Marco Drewes, Université catholique de Louvain

The Quest for the Origin of Matter

28. 06. 2021

Planck 2021

IPPP Durham, UK

Overview

Part I:
General Considerations

Part II:
Falsifyable Barygenesis Scenarios

- electroweak baryogenesis
- high scale leptogenesis
- low scale leptogenesis

Part III:
How to test Low Scale Leptogenesis?

- discovering heavy neutrinos
- the mixing pattern
- the Majorana mass
- combining everything: complementarity

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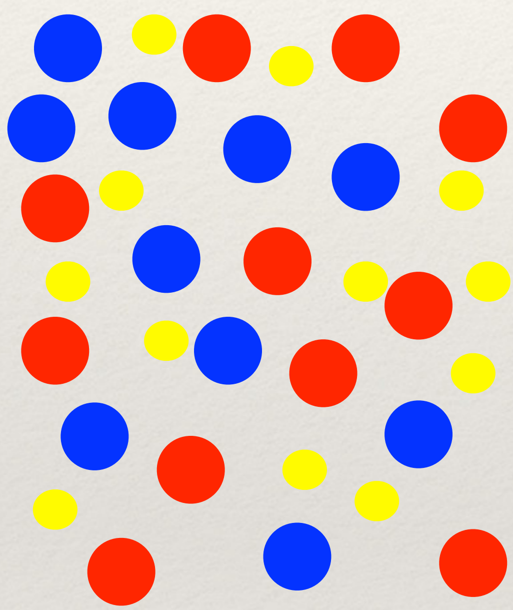
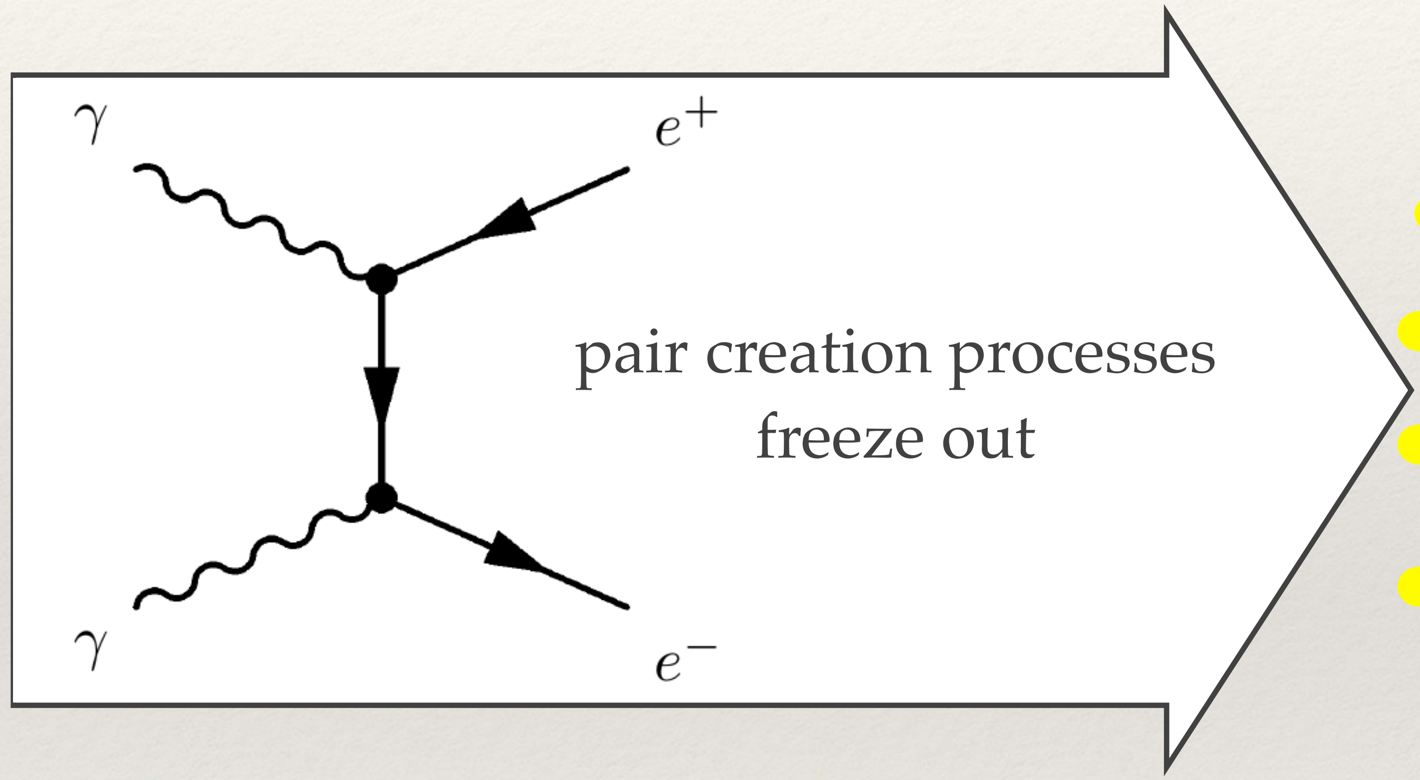
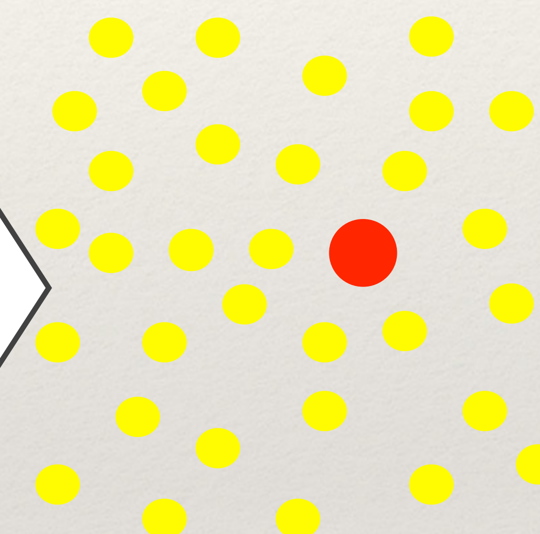
Baryon Asymmetry of the Universe

The observable universe contains almost no antimatter and a lot more photons than baryons. e.g. Canetti et al 1204.4186



$T > 2\,mc^2$





$T < 2\,mc^2$

CMB constraint on baryon-to-photon ratio η:

$6.03 \times 10^{-10} < \eta < 6.15 \times 10^{-10}$

(Planck Collaboration)

BBN constraint on baryon-to-photon ratio η:

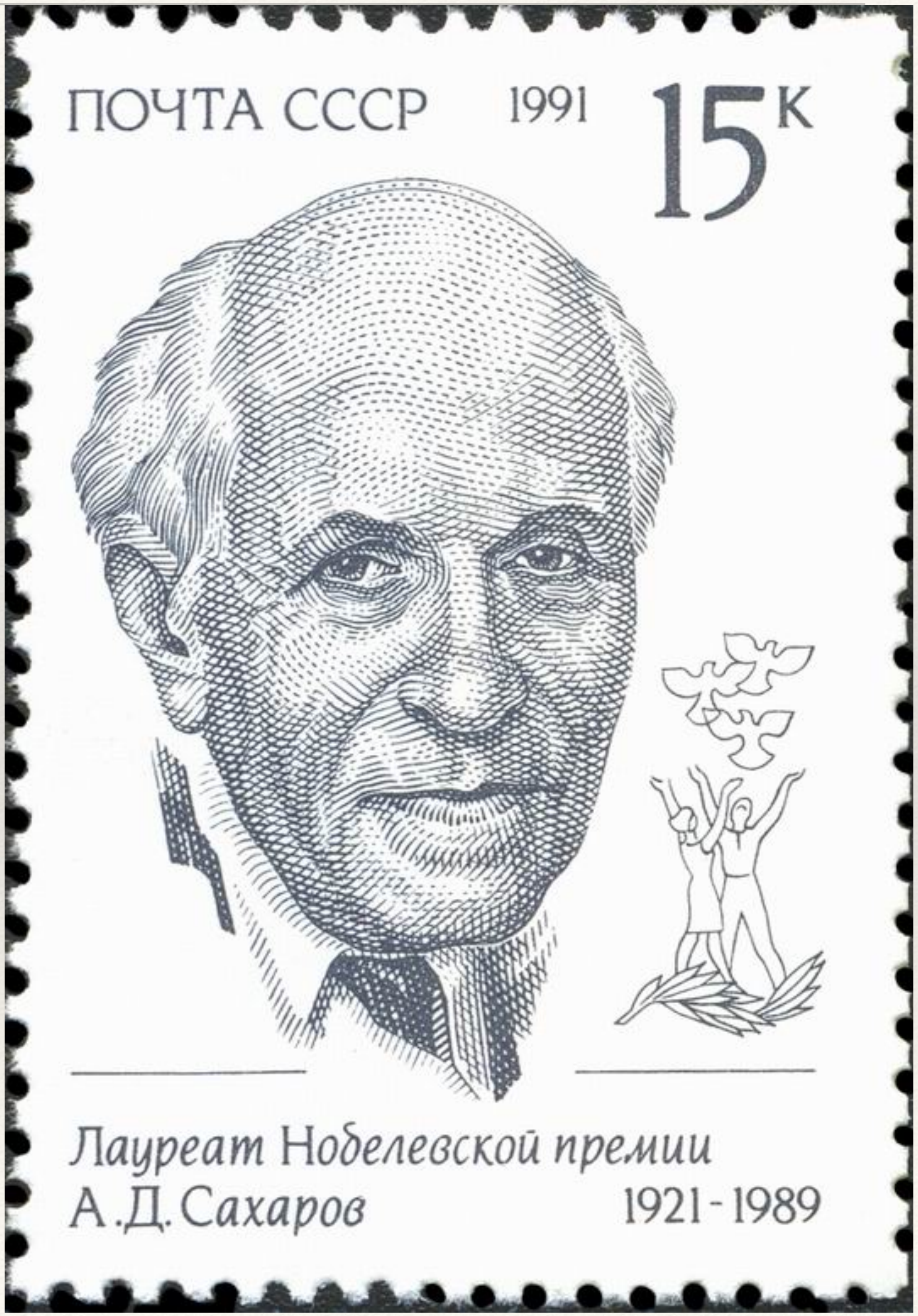
$5.8 \times 10^{-10} < \eta < 6.6 \times 10^{-10}$

(PDG)

Where does the asymmetry come from?

Sakharov Conditions (1967)

- Baryon number violation
- C and CP violation
- Deviation from thermal equilibrium



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Exists in Standard Model (sphaleron)

