Towards a common origin of neutrino & dark matter

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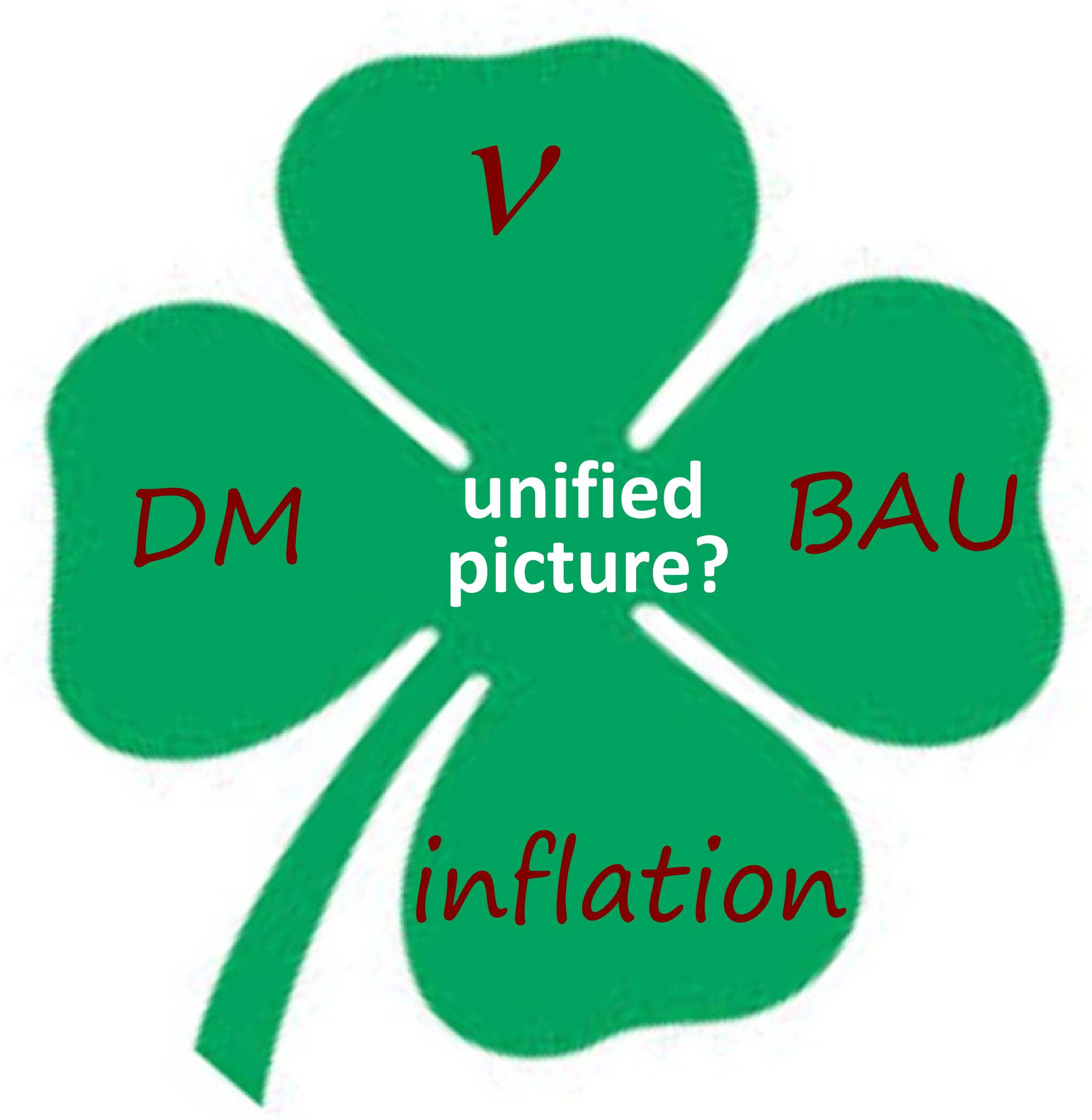
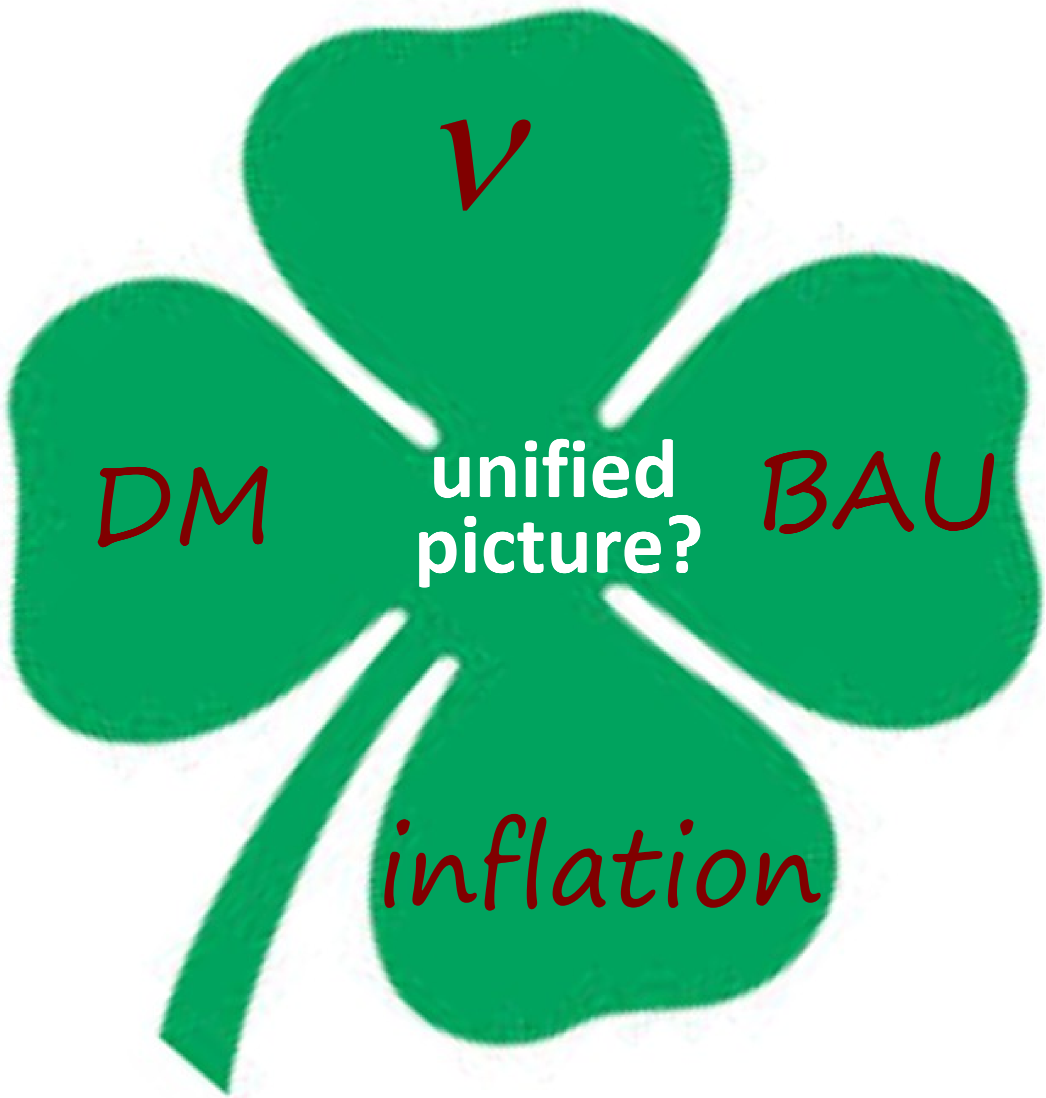
APP *23-28th June, 2014, Amsterdam*

In collaboration with Boucenna, Hirsch, Peinado, Shafi, Valle

Four-leaf clover



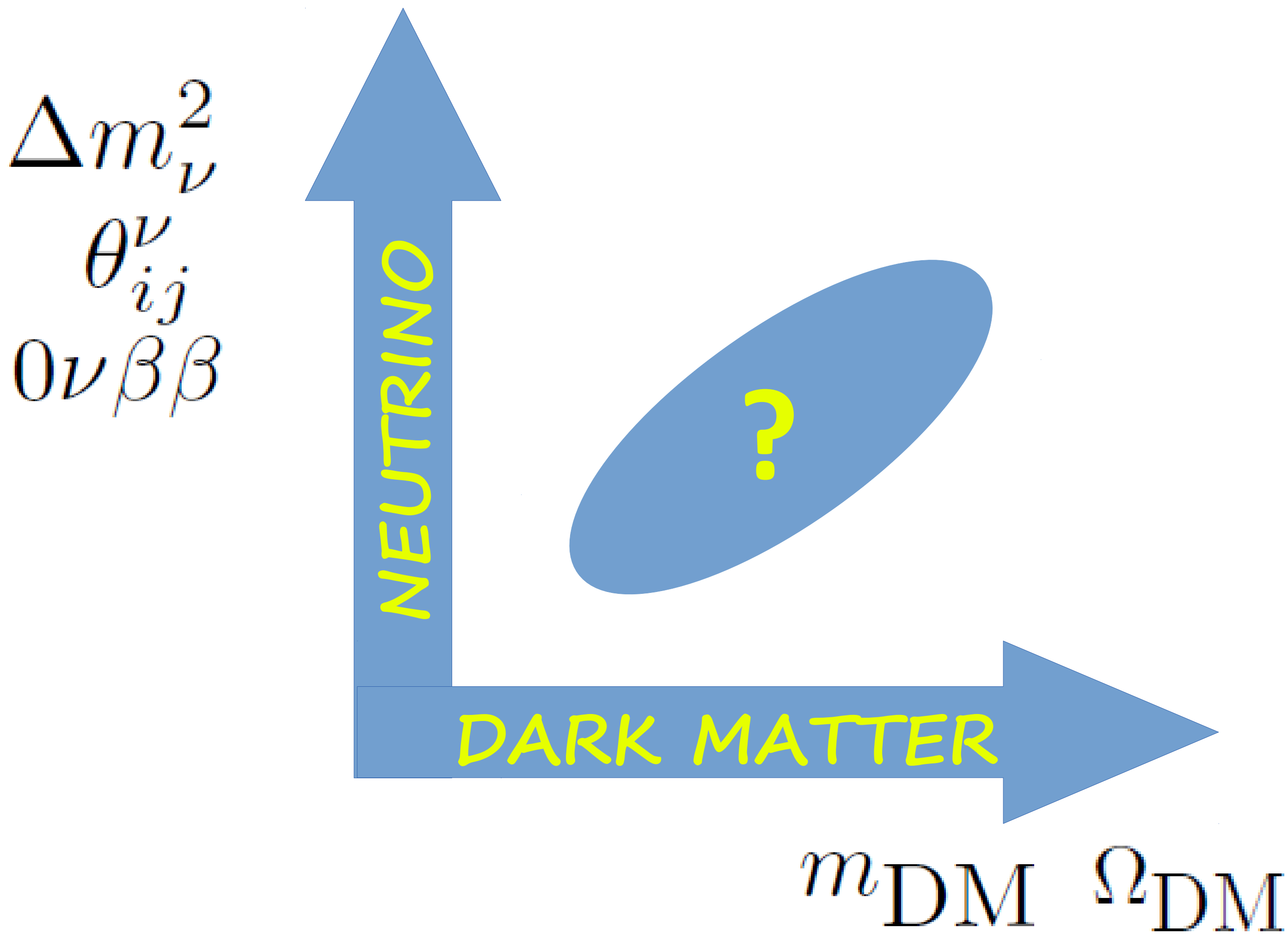
Five-leaf clover



G.F.Smoot 1405.2776

The dream!

