21 cm cosmology

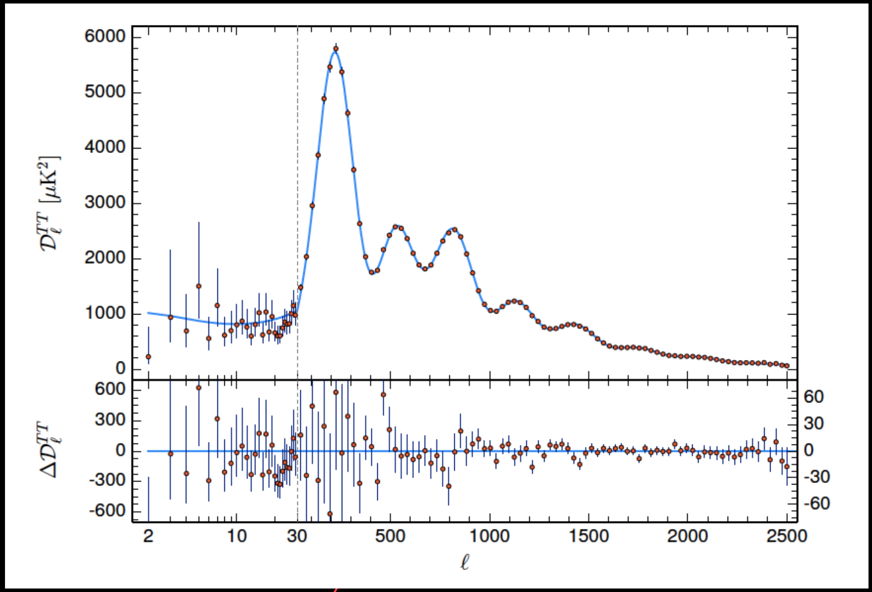
Introduction: cosmology and the early universe, updates from *Planck* 2018

Dark Matter of the Universe

(Hu, Dodelson, astro-ph/0110414)



(Planck 2018, 1807.06209)



(68% CL,TT,TE,EE+lowE+lensing)

$$\Omega_{CDM,0}h^2 = 0.1200 \pm 0.0012 \sim 5\Omega_{B,0}h^2$$

- Result consistent with indirect evidence of the existence of a non-baryonic dark matter component from a comparison between total matter contribution (from stellar and galactic dynamics) and the baryonic matter contribution (from CMB and BBN)

- Also consistent with models and simulations of structure formation

Sterile (RH) neutrino as warm Dark Matter

(Dodelson, Widrow '93; Fuller, Shi '98; Asaka, Blanchet, Shaposhnikov 2006)

- Within the see-saw mechanism a lightest RH neutrino with keV mass can be produced through the mixing with active neutrinos and play the role of warm dark matter. (Dodelson, Widrow '93)

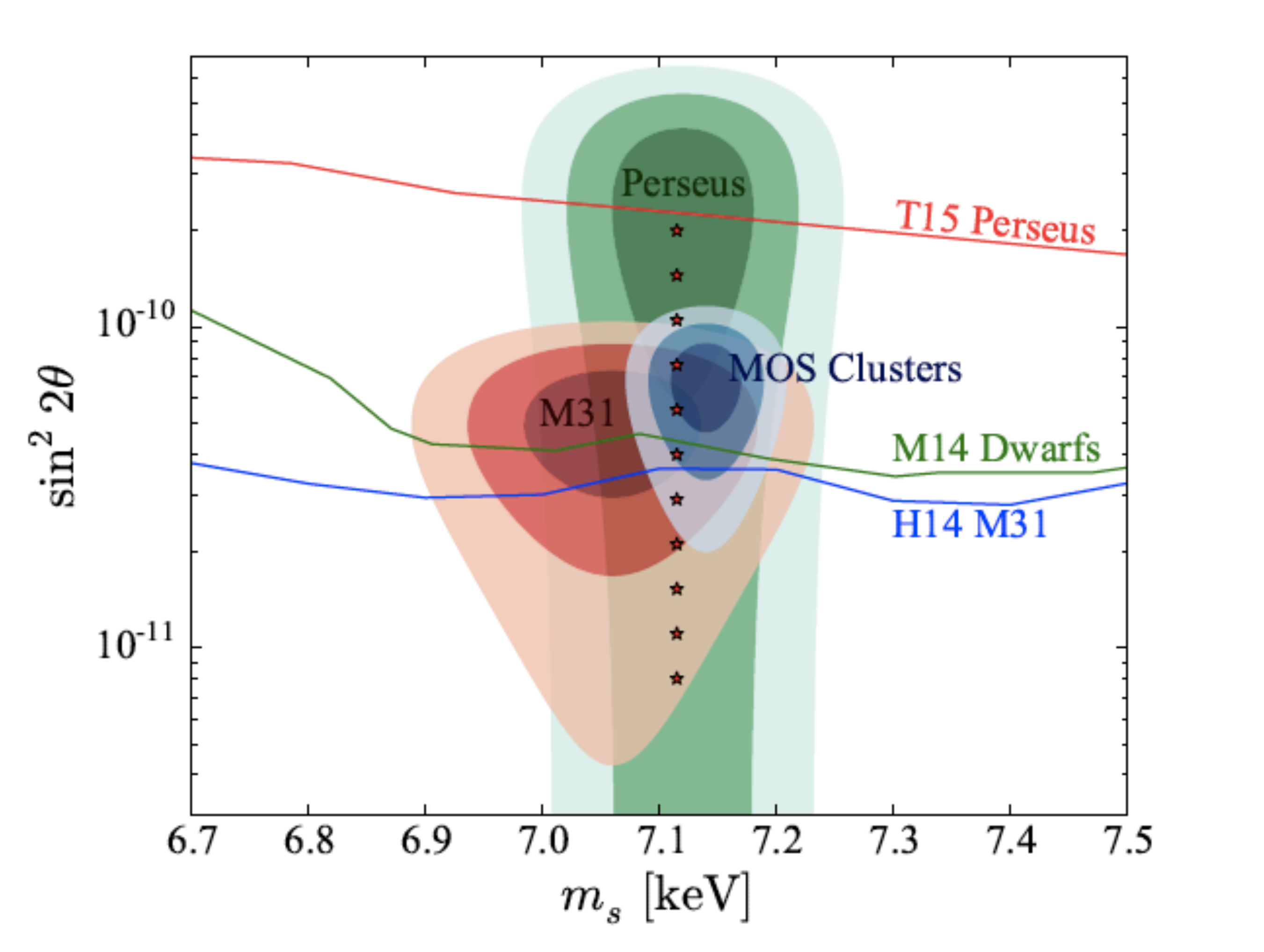
- The production can be enhanced (i.e., smaller mixing angles needed to get the correct abundance) in the presence of a large lepton asymmetry (Shi,Fuller '99)

- Considering 3 "seesaw" RH neutrinos, the lightest with a keV mass can be produced with the correct abundance and be stable and at the same time neutrino masses and mixing can be reproduced correctly (νMSM) (Asaka, Blanchet, Shaposhnikov 2006)

The RH neutrino decays radiatively with life-time much longer than the age of the universe emitting X-rays: can they explain the 3.5 keV line?

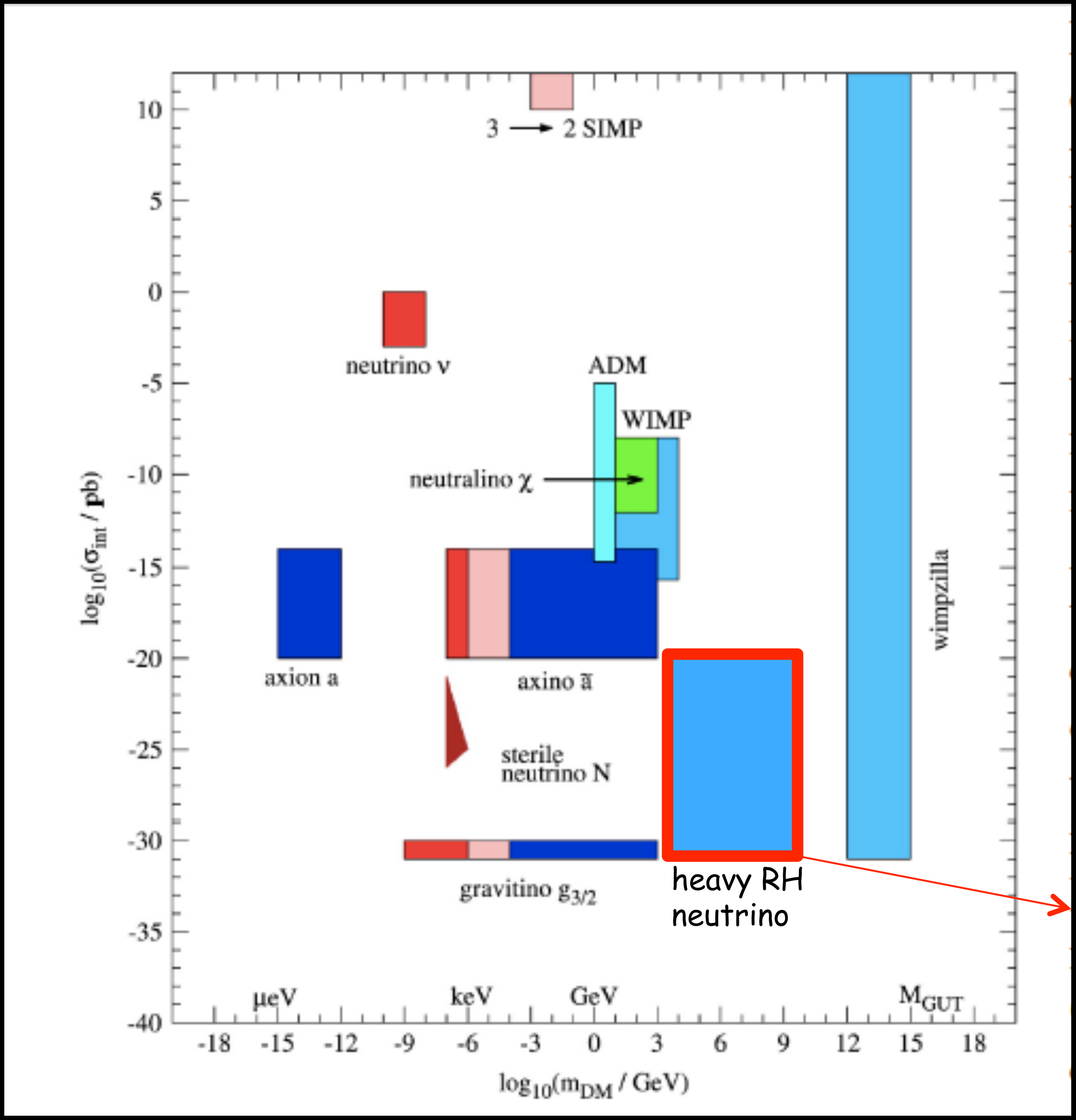
Sterile neutrino Dark Matter as an explanation of the 3.5 keV line?

(Venumadhav,Cyr-Racine,Abazajian,Hirata 1507.06655)



Beyond the WIMP paradigm

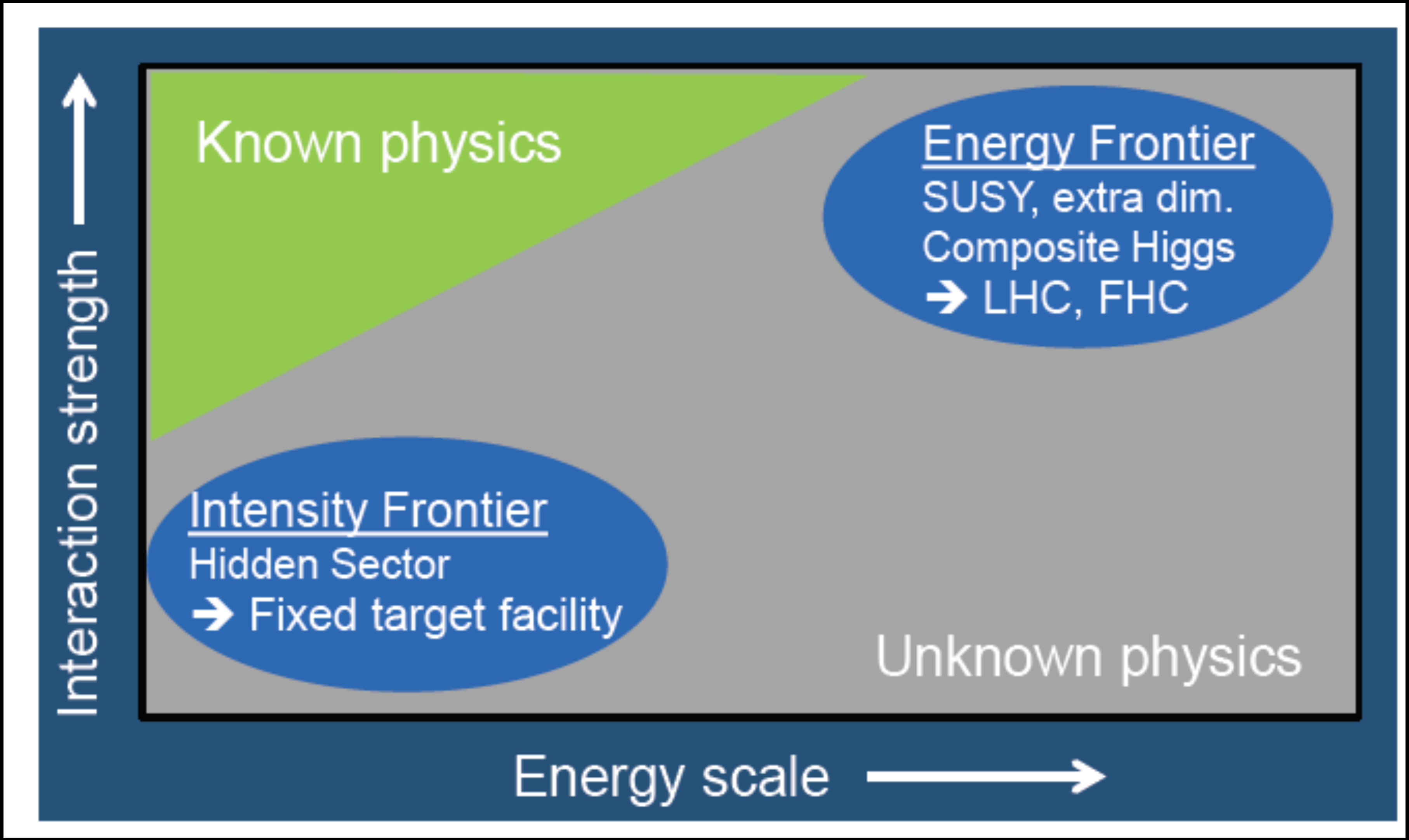
(from Baer et al.1407.0017)



(PDB, Anisimov '08)

