WHY ARE ν LIGHT?

(I) DIMENSIONAL ANALYSIS

LAWRENCE HALL
UC BERKELEY
2/04 KEK

A celebration:

$$m_\nu \propto \frac{v^2}{M_R}$$

Gell-Mann, Ramond, Slansky
Yanagida

WHAT WILL CONVINCE US?

- no low energy interactions
- leptogenesis — Fukugita, Yanagida (86)
- lepton flavor violation — Borzumati, Masiero (86); Hisano, Moroi, Tobe, Yamaguchi, Yanagida (95)
- a theory of flavor matrices with

★ $N_{observables} \gg N_{parameters}$

eg. SO(10)
Buchmuller
Pati
Raby

An Alternative:

$$m_\nu \propto \frac{v^2}{M}$$

OR

$$m_\nu \propto f$$

Spontaneous Breaking of Lepton Symmetries

Chikashige, Mohapatra, Peccei '80
Gelmini, Roncadelli '80
Georgi, Glashow, Nussinov '81

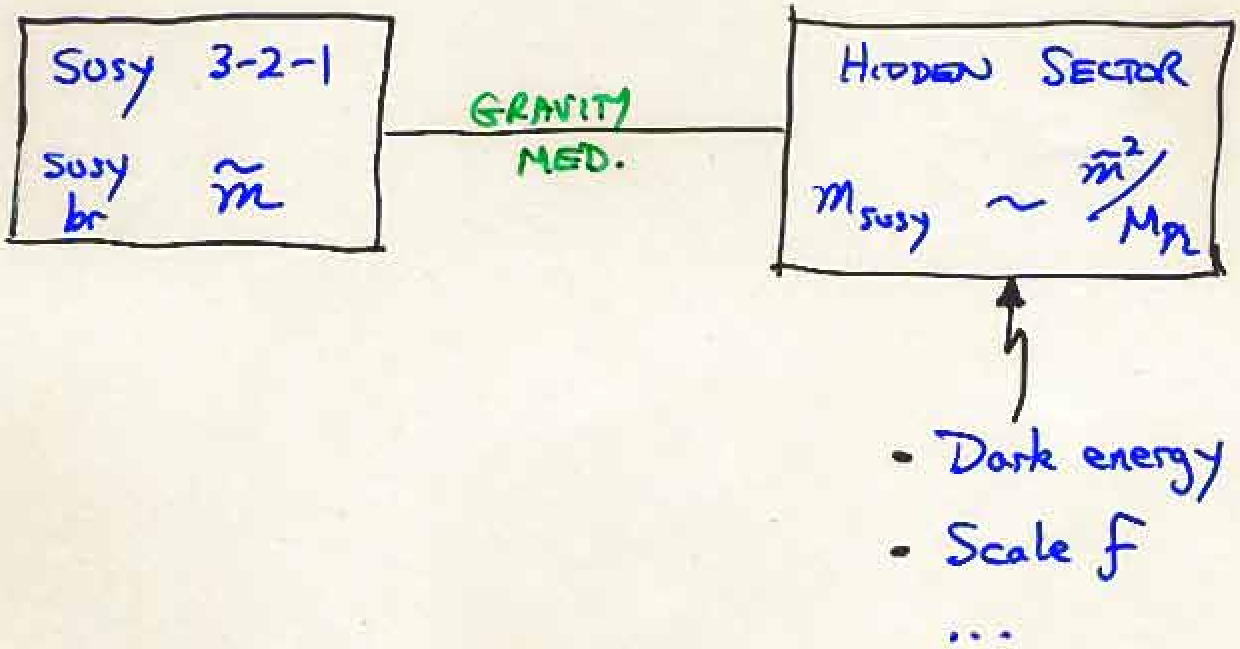
- studied phenomenology of the Majoron.
  not concerned with $f \ll v$ for why m_ν light.

- Today: Triplet MM excluded.
  Singlet MM — possible origin of M_R

HAVE WE NEGLECTED $f \ll v$?

OBJECTION:

- Hierarchy problem: $v \ll M_{Pl}$
- Isn't $f \ll v \ll M_{Pl}$ worse?
- **Generalized Seesaw** — Arkani-Hamed, Kolda, Hall, Murayama (00)



- Low f does not upset gauge coupling unification.

CLAIM:

> THEORIES WITH $m_\nu \propto f \ll v$
> CAN BE TESTED VIA CMB OBSERVATIONS.