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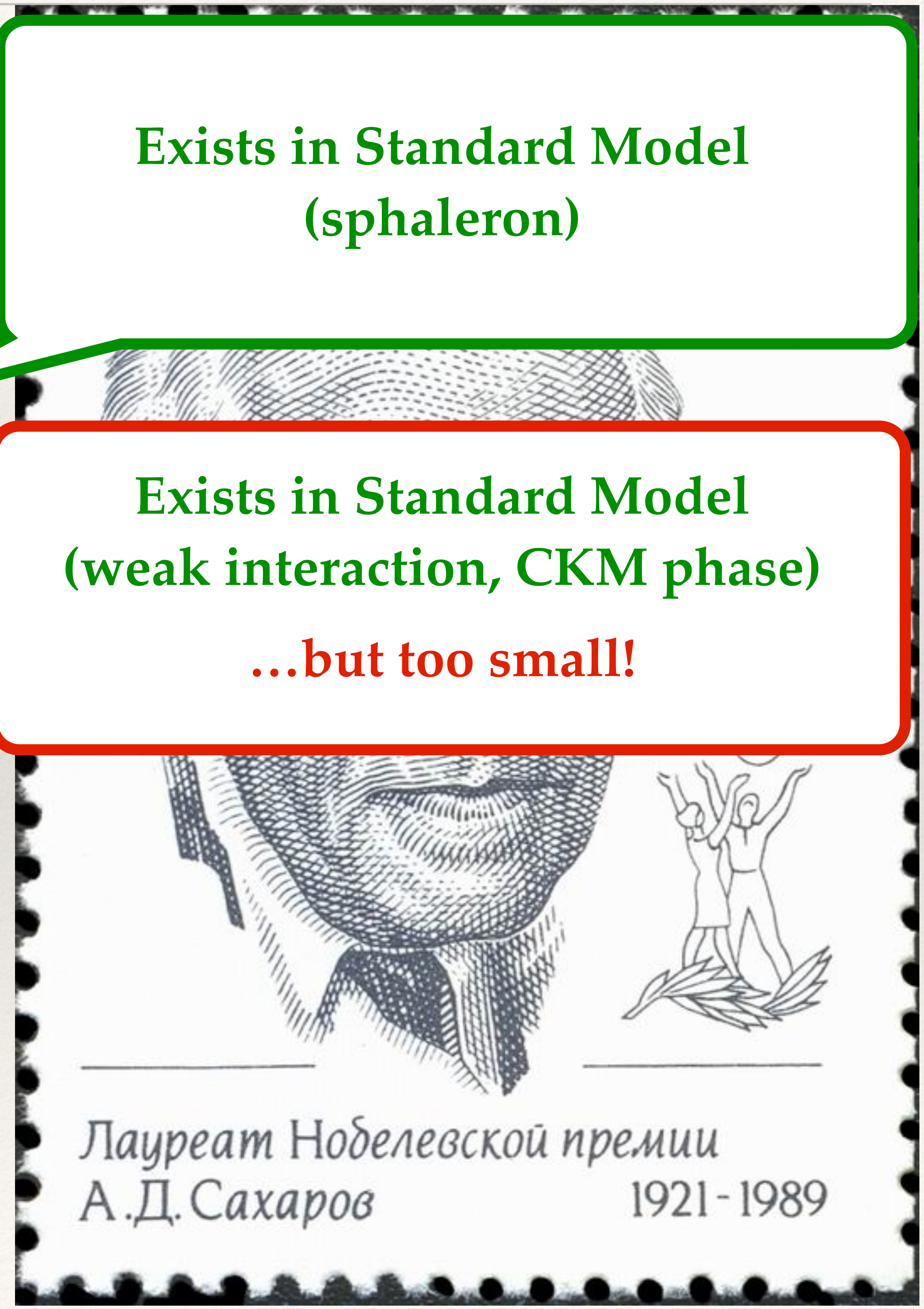
Exists in Standard Model (weak interaction, CKM phase)

…but too small!