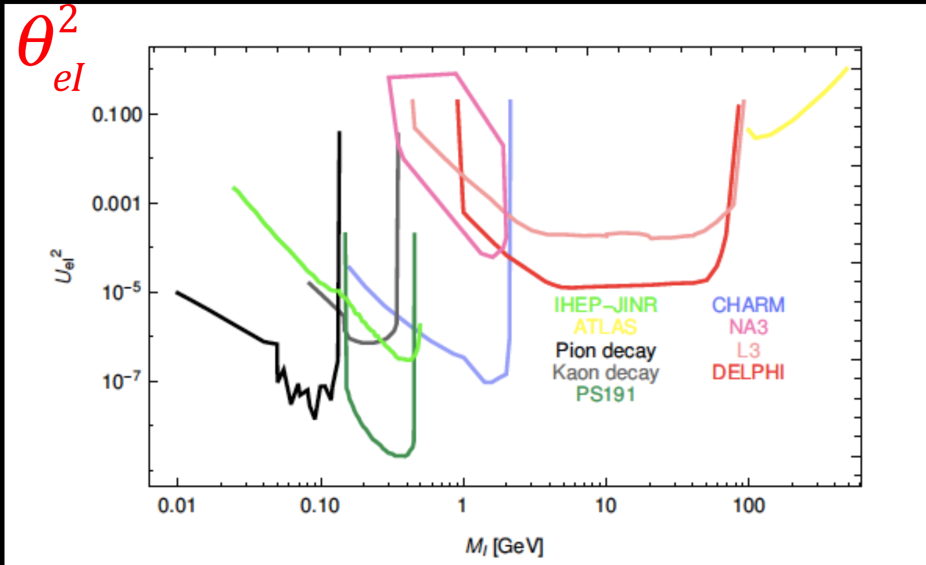
Right-handed neutrino laboratory searches

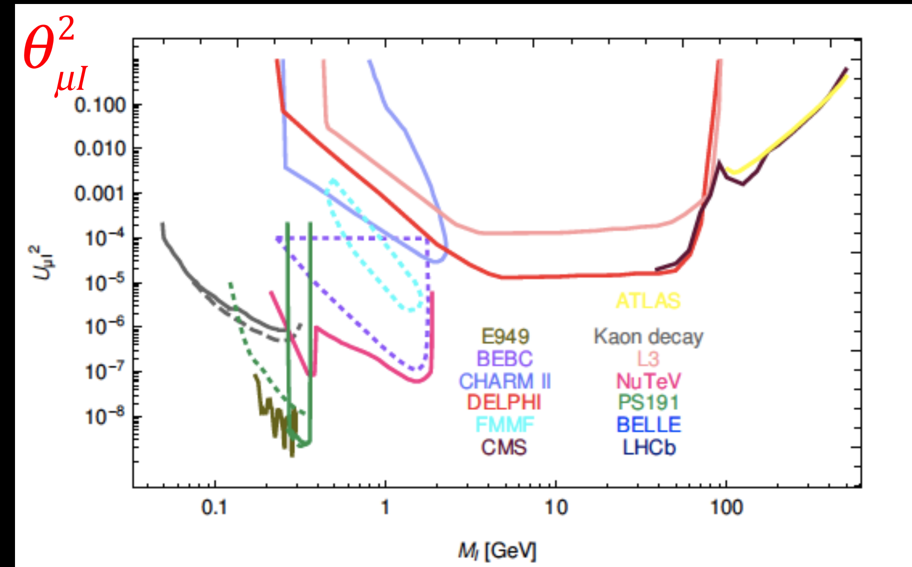
(SHIP proposal, 1504.04855)

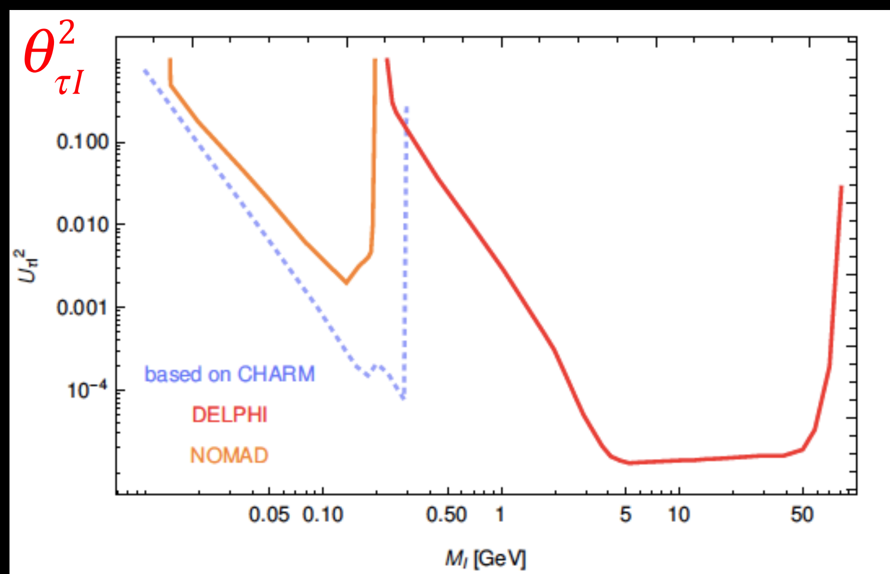


Searches with meson decays

(Drewes,Garbrecht 1502.00477)







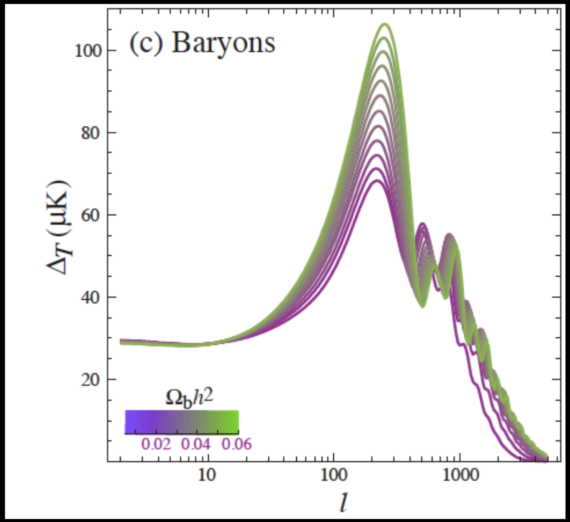
Plan

- ~10^{16} GeV — grand-unified models and leptogenesis
- $10^{2\text{-}13}$ GeV — matter-antimatter asymmetry (leptogenesis)
- keV-PeV — right-handed neutrinos as dark matter (and at colli
- meV-MeV — probing neutrino physics with standard cosmology
- μeV — probing neutrino decays with 21 cm cosmology

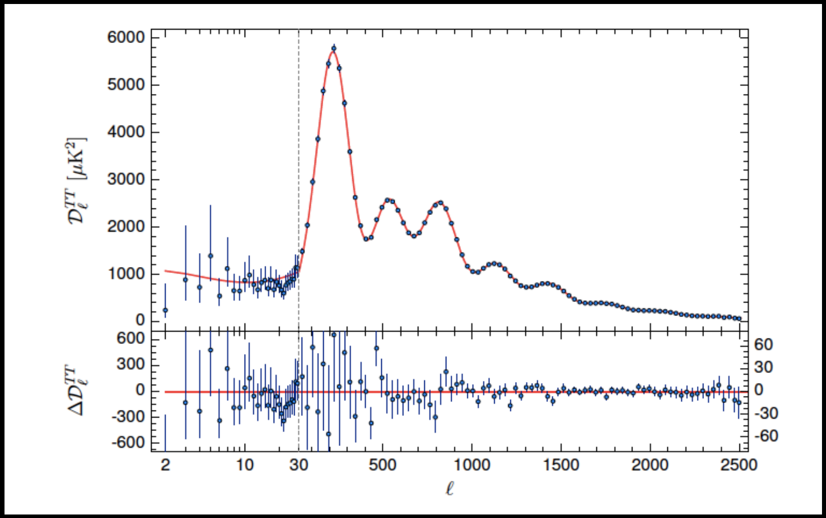
Introduction: cosmology and the early universe, updates from *Planck* 2018

Baryon asymmetry of the universe

(Hu, Dodelson, astro-ph/0110414)



(Planck 2018, 1807.06209)



(68% CL,TT,TE,EE+lowE+lensing)

$$\Omega_{B0} h^2 = 0.02237 \pm 0.00015$$

$$\eta_{B0} \equiv \frac{n_{B0} - \bar{n}_{B0}}{n_{\gamma 0}} \simeq \frac{n_{B0}}{n_{\gamma 0}} \simeq 273.5\,\Omega_{B0} h^2 \times 10^{-10} = (6.12 \pm 0.04) \times 10^{-10}$$

- Consistent with (older) BBN determination but more precise and accurate
- Asymmetry coincides with matter abundance since there is no evidence of primordial antimatter…..not so far at least (see AMS-02 results and Poulin,Salati,Cholis,Kamionkowski,Silk 1808.08961)

Matter-antimatter asymmetry of the Universe

- With initial vanishing asymmetry, a relic abundance of matter and antimatter would be incredibly small. Something should have segregated them prior to annihilations
- Symmetric Universe with matter- anti matter domains ?
- Excluded by CMB + cosmic rays (Cohen, De Rujula, Glashow '98)
- Pre-existing ? It conflicts with inflation (Dolgov '97)
- **dynamical generation at the end or after inflation is necessary (baryogenesis)** (Sakharov '67)
- Baryogenesis in the Standard Model ?
- $\eta_B^{SM} <<< \eta_B^{CMB}$

New Physics is needed!

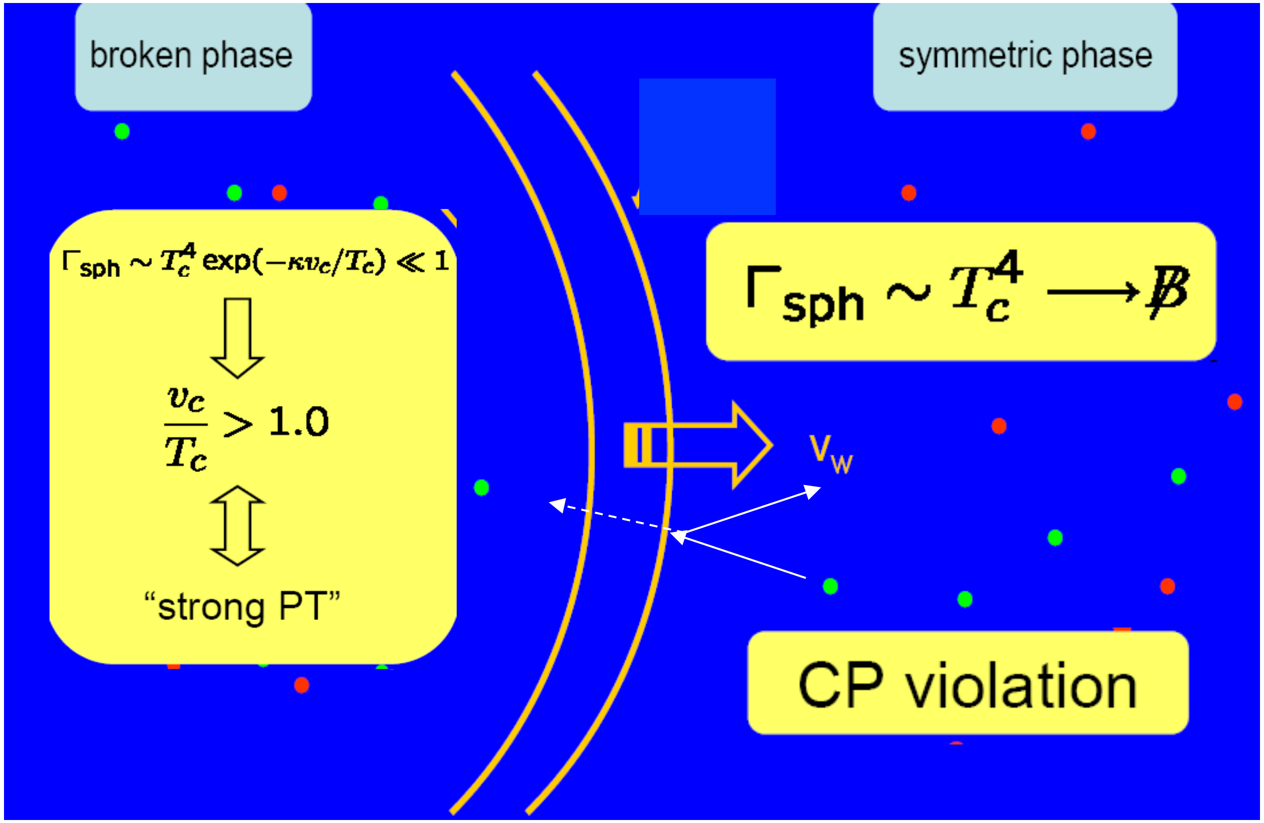
Baryogenesis in the Standard Model?

All 3 Sakharov conditions are fulfilled in the SM:

1. Baryon number violation if T $\gtrsim$ 100 GeV,
2. CP violation in the CKM matrix,
3. Departure from thermal equilibrium (arrow of time)
   from the expansion of the Universe

EWBG in the SM

If the EW phase transition (PT) is 1st order ⇒ **broken phase bubbles nucleate**



In the SM the ratio v_c/T_c is directly related to the Higgs mass and only for $M_h < 40$ GeV one can have a strong PT

⇒ EW baryogenesis in the SM is ruled out (also not enough CP)

⇒ New Physics is needed!

Models of Baryogenesis

- From phase transitions:

 - ELECTROWEAK BARYOGENESIS (EWBG)

 * in the SM (ruled out)

 * in the MSSM (gasping)

 * in the nMSSM

 * in the NMSSM

 * in the 2 Higgs model

 * ....

- Affleck-Dine:

 - at preheating

 - Q-balls

 - ....

