

# Lecture VIII: Cosmic Frontier Connections

M.J. Ramsey-Musolf

*U Mass Amherst*



AMHERST CENTER FOR FUNDAMENTAL INTERACTIONS

*Physics at the interface: Energy, Intensity, and Cosmic frontiers*

University of Massachusetts Amherst

<http://www.physics.umass.edu/acfi/>

ACFI NLDBD School  
10/31-11/3 2017

# Lecture VIII Goals

- *Provide some background on leptogenesis in the broader context of baryogenesis*
- *Discuss some implications of  $0\nu\beta\beta$ -decay searches for leptogenesis*
- *Provide some background on cosmological probes of neutrino mass\*\**
- *Invite questions !*

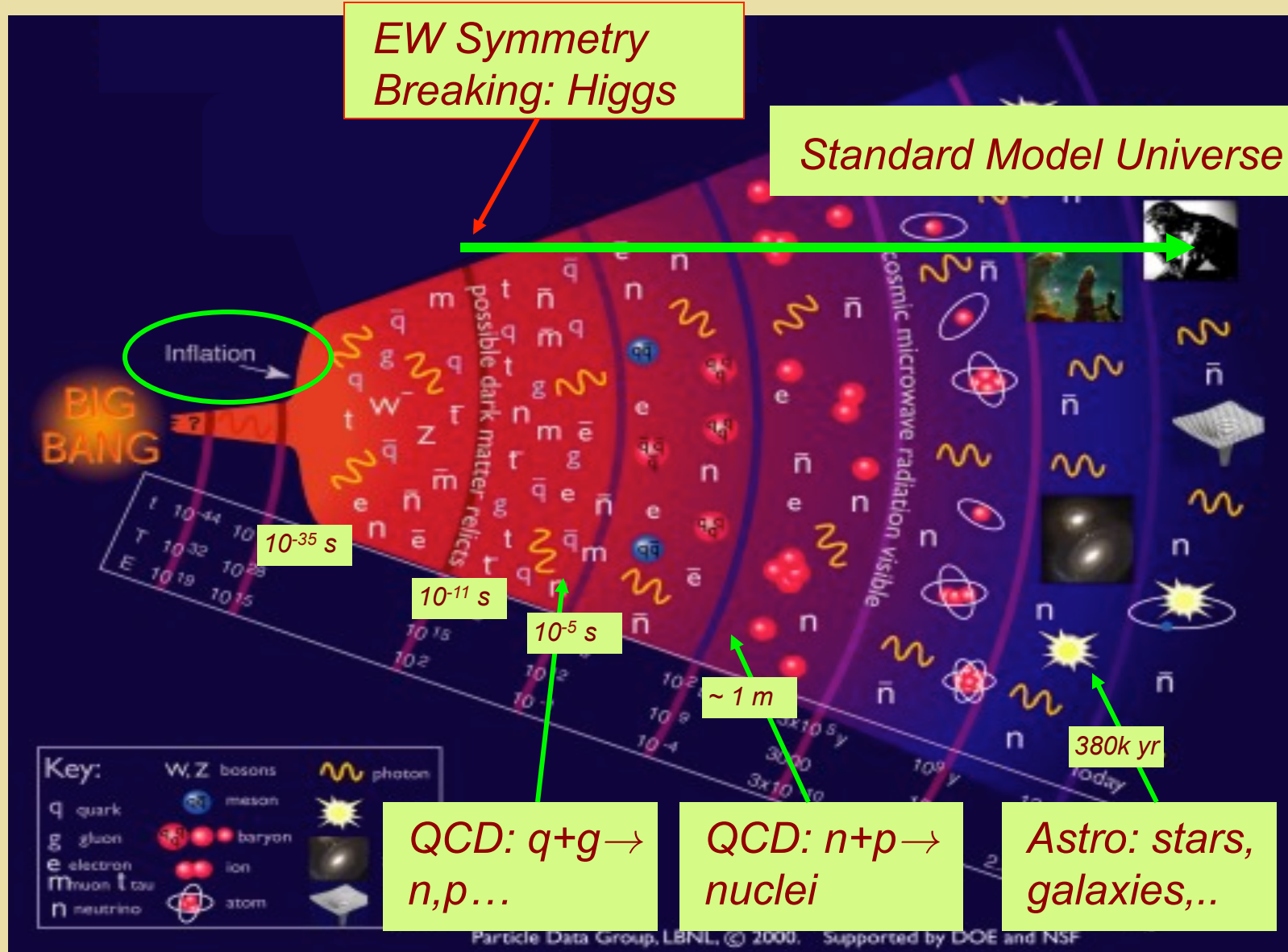
*\*\* Disclaimer: not my primary area of expertise*

# *Lecture VIII Outline*

- I. Origin of Matter: Leptogenesis*
- II. Neutrino Mass from Cosmology*

# *I. Origin of Matter: Leptogenesis*

# Symmetries & Cosmic History

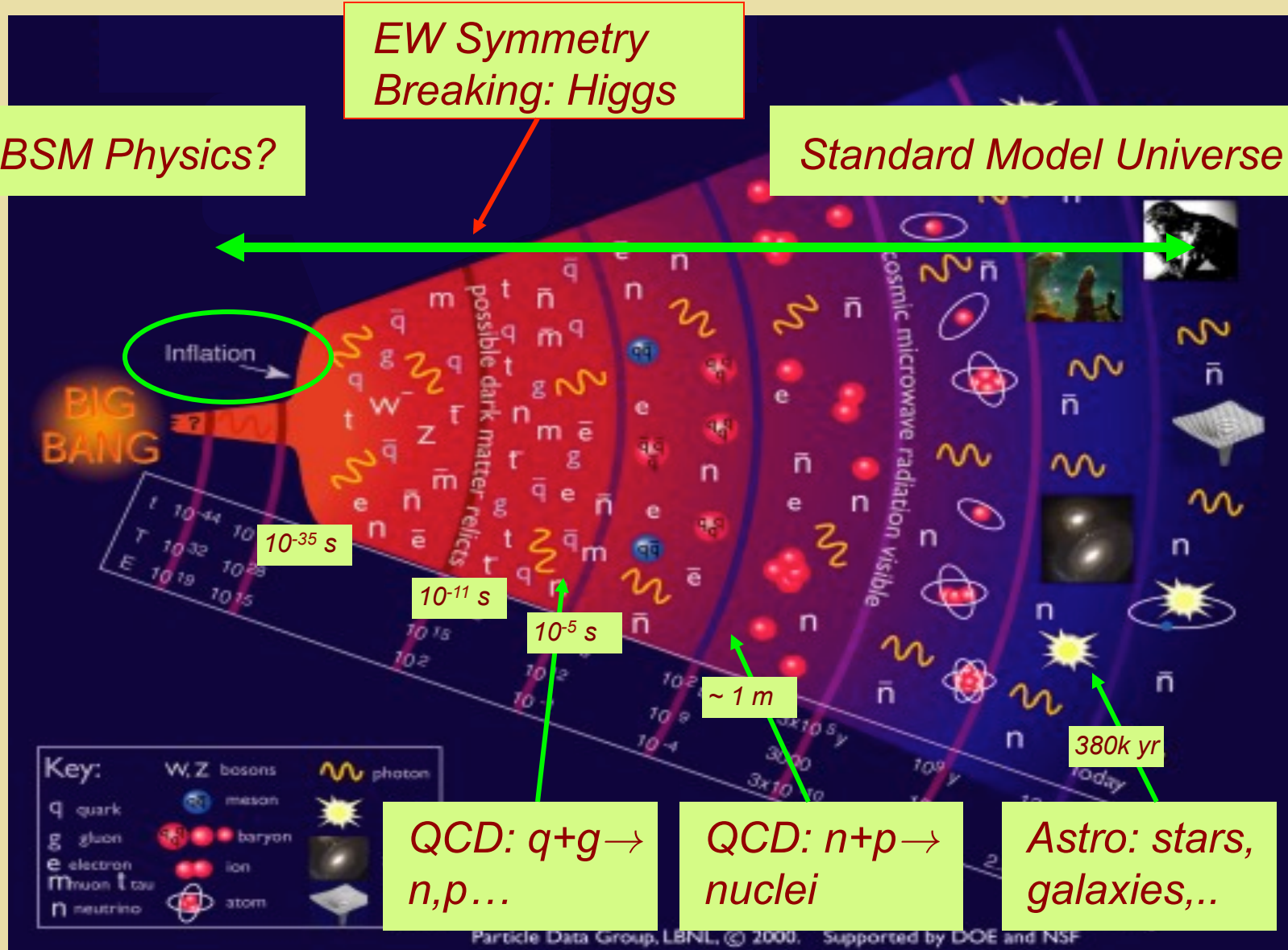


# Symmetries & Cosmic History

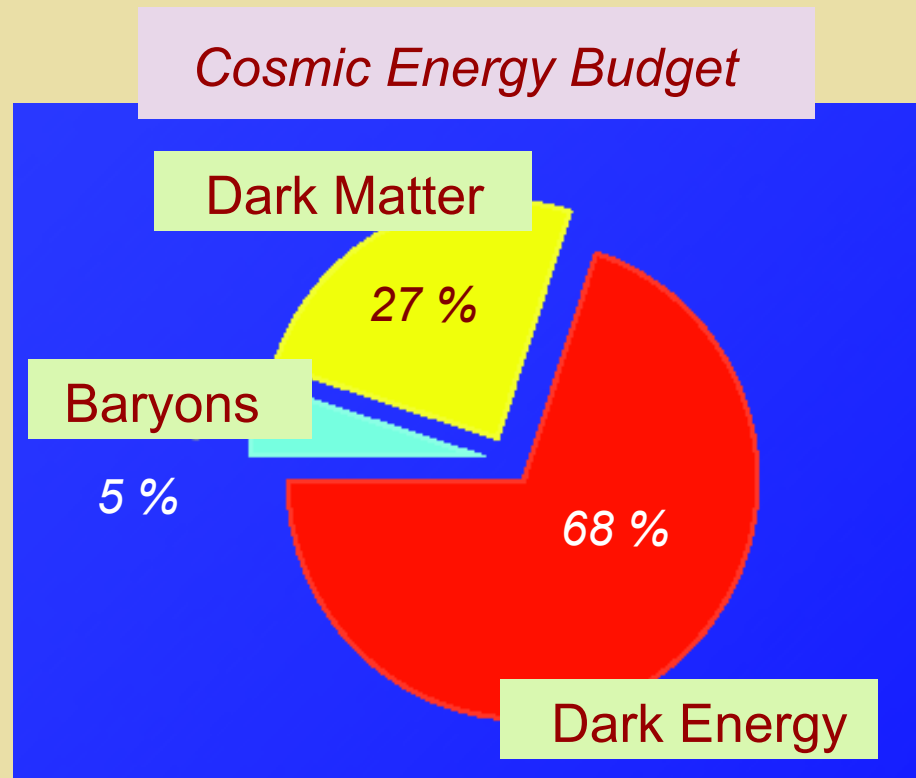
BSM Physics?

EW Symmetry  
Breaking: Higgs

Standard Model Universe

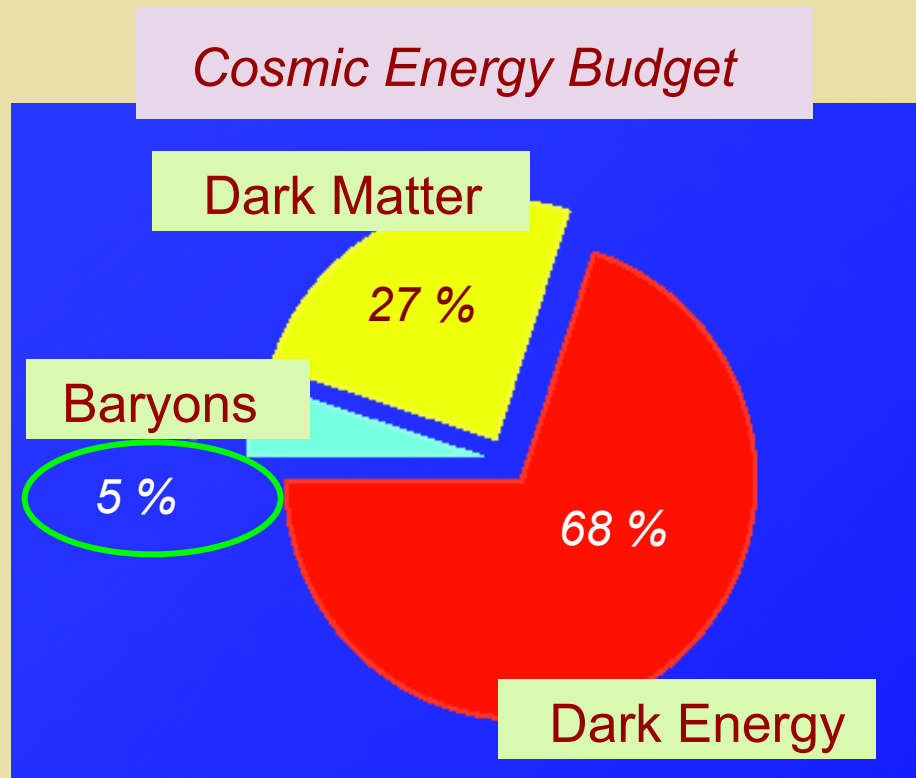


# *The Origin of Matter*



*Explaining the origin, identity, and relative fractions of the cosmic energy budget is one of the most compelling motivations for physics beyond the Standard Model*

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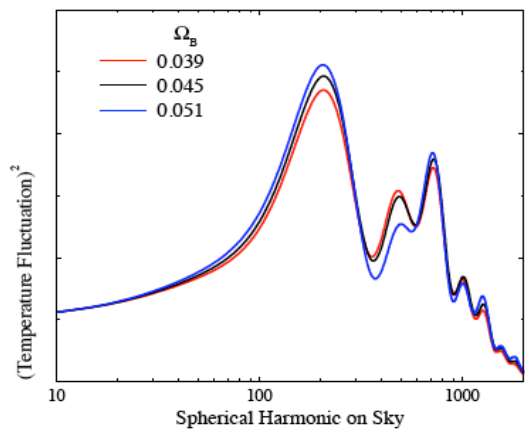


# Cosmic Baryon Asymmetry

$$Y_B = \frac{n_B}{s} = (8.59 \pm 0.11) \times 10^{-11}$$

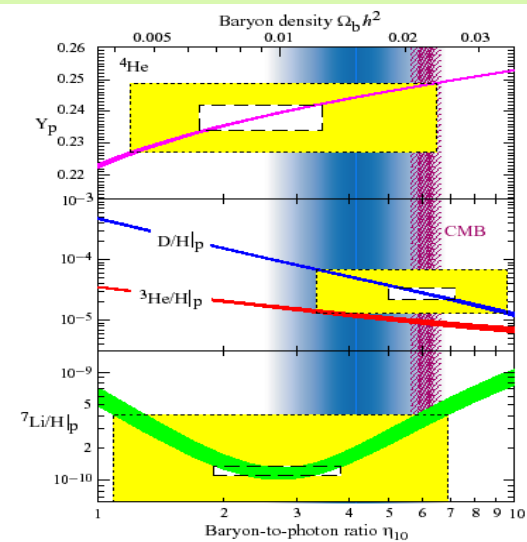
Cosmic Microwave Bcknd:

Shape of anisotropies depends on  $Y_B$



Big Bang Nucleosynthesis:

Light element abundances depend on  $Y_B$



# Symmetries & Cosmic History

BSM Physics?

EW Symmetry  
Breaking: Higgs

Standard Model Universe

How did we go from  
nothing to something ?

BIG BANG

Inflation

$10^{-35}$  s

$10^{-11}$  s

$10^{-5}$  s

$\sim 1$  m

380k yr

Key:

W, Z bosons	meson	photon
q quark	baryon	
g gluon	ion	
e electron	atom	
$\mu$ muon		
$\tau$ tau		
$\nu$ neutrino		

QCD:  $q+g \rightarrow n, p, \dots$

QCD:  $n+p \rightarrow$   
nuclei

Astro: stars,  
galaxies, ..

