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Leptogenesis and Baryogenesis

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Plan

- Lecture I: Cosmological background;
  Matter-antimatter asymmetry of the universe
  and models of Baryogenesis,

- Lecture II: Neutrino physics and Leptogenesis

- Lecture III: Leptogenesis and BSM physics

Lecture I

Cosmological background; Matter-antimatter asymmetry and models of Baryogenesis

References

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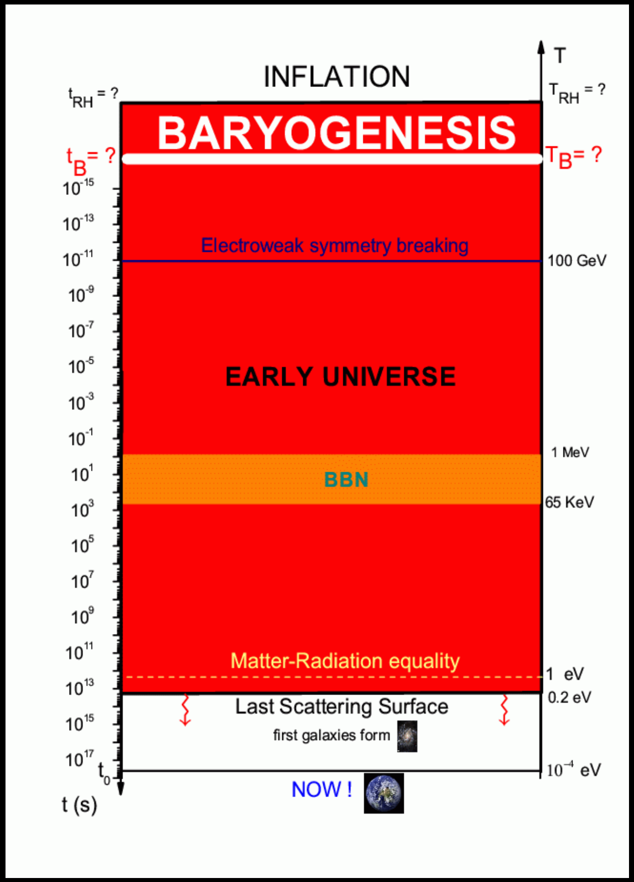

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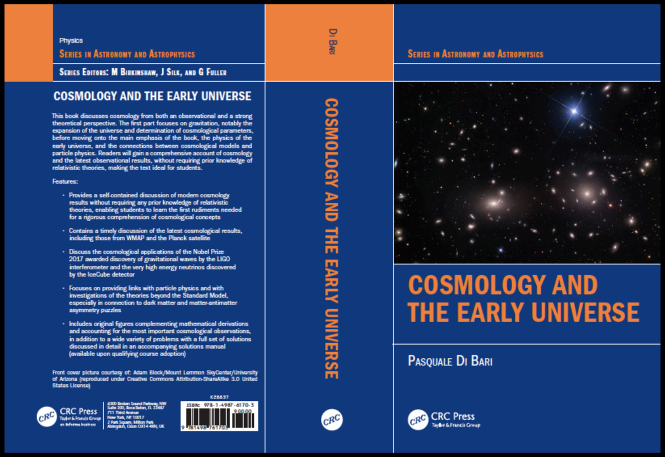


Geometry of the Universe

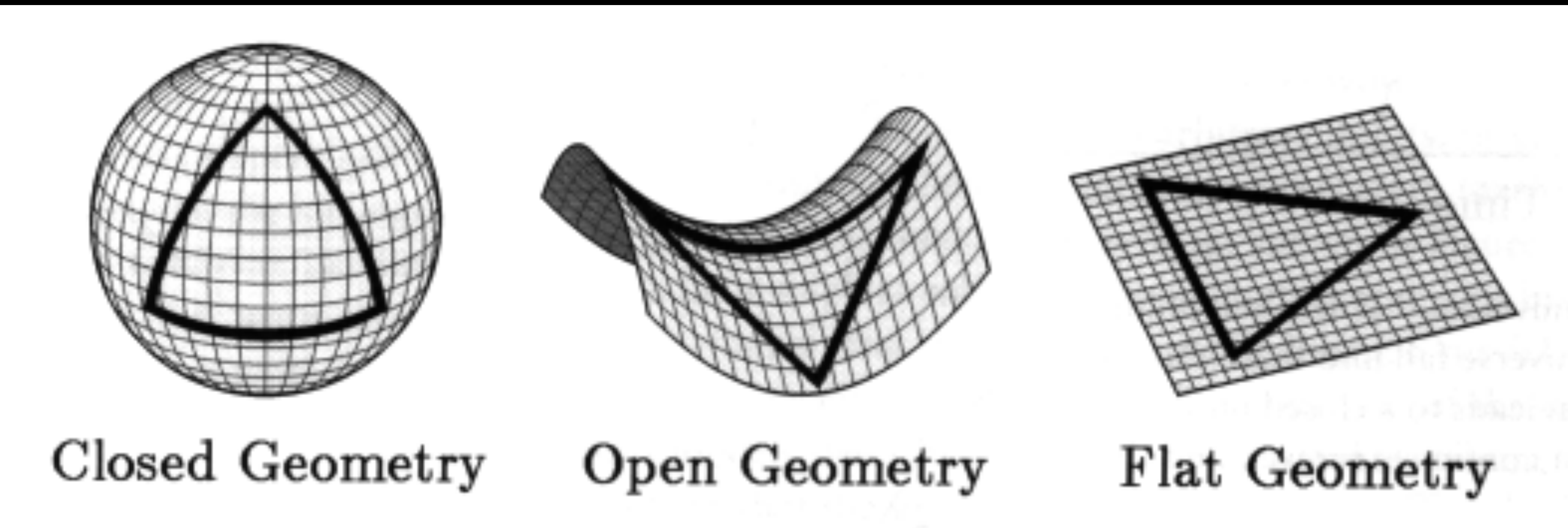
Assuming homogeneity and isotropy of space (cosmological principle)

⇒ Friedmann-Robertson-Walker metric (comoving system):

$$ds^2 = c^2\, dt^2 - a^2(t)\, R_0^2 \left(\frac{dr^2}{1 - k\, r^2} + r^2\, d\Omega^2\right)$$

$a(t) \equiv R(t)/R_0$ is the *scale factor*

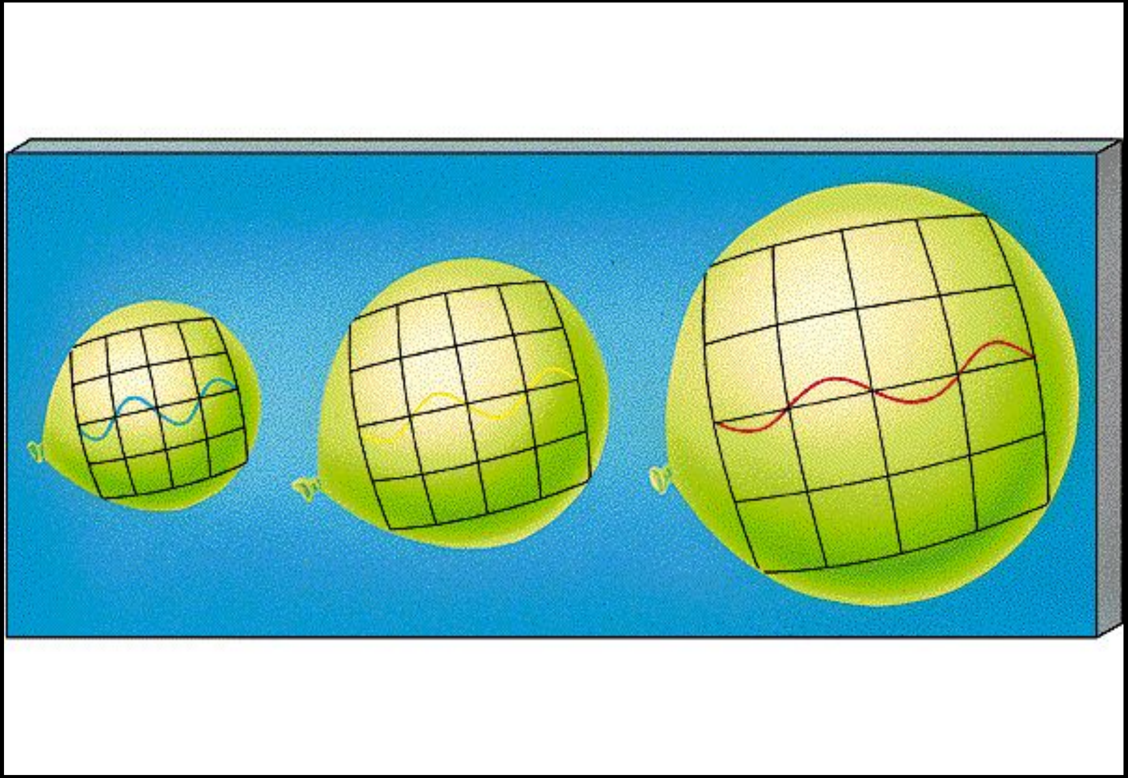
κ=+1 κ=-1 κ=0



Cosmological redshift

For photons: $|\vec{p}| = \hbar/\lambda$ $\Rightarrow$ $\lambda(t) = \lambda_0 \frac{R(t)}{R_0} = a(t)\,\lambda_0\,.$

The wavelength of photons is "stretched by the expansion" !



$$z \equiv \frac{\lambda_0}{\lambda_{\rm em}} - 1 \equiv \frac{R_0}{R_{\rm em}} - 1 = a_{\rm em}^{-1} - 1$$

Hubble's law from theory

$d_{pr,0}$

Proper distance

$$d_{\rm pr}(t) = a(t)\, R_0 \int_0^r \frac{dr'}{\sqrt{1 - k\, r'^2}} \Rightarrow \dot{d}_{\rm pr}(t) = \dot{a}(t)\, d_{\rm pr}(t_0)$$

Expansion rate

$$H(t) \equiv \frac{\dot{a}}{a}$$

Proper velocity

$$v_{\rm pr}(t) \equiv \dot{d}_{\rm pr}(t)$$

Lemaitre's equation

$$\dot{d}_{\rm pr}(t) = \dot{a}(t)\, d_{\rm pr,0}\,.$$

At the present time one can relate the proper distance to the luminosity distance and redshift:

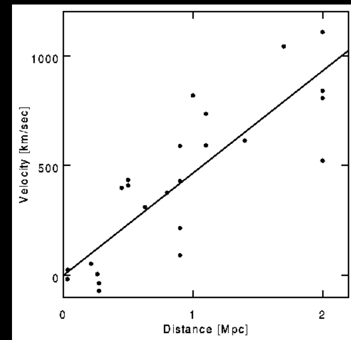
$$d_L(z) = (1+z)\, d_{\rm pr,0}(z) = c\, H_0^{-1} \left[z + z^2 \left(\frac{1-q_0}{2} \right) \right] + \mathcal{O}(z^3)\,.$$

Hubble's law

$$d_L(z) = c\, H_0^{-1}\, z + \mathcal{O}(z^2)$$

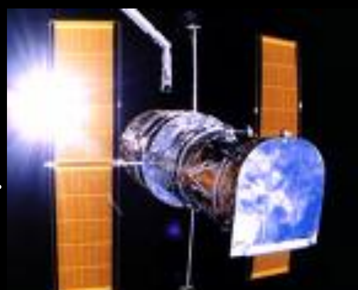
Hubble constant measurements

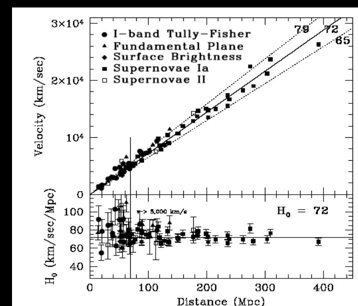
Edwin Hubble (1929)



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

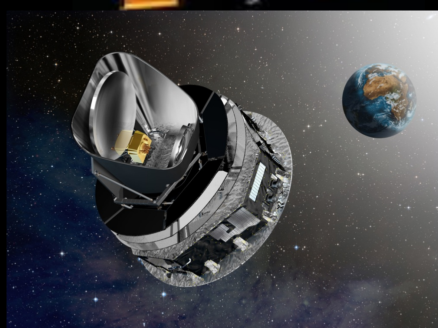
Hubble Space Telescope Key Project (2001)

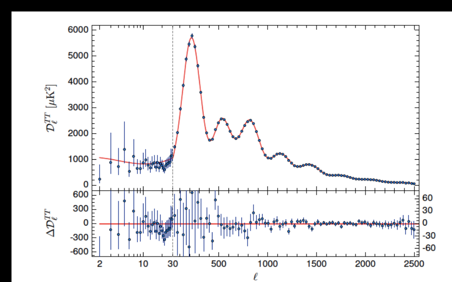




$$H_0 = (72 \pm 8)\, km\, s^{-1} Mpc^{-1}$$

Planck 2015 +ΛCDM



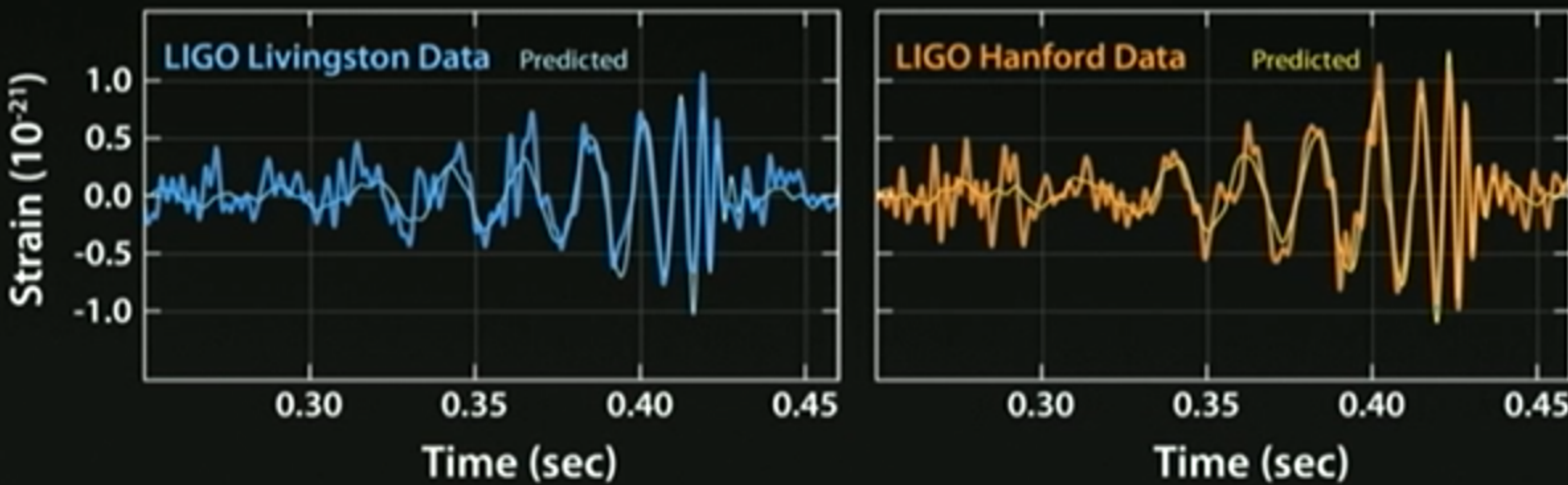


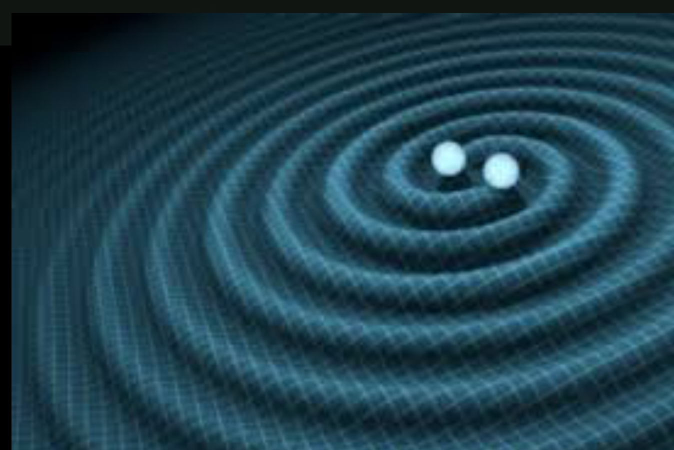
$$H_0 = (67.3 \pm 1.2)\, \mathrm{km\, s^{-1}\, Mpc^{-1}}$$

3.7σ tension

Hubble Space Telescope , Riess et al. (2018)

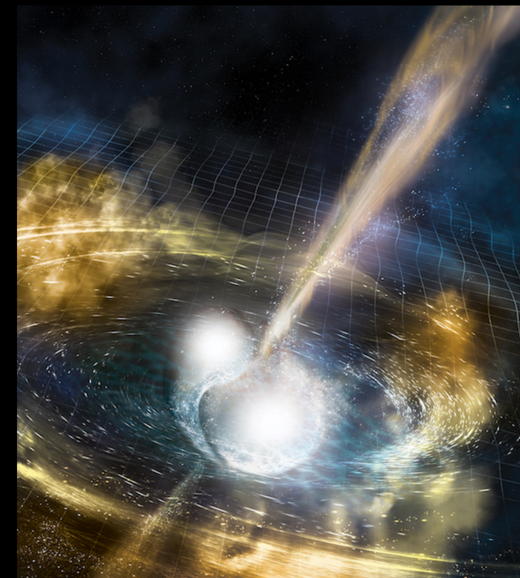
$$H_0 = (73.48 \pm 1.66)\, \mathrm{km\, s^{-1}\, Mpc^{-1}}$$

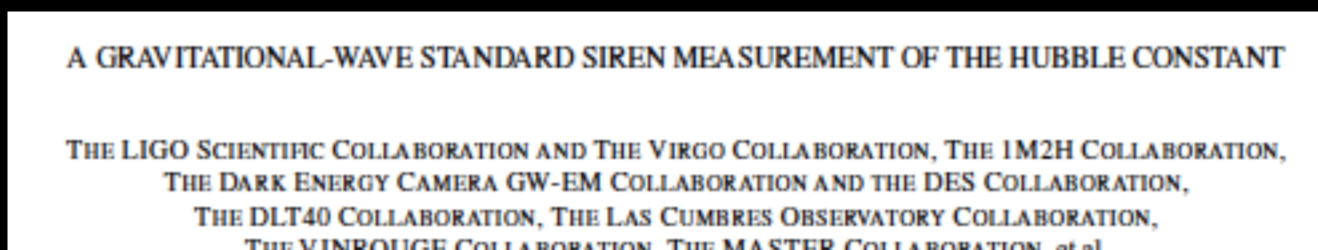

LIGO Livingston Data
Predicted
LIGO Hanford Data
Predicted
Strain (10-21)
1.0
0.5
0.0
-0.5
-1.0
0.30
0.35
0.40
0.45
Time (sec)
Time (sec)



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

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

~50 more detections of standard sirens should reduce the error below and solve the current tension between Planck and HST measurements

Fundamental equations of Friedmann cosmology

Einstein equations

$$G_{\mu\nu} = 8\pi G\, T_{\mu\nu} \;\Rightarrow\; \left(\frac{\dot a}{a}\right)^2 \equiv H^2 = \frac{8\pi G}{3}\varepsilon - \frac{k}{a^2 R_0^2}$$

Friedmann equation

Energy-momentum tensor conservation

$$T^{\mu\nu}{}_{;\nu} = 0 \;\Rightarrow\; \frac{d(\varepsilon a^3)}{dt} = -p\frac{da^3}{dt}$$

Fluid equation

Friedmann equation + Fluid equation

$$\Rightarrow\; \ddot a = -4\pi G(\varepsilon + 3p)a$$

acceleration equation

Critical energy density

$$\varepsilon_c \equiv \frac{3H^2}{8\pi G}$$

energy density parameter

$$\Omega \equiv \frac{\varepsilon}{\varepsilon_c} = \sum_i \Omega_{X_i}$$

$$k \equiv H_0^2 R_0^2 (\Omega_0 - 1) \;\Rightarrow$$

- $\Omega_0 < 1 \Leftrightarrow k = -1 \;\Leftrightarrow$ open Universe
- $\Omega_0 = 1 \Leftrightarrow k = 0 \;\Leftrightarrow$ flat Universe ;
- $\Omega_0 > 1 \Leftrightarrow k = +1 \Leftrightarrow$ closed Universe

Building a cosmological model: general strategy

- Assume an equation of state: $p=p(\varepsilon)$
- Plug the equation of state into the fluid equation

$$\frac{d(\varepsilon a^3)}{dt} = -p\frac{da^3}{dt} \Rightarrow \varepsilon = \varepsilon(a)$$

- Finally plug $\varepsilon(a)$ into the Friedmann equation

$$\dot{a}^2(t) = H_0^2\,\Omega_0\,a^2(t)\,\frac{\varepsilon(t)}{\varepsilon_0} + H_0^2\,(1-\Omega_0) \Rightarrow a=a(t) \Rightarrow \varepsilon = \varepsilon(t)$$

- Example: Matter universe

$p_M=0 \Rightarrow \varepsilon_M = \varepsilon_{M0}/a^3 \Rightarrow$ (flat universe) $a(t)= (t/t_0)^{2/3}$, $t_0=2H_0^{-1}/3$

Flat Universe with 1 fluid : summary of the results

	equation of state	fluid equation	Friedmann equation (Flat Universe)	Age of the Universe (Flat Universe)	energy density vs. time (Flat Universe)
Matter Universe	$p_M = 0$	$\varepsilon_M(a) = \frac{\varepsilon_{M,0}}{a^3} \propto a^{-3}$	$a(t) = \left(\frac{t}{t_0}\right)^{\frac{2}{3}}$	$t_0 = \frac{2}{3} H_0^{-1} = (9.40 \pm 0.15)\,\mathrm{Gyr}$	$\varepsilon_M(t) = \varepsilon_0 \left(\frac{t_0}{t}\right)^2$
Radiation Universe	$p_R = \frac{1}{3}\varepsilon_R$.	$\varepsilon_R = \frac{\varepsilon_{R,0}}{a^4} \propto a^{-4}$	$a(t) = \left(\frac{t}{t_0}\right)^{1/2}$	$t_0 = \frac{1}{2} H_0^{-1} = (7.05 \pm 0.12)\,\mathrm{Gyr}$	$\varepsilon_R(t) = \varepsilon_0 \left(\frac{t_0}{t}\right)^2$
	if	$\varepsilon_R \propto T_R^4, \Rightarrow T_R \propto a^{-1}$			
Fluids with constant p/ε	$p = \omega\,\varepsilon$ $(\omega \neq -1)$	$\varepsilon(a) = \frac{\varepsilon_0}{a^{3(1+\omega)}}$	$a(t) = \left(\frac{t}{t_0}\right)^{\frac{2}{3(1+\omega)}}$ $\omega > -1$	$t_0 = \frac{2}{3(1+\omega)} H_0^{-1}$	$\varepsilon(t) = \varepsilon_0 \left(\frac{t_0}{t}\right)^2$
de Sitter model	p=-ε ω=-1	$\varepsilon = \varepsilon_0 = \mathrm{const}$	$a(t) = e^{H_0 (t - t_0)}$	INFINITE !	$\varepsilon = \varepsilon_0 = \mathrm{const}$

Matter-radiation equality

Consider and admixture of 2 fluids: matter (M) and radiation (R) :

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

with equations of state:

$$p_M = 0, \; p_R = \frac{1}{3}\varepsilon_R \; ,$$

That, from the fluid equation, lead to :

$$\varepsilon_M = \frac{\varepsilon_{M,0}}{a^3}, \quad \varepsilon_R = \frac{\varepsilon_{R,0}}{a^4}$$

The equality matter-radiation time is defined as:

$$\frac{\varepsilon_{M0}}{a_{eq}^3} = \frac{\varepsilon_{R0}}{a_{eq}^4} \Rightarrow a_{eq} = \frac{\varepsilon_{R0}}{\varepsilon_{M0}} = \frac{\Omega_{R0}}{\Omega_{M0}}$$

Friedmann cosmology as a conservative system

In terms of H_0 and Ω_0 the Friedmann equation can be recast as:

$$\frac{\dot{a}^2}{H_0^2} = \Omega_0 \frac{\varepsilon a^2}{\varepsilon_0} + (1 - \Omega_0)$$

If $\varepsilon = \varepsilon(a)$ then we can define:

$$V(a) = -\Omega_0 \frac{\varepsilon a^2}{\varepsilon_0}, \quad E_0 \equiv 1 - \Omega_0 \;\Rightarrow\; \frac{\dot{a}^2}{H_0^2} + V(a) \equiv E(a) = E_0$$

Showing that the Friedmann equation has an integral of motion, E(a) , and is, therefore, a conservative system: this will be useful to find the set of solutions for specific models

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:

$$p_M = 0, \; p_R = \frac{1}{3}\varepsilon_R, \; p_\Lambda = -\varepsilon_\Lambda$$

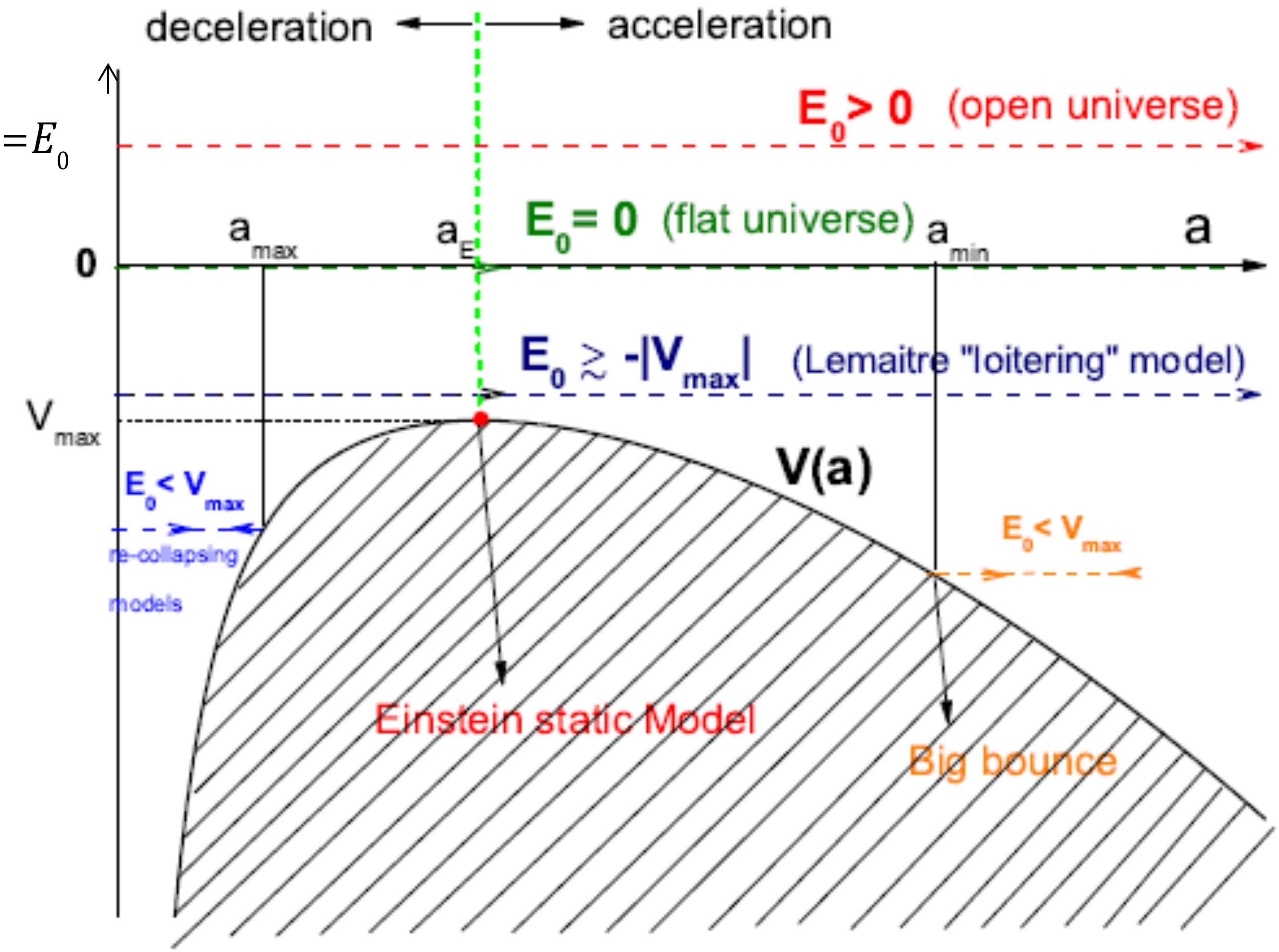
That, from the fluid equation, lead to :

$$\varepsilon_M = \frac{\varepsilon_{M,0}}{a^3}, \; \varepsilon_R = \frac{\varepsilon_{R,0}}{a^4}, \quad \varepsilon_\Lambda = \varepsilon_{\Lambda,0}$$

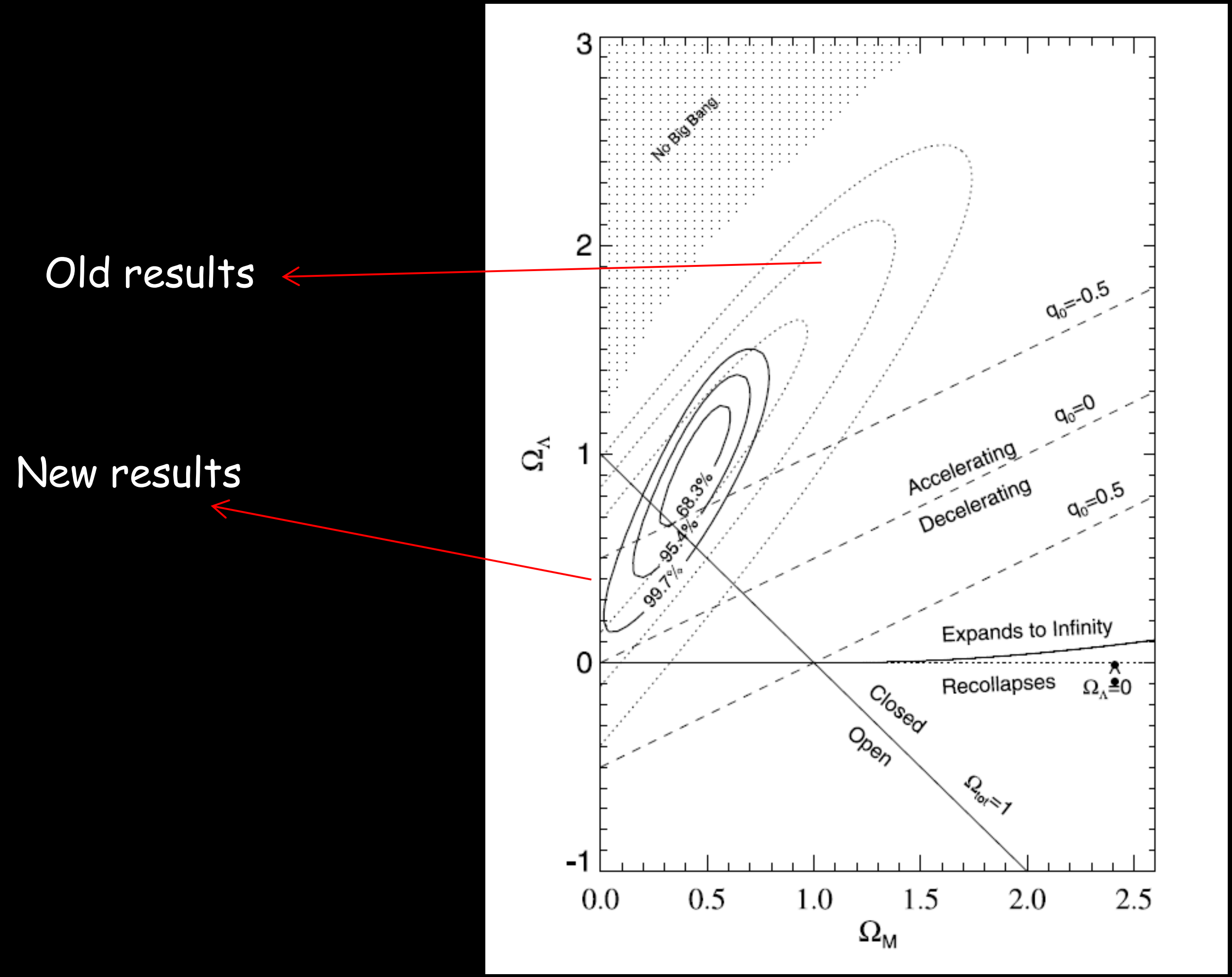
$$\Rightarrow V(a) = -a^2\left(\frac{\Omega_{R,0}}{a^4} + \frac{\Omega_{M,0}}{a^3} + \Omega_{\Lambda,0}\right)$$

Lemaitre models

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

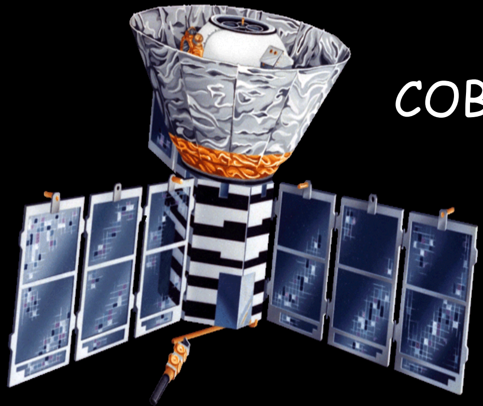


Supernovae type Ia

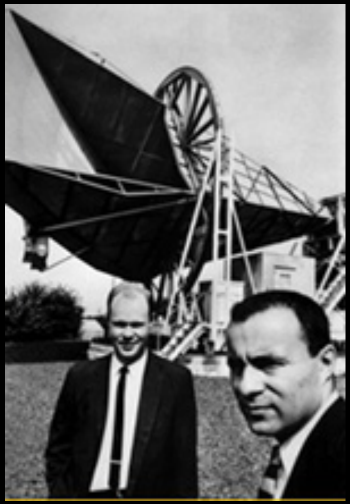


A. G. Riess *et al.* [Supernova Search Team Collaboration], *Type Ia Supernova Discoveries at z¿1 From the Hubble Space Telescope: Evidence for Past Deceleration and Constraints on Dark Energy Evolution*, Astrophys. J. **607** (2004) 665.