- From Black Hole evaporation
- Spontaneous Baryogenesis
- Gravitational baryogenesis
- Gravitational leptogenesis

- From heavy particle decays:

 - GUT Baryogenesis

 - LEPTOGENESIS

it requires neutrino masses and mixing

Neutrino mixing parameters

Pontecorvo-Maki-Nakagawa-Sakata matrix

$$|\nu_\alpha\rangle = \sum_i U^\star_{\alpha i}\,|\nu_i\rangle$$

$$U_{\alpha i} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix}$$

$$\alpha_{31} = 2(\sigma - \rho)$$
$$\alpha_{21} = -2\rho$$

$$= \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \cdot \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \cdot \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \cdot \begin{pmatrix} e^{i\rho} & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & e^{i\sigma} \end{pmatrix}$$

Atmospheric, LB | Reactor, Accel.,LB CP violating phase | Solar,Reactor | bb0v decay

$c_{ij} = \cos\theta_{ij},\ and\ s_{ij} = \sin\theta_{ij}$

(νFIT collaboration, January 2018)

NO favoured over IO
($\Delta\chi^2$ (IO-NO)=4.14⇒ ~2σ)

3σ ranges(NO):

$\theta_{12} = [31.42^\circ, 36.05^\circ]$

$\theta_{13} = [8.09^\circ, 8.98^\circ]$

$\theta_{23} = [40.3^\circ, 51.5^\circ]$

$\delta = [-216^\circ, +14^\circ]$

$\rho,\sigma = [-180^\circ, +180^\circ]$

3σ ranges (IO):

$\theta_{12} = [31.43^\circ, 36.06^\circ]$

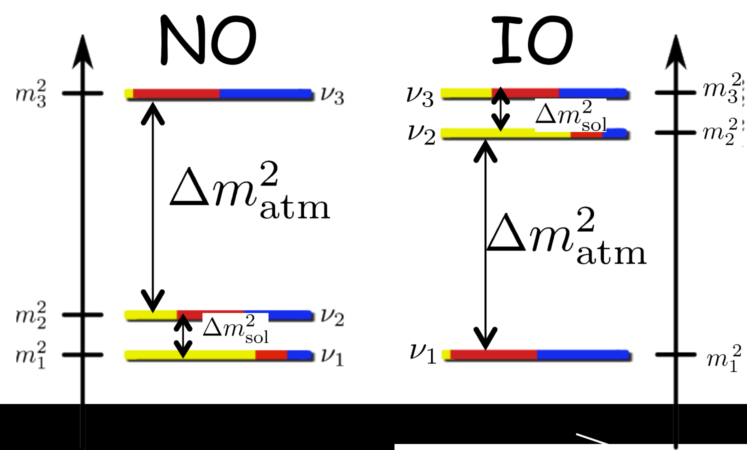
$\theta_{13} = [8.14^\circ, 9.01^\circ]$

$\theta_{23} = [38^\circ, 53^\circ]$

$\delta = [-168^\circ, -6^\circ]$

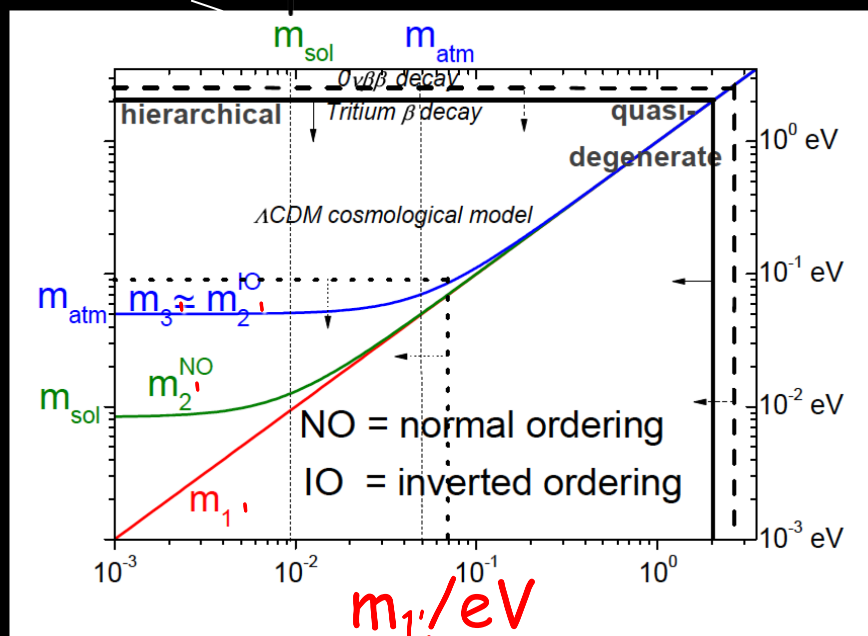
$\rho,\sigma = [-180^\circ, +180^\circ]$

Neutrino masses: $m_{1'} < m_{2'} < m_{3'}$



$$m_{\rm atm} \equiv \sqrt{\Delta m^2_{\rm atm} + \Delta m^2_{\rm sol}} \simeq 0.05\,{\rm eV}$$

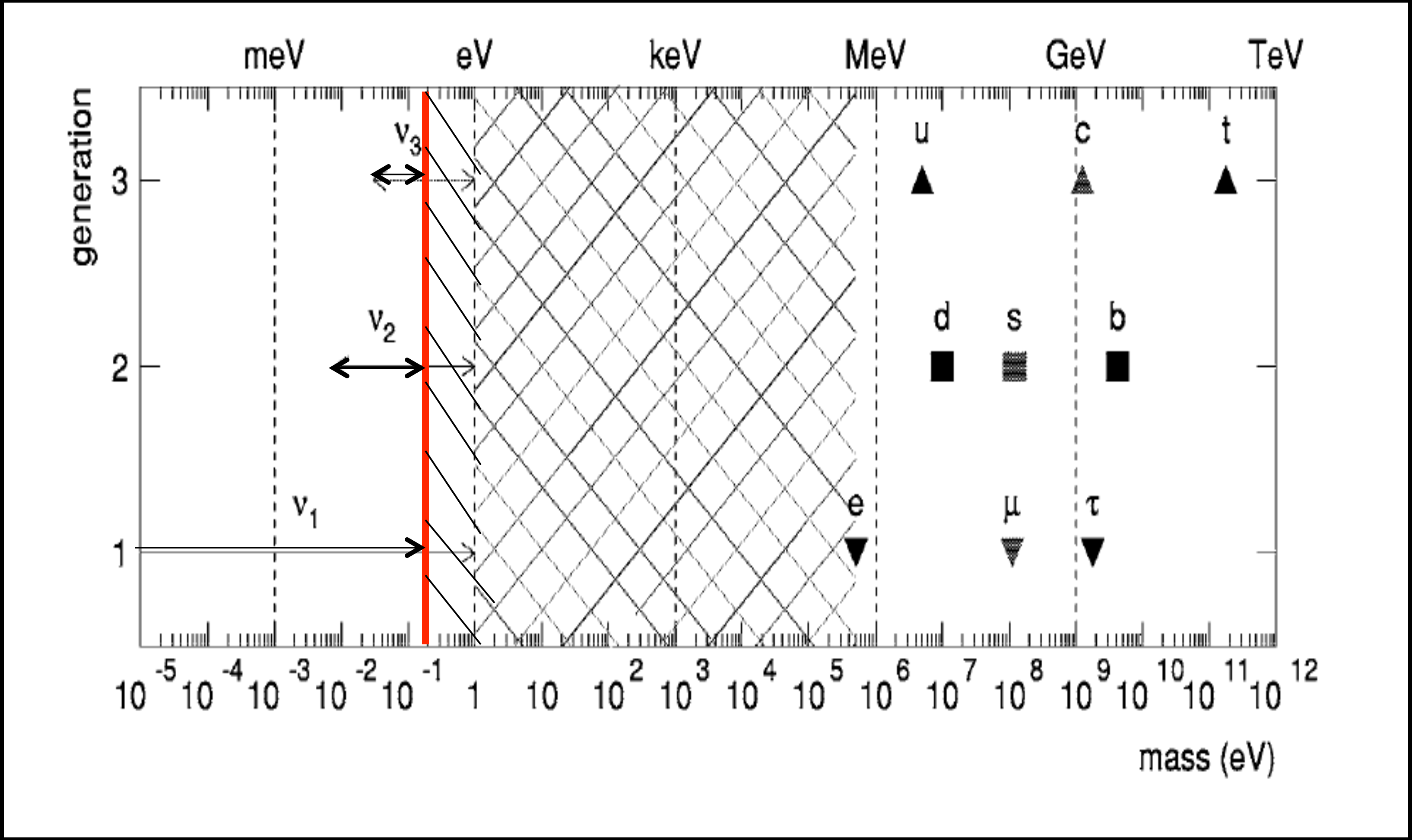
$$m_{\rm sol} \equiv \sqrt{\Delta m^2_{\rm sol}} \simeq 0.009\,{\rm eV}$$



$$Planck2015 \Rightarrow \Sigma_i m_i \leq 0.23\ {\rm eV} \Rightarrow m_{1'}^{NO(IO)} \leq 0.071\ (0.066)\ {\rm eV}$$

One could just explain neutrino masses and mixing as for the other massive fermions just with EWSSB via Higgs mechanism but neutrinos are quite special:

1) much lighter than all other fermions:



2) neutral ⇒ Majorana mass terms are possible

Minimally extended SM

$$\mathcal{L} = \mathcal{L}_{SM} + \mathcal{L}_Y^\nu$$

$$-\mathcal{L}_Y^\nu = \overline{\nu_L}\, h^\nu\, \nu_R\, \phi \Rightarrow -\mathcal{L}_{\rm mass}^\nu = \overline{\nu_L}\, m_D\, \nu_R$$

Dirac mass term

(in a basis where charged lepton mass matrix is diagonal)

diagonalising m_D : $m_D = V_L^\dagger D_{m_D} U_R$ $\quad D_{m_D} \equiv \begin{pmatrix} m_{D1} & 0 & 0 \\ 0 & m_{D2} & 0 \\ 0 & 0 & m_{D3} \end{pmatrix}$

$\Rightarrow$ neutrino masses: $m_i = m_{Di}$

leptonic mixing matrix: $U = V_L^\dagger$

Too many unanswered questions:

- Why neutrinos are much lighter than all other fermions?
- Why large mixing angles?
- Cosmological puzzles?
- Why not a Majorana mass term as well?

Minimal seesaw mechanism (type I)

• Dirac + (Right-Right) Majorana mass terms

(Minkowski '77; Gell-mann, Ramond, Slansky; Yanagida; Mohapatra, Senjanovic '79)

$$\mathcal{L}^{\nu}_{\rm mass} = -\frac{1}{2}\left[(\bar{\nu}^c_L, \bar{\nu}_R)\begin{pmatrix} 0 & m_D^T \\ m_D & M \end{pmatrix}\begin{pmatrix} \nu_L \\ \nu^c_R \end{pmatrix}\right] + h.c.$$

In the see-saw limit ($M \gg m_D$) the mass spectrum splits into 2 sets:

- 3 light Majorana neutrinos with masses (seesaw formula):

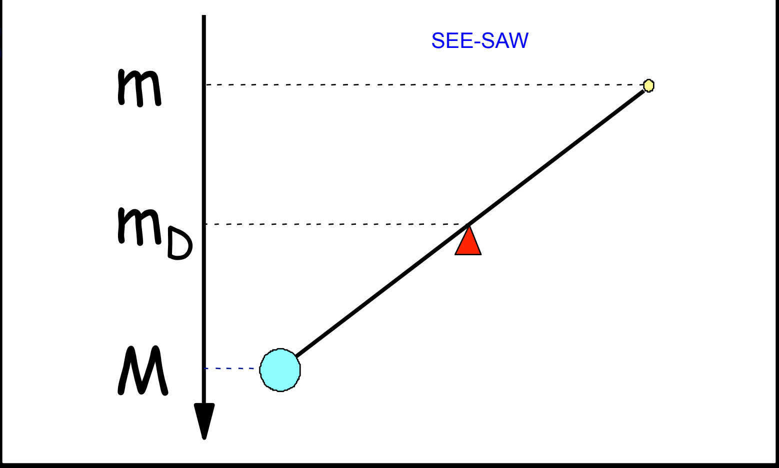
$$\mathrm{diag}(m_1, m_2, m_3) = -U^{\dagger}\, m_D\, \frac{1}{M}\, m_D^T\, U^{\star}$$

- 3 very heavy Majorana RH neutrinos N_1, N_2, N_3 with masses $M_3 > M_2 > M_1 \gg m_D$

1 generation toy model example (U=1):

$m_D \sim m_{top} \sim 200$ GeV,
$M \sim 0.1\ \Lambda_{GUT} \sim 10^{15}$GeV

$\Rightarrow m \sim m_{atm} \sim 0.05$eV



Minimal scenario of leptogenesis

(Fukugita, Yanagida '86)

- Thermal production of RH neutrinos

$T_{RH} \gtrsim T_{lep} \simeq M_i / (2\div 10)$

heavy neutrinos decays $N_i \xrightarrow{\Gamma} L_i + \phi^\dagger \qquad N_i \xrightarrow{\bar{\Gamma}} \bar{L}_i + \phi$

total CP asymmetries $\varepsilon_i \equiv -\dfrac{\Gamma - \bar{\Gamma}}{\Gamma + \bar{\Gamma}}$

$$\Rightarrow N_{B-L}^{fin} = \sum_{i=1,2,3} \varepsilon_i \times \kappa_i^{fin}$$

efficiency factors

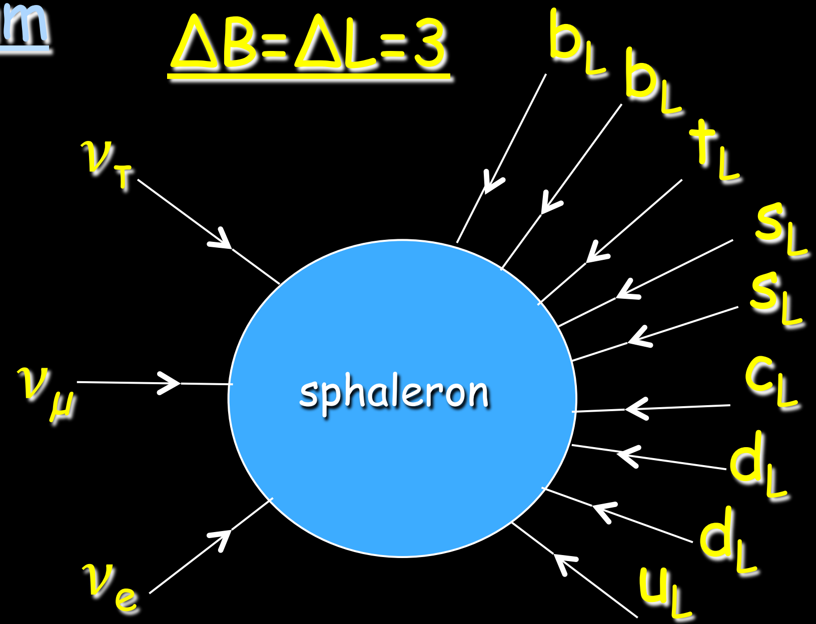
- Sphaleron processes in equilibrium

$\Rightarrow T_{lep} \gtrsim T_{sphalerons}^{off} \sim 100$ GeV

(Kuzmin, Rubakov, Shaposhnikov '85)

$$\Rightarrow \eta_{B0}^{lep} = \frac{a_{sph} N_{B-L}^{fin}}{N_\gamma^{rec}} \simeq 0.01 N_{B-L}^{fin}$$

