VIII International Pontecorvo Neutrino Physics School 2019

Sinaia, Romania, 1-10 September, 2019

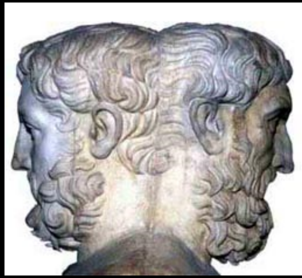
Leptogenesis

(how neutrinos might have created the excess of matter over anti-matter that survived annihilations until today forming galaxies, stars, planets, Sinaia, you and myself!)

Pasquale Di Bari

(University of Southampton)

The double side of Leptogenesis



Cosmology (early Universe)

Neutrino Physics, New Physics

- *Cosmological Puzzles* :

1. Dark matter
2. Matter - antimatter asymmetry
3. Inflation
4. Accelerating Universe

- *New stage in early Universe history* :

T

T	Stage
< 10^{14} GeV	Inflation
	Leptogenesis
100 GeV	EWSSB
0.1- 1 MeV	BBN
0.1- 1 eV	Recombination

Leptogenesis complements
low energy neutrino experiments
testing the
high energy parameters
of the seesaw mechanism

$\Rightarrow$ precious information
to understand what
kind of new physics is
responsible for the neutrino
masses and mixing:
a *model builders compass*

Neutrino Physics

Lectures by:

S. Bilenky, B. Kayser, A. Smirnov, C. Giunti, D. Gorbunov,…….

At this stage we are all well equipped on neutrino physics !

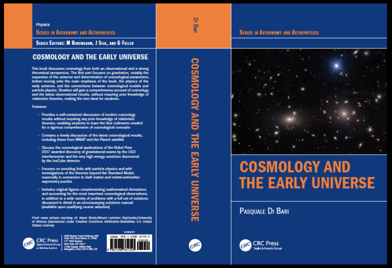
Plan

- Cosmological background
- Baryogenesis
- Minimal leptogenesis
- Vanilla leptogenesis
- Adding flavor to vanilla leptogenesis
- Leptogenesis and neutrino mass models
- Unifying neutrino masses and mixing, leptogenesis and dark matter
- Final considerations

References (reviews)

Cosmological background

- PDB, *Cosmology and the early universe,* CRC Press, May 2018.



On leptogenesis

- PDB, *An introduction to leptogenesis and neutrino properties,* Contemp. Physics 53 (2012) no. 4, 315-338, arXiv 1206.3168;
- Steve Blanchet, PDB, *The minimal scneario of leptogenesis,* **New J.Phys. 14 (2012) 125012, arXiv 1211.0512;**
- **B.Dev, PDB, B.Garbrecht, S. Lavignac, P. Millington, D. Teresi,** ***Flavour effects in leptogenesis,*** arXiv 1711,02861.

Unifying neutrino masses, leptogenesis and dark matter

- PDB, *Neutrino masses, leptogenesis and dark matter,* arXiv 1904.11971.

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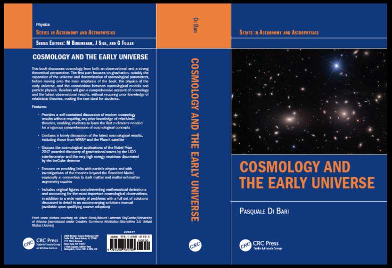

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Unifying neutrino masses, leptogenesis and dark matter

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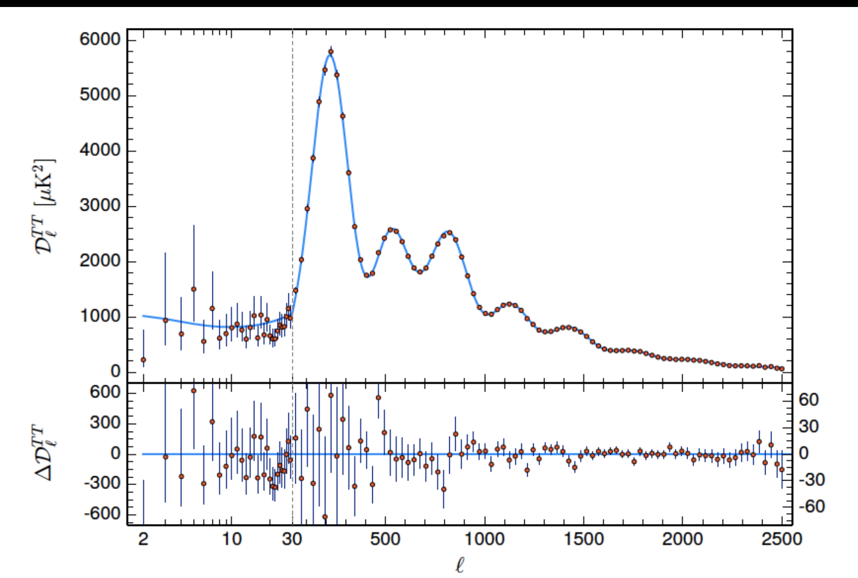
Cosmological Background

ΛCDM model

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

ΛCDM best fit to the *Planck* 2018 data (TT+TE+EE+low E+lensing)
(Planck Collaboration, *arXiv 1807.06209*)



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

(Planck 2018 results, 1807.06209)

Planck results are in good agreement with BAO, SNe and galaxy lensing observations.
The only significant (~4σ) tension is with local measurement of the Hubble constant

In the ΛCDM model, expansion is described by a flat Friedmann-Lemaitre cosmological model

Geometry of the Universe

Assuming homogeneity and isotropy of space (cosmological principle)

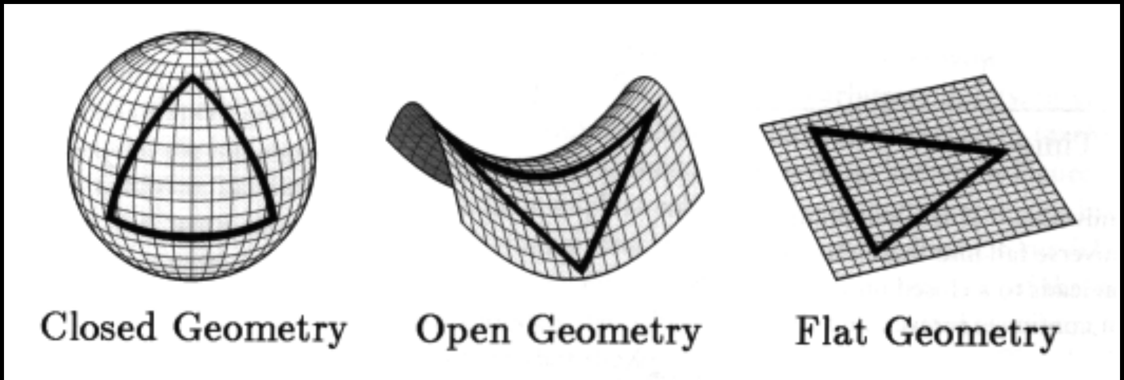
$\Rightarrow$ Friedmann-Robertson-Walker metric (in the comoving system):

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

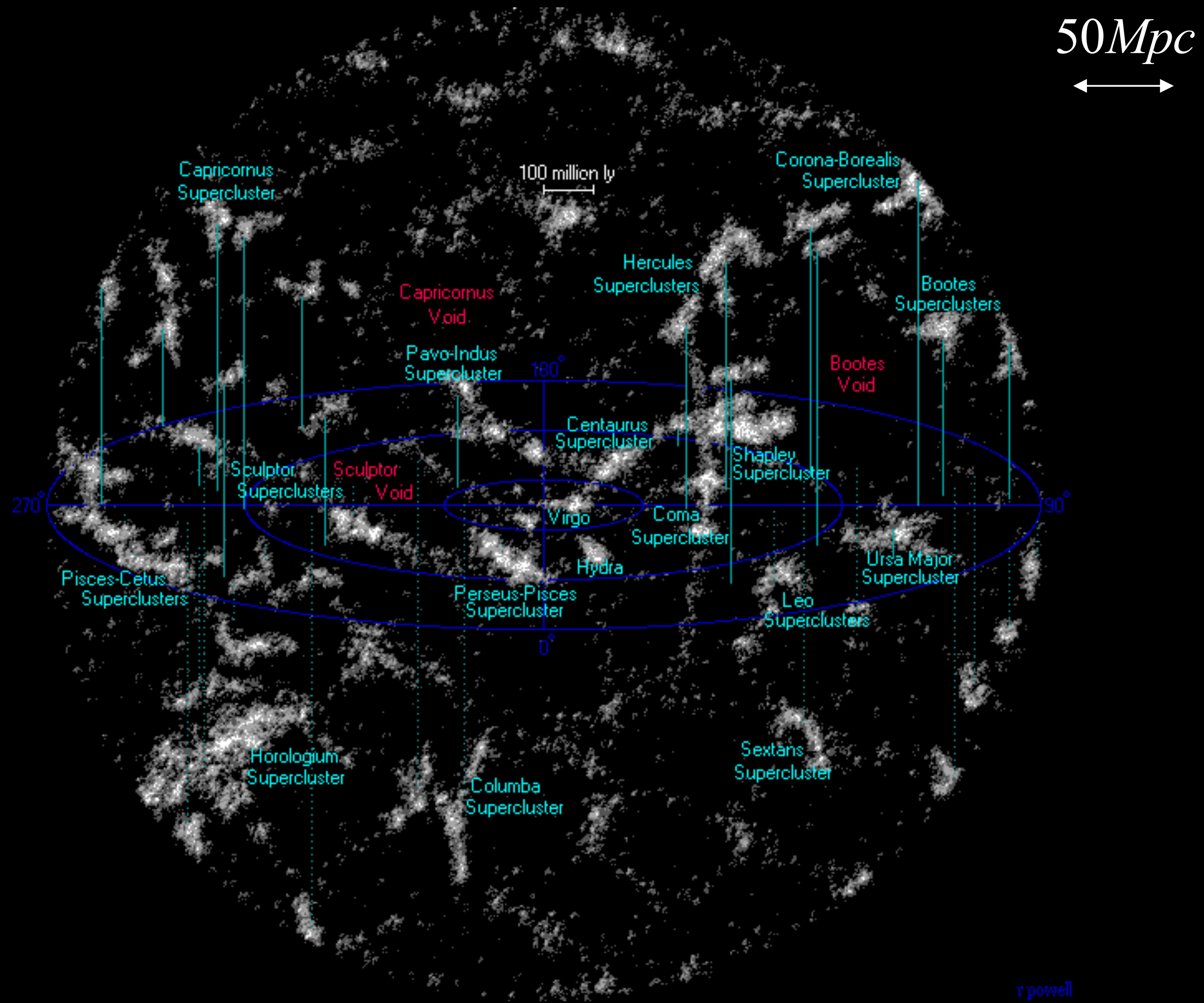
scale factor $\quad a(t) \equiv \dfrac{R(t)}{R_0} \quad \Rightarrow \quad$ dynamics

curvature parameter $\quad k = -1, 0 + 1 \quad \Rightarrow \quad$ geometry

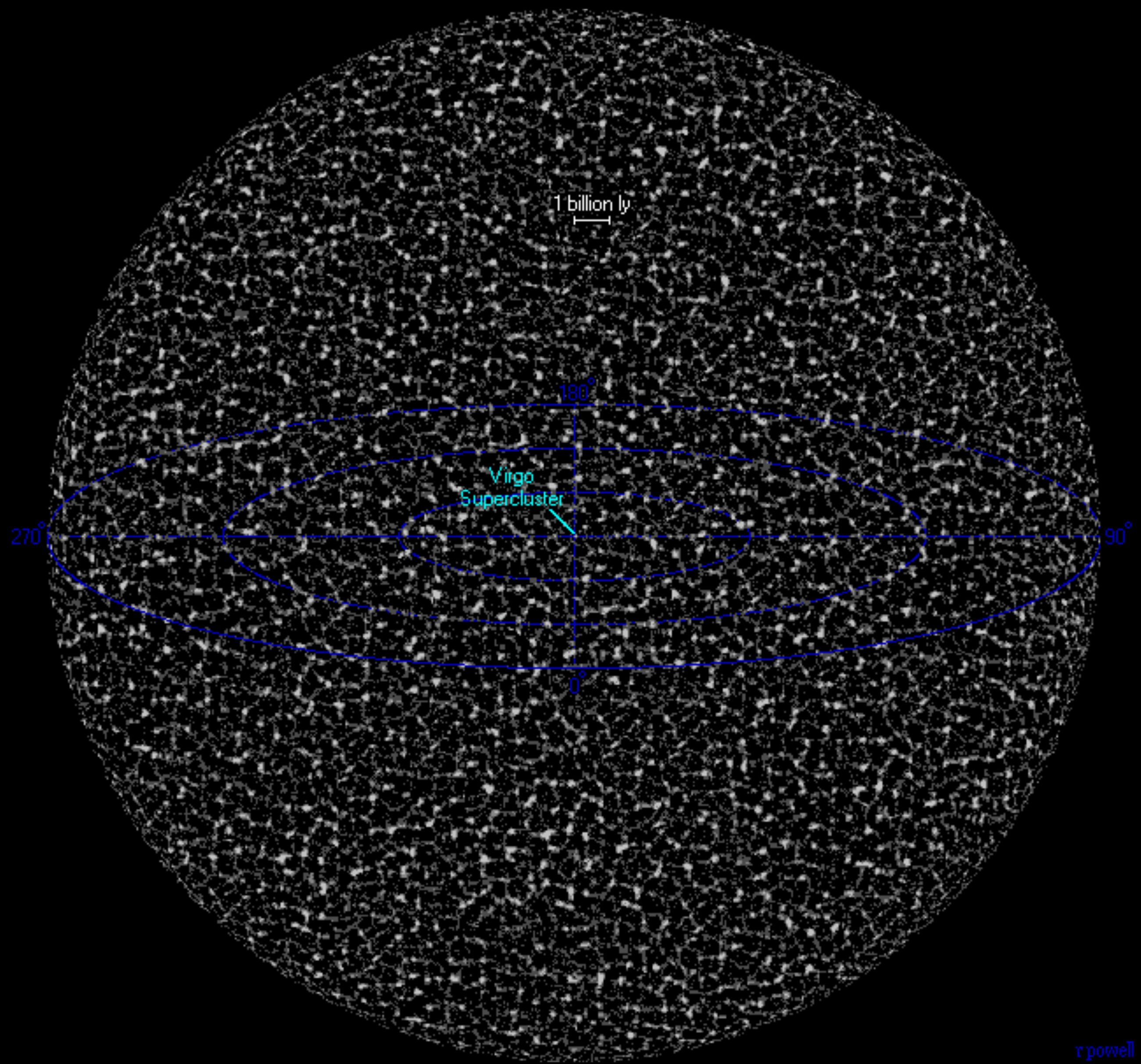
κ=+1 κ=-1 κ=0



our Neighbouring Superclusters: Virgo Supercluster at the centre



On distance scales greater than the size of superclusters of galaxies (~100 Mpc) the Universe appears smooth, with no further structures



Dynamics of the Universe

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

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

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

Dynamics of the Universe

Einstein equations

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

expansion rate (H)

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

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

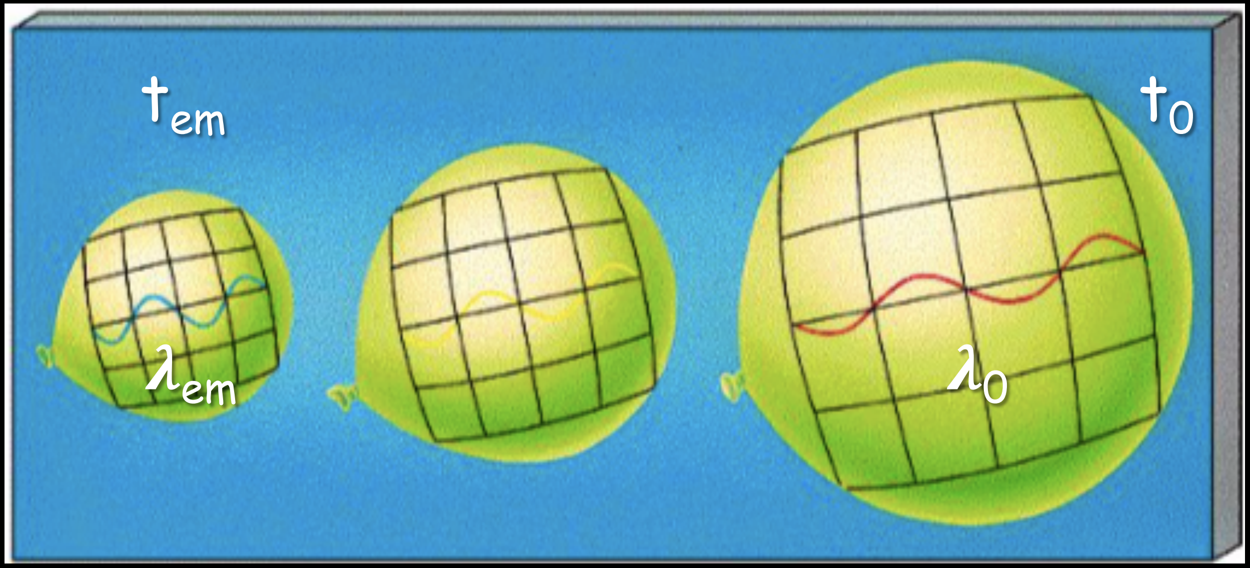
$$k \equiv H_0^2 R_0^2 (\Omega_0 - 1) \Rightarrow \begin{cases} \bullet\ \Omega_0 < 1 \Leftrightarrow k = -1 \text{ (open Universe)} \\ \bullet\ \Omega_0 = 1 \Leftrightarrow k = 0 \text{ (\textit{flat} Universe)} \\ \bullet\ \Omega_0 > 1 \Leftrightarrow k = +1 \text{ (\textit{closed} Universe)} \end{cases}$$

Hubble constant (H_0)

Cosmological redshifts

Momentum redshift ($|\vec{p}| \propto a^{-1}$) $\Longrightarrow$ the wavelength of photons is "stretched by the expansion":

$$\lambda(t) = \lambda_0 \frac{R(t)}{R_0} = a(t)\,\lambda_0$$



cosmological redshift $z \equiv \dfrac{\lambda_0 - \lambda_{em}}{\lambda_{em}} = a_{em}^{-1} - 1$

Hubble's law from theory $d_{pr,0}(r)$

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

expansion rate $$H \equiv \frac{\dot{a}}{a}$$

proper velocity $$v_{pr}(t,r) \equiv \dot{d}_{pr}(t,r)$$

Lemaitre's equation $$v_{pr}(t,r) = H(t)\, d_{pr}(t,r)$$

Hubble's law $$z \simeq \frac{H_0 d_L}{c}$$

$\left(z = \frac{v}{c} \right.$? Just n.r. Doppler effect ? $\left. \right)$

Hubble's law from theory $d_{pr,0}(r)$

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

expansion rate $H \equiv \frac{\dot{a}}{a}$

proper velocity $v_{pr}(t,r) \equiv \dot{d}_{pr}(t,r)$

Lemaitre's equation (1927) $v_{pr}(t,r) = H(t)\, d_{pr}(t,r)$

Exercise

STEP 1 $d_{pr,0}(r_{em}) \equiv \int_{t_{em}}^{t_0} \frac{c\,dt}{a(t)}$

deceleration parameter $q_0 \equiv -\frac{\ddot{a}_0}{H_0^2}$

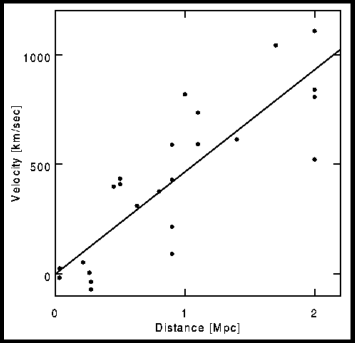
STEP 2 $d_{pr,0}(z) \equiv cH_0^{-1}\left[z - z^2\left(\frac{1+q_0}{2}\right)\right] + O(z^3)$

STEP 3+4 $d_L(z) = (1+z)d_{pr,0}(z) \equiv cH_0^{-1}\left[z + z^2\left(\frac{1-q_0}{2}\right)\right] + O(z^3)$

Hubble's law (1929) $z \simeq \frac{H_0 d_L}{c}$

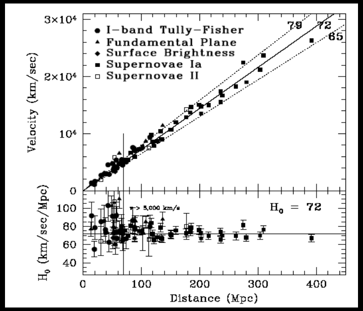
Hubble constant measurements

Edwin Hubble (1929)



$$H_0 \simeq 500\ \mathrm{km\ \ s^{-1}\ Mpc^{-1}}$$

Hubble Space Telescope (HST) Key Project (2001)



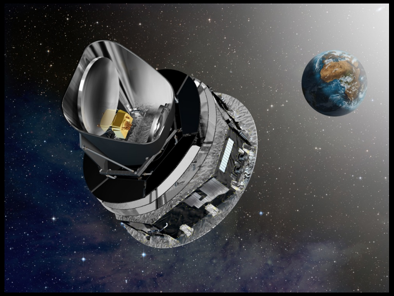
$$H_0 \simeq (72 \pm 8)\ \mathrm{km\ \ s^{-1}\ Mpc^{-1}}$$

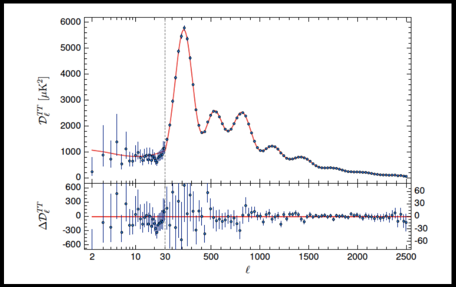
Riess et al. (2019)arXiv 1903.07603

$$H_0 \simeq (74.03 \pm 1.42)\ \mathrm{km\ \ s^{-1}\ Mpc^{-1}}$$

~4.3.σ tension !!!

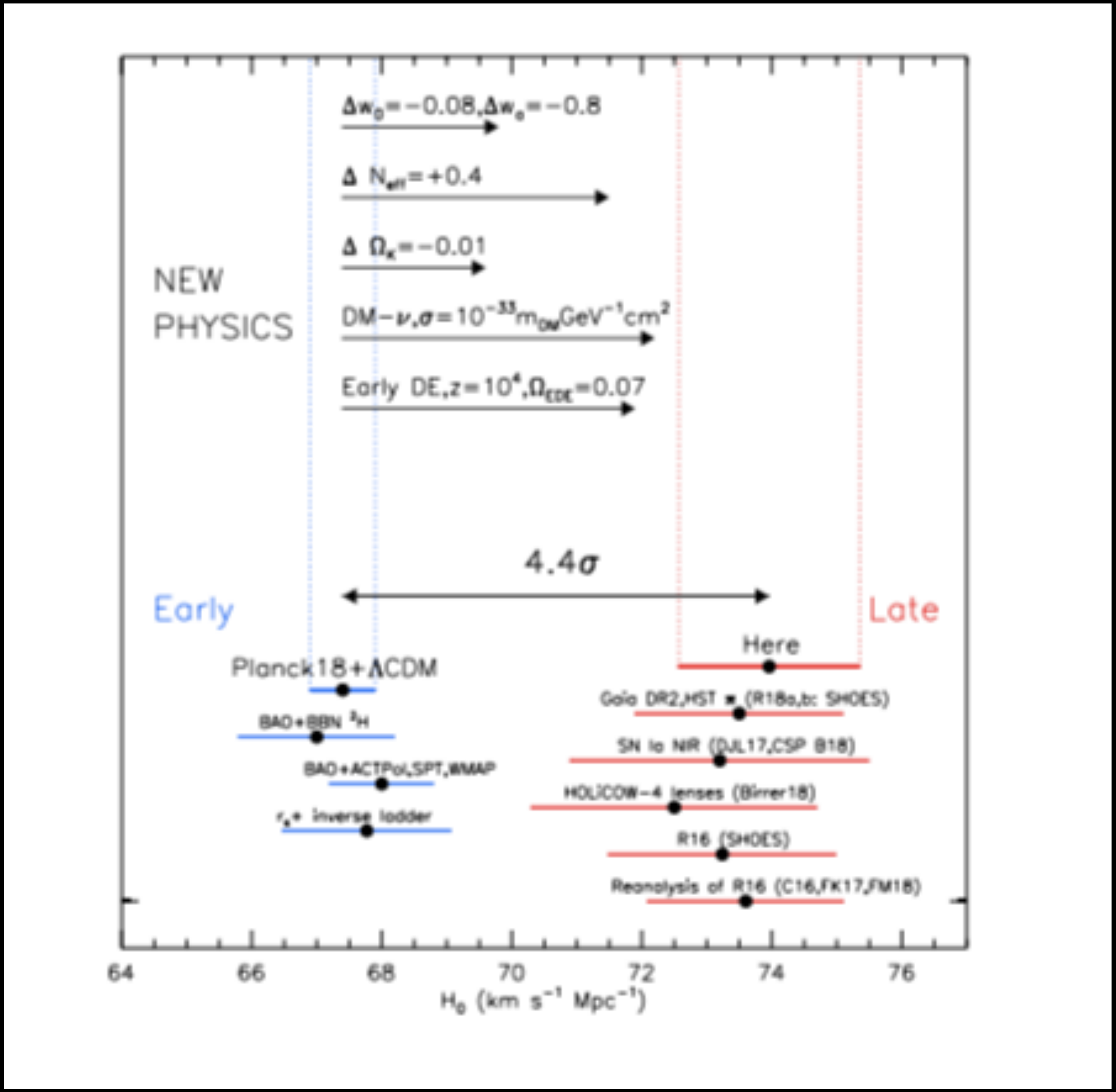
Planck 2018 (CMB+BAO) assuming ΛCDM



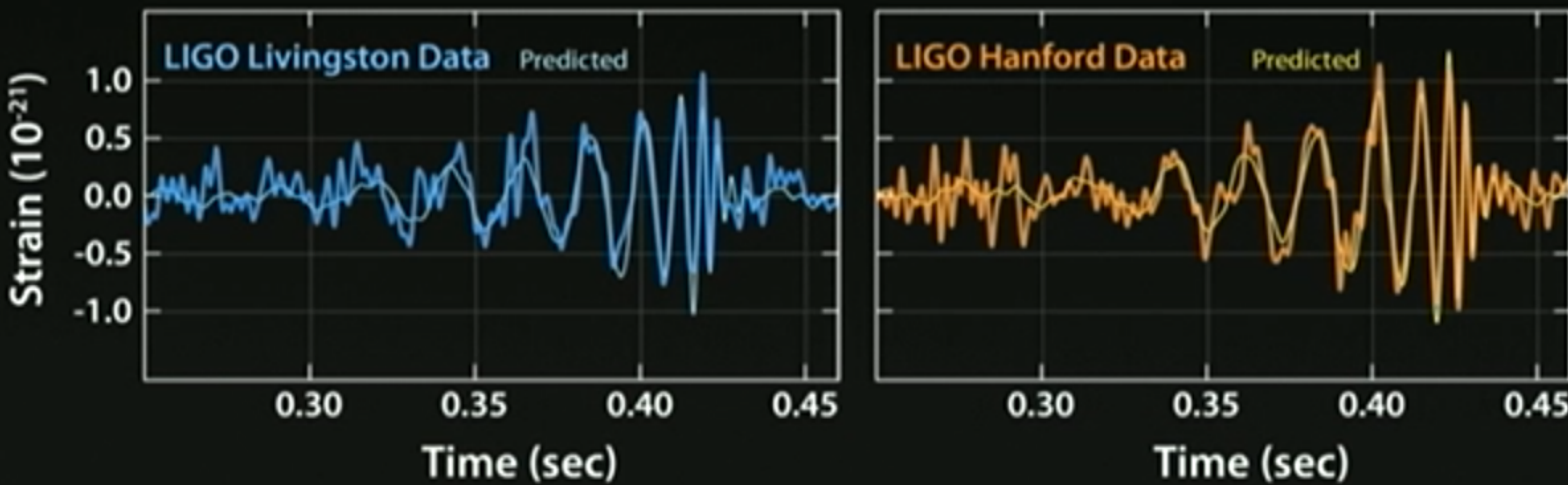


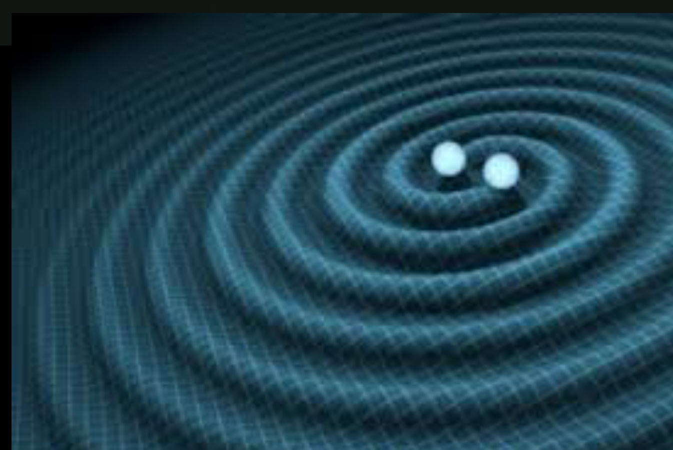
$$H_0 \simeq (67.66 \pm 0.42)\ \mathrm{km\ \ s^{-1}\ Mpc^{-1}}$$