The discovery of the cosmic microwave background radiation



COBE satellite

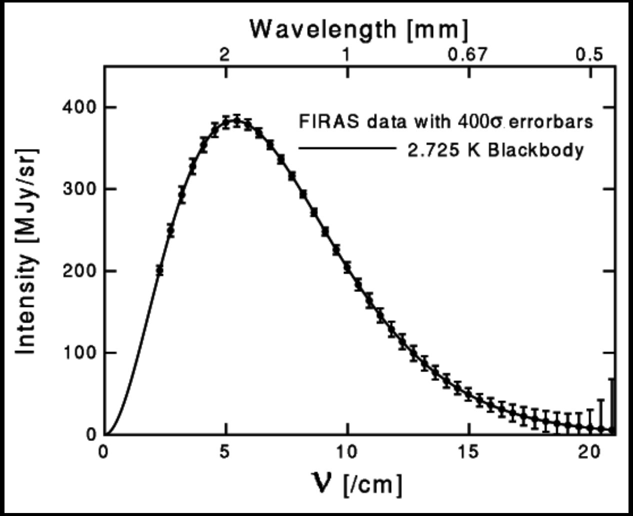


Penzias and Wilson (1965)

$T_{\gamma 0} = (3.5 \pm 1)\ ^0K$

FIRAS instrument of COBE (1990)

$T_{\gamma 0} = (2.725 \pm 0.002)\ ^0K \Rightarrow n_{\gamma 0} \simeq 411\ \ cm^{-3}$



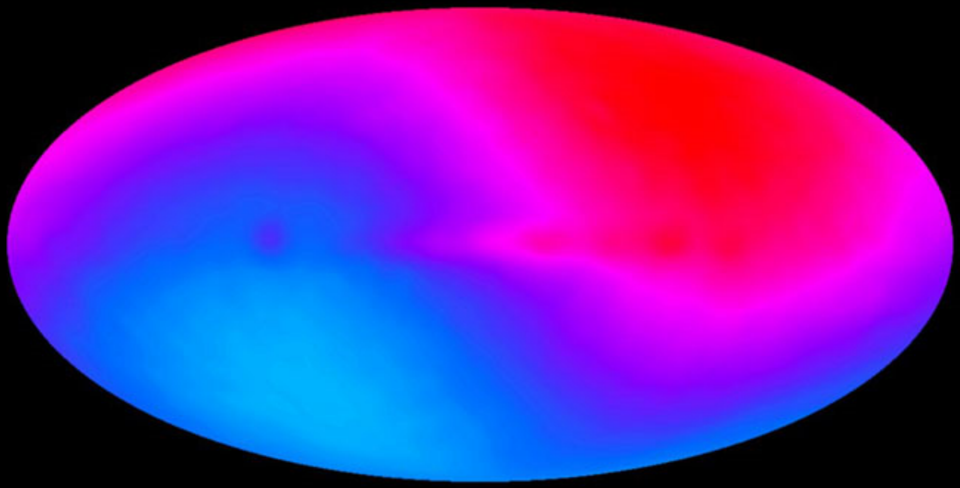
$\Rightarrow\ \Omega_{\gamma 0} \simeq 0.54 \times 10^{-4}$

$$\frac{\Delta T}{T}(\theta,\phi) = \sum_{\ell=0}^{\infty} \sum_{m=-\ell}^{m=\ell} a_{\ell m} Y_{\ell m}(\theta,\phi) \, .$$

$$\Delta\theta = \frac{180°}{\ell} .$$

Example: the dipole anisotropy (ΔΘ=180°) corresponds to l =1

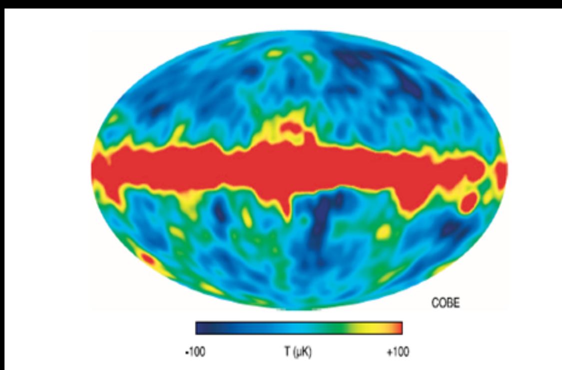
COBE DMR microwave map of the sky in Galactic coordinates: temperature variation with respect to the mean value <T> =2.725 K. The color change indicates a fluctuation of $\Delta T \sim 3.5$ mK $\Rightarrow \Delta T/T \sim 10^{-3}$



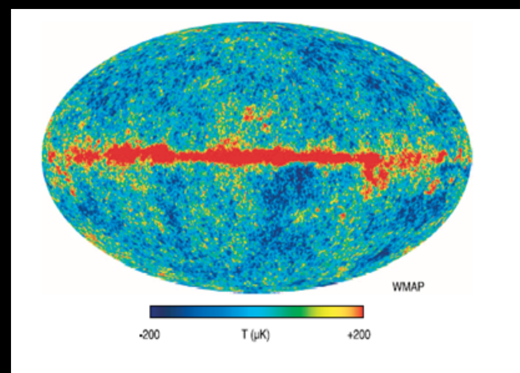
CMB temperature anisotropies

After subtraction of the dipole anisotropy, higher multipole anisotropies are measured with a much lower amplitude than the dipole anisotropy $\Rightarrow T/T \sim 10^{-5}$

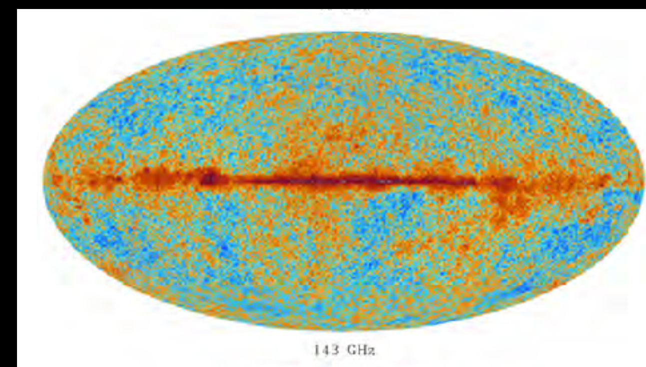
COBE (1992)



WMAP (2003)

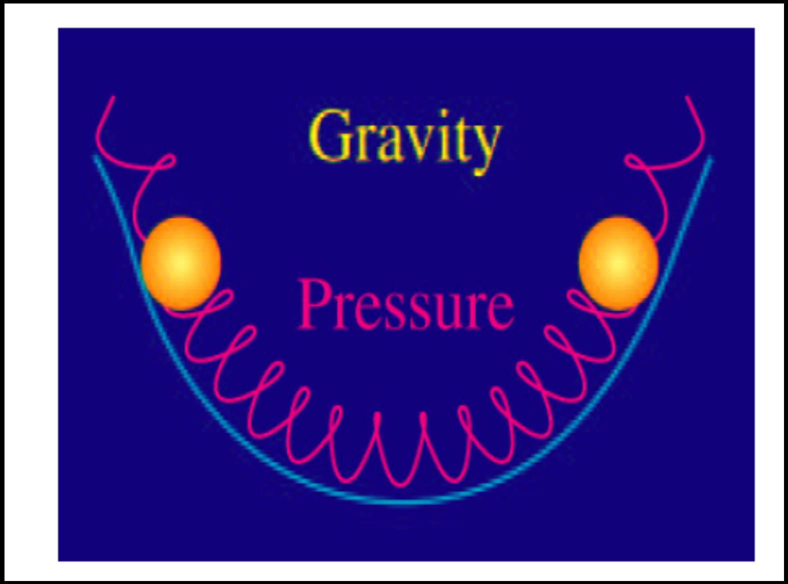


Planck (2013)

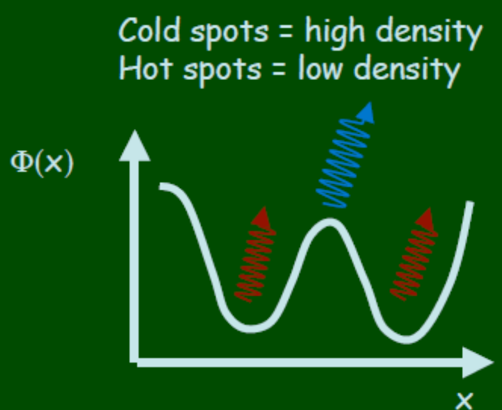


The angular resolution of COBE was about $\delta\Theta^{COBE} \simeq 7°$, that one of WMAP is $\delta\Theta^{WMAP} \simeq 10'$, while that one of Planck is $\delta\Theta^{Planck} \simeq 3'$

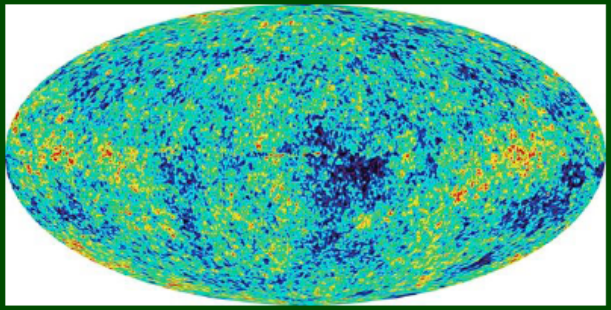
Acoustic oscillations



- Photons escape from gravitational potential

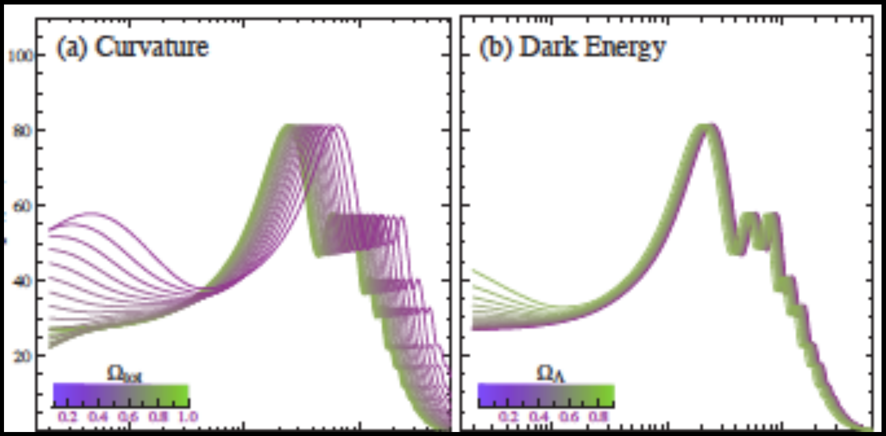


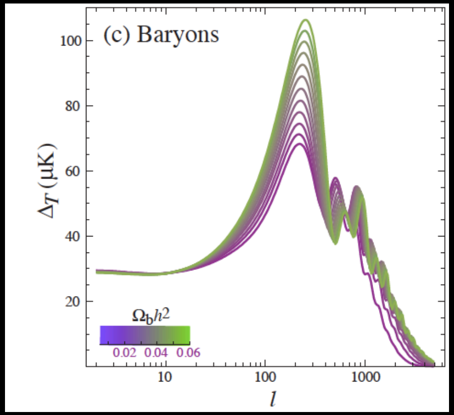
- ...Translate into fluctuations in the blackbody photon temp at ~1/100,000 level

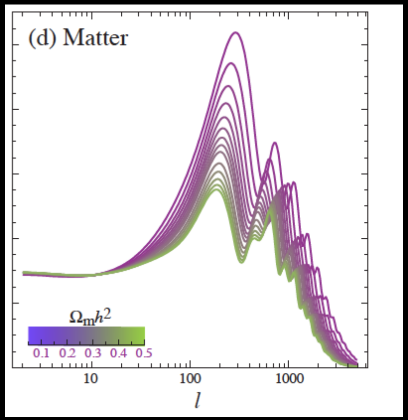


Cosmic ingredients

(Hu, Dodelson, astro-ph/0110414)





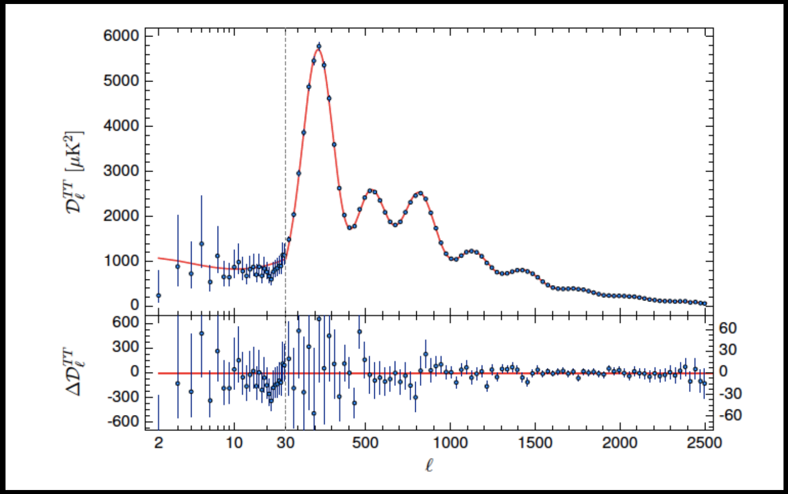


$$\Omega_0 = 1.005 \pm 0.005 \qquad \Omega_{\Lambda 0} = 0.685 \pm 0.013 \qquad \Omega_{B0} h^2 = 0.02222 \pm 0.00023$$

$$\boxed{\Omega_{CDM,0} h^2 = 0.1198 \pm 0.0015 \sim 5\Omega_{B,0} h^2}$$

$$h \equiv \frac{H_0}{100 km\, s^{-1}\ Mpc^{-1}} = 0.67 \pm 0.1$$

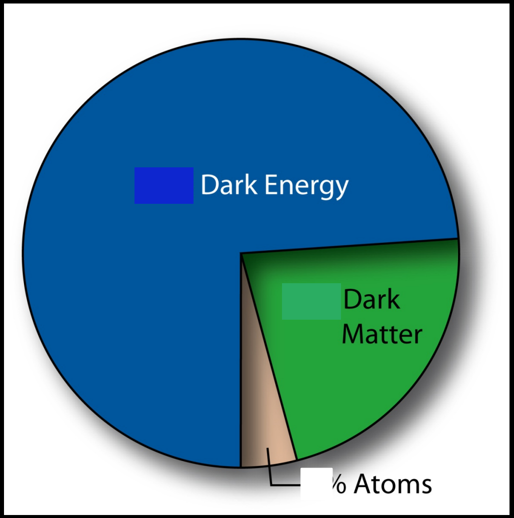
(Planck 2015, 1502.01589)



$$\Omega_{B0} \simeq 0.048$$

$$\Omega_{CDM,0} \simeq 0.26$$

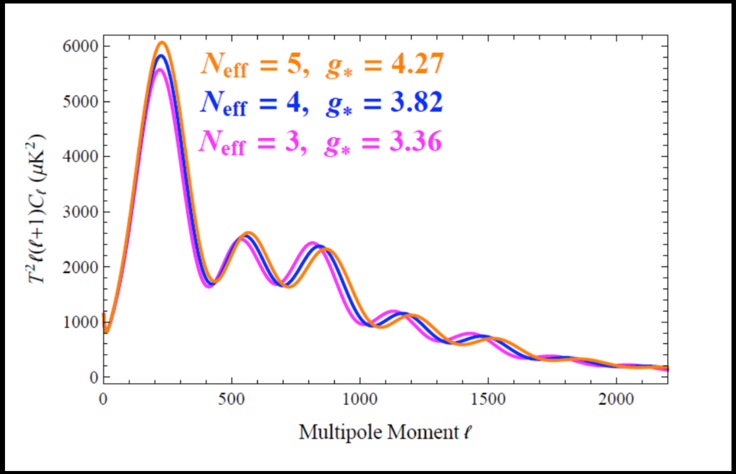
$$\Omega_{M,0} \simeq 0.308$$

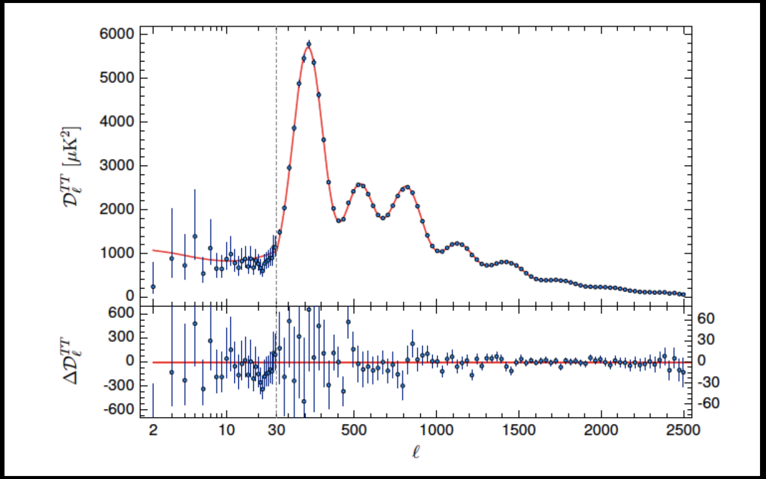


Radiation at CMB decoupling

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

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





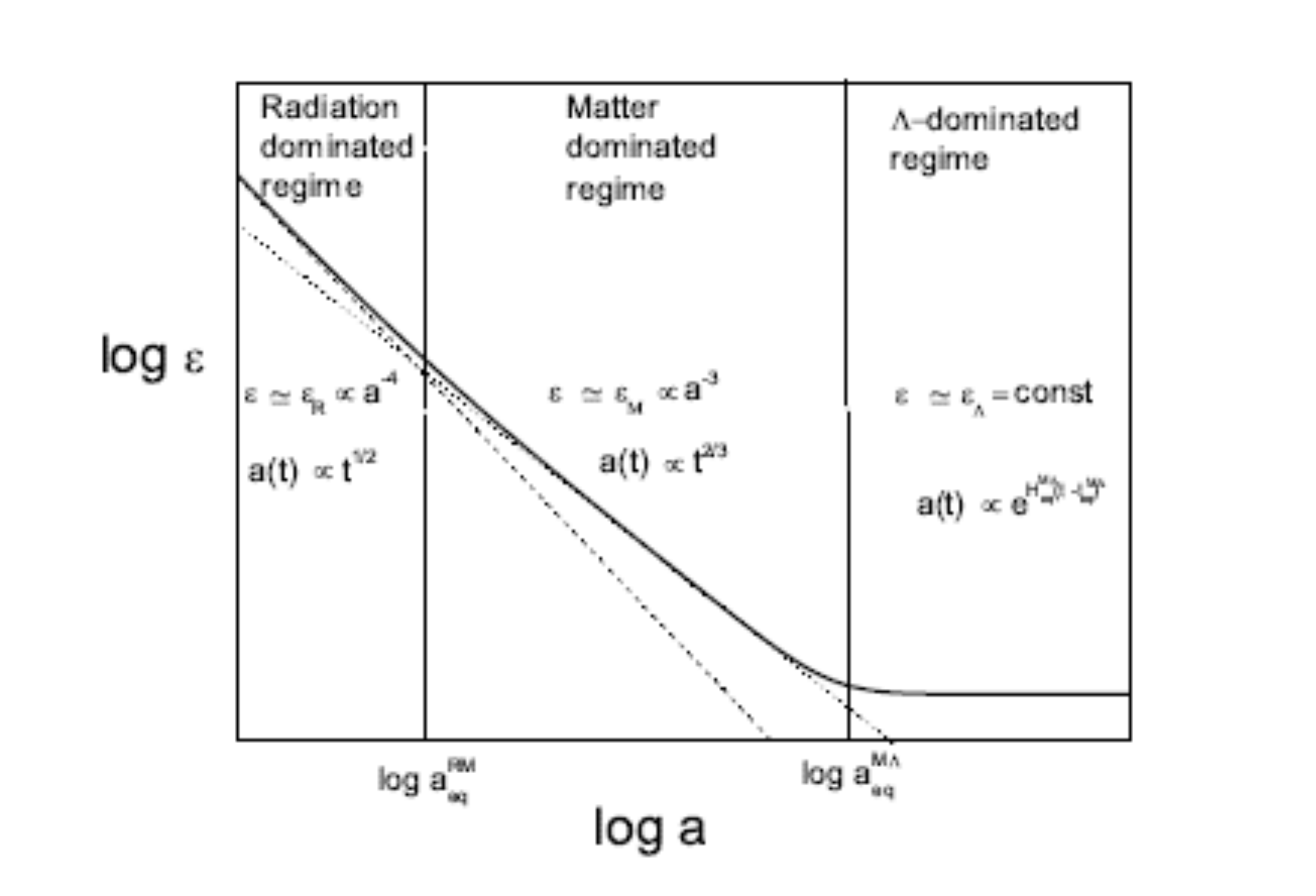
(Planck 2015, 1502.10589)

TT+TE+EE+lensing ⟶ $N_\nu^{rec} = 2.94 \pm 0.38$

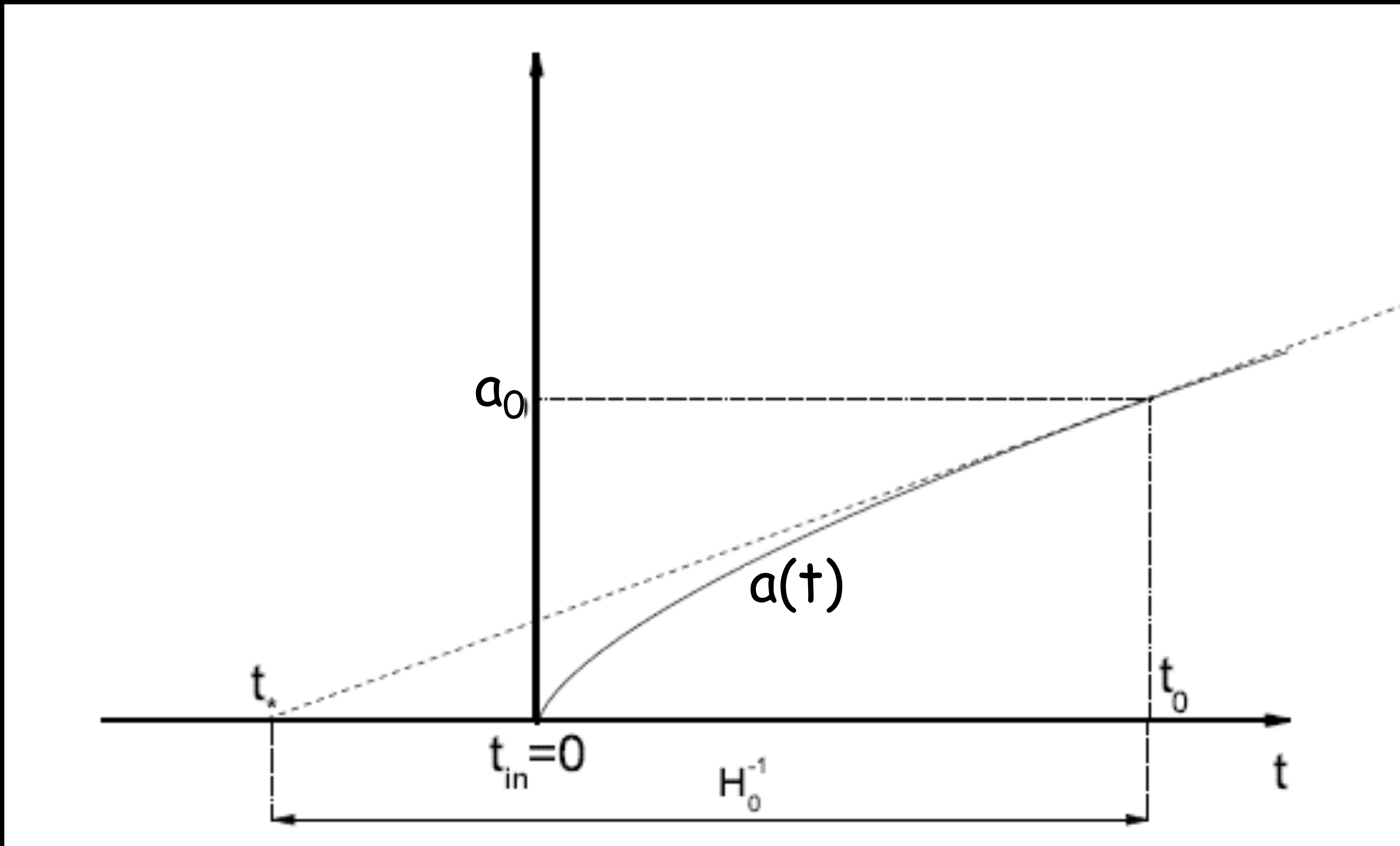
This proves the presence of neutrinos at recombination and also places a stringent upper bound on the amount of dark radiation ⇒ strong constraints on BSM models

But what is the condition for neutrinos to be thermalised?

Flat Radiation-Matter-Λ model



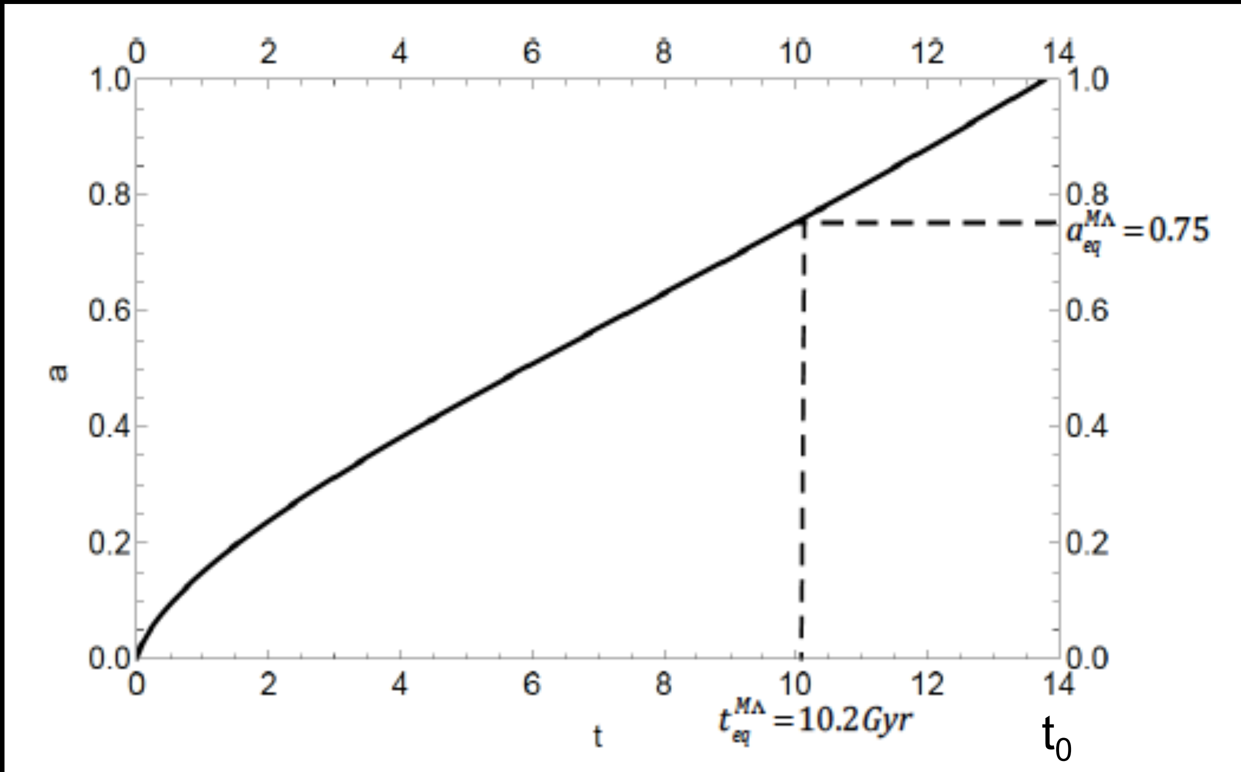
Age of the Universe: in general



$$a_0 = \dot{a}_0\,(t_0 - t_\star)$$

$$H_0^{-1} = (a_0/\dot{a}_0) = t_0 - t_\star$$

Age of the universe in the ΛCDM model



$$\Omega_{\Lambda 0} = 0.692$$

$$\Omega_{M0} = 0.308$$

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

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

Baryon-to-photon number ratio and recombination

Fractional ionization

$$X \equiv \frac{n_p}{n_p + n_H} = \frac{n_e}{n_B}$$

$$\frac{1-X}{X^2} \simeq 3.84\,\eta_B \left(\frac{T}{m_e\,c^2}\right)^{3/2} e^{Q/T}$$

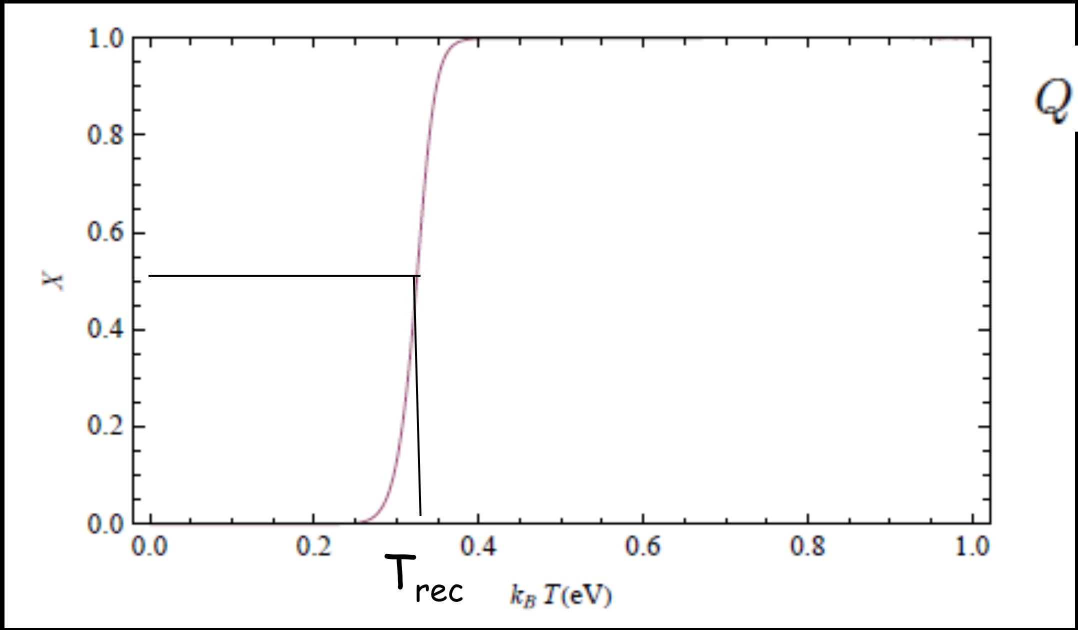
Saha equation

Baryon-to-photon number ratio

$$\eta_B \equiv \frac{n_B}{n_\gamma} \simeq \frac{\Omega_B\,\varepsilon_c}{m_p\,c^2\,n_\gamma}$$

$$\eta_{B,0} \simeq 273.5\,\Omega_{B,0} h^2 \times 10^{-10}$$

$$\eta_{B,0}^{(CMB)} = (6.08 \pm 0.06) \times 10^{-10}$$



$$Q \equiv (m_p + m_e - m_H)\,c^2 \simeq 13.6\,\mathrm{eV}$$

$$T_{\mathrm{rec}} \simeq \frac{Q}{42} \simeq 0.32\,\mathrm{eV}$$

Decoupling and recombination

Matter and Radiation are coupled until the Thomson scatterings

$$\gamma + e^- \leftrightarrow \gamma + e^-$$

of photons on free electrons are fast enough: $\Gamma \gtrsim H$

$$\Gamma \equiv \tau^{-1} = n_e \, \sigma_e \, c$$

$$n_e(a) = \frac{n_{B,0}}{a^3} X(a)$$

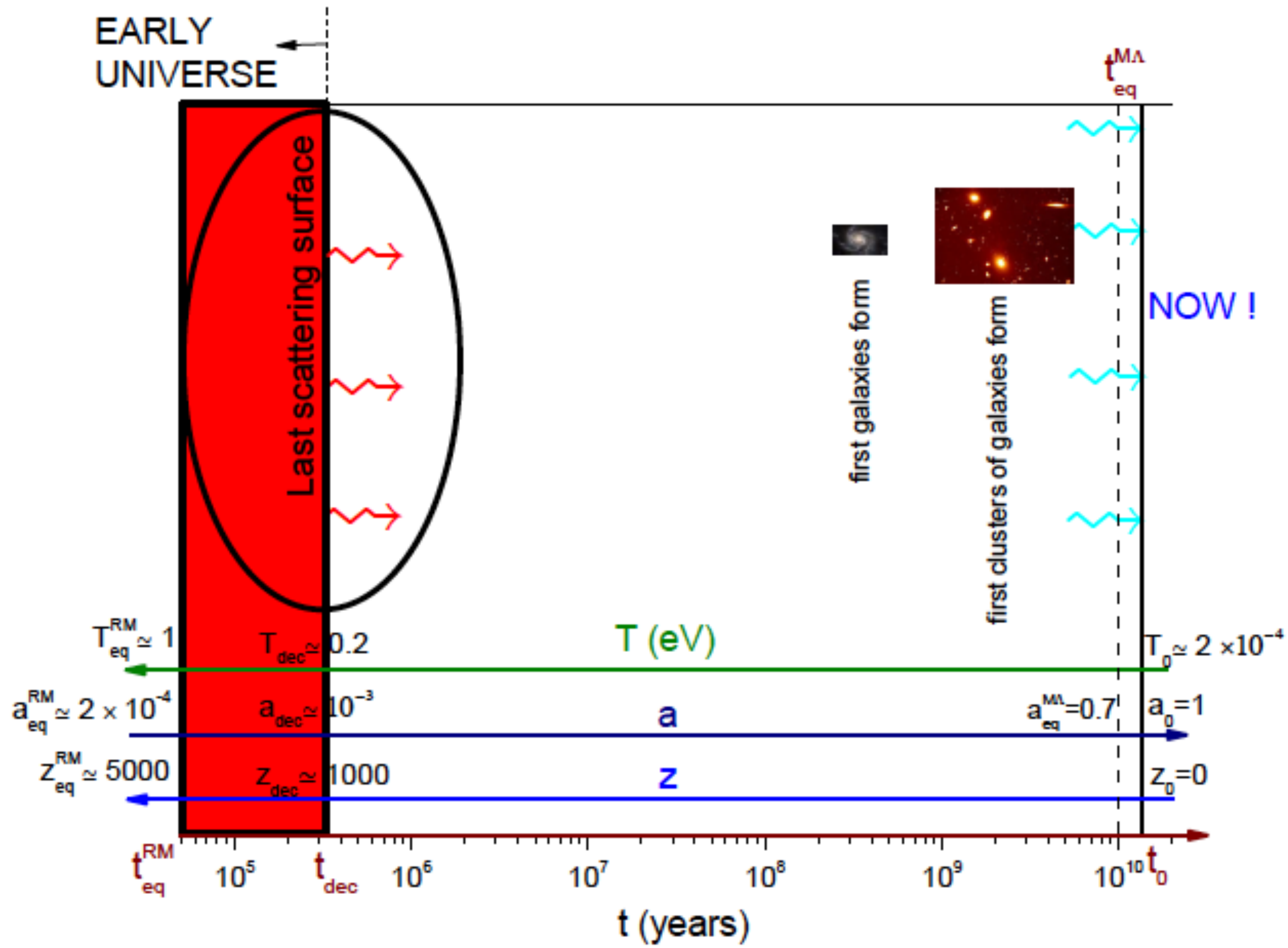
Expansion of the Universe

It takes into account the "recombination" of electrons with protons to form Hydrogen athoms,

$$\Gamma \gtrsim H \Rightarrow n_e(a) \, \sigma_e \, c \gtrsim H$$

$$a \lesssim a_{\rm dec} \simeq 8.8 \times 10^{-4} \,, \quad z \gtrsim z_{\rm dec} \simeq 1130 \,, \quad k_B T \gtrsim k_B T_{\rm dec} \simeq 0.26 \, {\rm eV}$$

$$t_{\rm dec} \simeq \frac{t_{\rm eq}^{M\Lambda}}{(a_{\rm eq}^{M\Lambda} \, z_{\rm dec})^{\frac{3}{2}}} \simeq 400{,}000 \, {\rm yr}$$


EARLY
UNIVERSE
Last scattering surface
first galaxies form
first clusters of galaxies form
NOW !
$t_{eq}^{M\Lambda}$
$T_{eq}^{RM} \simeq 1$
$T_{dec} \simeq 0.2$
T (eV)
$T_0 \simeq 2 \times 10^{-4}$
$a_{eq}^{RM} \simeq 2 \times 10^{-4}$
$a_{dec} \simeq 10^{-3}$
a
$a_{eq}^{M\Lambda}=0.7$
$a_0=1$
$z_{eq}^{RM} \simeq 5000$
$z_{dec} \simeq 1000$
z
$z_0=0$
t_{eq}^{RM}
10^5
t_{dec}
10^6
10^7
10^8
10^9
10^{10}
t_0
t (years)