$\Delta B = \Delta L = 3$



Vanilla leptogenesis ⇒ upper bound on ν masses

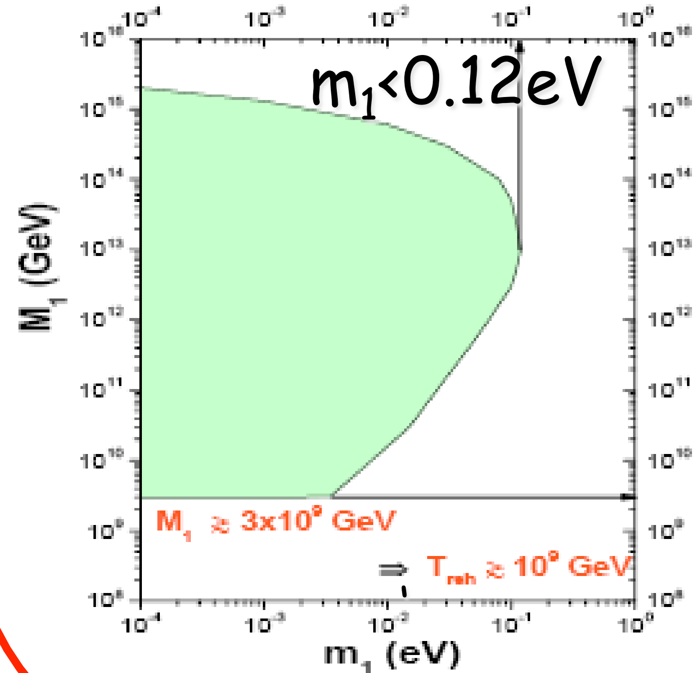
(Buchmüller, PDB, Plümacher '04; Blanchet, PDB '07)

$$\eta_B^{\max}(m_1, M_1) \geq \eta_B^{CMB}$$

1) Lepton flavor composition is neglected

$$N_i \xrightarrow{\Gamma} \ell_i + \phi^\dagger \qquad N_i \xrightarrow{\bar{\Gamma}} \bar{\ell}_i + \phi$$

2) Hierarchical spectrum ($M_2 \gtrsim 2M_1$)



3) Strong lightest RH neutrino wash-out

$$\eta_{B0} \simeq 0.01 N_{B-L}^{final} \simeq 0.01 \varepsilon_1 \kappa_1^{fin}(K_1, m_1)$$

decay parameter: $K_1 \equiv \frac{\Gamma_{N_1}(T=0)}{H(T=M_1)}$

All the asymmetry is generated by the lightest RH neutrino

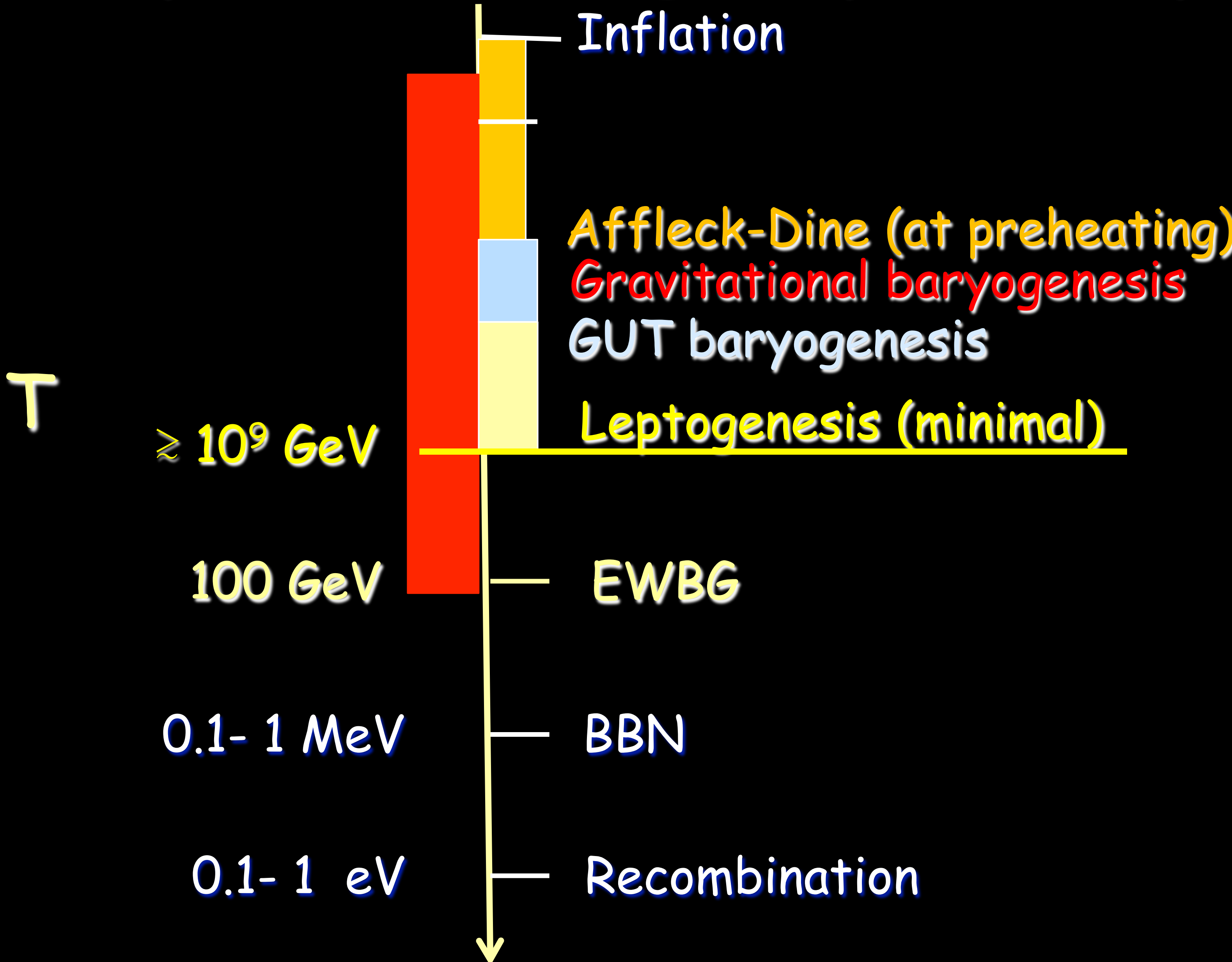
No dependence on the leptonic mixing matrix U: it cancels out

4) Barring fine-tuned cancellations

(Davidson, Ibarra '02)

$$\varepsilon_1 \leq \varepsilon_1^{\max} \simeq 10^{-6} \left(\frac{M_1}{10^{10}\,\mathrm{GeV}}\right) \frac{m_{\mathrm{atm}}}{m_1 + m_3}$$

A pre-existing asymmetry?



Independence of the initial conditions (strong thermal leptogenesis)

(Buchmüller, PDB, Plümacher '04)

wash-out of a pre-existing asymmetry $N_{B-L}^{P,\mathrm{initial}}$

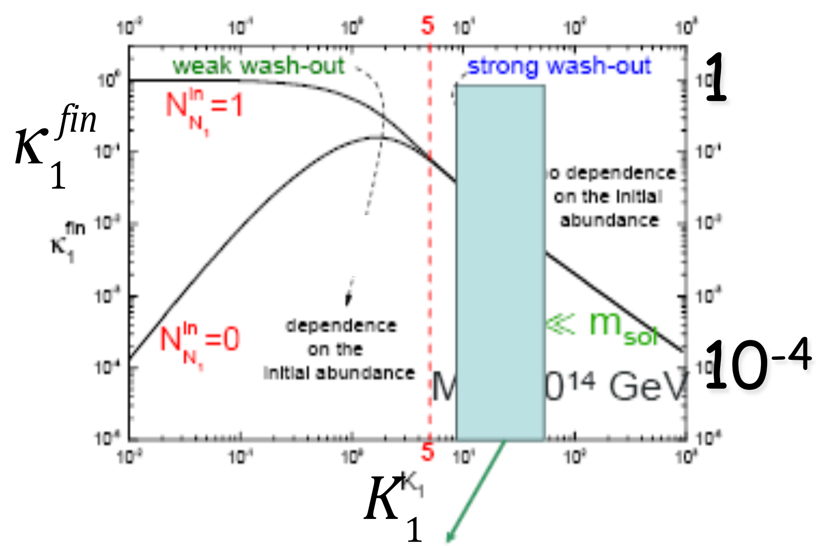
$$N_{B-L}^{\mathrm{p,final}} = N_{B-L}^{\mathrm{p,initial}} \, e^{-\frac{3\pi}{8}\,K_1} \ll N_{B-L}^{\mathrm{f},N_1}$$

Just a coincidence?

decay parameter: $K_1 \equiv \dfrac{\Gamma_{N_1}}{H(T=M_1)} \sim \dfrac{m_{\mathrm{sol,atm}}}{m_\star \sim 10^{-3}\,\mathrm{eV}} \sim 10 \div 50$

equilibrium neutrino mass: $m_* = \dfrac{16\pi^{5/2}\sqrt{g_*}}{3\sqrt{5}} \dfrac{v^2}{M_{\mathrm{Pl}}} \simeq 1.08 \times 10^{-3}\,\mathrm{eV}$.

independence of the initial N_1-abundance as well



$$K_{\mathrm{sol}} \simeq 9 \lesssim K_1 \lesssim 50 \simeq K_{\mathrm{atm}}$$

Plan

~10^{16} GeV — grand-unified models and leptogenesis

10^{2-13} GeV — matter-antimatter asymmetry (leptogenesis)

keV-PeV — right-handed neutrinos as dark matter (and at colli

meV-MeV — probing neutrino physics with standard cosmology

μeV — probing neutrino decays with 21 cm cosmology

Introduction: cosmology and the early universe, updates from *Planck* 2018

SO(10)-inspired leptogenesis

(Branco et al. '02; Nezri, Orloff '02; Akhmedov, Frigerio, Smirnov '03)

$$m_D = V_L^\dagger \, D_{m_D} \, U_R$$

$$D_{m_D} = \mathrm{diag}\{m_{D1}, m_{D2}, m_{D3}\}$$

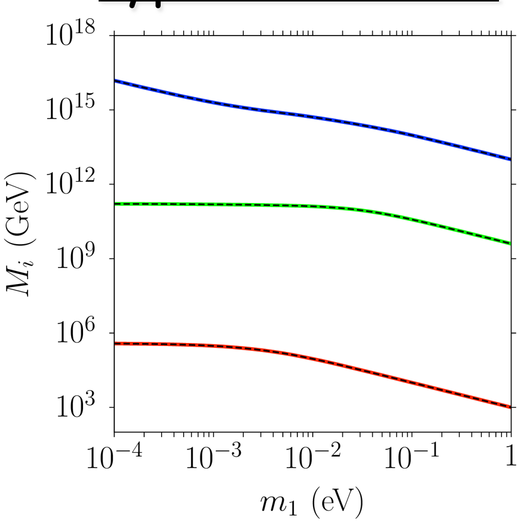
SO(10)-inspired conditions:

1) $m_{D1} = \alpha_1 \, m_u \, , \; m_{D2} = \alpha_2 \, m_c \, , \; m_{D3} = \alpha_3 \, m_t \, , \quad (\alpha_i = \mathcal{O}(1))$

2) $V_L \simeq V_{CKM} \simeq I$

From the seesaw formula: $U_R = U_R\,(U, m_i; \alpha_i, V_L)$, $M_i = M_i\,(U, m_i; \alpha_i, V_L)$ $\Rightarrow$ $\eta_{B0} = \eta_{B0}\,(U, m_i; \alpha_i, V_L)$

typical solutions



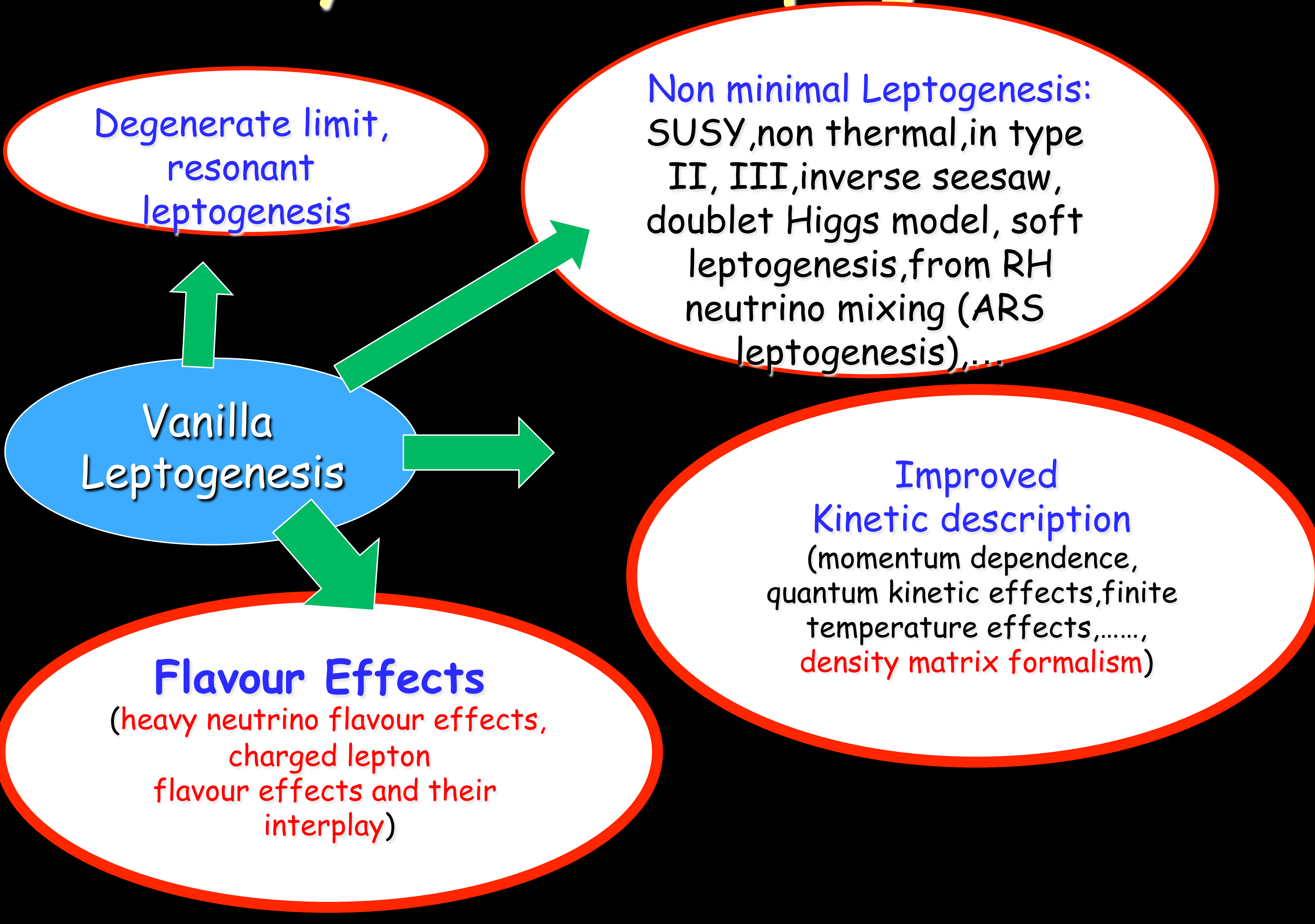
since $M_1 \ll 10^9$ GeV $\Rightarrow$ $\eta_B^{(N1)} \ll \eta_B^{CMB}$

RULED OUT ?