....pheno connection between ν & DM



Majoron

Chikashige,Mohapatra,Peccei,81
Gelmini,Roncadelli, 81
Schechter,Valle, 82

$$y\,\bar{L}\,H^* N_R + h\,\sigma\,\overline{N^c_R}\,N_R$$

If neutrino are Majorana particles

ungauged global $U(1)_{Lep}$ -2   +1   +1

Spontaneously broken $\sigma = \langle\sigma\rangle + \rho + i\,J$

Nambu-Goldstone boson

Majoron can get a mass (pNGB) from
U(1)-explicitly break global terms
or for instance, from
non-perturbative gravitational effects

$$\lambda\,\sigma^5/Mpl + ..$$

(Coleman 88,Giddings-Strominger 88)

$$mJ \sim \lambda^{1/2}\left(\frac{\langle\sigma\rangle^3}{Mpl}\right)^{1/2} = \lambda^{1/2}\left(\frac{\langle\sigma\rangle}{v_{SM}}\right)^{3/2} * \mathrm{KeV}$$

Akhmedov,Berezhiani,Mohapatra,Senjanovic 93

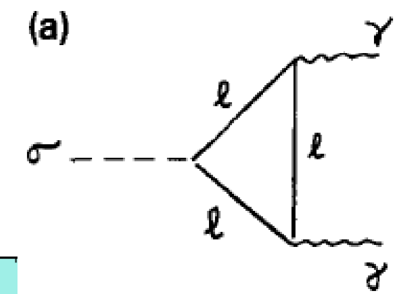
Majoron: decaying warm DM

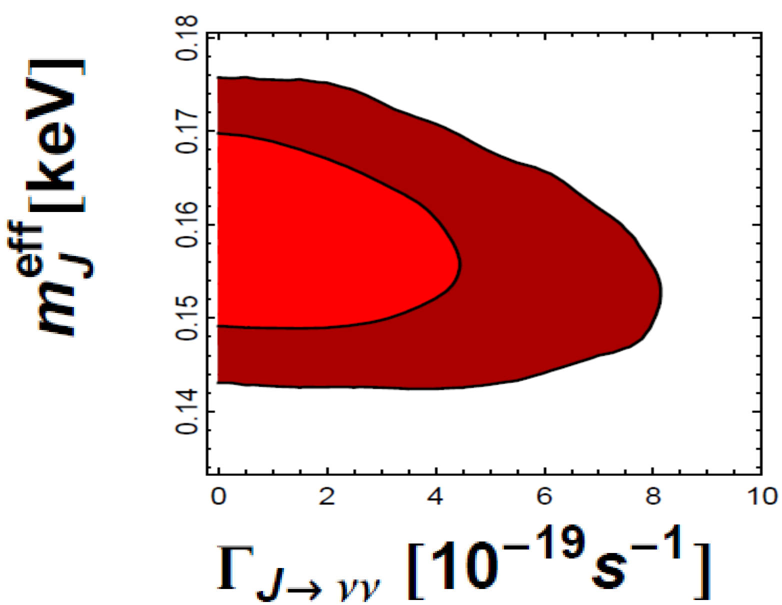
Berezinsky,Valle 93
Lattanzi,Valle 07

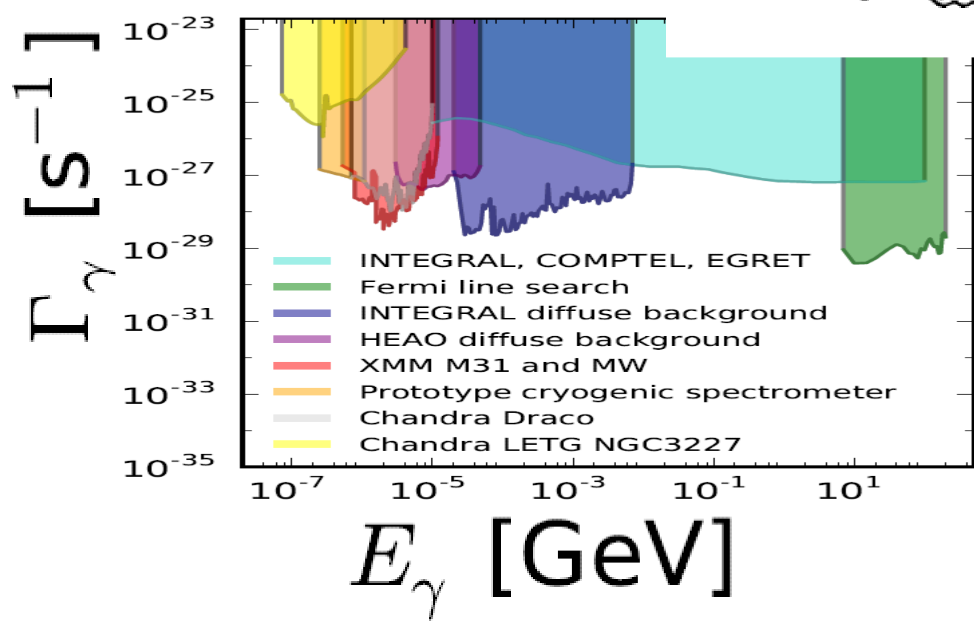
-thermal production

-non-thermal production

for instance through freeze-in (Frigerio,Hambye,Masso,11')



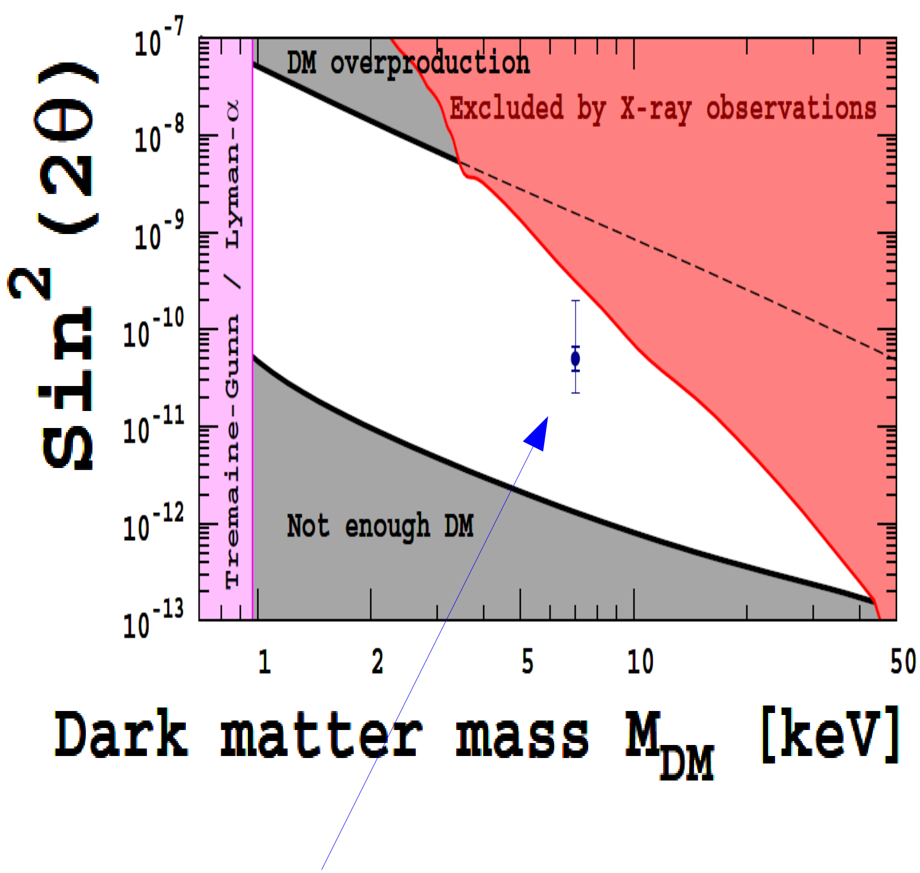




Lattanzi,Sorensen,Tortola,Valle 13

Sterile ν as DM

$y \bar{L} H^* N_R + M \bar{N}_R^c N_R$ Warm DM (KeV)



3.5KeV X-ray line, Boyarsky el al, 1402.4119

Non-thermal production

- Neutrino oscillation (Dodelson,Widrow)
- lepton asymm (Shi, Fuller)
- νMSM (Laine, Shaposhnikov)
- scalar decay (Kusenko)
- FIMP decay (Merle,Niro,Schmidt)
- subdominant DM (Palazzo, Cumberbatch,Slosar,Sik)

thermal production

- gauge+diliution (Bezrukov, Hettmansperger, Lindner)
- thermal+dilution (King,Merle)

Discrete Dark Matter

Hirsch, SM, Peinado, Valle PRD 10'
Meloni,SM,Peinado, PLB 11'
Boucenna et al, JHEP 11'
Meloni,SM,Peinado, PLB 11'
Toorop,Bazzocchi,M, NPB 12'
Boucenna et al, PRD 12'

The flavor symmetry stabilizes the DM

$$G_f \xrightarrow[\text{spontaneously}]{} Z_2$$

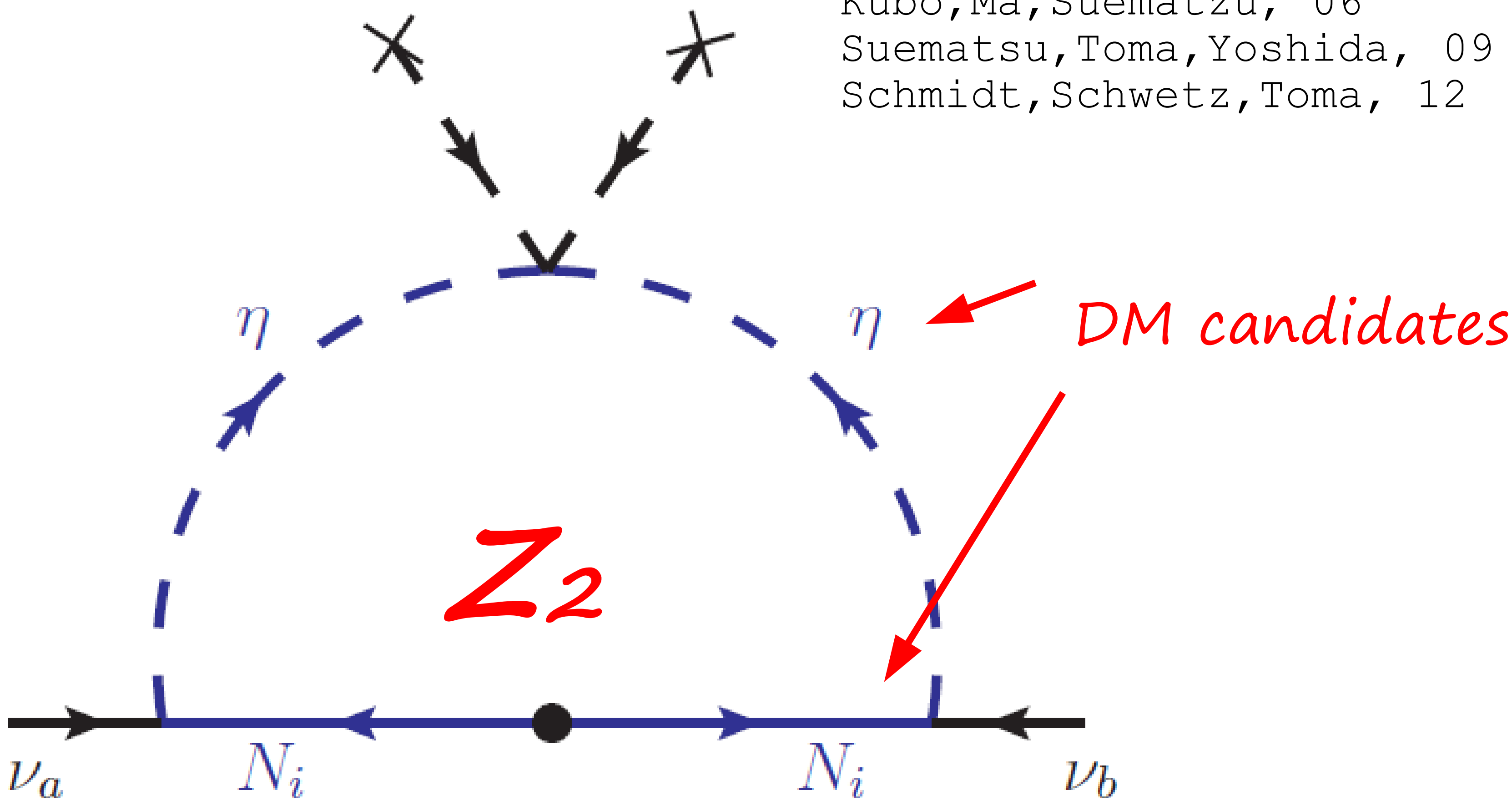
stabilize the DM
(typically imposed by hand)

$$(r1,\ r2,\ r3,\ldots) \longrightarrow (+r1,\ \underbrace{-r2,\ -r3}_{\text{DM candidates}},\ldots)$$

G_f - multiplet

Radiative scotogenic model

Ma, 06
Kubo,Ma,Suematzu, 06
Suematsu,Toma,Yoshida, 09
Schmidt,Schwetz,Toma, 12



tight link between ν & DM

HOWEVER DM AND ν PHENO ALMOST UNRELATED...

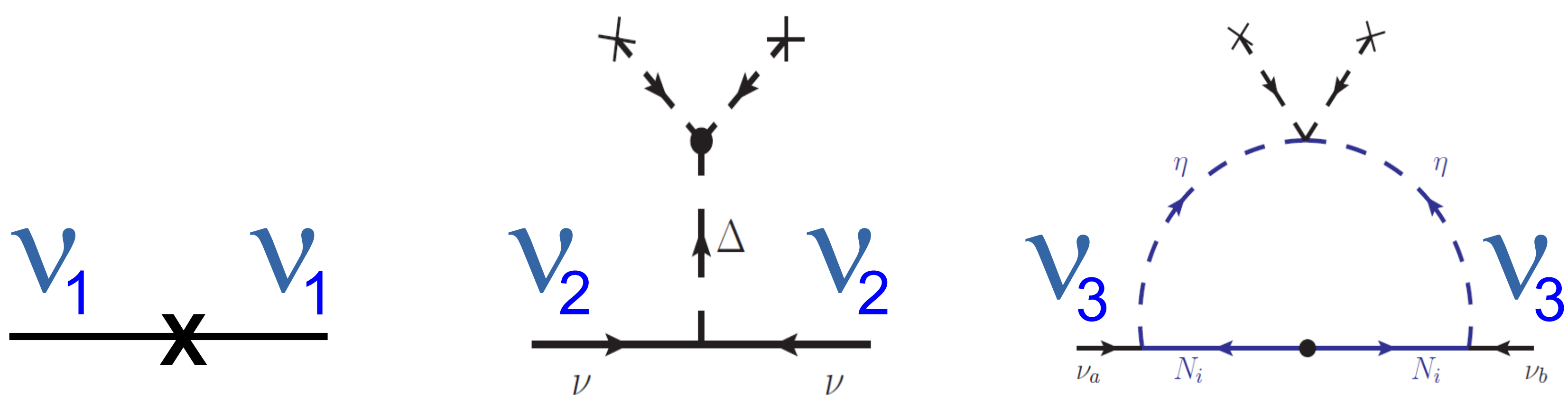
For a review see Boucenna,SM,Valle 1404.3751

