Late ν masses:

(i) Mini Z' Burst

(ii) Electroweak Leptogenesis

Gilad Perez

LBNL, Berkeley

Haim Goldberg, Ina Sarcevic & GP, hep-ph/0505221;

Lawrence Hall, Hitoshi Murayama & GP, hep-ph/0504248, to appear in PRL.

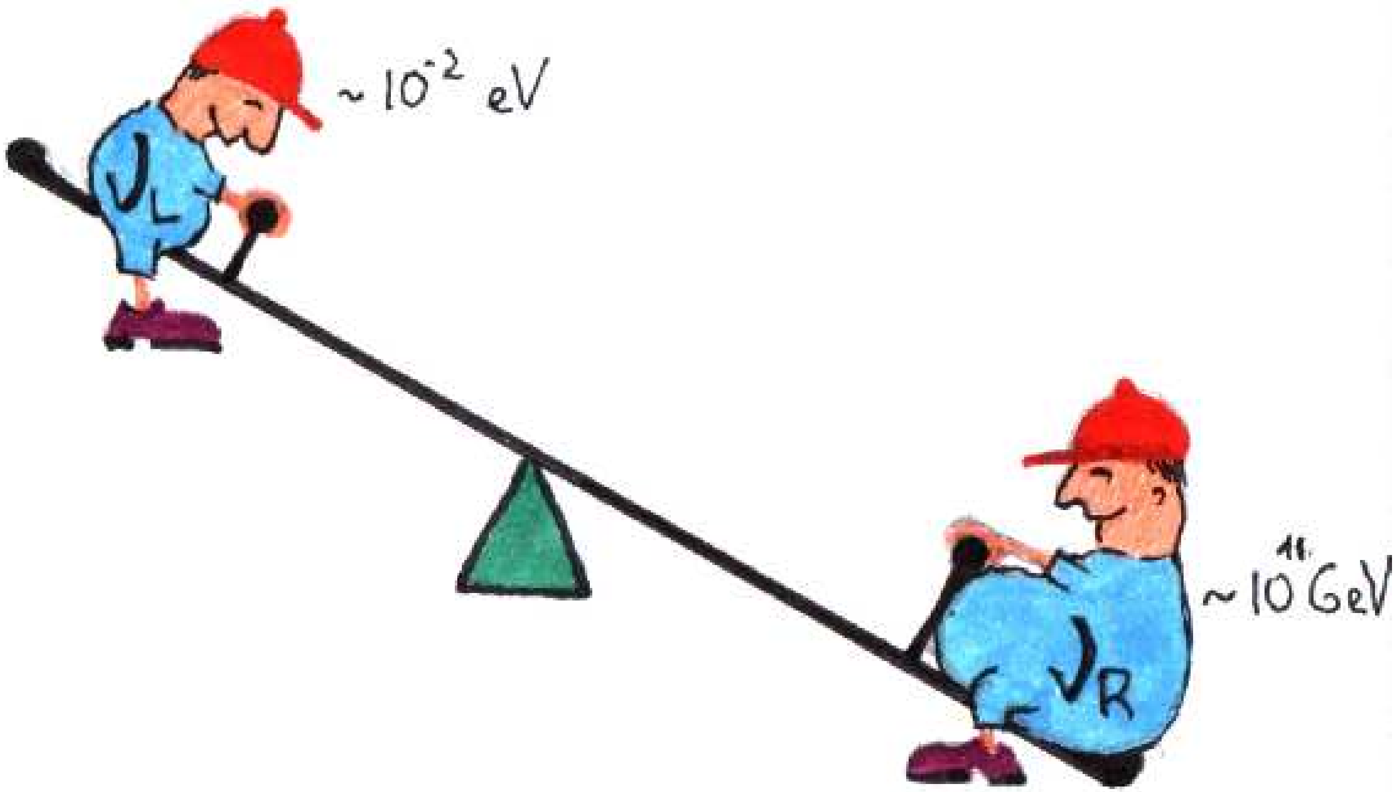
Outline

- Intro' - late ν masses.
- Resonance, accumulative resonance.
- Source and detection.
- EW leptogen': model & mechanism.
- (Constraints & predictions.)
- Conclusions.

Introduction

- Common wisdom to $m_\nu \ll M_W$:
- Seesaw - $\mathbf{M_N} \gg M_W$.
- $m_\nu \sim M_W^2 \,/\, \mathbf{M_N}$.

Classic Seesaw



Motivation

- Common wisdom to $m_\nu \ll M_W$:
- Seesaw - $\mathbf{M_N} \gg M_W$.
- Beautiful, impossible to directly test.
- Or: m_ν from IR sym' breaking!

Brief example - U(1)$_{L/N}$

Chacko, Hall, Okui & Oliver; Davoudiasl, Kitano, Kribs & Murayama.

- $m_{\nu_D} = \left(\frac{f}{\Lambda}\right)^n v \Leftrightarrow \left(\frac{\phi}{\Lambda}\right)^n LNH\,.$

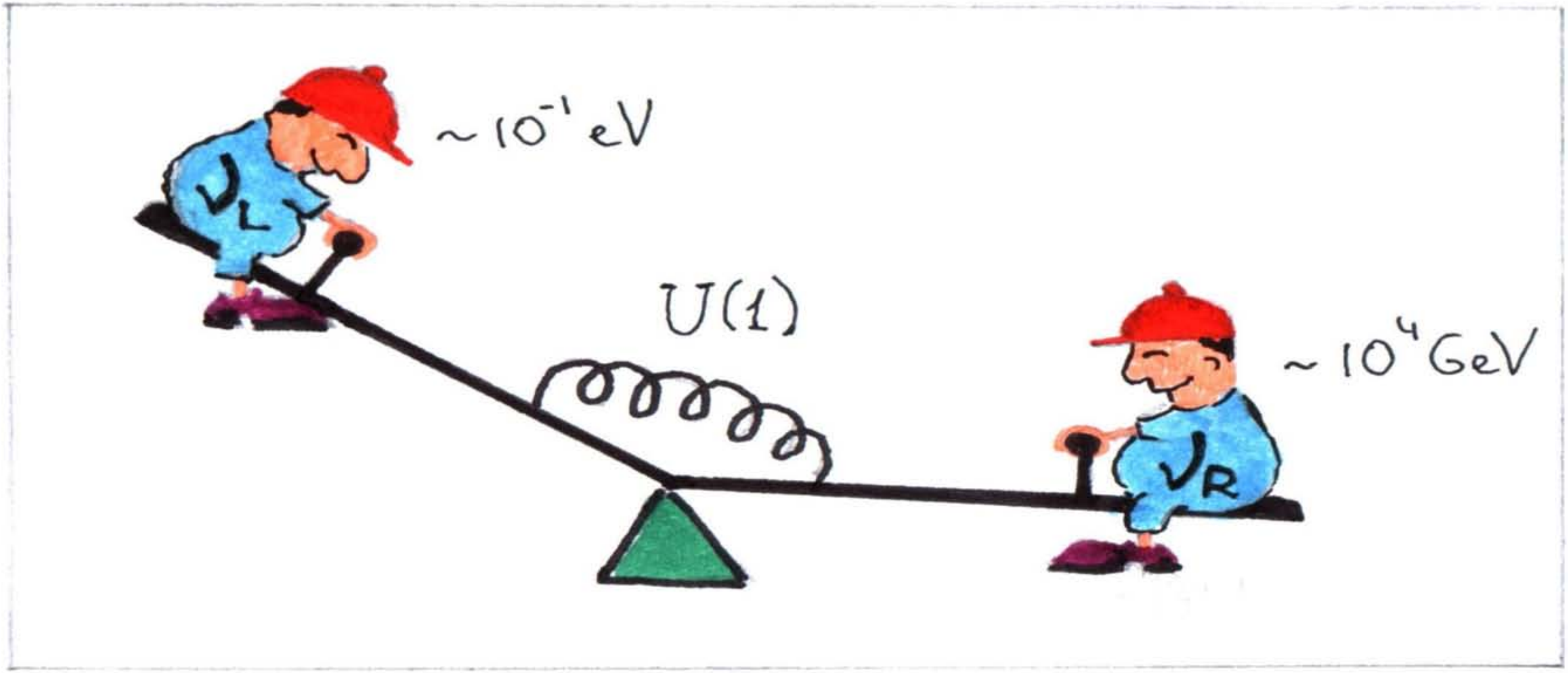
- $m_{\nu_M} = \left(\frac{f}{\Lambda}\right)^{2n} \frac{v^2}{\Lambda} \leftrightarrow \left(\frac{\phi}{\Lambda}\right)^{2n} LL\frac{HH}{\Lambda}\,.$

- $f = \langle\phi\rangle \sim m_\phi < M_W$!

- Below M_W: $\mathcal{L}_\nu \sim y_\nu\,\phi\,\nu\nu\,.$

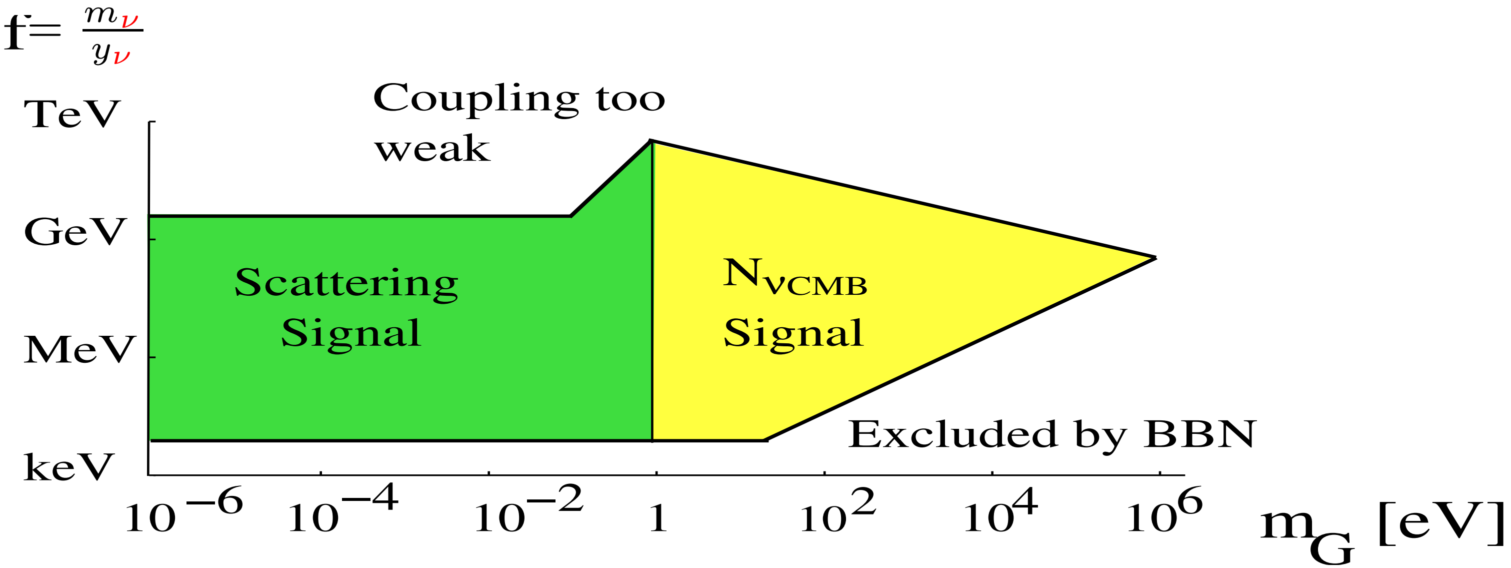
(Late ν masses)