hep-ph/0312267

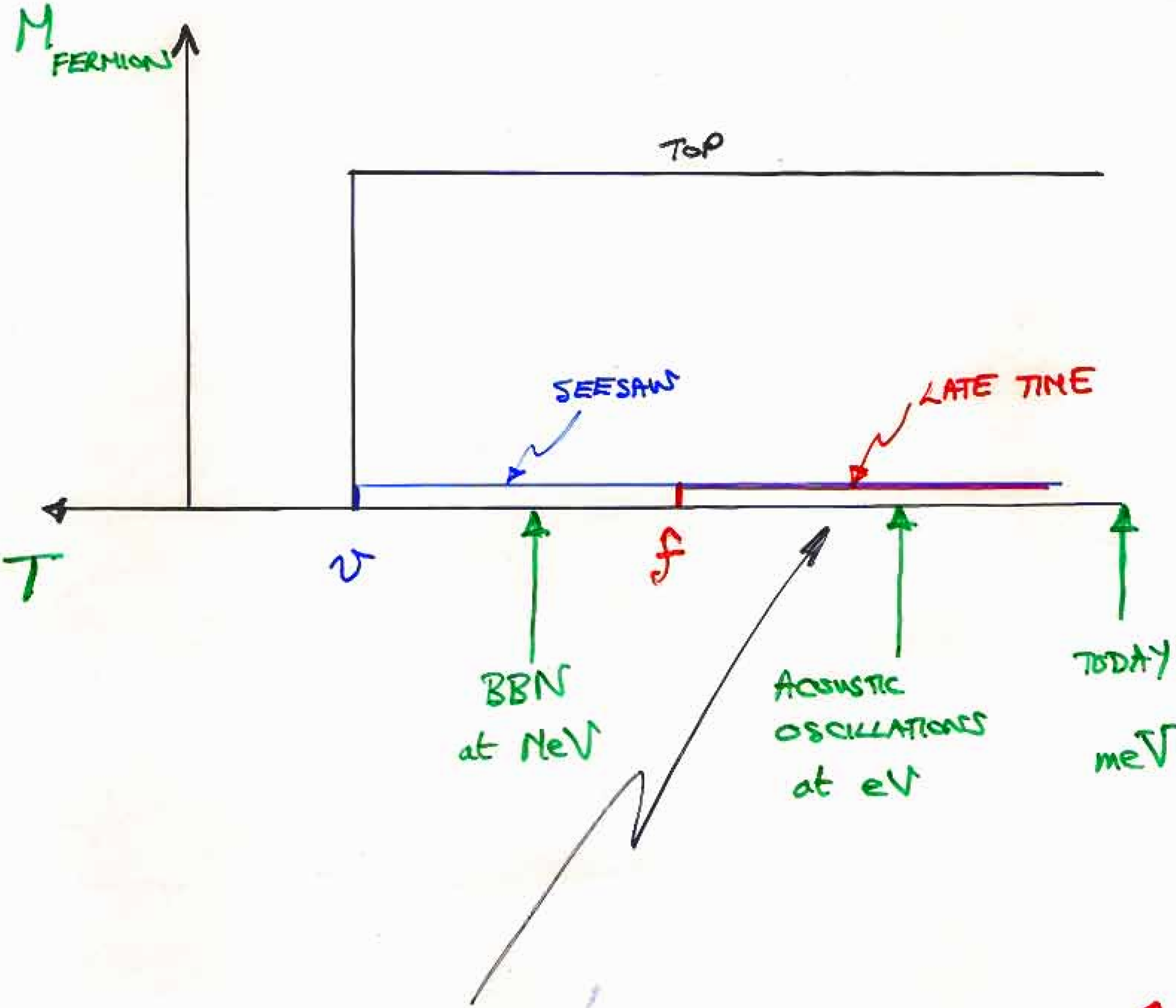
Chacko
Hall
Okui
Oliver

(II) LATE TIME ν MASSES

(III) THE CMB SIGNALS

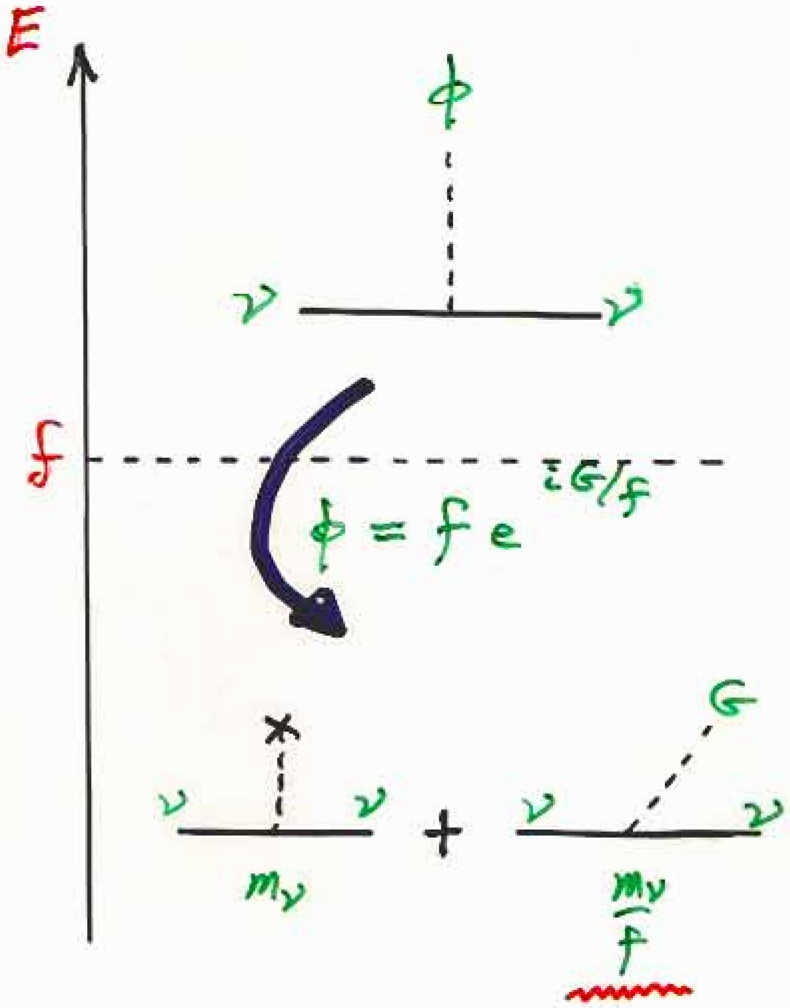
(IV) LSND

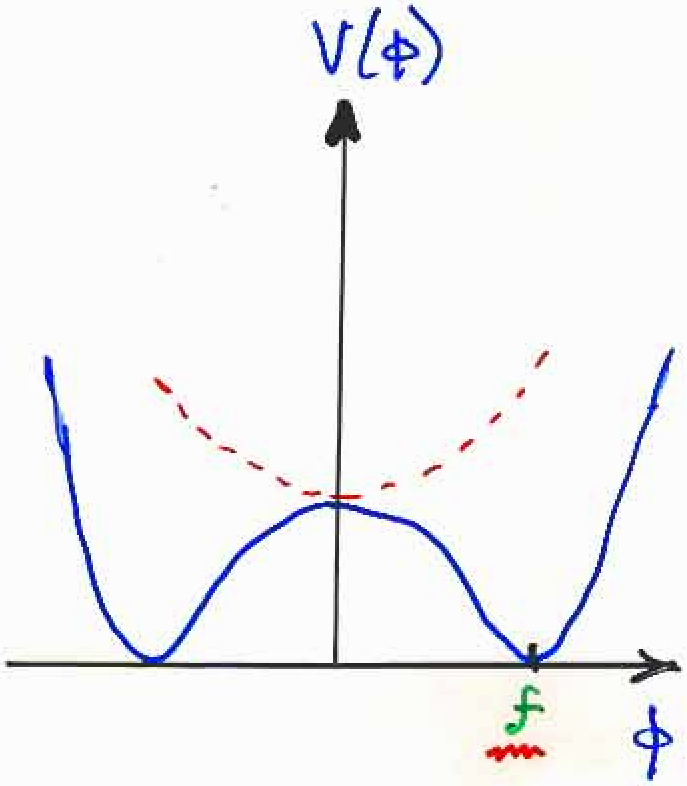
COSMOLOGICAL EVOLUTION OF MASSES



- ARE G PRODUCED IN EARLY UNIVERSE?
- CAN THEY AFFECT ACOUSTIC OSCILLATIONS?

SPONTANEOUS BREAKING OF LEPTON FLAVOR SYMM.





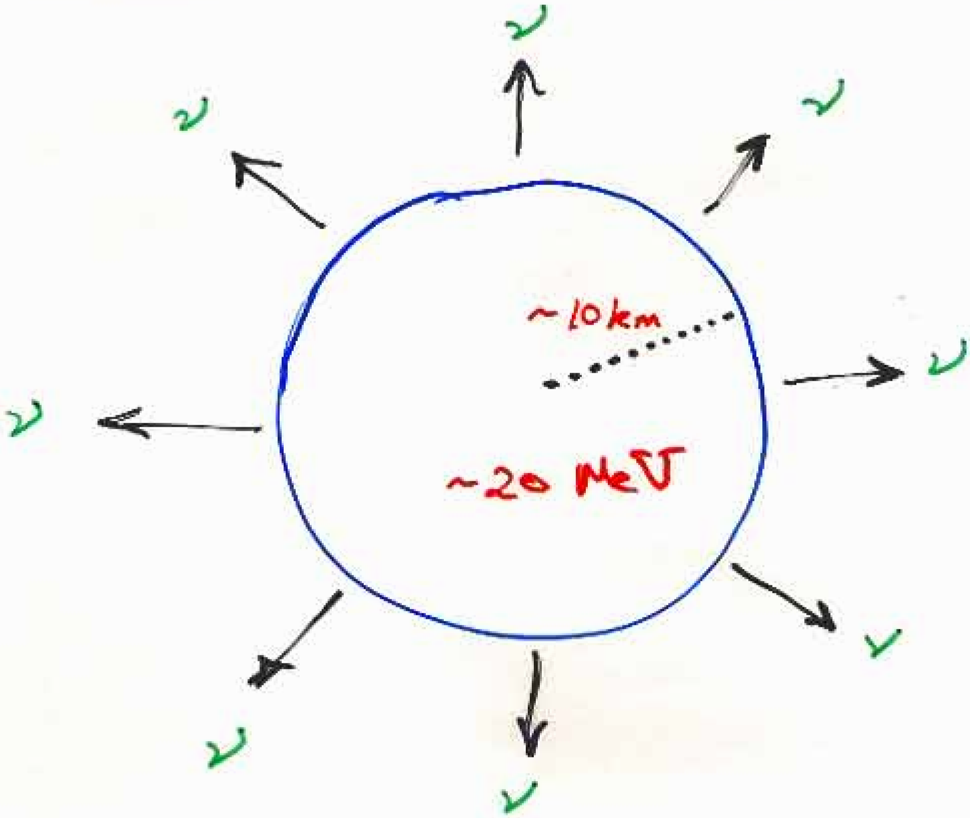
VARIATIONS

- Form of symmetry ($U(1)$, $SU(3)$, ...), { # G / flavor structure
- Spectrum of G
- Dirac or Majorana

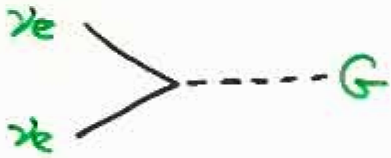
QUESTIONS

- Constraints ?
- Origin of 

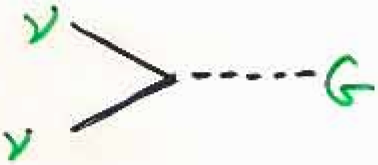
THE SUPERNOVA CONSTRAINT



COOLING BY SURFACE EMISSION OF ν IN ~ 10 secs

- 

deleptonizes core

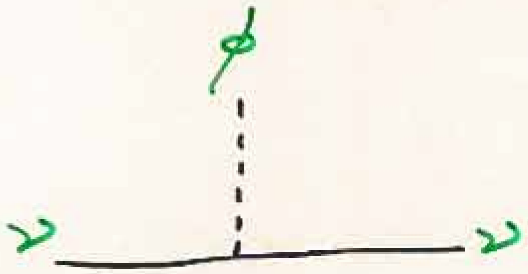
- 

cooling by volume emission of G

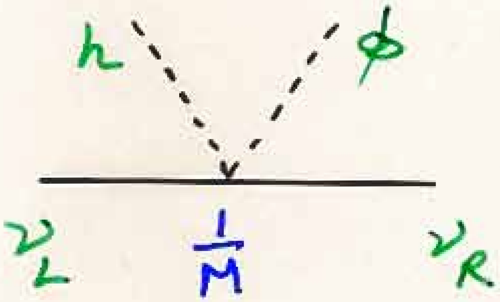
Complicated.
Depends on m_G.

$$f \gtrsim 10 \text{ keV}$$

ORIGIN OF INTERACTION.