$\nu \leftarrow$ pheno $\rightarrow$ DM in Scotogenic

M_ν - diagonal

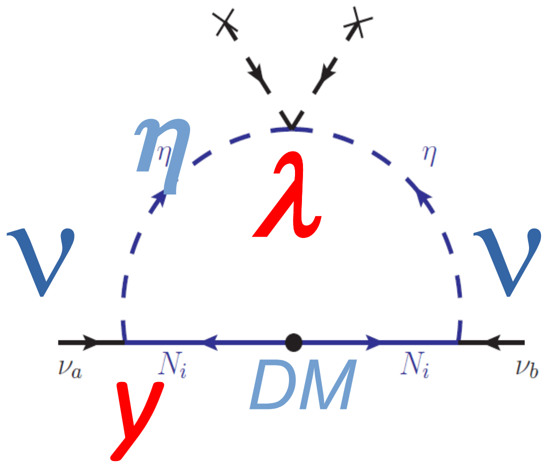
M_{lep} - arbitrary

lepton mixing



$m1 = 0$ $\quad$ $m2 = (\Delta m^2_{\odot})^{1/2}$ $\quad$ $m3 = (\Delta m^2_{@})^{1/2}$

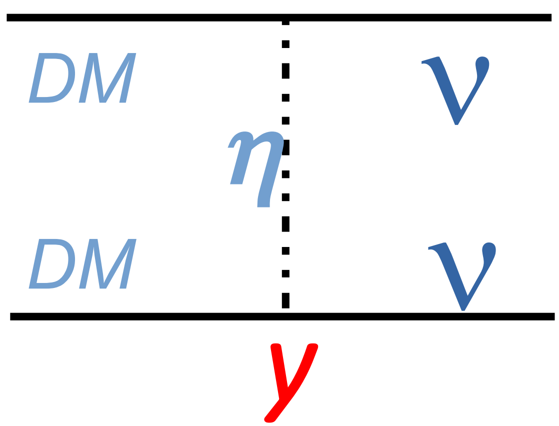
$\nu \leftarrow$ pheno $\rightarrow$ DM in Scotogenic



$$= \lambda \frac{y^2 \, v^2}{m_{dm}} \, \mathrm{I}\left(\frac{m_\eta}{m_{dm}}\right) = \left(\Delta m^2_{@}\right)^{1/2}$$

2 equations

$$\Omega_{dm} = \mathrm{f}(m_{dm}, y, m_\eta)$$



$$\boxed{\lambda \;,\; y \;,\; m_{dm} \;,\; m_\eta}$$

too many free parameters

Radiative ν mass in 3-3-1

$$\mathrm{SU}(3)_c \otimes \mathrm{SU}(3)_L \otimes \mathrm{U}(1)_X$$

Singer,Schechter,Valle 80&83
Pisano,Pleitez, 92
Frampton, 92
Foot,Long,Tran 94

- anomaly cancellation → **number of families = number of colors**

giving a reason for having 3 generations of fermions

- New quarks & gauge bosons that can be produced @LHC and give rise to tree-level FCNC

Buras,Fazio,Girrbach, Carlucci 12,13,14

- Lepton number violated by gauge interactions

Singer,Schechter,Valle 80&83

Radiative ν mass in 3-3-1

Boucenna,SM,Valle,PRD 14'

$$\psi_L^\ell = \begin{pmatrix} \ell^- \\ \nu_\ell \\ N_\ell^c \end{pmatrix}_L \quad \begin{array}{c} \text{Lepton number} \\ -1 \\ -1 \\ +1 \end{array}$$

@ tree-level neutrinos are pure Dirac

$$N_L^c \equiv (N^c)_L \equiv (\nu_R)^c$$

Radiative ν mass in 3-3-1

Boucenna,SM,Valle,PRD 14'

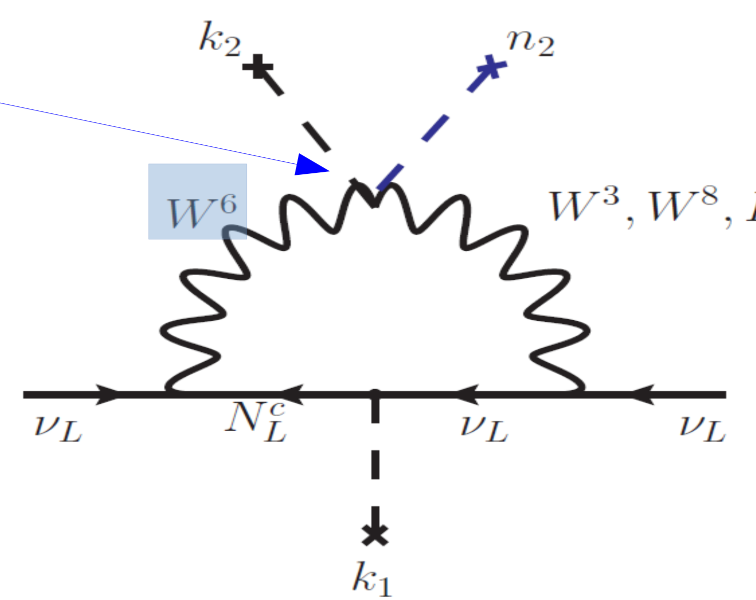
Lepton number

$$\psi_L^\ell = \begin{pmatrix} \ell^- \\ \nu_\ell \\ N_\ell^c \end{pmatrix}_L \quad \begin{matrix} -1 \\ -1 \\ +1 \end{matrix}$$

@ tree-level neutrinos are pure Dirac

$$N_L^c \equiv (N^c)_L \equiv (\nu_R)^c$$

@ 1-loop neutrinos get Majorana mass



Lepton number violated in gauge interactions ΔL=2

$$\begin{pmatrix} W^3 + \frac{1}{\sqrt{3}}W^8 & W_{12}^+ & W_{45}^+ \\ W_{12}^- & -W^3 + \frac{1}{\sqrt{3}}W^8 & W^6 - iW^7 \\ W_{45}^- & W^6 + iW^7 & -\frac{2}{\sqrt{3}}W^8 \end{pmatrix}$$

Radiative ν mass in 3-3-1

Boucenna,SM,Valle,PRD 14'

$$SU(3)_L \otimes U(1)_X \xrightarrow{n_{1,2}} SU(2)_L \otimes U(1)_Y \xrightarrow{k_{1,2}} U(1)_Q$$

$$\langle\phi_1\rangle = \begin{bmatrix} k_1 \\ 0 \\ 0 \end{bmatrix}, \langle\phi_2\rangle = \begin{bmatrix} 0 \\ 0 \\ n_1 \end{bmatrix}, \langle\phi_3\rangle = \begin{bmatrix} 0 \\ k_2 \\ n_2 \end{bmatrix}$$

scalar DM candidate – like inert DM, but...

$$\mathcal{L}_{\mathrm{Kin}} = \sum_i (D^\mu \phi_i)^\dagger (D_\mu \phi_i) \longrightarrow \quad m_{W',Z'} \sim n_1 \sim m_{DM}$$

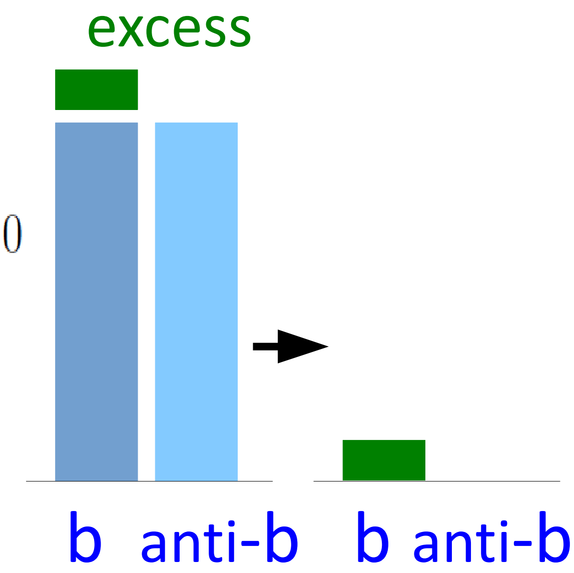
neutrino mass ⟷ **W',Z' bosons masses** ⟷ **Dark Matter mass**

Asymmetric DM

For a review see
Sannino; Petraki,Volkas;
Zurek;

The present-day
Visible Matter density
has due to BAU

$$\eta(B) \equiv \frac{n_b - \bar{n}_b}{s} \simeq 10^{-10}$$



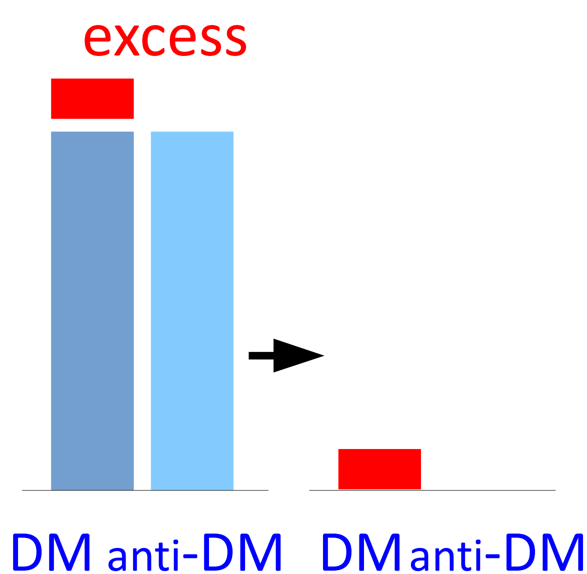
$$\Omega_{DM} \simeq 5\,\Omega_B$$

common origin for DM & B

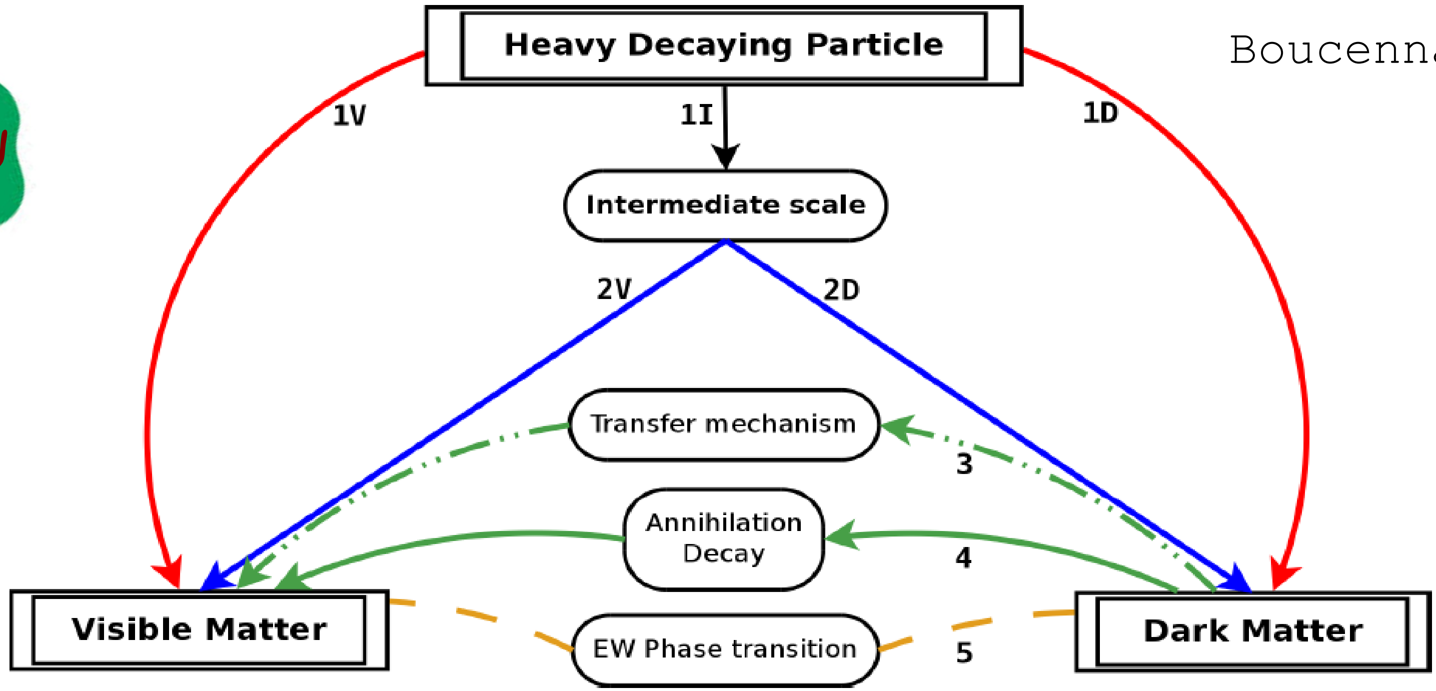
ADM hypotesis:

the DM density is due to
DM particle/antiparticle asymm

$$\eta(DM) \equiv \frac{n_{DM} - \bar{n}_{DM}}{s}$$



$$\eta(B) \sim \eta(DM) \rightarrow m_{DM} \sim \frac{\Omega_{DM}}{\Omega_B}\, m_p$$