Hubble constant: tension between "late" and "early" (ΛCDM) measurements



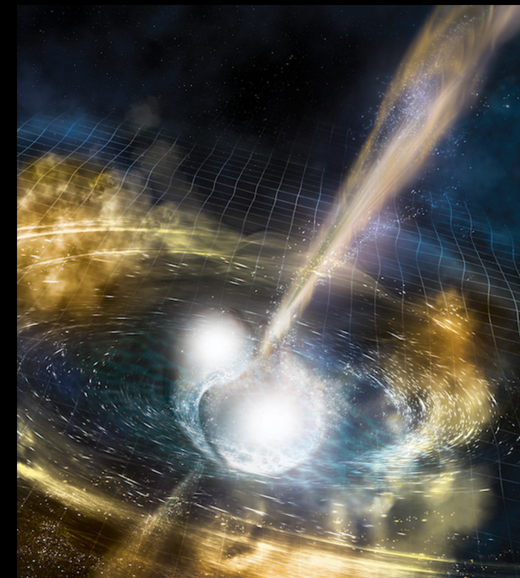
From Riess et al. (2019) arXiv 1903.07603


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

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:

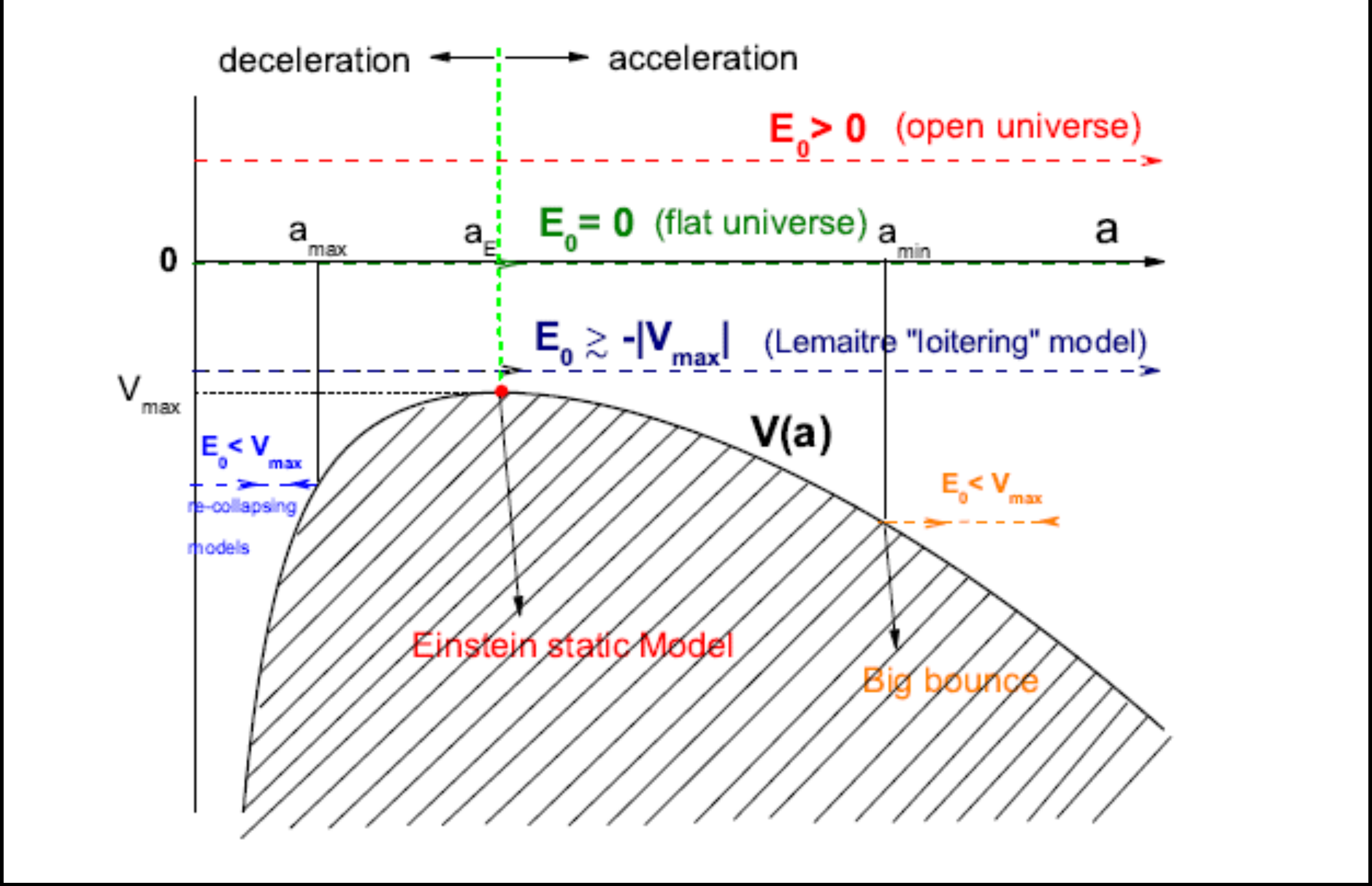
$$p_M = 0, \; p_R = \frac{1}{3}\varepsilon_R, \; p_\Lambda = -\varepsilon_\Lambda$$

That, from the fluid equation, lead to :

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

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

Lemaitre models:
effective potential analysis



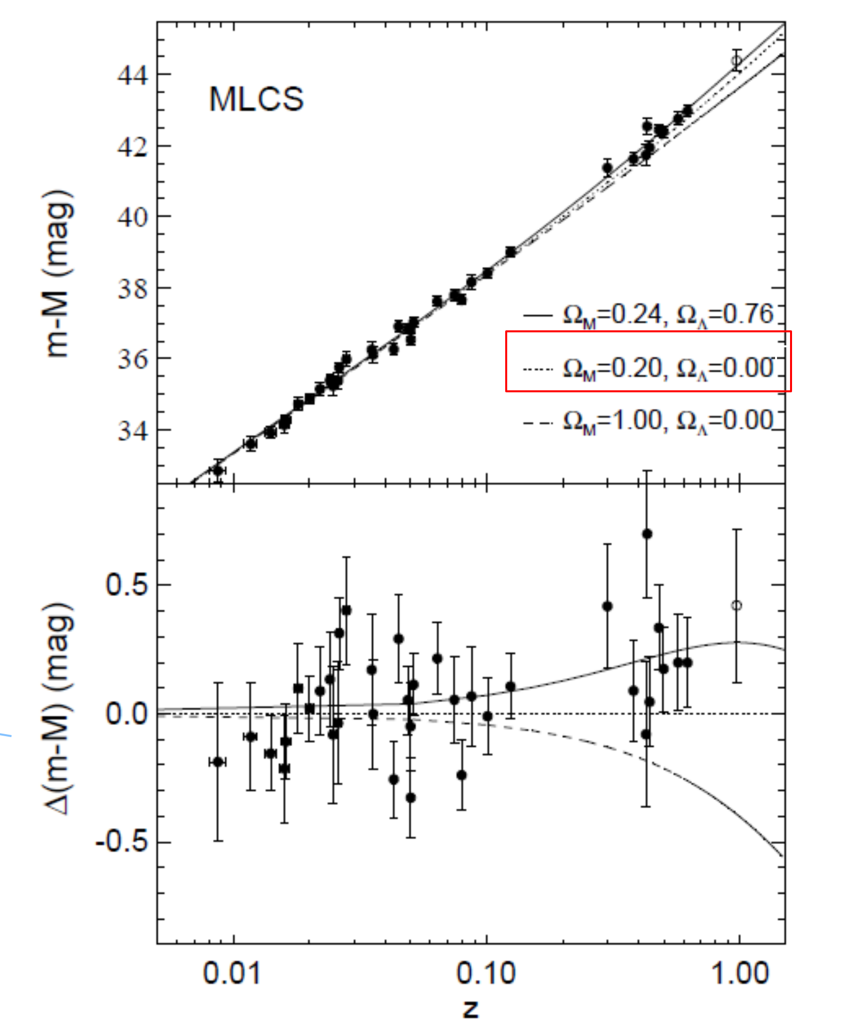
High-z Supernova Search Team

OBSERVATIONAL EVIDENCE FROM SUPERNOVAE FOR AN ACCELERATING UNIVERSE AND A COSMOLOGICAL CONSTANT

ADAM G. RIESS,[1] ALEXEI V. FILIPPENKO,[1] PETER CHALLIS,[2] ALEJANDRO CLOCCHIATTI,[3] ALAN DIERCKS,[4] PETER M. GARNAVICH,[2] RON L. GILLILAND,[5] CRAIG J. HOGAN,[4] SAURABH JHA,[2] ROBERT P. KIRSHNER,[2] B. LEIBUNDGUT,[6] M. M. PHILLIPS,[7] DAVID REISS,[4] BRIAN P. SCHMIDT,[8,9] ROBERT A. SCHOMMER,[7] R. CHRIS SMITH,[7,10] J. SPYROMILIO,[6] CHRISTOPHER STUBBS,[4] NICHOLAS B. SUNTZEFF,[7] AND JOHN TONRY[11]

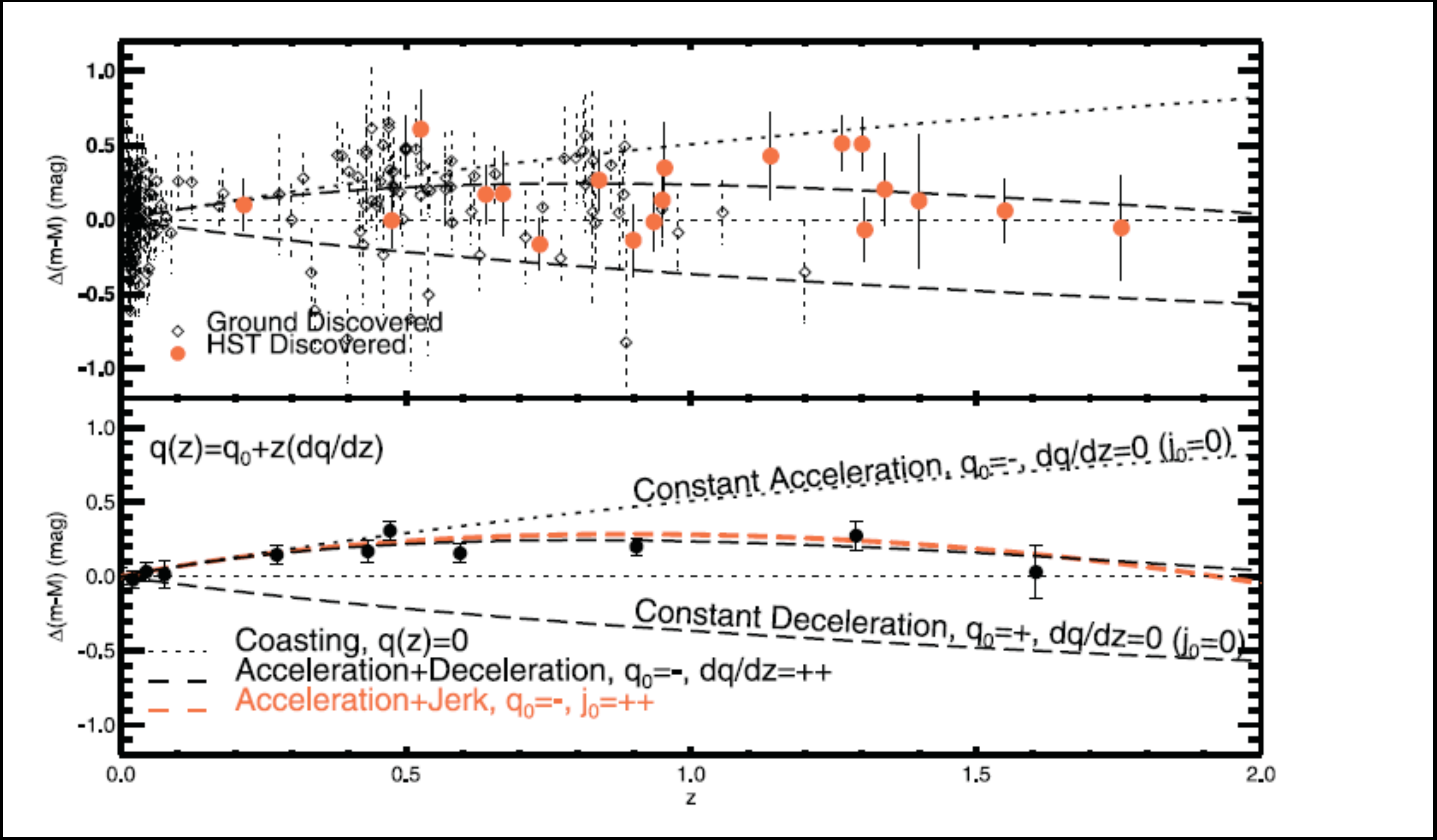
Received 1998 March 13; revised 1998 May 6

$$m - M = 5\log\left(\frac{d_L}{1\,\mathrm{Mpc}}\right) + 25$$



Differences with respect to The values predicted by the open model

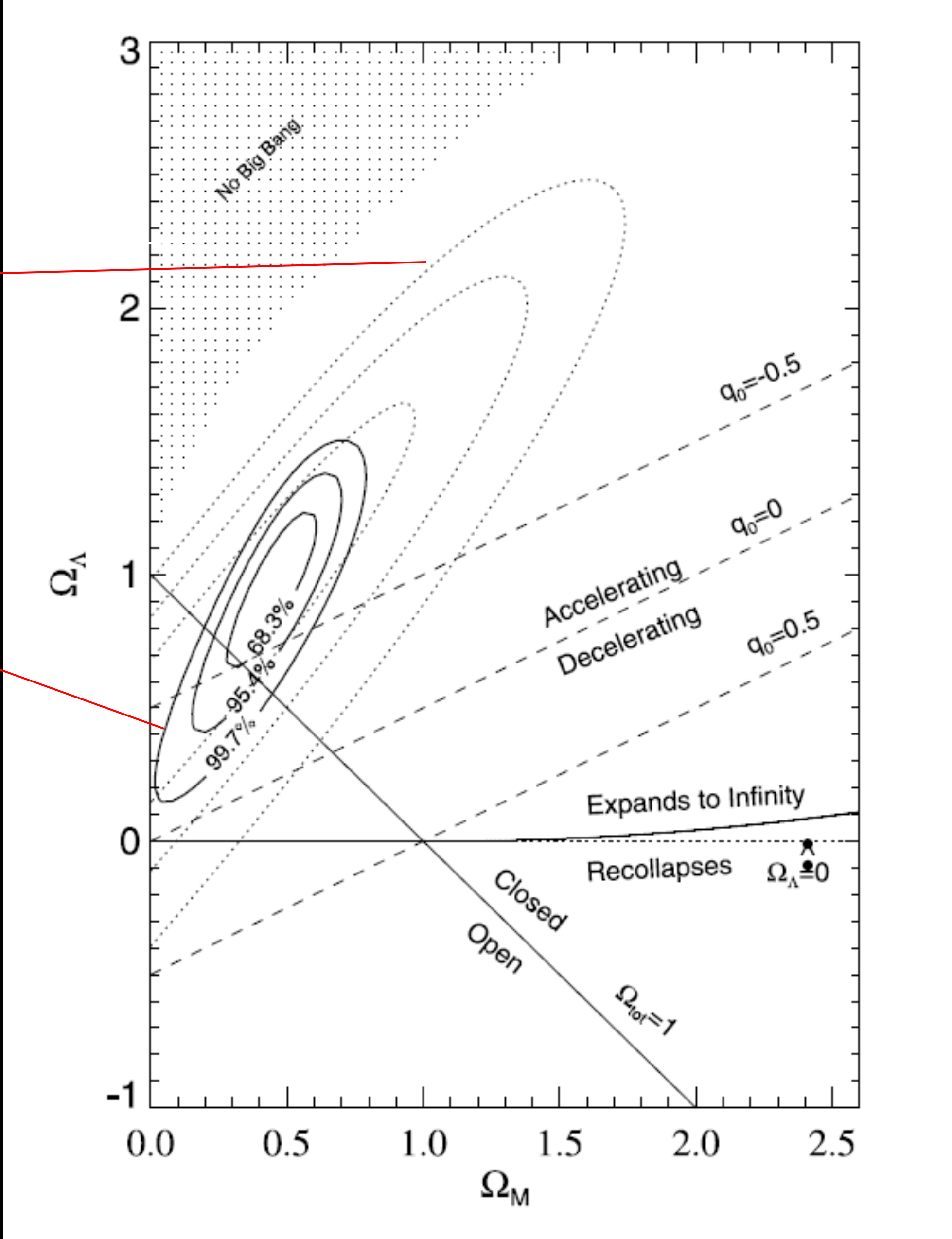
New results



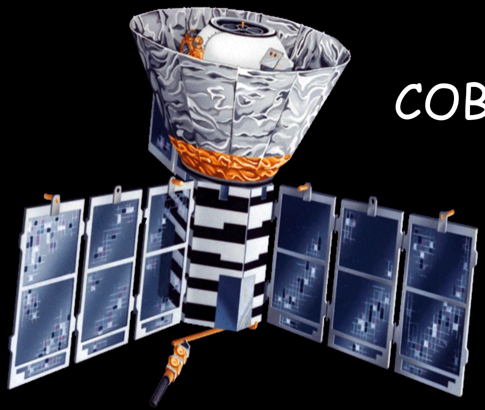
A. G. Riess *et al.* [Supernova Search Team Collaboration], *Type Ia Supernova Discoveries at z¿1 From the Hubble Space Telescope: Evidence for Past Deceleration and Constraints on Dark Energy Evolution*, Astrophys. J. **607** (2004) 665.

Old results

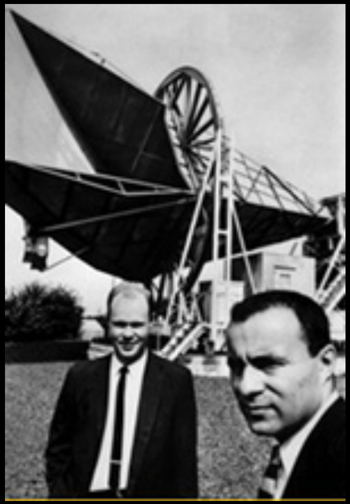
New results



The discovery of the cosmic microwave background radiation



COBE satellite

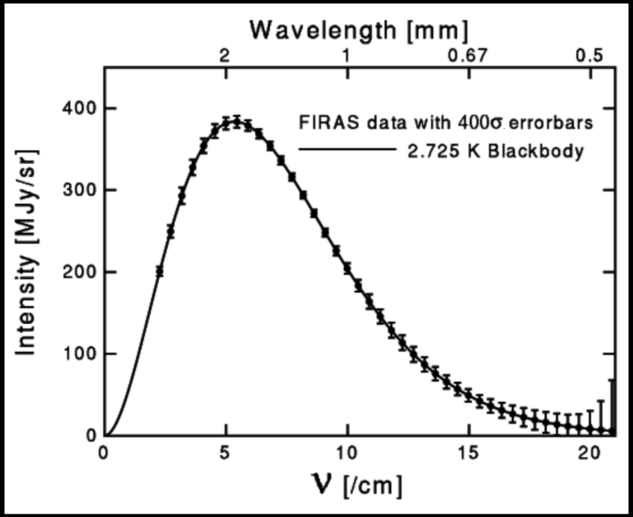


Penzias and Wilson (1965)

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

FIRAS instrument of COBE (1990)

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

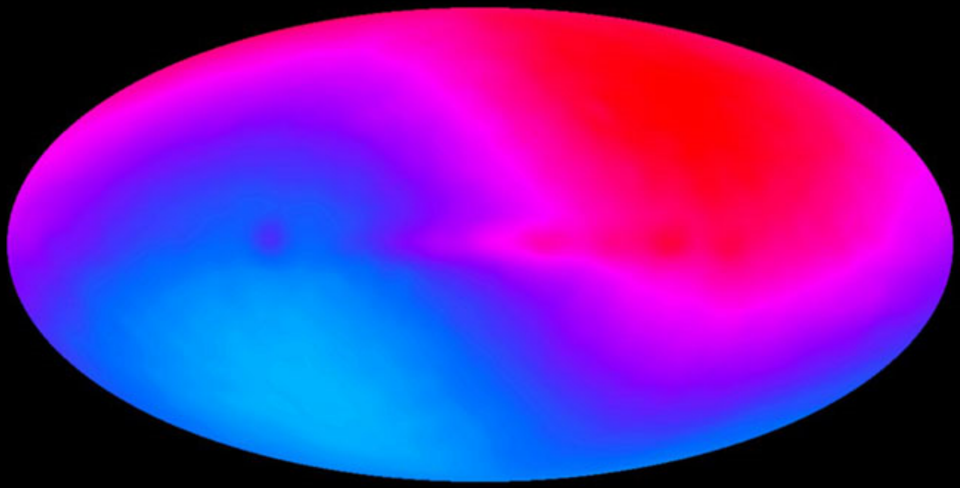


$$\frac{\Delta T}{T}(\theta, \phi) = \sum_{\ell=0}^{\infty} \sum_{m=-\ell}^{m=\ell} a_{\ell m} Y_{\ell m}(\theta, \phi) .$$

$$\Delta\theta = \frac{180°}{\ell}.$$

Example: the dipole anisotropy ($\Delta\theta$=180°) corresponds to l =1

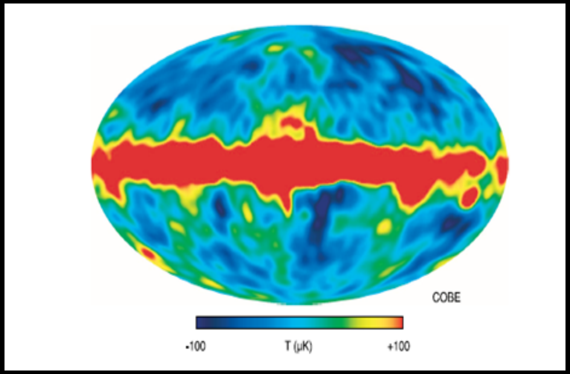
COBE DMR microwave map of the sky in Galactic coordinates: temperature variation with respect to the mean value <T> =2.725 K. The color change indicates a fluctuation of $\Delta T \sim 3.5$ mK $\Rightarrow \Delta T/T \sim 10^{-3}$



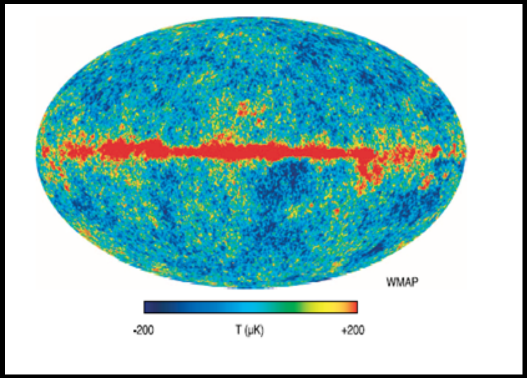
CMB temperature anisotropies

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

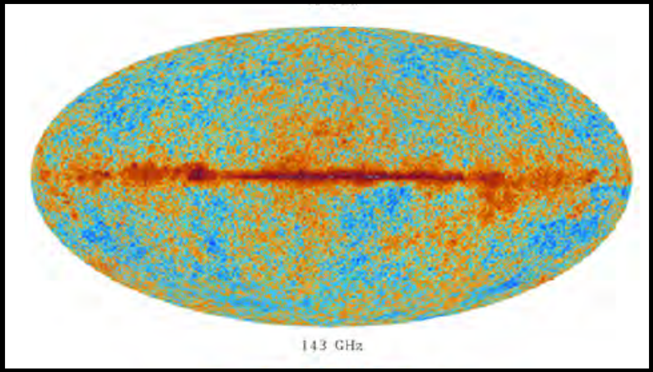
COBE (1992)



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 $\delta\Theta^{Planck} \simeq 3'$

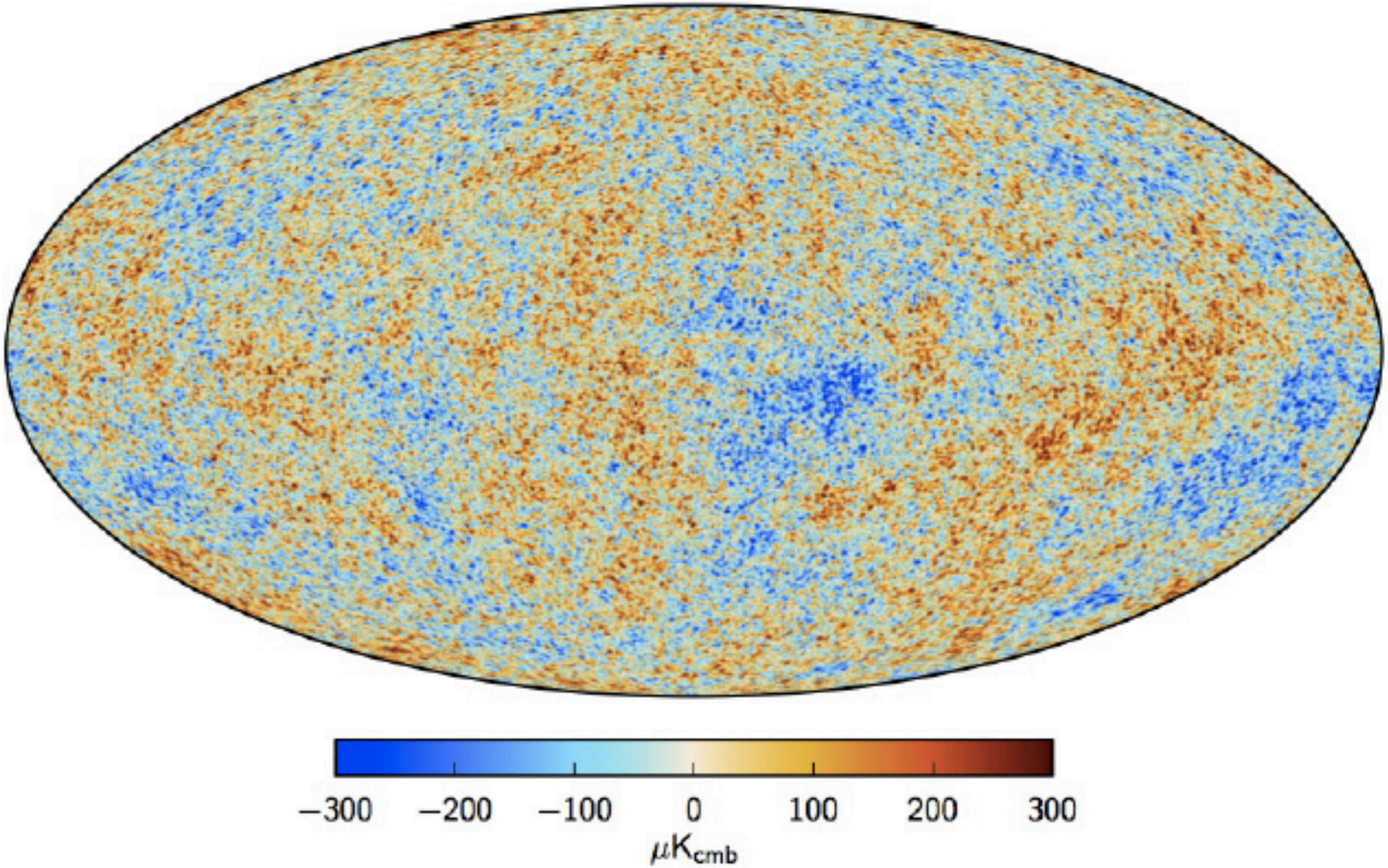


Fig. 9. Maximum posterior CMB intensity map at 5′ resolution derived from the joint baseline analysis of *Planck*, WMAP, and 408 MHz observations. A small strip of the Galactic plane, 1.6 % of the sky, is filled in by a constrained realization that has the same statistical properties as the rest of the sky.