# *Ingredients for Baryogenesis*



- *B violation (sphalerons)*
- *C & CP violation*
- *Out-of-equilibrium or CPT violation*

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*Standard Model*

*BSM*

✓

✓

✗

✓

✗

✓

# Ingredients for Baryogenesis



Scenarios: *leptogenesis, EW baryogenesis, Affleck-Dine, asymmetric DM, cold baryogenesis, post-sphaleron baryogenesis...*

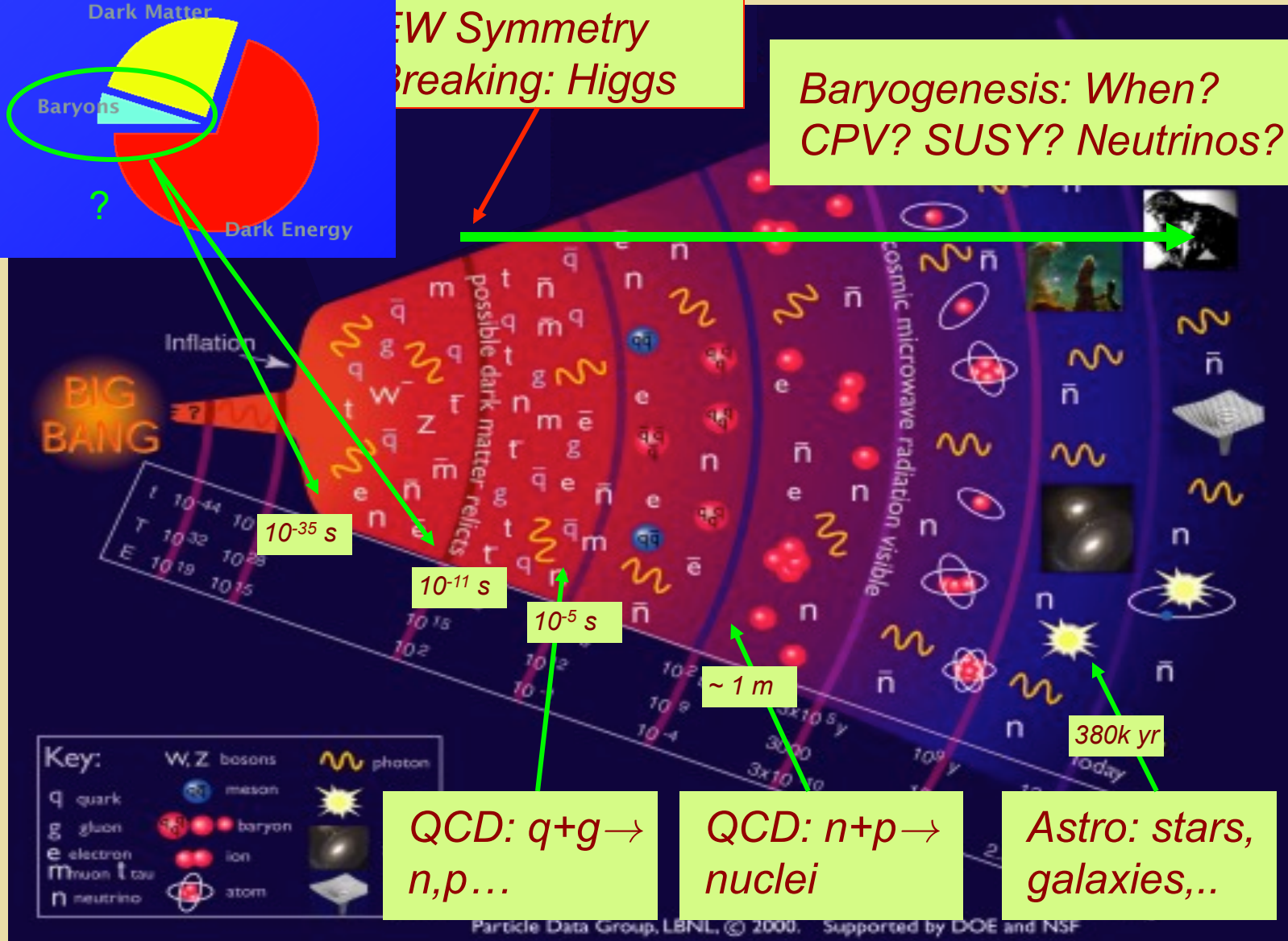
	<i>Standard Model</i>	<i>BSM</i>
• <i>B violation (sphalerons)</i>	✓	✓
• <i>C &amp; CP violation</i>	✗	✓
• <i>Out-of-equilibrium or CPT violation</i>	✗	✓

# Symmetries & Cosmic History



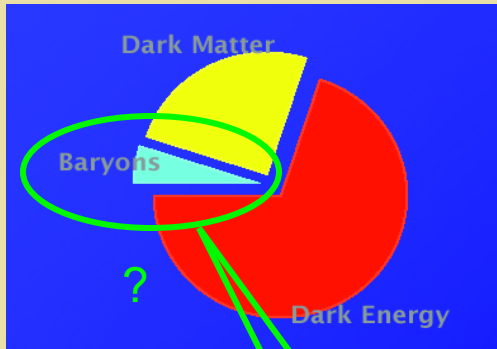
EW Symmetry  
Breaking: Higgs

Baryogenesis: When?  
CPV? SUSY? Neutrinos?





# Symmetries & Cosmic History

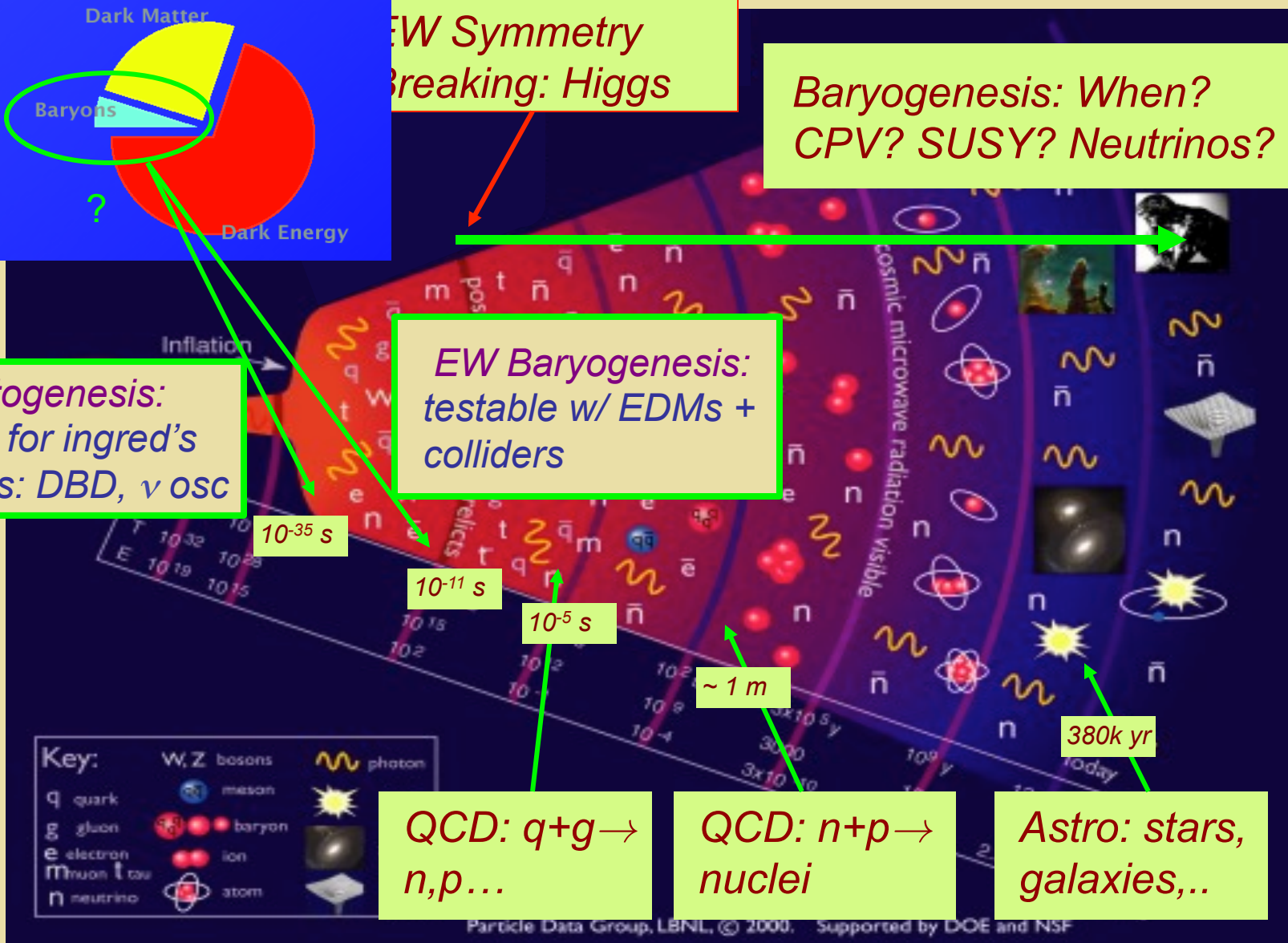


EW Symmetry Breaking: Higgs

Baryogenesis: When?  
CPV? SUSY? Neutrinos?

Leptogenesis:  
look for ingred's  
w/  $\nu$ s: DBD,  $\nu$  osc

EW Baryogenesis:  
testable w/ EDMs +  
colliders



$10^{-35}$  s

$10^{-11}$  s

$10^{-5}$  s

$\sim 1$  m

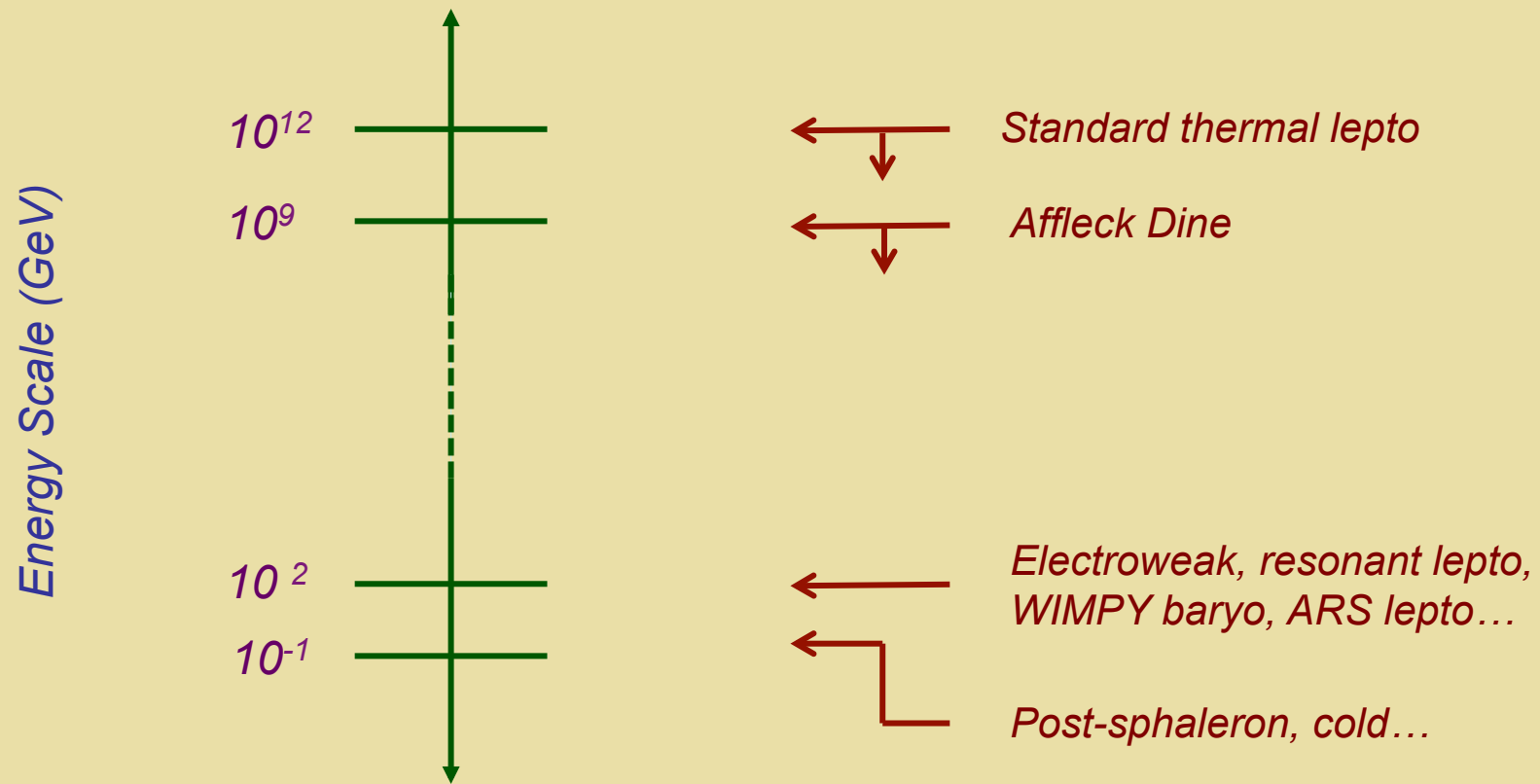
380k yr

QCD:  $q+g \rightarrow n, p, \dots$

QCD:  $n+p \rightarrow$  nuclei

Astro: stars, galaxies, ..

# Baryogenesis Scenarios

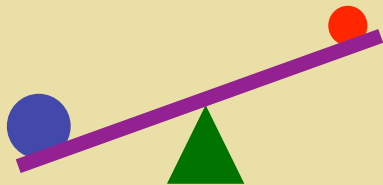




## What Questions Does It Address ?

- *Is the neutrino its own antiparticle ?*
- *Why is there more matter than antimatter ?*
- *Why are neutrino masses so small?*

“See saw mechanism”



“Leptogenesis”

$$\nu = \bar{\nu}$$

Heavy neutrino decays in early universe generate baryon asym

New heavy neutrino-like particle =  
its own anti-particle

# Neutrinos and the Origin of Matter

- *Heavy neutrinos decay out of equilibrium in early universe*
- *Majorana neutrinos can decay to particles and antiparticles*
- *Rates can be slightly different (CP violation)*

$$\Gamma(N \rightarrow \ell H) \neq \Gamma(N \rightarrow \bar{\ell} H^*)$$

- *Resulting excess of leptons over anti-leptons partially converted into excess of quarks over anti-quarks by Standard Model sphalerons*

# Neutrinos and the Origin of Matter

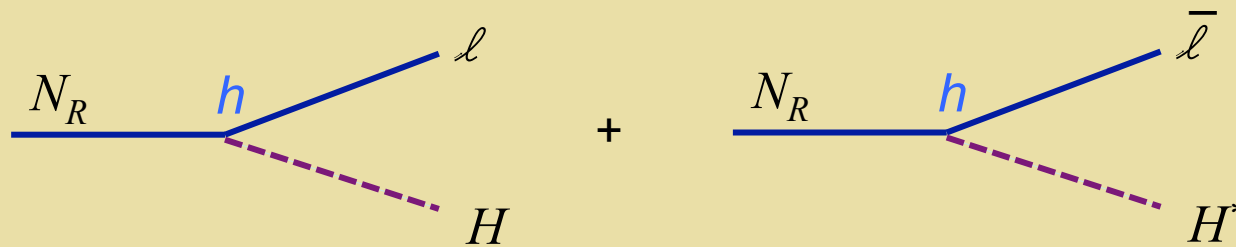
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# Neutrinos and the Origin of Matter

- Heavy neutrinos decay out of equilibrium in early universe



$$\Gamma_N \equiv \Gamma(N_R \rightarrow \ell H) + \Gamma(N_R \rightarrow \bar{\ell} H^*) = \frac{|h|^2}{8\pi} M_N$$