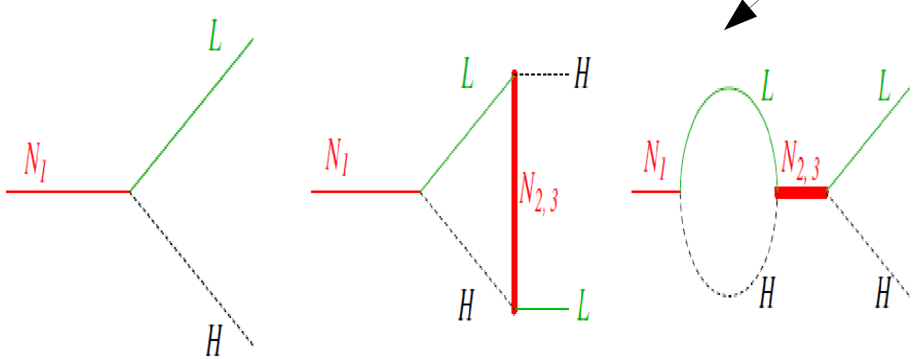
Boucenna,SM 13'

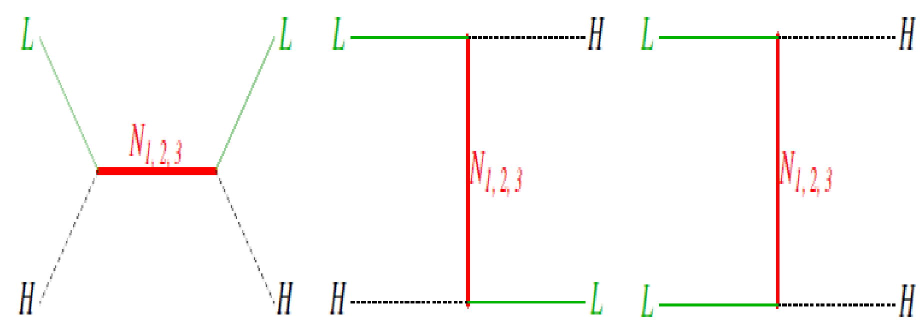
Model	DM	HS	BAU	$\mathcal{O}(M_{DM})$	Signal	Diagram
Two singlets EWBG[9]	$\mathcal{WIMP}$	✗	EWPHT	$2-225$ GeV	DD-ID-CO	5^*
EW cogenesis [53]	$\mathcal{WIMP}$	✗	EWPHT	GeV-TeV	CO	5^*
WIMPy L$^{(\dagger)}$[15]	$\mathcal{WIMP}$	✗	ANNIH	TeV	ID-CO	T-4^*
WIMPy Q$^{(\dagger)}$[15]	$\mathcal{WIMP}$	✗	ANNIH	500GeV	DD-ID-CO	T-4^*
Meta-stable WIMP[19]	$\mathcal{WIMP}$	✗	DECAY	GeV-TeV	CO	T-4^*
Kitano-Low [26]	$\mathcal{ADM}$	✣	DECAY	GeV	CO	1^*_V-1^*_I-T-2_D
Hylogenesis [42]	$\mathcal{ADM}$	✓	DECAY	5 GeV	IND-DD	1^*_V-1^*_D-T
ADM Leptog [43]	$\mathcal{ADM}$	✓	DECAY	KeV–10 TeV	DD-ID	1^*_V-1^*_D-T
Darkogenesis [49]	$\mathcal{ADM}$	✓	TRANS	$5-15$ GeV	GW	$*$-3-$*$
Baryogenesis from DM [46]	$\mathcal{ADM}$	✓	TRANS	3 GeV	DD-CO	1_D*-3-$*$
Aidnogenesis [48]	$\mathcal{ADM}$	✓	DECAY	6 GeV	DD-FCNC -CO	1^*_V-$\bar{3}$-$*$-T
Xogenesis [49]	$\mathcal{ADM}$	✓	TRANS	100GeV–TeV	CO	$*$-3-$*$
Pangenesis [38]	$\mathcal{ADM}$	✓	AFDIN	1.6–5 GeV	DD-CO	$*$-1^*_I-T-2_V-2_D
Cladogenesis [51]	$\mathcal{NTDM}$	✣	DECAY	5-500GeV	-	1_I-1_D-2^*_V

leptogenesis

For a review see
Buchmuller, Di Bari, Plumacher
Davidson, Nardi, Nir
Pilaftis, Underwood,
Hambye et al
Barbieri et al

$$Y_{\mathcal{B}-\mathcal{L}} = -\epsilon_{N_1}\ \eta\ Y^{\rm eq}_{N_1}$$





$$\epsilon_{N_1} \equiv \frac{\gamma^{\rm eq}(N_1 \to HL) - \gamma^{\rm eq}(N_1 \to \bar{H}\bar{L})}{\gamma^{\rm eq}(N_1 \to HL) + \gamma^{\rm eq}(N_1 \to \bar{H}\bar{L})}$$

CP violation in N1 decays

Lepton asymmetry
washout processes

Inflation & Majoron DM in the seesaw mechanism

Boucenna,SM,Shafi,Valle 1404.3198
(see also Okada,Nefer,Shafi,14';
Okada,Shafi,13'; Nefer,Shafi,13')

$$\mathcal{L}_y = -Y_D^{ij}\,\overline{\ell_L^j}\,i\tau_2\Phi^*\nu_R^i - \frac{1}{2}Y_N^i\,\sigma\,\overline{\nu_R^{ic}}\;\nu_R^i + \mathrm{h.c.}$$

$$\sigma = v_L + \rho + i\,J$$

inflation

DM

Type-I ssesaw

$$m_\nu \simeq Y_D Y_N{}^{-1} Y_D{}^T \frac{{v_2}^2}{v_L}$$

Inflation & Majoron DM & ν

$\sigma = v_L + \rho + i\, J$

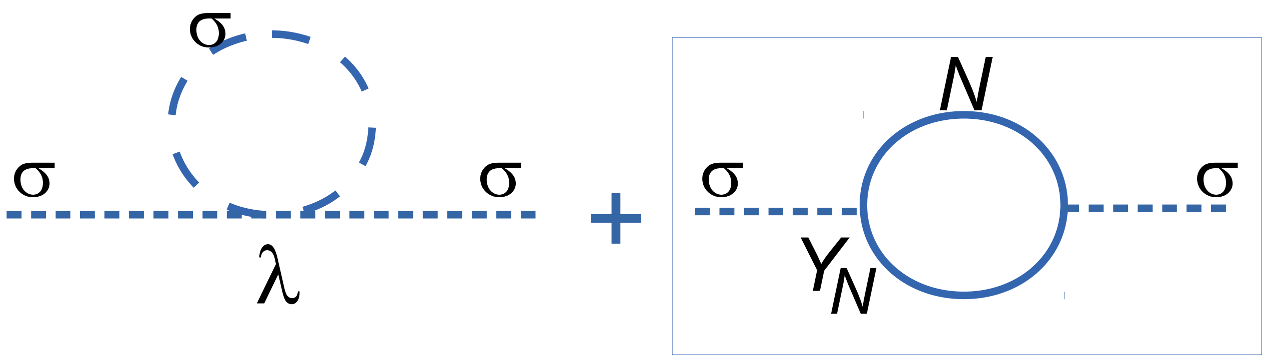
$$V = \lambda \left[\frac{1}{4}\left(\rho^2 - v_{\rm L}^2\right)^2 + a \log\left[\frac{\rho}{v_{\rm L}}\right] \rho^4 + V_0 \right]$$

tree-level

Coleman-Weinberg radiative corrections

$$a = \frac{\beta_\lambda}{16\pi^2\lambda}$$

$$\beta_\lambda = 20\lambda^2 + 2\lambda\left(\sum_i (Y_N^i)^2\right) - \sum_i (Y_N^i)^4 \underset{\lambda \ll Y_N}{\simeq} -\sum_i (Y_N^i)^4$$



from curvature perturbation $\Delta_{\mathcal{R}}$

Inflation & Majoron DM & ν

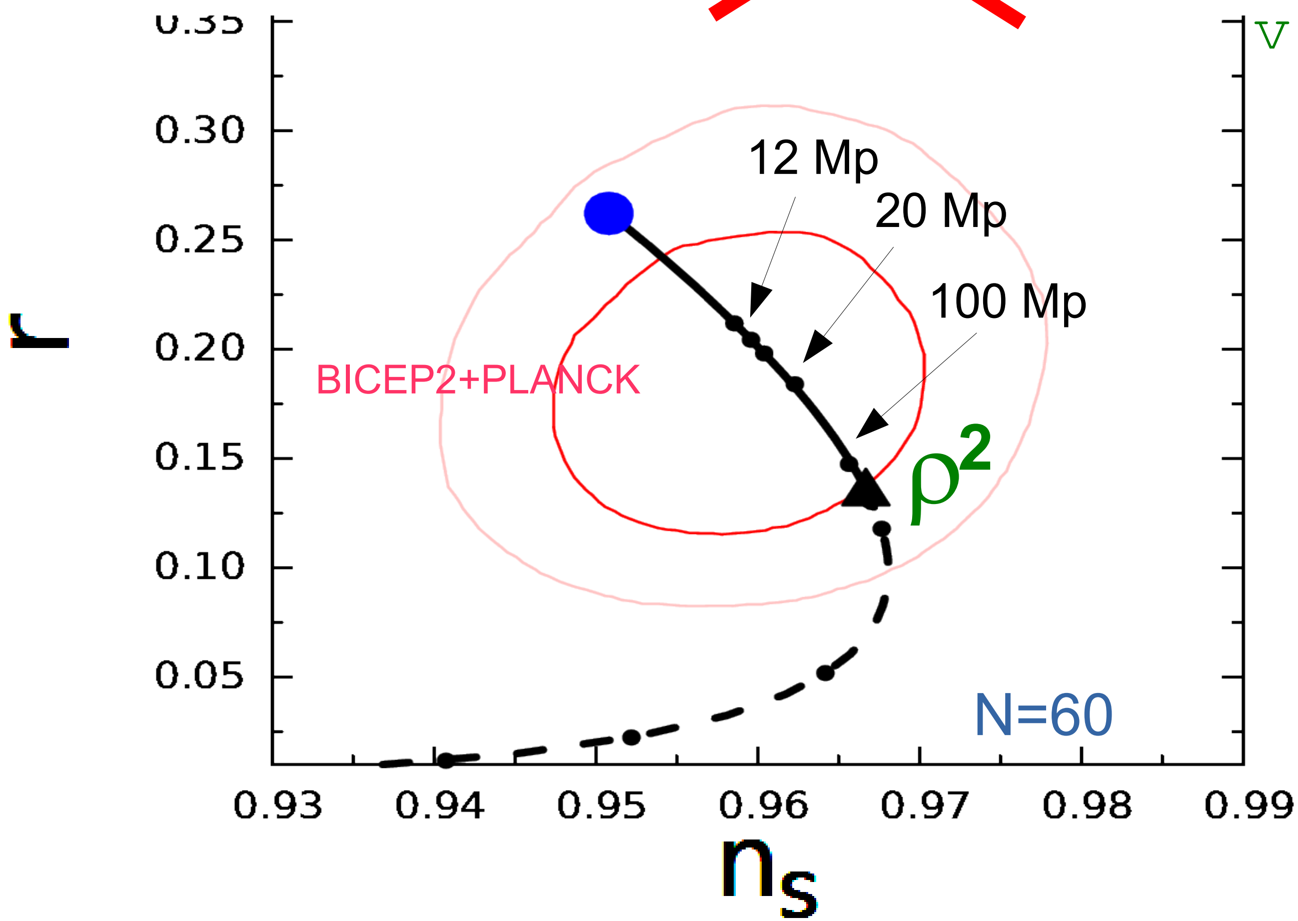
ν DM BAU infl

1) $\boxed{v_L > M_P}$ $v_L = 10^3\,M_P$ $\xrightarrow{\nu\text{ mass}}$ $\boxed{Y_N \approx 10^{-6}}$

trans-planckian

$$V = \lambda\left[\frac{1}{4}\left(\rho^2 - v_L^2\right)^2 + \cancel{a\log\left[\frac{\rho}{v_L}\right]}\rho^4 + V_0\right] \sim \rho^2$$

