Lecture VIII: Cosmic Frontier Connections

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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*

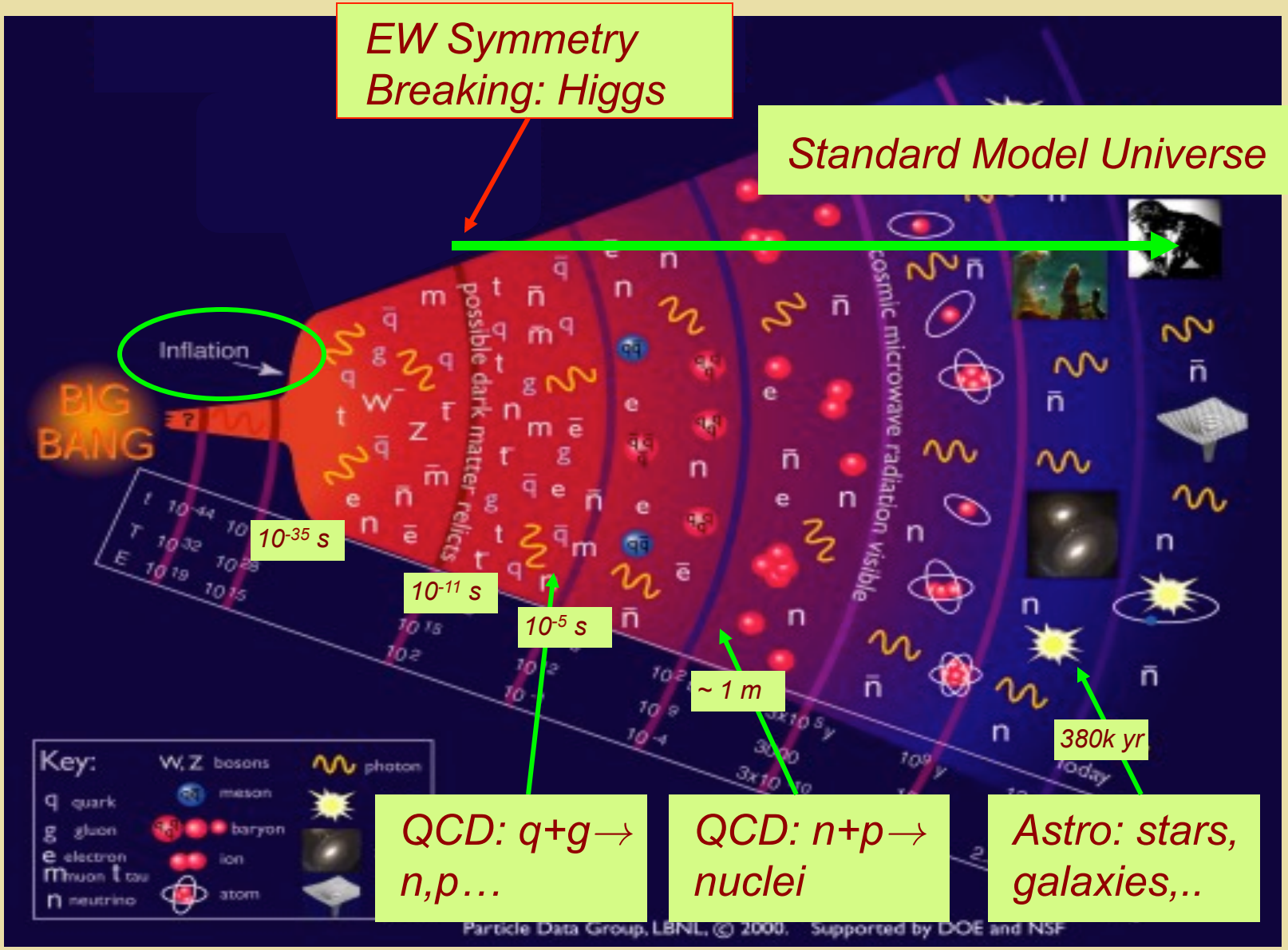
Lecture VIII Outline

I. Origin of Matter: Leptogenesis

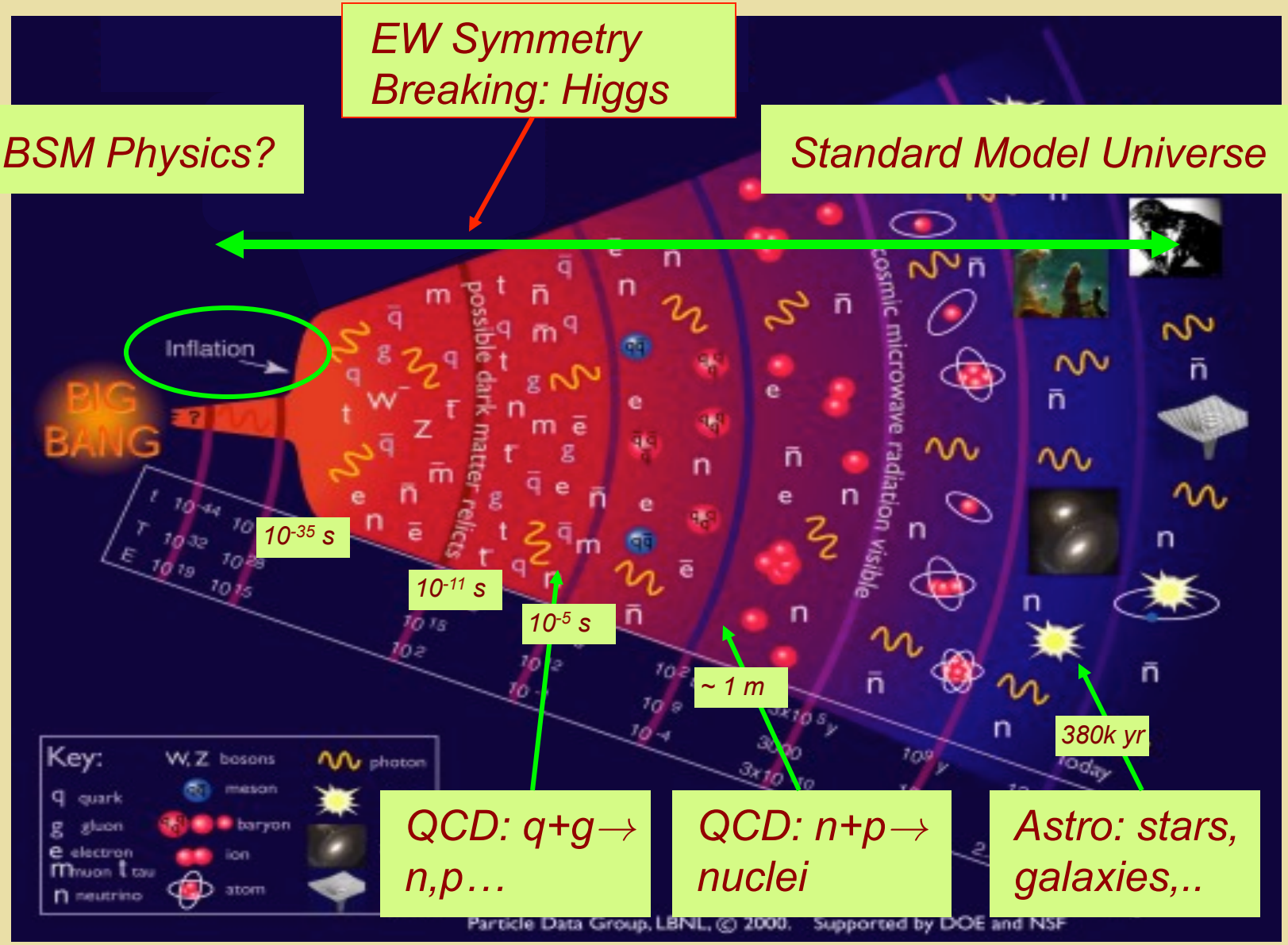
II. Neutrino Mass from Cosmology

I. Origin of Matter: Leptogenesis

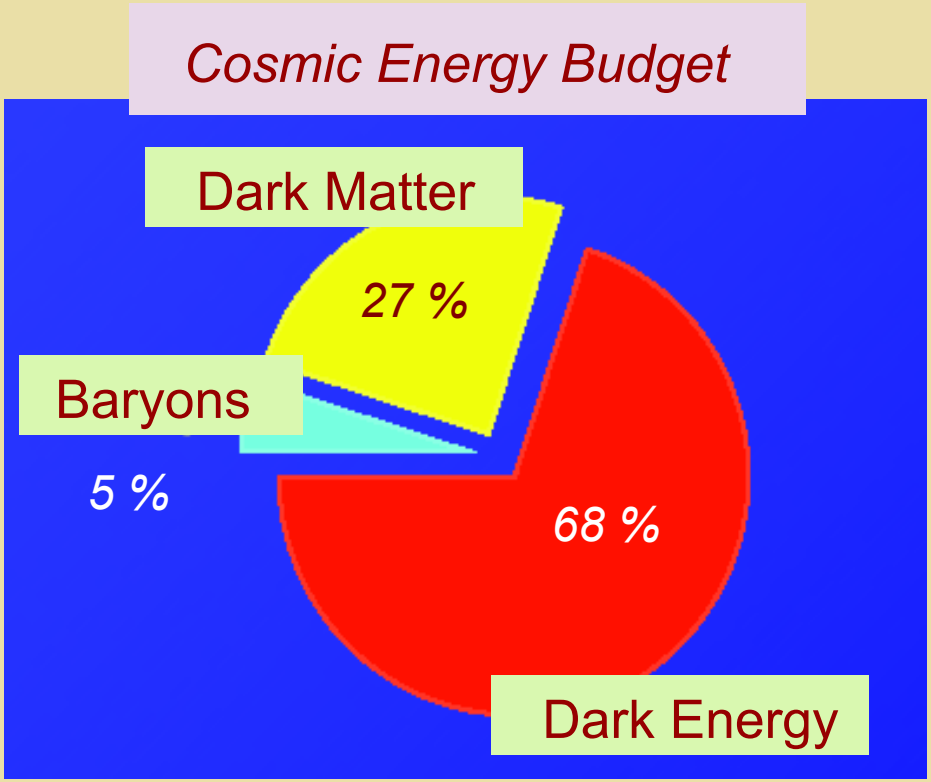
Symmetries & Cosmic History



Symmetries & Cosmic History

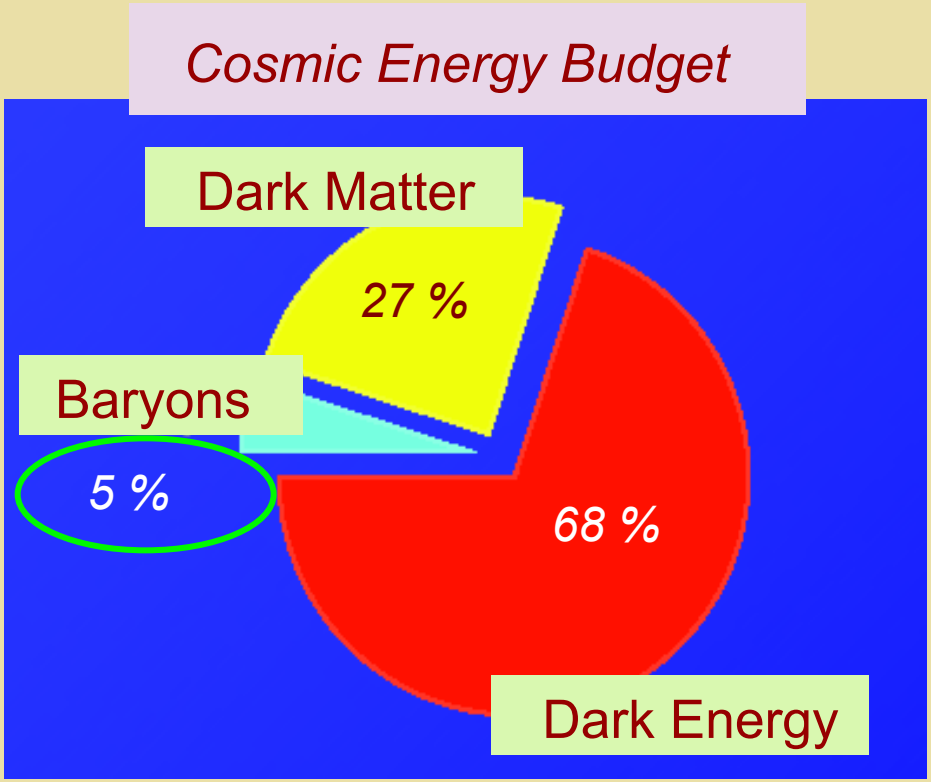


The Origin of Matter



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

The Origin of Matter



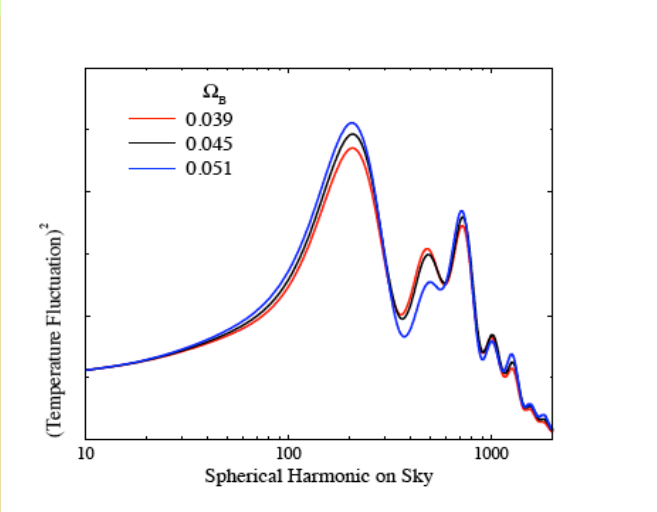
Explaining the origin, identity, and relative fractions of the cosmic energy budget is one of the most compelling motivations for physics beyond the Standard Model

Cosmic Baryon Asymmetry

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

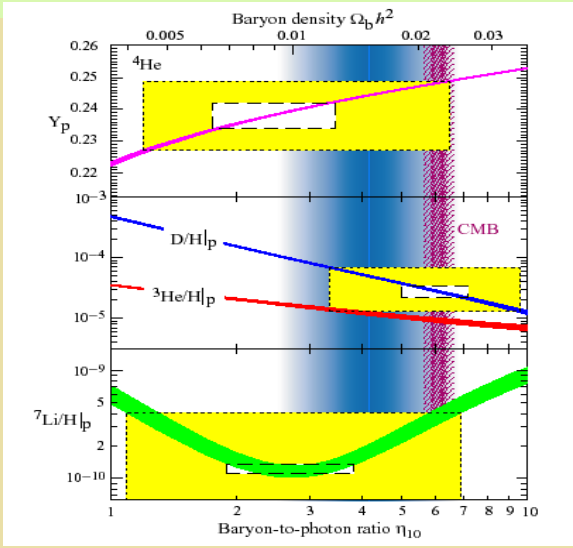
Cosmic Microwave Bcknd:

Shape of anisotropies depends on Y_B



Big Bang Nucleosynthesis:

Light element abundances depend on Y_B



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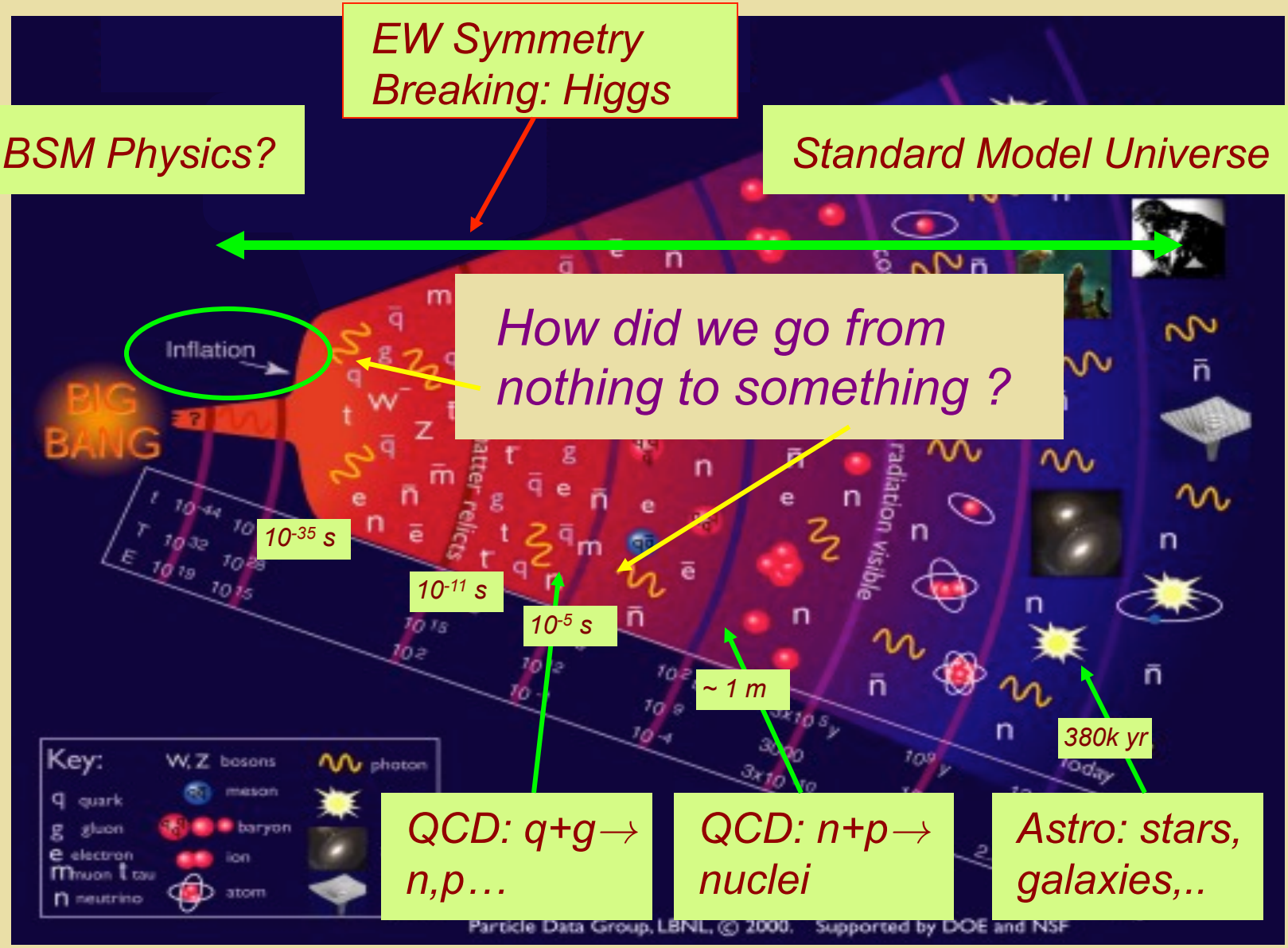


Ingredients for Baryogenesis

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

Ingredients for Baryogenesis

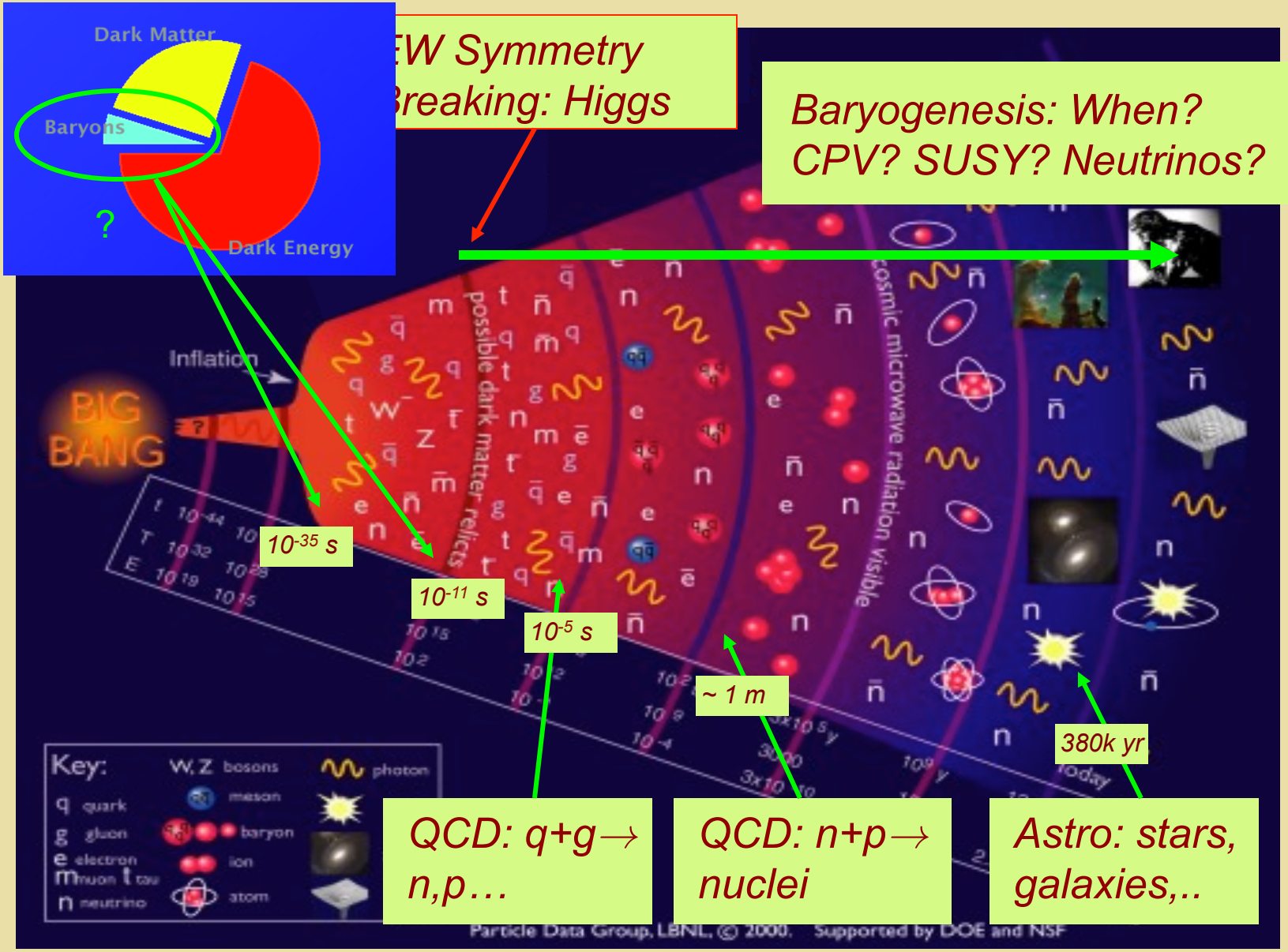
	Standard Model	*BSM*
• *B violation (sphalerons)*	✔	✔
• *C & CP violation*	✖	✔
• *Out-of-equilibrium or CPT violation*	✖	✔

Ingredients for Baryogenesis

Scenarios: leptogenesis, EW baryogenesis, Afflek-Dine, asymmetric DM, cold baryogenesis, post-sphaleron baryogenesis…

	Standard Model	*BSM*
• *B violation (sphalerons)*	✔	✔
• *C & CP violation*	✖	✔
• *Out-of-equilibrium or CPT violation*	✖	✔

Symmetries & Cosmic History



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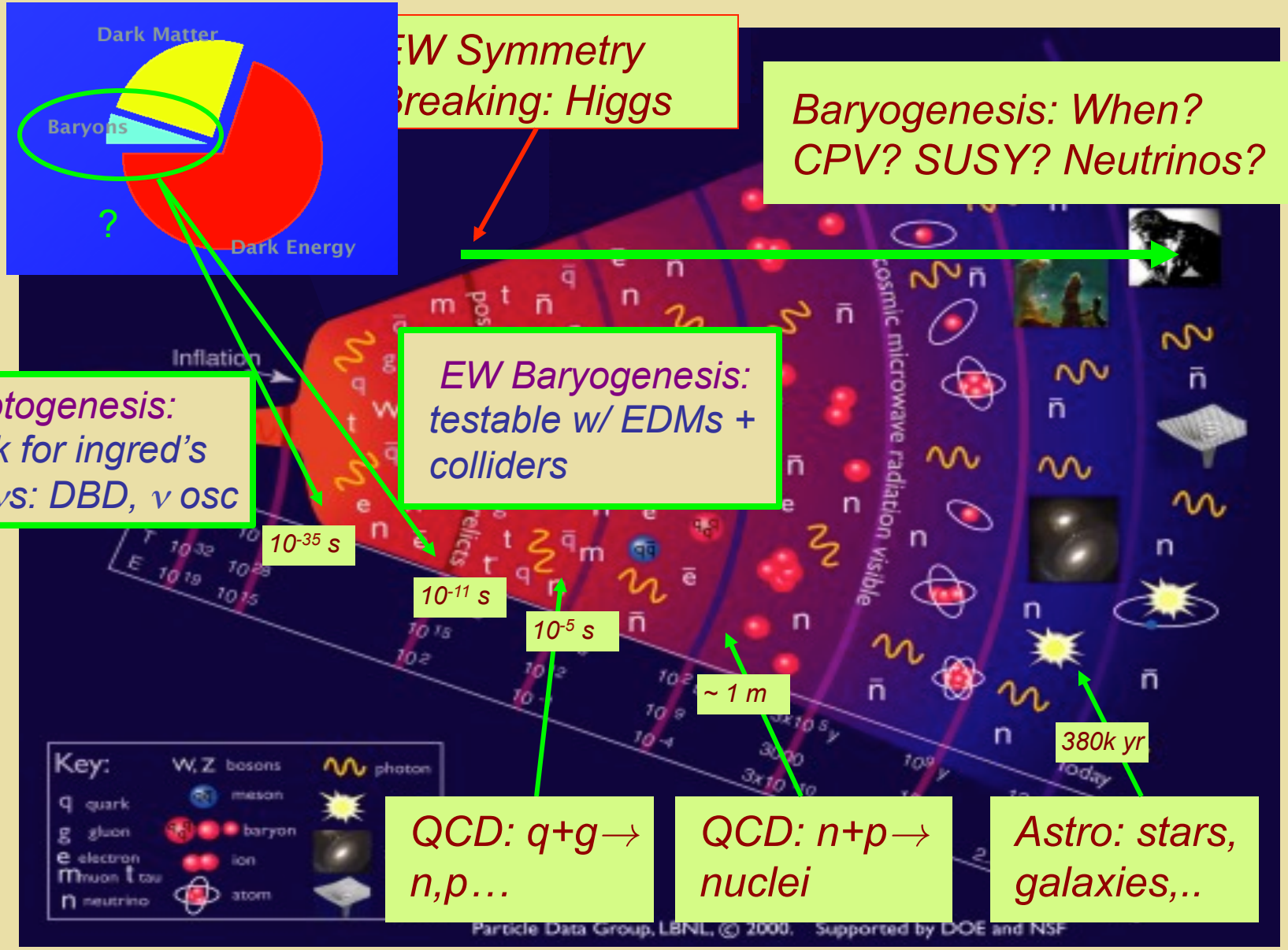
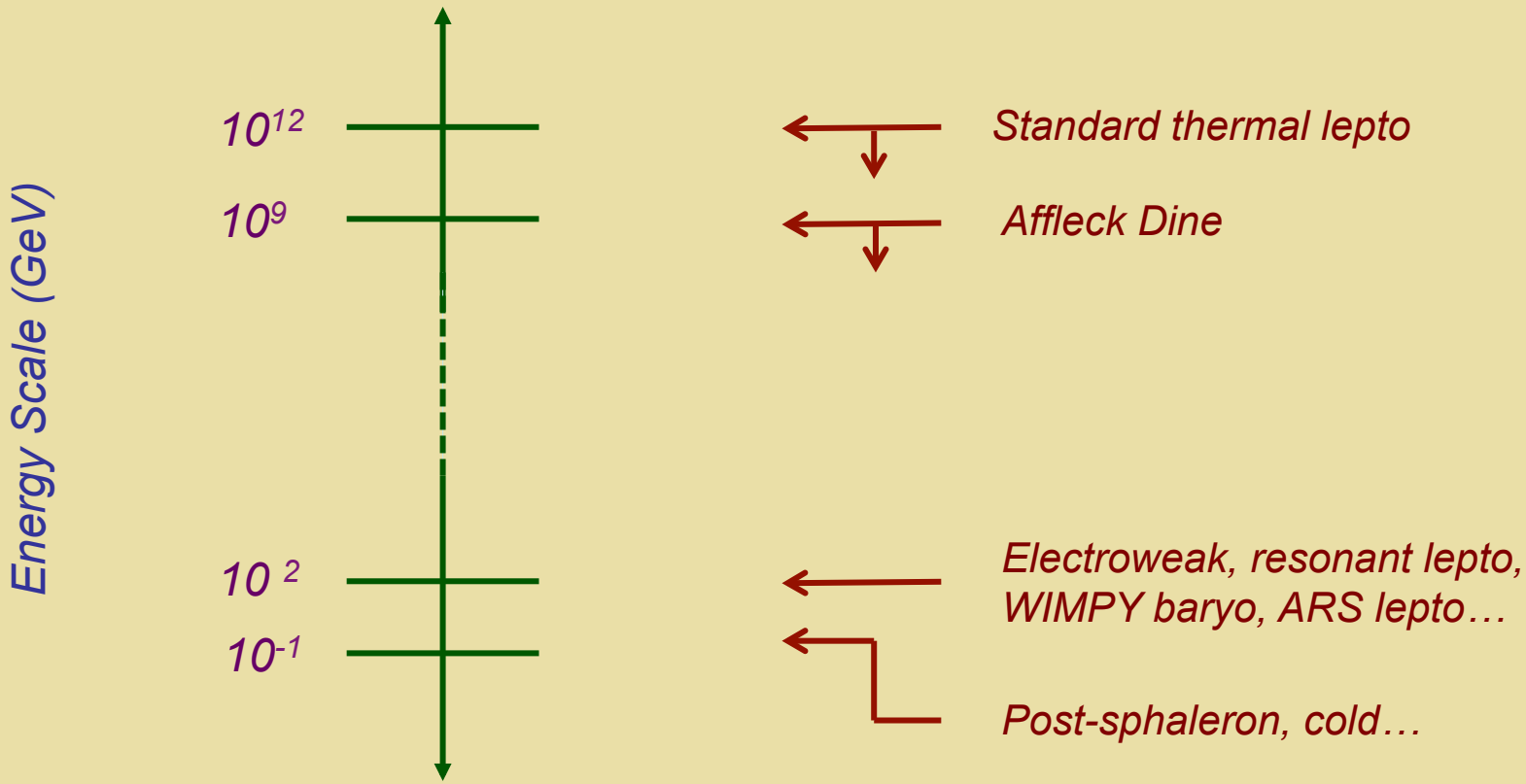


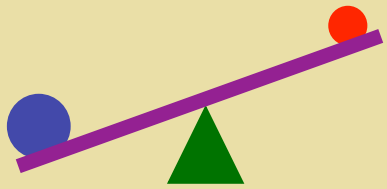
Baryogenesis Scenarios



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"

$\nu = \overline{\nu}$

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)*

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

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

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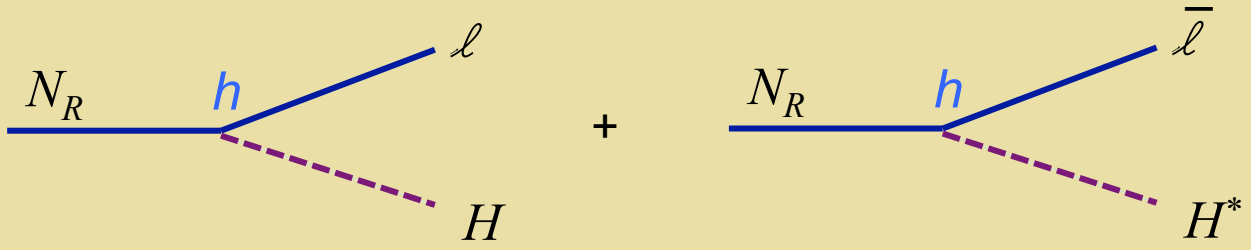


$$\Gamma_N \equiv \Gamma(N_R \to \ell H) + \Gamma(N_R \to \bar{\ell} H^*) = \frac{|h|^2}{8\pi} M_N$$

