Neutrinos: the Ghosts of Christmas Past and Present

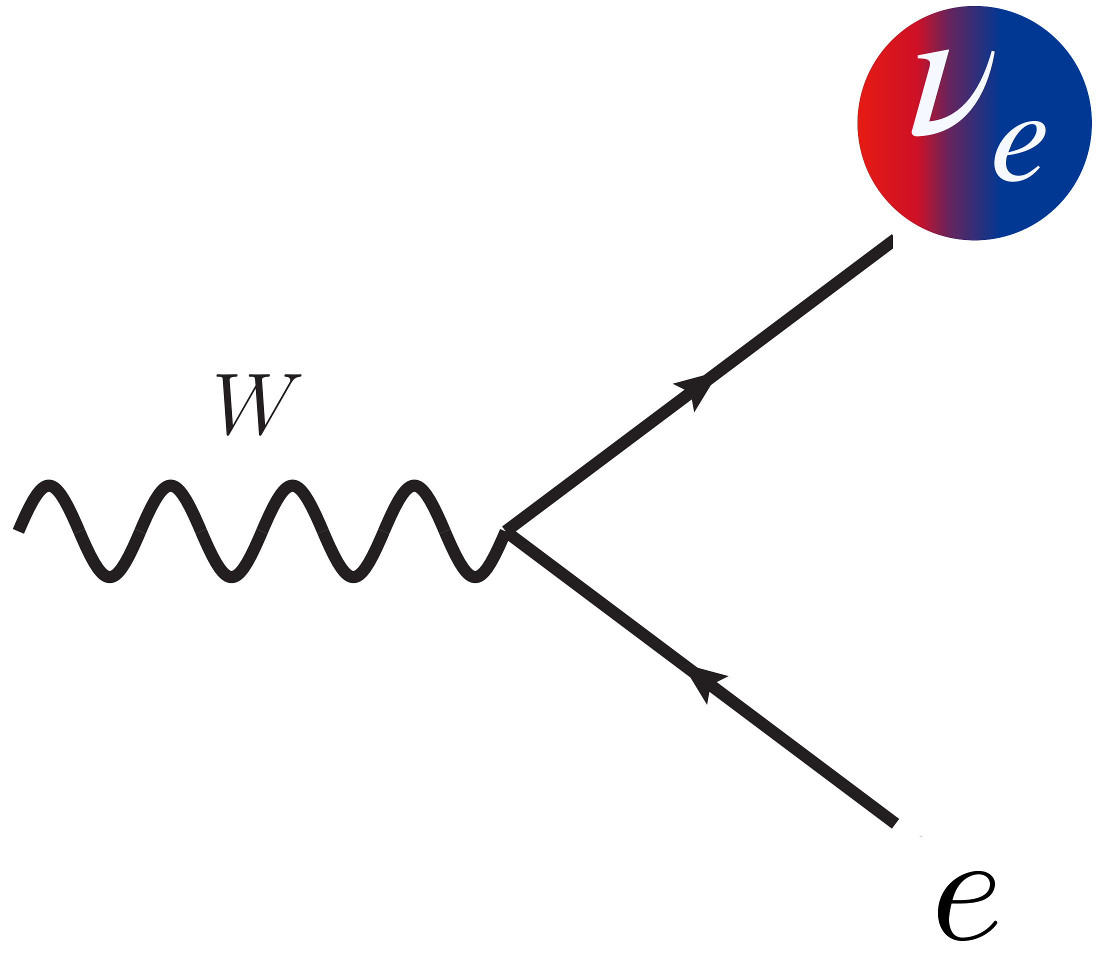
$$m_\nu = \frac{Y_\nu^2 v^2}{M_N}$$

$$\sigma = \frac{G_F^2 s}{\pi}$$

Jessica Turner
Institute for Particle Physics Phenomenology, Durham University

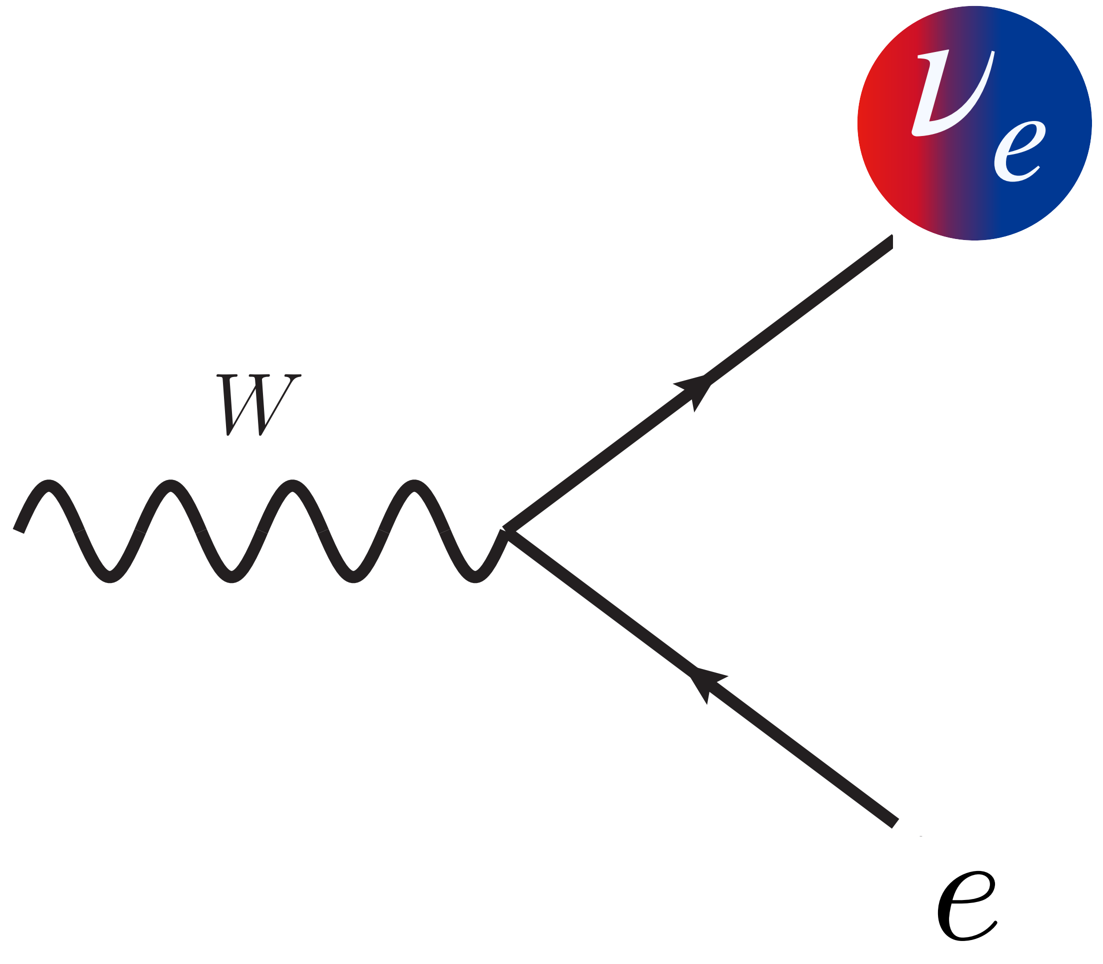
Neutrino Oscillations

Production

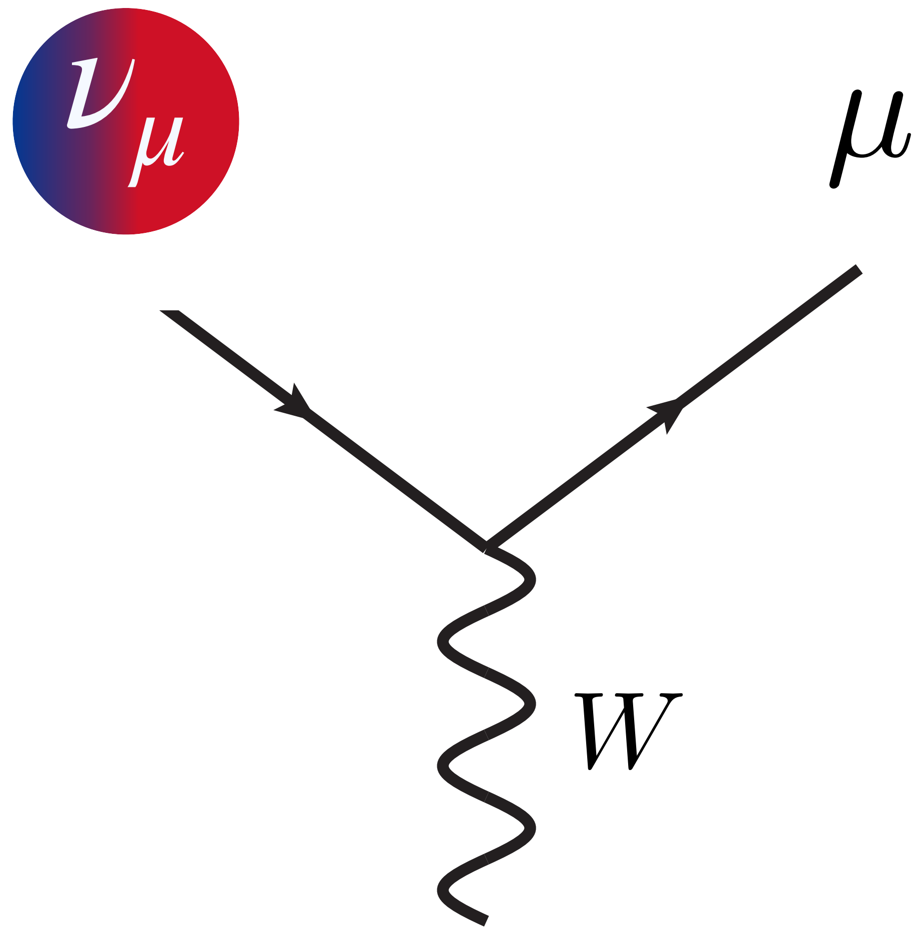


Neutrino Oscillations

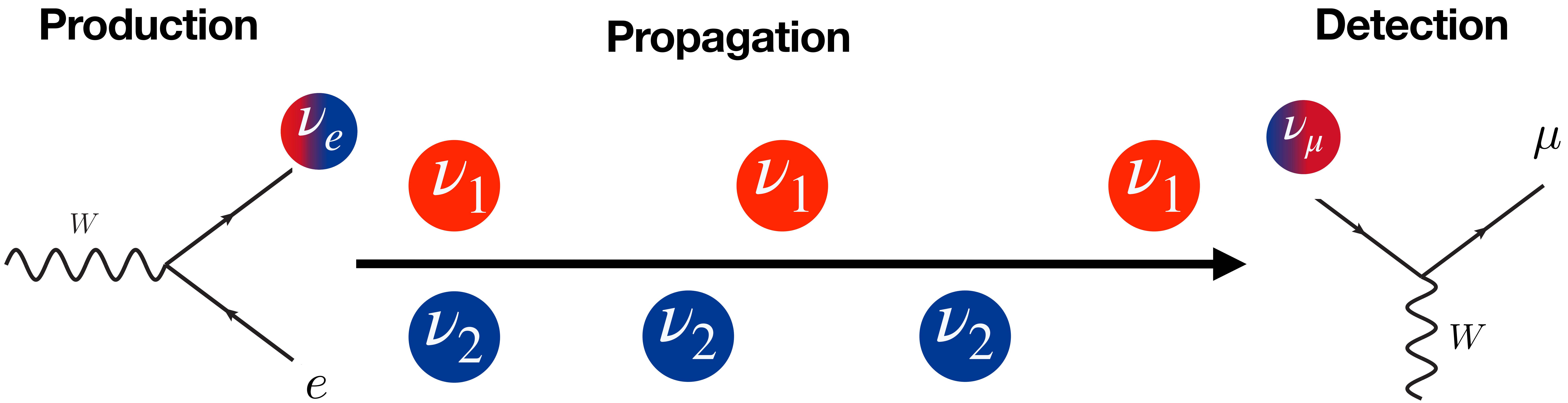
Production



Detection



Neutrino Oscillations



Neutrino Oscillations

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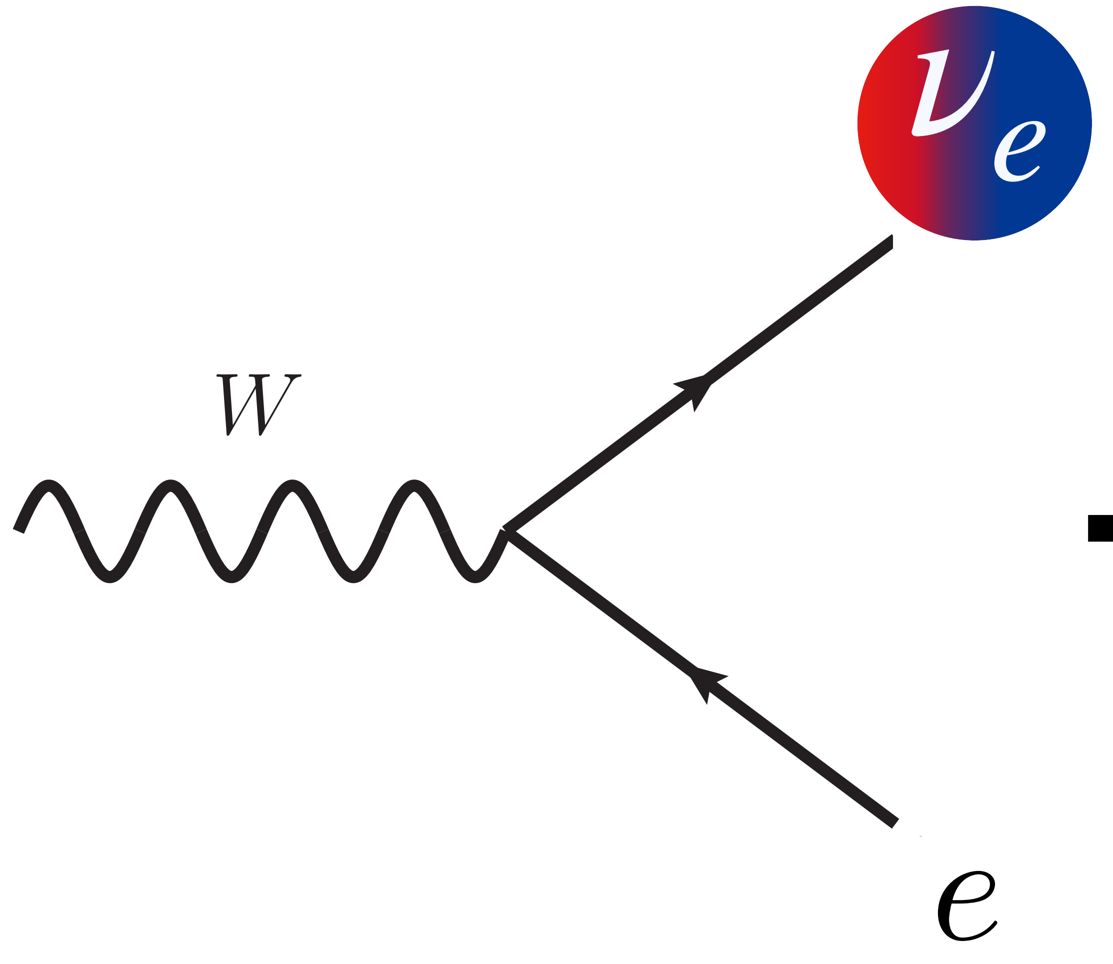
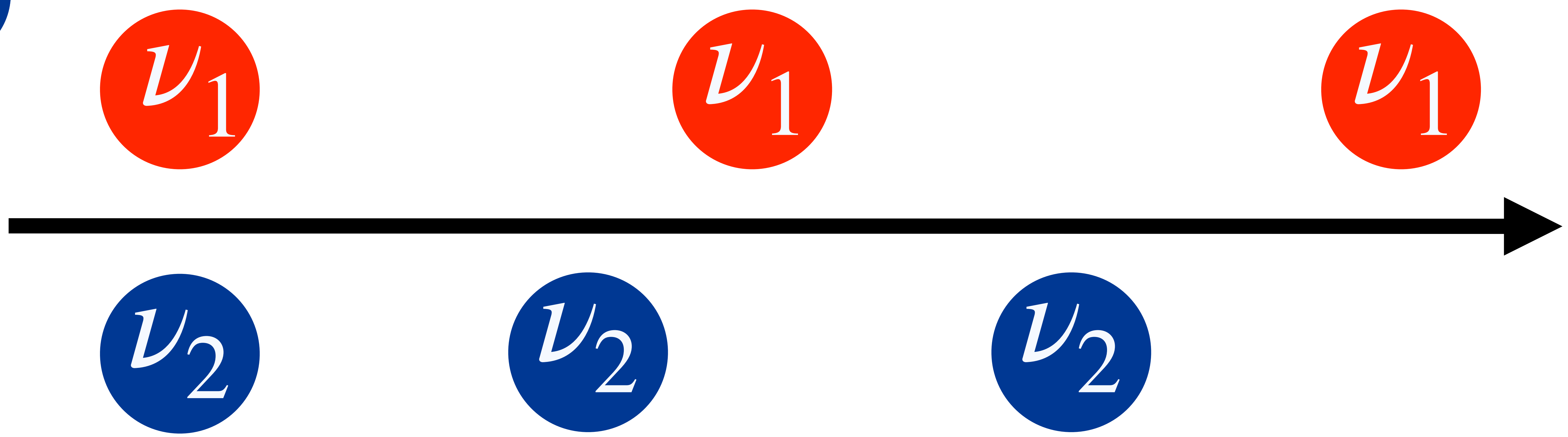
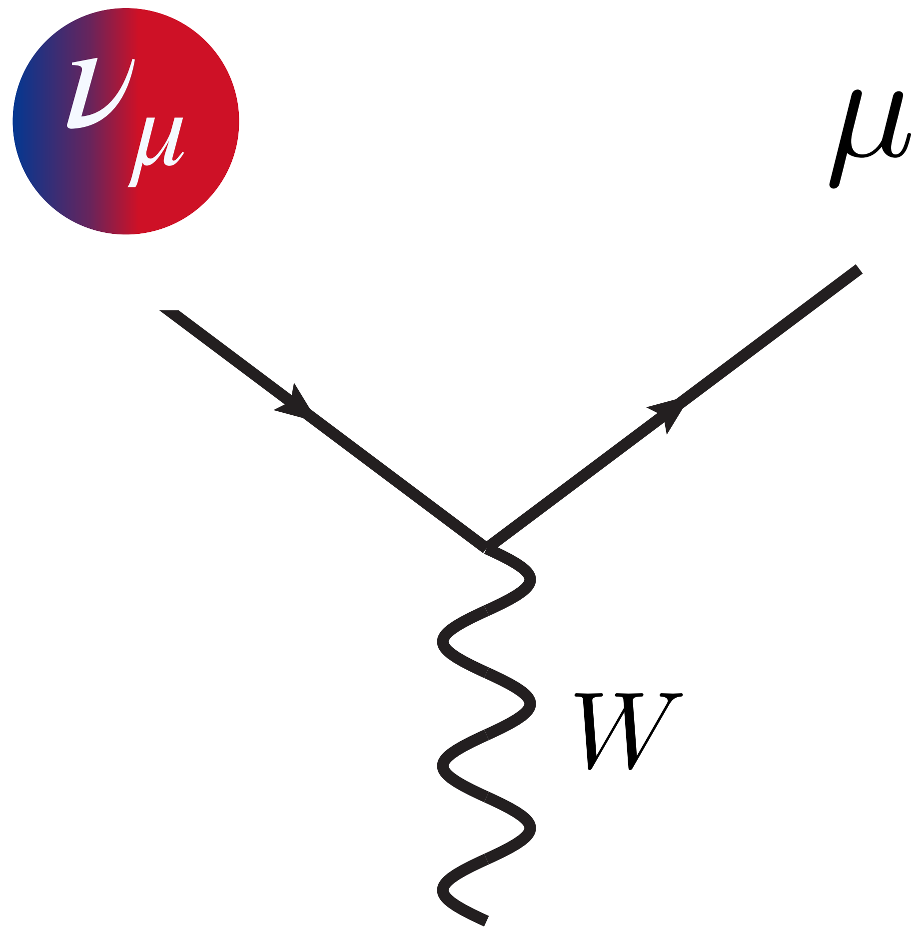


Propagation



Detection



$$|\nu_e\rangle = \sum_i U_{ei} |\nu_i\rangle$$

Flavour states superposition massive states

$$\begin{aligned} \nu_1 &: \quad e^{-iE_1 t} \\ \nu_2 &: \quad e^{-iE_2 t} \\ \nu_3 &: \quad e^{-iE_3 t} \end{aligned}$$

Massive states: Hamiltonian eigenstates

$$\langle \nu_\mu |$$

Projection over flavour states

Neutrino Oscillations

Simplified two neutrino case

$$|\nu(t)\rangle = -\sin(\theta)e^{-iE_1 t}|\nu_1\rangle + \cos(\theta)e^{-iE_2 t}|\nu_2\rangle$$

Probability for ν_e to transform to ν_μ

$$P\left(\nu_e \rightarrow \nu_\mu\right) = \sin^2(2\theta)\sin^2 \frac{\left(m_2^2 - m_1^2\right) L}{4E}$$

Neutrino Oscillations

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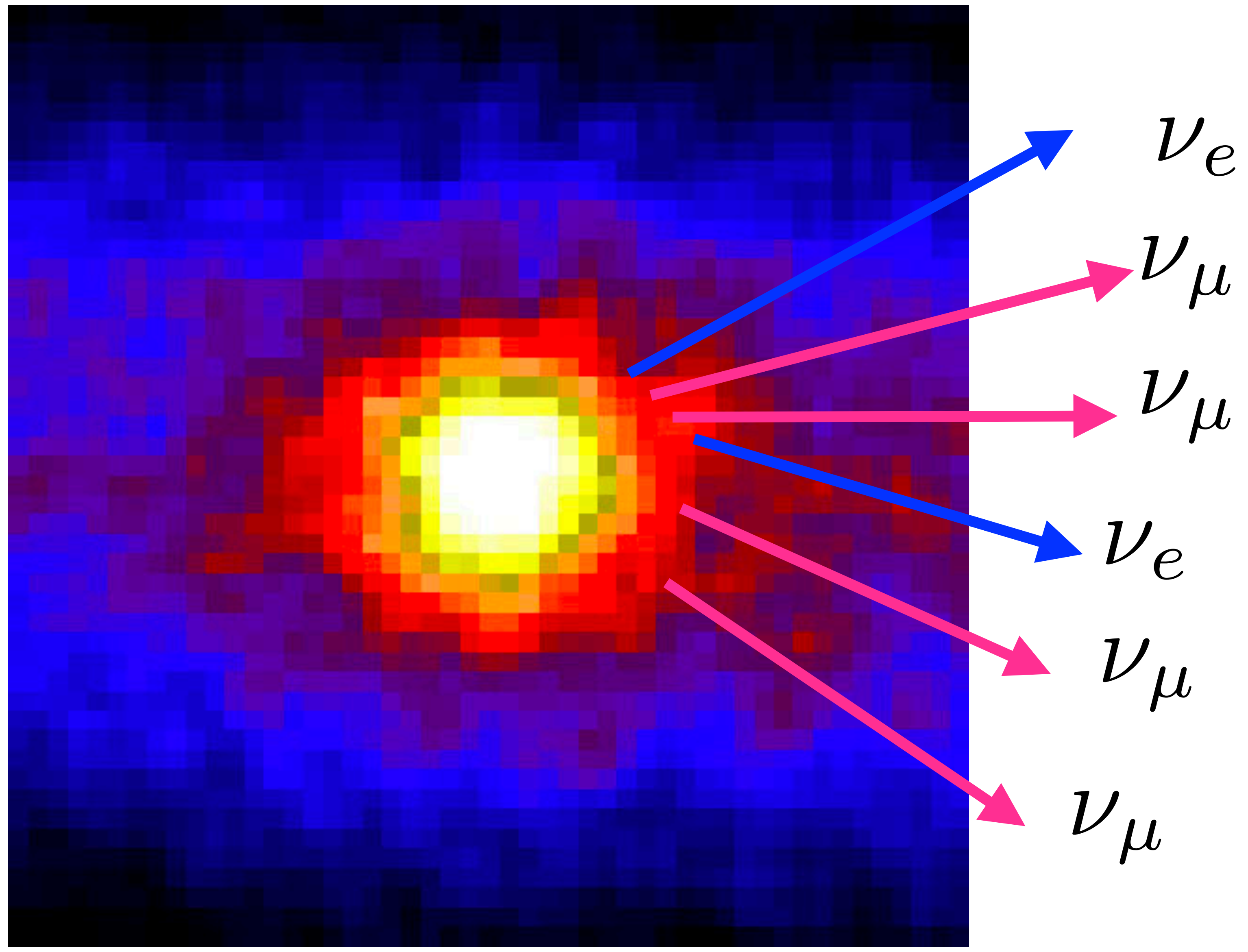
Mixing angles: misalignment between massive and flavour states

Neutrino masses

Neutrinos: Ghosts of Christmas Past

Ghosts of Christmas Past: Solar Neutrinos



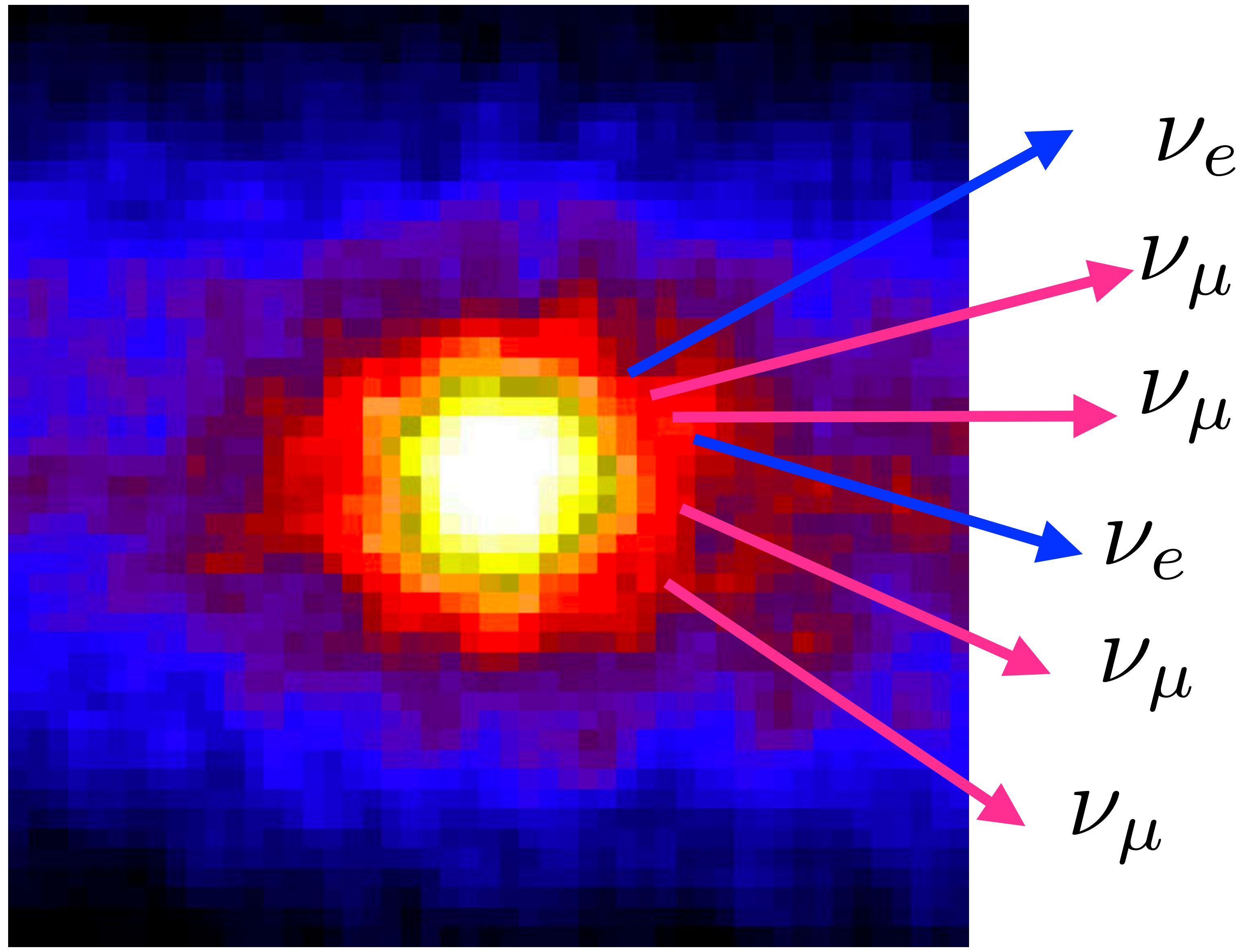
- Sun emits $\mathcal{O}(\mathrm{MeV})\ \nu_e$ via nuclear fusion
- Homestake searched for solar neutrinos (1970)

$$\nu_\mathrm{e} + {}^{37}\mathrm{Cl} \longrightarrow {}^{37}\mathrm{Ar}^{+} + \mathrm{e}$$

Nobel 2002

- Bahcall calculated solar neutrino flux. Counting radiative argon $\Longrightarrow$ deficit

Ghosts of Christmas Past: Solar Neutrinos



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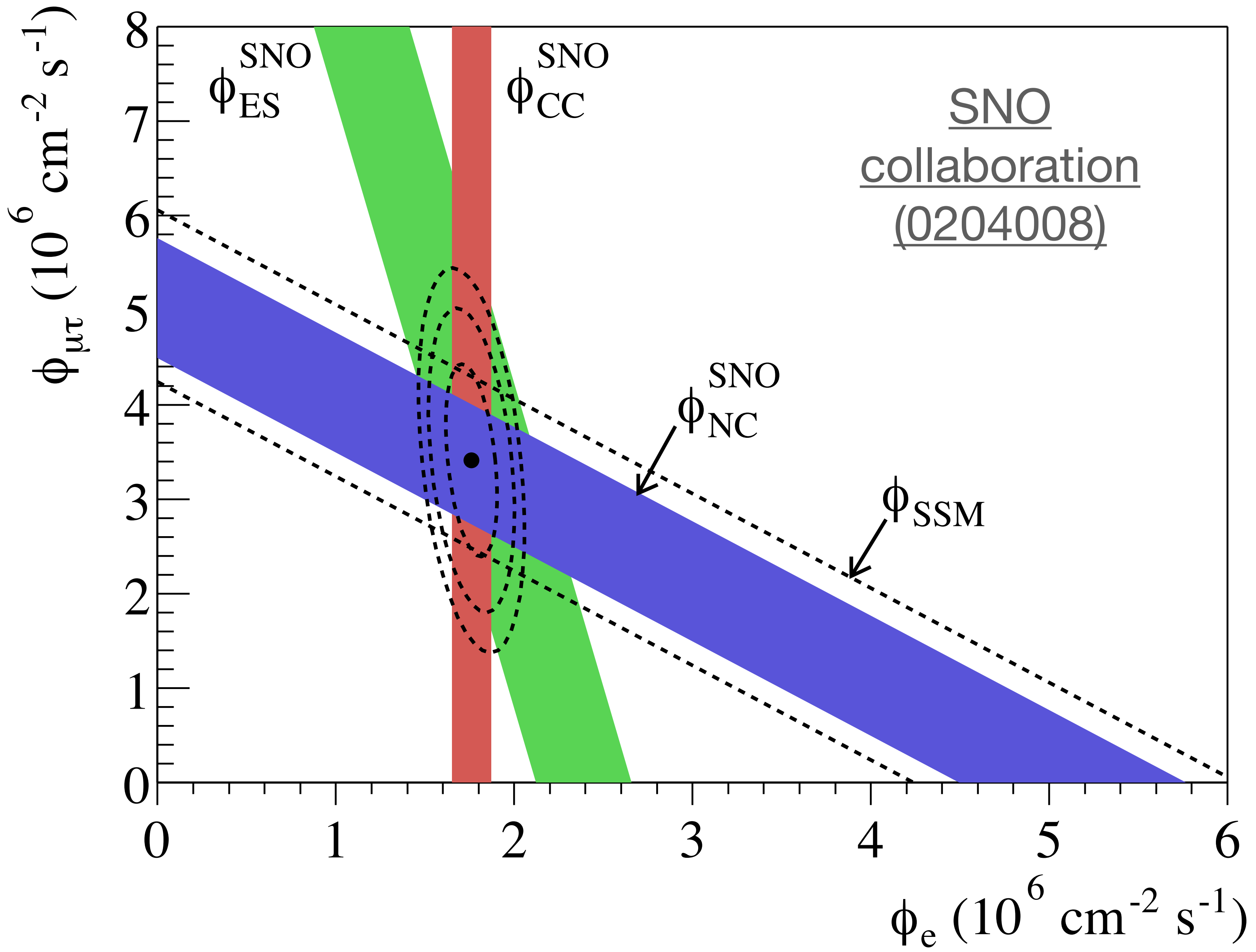
$$\nu_\mathrm{e} + {}^{37}\mathrm{Cl} \longrightarrow {}^{37}\mathrm{Ar}^{+} + \mathrm{e}$$

Nobel 2002

- SNO (2002) resolved solar neutrino problem by detecting solar ν_e appearance and solar ν_e disappearance

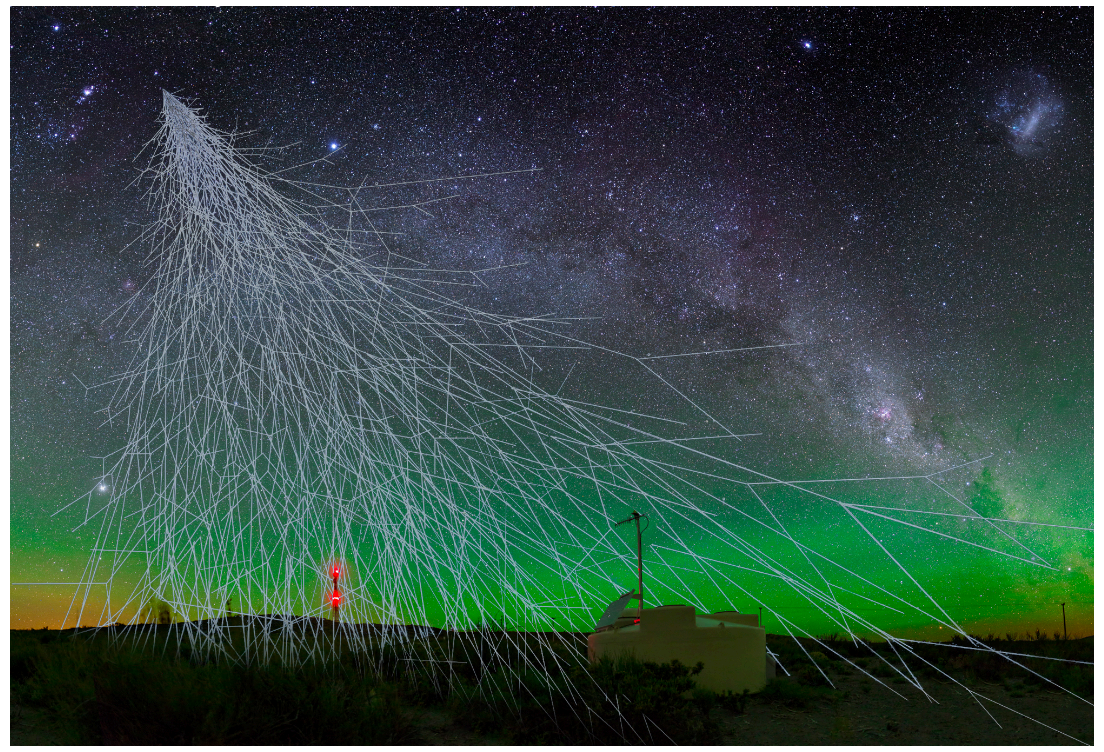
$\nu_e + d \to p + p + e^-$	Charged current (CC)
$\nu_x + d \to p + n + \nu_x$	Neutral current (NC)
$\nu_x + e^- \to \nu_x + e^-$	Elastic scattering (ES)



SNO collaboration (0204008)

Nobel 2015

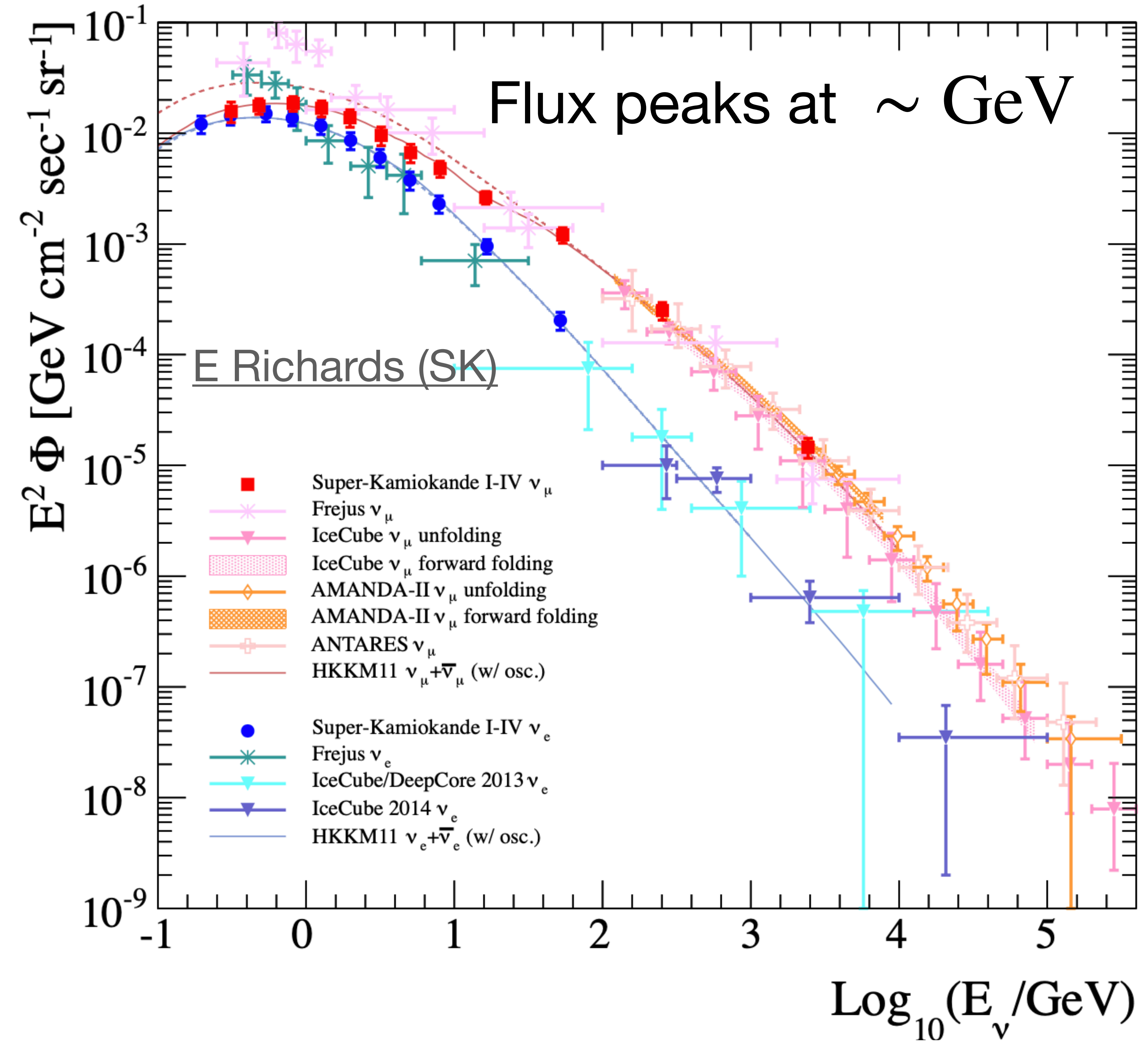
Ghosts of Christmas Past: Atmospheric Neutrinos



Decay of mesons produce flux of atmospheric neutrinos which spans MeV - TeV scale

$$\pi^\pm \to \mu^\pm + \nu_\mu \, (\bar{\nu}_\mu)$$
$$K^\pm \to \mu^\pm + \nu_\mu \, (\bar{\nu}_\mu)$$
$$\mu^\pm \to e^\pm + \nu_e \, (\bar{\nu}_e) + \bar{\nu}_\mu \, (\nu_\mu)$$

$$\frac{\nu_e + \bar{\nu}_e}{\nu_\mu + \bar{\nu}_\mu} \sim \frac{1}{2} \quad E_\nu \lesssim 1\text{GeV}$$



DETECTION OF MUONS PRODUCED BY COSMIC RAY NEUTRINOS DEEP UNDERGROUND

C. V. ACHAR, M. G. K. MENON, V. S. NARASIMHAM, P. V. RAMANA MURTHY and B. V. SREEKANTAN,
Tata Institute of Fundamental Research, Colaba, Bombay