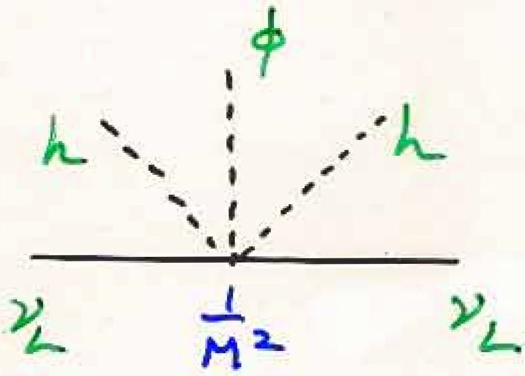


DIRAC



$$m_\nu = \left(\frac{v}{M}\right) f$$

MAJORANA



$$m_\nu = \left(\frac{v}{M}\right)^2 f$$

Since $m_\nu \lesssim \text{eV}$ & $f \gtrsim \text{keV}$ there are two contributions to smallness of m_ν

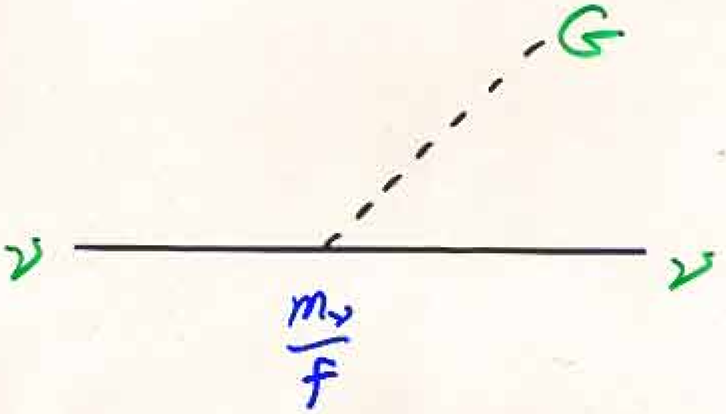
1. $f \ll v$ (ORIGINAL IDEA)

2. $\frac{v}{M} \ll 1$ (cf SEESAW!)

* BUT $\phi \longrightarrow \phi^2$ *

Two Free Parameters.

f



m_G

$= 0$ (exact Goldstone boson)

small but non-zero (pseudo-Goldstone boson e.g. axion)

For example, from gravitational effects:

$$m_G^2 \simeq \frac{f^3}{M_{Pl}}$$

III

THE CMB SIGNALS

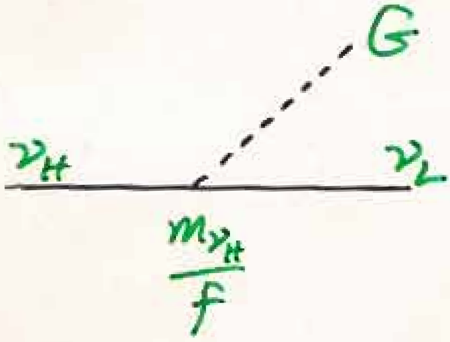
- G, ν_R PRODUCTION

- EFFECTS ON ACOUSTIC OSCILLATIONS

- RANGE OF f, m_G

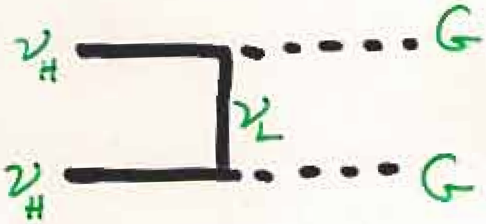
COSMOLOGICAL PRODUCTION OF G, ν_R

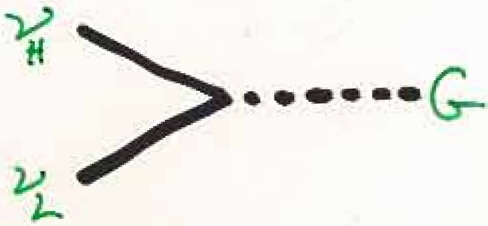
- Majorana case

- 

  no ν_R

- G production:



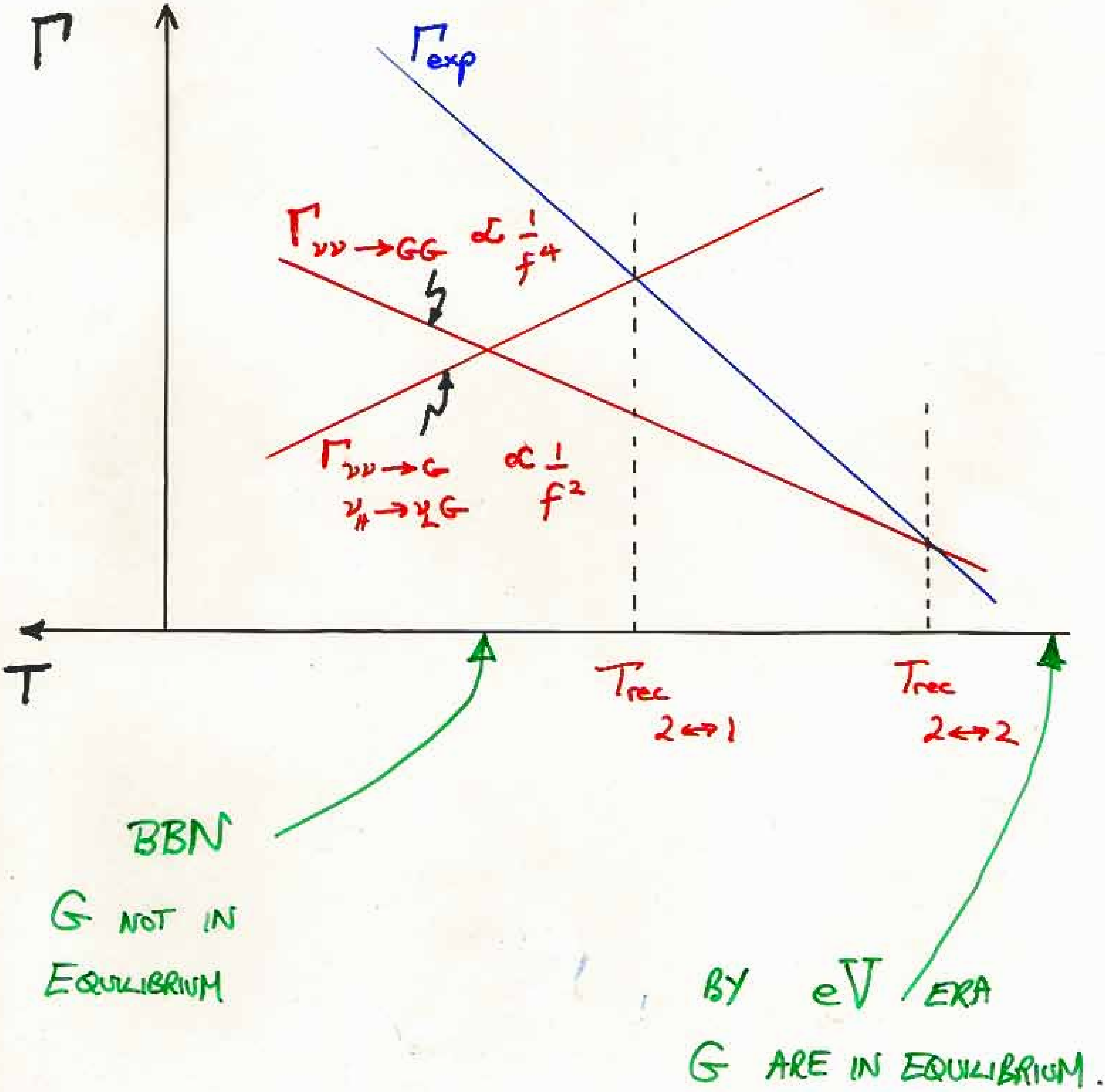


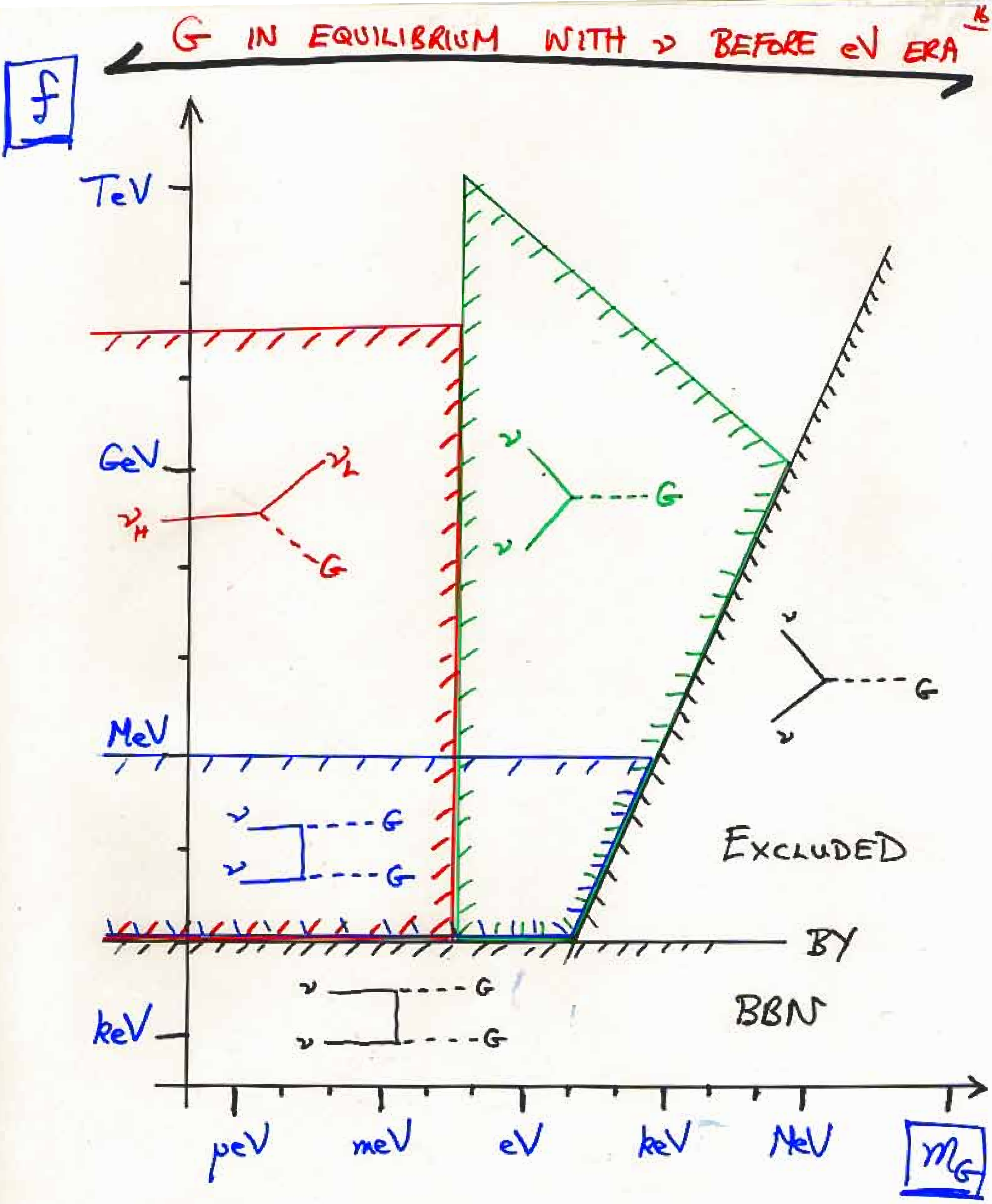
$(m_G > m_{\nu_H})$

$(m_{\nu_H} > m_G)$

Study Reaction Rates:

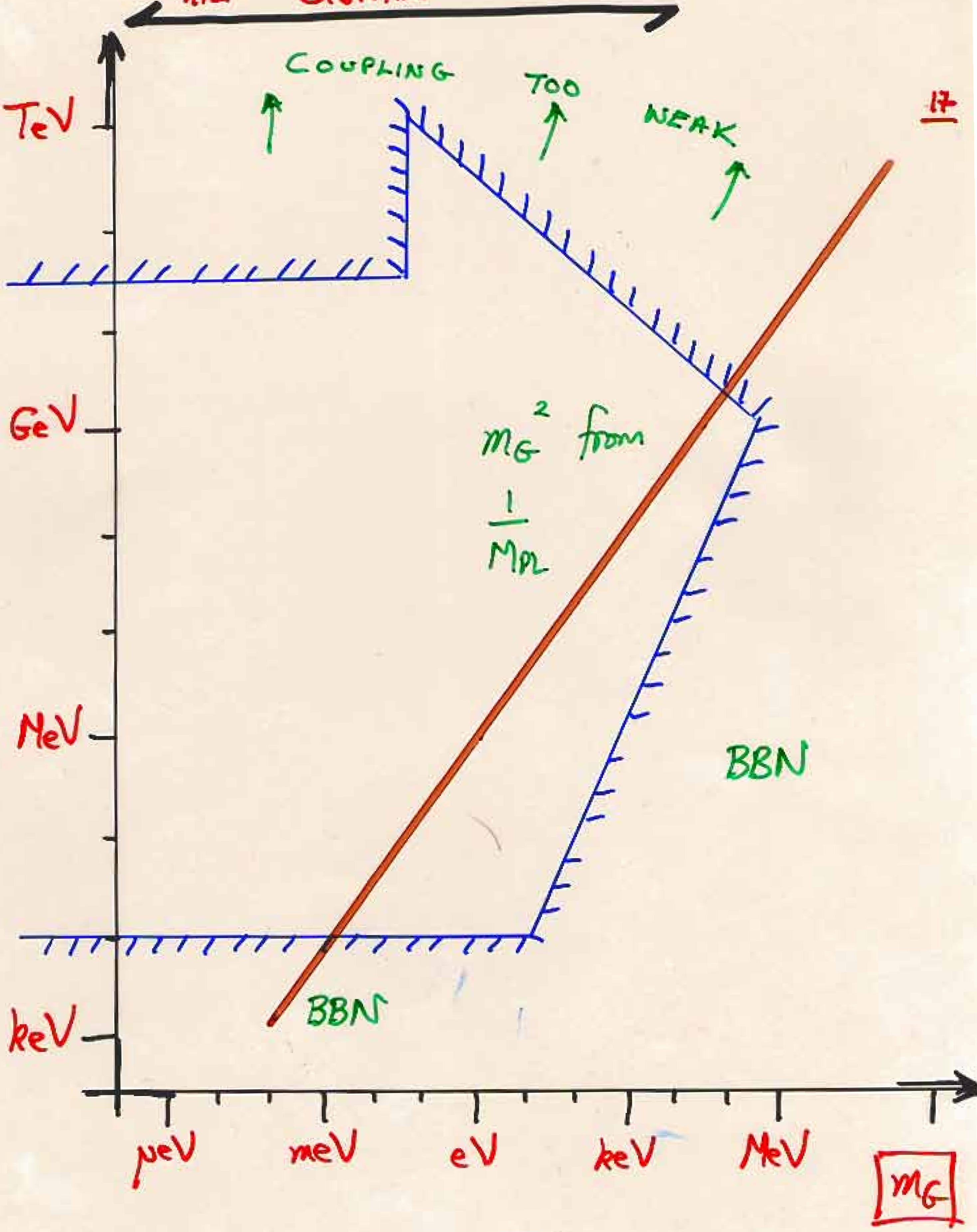
G PRODUCTION REACTION RATES.