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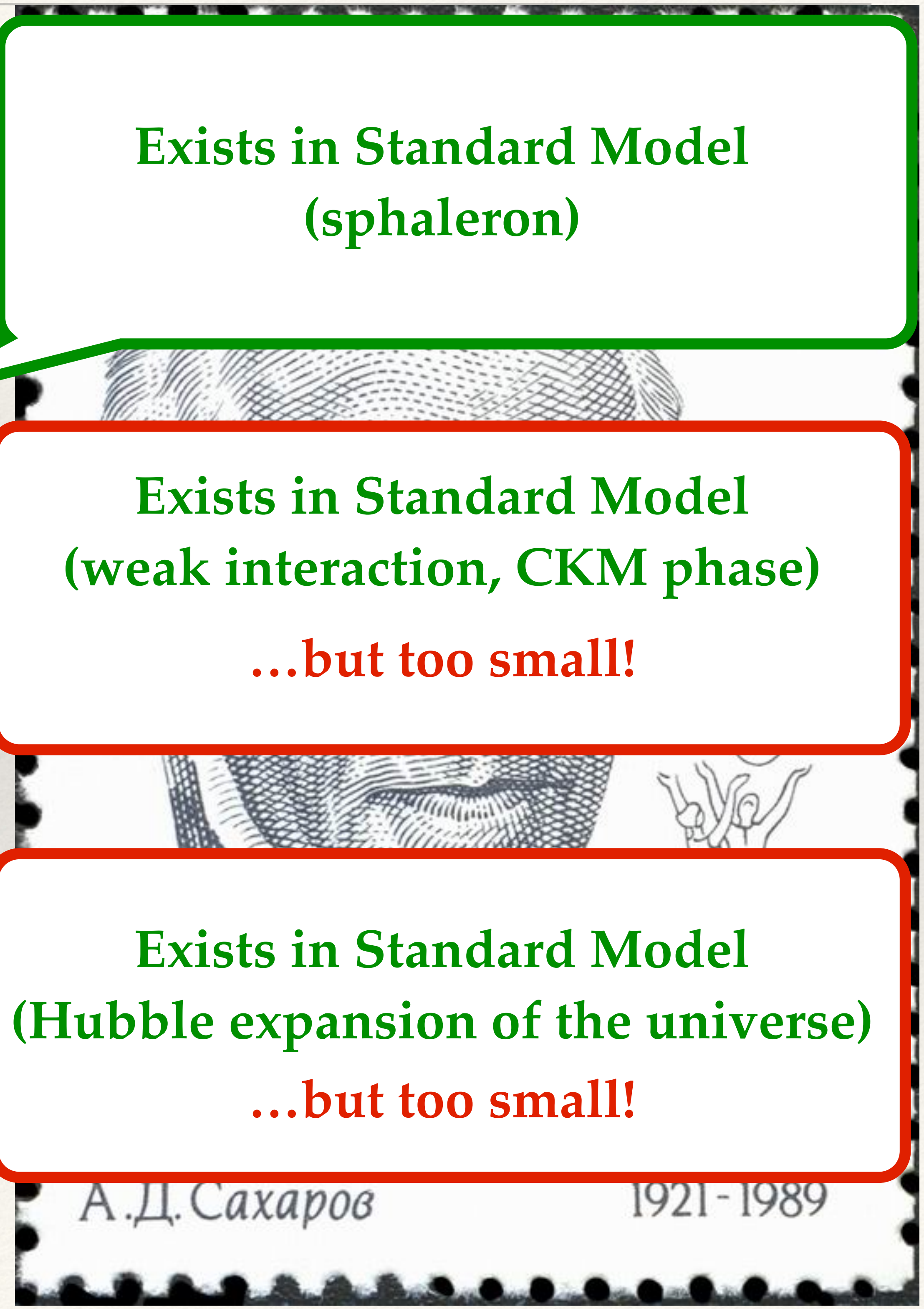
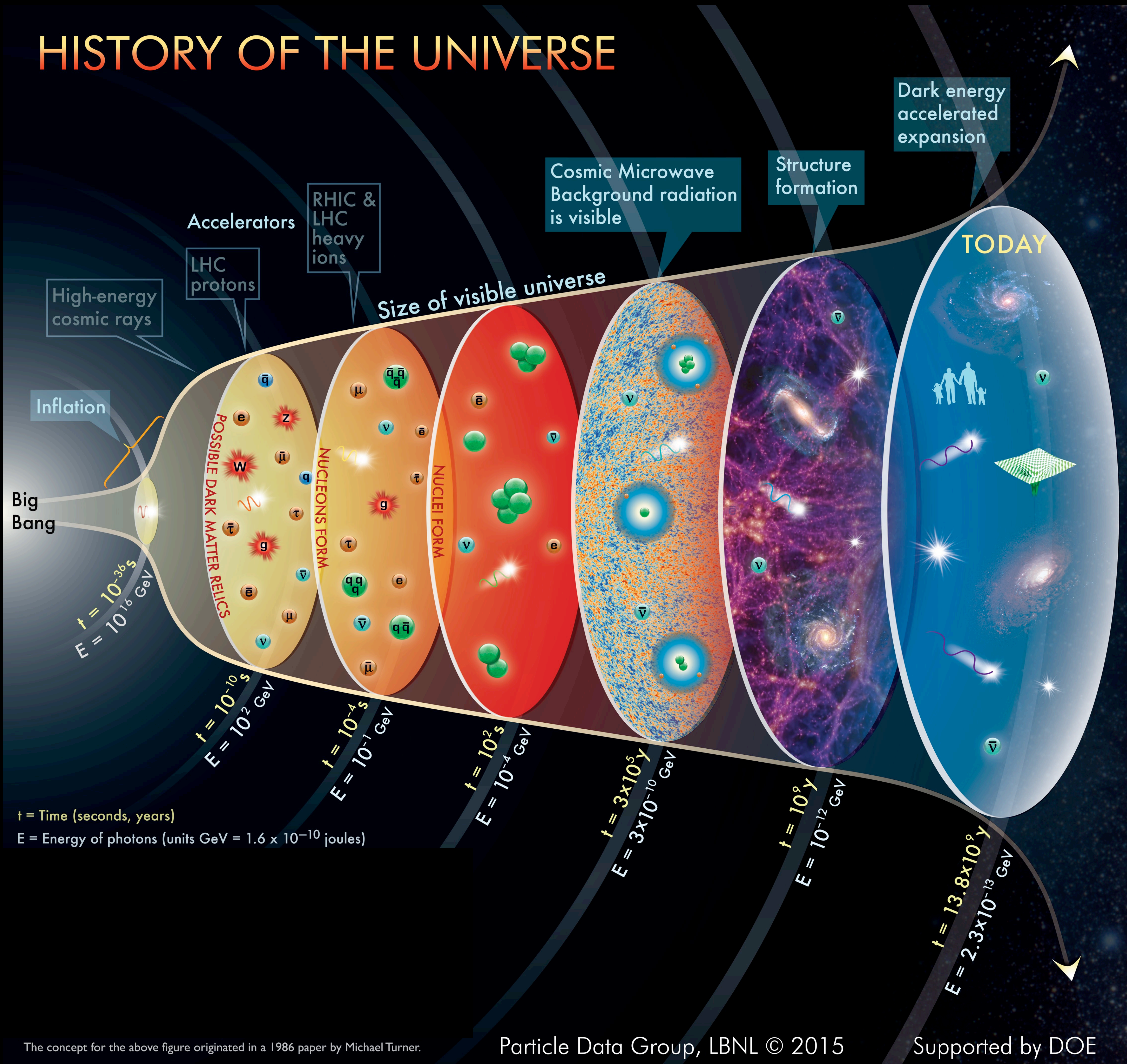
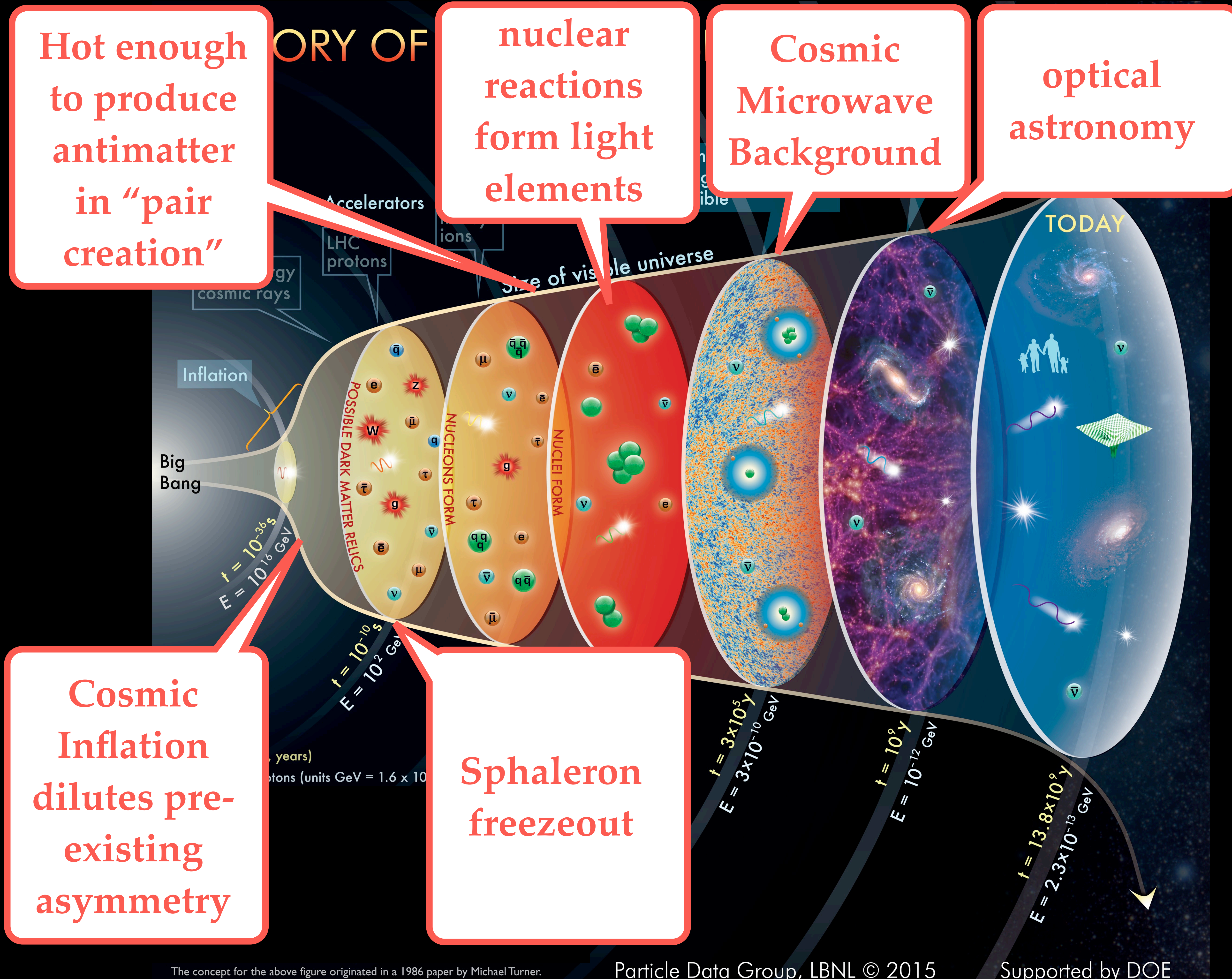
Exists in Standard Model (sphaleron)