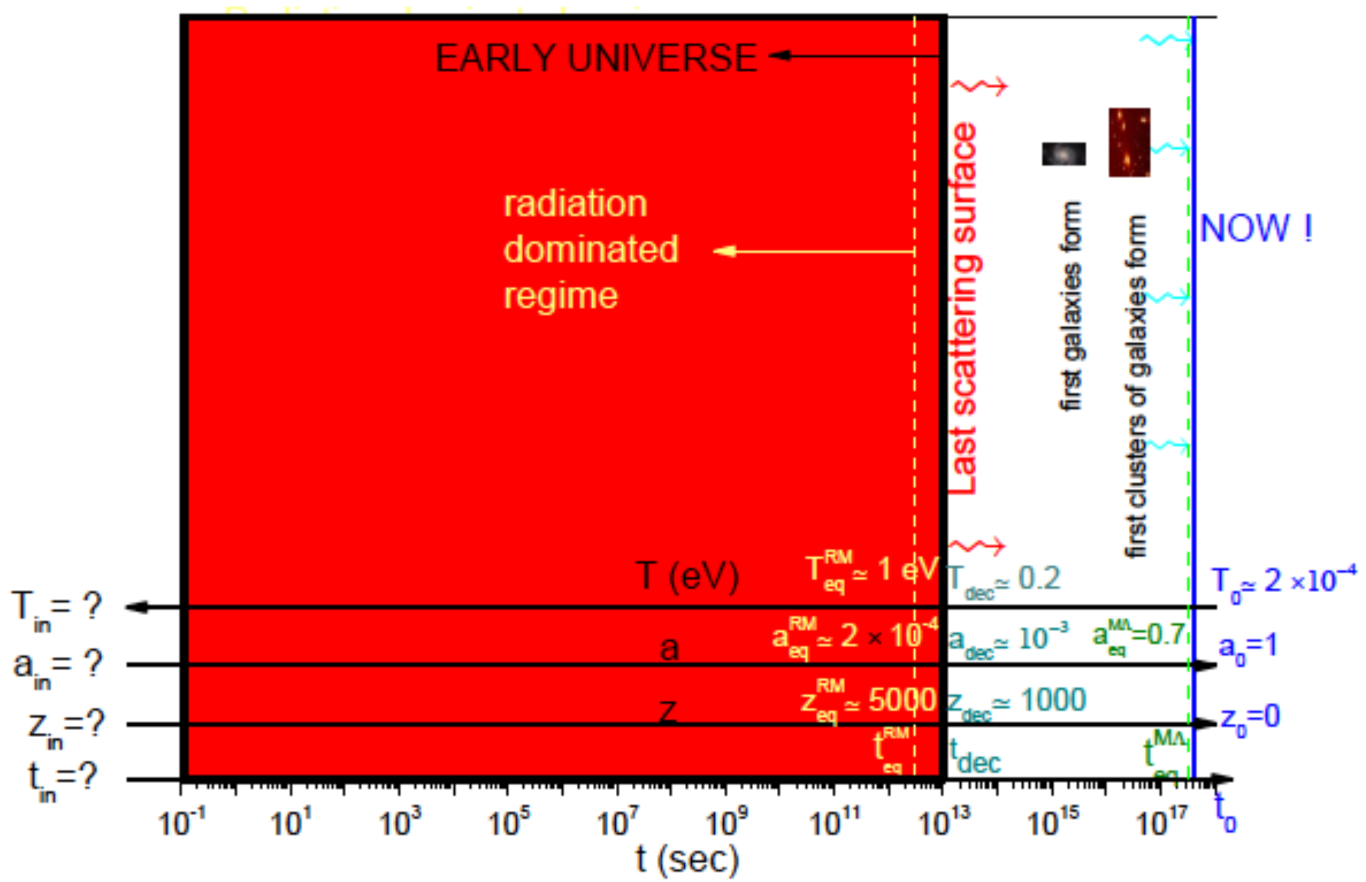
Matter-radiation equality in numbers

$$\frac{\varepsilon_{M0}}{a_{eq}^3}=\frac{\varepsilon_{R0}}{a_{eq}^4}\Rightarrow a_{eq}=\frac{\varepsilon_{R0}}{\varepsilon_{M0}}=\frac{\Omega_{R0}}{\Omega_{M0}}=\frac{0.90\times10^{-4}}{0.31}\simeq 2.9\times10^{-4}$$

$$z_{eq}=\frac{1}{a_{eq}}-1\simeq 3400$$

$$t_{eq}\simeq t_{eq}^{M\Lambda}\left(\frac{a_{eq}}{a_{eq}^{M\Lambda}}\right)^{\frac{3}{2}}\approx 50{,}000\,yr$$

History of The Early Universe



The Early Universe is mainly in a radiation dominated regime

$$H^2 = \frac{8\pi G}{3} \varepsilon_R \,,$$

$$\varepsilon_R = g_R \frac{\pi^2}{30} \frac{(k_B T)^4}{(\hbar c)^3}$$

$T \gg m_{X_{\rm b,f}} c^2/2,$

$$g_R(T) \simeq \sum_{X_{\rm b}} g_{X_{\rm b}} + \frac{7}{8} \sum_{X_{\rm f}} g_{X_{\rm f}}$$

Number of ultra-relativistic degrees of freedom

$$H(T) = \sqrt{g_R} \sqrt{\frac{8\pi^3 G}{90}} T^2 \simeq 0.21 \sqrt{g_R} \left(\frac{k_B T}{\rm MeV}\right)^2 s^{-1} \,.$$

$$t = \frac{1}{2\sqrt{g_R} T^2} \sqrt{\frac{90}{8\pi^3 G}} \simeq \frac{2.4\,{\rm s}}{\sqrt{g_R}} \left(\frac{\rm MeV}{k_B T}\right)^2 \,.$$

$T^{\nu}_{\rm dec}$ ← 1 MeV

$$g_R(T \gtrsim 1\,{\rm MeV}) = g_R^{\gamma+e^\pm+3\nu} = 2 + \frac{7}{8}(4 + 2\times 3) = \frac{43}{4} = 10.75 \,.$$

$\sim m_e$ ← 0.5 MeV

$$g_R(k_B T \lesssim 0.5\,{\rm MeV}) \simeq 2 + 3\,\frac{7}{4}\left(\frac{4}{11}\right)^{4/3} \simeq 3.36 \,.$$

Neutrino decoupling ⇒ relic neutrinos

$$\Rightarrow n_{\nu_\alpha}(T) = \frac{3}{4}\,\frac{\xi(3)}{\pi^2}\,g_\nu\,T^3 \;\; \text{for } T \gtrsim T^{\rm dec}_{\nu_\alpha}$$

$$\left.\frac{\Gamma_{\nu_{\rm weak}}}{H}\right|_{T^{\rm dec}_{\nu_\alpha}} \sim \left.\frac{n_{\nu_\alpha}\langle\sigma\, v\rangle}{H}\right|_{T^{\rm dec}_{\nu_\alpha}} \sim \left.\frac{y_\alpha\, G_F^2\, T^5}{\sqrt{2.8 g_R}\,\frac{T^2}{M_{\rm Pl}}}\right|_{T^{\rm dec}_{\nu_\alpha}} = 1 \Rightarrow T^{\rm dec}_{\nu_\alpha} \simeq y_\alpha^{-\frac{1}{3}}\, 1.5\,{\rm MeV}$$

For T< T_ν^{dec} neutrinos are decoupled and their number in the comoving volume remains constant and one expects that at present there is a relic neutrino background together with CMBR with a temperature::

$$T_{\nu 0} \simeq \left(\frac{4}{11}\right)^{\frac{1}{3}}\, T_{\gamma 0} \simeq 1.96\,^0K$$

Big Bang Nucleosynthesis

George Gamow
(1904-1968)

$$\begin{aligned} n &\leftrightarrow p + e^- + \bar{\nu}_e \\ n + e^+ &\leftrightarrow p + \bar{\nu}_e \\ n + \nu_e &\leftrightarrow p + e^- . \end{aligned}$$

Neutrons-protons inter-converting processes

At the equilibrium: $\left(\frac{n_n}{n_p}\right) \simeq \left(\frac{n_n}{n_p}\right)_{\rm eq} \simeq e^{-\frac{Q_n}{k_B T}}$ $\quad Q_n = (m_n - m_p)\, c^2 \simeq 1.29\,{\rm MeV}$

Equilibrium holds until $\Gamma_{n\leftrightarrow p} \simeq G_F^2 T^5 \gtrsim H \Longrightarrow T \gtrsim T_{\rm fr} = \frac{\sqrt{2.4}}{g_R^{1/4}} \left(\frac{\rm sec}{t_{\rm fr}}\right)^{1/2} {\rm MeV} \simeq 0.85\,{\rm MeV}$ Freeze-out temperature

At the freeze-out: $\frac{n_n}{n_p}(T_{\rm fr}) = e^{-\frac{Q_n}{T_{\rm fr}}} \simeq e^{-\frac{1.29}{0.85}} \simeq 0.22$ $\quad t_{\rm fr} \simeq 1.0\,{\rm sec}$

After the freeze-out neutrons start to decay prior to nucleosynthesis at $t_{\rm nuc} \simeq 310\,s$

$\tau_n \simeq 885\,{\rm s}$ Life time of neutrons

$$\frac{(n_n/n_p)_{\rm nuc}}{(n_n/n_p)_{\rm fr}} = e^{-\frac{t_{\rm nuc}}{\tau}} = e^{-\frac{310}{885}} \simeq 0.7 \Longrightarrow (n_n/n_p)_{\rm nuc} \simeq 0.154 \Longrightarrow Y_p = 2\,\frac{(n_n/n_p)_{\rm nuc}}{1+(n_n/n_p)_{\rm nuc}} \simeq 0.267$$

Big Bang Nucleosynthesis

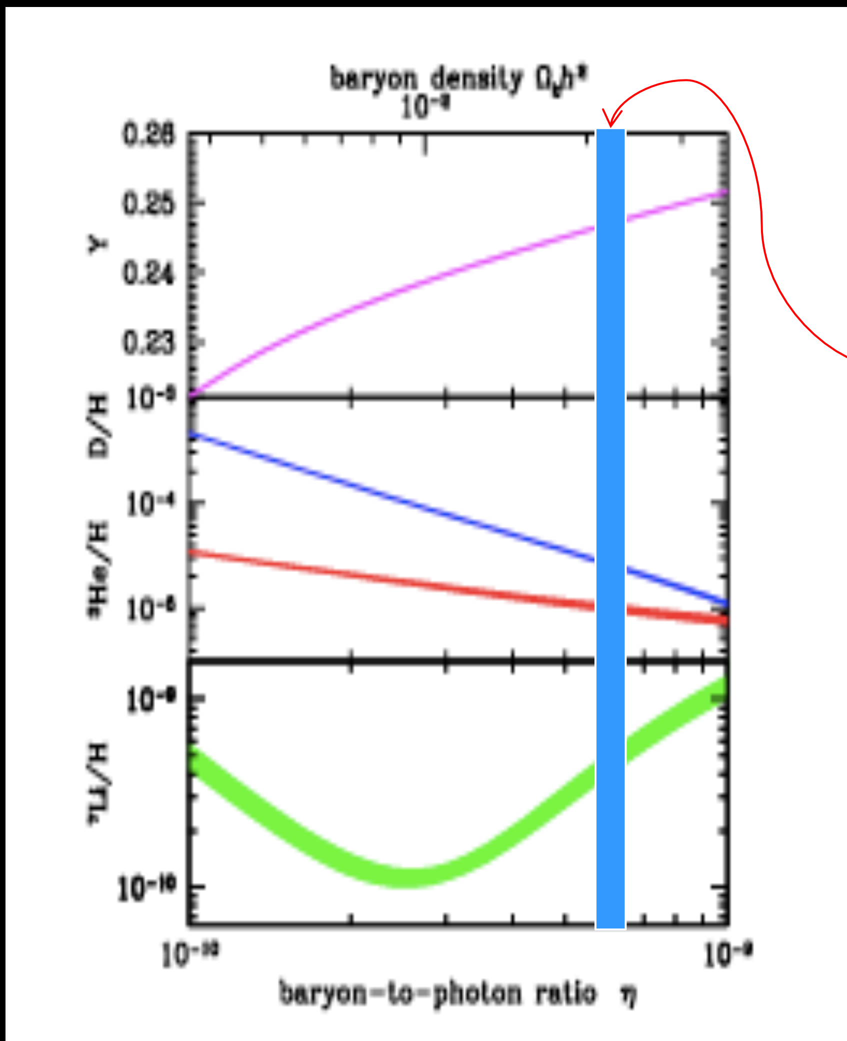
Relevant nuclear processes

$$
\begin{array}{rrcl}
1) & p + n & \leftrightarrow & D + \gamma \\
2) & D + n & \leftrightarrow & T + \gamma \\
3) & {}^3He + n & \leftrightarrow & {}^4He + \gamma \\
4) & {}^6Li + n & \leftrightarrow & {}^7Li + \gamma \\
5) & {}^3He + n & \leftrightarrow & T + p \\
6) & {}^7Be + n & \leftrightarrow & {}^7Li + p \\
7) & {}^7Li + n & \leftrightarrow & {}^3He + {}^4He \\
8) & {}^7Be + n & \leftrightarrow & {}^4He + {}^4He \\
9) & D + p & \leftrightarrow & {}^3He + \gamma \\
10) & T + p & \leftrightarrow & {}^4He + \gamma \\
11) & {}^6Li + p & \leftrightarrow & {}^7Be + \gamma \\
12) & {}^7Li + p & \leftrightarrow & {}^4He + {}^4He \\
13) & D + {}^4He & \leftrightarrow & {}^6Li + \gamma \\
14) & T + {}^4He & \leftrightarrow & {}^7Li + \gamma \\
15) & {}^3He + {}^4He & \leftrightarrow & {}^7Be + \gamma \\
16) & D + D & \leftrightarrow & {}^3He + n \\
17) & D + D & \leftrightarrow & T + p \\
18) & D + T & \leftrightarrow & {}^4He + p \\
19) & D + {}^3He & \leftrightarrow & {}^4He + n \\
20) & {}^3He + {}^3He & \leftrightarrow & {}^4He + p + p \\
21) & D + {}^7Li & \leftrightarrow & {}^4He + {}^4He + n \\
22) & D + {}^7Be & \leftrightarrow & {}^4He + {}^4He + p
\end{array}
$$

Deuterium bottleneck:
No other element can
Form before Deuterium.
This delays the synthesis
of He-4

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 ^4He abundance (Y) one finds:

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

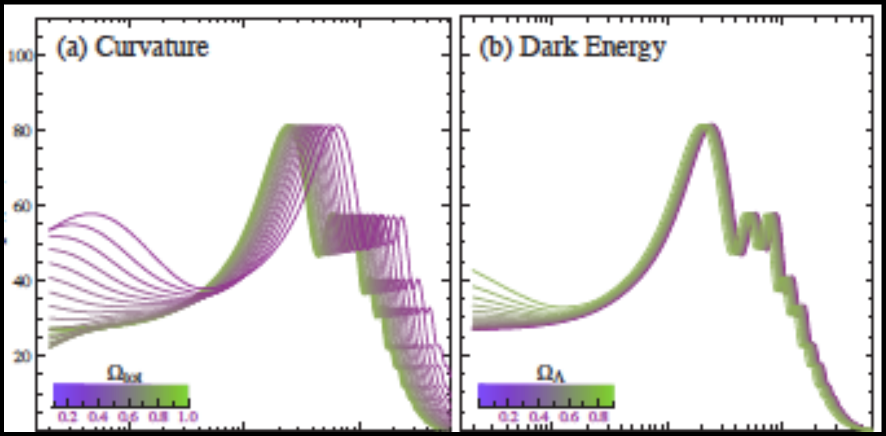
And from Deuterium abundance:

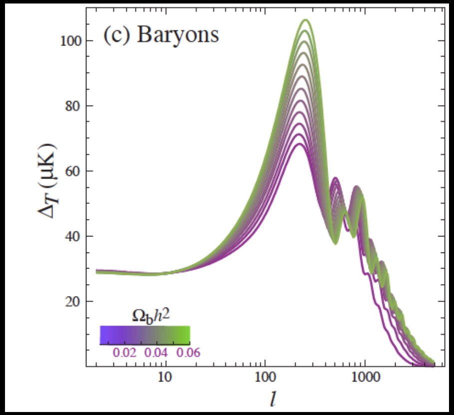
$$N_\nu (t_{nuc} \simeq 300s) = 2.8 \pm 0.3$$

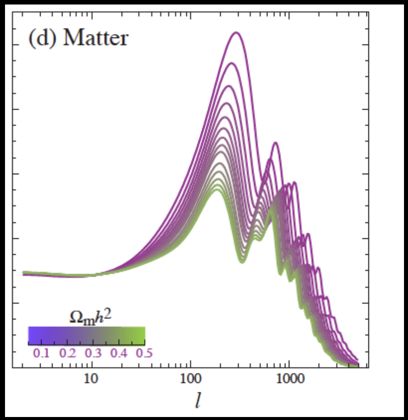
This shows that $T_{RH} \gg T_\nu^{dec} \sim 1$ MeV and again NO DARK RADIATION

Cosmic ingredients

(Hu, Dodelson, astro-ph/0110414)



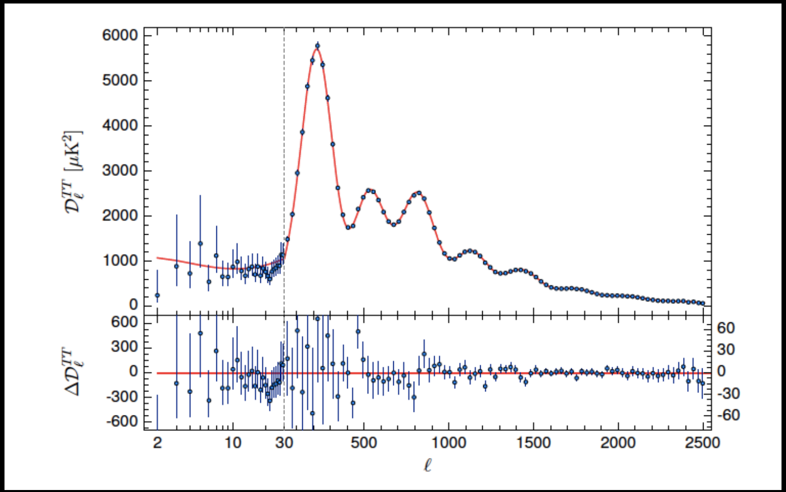




$$\Omega_0 = 1.005 \pm 0.005 \qquad \Omega_{\Lambda 0} = 0.685 \pm 0.013 \qquad \Omega_{B0} h^2 = 0.02222 \pm 0.00023 \qquad \Omega_{CDM,0} h^2 = 0.1198 \pm 0.0015 \sim 5 \Omega_{B,0} h^2$$

$$h \equiv \frac{H_0}{100 km\, s^{-1}\ Mpc^{-1}} = 0.67 \pm 0.1$$

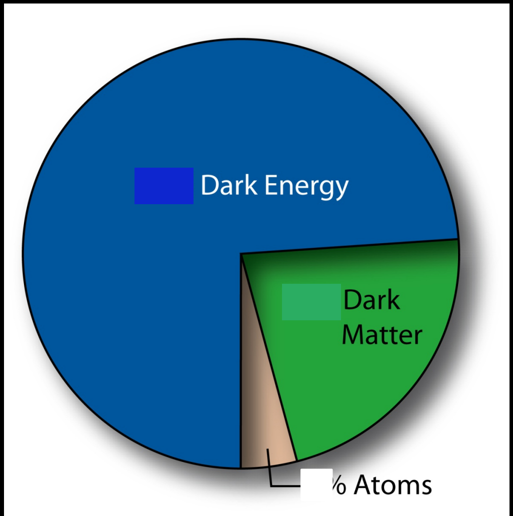
(Planck 2015, 1502.01589)



$$\Omega_{B0} \simeq 0.048$$

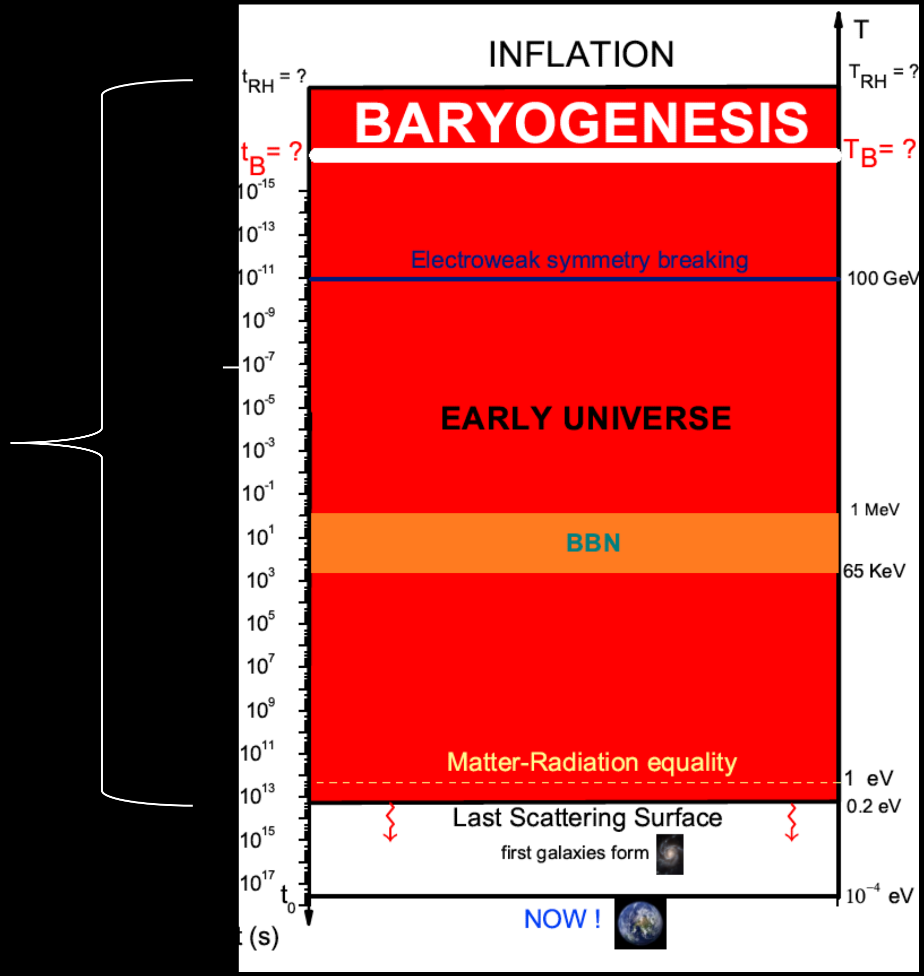
$$\Omega_{CDM,0} \simeq 0.26$$

$$\Omega_{M,0} \simeq 0.308$$



Cosmological puzzles

dark
matter
production



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

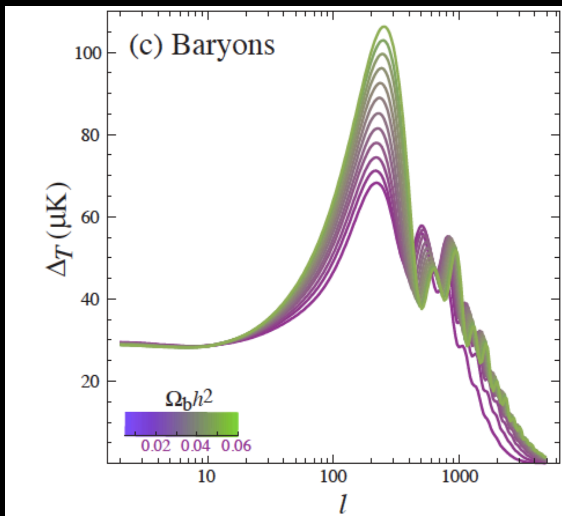
Number of ultra-relativistic degrees of freedom vs. T

T	g_R	Particle content
$m_e\, c^2/2 \simeq 0.25\,\mathrm{MeV} \gg T \geq T_0$	3.36	$\gamma + 3$ massless $\nu's$
$m_\mu\, c^2/2 \simeq 50\,\mathrm{MeV} \gg T \gg m_e\, c^2/2$	$43/4 = 10.75$	$\ldots + e^\pm$
$m_\pi\, c^2/2 \simeq 75\,\mathrm{MeV} \gg T \gg m_\mu\, c^2/2$	$57/4 = 14.25$	$\ldots + \mu^\pm$
$T_{\mathrm{qh}} \simeq 150\,\mathrm{MeV} \gg T \gg m_\pi\, c^2/2$	$69/4 = 17.25$	$\ldots + \pi^0, \pi^\pm$
$m_\tau\, c^2/2 \gtrsim m_c\, c^2/2 \simeq 0.65\,\mathrm{GeV} \gg T \gtrsim T_{\mathrm{qh}}$	61.75	$\ldots +$ u,d,s quarks + 8 gluons
$m_b\, c^2/2 \simeq 2\,\mathrm{GeV} \gg T \gg m_\tau\, c^2/2$	75.75	$\ldots + \tau^\pm +$ c quark
$m_{W,Z,H^0}\, c^2/2 \simeq 40\,\mathrm{GeV} \gg T \gg m_b\, c^2/2$	86.25	$\ldots +$ b quark
$m_t\, c^2/2 \simeq 90\,\mathrm{GeV} \gg T \gg m_{W,Z,H^0}\, c^2/2$	96.25	$\ldots + W^\pm,\ Z^0,\ H^0$ bosons
$T \gg m_t\, c^2/2$	106.75	$\ldots +$ top quark

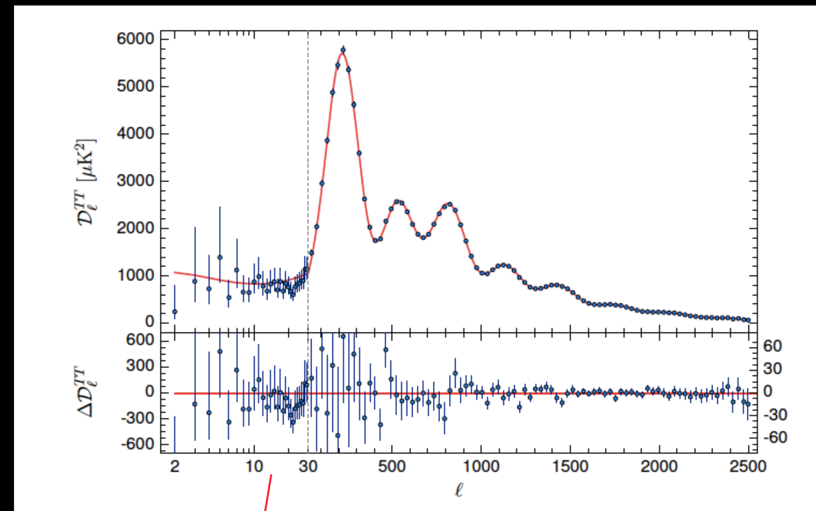
TABLE 13.1 Dependence of g_R on temperature in the standard model.

The baryon asymmetry of the Universe

(Hu, Dodelson, astro-ph/0110414)



(Planck 2015, 1502.10589)



$$\Omega_{B0} h^2 = 0.02230 \pm 0.00014$$

$$\eta_{B0} \equiv \frac{n_{B0} - \bar{n}_{B0}}{n_{\gamma 0}} \simeq \frac{n_{B0}}{n_{\gamma 0}} \simeq 273.5\,\Omega_{B0} h^2 \times 10^{-10} = (6.10 \pm 0.04) \times 10^{-10}$$

- Consistent with (older) BBN determination but more precise and accurate

Matter-antimatter asymmetry of the Universe

- 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)
- A Standard Model baryogenesis ? $\eta_B^{SM} <<< \eta_B^{CMB}$
- **New Physics is needed!**

Models of Baryogenesis

- From phase transitions:
  - ELECTROWEAK BARYOGENESIS (EWBG)
    - * in the SM
    - * in the MSSM
    - * 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
- …………………………
- From heavy particle decays:
  - GUT Baryogenesis
  - LEPTOGENESIS

Baryogenesis in the SM ?

All 3 Sakharov conditions are fulfilled in the SM

1. baryon number violation if T ~ 100 GeV,
2. CP violation in the quark CKM matrix,
3. departure from thermal equilibrium (an arrow of time)

from the expansion of the Universe

Baryon Number Violation at finite T

('t Hooft '76)

Even though at T= 0 baryon number violating processes are inhibited, at finite T:

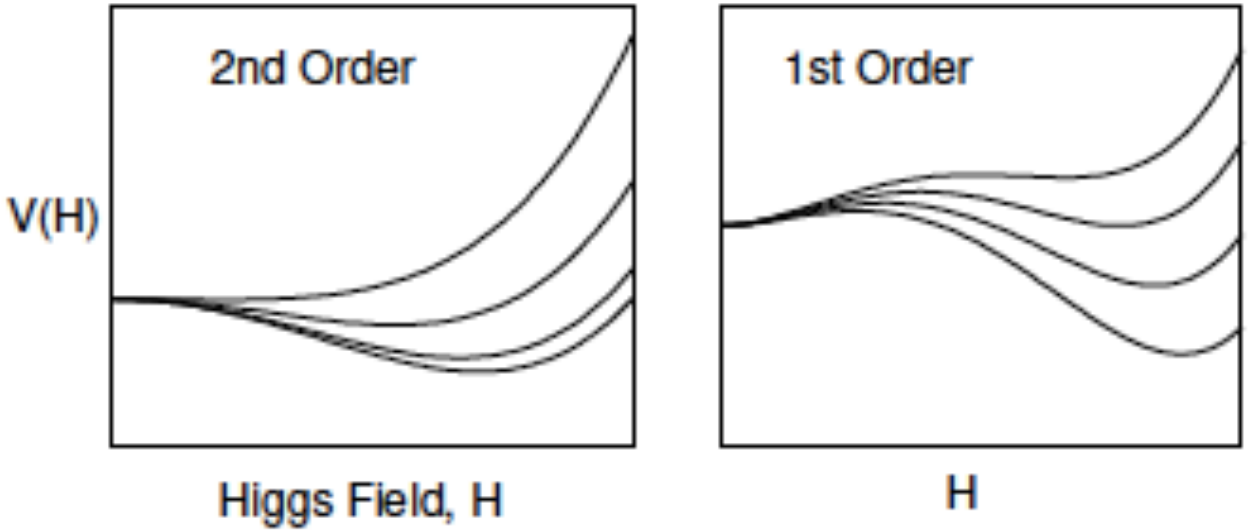
$$\Gamma(\Delta B \neq 0) \propto T^4 \exp\left[-\kappa \frac{v(T)}{T}\right]$$

$$v \equiv \langle \Phi \rangle = \begin{cases} 0 \text{ for } T \gtrsim T_c \text{ (unbroken phase)} \\ v(T_c) \text{ for } T \lesssim T_c \text{ (broken phase)} \end{cases}$$

- Baryon number violating processes are unsuppressed at $T \gtrsim T_c \simeq 100$ GeV
- Anomalous processes violate lepton number as well but preserve B-L !

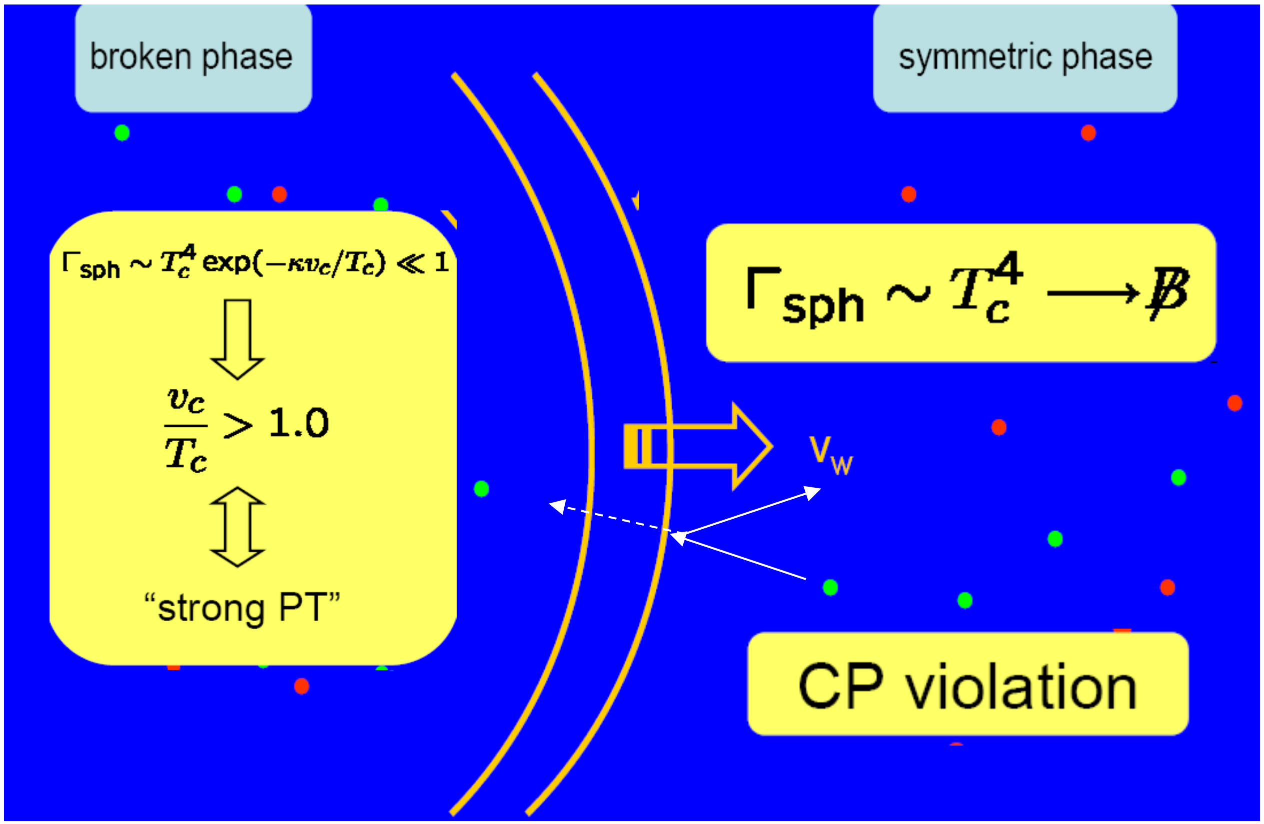
There can be enough departure from thermal equilibrium ?

1st or 2nd order PT?



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

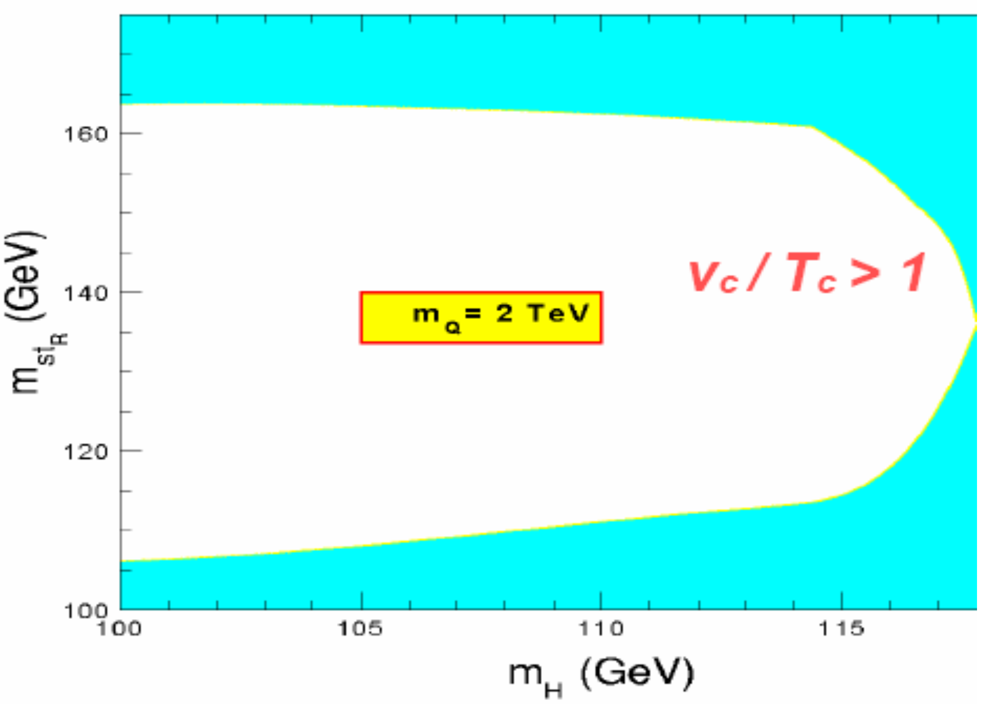
⇒ EW baryogenesis in the SM is ruled out (also not enough CP)

⇒ New Physics is needed!