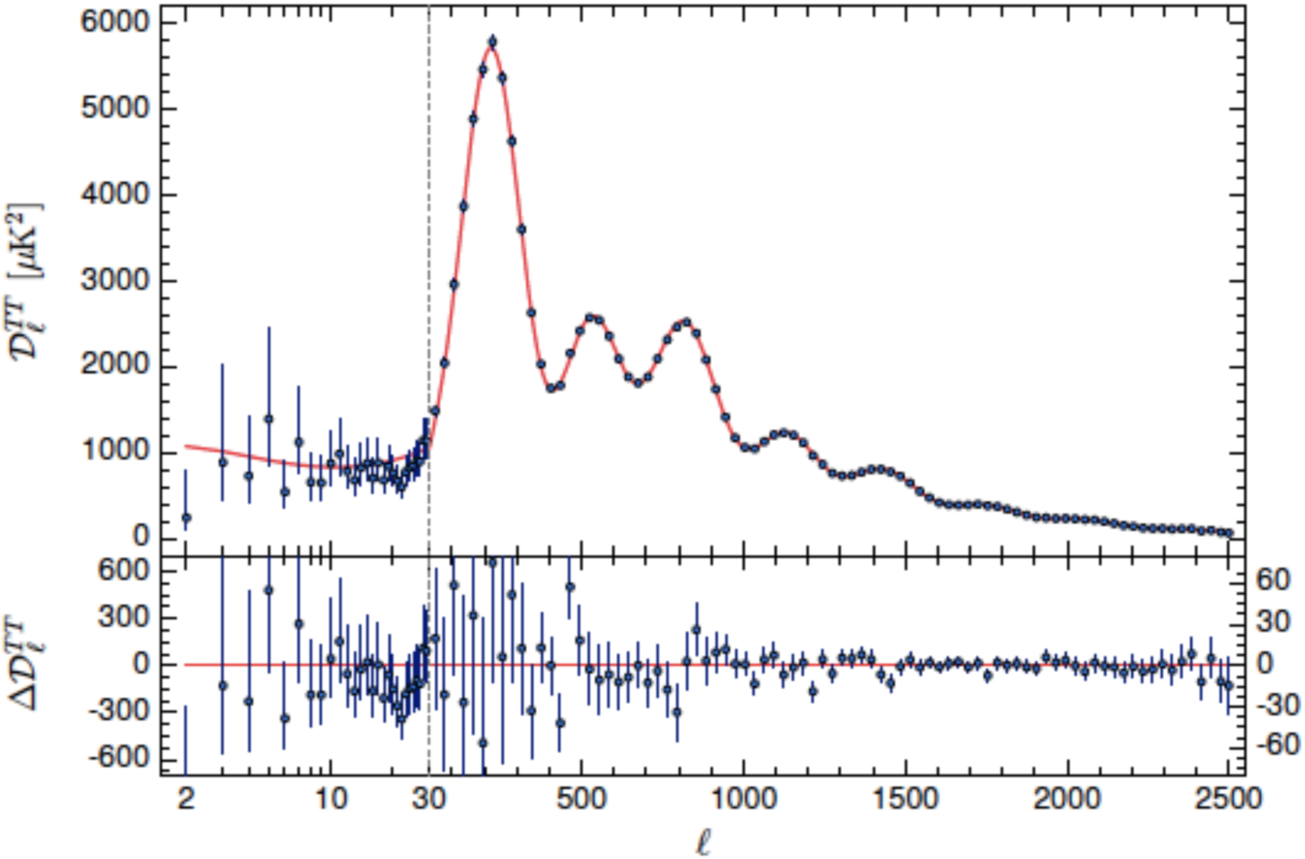
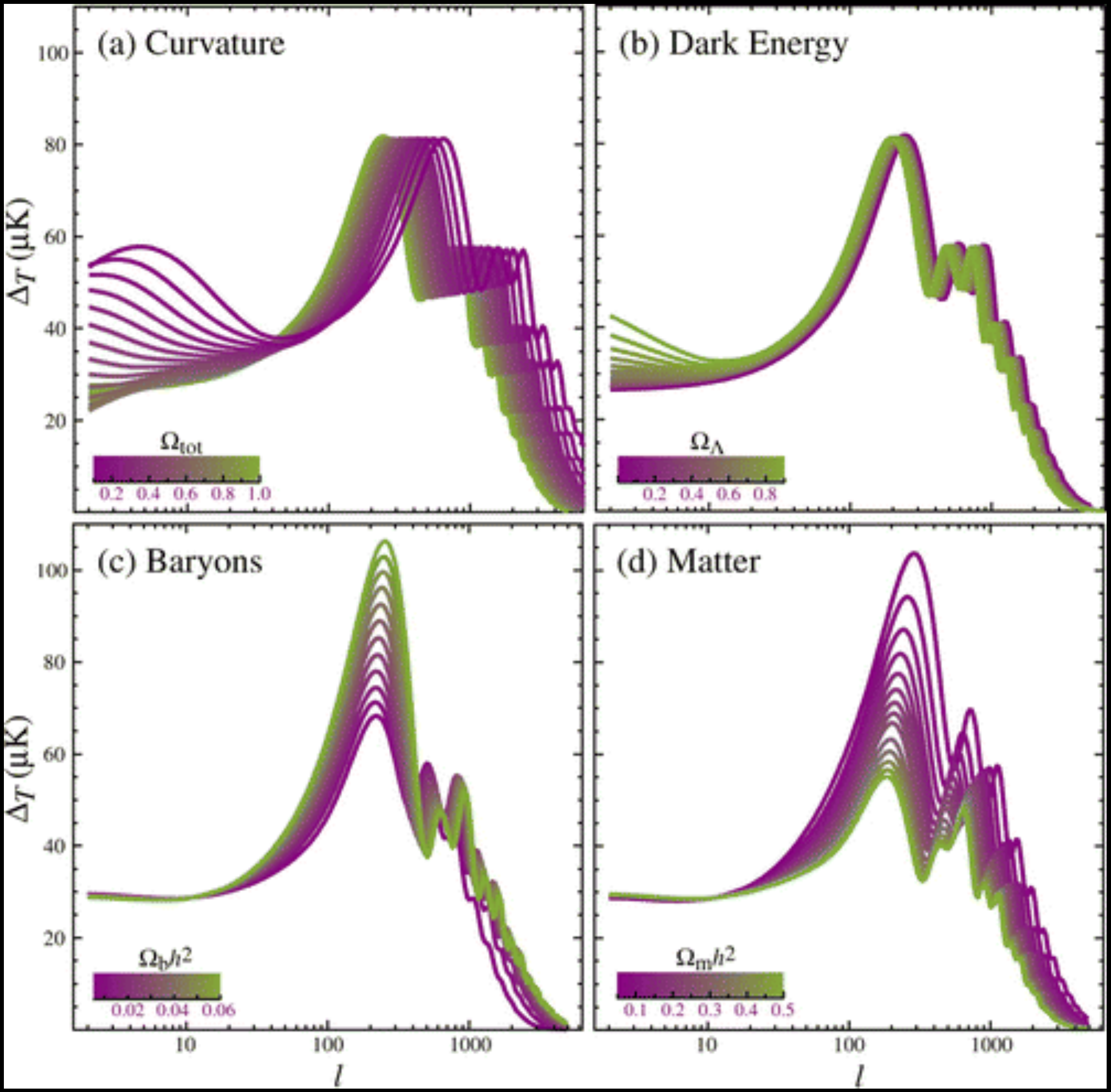


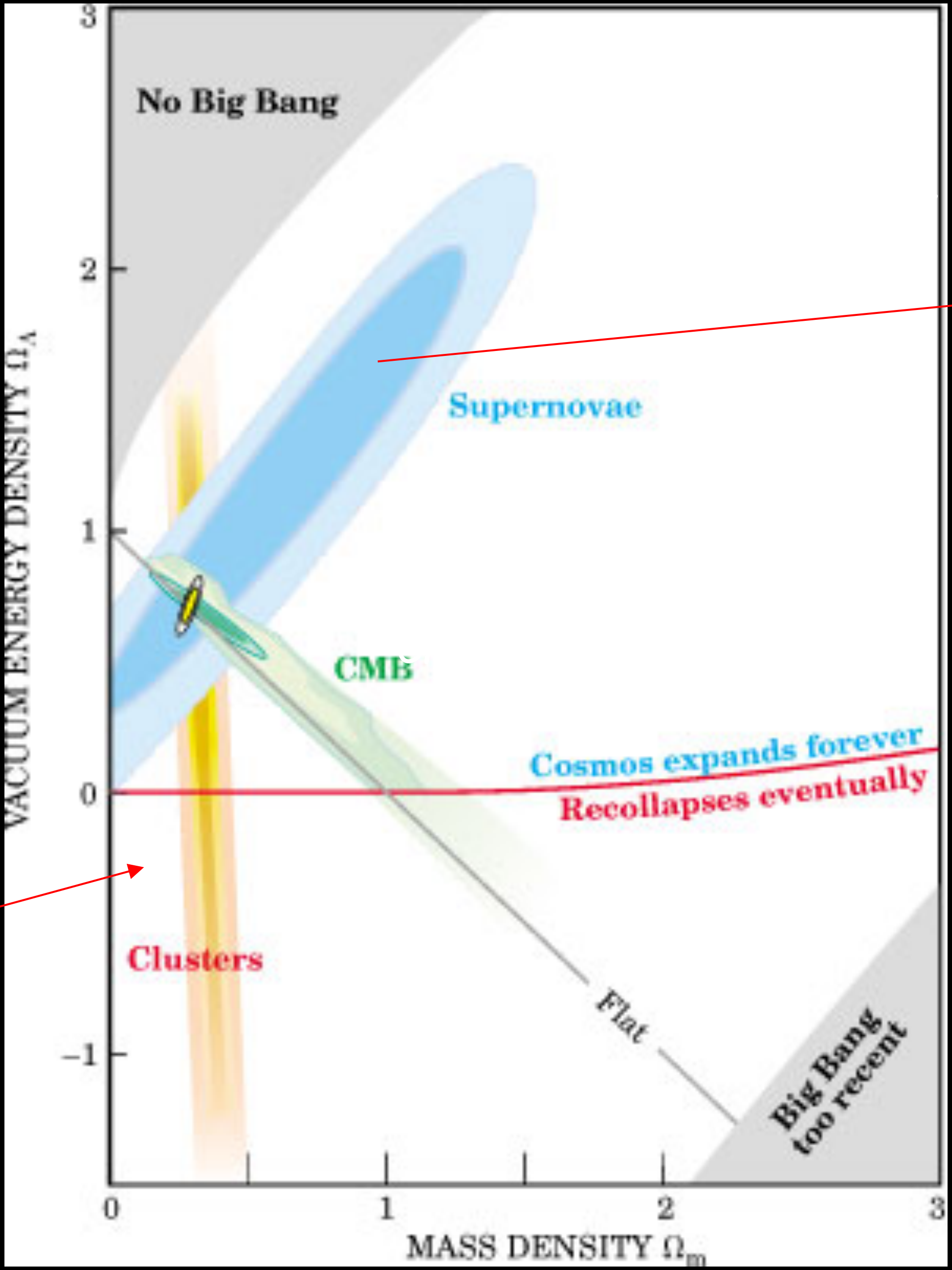
Fig. 11. The *Planck* 2015 temperature power spectrum. At multipoles $\ell \geq 30$ we show the maximum likelihood frequency-averaged temperature spectrum computed from the cross-half-mission likelihood with foreground and other nuisance parameters determined from the MCMC analysis of the base ΛCDM cosmology. In the multipole range $2 \leq \ell \leq 29$, we plot the power spectrum estimates from the Commander component-separation algorithm computed over 94 % of the sky. The best-fit base ΛCDM theoretical spectrum fitted to the PlanckTT+lowP likelihood is plotted in the upper panel. Residuals with respect to this model are shown in the lower panel. The error bars show $\pm 1\,\sigma$ uncertainties. From Planck Collaboration XIII (2015).

Planck
(2015)



http://map.gsfc.nasa.gov/resources/camb_tool/index.html

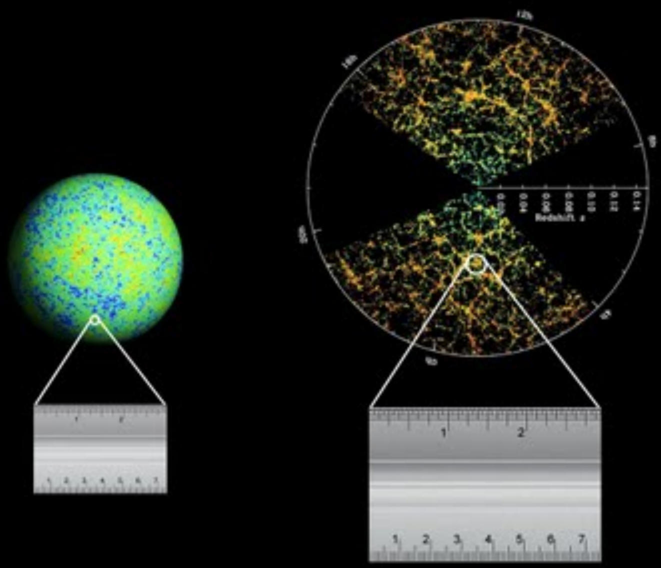
“Cosmic Concordance”

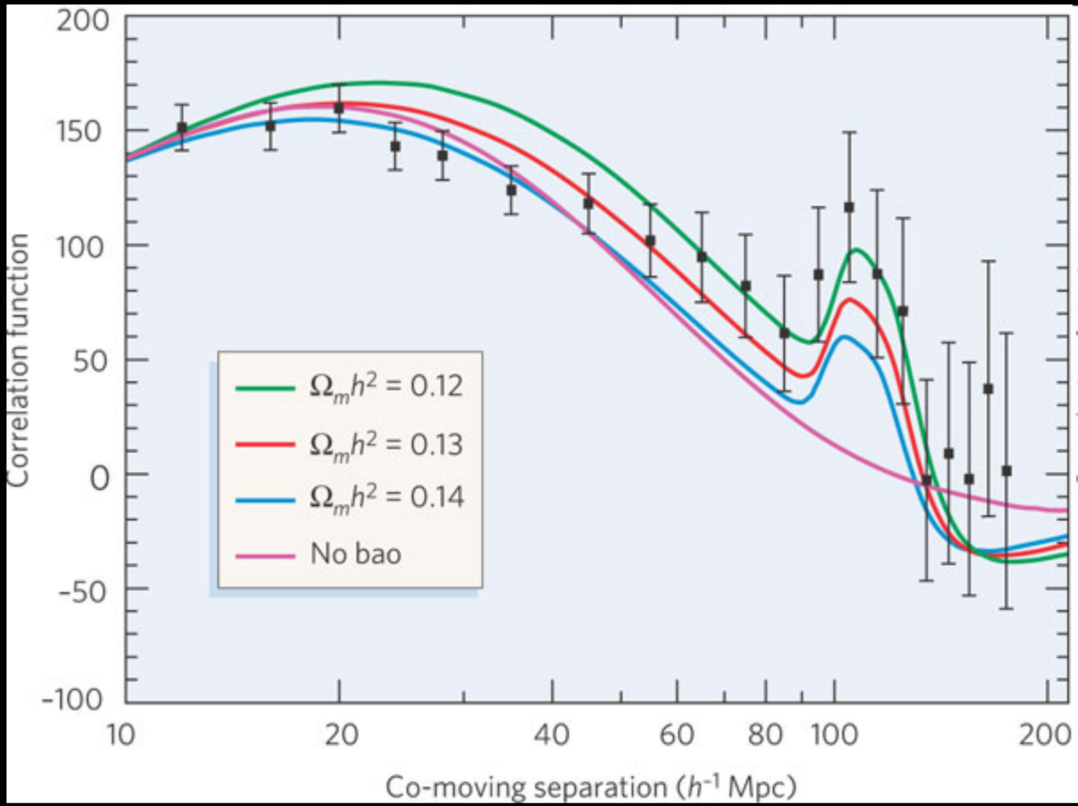


$$\Omega_{\Lambda,0} \simeq 1.5\,\Omega_{M,0} + 0.25$$

Galaxy Surveys
(Dark Matter)

Baryon acoustic oscillations (BAO)

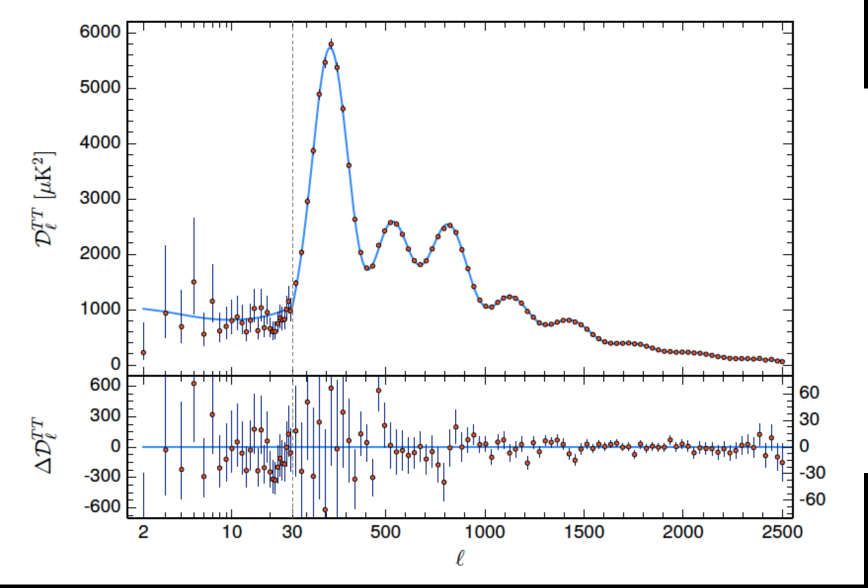




ΛCDM model

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

ΛCDM best fit to the *Planck* 2018 data (TT+TE+EE+low E+lensing)
(Planck Collaboration, *arXiv 1807.06209*)



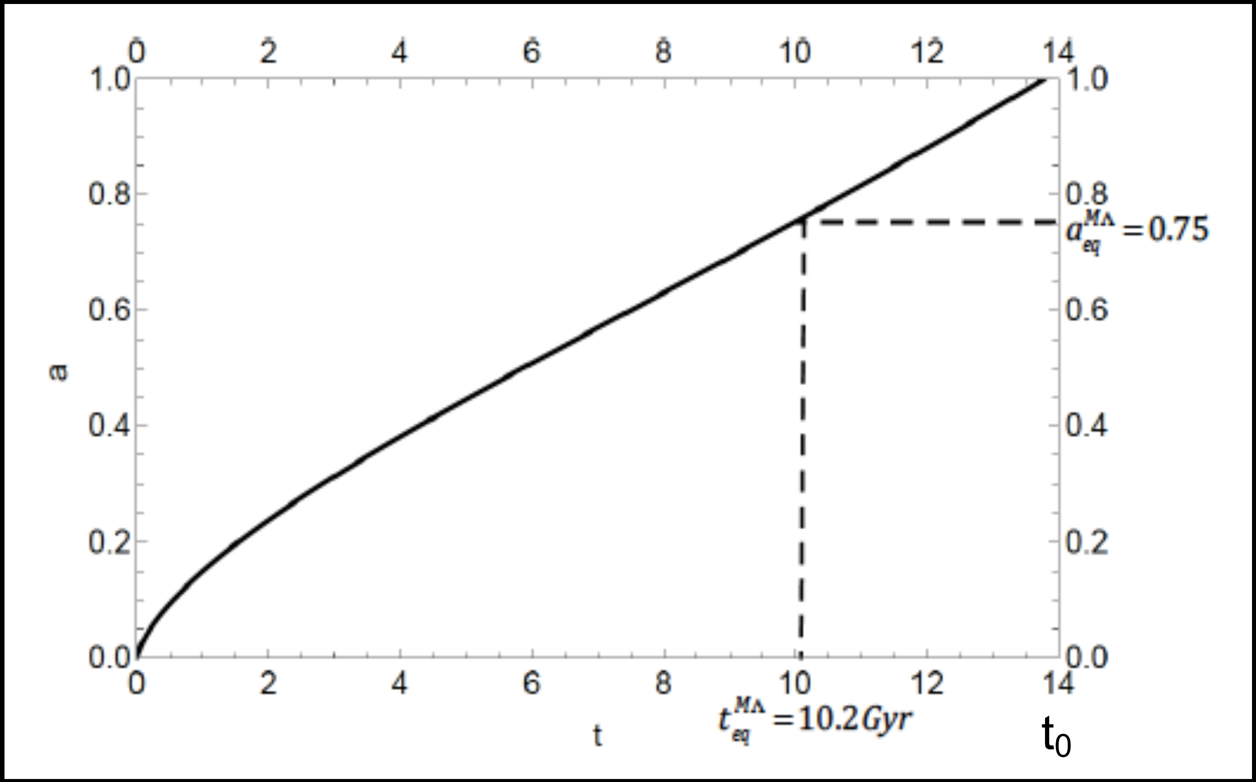
Parameter	TT,TE,EE+lowE+lensing 68% limits	TT,TE,EE+lowE+lensing+BAO 68% limits
$\Omega_b h^2$	0.02237 ± 0.00015	0.02242 ± 0.00014
$\Omega_c h^2$	0.1200 ± 0.0012	0.11933 ± 0.00091
$100\theta_{MC}$	1.04092 ± 0.00031	1.04101 ± 0.00029
τ	0.0544 ± 0.0073	0.0561 ± 0.0071
$\ln(10^{10} A_s)$	3.044 ± 0.014	3.047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

(Planck 2018 results, 1807.06209)

Planck results are in good agreement with BAO, SNe and galaxy lensing observations. The only significant (~4σ) tension is with local measurement of the Hubble constant

In the ΛCDM model, expansion is described by a flat Friedmann-Lemaitre cosmological model

Age of the universe in the ΛCDM model



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

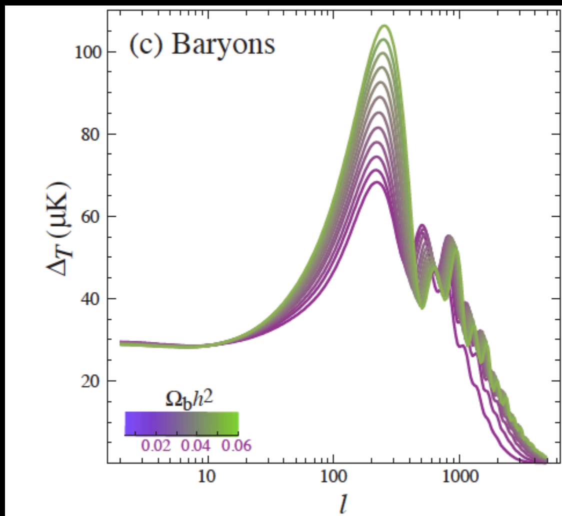
$$\Omega_{M0} = 0.308$$

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

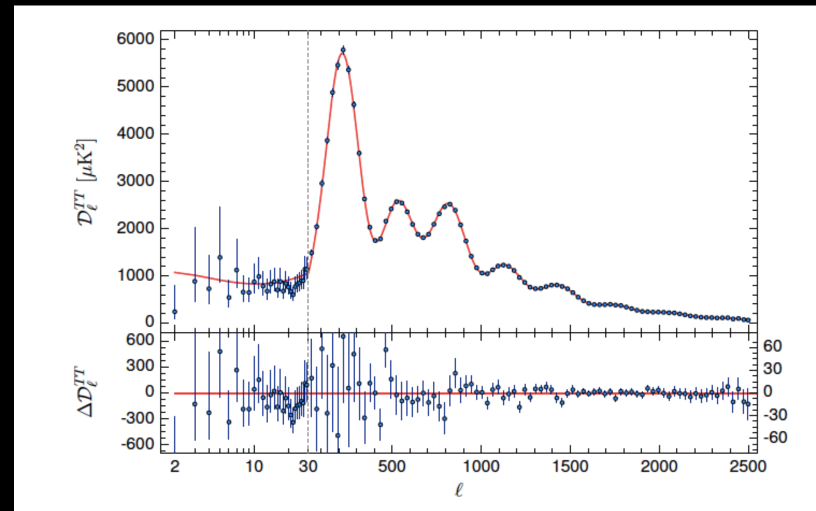
$$t_0 = \frac{2 H_0^{-1}}{3\sqrt{\Omega_{\Lambda 0}}} \ln\left[\frac{1+\sqrt{\Omega_{\Lambda 0}}}{\sqrt{1-\Omega_{\Lambda 0}}}\right] \simeq 13.8 Gyr$$