Hubble rate

$$H(T) \sim 1.66 g_* \frac{T^2}{M_P}$$

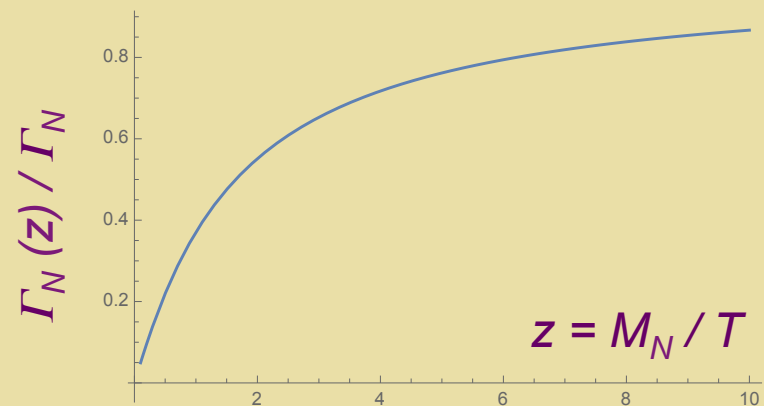
# Neutrinos and the Origin of Matter

- *Heavy neutrinos decay out of equilibrium in early universe*

*Simple estimation*

$$\Gamma_N \lesssim H(T=M_N)$$

$$\Gamma_N(z) = \frac{K_1(z)}{K_2(z)} \Gamma_N$$



# Neutrinos and the Origin of Matter

- *Heavy neutrinos decay out of equilibrium in early universe*

Simple estimation

$$\Gamma_N \lesssim H(T=M_N) \quad \longrightarrow$$

$$m_1 \approx m_*$$

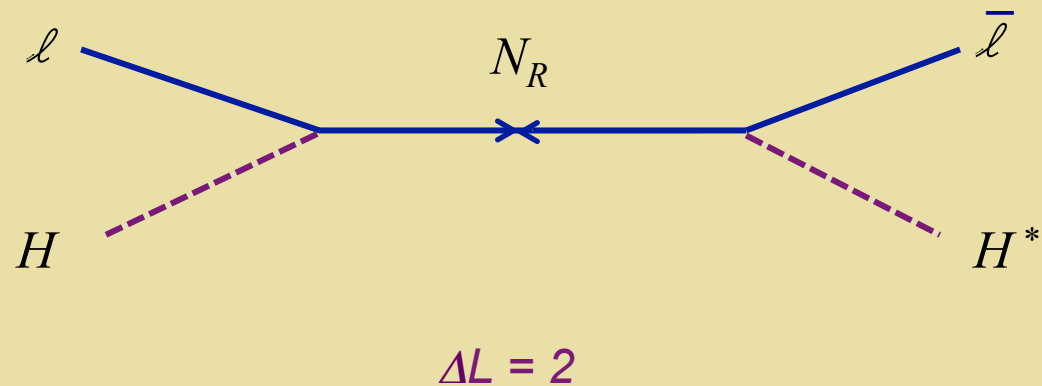
$$m_1 \approx \frac{m_D^2}{M_N}$$

$$m_* = 8\pi * (1.66g_*) \frac{v^2}{M_P} \quad \sim \text{few } \times 10^{-3} \text{ eV}$$

# Neutrinos and the Origin of Matter

- *Heavy neutrinos decay out of equilibrium in early universe*

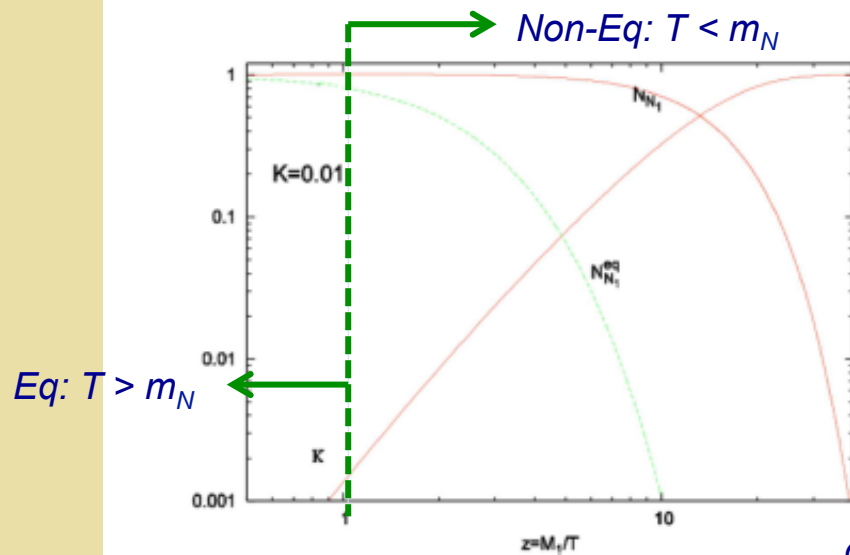
*Washout processes*



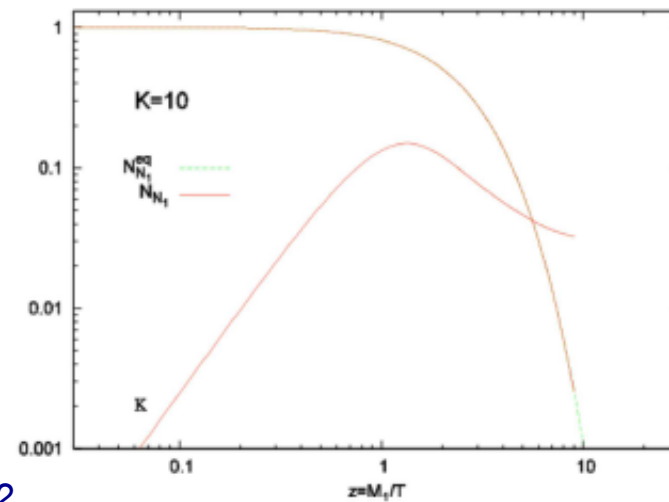
# Neutrinos and the Origin of Matter

- *Heavy neutrinos decay out of equilibrium in early universe*

*Complete calculation: Boltzmann equations*



di Bari '12





# Neutrinos and the Origin of Matter

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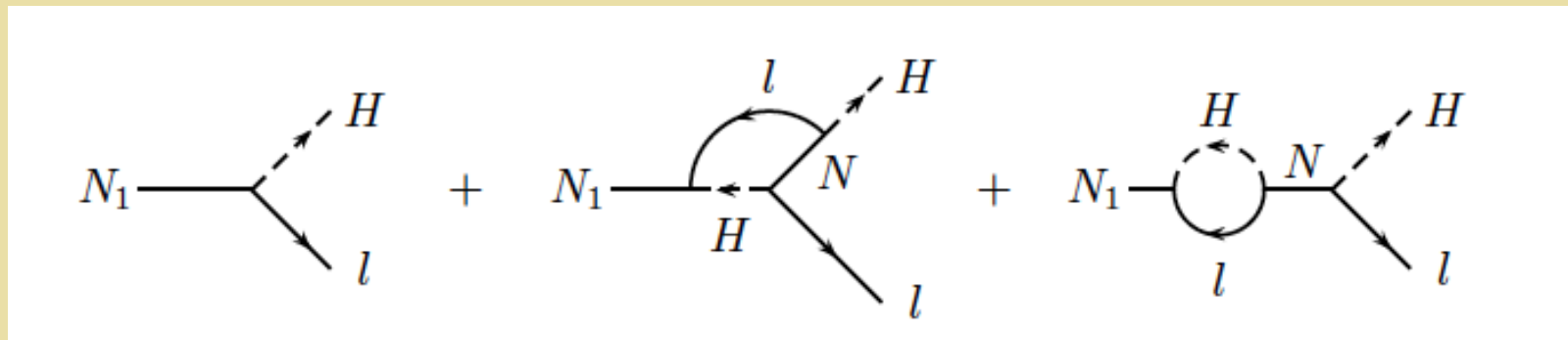
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# Neutrinos and the Origin of Matter

## CPV Asymmetry



Tree-level CPV

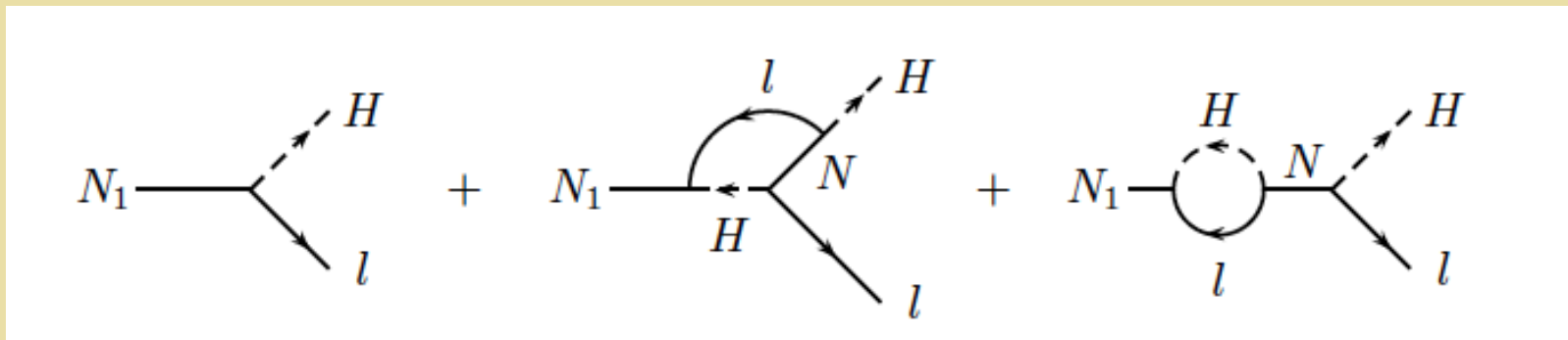
X

One-loop "absorptive part"

$$\varepsilon_1 \simeq \frac{3}{16\pi} \frac{1}{(hh^\dagger)_{11}} \sum_{i=2,3} \text{Im} \left[ (hh^\dagger)_{i1}^2 \right] \frac{M_1}{M_i}$$

# Neutrinos and the Origin of Matter

## CPV Asymmetry



Tree-level CPV

X

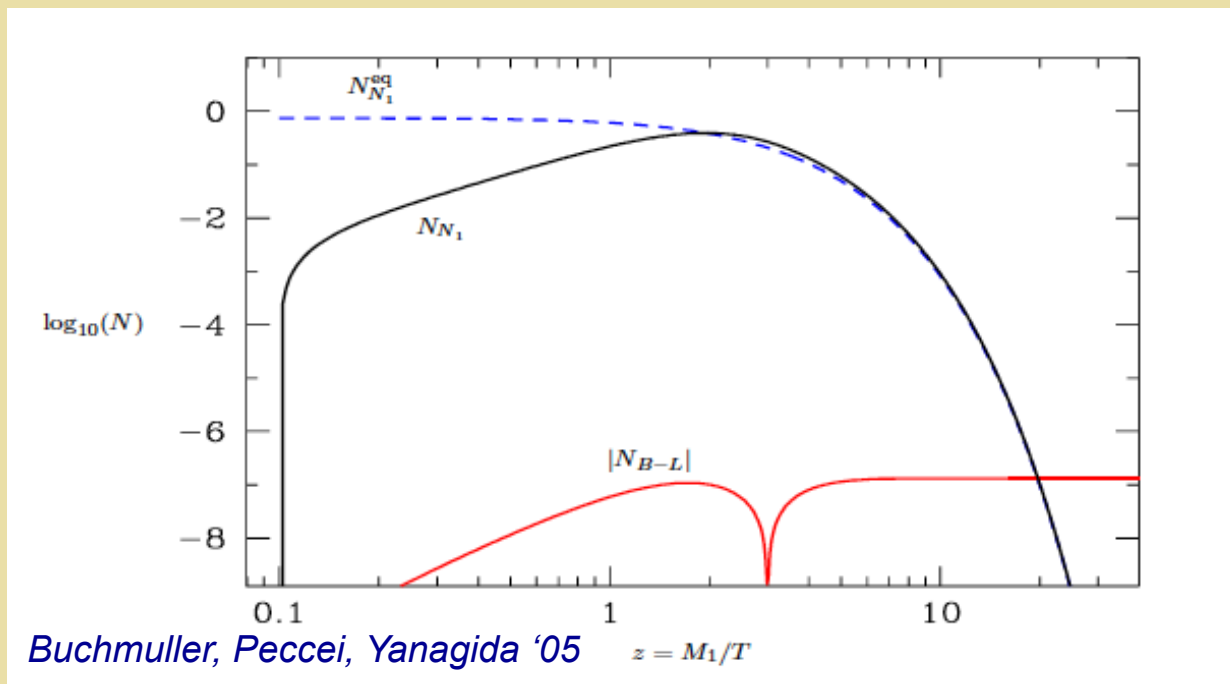
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CPV phases  
but not same  
as  $\phi_{PMNS}$

# Neutrinos and the Origin of Matter

*Putting pieces together: B-L asymmetry*



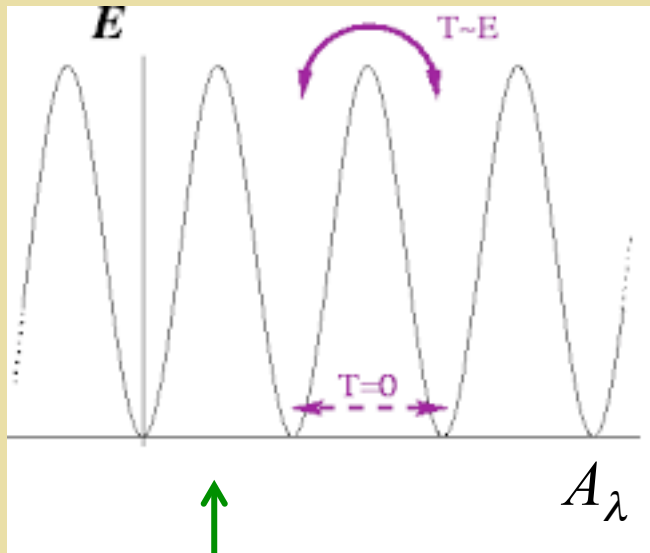
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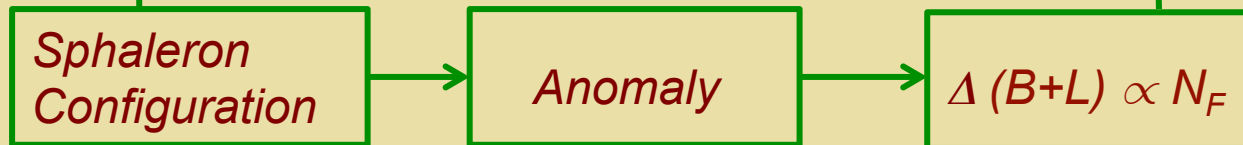
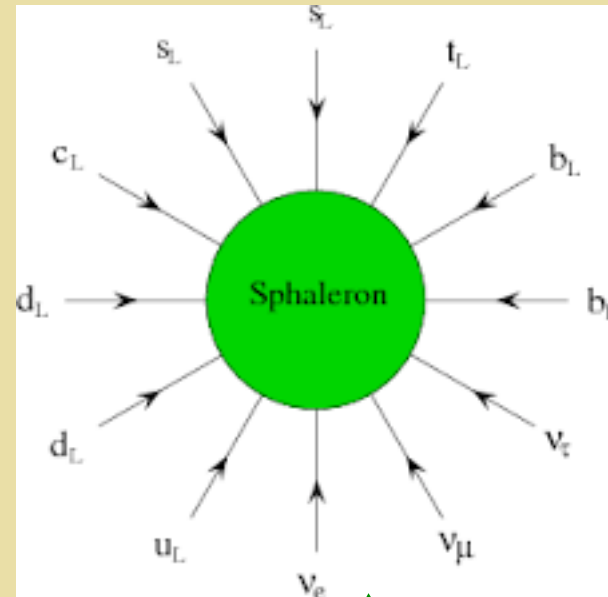
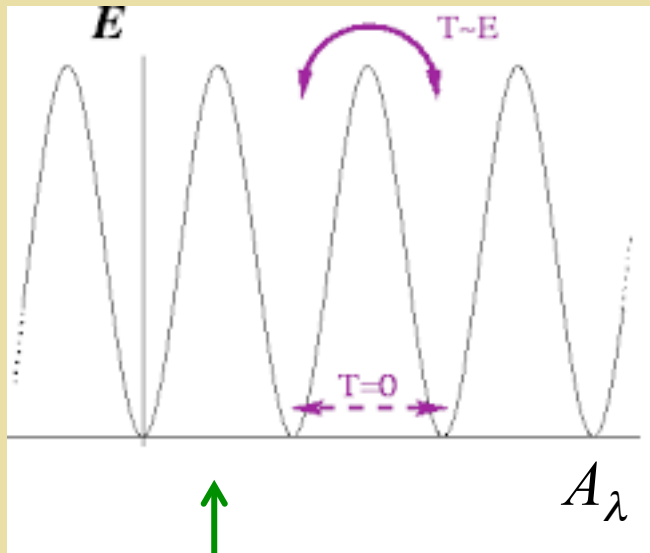
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# Electroweak Sphalerons