v >> Mp



Inflation & Majoron DM & ν

ν DM BAU infl

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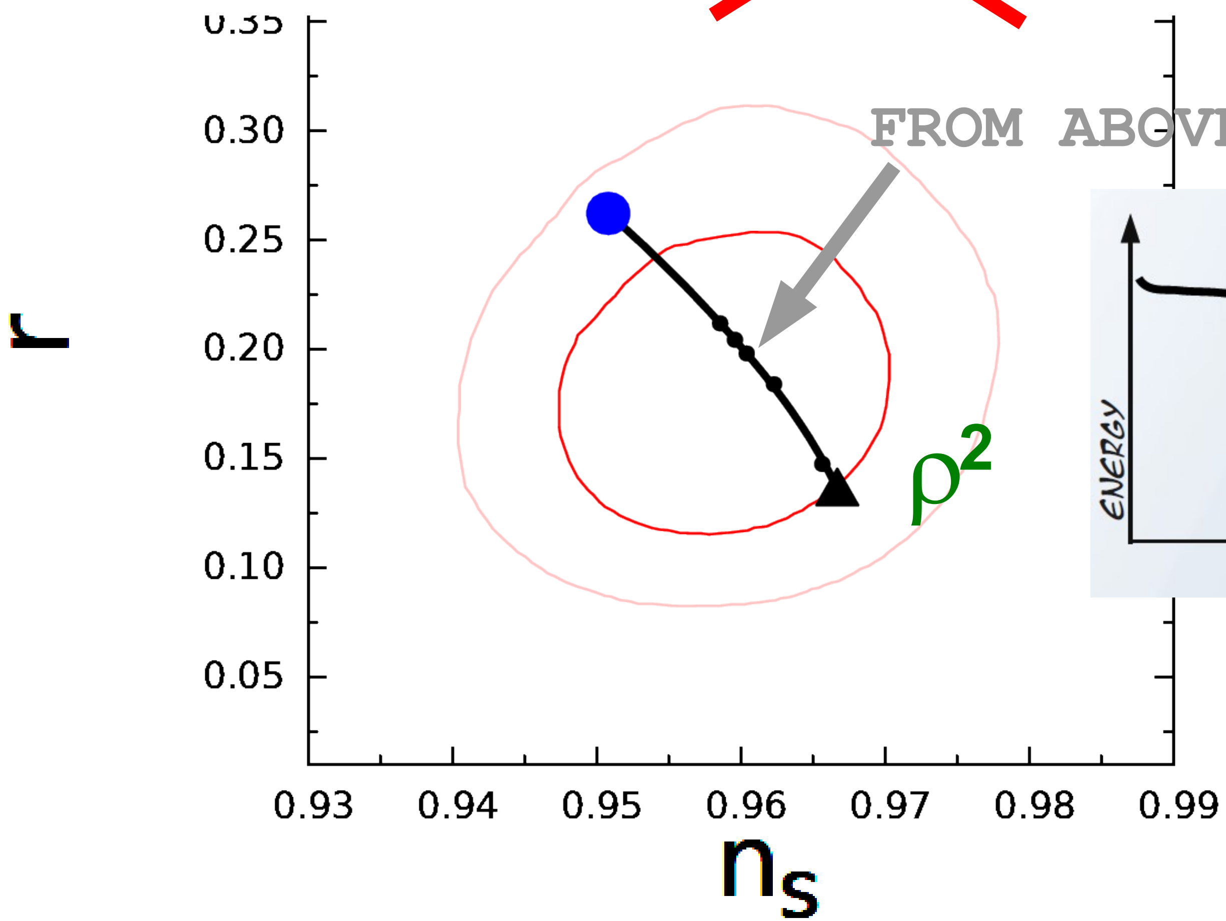
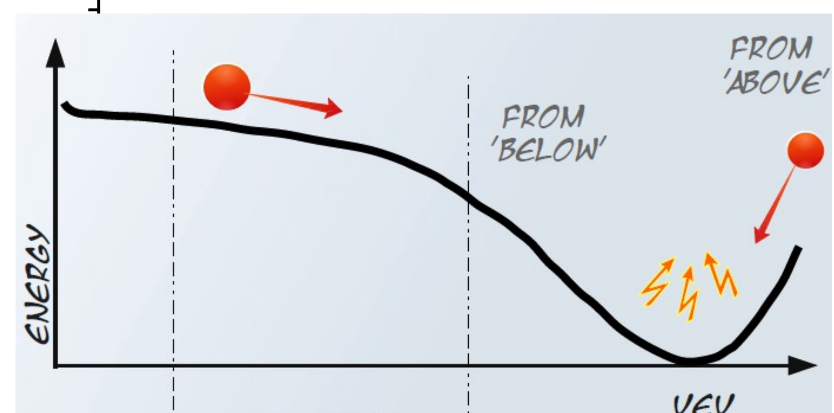




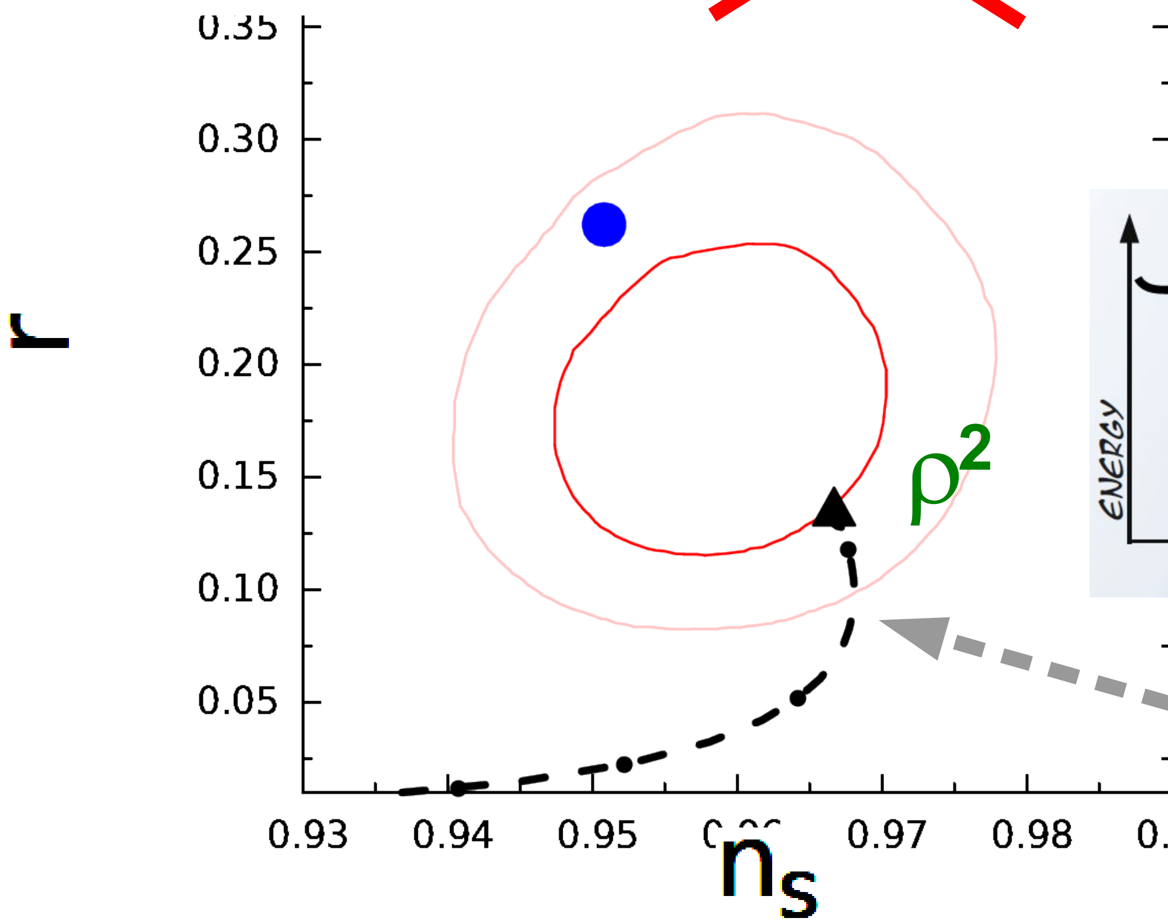
Inflation & Majoron DM & ν

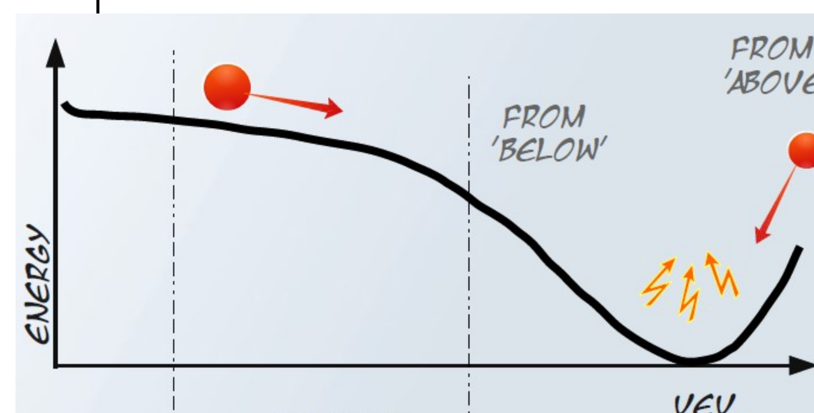
1) $\boxed{v_{\mathrm{L}} > M_P}$ $\quad v_{\mathrm{L}} = 10^3\,\mathrm{M_P} \xrightarrow{\nu \text{ mass}} \boxed{Y_N \approx 10^{-6}}$

trans-planckian

$$V = \lambda\left[\frac{1}{4}\left(\rho^2 - v_{\mathrm{L}}^2\right)^2 + \cancel{a \log\left[\frac{\rho}{v_{\mathrm{L}}}\right]\rho^4} + V_0\right] \sim \rho^2$$

v >> Mp



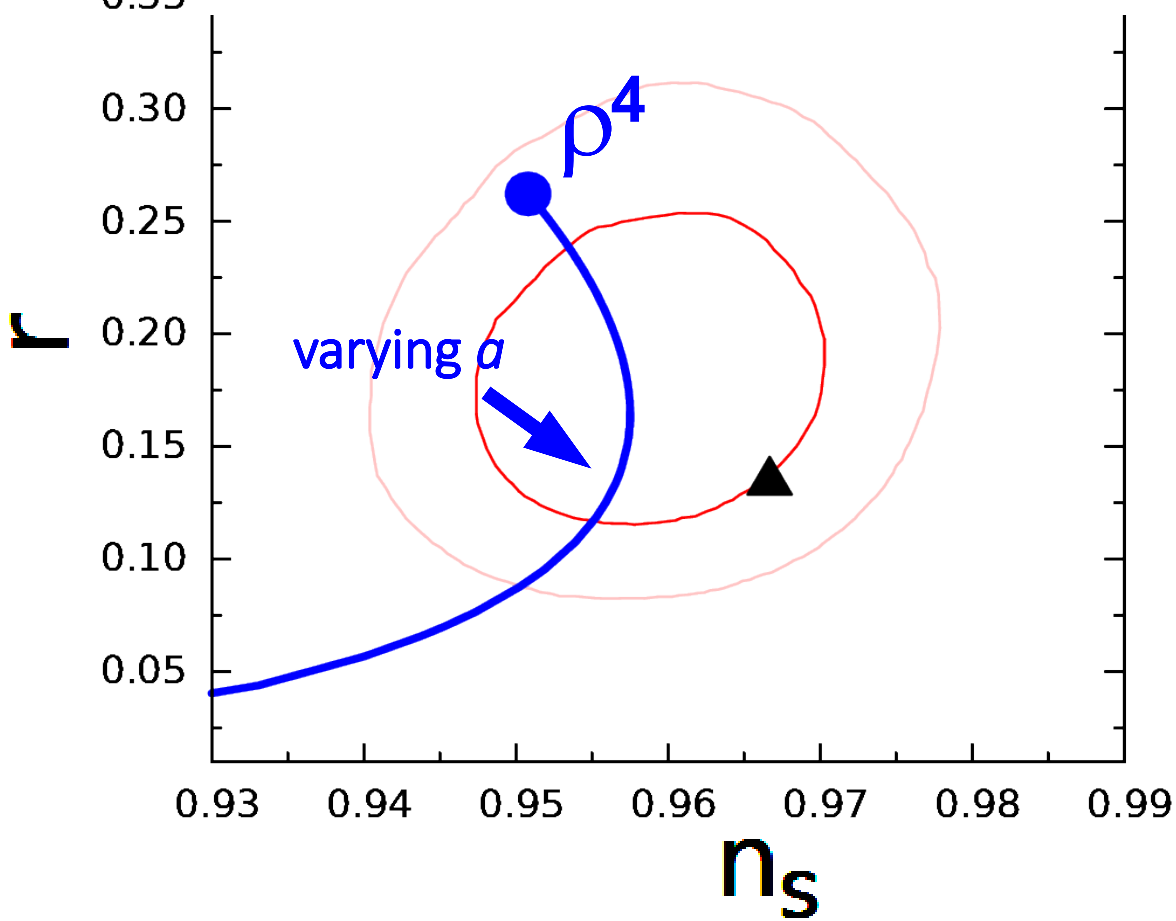


Inflation & Majoron DM & ν

2) $\boxed{v_L \ll M_P}$ $\xrightarrow{\nu \text{ mass}}$ $\boxed{Y_N \sim 10^{-3}}$