Baryon asymmetry of the universe

(Hu, Dodelson, astro-ph/0110414)



(Planck 2018, 1807.06209)



(CMB+BAO)

$$\Omega_{B0} h^2 = 0.02242 \pm 0.00014$$

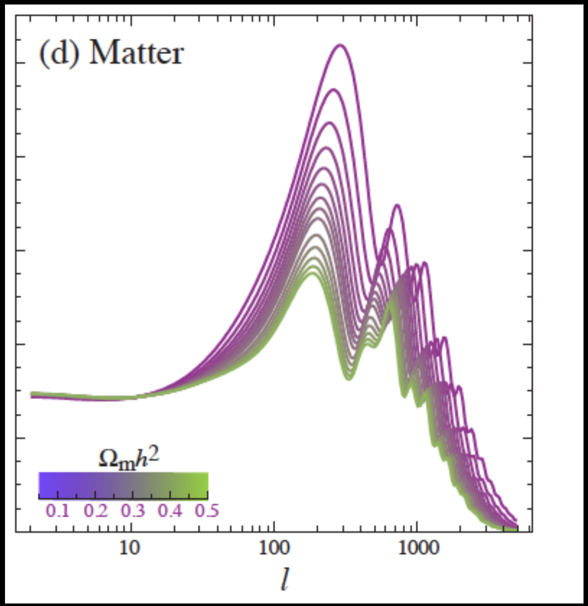
$$\eta_{B0} \equiv \frac{n_{B0} - \bar{n}_{B0}}{n_{\gamma 0}} \simeq \frac{n_{B0}}{n_{\gamma 0}} \simeq 273.5\,\Omega_{B0} h^2 \times 10^{-10} = (6.12 \pm 0.04) \times 10^{-10} = \eta_{B0}^{CMB}$$

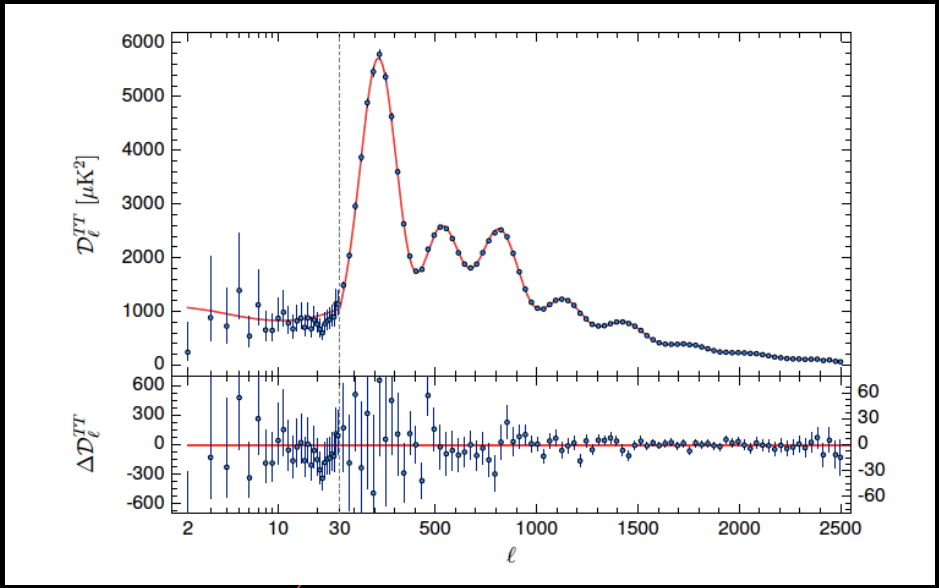
- Consistent with (older) BBN determination but more precise and accurate
- Asymmetry coincides with matter abundance since there is no evidence of primordial antimatter.....not so far at least (see AMS-02 results and Poulin,Salati,Cholis,Kamionkowski,Silk 1808.08961)

The Dark Matter of the Universe

(Hu, Dodelson, astro-ph/0110414)

(Planck 2018, 1807.06209)





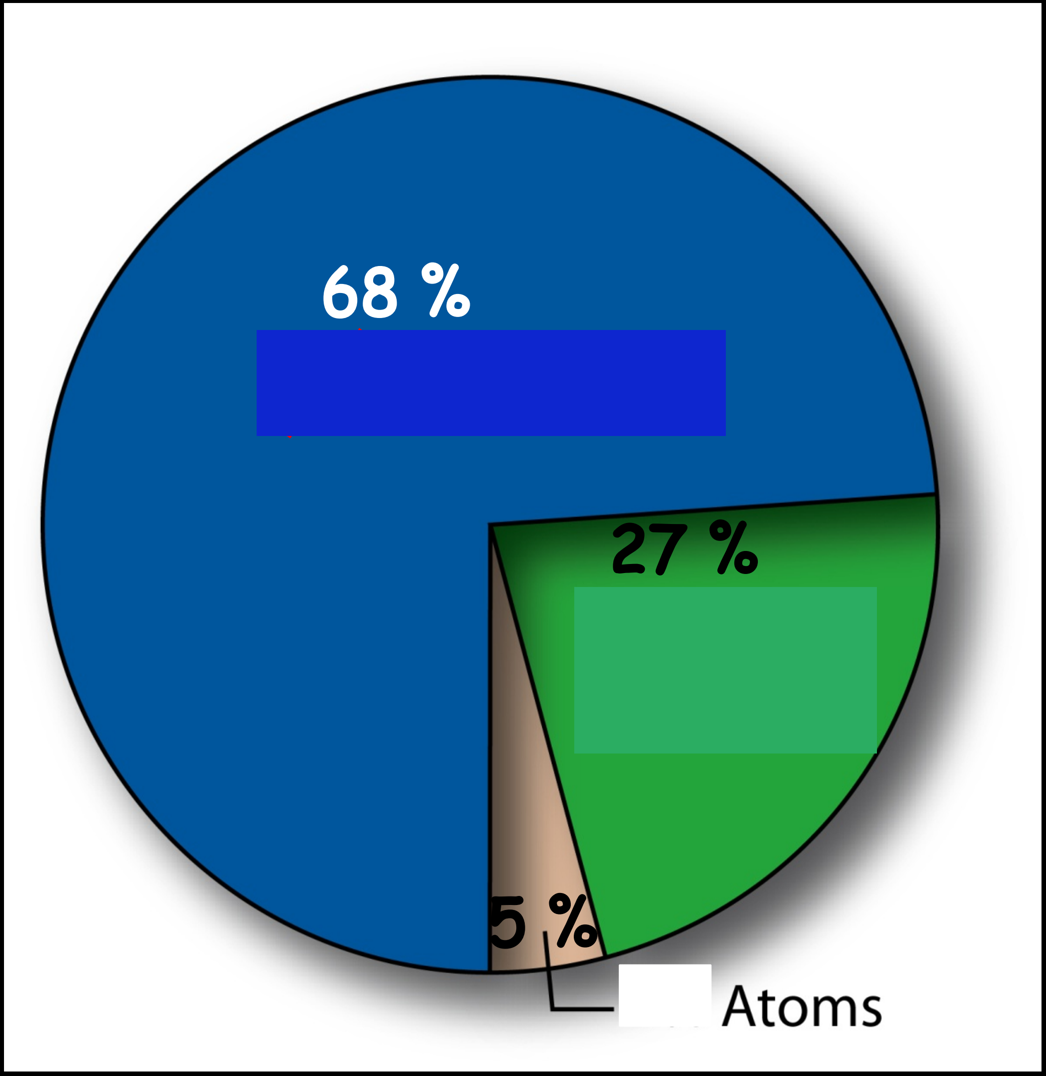
(CMB + BAO)

$$\Omega_{CDM\,0} h^2 = 0.11933 \pm 0.00091 \sim 5\,\Omega_{B0} h^2$$

The matter-energy budget in the ΛCDM model at t_0

Atoms only make up 5% of the mass of the Universe

the rest is unknown Dark Energy and Dark Matter



1 parameter deviations from the ΛCDM model

(Planck Collaboration 2018, arXiv 1807.06209)

95% CL constraints

Parameter	TT, TE, EE+lowE+lensing	TT, TE, EE+lowE+lensing+BAO
Ω_K	$-0.011^{+0.013}_{-0.012}$	$0.0007^{+0.0037}_{-0.0037}$
Σm_ν [eV]	< 0.241	< 0.120
$N_{\rm eff}$	$2.89^{+0.36}_{-0.38}$	$2.99^{+0.34}_{-0.33}$
$Y_{\rm P}$	$0.239^{+0.024}_{-0.025}$	$0.242^{+0.023}_{-0.024}$
$dn_s/d\ln k$	$-0.005^{+0.013}_{-0.013}$	$-0.004^{+0.013}_{-0.013}$
$r_{0.002}$	< 0.101	< 0.106
w_0	$-1.57^{+0.50}_{-0.40}$	$-1.04^{+0.10}_{-0.10}$

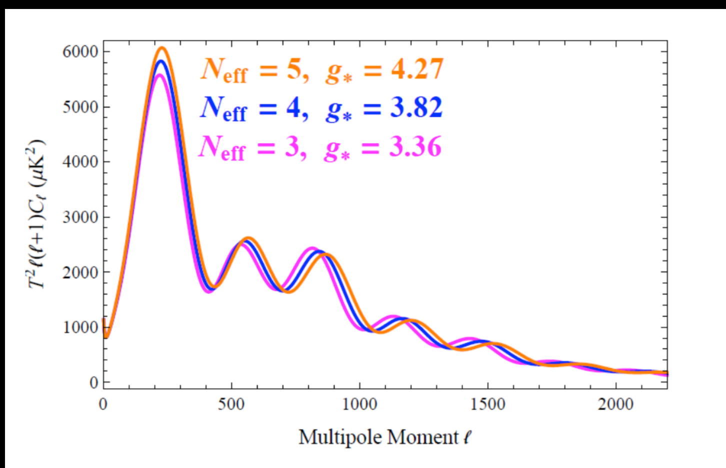
$$\sum_i m_i < 0.12\ \mathrm{eV}$$

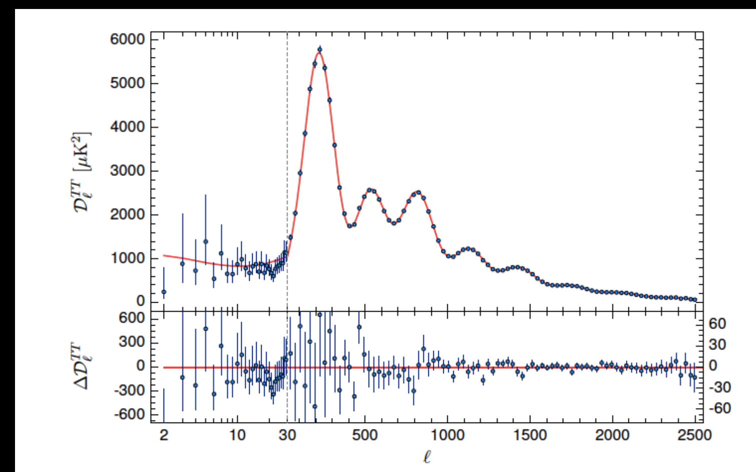
Most stringent upper bound on the absolute neutrino mass scale

Radiation at matter-radiation 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)

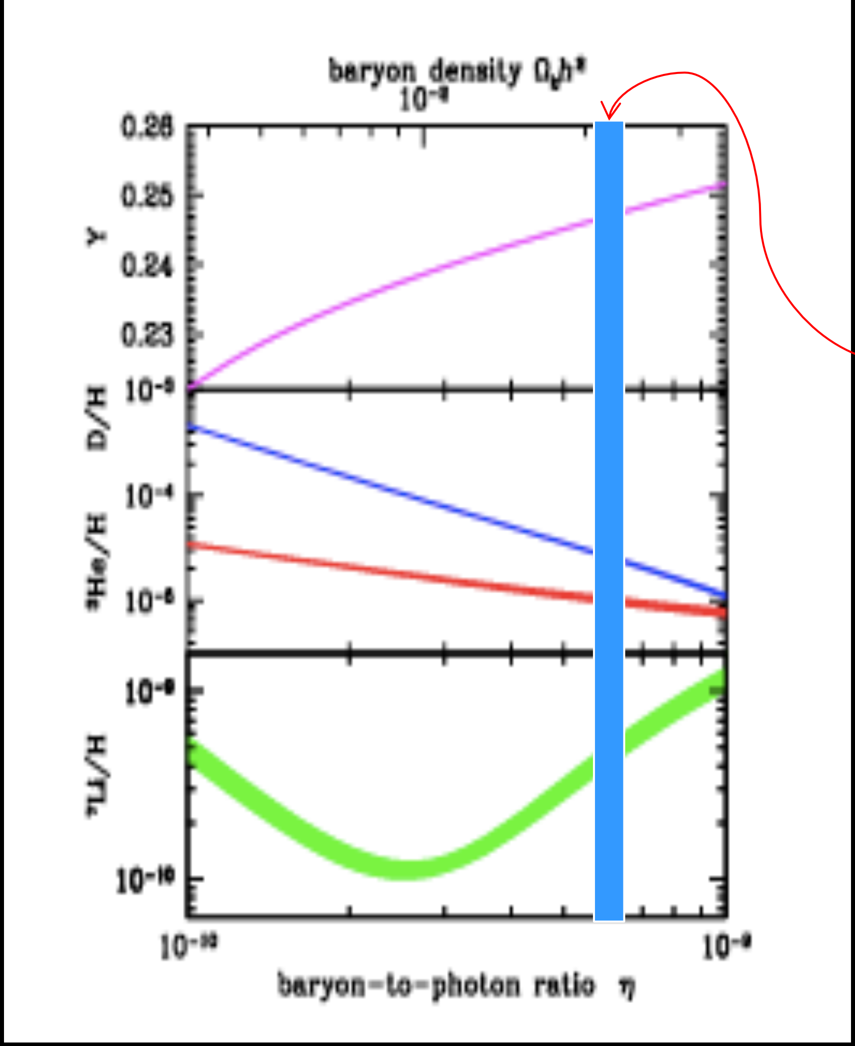
TT+TE+EE+lensing $\longrightarrow$ $N_\nu^{rec} = 2.94 \pm 0.38$

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?

Big Bang nucleosynthesis+CMB

(PDB hep-ph/0108182)



(Cyburt, Field, Olive, Yeh 1505.01076)

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

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

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

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

And from Deuterium abundance:

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

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

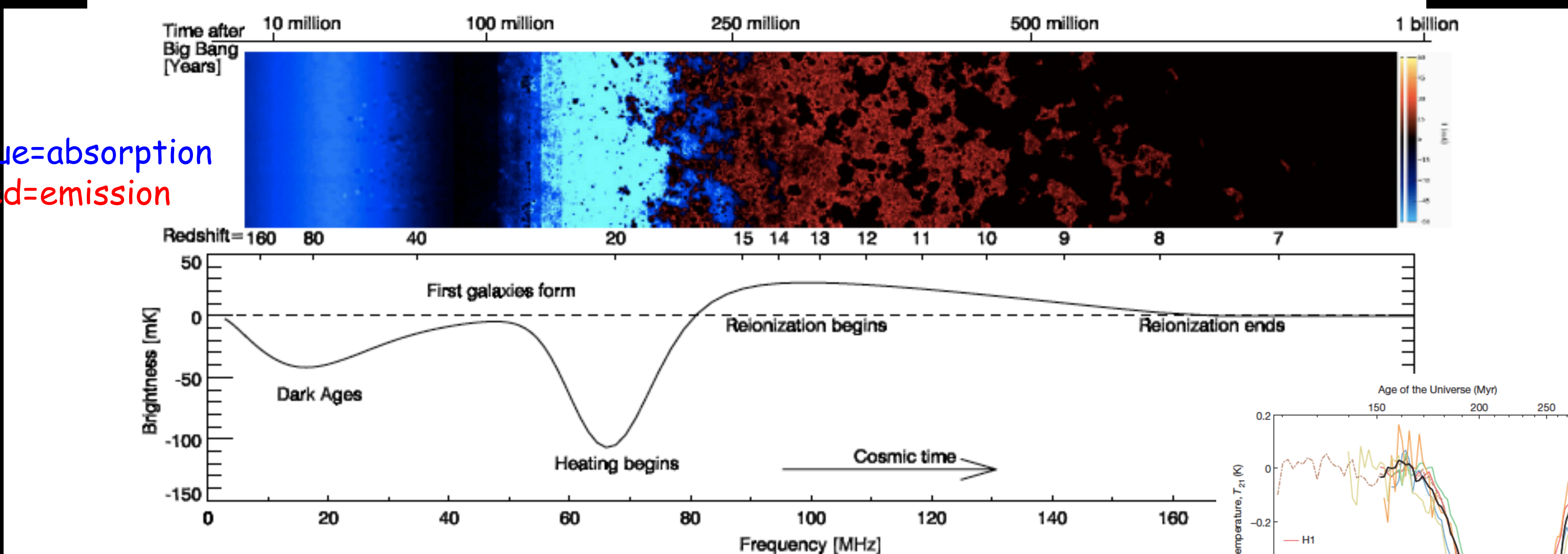
21 cm cosmology (global signal)

- 21 cm line (emission or absorption) is produced by hyperfine transitions between the two energy levels of 1s ground state of Hydrogen atoms. The energy splitting between the two level is $E_{21}=5.87\times\mu eV$
- The 21cm brightness temperature parametrises the brightness contrast :

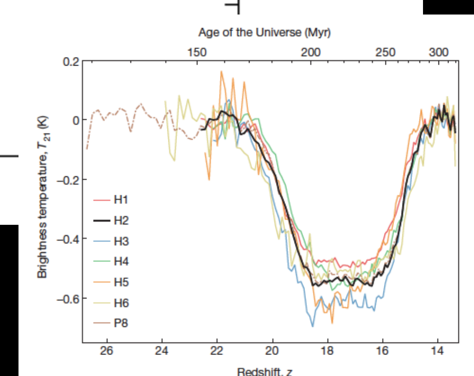
$$T_{21}(z) \simeq 23\,\mathrm{mK}\,(1+\delta_B)\,x_{H_I}(z)\left(\frac{\Omega_B h^2}{0.02}\right)\left[\left(\frac{0.15}{\Omega_m h^2}\right)\left(\frac{1+z}{10}\right)\right]^{1/2}\left[1-\frac{T_\gamma(z)}{T_S(z)}\right],$$

spin temperature

Blue=absorption
Red=emission

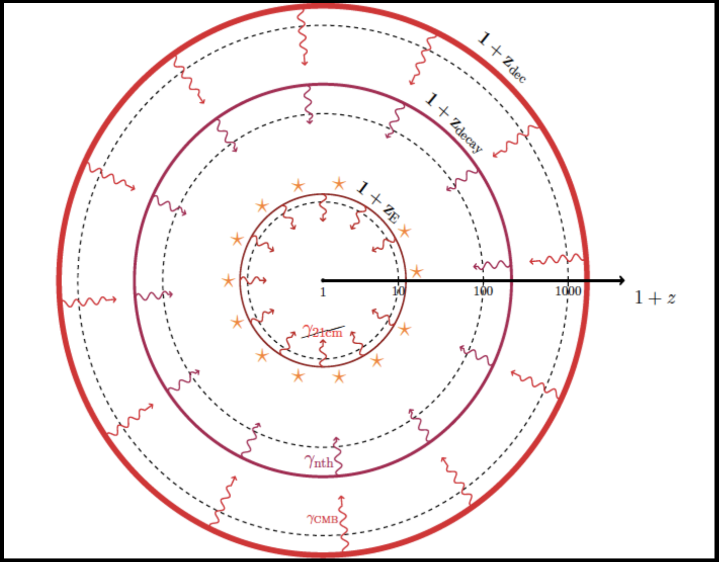


EDGES (anomalous) signal



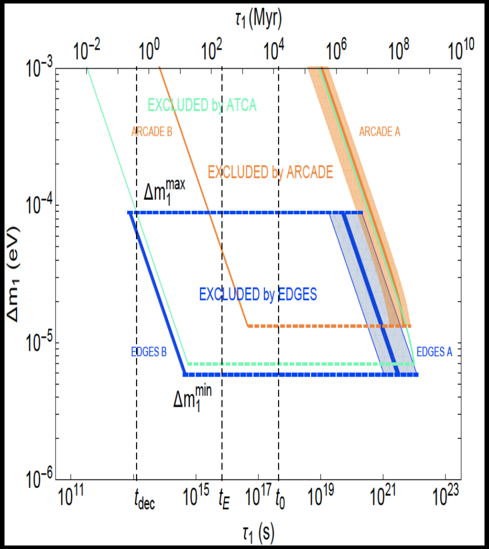
EDGES anomaly and radiative neutrino decays into sterile neutrinos

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



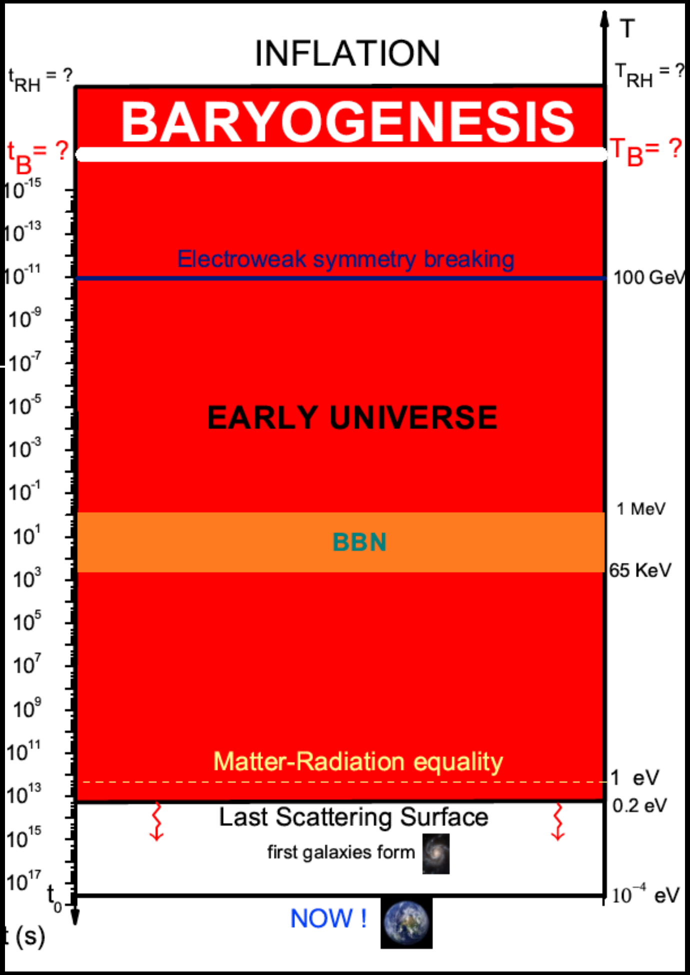
- We have considered the possibility that $\nu_i \to \nu_s + \gamma$ with $m_i - m_s = E_{21}\, z_{decay}/z_E$

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



Cosmological puzzles

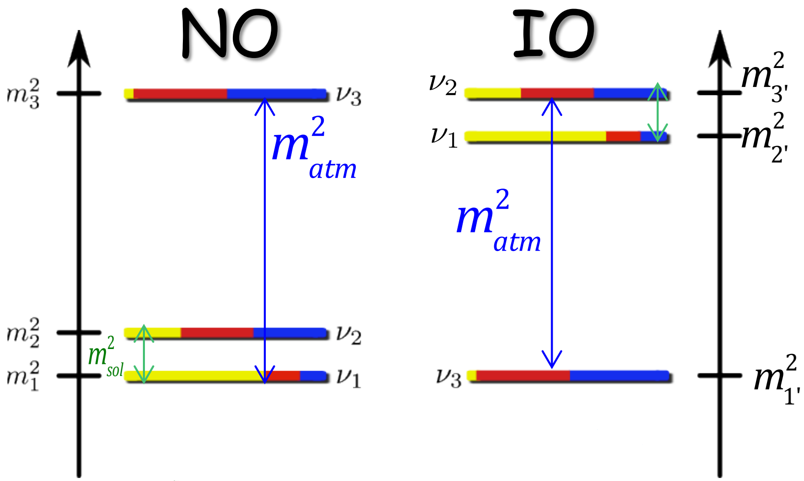
dark matter production



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, in particular one can naturally have leptogenesis to explain the matter-antimatter asymmetry (talk by D. Gorbunov)

Leptogenesis (minimal scenario)

Neutrino masses ($m_{1'} < m_{2'} < m_{3'}$)



$$NO: m_2 = \sqrt{m_1^2 + m_{sol}^2}, \quad m_3 = \sqrt{m_1^2 + m_{atm}^2}$$

$$IO: m_{2'} = \sqrt{m_{1'}^2 + m_{atm}^2 - m_{sol}^2}, \quad m_{3'} = \sqrt{m_{1'}^2 + m_{atm}^2}$$

m_{sol} = (8.6 ± 0.1) *meV*

m_{atm} = (50.3 ± 0.3) *meV*

(νfit 2019)

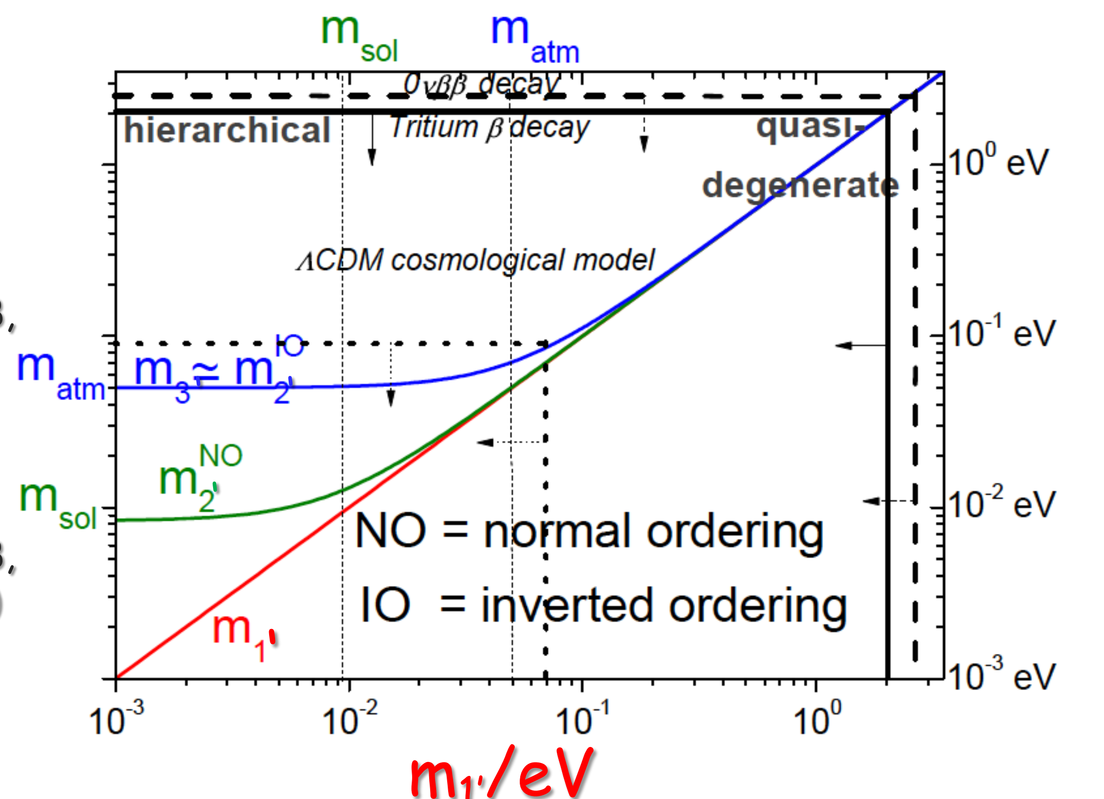
$\sum_i m_i < 0.24$ eV (95%*CL*) (Planck 2018, only CMB)