Seesaw/Dirac + IR NP



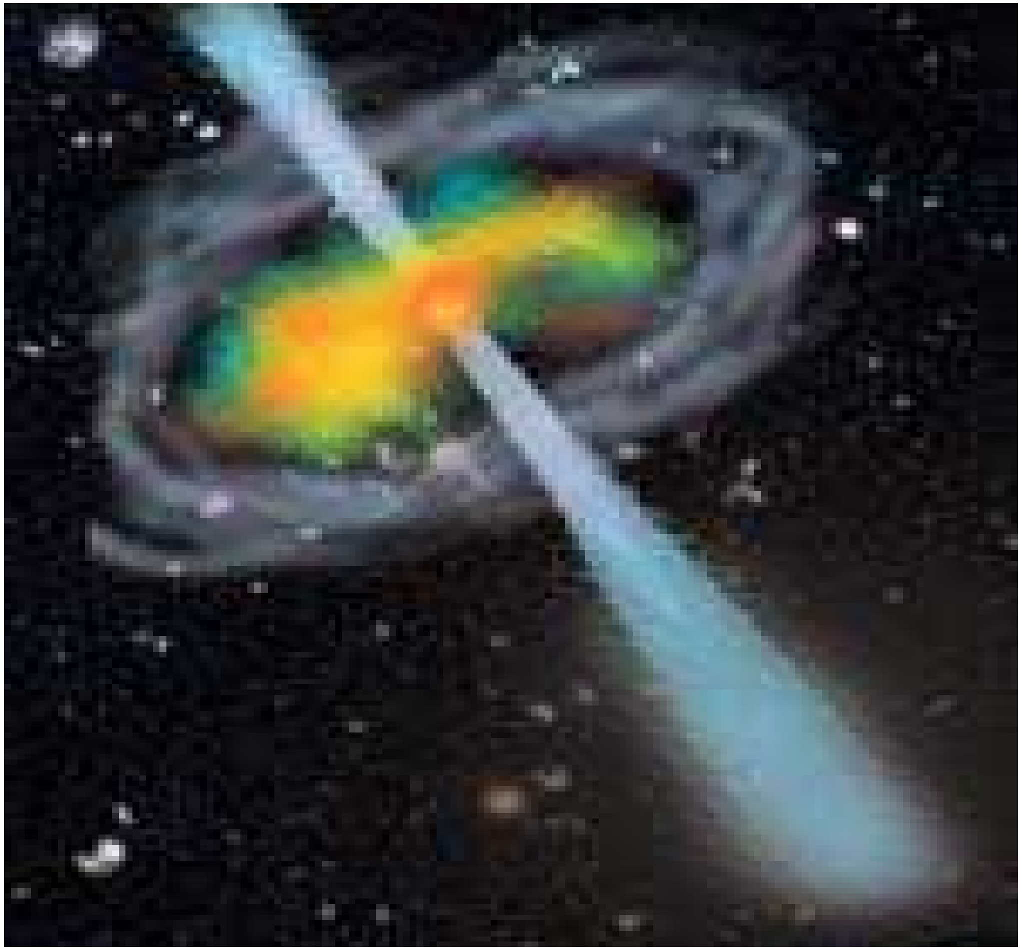
Is it testable ?

- CMB - Relativistic d.o.f!! Chacko, Hall, Okui & Oliver.



- ϕ / mini Z' burst.
- EW Leptogenesis.

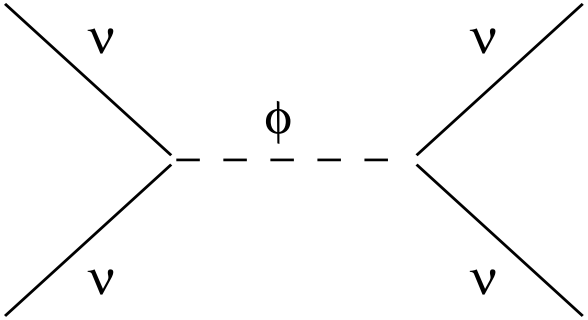
Accumulative Resonance



Main Idea

Step I - Resonance

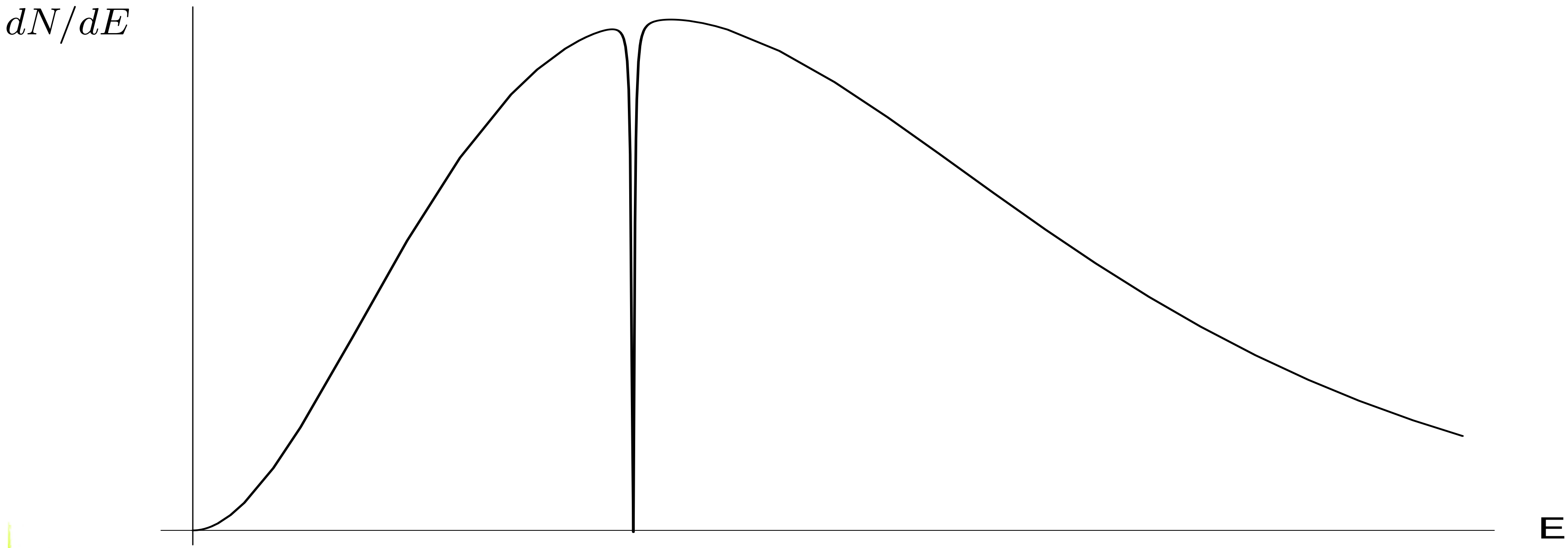
- ϕ Burst!



- UV Supernova ν + CMB $\nu \Longrightarrow \phi$.
- $\phi \Longrightarrow \nu\, \nu$.
- $E_\nu^{\mathrm{final}} \sim 0 \; - \; E_\nu^{\mathrm{SN}}$.

Step I - Resonance

- Assume only $\mathcal{L} = y_\nu \phi \nu \nu \sim \left(\frac{\phi^2 H^2 L^2}{M^3}\right)$
- $\Gamma_\phi \ll m_\nu \Rightarrow$ Unobservable!



Step II - Accumulative Resonance

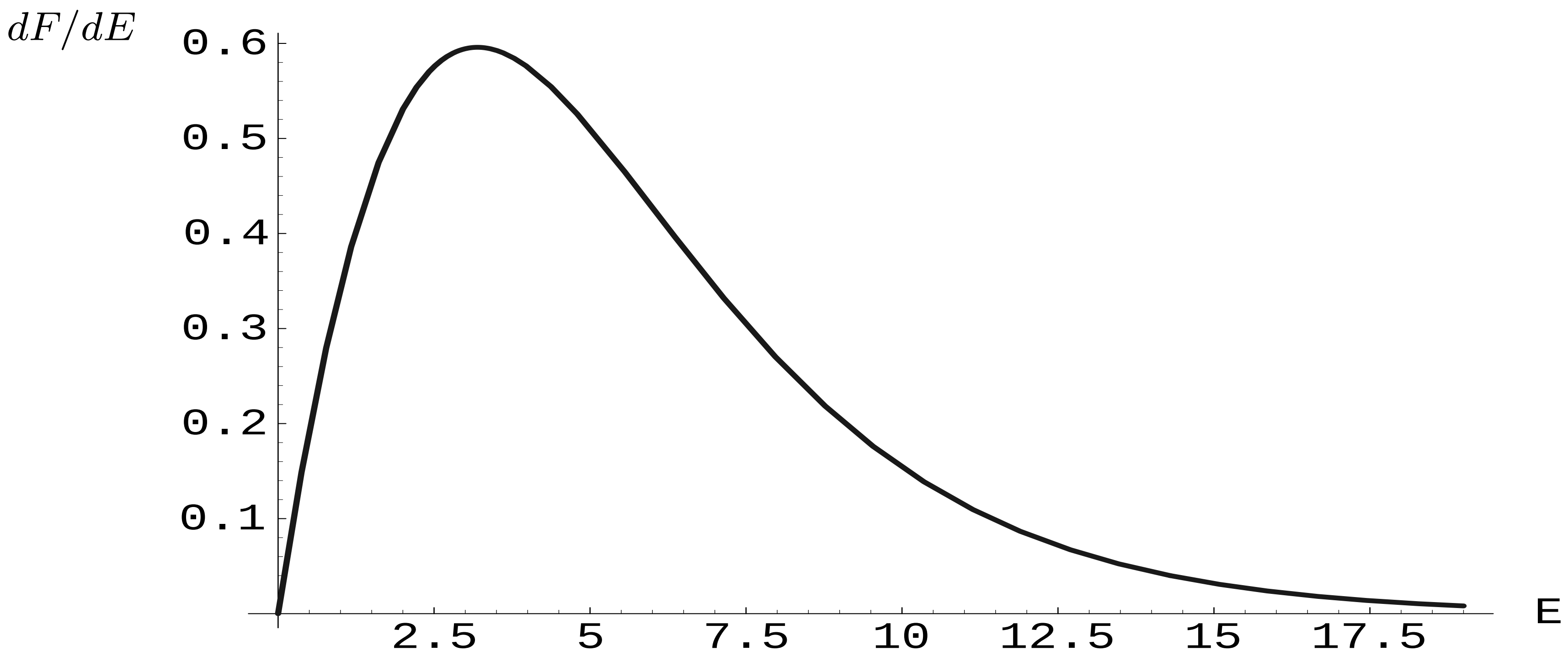
- SN ν comes from far away, $z \lesssim 3$.
- Expansion $\Rightarrow$ shift ; ${E_\nu}^{\rm Obs} \sim \frac{{E_\nu}^{\rm SN}}{(1+z)}$.
- $m_\phi \lesssim {E_\nu}^{\rm SN} \lesssim m_\phi(1+z) \Leftrightarrow$ Resonance.

$$\Downarrow$$

Accumulative Resonance !!