K. HINOTANI and S. MIYAKE,
Osaka City University, Osaka, Japan

D. R. CREED, J. L. OSBORNE, J. B. M. PATTISON and A. W. WOLFENDALE
University of Durham, Durham, U.K.

Received 12 July 1965

First detection in 1965

Ghosts of Christmas Past: Atmospheric Neutrinos

Decay of mesons produce flux of atmospheric neutrinos which spans MeV - TeV scale

$$\pi^{\pm} \rightarrow \mu^{\pm} + \nu_{\mu} \, (\bar{\nu}_{\mu})$$
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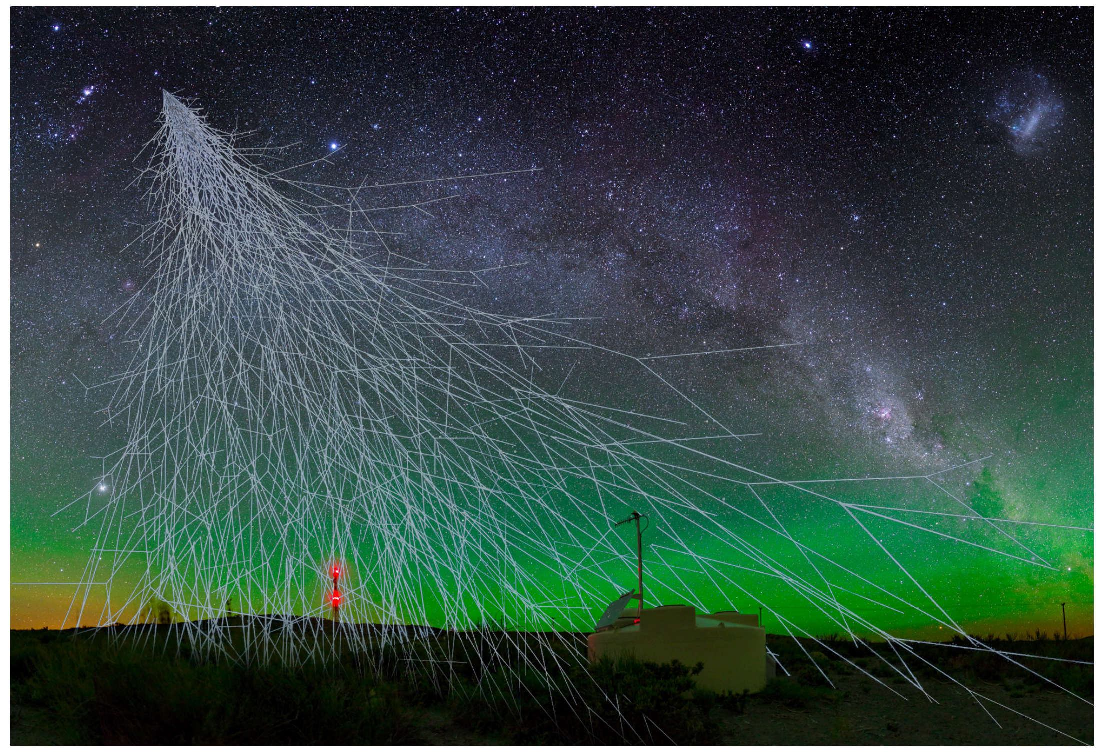
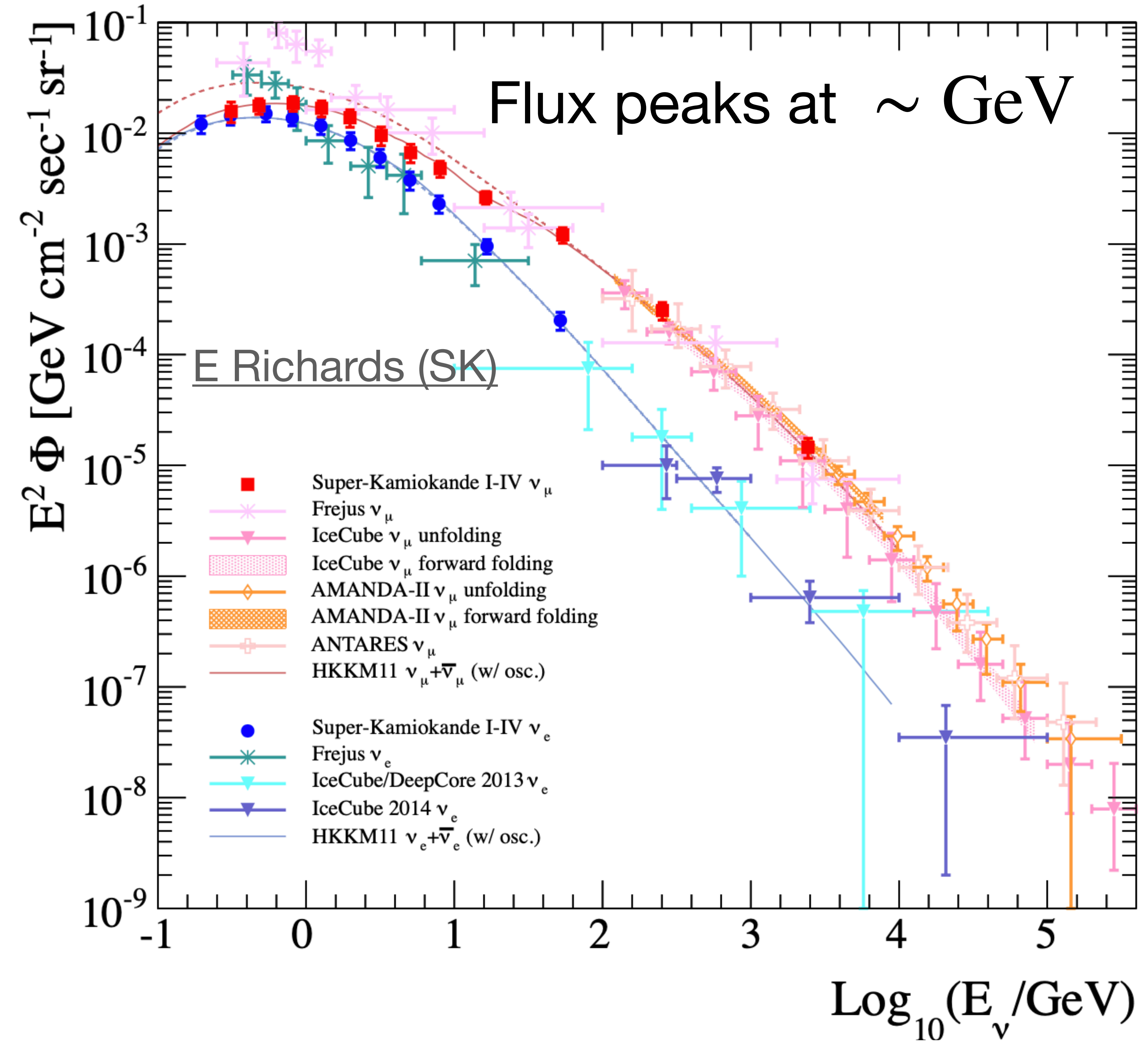
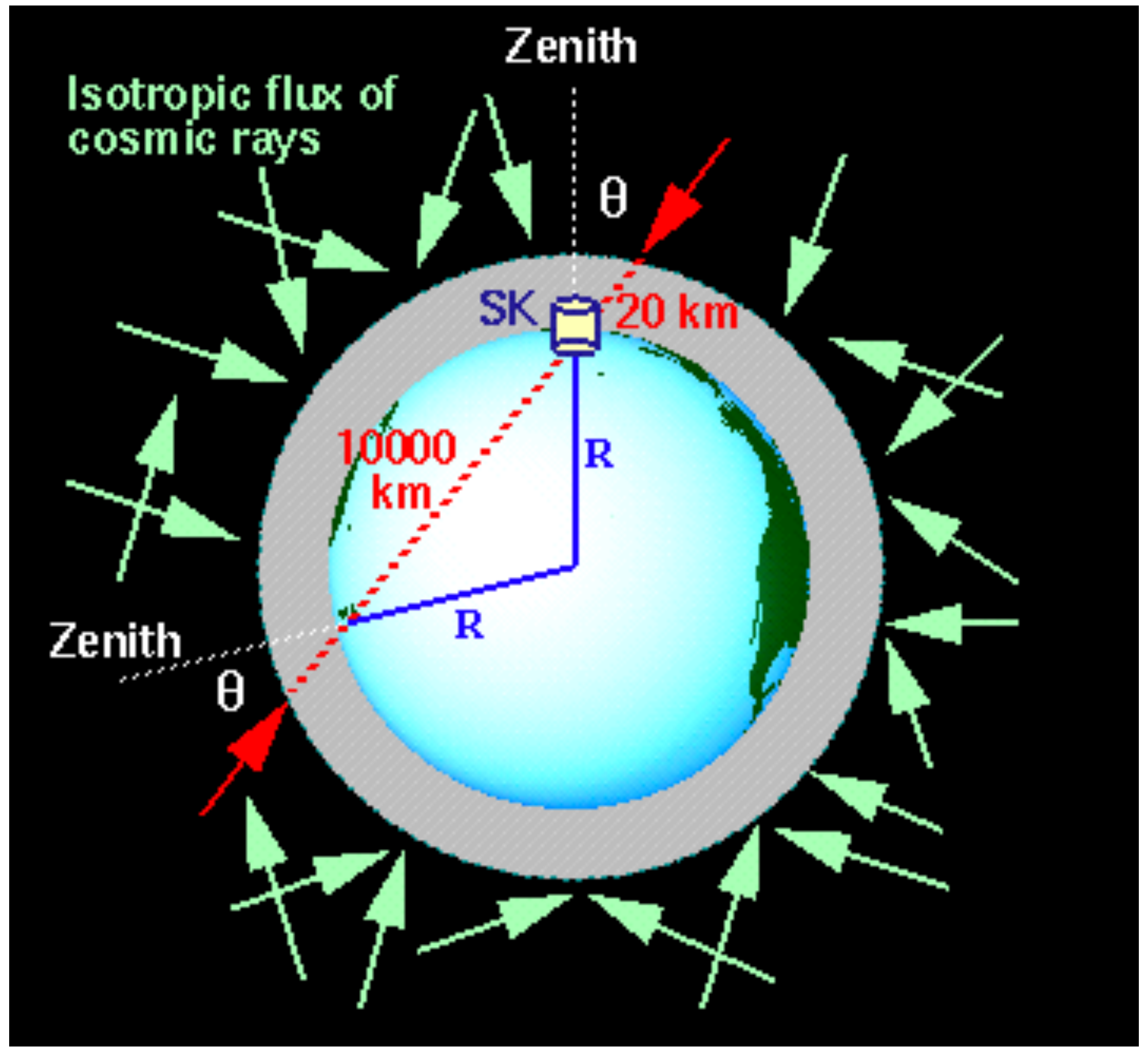
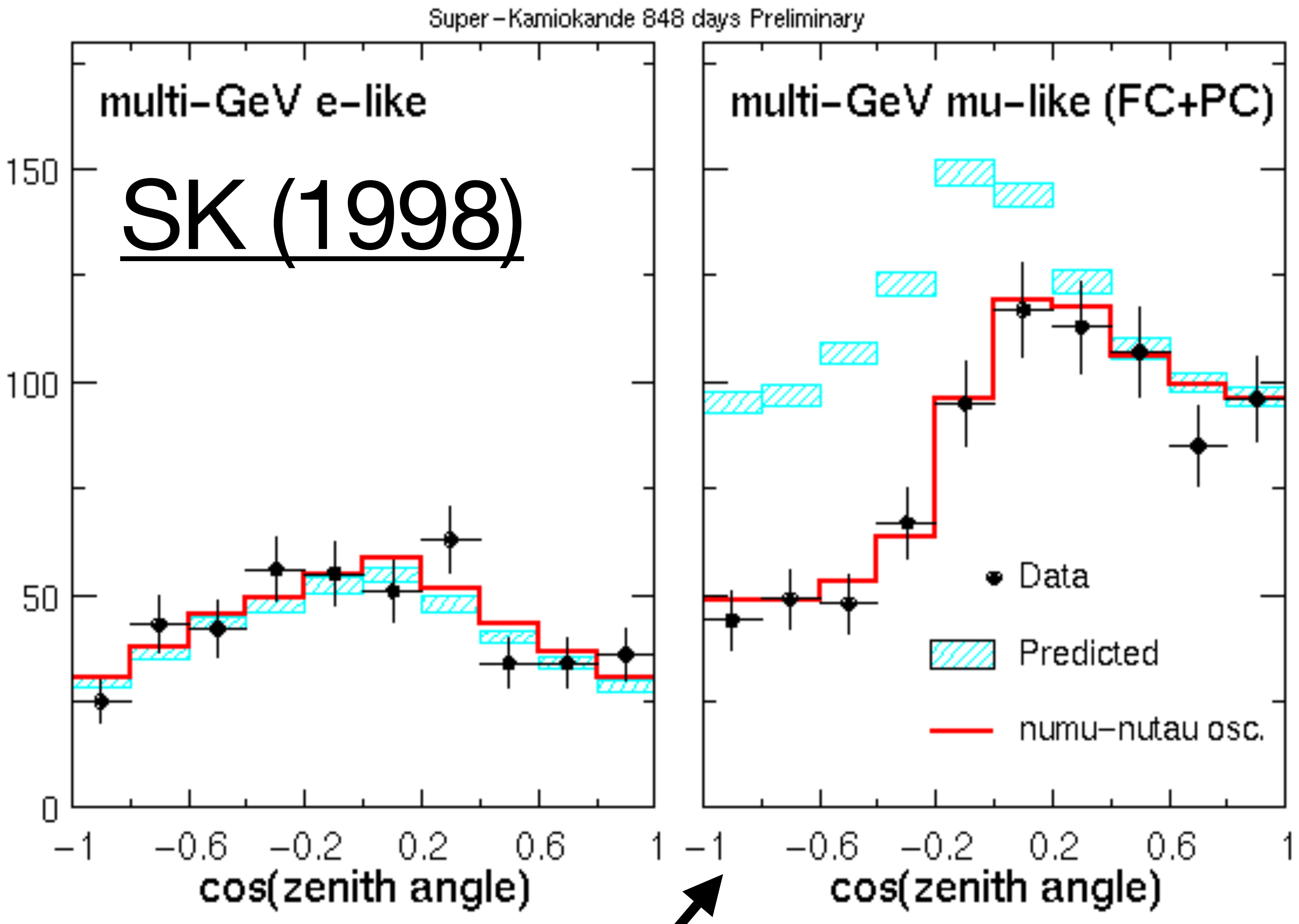


Nobel 2015







Upward going

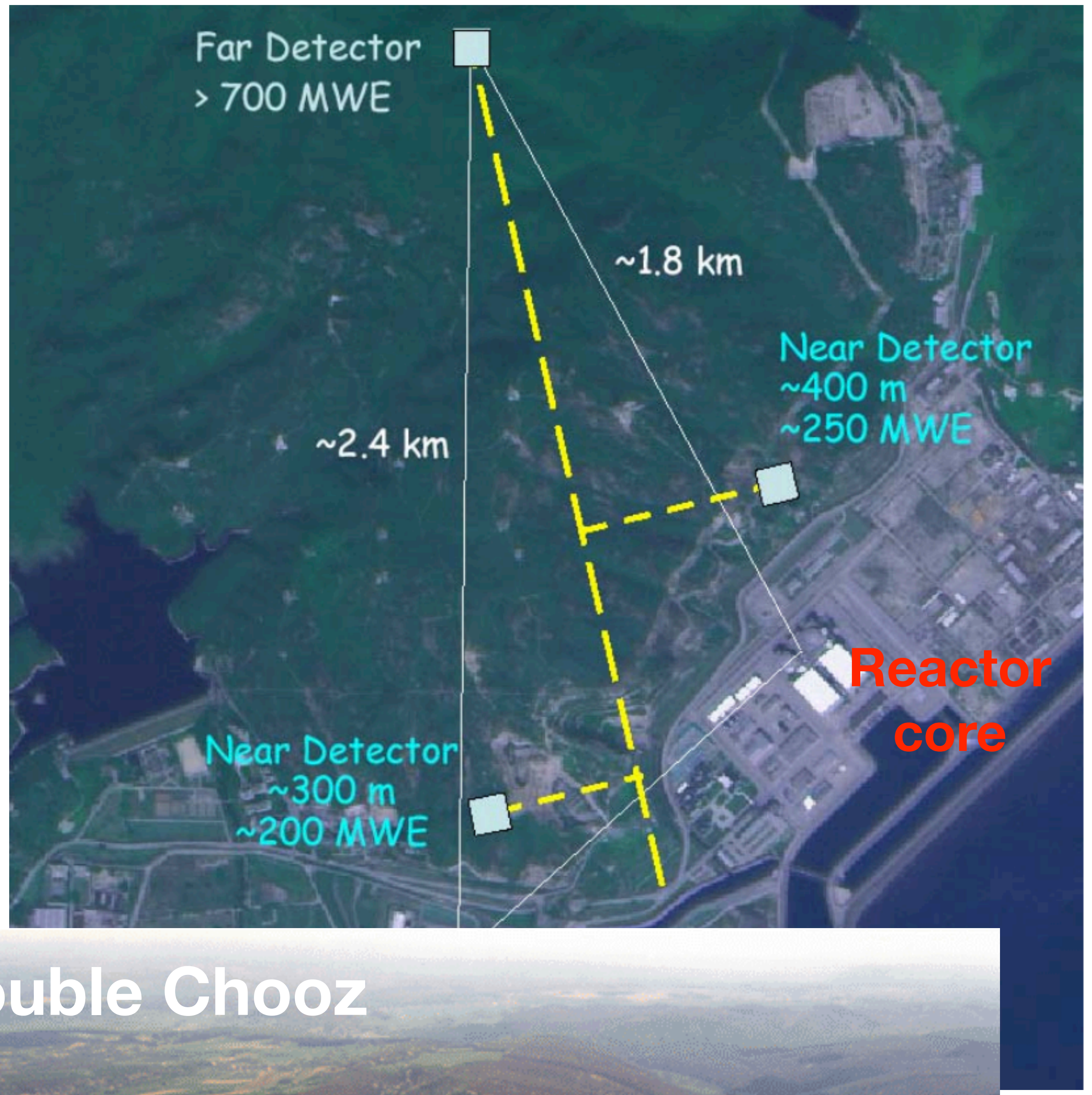
Ghosts of Christmas Past: Reactor Neutrinos

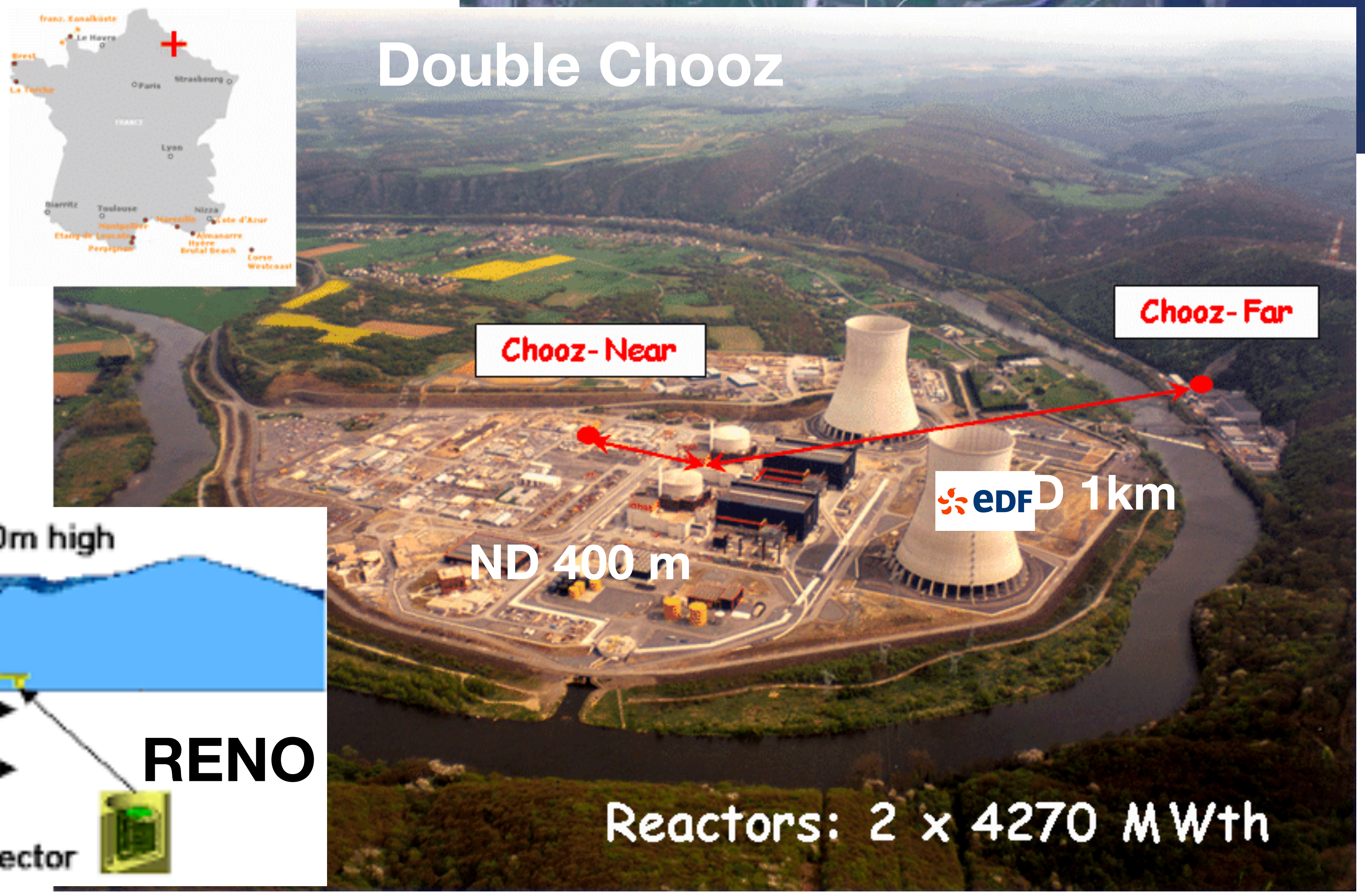
- Reactors produce MeV scale $\overline{\nu}_e$
- Detectors km baseline using IBD to detect neutrinos: $\overline{\nu}_e + p \longrightarrow e^+ + n$

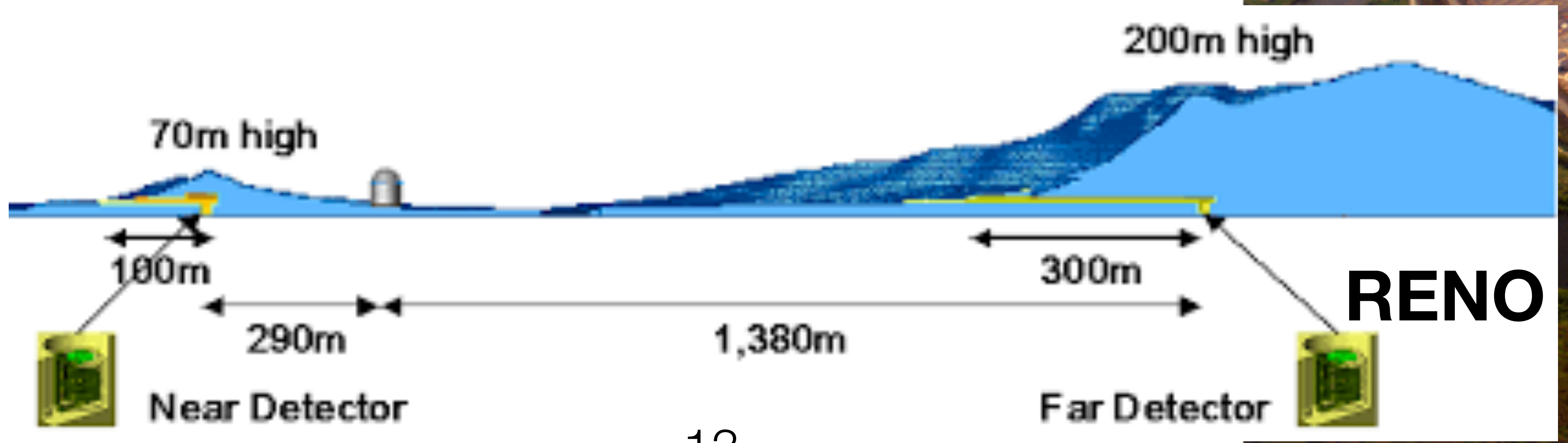
$$P\left(\overline{\nu}_e \to \overline{\nu}_e\right) = 1 - \sin^2\left(2\theta_{13}\right)\sin^2\frac{\Delta m^2_{31} L}{4E}$$

- 2012 big year for particle physics precision measurement on $\theta_{13} \approx 8^\circ$ by reactor experiments

Daya Bay



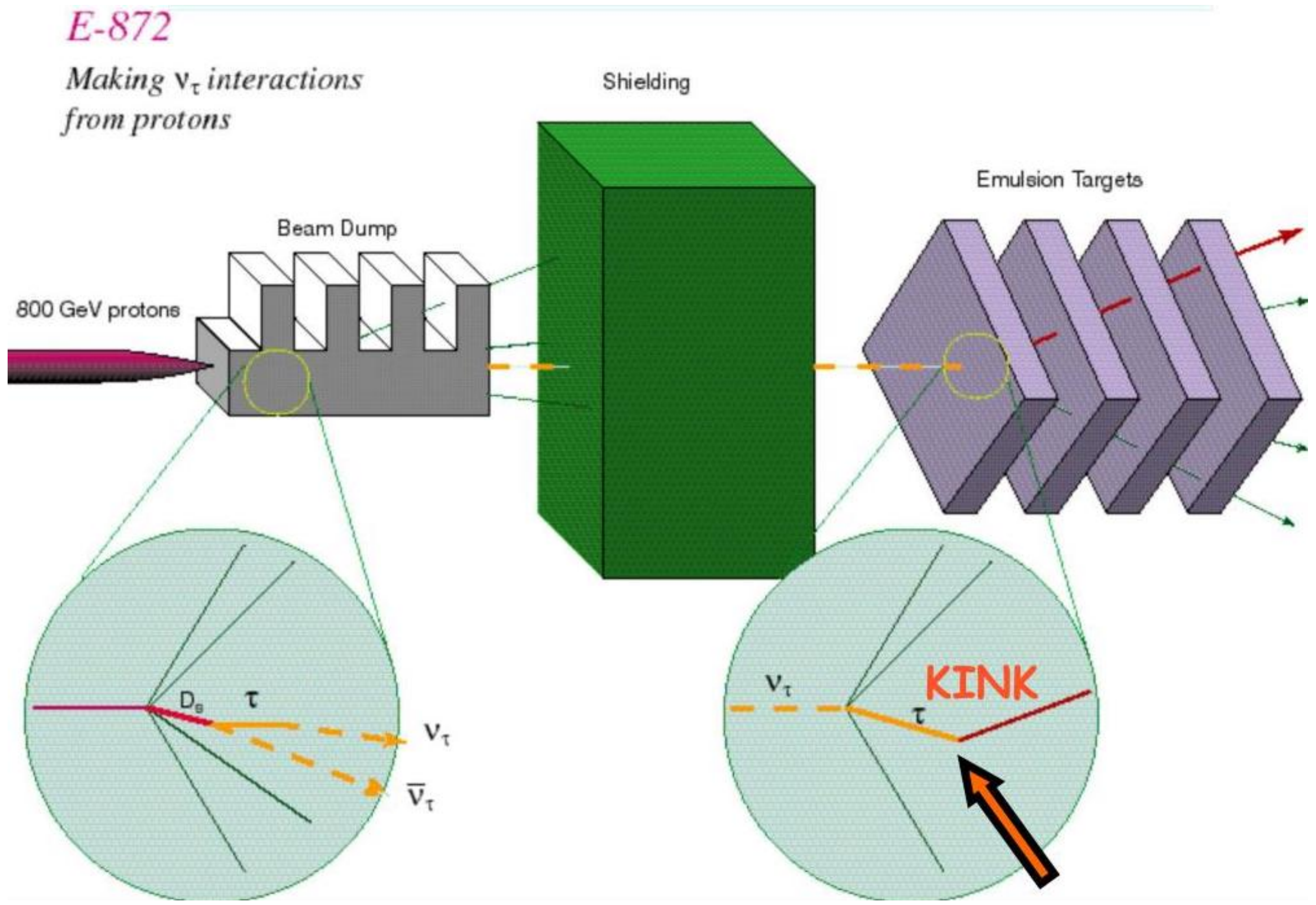




Ghosts of Christmas Past: Tau Neutrinos

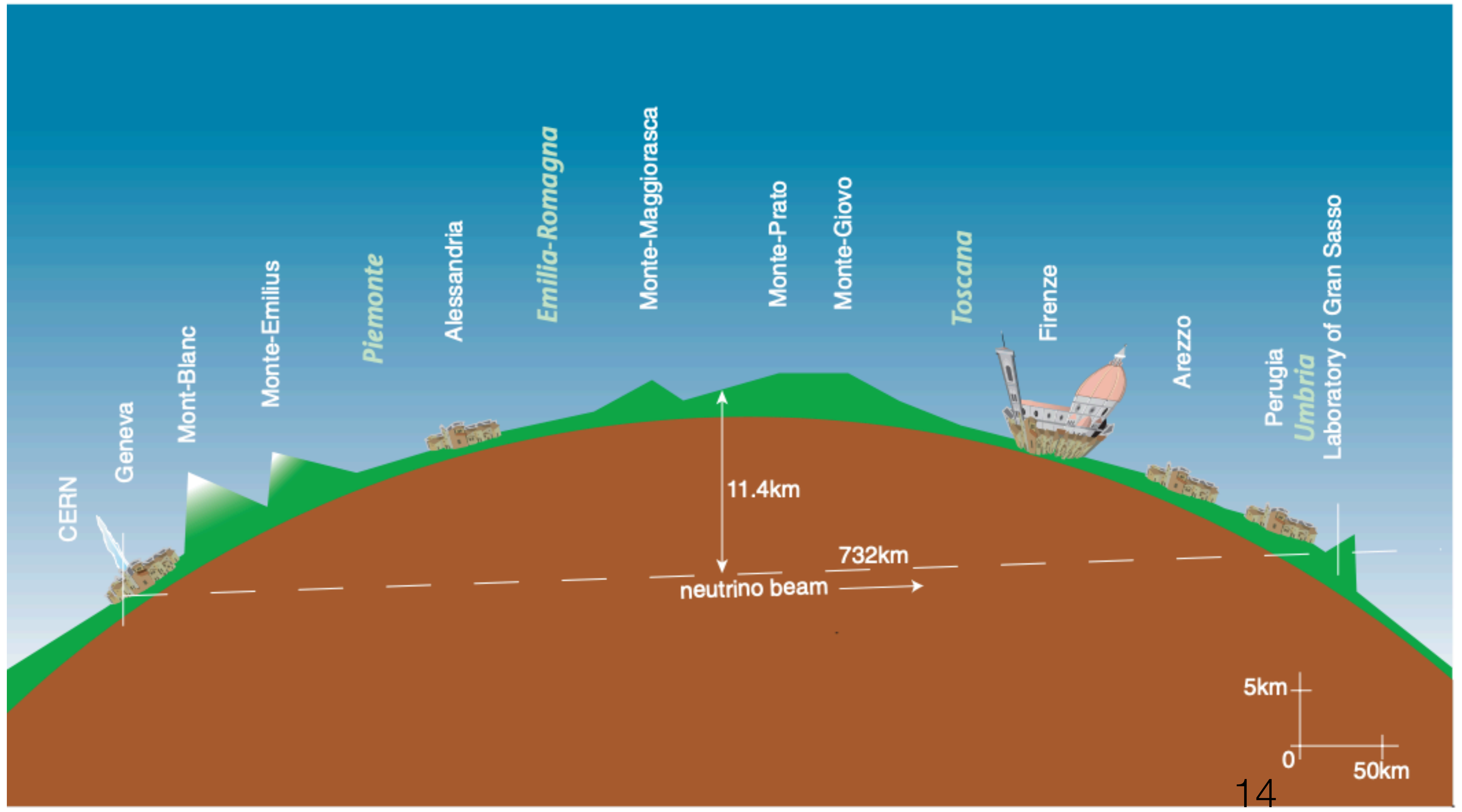
- Only 14 ν_τ have ever been observed: 4 by DONUT, direct observation (1997-2000)

- 10 ν_τ observed by OPERA (2010-2012): ν_μ beam oscillates to ν_τ

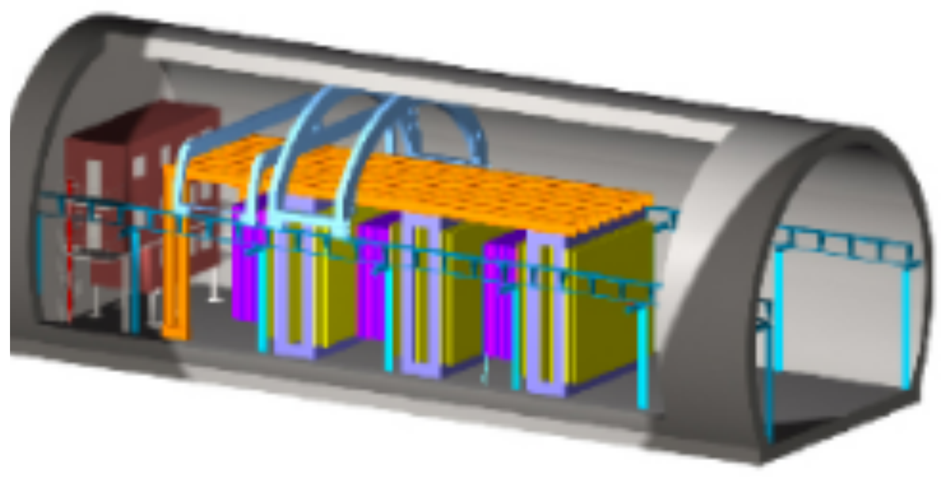


Both DONUT And OPERA could Observe mm-scale Tau kink

ν_μ →

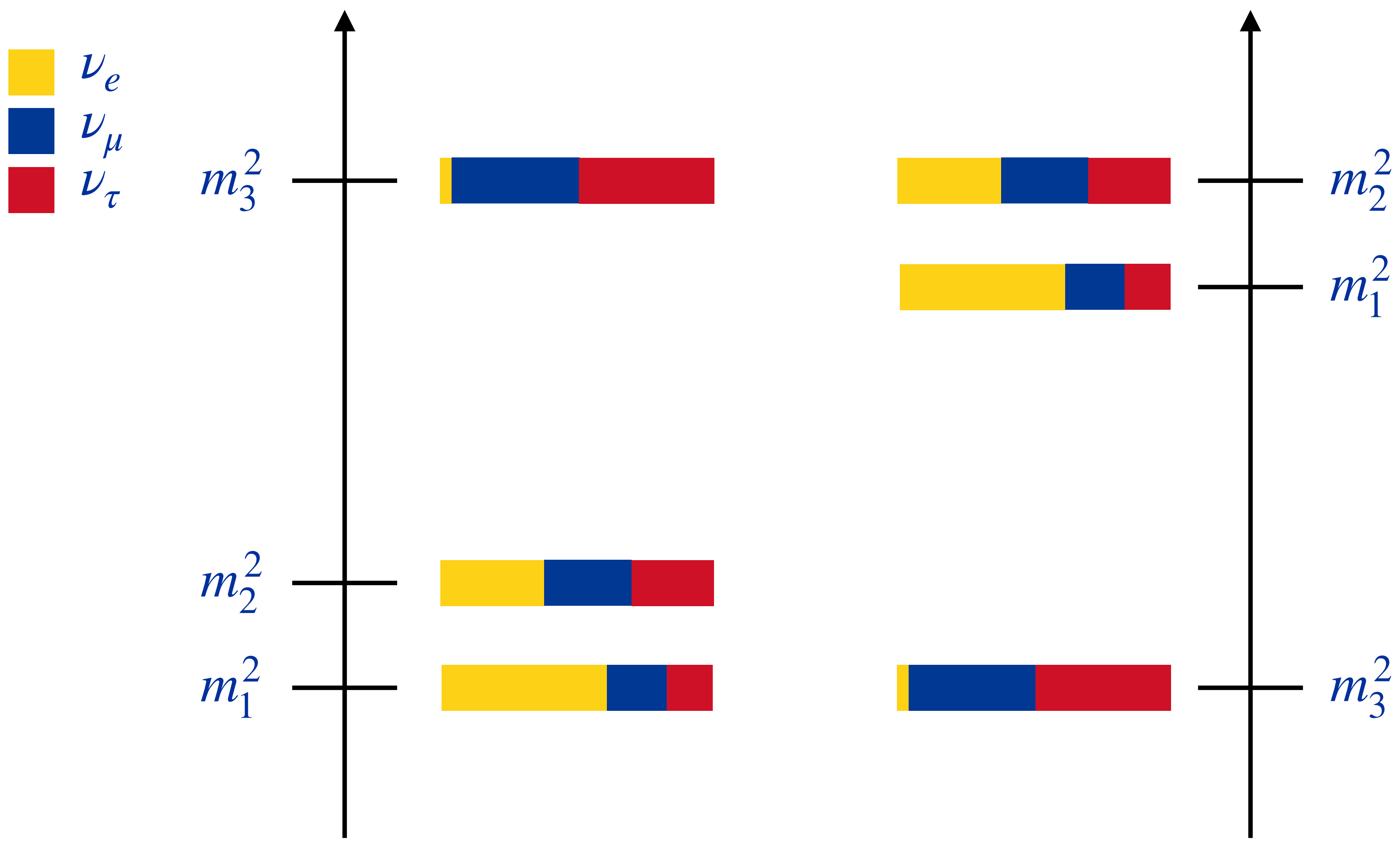


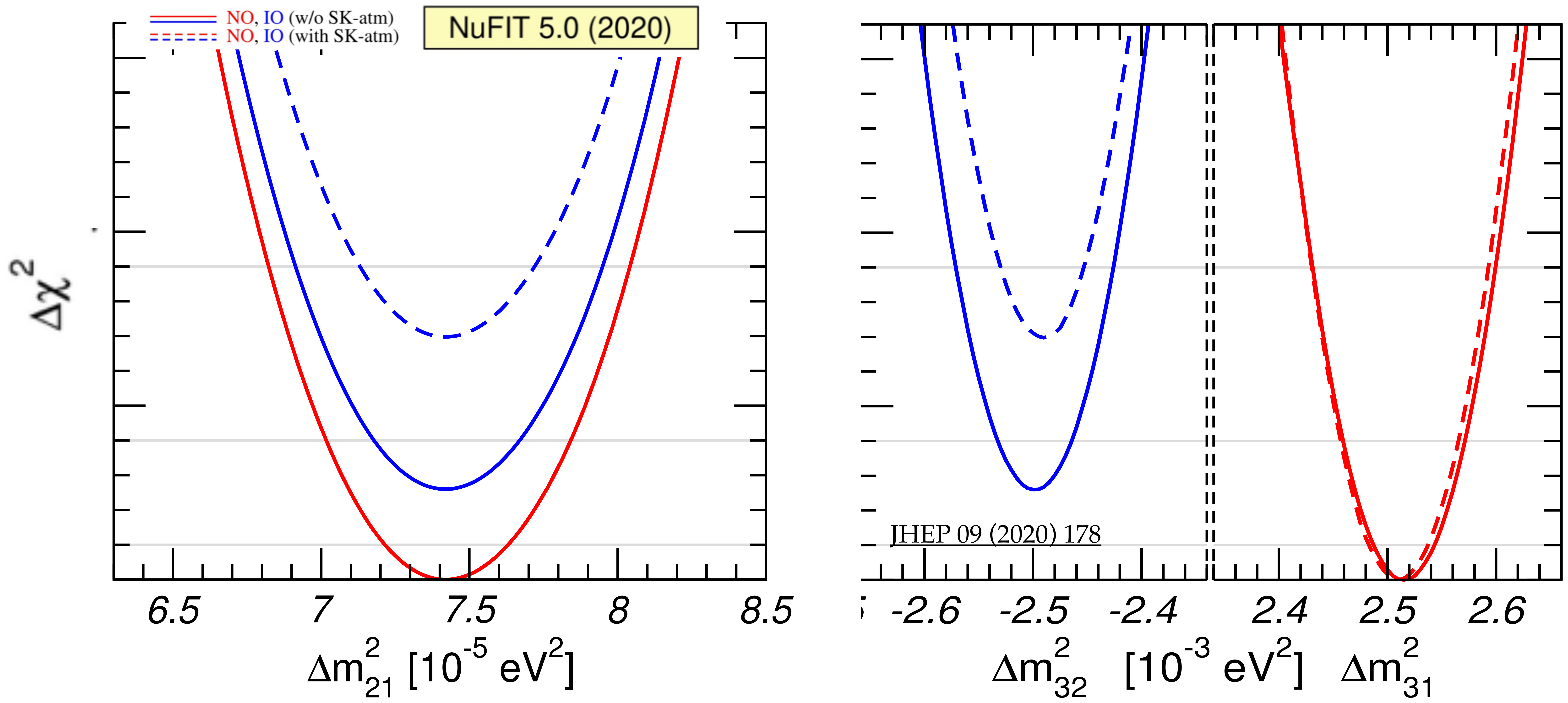
OPERA detector emulsion cloud chamber



Neutrinos: Ghosts of Christmas Present

Ghost of Christmas Present: Current Global Picture





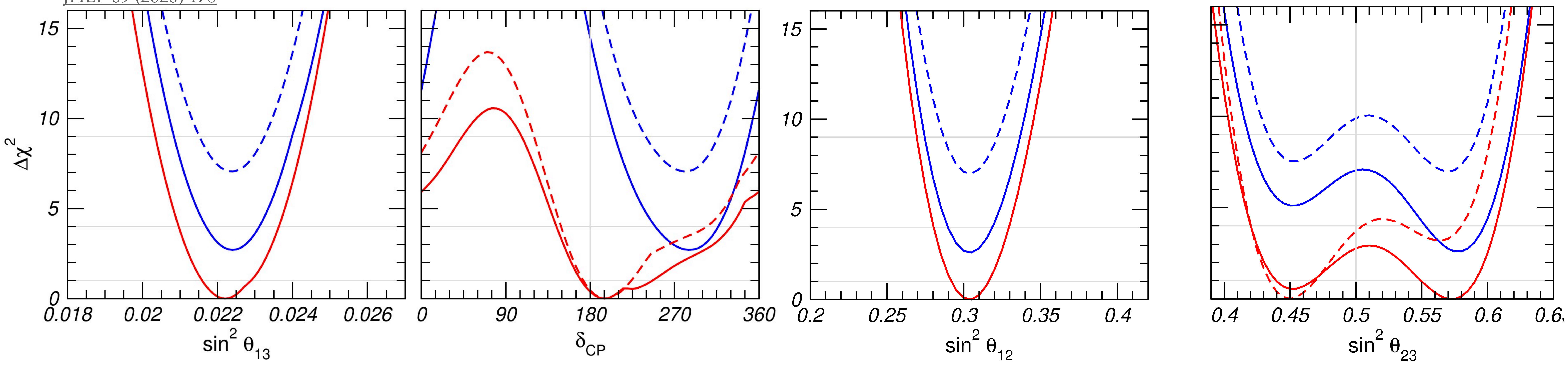
Many neutrino experiments, here $\Delta\chi^2$ from NuFIT collaboration but there are also Valencia (2006.11237) and Bari (2003.08511) groups

Ghost of Christmas Present: Current Global Picture

Atmospheric · **Reactor** · **Solar**

$$\begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \cdot \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta_{\mathrm{CP}}} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta_{\mathrm{CP}}} & 0 & c_{13} \end{pmatrix} \cdot \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \cdot \underbrace{\begin{pmatrix} e^{i\eta_1} & 0 & 0 \\ 0 & e^{i\eta_2} & 0 \\ 0 & 1 & \end{pmatrix}}_{?}$$

JHEP 09 (2020) 178



$\theta_{13,\mathrm{bf}} = 8.57^\circ$ $\quad\delta_{\mathrm{CP,bf}} = 194^\circ$ $\quad\theta_{12,\mathrm{bf}} = 33.44^\circ$ $\quad\theta_{23,\mathrm{bf}} = 49.2^\circ$

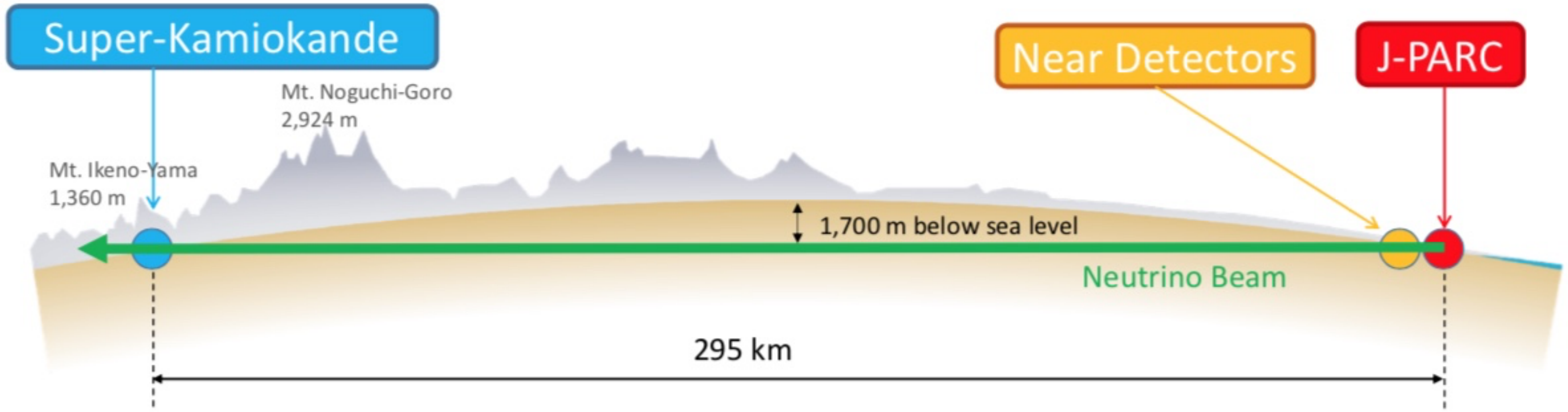
Little direct observation of tau neutrino contributes significantly to poor knowledge of mixing angles and if mixing is unitary.

CP-violating phase & mass ordering

NOvA and T2K are **long baseline, accelerator oscillation** experiment measure δ_{CP} and the mass ordering.