$\Rightarrow m_{1'} \leq 0.07$ eV

$\sum_i m_i < 0.12\ eV$ (95% *CL*) (Planck 2018, CMB + BAO)

$\Rightarrow m_{1'} \leq 0.03$ eV (NO)

$m_{1'} \leq 0.016$ eV (IO)



Neutrino mixing: $\nu_\alpha = \sum_i U_{\alpha i} \nu_i$

$$U_{\alpha i} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix} \begin{pmatrix} e^{i\rho} & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & e^{i\sigma} \end{pmatrix}$$

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

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

Atmospheric, LB | Reactors, Accel.,LB CP violating phase | Solar,Reactors | ββ0ν decay

$c_{ij} \equiv \cos\theta_{ij}$, $s_{ij} \equiv \sin\theta_{ij}$

3σ ranges (NO) (νfit July 2019)

$\theta_{12} = [31.6^\circ, 36.3^\circ]$

$\theta_{13} = [8.2^\circ, 9.0^\circ]$

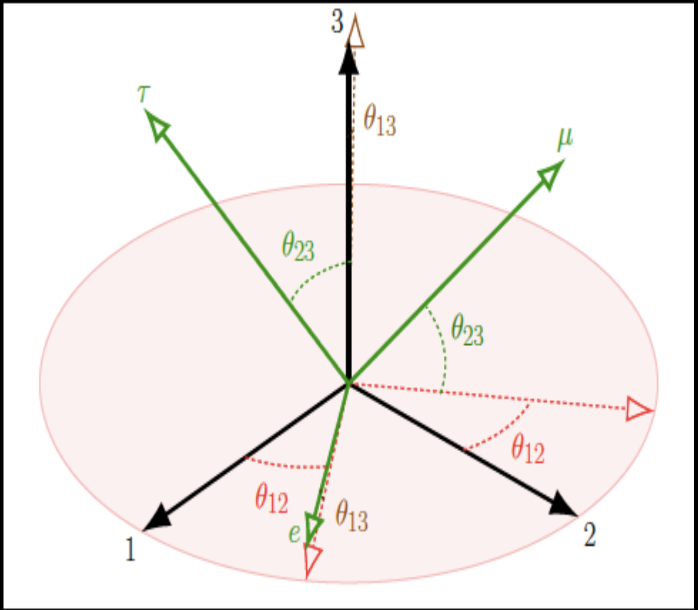
$\theta_{23} = [41.1^\circ, 51.3^\circ]$

$\delta = [144^\circ, 357^\circ]$

$\rho, \sigma = [0, 360^\circ]$

NO favoured over IO:

$\Delta\chi^2$ (IO-NO)=10.6



Minimally extended SM

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

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

Dirac mass term

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

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

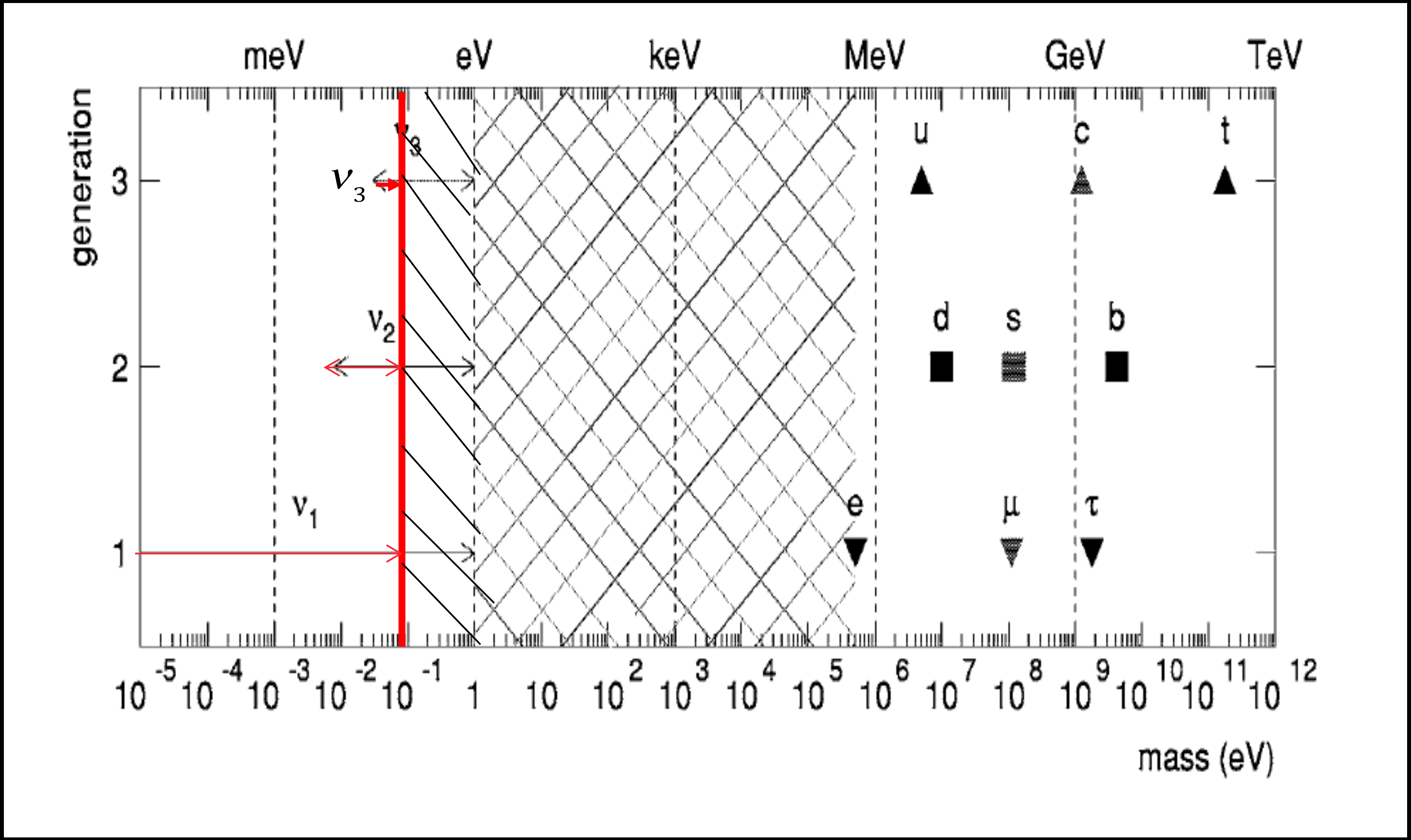
$\Rightarrow$ neutrino masses: $m_i = m_{Di}$

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

Neutrinos are of course predicted to be Dirac neutrinos

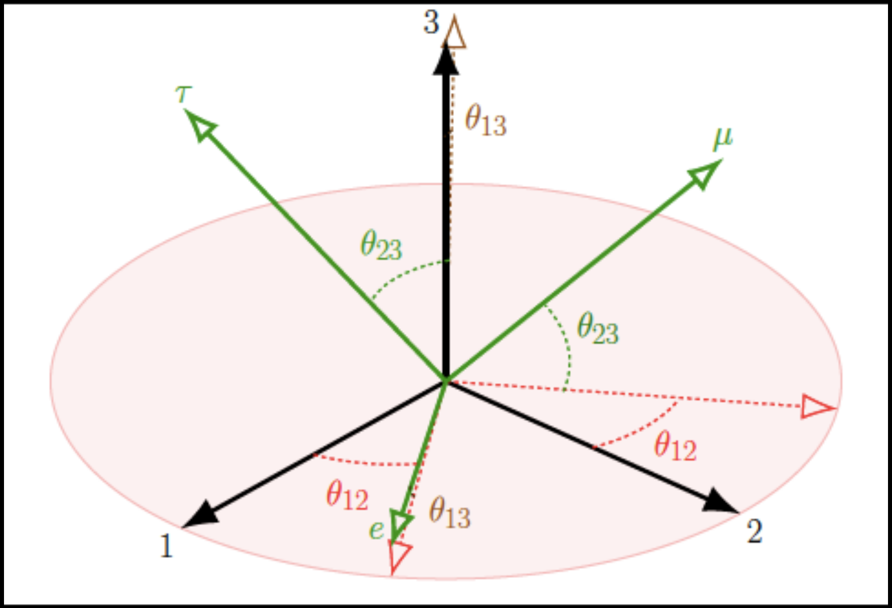
Though minimal, one is left with too many unanswered questions!

Why neutrinos are much lighter than all other fermions ?

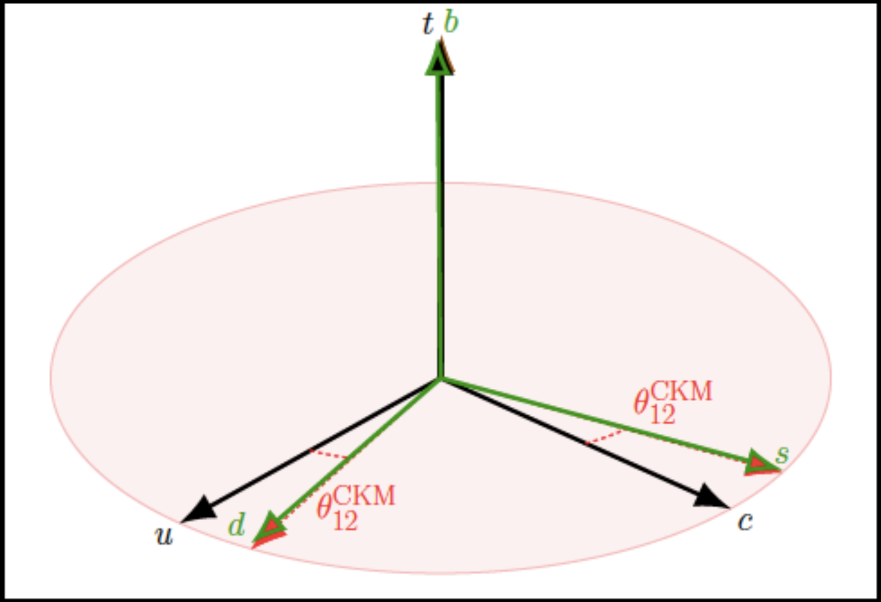


Why are leptonic mixing angles much larger than quark mixing angles ?

lepton flavour space



quark flavour space



(from PDB, Michele Re Fiorentin, Rome Samanta arXiv:submit/2514030)

- Cosmological puzzles?
- Why not a Majorana mass term as well?

Minimal seesaw mechanism (type I)

•Dirac + (right-right) Majorana mass terms

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

violates lepton number

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

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

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

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

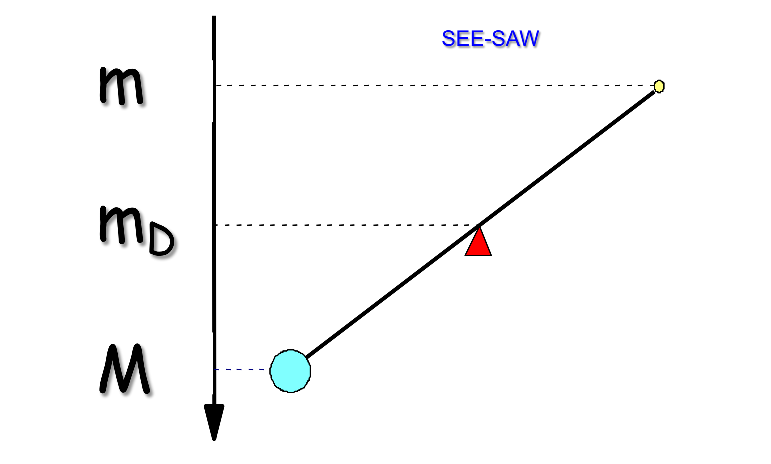
- 3(?) very heavy Majorana neutrinos N_1, N_2, N_3 with $M_3 > M_2 > M_1 \gg m_D$

1 generation toy model :

$m_D \sim m_{top}$,

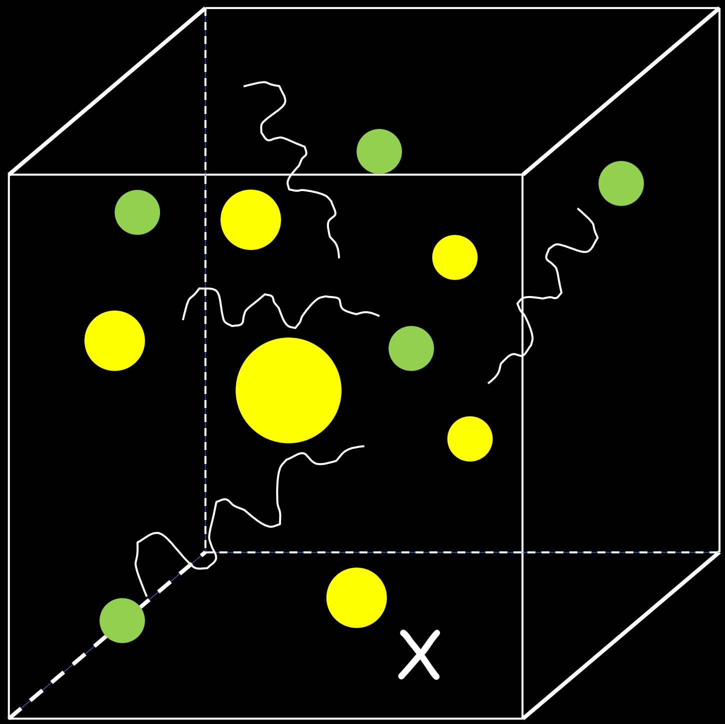
$m \sim m_{atm} \sim 50$ meV

$\Rightarrow M \sim M_{GUT} \sim 10^{16}$GeV



Abundances in the early Universe

portion of comoving volume



$\ell(t)=a(t)\,\ell_0$

$$N_X(t) = n_X(t)\, a^3(t)\, \ell_0^3$$

How to choose ℓ_0? Different options, in our case the most convenient way to normalize abundances is to impose:

$$N_{N_i}^{eq}(T \gg M_i) = 1$$

Exercise: calculate corresponding ℓ_0

Minimal scenario of leptogenesis

(Fukugita, Yanagida '86)

- Type I seesaw mechanism
- Thermal production of RH neutrinos: $T_{RH} \gtrsim T_{lep} \simeq M_i / (2\div10)$

heavy neutrinos decay $N_I \xrightarrow{\Gamma_I} L_I + \phi^\dagger \qquad N_I \xrightarrow{\overline{\Gamma}} \overline{L}_I + \phi$

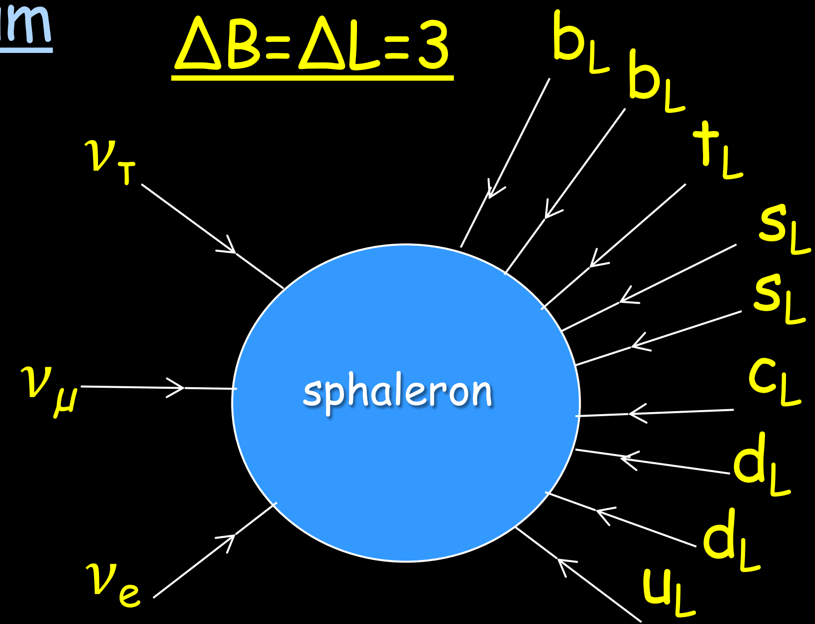
total CP asymmetries $\varepsilon_I \equiv -\dfrac{\Gamma - \overline{\Gamma}}{\Gamma + \overline{\Gamma}}$ $\Rightarrow$ N_{B-L} production

- Sphaleron processes in equilibrium

$\Rightarrow\; T_{lep} \gtrsim T^{off}_{sphalerons} \sim$ **140 GeV**

(Kuzmin, Rubakov, Shaposhnikov '85)

ΔB=ΔL=3



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

Seesaw parameter space

Problem: too many parameters

$$m_\nu = -m_D \frac{1}{M} m_D^T \Leftrightarrow \boxed{\Omega^T \Omega = I}$$

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

(Casas, Ibarra'01)

Orthogonal parameterisation

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

light neutrino parameters

heavy neutrino parameters escaping experimental information

The orthogonal matrix entries Ω_{iJ} tell how much a light neutrino mass m_i is dominated by the inverse heavy neutrino mass $1/M_J$

Leptogenesis complements low energy neutrino experiments constraining heavy neutrinos properties

Vanilla leptogenesis

Vanilla leptogenesis

1) Flavor composition of final leptons is neglected

$$N_i \xrightarrow{\Gamma} l_i\, H^\dagger \qquad\qquad N_i \xrightarrow{\bar\Gamma} \bar{l}_i\, H$$

Total CP asymmetries

$$\varepsilon_i \equiv -\frac{\Gamma_i - \bar\Gamma_i}{\Gamma_i + \bar\Gamma_i}$$

If $\varepsilon_i \neq 0$ a **lepton asymmetry** is generated from N_i decays and partly converted into a **baryon asymmetry** by sphaleron processes **if $T_{reh} \gtrsim 100$ GeV**

$$N_{B-L}^{\rm fin} = \sum_i \varepsilon_i \kappa_i^{\rm fin} \Rightarrow \eta_B = a_{\rm sph} \frac{N_{B-L}^{\rm fin}}{N_\gamma^{\rm rec}}$$

baryon-to-photon number ratio

efficiency factors $\simeq$ # of N_i decaying out-of-equilibrium

Successful leptogenesis : $\eta_{B0} = \eta_{B0}^{CMB} = (6.12 \pm 0.04) \times 10^{-10}$

2) Hierarchical heavy RH neutrino spectrum

$$M_2 \gtrsim 3M_1$$

3) Asymmetry from N_2 decays strongly wash-out by lightest RH neutrino inverse decays

decay parameter: $$K_1 = \frac{\Gamma_1(T=0)}{H(T=M_1)} \gg 1$$

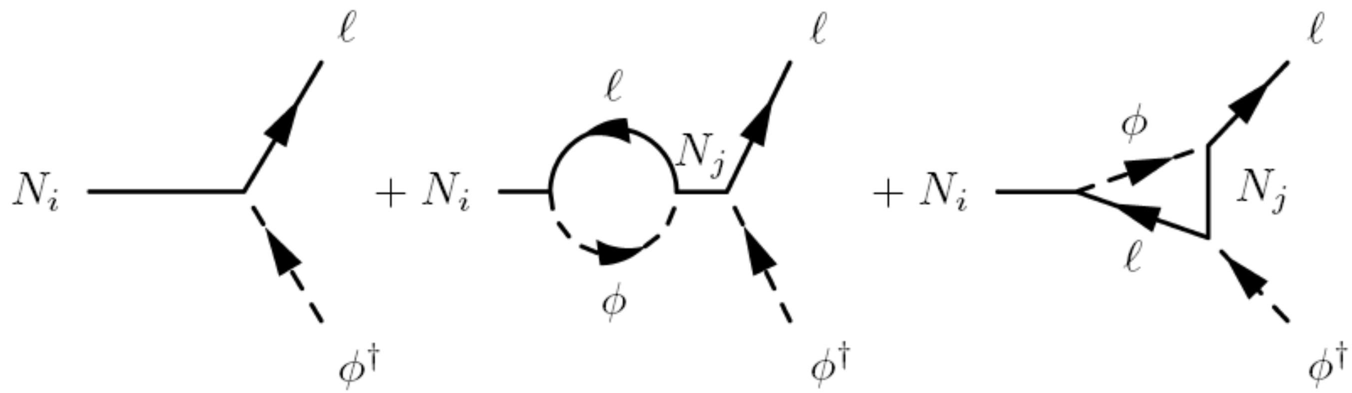
Under these three assumptions one obtains a N_1-dominated scenario:

$$\Rightarrow \quad N_{B-L}^{\rm fin} = \sum_i \varepsilon_i \, \kappa_i^{\rm fin} \simeq \varepsilon_1 \, \kappa_1^{\rm fin}$$

$$\eta_{B0}^{lep} = \frac{a_{sph} N_{B-L}^{fin}}{N_\gamma^{rec}} = a_{sph} \frac{g_S^{SM}}{g_S^{rec}} \varepsilon_1 \kappa_1^{fin} \simeq \frac{1}{3} \frac{3.91}{106.75} \varepsilon_1 \kappa_1^{fin} \simeq 0.01 \, \varepsilon_1 \kappa_1^{fin}$$

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 !

Efficiency factor

decay parameter

$$K_1 = \frac{\Gamma_1(T=0)}{H(T=M_1)} \gg 1$$

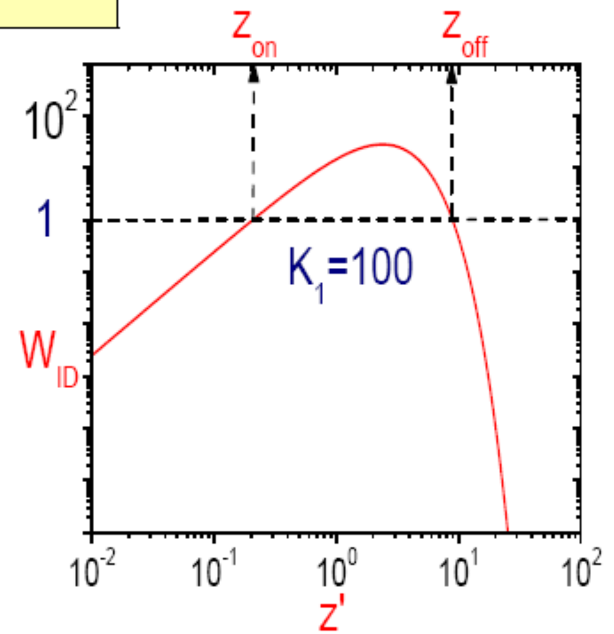
$$z \equiv \frac{M_1}{T}$$

rate equations

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

$$\frac{dN_{B-L}}{dz} = -\varepsilon_1\,\frac{dN_{N_1}}{dz} - W_1\,N_{B-L}$$

$$D_1 = \frac{\Gamma_1(T)}{H\,z} = K_1\,z\,\left\langle\frac{1}{\gamma}\right\rangle, \quad W_1 \propto D_1 \propto K_1$$

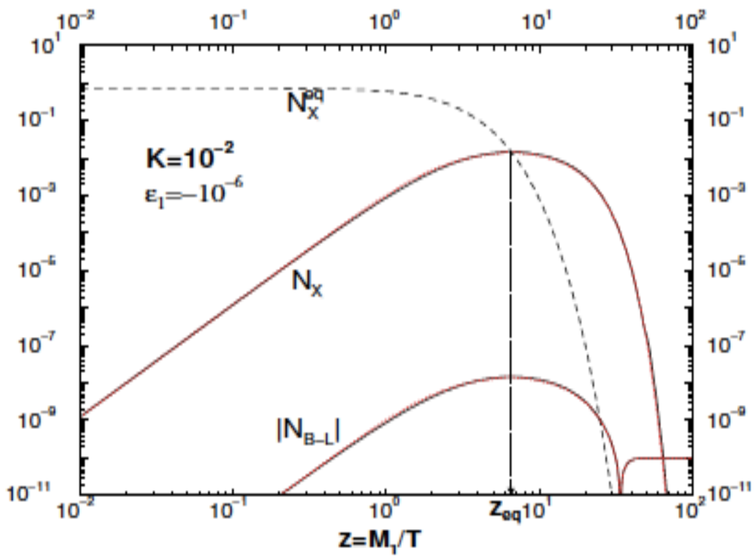


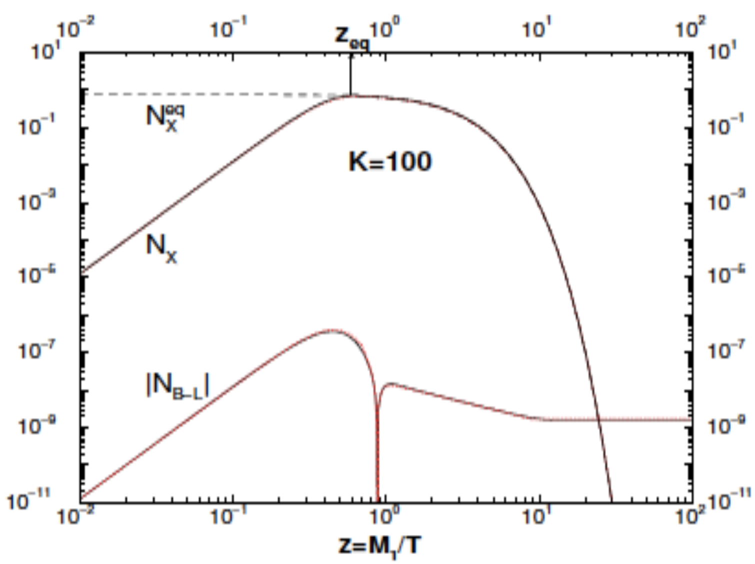
$$N_{B-L}(z;K_1,z_{\rm in}) = N_{B-L}^{\rm in}\,e^{-\int_{z_{\rm in}}^{z} dz'\,W_1(z')} + \varepsilon_1\,\kappa_1(z)$$