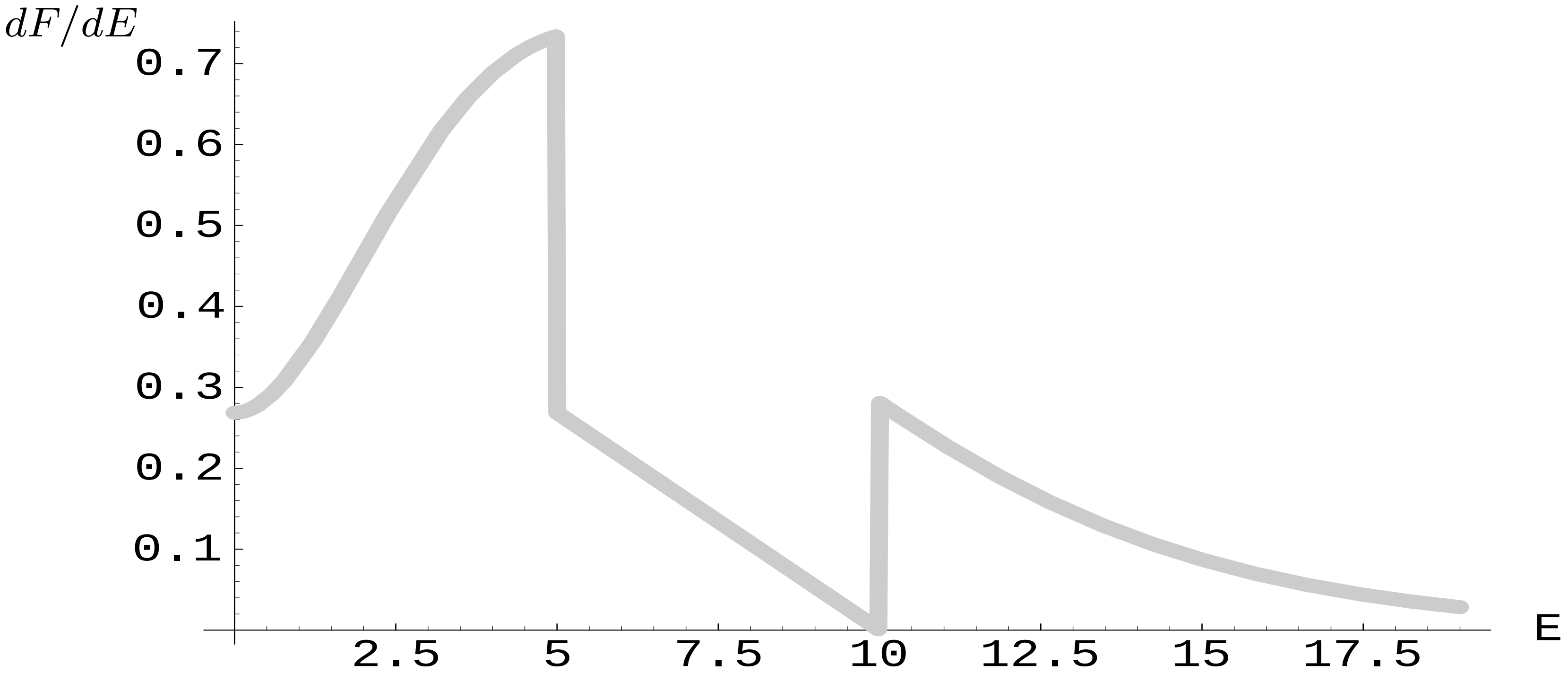
No Resonance

$$z^{\mathrm{SN}} = 2\,.$$



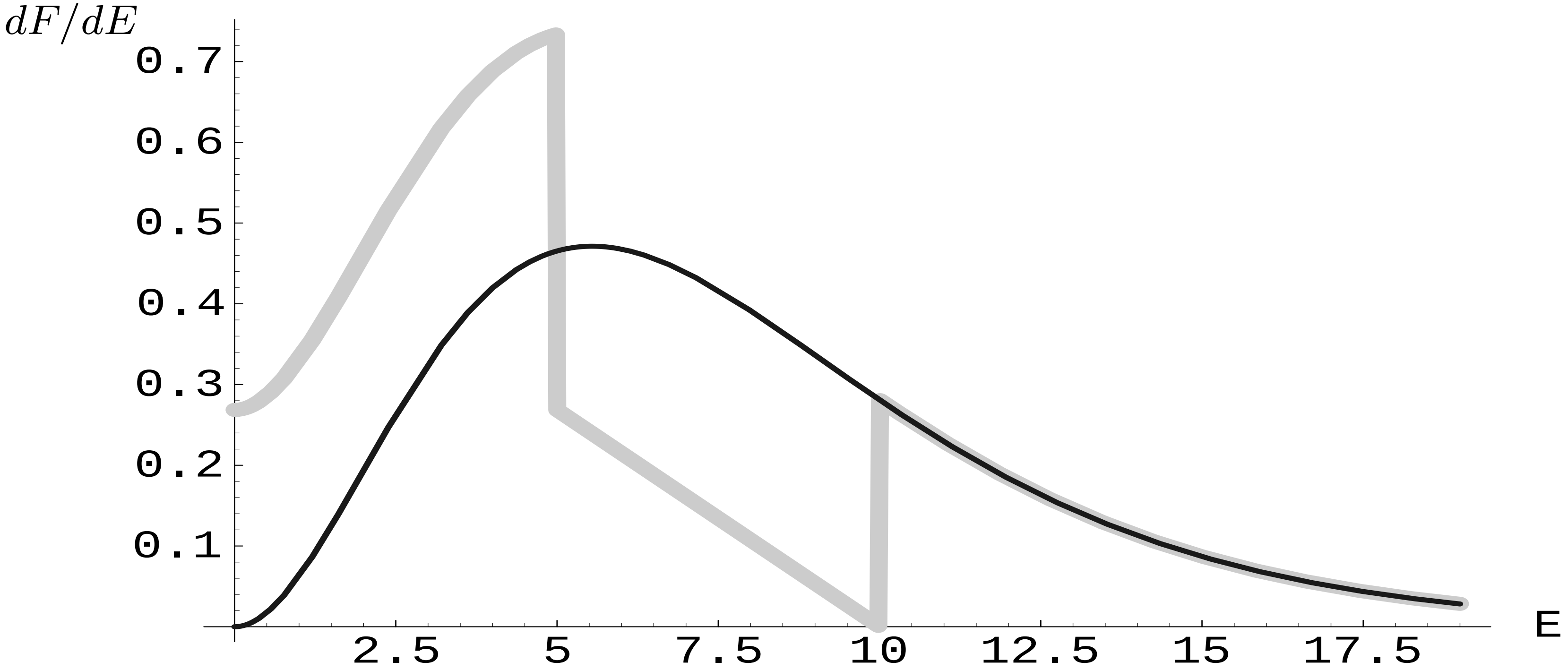
Accumulative Resonance

$$m_{\phi} \simeq 1\,\text{KeV}\,, \quad z^{\text{SN}} = 2\,.$$

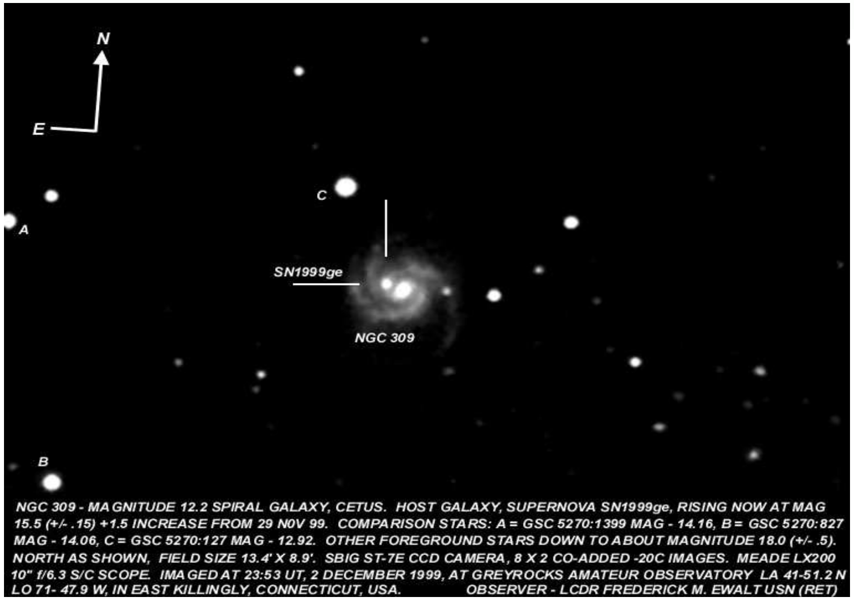


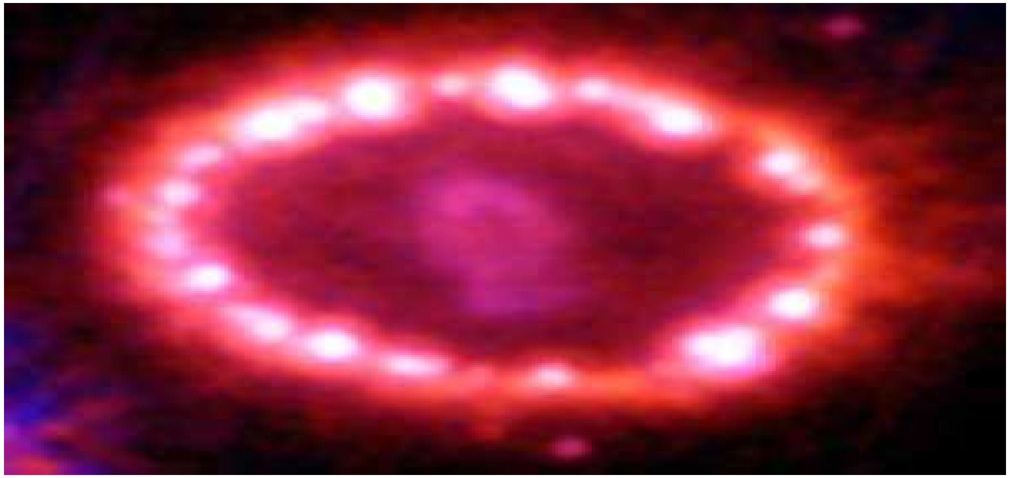
Comparison

$m_{\phi} \simeq 1$ KeV , $z^{\rm SN} = 2$; z indep' dip!



The source


N
E
C
A
SN1999ge
NGC 309
B
NGC 309 - MAGNITUDE 12.2 SPIRAL GALAXY, CETUS. HOST GALAXY, SUPERNOVA SN1999ge, RISING NOW AT MAG 15.5 (+/- .15) +1.5 INCREASE FROM 29 N0V 99. COMPARISON STARS: A = GSC 5270:1399 MAG - 14.16, B = GSC 5270:827 MAG - 14.06, C = GSC 5270:127 MAG - 12.92. OTHER FOREGROUND STARS DOWN TO ABOUT MAGNITUDE 18.0 (+/- .5). NORTH AS SHOWN, FIELD SIZE 13.4' X 8.9'. SBIG ST-7E CCD CAMERA, 8 X 2 CO-ADDED -20C IMAGES. MEADE LX200 10" f/6.3 S/C SCOPE. IMAGED AT 23:53 UT, 2 DECEMBER 1999, AT GREYROCKS AMATEUR OBSERVATORY LA 41-51.2 N LO 71- 47.9 W, IN EAST KILLINGLY, CONNECTICUT, USA.
OBSERVER - LCDR FREDERICK M. EWALT USN (RET)



Simplyfing the source - SN

- Gained "reasonable" control on R_{SN} .
- Naive SN ν spectra (no pinching).
- No MSW in the SN.
- Shock wave effects are subdominant.