14kton liquid scintillator detector

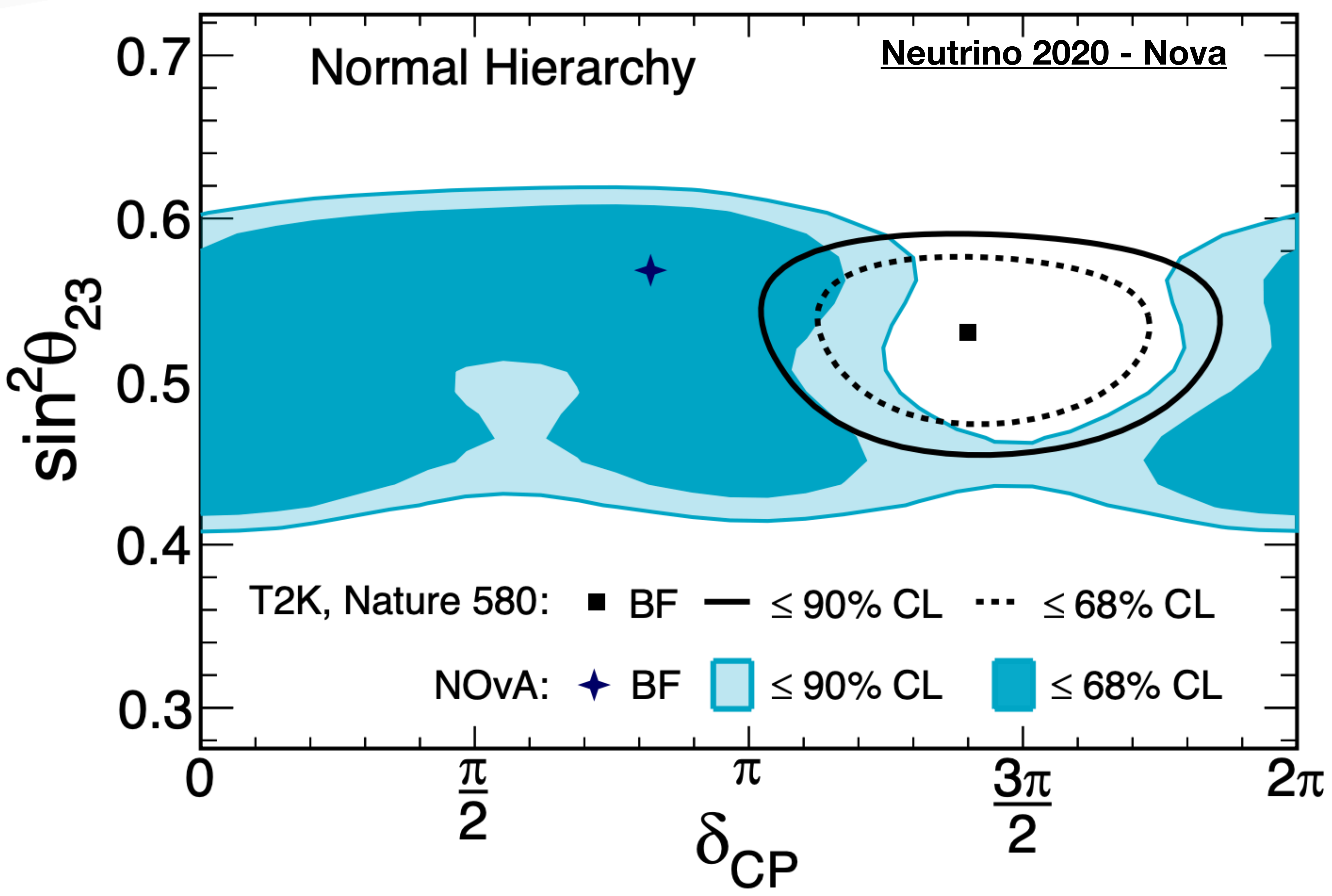
50kton water Cherenkov detector



$$P\left(\nu_\mu \rightarrow \nu_e\right) - P\left(\overline{\nu_\mu} \rightarrow \overline{\nu_e}\right) \propto \delta_{CP}$$

CP-violating phase & mass ordering

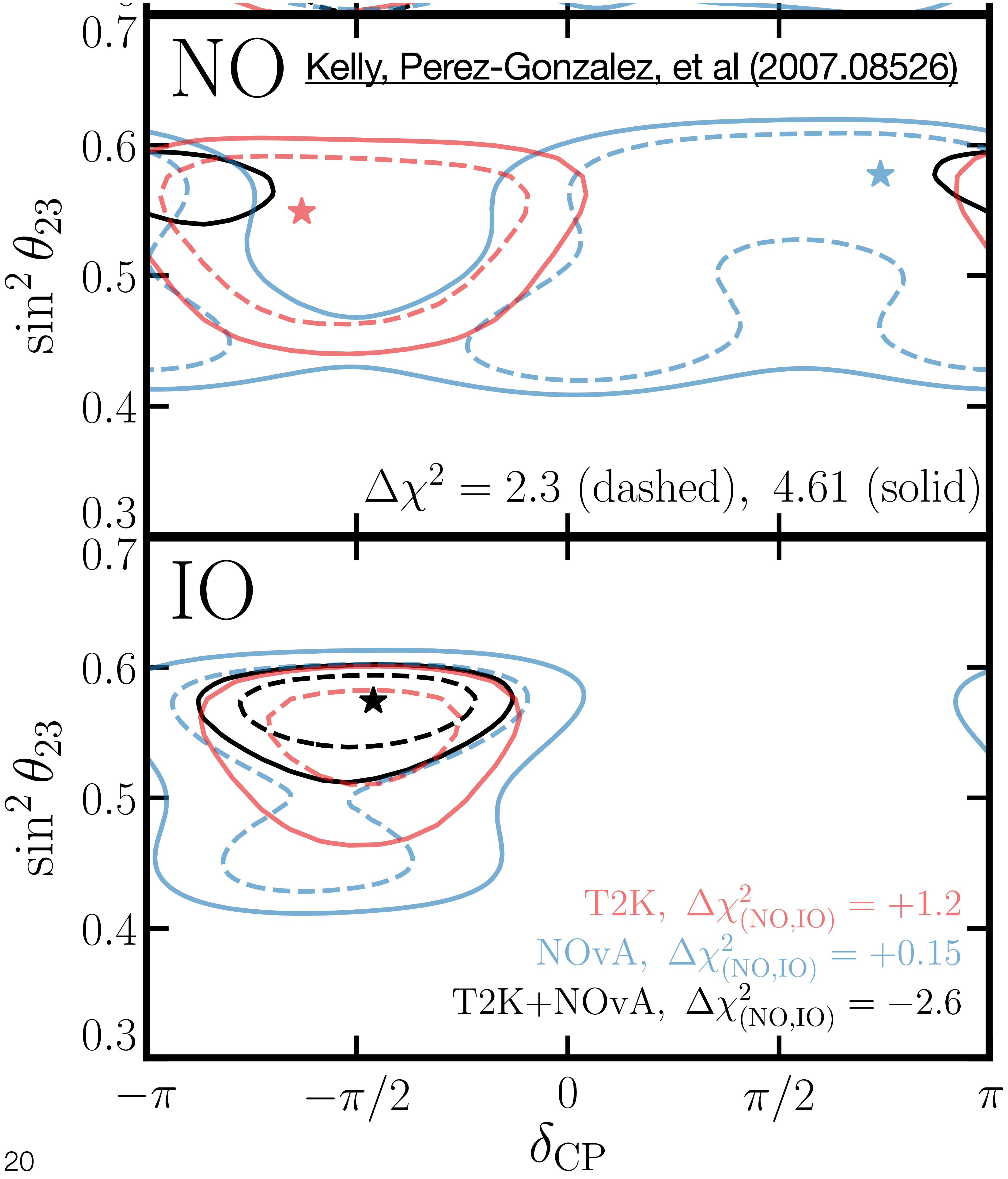
NOvA and T2K are **long baseline, accelerator oscillation** experiment measure δ_{CP} and the mass ordering.



Both experiments **favour normal ordering** with T2K favouring maximal CP violation and NOvA showing preference for near CP conservation

CP-violating phase & mass ordering

- Recent combination of T2K and NOvA data $\Longrightarrow$ inverted ordering preferred
- Preference NO comes from degeneracies between MO, octant, and δ_{CP}
- Not first disagreement between T2K and NOvA (octants differed at more than 3σ circa 2016).



Ghost of Christmas Present: Current Global Picture

Atmospheric **Reactor** **Solar**

$$\begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \cdot \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta_{\text{CP}}} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta_{\text{CP}}} & 0 & c_{13} \end{pmatrix} \cdot \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \cdot \underbrace{\begin{pmatrix} e^{i\eta_1} & 0 & 0 \\ 0 & e^{i\eta_2} & 0 \\ 0 & 1 & \end{pmatrix}}_{?}$$

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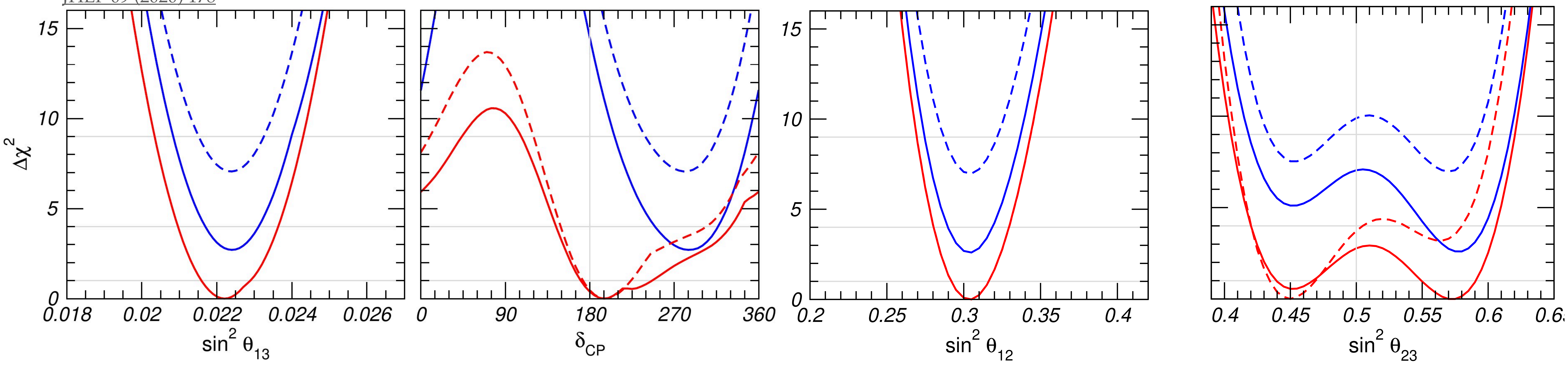


$\theta_{13,\text{bf}} = 8.57^\circ$ $\delta_{\text{CP},\text{bf}} = 194^\circ$ $\theta_{12,\text{bf}} = 33.44^\circ$ $\theta_{23,\text{bf}} = 49.2^\circ$

η_1, η_2 Majorana phases which are observable if neutrinos are their own antiparticle. Possible given neutrinos are electrically neutral.

Nature of Neutrinos

- Charged particles can be distinguished from their antiparticle.
- Neutrinos electrically neutral $\Longrightarrow$ Majorana ($\nu = C\overline{\nu}^T$) or Dirac.

Dirac Neutrinos

- Add right-handed neutrinos
- Assume that lepton number conserved
- Higgs mechanism provides mass to neutrinos

$$\mathcal{L}_\nu \supset Y_{\alpha i} L^\alpha H N^i \qquad Y \sim 10^{-12}$$

Justify small Yukawas. . . .

Nature of Neutrinos

Yukawa coupling forbidden at tree-level as RHN is charged under a new (gauge/global) symmetry spontaneously broken

$$\lambda_{\alpha i} L^\alpha H N^i \to \frac{\kappa_{\alpha i}}{\Lambda} \left(L^\alpha H\right)\left(N^i \Phi\right)$$

Φ spontaneously breaks the new symmetry at $v_\Phi \implies \lambda = \dfrac{\kappa v_\Phi}{\Lambda}$ De Gouvea & Hernandez (1507.00916)

Gauged chiral symmetry for RHNS $\implies$ no Majorana masses allowed

Heavy messenger sector including dark matter and Z'

Can also add new Higgs doublet (very small vev) that only couples to neutrinos

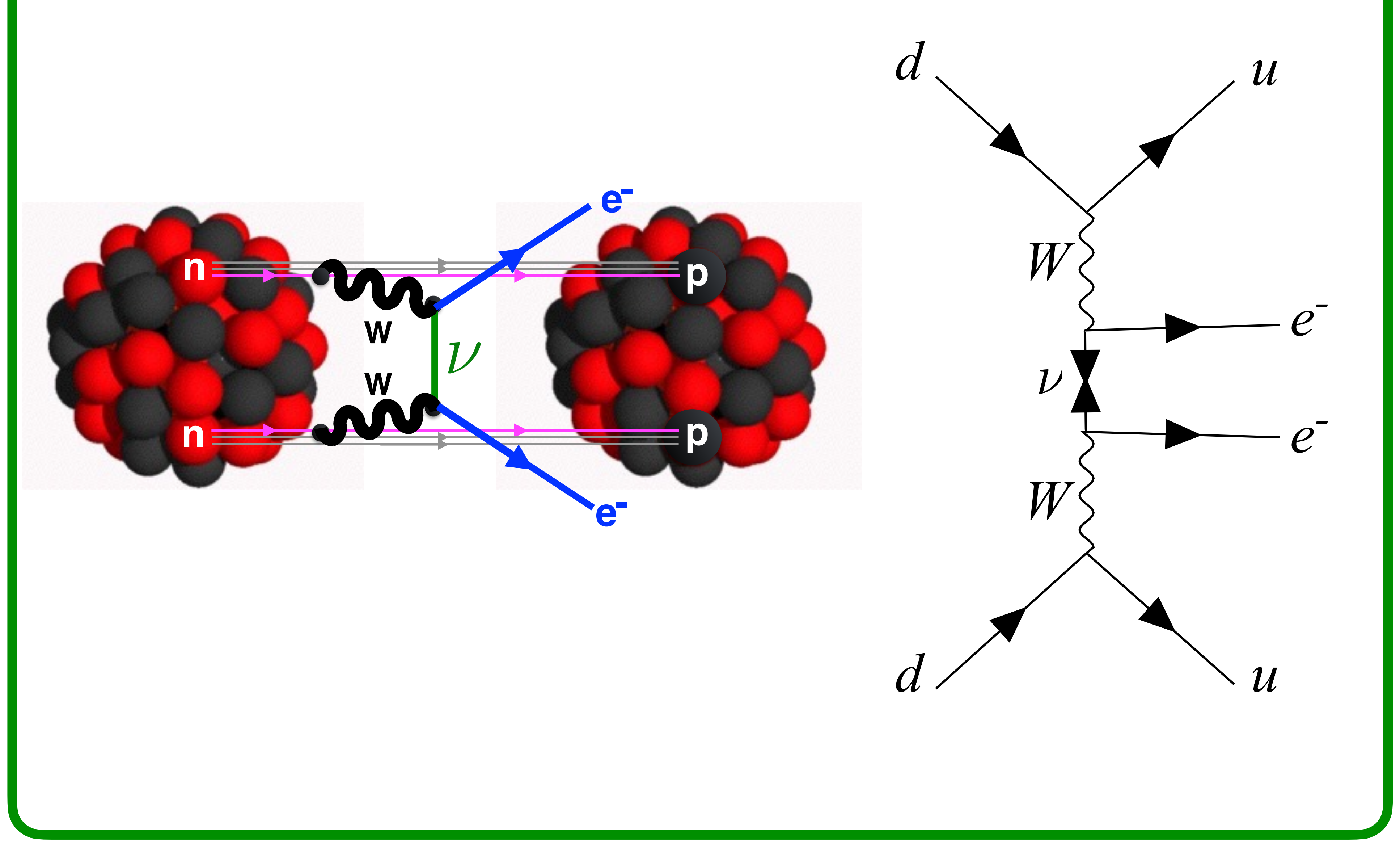
Davidson & Logan (0906.3335)

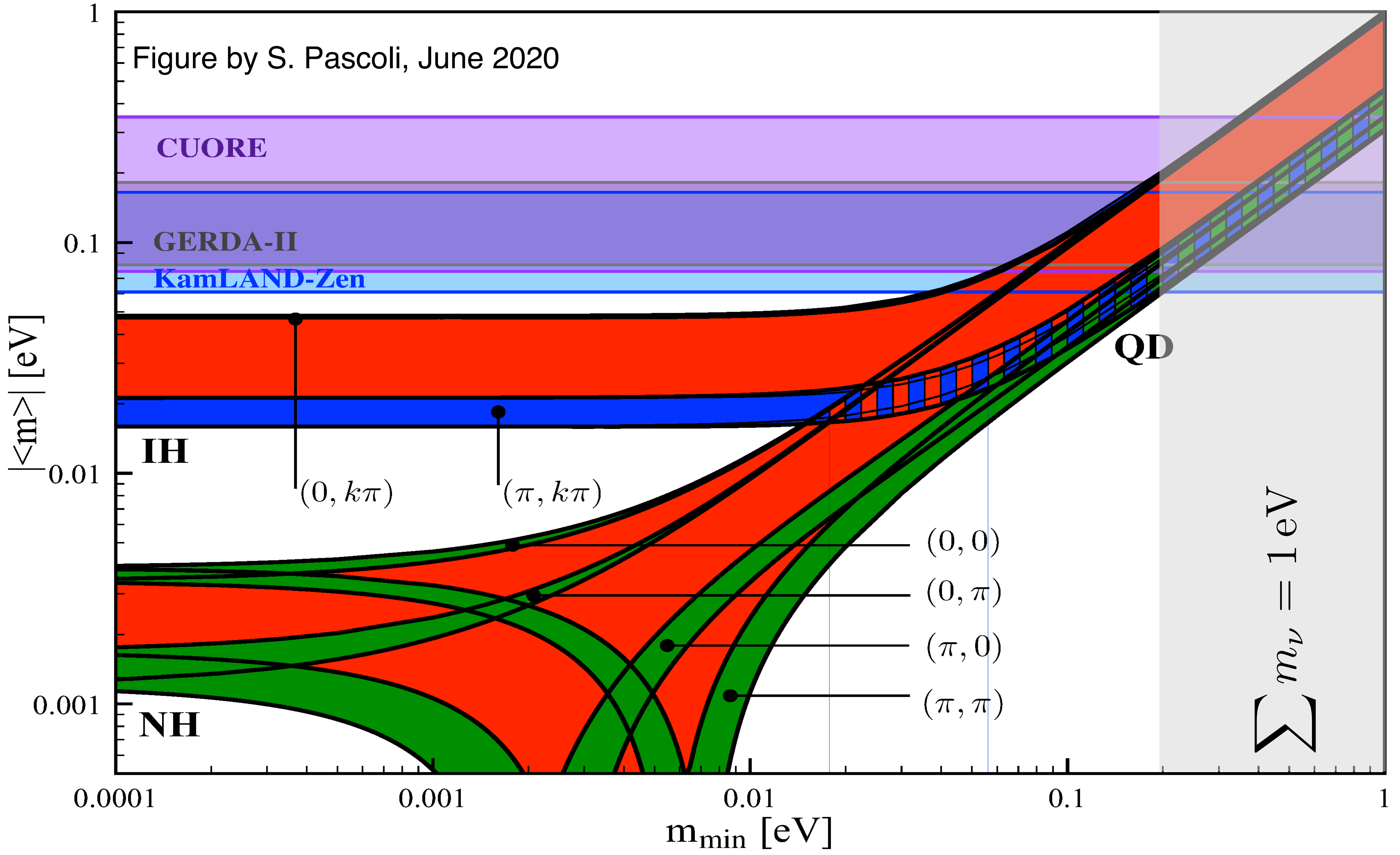
Machado, Perez-Gonzalez et al(1507.07550)

Lepton Number Violation

- If neutrinos are Majorana $\Longrightarrow$ lepton number not conserved.

$$(A, Z) \to (A, Z+2) + 2e^-$$





$$|<m>| = \left| m_1 \sin^2\theta_{12} + m_2 \cos^2\theta_{12} e^{i\alpha_{21}} + m_3 \sin^2\theta_{13} e^{i\alpha_{31}} \right|$$

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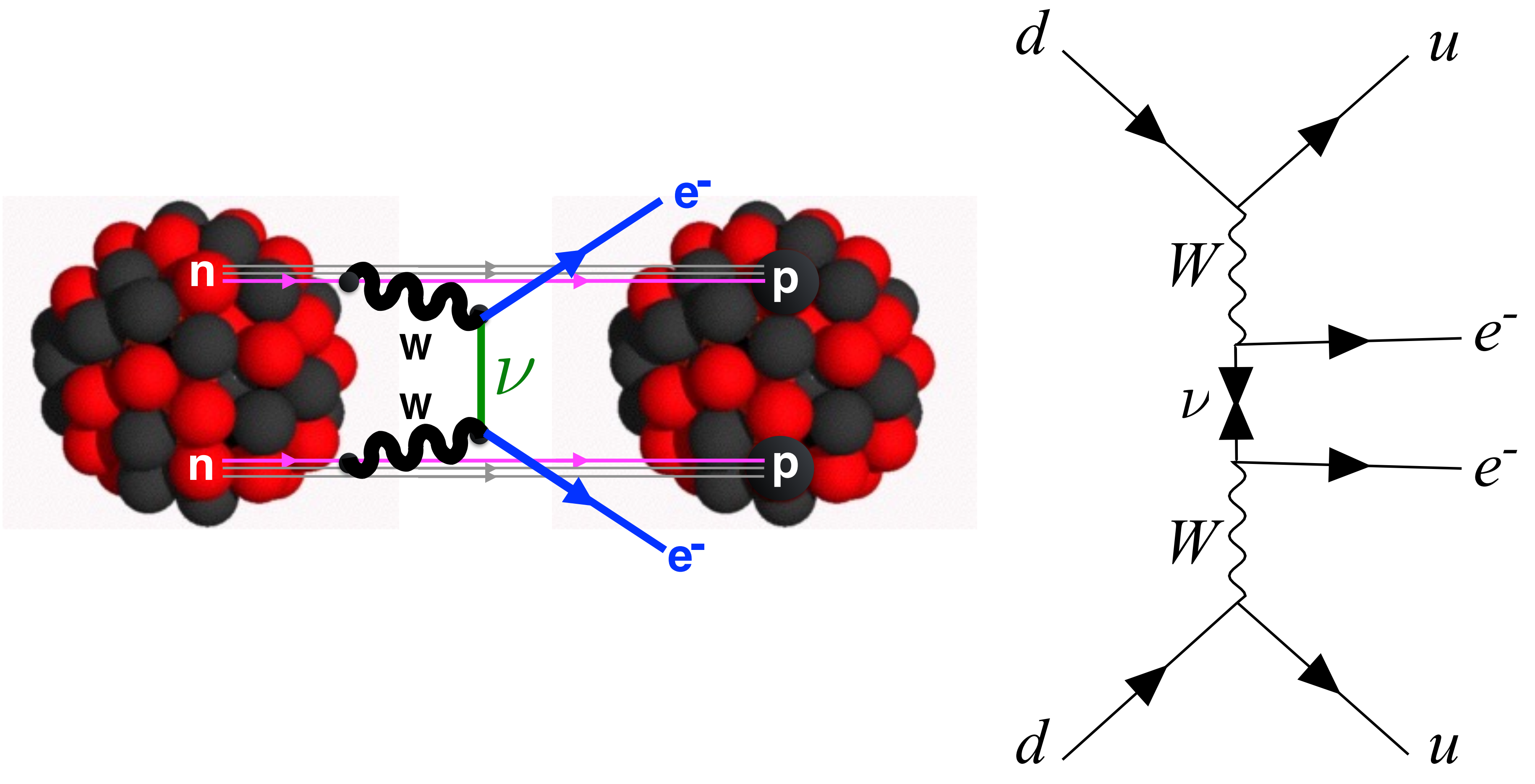

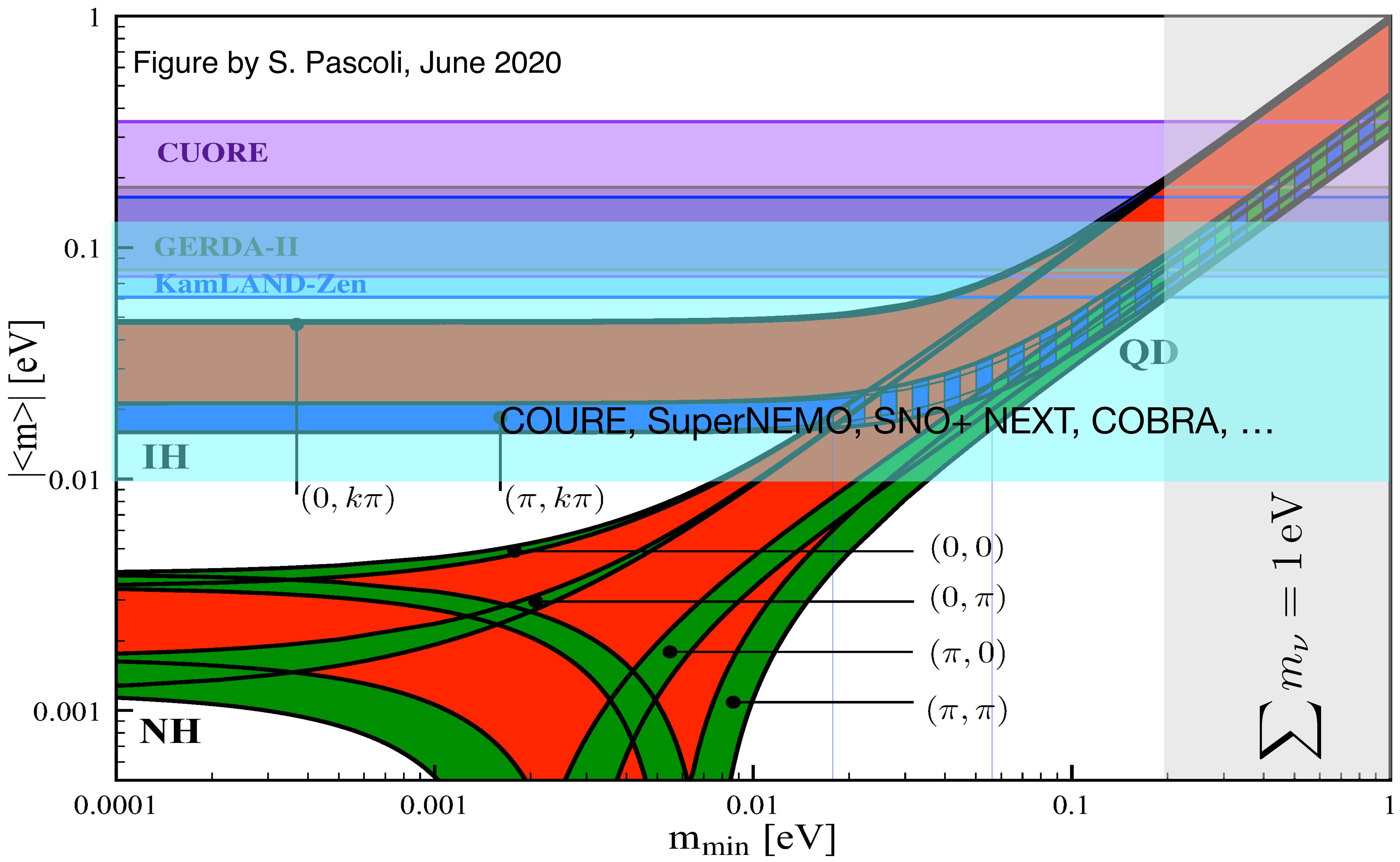

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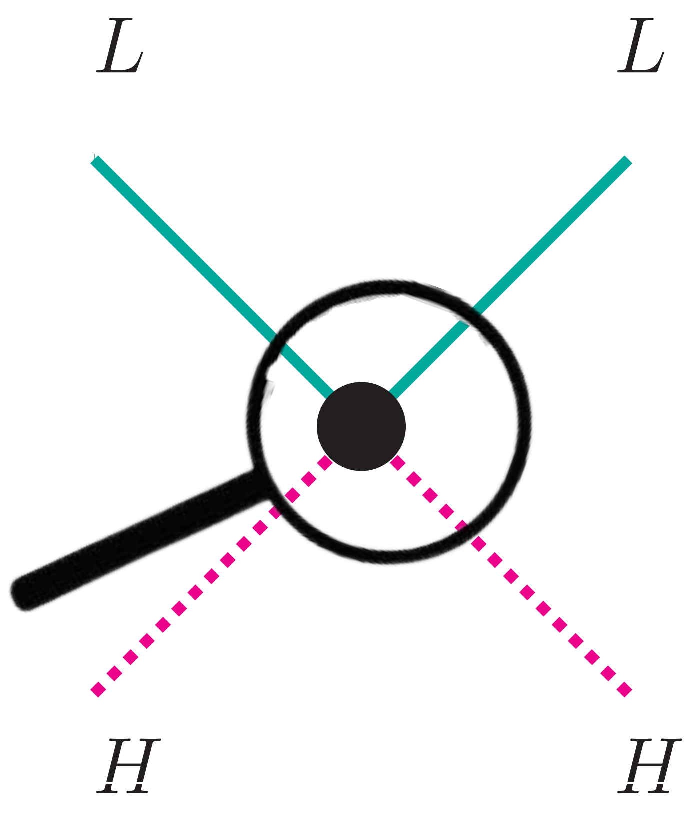
Majorana Neutrinos

Treat SM as an effective field theory

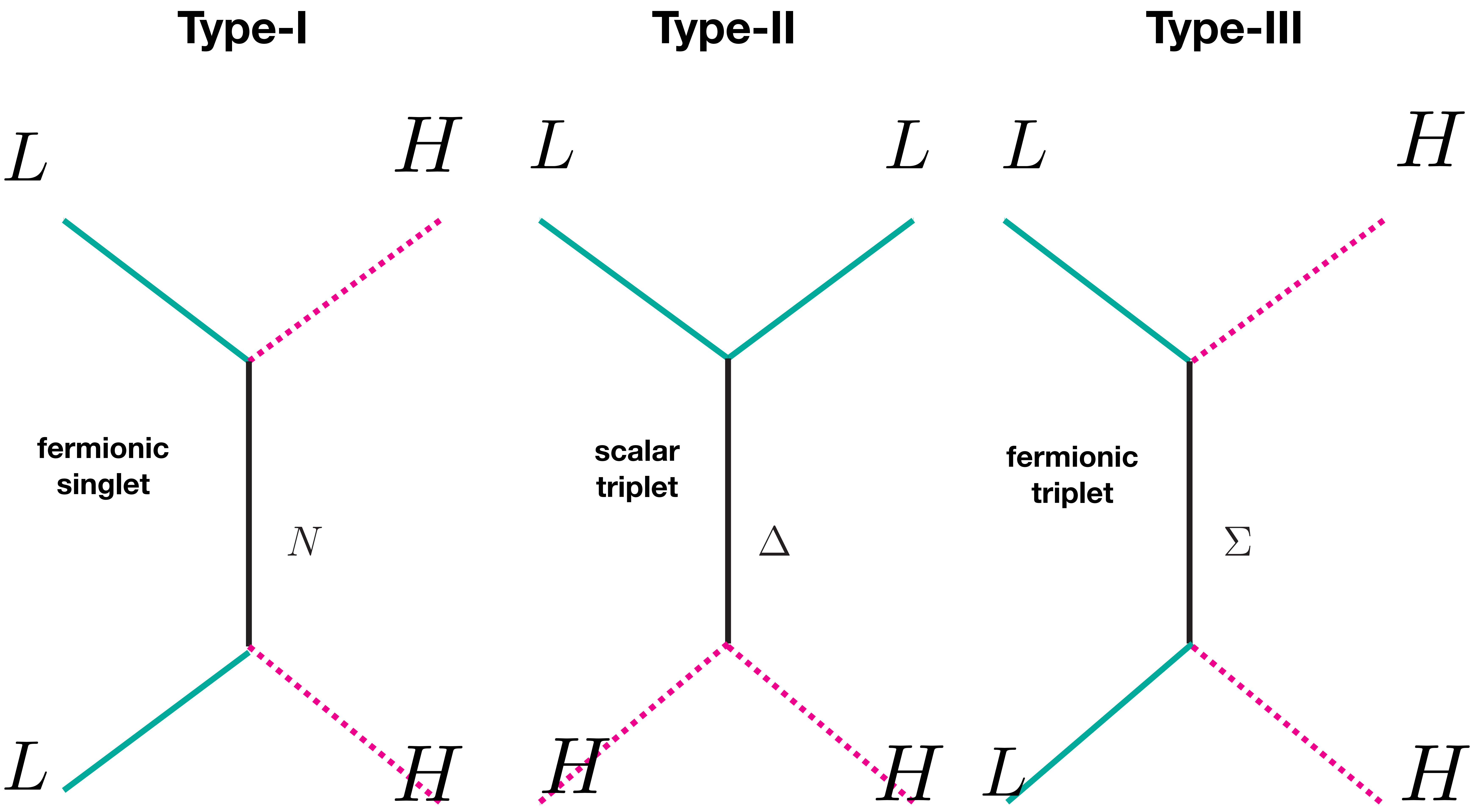


$$\mathcal{L}_\nu \supset Y_{\alpha\beta} \frac{L^\alpha H L^\beta H}{\Lambda} + \mathcal{O}\left(\frac{1}{\Lambda^2}\right) + \cdots$$

Weinberg

- Dimension-5 operator violated lepton number by two units
- After EWSB: $m_{\alpha\beta} = Y_{\alpha\beta} v^2/\Lambda$

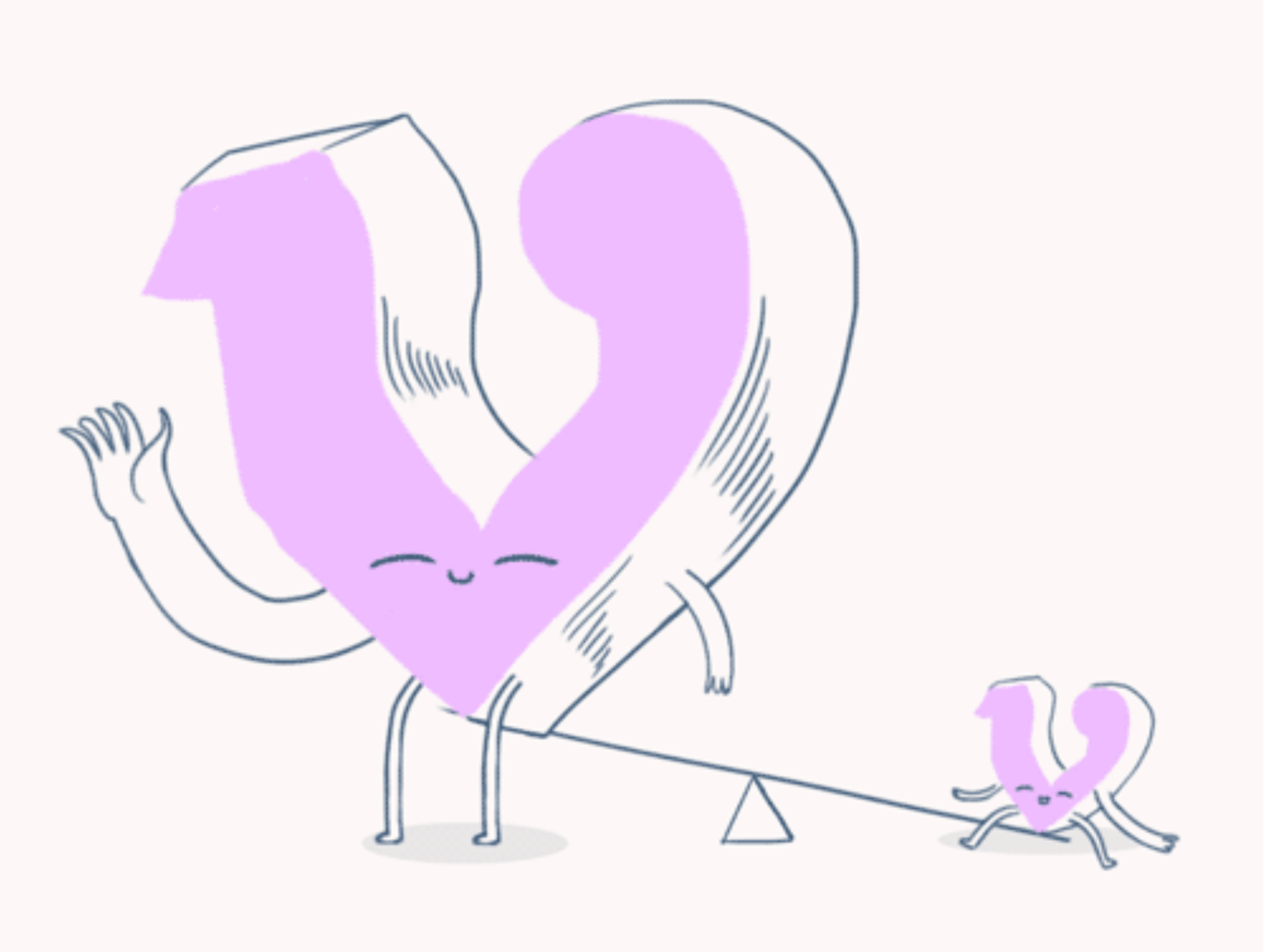
Majorana Neutrinos



- Dimension-5 operator violated lepton number by two units
- After EWSB: $m_\nu = \dfrac{Y^2 v^2}{M}$

Majorana Neutrinos

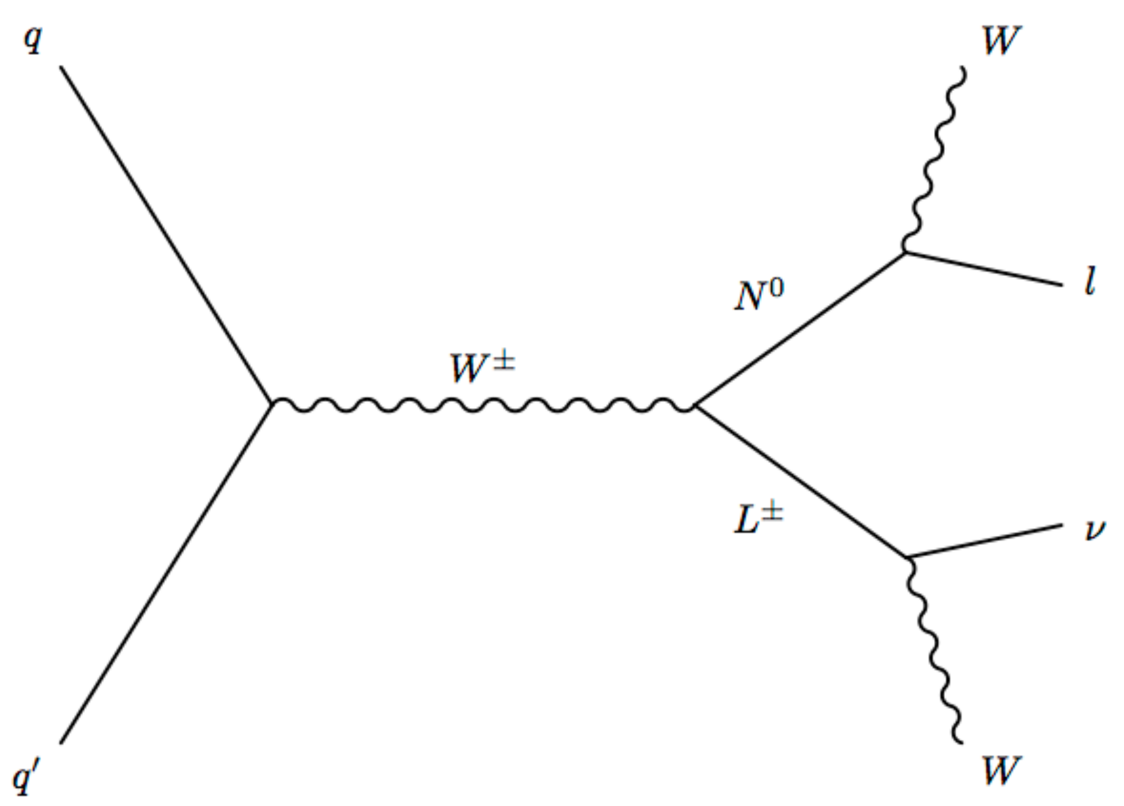
$$m_\nu = \frac{Y^2 v^2}{M} \qquad Y \sim 1 \implies M \sim 10^{14}\,\mathrm{GeV}$$

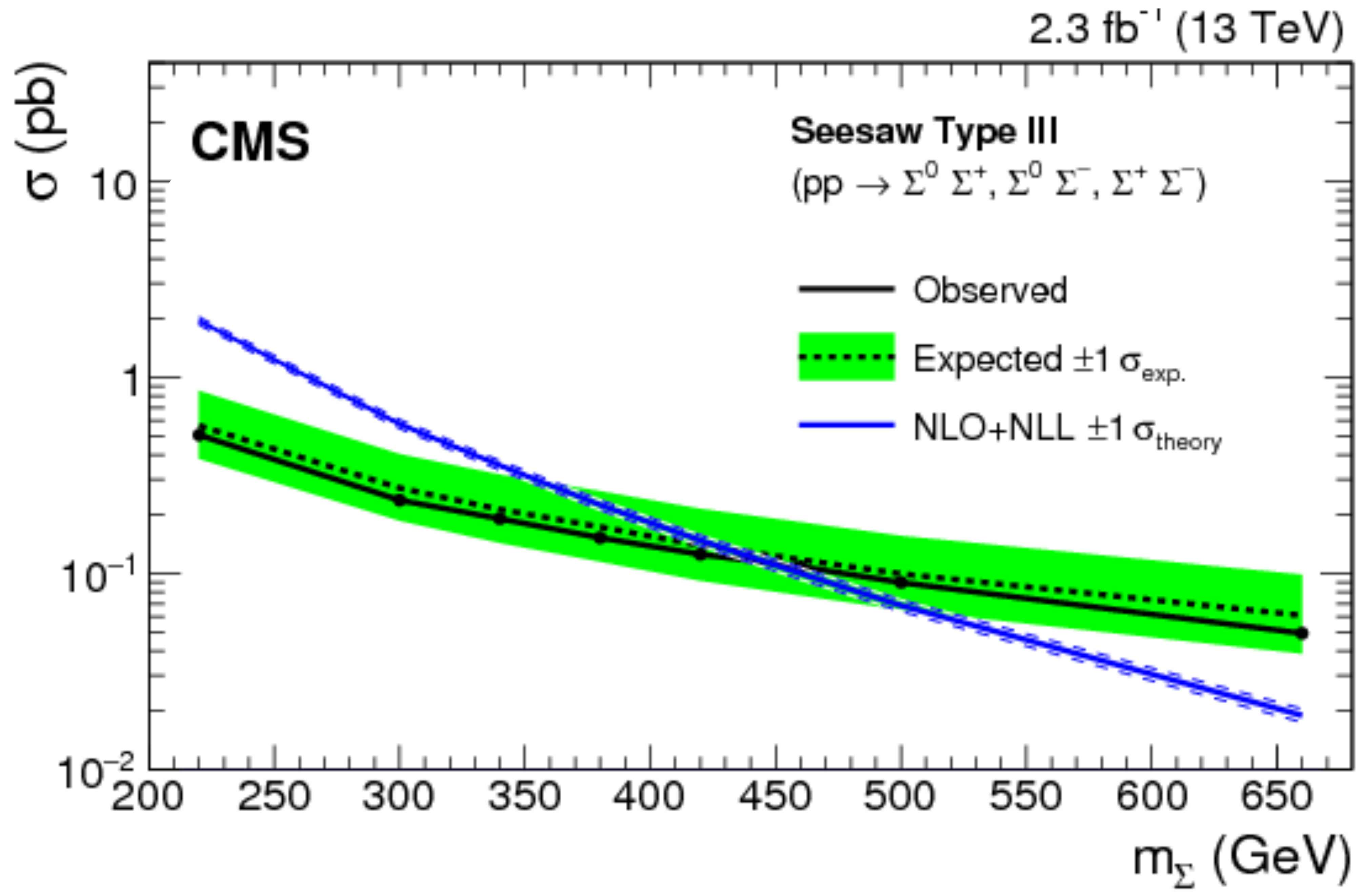


LHC range $\qquad Y \sim 10^{-6} \implies M \sim 100\,\mathrm{GeV}$

Type -II & III easier to test as because new states EW charged

Fermionic triplet - Type III





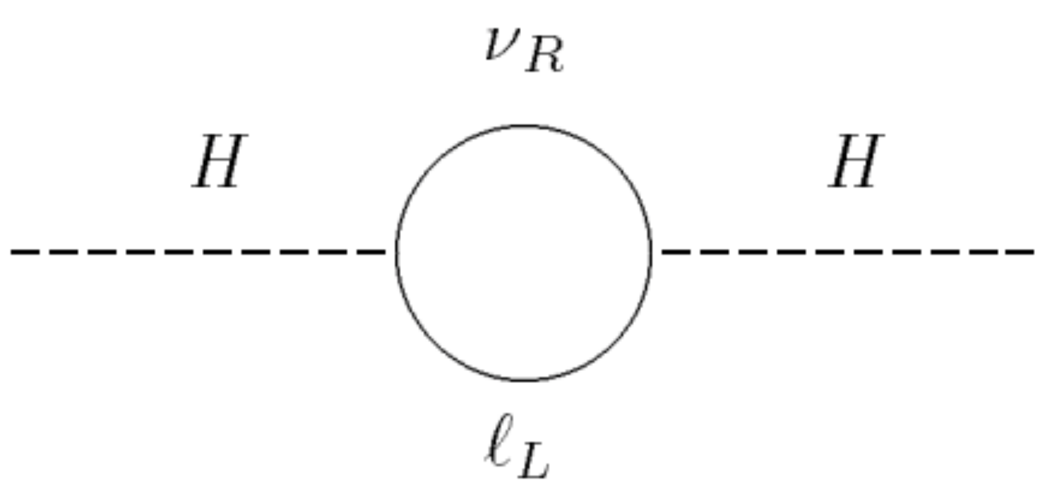
Majorana Neutrino Masses: Tree-level

Type-I seesaw

pros	cons
Simple	In most regimes tough to test
Can explain BAU	Exacerbates hierarchy problem
Predicted by GUTs	
Some circumstantial evidence	
Can radiative generate electroweak scale	

Trott & Brivio

Vissani



Mass RHN

high-scale leptogenesis — $\mathcal{O}(10^{12})$ GeV

Fukugida & Yanagida *Phys.Lett. B17 45-47* (1986)

intermediate scale leptogenesis — $\mathcal{O}(10^{6})$ GeV

Racker, Rius & Pena *JCAP 1207 030* (2013)

resonant leptogenesis — $\mathcal{O}(10^{3})$ GeV

Pilaftis & Underwood *Nucl.Phys. B692 303* (2004)

leptogenesis via oscillations — $\mathcal{O}(1)$ GeV

Akhmedov, Rubakov & Smirnov *Phys.Rev.Lett. 81 1359-1362* (1998)