Note that high energy CP violating phases are expressed in terms of low energy CP violating phases:

$$\Omega = D_m^{-\frac{1}{2}} \, U^\dagger \, V_L^\dagger \, D_{m_D} \, U_R \, D_M^{-\frac{1}{2}}$$

Beyond vanilla Leptogenesis



Charged lepton flavour effects

(Abada et al '06; Nardi et al. '06; Blanchet, PDB, Raffelt '06; Riotto, De Simone '06)

Flavor composition of lepton quantum states matters!

$$|l_1\rangle = \sum_\alpha \langle l_\alpha|l_1\rangle\, |l_\alpha\rangle \qquad (\alpha = e, \mu, \tau)$$

$$|\bar{l}_1'\rangle = \sum_\alpha \langle l_\alpha|\bar{l}_1'\rangle\, |\bar{l}_\alpha\rangle$$

- T << 10^{12} GeV ⇒ τ-Yukawa interactions are fast enough break the coherent evolution of $|l_1\rangle$ and $|\bar{l}_1'\rangle$

⇒ incoherent mixture of a τ and of a μ+e components ⇒ 2-flavour regime

- T << 10^9 GeV then also μ-Yukawas in equilibrium ⇒ 3-flavour regime

M_1

UNFLAVOURED $\qquad N_{B-L}^{final} = \varepsilon_1 \kappa_1^{fin}$

~ 10^{12} GeV — TRANSITION REGIME: DENSITY MATRIX APPROACH NEEDED

2 Flavour regime (τ, e+μ) $\qquad \varepsilon_{1\tau}\kappa_1^{fin}(K_{1\tau}) + \varepsilon_{1e+\mu}\kappa_1^{fin}(K_{1e+\mu})$

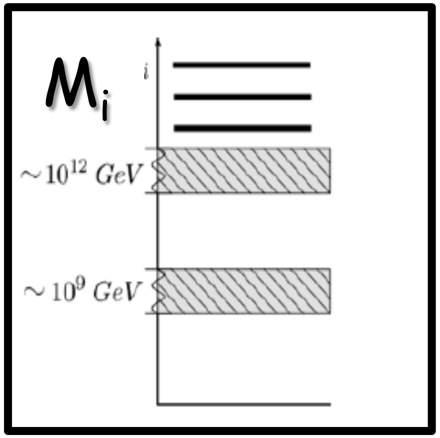
~ 10^{9} GeV — TRANSITION REGIME: DENSITY MATRIX APPROACH NEEDED

3 Flavour regime (e, μ, τ) $\qquad \varepsilon_{1\tau}\kappa_1^{fin}(K_{1\tau}) + \varepsilon_{1\mu}\kappa_1^{fin}(K_{1\mu}) + \varepsilon_{1e}\kappa_1^{fin}(K_{1e})$

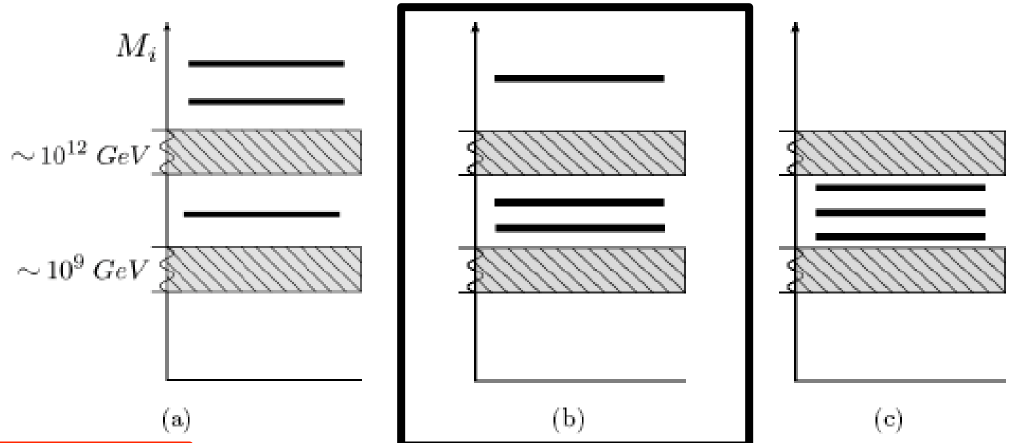
Heavy neutrino lepton flavour effects: 10 hierarchical scenarios

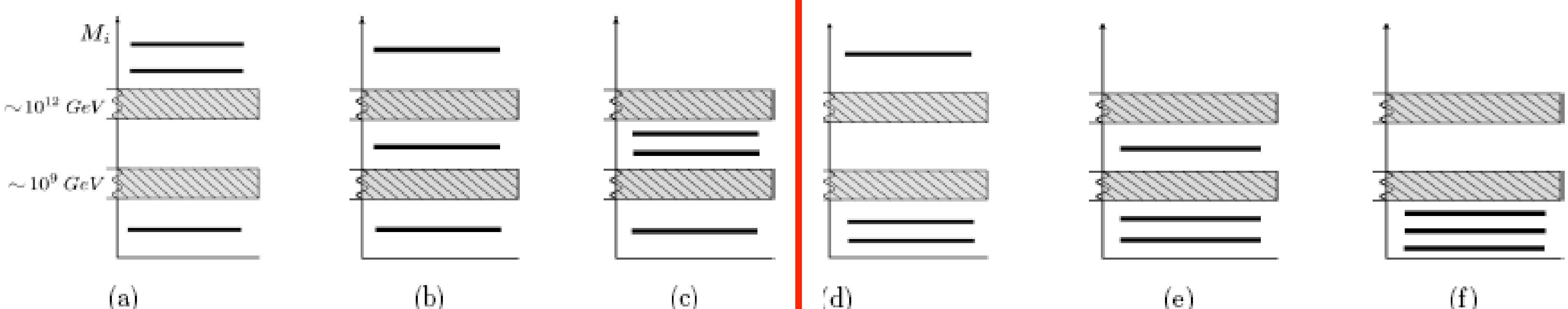
Typically rising in discrete flavour models

Heavy neutrino flavored scenario



2 RH neutrino scenario



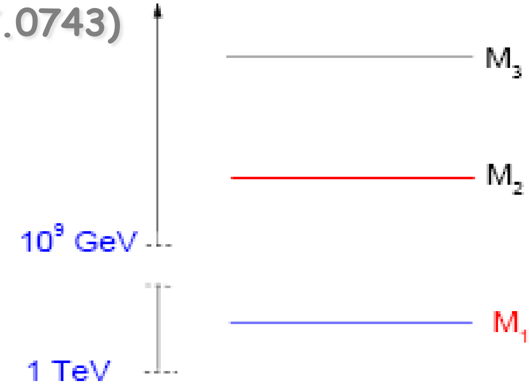


N_2 -dominated scenario:

- ☛ N_1 produces negligible asymmetry;
- ☛ It emerges naturally in SO(10)-inspired models;
- ☛ It is the only one that can realise STRONG THERMAL LEPTOGENESIS

The N_2-dominated scenario

(PDB hep-ph/0502082, Vives hep-ph/0512160;Blanchet,PDB 0807.0743)



- Unflavoured case: asymmetry produced from N_2 - RH neutrinos is typically washed-out

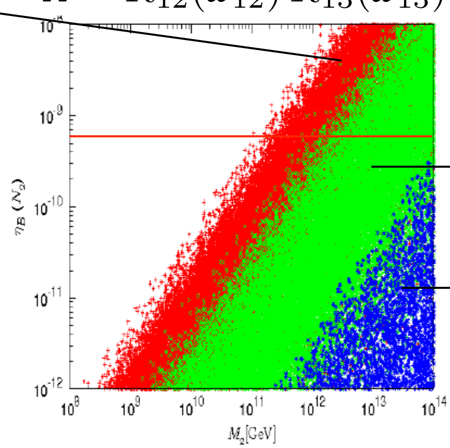
$$\eta_{B0}^{lep(N_2)} \simeq 0.01 \cdot \varepsilon_2 \cdot \kappa^{fin}(K_2) \cdot e^{-\frac{3\pi}{8}K_1} << \eta_{B0}^{CMB}$$

- Adding flavour effects: lighest RH neutrino wash-out acts on individual flavour ⇒ much weaker

$$N_{B-L}^{\rm f}(N_2) = P_{2e}^0\, \varepsilon_2\, \kappa(K_2)\, e^{-\frac{3\pi}{8}\, K_{1e}} + P_{2\mu}^0\, \varepsilon_2\, \kappa(K_2)\, e^{-\frac{3\pi}{8}\, K_{1\mu}} + P_{2\tau}^0\, \varepsilon_2\, \kappa(K_2)\, e^{-\frac{3\pi}{8}\, K_{1\tau}}$$

no N_1 wash-out
for $M_1 \lesssim T_{sph} \simeq 140$ GeV
(PDB,Re Fiorentin 1512.06739)

$$\Omega = R_{12}(\omega_{12})\, R_{13}(\omega_{13})$$



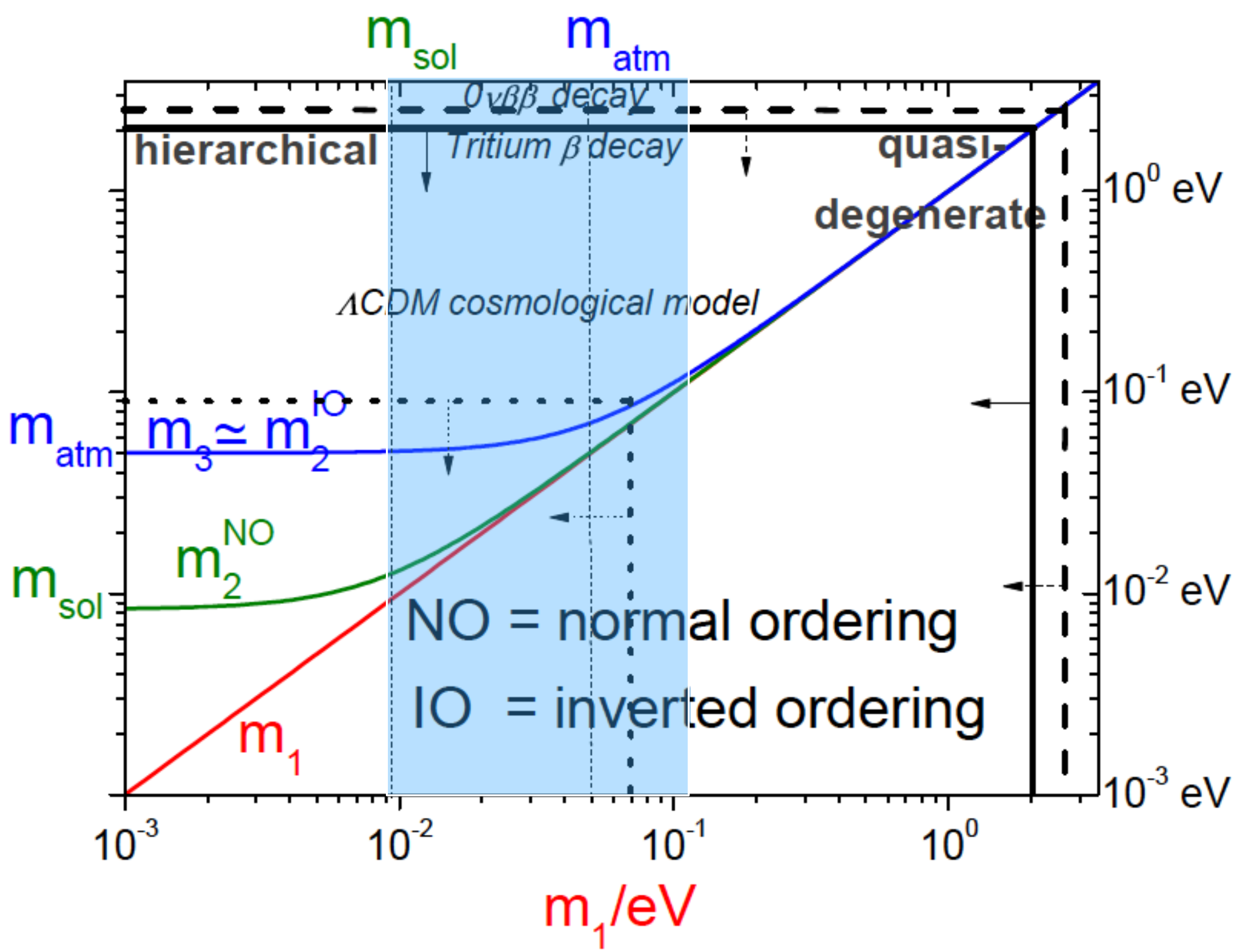
with flavor effects

unflavored case

- With flavor effects the domain of successful N_2 dominated leptogenesis greatly enlarges
- Existence of the heaviest RH neutrino N_3 is necessary for the $\varepsilon_{2\alpha}$'s not to be negligible

A lower bound on neutrino masses imposing independence of the initial conditions

(PDB, Sophie King, Re Fiorentin 1401.6185)



$$0.01\ \text{eV} \lesssim m_1 \lesssim 0.1\ \text{eV (NO)}$$

SO(10)-inspired leptogenesis

(Branco et al. '02; Nezri, Orloff '02; Akhmedov, Frigerio, Smirnov '03)

$$m_D = V_L^\dagger \, D_{m_D} \, U_R$$

$$D_{m_D} = \mathrm{diag}\{m_{D1}, m_{D2}, m_{D3}\}$$

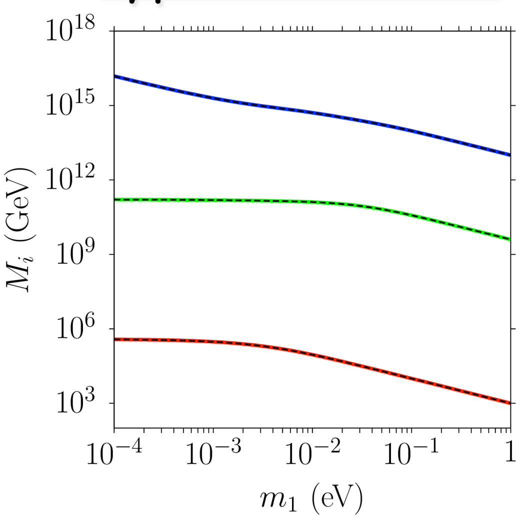
SO(10)-inspired conditions:

1) $m_{D1} = \alpha_1 \, m_u \, , \, m_{D2} = \alpha_2 \, m_c \, , \, m_{D3} = \alpha_3 \, m_t \, , \quad (\alpha_i = \mathcal{O}(1))$