EWBG in the MSSM

(Carena, Quiros, Wagner '98)

- Additional bosonic degrees of freedom (dominantly the light stop contribution) can make the EW phase transition more strongly first order if :



•With the discovery of Higgs boson with a mass m_H~126 GeV the EWBG in MSSM is basically dead (D.Curtin et al.arXiv:1203.2932) though very ad hoc loopholes have been found

EWBG in the nMSSM

(Menon, Morissey, Wagner'04; Balazs, Carena, Freitas, Wagner et al. `07)

- The `μ-problem' in the MSSM can be solved introducing a singlet chiral superfield $\Rightarrow$ the mass of the (CP-even) Higgs boson responsible for EWSB can be easily much higher than the Higgs mass

Discrete symmetries have to be imposed to solve the *domain wall problem*, Two popular options :

`Next-to-MSSM' (NMSSM) based on Z_3

`nearly-MSSM' (nMSSM) based on Z_5 or Z_7

- The nMSSM is interesting for EWBG because strong first order phase transition does not require too light Higgs and stop masses;
- However chargino and Higgs mass parameters are required to be in the range testable at LHC and ILC
- Constraints from EDM's are still present but weaker than in the MSSM; new experiments will improve current upper bound on the electron EDM and in many scenarios non zero value is expected
- At the same time neutralino is the LSP and can be the Dark Matter for masses about 30-45 GeV

Is EWBG in general still alive ?

(See J.Cline 1704.08911 *"Is EWBG dead?"*, for a review on the status of EWBG)

2 attitudes:

- **Optimistic**: EWBG in the MSSM has strong constraints but these can be relaxed within other frameworks:
  - in the NMSSM
    (Pietroni '92,Davies et al. '96, Huber and Schmidt '01)
  - in the nMSSM
    (Wagner et al. '04)
  - in left-right symmetric models at B-L symmetry breaking
    (Mohapatra and Zhang '92)
  - all these models also start to be strongly constrained!
  - adding a scalar singlet (Choi,Volkas '93, Espinosa et al'15, J.Cline et al '17.)
- **Pessimistic**: Still viable models start to be too *ad hoc* and we need some other mechanism: LEPTOGENESIS!

t_{dec}

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Please see the **scheme notes** for more information, including eligibility criteria and the application process.

Lecture III

Leptogenesis:
Minimal scenario,
Flavour effects,
BSM models.

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 $\varepsilon_i \equiv -\frac{\Gamma - \bar{\Gamma}}{\Gamma + \bar{\Gamma}}$ $\Rightarrow N_{B-L}^{fin} = \sum_{i=1,2,3} \varepsilon_i \times \kappa_i^{fin}$ ← efficiency factors

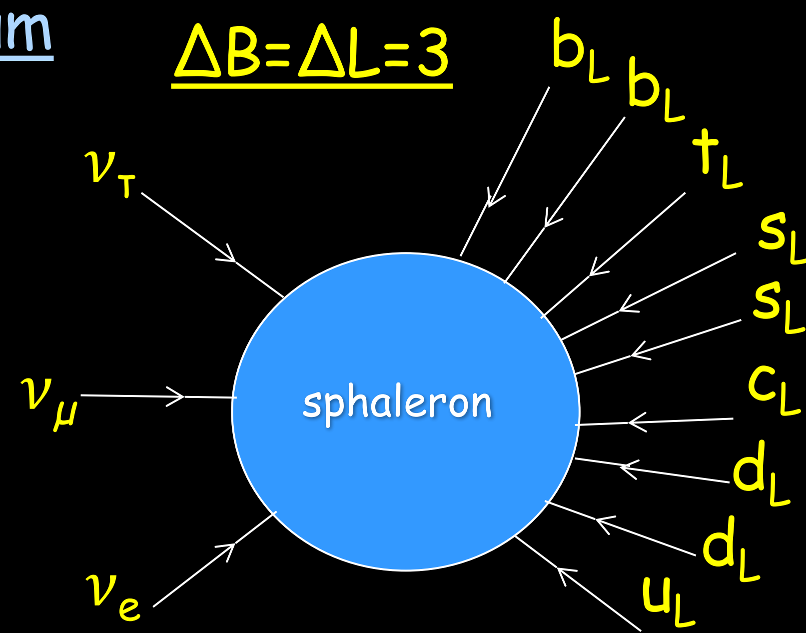
- Sphaleron processes in equilibrium

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

(Kuzmin, Rubakov, Shaposhnikov '85)

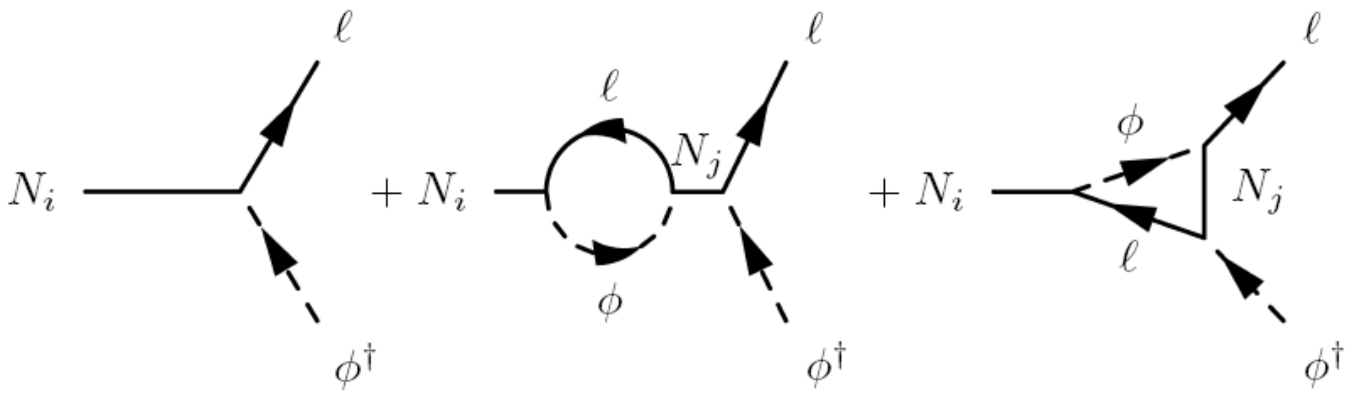
$$\Rightarrow \eta_{B0}^{lep} = \frac{a_{sph} N_{B-L}^{fin}}{N_\gamma^{rec}} \simeq 0.01 N_{B-L}^{fin}$$

ΔB=ΔL=3



Total CP asymmetries

(Flanz, Paschos, Sarkar'95; Covi, Roulet, Vissani'96; Buchmüller, Plümacher'98)



$$\varepsilon_i \simeq \frac{1}{8\pi\, v^2\, (m_D^\dagger\, m_D)_{ii}} \sum_{j\neq i} \mathrm{Im}\left[(m_D^\dagger\, m_D)^2_{ij}\right] \times \left[f_V\left(\frac{M_j^2}{M_i^2}\right) + f_S\left(\frac{M_j^2}{M_i^2}\right)\right]$$

It does not depend on U !

N_1 dominated scenario (N_1 leptogenesis)

$$z \equiv \frac{M_1}{T}$$

$$\frac{dN_{N_1}}{dz} = -D_1 \left(N_{N_1} - N_{N_1}^{\rm eq}\right)$$

$$\frac{dN_{B-L}}{dz} = -\varepsilon_1 \frac{dN_{N_1}}{dz} - W_{ID}\, N_{B-L}$$

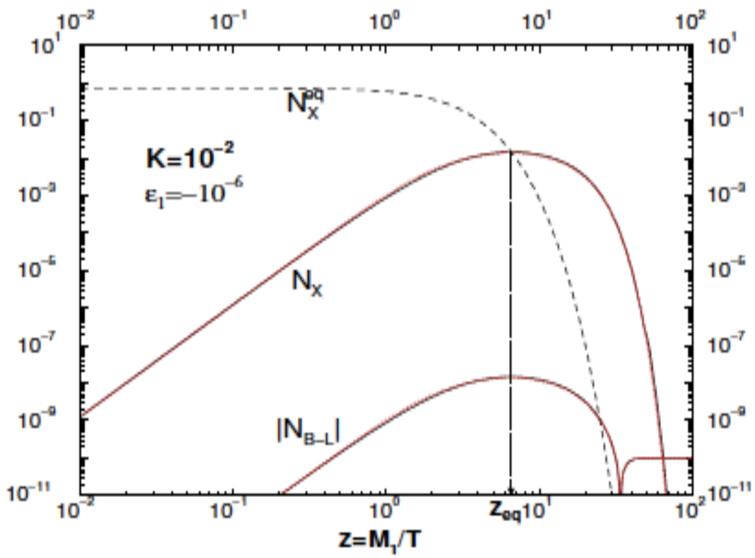
$$D_1 = \frac{\Gamma_{D,1}}{H\,z} = K_1\, z \left\langle \frac{1}{\gamma} \right\rangle , \quad W_{ID} \propto D_1 \propto K_1$$

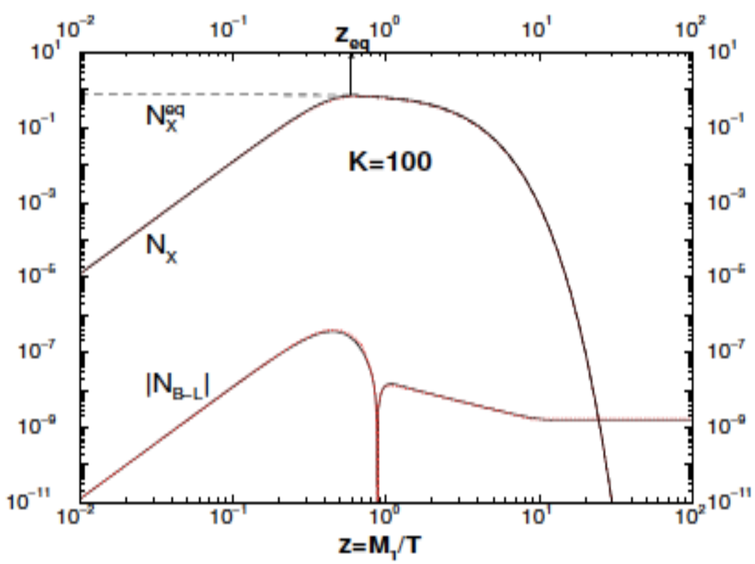
$$N_{B-L}(z; K_1, z_{\rm in}) = N_{B-L}^{\rm in}\, e^{-\int_{z_{\rm in}}^{z} dz'\, W_{ID}(z')} + \varepsilon_1\, \kappa_1(z)$$

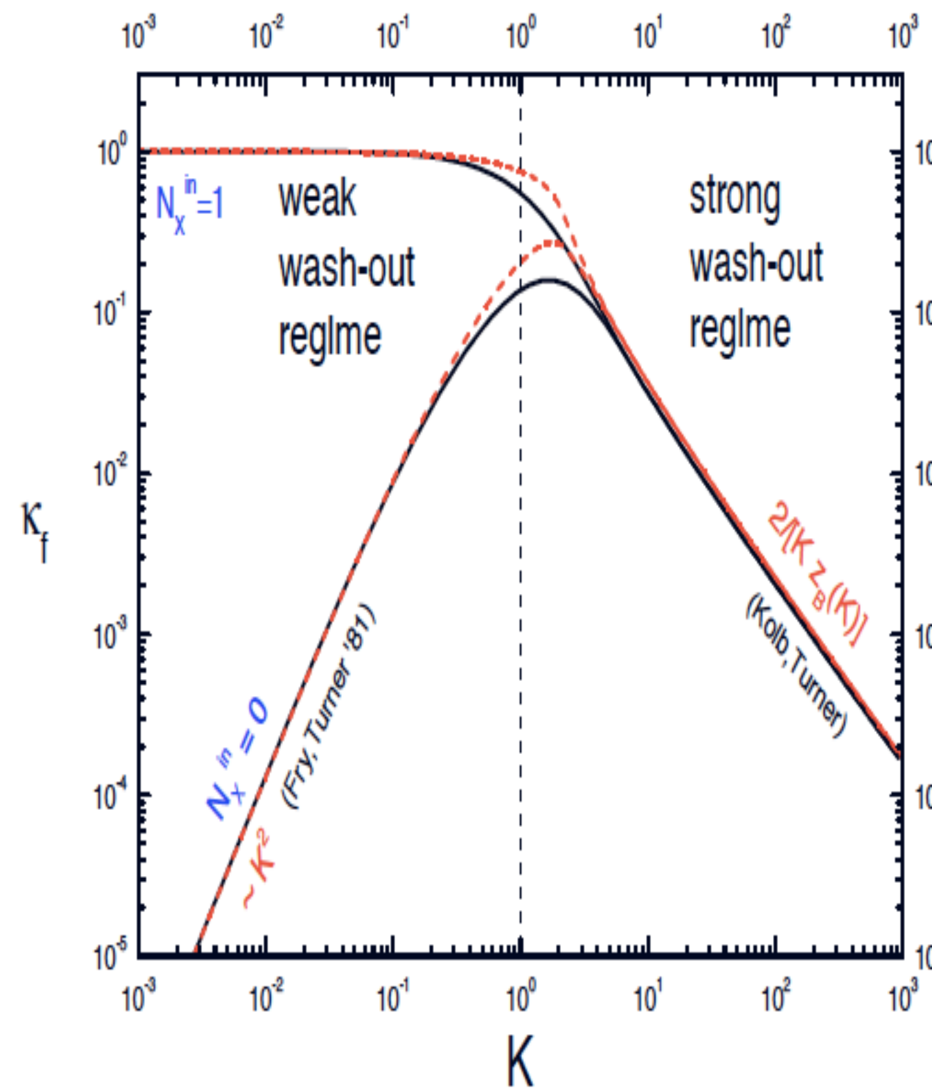
$$\kappa_1(z; K_1, z_{\rm in}) = -\int_{z_{\rm in}}^{z} dz' \left[\frac{dN_{N_1}}{dz'}\right] e^{-\int_{z'}^{z} dz''\, W_{ID}(z'')}$$

- Weak wash-out regime for $K_1 \lesssim 1$ (out-of-equilibrium picture recovered for $K_1 \to 0$)
- Strong wash-out regime for $K_1 \gtrsim 1$

Weak and strong wash-out: comparison







Seesaw parameter space

Imposing $\eta_{B0}^{lep} \simeq \eta_{B0}^{CMB} \simeq 6\times 10^{-10}$ $\Rightarrow$ can we test seesaw and leptog.?

<u>Problem: too many parameters</u>

(Casas, Ibarra'01) $m_\nu = -m_D \frac{1}{M} m_D^T \Leftrightarrow \boxed{\Omega^T \Omega = I}$

Orthogonal parameterisation

$$\boxed{m_D} = \boxed{U \begin{pmatrix} \sqrt{m_1} & 0 & 0 \\ 0 & \sqrt{m_2} & 0 \\ 0 & 0 & \sqrt{m_3} \end{pmatrix} \Omega \begin{pmatrix} \sqrt{M_1} & 0 & 0 \\ 0 & \sqrt{M_2} & 0 \\ 0 & 0 & \sqrt{M_3} \end{pmatrix}}$$

(in a basis where charged lepton and Majorana mass matrices are diagonal)

light neutrino parameters

heavy neutrino parameters (escaping experimental information)

- ❑ Popular solution in the LHC era: TeV Leptogenesis but no signs so far of new physics at the TeV scale (or below) able to address the problem

- ❑ Insisting with high scale leptogenesis is challenging but there are a few strategies able to reduce the number of parameters

Vanilla leptogenesis ⇒ upper bound on ν masses

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

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

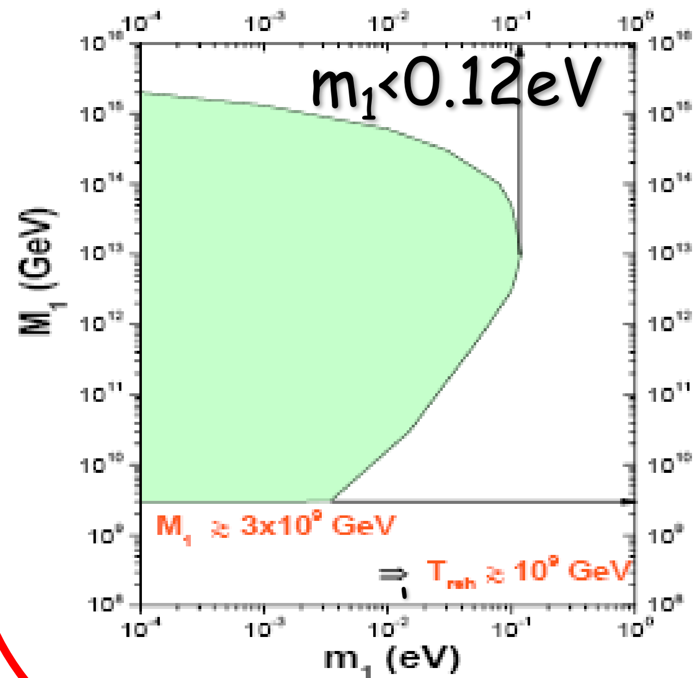
All the asymmetry is generated by the lightest RH neutrino

4) Barring fine-tuned cancellations

(Davidson, Ibarra '02)

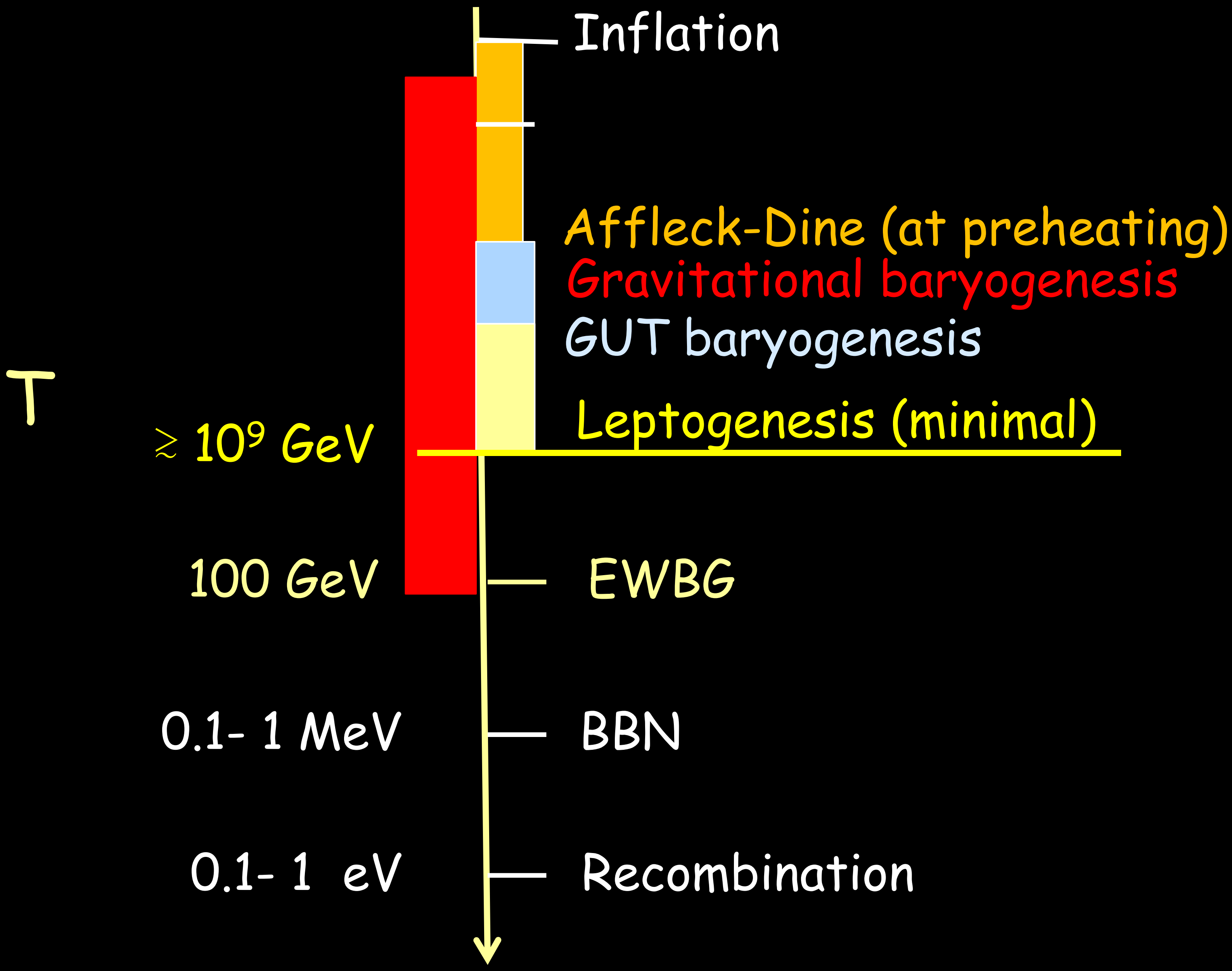
$$\varepsilon_1 \leq \varepsilon_1^{\max} \simeq 10^{-6} \left(\frac{M_1}{10^{10}\,\text{GeV}}\right) \frac{m_{\rm atm}}{m_1 + m_3}$$

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



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

A pre-existing asymmetry?



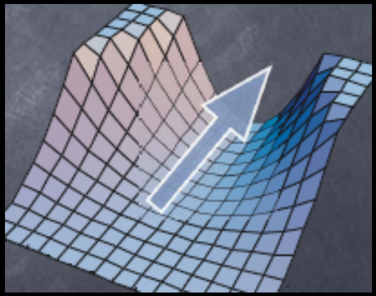
Affleck-Dine Baryogenesis

(Affleck, Dine '85)

In the Supersymmetric SM there are many "flat directions" in the space of a field composed of squarks and/or sleptons

$$V(\phi) = \sum_i \left| \frac{\partial W}{\partial \phi_i} \right|^2 + \frac{1}{2} \sum_A \left(\sum_{ij} \phi_i^* (t_A)_{ij} \phi_j \right)^2$$

F term D term



A flat direction can be parametrized in terms of a complex field (AD field) that carries a baryon number that is violated dynamically during inflation

$$\frac{n_B}{s} \sim 10^{-10} \left(\frac{m_{3/2}}{m_\Phi} \right) \left(\frac{m_\Phi}{\mathrm{TeV}} \right)^{-\frac{1}{2}} \left(\frac{M}{M_P} \right)^{\frac{3}{2}} \left(\frac{T_R}{10\,\mathrm{GeV}} \right)$$

The final asymmetry is $\propto T_{RH}$ and the observed one can be reproduced for low values $T_{RH} \sim 10$ GeV !

Gravitational Baryogenesis

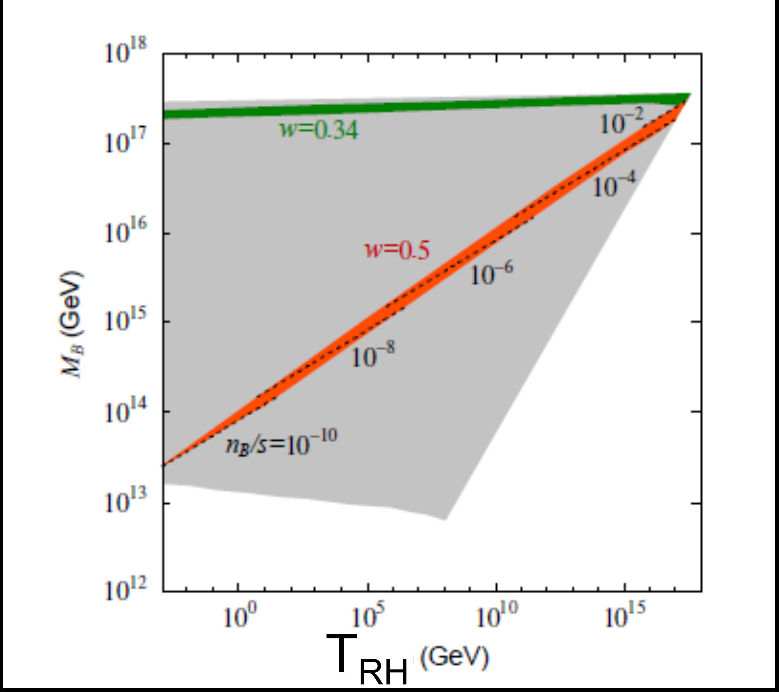
(Davoudiasl, Kribs, Kitano, Murayama, Steinhardt '04)

The key ingredient is a CP violating interaction between the derivative of the Ricci scalar curvature R and the baryon number current J^m:

$$\frac{1}{M_*^2}\int d^4x\sqrt{-g}(\partial_\mu \mathcal{R})J^\mu$$

Cutoff scale of the effective theory

It is natural to have this operator in quantum gravity and in supergravity



It works efficiently and asymmetries even much larger than the observed one are generated for $T_{RH} \gg 100$ GeV

Independence of the initial conditions (strong thermal leptogenesis)

(Buchmüller, PDB, Plümacher '04)

wash-out of a pre-existing asymmetry N^{p}_{B-L}

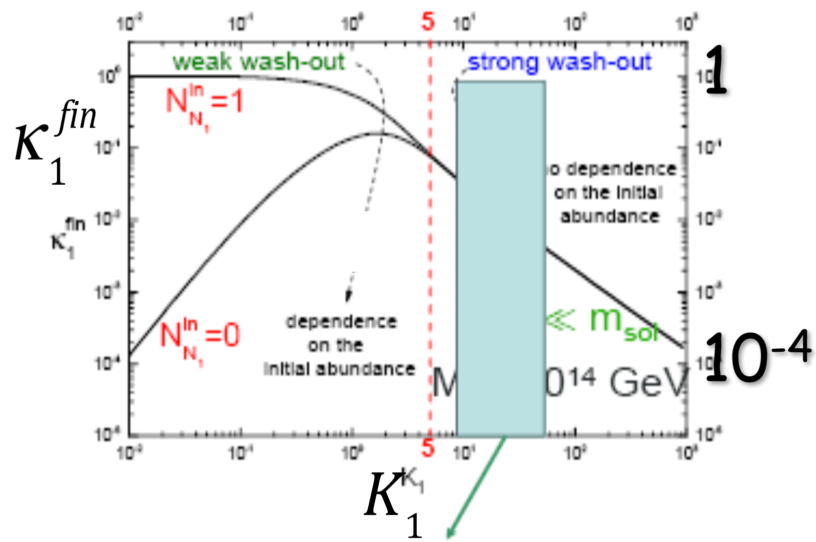
Just a coincidence?

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

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

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

independence of the initial N_1-abundance as well



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

SO(10)-inspired leptogenesis

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

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

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

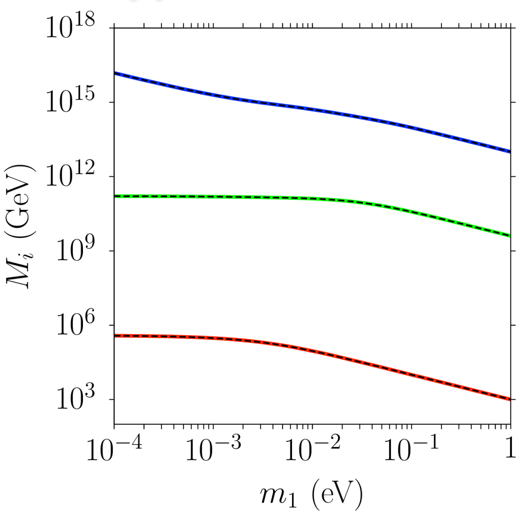
SO(10)-inspired conditions:

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 $\Rightarrow \eta_B^{(N1)} \ll \eta_B^{CMB}$

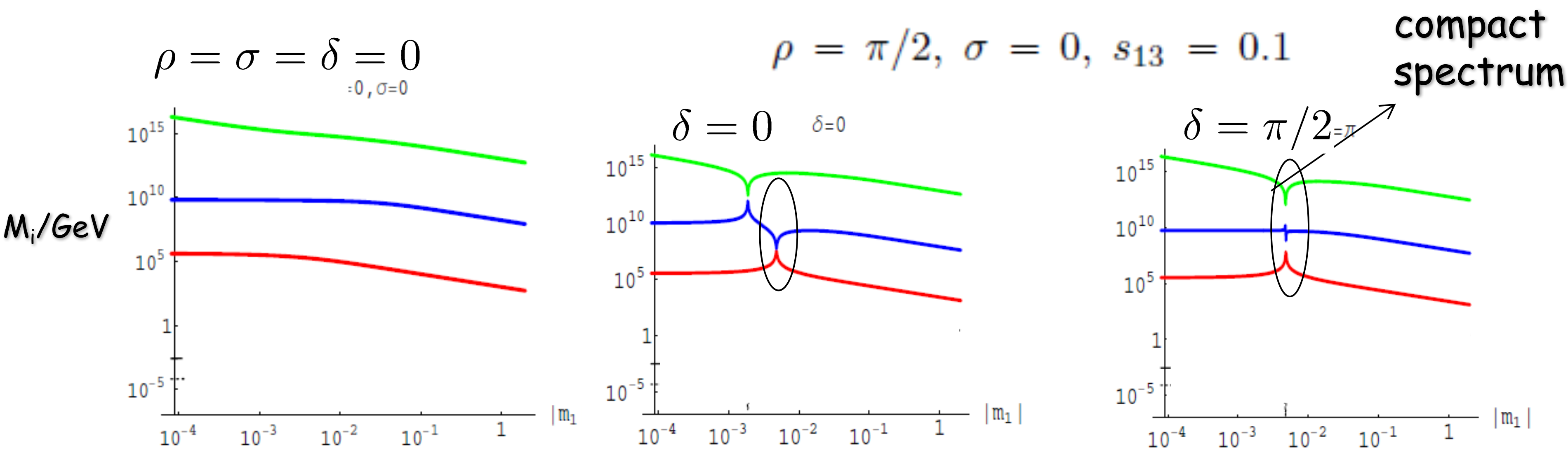
RULED OUT ?