Hubble rate

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

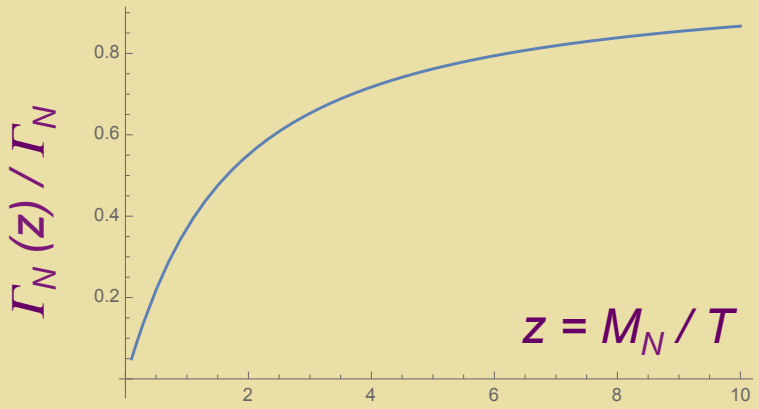
Neutrinos and the Origin of Matter

- *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 $\Gamma_N \lesssim H(T=M_N)$ ➡

$$m_1 \approx m_*$$

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

$$m_* = 8\pi * (1.66 g_*) \frac{v^2}{M_P}$$ ~ *few x 10^{-3} eV*

Neutrinos and the Origin of Matter

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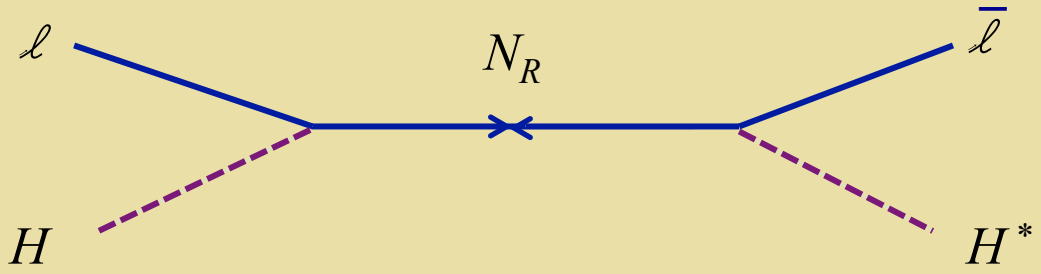
Washout processes

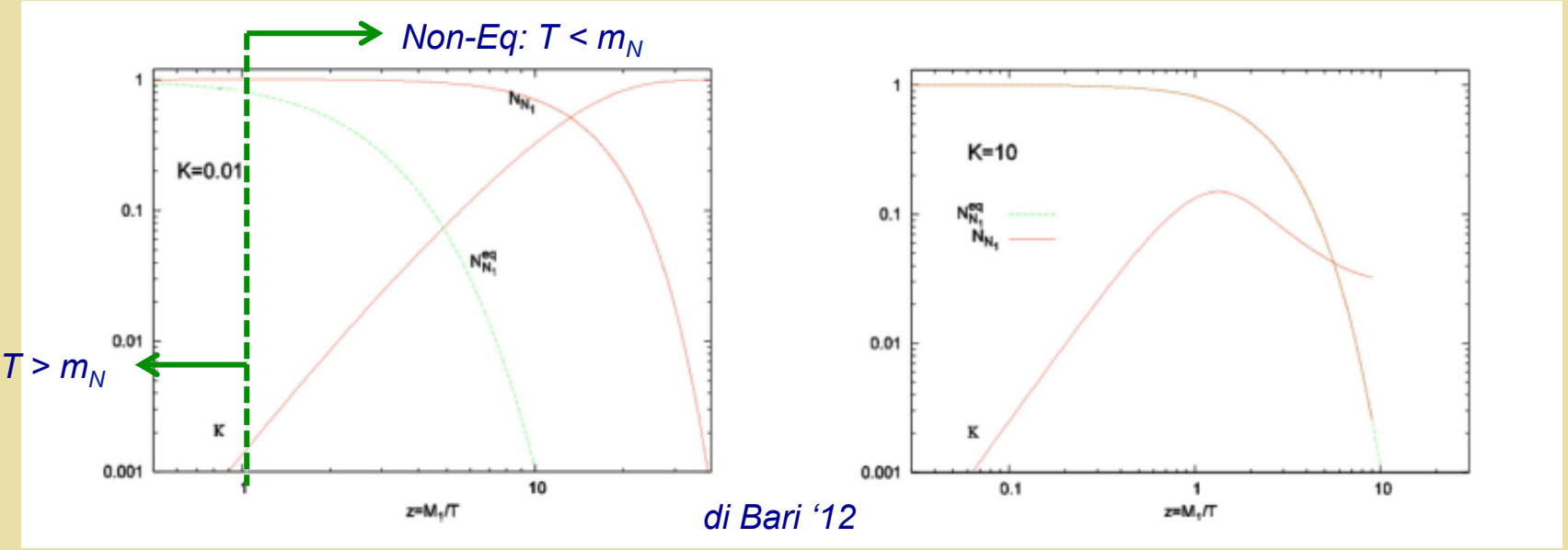


$\Delta L = 2$

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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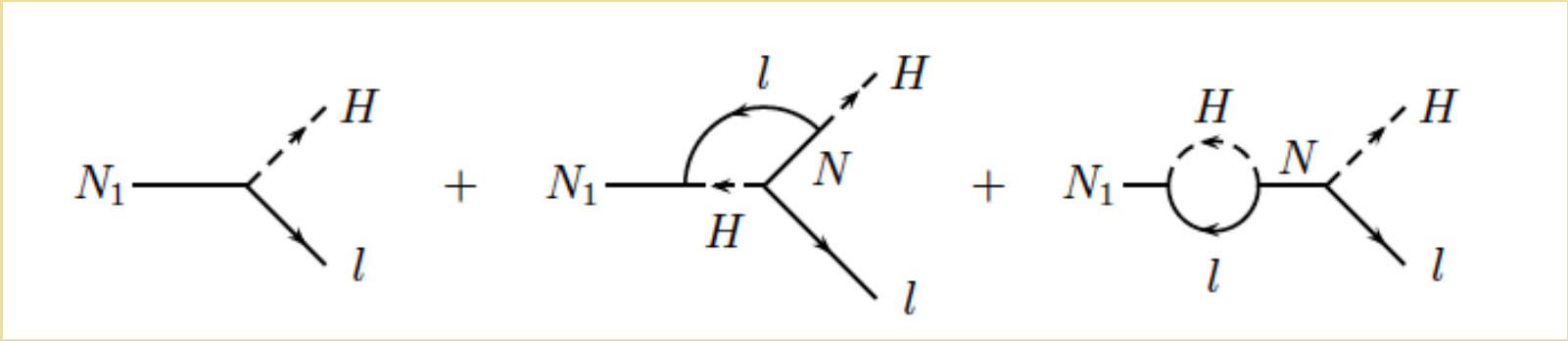
Neutrinos and the Origin of Matter

CPV Asymmetry



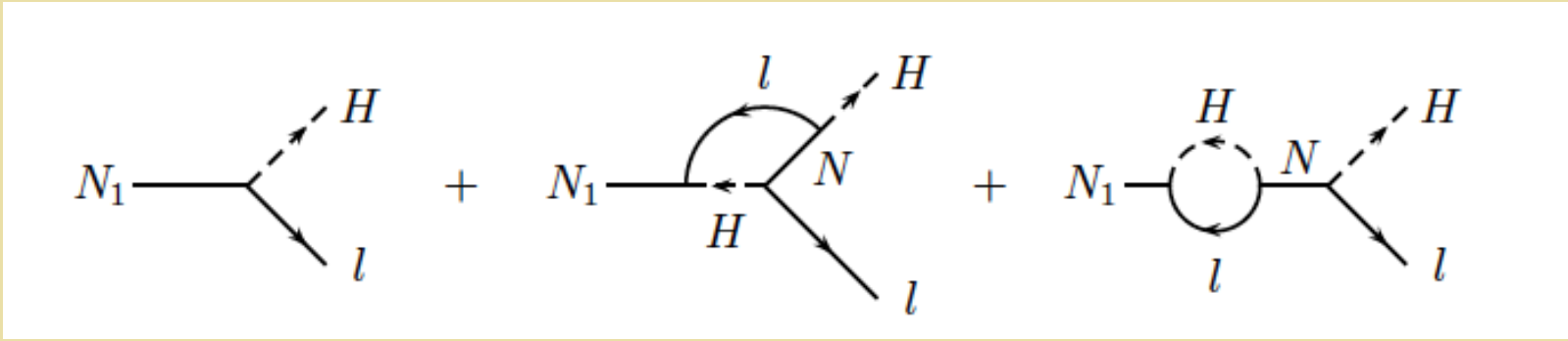
Tree-level CPV X *One-loop "absoprtive part"*

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

Buchmuller, Peccei, Yanagida '05

Neutrinos and the Origin of Matter

CPV Asymmetry



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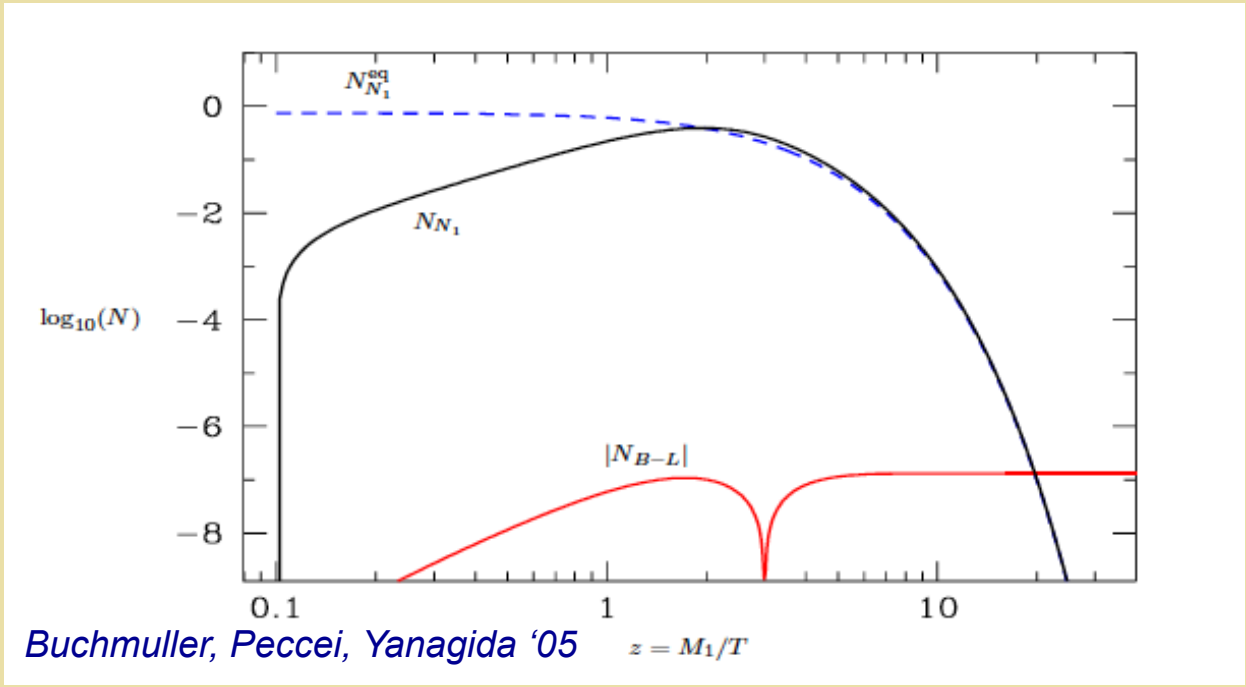
CPV phases but not same as ϕ_{PMNS}

Buchmuller, Peccei, Yanagida '05

Neutrinos and the Origin of Matter

Putting pieces together: B-L asymmetry



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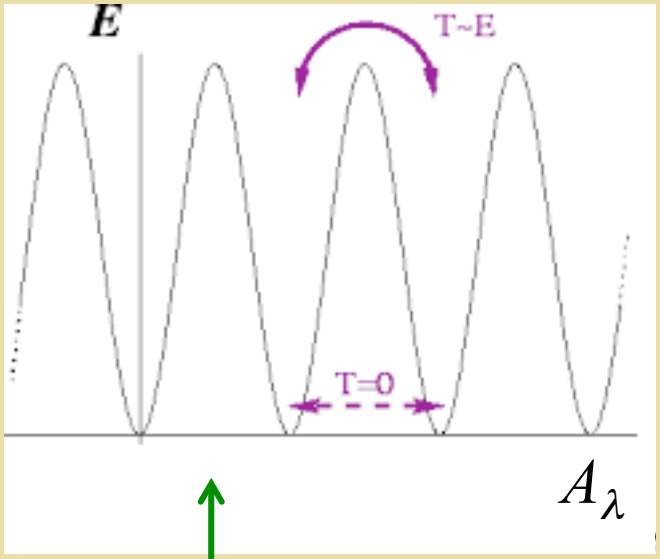
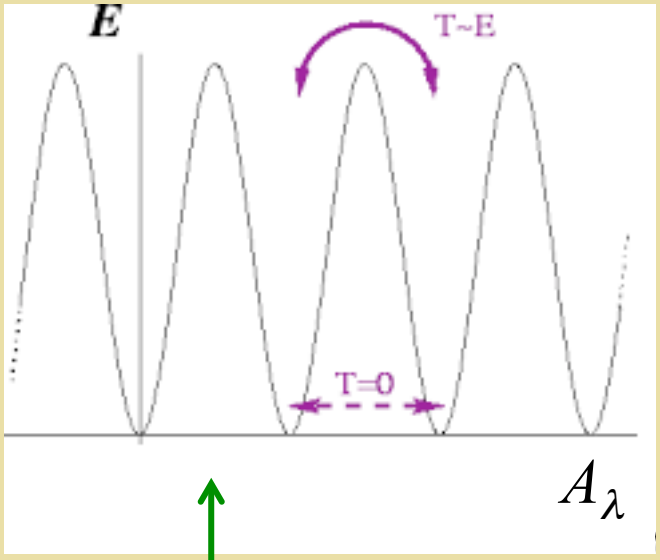
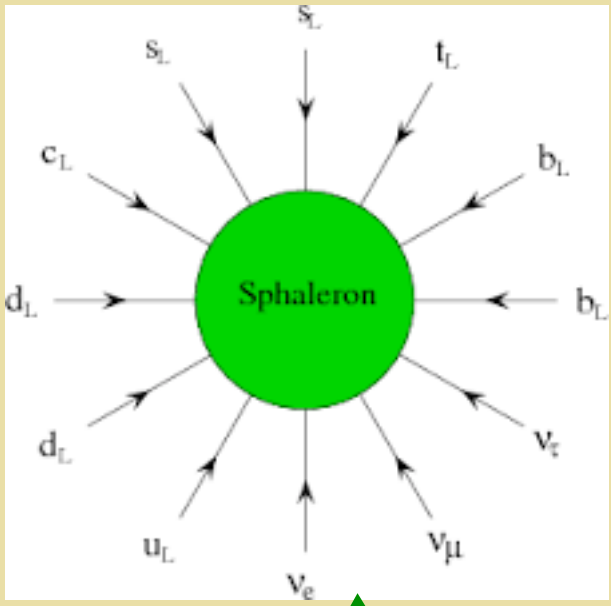
Electroweak Sphalerons



Sphaleron Configuration

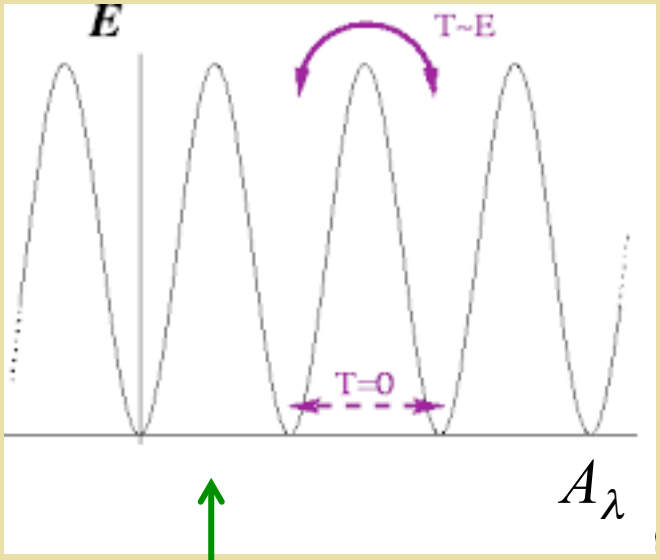
Electroweak Sphalerons

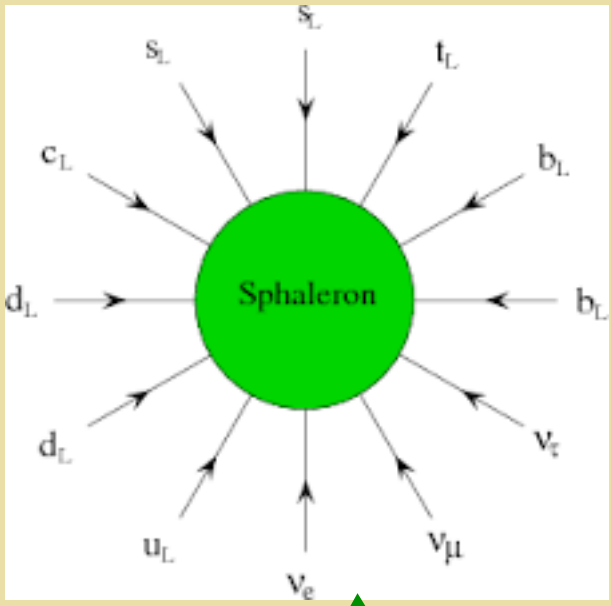




Sphaleron Configuration → *Anomaly* → $\Delta (B+L) \propto N_F$

Electroweak Sphalerons





Sphaleron Configuration → Anomaly → $\Delta (B+L) \propto N_F$

EW sphalerons convert B-L asymmetry to Y_B

Davidson-Ibarra Bound

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

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

Davidson, Ibarra '02

TeV Scale LNV ?