Exists in Standard Model (weak interaction, CKM phase) …but too small!

Exists in Standard Model (Hubble expansion of the universe) …but too small!




HISTORY OF THE UNIVERSE
Dark energy accelerated expansion
Structure formation
Cosmic Microwave Background radiation is visible
RHIC & LHC heavy ions
Accelerators
LHC protons
High-energy cosmic rays
Size of visible universe
Inflation
Big Bang
TODAY
POSSIBLE DARK MATTER RELICS
NUCLEONS FORM
NUCLEI FORM
$t = 10^{-36}$ s
$E = 10^{16}$ GeV
$t = 10^{-10}$ s
$E = 10^{2}$ GeV
$t = 10^{-4}$ s
$E = 10^{-1}$ GeV
$t = 10^{2}$ s
$E = 10^{-4}$ GeV
$t = 3x10^{5}$ y
$E = 3x10^{-10}$ GeV
$t = 10^{9}$ y
$E = 10^{-12}$ GeV
$t = 13.8x10^{9}$ y
$E = 2.3x10^{-13}$ GeV
t = Time (seconds, years)
E = Energy of photons (units GeV = 1.6×10^{-10} joules)
The concept for the above figure originated in a 1986 paper by Michael Turner.
Particle Data Group, LBNL © 2015
Supported by DOE


Hot enough to produce antimatter in “pair creation”
nuclear reactions form light elements
Cosmic Microwave Background
optical astronomy
Cosmic Inflation dilutes pre-existing asymmetry
Sphaleron freezeout
ORY OF
Accelerators
LHC protons
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years)
tons (units GeV = 1.6 x 10
The concept for the above figure originated in a 1986 paper by Michael Turner.
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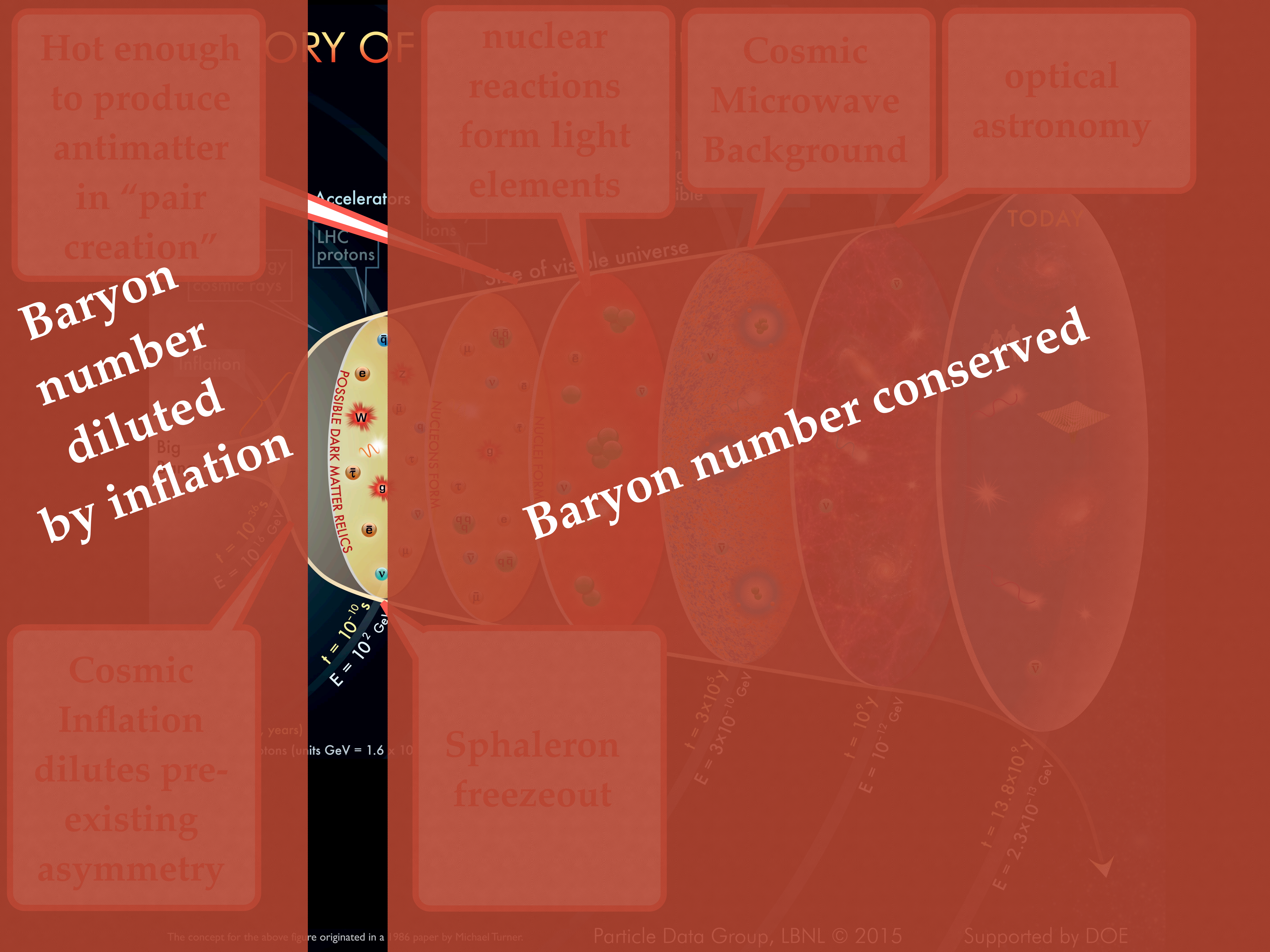