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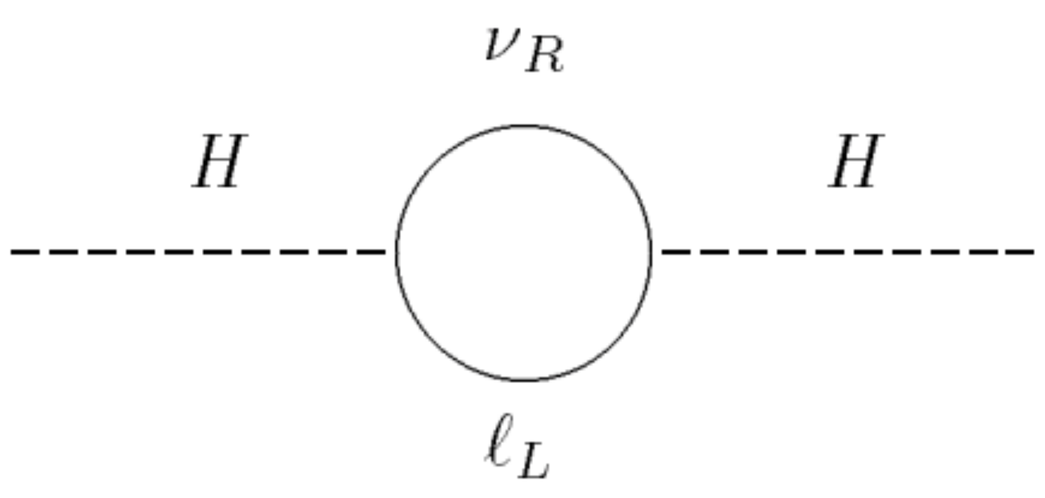
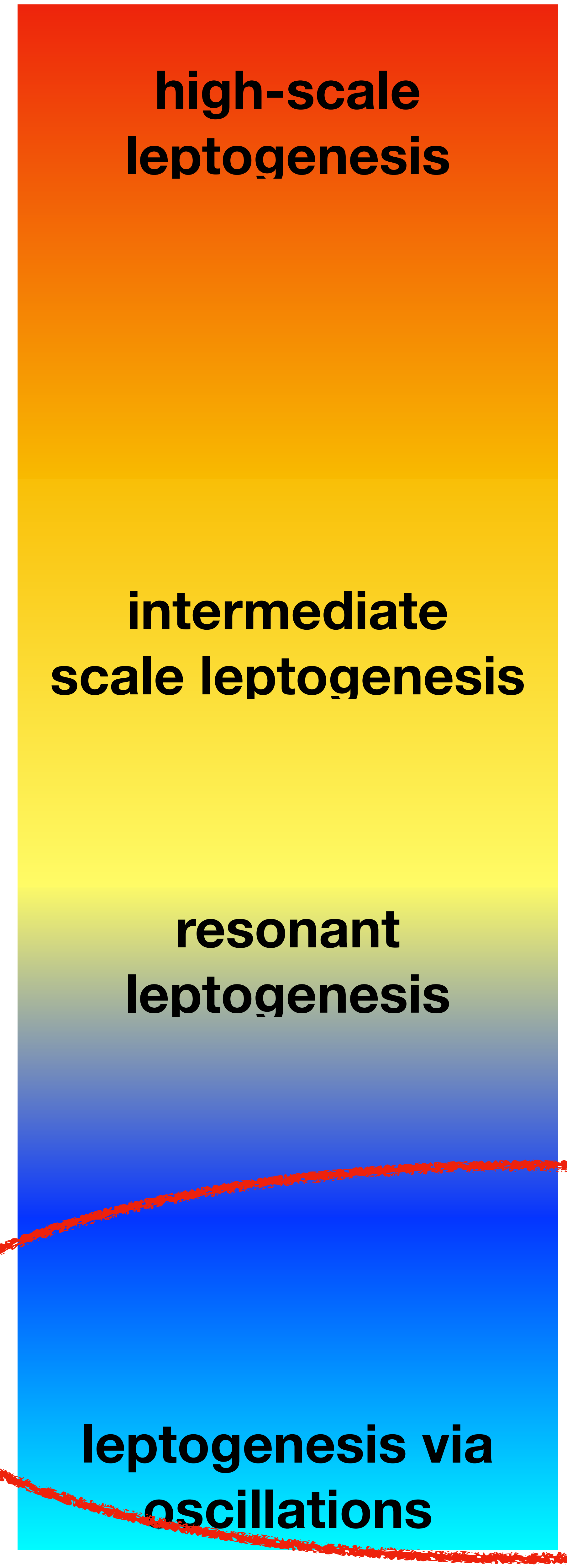


Mass RHN



$\mathcal{O}(10^{12})$ GeV

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$\mathcal{O}(10^{3})$ GeV

Pilaftis & Underwood *Nucl.Phys. B692 303* (2004)

$\mathcal{O}(1)$ GeV

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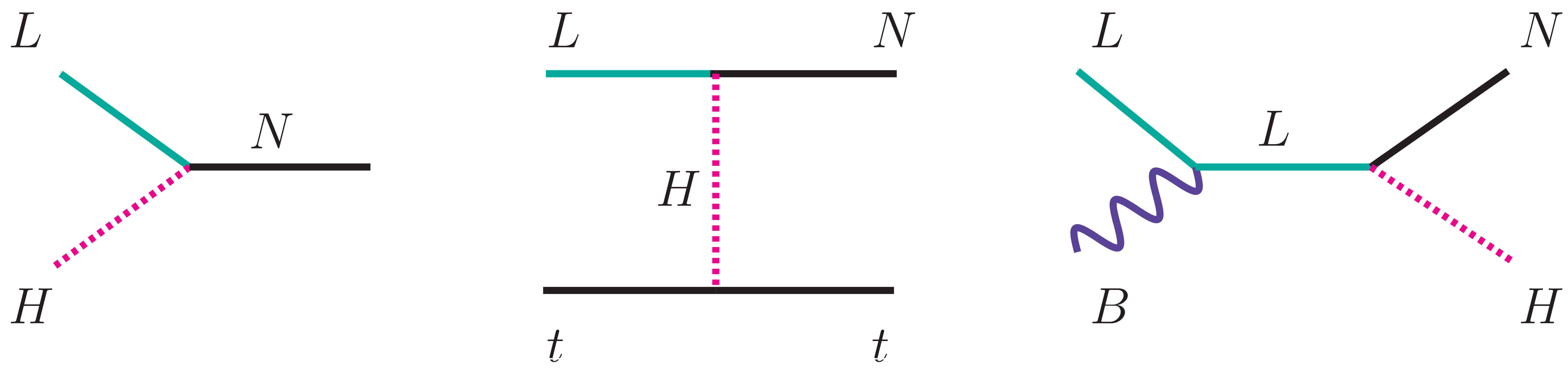
Leptogenesis via oscillations

- highly degenerate RHNs produced via scattering at $T > T_{EW}$



Akhmedov, Rubakov & Smirnov (1998)

- small Yukawa couplings → RHNs may not have equilibrated by the EWPT
- RHNs CP-violating oscillations → source of lepton number and flavour asymmetry.

Leptogenesis via Oscillations with 2 RHNs

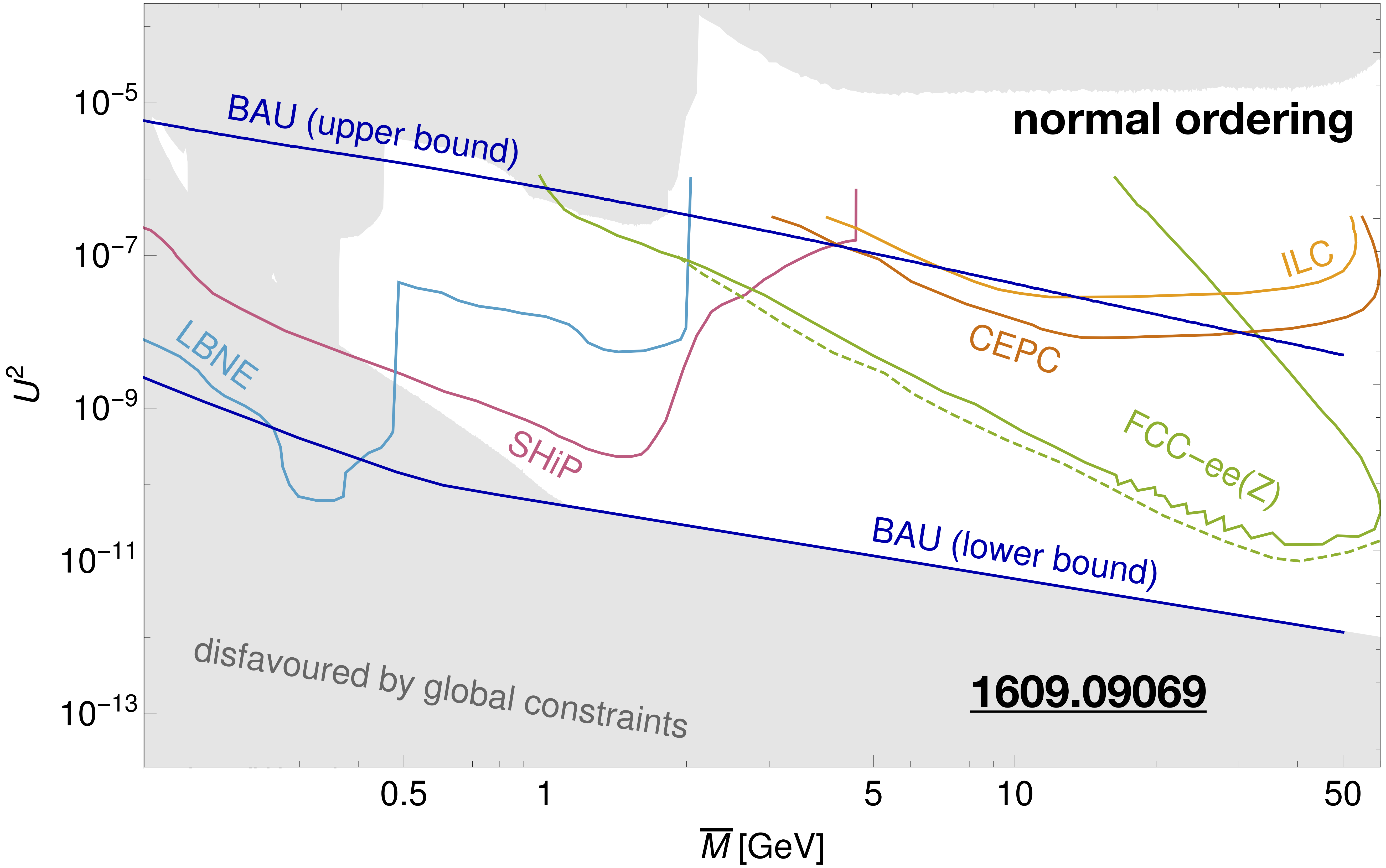
- GeV-scale RHNs → rich phenomenology

$$Y = \frac{1}{v} U \sqrt{m} R^T \sqrt{M}$$

4 masses, 4 angles, 3 phases (2 masses + 3 angles measured)

Casas & Ibarra, *Nucl.Phys. B618 (2001) 171-204*

$$\nu_\alpha = U_{\alpha i}\nu_i + \Theta_{\alpha I} N_I^c \qquad |U|^2 = \sum_{\alpha I} |\Theta_{\alpha I}|^2 \qquad \overline{M} = \frac{M_1 + M_2}{2}$$



Drewes et al (1611.08504)

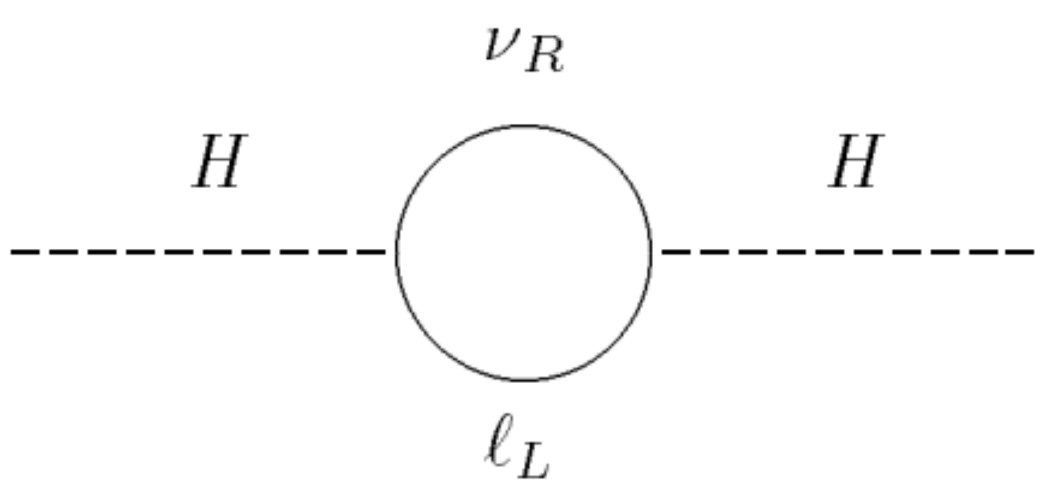
Majorana Neutrino Masses: Tree-level

Type-I seesaw

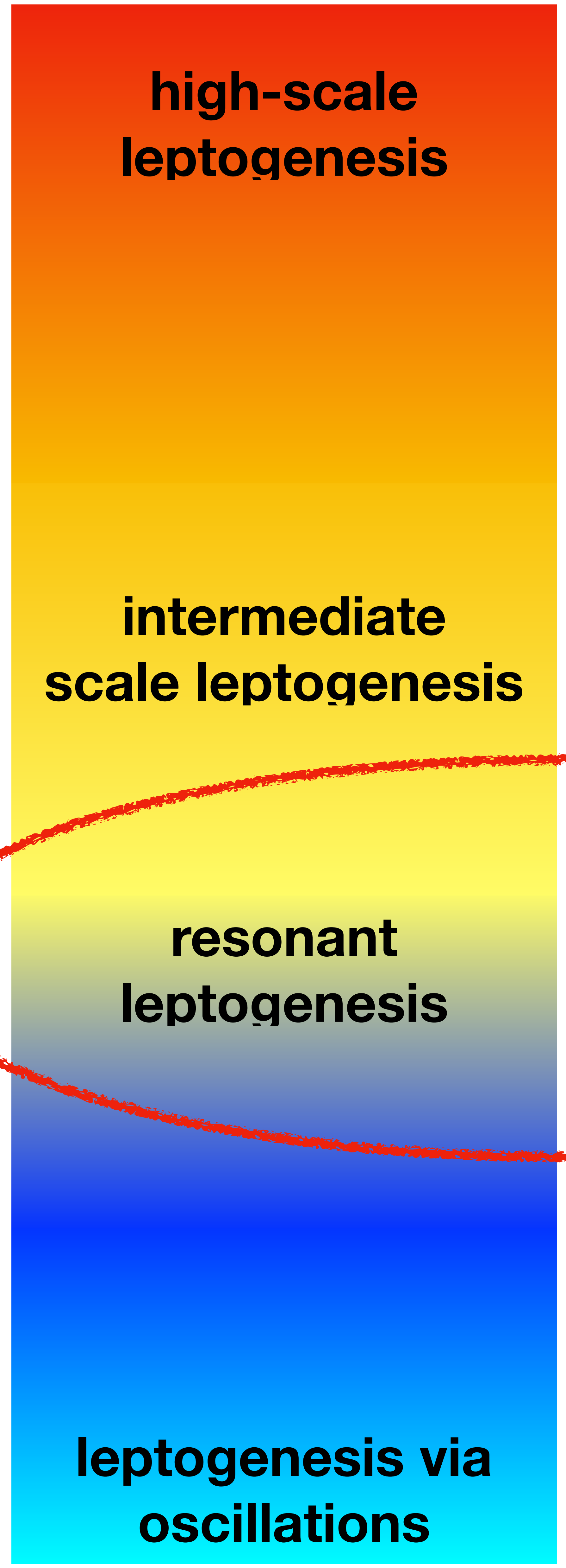
pros	cons
Simple	In most regimes tough to test
Can explain BAU	Exacerbates hierarchy problem
Predicted by GUTs	
Some circumstantial evidence	
Can radiative generate electroweak scale	

Trott & Brivio

Vissani



Mass RHN



$\mathcal{O}(10^{12})$ GeV

Fukugida & Yanagida *Phys.Lett. B17 45-47* (1986)

$\mathcal{O}(10^{6})$ GeV

Racker, Rius & Pena *JCAP 1207 030* (2013)

$\mathcal{O}(10^{3})$ GeV

Pilaftis & Underwood *Nucl.Phys. B692 303* (2004)

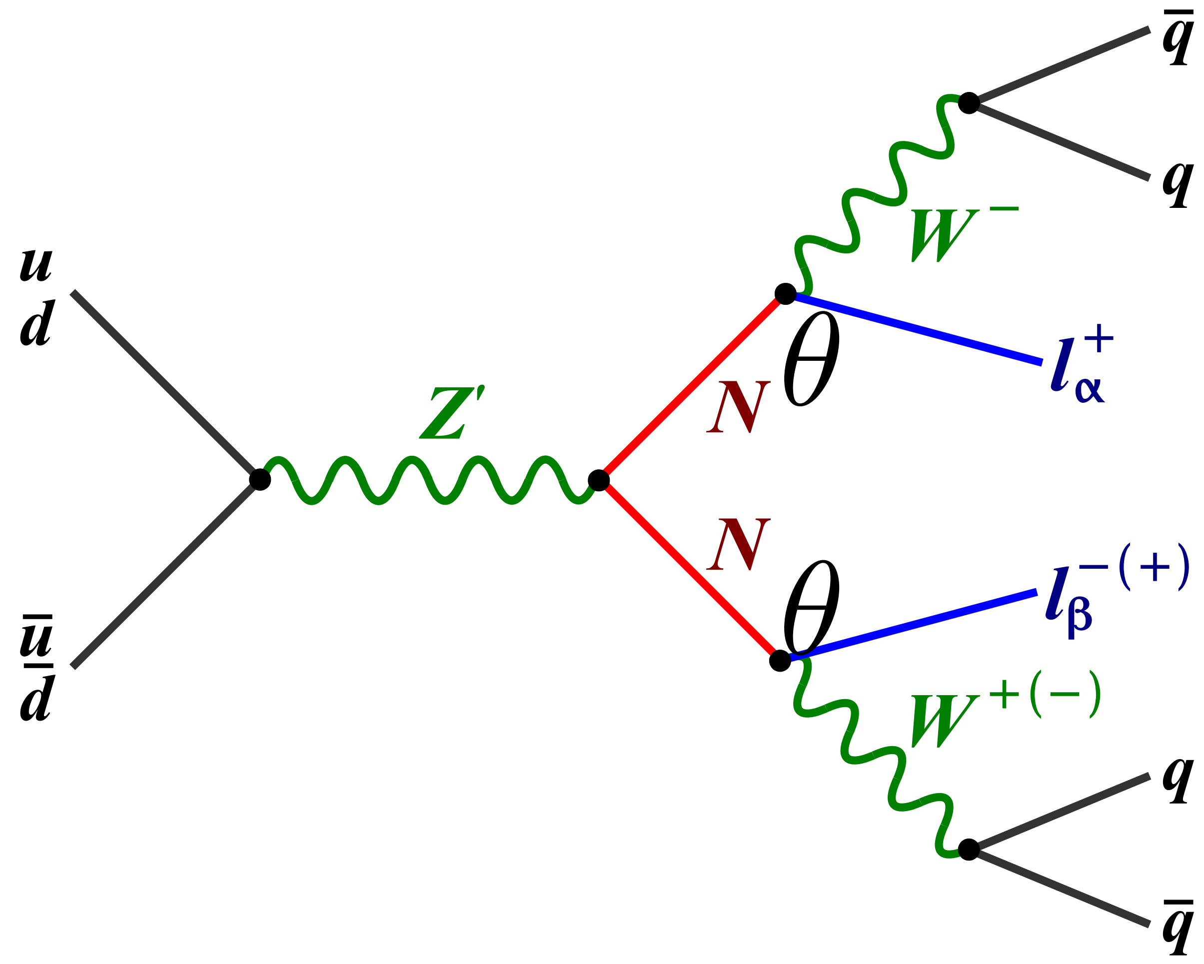
$\mathcal{O}(1)$ GeV

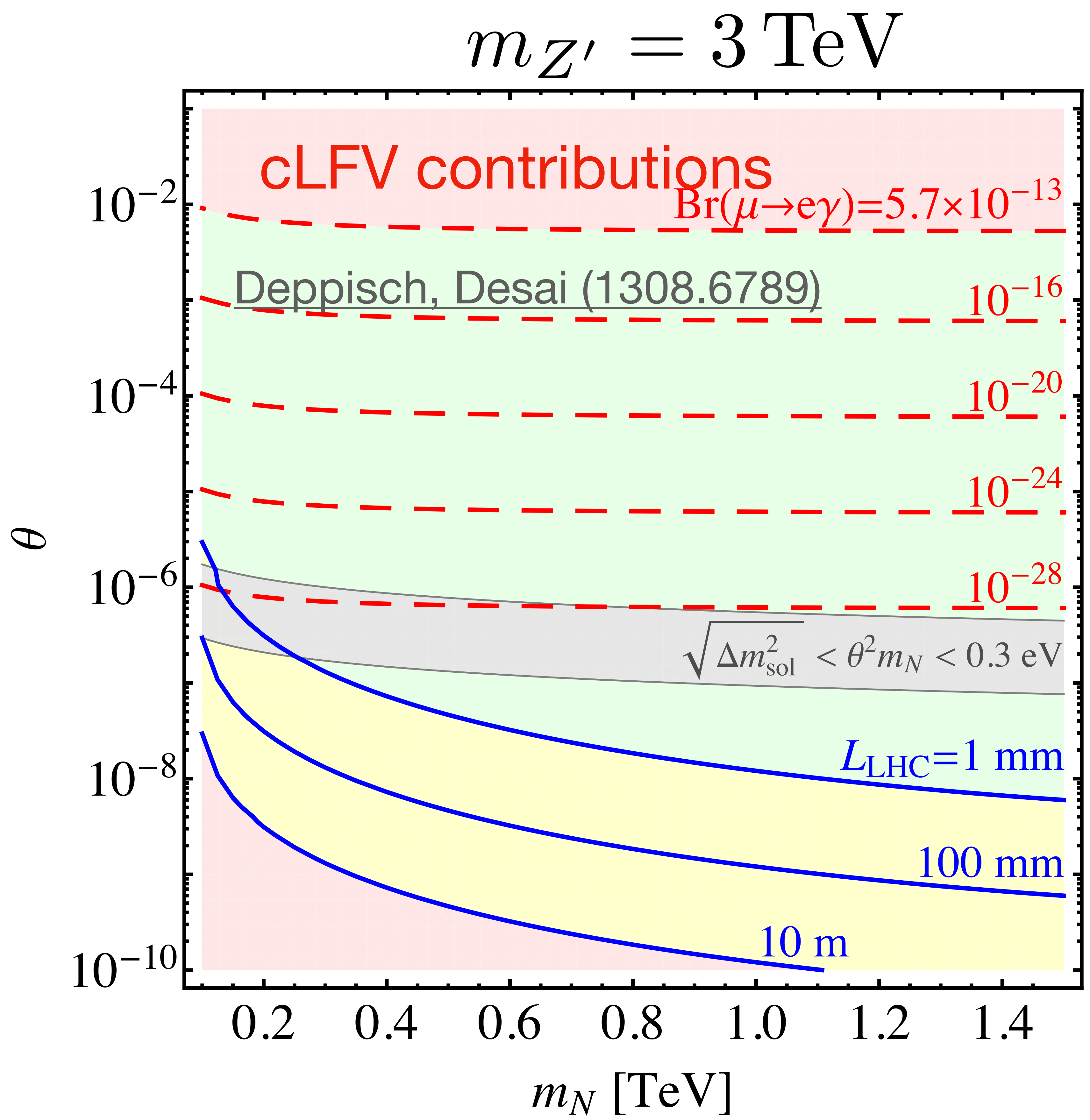
Akhmedov, Rubakov & Smirnov *Phys.Rev.Lett. 81 1359-1362* (1998)

Majorana Neutrino Masses: Tree-level

Regime where RHNs decay width similar to their mass differences. Mass range ~ TeV

Harder to test. RHN masses explained by additional $U(1)_{B\text{-}L}$ symmetry and can be sufficiently long-lived → displaced-vertex signature searched for at LHC, MATHUSLA or SHiP.





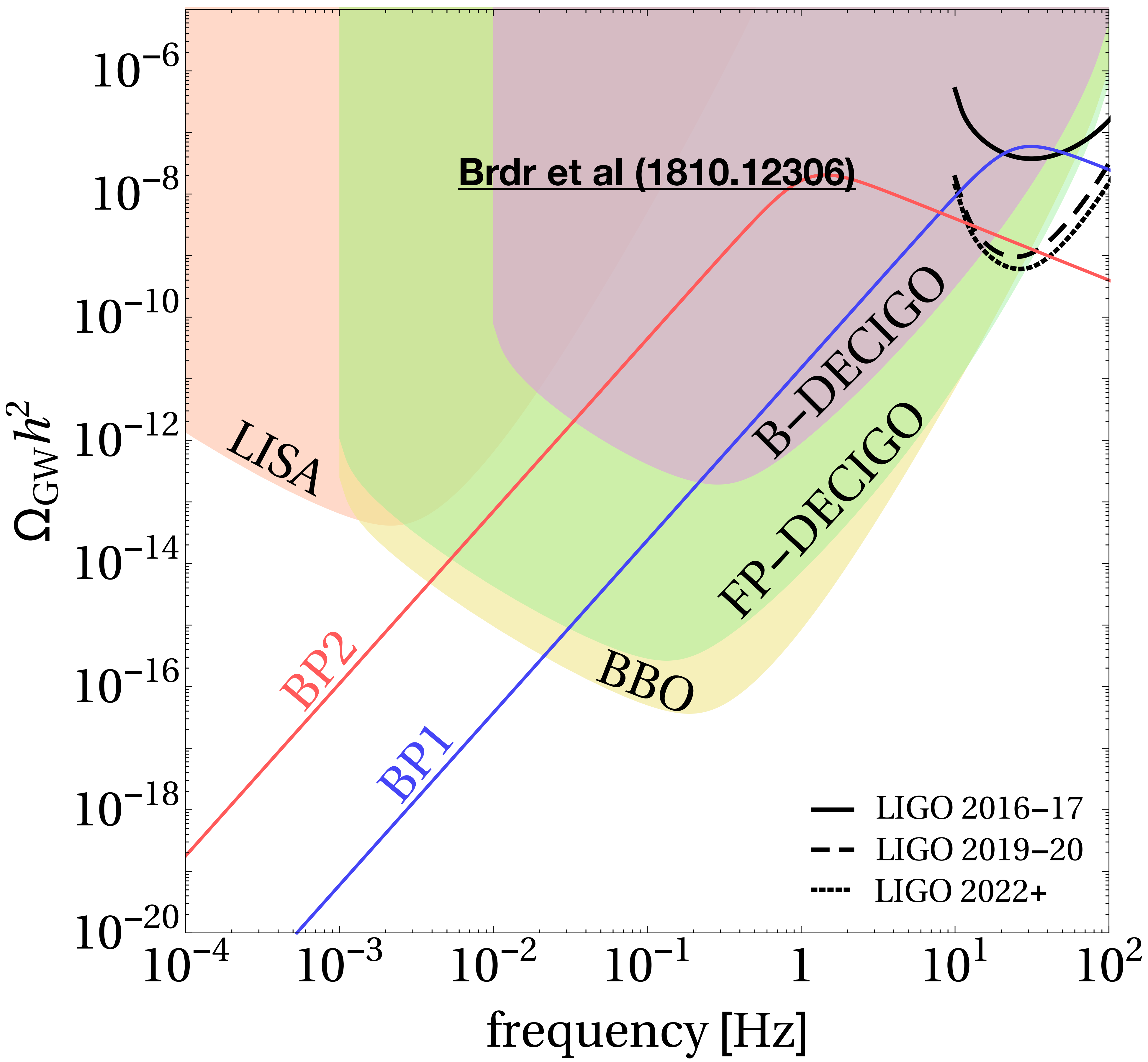
Majorana Neutrino Masses: Tree-level

Increasing interest with using gravitational waves to high scale neutrino mass models

UV-completion based on scale invariance above mass of RHNs.

New scalar breaks scale-invariance $\Longrightarrow$ generates mass for RHNs and strong first order phase transition

Resonant Leptogenesis + dynamical generation of EW scale



Majorana Neutrino Masses: Radiative low scale

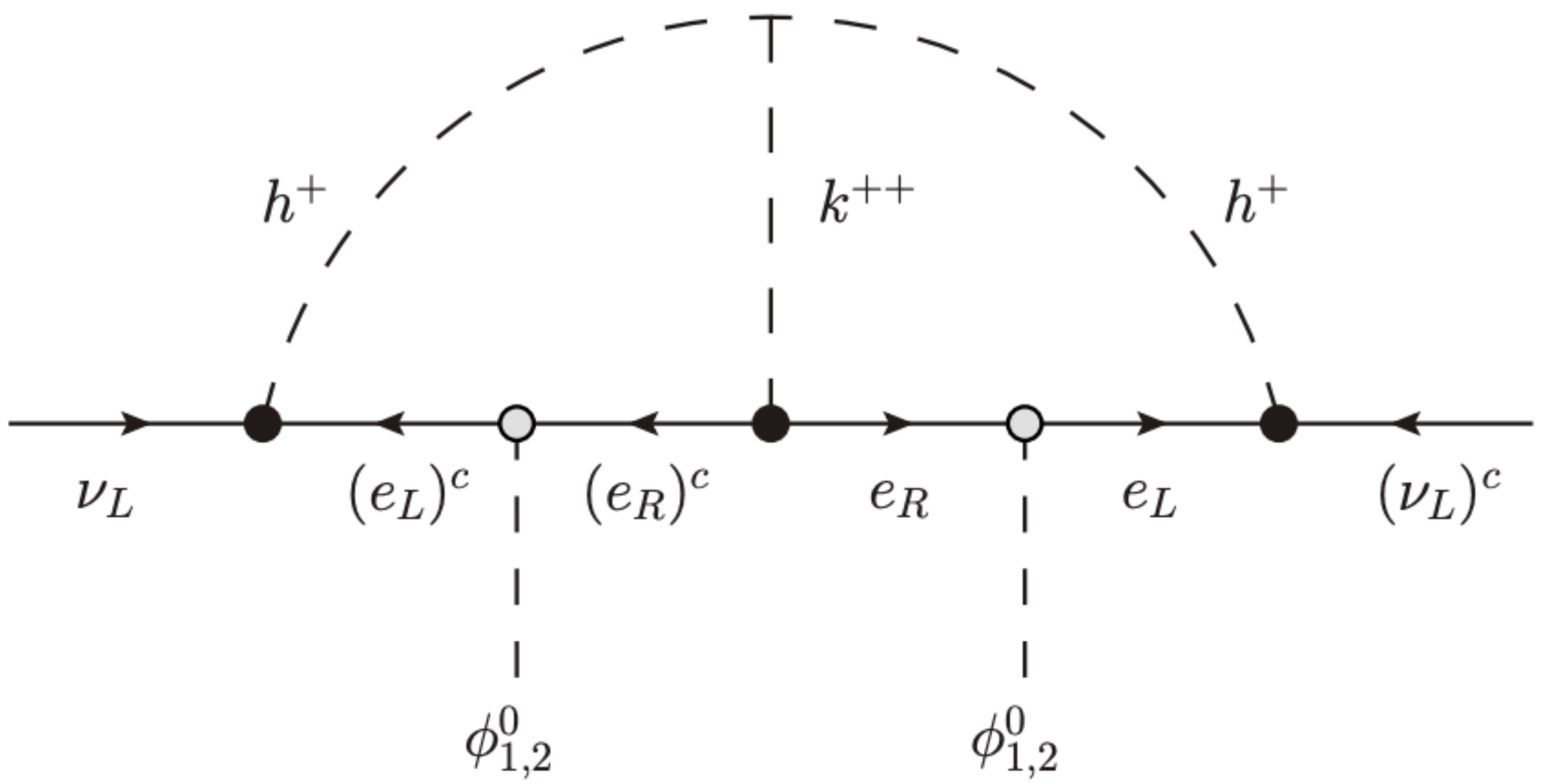
- Neutrino masses zero at tree-level, non-zero at n-loop level
- Loop suppression $\Longrightarrow$ small neutrino mass new physics is around **TeV-scale**

$$m_\nu \sim \frac{v^2}{M} \times \left(\frac{1}{16\pi^2}\right)^n$$

Zee-Babu model

- Rich scalar sector: h^+, k^{++}

$$\mathcal{L}_{ZB} = f\overline{\tilde{\ell}_L}\ell_L h^+ + g\overline{e^c_R}e_R k^{++} + \mu_{ZB} h^+ h^+ k^{--}$$



Majorana Neutrino Masses: Radiative low scale

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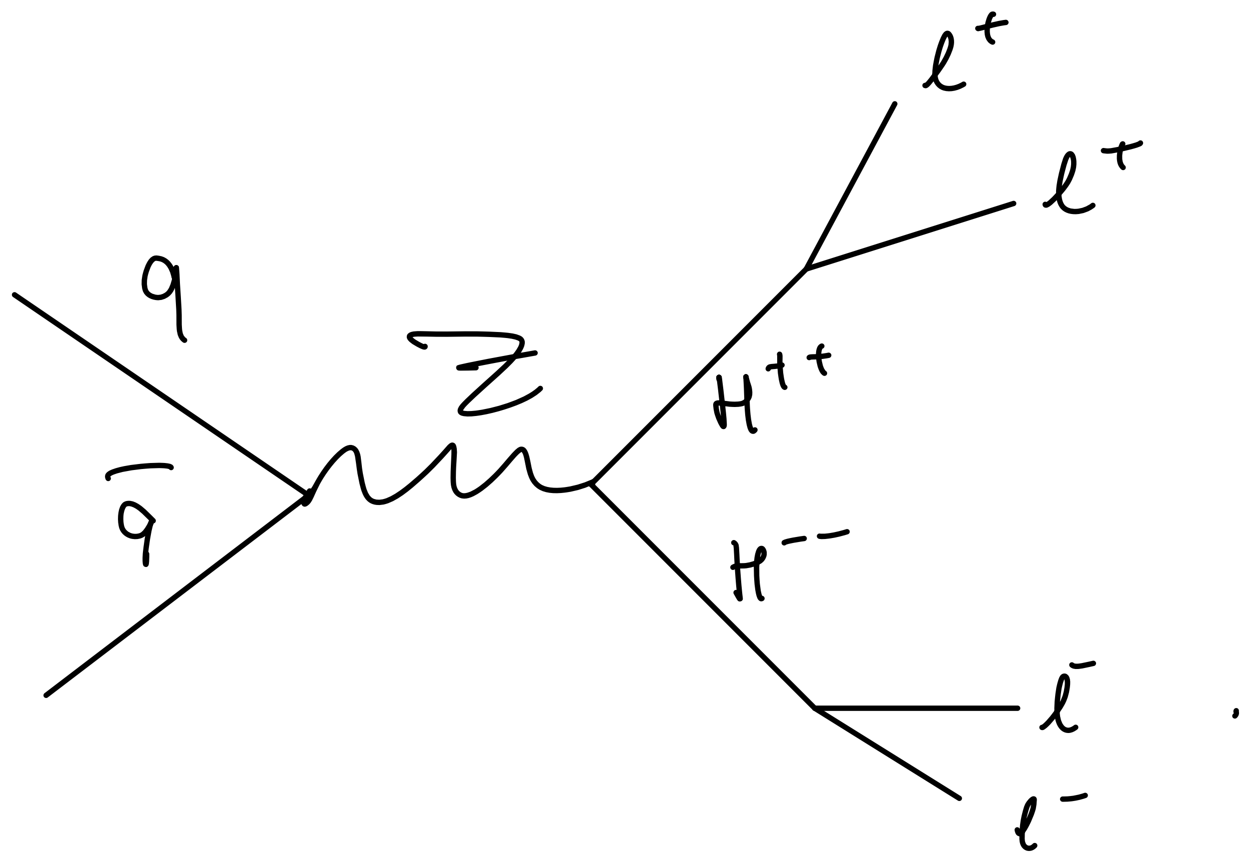
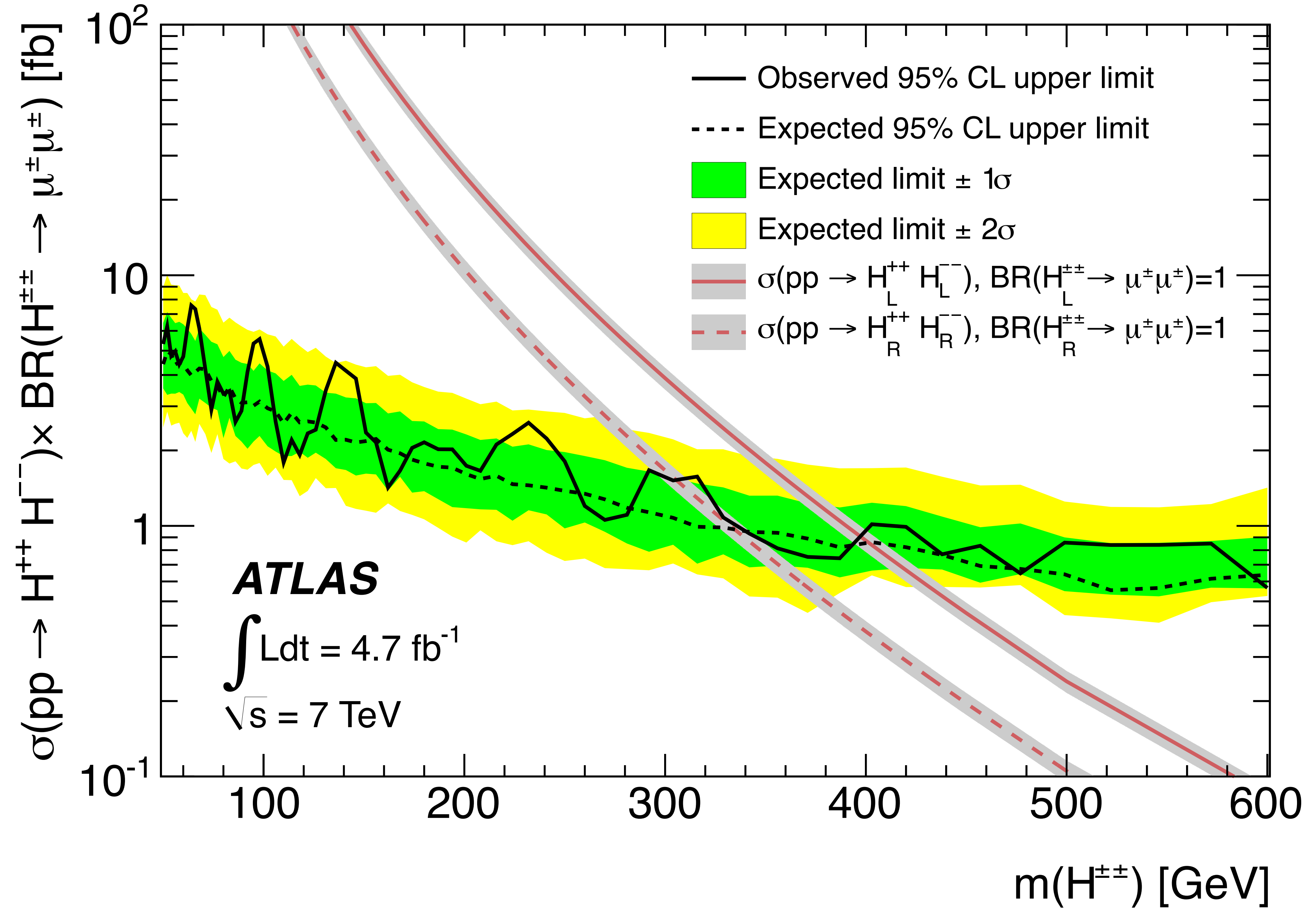
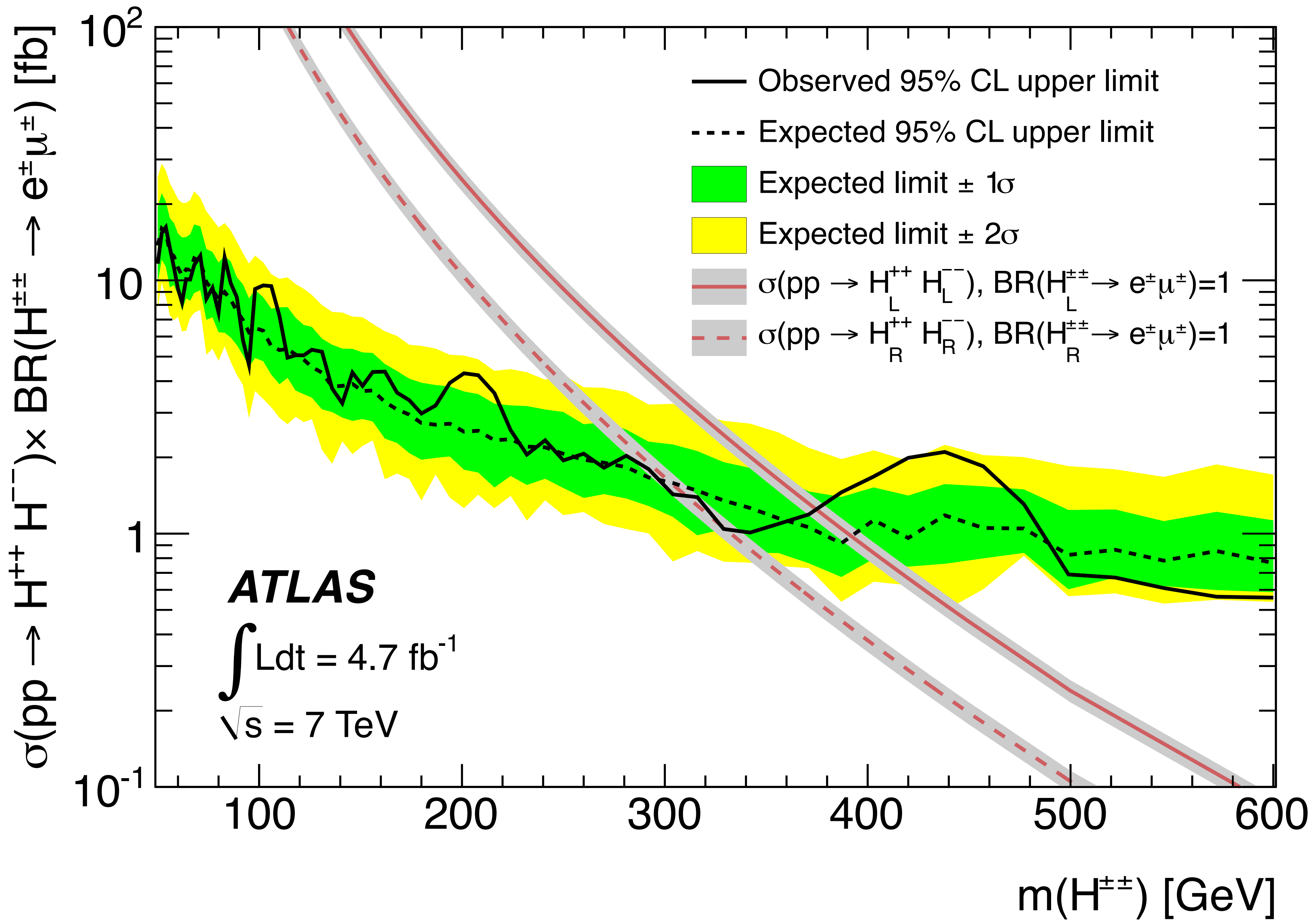


Doubly charged scalars can be searched for at the LHC (like-sign dilepton searches)