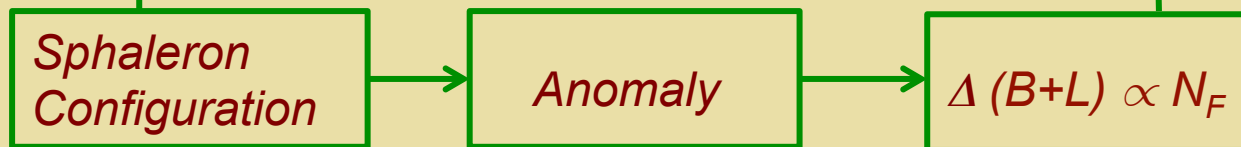
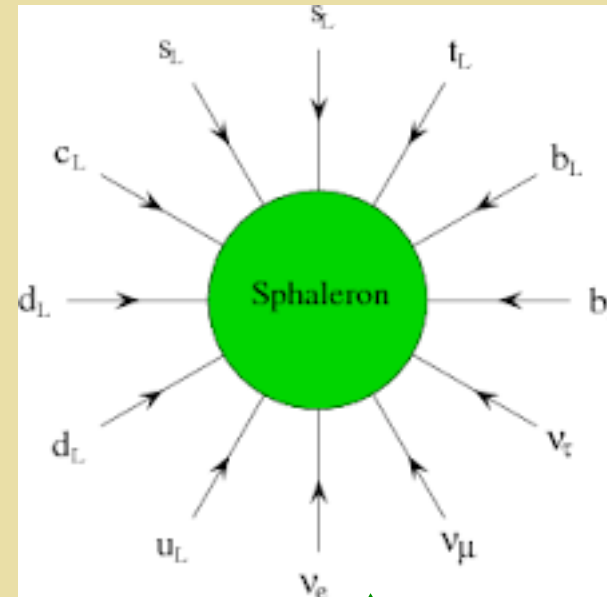
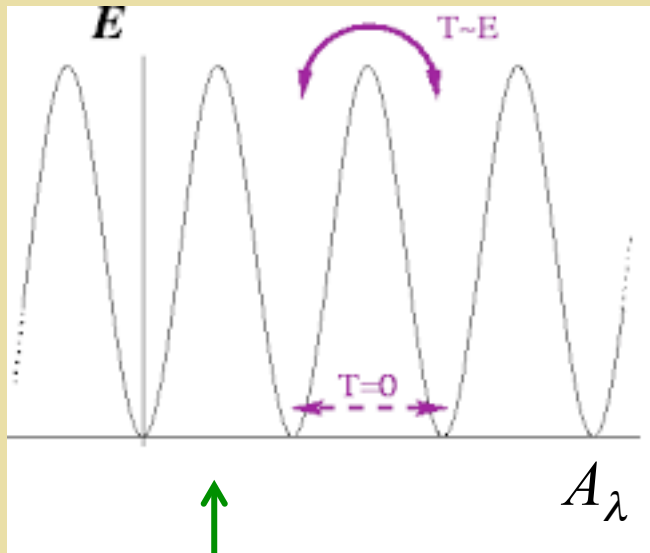
Sphaleron  
Configuration

# Electroweak Sphalerons





# Electroweak Sphalerons



*EW sphalerons convert B-L asymmetry to  $Y_B$*

# Davidson-Ibarra Bound

$$|\epsilon_1| \lesssim \frac{3}{8\pi} \frac{M_{N1} m_{\nu 3}}{\langle H^0 \rangle^2}$$



$$M_{N1} \gtrsim 10^9 \text{ GeV}$$

# TeV Scale LNV ?

$$\mathcal{L}_{\text{mass}} = y \bar{L} \tilde{H} \nu_R + \text{h.c.}$$

*Dirac*

$$\mathcal{L}_{\text{mass}} = \frac{y}{\Lambda} \bar{L}^c H H^T L + \text{h.c.}$$

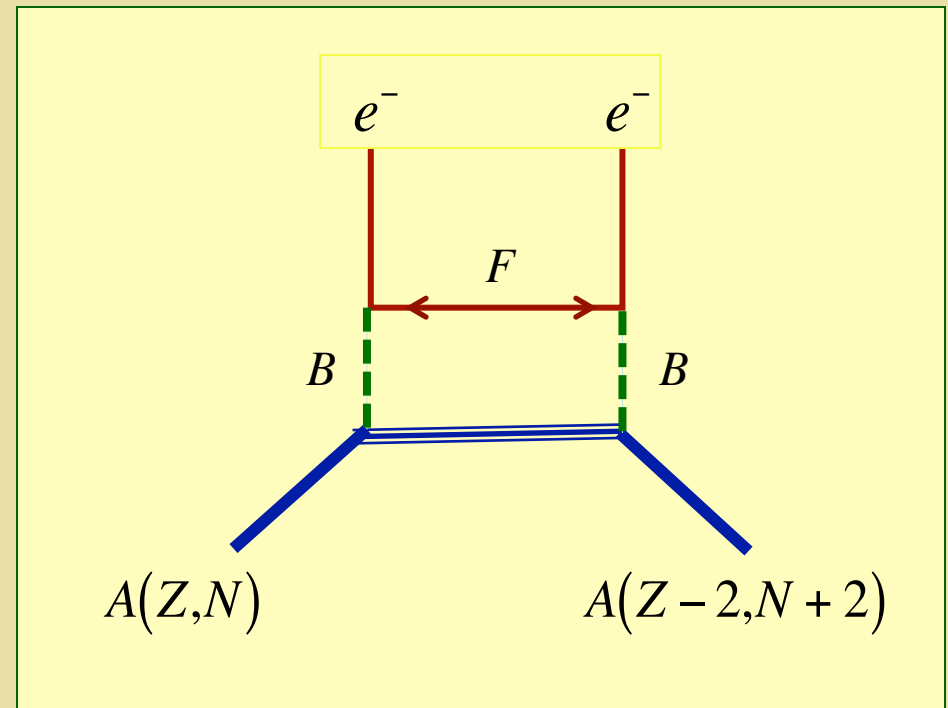
*Majorana*

## TeV LNV Mechanism

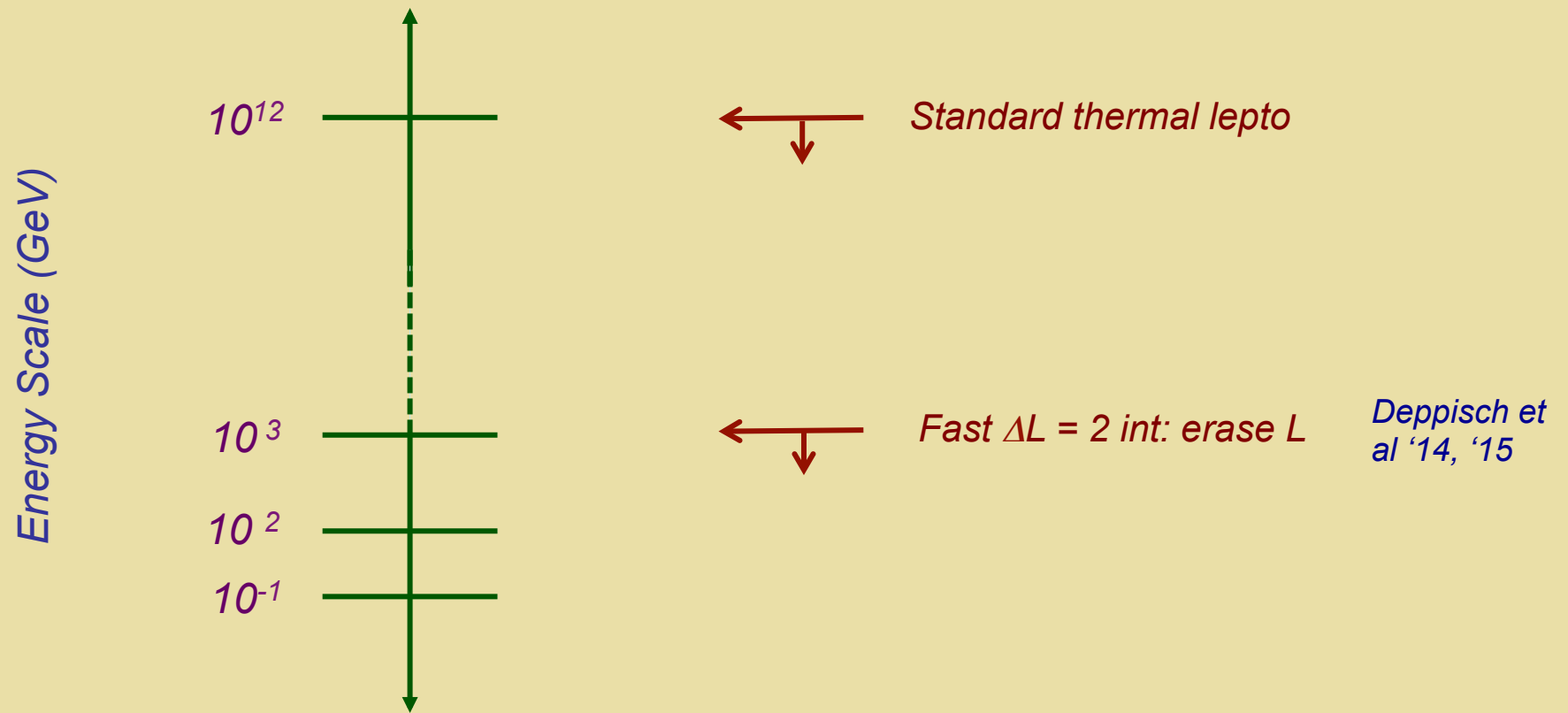
$$\frac{A_H}{A_L} \sim \frac{M_W^4 \bar{k}^2}{\Lambda^5 m_{\beta\beta}}$$

***O(1)*** for  $\Lambda \sim 1 \text{ TeV}$

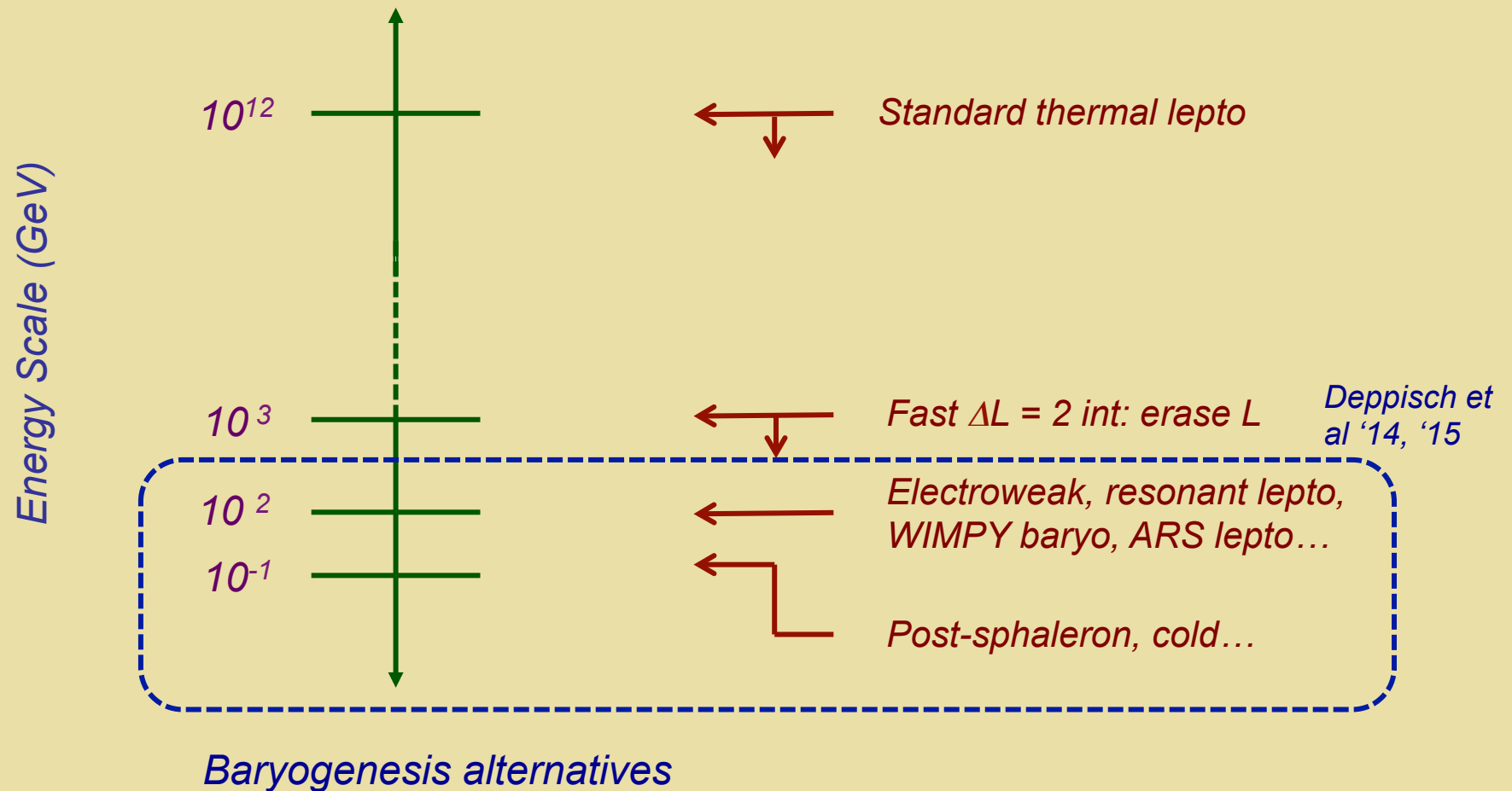
***Implications***



# TeV LNV & Leptogenesis



# TeV LNV & Leptogenesis

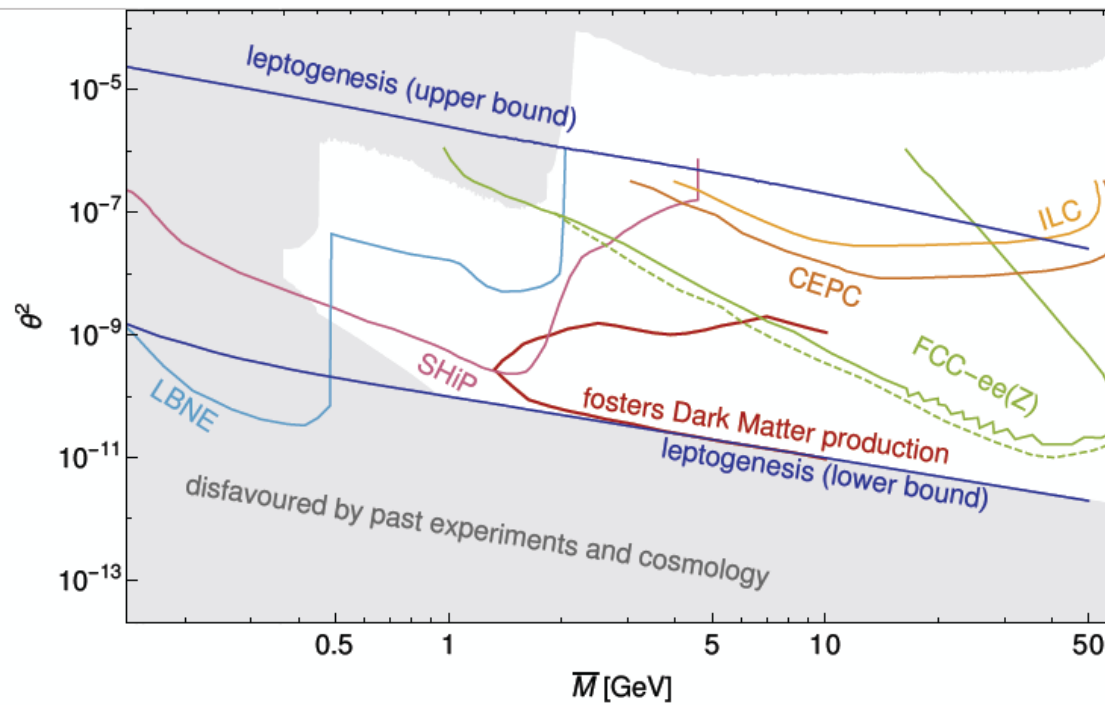


# Low Scale “ARS” Leptogenesis

1. 3 Singlet RH neutrinos:  $N_A, N_B, N_C$
2.  $L^{\text{TOT}} = L^{\text{SM}} + L_A + L_B + L_C$
3.  $N_k$  oscillations + CPV  $\rightarrow L_A \neq 0, L_B \neq 0, L_C \neq 0$  but  $L^{\text{TOT}} = 0$
4. Yukawa interactions:  $L_k \Leftrightarrow H + \ell_k$  in equilibrium above  $T_{EW}$  for  $k=A, B$  but not for  $k=C$
5. Lepton number for  $\ell_{A,B}$  converted to  $n_B$  by EW sphalerons
6. Conditions 4  $\rightarrow M_{N_k}$  can be  $\sim O(\text{GeV})$

# Low Scale “ARS” Leptogenesis

## Global analysis and cosmology




plot to be updated in MaD/Garbrecht/Gueter/Klaric 1609.09069 [references to origin of sensitivity estimates given therein]

## *II. Neutrino Mass from Cosmology*



# ACFI Workshop

UMassAmherst



**AMHERST CENTER FOR FUNDAMENTAL INTERACTIONS**  
*Physics at the interface: Energy, Intensity, and Cosmic frontiers*  
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## Neutrino Mass: From the Terrestrial Laboratory to the Cosmos

**Date:** Monday, December 14, 2015 - 9:00am to Wednesday, December 16, 2015 - 2:00pm  
**Location:** Lederle Graduate Research Tower (LGRT) 419B, UMass Amherst

The goal of the workshop is to bring together a small group of theorists, experimentalists, and observers to address the relative implications of terrestrial, astrophysical, and cosmological probes of neutrino mass. With the prospect of order of magnitude improvements in the sensitivities of kinematic mass determinations, two-order of magnitude improvements in the lifetime sensitivity of neutrinoless double beta-decay searches, and significant advances in determinations of the sum of neutrino masses from large scale structure and the CMB, it is timely to delineate what a comparison of results from these, other laboratory and cosmological probes, and simulations might imply.