The source - SN

- Total dif' flux:

$$\left.\frac{dF}{dE_\nu}\right|_{\rm Tot} \propto \int_0^3 dz\, R_{\rm SN}\, \left.\frac{dF}{dE_\nu}\right|_{\rm SN} J(z)\,.$$

- Thermal flux:

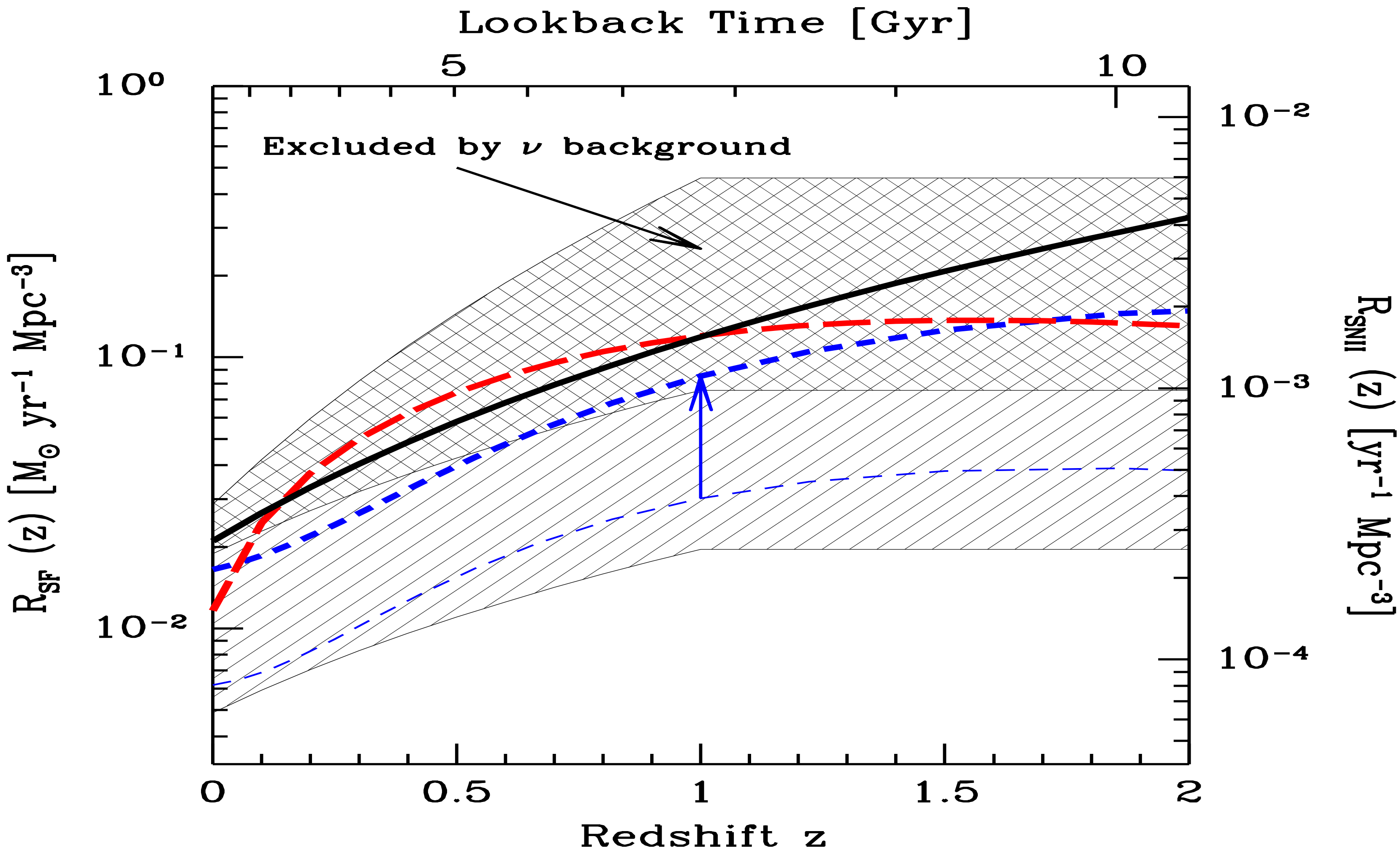
$$\left.\frac{dF}{dE_\nu}\right|_{\rm SN} = \frac{{E_\nu}^2}{e^{E_\nu/T_\nu}+1}\,, \qquad T_\nu \sim 5-8 \text{ MeV.}$$

- Density (Distance=Significance):

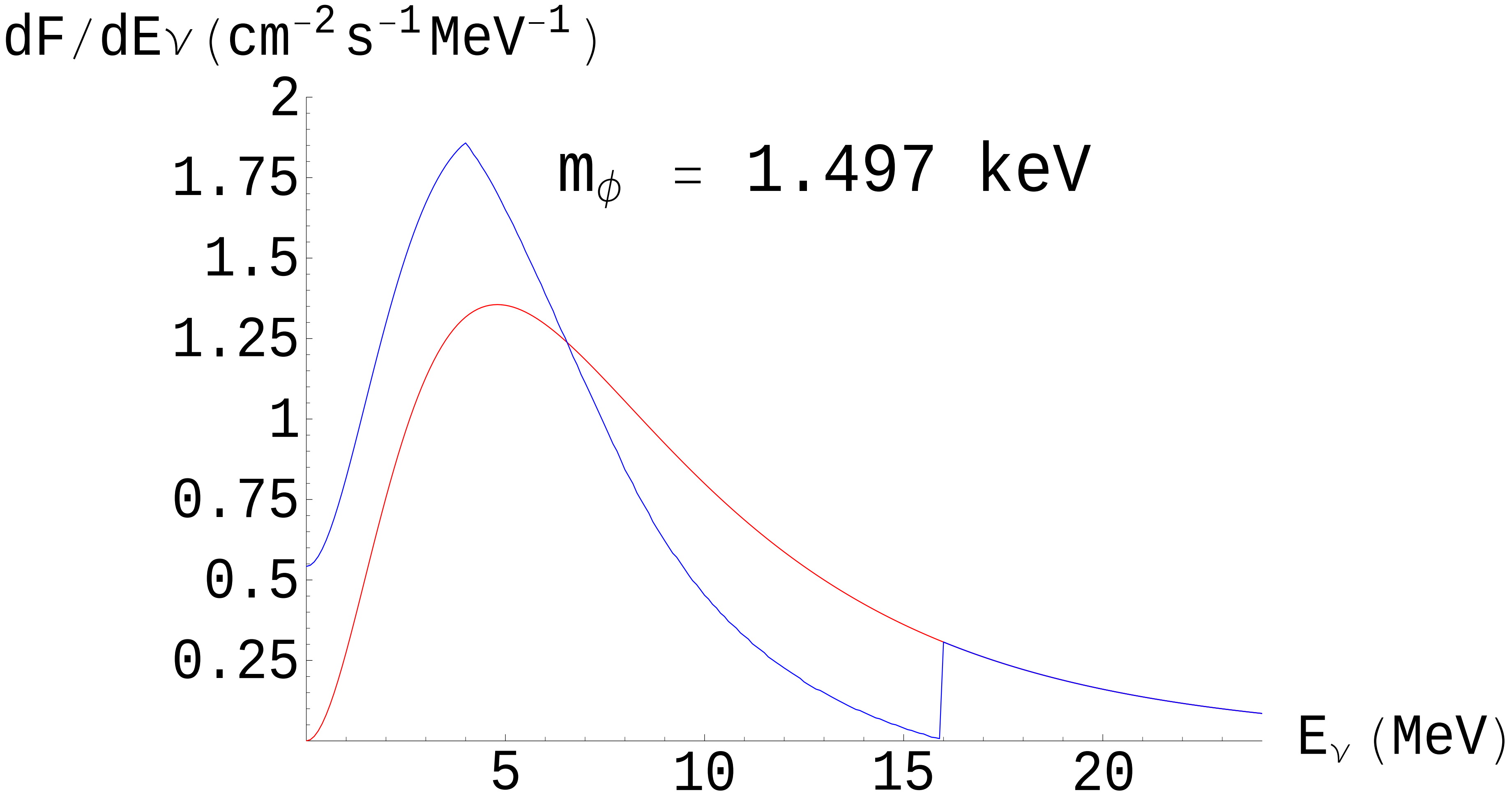
$$R_{\rm SN} \sim \text{ SN } \left(1+z^{\rm SN}\right)^\alpha \qquad \alpha = 0-3\,.$$

Estimation of R_{SN}

Strigari, Beacom, Walker & Zhang



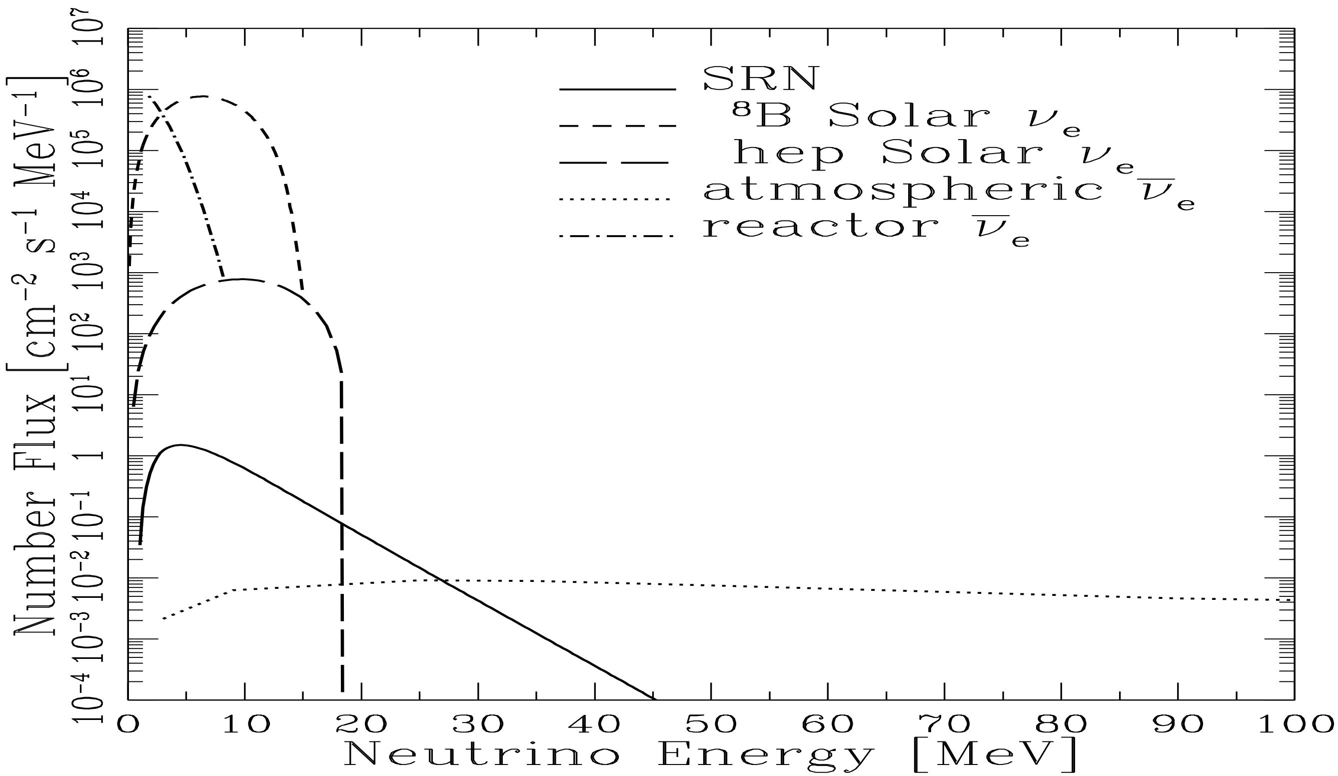
The "Forest" - z Integration!