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

Dirac

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

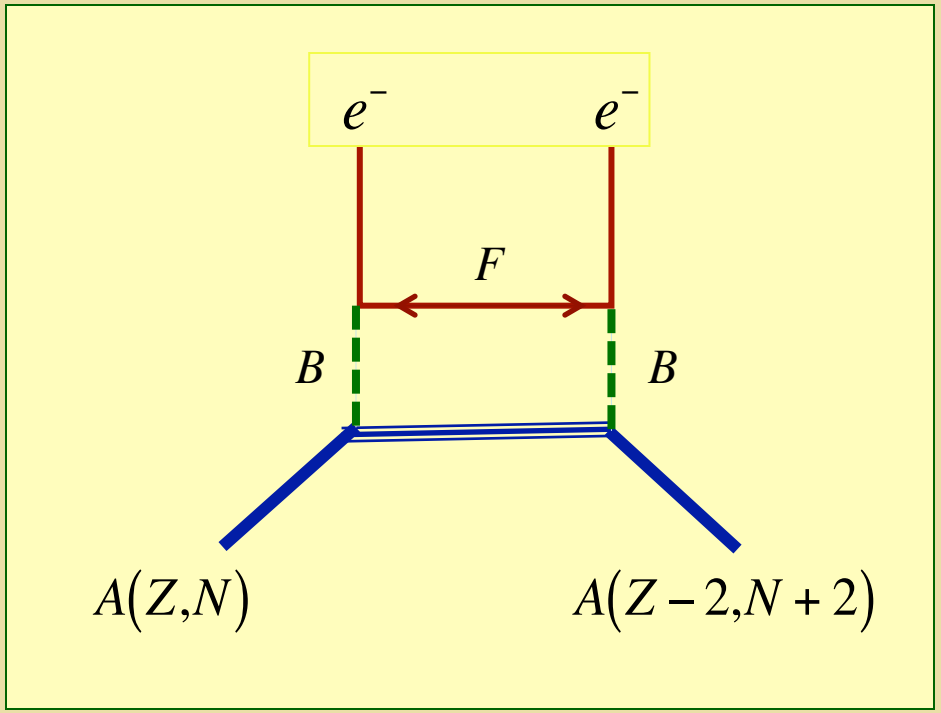
Majorana

TeV LNV Mechanism

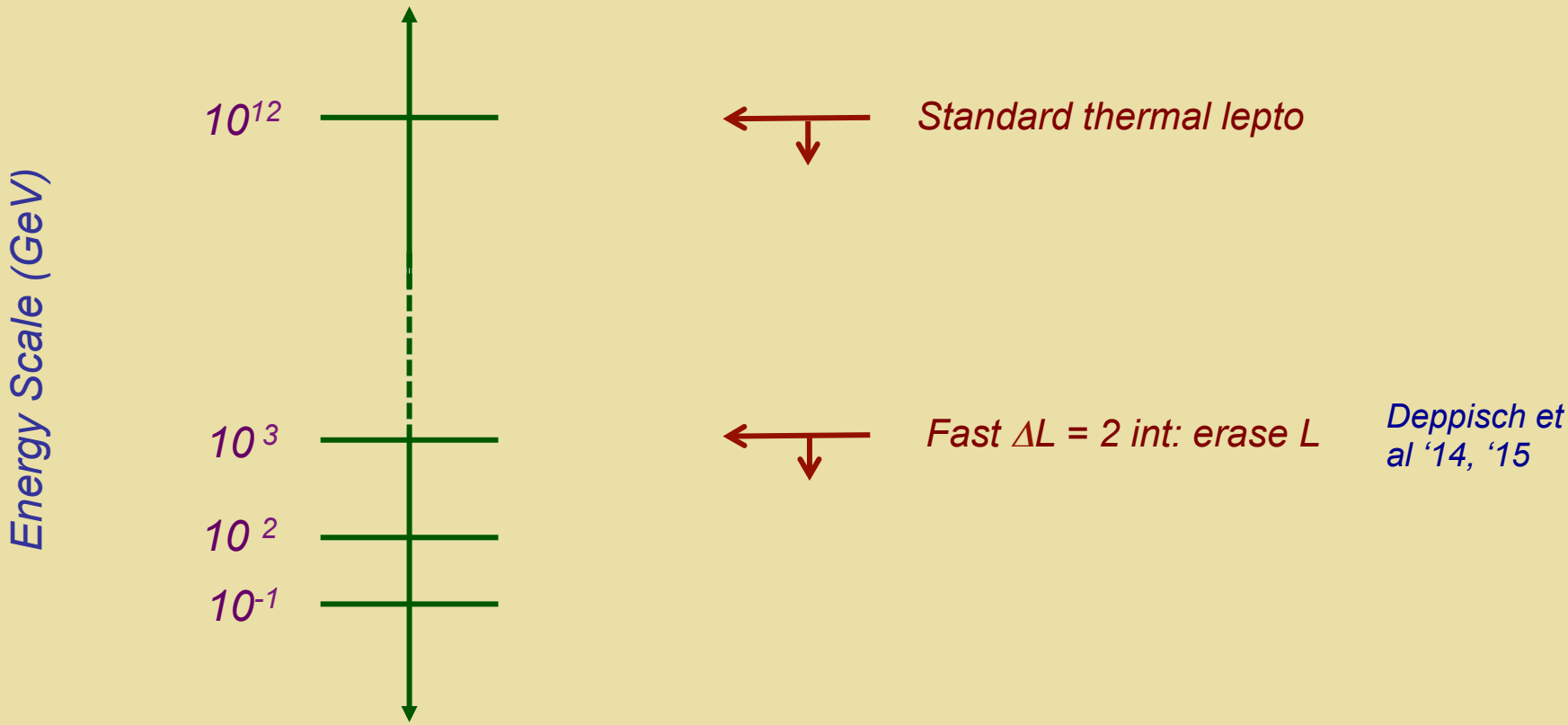
$$\frac{A_H}{A_L} \sim \frac{M_W^4 \bar{k}^2}{\Lambda^5 m_{\beta\beta}}$$

O(1) for Λ ~ 1 TeV

Implications



TeV LNV & Leptogenesis



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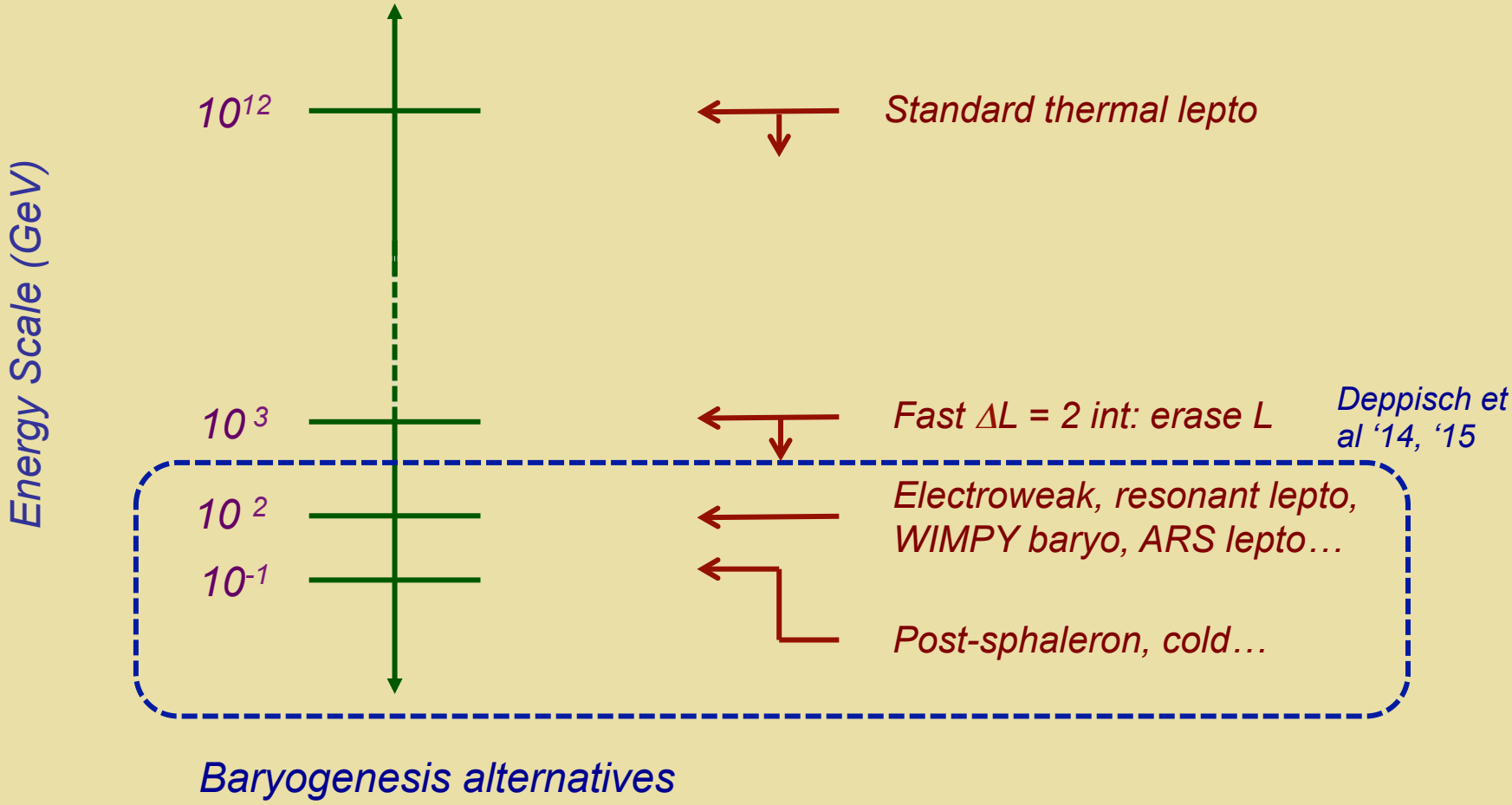
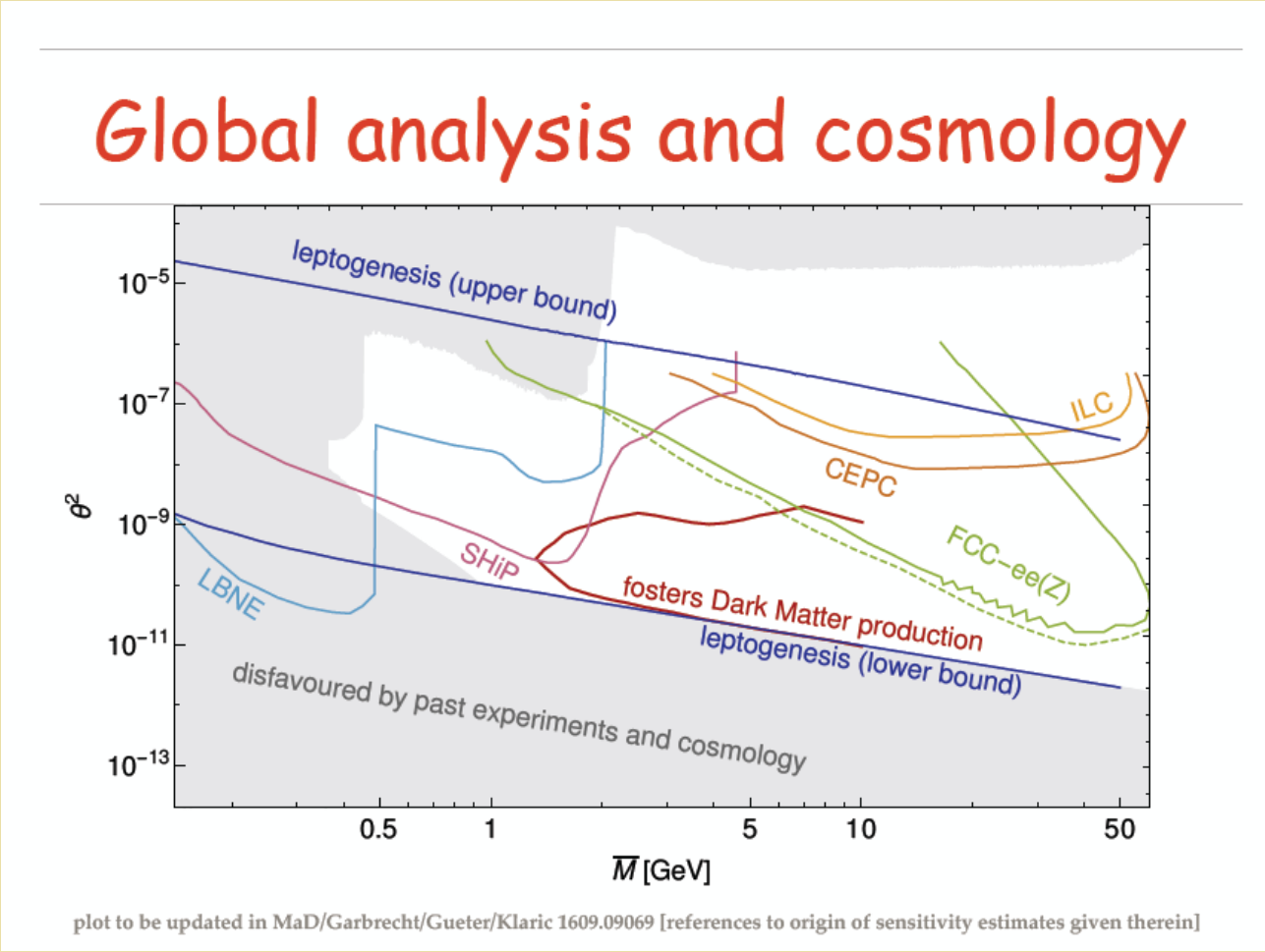


Low Scale "ARS" Leptogenesis

1. 3 Singlet RH neutrinos: N_A , N_B , N_C
2. $L^{TOT} = L^{SM} + L_A + L_B + L_C$
3. N_k oscillations + CPV $\rightarrow$ $L_A \neq 0$, $L_A \neq 0$, $L_A \neq 0$ but $L^{TOT} = 0$
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_{Nk} can be ~ O(GeV)