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

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

Crossing level solutions

(Akhmedov, Frigerio, Smirnov hep-ph/0305322)

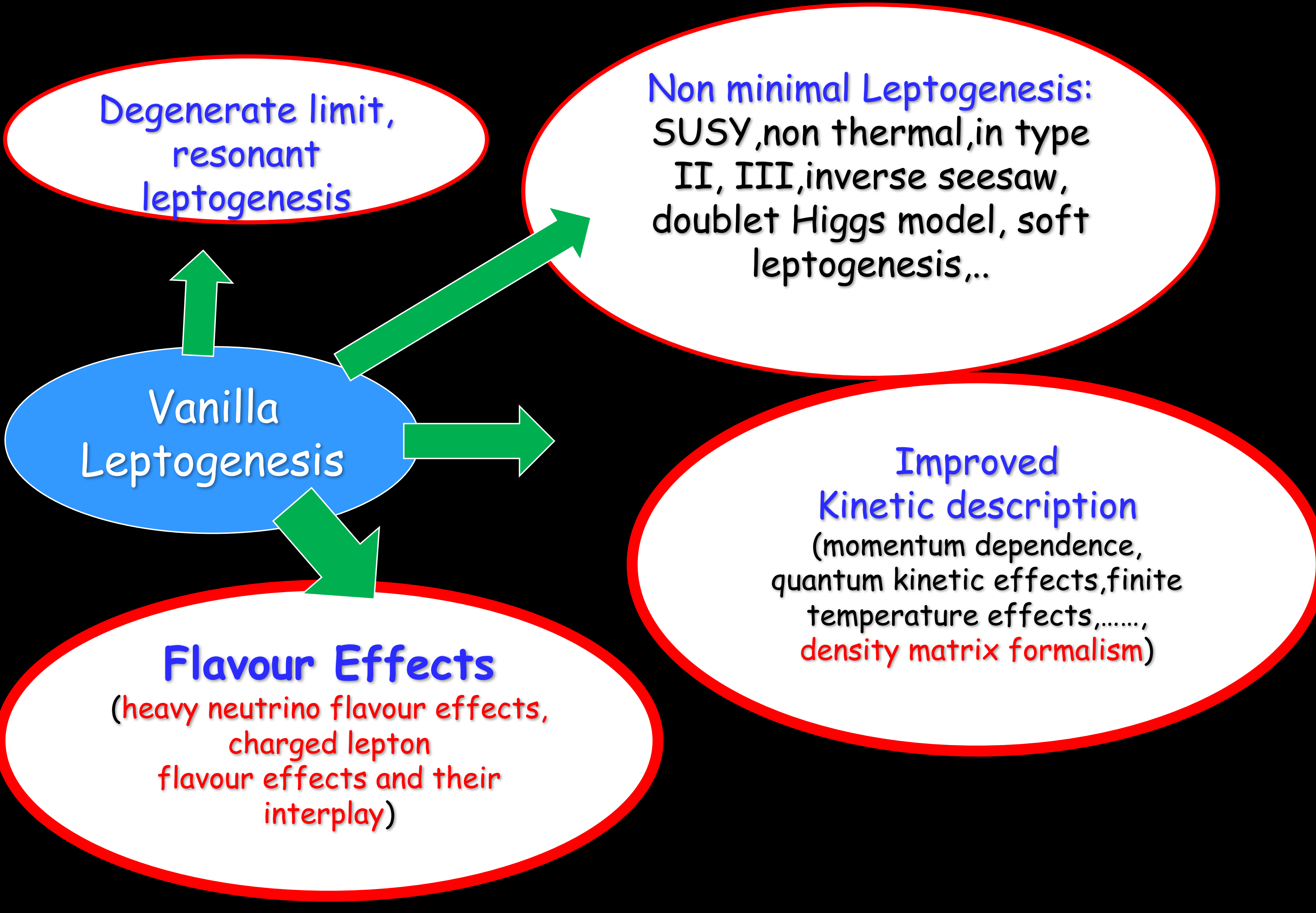


- About the crossing levels the N_1 CP asymmetry is enhanced

- The correct BAU can be attained for a fine tuned choice of parameters but even more importantly these solutions imply huge fine-tuned cancellations in the seesaw formula. Many realistic models have made use of these solutions

(e.g. Ji, Mohapatra,Nasri '10; Buccella, Falcone, Nardi, '12; Altarelli, Meloni '14, Feng, Meloni, Meroni, Nardi '15; Addazi, Bianchi, Ricciardi 1510.00243)

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 ∝+e components ⇒ 2-flavour regime

- T << 10^9 GeV then also ∝-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) $\qquad \varepsilon_{1\tau}\kappa_1^{fin}(K_{1\tau}) + \varepsilon_{1\mu}\kappa_1^{fin}(K_{1\mu}) + \varepsilon_{1e}\kappa_1^{fin}(K_{1e})$

Two fully flavoured regime

- Classic Kinetic Equations (in their simplest form)

$$\frac{dN_{N_1}}{dz} = -D_1 \left(N_{N_1} - N_{N_1}^{\rm eq}\right)$$

$$\frac{dN_{\Delta_\alpha}}{dz} = -\varepsilon_{1\alpha} \frac{dN_{N_1}}{dz} - P_{1\alpha}^0 W_1 N_{\Delta_\alpha}$$

$$\Rightarrow \quad N_{B-L} = \sum_\alpha N_{\Delta_\alpha} \qquad (\Delta_\alpha \equiv B/3 - L_\alpha)$$

(α = τ, e+μ)

$$P_{1\alpha} \equiv |\langle l_\alpha | l_1 \rangle|^2 = P_{1\alpha}^0 + \Delta P_{1\alpha}/2 \qquad \left(\sum_\alpha P_{1\alpha}^0 = 1 \right)$$

$$\bar{P}_{1\alpha} \equiv |\langle \bar{l}_\alpha | \bar{l}_1' \rangle|^2 = P_{1\alpha}^0 - \Delta P_{1\alpha}/2 \qquad \left(\sum_\alpha \Delta P_{1\alpha} = 0 \right)$$

$$\Rightarrow \boxed{\varepsilon_{1\alpha} \equiv -\frac{P_{1\alpha}\Gamma_1 - \bar{P}_{1\alpha}\bar{\Gamma}_1}{\Gamma_1 + \bar{\Gamma}_1} = P_{1\alpha}^0 \varepsilon_1 + \Delta P_{1\alpha}(\Omega, U)/2}$$

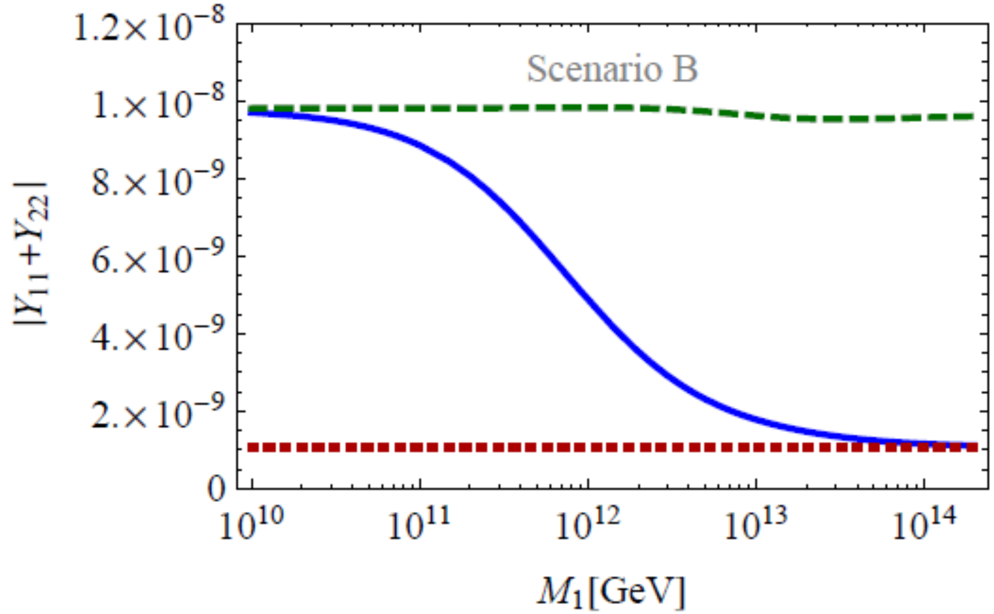
$$\Rightarrow N_{B-L}^{\rm fin} = \sum_\alpha \varepsilon_{1\alpha} \kappa_{1\alpha}^{\rm fin} \simeq 2\,\varepsilon_1 \kappa_1^{\rm fin} + \frac{\Delta P_{1\alpha}}{2} \left[\kappa^{\rm f}(K_{1\alpha}) - \kappa^{\rm fin}(K_{1\beta})\right]$$

Flavoured decay parameters: $K_{i\alpha} \equiv P_{i\alpha}^0 K_i = \left| \sum_k \sqrt{\frac{m_k}{m_\star}}\, U_{\alpha k} \Omega_{ki} \right|^2$

Density matrix formalism to describe the transition regimes

(De Simone, Riotto '06; Beneke, Gabrecht, Fidler, Herranen, Schwaller '10, Blanchet,PDB,Jones,Marzola '11)

$$\frac{dN_{\alpha\beta}^{B-L}}{dz} = \varepsilon_{\alpha\beta}^{(1)}\, D_1\, (N_{N_1} - N_{N_1}^{\rm eq}) - \frac{1}{2}\, W_1\, \{\mathcal{P}^{0(1)}, N^{B-L}\}_{\alpha\beta} - \frac{{\rm Im}(\Lambda_\tau)}{H\, z}(\sigma_1)_{\alpha\beta}\, N_{\alpha\beta}^{B-L}\ ,$$



Fully two-flavoured regime limit

Unflavoured regime limit

Three main implications of flavour effects

- Lower bound on M_1 (an therefore on T_{RH}) is not relaxed
  upper bound on m_1 is slightly relaxed to ~0.2eV

- In the case of real $\Omega \Rightarrow$ all CP violation stems from low energy phases;
  if also Majorana phases are CP conserving only δ would be responsible for the asymmetry: $\Rightarrow$ DIRAC PHASE LEPTOGENESIS: $\eta_{B0} \propto |\sin\delta| \sin\Theta_{13}$

- Asymmetry produced from heavier RH neutrinos also contributes to the asymmetry and has to be taken into account:
  IT OPENS NEW INTERESTING OPPORTUNITIES

Remarks on the role of δ in leptogenesis

Dirac phase leptogenesis:

- It could work but only for $M_1 \gtrsim 5\times10^{11}$ GeV (plus other conditions on Ω)
  $\Rightarrow$density matrix calculation needed!

- No reasons for Ω to be real except when it is a permutation of identity (from discrete flavour models) but then all CP asymmetries would vanish!
  So one needs quite a special Ω

- In general the contribution from δ is *overwhelmed* by the high energy phases in Ω

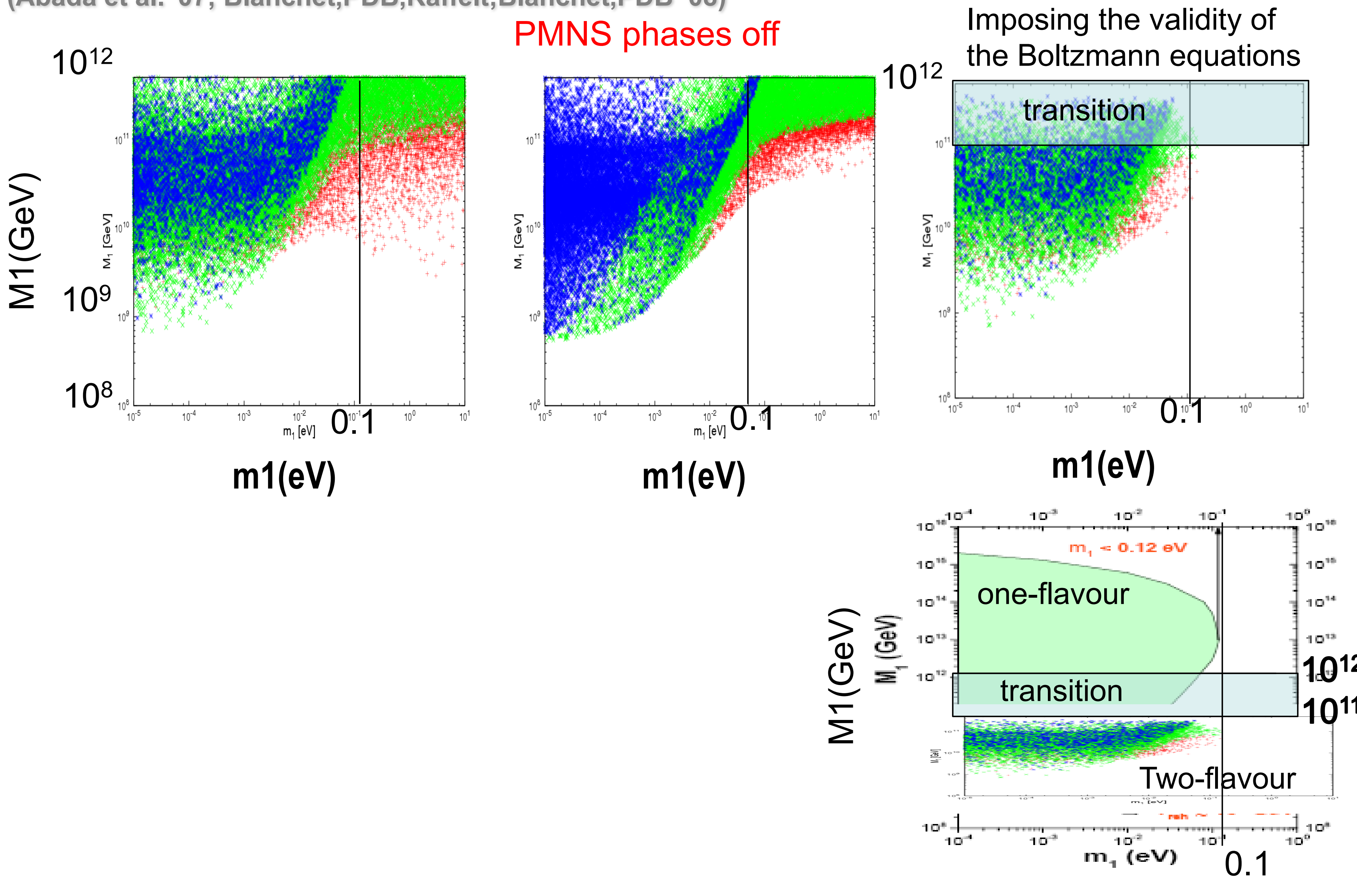
General considerations:

- CP violating value of δ is strictly speaking neither necessary nor sufficient condition for successful leptogenesis and no specific value is favoured model independently but….

- ….it is important to exclude CP conserving values since from $m_D = U\sqrt{D_m}\,\Omega\sqrt{D_M}$ one expects for generic m_D that if there are phases in U then there are also phases in Ω, vice-versa if there are no phases in U one might suspect that also Ω is real (disaster!):
  discovering CP violating value of δ would support a complex m_D

Neutrino mass bounds and role of PMNS phases

(Abada et al.' 07; Blanchet,PDB,Raffelt;Blanchet,PDB '08)



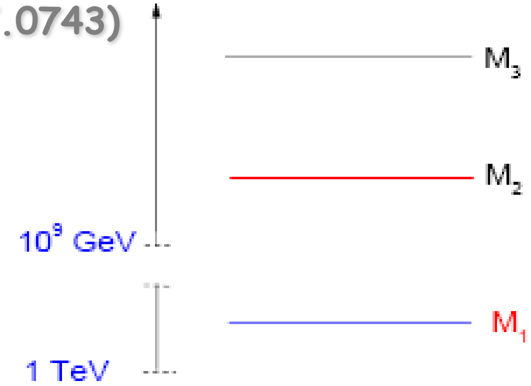
The N_2-dominated scenario

(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 $\Rightarrow$ much weaker

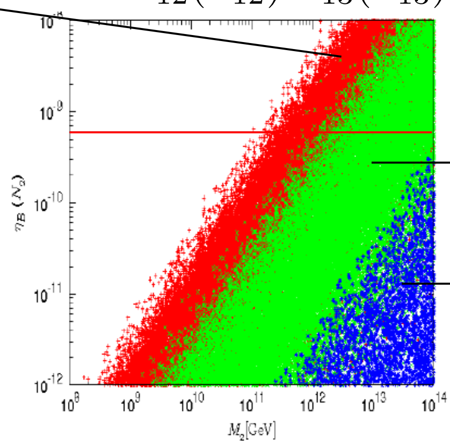


$$N_{B-L}^{\rm f}(N_2) = P_{2e}^0\, \varepsilon_2\, \kappa(K_2)\, e^{-\frac{3\pi}{8}\, K_{1e}} + P_{2\mu}^0\, \varepsilon_2\, \kappa(K_2)\, e^{-\frac{3\pi}{8}\, K_{1\mu}} + P_{2\tau}^0\, \varepsilon_2\, \kappa(K_2)\, e^{-\frac{3\pi}{8}\, K_{1\tau}}$$

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**

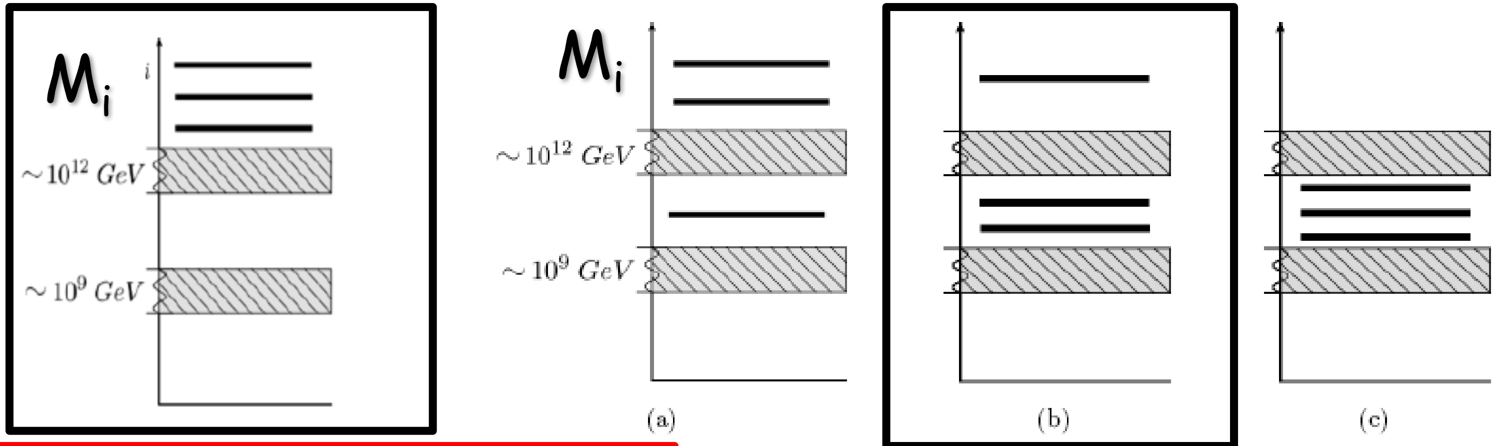
Heavy neutrino lepton flavour effects: 10 hierarchical scenarios

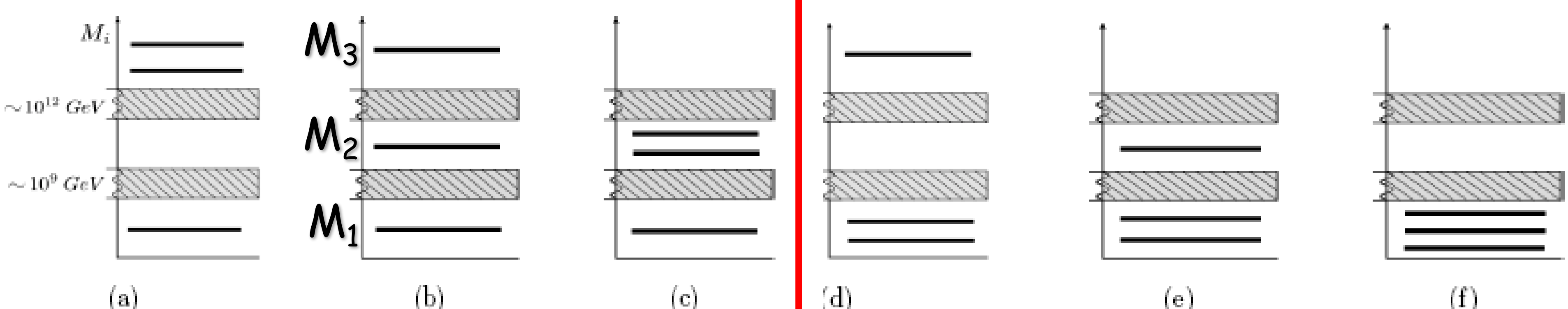
(Bertuzzo, PDB, Marzola, 1007.1641)

Typically rising in discrete symmetries flavour Models

Heavy neutrino flavored scenario

2 RH neutrino scenario





N_2 -dominated scenario:

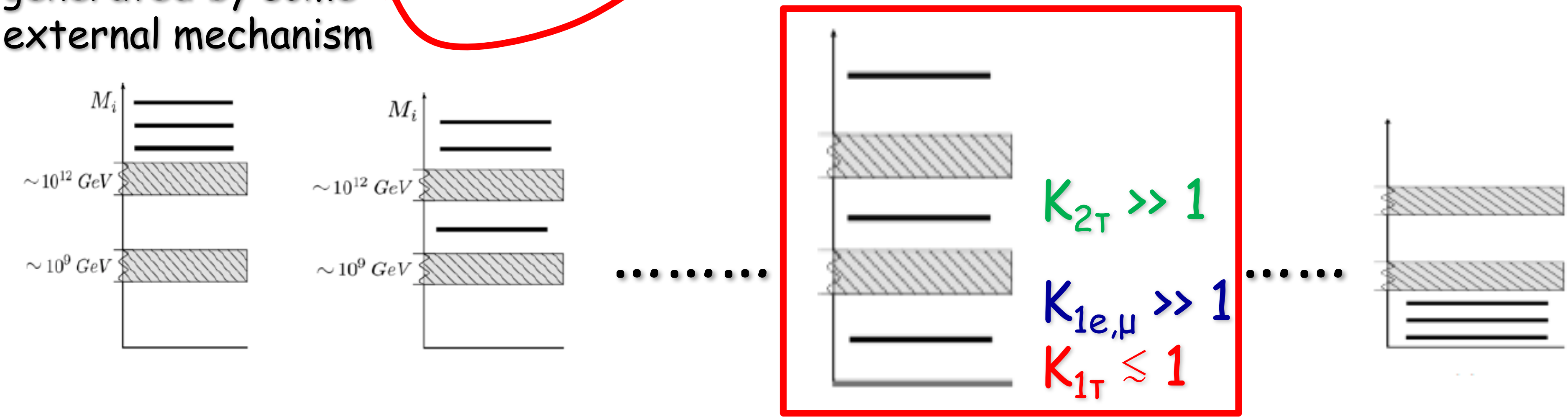
- N_1 produces negligible asymmetry;
- It emerges naturally in SO(10)-inspired models;
- It is the only one that can realise STRONG THERMAL LEPTOGENESIS

The problem of the initial conditions in flavoured leptogenesis

Residual "pre-existing" asymmetry possibly generated by some external mechanism

$$N^{\rm f}_{B-L} = N^{\rm p,f}_{B-L} + N^{\rm lep,f}_{B-L}$$

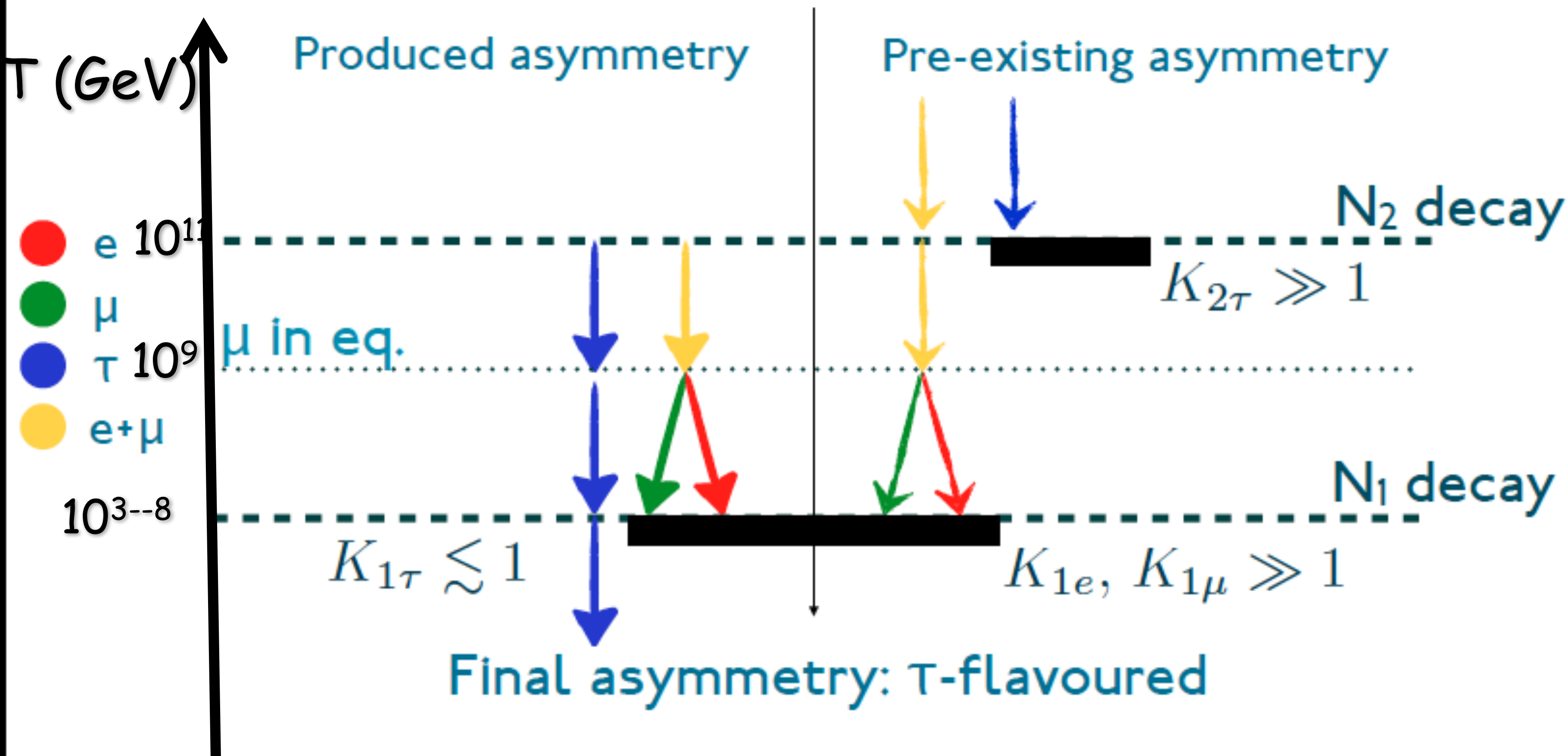
Asymmetry generated from leptogenesis



The conditions for the wash-out of a pre-existing asymmetry ('**strong thermal leptogenesis**') can be realised only within a N_2-dominated scenario where the final asymmetry is dominantly produced in the tauon flavour

(Bertuzzo,PDB,Marzola '10)

How is STL realised? - A cartoon



Strong thermal leptogenesis conditions

$K_{2\tau} \gg 1$ $\quad$ $K_{1e},\, K_{1\mu} \gg 1$ $\quad$ $K_{1\tau} \lesssim 1$

Courtesy of Michele Re Fiorentin

A lower bound on neutrino masses (NO)

(PDB, Sophie King, Michele Re Fiorentin 2014)

$N^{P,i}_{B-L} = 0.001, 0.01, 0.1$

$\max[|\Omega_{21}|^2] = 2$

Starting from the flavoured decay parameters:

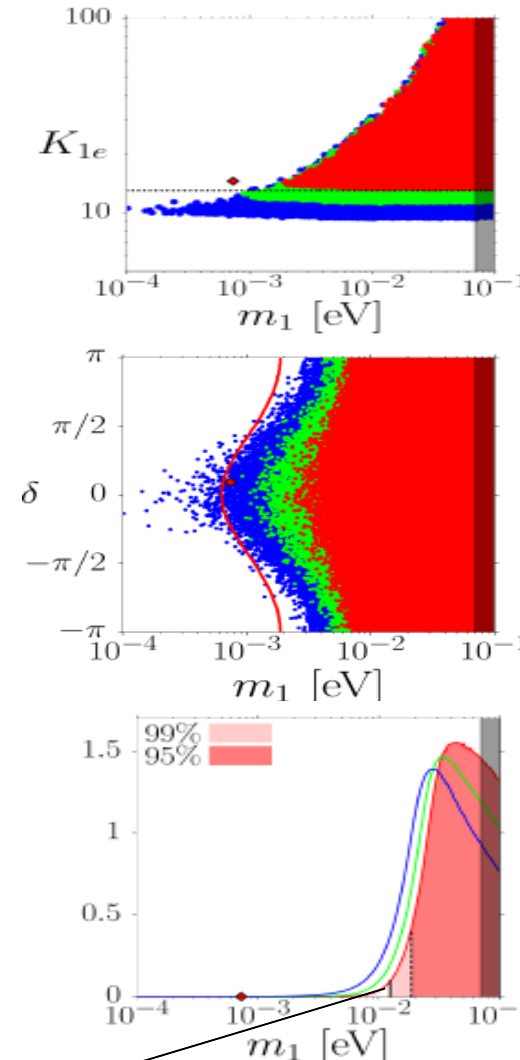
$$K_{i\beta} \equiv p^0_{i\beta}\, K_i = \left|\sum_k \sqrt{\frac{m_k}{m_\star}}\, U_{\beta k}\, \Omega_{ki}\right|^2$$

and imposing $K_{1\tau} \gtrsim 1$ and $K_{1e}, K_{1\mu} \gtrsim K_{st} \simeq 10$ ($\alpha = e,\mu$)

$$m_1 > m_1^{\rm lb} \equiv m_\star \max_\alpha \left[\left(\frac{\sqrt{K_{\rm st}} - \sqrt{K^{0,\max}_{1\alpha}}}{\max[|\Omega_{11}|]\left|U_{\alpha 1} - \frac{U_{\tau 1}}{U_{\tau 3}}\, U_{\alpha 3}\right|}\right)^2\right]$$

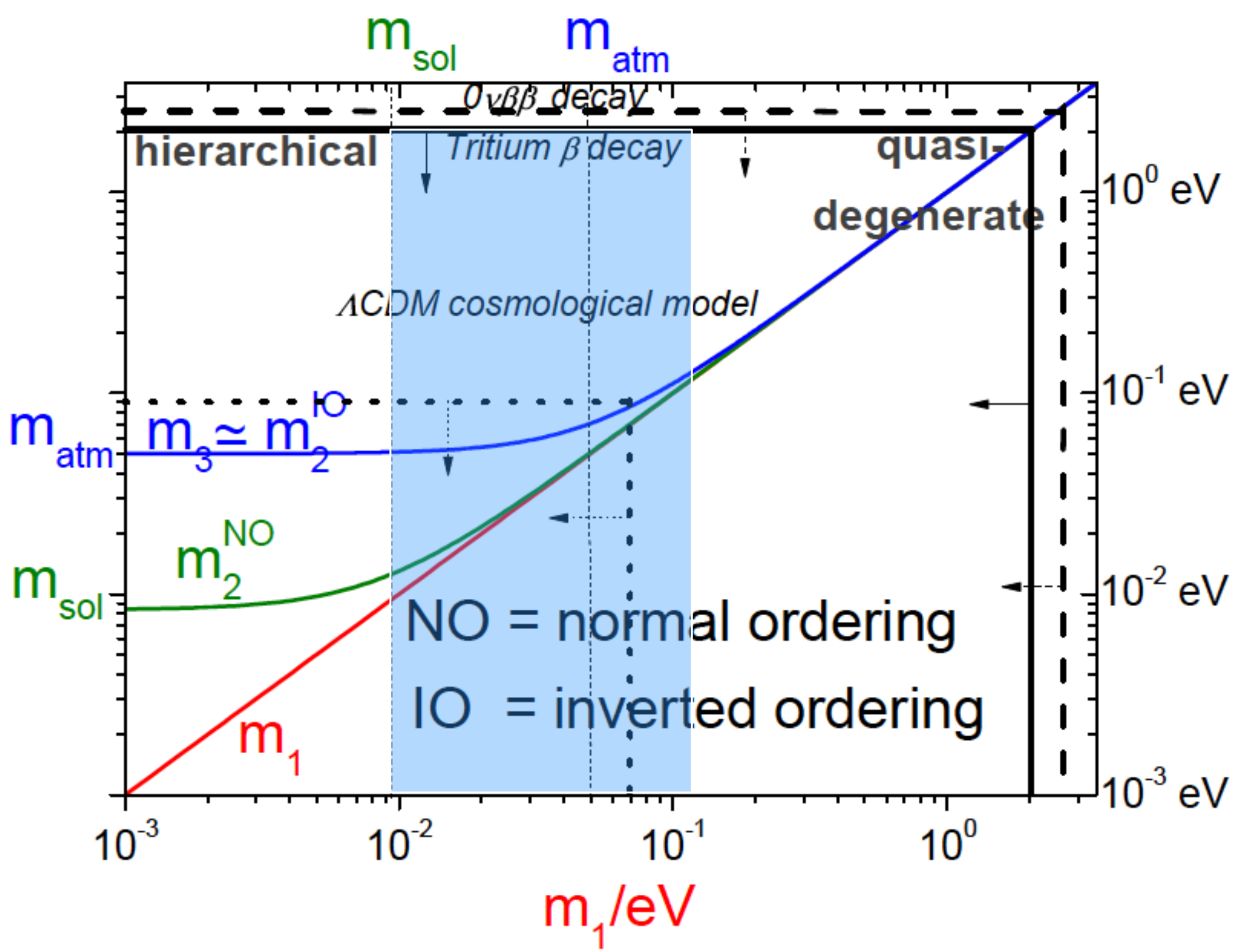
$$K^{0,\max}_{1\alpha} \equiv \left(\max[|\Omega_{21}|]\sqrt{\frac{m_{\rm sol}}{m_\star}}\left|U_{\alpha 2} - \frac{U_{\tau 2}}{U_{\tau 3}}\, U_{\alpha 3}\right| + \left|\frac{U_{\alpha 3}}{U_{\tau 3}}\right| \sqrt{K^{\max}_{1\tau}}\right)^2$$

- The lower bound exists if $\max[|\Omega_{21}|]$ is not too large)



$m_1 \gtrsim 10$ meV $\Rightarrow \Sigma_i\, m_i \gtrsim 75$ meV

A new neutrino mass window for leptogenesis



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

SO(10)-inspired leptogenesis

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

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

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

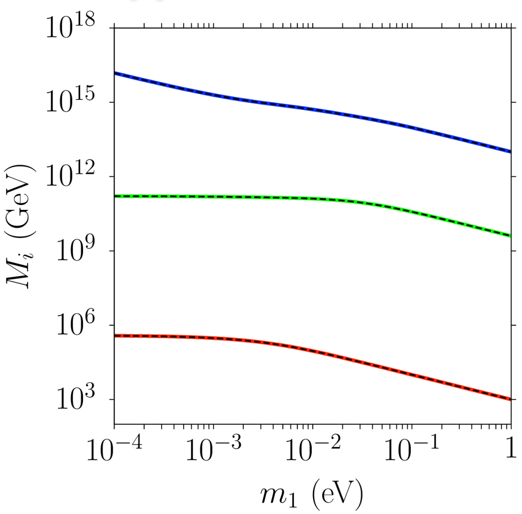
SO(10)-inspired conditions:

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: $U_R = U_R\,(U, m_i; \alpha_i, V_L)$, $M_i = M_i\,(U, m_i; \alpha_i, V_L)$ $\Rightarrow$ $N_{B0} = N_{B0}\,(U, m_i; \alpha_i, V_L)$

typical solutions



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

RULED OUT ?