2) $V_L \simeq V_{CKM} \simeq I$

From the seesaw formula: $U_R = U_R\,(U, m_i; \alpha_i, V_L)$, $M_i = M_i\,(U, m_i; \alpha_i, V_L)$ $\Rightarrow \eta_{B0} = \eta_{B0}\,(U, m_i; \alpha_i, V_L)$

typical solutions

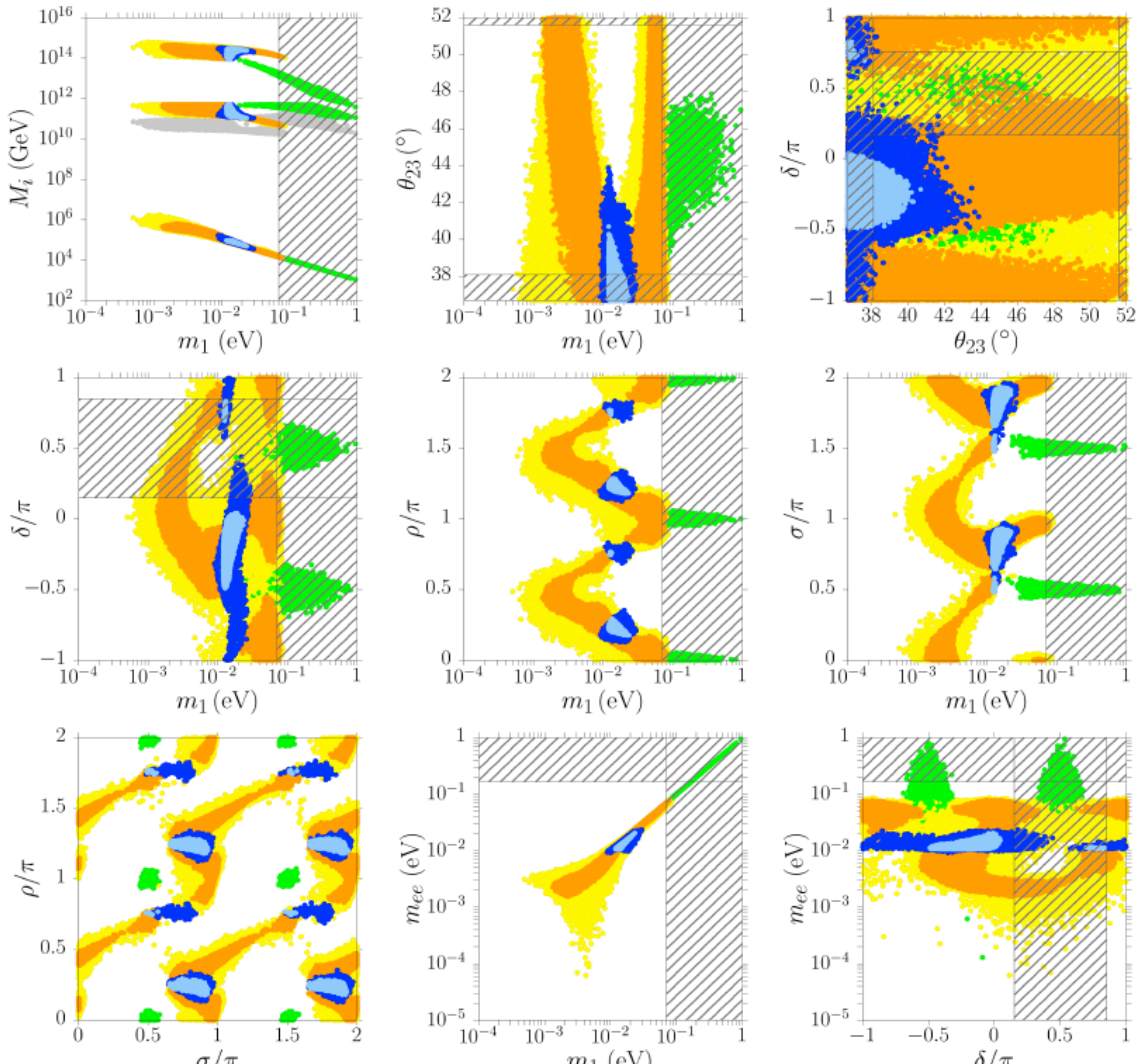


since $M_1 \ll 10^9$ GeV $\Rightarrow \eta_B^{(N1)} \ll \eta_B^{CMB}$

RULED OUT ?

Note that high energy CP violating phases are expressed in terms of low energy CP violating phases:

$$\Omega = D_m^{-\frac{1}{2}} \, U^\dagger \, V_L^\dagger \, D_{m_D} \, U_R \, D_M^{-\frac{1}{2}}$$



M_i (GeV)
m_1 (eV)
θ_{23} (°)
m_1 (eV)
δ/π
θ_{23} (°)
δ/π
m_1 (eV)
ρ/π
m_1 (eV)
σ/π
m_1 (eV)
ρ/π
σ/π
m_{ee} (eV)
m_1 (eV)
m_{ee} (eV)
δ/π

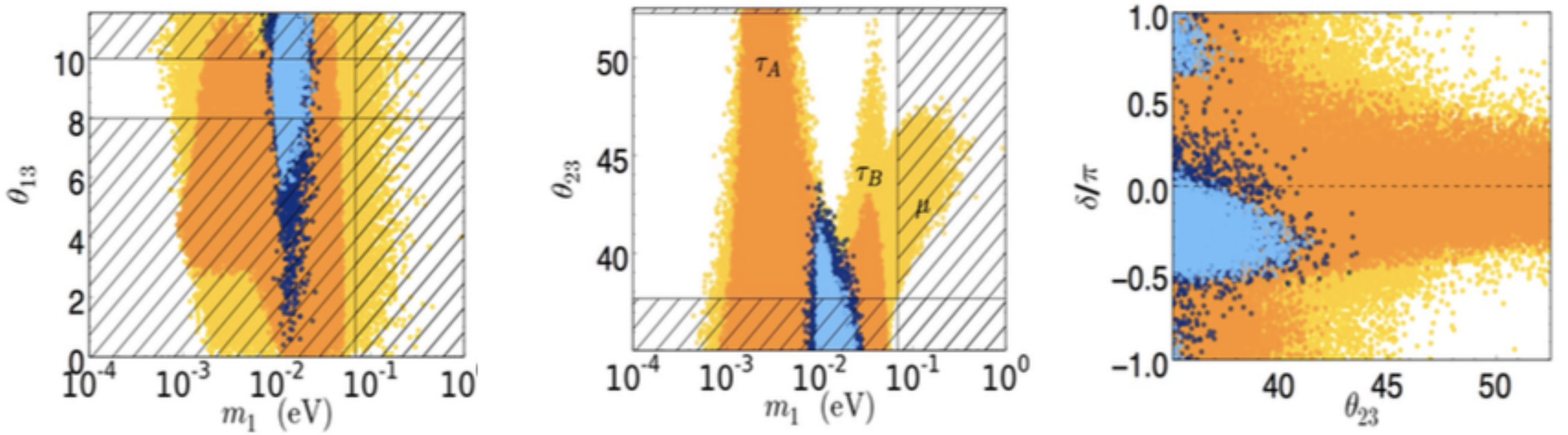
Strong thermal SO(10)-inspired (STSO10) solution

(PDB, Marzola 09/2011, DESY workshop; 1308.1107; PDB, Re Fiorentin, Marzola 1411.5478)

- Strong thermal leptonesis condition can be satisfied for a subset of the solutions only for NORMAL ORDERING

$\alpha_2=5$

- yellow regions: $N_{B-L}^{pre-ex}=0$ ($I \lesssim V_L \lesssim V_{CKM}$; $V_L = I$)
- blue regions: $N_{B-L}^{pre-ex}=10^{-3}$ ($I \lesssim V_L \lesssim V_{CKM}$; $V_L = I$)

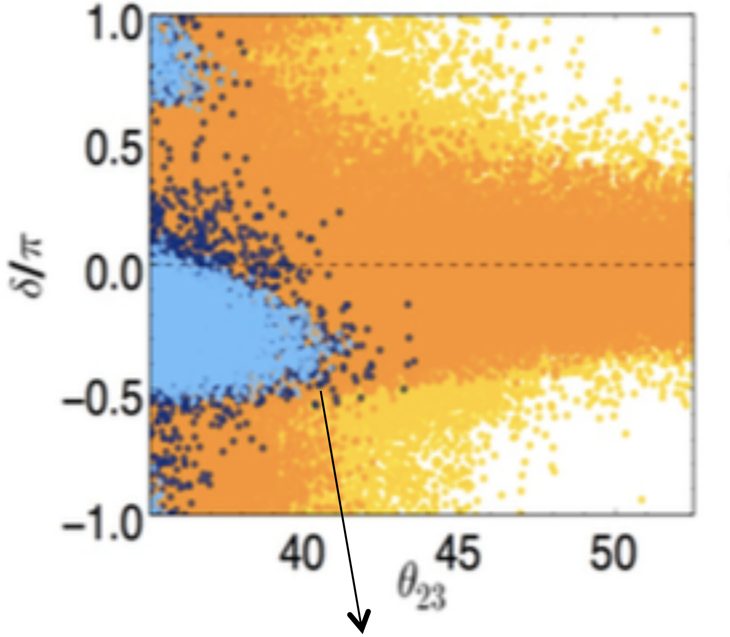


- Absolute neutrino mass scale: $8 \lesssim m_1/\text{meV} \lesssim 30 \Leftrightarrow 70 \lesssim \sum_i m_i/\text{meV} \lesssim 120$
- Non-vanishing Θ_{13};
- Θ_{23} strictly in the first octant;

Strong thermal SO(10)-inspired solution :δ vs. Θ_{23}

(PDB, Marzola, Invisibles workshop June 2012 and arXiv 1308.1107)

➢ NORMAL ORDERING

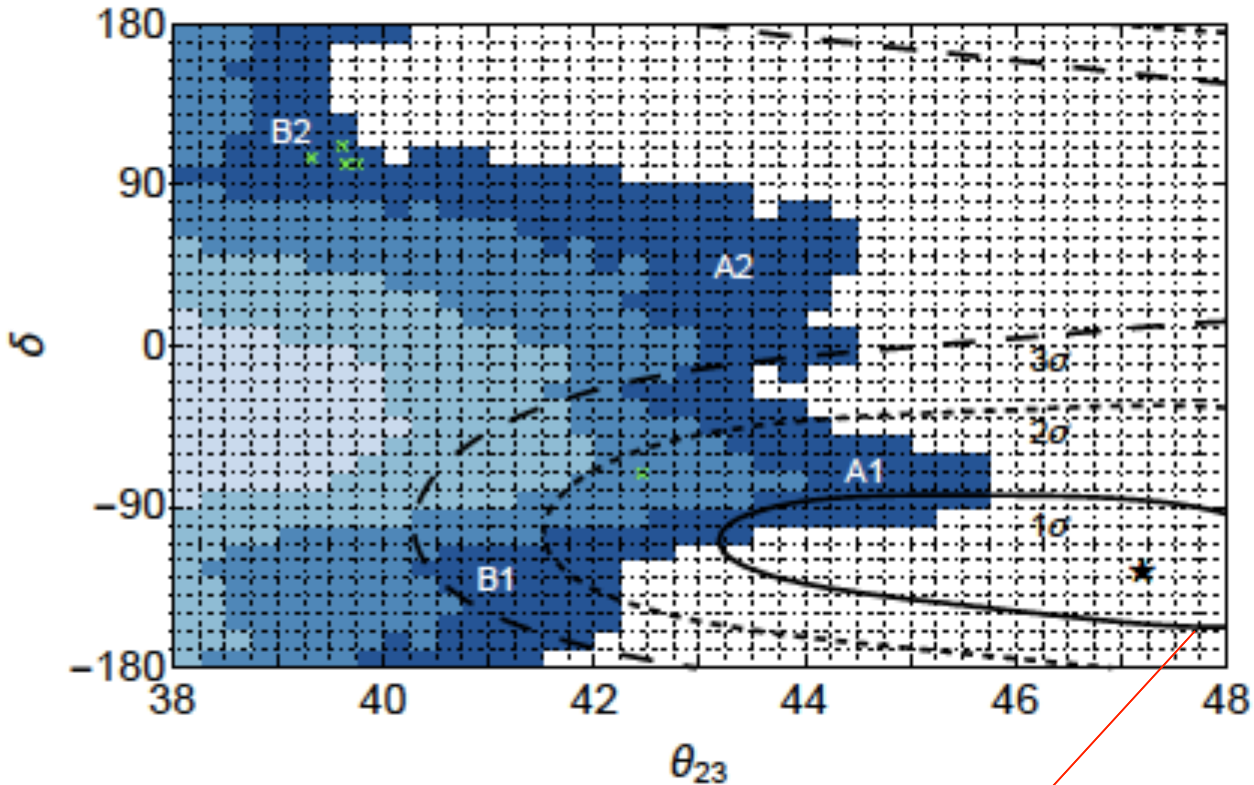


- For values of $\theta_{23} \gtrsim 38^0$ the Dirac phase is predicted to be $\delta \sim -60^0$: the exact range depends on Θ_{23} but in any case $\cos\delta > 0$
- The new experimental results seem to support this solution: a precise determination of Θ_{23} and δ can further test this solution.
- The current data also slightly favour NO compared to IO (at ~2σ)

Strong thermal SO(10)-inspired solution : δ vs. θ_{23}

(PDB, Marco Chianese 2018)

$$\alpha_2 = 5 \qquad N_{B-L}^{p,i} = 10^{-3}$$



Latest ν fit collaboration experimental constraints
(see http://www.nu-fit.org)

A popular class of SO(10) models

(Fritzsch, Minkowski, Annals Phys. 93 (1975) 193-266; R.Slansky, Phys.Rept. 79 (1981) 1-128; G.G. Ross, GUTs, 1985; Dutta, Mimura, Mohapatra, hep-ph/0507319; G. Senjanovic hep-ph/0612312)

In SO(10) models each SM particles generation + 1 RH neutrino are assigned to a single 16-dim representation. Masses of fermions arise from Yukawa interactions of two 16s with vevs of suitable Higgs fields. Since:

$$16 \otimes 16 = 10_{\rm S} \oplus \overline{126}_{\rm S} \oplus 120_{\rm A}\,,$$

The Higgs fields of renormalizable SO(10) models can belong to 10-, 126-,120-dim representations yielding Yukawa part of the Lagrangian

$$\mathcal{L}_Y = 16\,(Y_{10}10_H + Y_{126}\overline{126}_H + Y_{120}120_H)\,16\,.$$

After SSB of the fermions at M_{GUT}=2x10^{16} GeV one obtains the masses:

up-quark mass matrix	$M_u = v^u_{10}Y_{10} + v^u_{126}Y_{126} + v^u_{120}Y_{120}\,,$
down-quark mass matrix	$M_d = v^d_{10}Y_{10} + v^d_{126}Y_{126} + v^d_{120}Y_{120}\,,$
neutrino mass matrix	$M_D = v^u_{10}Y_{10} - 3v^u_{126}Y_{126} + v^D_{120}Y_{120}\,,$
charged lepton mass matrix	$M_l = v^d_{10}Y_{10} - 3v^d_{126}Y_{126} + v^l_{120}Y_{120}\,,$
RH neutrino mass matrix	$M_R = v^R_{126}Y_{126}\,,$
LH neutrino mass matrix	$M_L = v^L_{126}Y_{126}\,,$

Simplest case but clearly non-realistic: it predicts no mixing at all (both in quark and lepton Sectors). For realistic models one has to add at least the 126 contribution

NOTE: these models do respect SO(10)-inspired conditions

An example of realistic model:
SO(10)-inspired leptogenesis in the "A2Z model"

(S.F. King 2014)

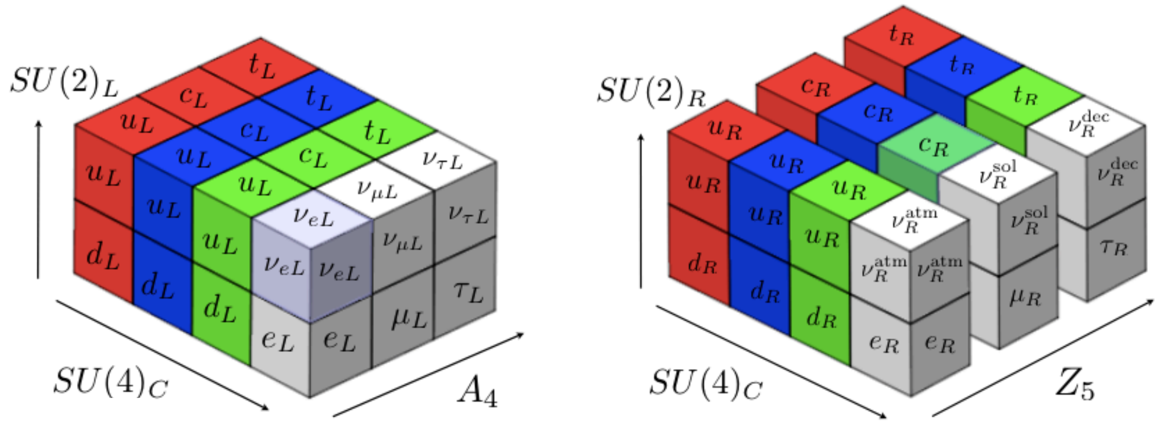


Figure 1: A to Z of flavour with Pati-Salam, where $A \equiv A_4$ and $Z \equiv Z_5$. The left-handed families form a triplet of A_4 and are doublets of $SU(2)_L$. The right-handed families are distinguished by Z_5 and are doublets of $SU(2)_R$. The $SU(4)_C$ unifies the quarks and leptons with leptons as the fourth colour, depicted here as white.