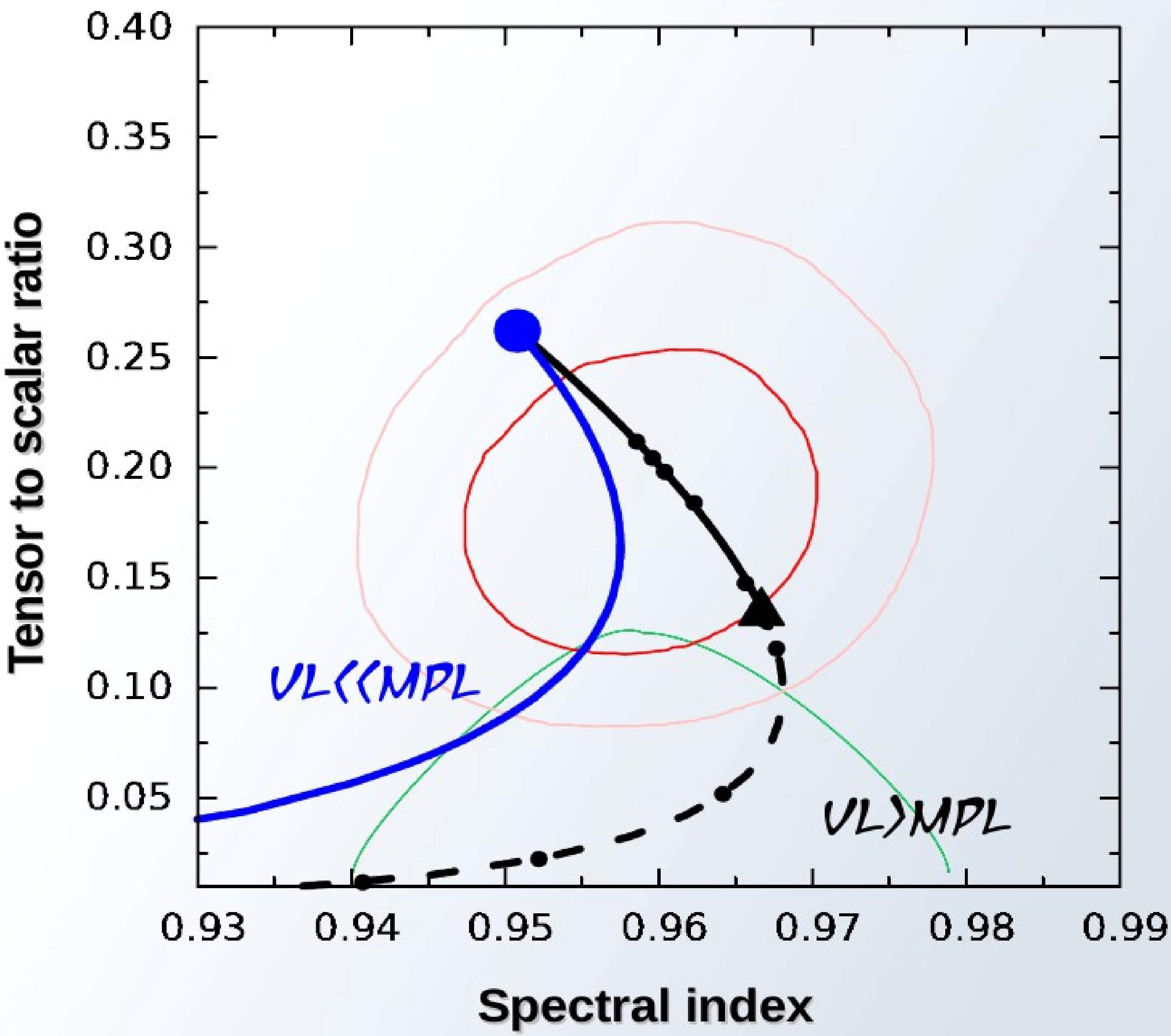
sub-planckian

$$V = \lambda\left[\frac{1}{4}\left(\rho^2 - v_L^2\right)^2 + a\log\left[\frac{\rho}{v_L}\right]\rho^4 + V_0\right] \sim \rho^4 \text{ + correc.}$$



a	n_s	r
-0.01279	0.952953	0.101404
-0.01265	0.957019	0.141706
-0.01261	0.957343	0.150727
-0.01256	0.957507	0.160678
-0.0125	0.957484	0.170937
-0.0124	0.957174	0.184759

Planck vs BICEP2



Planck vs BICEP2

Solutions above the VEV ($\rho > v_{\mathrm{L}}$)

$v_L\,(M_P)$	$\log_{10}(\lambda)$	n_s	r	$\alpha\,(10^{-4})$	$V^{1/4}\,(10^{16}\,\mathrm{GeV})$	$\rho_0\,(M_P)$	$\rho_e\,(M_P)$
1.	-12.8521	0.951168	0.260263	-7.96468	2.30678	22.2218	3.14626
5.	-13.0093	0.954908	0.237136	-7.05625	2.25373	24.2634	6.61037
10	-13.2351	0.958581	0.211972	-6.37463	2.1914	28.1285	11.5137
20.	-13.599	0.962148	0.184081	-5.89025	2.11546	37.1396	21.4642
50.	-14.2262	0.964453	0.159253	-5.80242	2.04021	66.1458	48.6058
100	-14.7789	0.965456	0.147557	-5.72255	2.00167	115.805	98.5958
500.	-16.1392	0.966211	0.137189	-5.66368	1.96554	515.506	498.588
1000.	-16.7367	0.9663	0.135828	-5.6565	1.96065	1015.47	998.587

Solutions below the VEV ($\rho < v_{\mathrm{L}}$)

$v_L\,(M_P)$	$\log_{10}(\lambda)$	n_s	r	$\alpha\,(10^{-4})$	$V^{1/4}\,(10^{16}\,\mathrm{GeV})$	$\rho_0\,(M_P)$	$\rho_e\,(M_P)$
8.	-13.9086	0.87488	0.000385304	-0.150585	0.452484	0.111018	6.70982
9.	-13.5255	0.900769	0.00148882	-0.460638	0.6344	0.27599	7.69622
10.	-13.3033	0.918822	0.00377031	-0.949789	0.800289	0.541141	8.68529
15.	-13.1004	0.95579	0.0279442	-3.49461	1.32046	3.17548	13.6523
20.	-13.2562	0.964198	0.0518562	-4.54129	1.54118	7.05055	18.6357
30.	-13.5959	0.967596	0.0798131	-5.09597	1.71661	16.0451	28.6191
50.	-14.0675	0.96807	0.102141	-5.30133	1.8258	35.3404	48.6058
500.	-16.1213	0.966555	0.131662	-5.63496	1.94544	484.653	501.416
1000.	-16.7278	0.966472	0.133065	-5.64214	1.9506	984.613	1001.42

Non-minimal gravitational coupling

(work in progress)

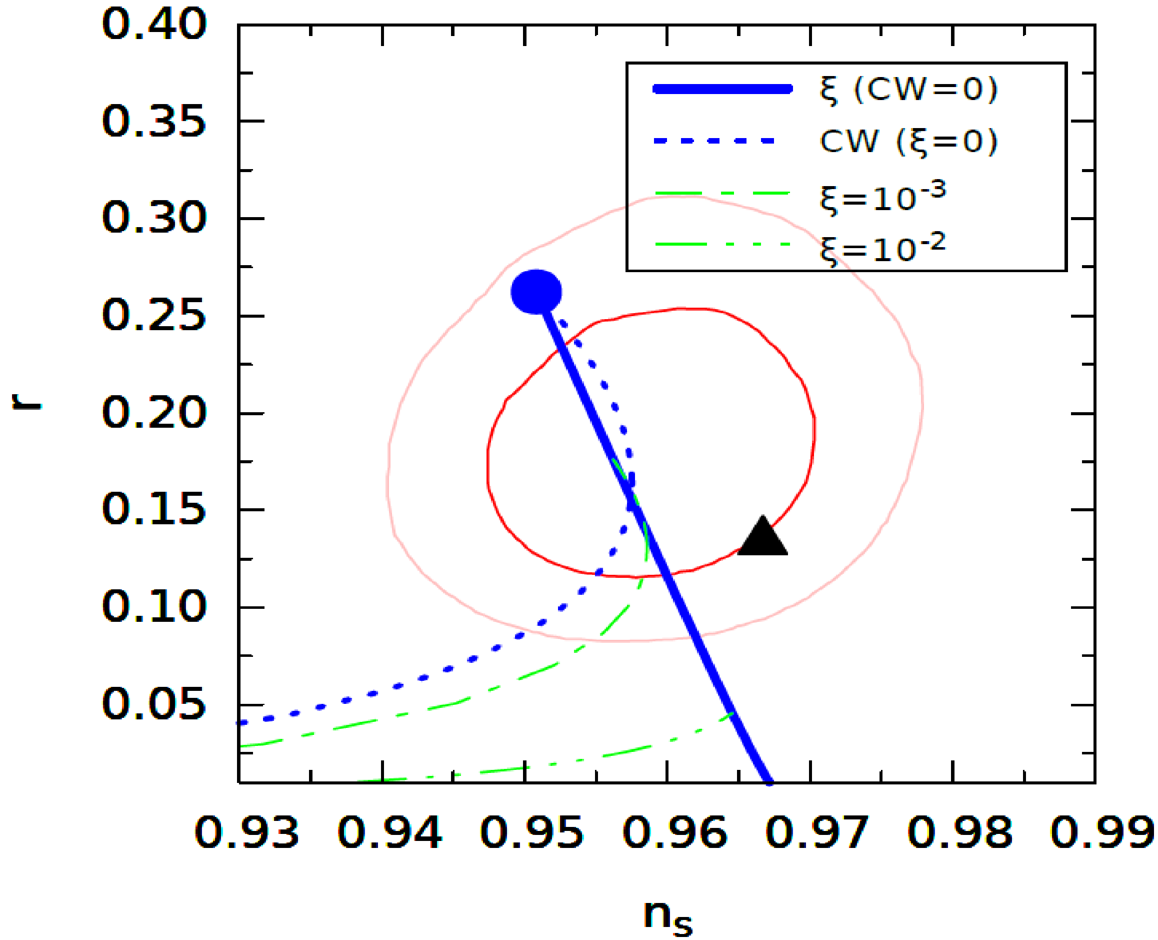
See for instance
DeSimone, Hertzberg, Wilczek, 09'
Okada, Rehman, Shafi, 10'
Okada, Nefer, Shafi, 14'
Haba, Takahashi 14'

$$S_J^{tree} = \int d^4x\sqrt{-g}\left[-\left(\frac{m_P^2 + \xi\phi^2}{2}\right)\mathcal{R} + \frac{1}{2}(\partial\phi)^2 - \frac{\lambda}{4!}\phi^4 - \frac{1}{2}y_N\phi\overline{N^c}N\right]$$

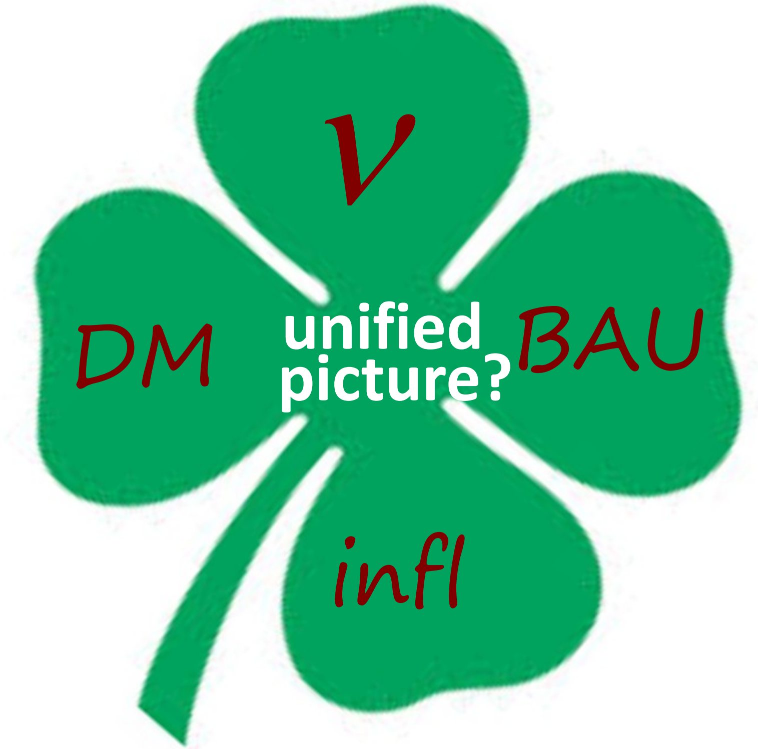
gravitational coupling term — quartic

$$V_E(\phi) = \frac{\frac{1}{4!}\lambda\,\phi^4 - \kappa\,\phi^4\ln(\phi/\mu)}{\left(1+\frac{\xi\,\phi^2}{m_P^2}\right)^2}$$

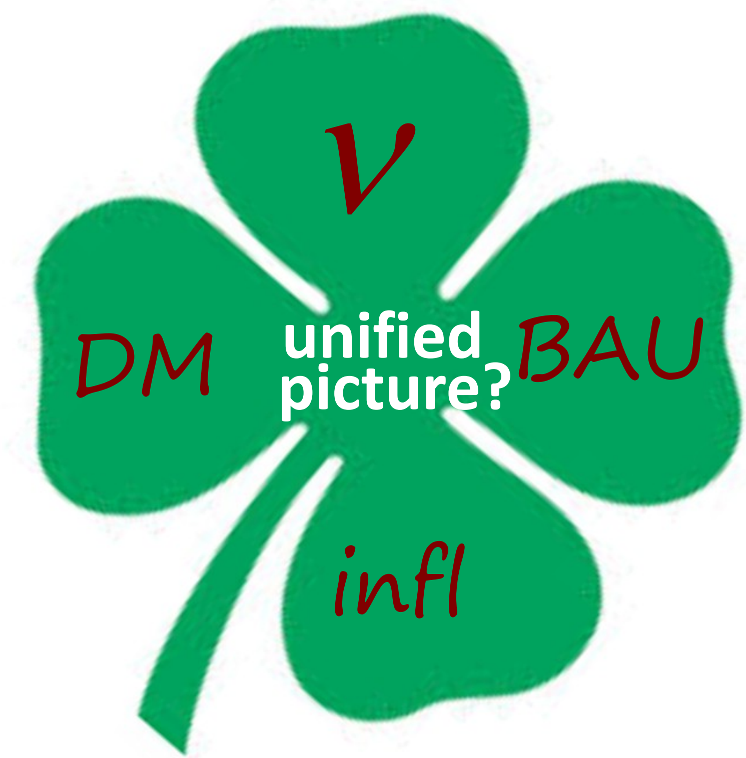
$$\kappa = y_N^4/(4\pi)^2$$



Conclusions



Conclusions

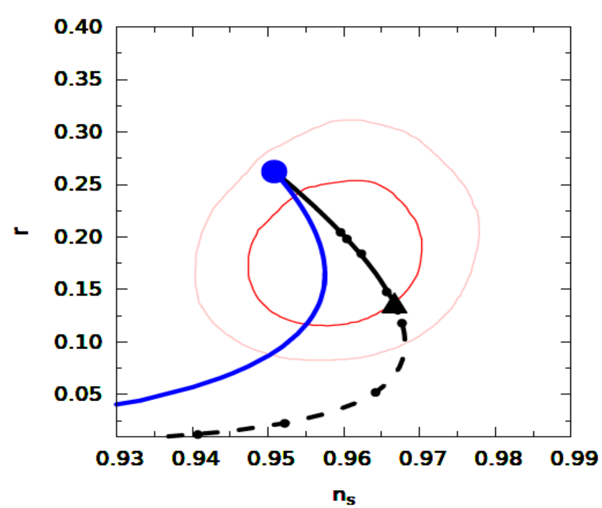


Neutrino ?