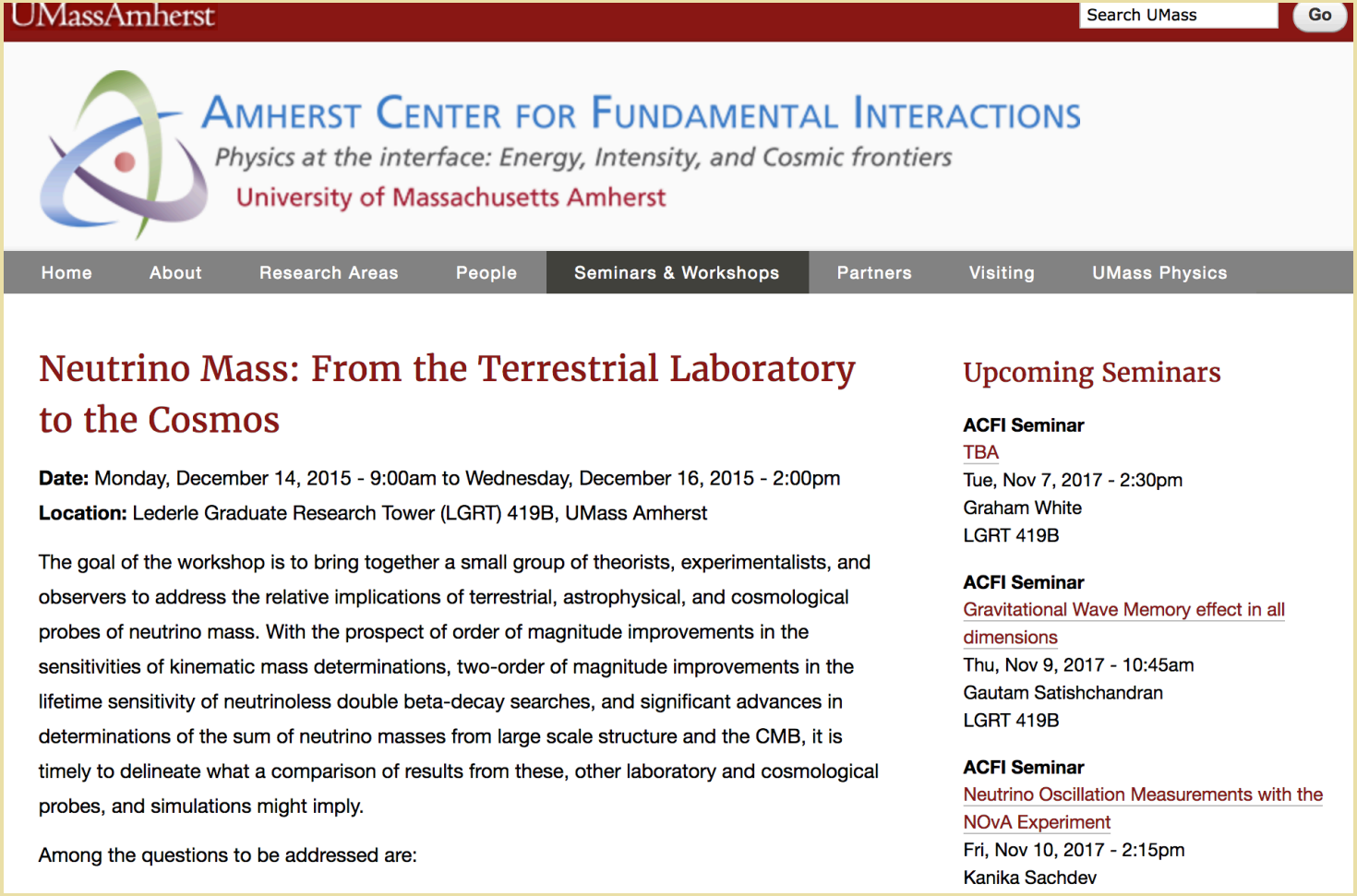
Akhmedov, Rubakov, Smirmov '98

Low Scale "ARS" Leptogenesis



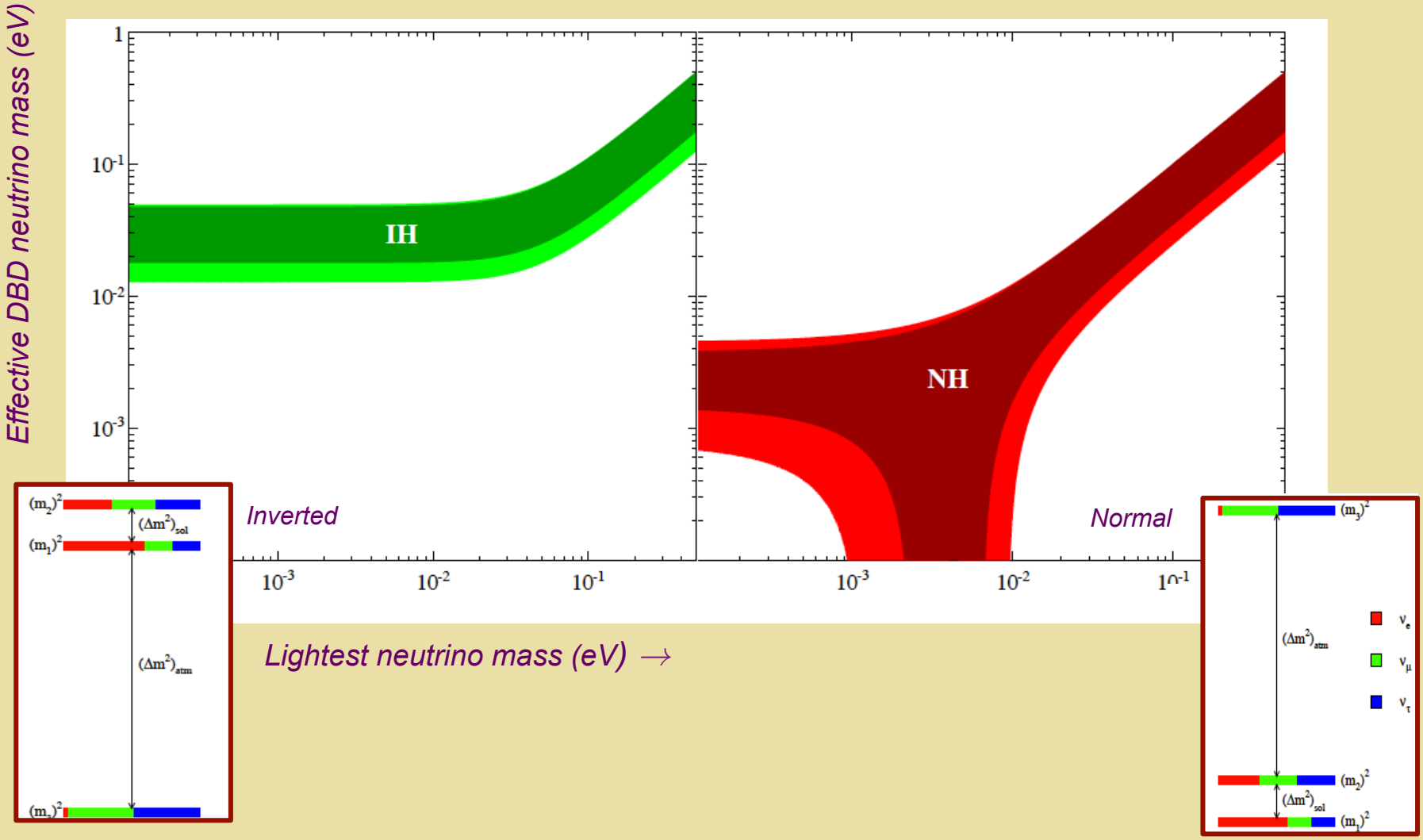
II. Neutrino Mass from Cosmology

ACFI Workshop



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

Three active light neutrinos



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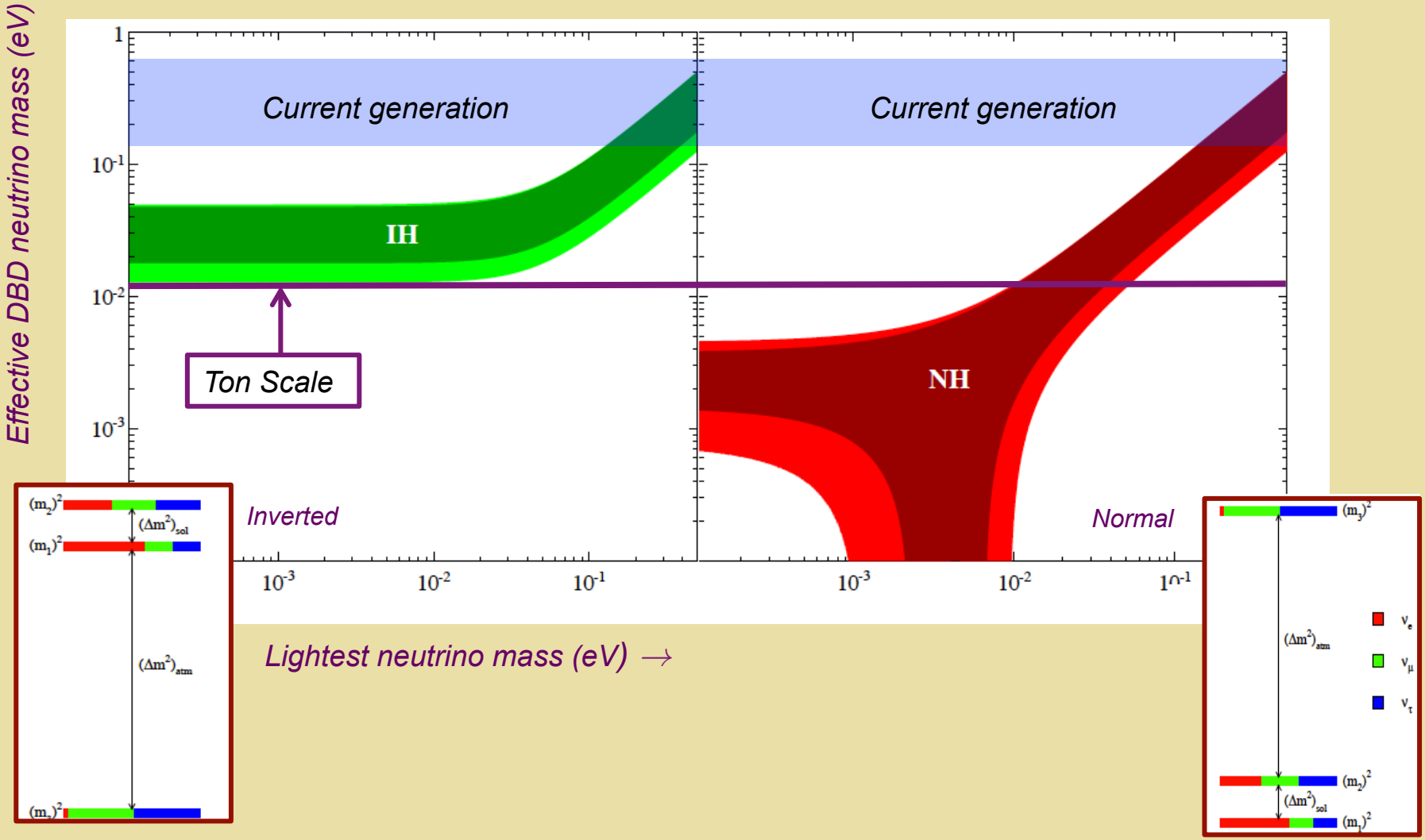

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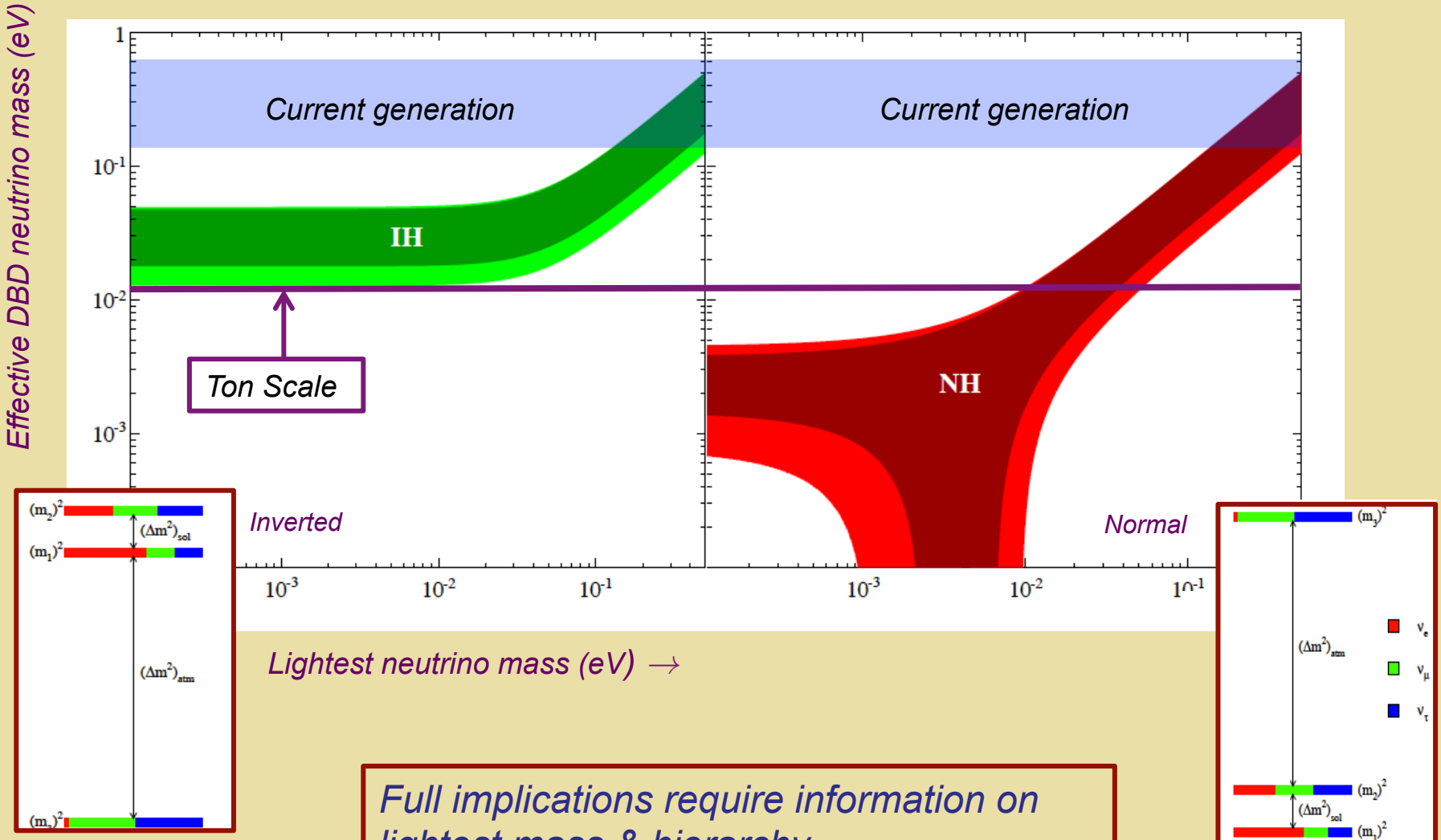
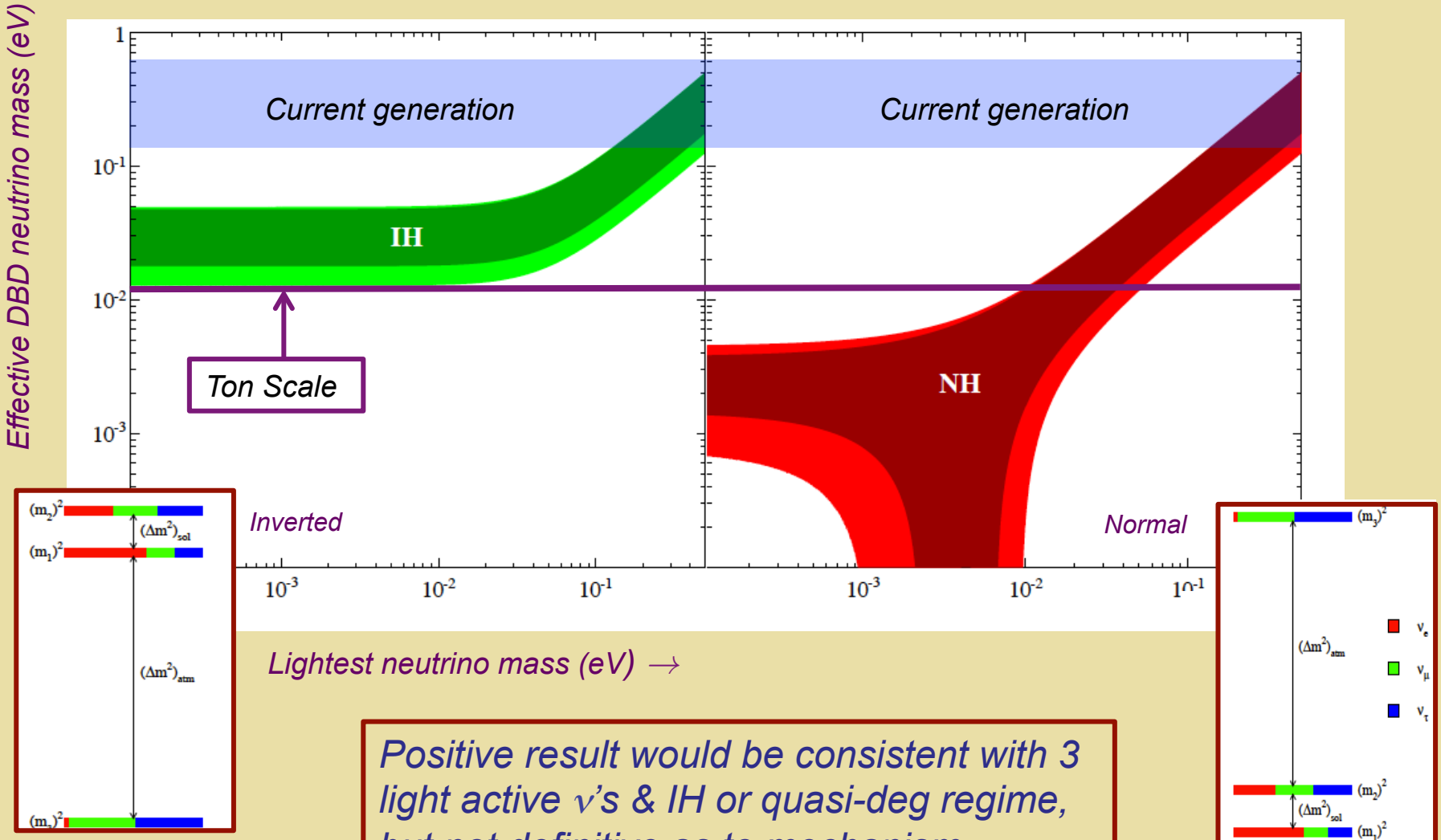