Among the questions to be addressed are:

## Upcoming Seminars

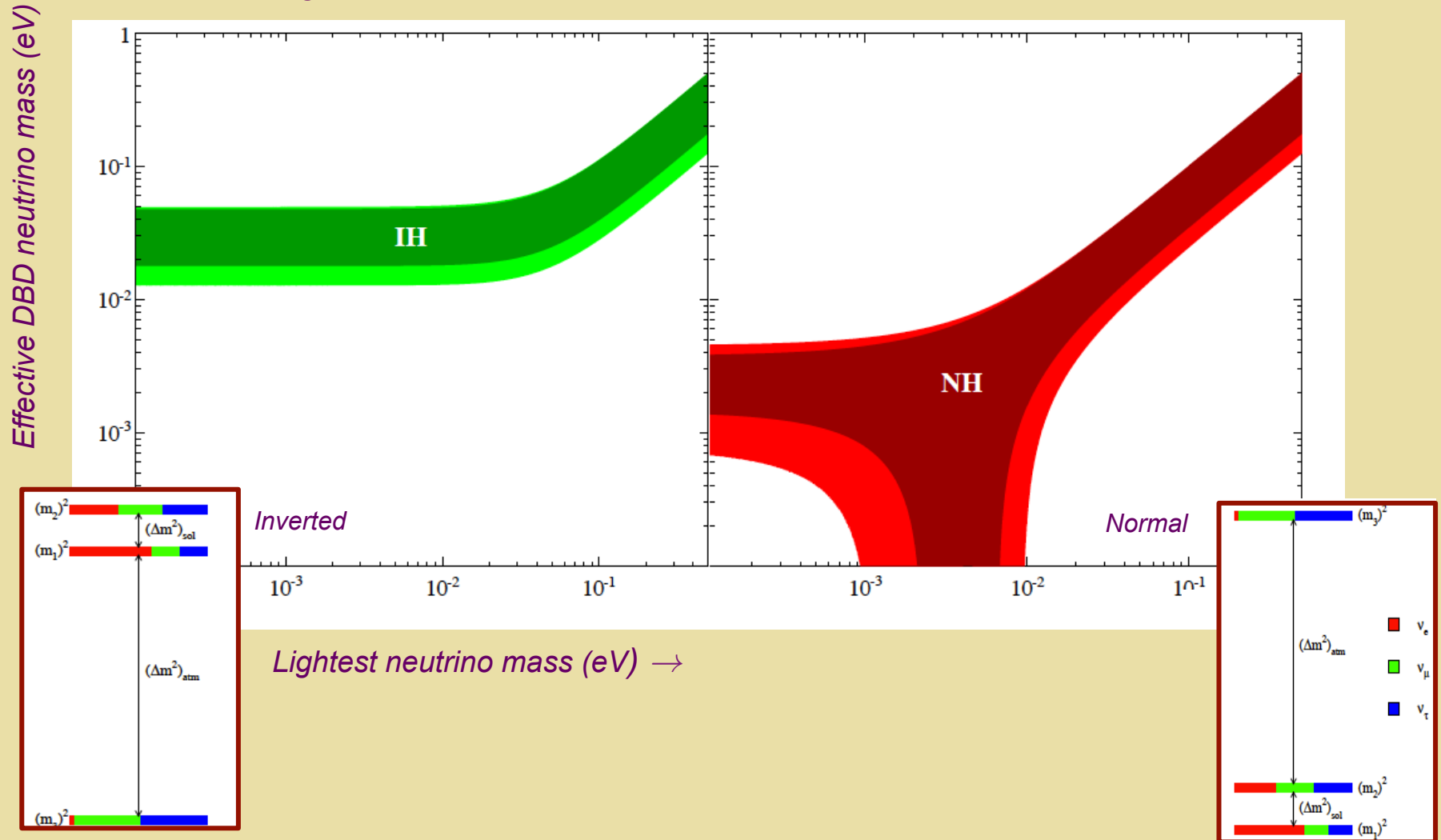
**ACFI Seminar**  
[TBA](#)  
Tue, Nov 7, 2017 - 2:30pm  
Graham White  
LGRT 419B

**ACFI Seminar**  
[Gravitational Wave Memory effect in all dimensions](#)  
Thu, Nov 9, 2017 - 10:45am  
Gautam Satishchandran  
LGRT 419B

**ACFI Seminar**  
[Neutrino Oscillation Measurements with the NOvA Experiment](#)  
Fri, Nov 10, 2017 - 2:15pm  
Kanika Sachdev

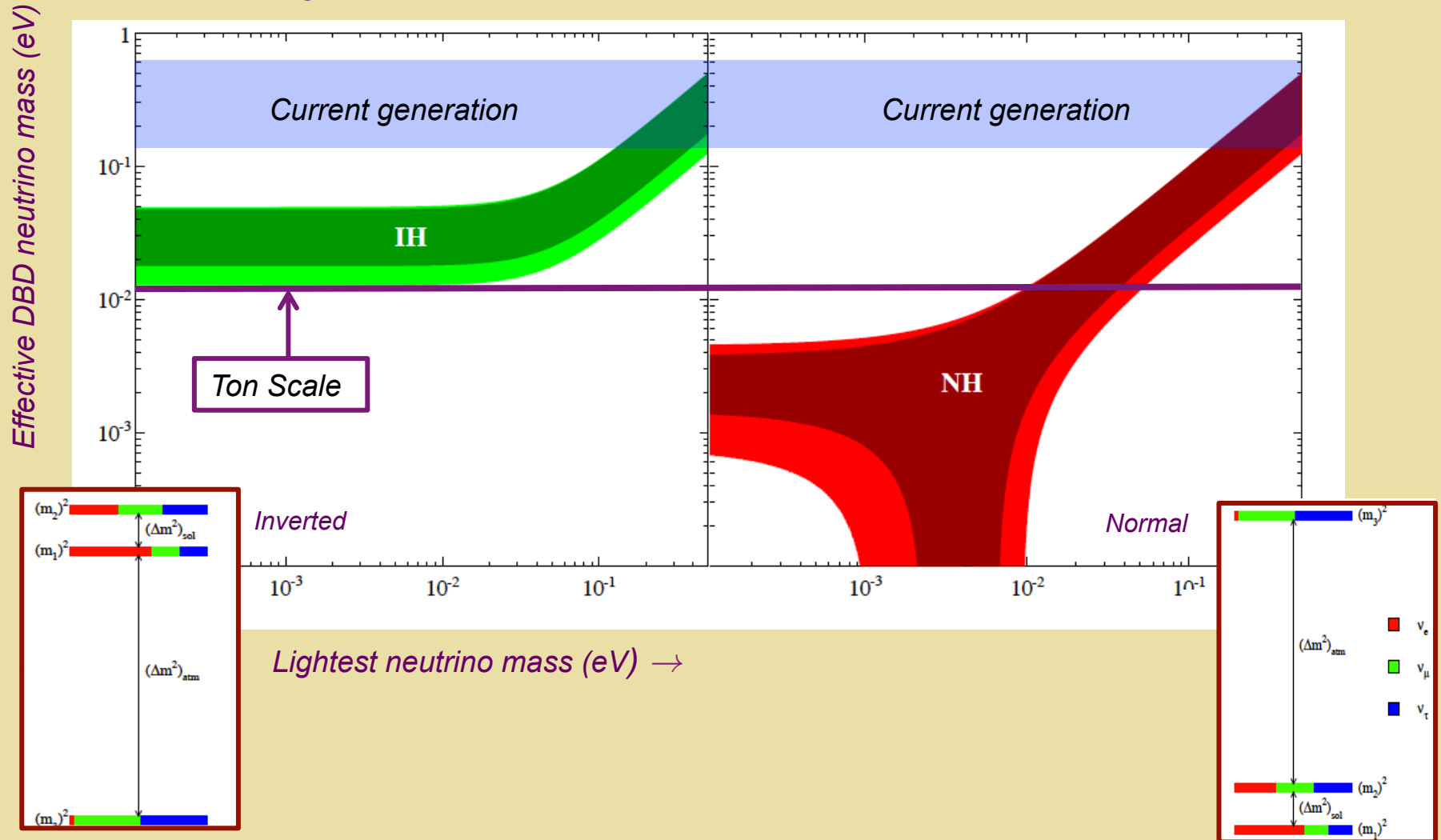
# $0\nu\beta\beta$ -Decay: Standard Mechanism

Three active light neutrinos



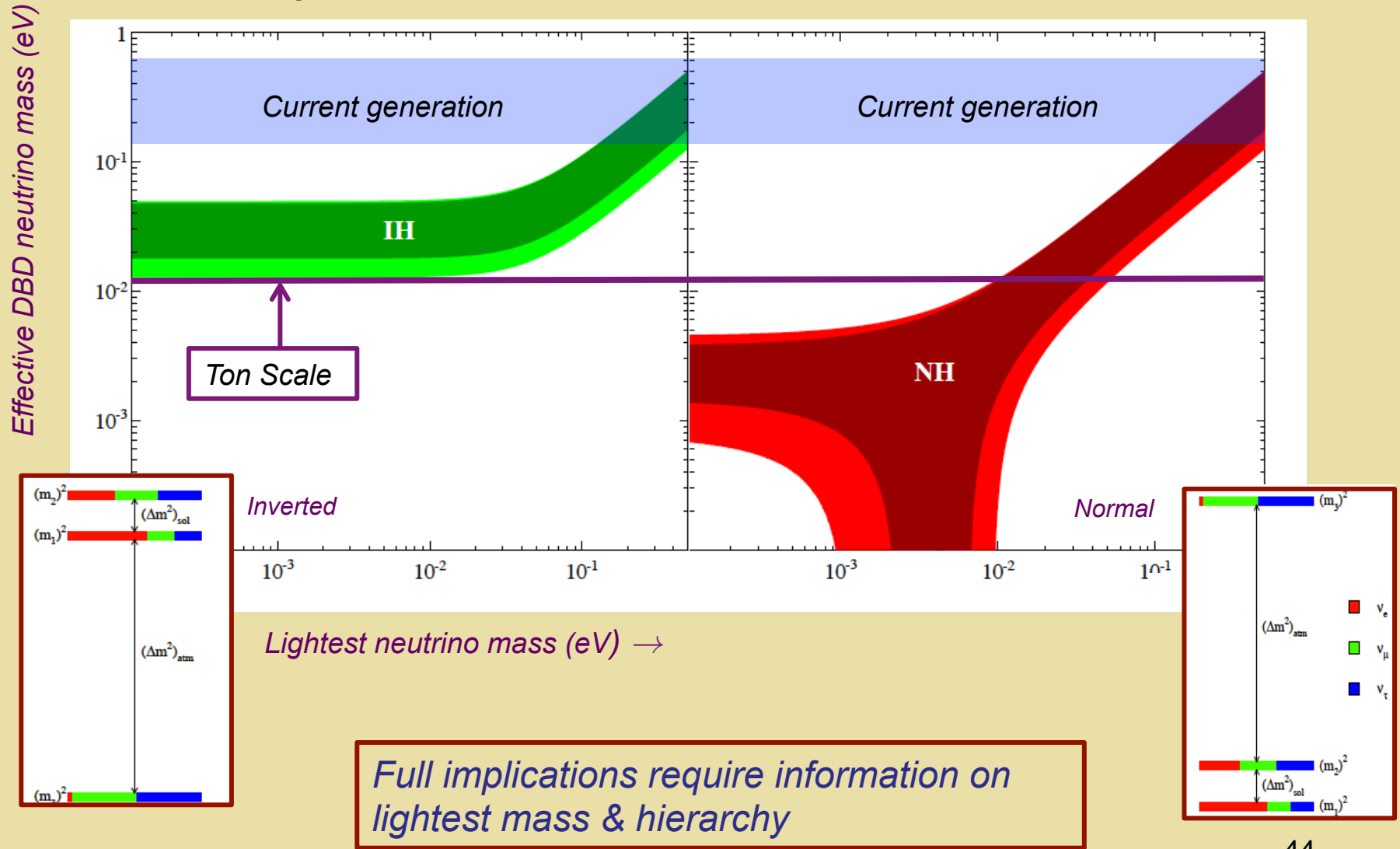
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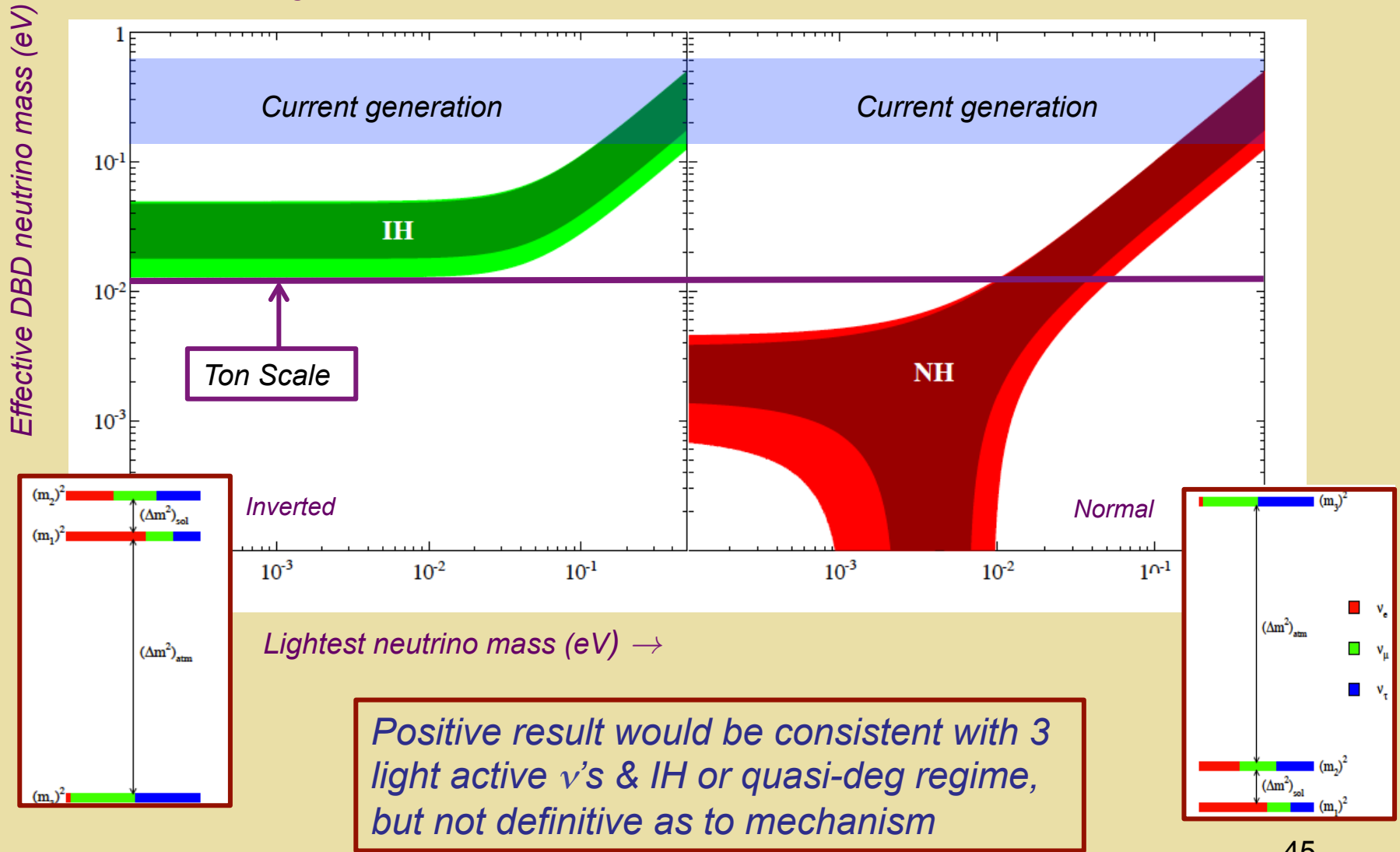
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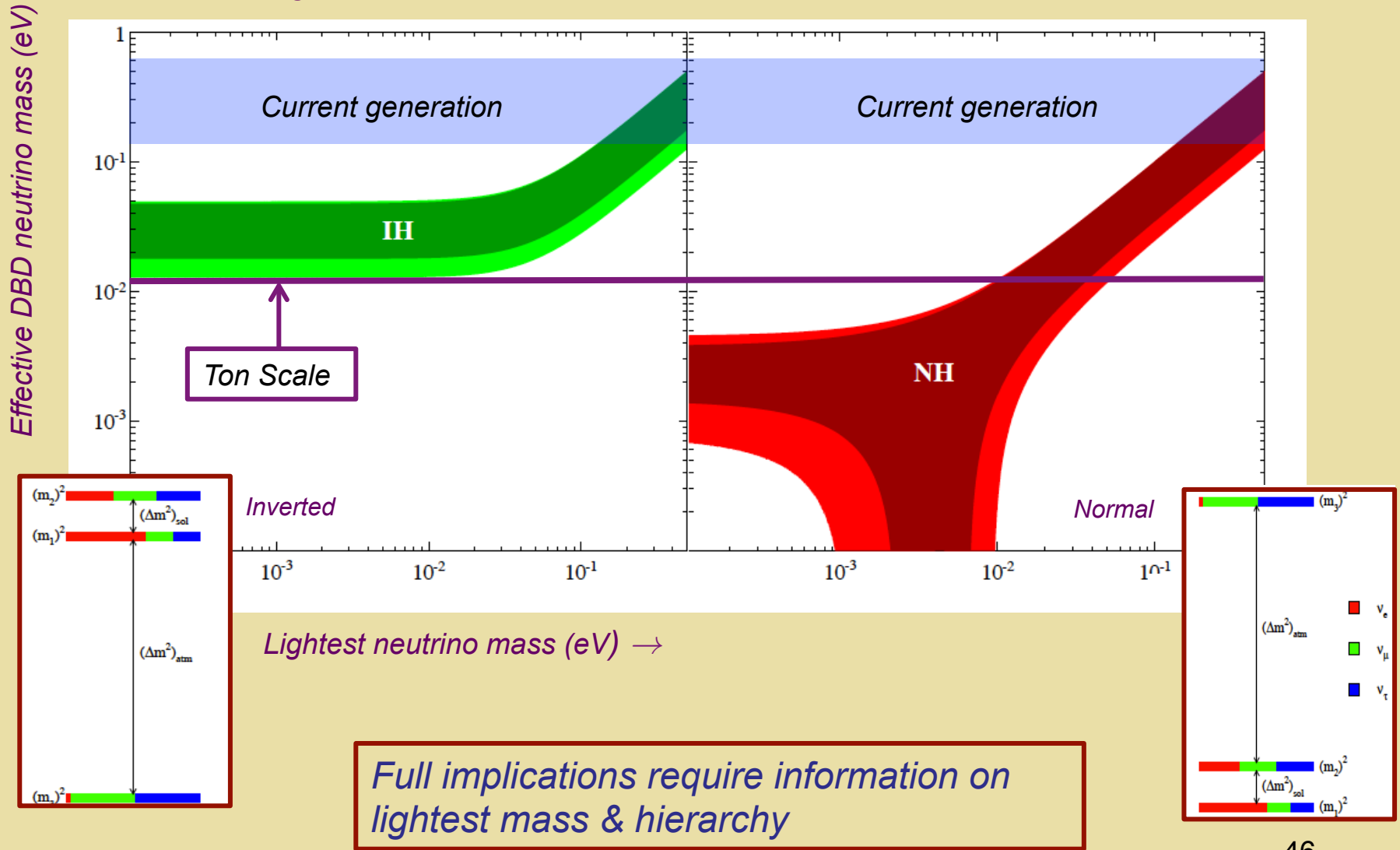
# Interpreting a Positive Result