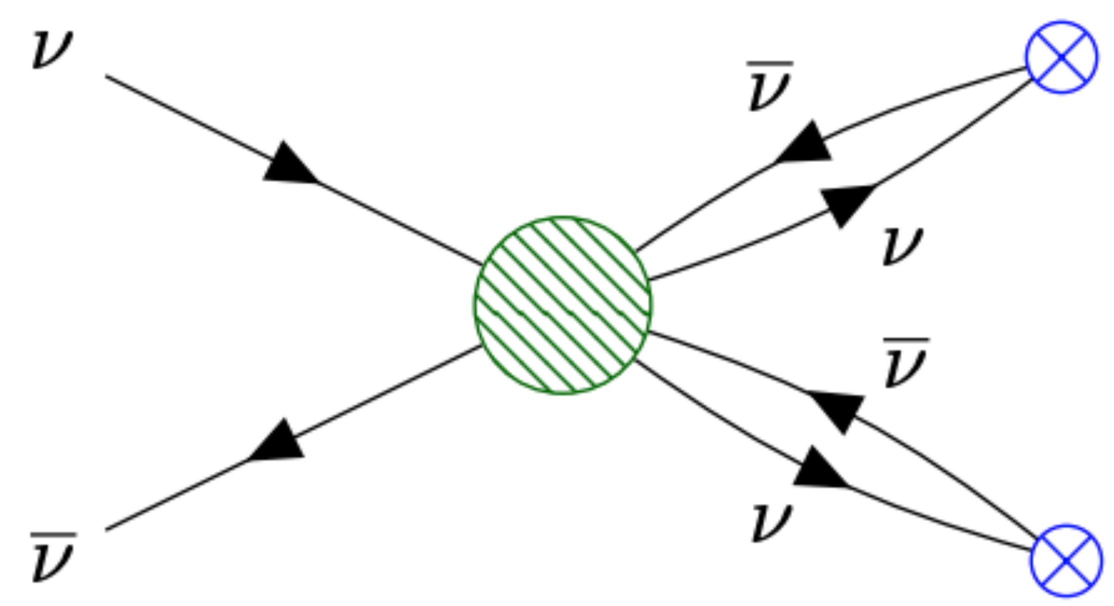
Zee-Babu model





What I have reviewed so far are popular models

Dvali & Funcke 1602.03191



Assume gravity has a theta term: $\mathcal{L}_G \supset \theta_G \tilde{R} R$

Postulate neutrinos have zero bare mass and condense via NP gravitational effects in analogue with QCD:

$$\mathcal{L} \supset g_v v \bar{\nu} \nu \qquad \Lambda_G \sim v \sim m_\nu \sim m_{\eta_\nu}$$

Neutrinos Dirac/ Majorana, rich phenomenology due to late time mass generation

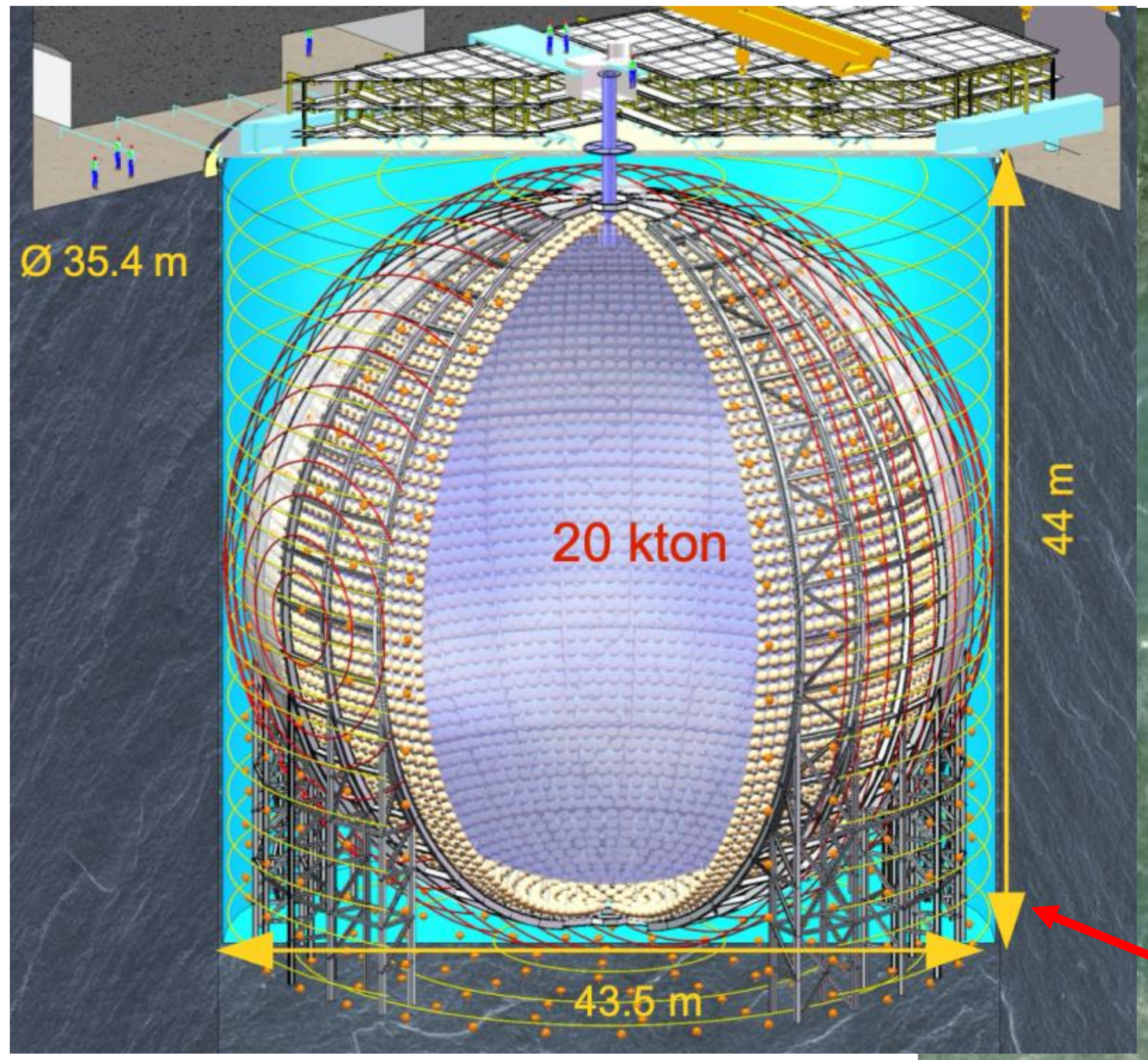
Use Schwinger-Dyson methods to calculate condensation strength.
Need a lot of new particle degrees of freedom or face tuning of $\Lambda_{\text{Planck}}/m_\nu$

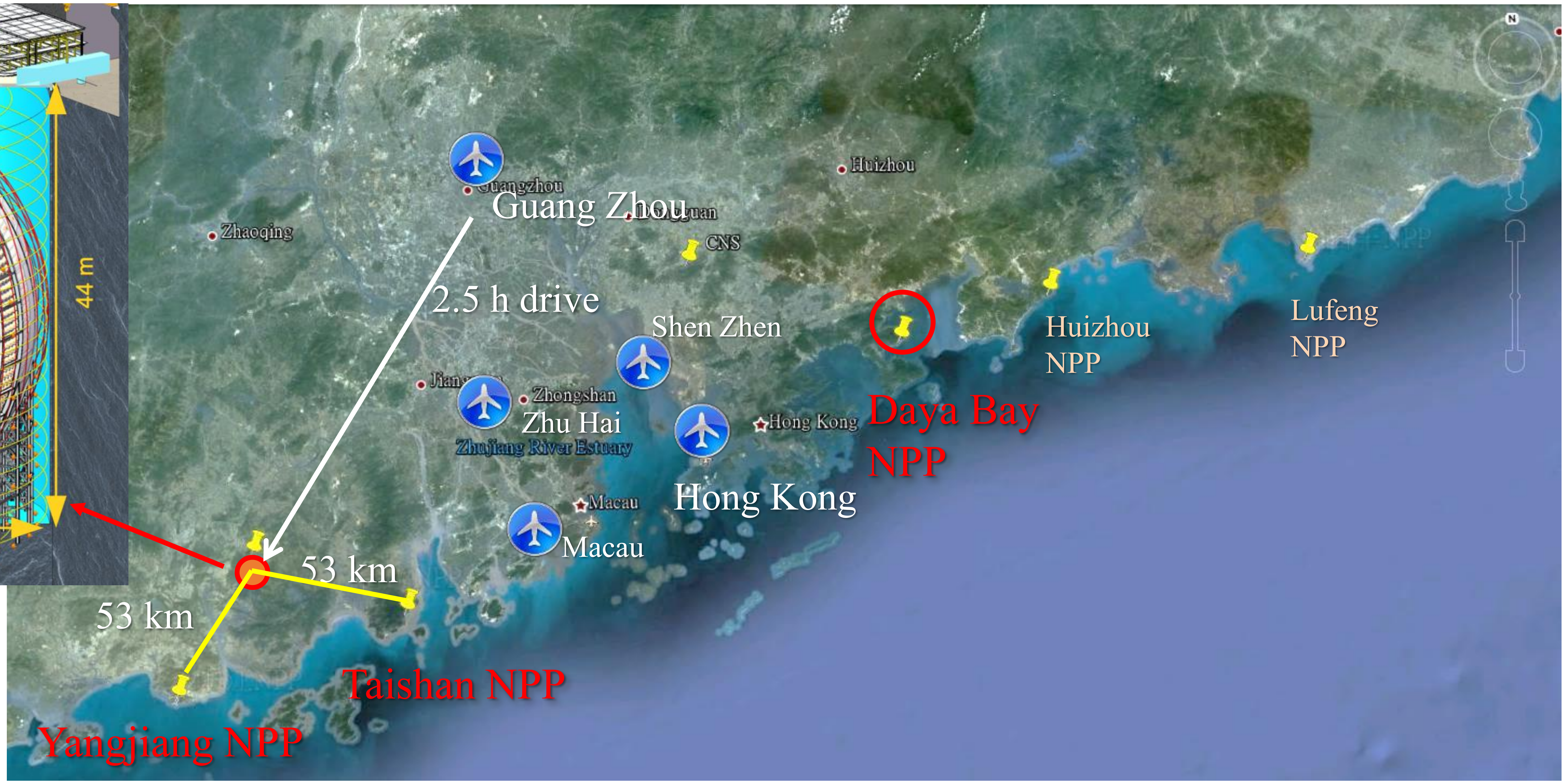
Barenboim, JT & Zhou 1909.04675

Neutrinos: Yet to come

The Future of Neutrinos: Mass Ordering

- JUNO medium baseline reactor experiment will start data taking next year.





The Future of Neutrinos: Mass Ordering

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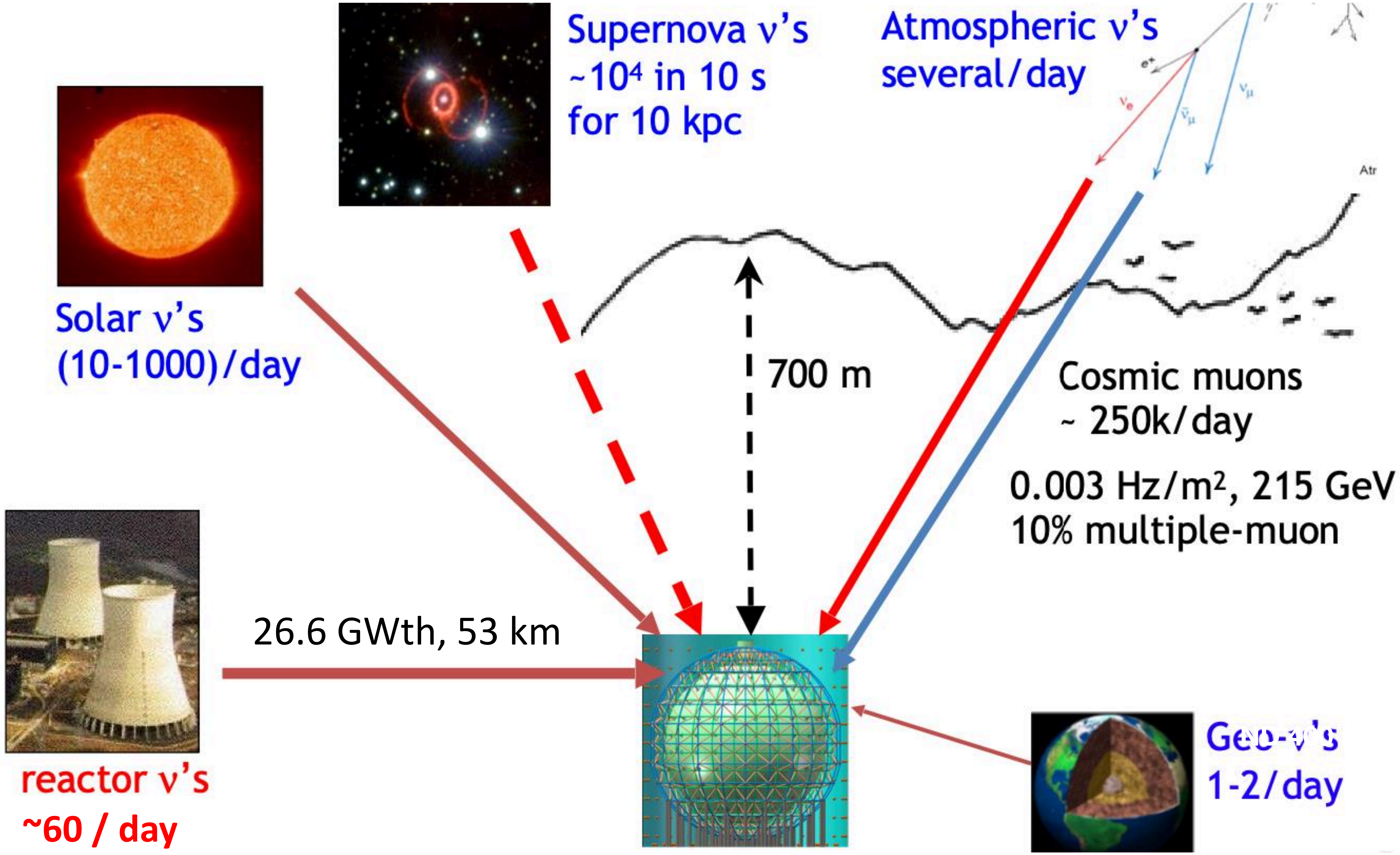
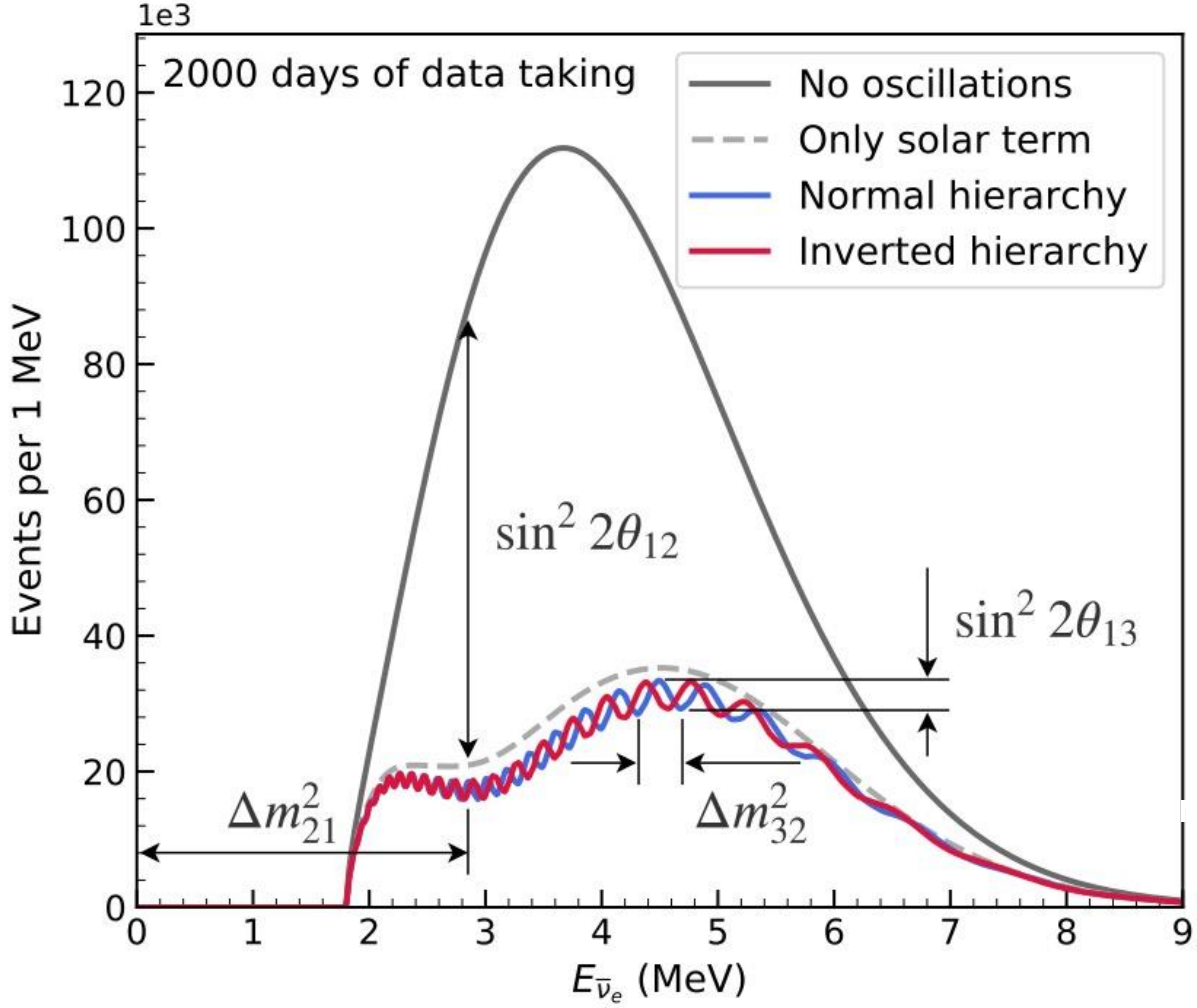


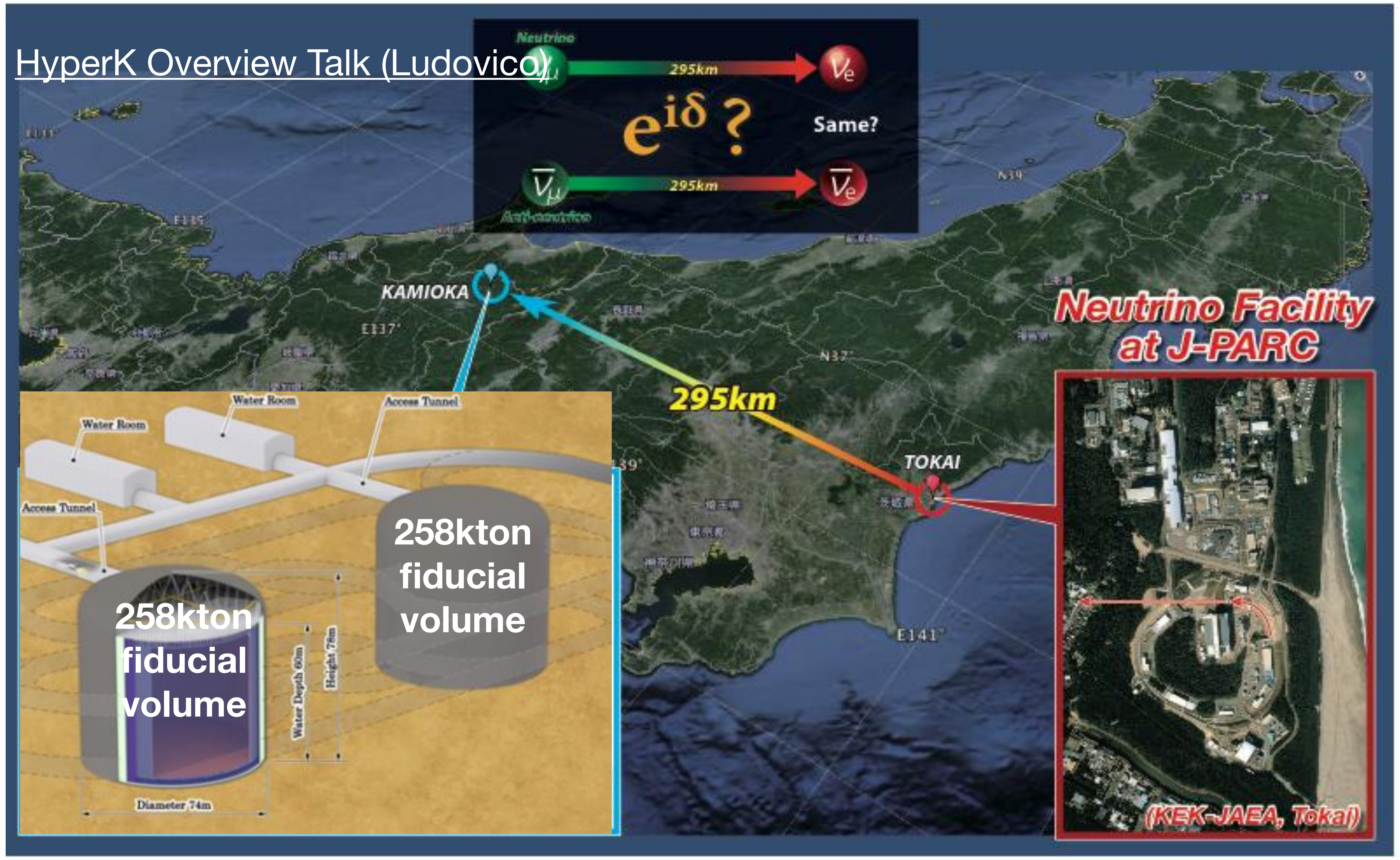
The Future of Neutrinos: Mass Ordering

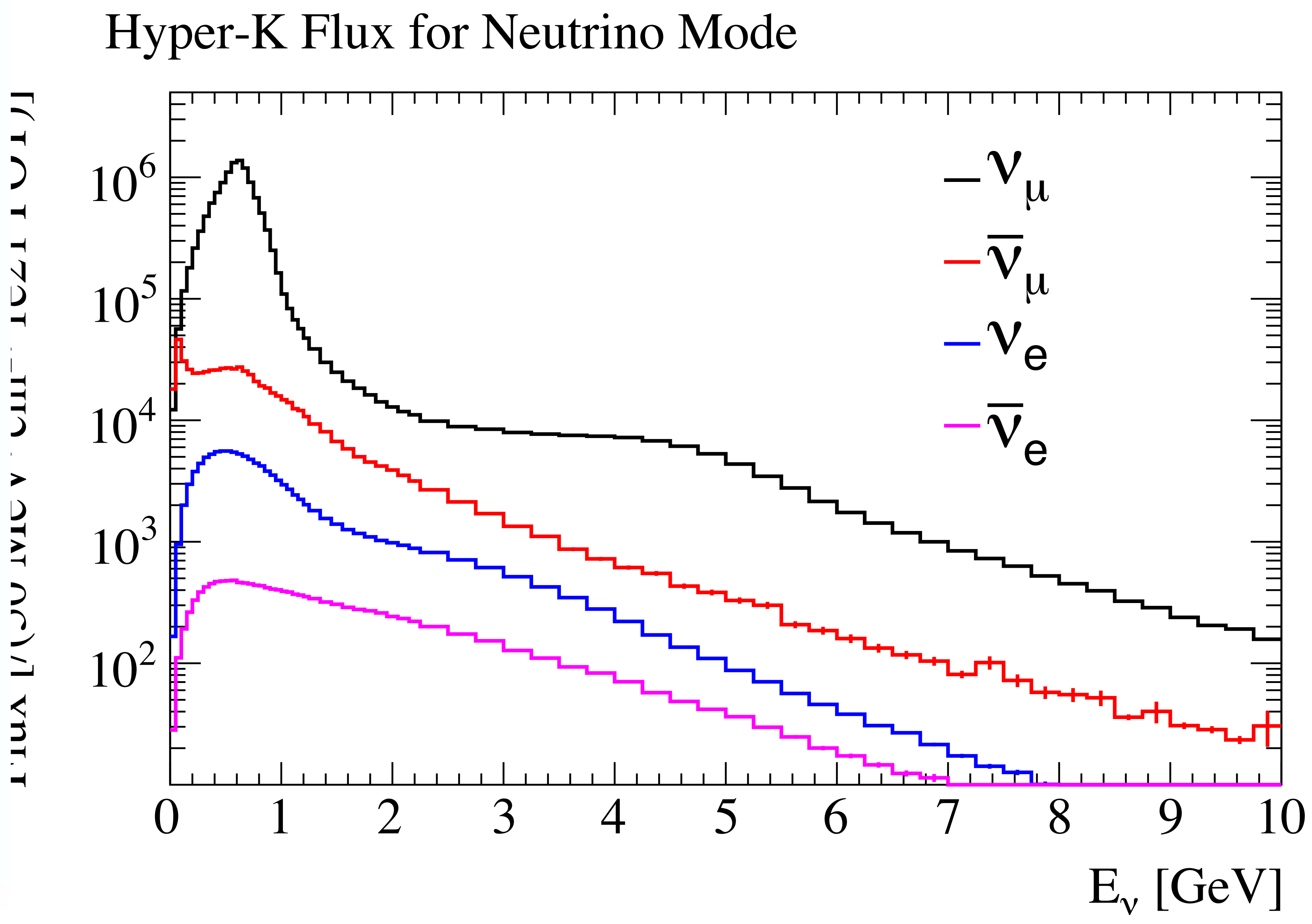
Precision measurement of $P(\bar{\nu}_e \rightarrow \bar{\nu}_e)$ will resolve mass ordering with 6 years of data taking.



The Future of Neutrinos

- HyperK next generation multipurpose water Cherenkov detector will start data-taking 2027. Similar technology to T2K.
- **physics goals:** CP-violation, mass ordering, proton decay, detect solar, atmospheric, and geoneutrinos…

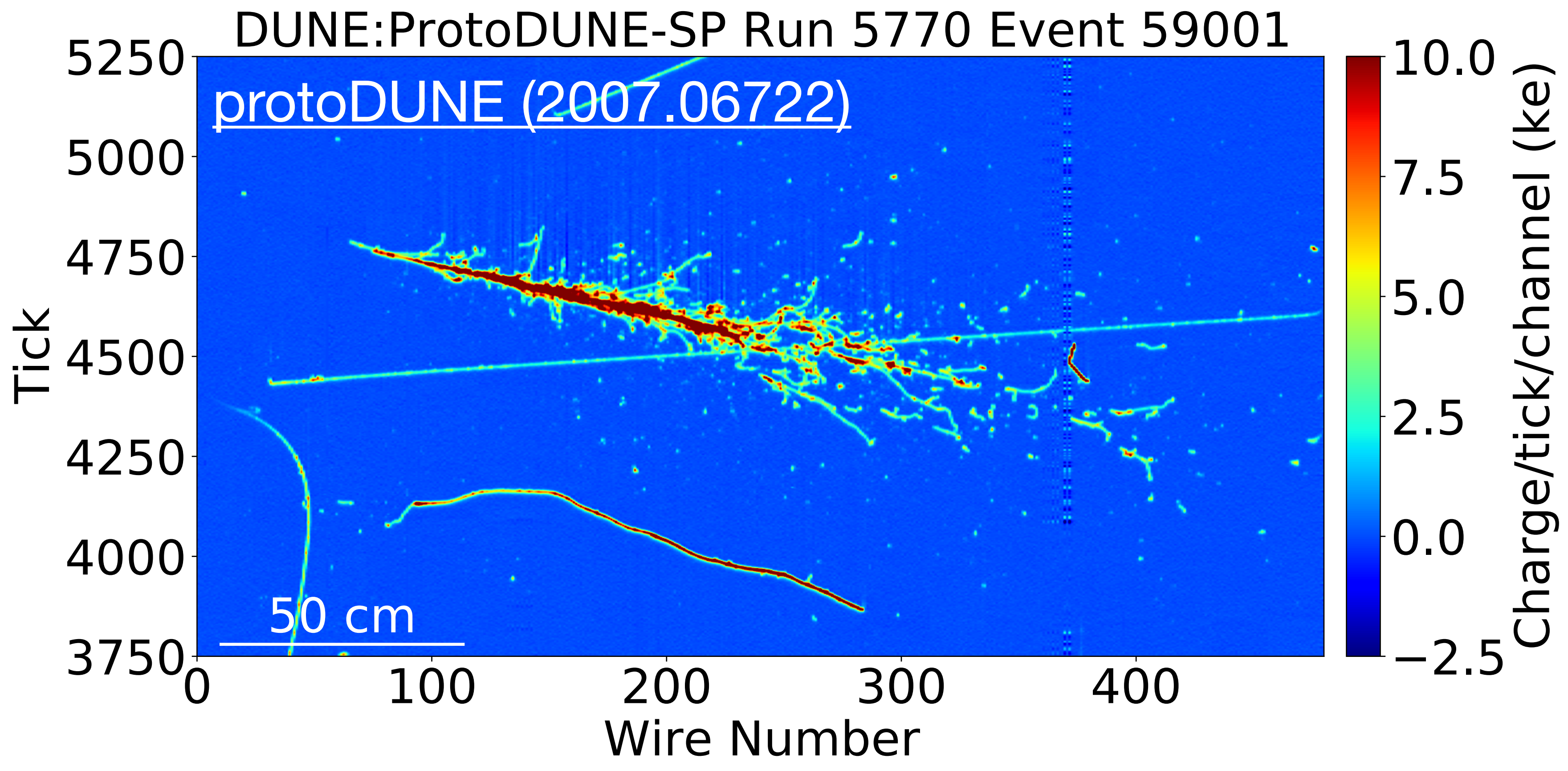




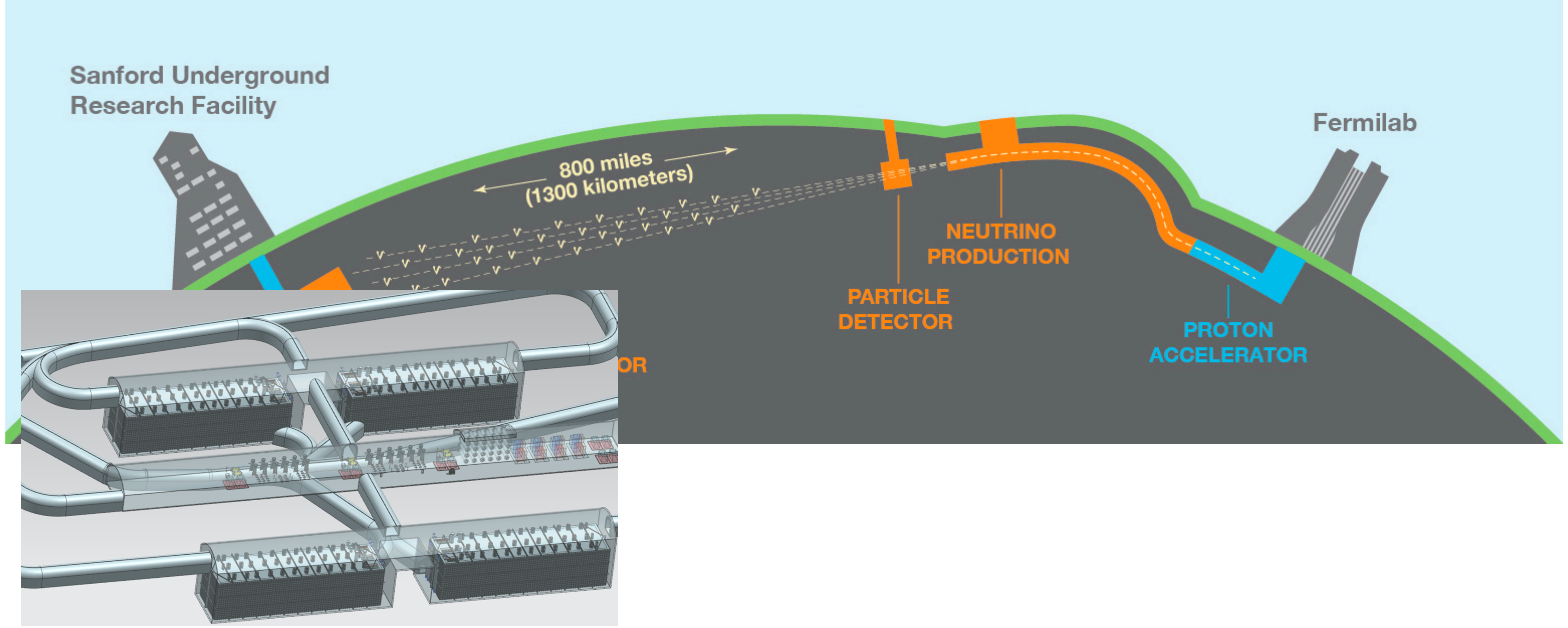
The Future of Neutrinos

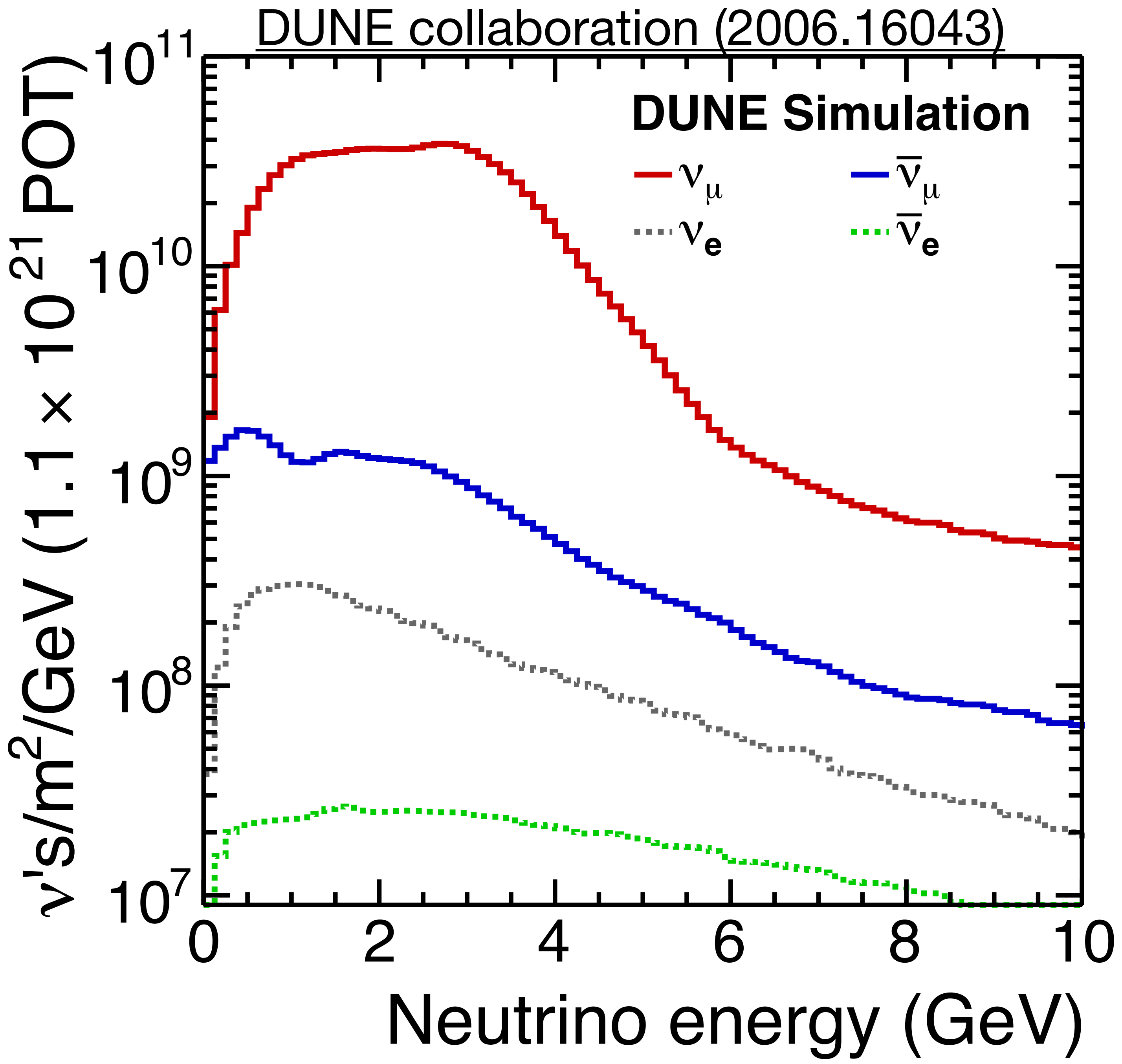
- DUNE LArTPC detector will start running 2026 (3 years no beam). Technology demonstrated by the Fermilab Short Baseline Neutrino Program (Kirsty Duffy's talk).
- **Physics goals:** very similar to HyperK