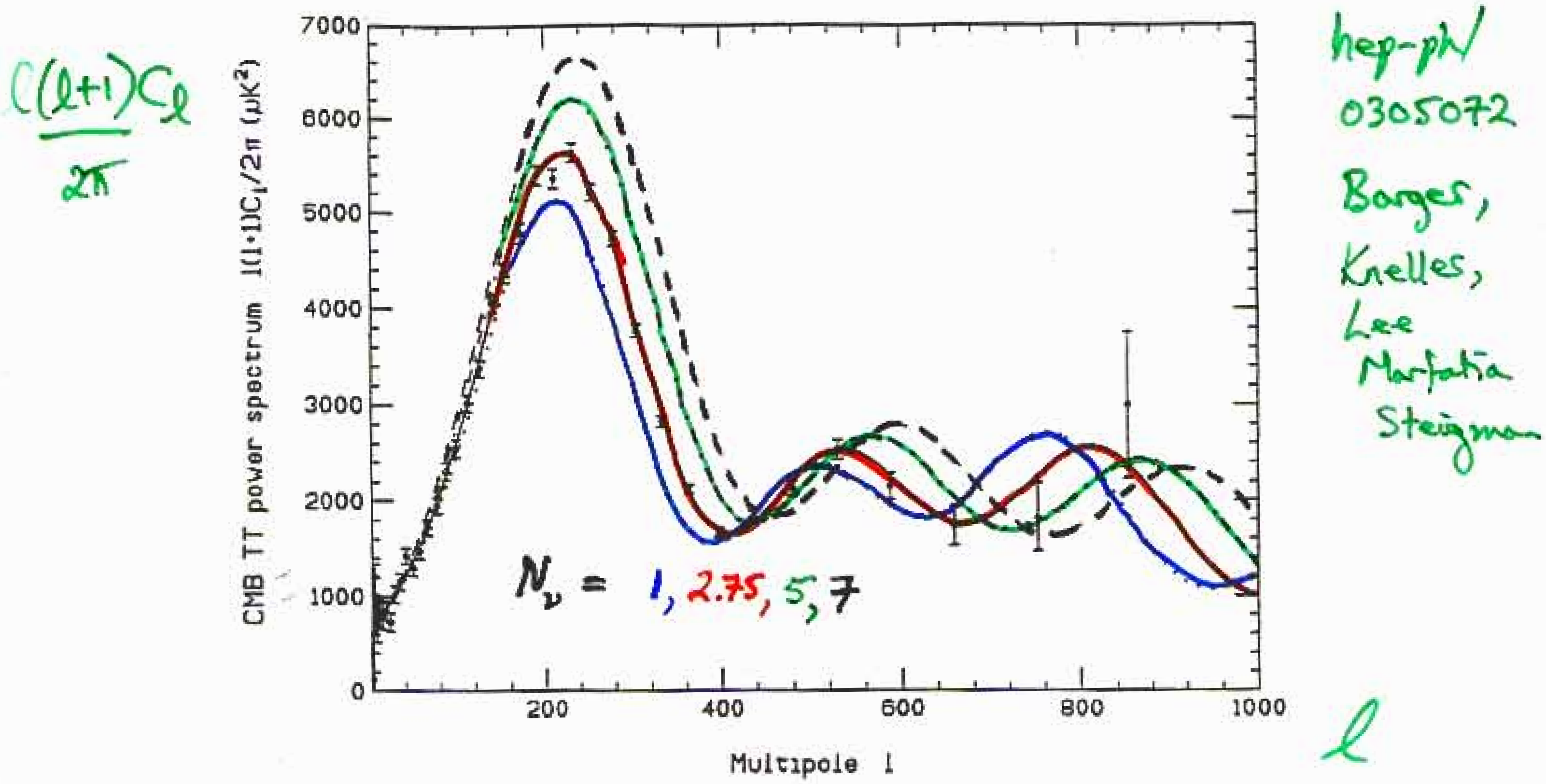

G IN EQUILIBRIUM WITH ν BEFORE eV ERA
f
TeV
GeV
MeV
keV
μeV
meV
eV
keV
MeV
m_G
EXCLUDED
BY
BBN

THE SIGNAL REGION

f



RADIATION ENERGY DENSITY AT eV ERA : $N_{\nu_{CMB}}$



As $N_\nu \uparrow$: smaller horizon at last scatter, $\ell_{peak} \uparrow$

$z_{eq} \downarrow$

less damping at first two peaks

WMAP 1st year : $1 \lesssim N_{\nu_{CMB}} \lesssim 6$

EXPECTATIONS FOR : PLANCK $\Delta N_{\nu_{CMB}} = \pm 0.20$

CMBPOL $\Delta N_{\nu_{CMB}} = \pm 0.05$

$\Delta N_{\nu_{CMB}}$ FROM G DECAY

RECOUPLING

$(\nu) \longrightarrow (\nu, G)$ $\Delta\rho_{rad} = 0$!

DECAY

$T < m_G$: $G \longrightarrow \nu\nu$ $\Delta S = 0$

$(\text{if } m_G > m_\nu)$ $\Delta\rho_{rad} \neq 0$

eg

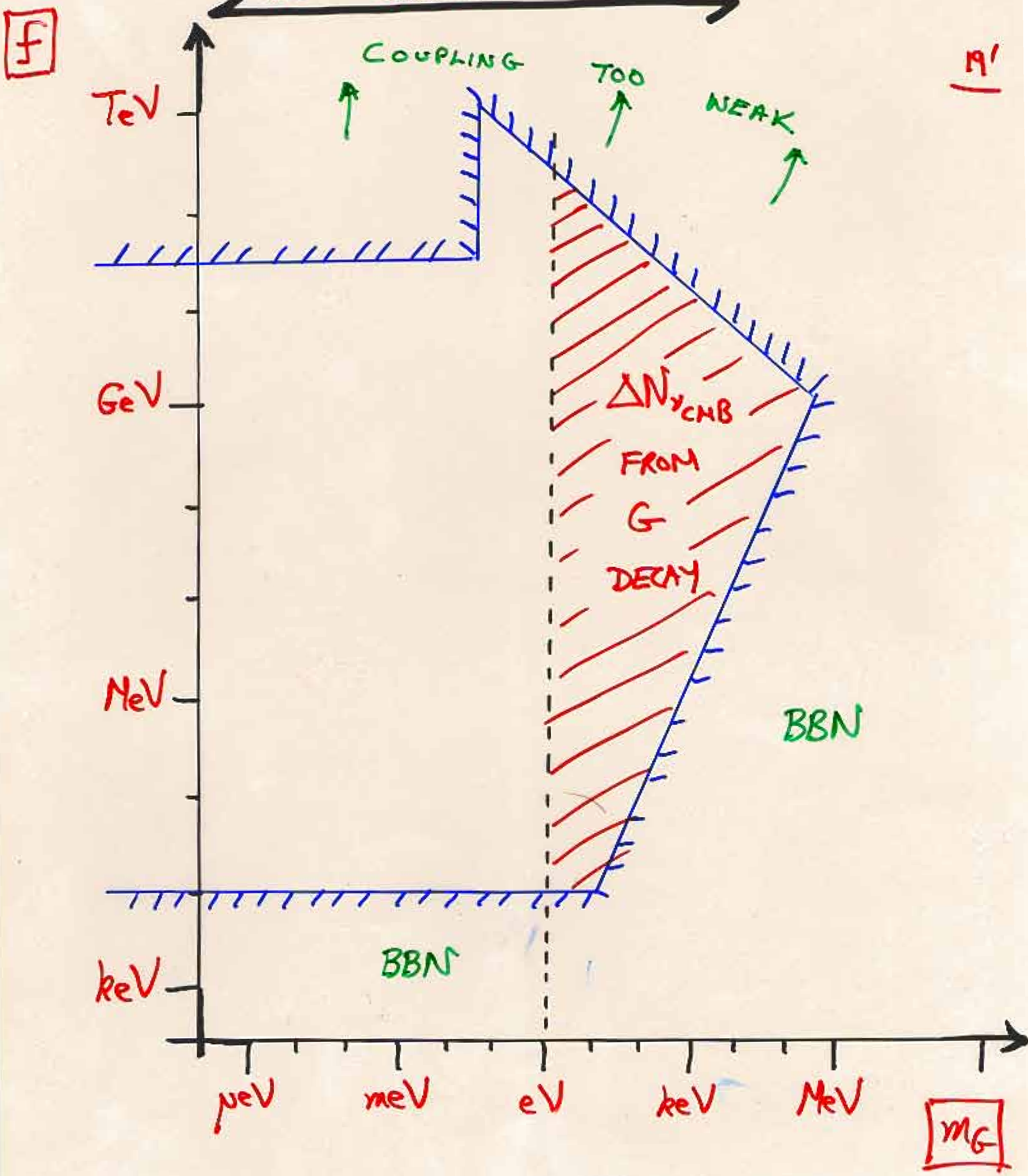
	n_G	DIRAC	MAJORANA
$U(1)$	1	3.09	3.18
$U(1)_L \times U(1)_R$	2	3.18	3.34
$SU(3)$	8	3.62	4.08
$SU(3)_L \times SU(3)_R$	16	4.08	—

(Signal Region)

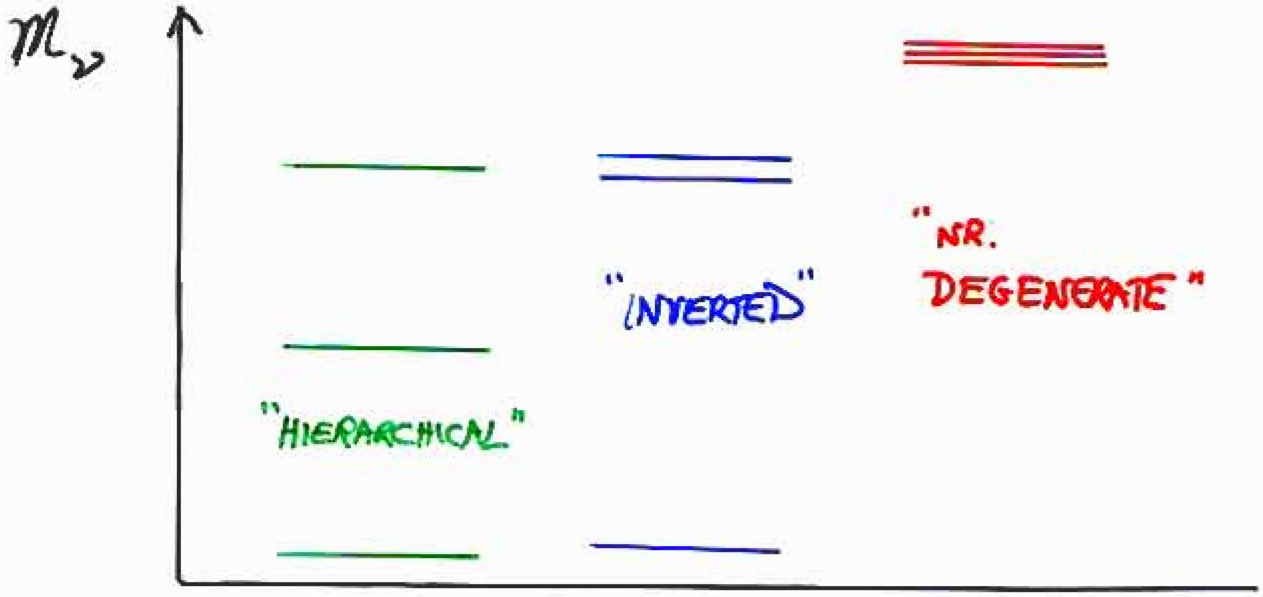
16'

19'

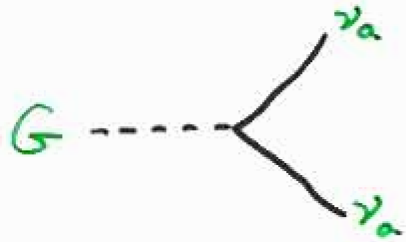
THE SIGNAL REGION



SENSITIVITY TO ν SPECTRUM.