Three active light neutrinos

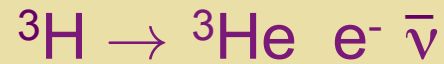


# Interpreting a Null Result: St'd Mechanism

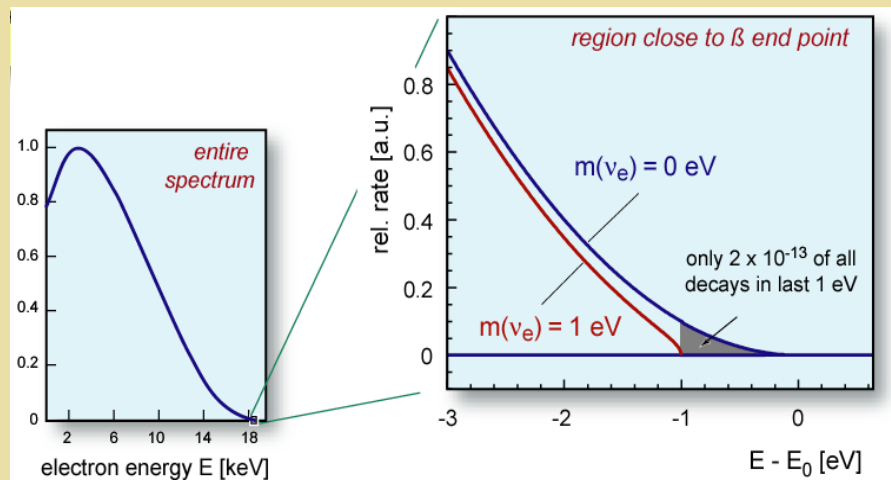
Three active light neutrinos



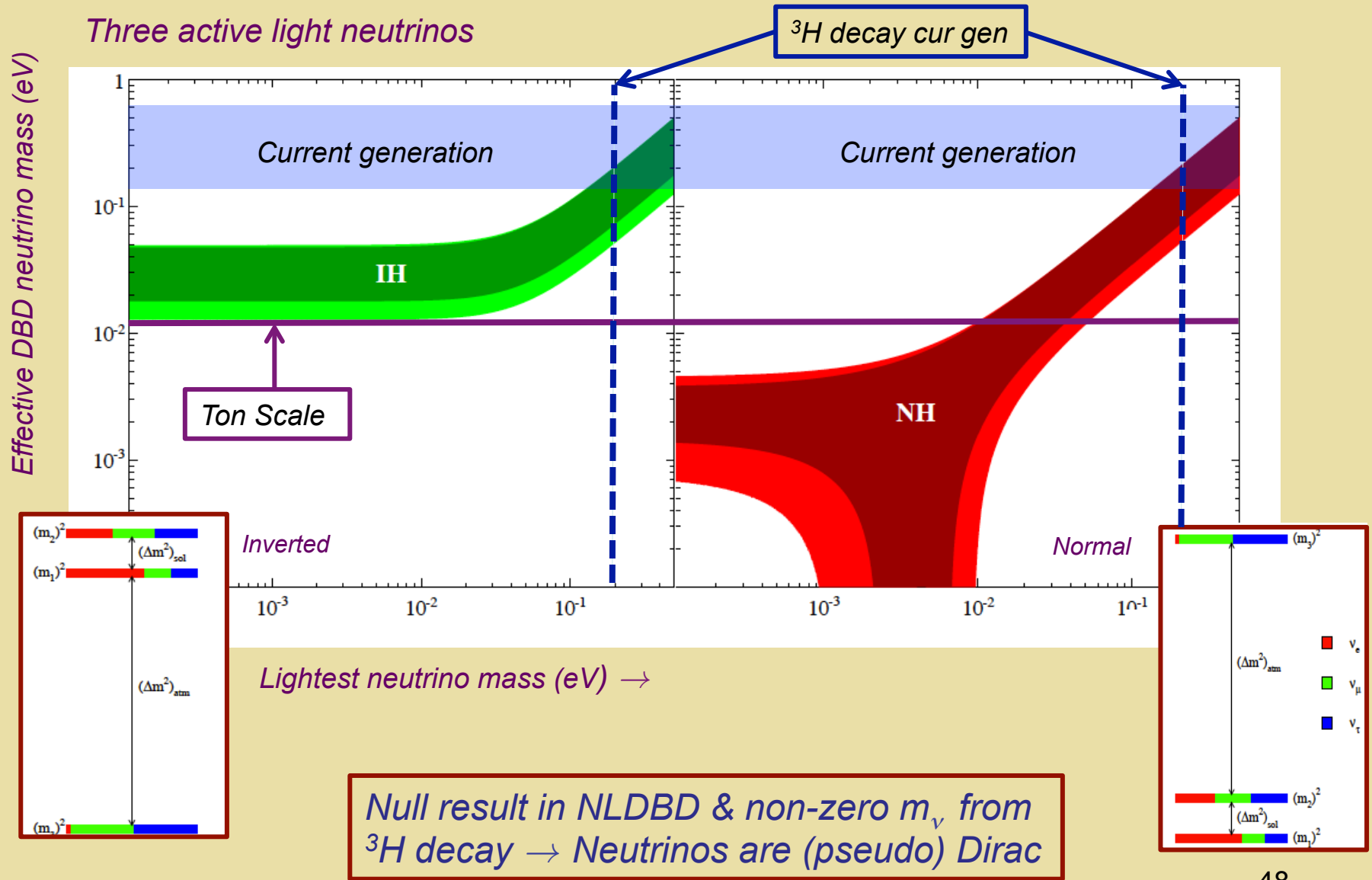
# Kinematic Neutrino Mass Measurements



*KATRIN*

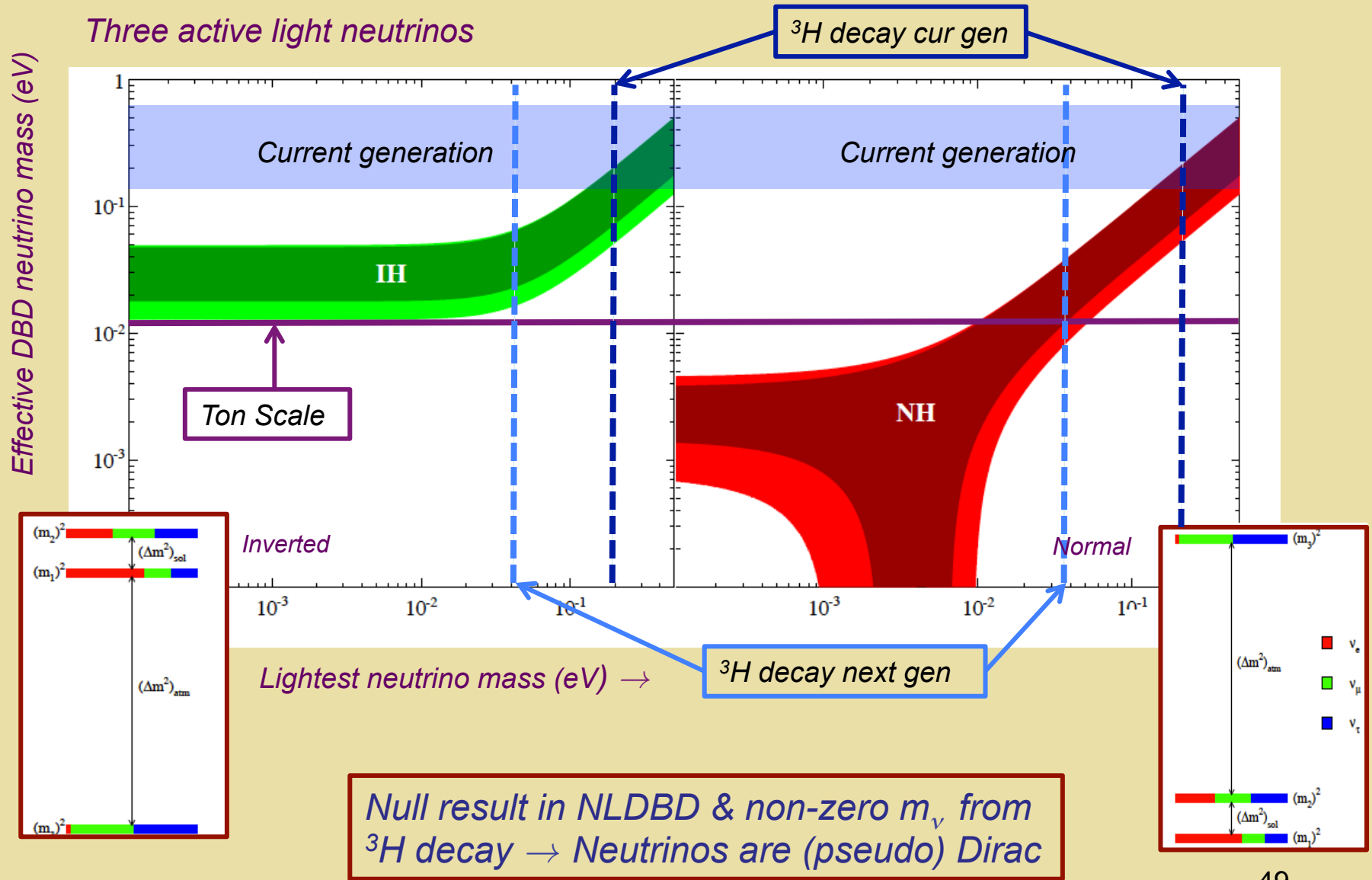


# St'd Mech: What Would a Null Result Imply ?





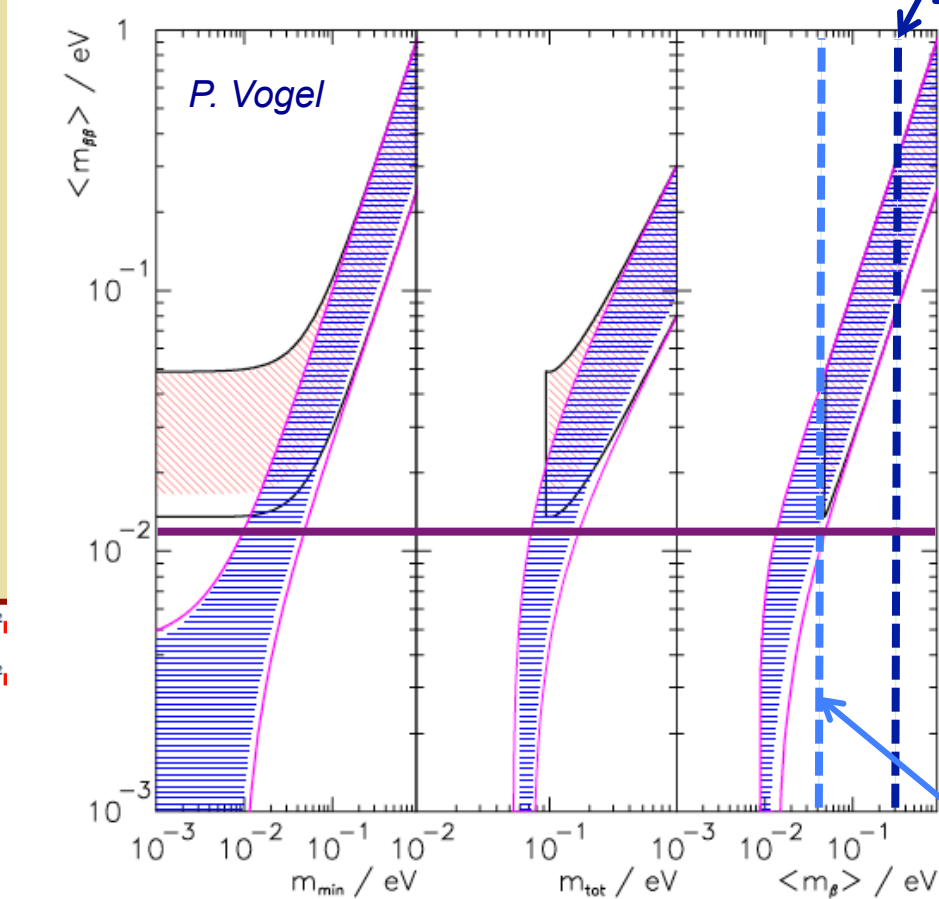
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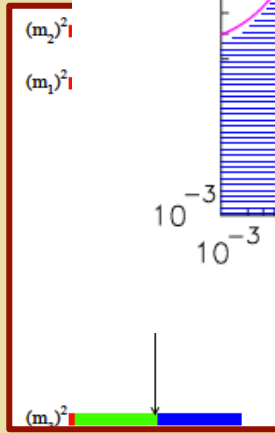
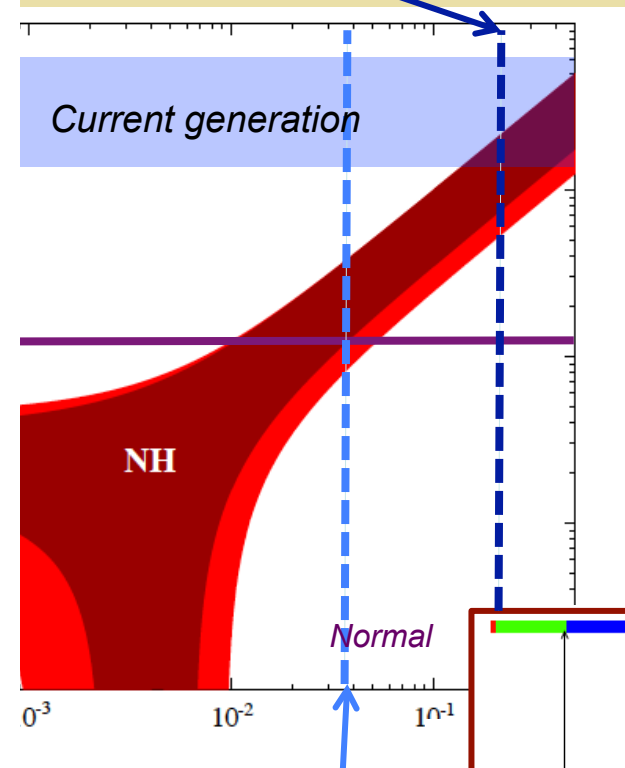