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

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

Imposing SO(10)-inspired conditions

Seesaw formula $m_\nu = -m_D \, \frac{1}{D_M} \, m_D^T \, .$

light neutrino mass matrix (flavour basis) $m_\nu = -U D_m U^T$

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

SO(10)-inspired conditions: $m_D \sim m_{\text{up quarks}}$

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

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

Majorana mass matrix (in the Yukawa basis)

A diagonalization problem:

$$U_R^\star \, D_M \, U_R^\dagger = M = D_{m_D} \, V_L^\star \, U^\star \, D_m^{-1} \, U^\dagger \, V_L^\dagger \, D_{m_D} = -D_{m_D} \tilde{m}_\nu^{-1} D_{m_D}$$

The predicted baryon asymmetry of the Universe from SO(10)-inspired leptogenesis

Right-handed neutrino masses

$$
\begin{aligned}
M_1 &\simeq \frac{\alpha_1^2\, m_{\rm u}^2}{|(\widetilde{m}_\nu)_{11}|}\,, \\
M_2 &\simeq \frac{\alpha_2^2\, m_{\rm c}^2}{m_1\, m_2\, m_3}\, \frac{|(\widetilde{m}_\nu)_{11}|}{|(\widetilde{m}_\nu^{-1})_{33}|}\,, \\
M_3 &\simeq \alpha_3^2\, m_{\rm t}^2\, |(\widetilde{m}_\nu^{-1})_{33}|\,,
\end{aligned}
$$

$$
V_L = \begin{pmatrix} c_{12}^L\, c_{13}^L & s_{12}^L\, c_{13}^L & s_{13}^L\, e^{-{\rm i}\,\delta_L} \\ -s_{12}^L\, c_{23}^L - c_{12}^L\, s_{23}^L\, s_{13}^L\, e^{{\rm i}\,\delta_L} & c_{12}^L\, c_{23}^L - s_{12}^L\, s_{23}^L\, s_{13}^L\, e^{{\rm i}\,\delta_L} & s_{23}^L\, c_{13}^L \\ s_{12}^L\, s_{23}^L - c_{12}^L\, c_{23}^L\, s_{13}^L\, e^{{\rm i}\,\delta_L} & -c_{12}^L\, s_{23}^L - s_{12}^L\, c_{23}^L\, s_{13}^L\, e^{{\rm i}\,\delta_L} & c_{23}^L\, c_{13}^L \end{pmatrix} {\rm diag}\left(e^{i\,\rho_L}, 1, e^{i\,\sigma_L}\right)
$$

Right-handed neutrino phases and mixing matrix

$$
\begin{aligned}
\Phi_1 &= {\rm Arg}[-\widetilde{m}^\star_{\nu 11}]\,, \\
\Phi_2 &= {\rm Arg}\left[\frac{\widetilde{m}_{\nu 11}}{(\widetilde{m}_\nu^{-1})_{33}}\right] - 2\,(\rho+\sigma) - 2\,(\rho_L+\sigma_L)\,, \\
\Phi_3 &= {\rm Arg}[-(\widetilde{m}_\nu^{-1})_{33}]\,,
\end{aligned}
$$

$$
D_\phi \equiv {\rm diag}(e^{-i\,\frac{\Phi_1}{2}}, e^{-i\,\frac{\Phi_2}{2}}, e^{-i\,\frac{\Phi_3}{2}})\,,
$$

$$
U_R \simeq \begin{pmatrix} 1 & -\frac{m_{D1}}{m_{D2}}\,\frac{\widetilde{m}^\star_{\nu 12}}{\widetilde{m}^\star_{\nu 11}} & \frac{m_{D1}}{m_{D3}}\,\frac{(\widetilde{m}_\nu^{-1})^\star_{13}}{(\widetilde{m}_\nu^{-1})^\star_{33}} \\ \frac{m_{D1}}{m_{D2}}\,\frac{\widetilde{m}_{\nu 12}}{\widetilde{m}_{\nu 11}} & 1 & \frac{m_{D2}}{m_{D3}}\,\frac{(\widetilde{m}_\nu^{-1})^\star_{23}}{(\widetilde{m}_\nu^{-1})^\star_{33}} \\ \frac{m_{D1}}{m_{D3}}\,\frac{\widetilde{m}_{\nu 13}}{\widetilde{m}_{\nu 11}} & -\frac{m_{D2}}{m_{D3}}\,\frac{(\widetilde{m}_\nu^{-1})_{23}}{(\widetilde{m}_\nu^{-1})_{33}} & 1 \end{pmatrix} D_\Phi\,,
$$

The predicted baryon asymmetry of the Universe from SO(10)-inspired leptogenesis

Flavoured decay parameters and CP asymmetries

$$K_{i\alpha} = \frac{\sum_{k,l} m_{Dk}\, m_{Dl}\, V_{Lk\alpha}\, V^{\star}_{Ll\alpha}\, U^{\star}_{Rki}\, U_{Rli}}{M_i\, m_{\star}}$$

Efficiency factors At the production

$$\kappa(K_{i\alpha}) \simeq \frac{2}{K_{i\alpha}\, z_{\rm B}(K_{i\alpha})}\left[1 - \exp\left(-\frac{1}{2} K_{i\alpha}\, z_{\rm B}(K_{i\alpha})\right)\right]$$

Final flavoured (B/3 – Lα) asymmetries

$$\begin{aligned} N^{\rm lep,f}_{\Delta_e} &\simeq \varepsilon_{2e}\, \kappa(K_{2e} + K_{2\mu})\, e^{-\frac{3\pi}{8} K_{1e}}, \\ N^{\rm lep,f}_{\Delta_\mu} &\simeq \varepsilon_{2\mu}\, \kappa(K_{2e} + K_{2\mu})\, e^{-\frac{3\pi}{8} K_{1\mu}}, \\ N^{\rm lep,f}_{\Delta_\tau} &\simeq \varepsilon_{2\tau}\, \kappa(K_{2\tau})\, e^{-\frac{3\pi}{8} K_{1\tau}}, \end{aligned}$$

Flavoured CP asymmetries

$$\varepsilon_{2\alpha} \simeq \frac{3}{16\,\pi\, v^2}\, \frac{|(\widetilde{m}_\nu)_{11}|}{m_1\, m_2\, m_3}\, \frac{\sum_{k,l} m_{Dk}\, m_{Dl}\, {\rm Im}[V_{Lk\alpha}\, V^{\star}_{Ll\alpha}\, U^{\star}_{Rk2}\, U_{Rl3}\, U^{\star}_{R32}\, U_{R33}]}{|(\widetilde{m}_\nu^{-1})_{33}|^2 + |(\widetilde{m}_\nu^{-1})_{23}|^2},$$

Final total asymmetry and baryon-to-photon ratio

$$N^{\rm p,f}_{B-L} = \sum_\alpha N^{\rm p,f}_{\Delta_\alpha},$$

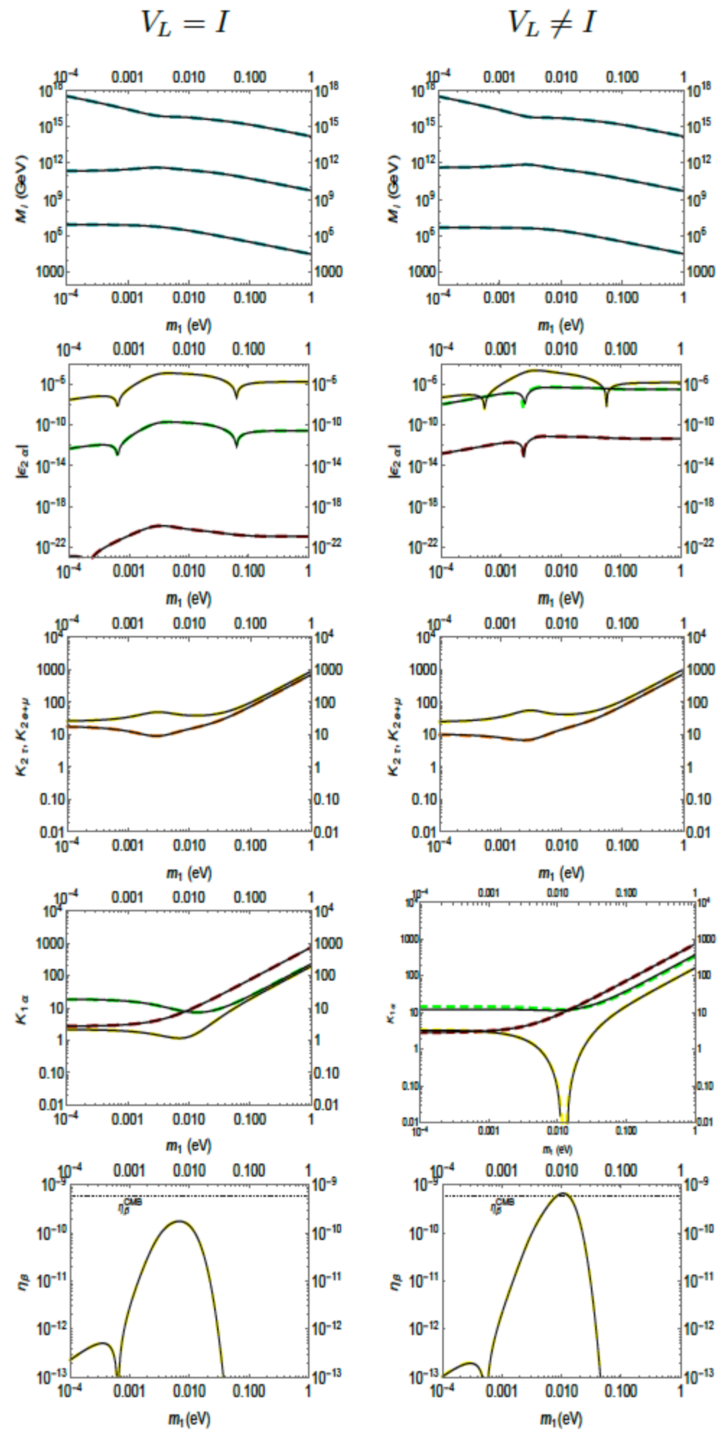
$$\eta_B^{\rm lep} = a_{\rm sph}\, \frac{N^{\rm lep,f}_{B-L}}{N_\gamma^{\rm rec}} \simeq 0.96 \times 10^{-2}\, N^{\rm lep,f}_{B-L}.$$

An example

$$(\alpha_1, \alpha_2, \alpha_3) = (5, 5, 5),$$

$$(\theta_{13}, \theta_{12}, \theta_{23}) = (8.4°, 33°, 42°)$$

$$(\delta, \rho, \sigma) = (-0.6\pi, 0.23\pi, 0.78\,\pi);$$

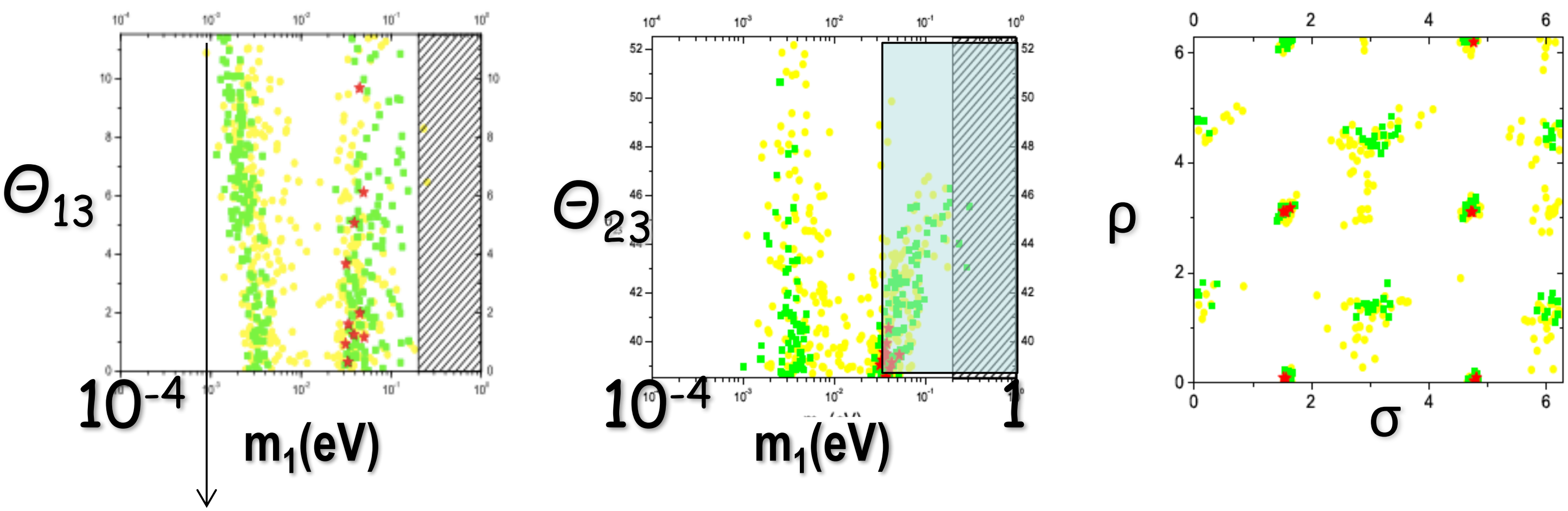


Rescuing SO(10)-inspired leptogenesis

(PDB, Riotto 0809.2285;1012.2343;He,Lew,Volkas 0810.1104)

- $I \lesssim V_L \lesssim V_{CKM}$
- dependence on α_1 and α_3 cancels out $\Rightarrow$only on $\alpha_2 \equiv m_{D2}/m_{charm}$

$\alpha_2=5$ $\alpha_2=4$ $\alpha_2=1$ **NORMAL ORDERING**



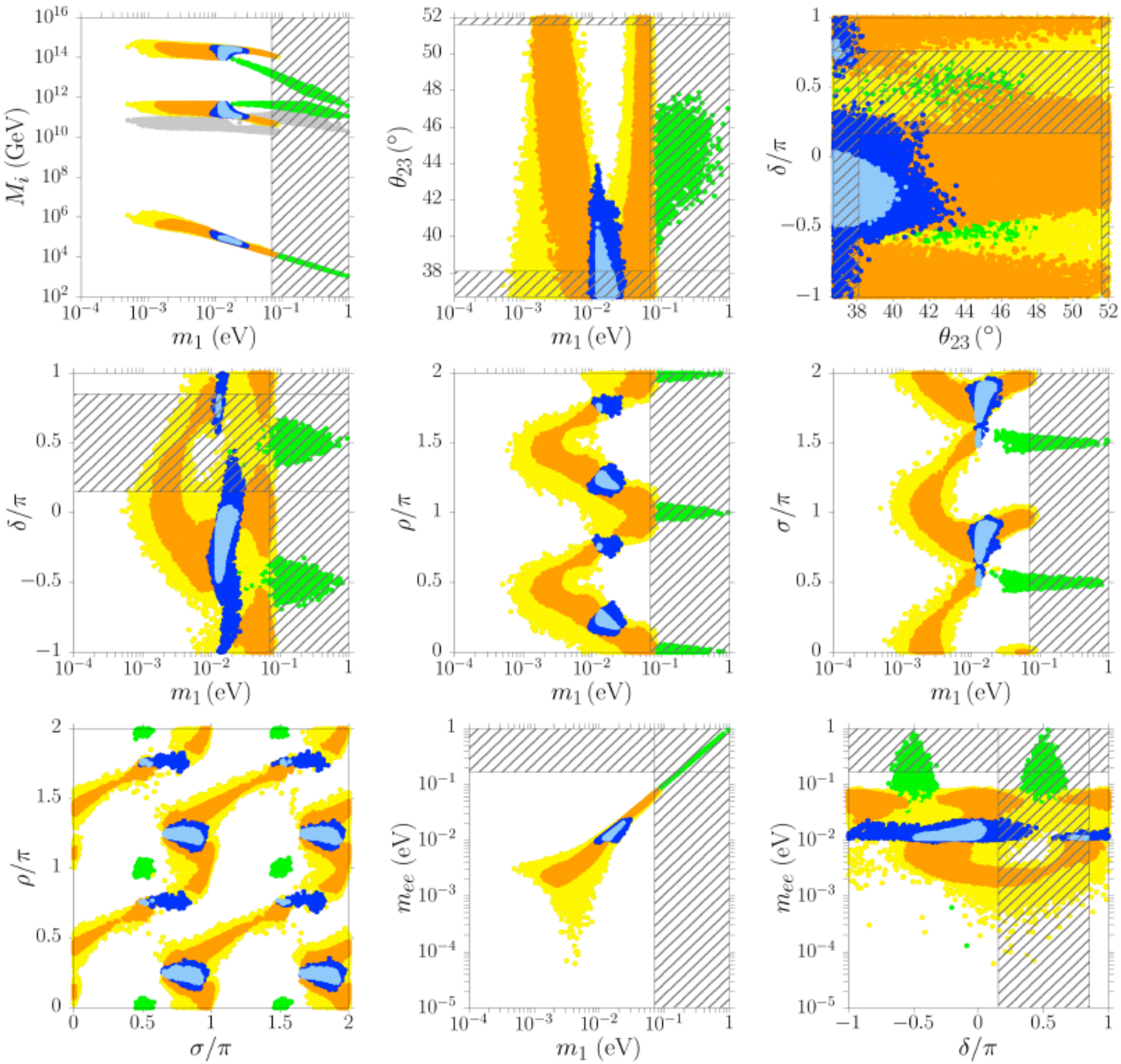
➢ Lower bound $m_1 \gtrsim 10^{-3}$ eV

➢ θ_{23} preferred in the first octant

➢ Majorana phases constrained about specific regions

➢ only marginal allowed regions for INVERTED ORDERING

* Type II seesaw contribution provides an alternative way (Abada et al. 080.2058)



M_i (GeV)
m_1 (eV)
θ_23 (°)
δ/π
ρ/π
σ/π
m_ee (eV)

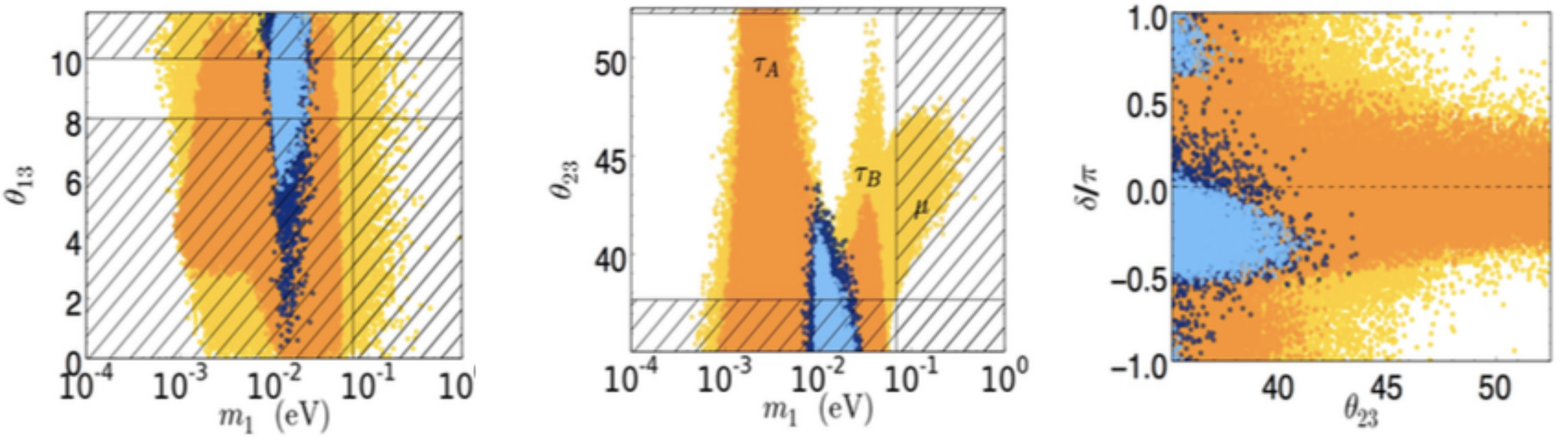
Strong thermal SO(10)-inspired (STSO10) solution

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



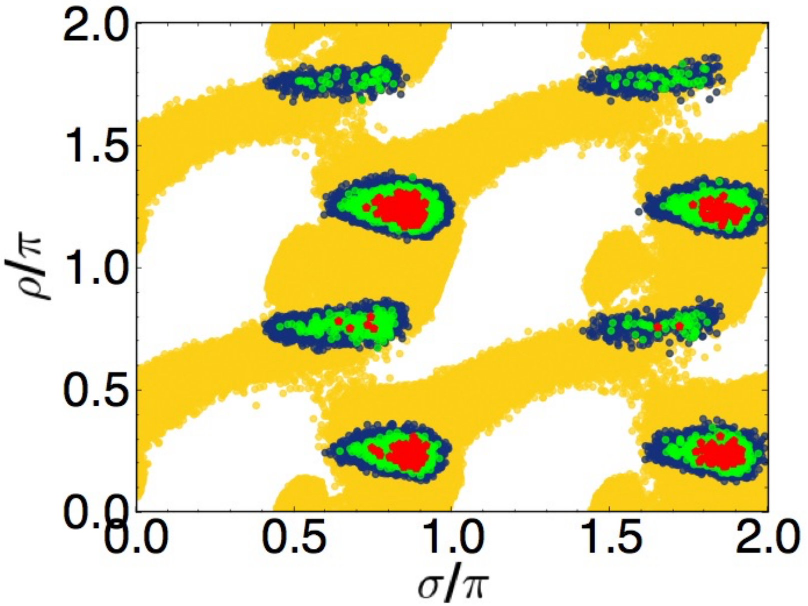
- Absolute neutrino mass scale: $8 \lesssim m_1/\text{meV} \lesssim 30 \Leftrightarrow 70 \lesssim \sum_i m_i/\text{meV} \lesssim 120$
- Non-vanishing Θ_{13};
- Θ_{23} strictly in the first octant;

STSO10: Majorana phases and neutrinoless double beta decay

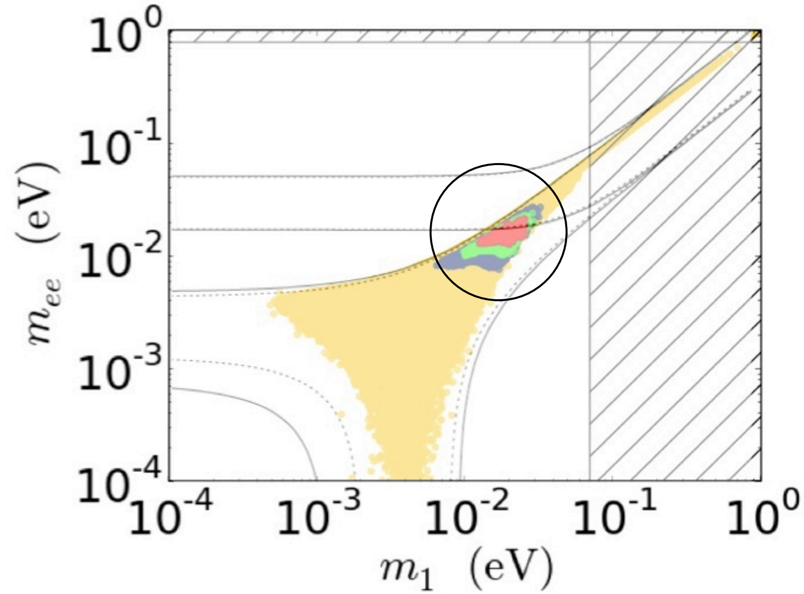
(PDB, Marzola1308.1107;PDB, Re Fiorentin, Marzola 1411.5478)

α_2=5 ➢ NORMAL ORDERING (N^p_{B-L}= 0, 0.001, 0.01, 0.1)

Majorana phases



$m_{ee} \simeq 0.8 m_1 \simeq 15$ meV



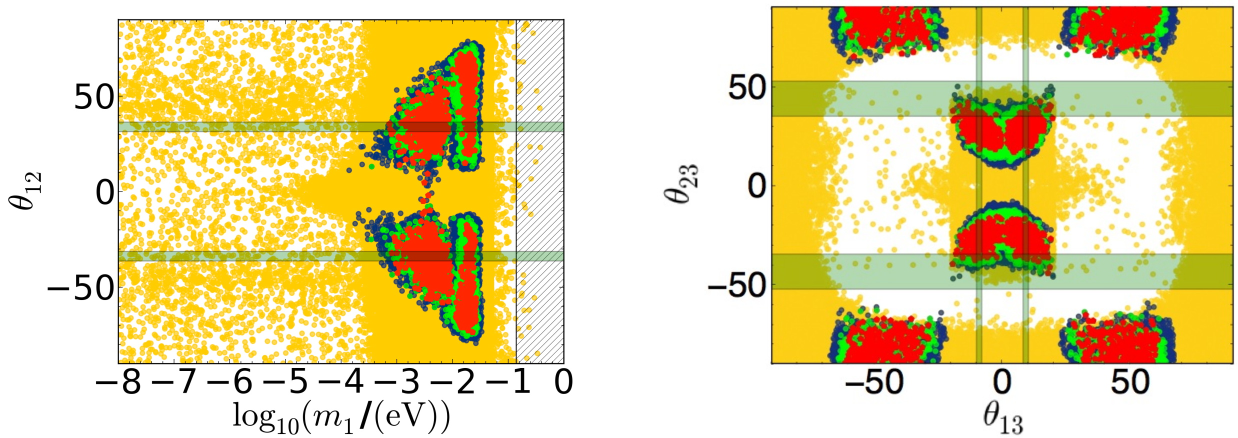
- ❑ Majorana phases are constrained around definite values
- ❑ Sharp prediction on the absolute neutrino mass scale: both on m_1 and m_{ee}
- ❑ Despite one has normal ordering, m_{ee} value might be within exp. Reach
- ❑ Cosmology should also at some point detect deviation from the Hier.Limit
- ❑ If also these predictions are satisfied exp, then $p \lesssim 0.01\%$

STSO10 solution: on the right track?

(PDB, Marzola '13)

What is the probability that the agreement is due to a coincidence?
This sets the statistical significance of the agreement

(N^p_{B-L} = 0, 0.001, 0.01, 0.1)



If the first octant is found then $p \lesssim 10\%$

If NO is found then $p \lesssim 5\%$

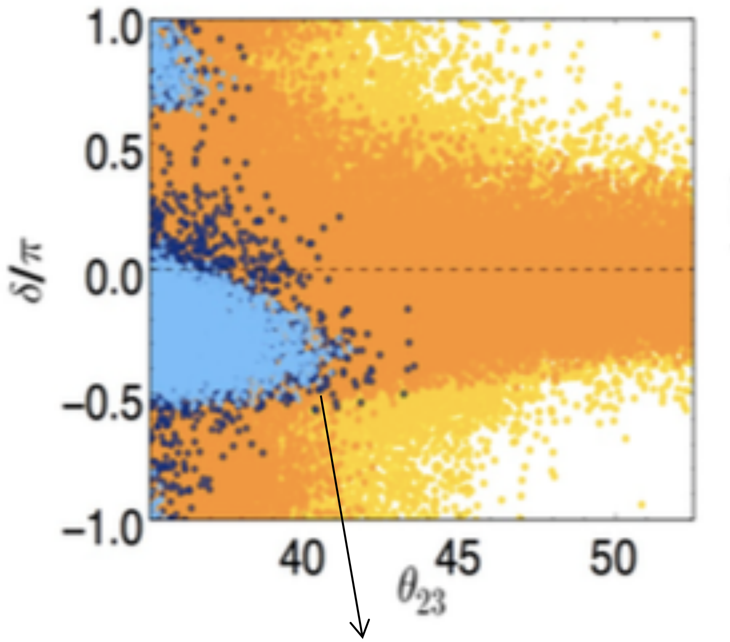
If $\sin\delta < 0$ is confirmed then $p \lesssim 2\%$

If $\cos\delta < 0$ is found then $p \lesssim 1\%$?

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

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

➢ NORMAL ORDERING

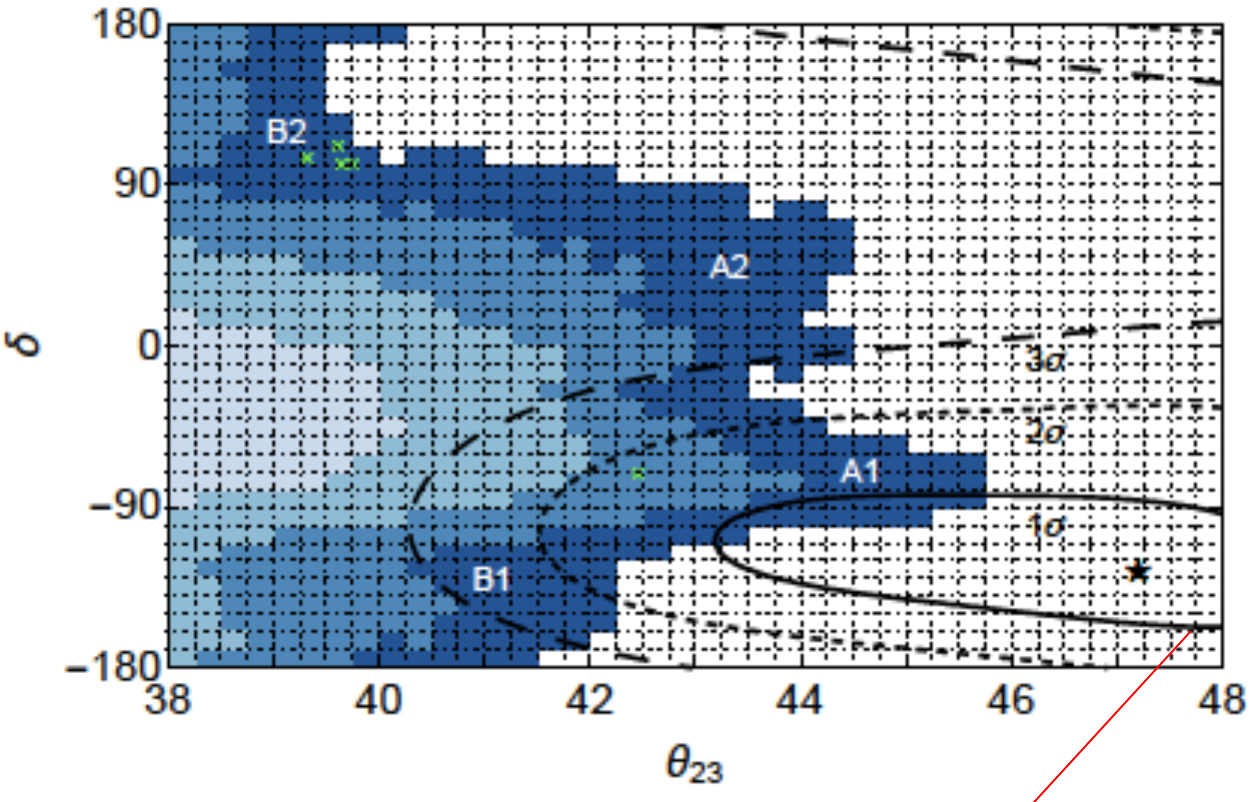


- For values of $\theta_{23} \gtrsim 38^0$ the Dirac phase is predicted to be $\delta \sim -60^0$: the exact range depends on θ_{23} but in any case $\cos\delta > 0$
- The new experimental results seem to support this solution: a precise determination of θ_{23} and δ can further test this solution.
- 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)

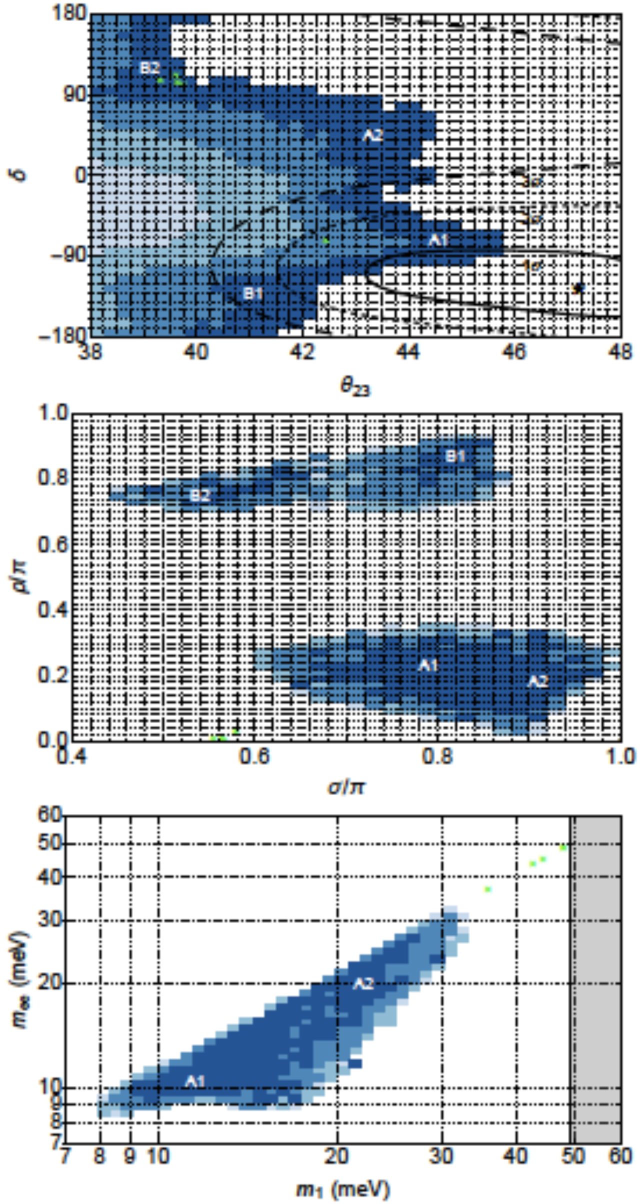
$$\alpha_2 = 5 \qquad N_{B-L}^{p,i} = 10^{-3}$$



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

Strong thermal SO(10)-inspired solution

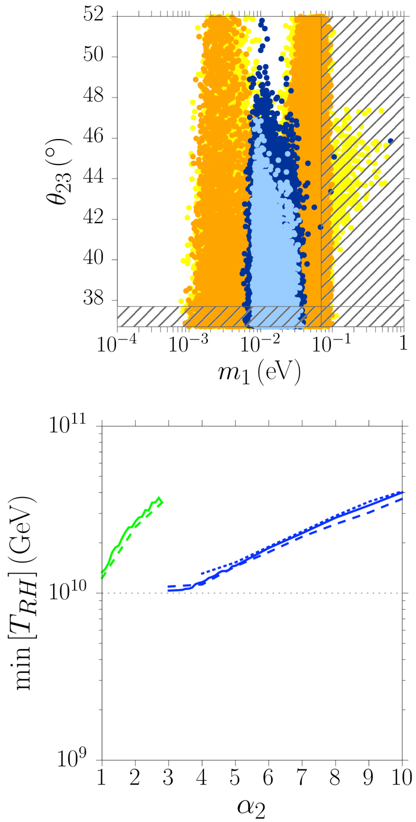
(PDB, Marco Chianese 2018)



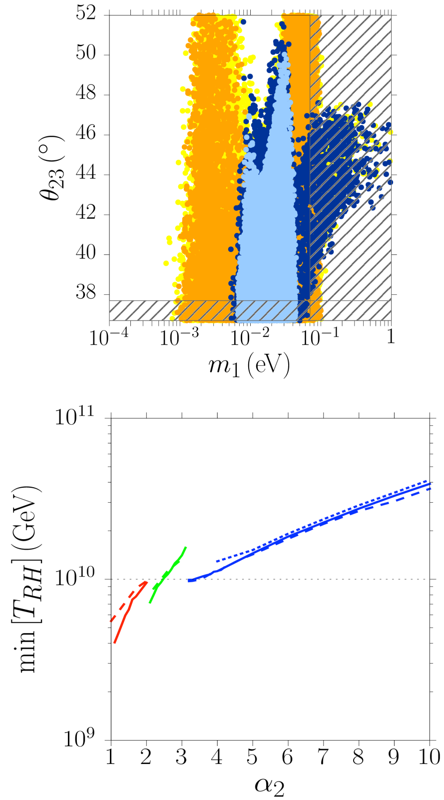
SUSY SO(10)-inspired leptogenesis

(PDB, Re Fiorentin, Marzola, 1512.06739)

$\tan\beta = 5$



$\tan\beta = 50$



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)

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

(S.F. King 2014)

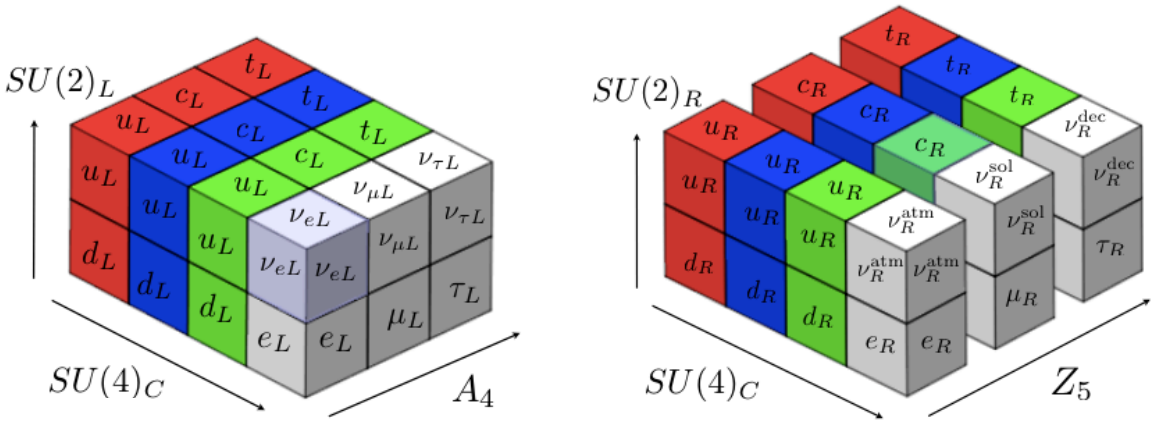


Figure 1: A to Z of flavour with Pati-Salam, where $A \equiv A_4$ and $Z \equiv Z_5$. The left-handed families form a triplet of A_4 and are doublets of $SU(2)_L$. The right-handed families are distinguished by Z_5 and are doublets of $SU(2)_R$. The $SU(4)_C$ unifies the quarks and leptons with leptons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

Neutrino sector:

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

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:

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

Leptogenesis in the "A2Z model"

(PDB, S.King 2015)

The only sizeable CP asymmetry is the tauon asymmetry but $K_{1\tau} \gg 1$!