6 GeV electron candidate

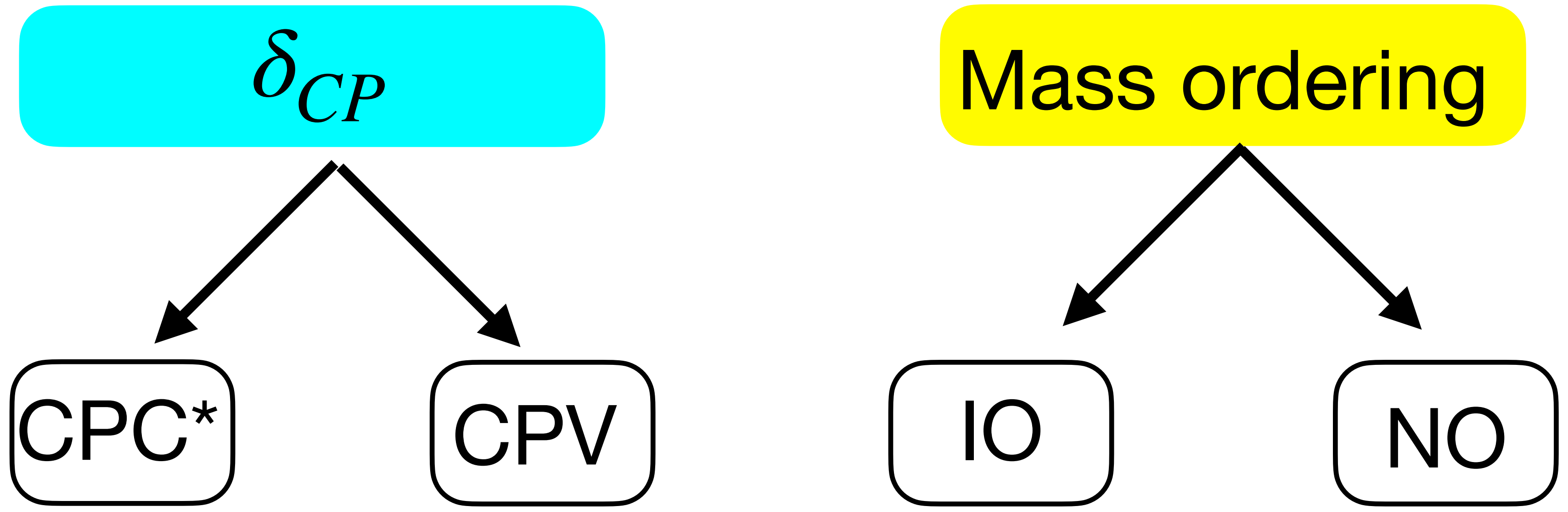


https://www.dunescience.org/

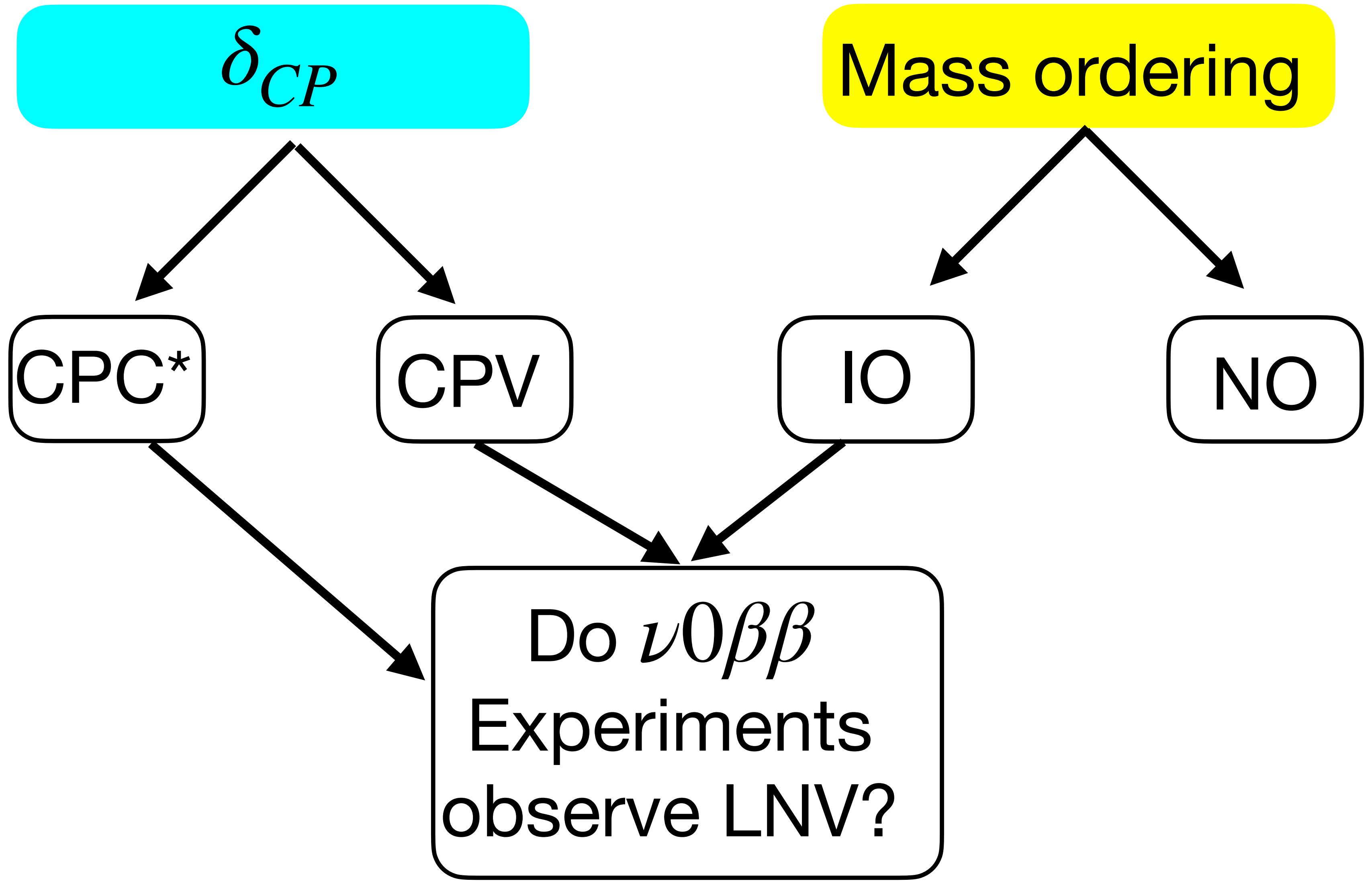




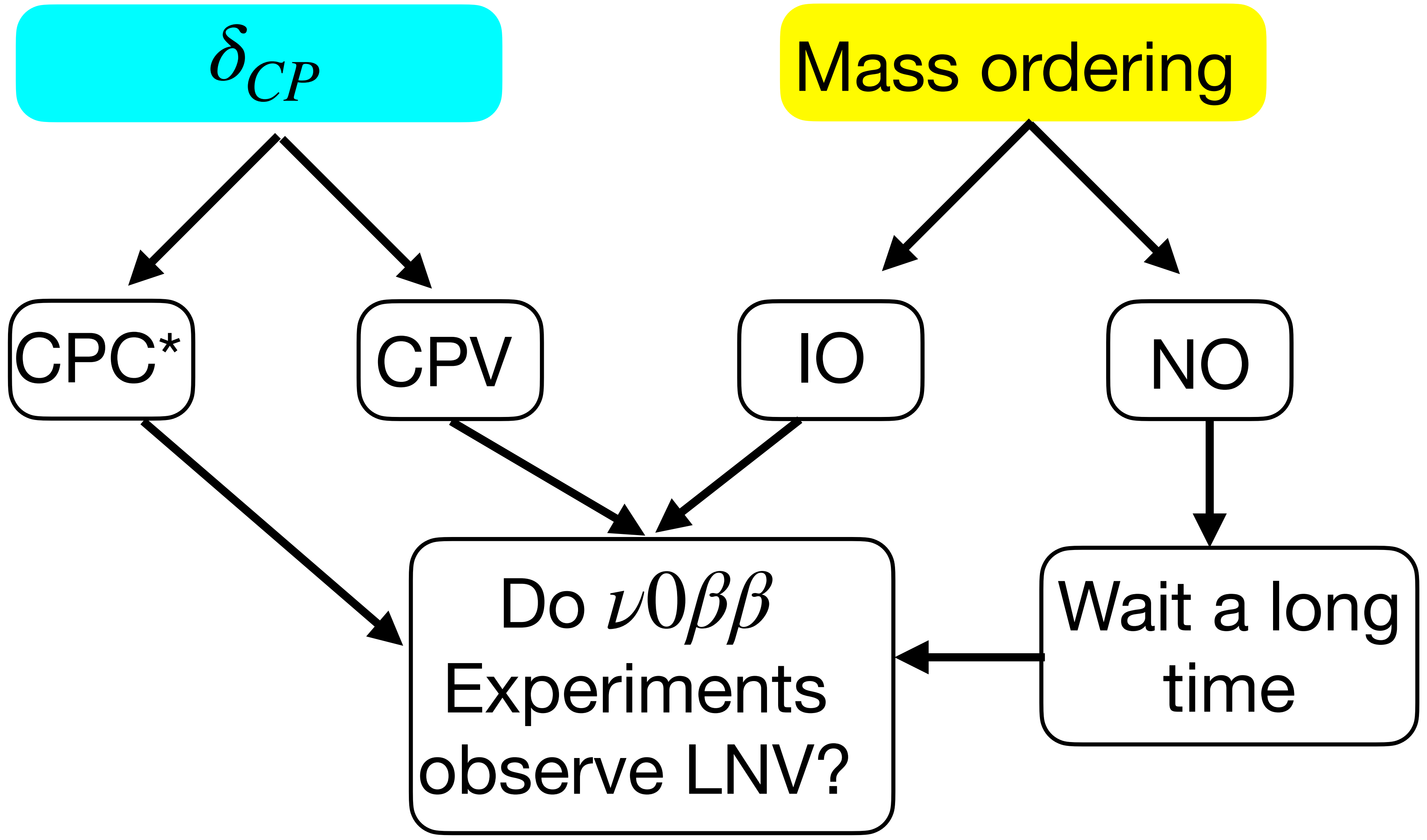
The Future of Neutrinos



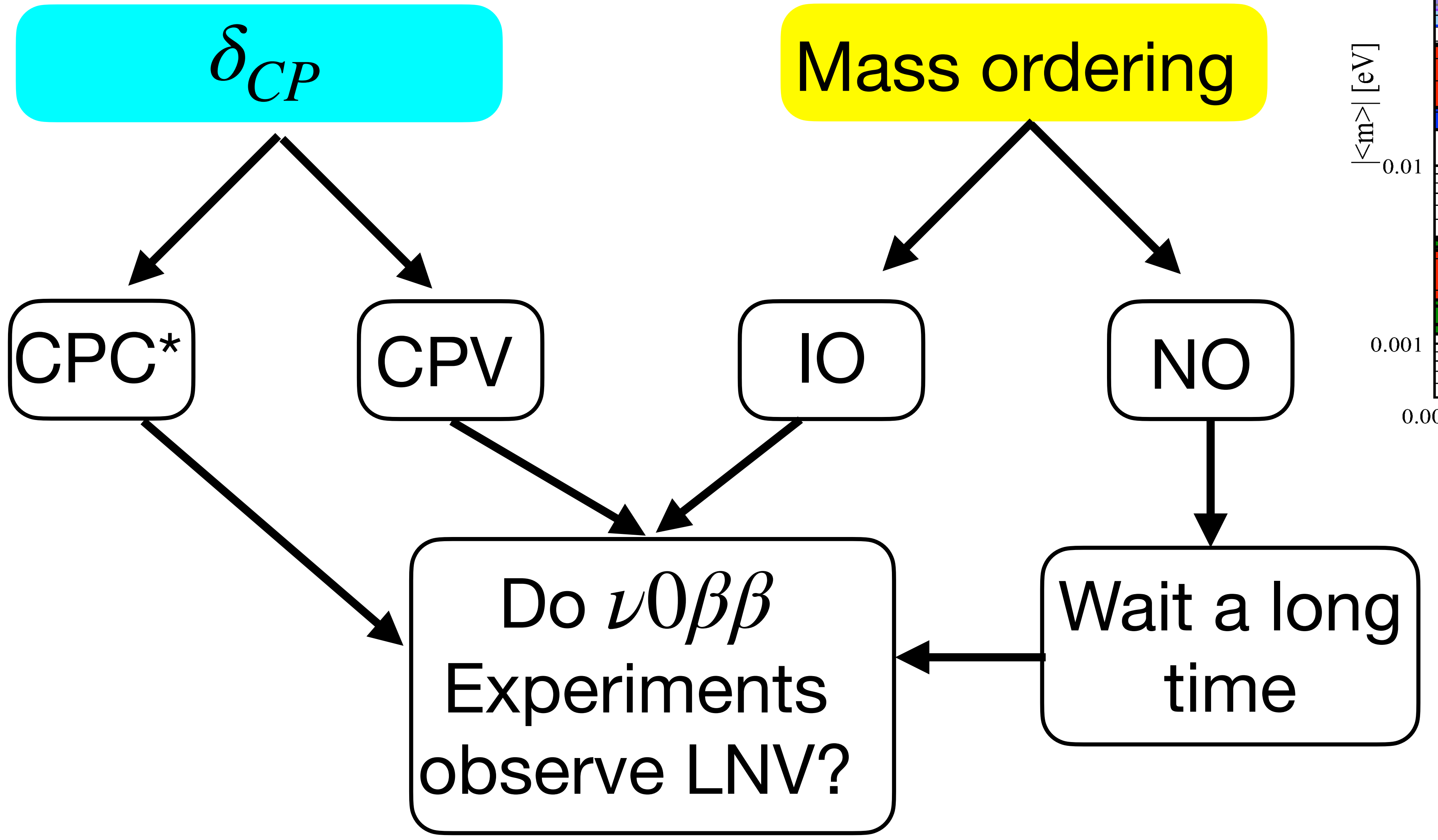
The Future of Neutrinos

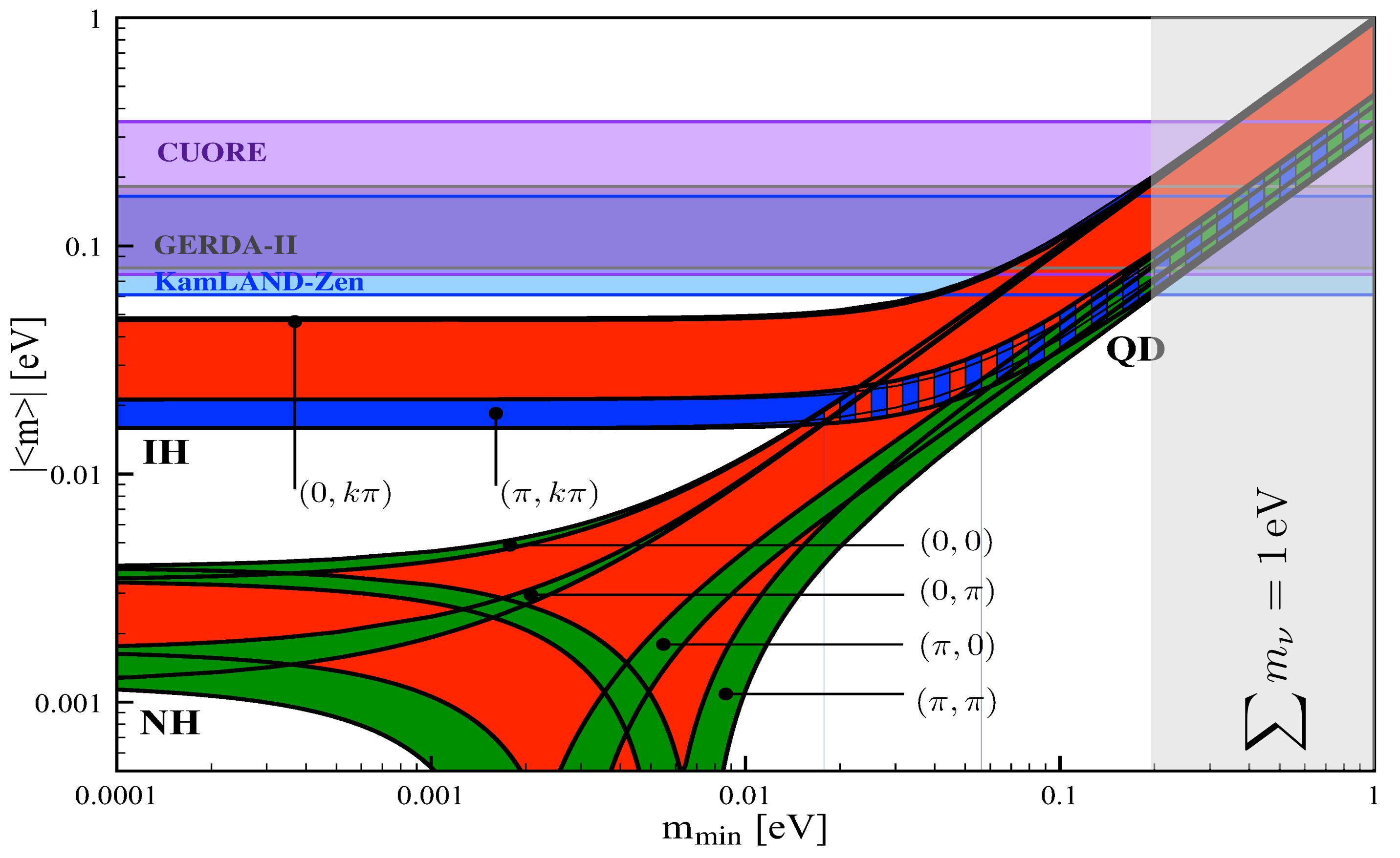


The Future of Neutrinos

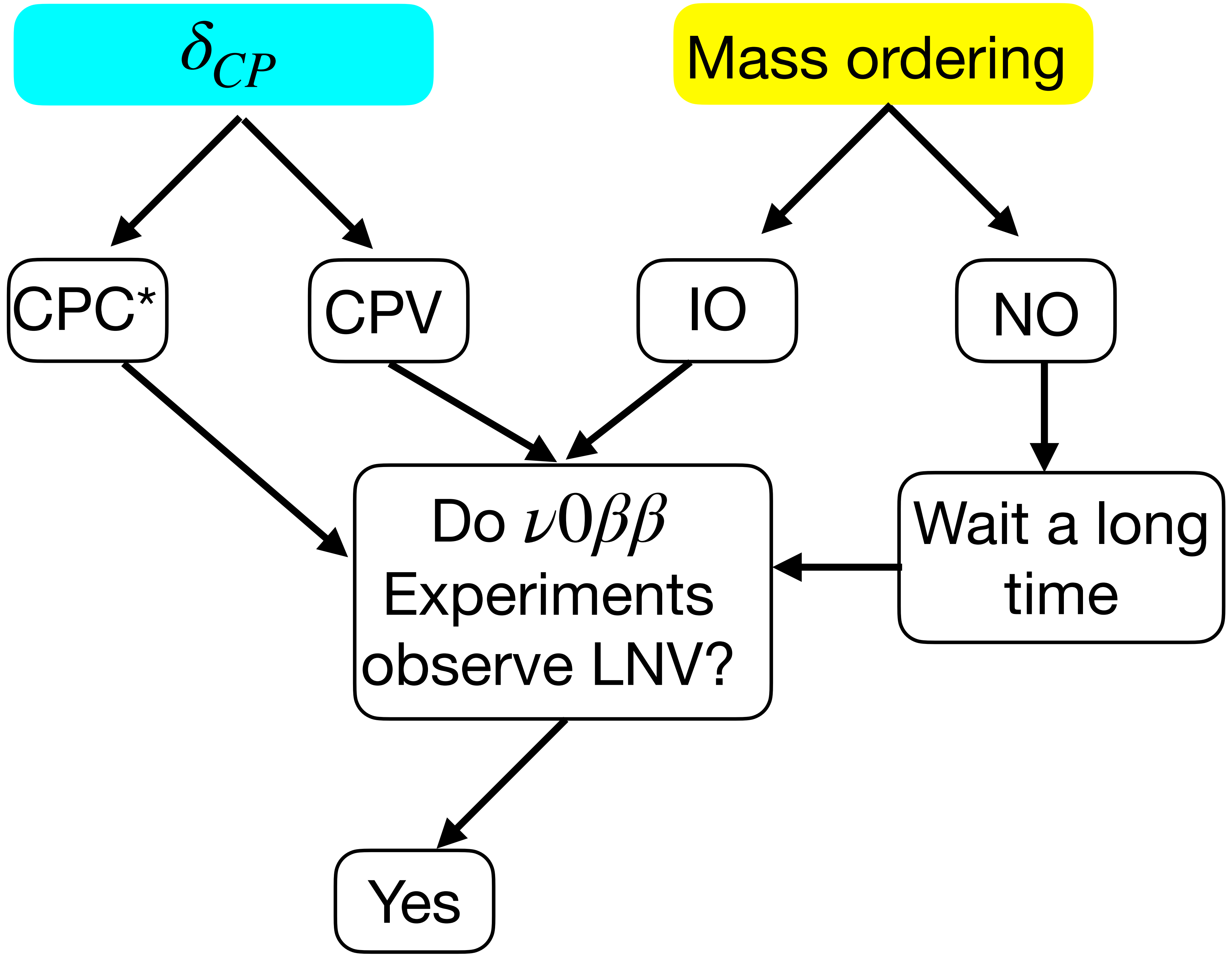


The Future of Neutrinos

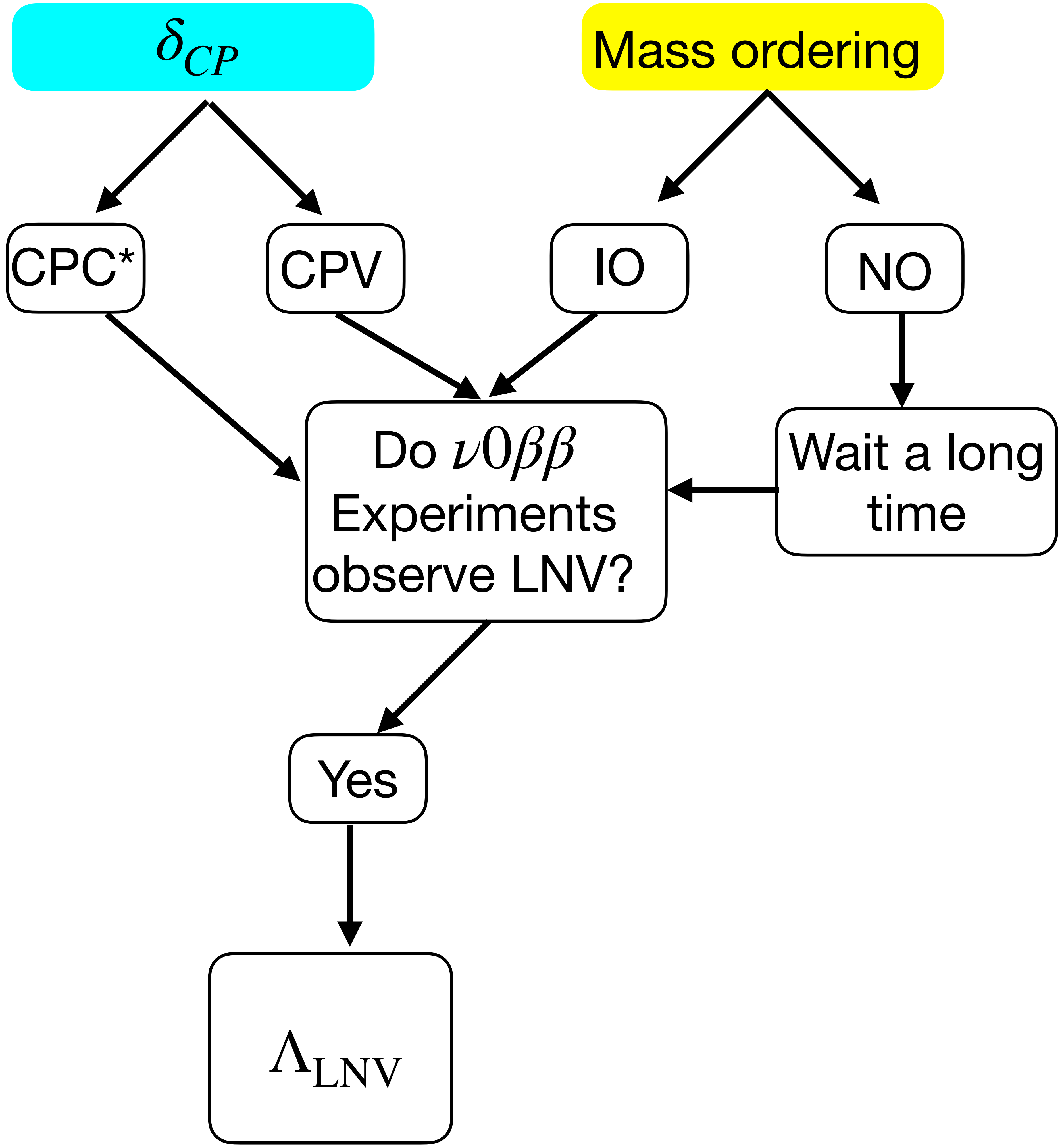




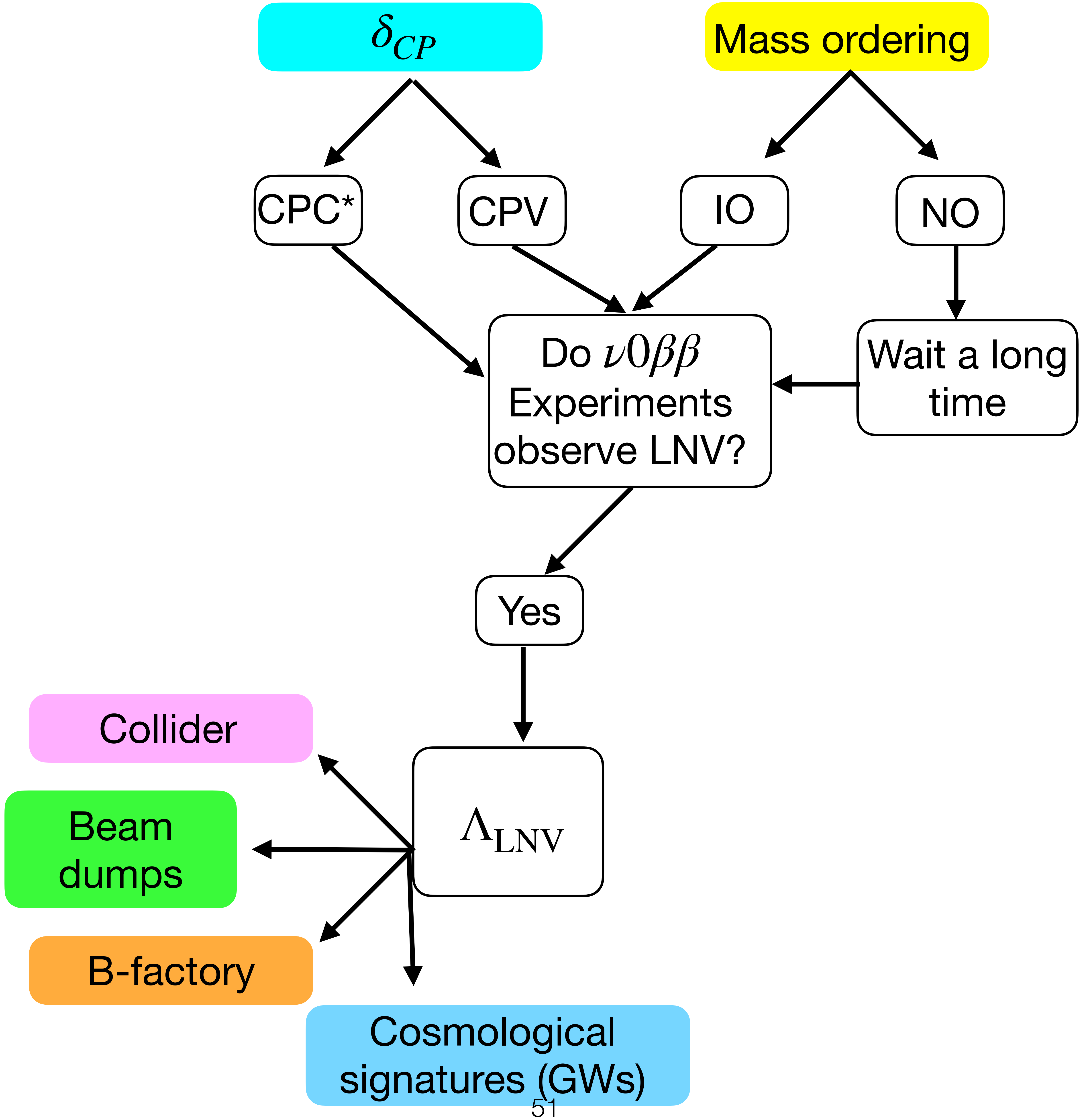
The Future of Neutrinos



The Future of Neutrinos



The Future of Neutrinos



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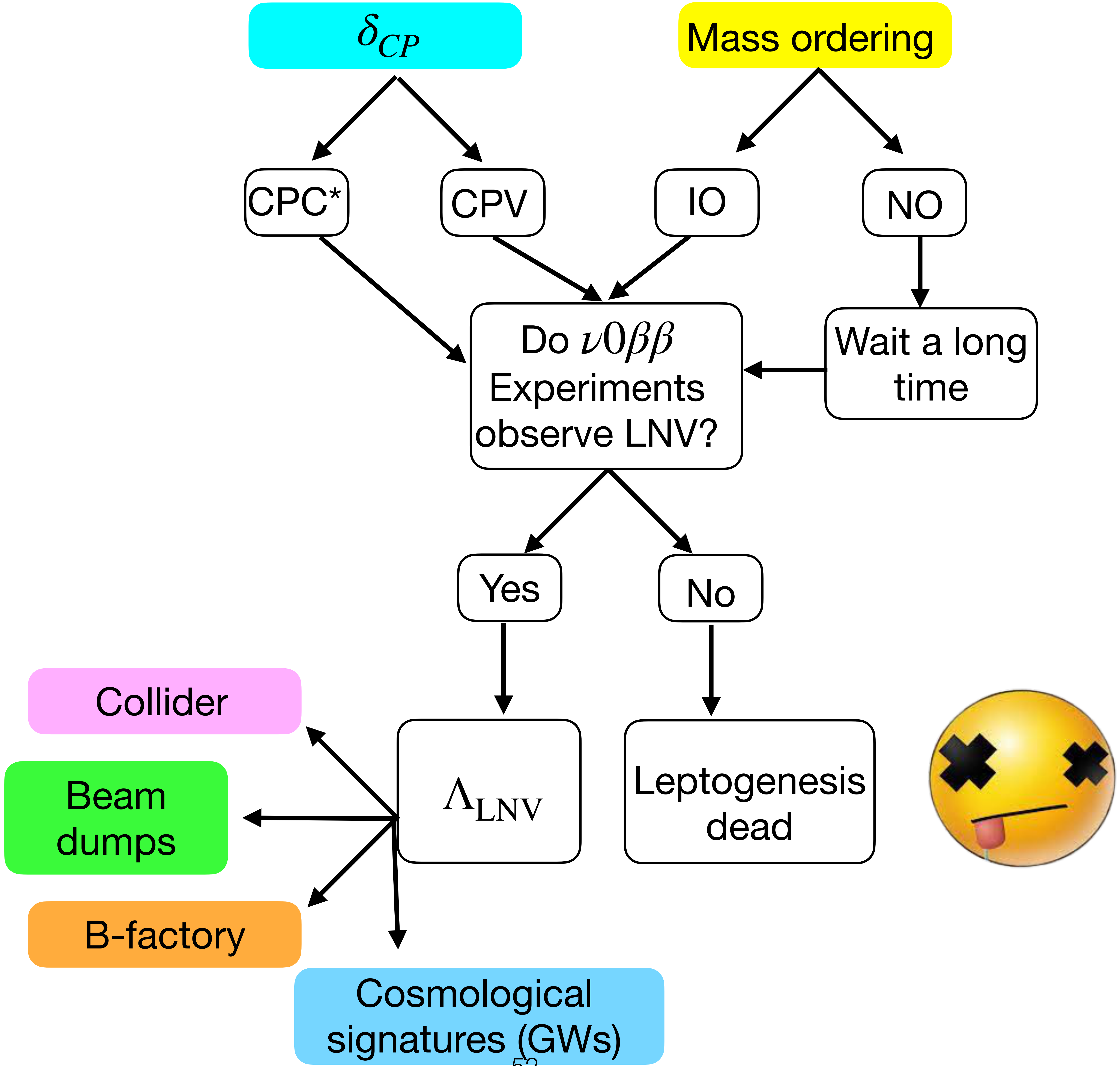
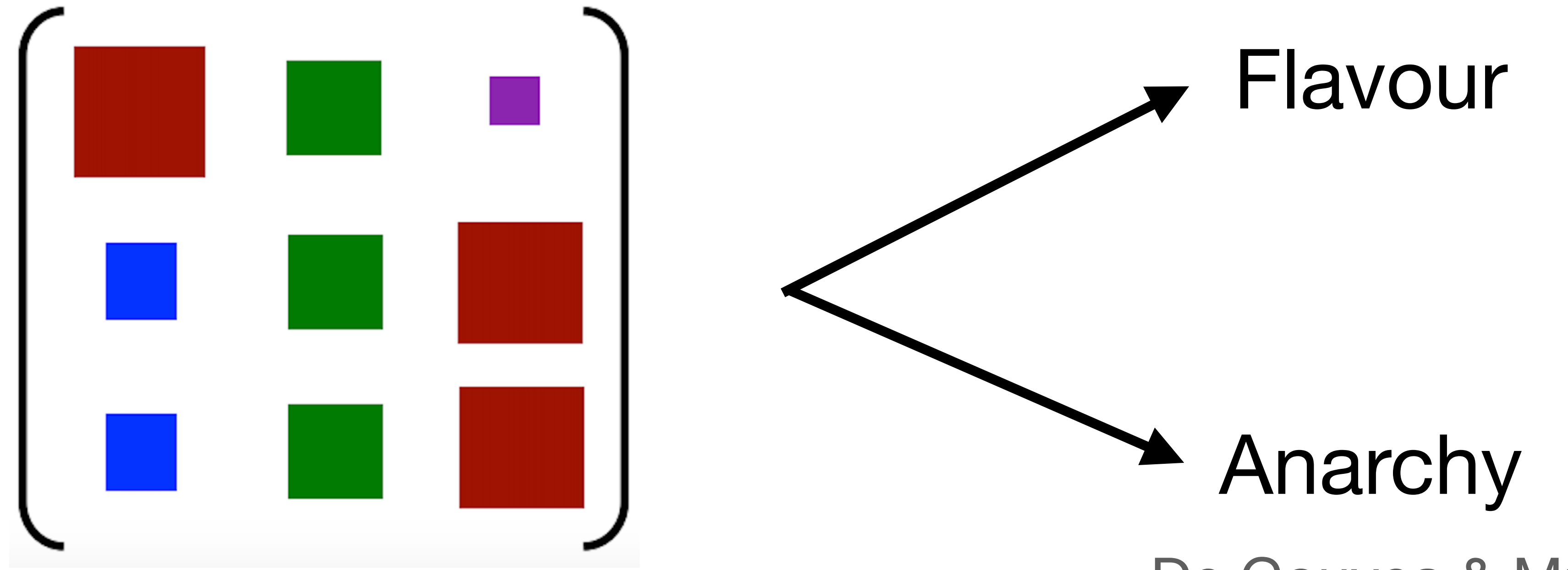


The Future of Neutrinos

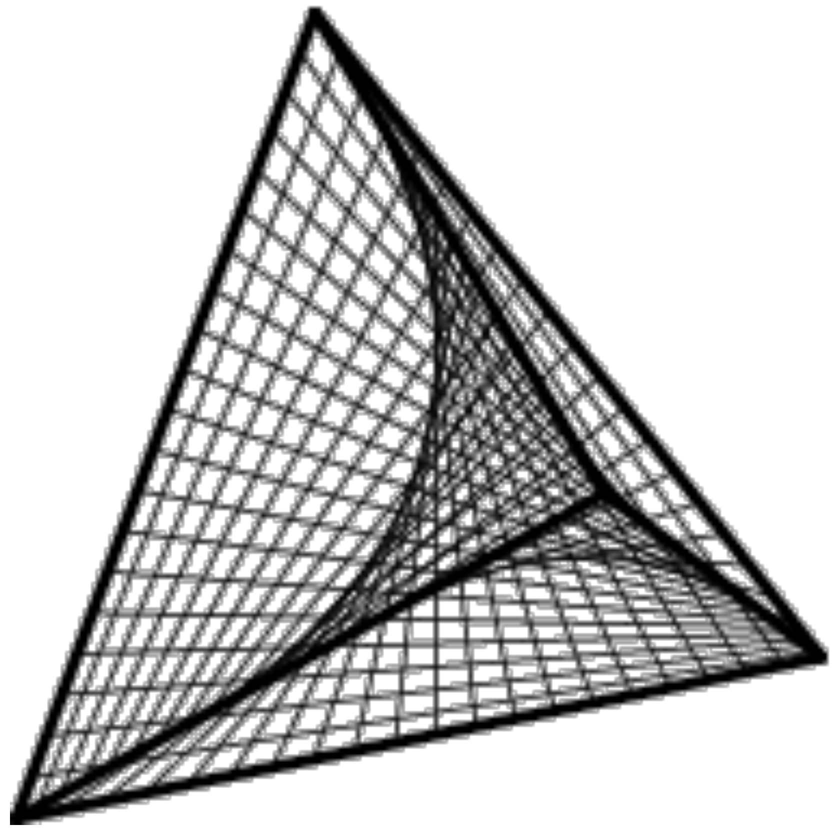
Frogatt & Nielsen

Precision determination of mixing angles

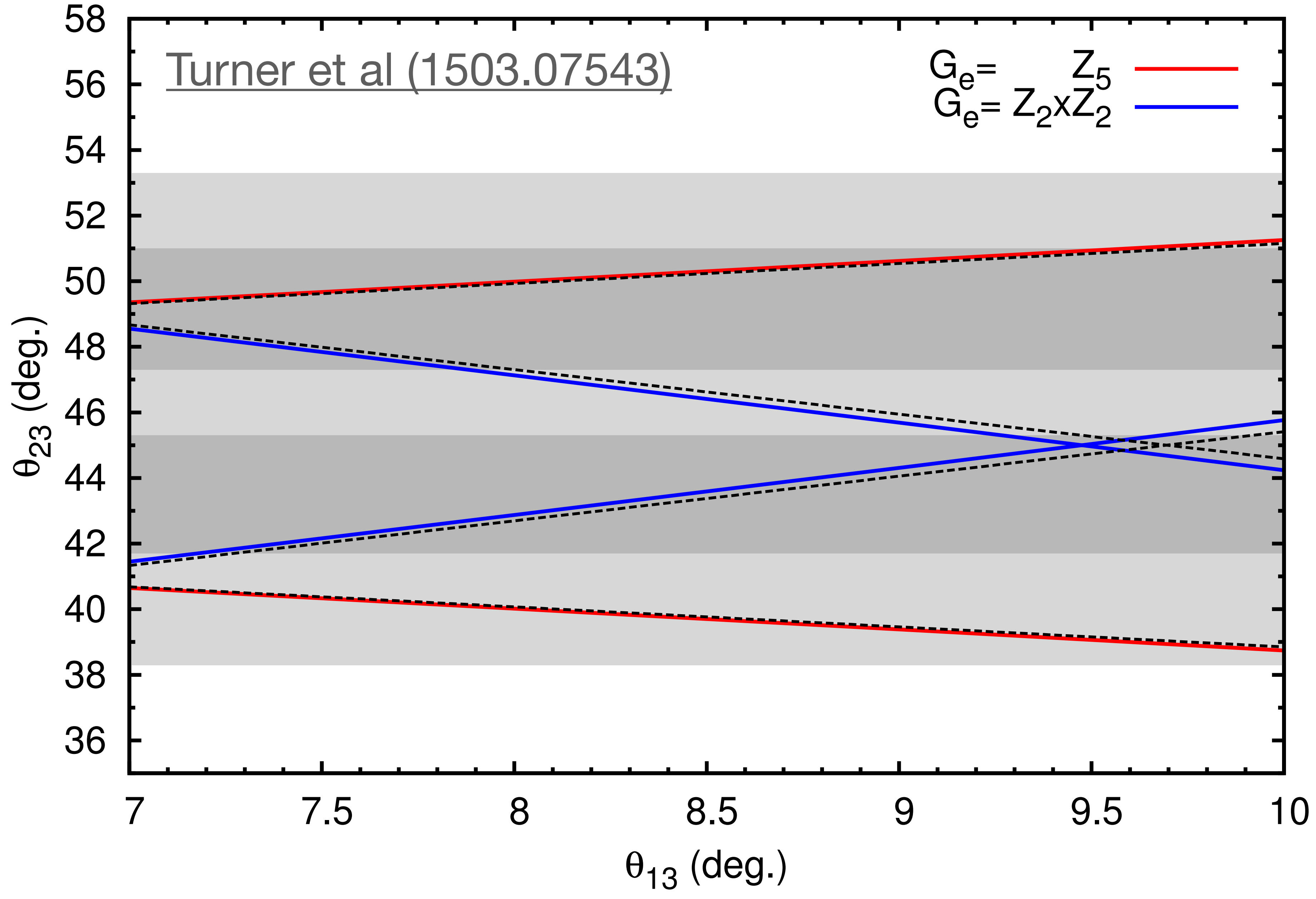


De Gouvea & Murayama

Discrete symmetries popular way to address "flavour puzzle"



$$U_{\rm TBM} = \begin{pmatrix} \frac{2}{\sqrt{6}} & \frac{1}{\sqrt{3}} & 0 \\ -\frac{1}{\sqrt{6}} & \frac{1}{\sqrt{3}} & \frac{1}{\sqrt{2}} \\ -\frac{1}{\sqrt{6}} & \frac{1}{\sqrt{3}} & -\frac{1}{\sqrt{2}} \end{pmatrix}$$

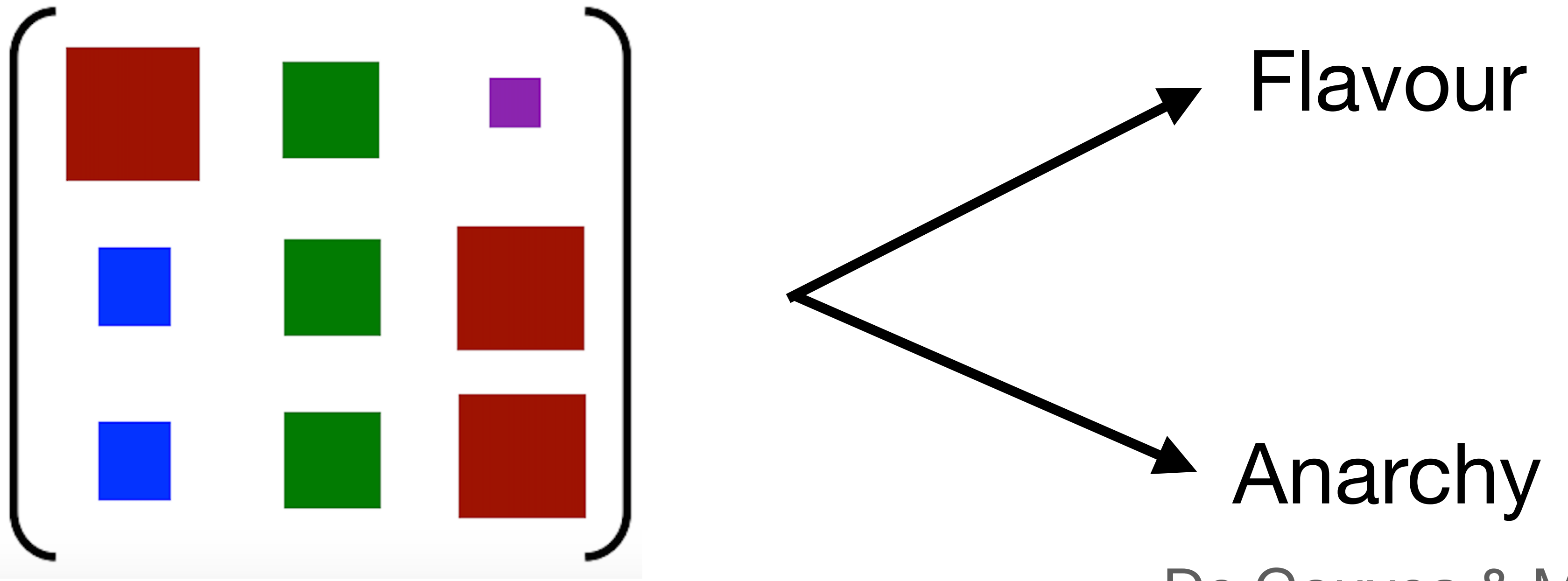


If flavour breaking scale is not high, we can search for cLFV, collider signatures

The Future of Neutrinos

Frogatt & Nielsen

Precision determination of mixing angles



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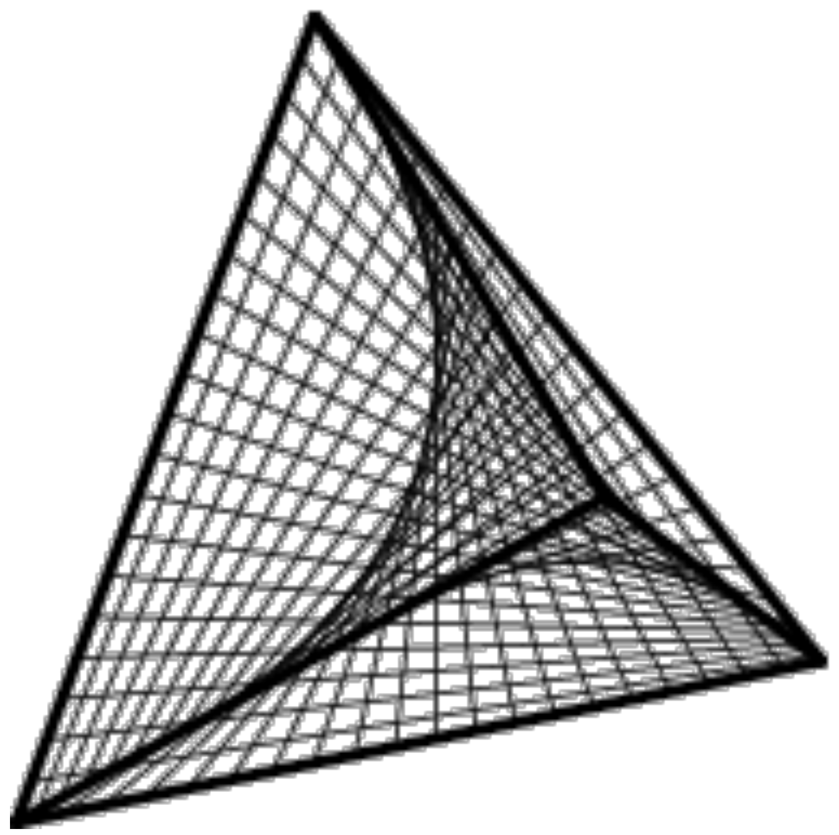
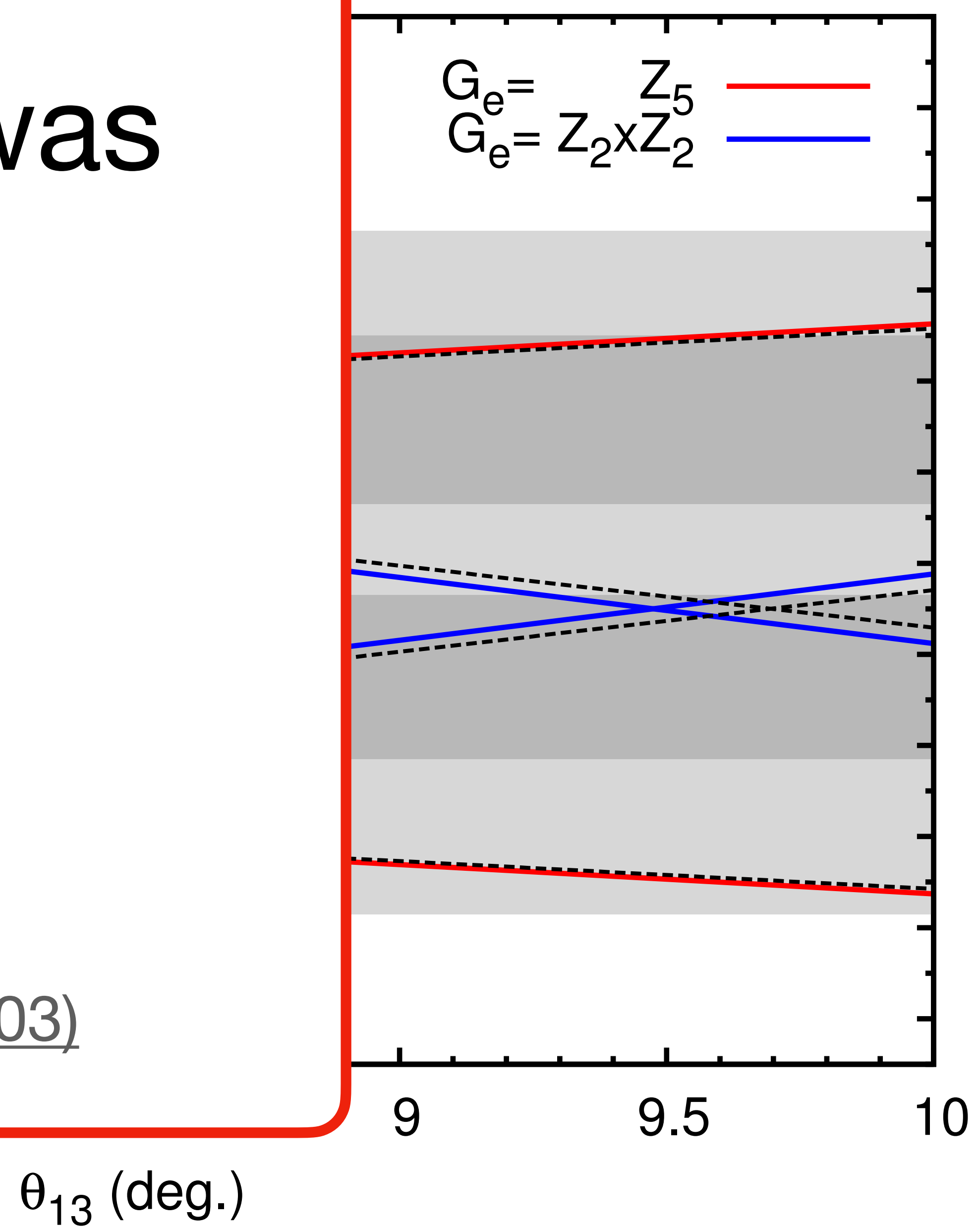


Interesting connection with GWs: if there was a discrete flavour symmetry you would get domain walls in the early Universe. The explicit breaking of the residual flavour symmetries can cause the domain walls to decay giving a GW signal

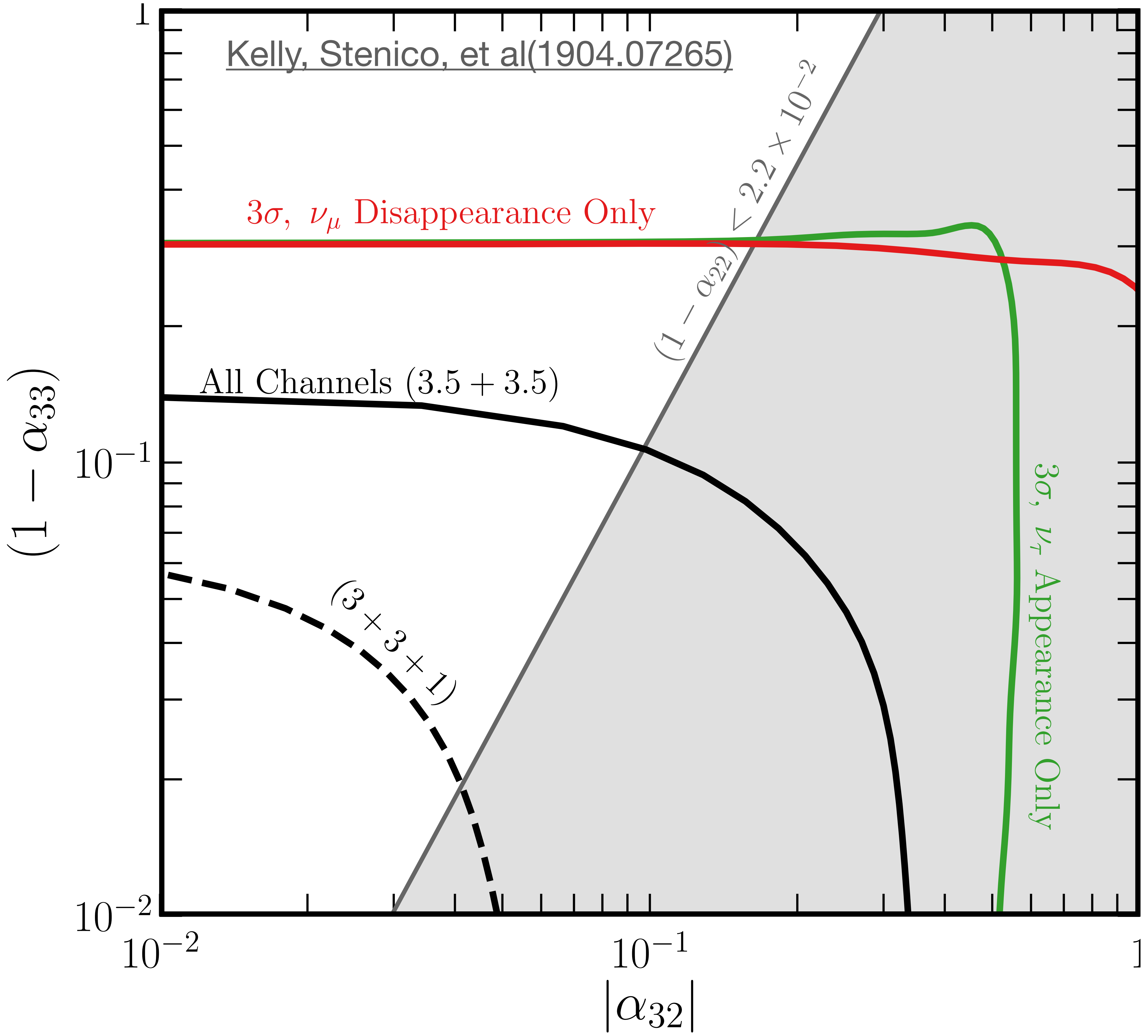
Pascoli, Zhou et al (2009.01903)

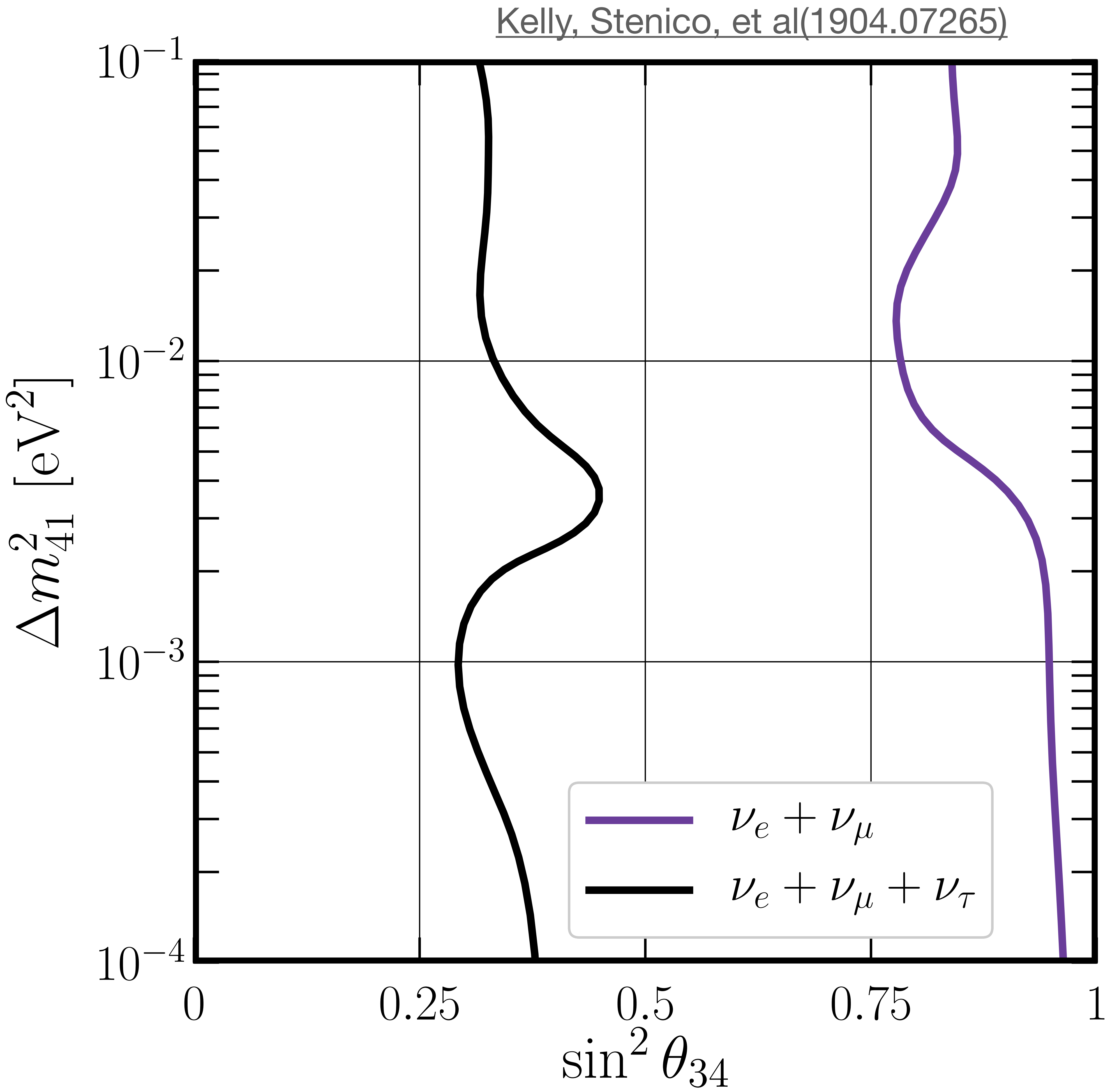


If flavour breaking scale is not high, we can search for cLFV, collider signatures

The Future of Neutrinos

Precision determination of mixing angles will also be improved by measuring tau neutrino appearance.