Neutrino sector:

$$Y'^{\nu}_{LR} = \begin{pmatrix} 0 & b e^{-i3\pi/5} & 0 \\ a e^{-i3\pi/5} & 4b e^{-i3\pi/5} & 0 \\ a e^{-i3\pi/5} & 2b e^{-i3\pi/5} & c e^{i\phi} \end{pmatrix}, \quad M'_R = \begin{pmatrix} M'_{11} e^{2i\xi} & 0 & M'_{13} e^{i\xi} \\ 0 & M'_{22} e^{i\xi} & 0 \\ M'_{13} e^{i\xi} & 0 & M'_{33} \end{pmatrix}$$

CASE A:

$$m^D_{\nu 1} = m_{\rm up}, \quad m^D_{\nu 2} = m_{\rm charm}, \quad m^D_{\nu 3} = m_{\rm top}$$

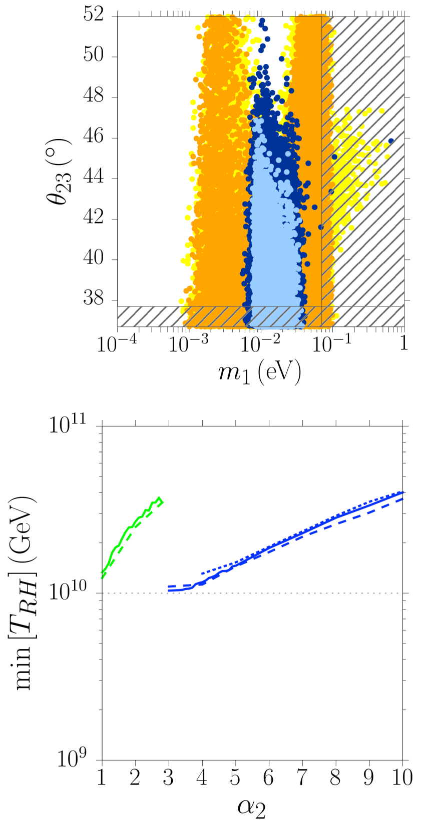
CASE B:

$$m^D_{\nu 1} \approx m_{\rm up}, \quad m^D_{\nu 2} \approx 3\, m_{\rm charm}, \quad m^D_{\nu 3} \approx \frac{1}{3}\, m_{\rm top}$$

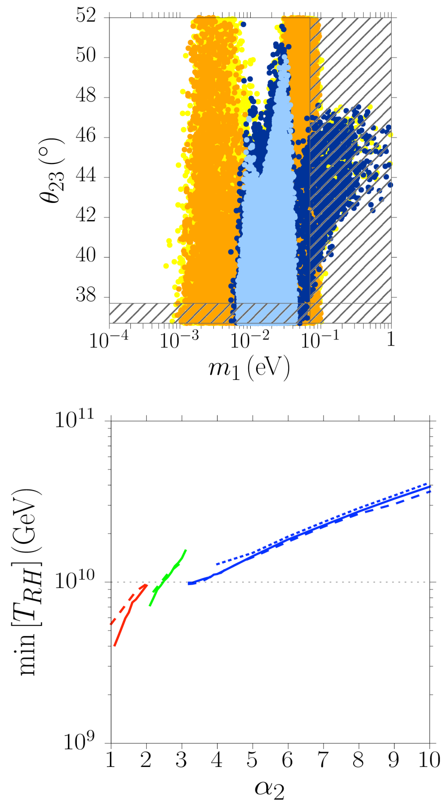
SUSY SO(10)-inspired leptogenesis

(PDB, Re Fiorentin, Marzola, 1512.06739)

tan β=5



tan β=50



It is possible to lower T_{RH} to values consistent with the gravitino problem for $m_g \gtrsim 30$ TeV

(Kawasaki, Kohri, Moroi, 0804.3745)

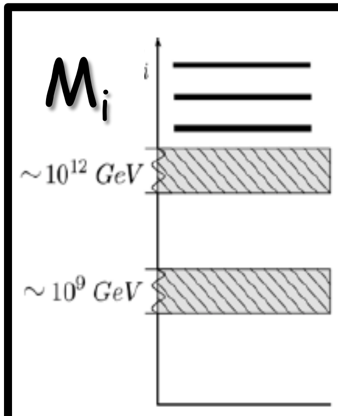
Alternatively, for lower gravitino masses, one has to consider non-thermal SO(10)-inspired leptogenesis

(Blanchet, Marfatia 1006.2857)

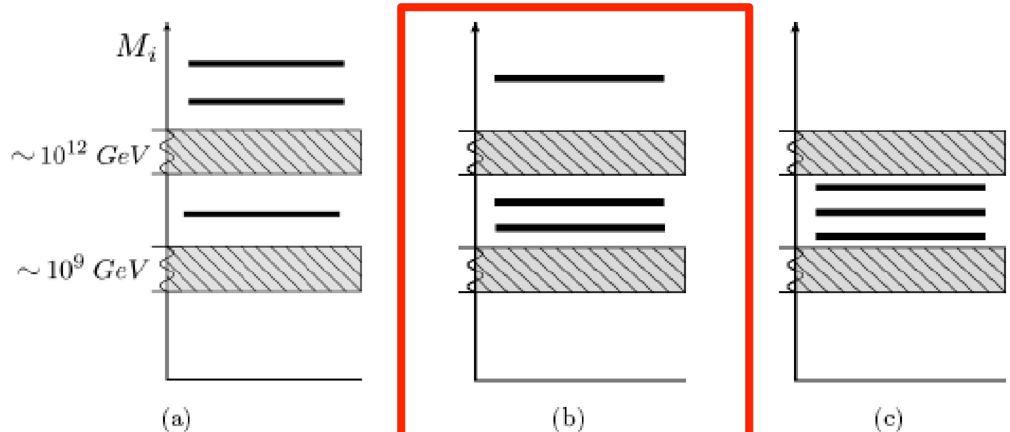
Heavy neutrino lepton flavour effects: 10 hierarchical scenarios

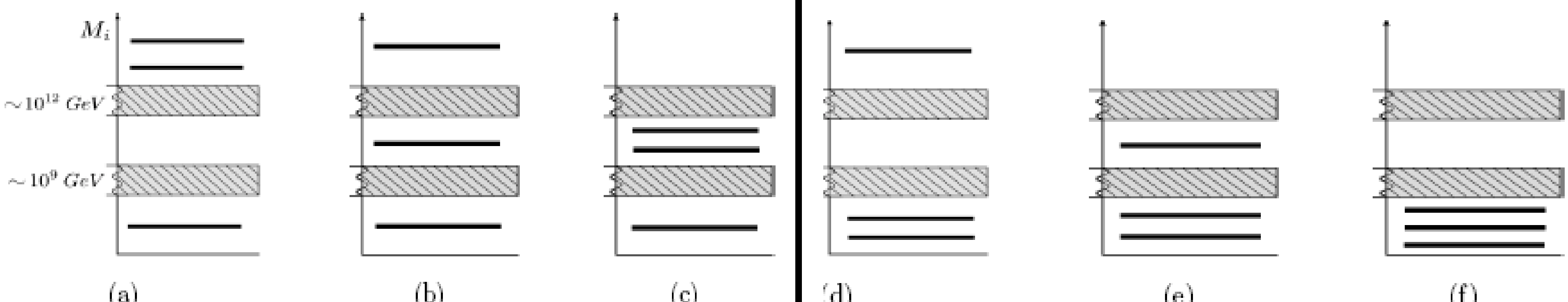
Typically rising in discrete flavour Models

Heavy neutrino flavored scenario



2 RH neutrino scenario



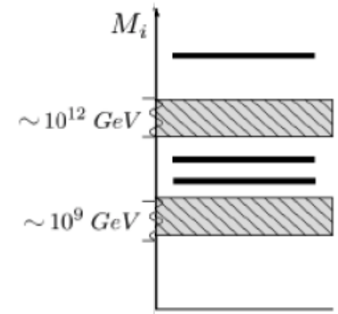


N_2 -dominated scenario:

- ☛ N_1 produces negligible asymmetry;
- ☛ It emerges naturally in SO(10)-inspired models;
- ☛ It is the only one that can realise STRONG THERMAL LEPTOGENESIS

2 RH neutrino models

(S.F. King hep-ph/9912492;Frampton,Glashow,Yanagida hep-ph/0208157;Ibarra,Ross2003; Antusch, PDB,Jones,King '11)



- They can be obtained from 3 RH neutrino models in the limit $M_3 \to \infty$
- Number of parameters get reduced to 11
- Contribution to asymmetry from both 2 RH neutrinos.

$$M_1 \gtrsim 2\text{x } 10^{10}\,\text{GeV} \Rightarrow T_{RH} \gtrsim 6 \times 10^9\,\text{GeV}$$

- 2 RH neutrino model can be also obtained from 3 RH neutrino models with 1 vanishing Yukawa eigenvalue ⇒ potential DM candidate

(A.Anisimov, PDB hep-ph/0812.5085)

An alternative solution: decoupling 1 RH neutrino ⇒ 2 RH neutrino seesaw

(Babu, Eichler, Mohapatra '89; Anisimov, PDB '08)

1 RH neutrino has vanishing Yukawa couplings (enforced by some symmetry such as Z_2):

$$m_D \simeq \begin{pmatrix} 0 & m_{De2} & m_{De3} \\ 0 & m_{D\mu 2} & m_{D\mu 3} \\ 0 & m_{D\tau 2} & m_{D\tau 3} \end{pmatrix}, \text{ or } \begin{pmatrix} m_{De1} & 0 & m_{De3} \\ m_{D\mu 1} & 0 & m_{D\mu 3} \\ m_{D\tau 1} & 0 & m_{D\tau 3} \end{pmatrix}, \text{ or } \begin{pmatrix} m_{De1} & m_{De2} & 0 \\ m_{D\mu 1} & m_{D\mu 2} & 0 \\ m_{D\tau 1} & m_{D\tau 2} & 0 \end{pmatrix},$$

What production mechanism? Turning on tiny Yukawa couplings?

Yukawa basis:

$$m_D = V_L^\dagger \, D_{m_D} \, U_R \,.$$

$$D_{m_D} \equiv v \, \mathrm{diag}(h_A, h_B, h_C), \text{ with } h_A \leq h_B \leq h_C.$$

$$\tau_{\rm DM} = \frac{4\pi}{h_A^2 \, M_{\rm DM}} \simeq 0.87 \, h_A^{-2} \, 10^{-23} \left(\frac{\rm GeV}{M_{\rm DM}}\right) \, {\rm s}$$

$$\Rightarrow \quad \tau_{DM} > \tau_{DM}^{\min} \simeq 10^{28} s \Rightarrow h_A < 3\times 10^{-26} \sqrt{\frac{GeV}{M_{DM}} \times \frac{10^{28} s}{\tau_{DM}^{\min}}}$$

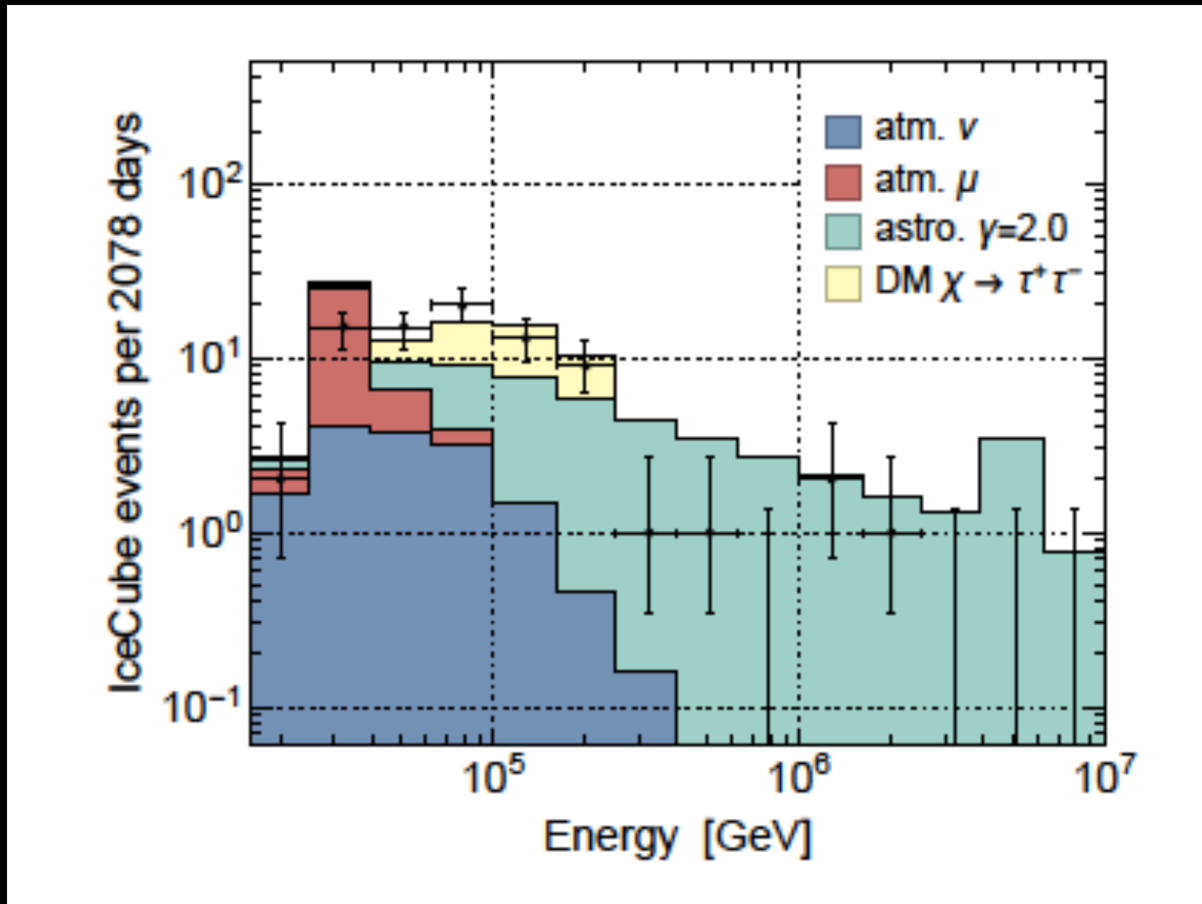
One could think of an abundance induced by RH neutrino mixing, considering that:

$$N_{DM} \simeq 10^{-9} (\Omega_{DM,0} h^2) N_\gamma^{prod} \frac{TeV}{M_{DM}}$$

It would be enough to convert just a tiny fraction of ("source") thermalised RH neutrinos but it still does not work with standard Yukawa couplings

An excess at E~100 TeV?