Full implications require information on lightest mass & hierarchy

Interpreting a Positive Result

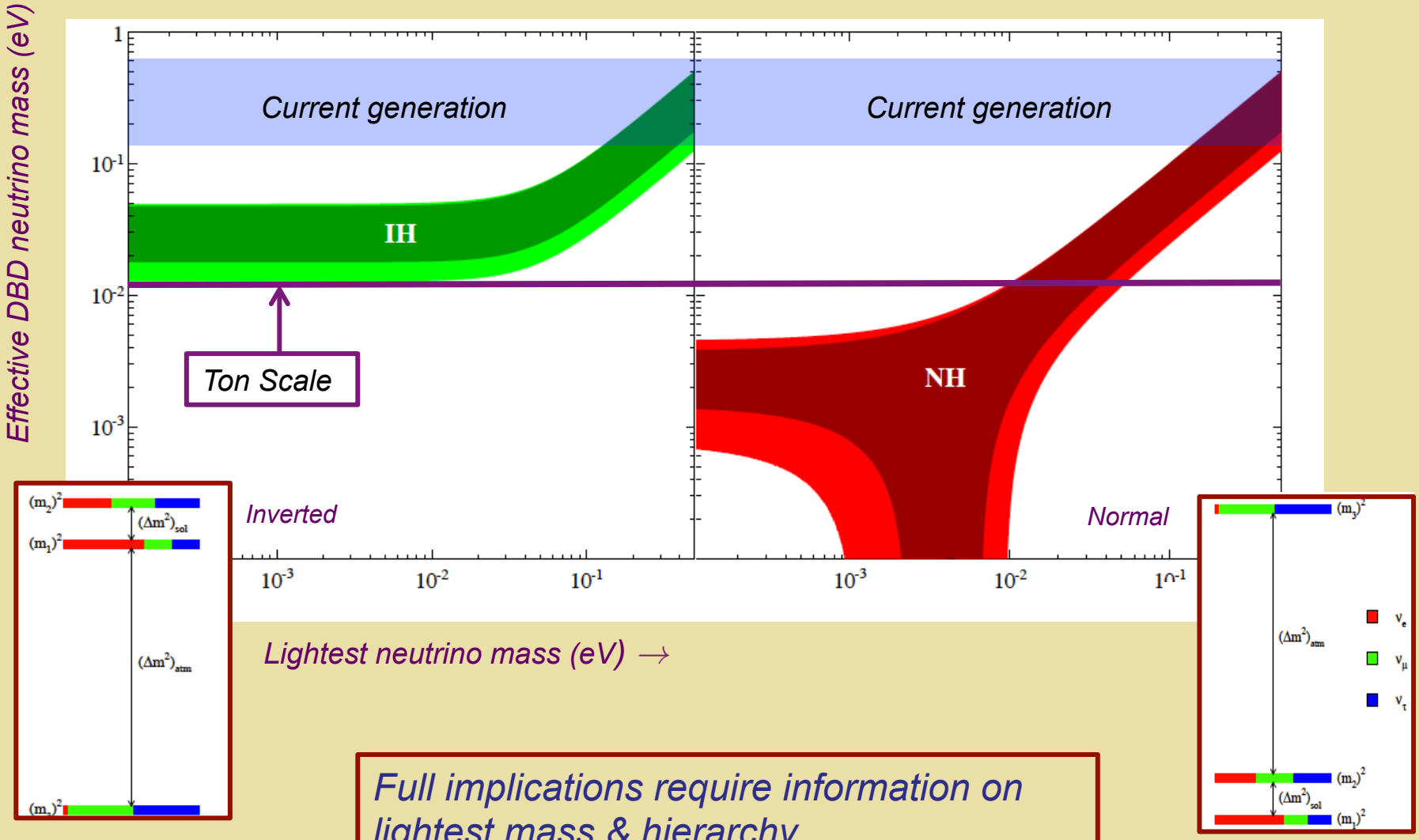
Three active light neutrinos



Positive result would be consistent with 3 light active ν's & IH or quasi-deg regime, but not definitive as to mechanism

Interpreting a Null Result: St'd Mechanism

Three active light neutrinos



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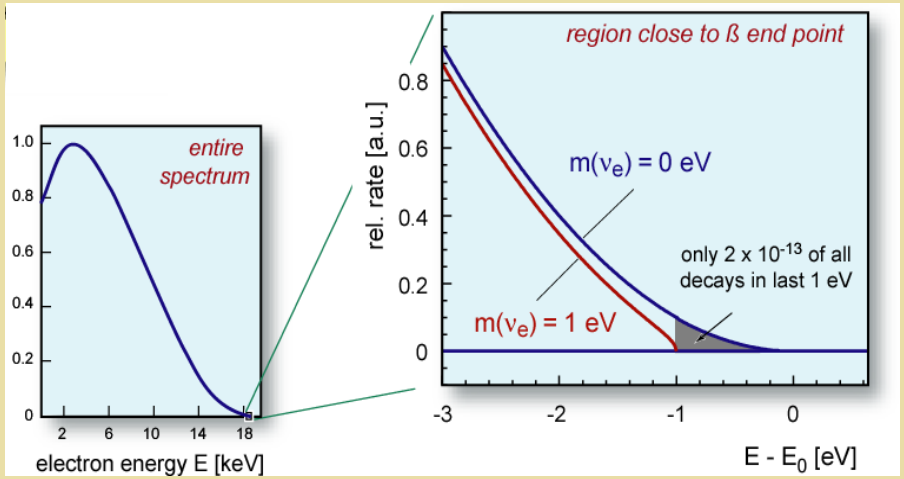
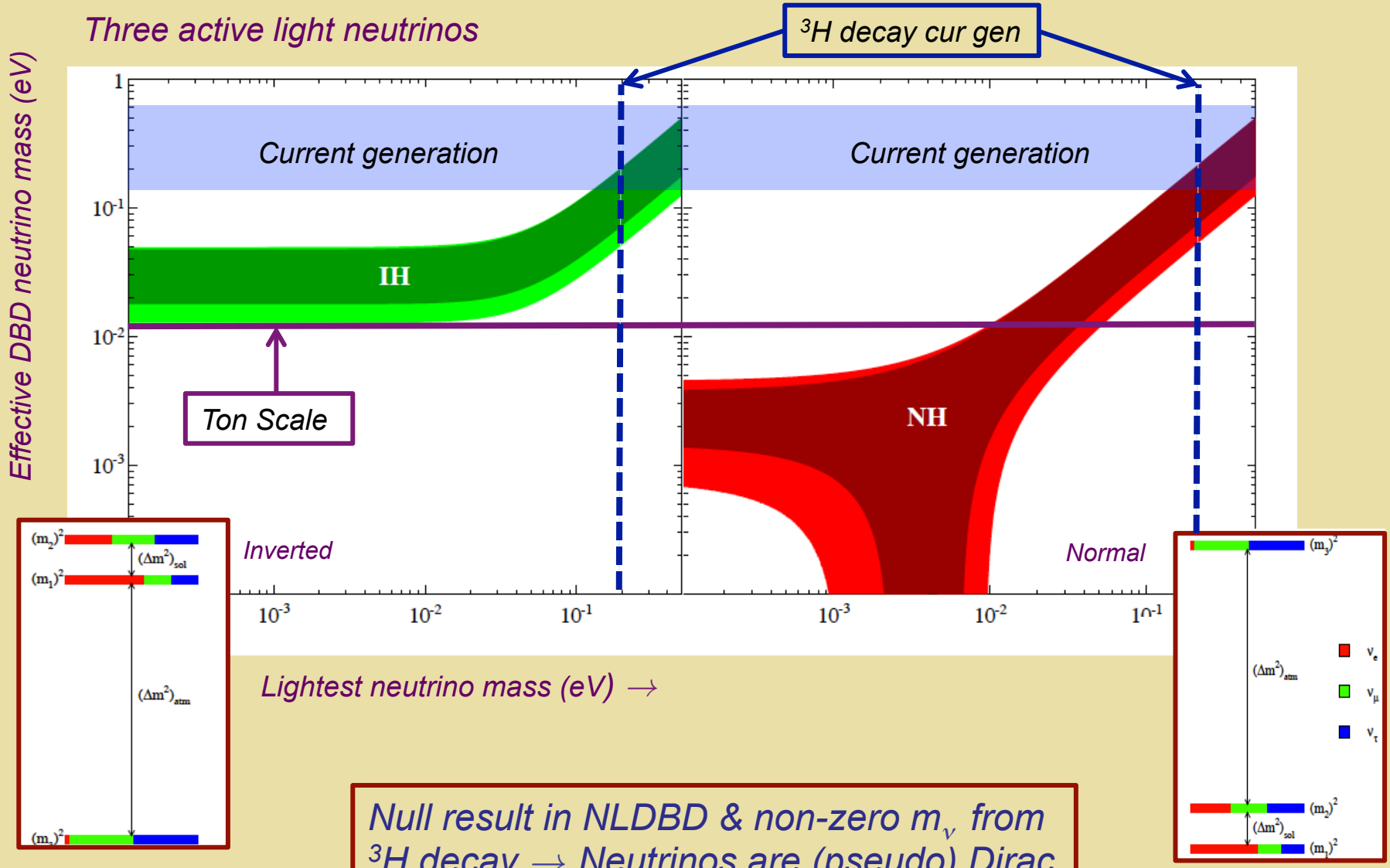
Kinematic Neutrino Mass Measurements

$^3H \rightarrow {}^3He \; e^- \; \bar{\nu}$



KATRIN

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



Null result in NLDBD & non-zero m_ν from ^{3}H decay → Neutrinos are (pseudo) Dirac

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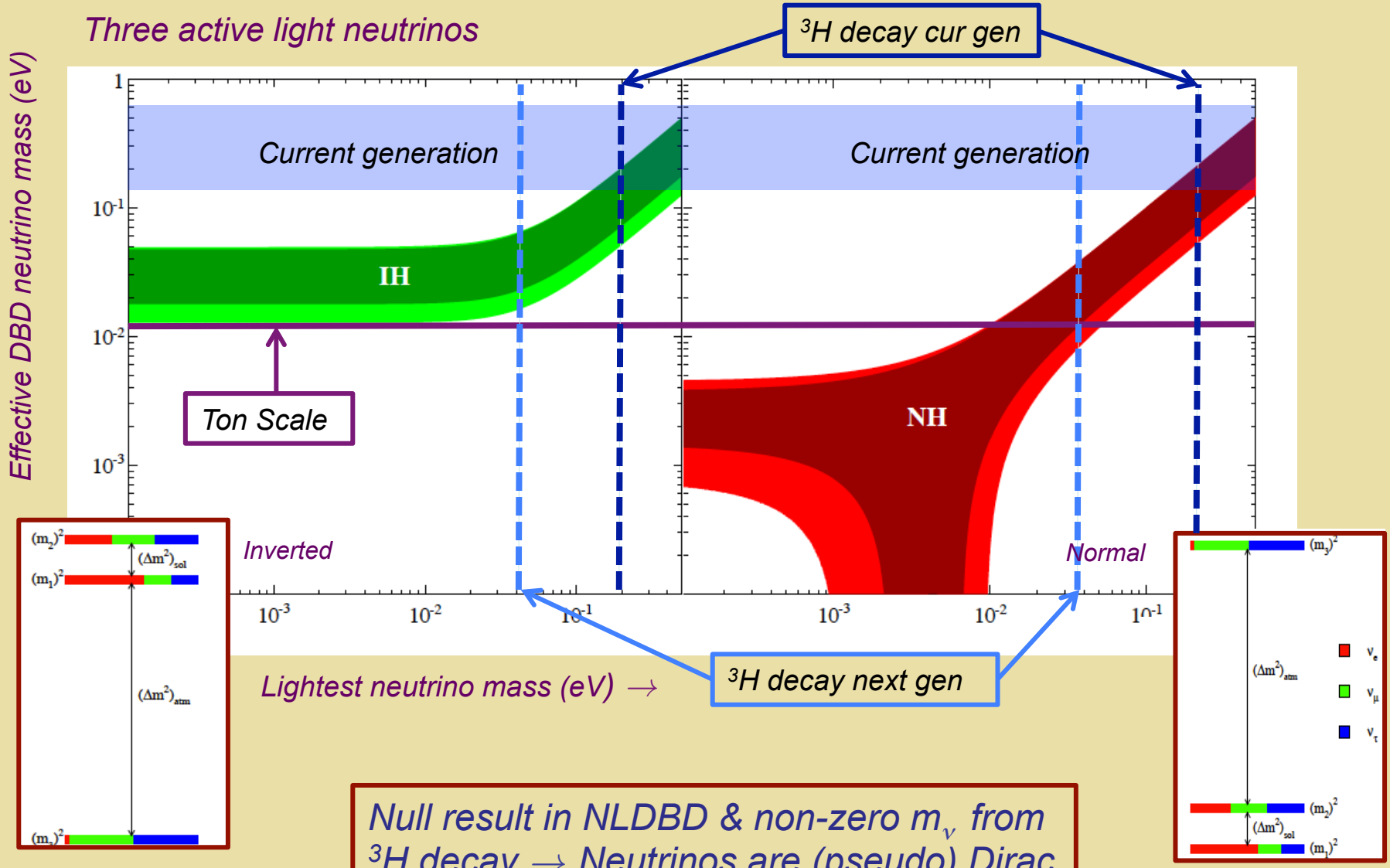