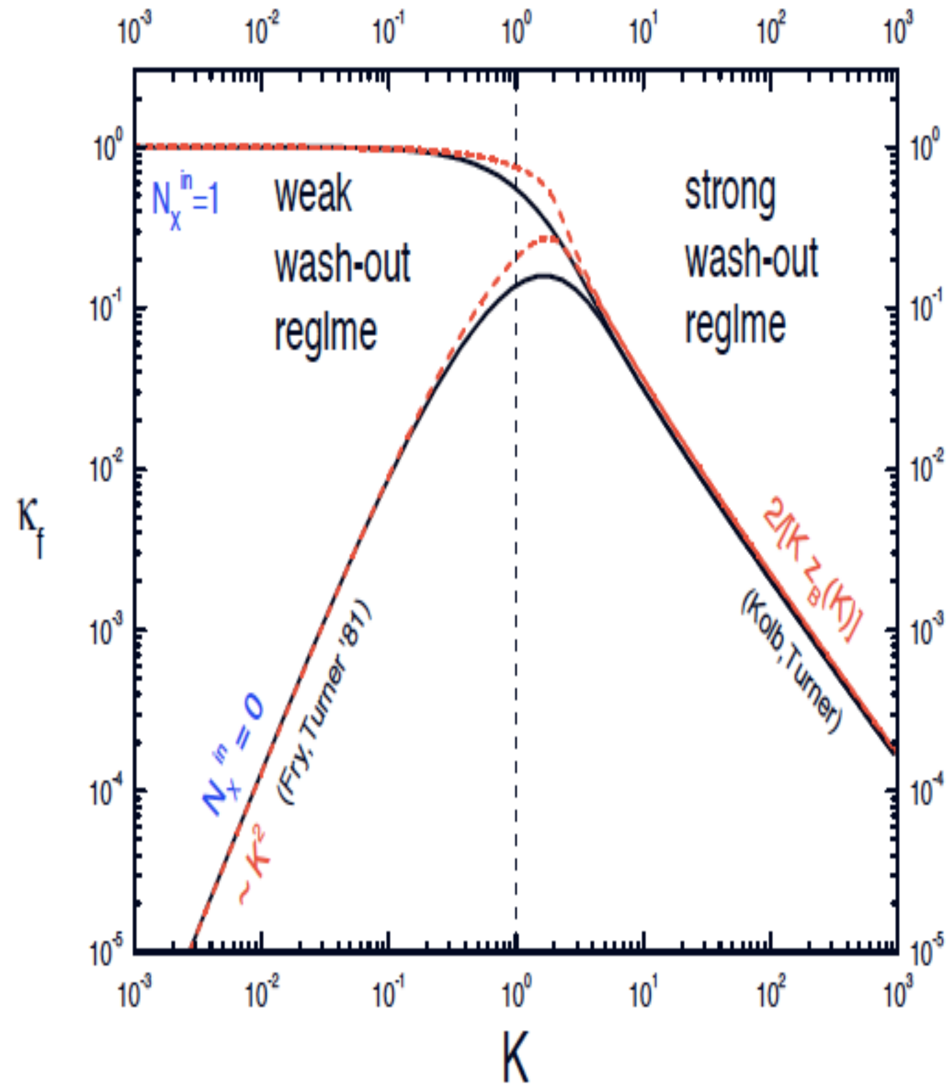
$$\kappa_1(z;K_1,z_{\rm in}) = -\int_{z_{\rm in}}^{z} dz'\,\left[\frac{dN_{N_1}}{dz'}\right]\,e^{-\int_{z'}^{z} dz''\,W_1(z'')}$$

- 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



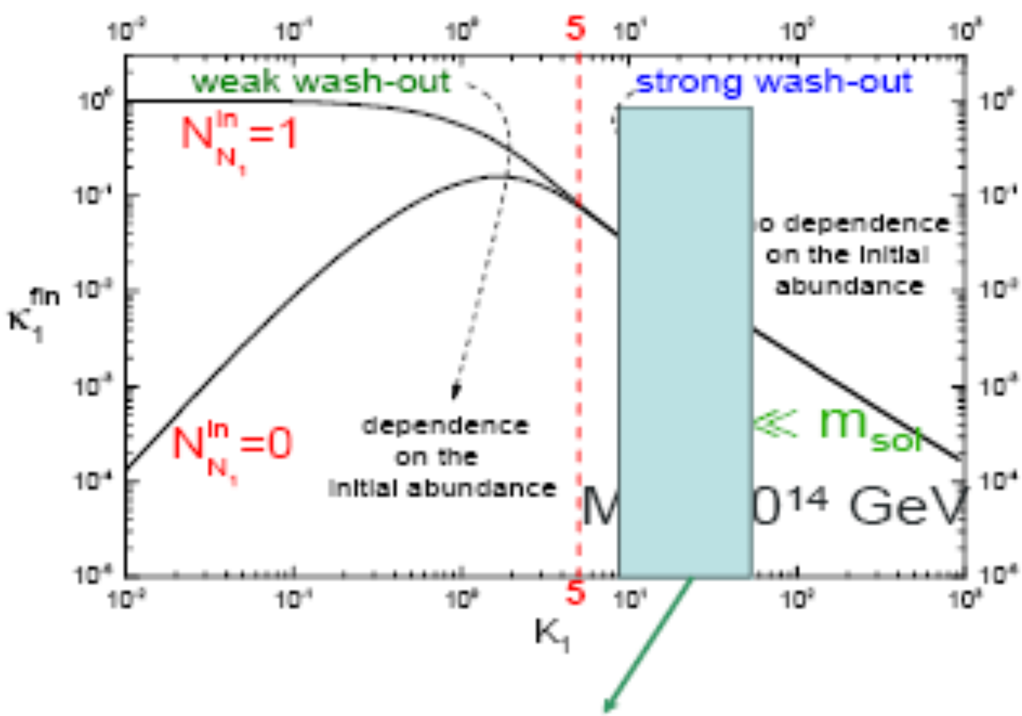




Leptogenesis "conspiracy"

The early Universe „knows" neutrino masses ...

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



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

Vanilla leptogenesis ⇒ upper bound on ν masses

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

1) Lepton flavor composition is neglected

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

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

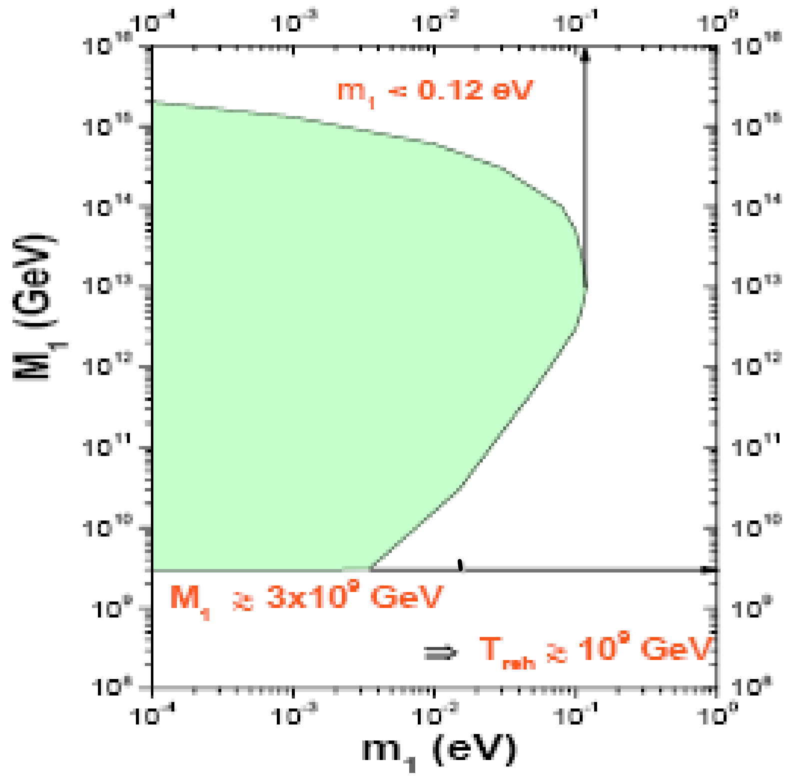
2) Hierarchical spectrum ($M_2 \gtrsim 2M_1$)

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

All the asymmetry is generated by the lightest RH neutrino

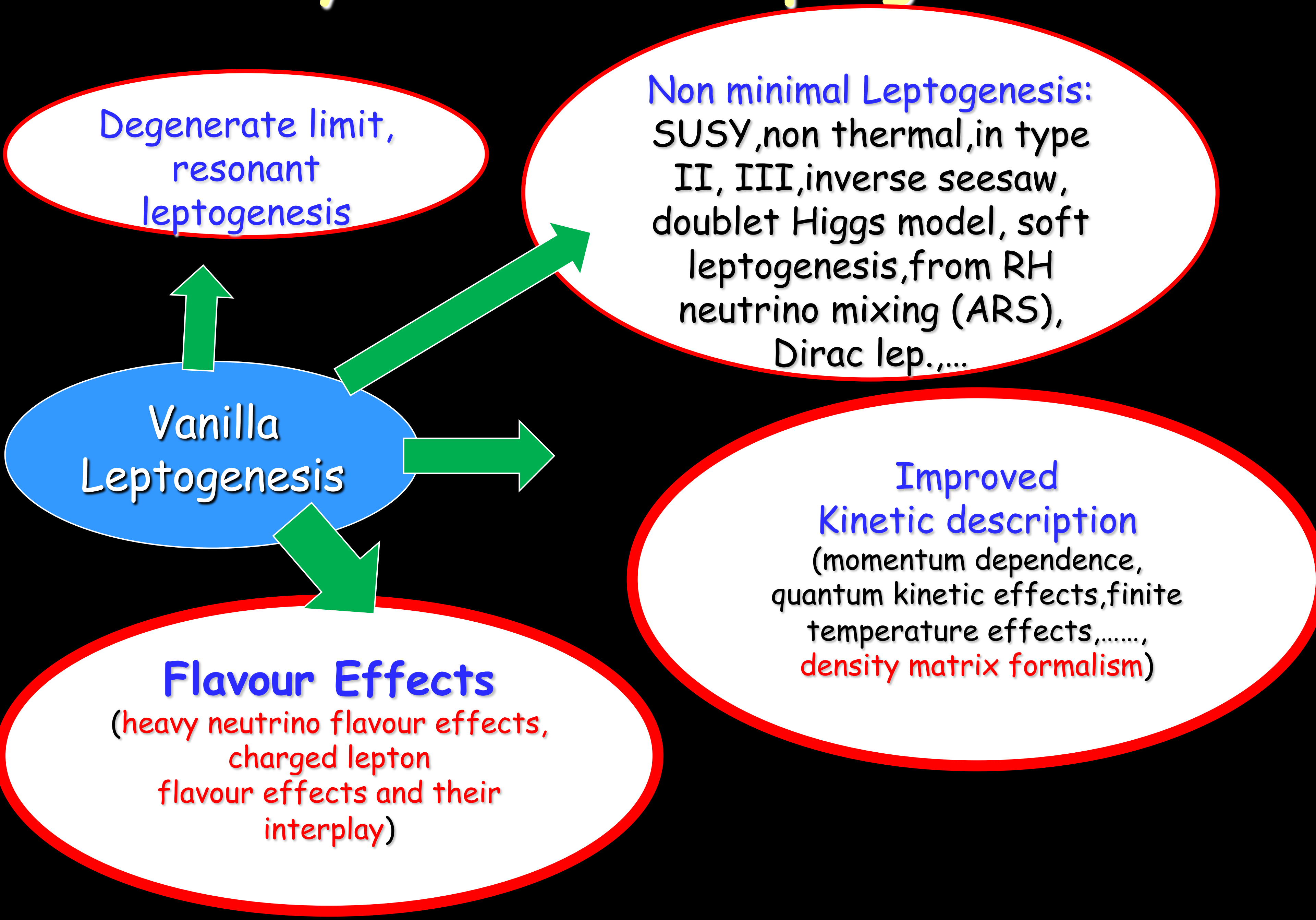


4) Barring fine-tuned cancellations

(Davidson, Ibarra '02)

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

Beyond vanilla Leptogenesis



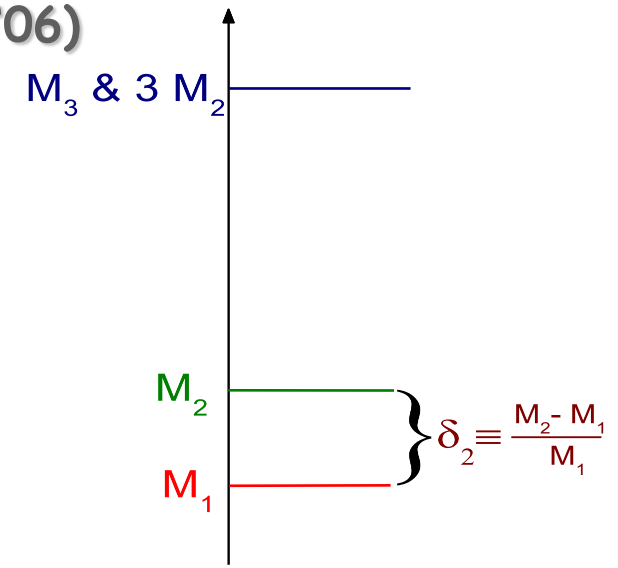
The degenerate limit

(Covi, Roulet, Vissani '96; Pilaftsis ' 97; Blanchet, PDB '06)

Different possibilities, for example:

- partial hierarchy: $M_3 \gg M_2$, M_1

$\Rightarrow \; |\varepsilon_3| \ll |\varepsilon_2|, |\varepsilon_1|$ and $\kappa_3^{\rm fin} \ll \kappa_2^{\rm fin}, \kappa_1^{\rm fin}$



CP asymmetries get enhanced $\propto 1/\delta_2$

$$\Rightarrow \mathbf{N}_{\mathbf{B-L}}^{\rm fin} \nearrow$$

For $\delta_2 \lesssim 0.01$ (**degenerate limit**) :

$$(M_1^{\rm min})_{\rm DL} \simeq 4\times 10^9\,{\rm GeV}\left(\frac{\delta_2}{0.01}\right) \quad \text{and} \quad (T_{\rm reh}^{\rm min})_{\rm DL} \simeq 5\times 10^8\,{\rm GeV}\left(\frac{\delta_2}{0.01}\right)$$

The reheating temperature lower bound is relaxed

The required tiny value of δ_2 can be obtained e.g. in ***radiative leptogenesis*** (Branco, Gonzalez, Joaquim, Nobre'04,'05)

Improved kinetic description

- Momentum dependence in Boltzmann equations

  (Hannestad ' 06; Hahn-Woernle, M. Plümacher, Y.Wong '09; Pastor, Vives'09)

- Kadanoff-Baym equations

  (Buchmüller,Fredenhagen '01; De Simone,Riotto '07; Garny,Hohenegger, Kartavtsev,Lindner '09; Anisimov,Buchmüller,Drewes,Mendizibal '09; Beneke, Garbrecht, Herranen, Schwaller '10)

  The asymmetry is directly calculated in terms of Green functions instead than in terms of number densities and they account for off-shell , memory and medium effects in a systematic way

At the moment all these analyses confirm what also happens for other effects (e.g. inclusion of scatterings) and that is expected: large theoretical uncertainties in the weak wash-out regime, limited corrections ($O(1)$) in the strong wash-out regime where the asymmetry is produced in a narrow range of temperatures for $T \ll M_i$ (Buchmüller,PDB,Plümacher

Non minimal leptogenesis

Non thermal leptogenesis

The RH neutrino production is non-thermal and typically associated to inflation. They are often motivated in order to obtain successful leptogenesis with low reheating temperature.

- RH neutrino production from inflaton decays (Shafi,Lazarides' 91)

- Leptogenesis from RH sneutrinos decays (Murayama,Yanagida ' 93)

- RH neutrinos can also be produced at the end of inflation during the pre-heating stage (Giudice,Peloso,Riotto,Tkachev99)

-The connections with low energy neutrino experiments become even looser in these scenarios, while they can be made with properties of CMBR anisotropies (Asaka, Hamaguchi,Yanagida '99)

Beyond the type I seesaw

It is motivated typically by two reasons:

- Again avoid the reheating temperature lower bound
- In order to get new phenomenological tests….the most typical motivation in this respect is quite obviously whether we can test the seesaw and leptogenesis at the LHC

Typically lowering the RH neutrino scale at TeV , the RH neutrinos decouple and they cannot be efficiently produced in colliders

Many different proposals to circumvent the problem:

- additional gauged U(1)B-L (King,Yanagida ’04)
- leptogenesis with Higgs triplet (type II seesaw mechanism)

(Ma,Sarkar ‘00 ; Hambye,Senjanovic ‘03; Rodejohann’04; Hambye,Strumia ‘05; Antusch ‘07)

- leptogenesis with three body decays (Hambye ‘01)
- see-saw with vector fields (Losada,Nardi ‘07)
- inverse seesaw mechanism and leptogenesis without B-L violation

Adding flavour to 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 to 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) $\qquad \varepsilon_{1\tau}\kappa_1^{fin}(K_{1\tau}) + \varepsilon_{1e+\mu}\kappa_1^{fin}(K_{1e+\mu})$

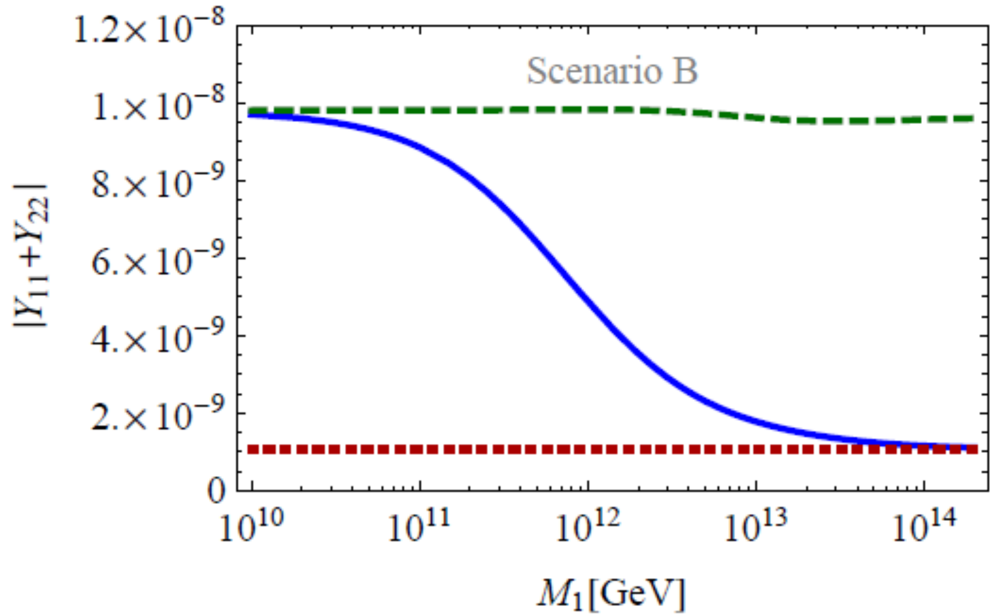
~ 10^9 GeV — TRANSITION REGIME: DENSITY MATRIX APPROACH NEEDED

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

Density matrix and CTP formalism to describe the transition regimes

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

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



Fully two-flavoured regime limit

Unflavoured regime limit

Flavoured Boltzmann equations

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

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

These 2 terms correspond respectively to 2 different flavor effects:

1) wash-out is in general reduced: $K_1 \rightarrow K_{1\alpha} \equiv K_1 \, P^0_{1\alpha}$

2) additional CP violating contribution $\left(|\bar{l}'_1\rangle \neq CP|l_1\rangle \right)$

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

- Classic Kinetic Equations (in their simplest form)

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

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

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

$$\Rightarrow N^{\rm fin}_{B-L} = \sum_\alpha \varepsilon_{1\alpha}\,\kappa^{\rm fin}_{1\alpha} \simeq 2\,\varepsilon_1\,\kappa^{\rm fin}_1 + \frac{\Delta P_{1\alpha}}{2}\left[\kappa^{\rm f}(K_{1\alpha}) - \kappa^{\rm fin}(K_{1\beta})\right]$$

The lower bounds on M_1 and on T_{reh} get relaxed:

(Blanchet,PDB '08)

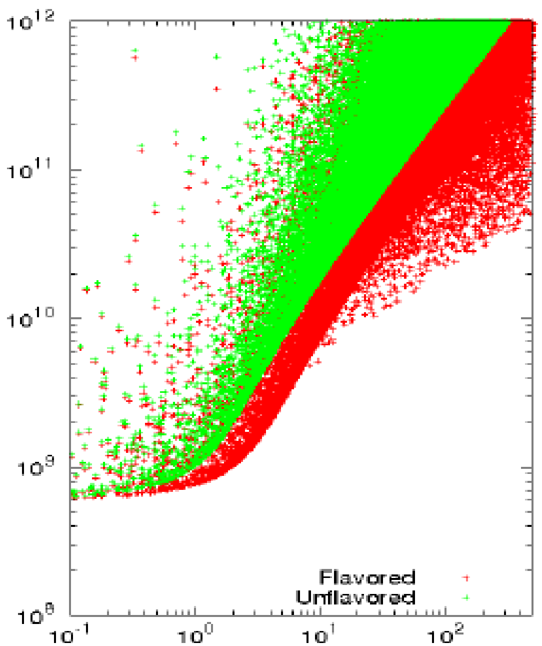
$$\frac{\Delta P_{i\alpha}}{2} \simeq \frac{1}{8\,\pi\,(h^\dagger\,h)_{ii}} \sum_{j\neq i} \left\{ \mathrm{Im}\left[h^\star_{\alpha i}\, h_{\alpha j} \left(\frac{3}{2\,\sqrt{x_j}} (h^\dagger h)_{ij} + \frac{1}{x_j} (h^\dagger h)_{ji} \right) \right] \right\}$$

$$x_j = \frac{M_j^2}{M_1^2}$$

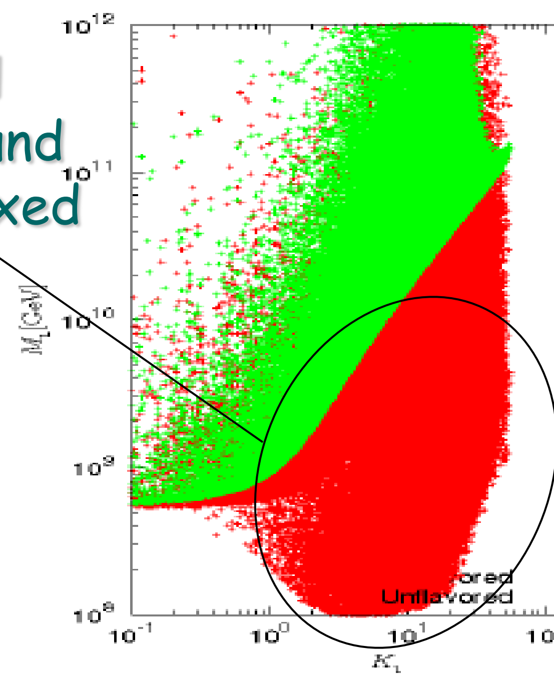
It dominates for $|\Omega_{ij}| \lesssim 1$ but is upper bounded because of Ω orthogonality:

$$\left| \frac{\Delta P_{1\alpha}}{2} \right| < \overline{\varepsilon}(M_1)\,\sqrt{P^0_{1\alpha}}$$

It is usually neglected but since it is not upper bounded by orthogonality, for $|\Omega_{ij}| \gtrsim 1$ it can be important



The usual lower bound gets relaxed

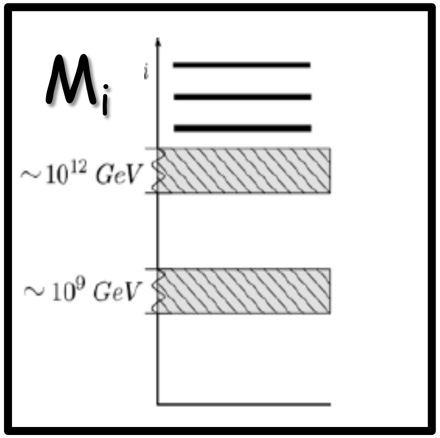


$|\Omega^2_{ij}| \lesssim 10$

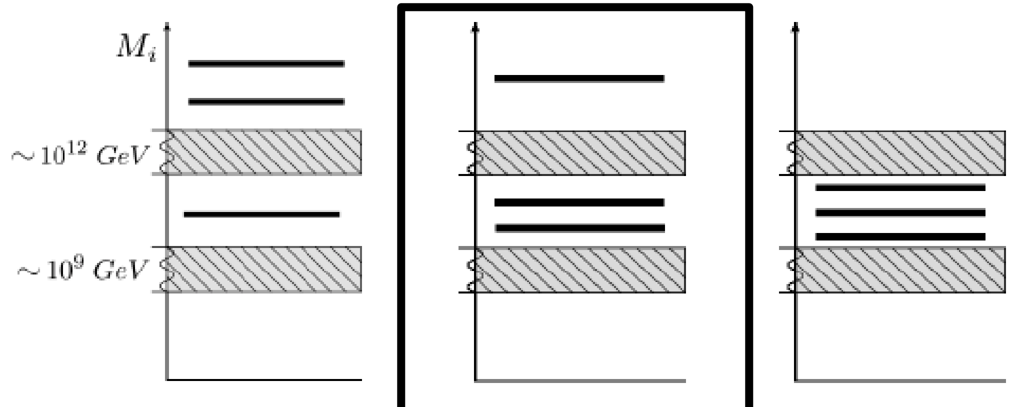
Heavy neutrino lepton flavour effects: 10 scenarios

Typically rising in discrete flavour symmetry models

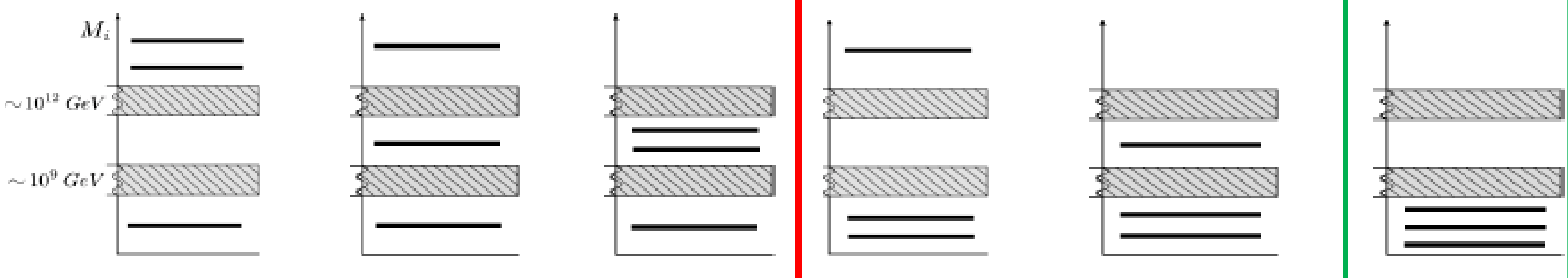
Heavy neutrino flavored scenario



2 RH neutrino scenario



(a) (b) (c)



(a) (b) (c) (d) (e) (f)

N_2 -dominated scenario:

- N_1 produces negligible asymmetry;
- It emerges naturally in SO(10)-inspired models;
- Only one compatible with strong thermal condition

Low scale leptogenesis

Example: ARS leptog, (Drewes et al.1711.02862)

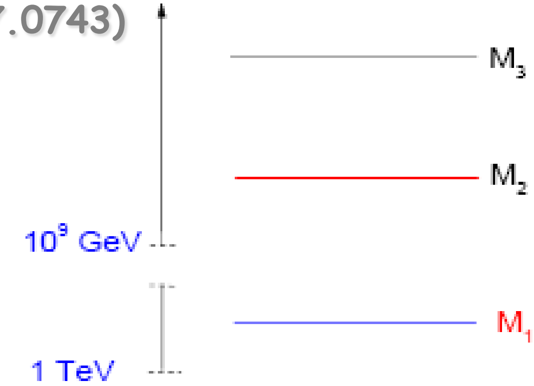
N_2 leptogenesis

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

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

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

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



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

- With flavor effects the domain of successful N_2 dominated leptogenesis greatly enlarges: the probability that $K_1 < 1$ is less than 0.1% but the probability that either K_{1e} or $K_{1\mu}$ or $K_{1\tau}$ is less than 1 is ~23%

  (PDB, Michele Re Fiorentin, Rome Samanta)

- Existence of the heaviest RH neutrino N_3 is necessary for the $\varepsilon_{2\alpha}$'s not to be negligible

- It is the only hierarchical scenario that can realise strong thermal leptogenesis (independence of the initial conditions) if the asymmetry is tauon-dominated and if $m_1 \gtrsim 10$ meV (corresponding to $\Sigma_i m_i \gtrsim 80$meV)

  (PDB, Michele Re Fiorentin, Sophie King arXiv 1401.6185)

- N_2-leptogenesis rescues SO(10)-inspired models!