Observation ??

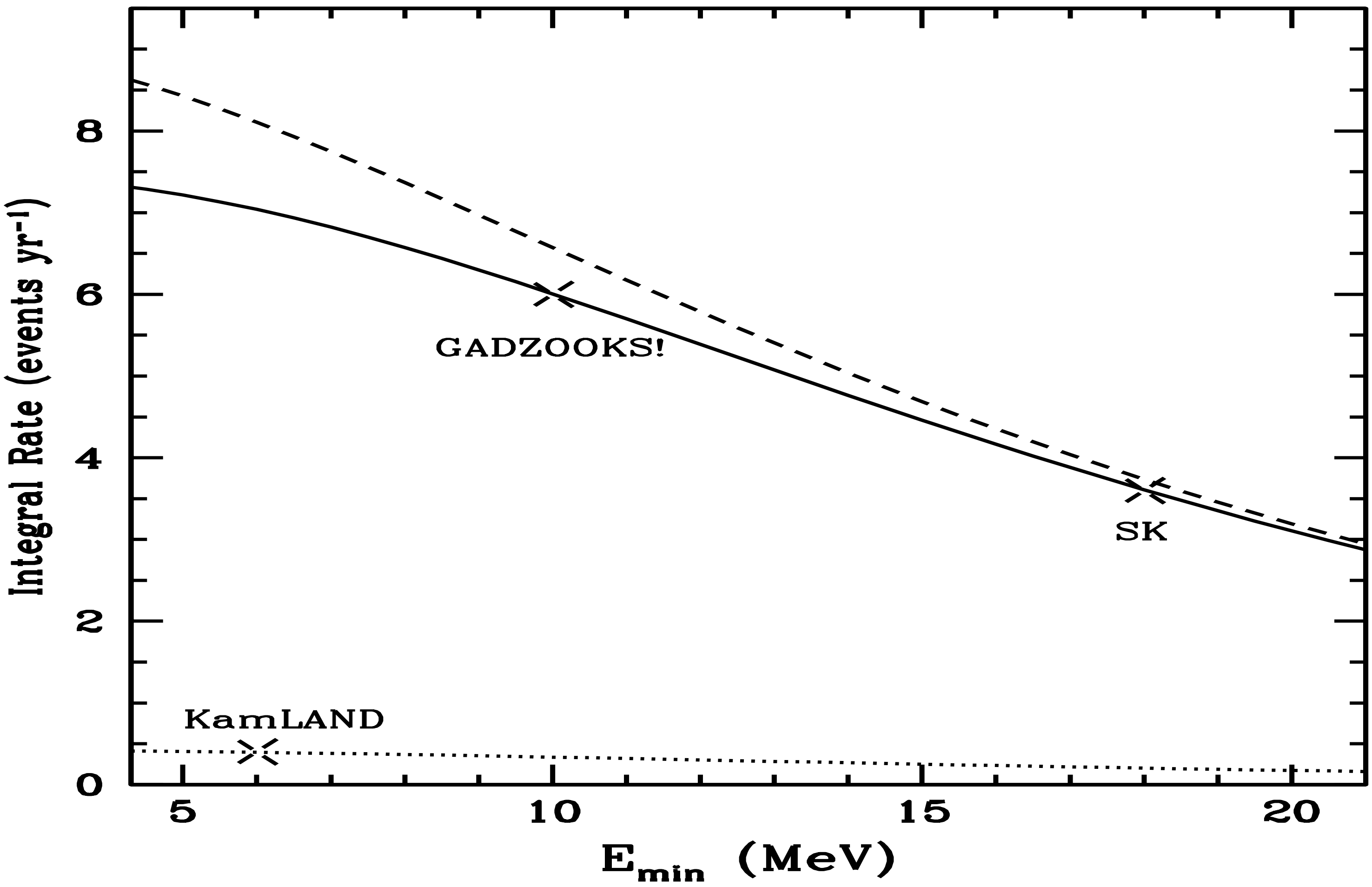
Experiments ?

- $E_\nu^{\mathrm{Sol}} \lesssim E_\nu^{\mathrm{SN}} \lesssim E_\nu^{\mathrm{Atm}}$.
- Within SK, KamLAND reach! Ando, Sato & Totani.



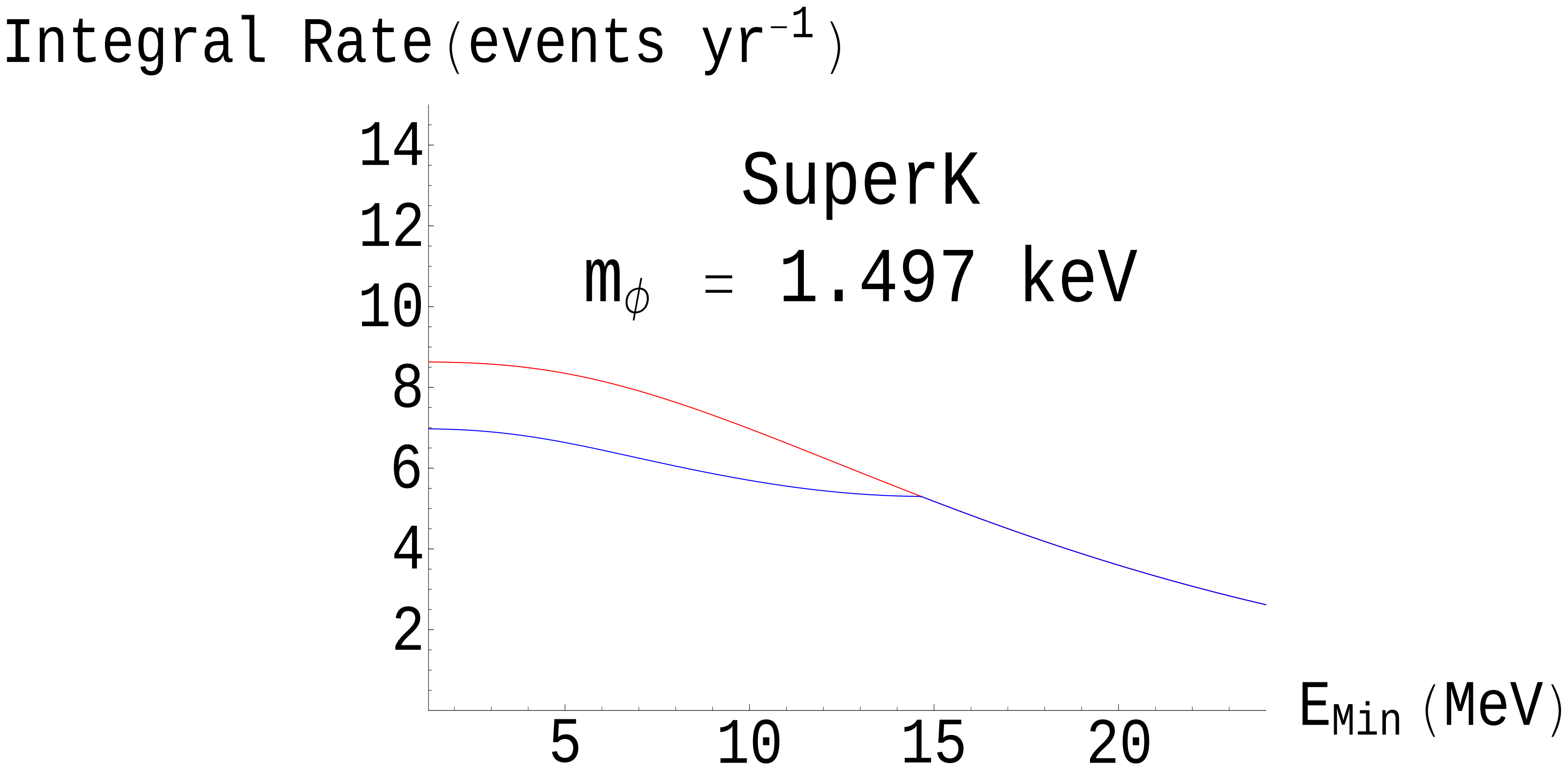
E Thresholds & Uncertainties

Sensitivity & threshold Strigari, Kaplinghat, Steigman & Walker.



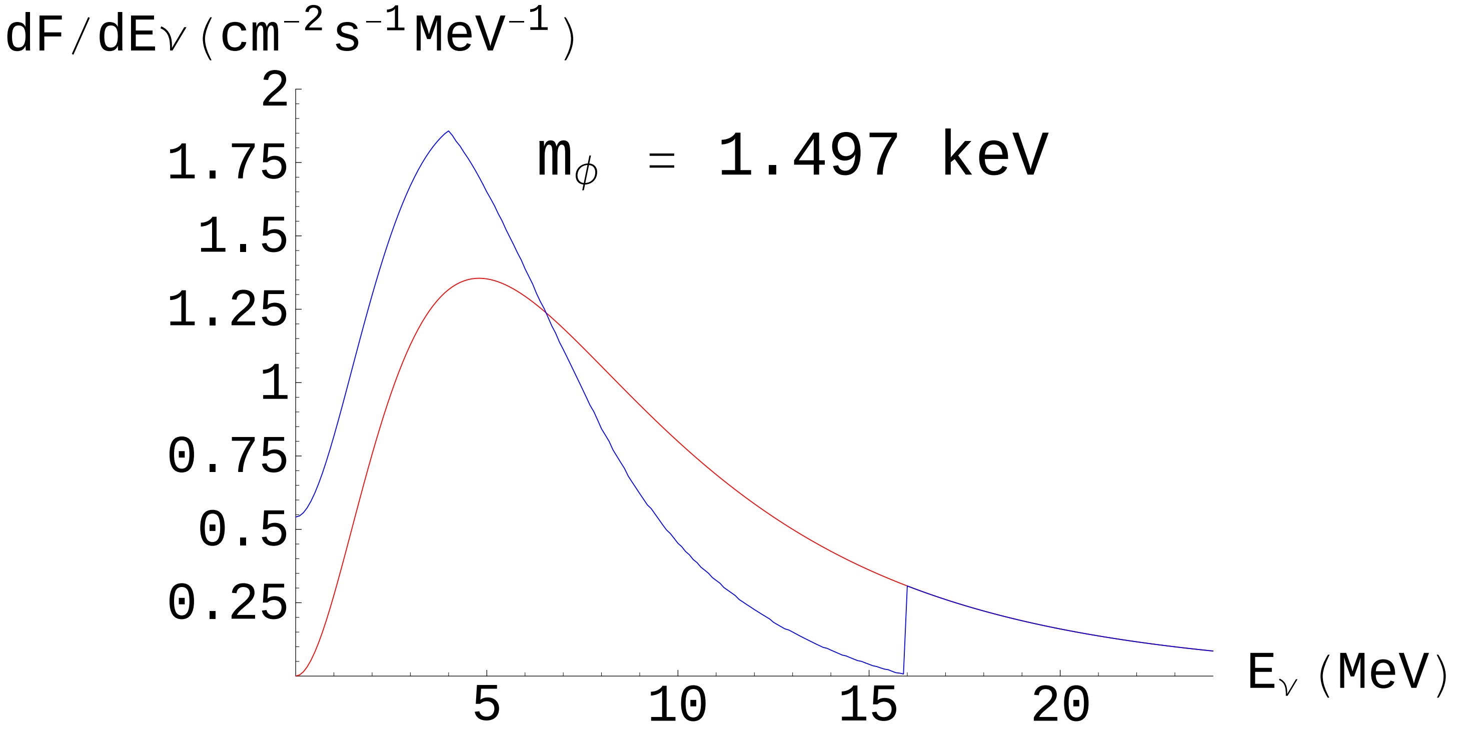
Comb' Exp' (SK+GADZOOKS+KamLand)

SK is unaffected !