GOLDSTONES COUPLE PROPORTIONAL TO MASS:



$\frac{m_{\nu_a}}{f}$

r_R	1,2,3	2,3	3

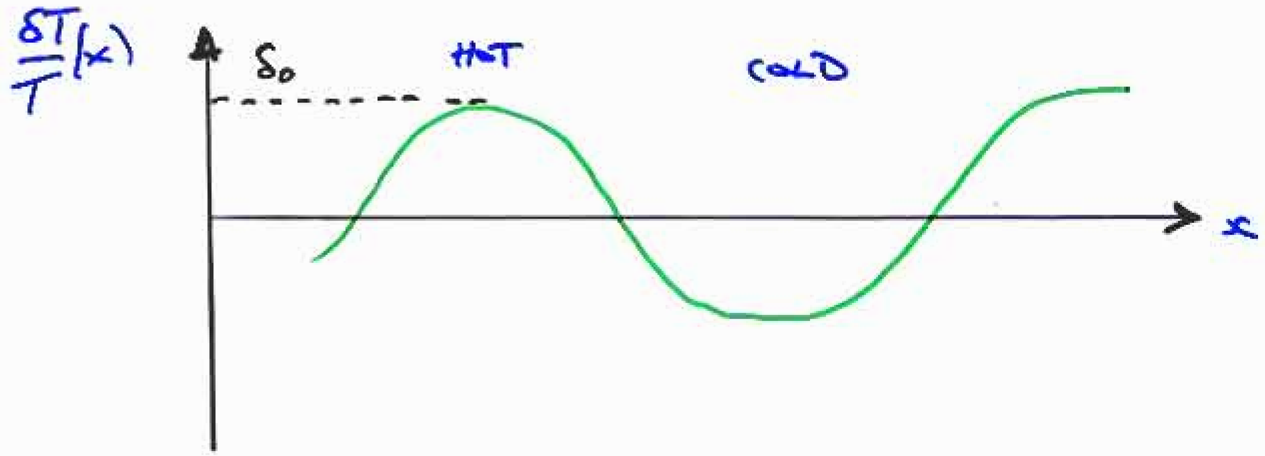
EXAMPLE

MAJORANA

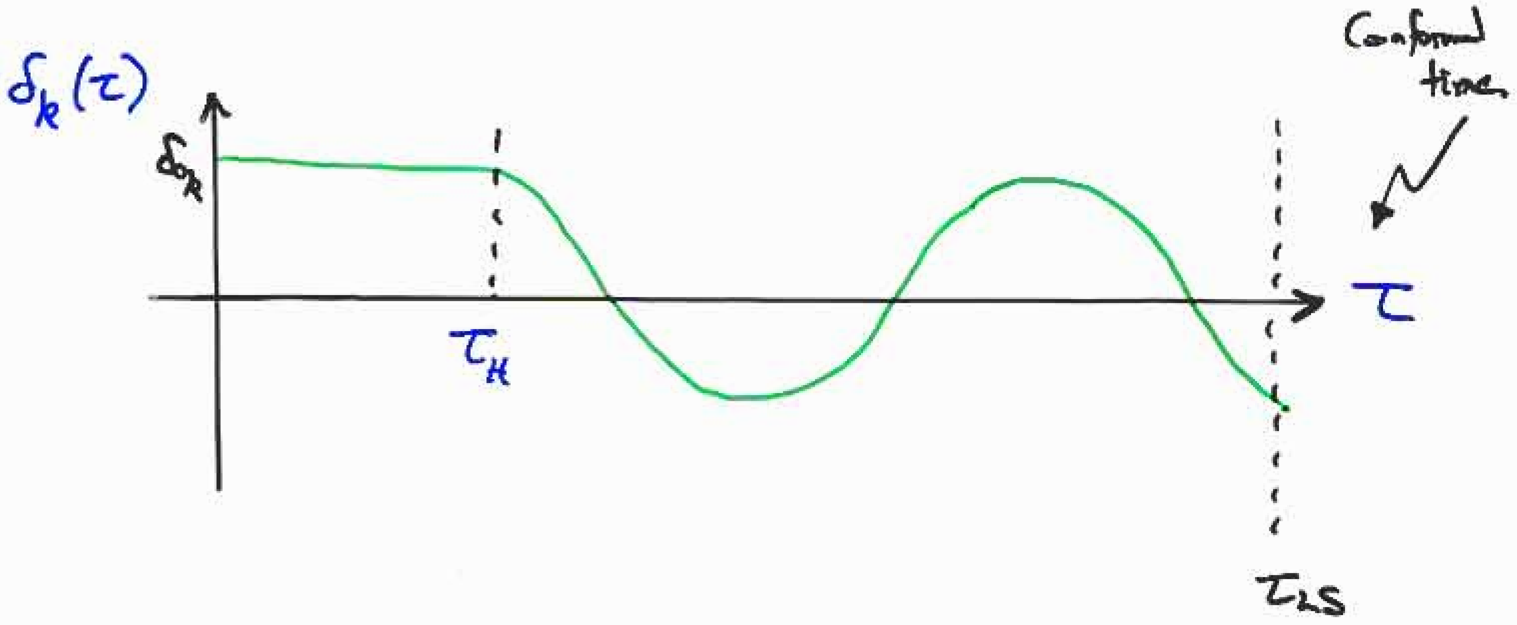
SU(3)

r_R	1	2	3
$N_{\nu_{CMB}}$	3.77	3.98	4.08

THE ν SCATTERING SIGNAL

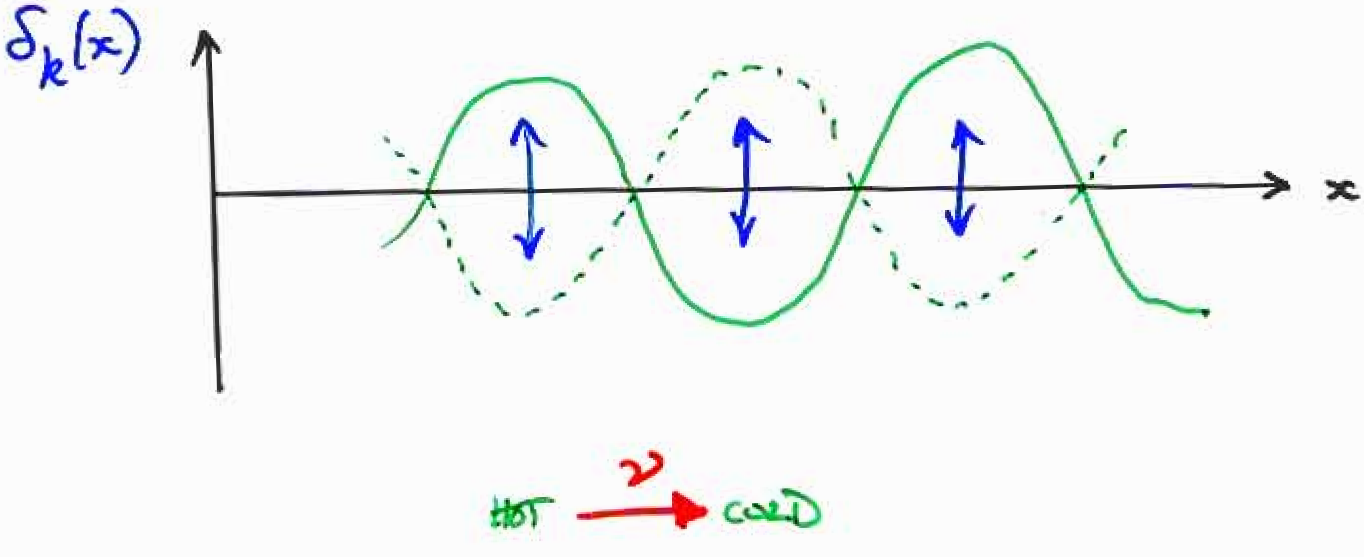


ONCE A FOURIER MODE ENTERS HORIZON, OSCILLATES AS A PRESSURE WAVE:



$$\delta_k(\tau) = \delta_{k_0} \cos\left[v_s k(\tau - \tau_H)\right]$$

IN STANDARD MODEL, ν FREE STREAM



Included in CMBFAST

Bashinsky & Seljak astro-ph/0310198 obtained analytic description:

$$\delta_k(\tau) = \delta_{k0}(1-\Delta)\cos\left[v_s k(\tau-\tau_H) + \delta\phi\right]$$

Challenge to observe. (Δ)

$\delta\phi$: $\frac{\pi}{5}\frac{\rho_\nu}{\rho_\nu+\rho_\gamma}$ NOT SMALL!