  $V_L \sim V_{CKM}$; $m_{D1}=\alpha_1\, m_{up}$; $m_{D2}=\alpha_2\, m_{charm}$; $m_{D3}=\alpha_3\, m_{top}$

Leptogenesis and neutrino mass models

An easy limit: all mixing from LH sector

In the flavour basis (both charged lepton mass and Majorana mass matrices are diagonal):

$$-\mathcal{L}^{\nu+\ell}_{\rm mass} = \overline{\alpha_L}\, m_\alpha\, \alpha_R + \overline{\nu_{L\alpha}}\, m_{D\alpha I}\, \nu_{RI} + \frac{1}{2}\,\overline{\nu^c_{RI}}\, M_I\, \nu_{RI} + \text{h.c.}$$

diagonalising again m_D with a bi-unitary transformation: $m_D = V_L^\dagger D_{m_D} U_R$

The seesaw formula becomes:

$$U\, D_m\, U^T = V_L^\dagger\, D_{m_D}\, U_R\, \frac{1}{D_M}\, U_R^T\, D_{m_D}\, V_L^\star$$

$$D_m \equiv diag(m_1, m_2, m_3) \quad D_{m_D} \equiv diag(m_{D1}, m_{D2}, m_{D3}) \quad D_M \equiv diag(M_1, M_2, M_3)$$

AN EASY LIMIT (typically realised imposing a flavour symmetry):

- $U_R = I$ $\Rightarrow$ again $U = V_L^\dagger$ and neutrino masses: $m_i = \dfrac{m_{Di}^2}{M_I}$

If also $m_{D1}=m_{D2}=m_{D3}=\lambda$ then simply: $M_I = \dfrac{\lambda^2}{m_i}$

This limit realises simple models with Ω=P (form dominance models)

A less easy limit: SO(10)-inspired models

(Branco et al. '02; Nezri, Orloff '02; Akhmedov, Frigerio, Smirnov '03,PDB, Riotto '08; PDB, Re Fiorentin '12)

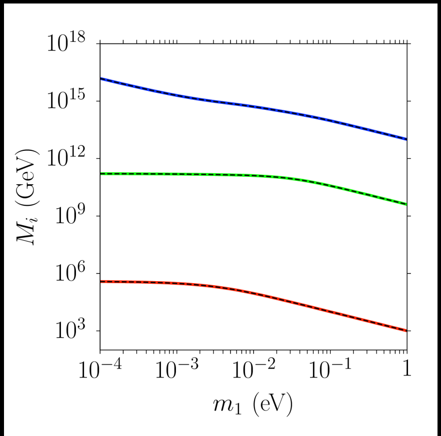
$$U\, D_m\, U^T = V_L^\dagger\, D_{m_D}\, U_R\, \frac{1}{D_M}\, U_R^T\, D_{m_D}\, V_L^\star$$

$$D_m \equiv diag(m_1,m_2,m_3) \quad D_{m_D} \equiv diag(m_{D1},m_{D2},m_{D3}) \quad D_M \equiv diag(M_1,M_2,M_3)$$

- $V_L = I \Rightarrow \quad M_1 = \frac{m_{D1}^2}{m_{\beta\beta}}; \quad M_2 = \frac{m_{D2}^2}{m_1 m_2 m_3} \frac{m_{\beta\beta}}{|(m_\nu^{-1})_{\tau\tau}|}; \quad M_3 = m_{D3}^2 \, |(m_\nu^{-1})_{\tau\tau}|$

If also: $m_{D1} = \alpha_1\, m_{up}; \quad m_{D2} = \alpha_2 m_{charm}; \; m_{D3} = \alpha_3 m_{top}; \quad \alpha_i = O(1)$

Barring fine-tuned solutions, one obtains a very hierarchical RH neutrino mass spectrum requiring N_2 leptogenesis: DOES IT WORK?



The analytical expressions for the M_i 's can be nicely extended for a generic V_L

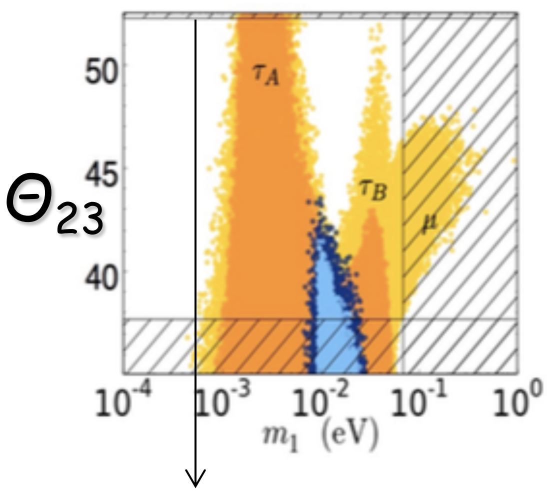
For $m_1 \rightarrow 0$ one recovers sequential dominance relations

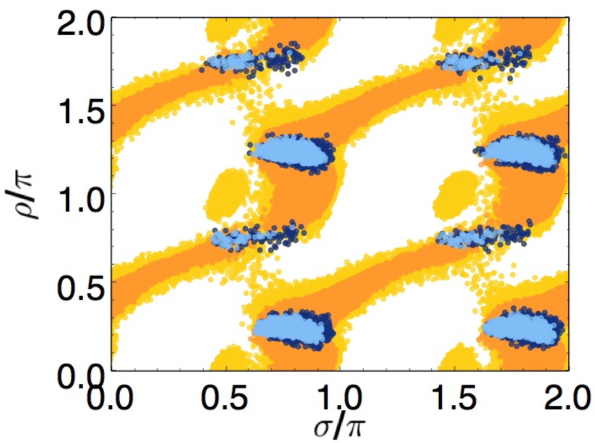
N_2 leptogenesis rescues SO(10)-inspired leptogenesis

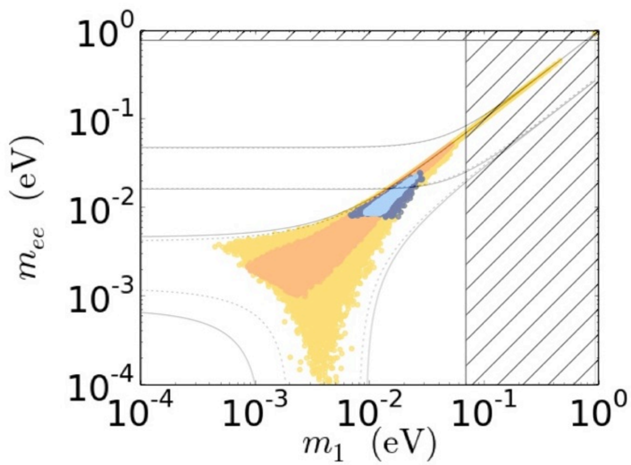
(PDB, Riotto 0809.2285;1012.2343;He,Lew,Volkas 0810.1104)

- dependence on α_1 and α_3 cancels out $\Rightarrow$ the asymmetry depends only on $\alpha_2 \equiv m_{D2}/m_{charm}$: $\eta_B \propto \alpha_2^2$

$\alpha_2=5$ NORMAL ORDERING $I \leq V_L \leq V_{CKM}$ $V_L = I$



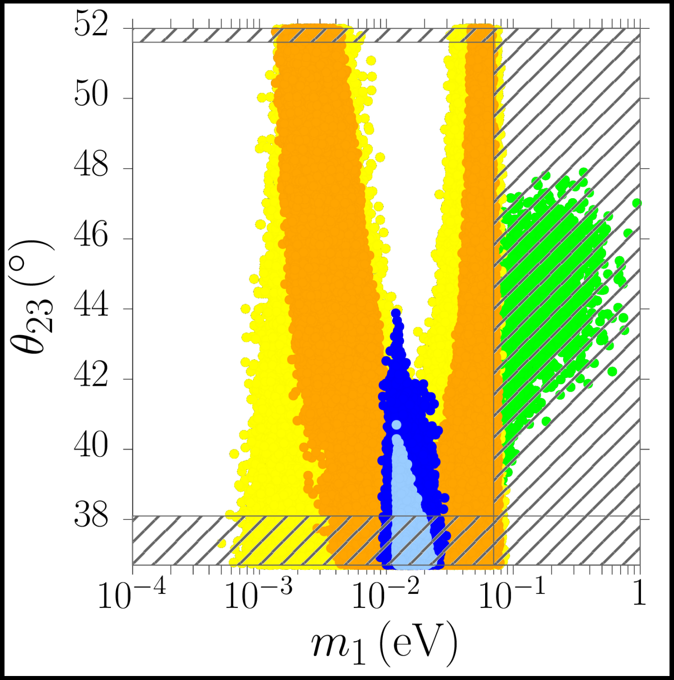


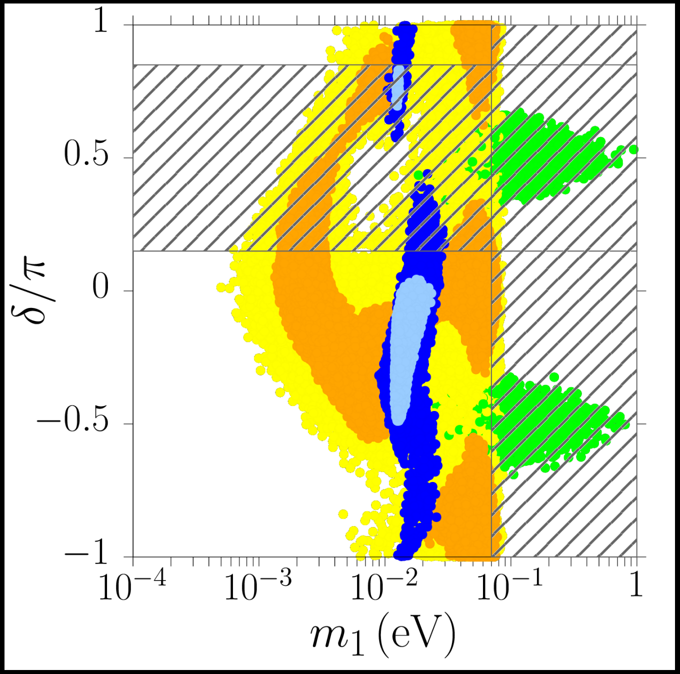


- ➢ Lower bound $m_1 \gtrsim 10^{-3}$ eV
- ➢ θ_{23} upper bound
- ➢ Majorana phases constrained about specific regions
- ➢ Effective $0\nu\beta\beta$ mass can still vanish but bulk of points above meV

- ➢ INVERTED ORDERING IS EXCLUDED
- ➢ What are the blue regions?

SO(10)-inspired leptogenesis confronting long baseline and absolute neutrino mass experiments





If the current tendency of data to favour second octant for θ_{23} is confirmed, then SO(10)-inspired leptogenesis predicts a deviation from the hierarchical limit that can be tested by absolute neutrino mass scale experiments (PDB, Samanta in preparation)

In particular current best fit values of δ and θ_{23} would imply $m_{ee} \gtrsim 10$ meV ⇒ testable signal at $00\beta\nu$ experiments

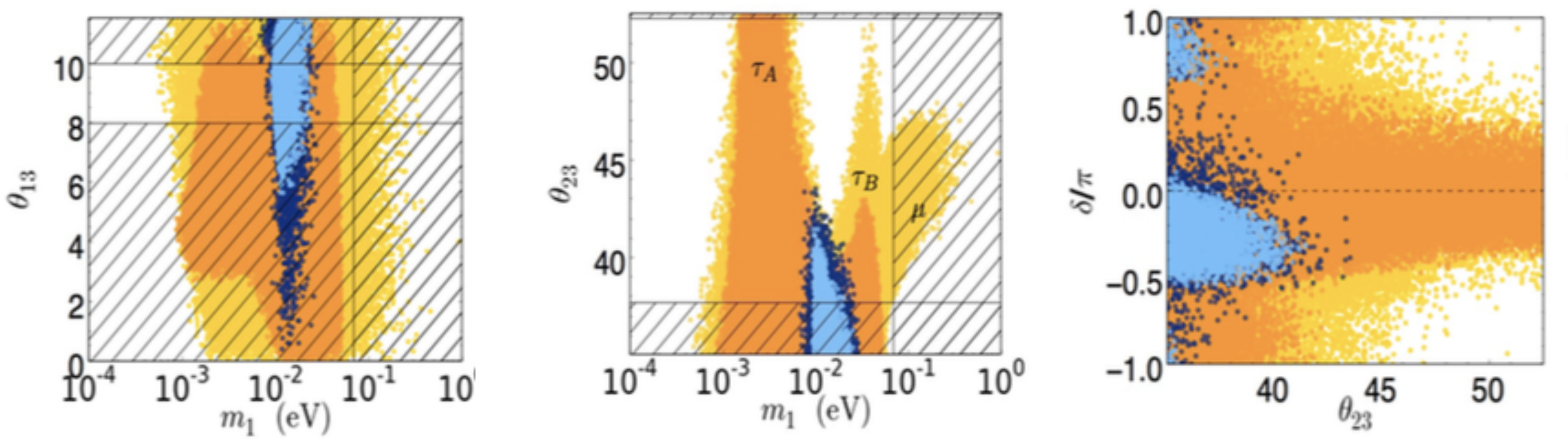
NOTICE THAT SO(10)-inspired leptogenesis clearly disproves the statement (fake news!) that high scale leptogenesis is "untestable"

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

$\alpha_2=5$ ❑ 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};

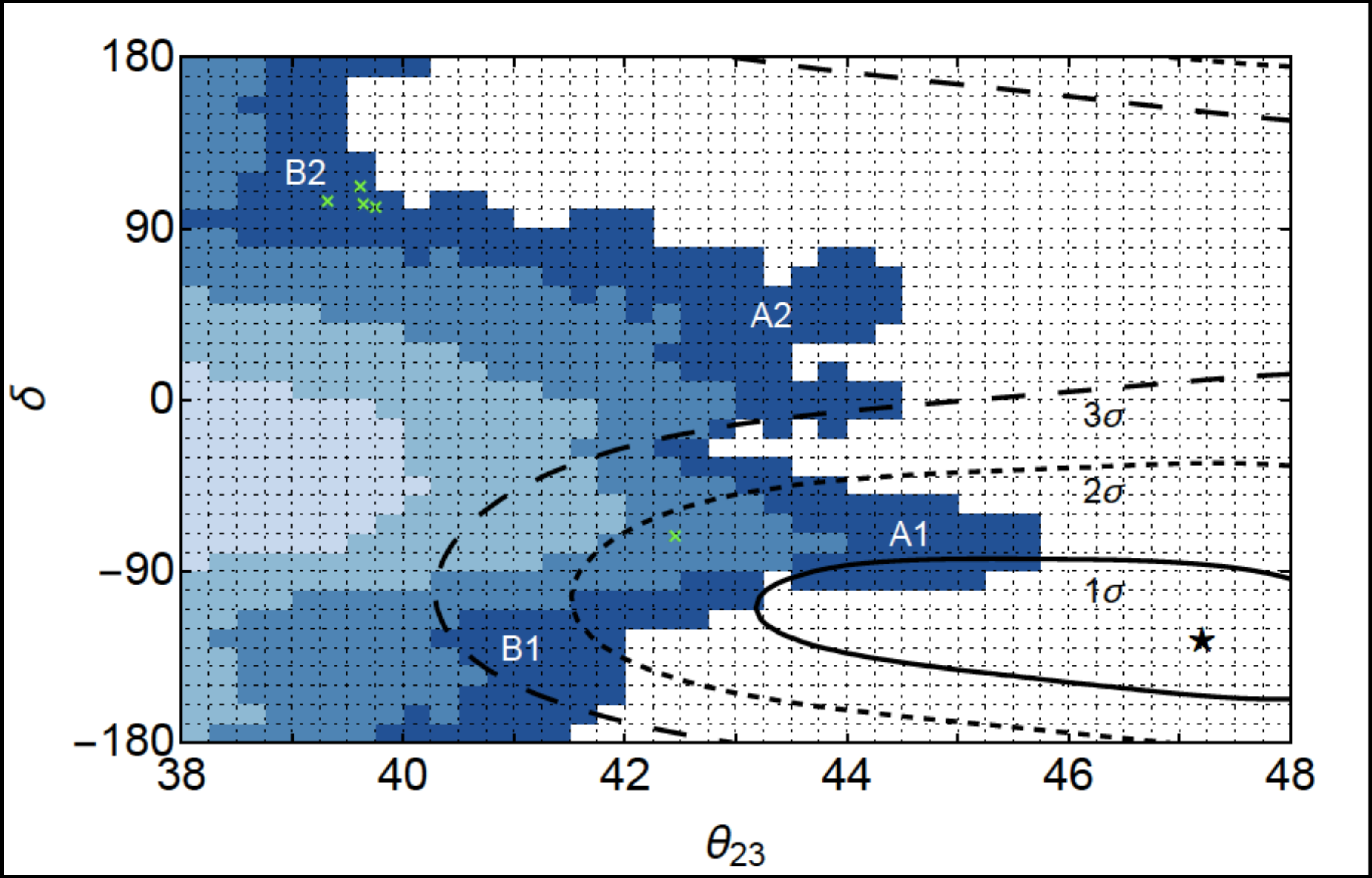
- Θ_{23} strictly in the first octant;

Strong SO(10)-inspired leptogenesis confronting long baseline experiments

(PDB, Marco Chianese 1802.07690)

Pre-existing initial asymmetry: $N_{B-L}^{p,i} = 10^{-3}$

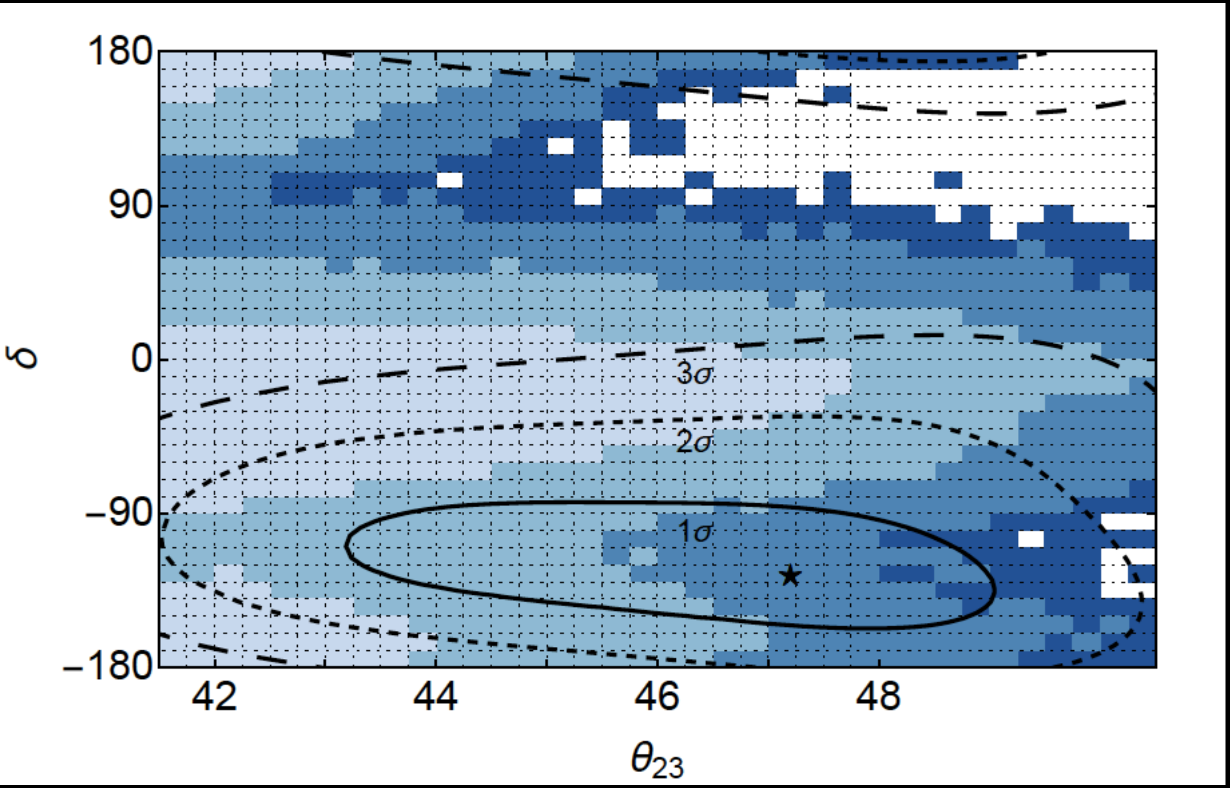
$$\alpha_2 = m_{D2} / m_{charm} = 5$$



Strong SO(10)-inspired leptogenesis confronting long baseline experiments
(PDB, Marco Chianese 1802.07690)

Pre-existing initial asymmetry: $N^{p,i}_{B-L} = 10^{-3}$

$$\alpha_2 = m_{D2} / m_{charm} = 6$$

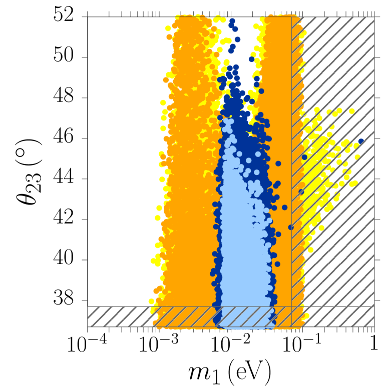


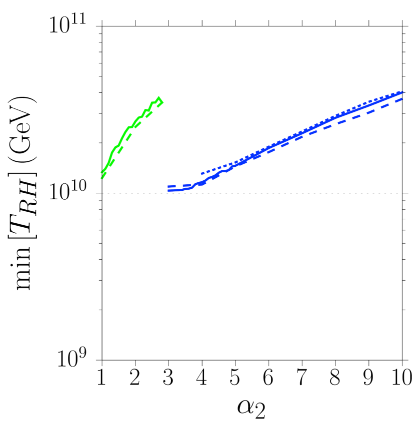
Second octant is compatible with strong thermal condition only if $\alpha_2 \gtrsim 6$: are there realistic models?

SUSY SO(10)-inspired leptogenesis

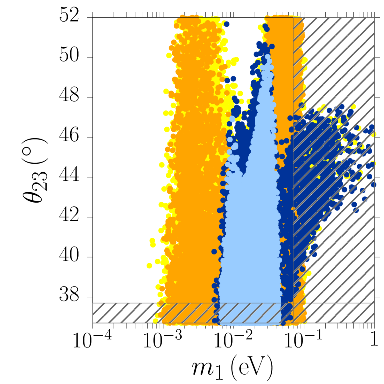
(PDB, Re Fiorentin, Marzola, 1512.06739)

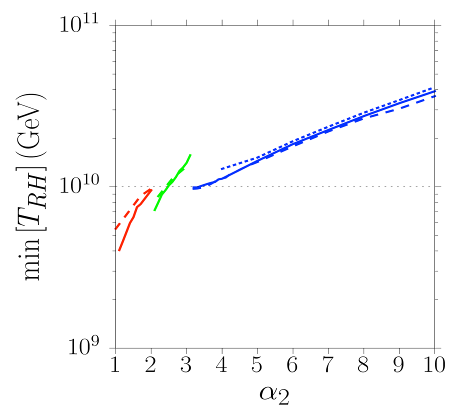
tan $\beta = 5$





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)

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.

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

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

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

up-quark mass matrix $M_u = v^u_{10}Y_{10} + v^u_{126}Y_{126} + v^u_{120}Y_{120}\,,$

down-quark mass matrix $M_d = v^d_{10}Y_{10} + v^d_{126}Y_{126} + v^d_{120}Y_{120}\,,$

neutrino mass matrix $M_D = v^u_{10}Y_{10} - 3v^u_{126}Y_{126} + v^D_{120}Y_{120}\,,$

charged lepton mass matrix $M_l = v^d_{10}Y_{10} - 3v^d_{126}Y_{126} + v^l_{120}Y_{120}\,,$

RH neutrino mass matrix $M_R = v^R_{126}Y_{126}\,,$

LH neutrino mass matrix $M_L = v^L_{126}Y_{126}\,,$

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

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

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

- Ohlsson, Pernow 1804.04560: a fit found for NO but minimum χ^2=18.4

- de Anda, King, Perdomo 1710.03229: SO(10) x S_4x Z_4^R x 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.