(Chianese, Morisi, Miele 1707.05241)



Proposed production mechanisms

Starting from a 2 RH neutrino seesaw model

$$m_D \simeq \begin{pmatrix} 0 & m_{De2} & m_{De3} \\ 0 & m_{D\mu2} & m_{D\mu3} \\ 0 & m_{D\tau2} & m_{D\tau3} \end{pmatrix}, \text{ or } \begin{pmatrix} m_{De1} & 0 & m_{De3} \\ m_{D\mu1} & 0 & m_{D\mu3} \\ m_{D\tau1} & 0 & m_{D\tau3} \end{pmatrix}, \text{ or } \begin{pmatrix} m_{De1} & m_{De2} & 0 \\ m_{D\mu1} & m_{D\mu2} & 0 \\ m_{D\tau1} & m_{D\tau2} & 0 \end{pmatrix},$$

many production mechanisms have been proposed:

- from $SU(2)_R$ extra-gauge interactions (LRSM) (Fornengo,Niro, Fiorentin);
- from inflaton decays (Anisimov,PDB'08; Higaki, Kitano, Sato '14);
- from resonant annihilations through SU(2)' extra-gauge interactions (Dev, Kazanas,Mohapatra,Teplitz, Zhang '16);
- From new $U(1)_Y$ interactions connecting DM to SM (Dev, Mohapatra,Zhang '16);
- From $U(1)_{B-L}$ interactions (Okada, Orikasa '12);
- ....

In all these models IceCube data are fitted through fine tuning of parameters responsible for decays (they are post-dictive)

RH neutrino mixing from Higgs portal

(Anisimov, PDB '08)

Assume new interactions with the **standard** Higgs:

$$\mathcal{L} = \frac{\lambda_{IJ}}{\Lambda}\,\phi^\dagger\,\phi\,\overline{N_I^c}\,N_J \qquad (I,J=A,B,C)$$

In general they are non-diagonal in the Yukawa basis: this generates a RH neutrino mixing.
Consider a 2 RH neutrino mixing for simplicity and consider medium effects:

From the Yukawa interactions: $V_J^Y = \frac{T^2}{8\,E_J}\,h_J^2$

From the new interactions: $V_{JK}^{\Lambda} \simeq \frac{T^2}{12\,\Lambda}\,\lambda_{JK}$

effective mixing Hamiltonian (in monocromatic approximation)

$$\Delta H \simeq \begin{pmatrix} -\frac{\Delta M^2}{4p} - \frac{T^2}{16p}\,h_S^2 & \frac{T^2}{12\widetilde{\Lambda}} \\ \frac{T^2}{12\widetilde{\Lambda}} & \frac{\Delta M^2}{4p} + \frac{T^2}{16p}\,h_S^2 \end{pmatrix} \Rightarrow \sin 2\theta_\Lambda^m = \frac{\sin 2\theta_\Lambda}{\sqrt{\left(1+v_S^Y\right)^2 + \sin^2 2\theta_\Lambda}}$$

$$\Delta M^2 \equiv M_S^2 - M_{DM}^2.$$

$$v_S^Y \equiv T^2\,h_S^2/(4\,\Delta M^2)$$

If $\Delta m^2 < 0$ ($M_{DM} > M_S$) There is a resonance for $v_S^Y=-1$ at:

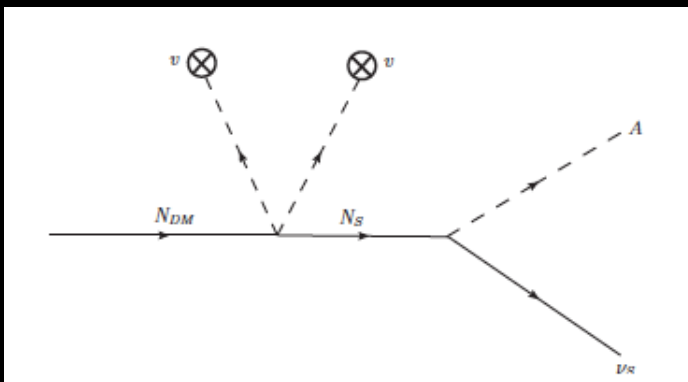
$$z_{res} \equiv \frac{M_{DM}}{T_{res}} = \frac{h_S\,M_{DM}}{2\sqrt{M_{DM}^2 - M_S^2}} \Rightarrow \Omega_{DM}\,h^2 \simeq \frac{0.15}{\alpha_S\,z_{res}}\left(\frac{M_{DM}}{M_S}\right)\left(\frac{10^{20}\,\text{GeV}}{\widetilde{\Lambda}}\right)^2\left(\frac{M_{DM}}{\text{GeV}}\right)$$

Constraints from decays

(Anisimov,PDB '08; Anisimov,PDB'10; P.Ludl.PDB,S.Palomarez-Ruiz'16)

2 body decays

DM neutrinos unavoidably decay today into A+leptons (A=H,Z,W) through the same mixing that produced them in the very early Universe



$$\theta_\Lambda^0 = \left(\frac{v^2}{\widetilde{\Lambda}}\right)^2 \frac{1}{\Gamma_S^2/4 + M_S^2\,\delta_{\rm DM}^2}$$

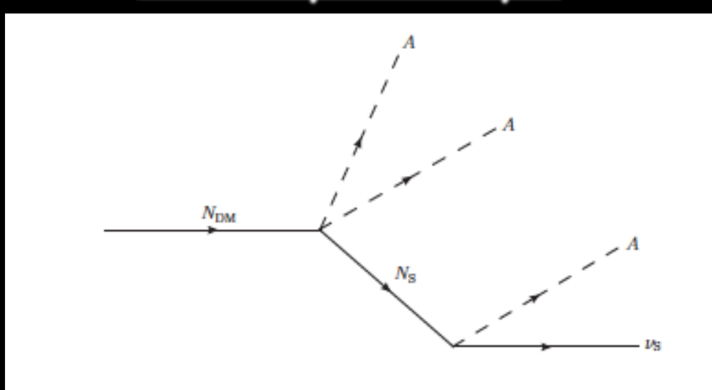
mixing angle today

Lower bound on M_{DM} ($\tau_{28} \equiv \tau_{DM}^{min}/10^{28}$s)

$$M_{\rm DM} \geq M_{\rm DM}^{\rm min} \simeq 2.5\times 10^{12}\, z_{\rm res}^{5/3}\, \tau_{28}^{1/3} \left[\frac{(1+M_{\rm S}/M_{\rm DM})^2}{4\,M_{\rm DM}/M_{\rm S}}\right]^{1/3} {\rm GeV}$$

4 body decays

$$N_{\rm DM} \to 2\,A + N_{\rm S} \to 3\,A + \nu_{\rm S}\ (A = W^\pm, Z, H).$$

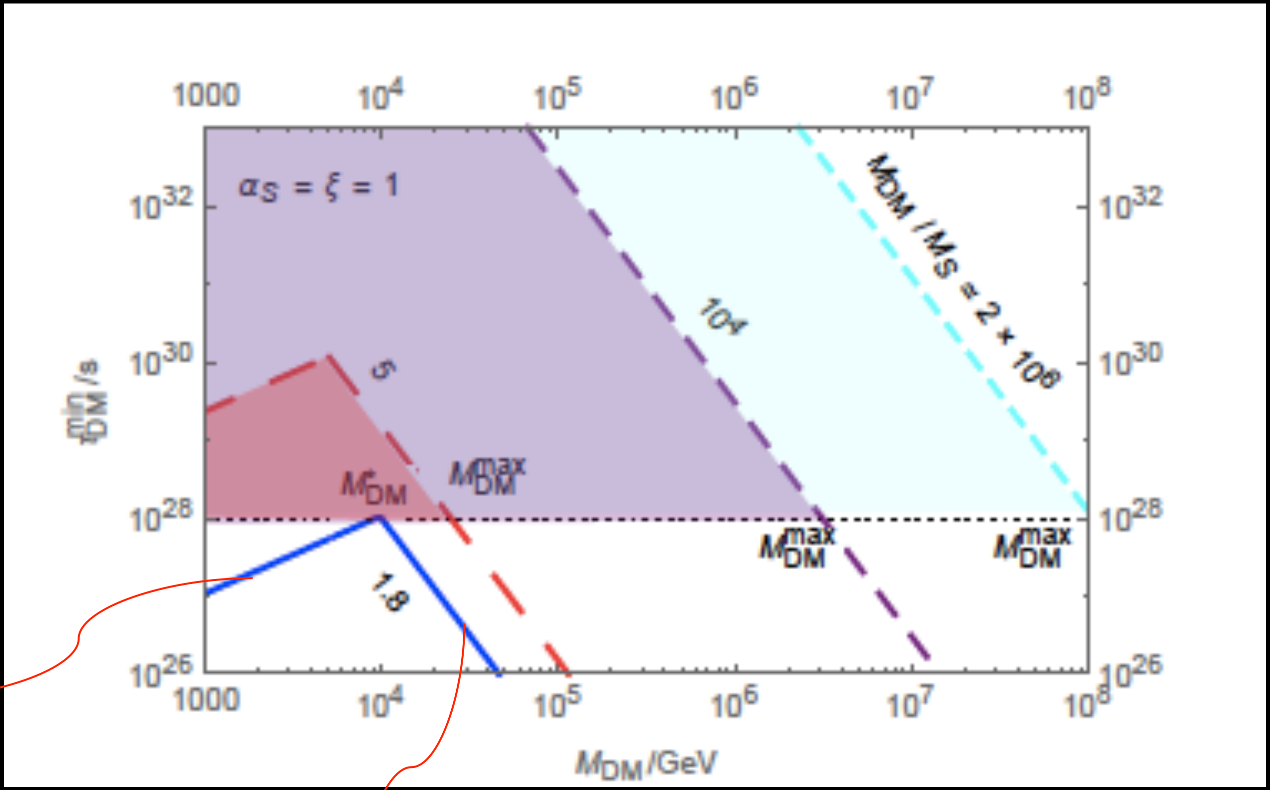


Upper bound on M_{DM} ($\tau_{28} \equiv \tau_{DM}^{min}/10^{28}$s)

$$M_{\rm DM} \lesssim M_{\rm DM}^{{\rm max}(A)} \simeq \frac{5\times 10^3\,{\rm GeV}}{\alpha_{\rm S}^{2/3}\, z_{\rm res}^{1/3}\, \tau_{28}^{1/3}} \left(\frac{M_{\rm DM}}{M_{\rm S}}\right)^{2/3}$$

3 body decays and annihilations also can occur but yield weaker constraints

Decays: a natural allowed window on M_{DM}



Lower bound from 2 body decays

Upper bound from 4 body decays

Increasing M_{DM}/M_S relaxes the constraints since it allows higher T_{res} (⇒more efficient production) keeping small N_S Yukawa coupling (helping stability)! But there Is an upper limit to T_{res} from usual upper limit on reheat temperature.

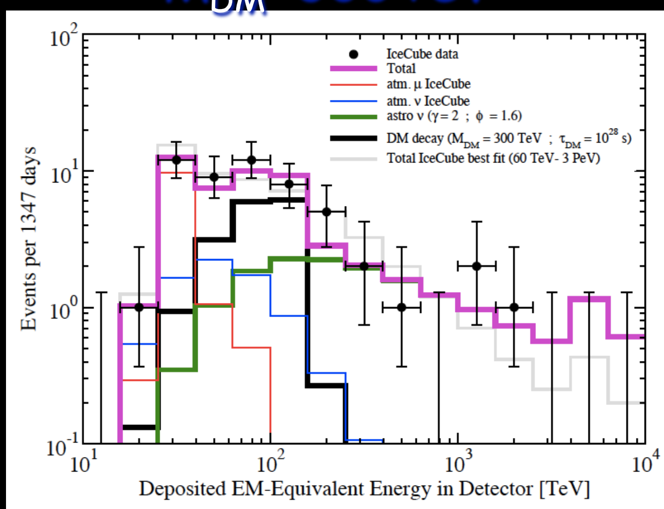
Decays:very high energy neutrinos at IceCube

(P.Ludl.PDB,S.Palomarez-Ruiz'16)

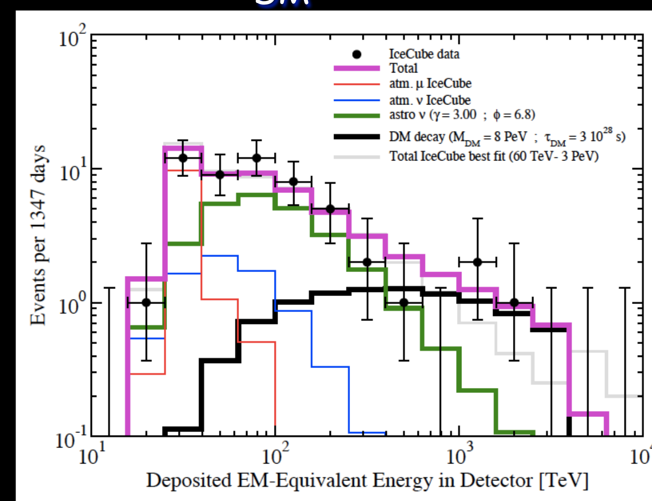
- Since the same interactions responsible for production also unavoidably induce decays ⇒ the model predicts high energy neutrino flux component at some level ⇒ testable at neutrino telescopes (Anisimov,PDB '08)

Neutrino events at IceCube: 2 examples of fits where a DM component in addition to an astrophysical component helps fitting HESE data:

M_{DM}=300TeV



M_{DM}=8 PeV



- Some authors claim there is an excess at (60-100) TeV taking into account also MESE data (Chianese,Miele,Morisi '16)

- But where are the γ 's in FERMI? Multimessenger analysis is crucial.