A SHIFT IN ℓ OF PEAKS.

Condition for nth peak:

$$v_s k_n (\tau_{LS} - \tau_H) + \delta\phi = n\pi$$

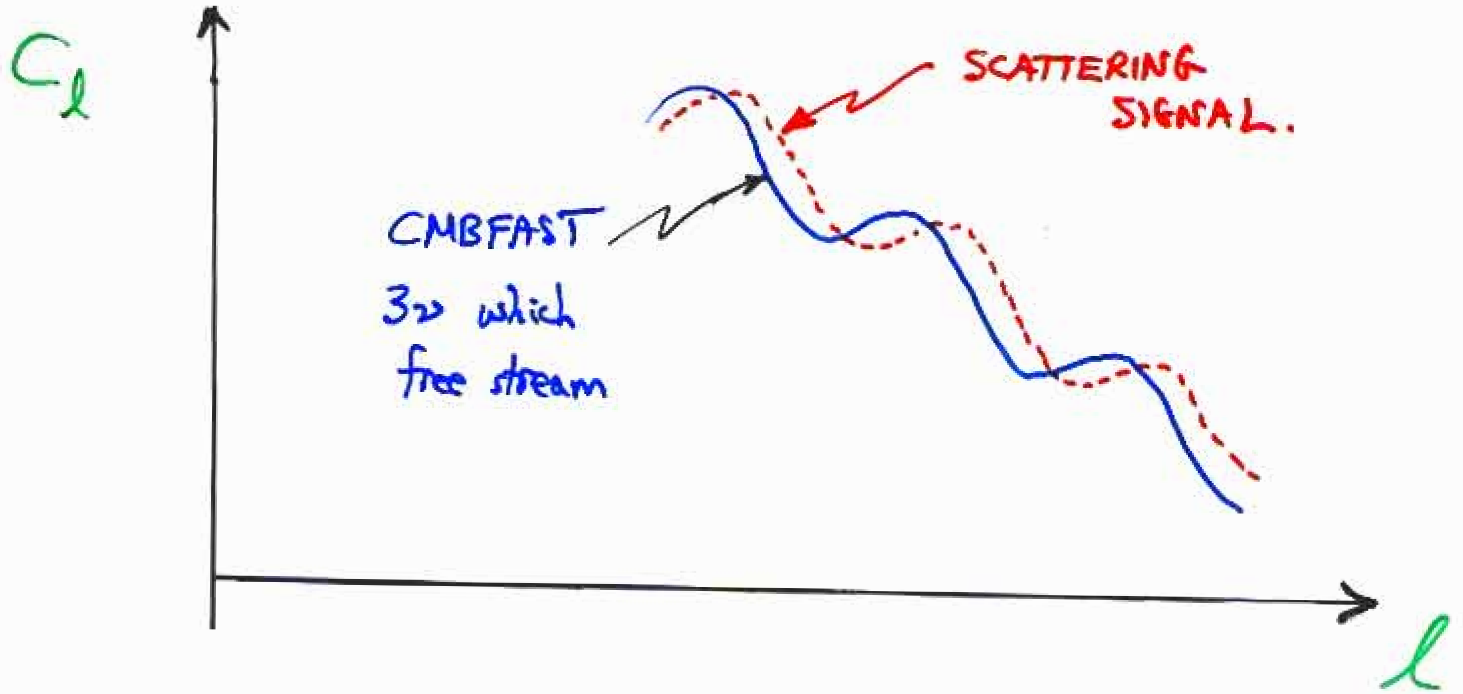
Translate $k_n \rightarrow \ell_n$

$$\boxed{\Delta \ell_n \simeq -7.8\, N_\nu}$$

- Other physical effects give $\Delta \ell_n$ which depends on n

- Need to go to very large ℓ to detect uniform shift of all peaks.

OUR SIGNAL : ν SCATT. PREVENTS FREE STREAMING



- No effect known which mimics this
- SIGNAL ⟹ Some /All of known ν have new interaction preventing free streaming at eV era.

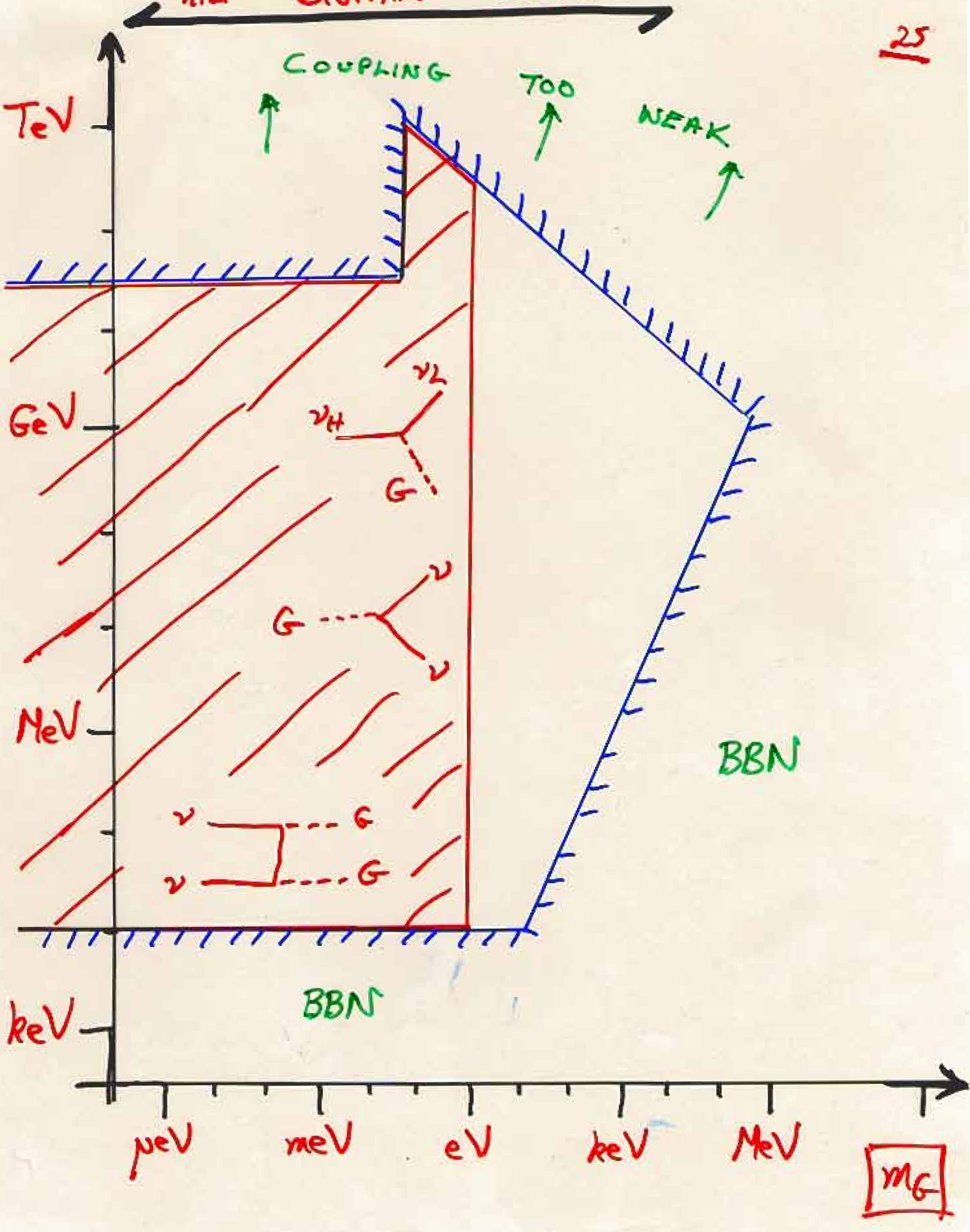
$$\Delta \ell_n = +7.8\, n_s$$

Sensitivity to spectrum. (Signal region)

Planck	$\Delta \ell_n = \pm 2$	(1σ)
CMBPOL	$\Delta \ell_n = \pm 1$	(1σ)

THE SIGNAL REGION

f



IV INCLUDING LSND.

IN PROGRESS
Chacko
Hall
Oliver
Perelstein

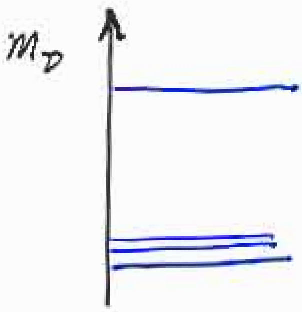
LSND

PRL 77 3082 (1996)

$\bar{\nu}_\mu \to \bar{\nu}_e$ $P \simeq 3.10^{-3}$

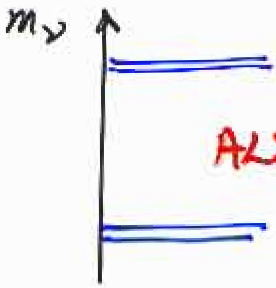
3-8σ stats.