In all recent fits a type II term does not seem to help and best fits are type I dominated

An example of realistic model combining GUT+discrete symmetry: SO(10)-inspired leptogenesis in the "A2Z model"

(S.F.King 2014, PDB, S.F.King 1507.06431)

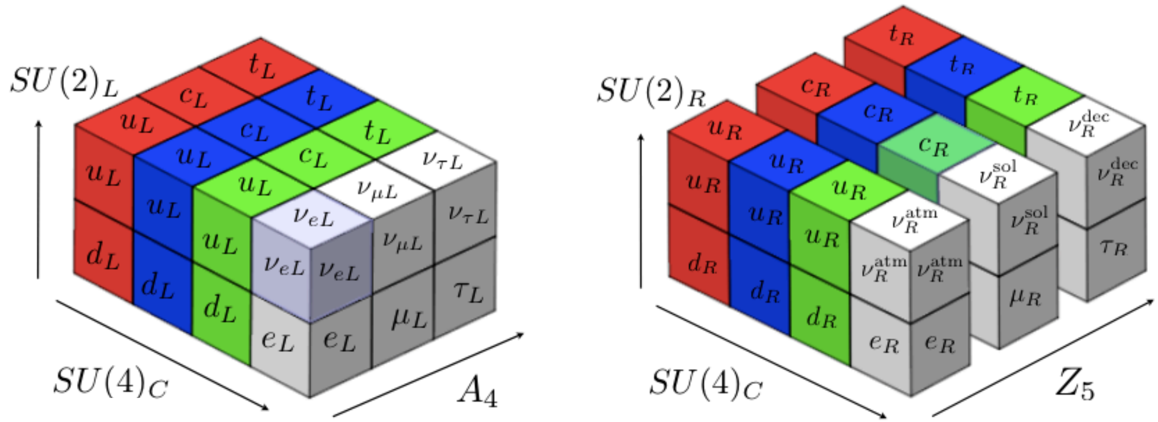
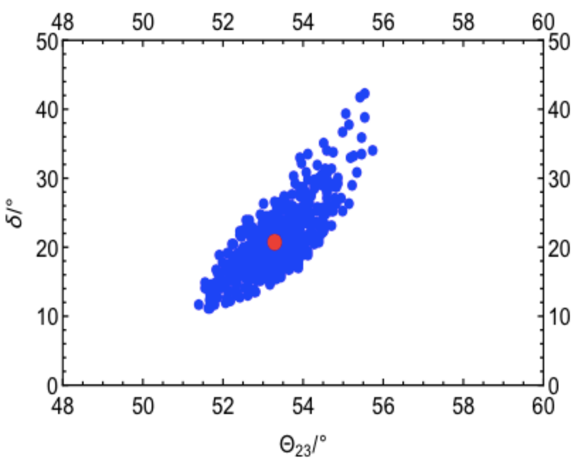
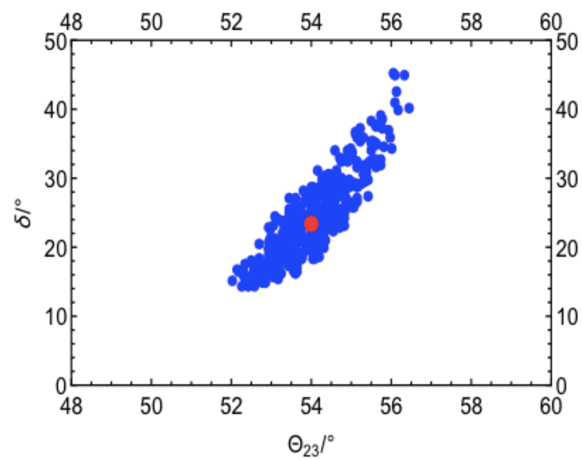


Figure 1: A to Z of flavour with Pati-Salam, where $A \equiv A_4$ and $Z \equiv Z_5$. The left-handed families form a triplet of A_4 and are doublets of $SU(2)_L$. The right-handed families are distinguished by Z_5 and are doublets of $SU(2)_R$. The $SU(4)_C$ unifies the quarks and leptons with leptons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





CASE A:

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

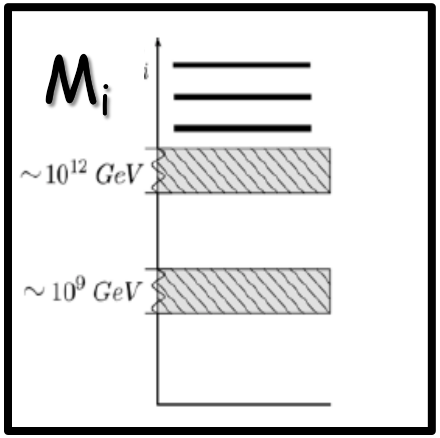
CASE B:

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

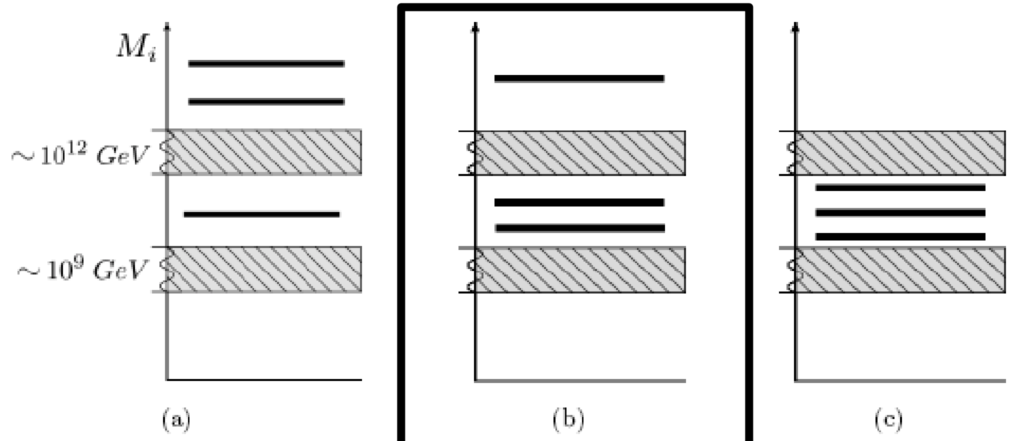
Heavy neutrino lepton flavour effects: 10 scenarios

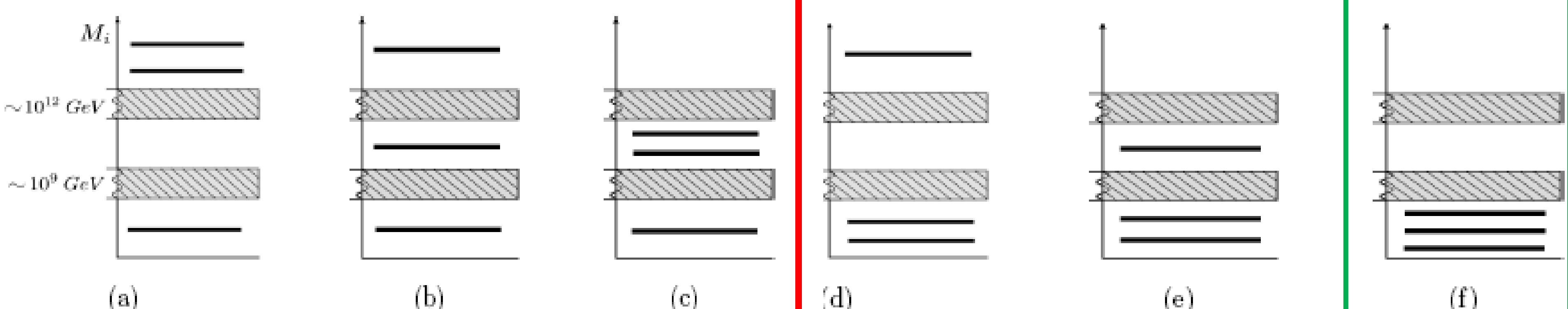
Typically rising in discrete flavour symmetry models

Heavy neutrino flavored scenario



2 RH neutrino scenario





N_2 -dominated scenario:

☛ N_1 produces negligible asymmetry;

Low scale leptogenesis

Example: ARS leptog, (lecture by D. Gorbunov)

2 RH neutrino models

(King hep-ph/9912492;Frampton,Glashow,Yanagida hep-ph/0208157;Ibarra,Ross2003; Antusch,King,Riotto'08; Antusch, PDB,Jones,King '11; King 1512.07531)

- They can be obtained from 3 RH neutrino models in the limit $M_3 \to \infty$ and correspondingly $m_1 \to 0$: hierarchical limit;
- Number of parameters gets reduced to 11;
- Still further conditions needed to get predictions!
- Contribution to asymmetry from both 2 RH neutrinos:

the contribution from the lightest (N_1) typically dominates but the contribution from next-to-lightest (N_2) opens new regions that correspons to light sequential dominated neutrino mass models realised in some GUT models. In any case there is still a lower bound

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

- 2 RH neutrino model realised for example in A4 x SU(5) SUSY GUT mode

with interesting link between "leptogenesis phase" and Dirac phase (F, Bjorkeroth, S.F. King 1505.05504)

- 2 RH neutrino model can be also obtained from 3 RH neutrino models

with 1 vanishing Yukawa eigenvalue ⇒ potential DM candidate

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

Unifying leptogenesis, neutrino masses and dark matter

A first solution : lowering the scale of the 3 RH neutrinos masses (νMSM)

(Asaka, Blanchet, Shaposhnikov '05) (lecture by D. Gorbunov)

For $M_1 \ll m_e \Rightarrow$ $\tau_{N_1} = 5\times 10^{26}\,\mathrm{sec}\left(\frac{M_1}{1\ \mathrm{keV}}\right)^{-5}\left(\frac{\overline{\Theta}^2}{10^{-8}}\right)^{-1}$ $\gg t_0$ $\left(|\overline{\theta}|^2 \equiv \sum_\alpha |m_{D\alpha 1}/M_1|^2\right)$

The production is induced by (non-resonant) RH-LH mixing at T~100 MeV:

$$\Omega_{N_1} h^2 \sim 0.1\left(\frac{\overline{\theta}}{10^{-4}}\right)^2\left(\frac{M_1}{keV}\right)^2 \sim \Omega_{DM,0} h^2$$

- The N_1's decay also radiatively and this produces constraints from X-rays (or opportunities to observe it).
- Considering also structure formation constraints, one is forced to consider a resonant production induced by a large lepton asymmetry L ~10^{-4} (3.5 keV line?). (Horiuchi et al. '14; Bulbul at al. '14; Abazajian '14)
- Not clear whether such a large lepton asymmetry can be produced by the same (heavier) RH neutrino decays

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: $m_D = V_L^\dagger \, D_{m_D} \, U_R \, .$ $\quad D_{m_D} \equiv v \, \mathrm{diag}(h_A, h_B, h_C)$, with $h_A \leq h_B \leq h_C$.

$$\tau_{\rm DM} = \frac{4\pi}{h_A^2 \, M_{\rm DM}} \simeq 0.87 \, h_A^{-2} \, 10^{-23} \left(\frac{\rm GeV}{M_{\rm DM}}\right) \, {\rm s} \quad \Rightarrow \quad \tau_{DM} > \tau_{DM}^{\min} \simeq 10^{28}\, s \Rightarrow h_A < 3\times 10^{-26} \sqrt{\frac{GeV}{M_{DM}} \times \frac{10^{28}\, s}{\tau_{DM}^{\min}}}$$

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

Proposed production mechanisms

Starting from a 2 RH neutrino seesaw model

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

many production mechanisms have been proposed:

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

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

RH neutrino mixing from Higgs portal

(Anisimov,PDB '08)

Assume new interactions with the standard Higgs:

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

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

From the Yukawa interactions:

$$V_J^Y = \frac{T^2}{8\,E_J}\,h_J^2$$

From the new interactions:

$$V_{JK}^\Lambda \simeq \frac{T^2}{12\,\Lambda}\,\lambda_{JK}$$

effective mixing Hamiltonian (in monocromatic approximation)

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

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

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

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

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

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
(more accurate calculation
employing density matrix
Solution is needed
PDB,Farrag,Katori in prep)

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

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

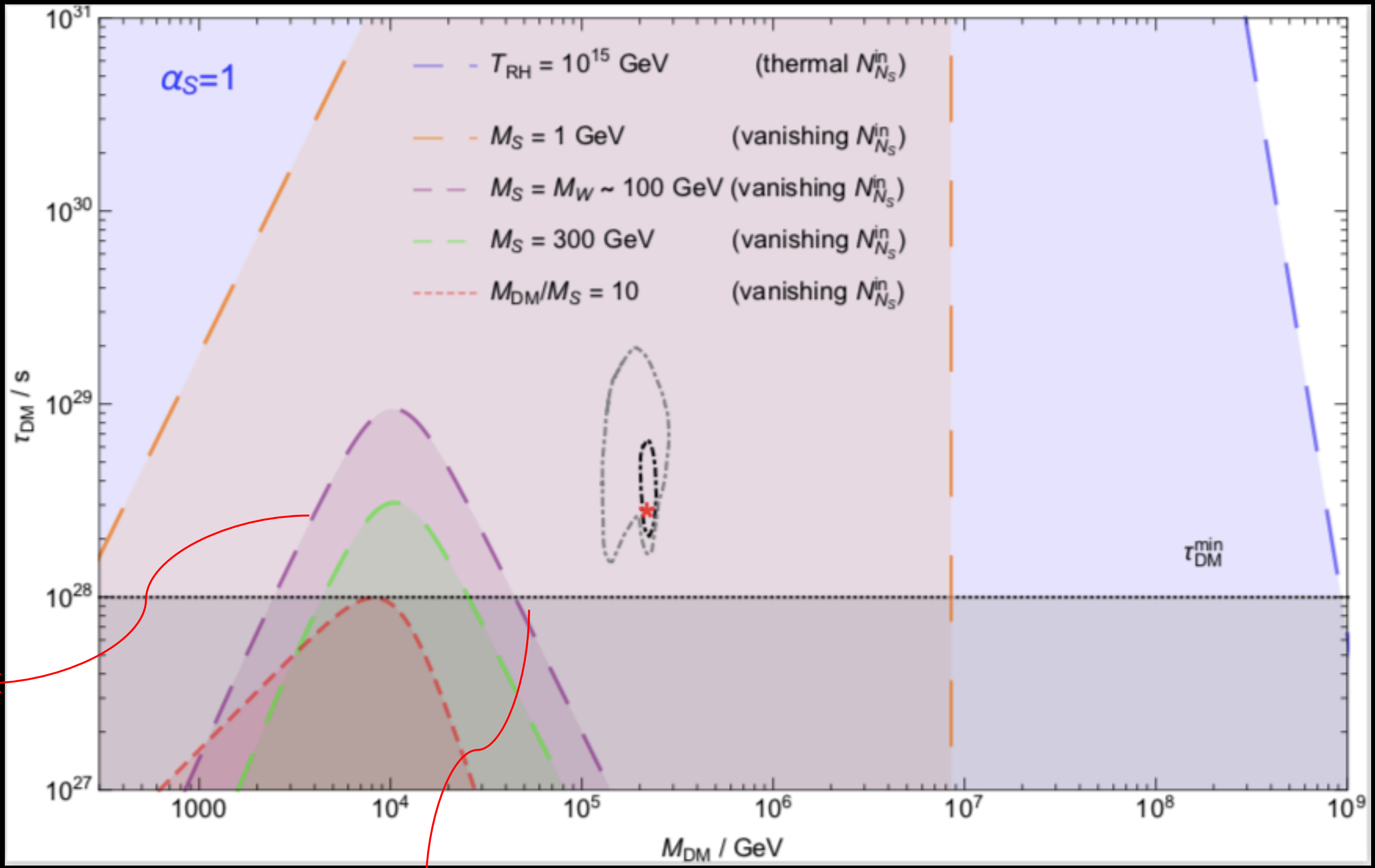
$$\Rightarrow \quad \Omega_{\rm DM}\,h^2 \simeq \frac{0.15}{\alpha_{\rm S}\,z_{\rm res}}\left(\frac{M_{\rm DM}}{M_{\rm S}}\right)\left(\frac{10^{20}\,{\rm GeV}}{\widetilde{\Lambda}}\right)^2\left(\frac{M_{\rm DM}}{\rm GeV}\right)$$

For successful dark-matter genesis $\Rightarrow$

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

2 options: either $\Lambda<M_{Pl}$ and λ_{AS}<<< 1 or $\lambda_{AS}\sim 1$ and $\Lambda>>>M_{Pl}$:
it is possible to think of models in both cases.

Decays: a natural allowed window on M_{DM}



Lower bound from 2 body decays

Upper bound from 4 body decays

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

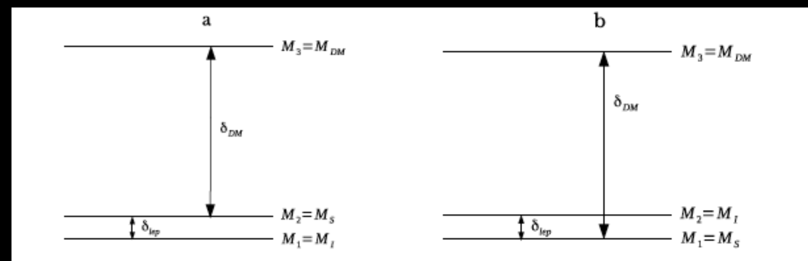
Unifying Leptogenesis and Dark Matter

(PDB, NOW 2006;Anisimov,PDB,0812.5085;PDB, P.Ludl,S. Palomarez-Ruiz 1606.06238+see recent v3)

- 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

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

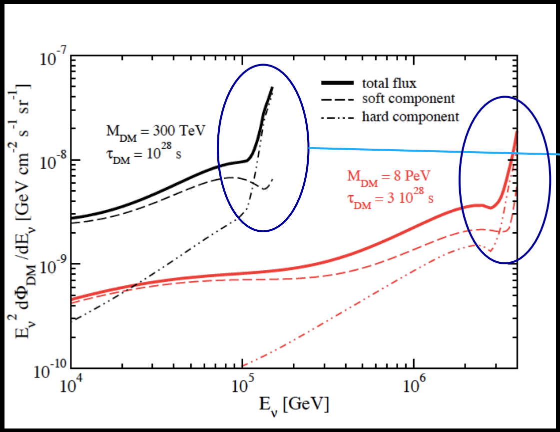
- $M_S \gtrsim 2\,T_{sph} \simeq 300$ GeV $\Rightarrow$ $10\ \text{TeV} \lesssim M_{DM} \lesssim 1\ \text{PeV}$
- $M_S \lesssim 10$ TeV
- $\delta_{lep} \sim 10^{-5} \Rightarrow$ leptogenesis is not fully resonant

Nicely predicted a signal at IceCube

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

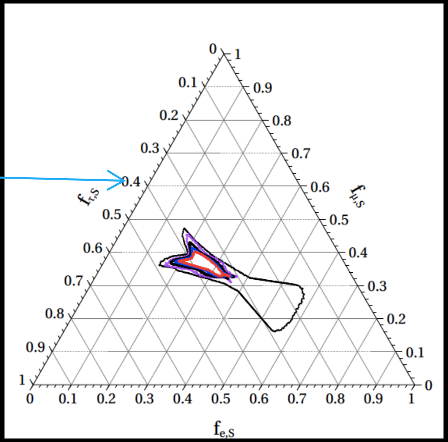
- DM neutrinos unavoidably decay today into A+leptons (A=H,Z,W) through the same mixing that produced them in the very early Universe
- Potentially testable high energy neutrino contribution

Energy neutrino flux



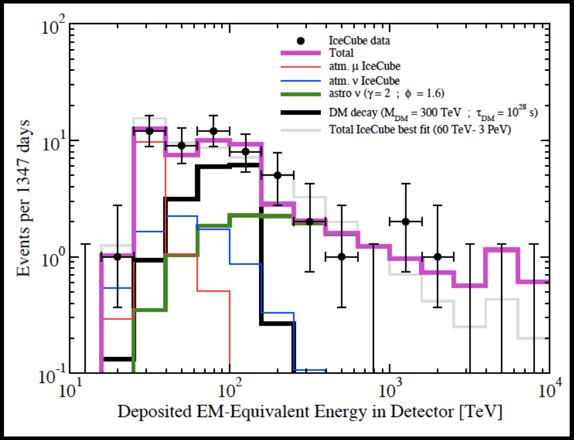
Hard component

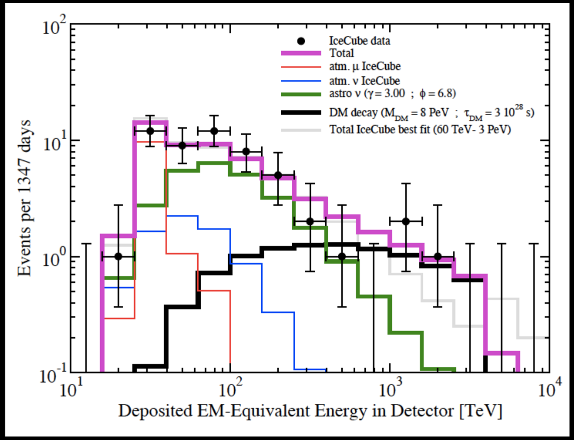
Flavour composition at the detector



Neutrino events at IceCube: 2 examples

M_{DM}=300TeV





M_{DM}=8 PeV

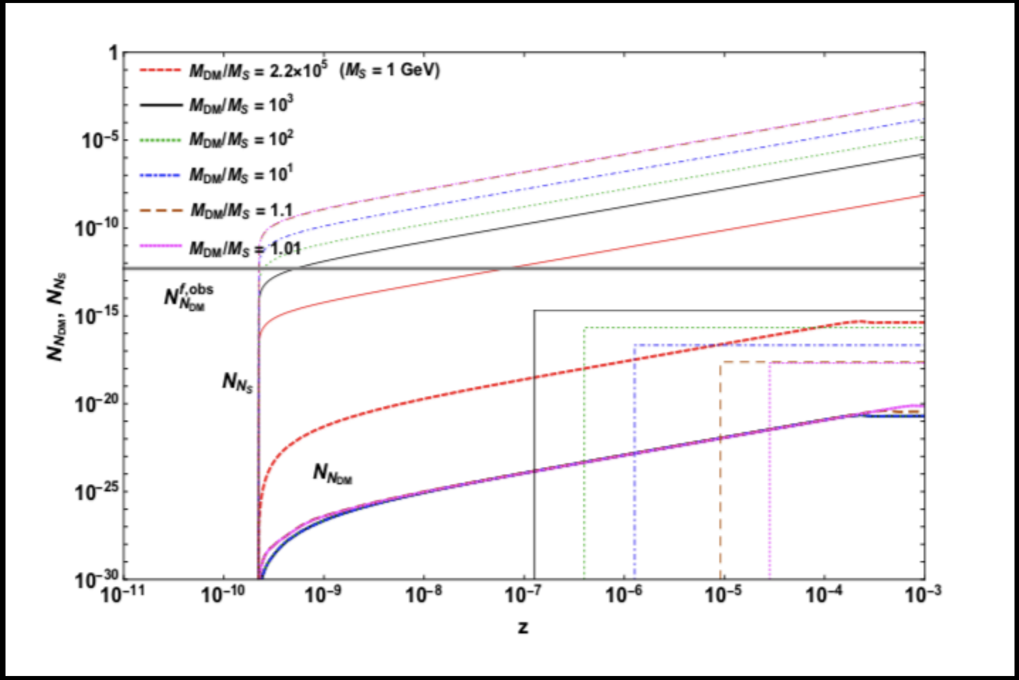
Density matrix calculation of the relic abundance

(P.Di Bari, K. Farrag, R. Samanta, Y. Zhou, 1908.00521)

Density matrix equation for the DM-source RH neutrino system

$$\frac{dN_{IJ}}{dt} = -i\,[\mathcal{H}, N]_{IJ} - \begin{pmatrix} 0 & \frac{1}{2}(\Gamma_D + \Gamma_S)\,N_{\rm DM-S} \\ \frac{1}{2}(\Gamma_D + \Gamma_S)\,N_{\rm S-DM} & (\Gamma_D + \Gamma_S)\,(N_{N_{\rm S}} - N_{N_{\rm S}}^{\rm eq}) \end{pmatrix}$$

A numerical solution shows that a Landau-Zener overestimated the relic Abundance by a few orders of magnitude (especially in the hierarchical case)



Density matrix calculation of the relic abundance

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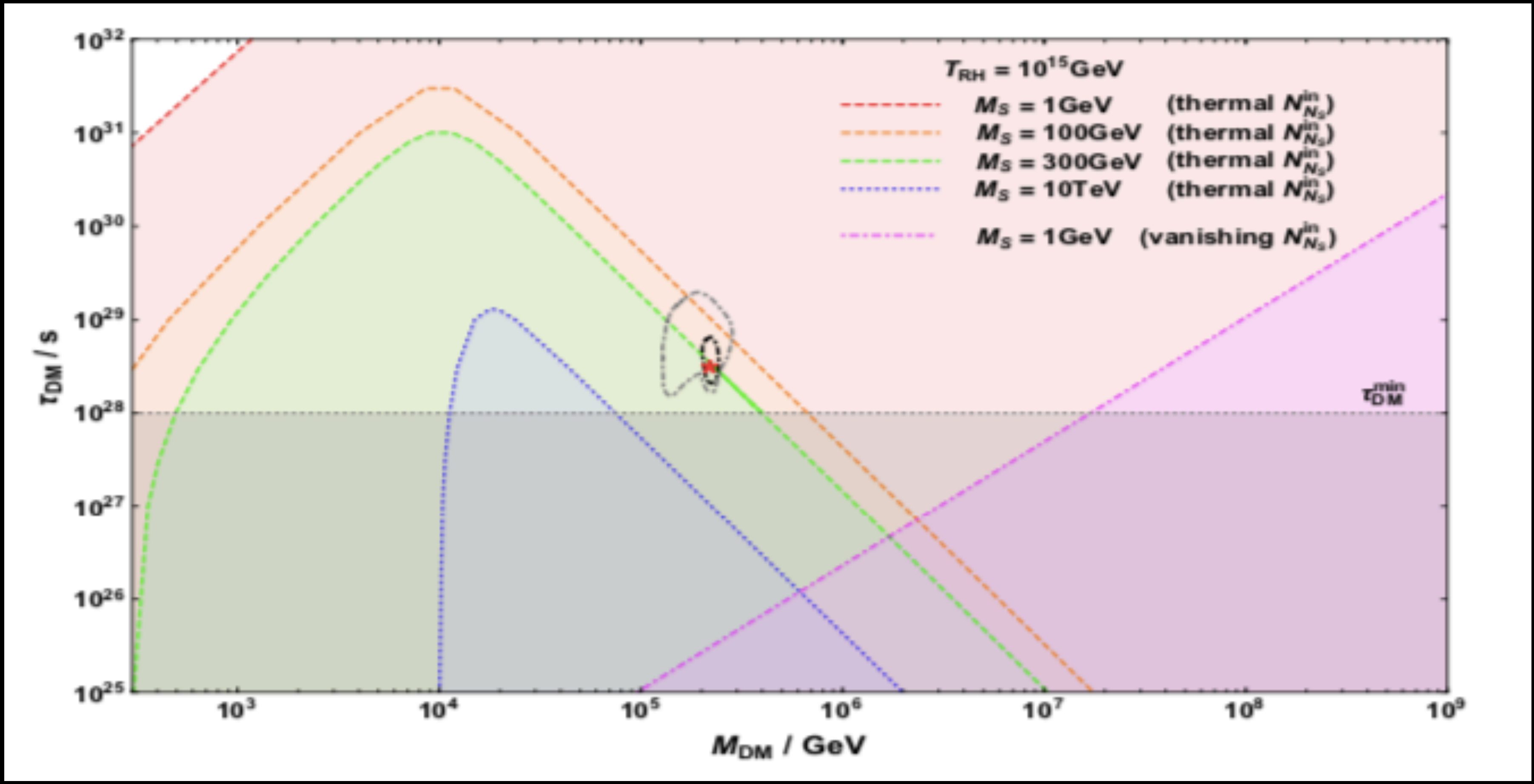

Solutions only for initial thermal N_S abundance, unless $M_S \sim 1$ GeV

SUMMARY

- Seesaw neutrino mass models are an attractive explanation of neutrino masses and mixing easily embaddable in realistic grandunified models (with or without flavour symmetries) but they are hard to test but…..

- ….leptogenesis helps in this respect: reproducing matter-antimatter asymmetry imposes important constraints and within specific classes of models can lead to predictions on low energy neutrino parameters (alternatively one can go to low scale leptogenesis, lecture by D. Gorbunov)

- Absolute neutrino mass scale experiments combined with neutrino mixing will in the next year test SO(10)-inspired leptogenesis predicting some deviation from the hierarchical limit. If $00\nu\beta$+CP violation is discovered, it would be a very strong case (discovery?) in favour of leptogenesis and would particularly favour SO(10)-inspired leptogenesis.
- If no deviation from the hierarchical limit is observed then two RH neutrino models will be favoured, in this case an intriguing unified picture of neutrino masses+ leptogenesis + dark matter is possible with the help of Higgs induced RH neutrino mixing (Anisimov operator)

- Density matrix calculations are crucial and seem to suggest new possibilities that are currently explored.