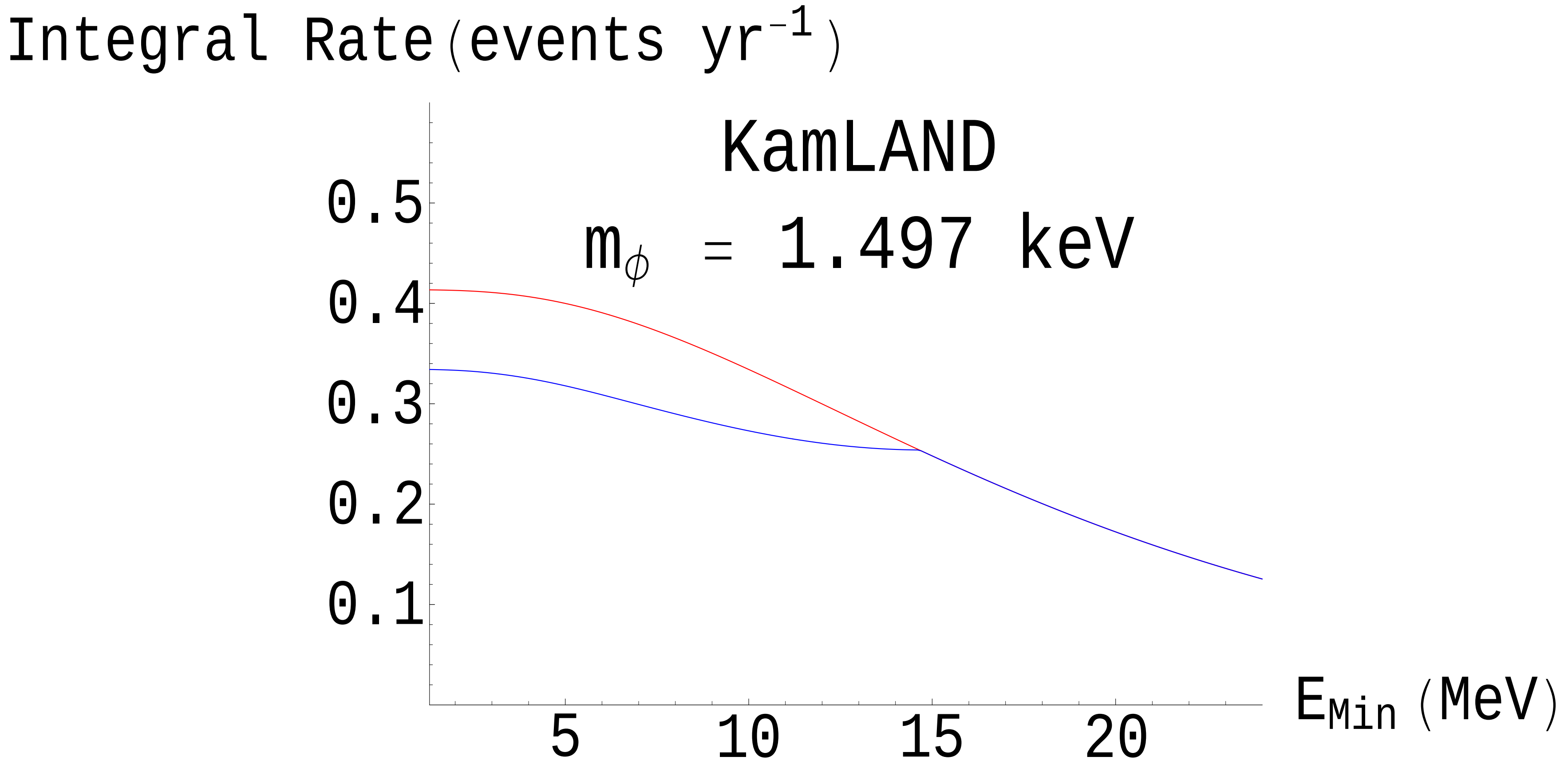
GADZOOKS (SK+Gad')

Depletion can be observed !



KamLand

Suppression of integrated flux!



Resonance: limitations

- Tiny range: $m_\phi = \sqrt{2 m_\nu{}^i E^{\rm SN}} \sim 1\,{\rm KeV}\,.$

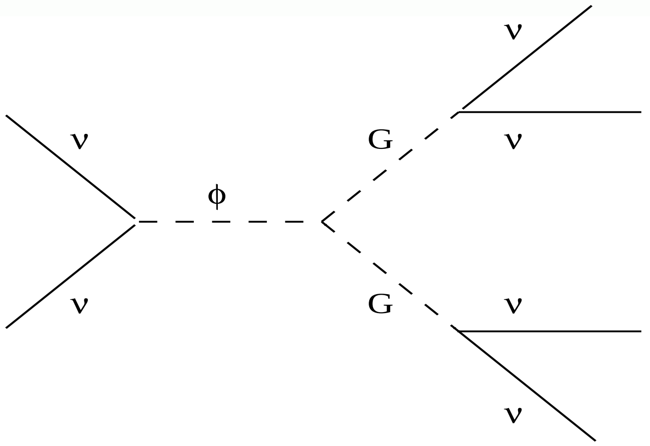
- Res' $\Leftrightarrow E^{\rm SN} H \lambda_{\rm mfp} \lesssim \Gamma_\phi\,.$

$$\Downarrow$$

$$y_\nu \geq \sqrt{m_\phi{}^3 H / 2\pi m_\nu T_\nu^3} \sim (1{-}10)\times 10^{-8}\,.$$

Non-Resonance process

- Degradation process:



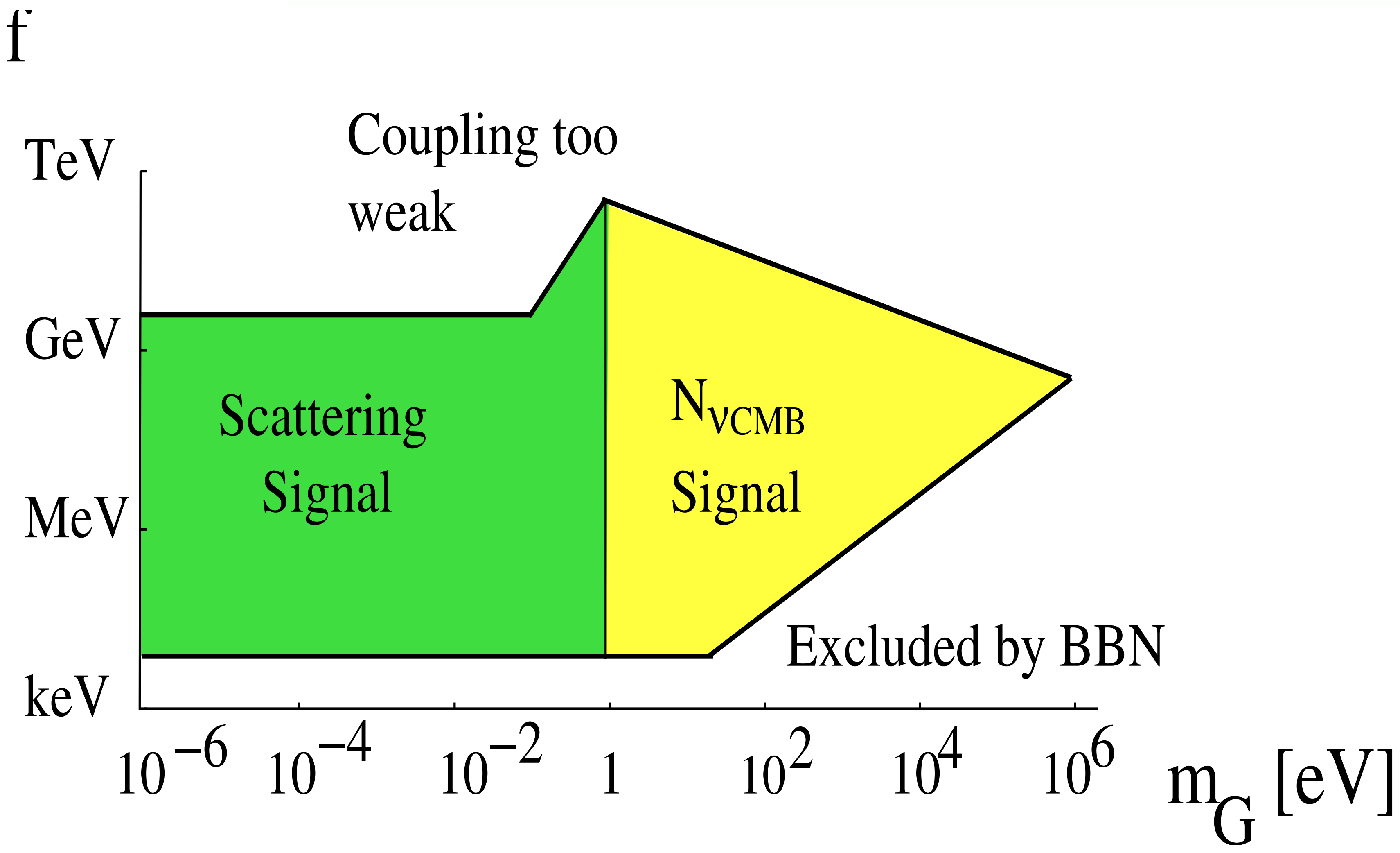
- Requires $H\lambda_{\mathrm{mfp}} \lesssim 1$.