A CHALLENGE FOR THEORY.



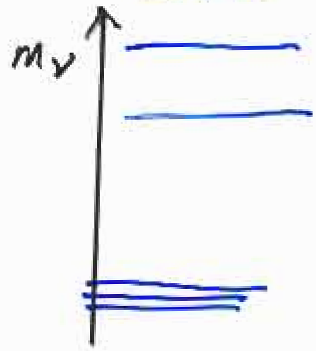
"3+1"

"2+2"



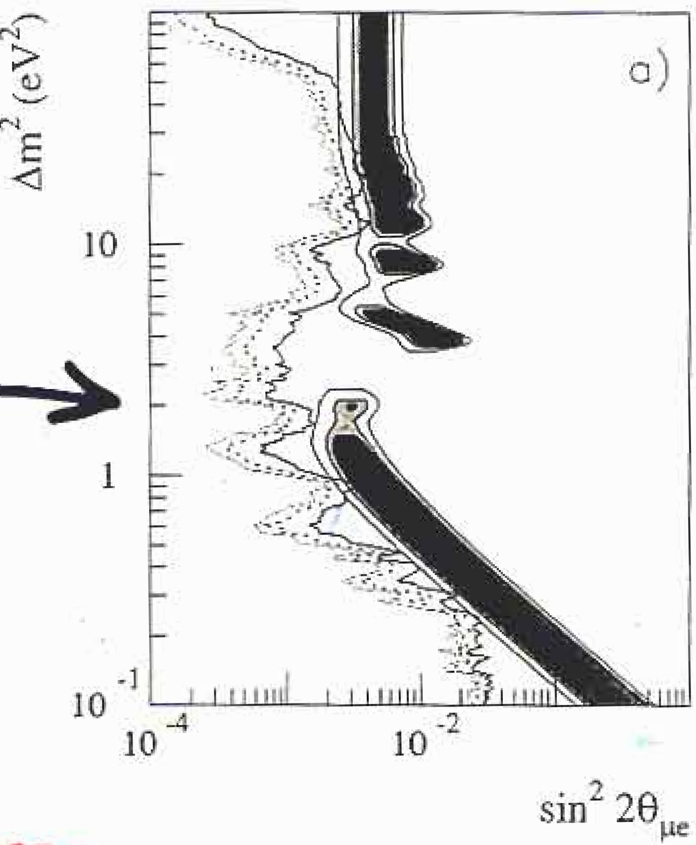
ALSO POOR

"3+2"



MUCH BETTER.

Sorel, Conrad, Shaevitz hep-ph/0305255



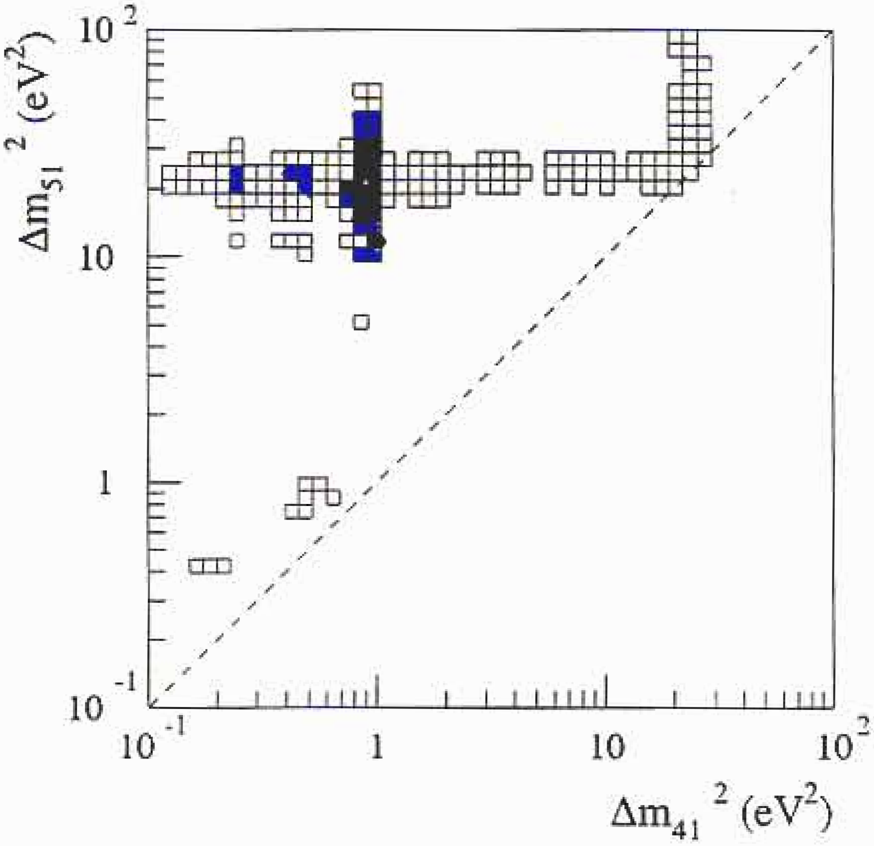
VERY POOR AGREEMENT WITH Bugey, Chooz, CCFR84 CDHS, KARMEN.

"3 + 2" FIT

90% C.L.

95% C.L.

99% C.L.



Sorel, Conrad Shaevitz hep-ph/0305255

PROBLEMS

- Why light sterile states (against seesaw)
- $\nu_{4,5}$ produced before BBN : $N_{\nu_{BBN}} \gtrsim 5$
- LSS + WMAP

  Very little HOT DM allowed $\sum_a m_{\nu_a} \leq 0.69$ eV

WHAT TO DO ?

CPT VIOLATION Murayama, Yanagida hep-ph/0010178

LATE TIME ν MASSES : PERFECT FIT

- Lepton flavour symmetries $\left\{ \begin{array}{l} \nu \\ \nu_s \end{array} \right.$ BOTH LIGHT

- $f < \text{MeV} \implies m_\nu = 0$ during BBN
  no oscill.
  $N_{\nu_{BBN}} = 3$

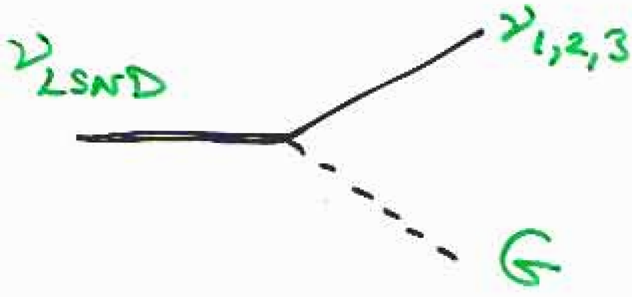
- $\nu_{4,5} \longrightarrow \nu_{1,2,3}\, G$ at $T \lesssim m_{4,5}$

  so $\sum_a m_{\nu_a}$ applies to $(m_{\nu_1} + m_{\nu_2} + m_{\nu_3})$

* $f < \text{MeV} \implies$ large couplings so signals must occur in CMB. *

$\Delta N_{\nu_{CMB}}$ SIGNAL

Now comes from decay of "LSND" neutrino :

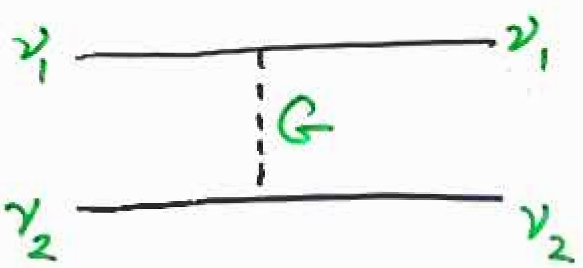


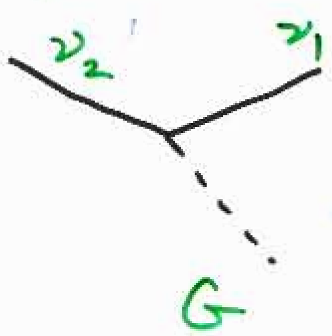
# ν_s	DIRAC	MAJ
1	3.26	3.22
2	3.48	3.42
3	3.68	3.60

(2 GOLDSTONES)

SCATTERING SIGNAL

Since $m_G \lesssim eV$ there must be a scattering signal from:





$n_s = 2$ OR 3

CONCLUSIONS

- A LOW SCALE OF LEPTON FLAVOR SYMMETRY BREAKING MAY CONTRIBUTE TO WHY ν ARE LIGHT $m_\nu \propto f$
- FOR A VERY WIDE RANGE OF (f, m_G) CMB SIGNALS WILL OCCUR.
- SCATT. SIGNAL $\Rightarrow$ Known ν possess new interaction at low energy.
- CAN PREDICT PRECISE NUMBERS FOR Δl_n , $\Delta N_{\nu_{CMB}}$
- SIMPLE TO UNDERSTAND LSND. GIVES **BOTH** SIGNALS.