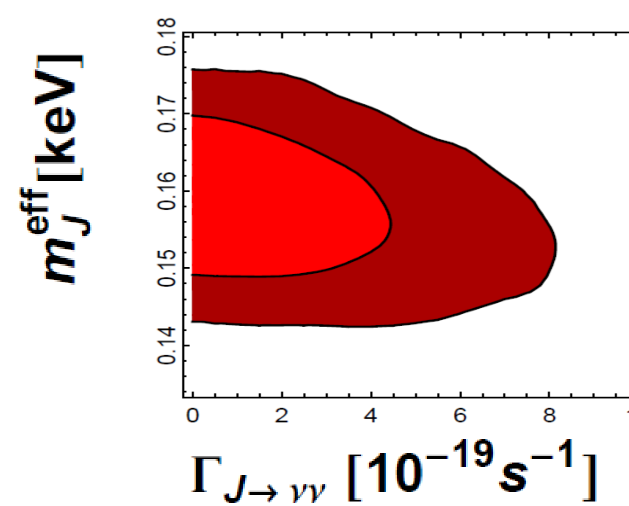
Leptogenesis ?

$$\sigma = \nu + \rho + i\,J$$

Inflation ?

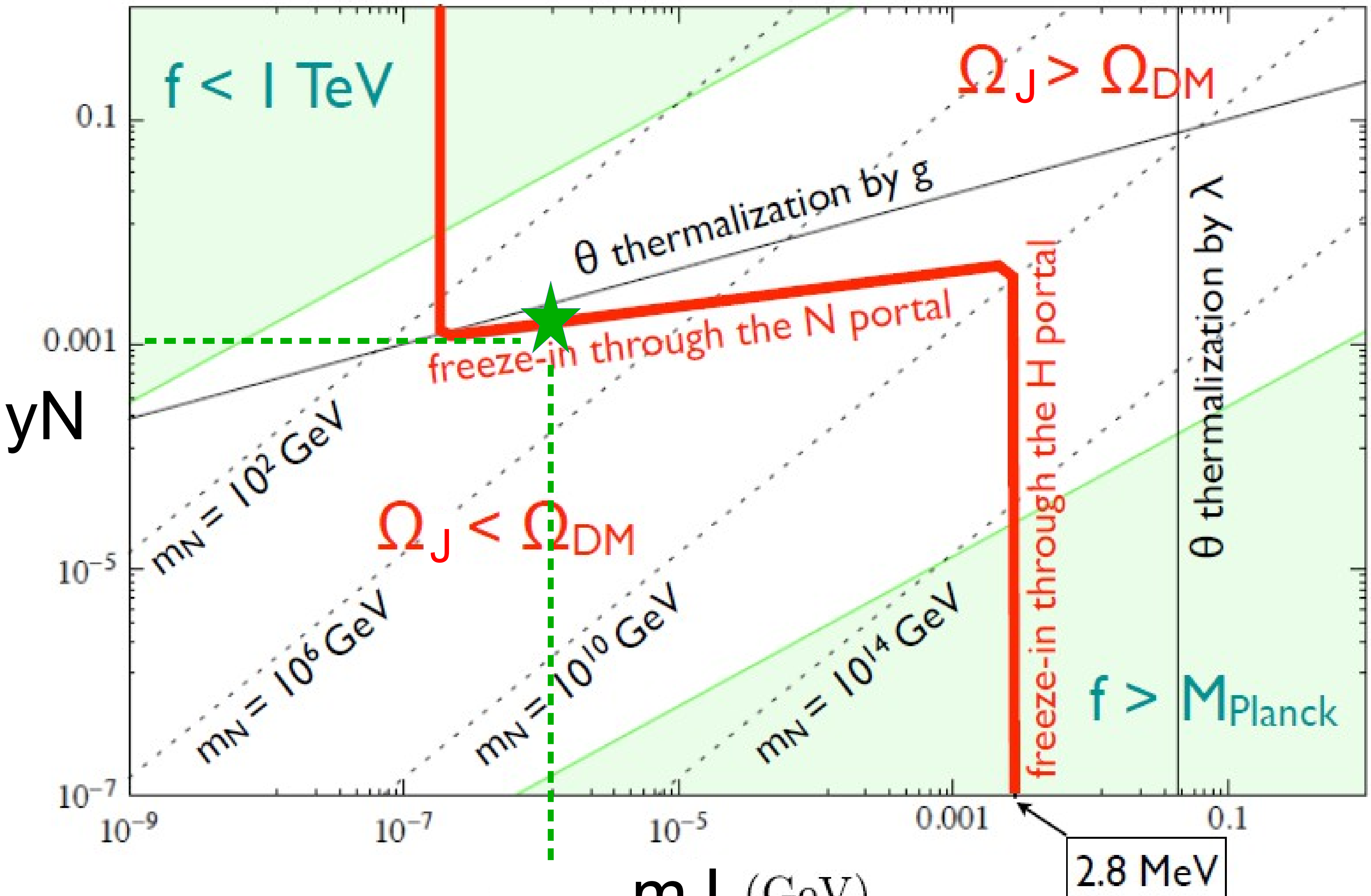


Dark Matter ?



Backup slides

Non-thermal freeze-in Majoron DM



From Frigerio's talk

	ψ_L^ℓ	ℓ_R	$Q_L^{1,2}$	Q_L^3	$\hat{u}_R$	$\hat{d}_R$	S	ϕ_1	ϕ_2	ϕ_3
$SU(3)_c$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{3}$	$\mathbf{3}$	$\mathbf{3}$	$\mathbf{3}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$
$SU(3)_L$	$\mathbf{3}^*$	$\mathbf{1}$	$\mathbf{3}$	$\mathbf{3}^*$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{3}^*$	$\mathbf{3}^*$	$\mathbf{3}^*$
$U(1)_X$	$-\frac{1}{3}$	-1	0	$+\frac{1}{3}$	$+\frac{2}{3}$	$-\frac{1}{3}$	0	$+\frac{2}{3}$	$-\frac{1}{3}$	$-\frac{1}{3}$
$\mathcal{L}$	$-\frac{1}{3}$	-1	$-\frac{2}{3}$	$+\frac{2}{3}$	0	0	1	$+\frac{2}{3}$	$-\frac{4}{3}$	$+\frac{2}{3}$

$$\psi_L^\ell = \begin{pmatrix} \ell^- \\ \nu_\ell \\ N_\ell^c \end{pmatrix}_L \qquad Q_L^1 = \begin{pmatrix} u \\ d \\ d' \end{pmatrix}_L , \; Q_L^2 = \begin{pmatrix} c \\ s \\ s' \end{pmatrix}_L , \; Q_L^3 = \begin{pmatrix} b \\ t \\ t' \end{pmatrix}_L$$

$$\hat{u}_R \equiv (u_R, c_R, t_R, t'_R)$$

$$\hat{d}_R \equiv (d_R, s_R, b_R, d'_R, s'_R)$$

$$\begin{aligned} Q &= T_3 + \frac{1}{\sqrt{3}} T_8 + X \\ L &= \frac{4}{\sqrt{3}} T_8 + \mathcal{L} \quad . \end{aligned}$$

$$\langle\phi_1\rangle = \begin{bmatrix} k_1 \\ 0 \\ 0 \end{bmatrix}, \langle\phi_2\rangle = \begin{bmatrix} 0 \\ 0 \\ n_1 \end{bmatrix}, \langle\phi_3\rangle = \begin{bmatrix} 0 \\ k_2 \\ n_2 \end{bmatrix}$$

$$SU(3)_L \otimes U(1)_X \xrightarrow{n_{1,2}} SU(2)_L \otimes U(1)_Y \xrightarrow{k_{1,2}} U(1)_Q$$

$$\mathcal{L}_{\rm Kin} = \sum_i (D^\mu \phi_i)^\dagger (D_\mu \phi_i) \qquad D_\mu \phi_i = \partial_\mu \phi_i + i\frac{g_1}{\sqrt{2}}\,\mathbf{W}_\mu . \phi_i + i\sqrt{2} g_2 X_i\, \mathbf{B}_\mu\, \phi_i$$

$$\mathbf{W}_\mu = \begin{pmatrix} W^3 + \frac{1}{\sqrt{3}} W^8 & W^+_{12} & W^+_{45} \\ W^-_{12} & -W^3 + \frac{1}{\sqrt{3}} W^8 & W^6 - iW^7 \\ W^-_{45} & W^6 + iW^7 & -\frac{2}{\sqrt{3}} W^8 \end{pmatrix}$$

$$(W^\pm_{12} \text{ and } W^\pm_{45}) \quad \rightarrow \quad W^\pm \text{ and } W'^\pm$$

$$W^3,\, W^6,\, W^8,\, B \quad \rightarrow \gamma\,, \quad Z\,, \quad Z'\,, \quad X$$

$$W^7 \equiv Y$$

$$\begin{aligned} m^2_W &= g_1^2\,(k_1^2 + \frac{k_2^2 n_1^2}{n_1^2 + n_2^2})\,, \\ m^2_{W'} &= g_1^2 (n_1^2 + n_2^2)\,, \\ m^2_Z &= \frac{g_1^2 (3g_1^2 + 4g_2^2)}{3g_1^2 + g_2{}^2}\,(k_1^2 + \frac{k_2^2 n_1^2}{n_1^2 + n_2^2})\,, \\ m^2_{Z'} &= \frac{4}{9}(3g_1^2 + g_2^2)(n_1^2 + n_2^2)\,, \\ m^2_X &= m^2_Y \;=\; g_1^2 (n_1^2 + n_2^2). \end{aligned}$$

$$
\begin{aligned}
\mathcal{L}_{NC} \quad & \supset \frac{g_1}{\sqrt{2}}\,\overline{\nu_L}\,\gamma_\mu\,\nu_L W^3 - \frac{g_1}{\sqrt{6}}\,\overline{\nu_L}\,\gamma_\mu\,\nu_L W^8 \\
& - \frac{g_1}{\sqrt{2}}\,\overline{N_L^c}\,\gamma_\mu\,\nu_L\,W^6 + \frac{\sqrt{2}g_2}{3}\overline{\nu_L}\,\gamma_\mu\,\nu_L B
\end{aligned}
$$

The mixing of W^6 with W^3, W^8 and B is proportional to the small parameter given by

$$
\epsilon \sim \frac{k_2 n_2}{n_1^2 + n_2^2} \ll 1
$$

$$\mathcal{L}_{\rm leptons} = y^{\ell}_{ij}\overline{\psi^i_L}\, l^j_R\, \phi_1 + y^a_{ij}\, \psi^{iT}_L C^{-1} \psi^j_L\, \phi_1 \\ + y^s_{ij}\, \overline{\psi^i_L}\, S^j\, \phi_2 + \text{h.c.}$$

y^a is antisymmetric

in the basis $(\nu_L,\, N^c,\, S)$

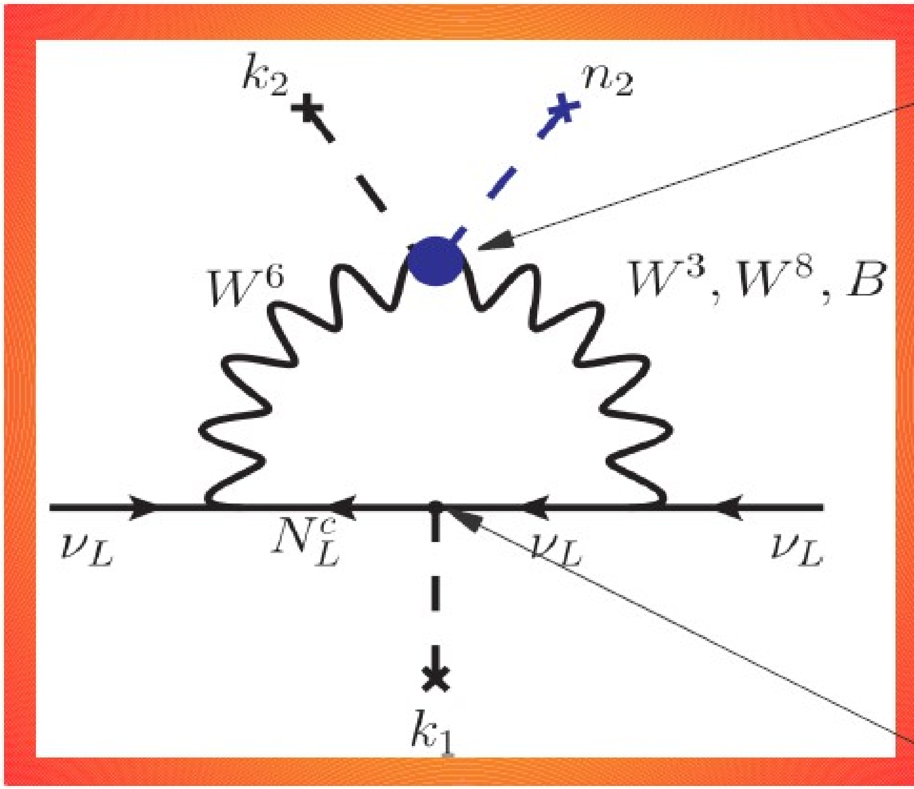
$$M_\nu = \begin{pmatrix} 0 & m_D & 0 \\ & 0 & M \\ & & 0 \end{pmatrix}$$

heavy states form Dirac pairs with masses M_{Di}

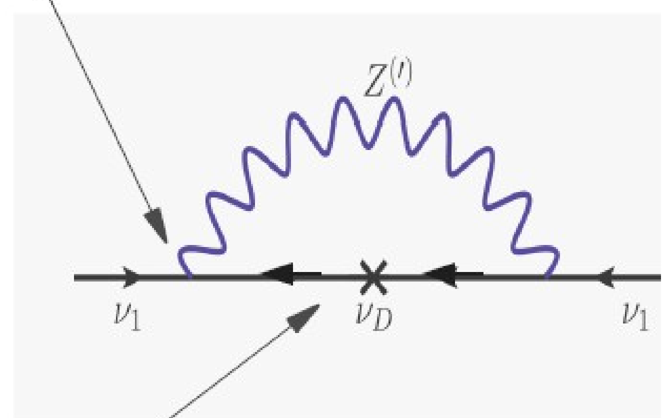
$$M_{Di} = (\sqrt{m_D \cdot m_D{}^T + M \cdot M^T})_i$$

$$\langle\phi_1\rangle = \begin{bmatrix} k_1 \\ 0 \\ 0 \end{bmatrix}, \langle\phi_2\rangle = \begin{bmatrix} 0 \\ 0 \\ n_1 \end{bmatrix}, \langle\phi_3\rangle = \begin{bmatrix} 0 \\ k_2 \\ n_2 \end{bmatrix}$$