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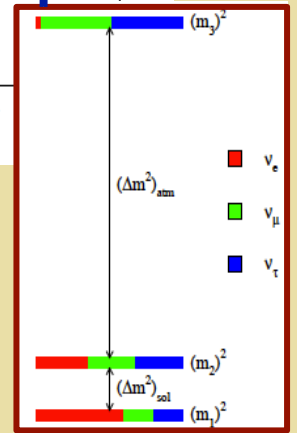
Effective DBD neutrino mass (eV)



$^3\text{H}$  decay cur gen

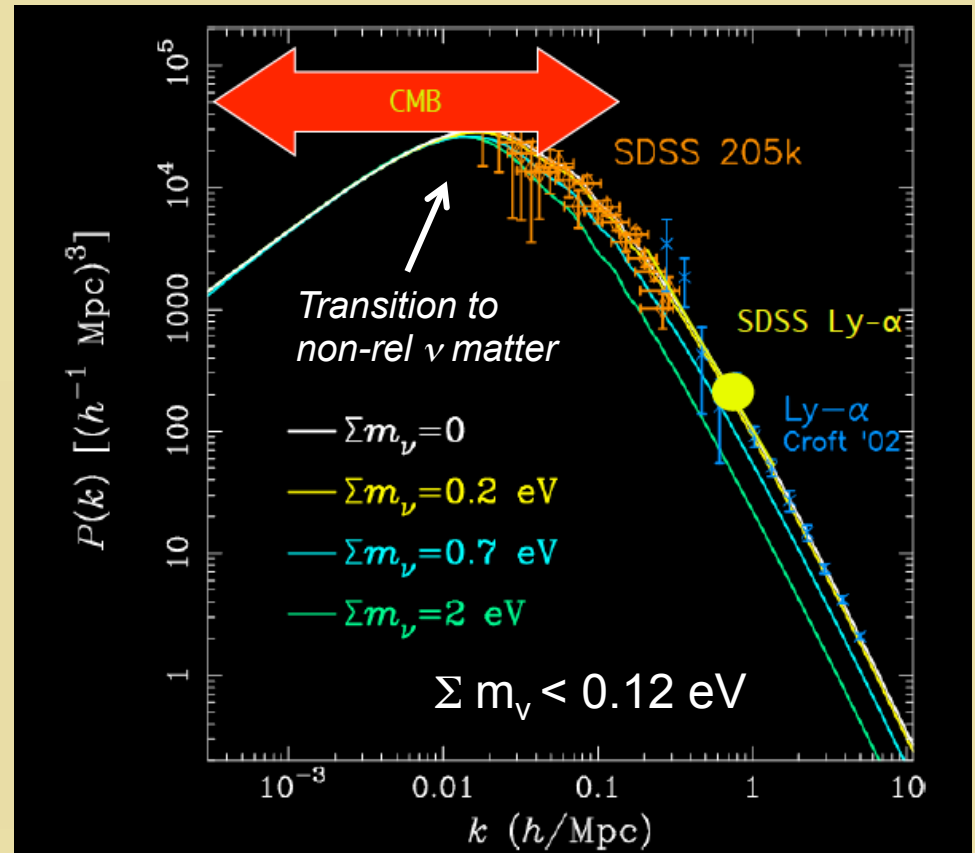
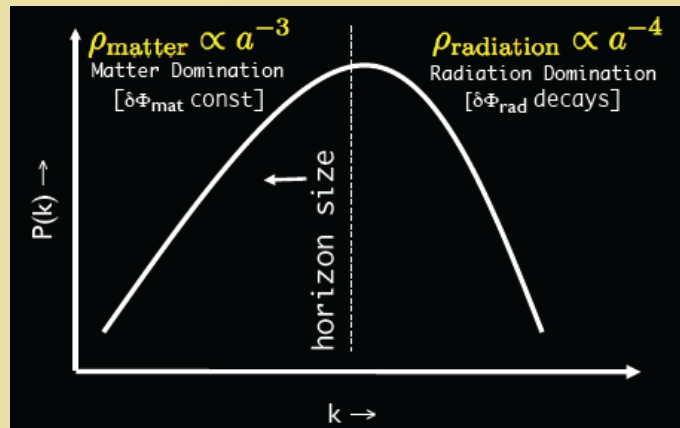
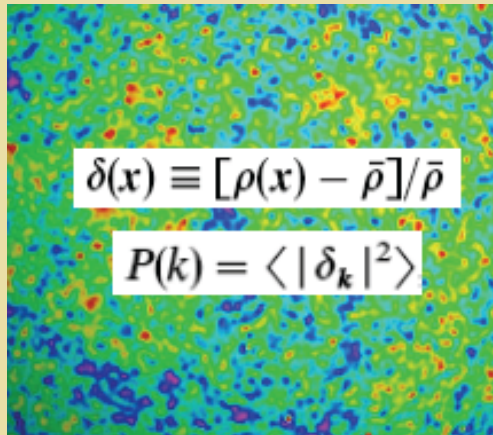


Null result in NLDBD & non-zero  $m_\nu$  from  $^3\text{H}$  decay  $\rightarrow$  Neutrinos are (pseudo) Dirac



# Neutrino Mass & Cosmology

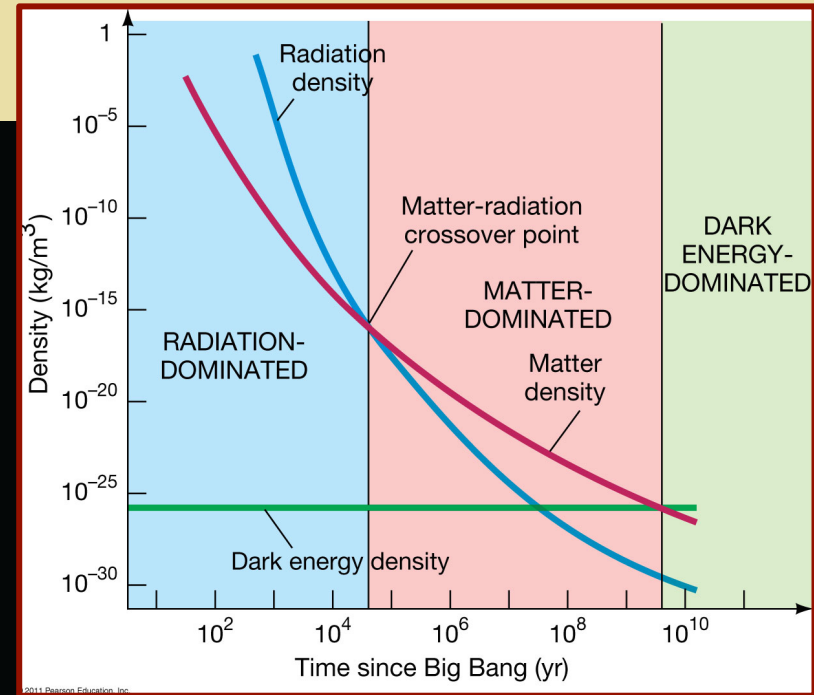
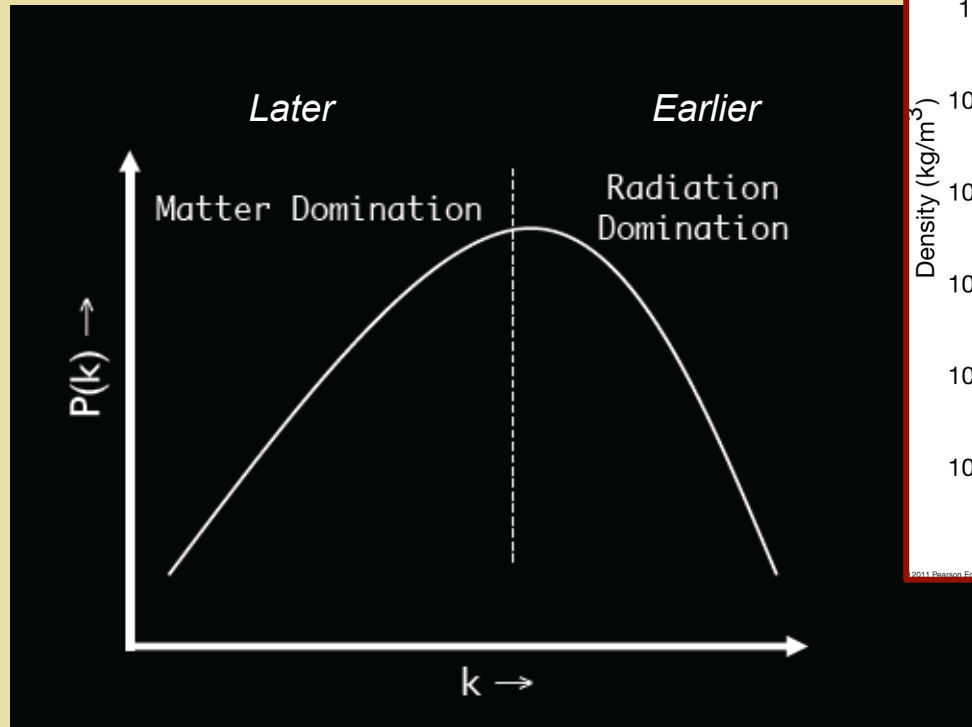
## Matter Power Spectrum



Massive neutrinos suppress power (relative to large scale power) at scales below free streaming scale