$$\Downarrow$$

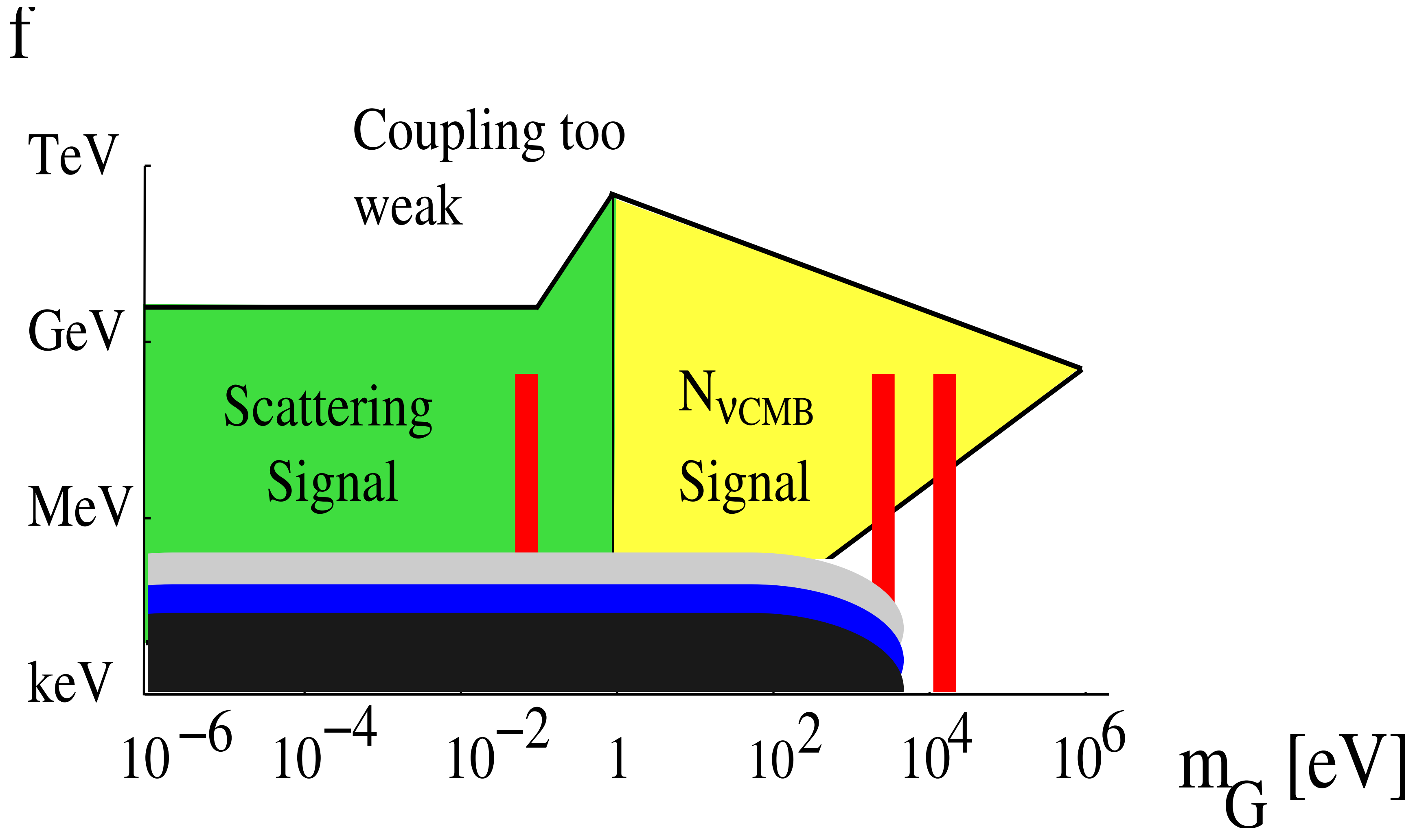
$$y_\nu \geq 10^{-6}(3000Mpc/D)^{1/4} .$$

- SN1987A, $D = 50$ Kpc $\Rightarrow y_\nu \lesssim 5 \times 10^{-5}$.
- Uno/HuperK will "see" O(Mpc) SN !

Comparison with Cosmology



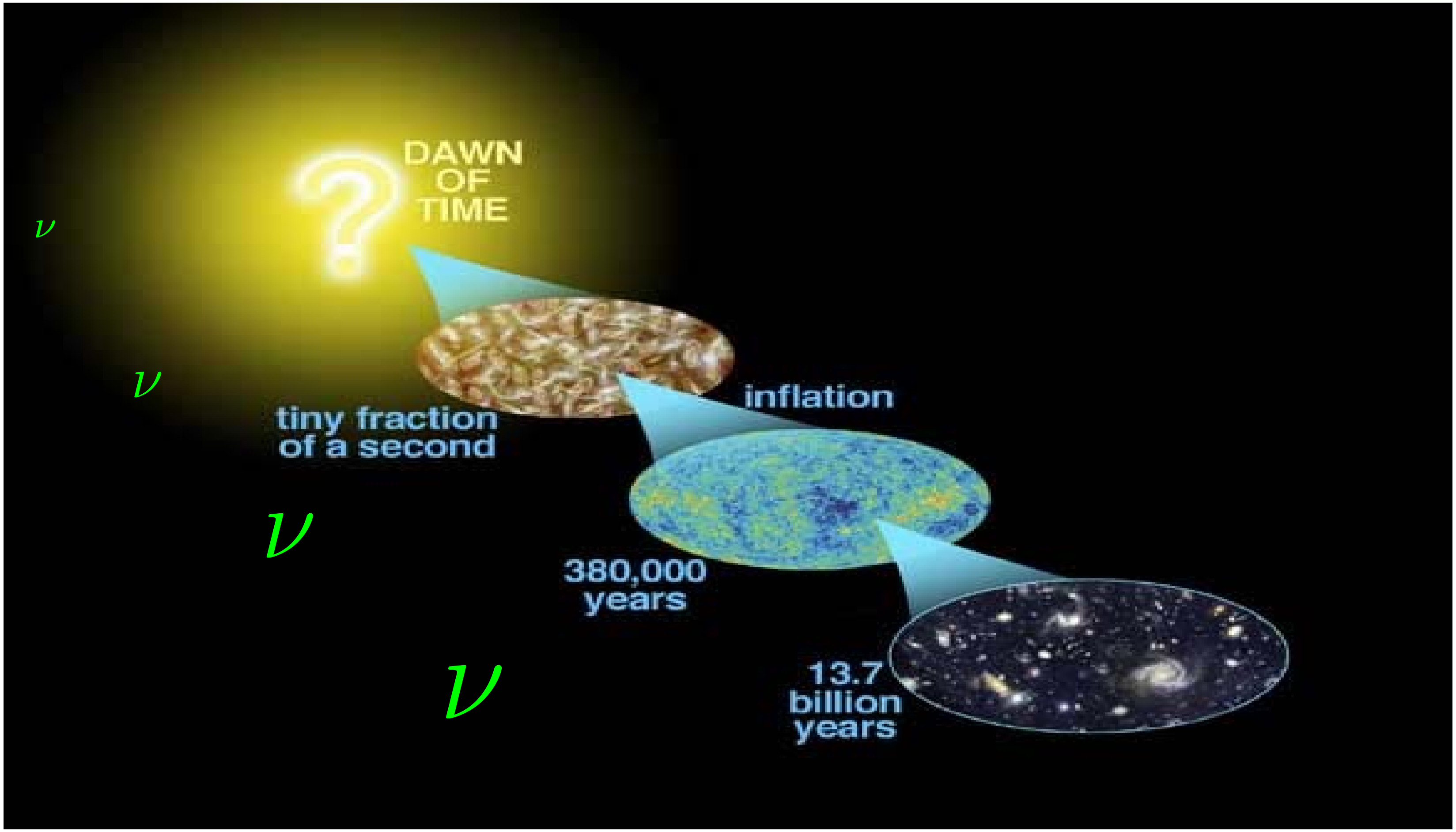
Comparison with Cosmology



Intermediate summary

- m_ν from IR NP require light d.o.f.
- Yield accumulated resonance - signal.
- 1987a directly excludes lower f.
- Future (GADZOOKS) exp': discover or constraint.
- Baryogenesis ??

Leptogenesis



Main idea: Leptogen' & late m_ν

- The scale is $\langle H \rangle$.
- Reno' model $\Rightarrow$ vector-like d.o.f L^c, L'.
- Neutrino anarchy $\Rightarrow$ CPV.
- $L' N \langle H \rangle$ int' $\Rightarrow$ reflection asymmetry.
- L' decay into SM leptons doublets.
- Sphalerons $\Rightarrow$ B production.

Leptogenesis & late ν masses

Majorana & Dirac renormalizable model

- **Dirac** non-reno': $m_{\nu_D} \Leftrightarrow \frac{\phi}{M} NLH.$
- Reno': $\mathcal{L}_{\rm D} = Y HNL' + M L^c L' + \phi L^c L.$
- **Majorana** non-reno': $m_{\nu_M} \Leftrightarrow \frac{\phi^2}{M^2} \frac{H^2 L^2}{M_N}.$
- Reno': $\mathcal{L}_{\rm M} =$
  $Y HNL' + M L^c L' + \phi L^c L + M_N NN.$

Sakharov conditions

(i) Baryon (B) violation.

(ii) CP violation (CPV).

(iii) Deviation from thermal equilibrium.

Sakharov conditions

(i) Baryon (B) violation -

$L' \leftrightarrow N \Longrightarrow$ **L** **+** sphalerons $\Longrightarrow$ B.

(ii) CP violation (CPV).

(iii) Deviation from thermal equilibrium.

Sakharov conditions

(i) Baryon (B) violation -

$L' \leftrightarrow N \Longrightarrow$ **L** **+** sphalerons $\Longrightarrow$ B.

(ii) CP violation (CPV) -

Y, M_N anarchic & misaligned.

(iii) Deviation from thermal equilibrium.

Sakharov conditions

(i) Baryon (B) violation -

$L' \leftrightarrow N \Longrightarrow$ **L** **+** sphalerons $\Longrightarrow$ B.

(ii) CP violation (CPV) -

Y, M_N anarchic & misaligned.

(iii) Deviation from thermal equilibrium -

Assume 1st order electroweak PT.