Hot enough to produce antimatter in "pair creation"
nuclear reactions form light elements
Cosmic Microwave Background
optical astronomy
Baryon number diluted by inflation
Baryon number conserved
Cosmic Inflation dilutes pre-existing asymmetry
Sphaleron freezeout
Accelerators
LHC protons
Size of visible universe
TODAY
POSSIBLE DARK MATTER RELICS
t = 10^-10 s
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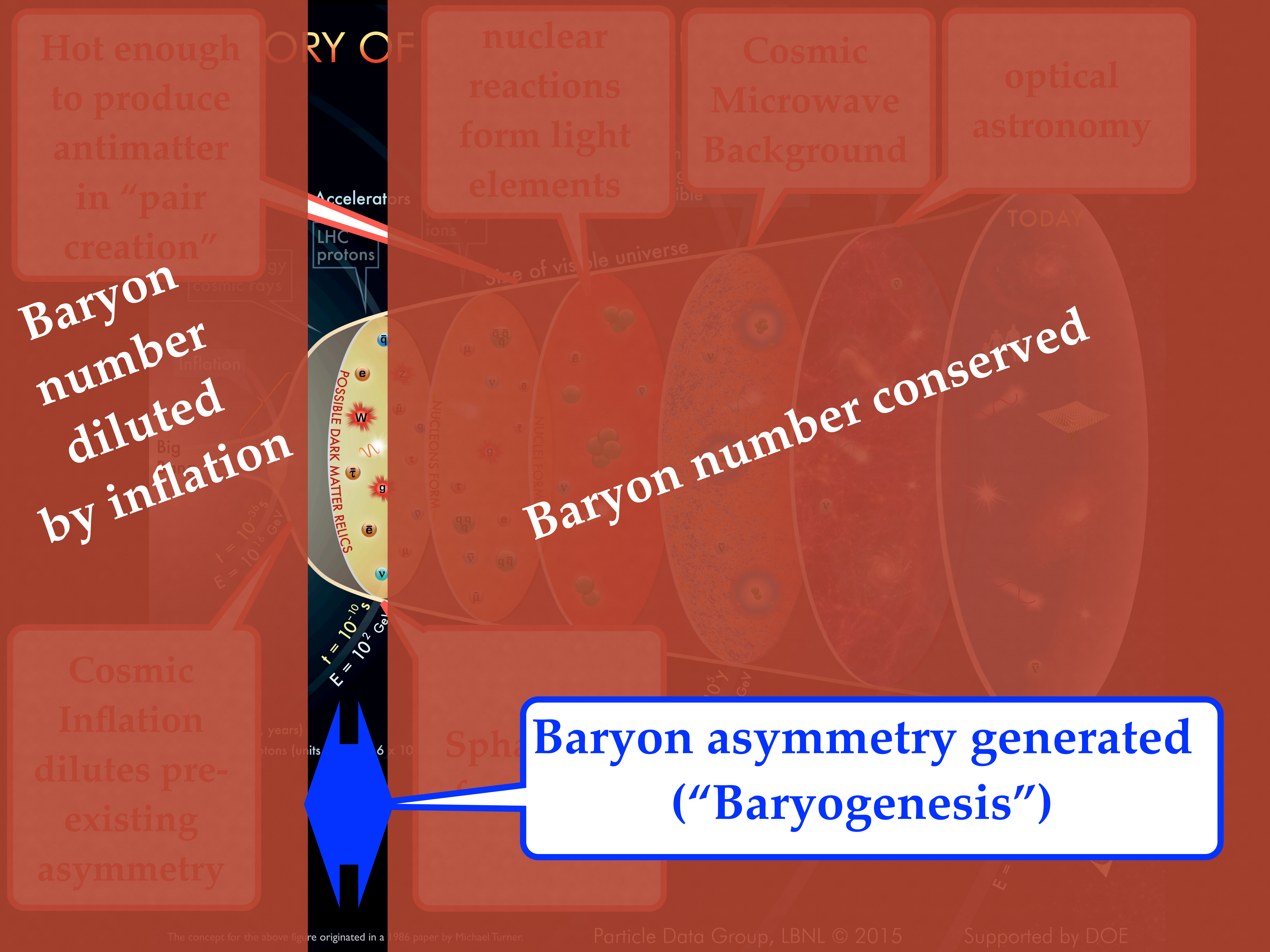
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NUCLEONS FORM
$t = 10^{-10}$ s
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Cosmic Inflation dilutes pre-existing asymmetry
Baryon asymmetry generated (“Baryogenesis”)
The concept for the above figure originated in a 1986 paper by Michael Turner.
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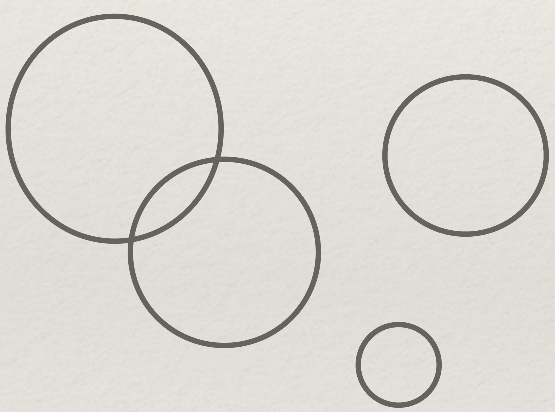
Where does the asymmetry come from?

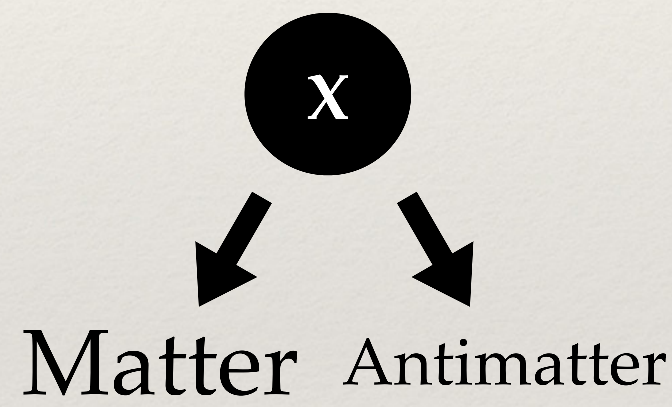
Baryogenesis requires New Physics!