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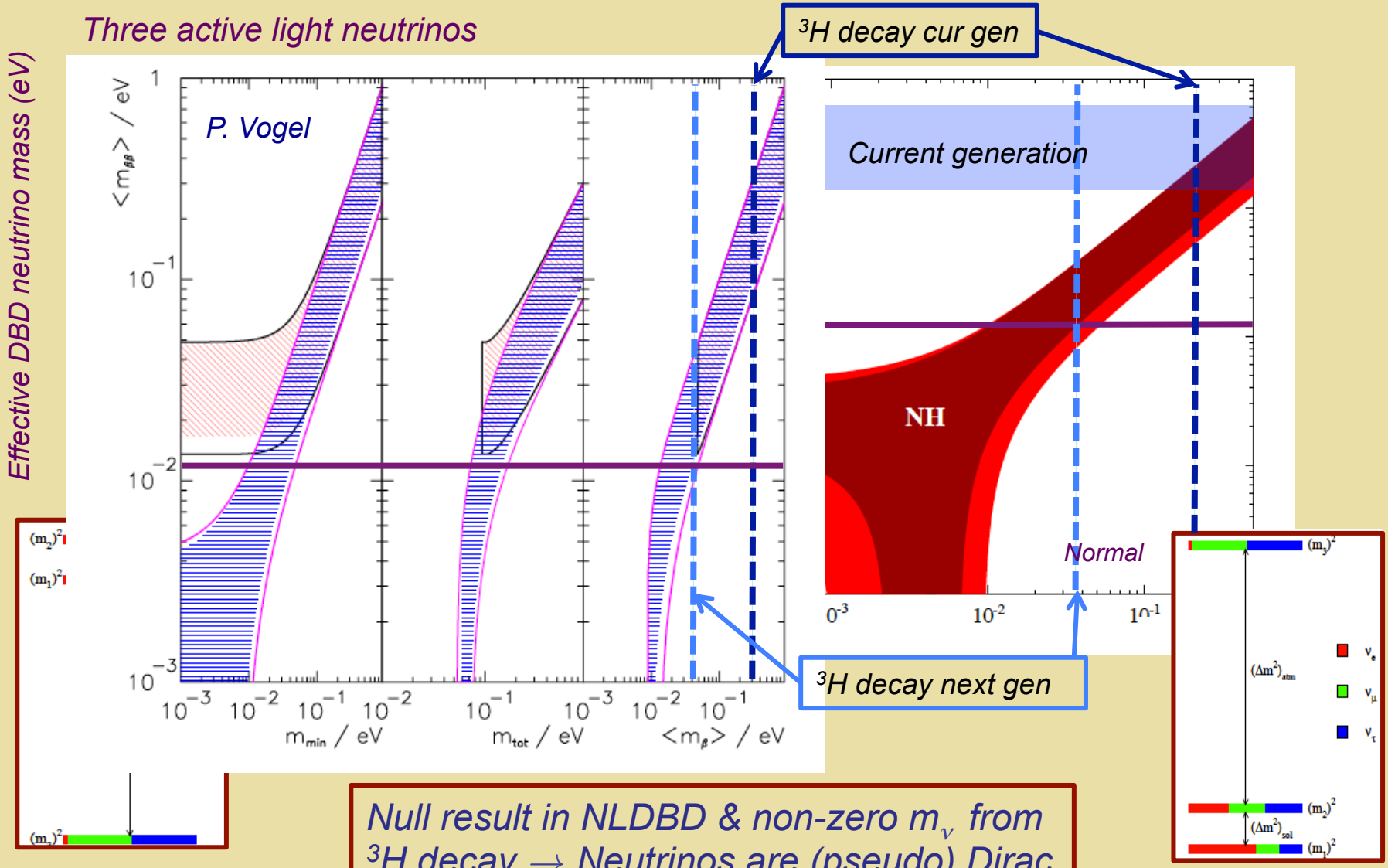

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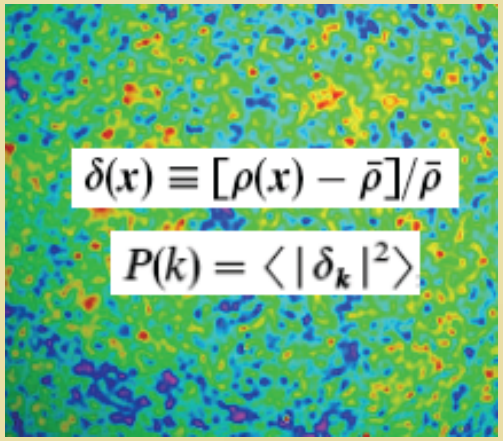
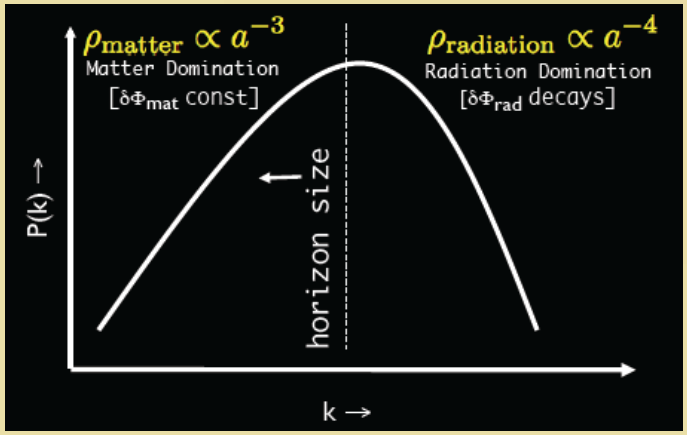
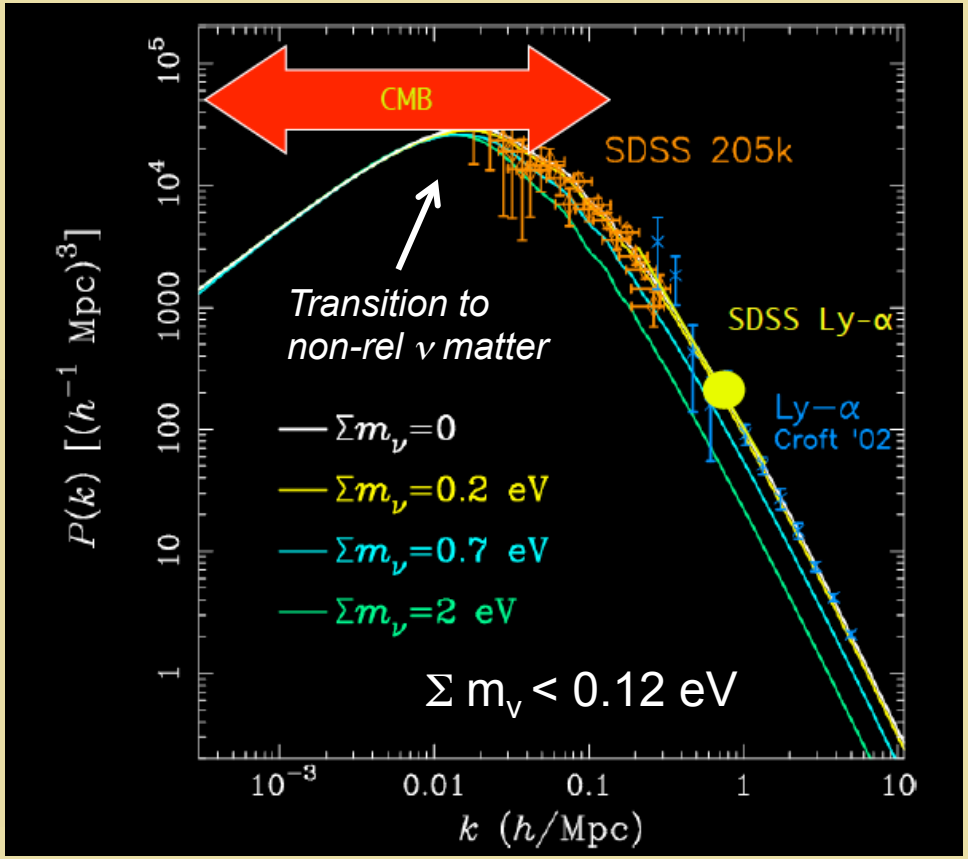
Neutrino Mass & Cosmology

Matter Power Spectrum





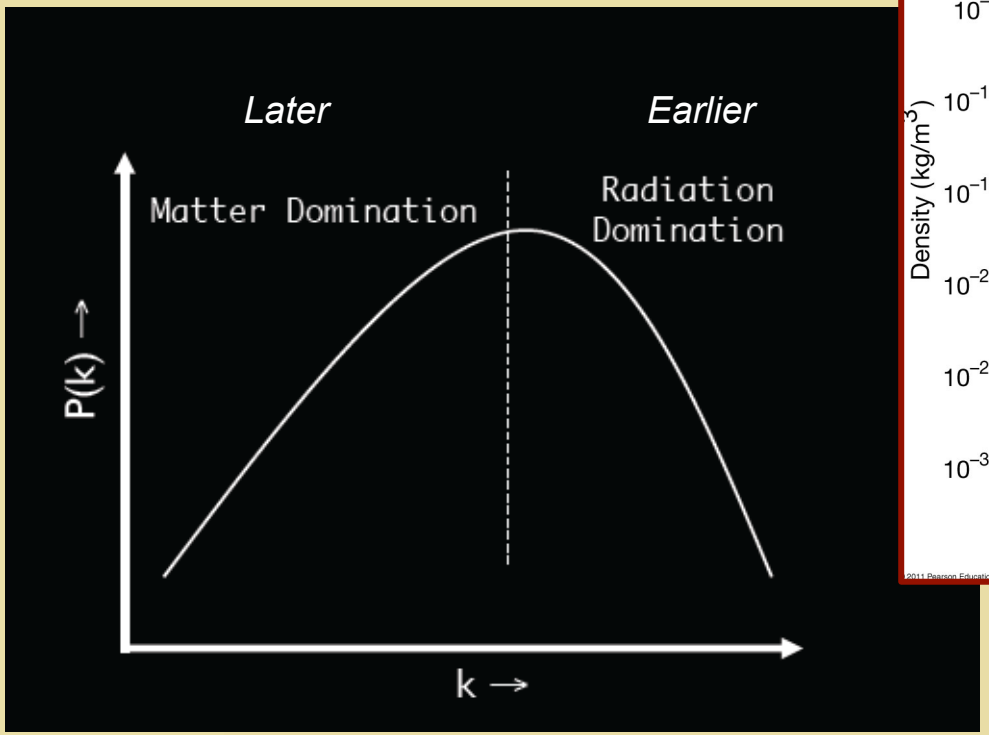


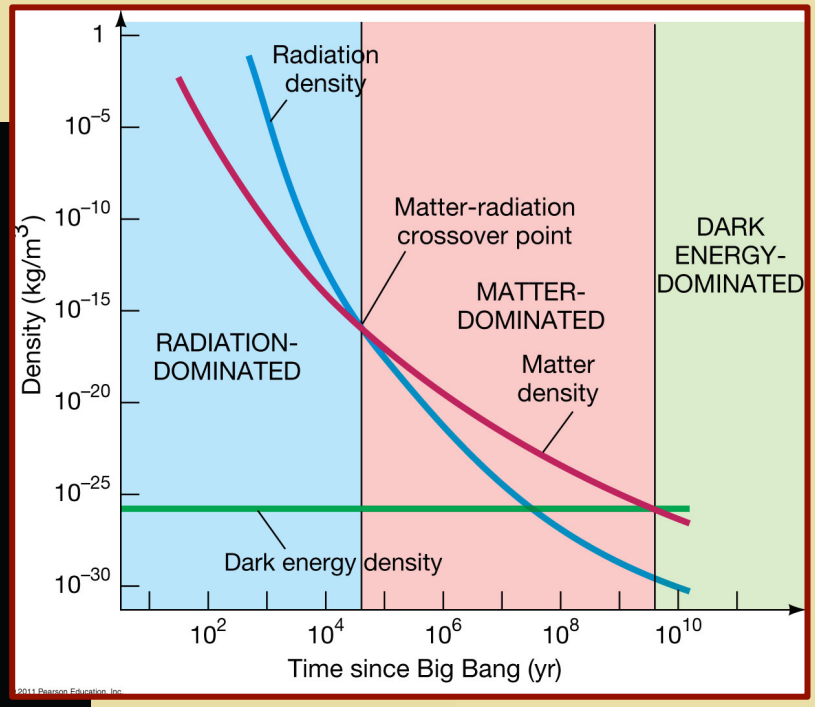
Massive neutrinos suppress power (relative to large scale power) at scales below free streaming scale

K. Abazajian ACFI neutrino mass workshop

Neutrino Mass & Cosmology

Matter Power Spectrum





J. Brau, U. Oregon

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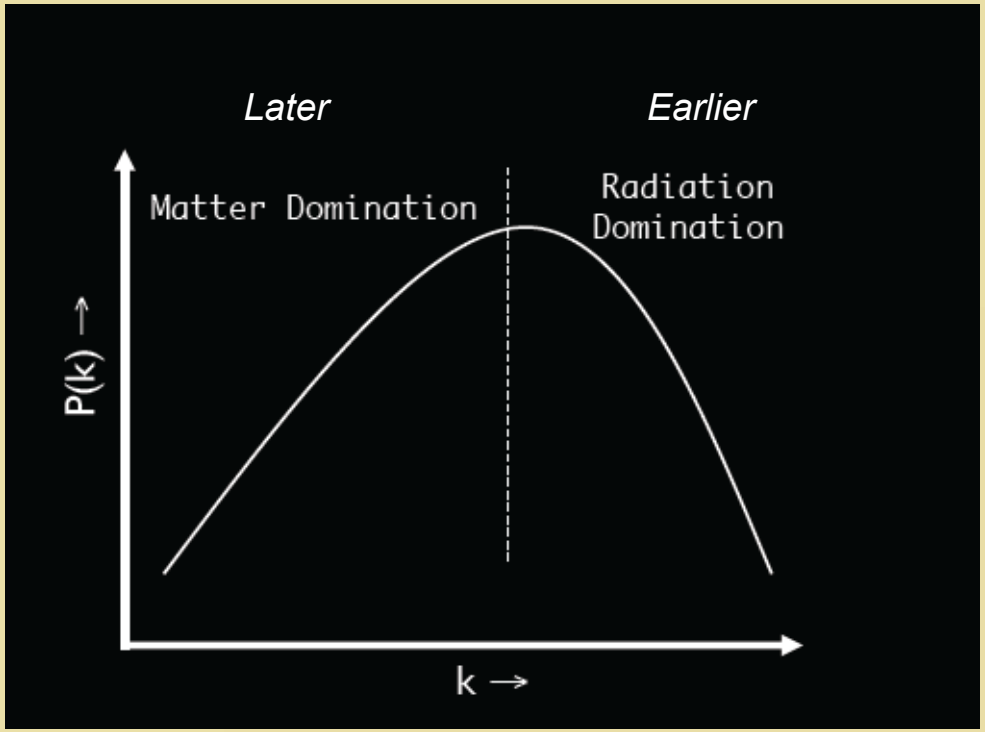


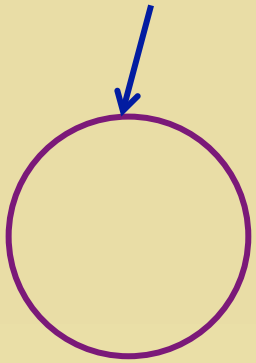
Neutrino Free Streaming

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

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

Free Streaming Scale

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



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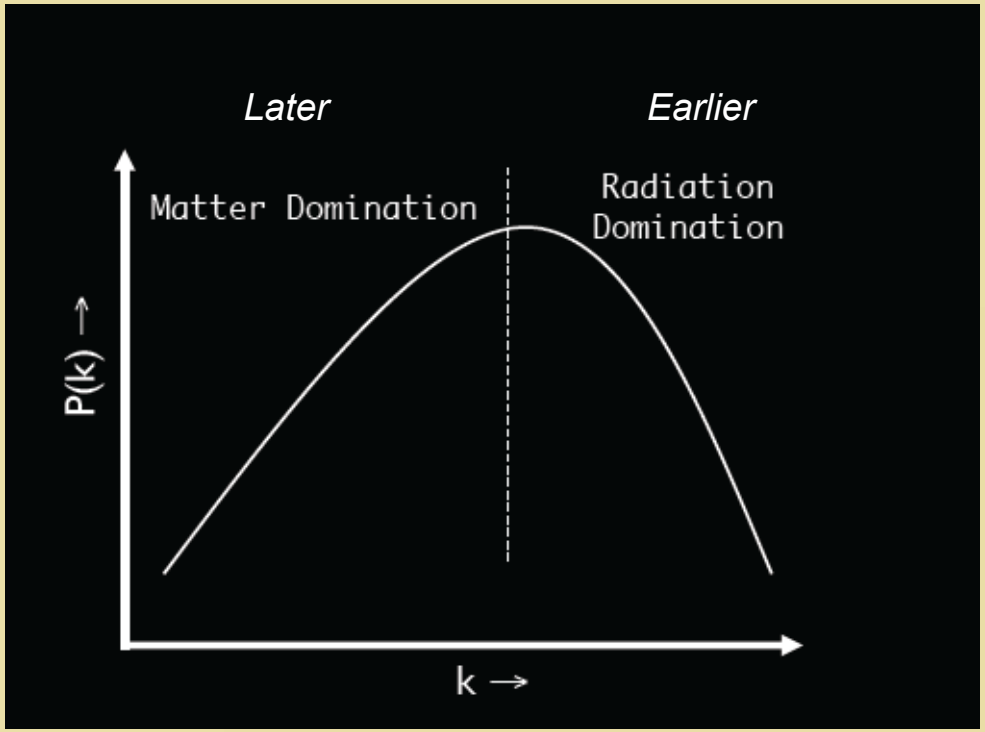