Estimation of B

- Crude estimate of B: Cohen, Kaplan & Nelson, ARNPS (93)

$$\frac{n_B}{s} \sim \left[\frac{\alpha_w^4}{g_*}\right] \times [\theta_{CP}] \sim 8 \times 10^{-11} \, .$$

- SM: Huet & Sather, PRD (95)

$$\frac{n_B}{s} \sim \left[\frac{\alpha_W^4}{100}\right] \times \left[J \, \frac{\Pi_q \Delta {m_q}^2}{T_c^{12}}\right] \lesssim 10^{-27}$$

- Electroweak leptogenesis:

$$\frac{n_B}{s} \sim \left[\frac{\alpha_W^4}{100}\right] \times F^{\rm kin} \left(M_N, Y\langle H\rangle, T_c\right) = ?$$

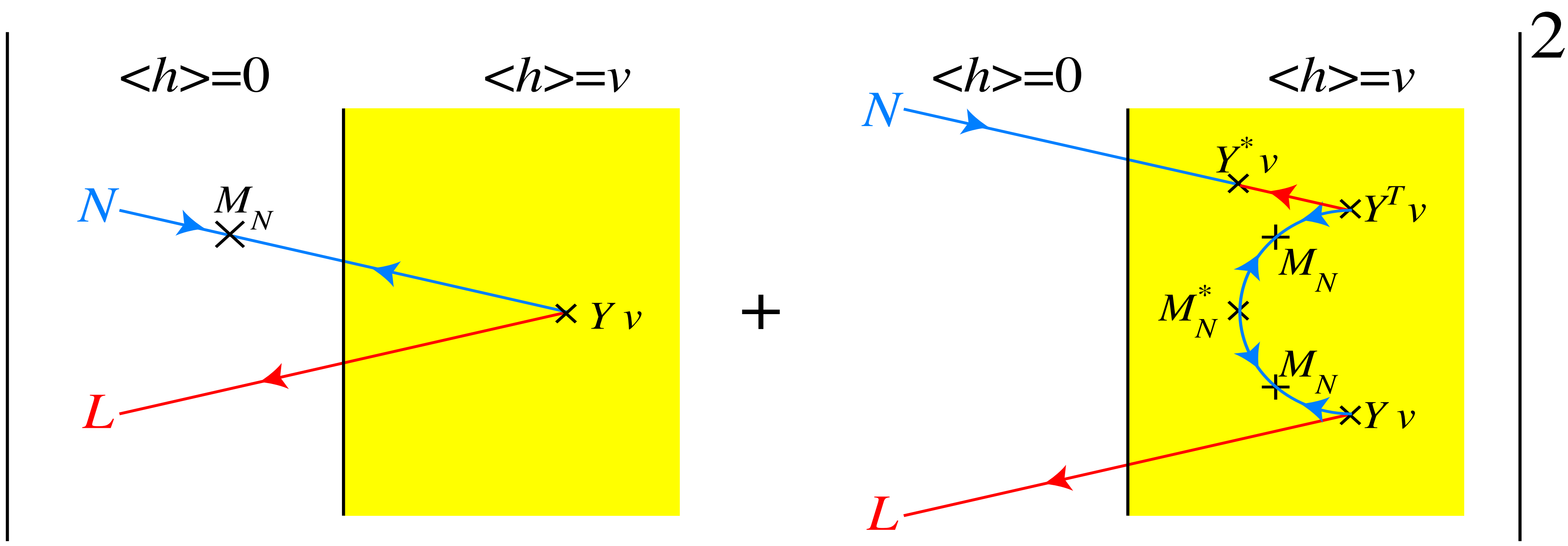
Semi-quantitative analysis

- CPV $\Leftrightarrow L'$-$\bar{L}'$ reflection asymmetry.
- $n_{L'} \propto \int dp_z \left[n^{L'}(p_z) - n^{N}(p_z)\right] \times \Delta^{CP}(E)$.
- $\Delta^{CP} \propto \mathrm{Tr}\left(\left|R_{L'N}\right|^2 - \left|\bar{R}_{L'N}\right|^2\right)$
- $\Delta^{CP} \Rightarrow$ perturb' $Y_{ii}v/T\,,\; M_{Nii}/E \ll 1\,,$

  via Green func' for 2 gen' sys'.

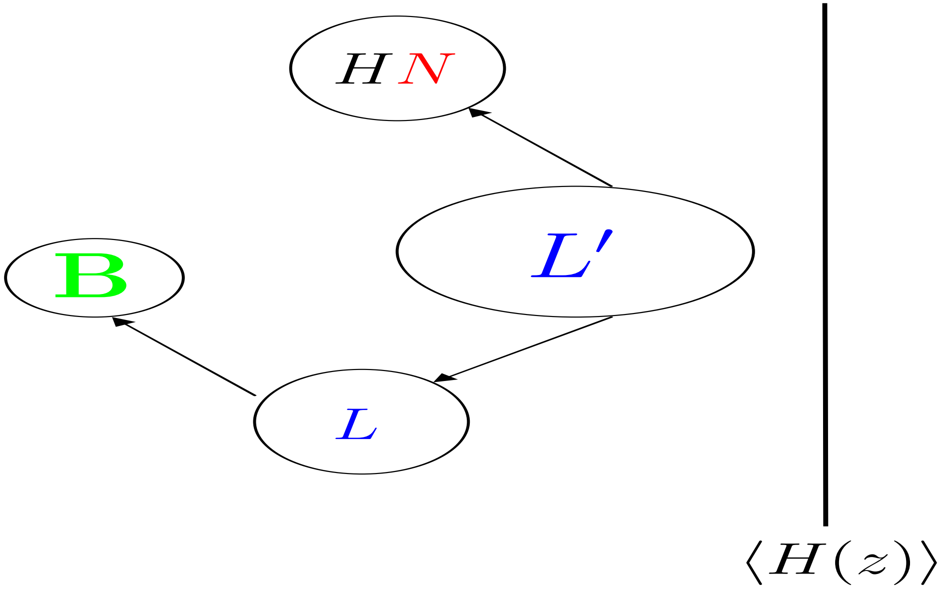
Green function expansion

- $\Delta^{CP} \propto \mathrm{Tr}\left(\left|R_{L'N}\right|^2 - \left|\bar{R}_{L'N}\right|^2\right) \propto \left[M_N^2, Y^2\right]$!



Sphaleron conversion

- L', L^c are vectoric $\Rightarrow$ no sphalerons !
- $L' \to NH \Rightarrow$ wash out.
- $L' \to \phi L \Rightarrow$ sphalerons $\Rightarrow$ B.
- Scales $\tau_{\rm wall} \sim \Gamma^{-1}_{L' \to X} \Rightarrow$ O(1) wash out !

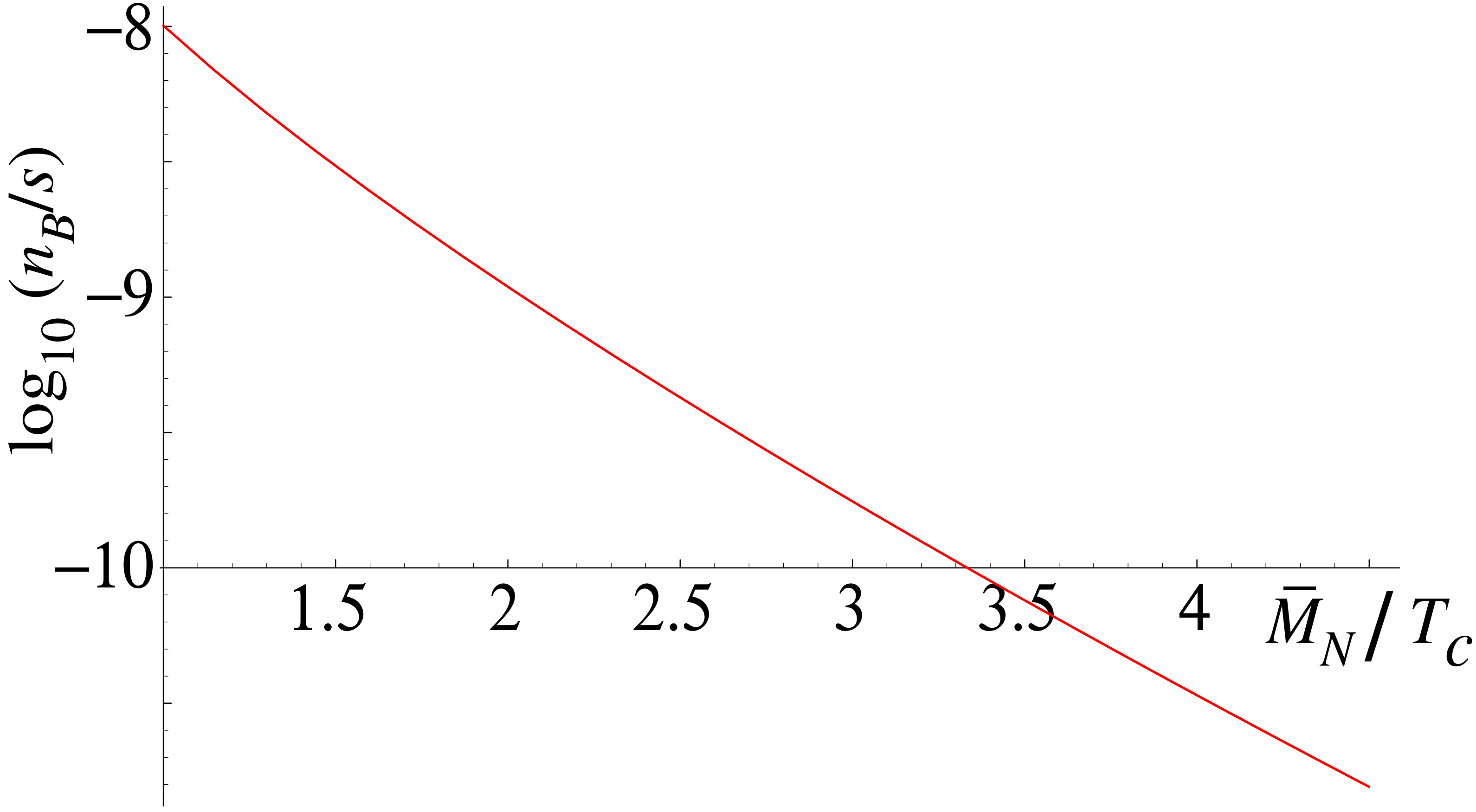


The resultant asymmetry

- $\int \frac{dn_{\rm B}}{dt} dt \sim \frac{dn_{\rm B}}{dt} \tau_{\rm w}$.
- $\tau_{\rm w} \approx N_{col}\, l_{mfp}/v_{\rm w} \sim 2/g_w^2\, v_{\rm w}\, T$.
- $\frac{n_{\rm B}}{s} \sim$
$\frac{\alpha_w^4}{g_* g_w^2} \left(\frac{Y_{ii} v}{M_{N\,ii}} \right)^{2N_G} \det \left[M_N{}^2, Y^2 \right] n^{L'} \left(\frac{M_{N\,ii}}{T_c} \right)$.

The resultant asymmetry

$$M_{N\,ii} \lesssim 4T_c \sim 4Y_{ii}\langle H\rangle$$



Constraints & testability

$$\mathcal{L} = Y H N L' + M_N N N + M L^c L' + y \phi L^c L.$$

- Electroweak, $\Delta\rho$, $\Rightarrow M_N \gtrsim 2.5 Y v$.
- Dirac: invisible $\Gamma_Z \Rightarrow M \gtrsim 4 Y v$.
- L flavor violation $\Rightarrow$ hierarchical y & no singlets $\Rightarrow L', L^c$.
- Collider: $L', L^c \Rightarrow E'^{\pm}$, $M_{E'} \lesssim 4 Y v$ ~TeV!

Natural models

- SUSY, Dirac: $W = LNH_u \frac{\phi}{M} + \frac{\phi^3}{3}$.
- $V \sim (\tilde{m}^2 + |y_\nu \phi|^2)(|\tilde{\nu}|^2 + |\tilde{n}|^2)$
  $+ |\phi^2 + y_\nu \tilde{\nu}\tilde{n}|^2 \leftrightarrow$ No tree-level $\tilde{m}_\phi$.
- $\tilde{m}_\phi{}^2 \sim \frac{-y_\nu{}^2 \tilde{m}^2}{16\pi^2}$, $f \sim \frac{y_\nu \tilde{m}}{4\pi} \sim \sqrt{\frac{m_\nu \tilde{m}}{4\pi}} \sim 10$KeV.
- $M_N \sim 1$TeV $\longrightarrow$ GM mechan'/RS.
- May drive a 1st order PT.

Conclusions

- Yield a CMBR signal.
- Yield accumulated resonance - signal.
- 1987a directly excludes lower f.
- Late ν masses $\Rightarrow$ baryogenesis.
- Testable: collider and LFV.
- No moduli/gravitino problem!

Mini Z' Burst & EW Leptogenesis

Gilad Perez