Flavour coupling (mainly due to the hypercharge Higgs asymmetry) is then crucial to produce the correct asymmetry:
(Antusch,PDB,Jones,King 2011)

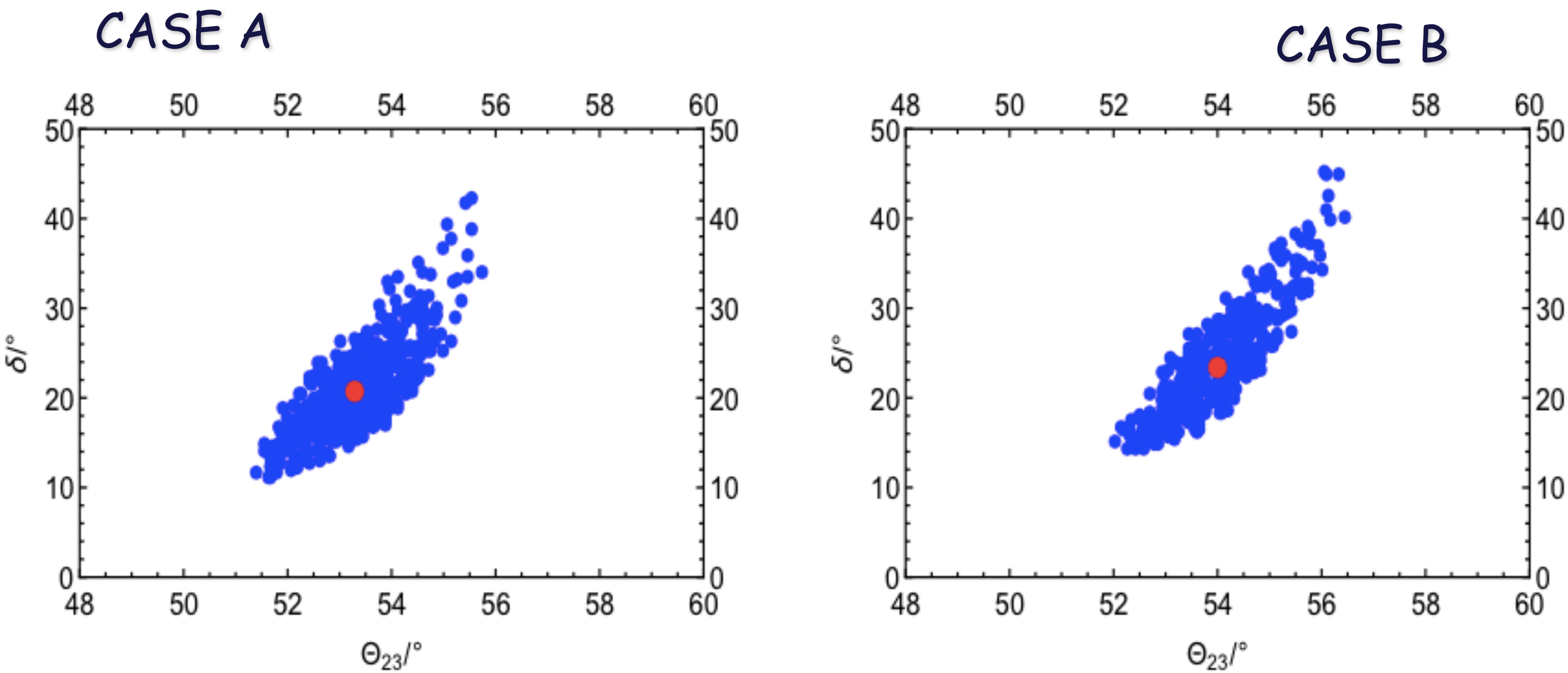
$$\eta_B \simeq \sum_{\alpha=e,\mu,\tau} \eta_B^{(\alpha)}, \qquad \eta_B^{(\tau)} \simeq 0.01\, \varepsilon_{2\tau}\, \kappa(K_{2\tau})\, e^{-\frac{3\pi}{8}\, K_{1\tau}}$$

$$\eta_B^{(e)} \simeq -0.01\, \varepsilon_{2\tau}\, \kappa(K_{2\tau})\, \frac{K_{2e}}{K_{2e}+K_{2\mu}}\, C^{(2)}_{\tau^\perp\tau}\, e^{-\frac{3\pi}{8}\, K_{1e}}$$

$$\eta_B^{(\mu)} \simeq -\left(\frac{K_{2\mu}}{K_{2e}+K_{2\mu}}\, C^{(2)}_{\tau^\perp\tau} - \frac{K_{1\mu}}{K_{1\tau}}\, C^{(3)}_{\mu\tau}\right)\, e^{-\frac{3\pi}{8}\, K_{1\mu}}\, .$$

There are 2 solutions (only for NO)

(PDB, S.F. King 1507.06431)



This region will be tested relatively quickly: it is now quite disfavoured by the new data

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:

$$16 \otimes 16 = 10_S \oplus \overline{126}_S \oplus 120_A ;$$

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	$M_u = v_{10}^u Y_{10} + v_{126}^u Y_{126} + v_{120}^u Y_{120}$,
down-quark mass matrix	$M_d = v_{10}^d Y_{10} + v_{126}^d Y_{126} + v_{120}^d Y_{120}$,
neutrino mass matrix	$M_D = v_{10}^u Y_{10} - 3 v_{126}^u Y_{126} + v_{120}^D Y_{120}$,
charged lepton mass matrix	$M_l = v_{10}^d Y_{10} - 3 v_{126}^d Y_{126} + v_{120}^l Y_{120}$,
RH neutrino mass matrix	$M_R = v_{126}^R Y_{126}$,
LH neutrino mass matrix	$M_L = v_{126}^L Y_{126}$,

→ 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

Recent fits within SO(10) models

- Joshipura Patel 2011; Rodejohann, Dueck '13 : **the obtained quite good fits especially including supersymmetry but no leptogenesis and usually compact Spectrum solutions very fine tuned**

- Babu, Bajc, Saad 1612.04329: they find a good fit with NO, hierarchical RH neutrino spectrum but no leptogenesis

- de Anda, King, Perdomo 1710.03229: $SO(10) \times S_4 \times Z_4^R \times Z_4^3$ model: it fits fermion parameters and also find successful leptogenesis respecting the constraints we showed: interesting prediction on neutrinoless double beta decay effective neutrino mass m_{ee} ~11 meV.

Recent fits within SO(10) models: an example

(Joshipura Patel 2011; Rodejohann, Dueck '13)

No type II seesaw contribution: it does not seem to help the fits

Minimal Model with $10_H + \overline{126}_H$ (MN, MS)

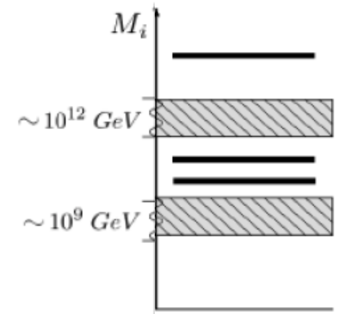
"full" Higgs Content $10_H + \overline{126}_H + 120_H$ (FN, FS)

Mod	Comments	$\langle m_\nu \rangle$ [meV]	δ^l_{CP} [rad]	$\sin^2 \theta^l_{23}$	m_0 [meV]	M_3 [GeV]	M_2 [GeV]	M_1 [GeV]	$\chi^2_{\min}$
MN	no RGE, NH	0.35	0.7	0.406	3.03	5.5×10^{12}	7.2×10^{11}	1.5×10^{10}	1.10
MN	RGE, NH	0.49	6.0	0.346	2.40	3.6×10^{12}	2.0×10^{11}	1.2×10^{11}	23.0
MS	no RGE, NH	0.38	0.27	0.387	2.58	3.9×10^{12}	7.2×10^{11}	1.6×10^{10}	9.41
MS	RGE, NH	0.44	2.8	0.410	6.83	1.1×10^{12}	5.7×10^{10}	1.5×10^{10}	3.29
FN	no RGE, NH	4.96	1.7	0.410	8.8	1.9×10^{13}	2.8×10^{12}	2.2×10^{10}	6.6×10^{-5}
FN	RGE, NH	2.87	5.0	0.410	1.54	9.9×10^{14}	7.3×10^{13}	1.2×10^{13}	11.2
FS	no RGE, NH	0.75	0.5	0.410	1.16	1.5×10^{13}	5.3×10^{11}	5.7×10^{10}	9.0×10^{-10}
FS	RGE, NH	0.78	5.4	0.410	3.17	4.2×10^{13}	4.9×10^{11}	4.9×10^{11}	6.9×10^{-6}
FN	no RGE, IH	35.37	5.4	0.590	35.85	2.2×10^{13}	4.9×10^{12}	9.2×10^{11}	2.5×10^{-4}
FN	RGE, IH	35.52	4.7	0.590	30.24	1.1×10^{13}	3.5×10^{12}	5.5×10^{11}	13.3
FS	no RGE, IH	44.21	0.3	0.590	6.27	1.2×10^{13}	4.2×10^{11}	3.5×10^{7}	3.9×10^{-8}
FS	RGE, IH	24.22	3.6	0.590	11.97	1.2×10^{13}	3.1×10^{11}	2.0×10^{3}	0.602

Recently Fong,Meloni,Meroni,Nardi(1412.4776) have included leptogenesis for the non-SUSY case obtaining successful leptogenesis: but such a compact RN neutrino spectrum implies huge fine-tuning. Too simplistic models? What solution: non renormalizable terms? Type II seesaw term? SUSY seems to improve the fits and also give 1 hier. solution

2 RH neutrino models

(PDB, NOW 2006;Anisimov,PDB 0812.5085;PDB, P.Ludl,S. Palomarez-Ruiz 1606.06238)
(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.

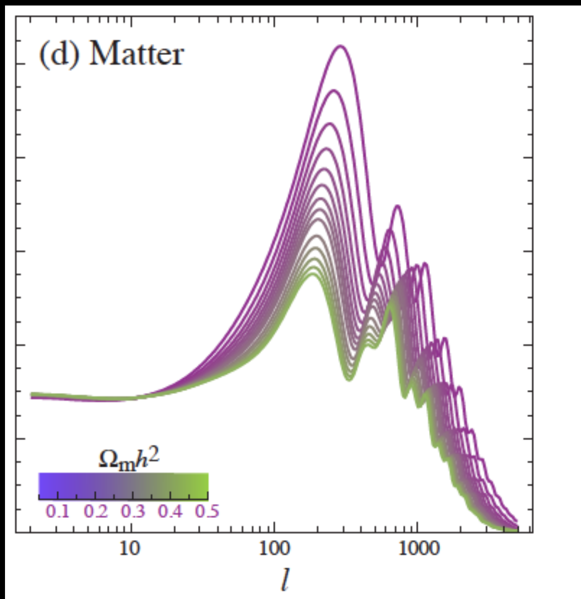
$$M_1 \gtrsim 2\text{x}\, 10^{10}\,\text{GeV} \Rightarrow T_{RH} \gtrsim 6 \times 10^{9}\,\text{GeV}$$

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

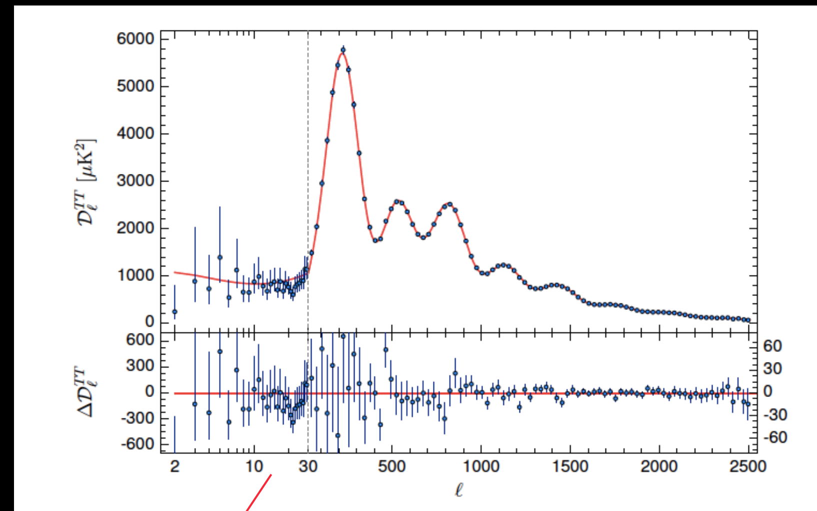
(A.Anisimov, PDB hep-ph/0812.5085)

The Dark Matter of the Universe

(Hu, Dodelson, astro-ph/0110414)



(Planck 2015, 1502.10589)

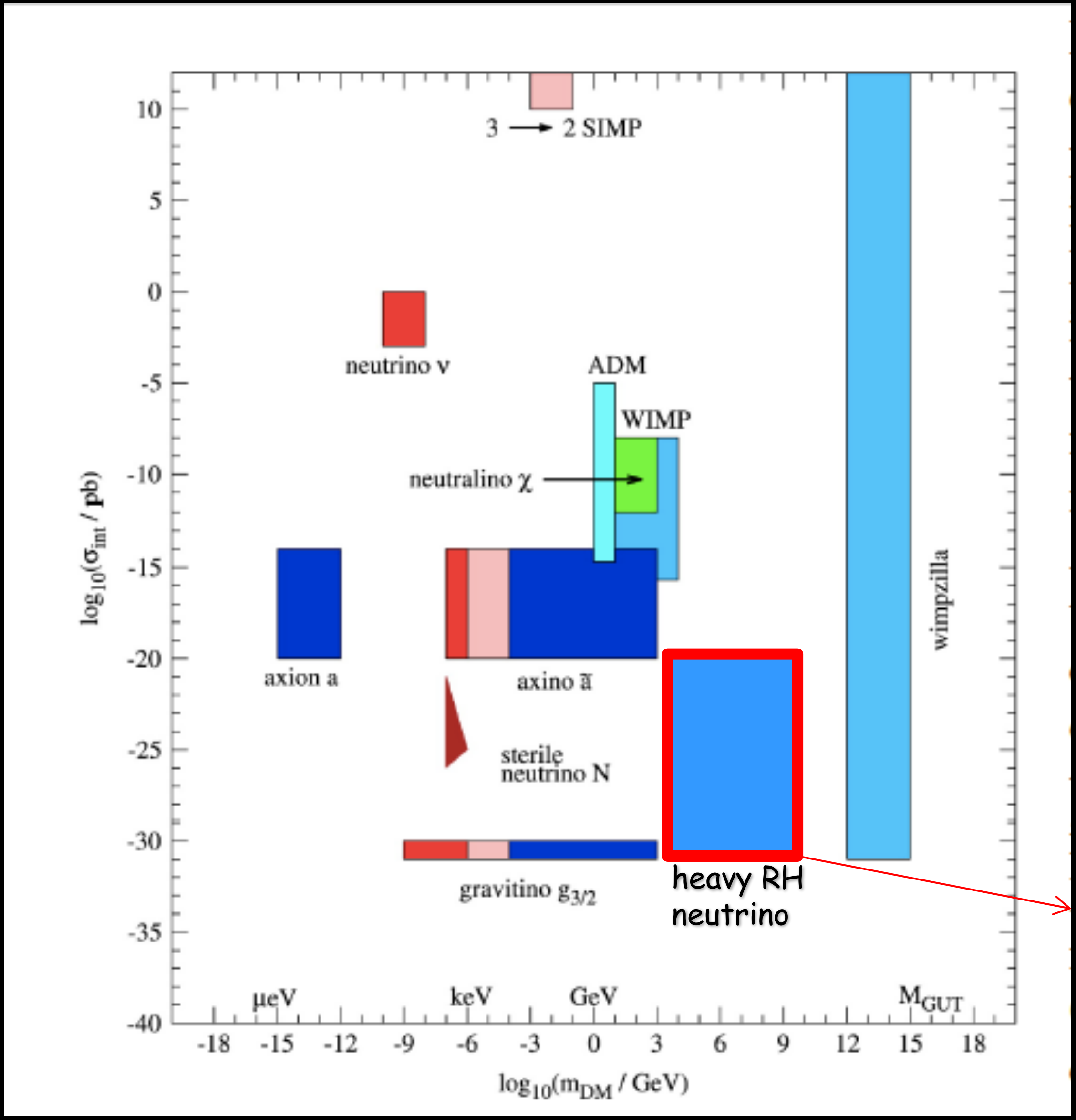


CMB +"ext"

$$\Omega_{CDM,0}h^2 = 0.1188 \pm 0.0010 \sim 5\Omega_{B,0}h^2$$

Beyond the WIMP paradigm

(from Baer et al.1407.0017)



(PDB, Anisimov '08)

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):

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

What production mechanism? Turning on tiny Yukawa couplings?

Yukawa basis:

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

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

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

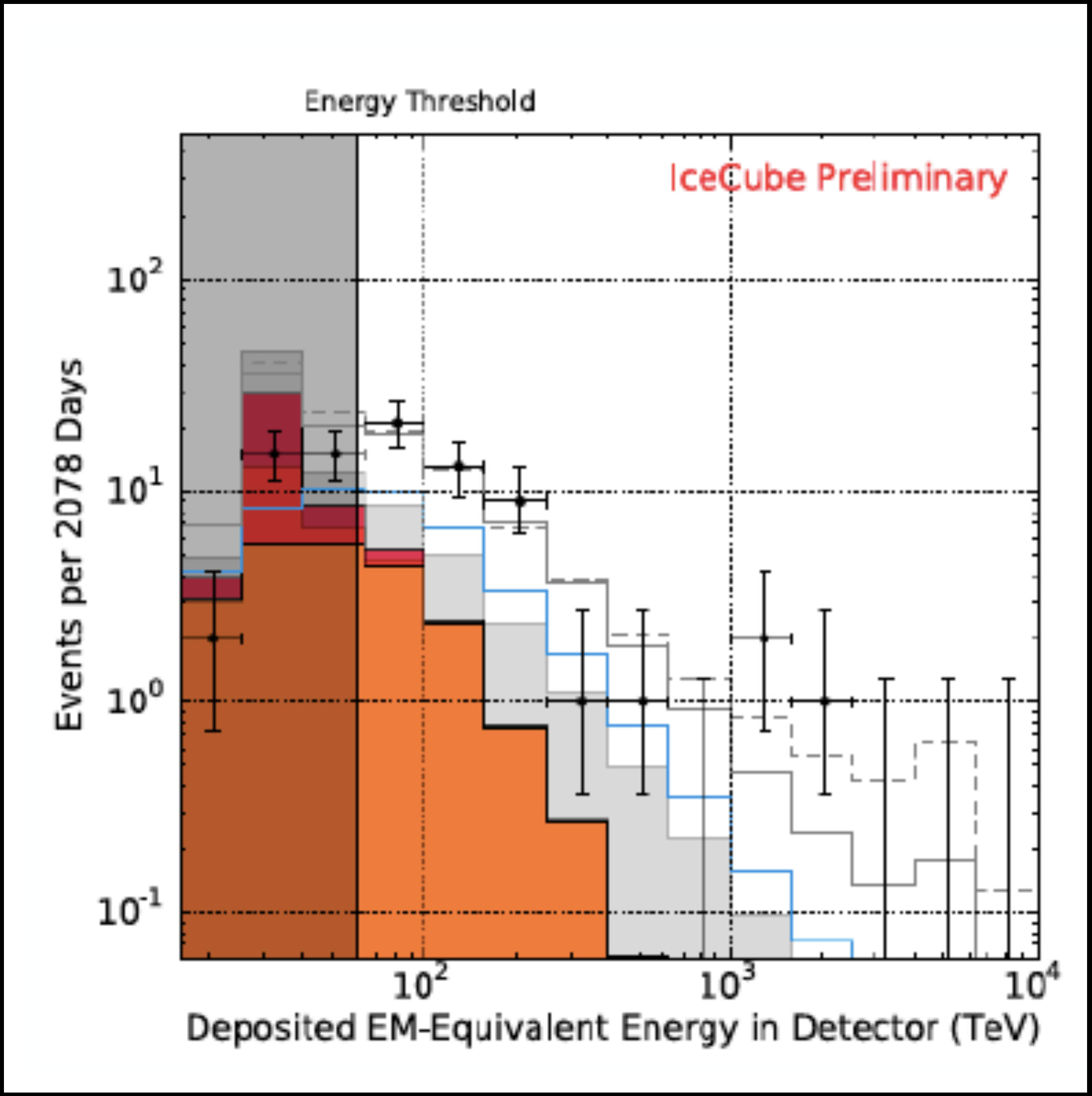
$$\Rightarrow \quad \tau_{DM} > \tau_{DM}^{\min} \simeq 10^{28} s \Rightarrow h_A < 3 \times 10^{-26} \sqrt{\frac{GeV}{M_{DM}} \times \frac{10^{28} s}{\tau_{DM}^{\min}}}$$

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

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

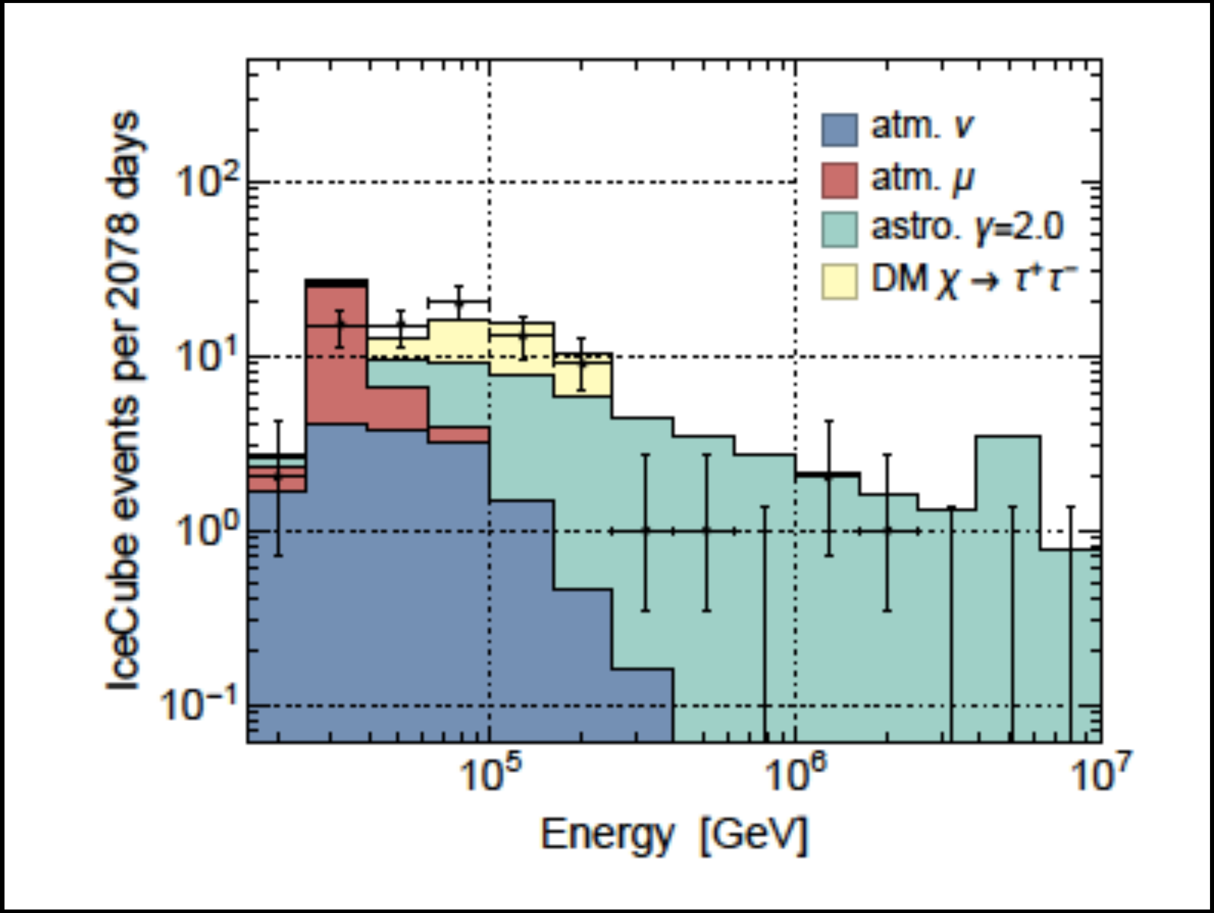
It would be enough to convert just a tiny fraction of ("source") thermalised RH neutrinos but it still does not work with standard Yukawa couplings

IceCube detection of very high energy neutrinos



(Talk by Halzen at PAHEN17, 25-26 September, Naples)

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:

$$\mathcal{L} = \frac{\lambda_{IJ}}{\Lambda}\,\phi^\dagger\,\phi\,\overline{N_I^c}\,N_J$$

(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)

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

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

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

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

$$z_{\rm res} \equiv \frac{M_{\rm DM}}{T_{\rm res}} = \frac{h_S\,M_{\rm DM}}{2\sqrt{M_{\rm DM}^2 - M_S^2}}$$

Non-adiabatic conversion

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

Adiabaticity parameter at the resonance

$$\gamma_{\rm res} \equiv \left.\frac{|E^{\rm m}_{\rm DM} - E^{\rm m}_{\rm S}|}{2\,|\dot{\theta}_m|}\right|_{\rm res} = \sin^2 2\theta_\Lambda(T_{\rm res})\,\frac{|\Delta M^2|}{12\,T_{\rm res}\,H_{\rm res}}\,,$$

Landau-Zener formula

$$\left.\frac{N_{N_{\rm DM}}}{N_{N_{\rm S}}}\right|_{\rm res} \simeq \frac{\pi}{2}\,\gamma_{\rm res}$$

(remember that we need only a small fraction to be converted so necessarily γ_{res}<<<1)

$$\Rightarrow \quad \Omega_{\rm DM}\,h^2 \simeq \frac{0.15}{\alpha_{\rm S}\,z_{\rm res}}\left(\frac{M_{\rm DM}}{M_{\rm S}}\right)\left(\frac{10^{20}\,{\rm GeV}}{\widetilde{\Lambda}}\right)^2\left(\frac{M_{\rm DM}}{\rm GeV}\right)$$

For successful dark-matter genesis

$$\Rightarrow \quad \widetilde{\Lambda}_{\rm DM} \simeq 10^{20}\sqrt{\frac{1.5}{\alpha_{\rm S}\,z_{\rm res}}\,\frac{M_{\rm DM}}{M_{\rm S}}\,\frac{M_{\rm DM}}{\rm GeV}}\;{\rm GeV}$$

2 options: either $\Lambda < M_{Pl}$ and λ_{AS}<<< 1 or λ_{AS}~ 1 and $\Lambda >>> M_{Pl}$:

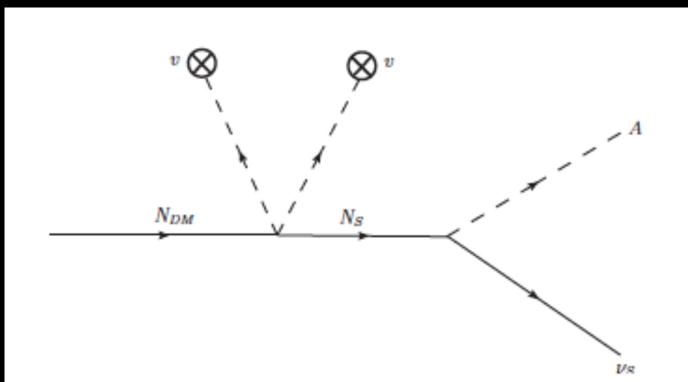
it is possible to think of models in both cases.

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



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

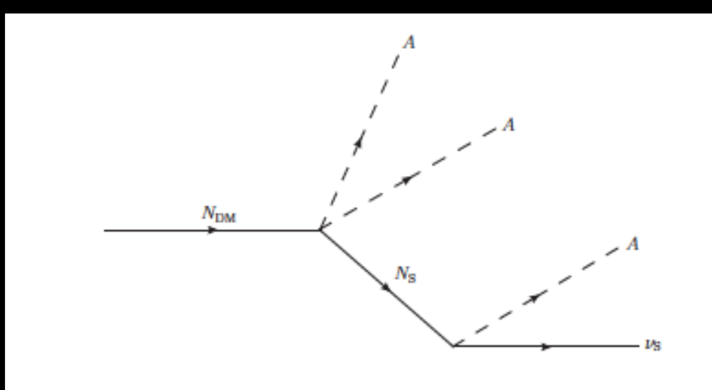
mixing angle today

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

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

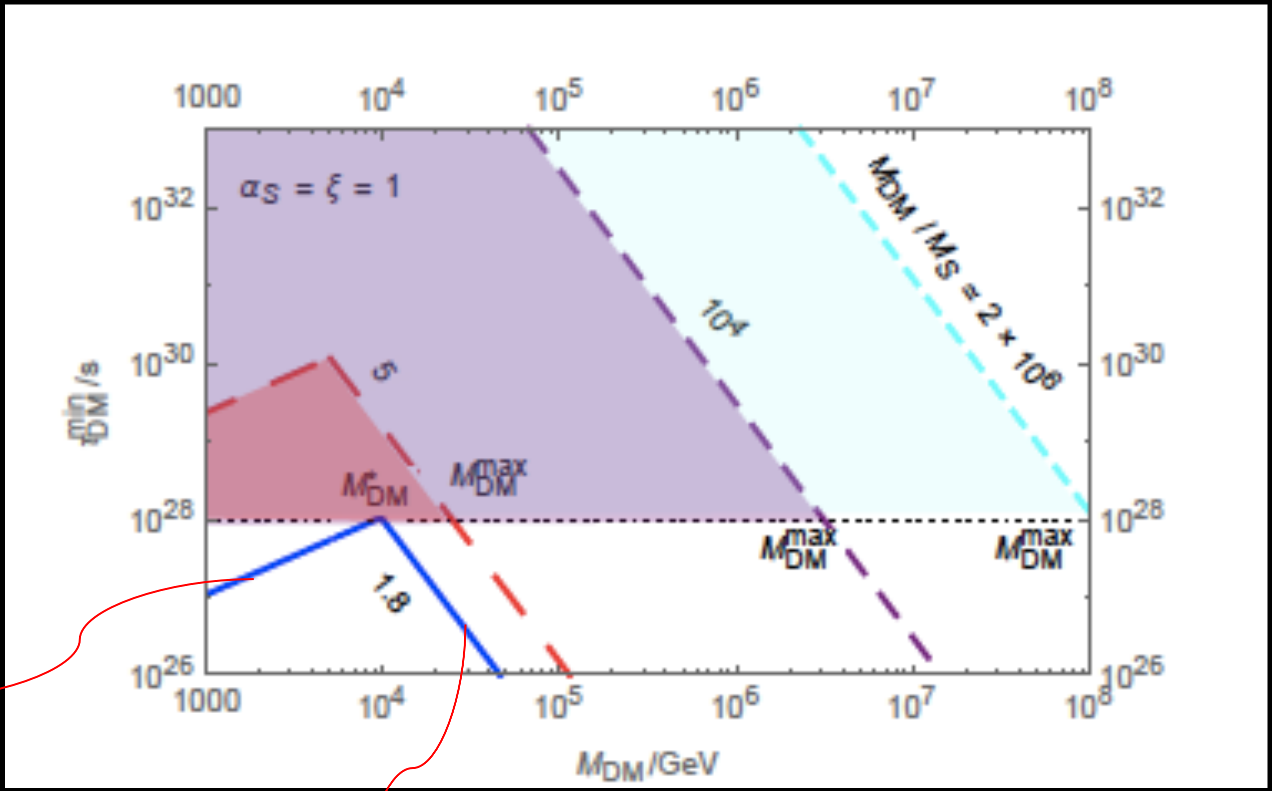


Upper bound on M_{DM} ($\tau_{28} \equiv \tau_{DM}^{min}/10^{28}$s)

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

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} ($\Rightarrow$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.

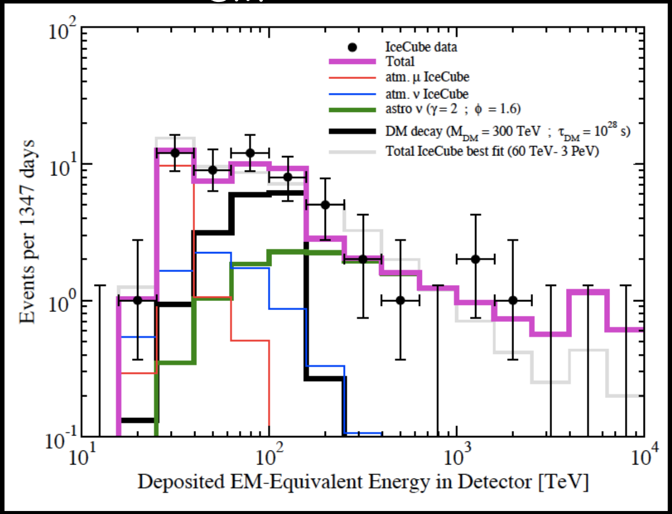
Decays:very high energy neutrinos at IceCube

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

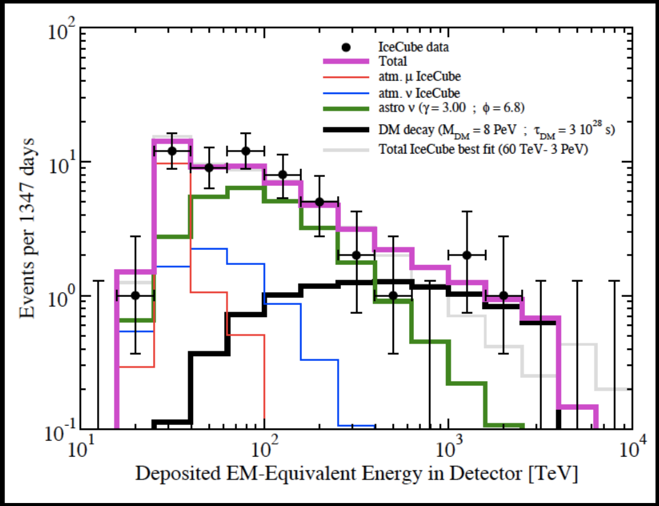
- Since the same interactions responsible for production also unavoidably induce decays ⇒ the model predicts high energy neutrino flux component at some level ⇒ testable at neutrino telescopes (Anisimov,PDB '08)

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.

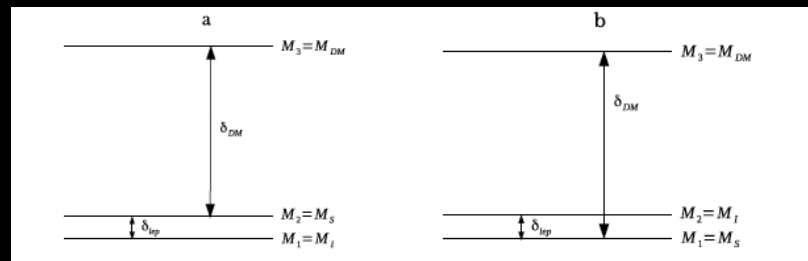
Unifying Leptogenesis and Dark Matter

(PDB, NOW 2006;Anisimov,PDB,0812.5085;PDB, P.Ludl,S. Palomarez-Ruiz 1606.06238)

- Interference between N_A and N_B can give sizeable CP decaying asymmetries able to produce a matter-antimatter asymmetry but since $M_{DM}>M_S$ necessarily $N_{DM}=N_3$ and $M_1 \simeq M_2 \Rightarrow$ leptogenesis with quasi-degenerate neutrino masses

$$\delta_{DM} \equiv (M_3 - M_S)/M_S$$

$$\delta_{lep} \equiv (M_2 - M_1)/M_1$$



$$\varepsilon_{i\alpha} \simeq \frac{\overline{\varepsilon}(M_i)}{K_i} \left\{ \mathcal{I}_{ij}^{\alpha}\, \xi(M_j^2/M_i^2) + \mathcal{J}_{ij}^{\alpha}\, \frac{2}{3(1 - M_i^2/M_j^2)} \right\}$$

(Covi,Roulet,Visssani '96)

$$\overline{\varepsilon}(M_i) \equiv \frac{3}{16\,\pi} \left(\frac{M_i\, m_{\rm atm}}{v^2} \right) \simeq 1.0 \times 10^{-6} \left(\frac{M_i}{10^{10}\,{\rm GeV}} \right),$$

$$\xi(x) = \frac{2}{3} x \left[(1+x) \ln\left(\frac{1+x}{x} \right) - \frac{2-x}{1-x} \right],$$

Analytical expression for the asymmetry:

$$\eta_B \simeq 0.01\, \frac{\overline{\varepsilon}(M_1)}{\delta_{\rm lep}}\, f(m_\nu, \Omega),$$

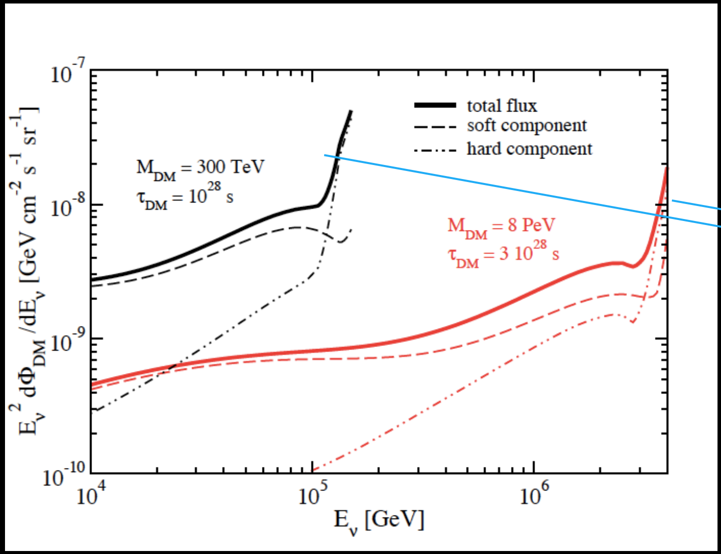
Efficiency factor

$$f(m_\nu, \Omega) \equiv \frac{1}{3} \left(\frac{1}{K_1} + \frac{1}{K_2} \right) \sum_{\alpha} \kappa(K_{1\alpha} + K_{2\alpha}) \left[\mathcal{I}_{12}^{\alpha} + \mathcal{J}_{12}^{\alpha} \right],$$

- $M_S \gtrsim 2\, T_{sph} \simeq 300$ GeV $\Rightarrow$ 10 TeV $\lesssim M_{DM} \lesssim$ 10 PeV
- $M_S \lesssim$ 10 TeV
- $\delta_{lep} \sim 10^{-5} \Rightarrow$ leptogenesis is not fully resonant

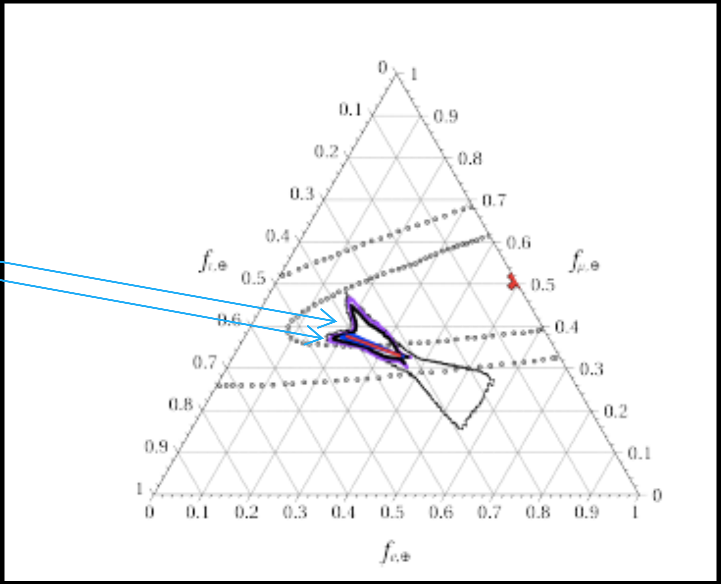
Decays: a distinct flavour composition

Energy neutrino flux



Hard component

Flavour composition at the detector (Normal Hierarchy)



For Normal Hierarchy it is interesting that the electron neutrino hard component is strongly suppressed (it can be even vanishing).