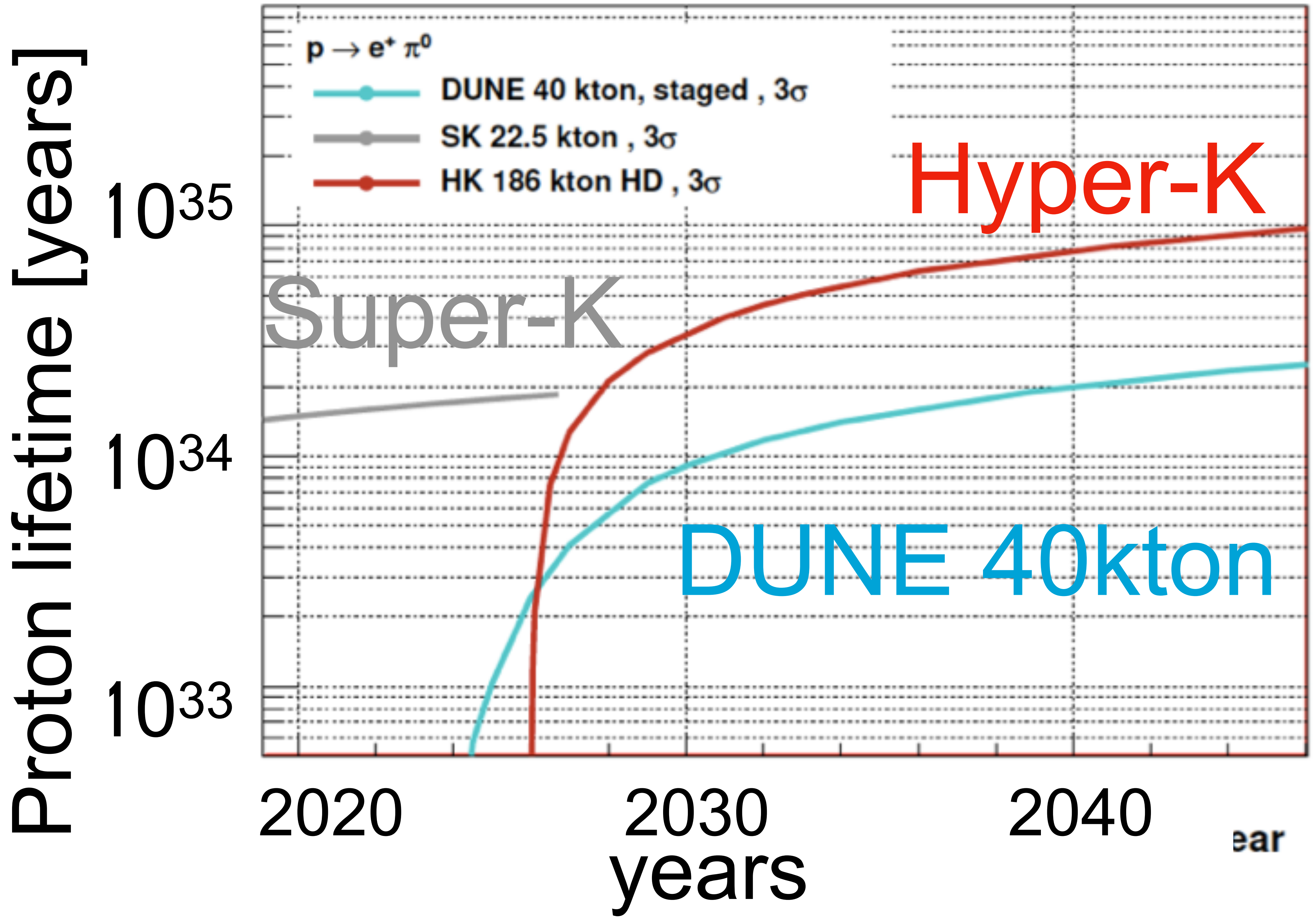




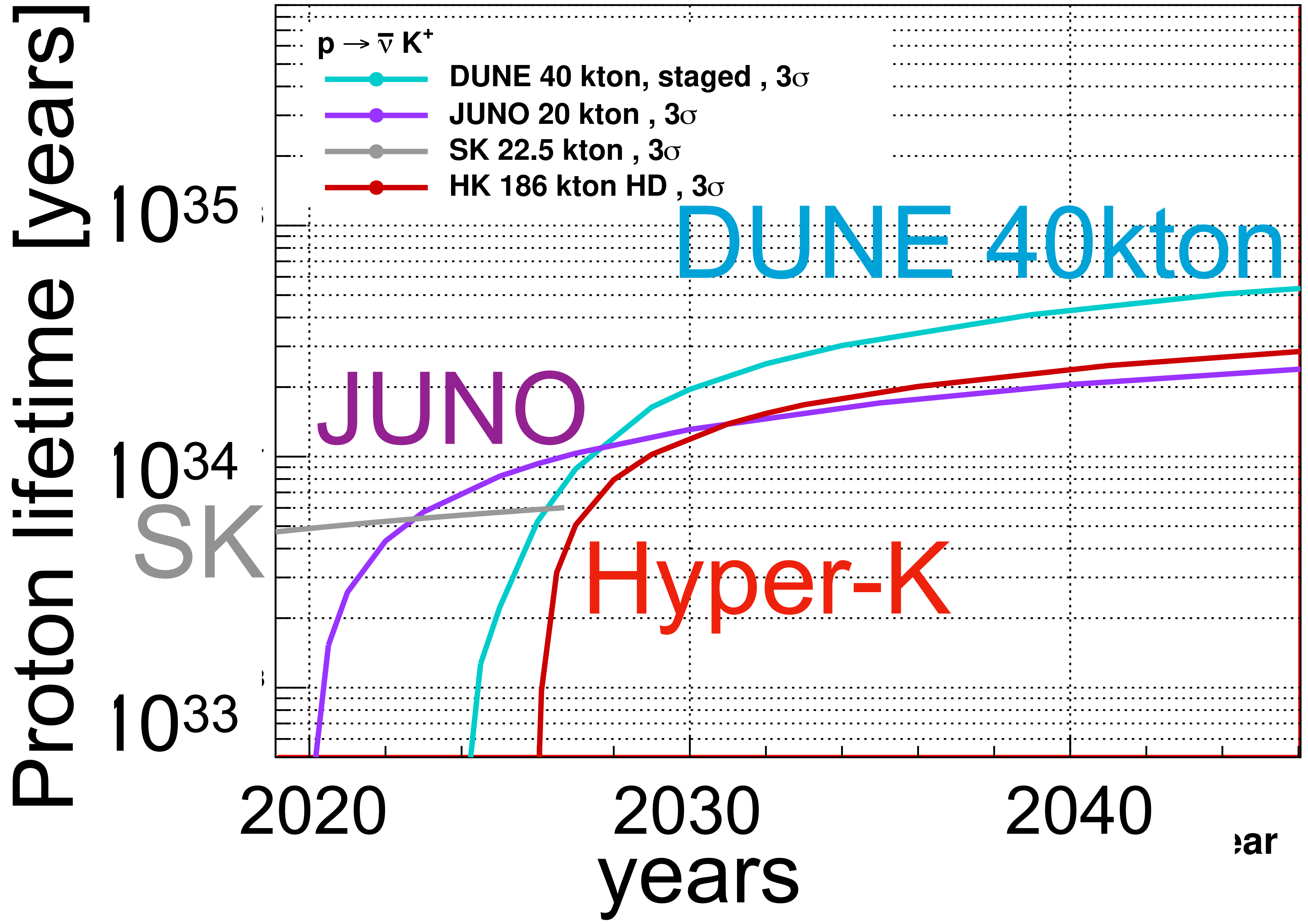
The Future of Neutrinos

Shiozawa (neutrino townhall 2018)

$p \to e^+\pi^0$ 3σ discovery



$p \to \nu K^+$ 3σ discovery

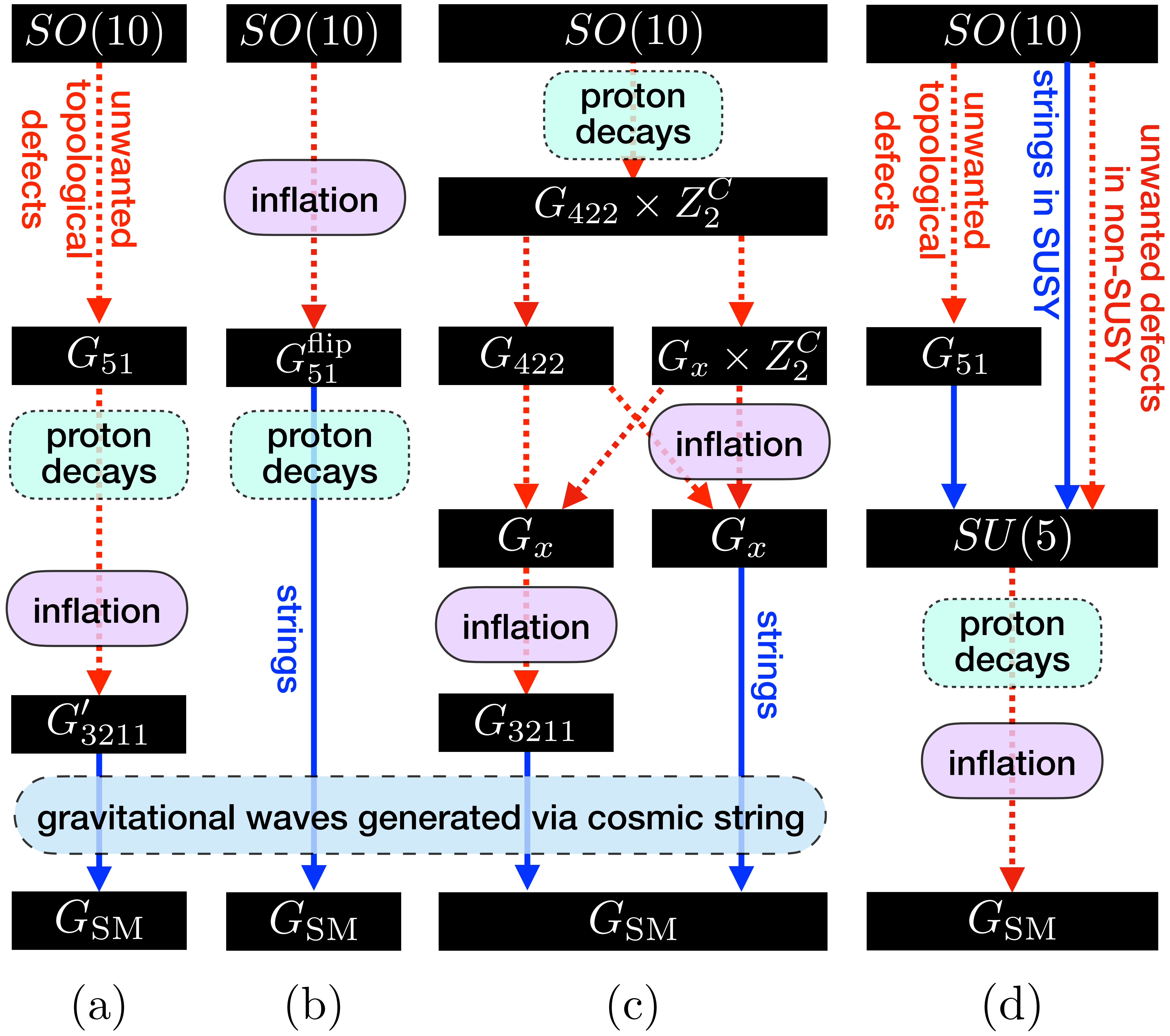


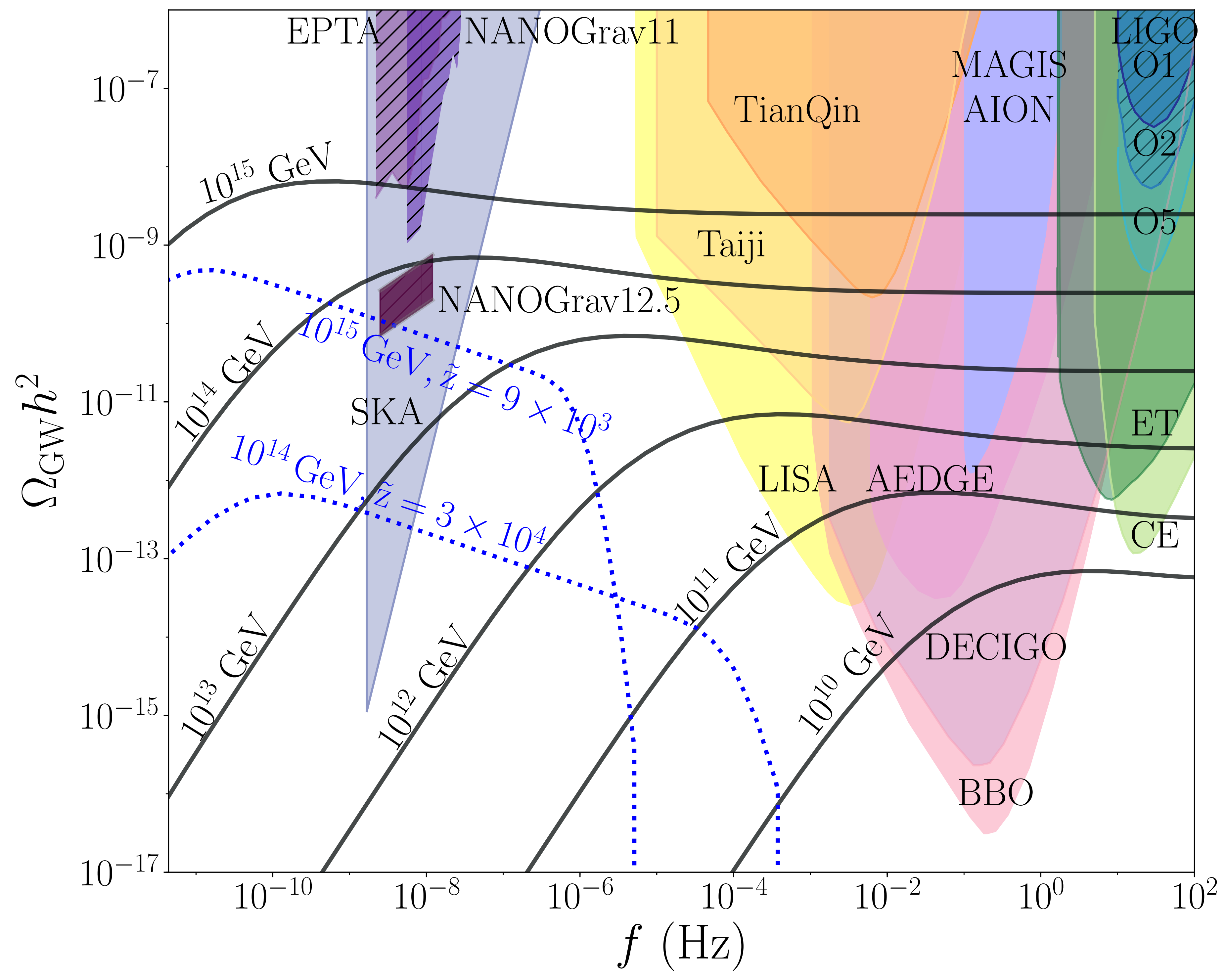
GUTs produce cosmic string networks $\Longrightarrow$ gravitational waves

Correlate limits (or observations!) from PD with observations/non-observations of GWs to assess symmetry breaking chains

The Future of Neutrinos

King, Pascoli, Turner, Zhou (2005.13549)





Observables		**Proton decays**
		$p \to \pi^0 e^+$ observed $\Rightarrow$ non-SUSY contribution indicated
GWs	Observed	• types (a) and (c) favoured • types (b) and (d) excluded
GWs	Marginal	• types (a) and (c) favoured • type (d) excluded • type (b) allowed if $p \to K^+ \bar{\nu}$ not observed and $\Lambda_{\rm pd} \sim \Lambda_{\rm cs}$

The Future of Neutrinos

- Axions at the DUNE near detector Kelly, Liu et al(2011.05995)
- Primordial black holes at DUNE De Romeri et al (2106.05013)
- Earth's tomography using DUNE Kelly, Perez-Gonzalez et al (2110.00003)
- Measuring the diffuse neutrino background at HyperK De Gouvea, Perez-Gonzalez et al (2007.13748)
- Boosted Dark Matter at HyperK & DUNE Necib et al (1610.03486)
- Lorentz violation HyperK Litchfield(NuFact 2019)
- Non-standard interactions (νEFT) at HyperK and DUNE NSI report (1907.00991)
- Supernovae neutrino detection DUNE report HyperK (2101.05269)
- Time varying neutrino masses Krnjaic, Machado, Necib (1705.06740)

There are many more interesting theories/physics cases and Experiments I didn't have time to discuss.

Carlo Giunti's website: http://www.nu.to.infn.it/exp/ where he keeps a list of ongoing/future neutrino experiments

Experiments

Filter this page

(Note: The process can take some time.)

Search Reset

Types of Neutrino Experiments

Accelerator Beam Dump | Astrophysical Neutrinos | Atmospheric Neutrinos

Electron Neutrino | Long-Baseline Neutrino Oscillations | Muon Neutrino

Neutrinoless Double Beta Decay | Short-Baseline Neutrino Oscillations | Solar Neutrinos

Supernova Neutrinos | Tau Neutrino

EXPAND ALL | COMPRESS ALL

Neutrino Experiments

AMANDA High-Energy Astrophysical Neutrinos, Supernova Neutrinos (Home, INSPIRE) References

ANTARES High-Energy Astrophysical Neutrinos (Home, INSPIRE) References

ARIANNA High-Energy Astrophysical Neutrinos (Home, INSPIRE) References

ArgoNeuT Neutrino Interactions (INSPIRE) References

Baikal High-Energy Astrophysical Neutrinos, Supernova Neutrinos (Home, INSPIRE) References

Baksan Atmospheric and Supernova SN1987A Neutrinos (Home, INSPIRE) References

BOREXino Solar Neutrinos (Home, INSPIRE) References

BEBC Accelerator SBL Oscillations, Neutrino Interactions (INSPIRE) References

BNL-E-734 Neutrino Interactions (INSPIRE) References

BNL-E-776 Accelerator SBL Oscillations (INSPIRE) References

BNL-E-816 Accelerator SBL Oscillations (INSPIRE) References

Bugey Reactor SBL Oscillations (INSPIRE) References

CCFR Accelerator SBL Oscillations, Muon Neutrino - Nucleon Scattering (Home, INSPIRE) References

CDHSW Accelerator SBL Oscillations, Muon Neutrino - Nucleon Scattering (INSPIRE) References

CERN-PS-191 Accelerator SBL Oscillations (INSPIRE) References

CHARM Accelerator SBL Oscillations (INSPIRE) References

Chooz Reactor LBL Oscillations (Home, INSPIRE) References

CHORUS Accelerator SBL Oscillations (Home, INSPIRE) References

COBRA Double Beta Decay (^{70}Zn, ^{116}Cd, ^{128}Te, ^{130}Te) (Home) References

CUORE Double Beta Decay (^{130}Te) (Home) References

CUORICINO Double Beta Decay (^{130}Te) (Home) References

DANSS Reactor SBL Oscillations (INSPIRE) References

Daya Bay Reactor LBL Oscillations (Home) References

DONUT Tau Neutrino Interactions (Home, INSPIRE) References

Double Chooz Reactor LBL Oscillations (Home) References

ELEGANT Double Beta Decay (^{48}Ca, ^{100}Mo) References

EXO Double Beta Decay (^{136}Xe) (Home) References

FNAL-E-0053 Accelerator SBL Oscillations (INSPIRE) References

FNAL-E-0531 Accelerator SBL Oscillations (INSPIRE) References

FNAL-E-0613 Accelerator SBL Oscillations (INSPIRE) References

Frejus Atmospheric Neutrinos, Proton Decay (INSPIRE) References

GALLEX Solar Neutrinos, SBL Oscillations with ^{51}Cr Neutrino Source (Home, INSPIRE) References

Gargamelle Accelerator SBL Oscillations, Neutrino Interactions (INSPIRE) References

Genova ^{187}Re Electron Neutrino Mass (Home, INSPIRE) References

GERDA Double Beta Decay (^{76}Ge) (Home) References

GEMMA Reactor Electron Antineutrino - Electron Scattering References

GLUE High-Energy Astrophysical Neutrinos (Home, INSPIRE) References

GNO Solar Neutrinos (Home, INSPIRE) References

Gosgen Reactor SBL Oscillations (INSPIRE) References

Gotthard Double Beta Decay (^{136}Xe) (Home) References

Heidelberg-Moscow Double Beta Decay (^{76}Ge) (Home) References

Homestake Solar Neutrinos (INSPIRE) References

ICARUS Accelerator Long Baseline Oscillations, Supernova Neutrinos, Proton Decay (Home, INSPIRE) References

IceCube High-Energy Astrophysical Neutrinos (Home, INSPIRE) References

IGEX Double Beta Decay (^{76}Ge) (INSPIRE) References

IHEP-JINR Accelerator SBL Oscillations, Neutrino-Nucleon Interactions (INSPIRE) References

ILL Reactor SBL Oscillations (INSPIRE) References

IMB Atmospheric Neutrinos, Supernova SN1987A Neutrinos, Proton Decay (Home, INSPIRE) References

K2K Accelerator Long Baseline Oscillations (Home, INSPIRE) References

Kamiokande Solar, Atmospheric and Supernova SN1987A Neutrinos, Proton Decay (Home, INSPIRE) References

KamLAND Reactor Long Baseline Oscillations, Supernova Neutrinos (Home, INSPIRE) References

KamLAND-Zen Double Beta Decay (^{136}Xe) (Home) References

KARMEN Accelerator SBL Oscillations (Home, INSPIRE) References

Krasnoyarsk Reactor SBL Oscillations (INSPIRE) References

LAMPF-0645 Accelerator SBL Oscillations (INSPIRE) References

LAMPF-0764 Accelerator SBL Oscillations (INSPIRE) References

LSD Supernova SN1987A Neutrinos, Astrophysical Neutrinos (INSPIRE) References

LSND Accelerator SBL Oscillations (Home, INSPIRE) References

LVD Supernova Neutrinos, Astrophysical Neutrinos (Home, INSPIRE) References

MACRO Atmospheric Neutrinos (Home, INSPIRE) References

Mainz Electron Neutrino Mass (Home, INSPIRE) References

MiBeta Electron Neutrino Mass (Home) References

MicroBooNE Accelerator SBL Oscillations, Neutrino Interactions (Home) References

MINERvA Neutrino Interactions (Home, INSPIRE) References

MiniBooNE Accelerator SBL Oscillations, Supernova Neutrinos (Home, INSPIRE) References

MINOS Accelerator Long Baseline Oscillations, Atmospheric Neutrinos (Home, INSPIRE) References

MUNU Reactor Electron Antineutrino - Electron Scattering (Home, INSPIRE) References

NEMO Double Beta Decay (^{82}Se, ^{100}Mo, ^{150}Nd) (Home, INSPIRE) References

NEOS Reactor Short-Baseline Oscillations (INSPIRE) References

Neutrino-4 Reactor SBL Oscillations (INSPIRE) References

NEXT Double Beta Decay (^{136}Xe) (Home) References

NOMAD Accelerator SBL Oscillations (Home, INSPIRE) References

NOVA Accelerator Long Baseline Oscillations (Home, INSPIRE) References

Nucifer Reactor SBL Oscillations (INSPIRE, Wikipedia) References

NUSEX Atmospheric Neutrinos, Proton Decay (INSPIRE) References

NuTeV Accelerator Muon Neutrino - Nucleon Scattering (Home, INSPIRE) Reference

OPERA Accelerator Long Baseline Oscillations (Home, INSPIRE) References

Palo Verde Reactor Long Baseline Oscillations (Home, INSPIRE) References

RENO Reactor LBL Oscillations (Home) References

RICE High-Energy Astrophysical Neutrinos, Supernova Neutrinos (Home, INSPIRE) References

Rovno Reactor SBL Oscillations (INSPIRE) References

SAGE Solar Neutrinos (Home, INSPIRE) References

Savannah River Reactor SBL Oscillations (INSPIRE) References

SciBooNE Accelerator Muon Neutrino - Nucleon Scattering (Home, INSPIRE) References

SKAT Accelerator SBL Oscillations, Neutrino-Nucleon Interactions (INSPIRE) References

SNO Solar and Supernova Neutrinos (Home, INSPIRE) References

SNO+ Neutrinoless Double Beta Decay (^{150}Nd), Solar, Reactor, Geo and Supernova Neutrinos (Home) References

Solotvina Double Beta Decay (^{116}Cd) References

Soudan 2 Atmospheric Neutrinos, Proton Decay (Home, INSPIRE) References

Super-Kamiokande Solar and Atmospheric Neutrinos, Proton Decay (Home, INSPIRE) References

T2K Accelerator Long Baseline Oscillations (Home, INSPIRE) References

TEXONO Electron Neutrino Interactions (Home, INSPIRE) References

TGV Double Beta Decay (^{48}Ca, ^{106}Cd) References

Troitsk Electron Neutrino Mass (Home, INSPIRE) References

Progress is contingent upon understanding neutrino nucleon interactions better and improved modelling of underlying nuclear physics!

Thank you for your attention

$$m_\nu = \frac{Y_\nu^2 v^2}{M_N}$$

$$\sigma = \frac{G_F^2 s}{\pi}$$

And enjoy the holidays!

Backup slides leptogenesis

Mass RHN

$\mathcal{O}(10^{12})$ GeV

Fukugida & Yanagida *Phys.Lett. B17 45-47* (1986) Buchmuller, Di Bari & Plumacher *New J.Phys. 6 105* (2004) Barbieri, Creminelli, Strumia & Tetradis *Nucl.Phys. B575 61-77* (2000)

$\mathcal{O}(10^{6})$ GeV

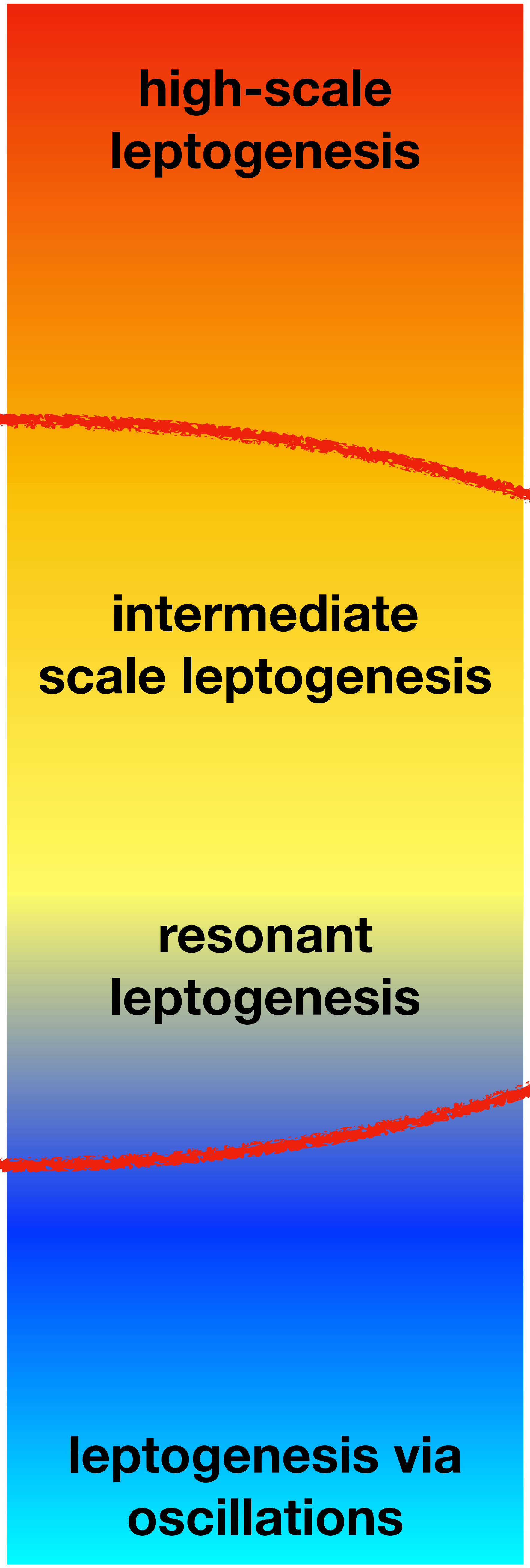
Racker, Rius & Pena *JCAP 1207 030* (2013) Moffat, Petcov, Pascoli, Schulz & Turner *Phys.Rev. D98 no.1, 015036* (2018)

$\mathcal{O}(10^{3})$ GeV

Pilaftis & Underwood *Nucl.Phys. B692 303-345* (2004) Abada, Aissaoui, Losada *Nucl.Phys. B728 55-66* (2005)

$\mathcal{O}(1)$ GeV

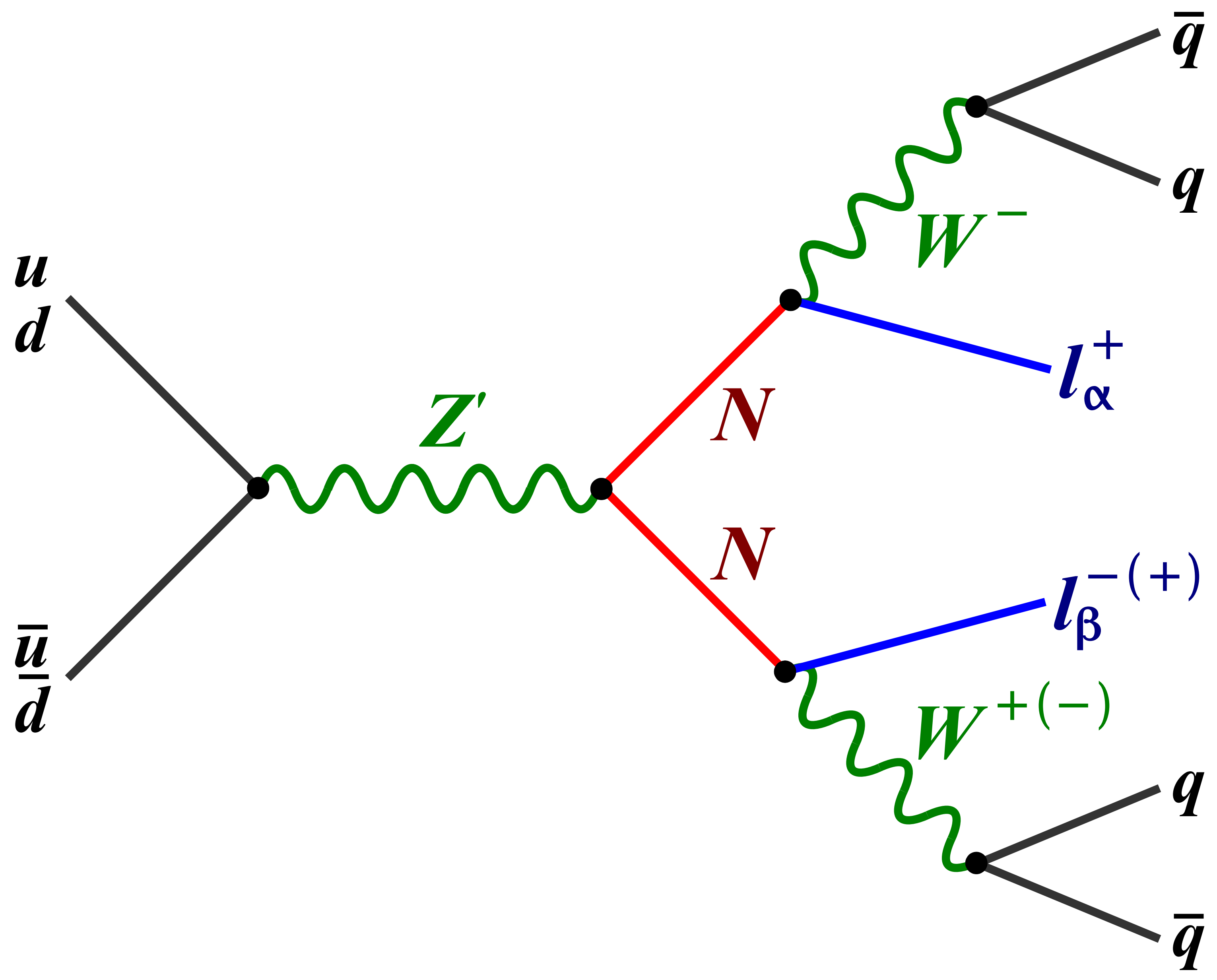
Akhmedov, Rubakov & Smirnov *Phys.Rev.Lett. 81 1359-1362* (1998) Asaka & Shaposhnikov *Phys.Lett. B620 17-26* (2005) Asaka, Eijima & Ishida *JHEP 1104 011*(2011)

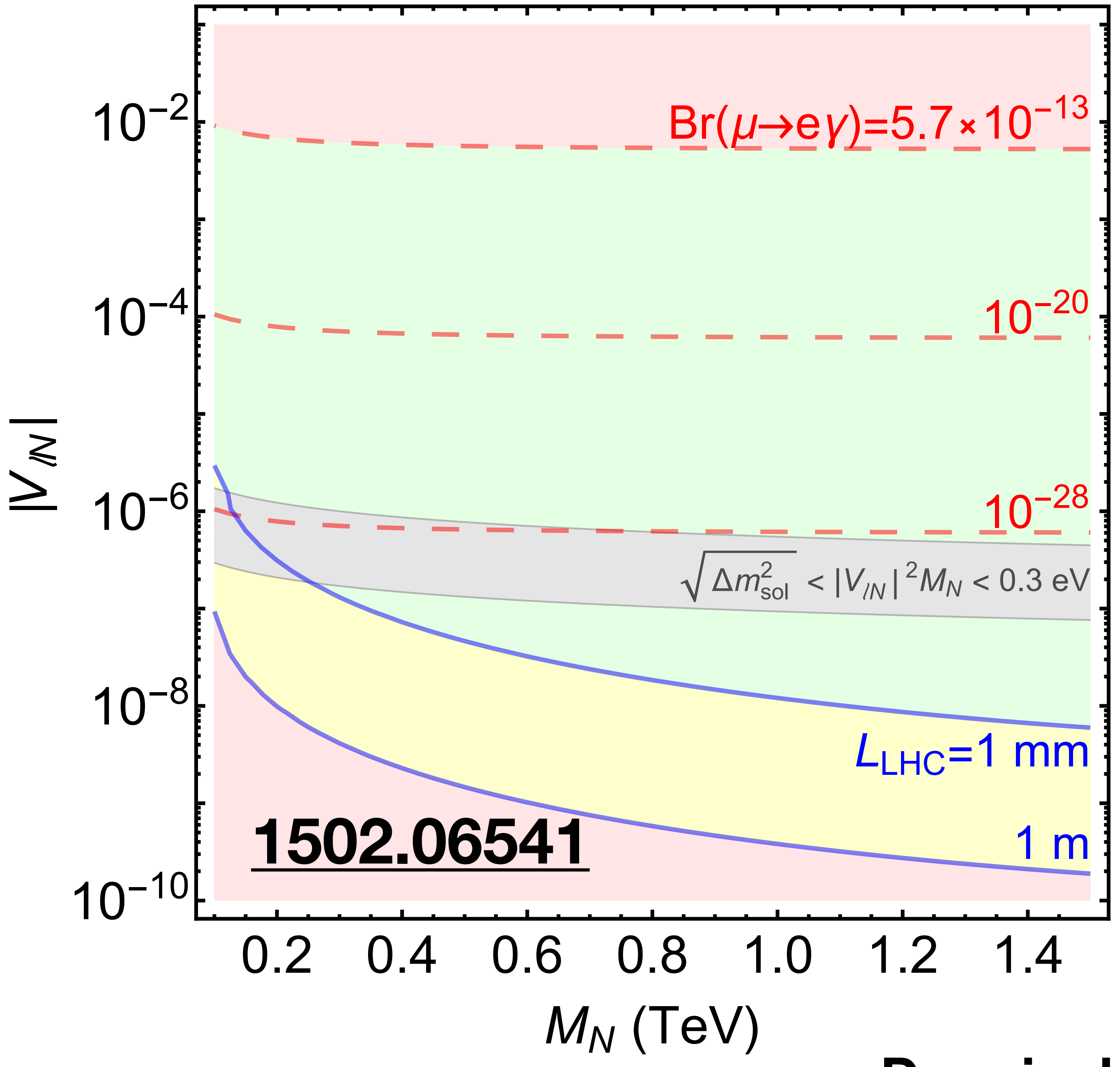


Resonant Leptogenesis

Pilaftis & Underwood *Nucl.Phys. B692 303-345*(2004) Abada, Aissaoui, Losada *Nucl.Phys. B728 55-66* (2005)

- RHNs decay width similar to their mass differences. Mass range ~ TeV
- RHN masses explained by additional $U(1)_{B-L}$ symmetry and can be sufficiently long-lived → displaced-vertex signature searched for at LHC, MATHUSLA or SHiP.