Lepton number is broken by $n_2 \neq 0$



$$\epsilon \sim \frac{k_2 n_2}{n_1^2 + n_2^2}$$



$$\beta \simeq m_D/M$$

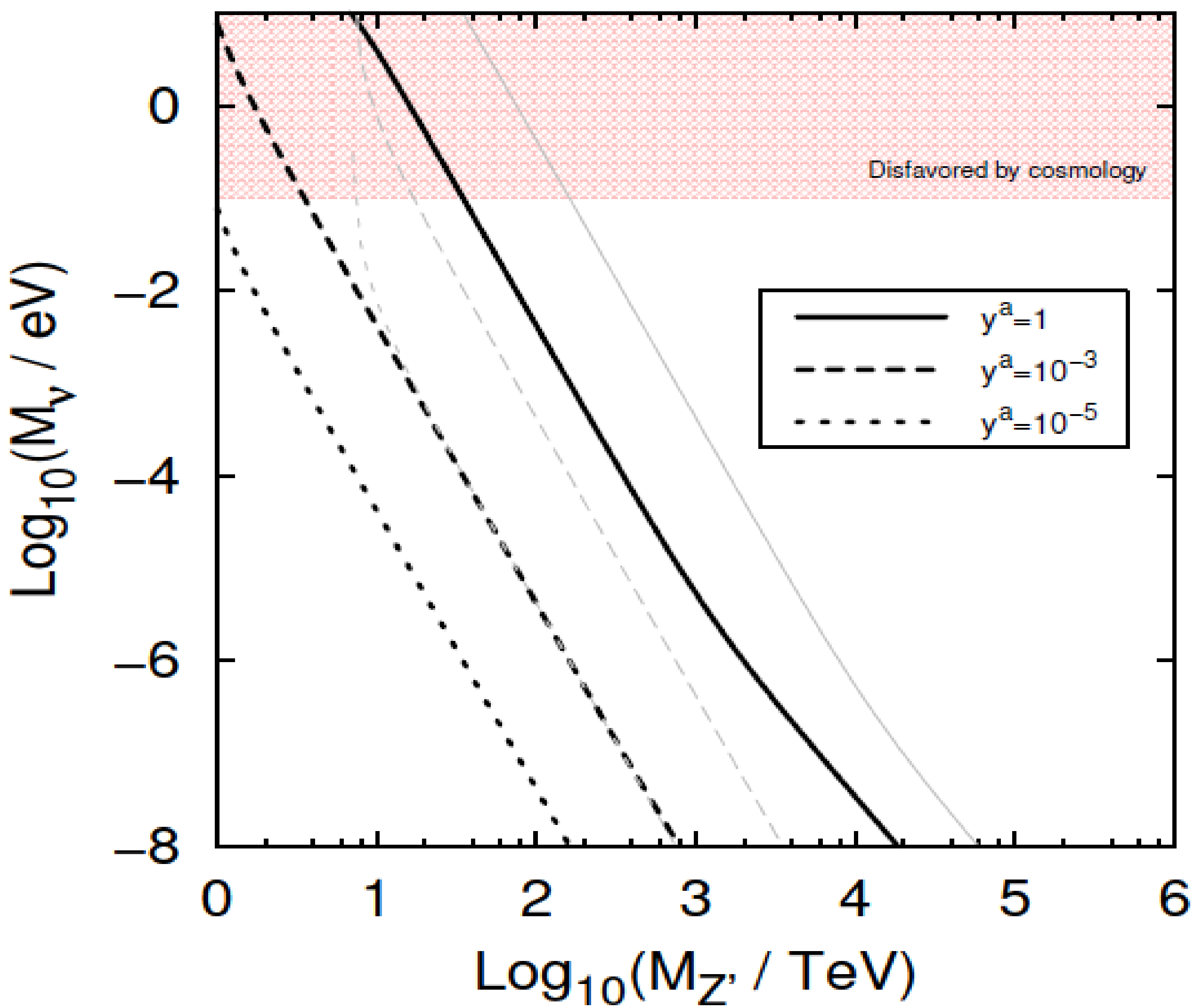
$$m_{\nu_{\rm light}} \simeq \frac{g^2\,\epsilon\,\beta}{16\pi^2} M_D \frac{m_{Z'}^2}{M_D^2 + m_{Z'}^2} \log\frac{m_{Z'}^2}{M_D^2}$$

in the basis (ν_L, N^c, S)

$$M_\nu = \begin{pmatrix} 0 & m_D & 0 \\ & 0 & M \\ & & 0 \end{pmatrix} \qquad U_\nu = \begin{pmatrix} c & -\frac{s}{\sqrt{2}} & \frac{s}{\sqrt{2}} \\ 0 & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \\ -s & -\frac{c}{\sqrt{2}} & \frac{c}{\sqrt{2}} \end{pmatrix}$$

$c \approx 1$ and $s \equiv \beta \simeq m_D/M \ll 1$

$$\begin{aligned} \nu_L &\simeq \nu_1 - \beta\,\nu_2 + \beta\,\nu_3\,; \\ N_L^c &\simeq \frac{1}{\sqrt{2}}(\nu_2 + \nu_3)\,; \\ S &\simeq -\beta\,\nu_1 + \frac{1}{\sqrt{2}}(-\nu_2 + \nu_3) \end{aligned}$$



(n_2) is fixed at 1 TeV (thick lines) and 10 TeV (thin lines)

The Yukawa Lagrangian of the quark sector is

$$\begin{aligned}\mathcal{L}_{\text{quarks}} &= y^u_{\alpha,i}\,\overline{Q^\alpha_L}\,\hat{u}^i_R\,\phi^*_1 + y^u_{3,i}\,\overline{Q^3_L}\,\hat{u}^i_R\,\phi_3 \\ &+ y^d_{3,i}\,\overline{Q^3_L}\,\hat{d}^i_R\,\phi_1 + y^d_{\alpha,i}\,\overline{Q^\alpha_L}\,\hat{d}^i_R\,\phi^*_3 + \text{h.c.} \qquad (21)\end{aligned}$$

and α=1,2. Contractions over i and α indices are assumed. The up (y^u) and down (y^d) quark mass matrices are respectively 4×4 and 5×5. Note that we made use of the same auxiliary parity symmetry to charge Q^3_L and $\hat{d}_R$. After spontaneous symmetry breaking, the top mass is proportional to k_2 while the bottom mass is proportional to k_1. Hence k_1 and k_2 determine the electroweak scale. On the other hand, the masses of the extra quarks d', s', t' are proportional to n_1 and n_2 which must be of the order of TeV or greater in order to escape detection at the LHC. Here we note a novel feature of this model, namely, that while the extra quarks have standard electric charges, they carry two units of lepton number, relating them directly to the lepton sector.

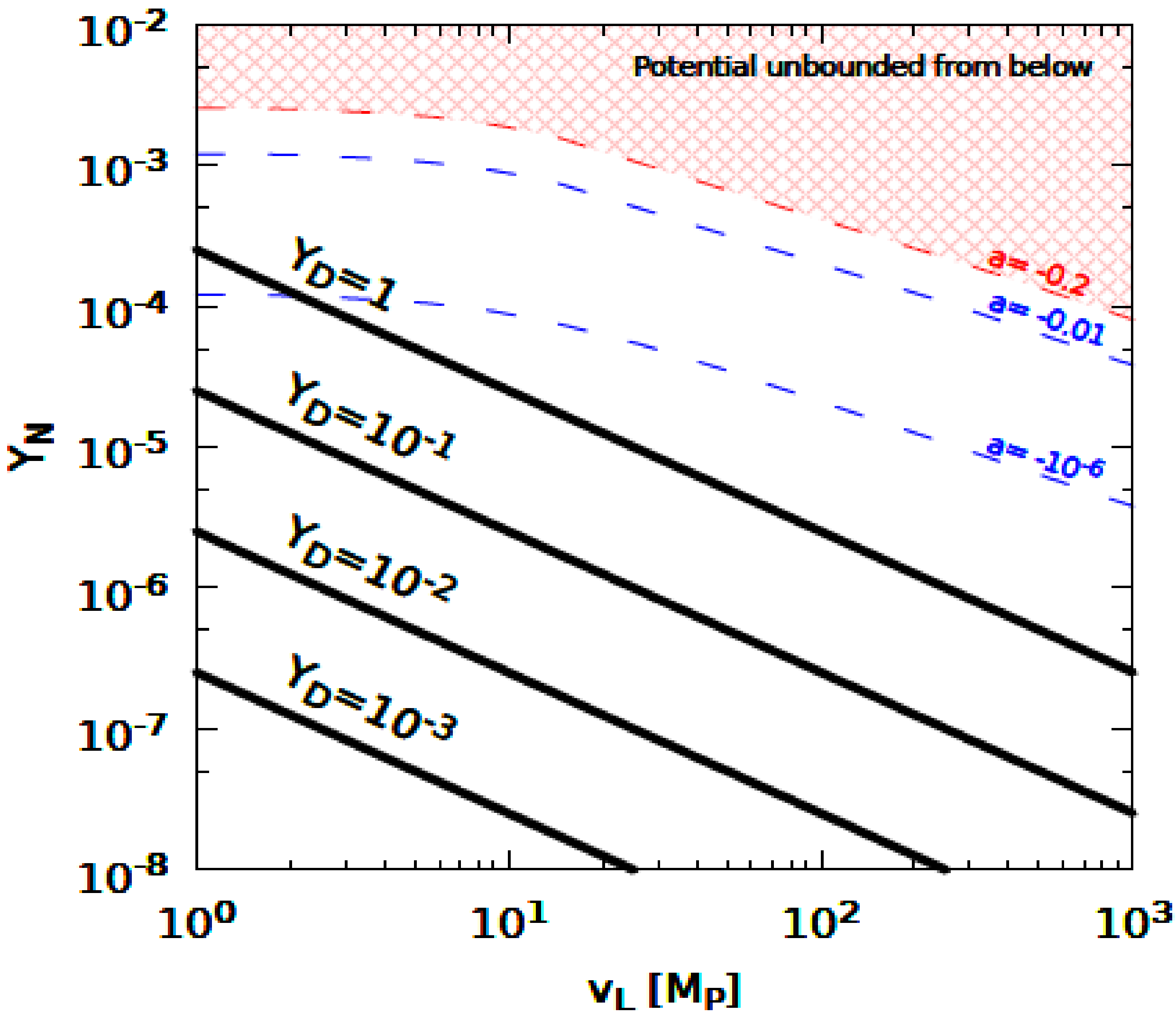


FIG. 3: Majoron inflation: Y_N vs. $v_{\rm L}$ for various Y_D. Dashed lines show some values of the coefficient a of the Coleman-Weinberg term in the potential. Solid black lines are upper bounds on Y_N for the corresponding Dirac neutrino Yukawa coupling Y_D.

$$\epsilon(\rho) = \frac{1}{2} M_P^2 \left(\frac{V'}{V}\right)^2 , \quad \eta(\rho) = M_P^2 \left(\frac{V''}{V}\right) \qquad \zeta^2(\rho) = M_P^4 \left(\frac{V' V'''}{V^2}\right)$$

$$n_s \simeq 1 - 6\epsilon + 2 , \quad r \simeq 16\epsilon ,$$

$$\alpha \equiv \frac{dn_s}{d\ln k} \simeq 16\epsilon\eta - 24\epsilon^2 - 2\zeta^2$$

$$\Delta_{\mathcal{R}}^2 = \left. \frac{V}{24\,\pi^2\, M_P^4\, \epsilon} \right|_{k_0} \qquad \Delta_{\mathcal{R}}^2 = 2.215 \times 10^{-9} \text{ to fit PLANCK CMB}$$

$$k_0 = 0.05\,\mathrm{Mpc}^{-1}$$

$$N = \frac{1}{\sqrt{2} M_P} \int_{\rho_e}^{\rho_0} \frac{d\rho}{\sqrt{\epsilon(\rho)}} \qquad \epsilon(\rho_e) \approx 1$$

Running spectral index