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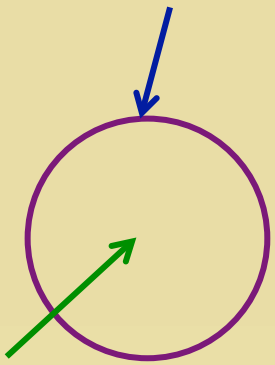

$\delta\rho_\nu$ *(power) suppressed for* $L < L_{fs}$

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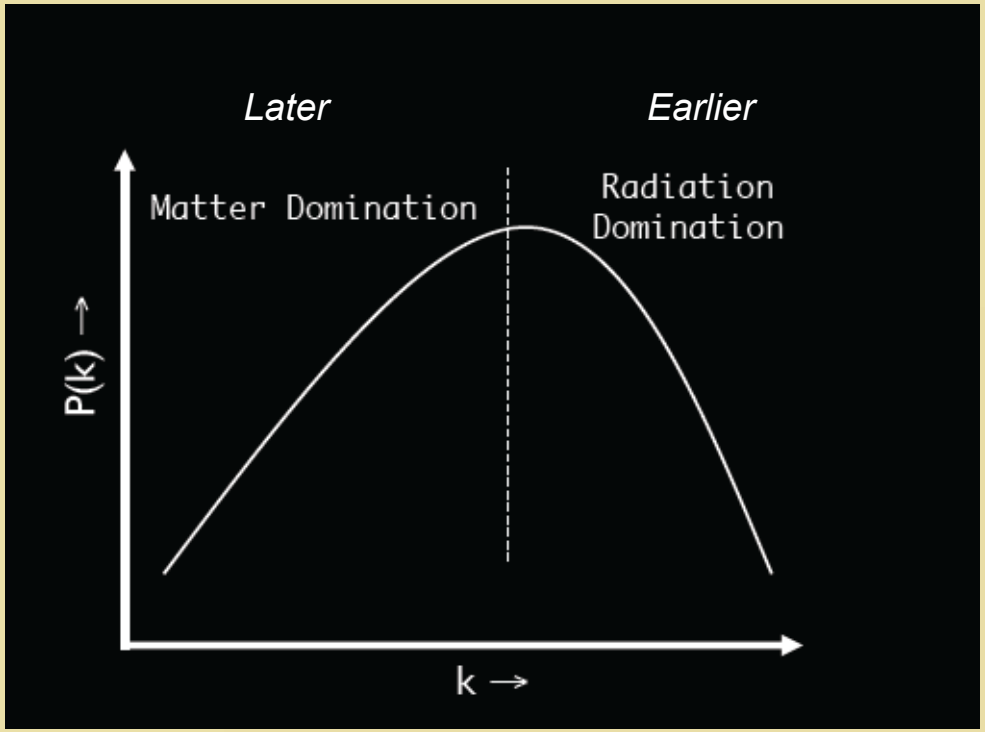

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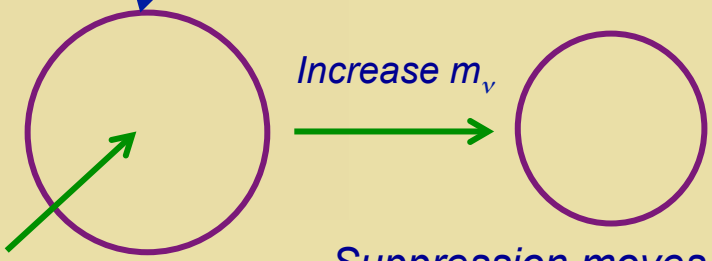
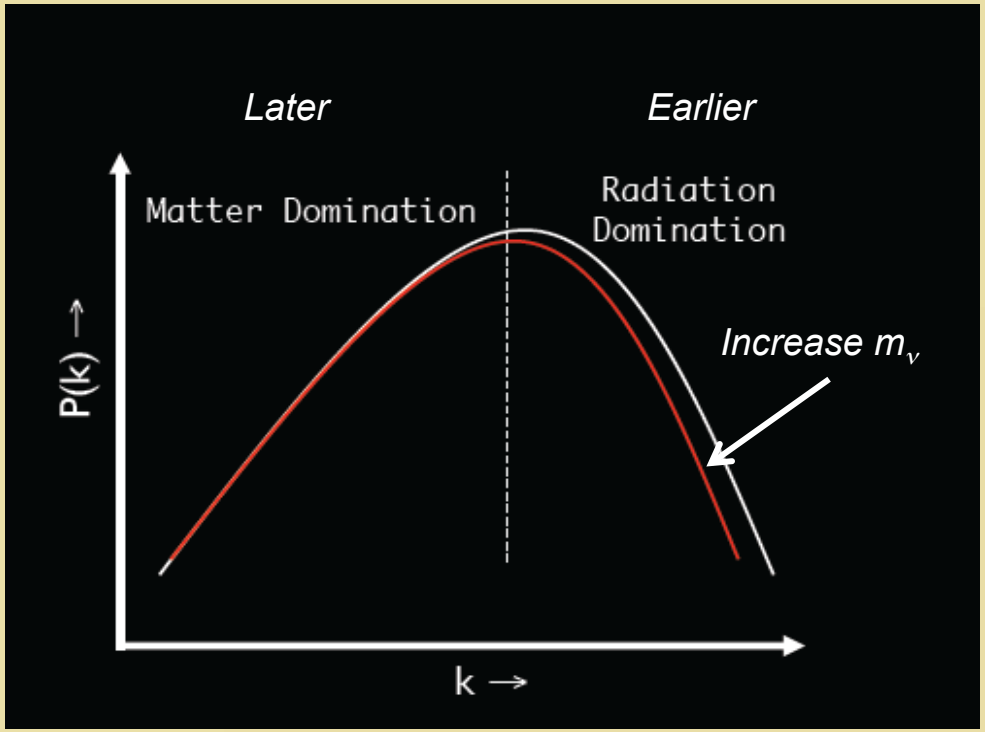


$\delta\rho_\nu$ (power) suppressed for $L < L_{fs}$

Suppression moves to smaller scales → Larger k

Neutrino Mass & Cosmology

Matter Power Spectrum



$\Sigma\, m_\nu < 0.12$ eV

Palanque-Dalabrouille '15

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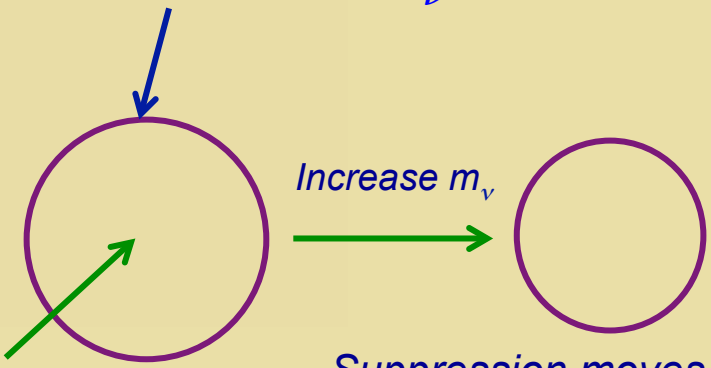

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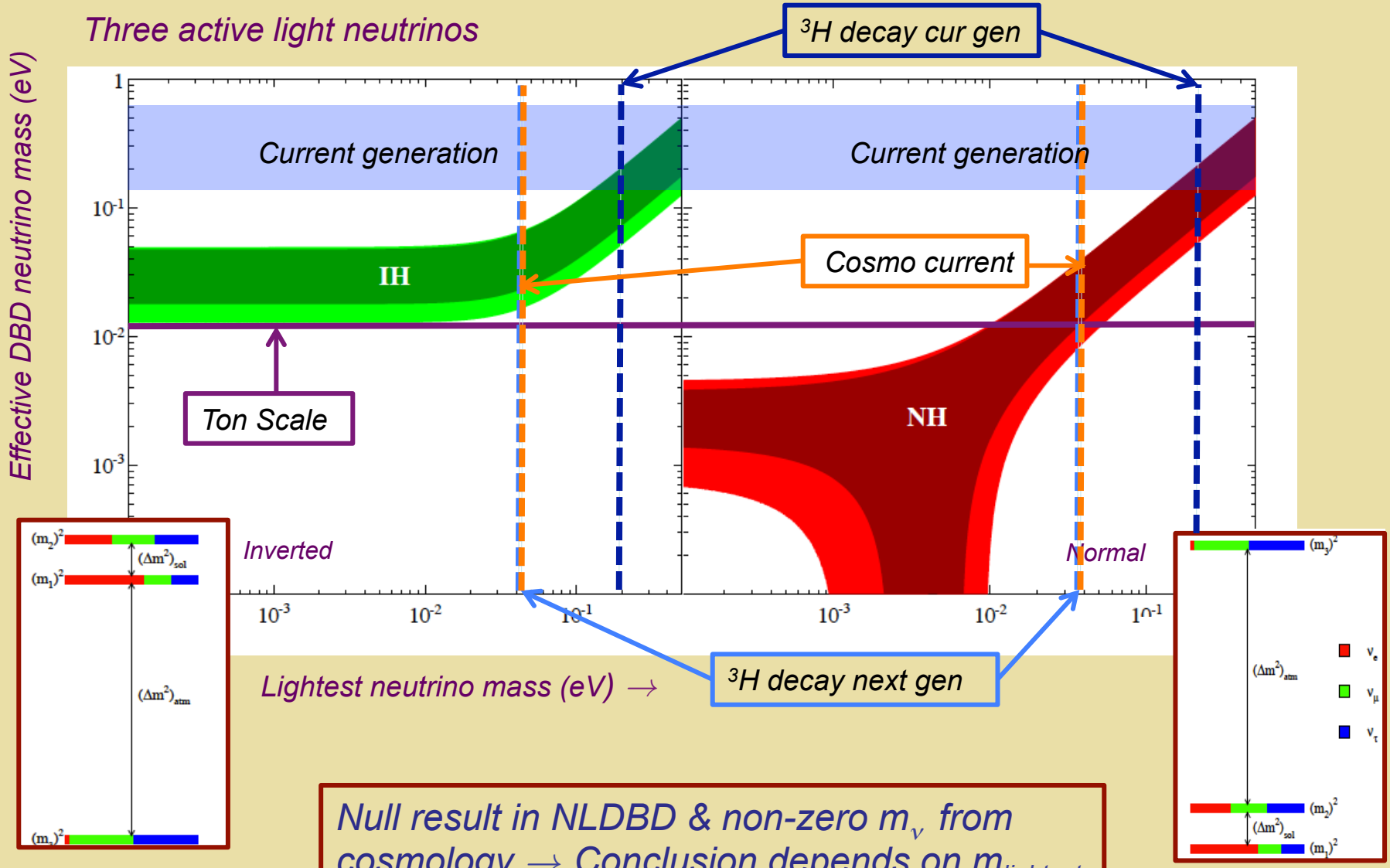
St'd Mech: What Would a Null Result Imply ?



Null result in NLDBD & non-zero m_ν from cosmology → Conclusion depends on $m_{lightest}$ & hierarchy

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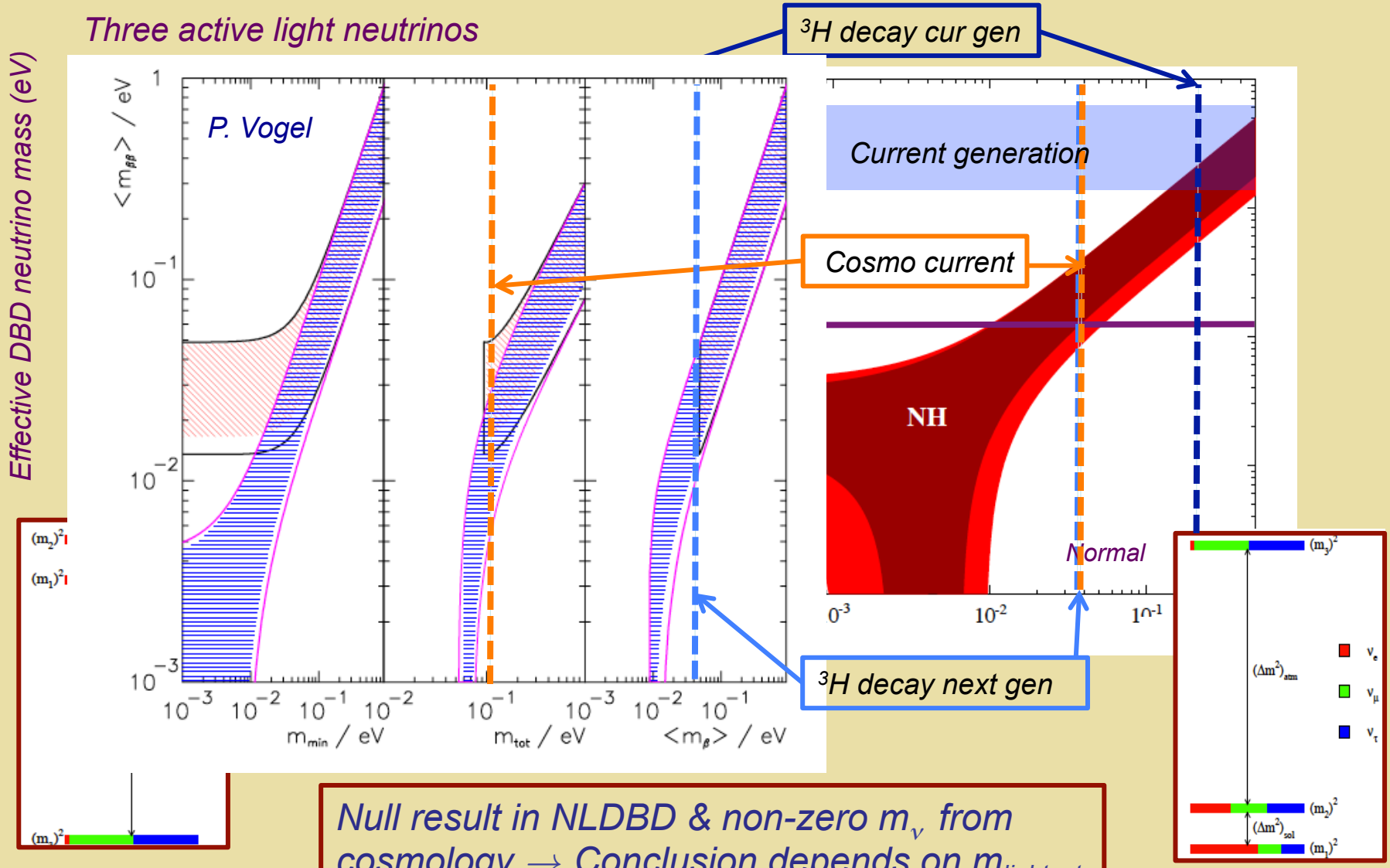

Null result in NLDBD & non-zero m_ν from cosmology → Conclusion depends on $m_{lightest}$ & hierarchy

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 Σm_ν 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 ?*