Deppisch, Dev & Pilaftsis *New J.Phys. 17 no.7, 075019* (2015)
Helo, Kovalenko & Hirsch *Phys.Rev. D89 073005* (2014)
Gago, Hernández, Jones-Pérez, Losada & Briceño *Nucl.Part.Phys.Proc. 273-275 2693-2695* (2016)
Antusch, Cazzato & Fischer *JHEP 1612 007* (2016)

Deppisch, Dev, Pilaftsis, New J.Phys. 17 (2015) no.7, 075019

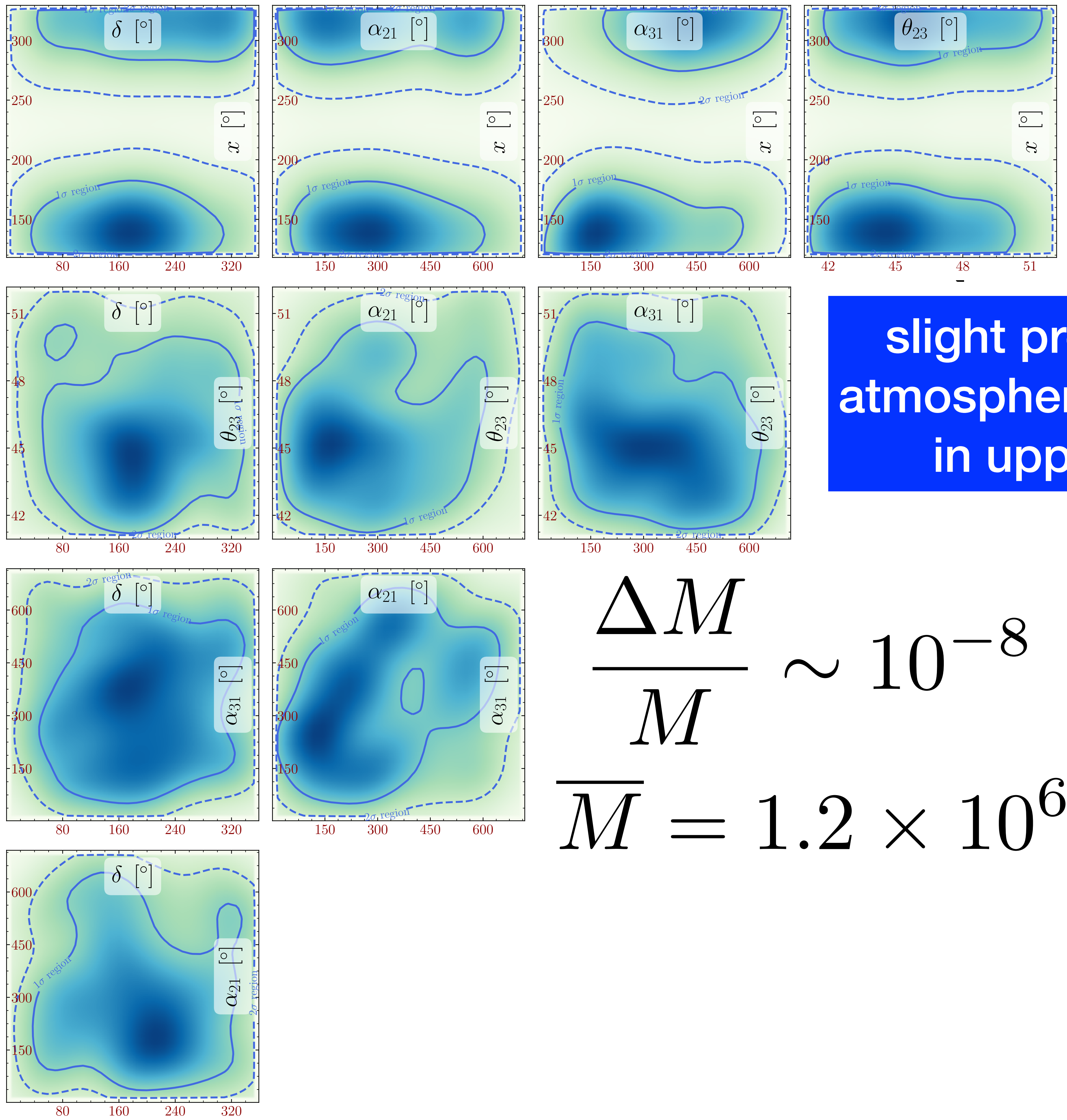
Resonant Leptogenesis in the Neutrino Option

- Assume Higgs potential vanishes at M
- Integrate out TeV RHN and RG evolve: Higgs potential produced for M ~ 10^3 TeV

Brdar, Hemboldt, Iwamoto, Schmitz *Phys.Rev. D100 075029* (2019)
Brivio, Moffat, Pascoli, Petcov, Turner *JHEP 1910 059* (2019)

Normal Ordering

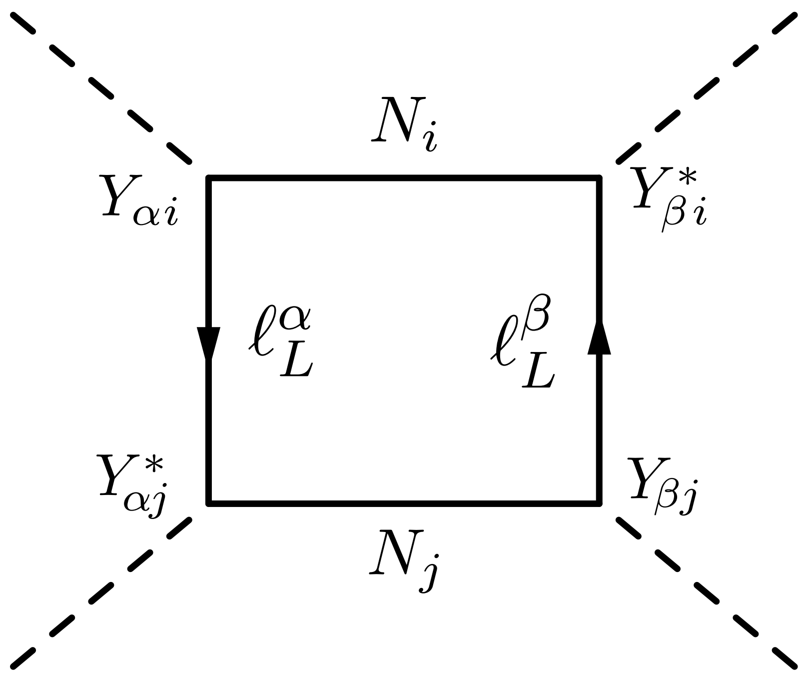
Brivio et al
<u>1905.12642</u>

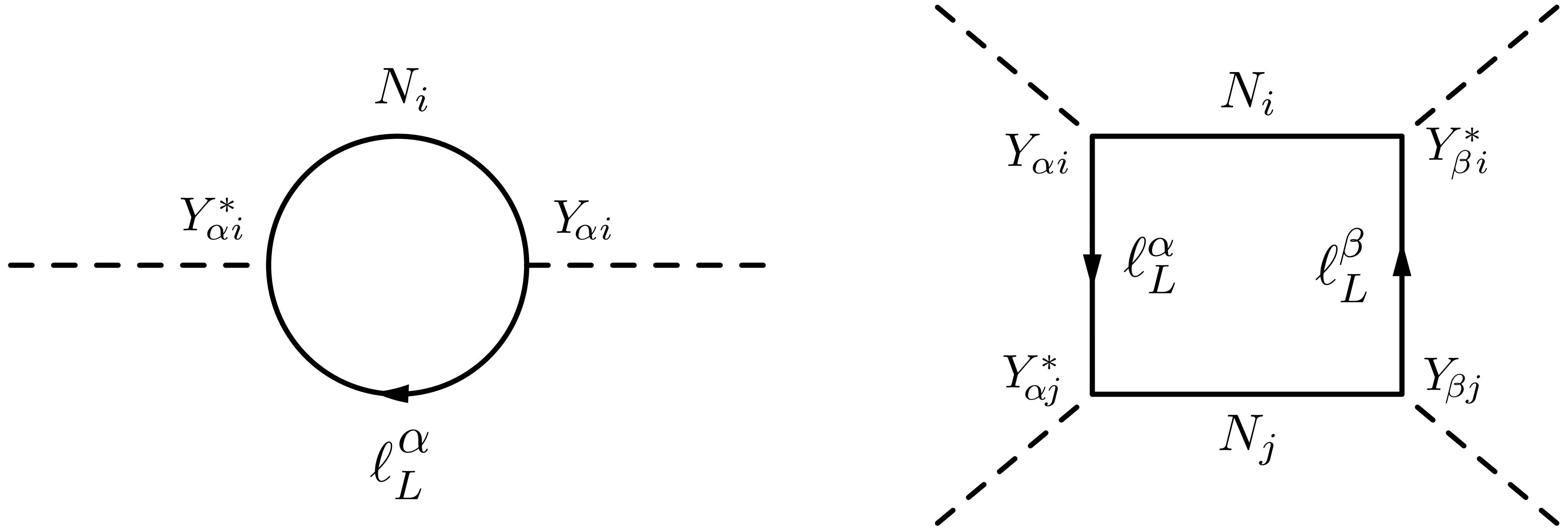


slight preference for atmospheric angle to be in upper octant.

$$\frac{\Delta M}{M} \sim 10^{-8}$$

$$\overline{M} = 1.2 \times 10^6 \,\mathrm{GeV}$$



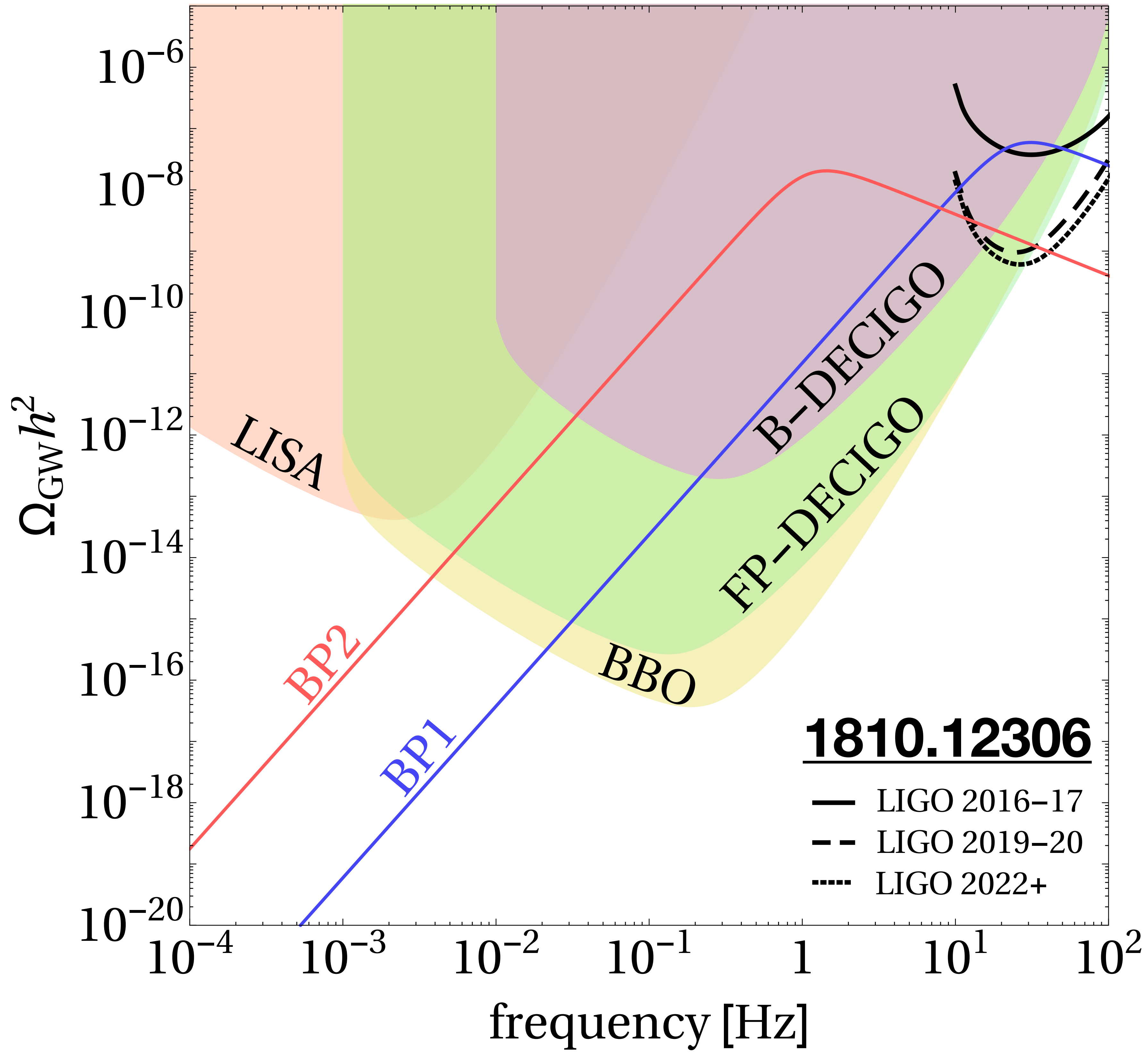


Scale invariance broken at quantum level

Resonant Leptogenesis in the Neutrino Option

- UV-completion of Neutrino Option (Brdar, Emonds, Helmboldt, Lindner) minimal renormalisable model based on classical scale invariance

- New scalar breaks scale-invariance → generates mass for RHNs and strong first order phase transition



Brdar, Emonds, Helmboldt, Lindner
Phys.Rev. D99 (2019) no.5, 055014

Mass RHN

$$\mathcal{O}(10^{12})\ \text{GeV}$$

Fukugida & Yanagida *Phys.Lett. B17 45-47* (1986) Buchmuller, Di Bari & Plumacher *New J.Phys. 6 105* (2004) Barbieri, Creminelli, Strumia & Tetradis *Nucl.Phys. B575 61-77* (2000)

high-scale leptogenesis

$$\mathcal{O}(10^{6})\ \text{GeV}$$

Racker, Rius & Pena *JCAP 1207 030* (2013) Moffat, Petcov, Pascoli, Schulz & Turner *Phys.Rev. D98 no.1, 015036* (2018)

intermediate scale leptogenesis

$$\mathcal{O}(10^{3})\ \text{GeV}$$

Pilaftis & Underwood *Nucl.Phys. B692 303-345* (2004) Abada, Aissaoui, Losada *Nucl.Phys. B728 55-66* (2005)

resonant leptogenesis

$$\mathcal{O}(1)\ \text{GeV}$$

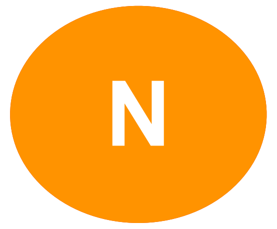
Akhmedov, Rubakov & Smirnov *Phys.Rev.Lett. 81 1359-1362* (1998) Asaka & Shaposhnikov *Phys.Lett. B620 17-26* (2005) Asaka, Eijima & Ishida *JHEP 1104 011*(2011)

leptogenesis via oscillations

Difficult to test as RHNs very heavy however gravitational waves offer an additional telescope on high-scale leptogenesis

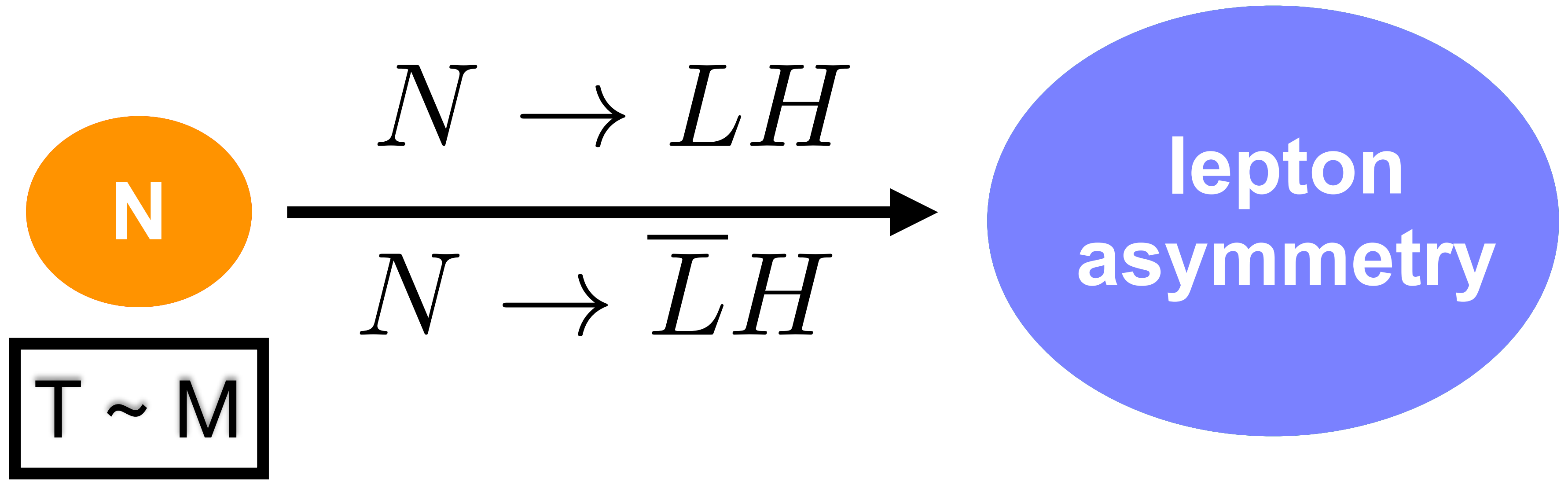
Thermal leptogenesis

Fukugida, Yanagida



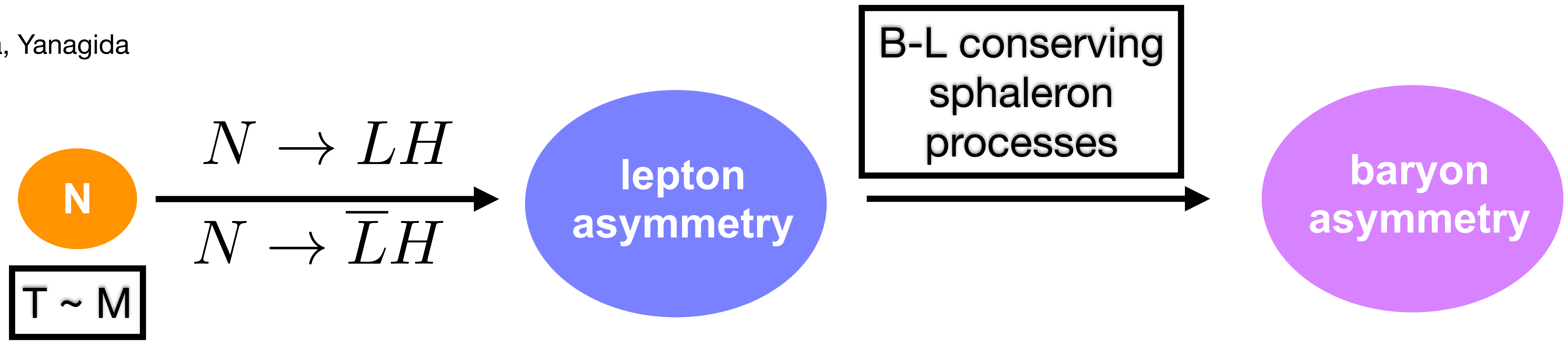
Thermal leptogenesis

Fukugida, Yanagida



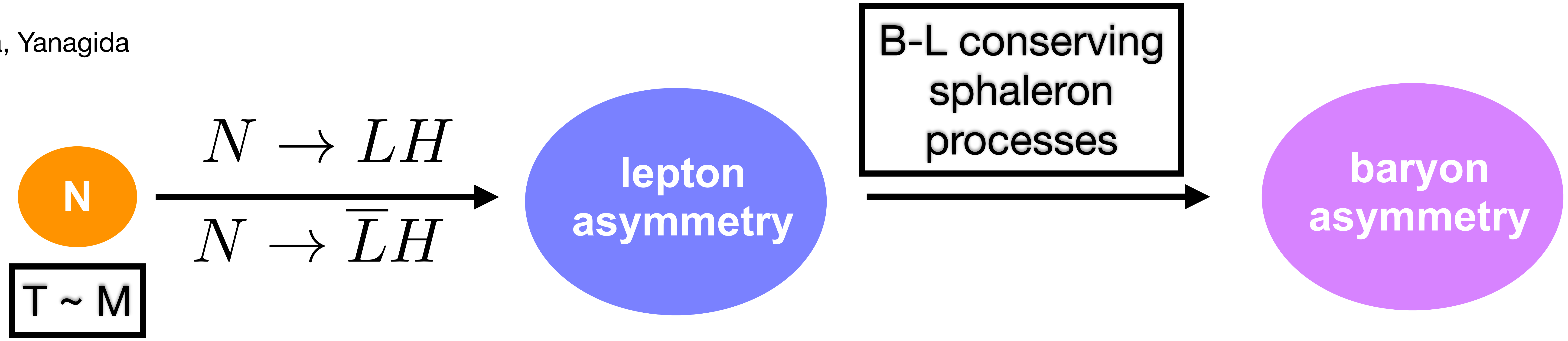
Thermal leptogenesis

Fukugida, Yanagida



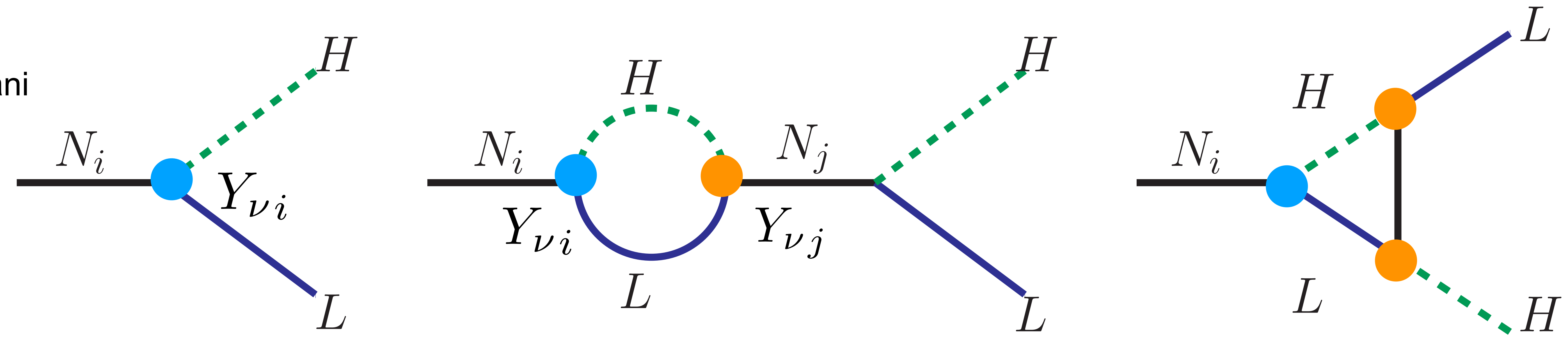
Thermal leptogenesis

Fukugida, Yanagida



Decay asymmetry from interference between tree and loop level diagrams

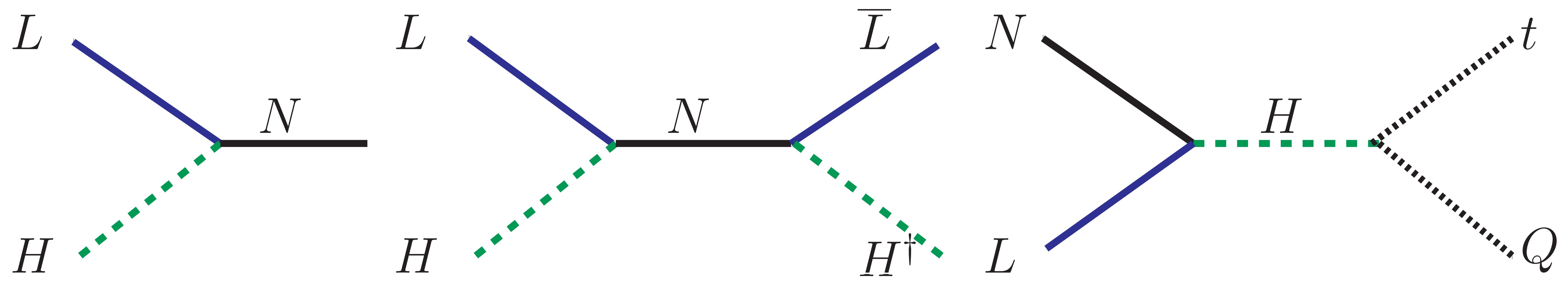
Covi, Roulet, Vissani



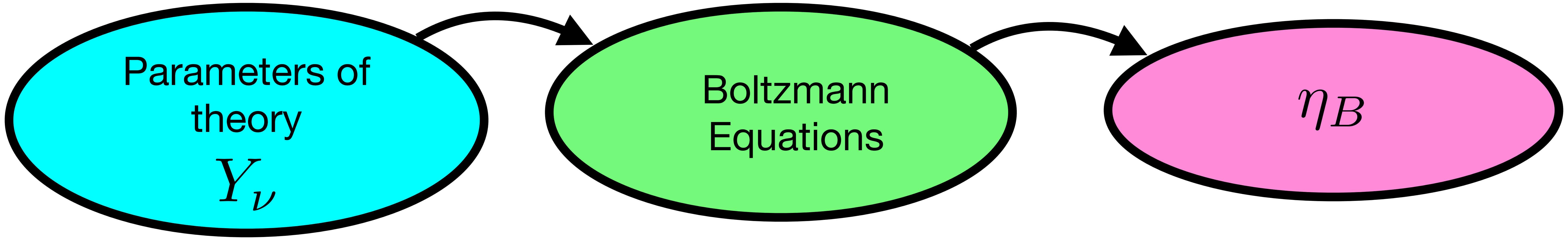
$$\epsilon_i = \frac{\Gamma_i - \overline{\Gamma}_i}{\Gamma_i + \overline{\Gamma}_i}$$

Thermal leptogenesis

Washout and scattering processes



inverse Decays ΔL=2 ΔL=1

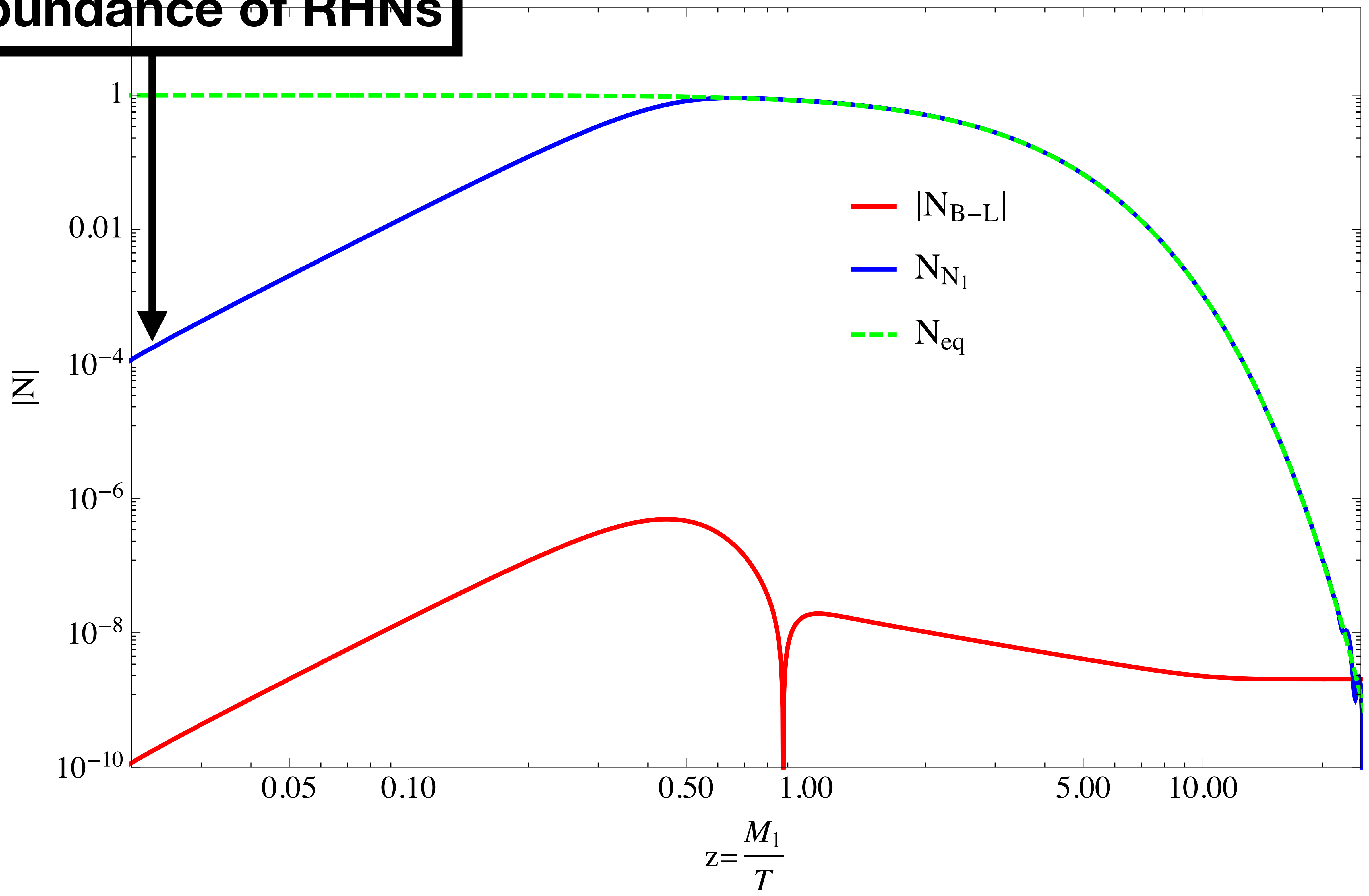


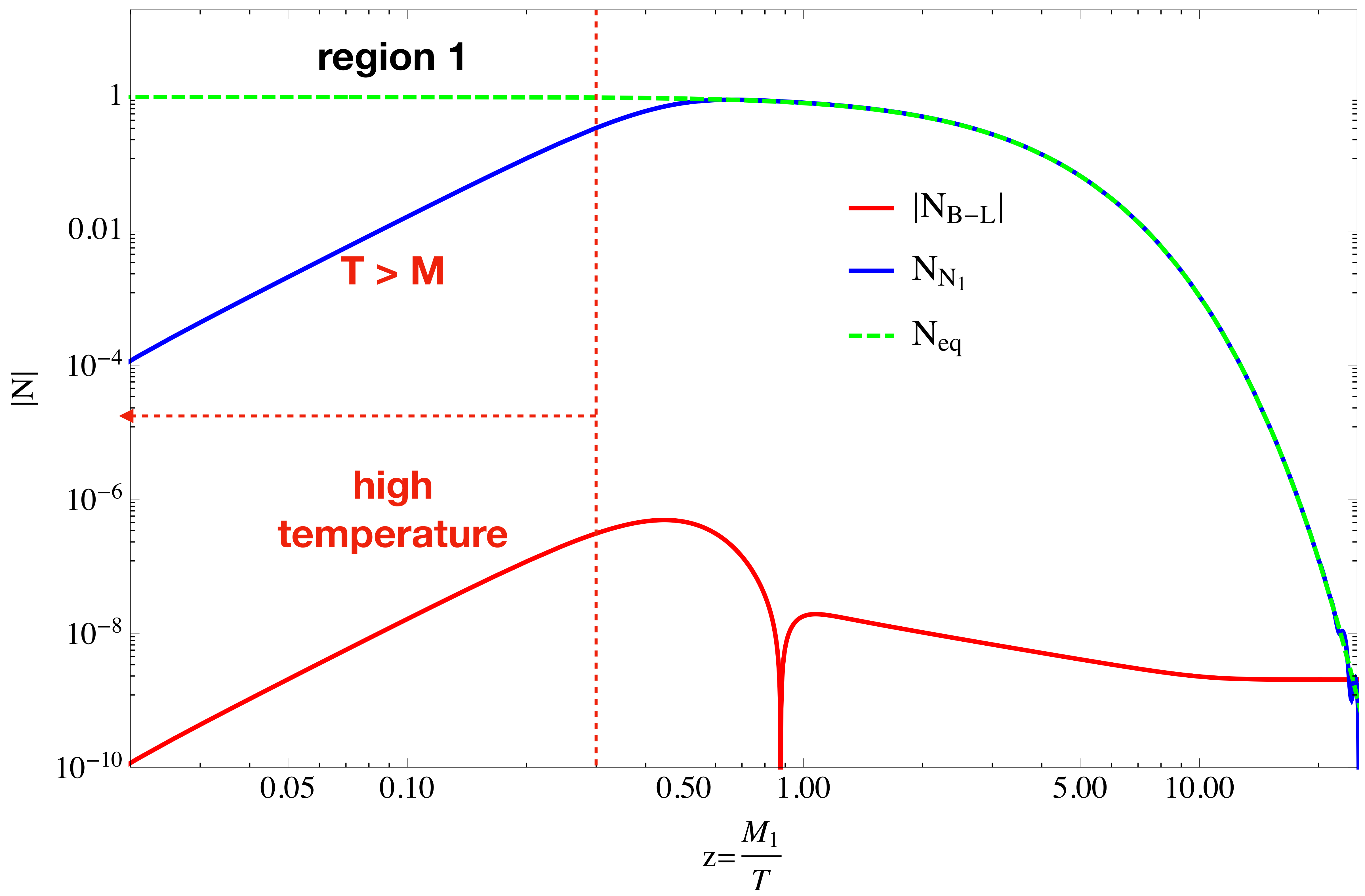
$$\frac{dn_{N_i}}{dz} = -\, D_i (n_{N_i} - n_{N_i}^{\rm eq}),$$

source **sink**

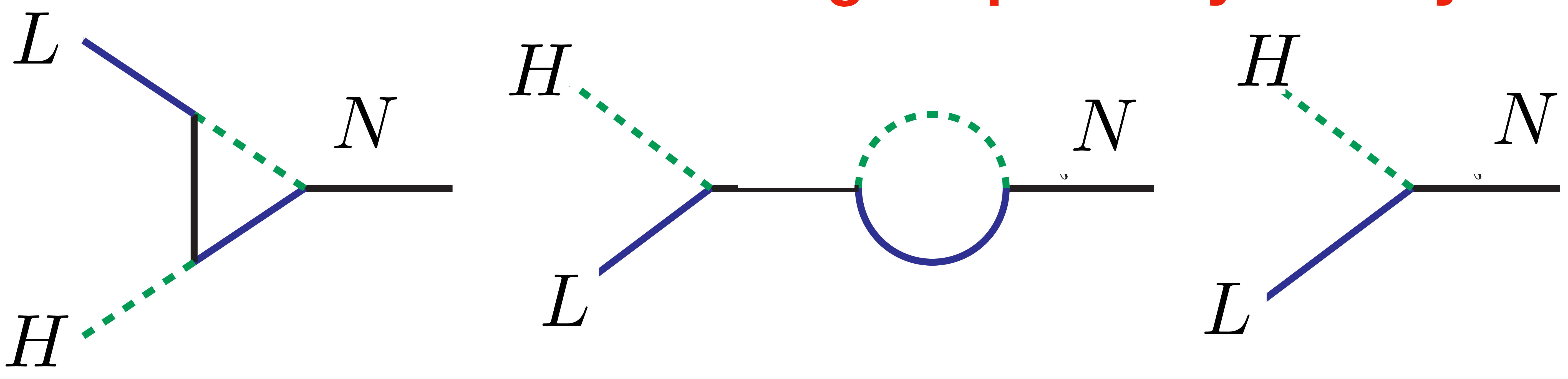
$$\frac{dn_{B-L}}{dz} = \sum_{i=1}^{3} \left(\epsilon^{(i)} D_i (n_{N_i} - n_{N_i}^{\rm eq}) - W_i n_{B-L} \right).$$

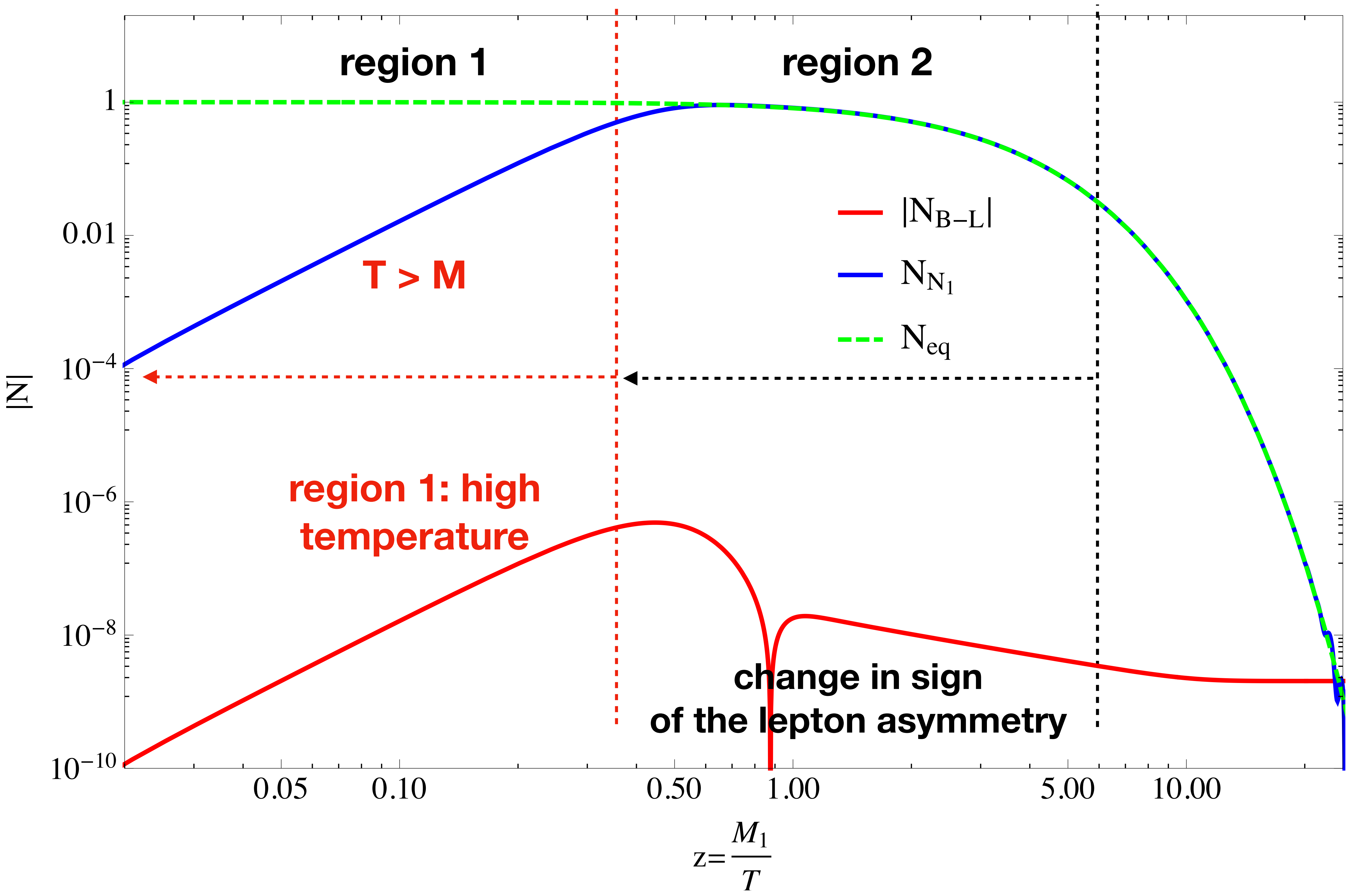
assume zero initial abundance of RHNs

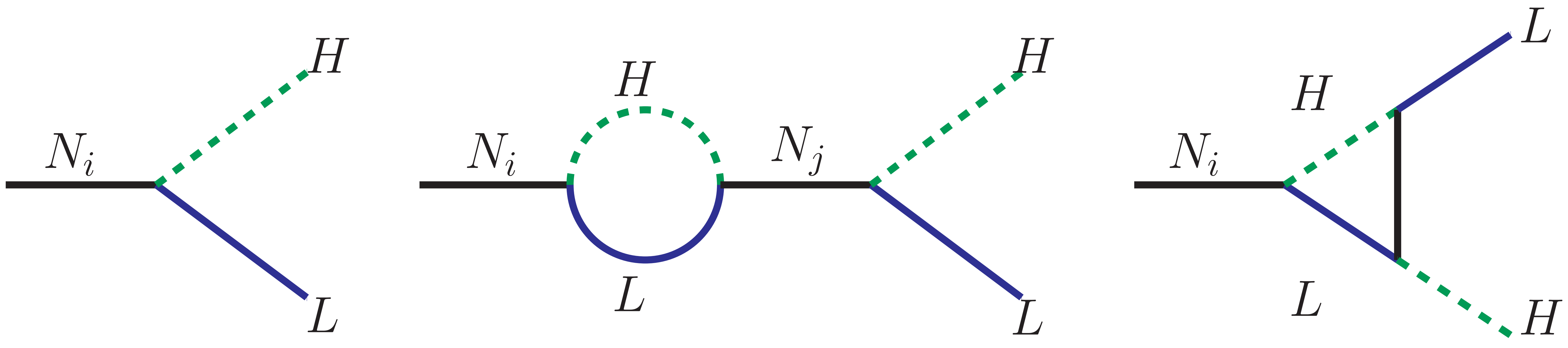


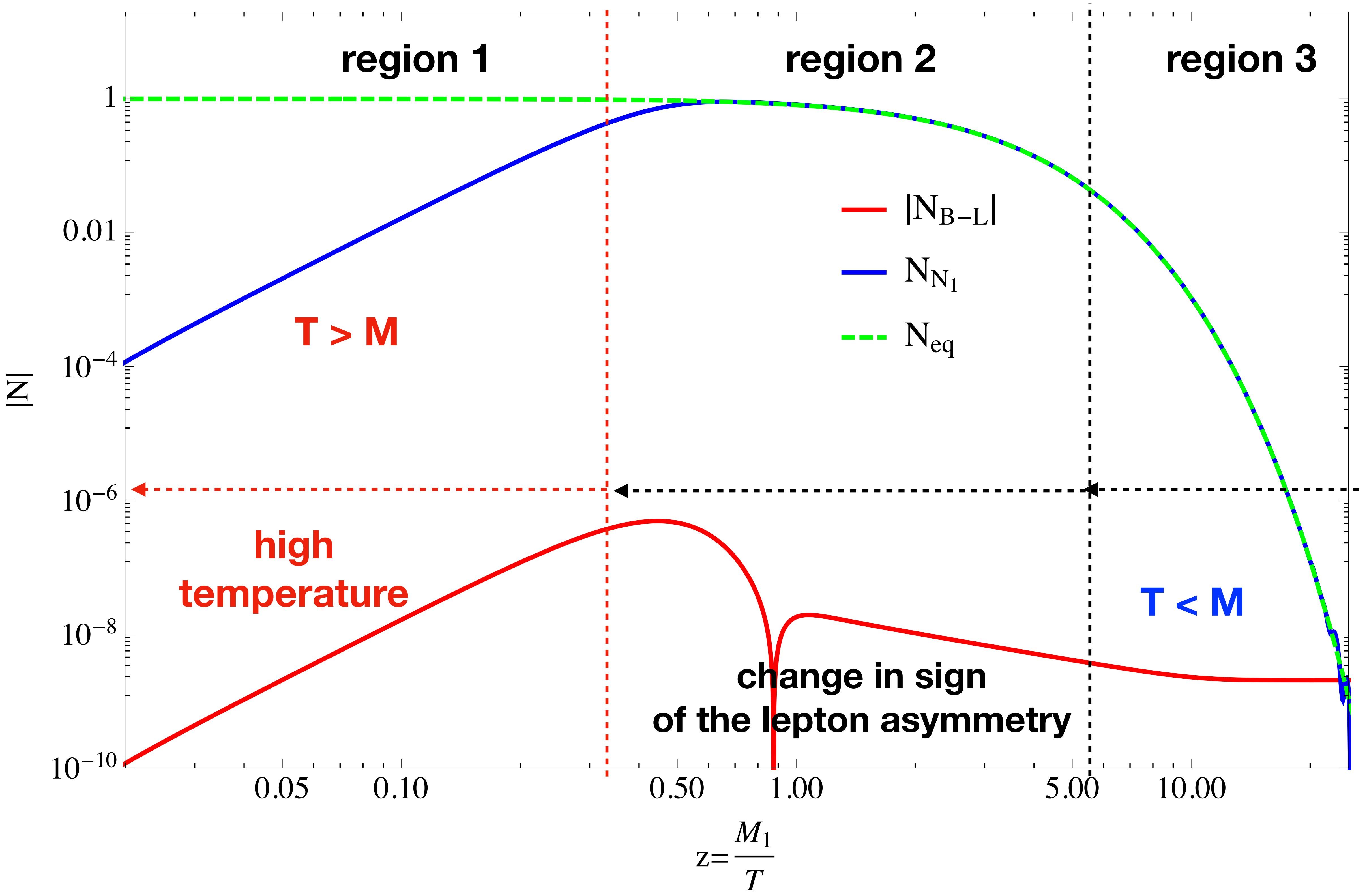


Region 1: leptons and Higgs have enough energy to inverse decay creating a lepton asymmetry




region 1
region 2
1
0.01
10^{-4}
10^{-6}
10^{-8}
10^{-10}
|N|
T > M
$|N_{B-L}|$
N_{N_1}
N_{eq}
region 1: high temperature
change in sign of the lepton asymmetry
0.05
0.10
0.50
1.00
5.00
10.00
$z=\frac{M_1}{T}$


N_i
H
L
N_i
H
L
N_j
H
L
N_i
H
L
L
H



<u>Region 3:</u> At T < M, RHN abundance is depleted. Lepton asymmetry freezes out.

Primordial Black holes induced leptogenesis

Work in collaboration with **Yuber Perez Gonzalez**: 2010.03565

Astrophysical BHs require $M > 3M_\odot$

For smaller BH mass (between Planck and solar mass scale) require large perturbations in the early Universe : **bubble collision, collapse of density perturbations…**

Carr et al, 0912.5297

Hawking, 1975

$r_S \sim \lambda_C \longrightarrow$ PBHs evaporate by emitting particles

$$\frac{dM}{dt} = -\sum_a \frac{g_a}{2\pi^2} \int_0^\infty \frac{\sigma_{\rm abs}^{s_a}(GMp)\, p^3\, dp}{\exp[E_a(p)/T_{\rm BH}] - (-1)^{2s_a}}$$

$$T_{\rm BH} = \frac{1}{8\pi GM} \approx 1.06 \left(\frac{10^{13}\ {\rm g}}{M}\right)\ {\rm GeV}\,.$$

PBHs are totally indiscriminate in their particle production: just need T_{BH} to be close to particle mass