Cosmic phase transition?



Electroweak baryogengesis,
…

Decay of a heavy particle?



GUT baryogengesis,
leptogenesis,
…

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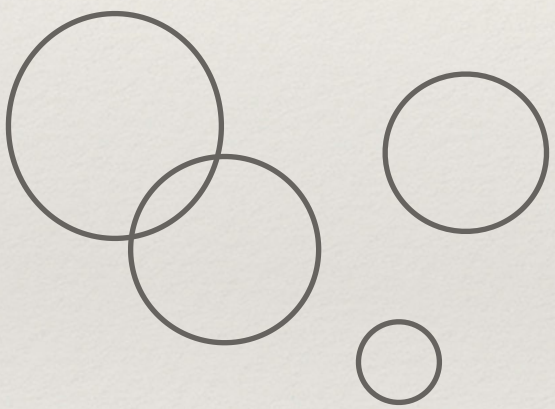
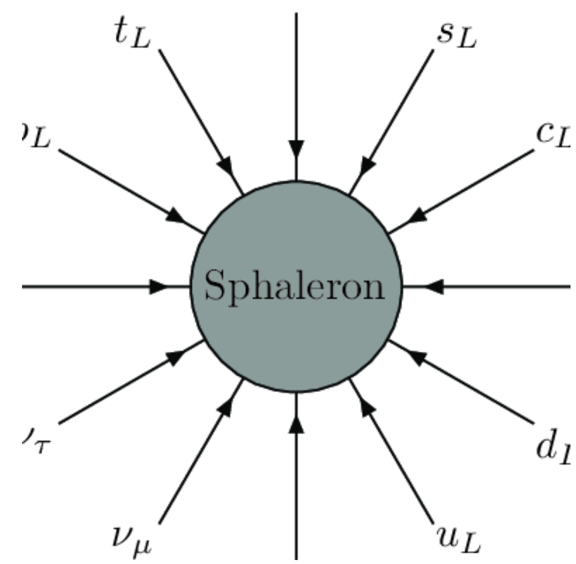


Electroweak baryogengesis,

…

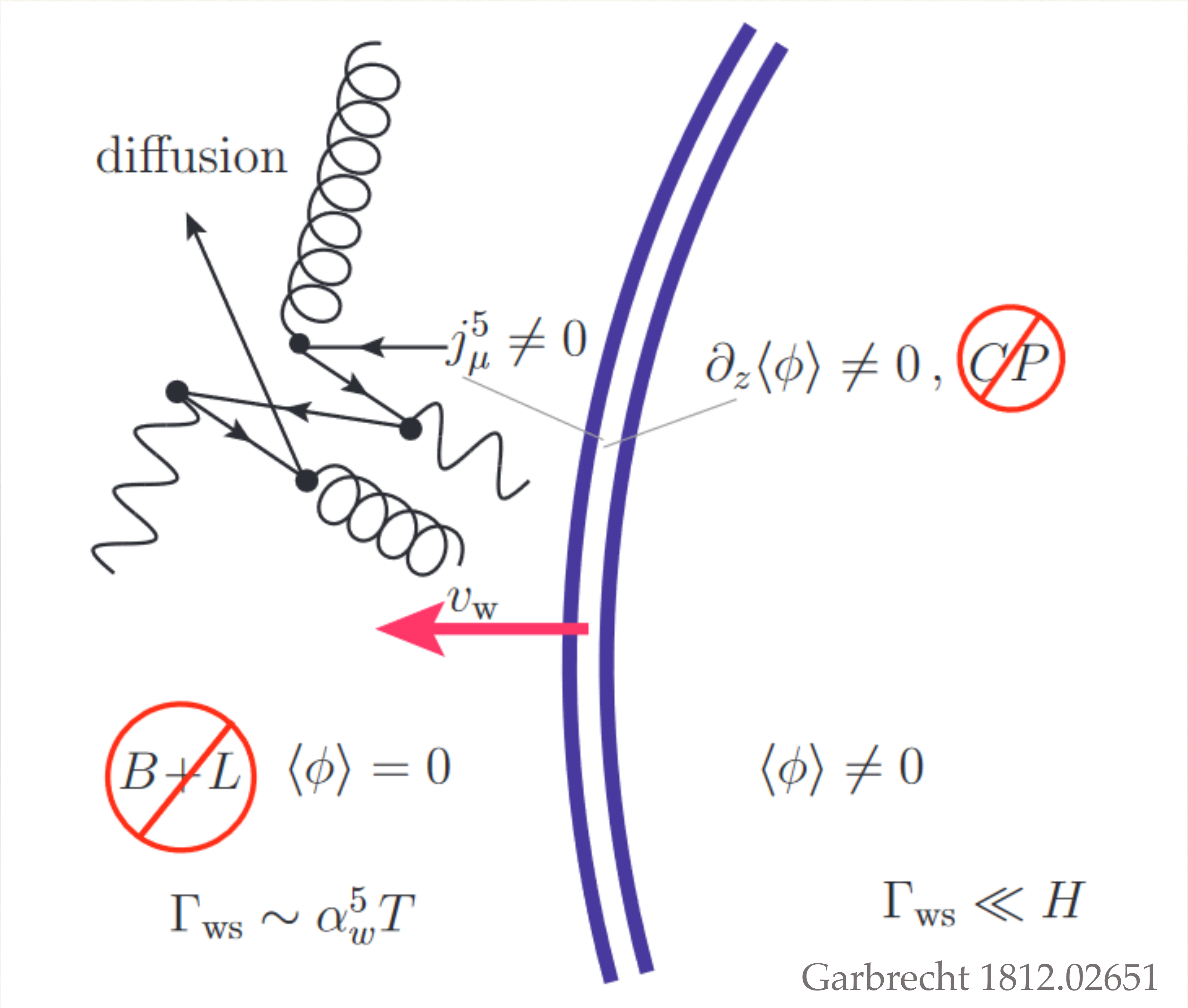
Electroweak Baryogenesis

Kuzmin/Rubakov/Shaposhnikov



- Uses SM sphaleron for B violation
- Needs first order phase transition for deviation from equilibrium
- Needs new CP violation