At the detector this is smeared out by mixing but it might be still testable in future.

Summary

- Neutrinos in Cosmology is not just a topic with important historical results but it is still one of the best motivated routes to understand the cosmological puzzles

- High energy scale leptogenesis is the most attractive scenario of baryogenesis in the absence of new physics at TeV scale or below

- N_2-dominated scenario is naturally realised in SO(10)-inspired models and also to satisfy STRONG THERMAL LEPTOGENESIS

- STRONG SO(10) thermal solution has strong predictive power and current data are encouraging.
  Deviation of neutrino masses from the hierarchical limits is expected;
  Despite NO neutrinoless double beta decay signal still detectable (when?)

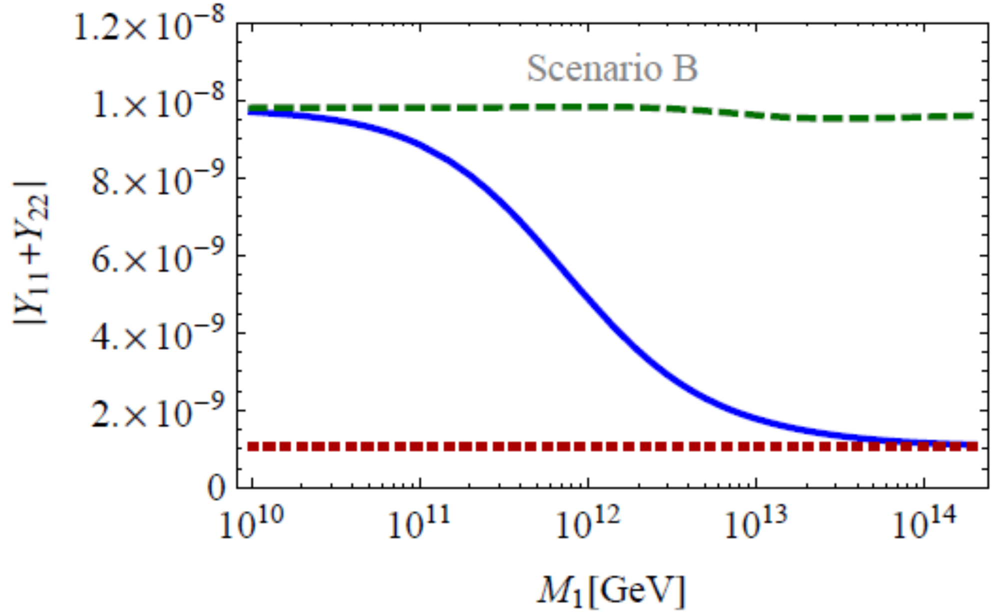
- Study of realistic models

- A unified scenario of DM and resonant leptogenesis can be tested with IceCube high energy neutrino data.

Density matrix and CTP formalism to describe the transition regimes

(De Simone, Riotto '06; Beneke, Gabrecht, Fidler, Herranen, Schwaller '10)

$$\frac{dY_{\alpha\beta}}{dz} = \frac{1}{szH(z)}\left[(\gamma_D+\gamma_{\Delta L=1})\left(\frac{Y_{N_1}}{Y_{N_1}^{eq}}-1\right)\epsilon_{\alpha\beta}-\frac{1}{2Y_\ell^{eq}}\left\{\gamma_D+\gamma_{\Delta L=1},Y\right\}_{\alpha\beta}\right]-\left[\sigma_2\mathrm{Re}(\Lambda)+\sigma_1|\mathrm{Im}(\Lambda)|\right]Y_{\alpha\beta}$$

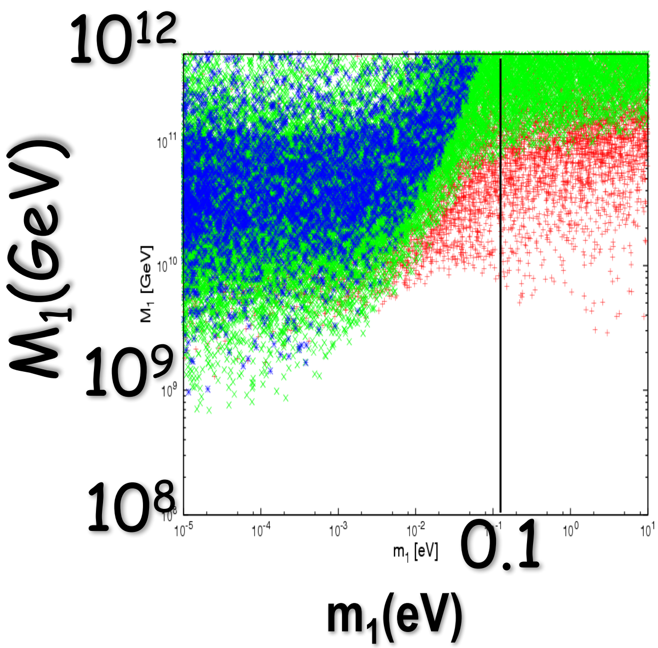


Fully two-flavoured regime limit

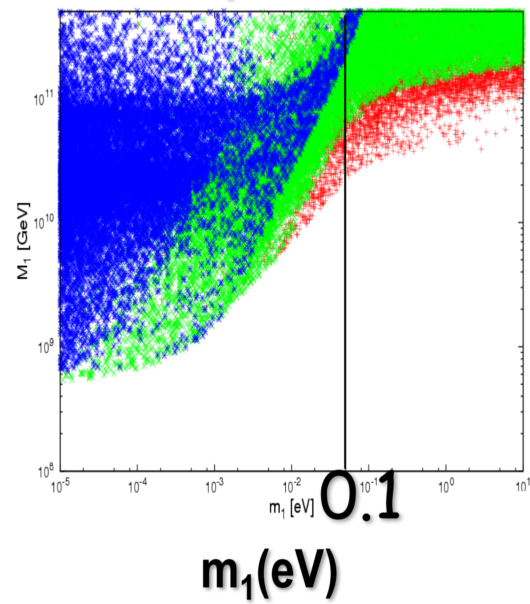
Unflavoured regime limit

Neutrino mass bounds and role of PMNS phases

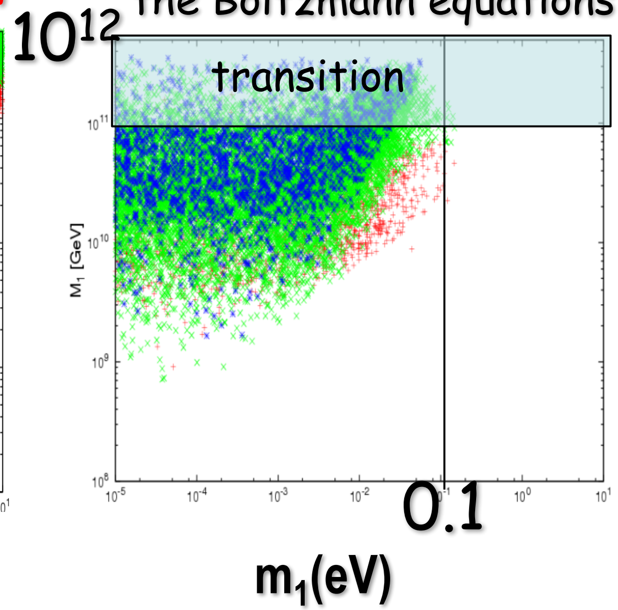
(Abada et al.' 07; Blanchet,PDB,Raffelt;Blanchet,PDB '08)

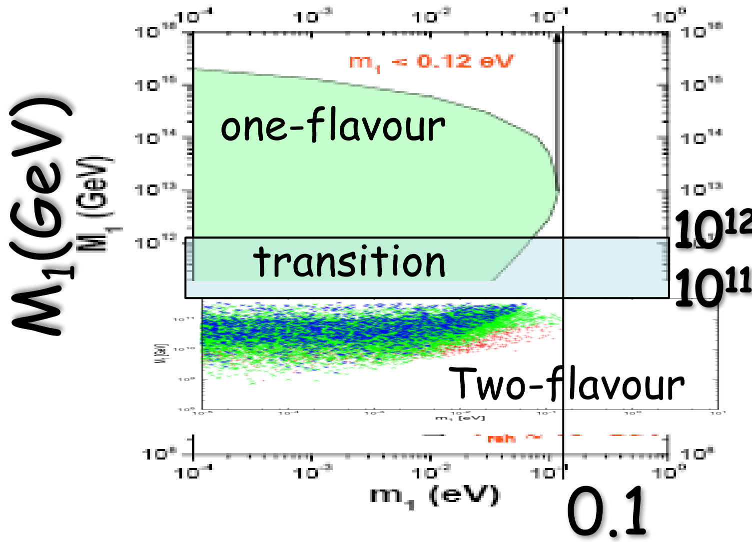


PMNS phases off



Imposing the validity of the Boltzmann equations





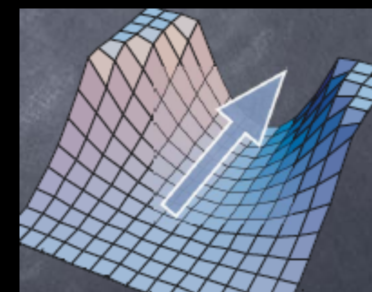
Affleck-Dine Baryogenesis

(Affleck, Dine '85)

In the Supersymmetric SM there are many "flat directions" in the space of a field composed of squarks and/or sleptons

$$V(\phi) = \sum_i \left|\frac{\partial W}{\partial \phi_i}\right|^2 + \frac{1}{2}\sum_A \left(\sum_{ij} \phi_i^* (t_A)_{ij} \phi_j\right)^2$$

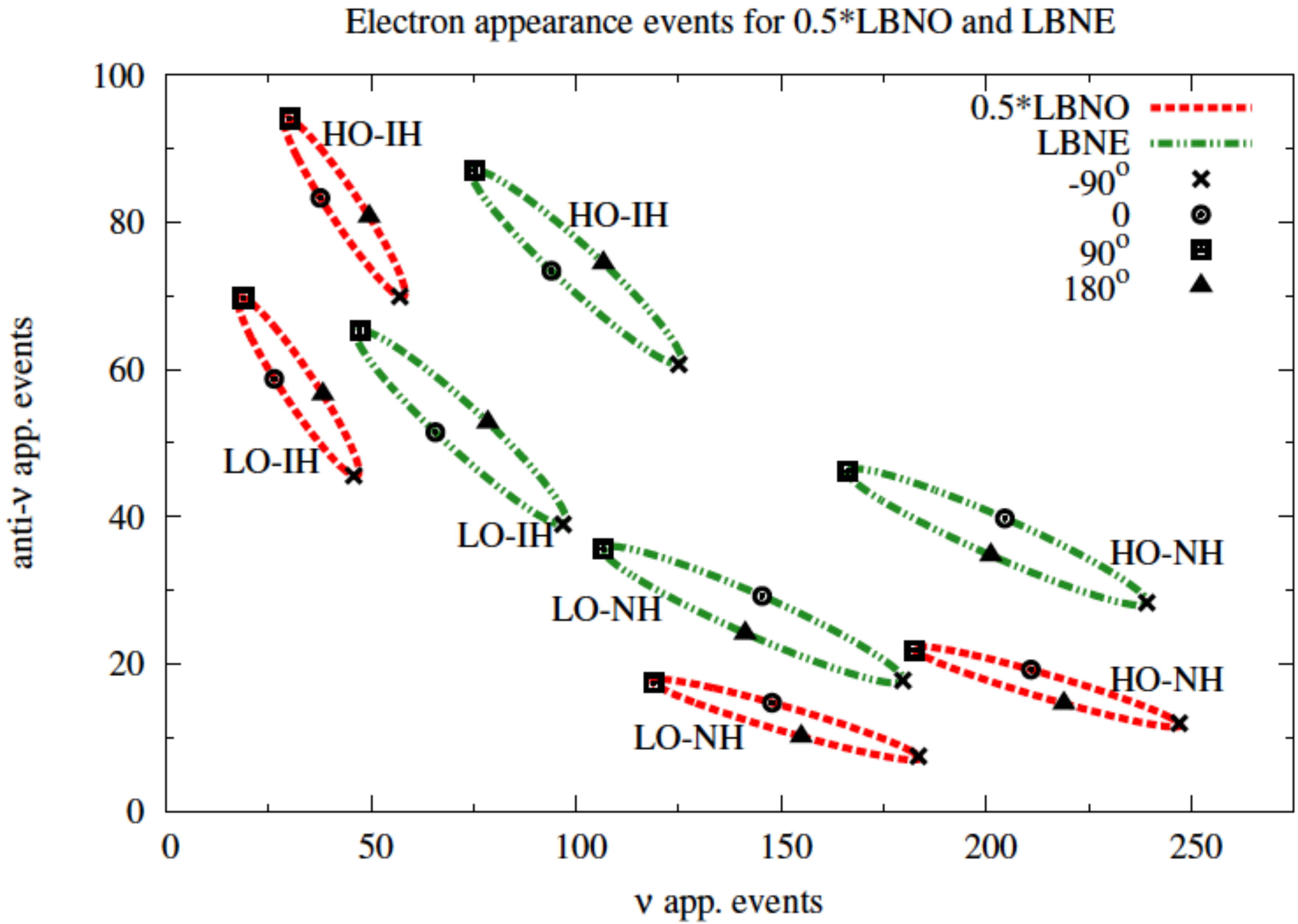
F term D term



A flat direction can be parametrized in terms of a complex field (AD field) that carries a baryon number that is violated dynamically during inflation

$$\frac{n_B}{s} \sim 10^{-10} \left(\frac{m_{3/2}}{m_\Phi}\right) \left(\frac{m_\Phi}{\mathrm{TeV}}\right)^{-\frac{1}{2}} \left(\frac{M}{M_P}\right)^{\frac{3}{2}} \left(\frac{T_R}{10\,\mathrm{GeV}}\right)$$

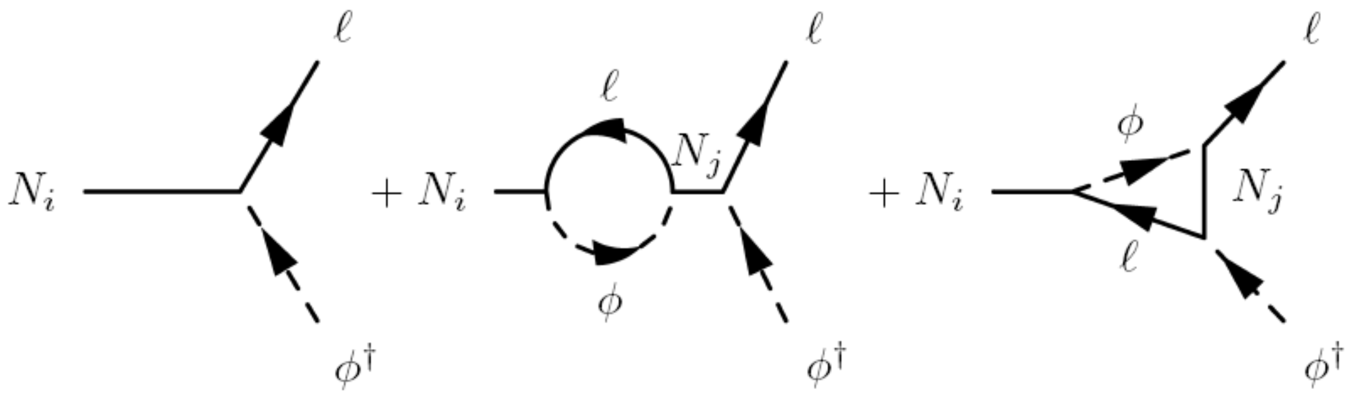
The final asymmetry is $\propto$ T_{RH} and the observed one can be reproduced for low values $T_{RH} \lesssim 10$ GeV !



Electron appearance events for 0.5*LBNO and LBNE
0.5*LBNO
LBNE
-90°
0
90°
180°
HO-IH
HO-IH
LO-IH
LO-IH
LO-NH
LO-NH
HO-NH
HO-NH
anti-ν app. events
ν app. events
0
20
40
60
80
100
0
50
100
150
200
250

Total CP asymmetries

(Flanz,Paschos,Sarkar'95; Covi,Roulet,Vissani'96; Buchmüller,Plümacher'98)



$$\varepsilon_i \simeq \frac{1}{8\pi\, v^2\, (m_D^\dagger\, m_D)_{ii}} \sum_{j\neq i} \mathrm{Im}\left[(m_D^\dagger\, m_D)^2_{ij}\right] \times \left[f_V\left(\frac{M_j^2}{M_i^2}\right) + f_S\left(\frac{M_j^2}{M_i^2}\right)\right]$$

It does not depend on U !

Additional contribution to CP violation:

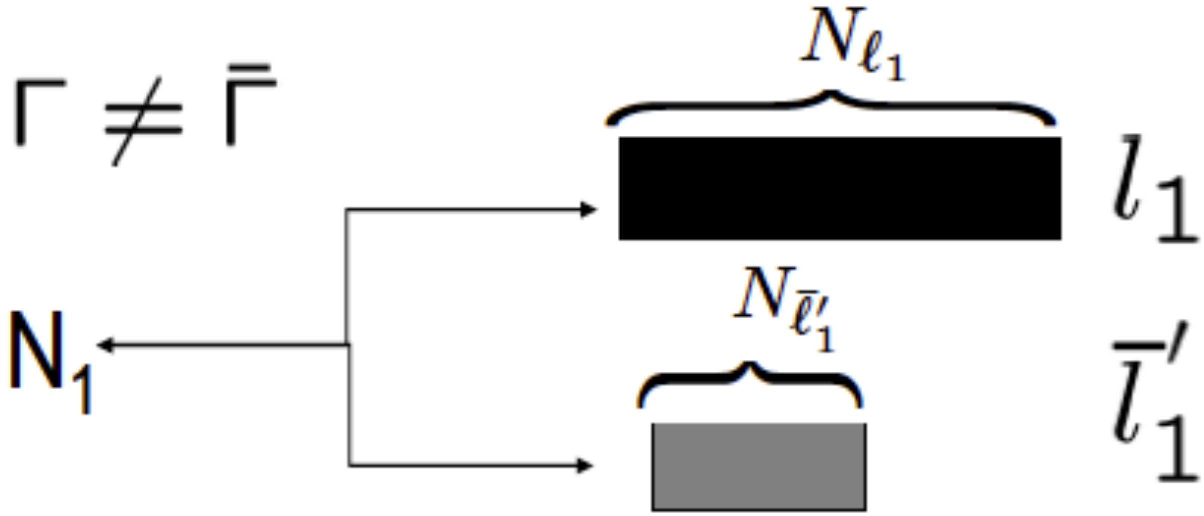
(Nardi, Racker, Roulet '06)

(α = τ, e+μ)

$$\varepsilon_{1\alpha} = P^0_{1\alpha}\,\varepsilon_1 + \frac{\Delta P_{1\alpha}}{2}$$

depends on U !

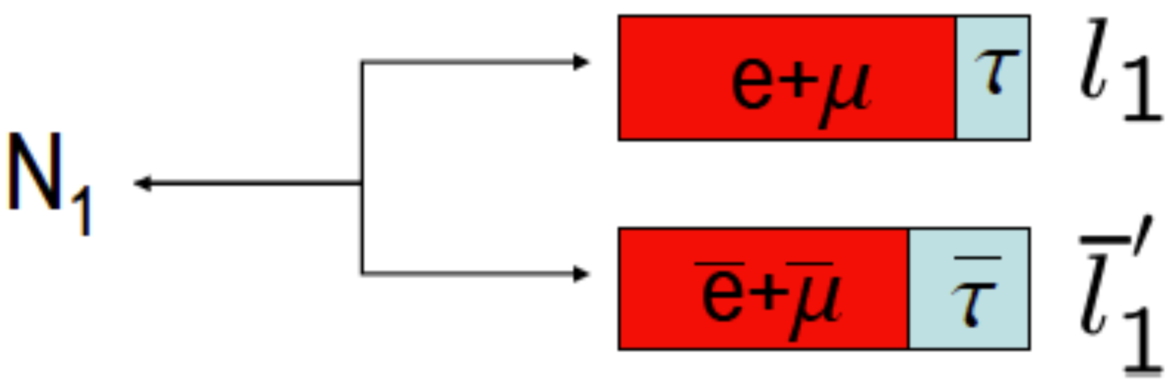
1) $\Gamma \neq \bar{\Gamma}$



$\Rightarrow \; P^0_{1\alpha}\,\varepsilon_1$

2) $|\bar{l}'_1\rangle \neq CP|l_1\rangle$

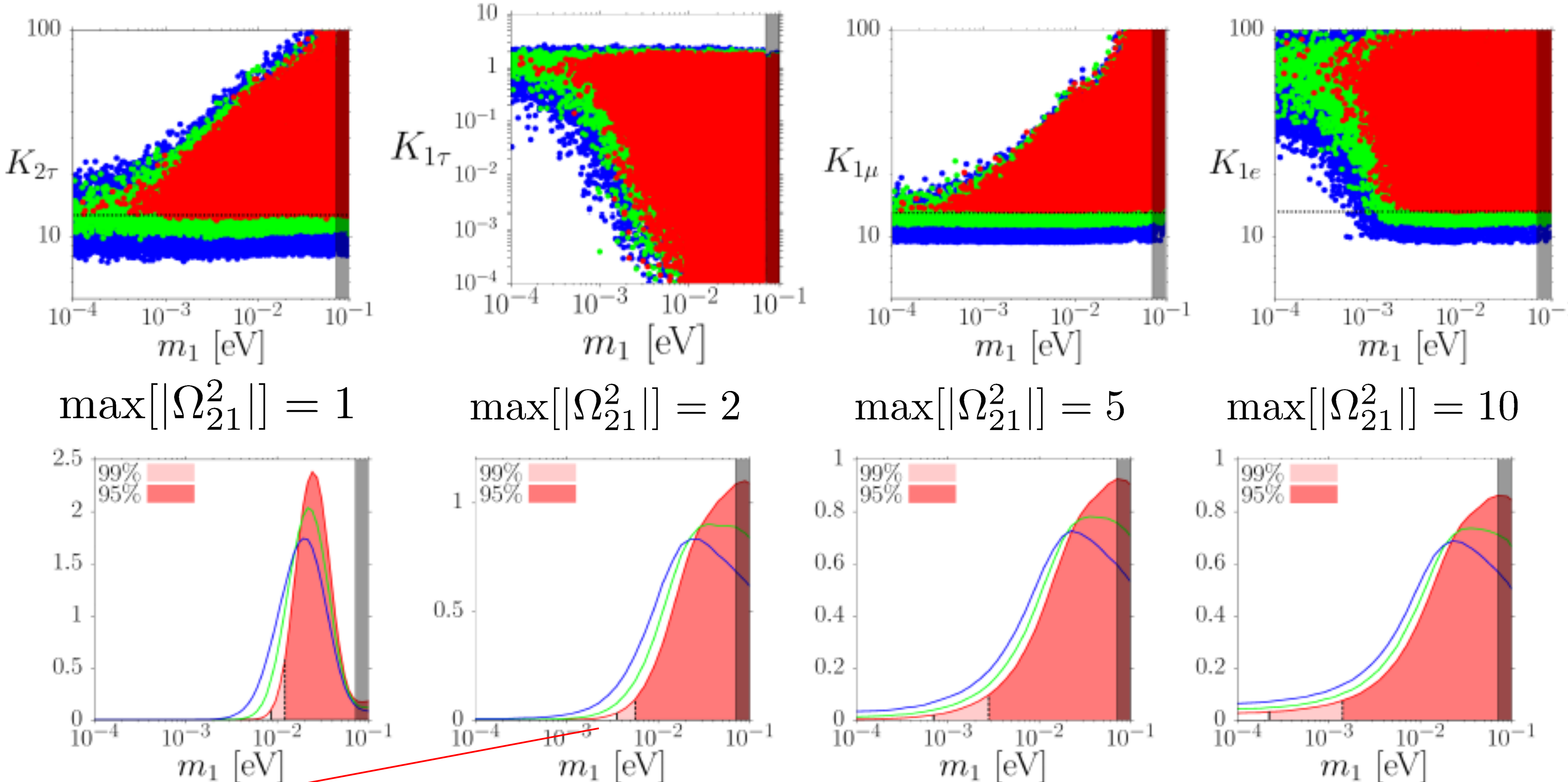
+



$\Rightarrow \; \frac{\Delta P_{1\alpha}}{2}$

A lower bound on neutrino masses (IO)

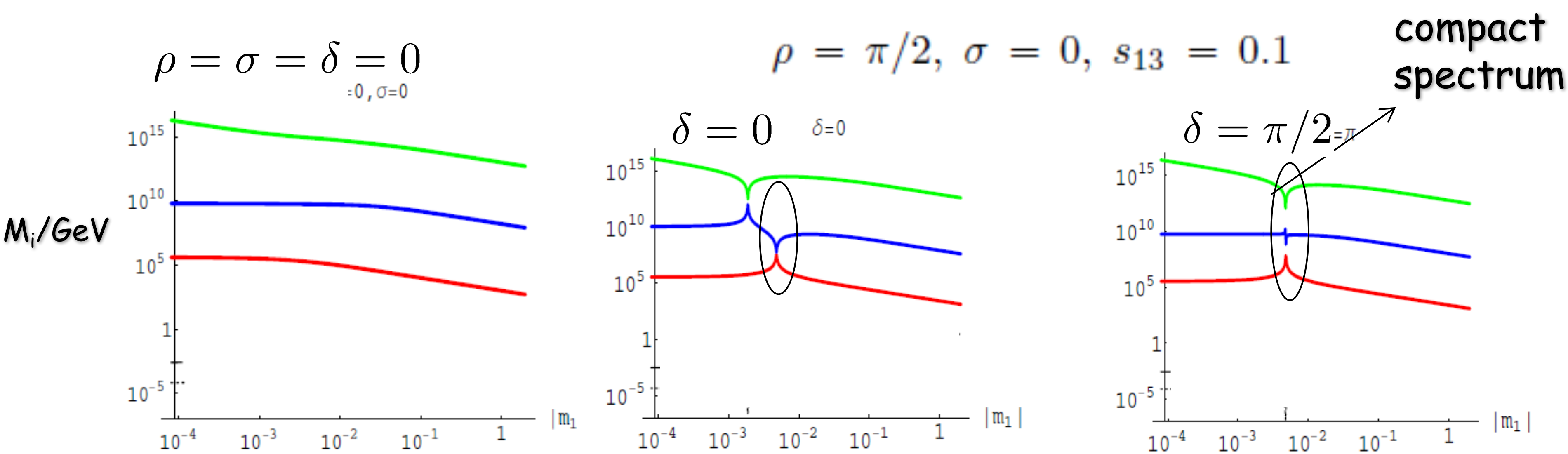
$N^{p,i}_{B-L}$ = 0.001, 0.01, 0.1 $\max[|\Omega^2_{21}|] = 2$ INVERTED ORDERING



$m_1 \gtrsim 3$ meV $\Rightarrow \Sigma_i\, m_i \gtrsim 100$ meV (not necessarily deviation from HL)

Crossing level solutions

(Akhmedov, Frigerio, Smirnov hep-ph/0305322)

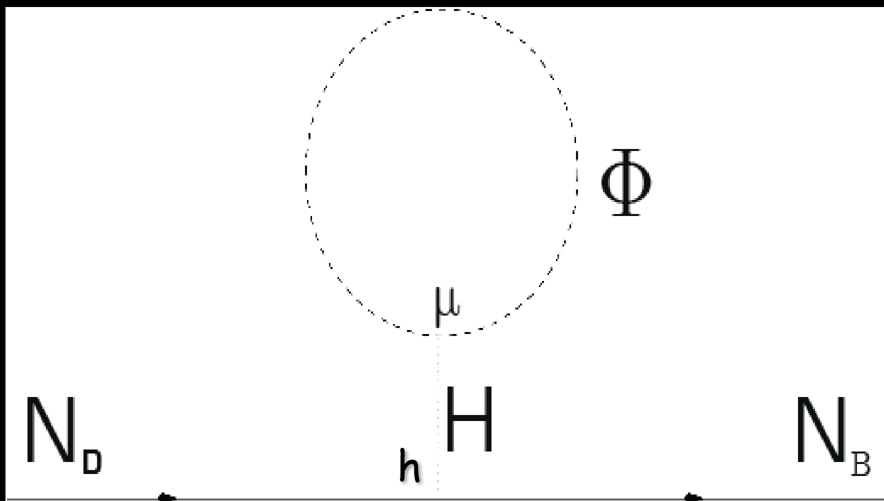


- About the crossing levels the N_1 CP asymmetry is enhanced
- The correct BAU can be attained for a fine tuned choice of parameters: many realistic models have made use of these solutions

(e.g. Ji, Mohapatra,Nasri '10; Buccella, Falcone, Nardi, '12; Altarelli, Meloni '14, Feng, Meloni, Meroni, Nardi '15; Addazi, Bianchi, Ricciardi 1510.00243)

A possible GUT origin

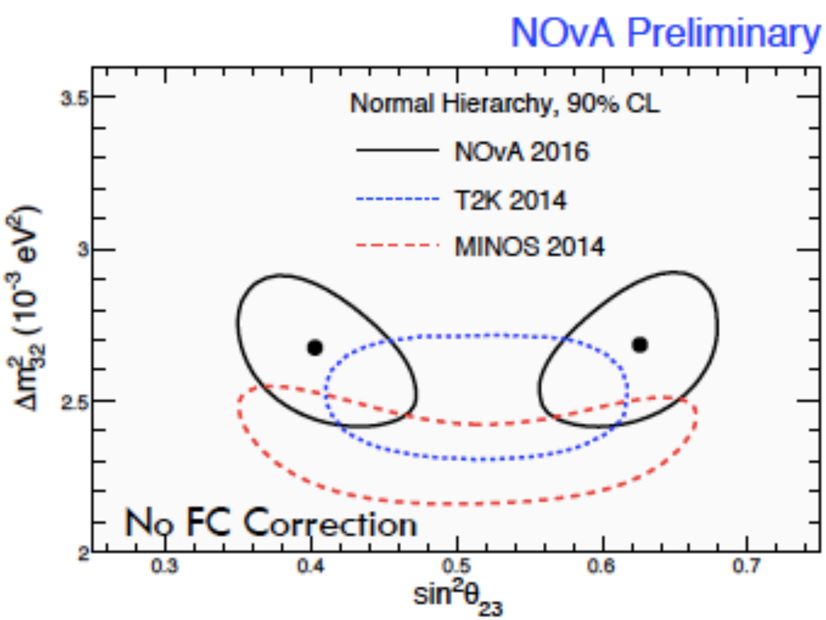
(Anisimov,PDB, 2010, unpublished)

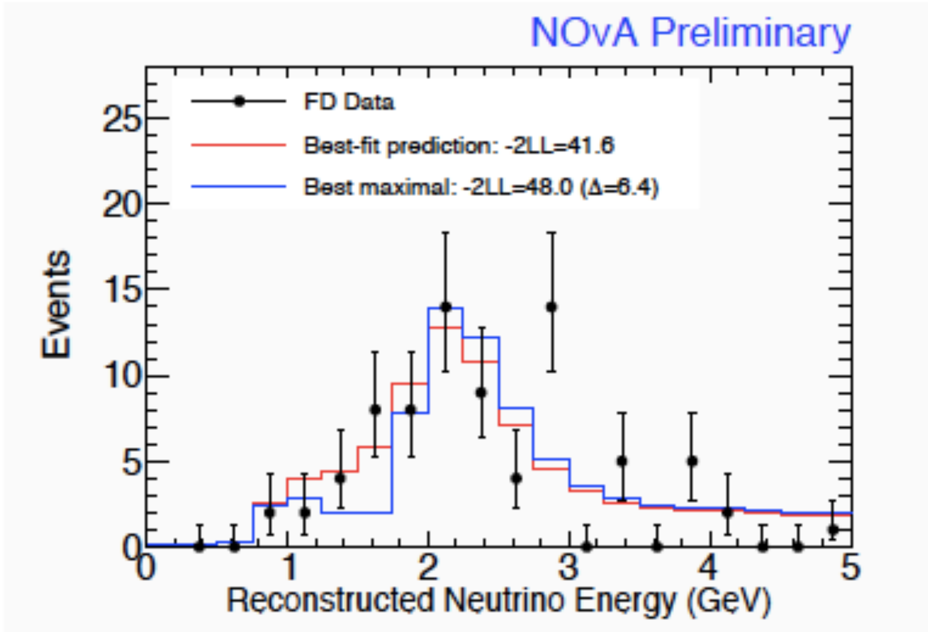


$$\frac{1}{\Lambda_{\rm eff}} = \frac{h\mu}{M_{\rm GUT}^2}$$

$$\Lambda_{\rm eff} >> M_{\rm GUT}\,!$$

NOvA results (Neutrino 2016)





Best Fit (in NH):

$$|\Delta m^2_{32}| = 2.67 \pm 0.12 \times 10^{-3} \mathrm{eV}^2$$

$$\sin^2\theta_{23} = 0.40^{+0.03}_{-0.02} (0.63^{+0.02}_{-0.03})$$

Maximal mixing excluded at 2.5σ

Some tension with T2K results not detecting any deviation from maximal mixing