# Neutrino Mass & Cosmology

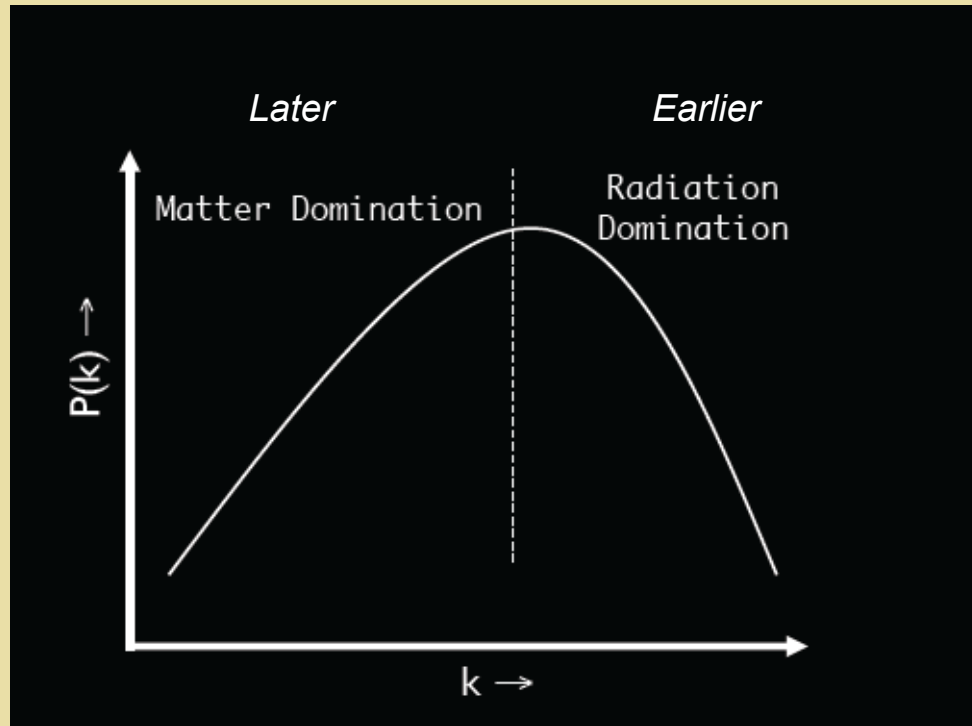
## Matter Power Spectrum



*J. Brau, U. Oregon*

# Neutrino Mass & Cosmology

## Matter Power Spectrum



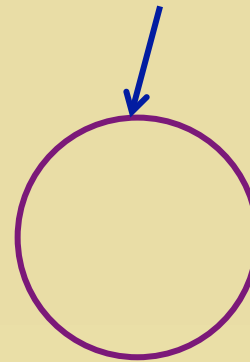
## Neutrino Free Streaming

$$\Omega_M = \Omega_\nu + \Omega_{DM} + \Omega_B$$

$$\delta\rho_\nu \longleftrightarrow \delta\rho_{DM}$$

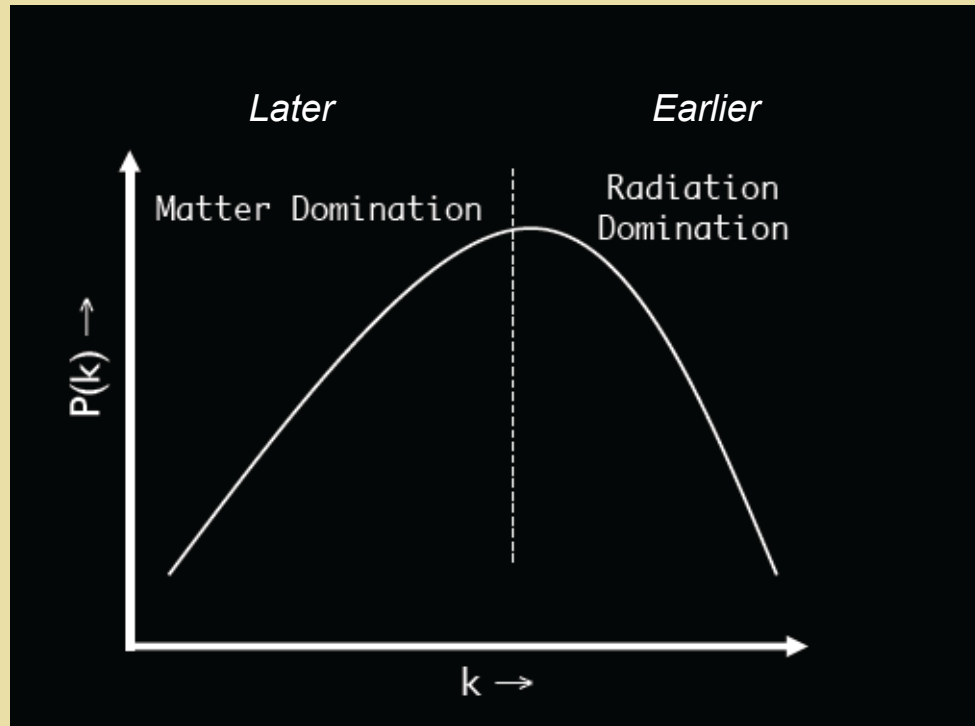
## Free Streaming Scale

$$L_{fs} \propto m_\nu^{-1/2}$$



# Neutrino Mass & Cosmology

## Matter Power Spectrum



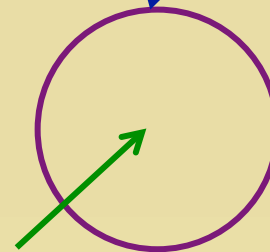
## Neutrino Free Streaming

$$\Omega_M = \Omega_\nu + \Omega_{DM} + \Omega_B$$

$$\delta\rho_\nu \leftrightarrow \delta\rho_{DM}$$

## Free Streaming Scale

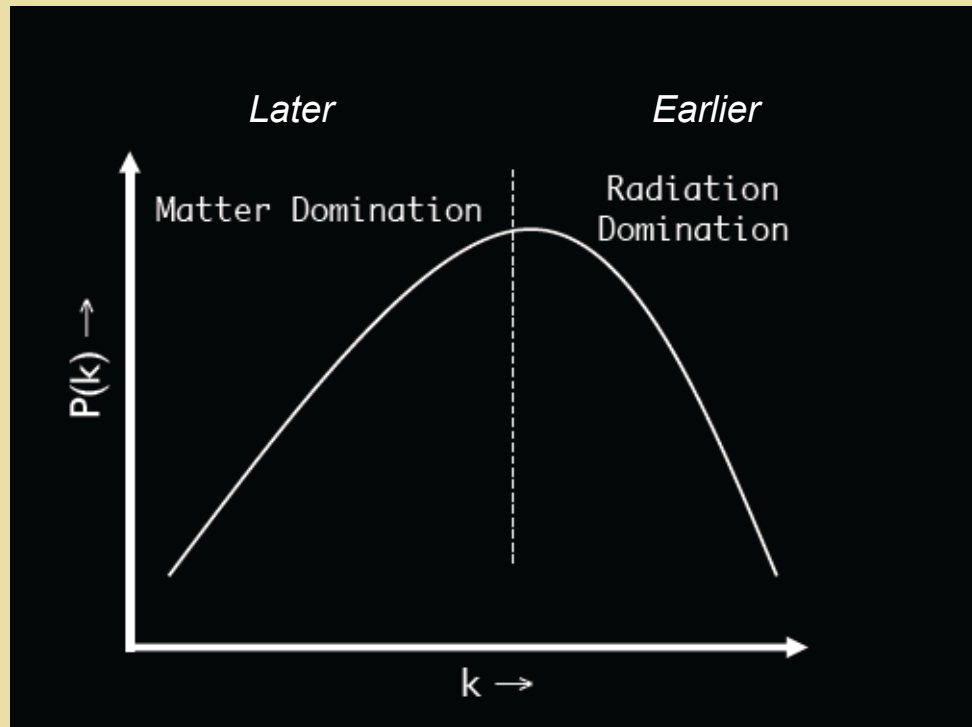
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$\delta\rho_\nu$  (power) suppressed  
for  $L < L_{fs}$

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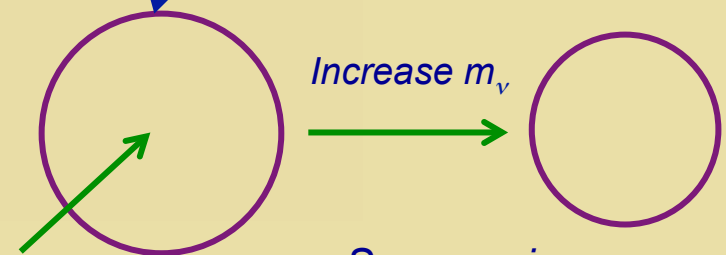
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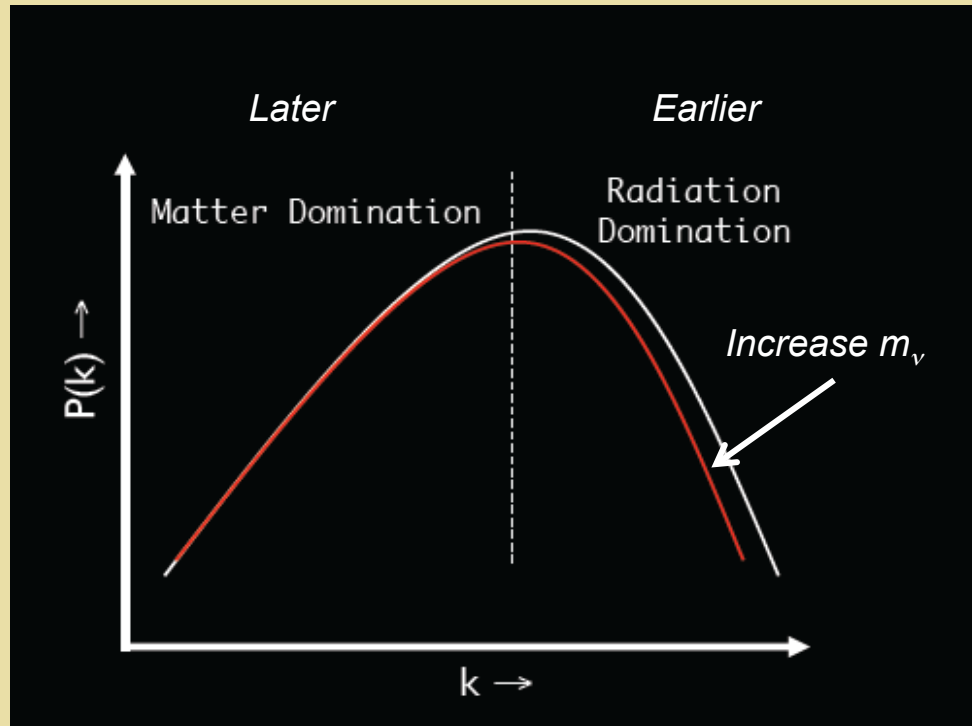
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Suppression moves  
to smaller scales  $\rightarrow$   
Larger  $k$

# Neutrino Mass & Cosmology

## Matter Power Spectrum



$$\Sigma m_\nu < 0.12 \text{ eV}$$

Palanque-Dalabrouille '15

$\delta\rho_\nu$  (power) suppressed  
for  $L < L_{fs}$

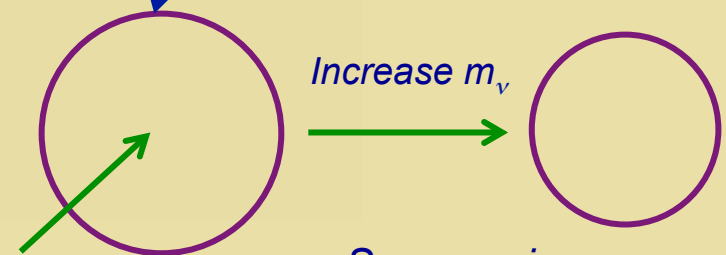
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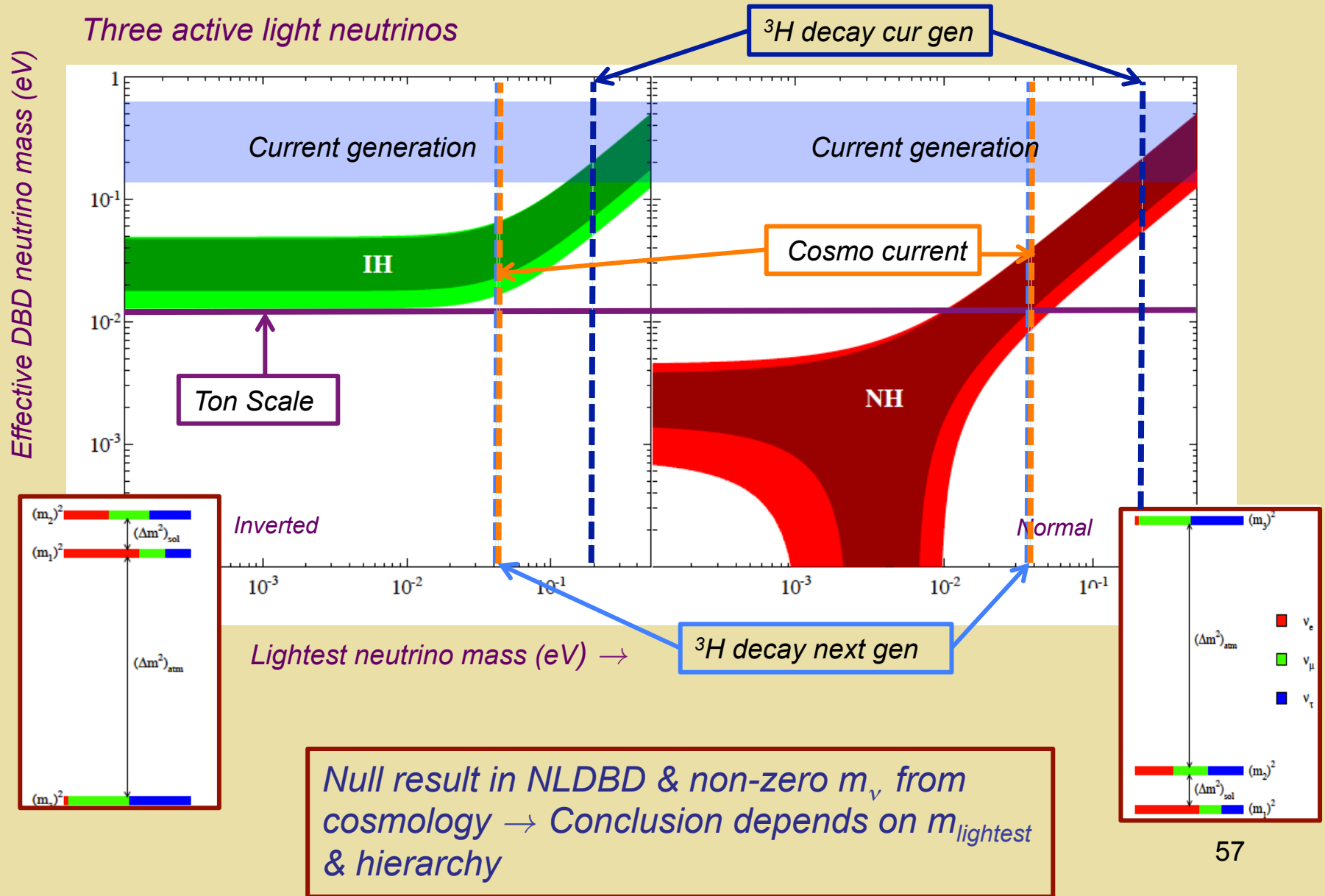
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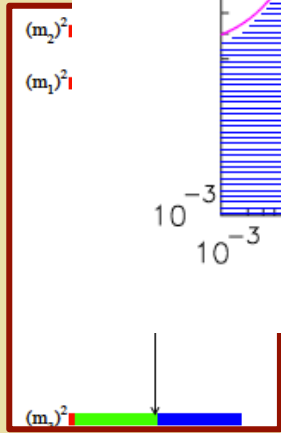
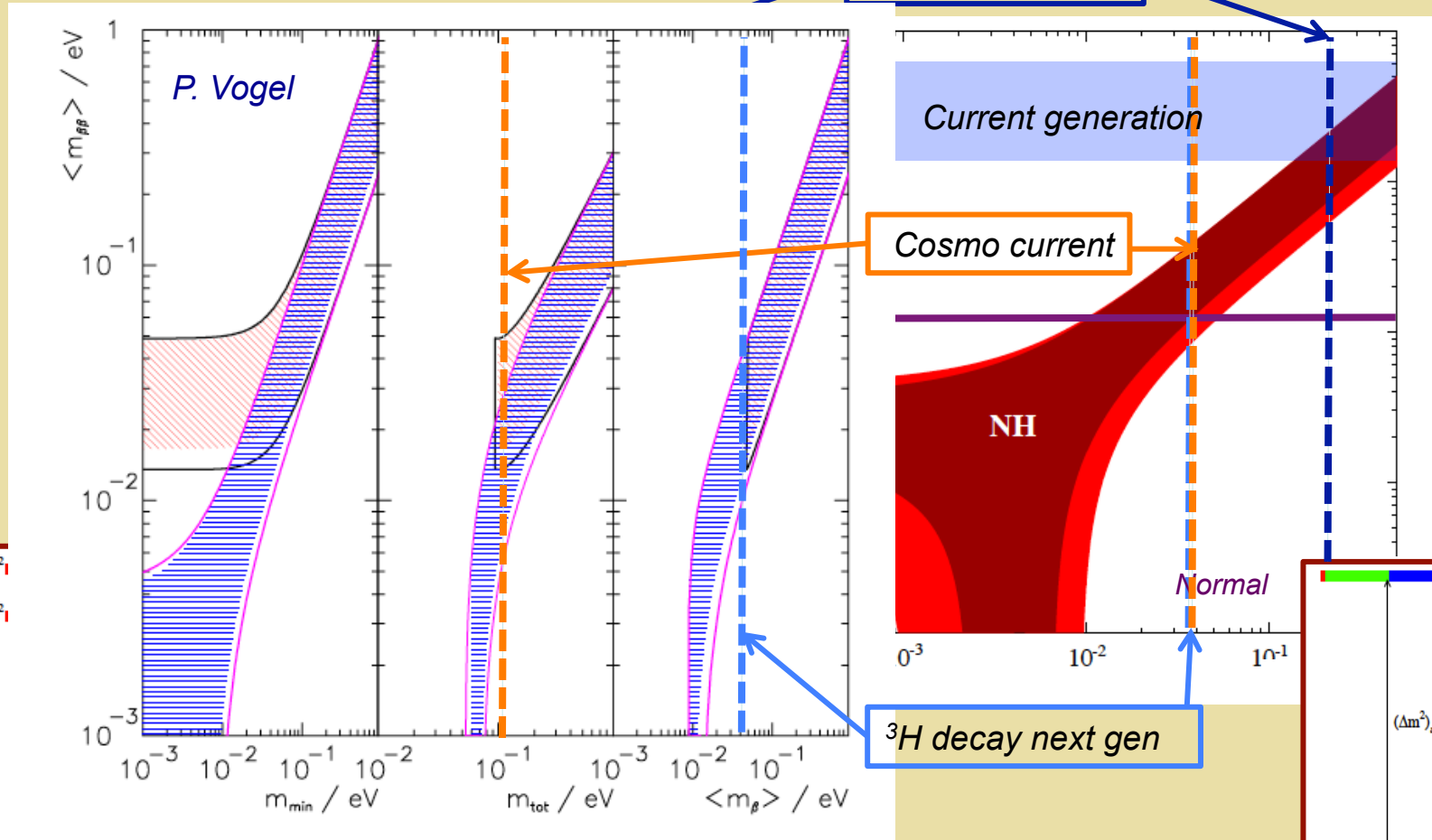
# St'd Mech: What Would a Null Result Imply ?



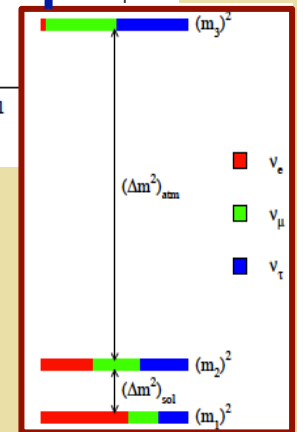
# St'd Mech: What Would a Null Result Imply ?

Three active light neutrinos

Effective DBD neutrino mass (eV)



Null result in NLDBD & non-zero  $m_\nu$  from cosmology  $\rightarrow$  Conclusion depends on  $m_{\text{lightest}}$  & hierarchy



## Lecture VIII Summary

- *Simplest type I see-saw mechanism with Majorana  $3 N_R + CPV$  provides ingredients for baryogenesis via thermal leptogenesis*
- *“Standard leptogenesis”  $\rightarrow M_{N1} > 10^9$  GeV*
- *Observation of  $0\nu\beta\beta$ -decay consistent with “standard mechanism” would demonstrate existence of one key ingredient for thermal leptogenesis*
- *Discovery of TeV scale (and below) LNV ( $0\nu\beta\beta$ -decay + LHC...) would preclude high scale leptogenesis & point to alternate, low-scale scenarios (ARS lepto, EW baryo...)*
- *Precision cosmology (large scale structure, CMB) places tight constraints on  $\Sigma m_\nu$  for the three light active neutrinos, squeezing the viability of the IH region for  $m_{\beta\beta}$*
- *Challenge for theory: are there any well-motivated loopholes to cosmological constraints ?*