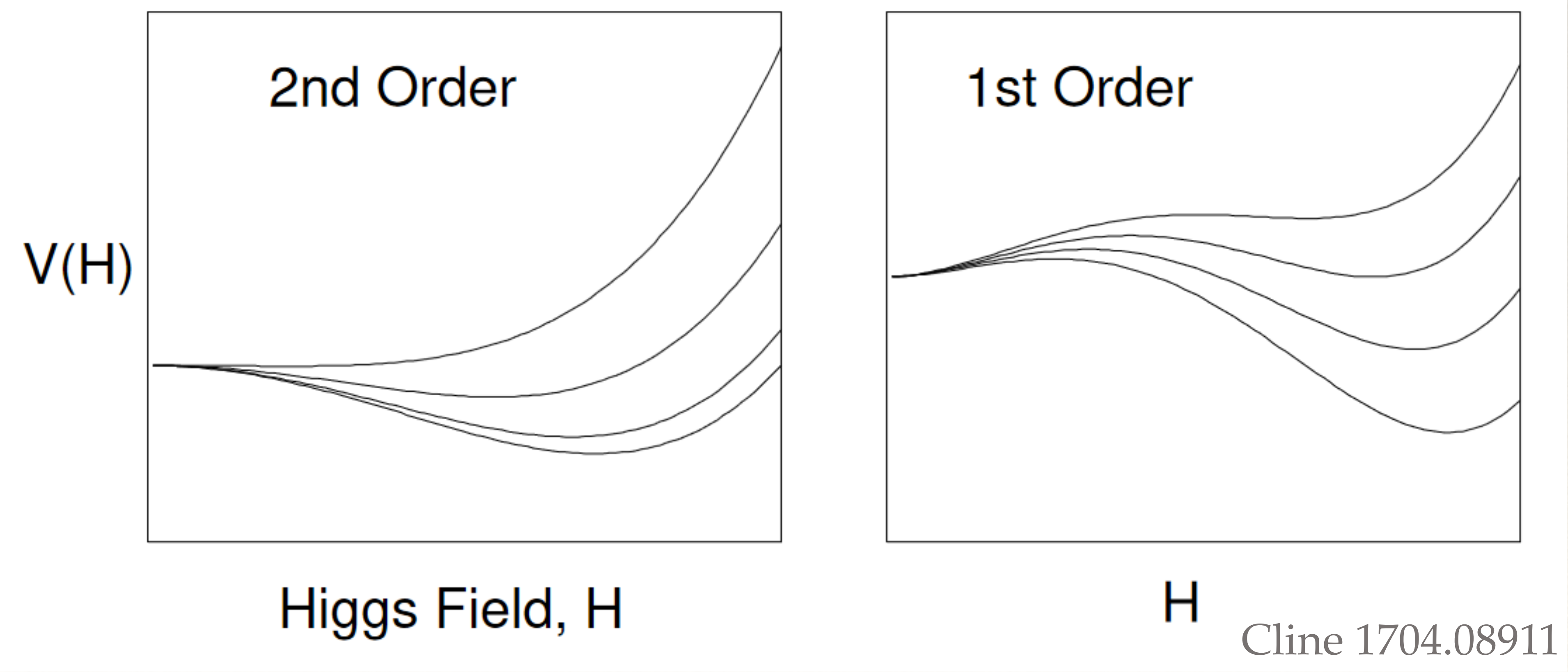
Electroweak Baryogenesis



for a review, see also Morrissey / Ramsey-Musolf 1206.2942

EWBG: Nonequilibrium Condition

- Needs first order phase transition to create deviation from equilibrium
- Occurs for sizeable cubic term in Higgs finite temperature effective potential
- Typically achieved by extending scalar sector, either by direct coupling to SM Higgs ("Higgs portal") or through loops (e.g. MSSM)



Cline 1704.08911

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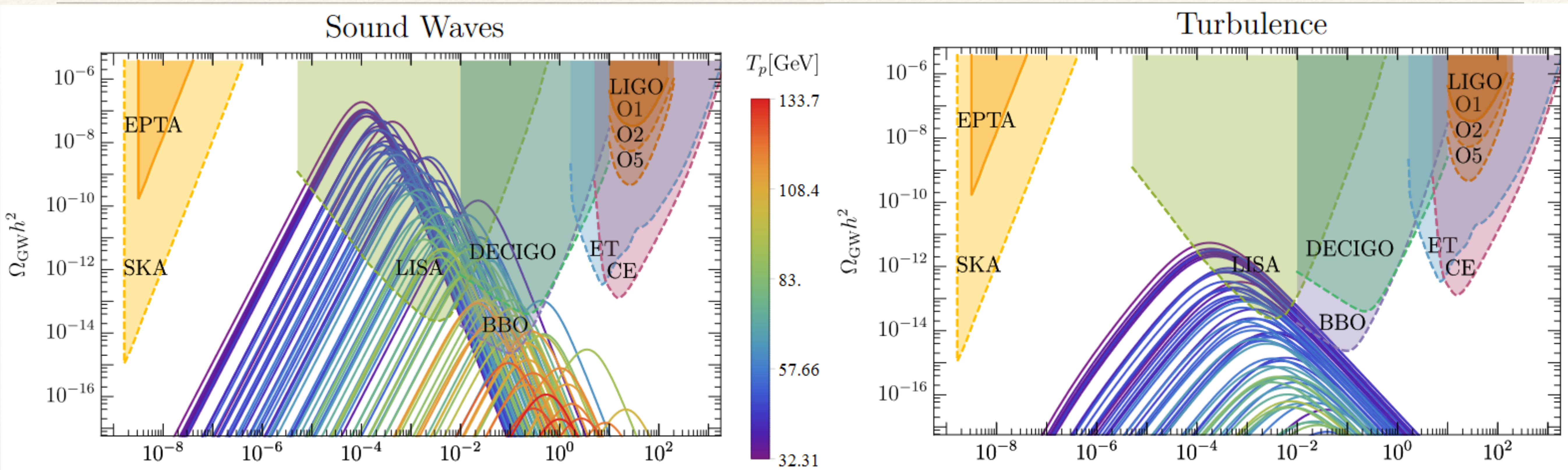
Signatures

- collider searches for new scalars
- GW signature from phase transition

EWBG: Nonequilibrium Condition



Beniwal et al 1810.02380

Signatures

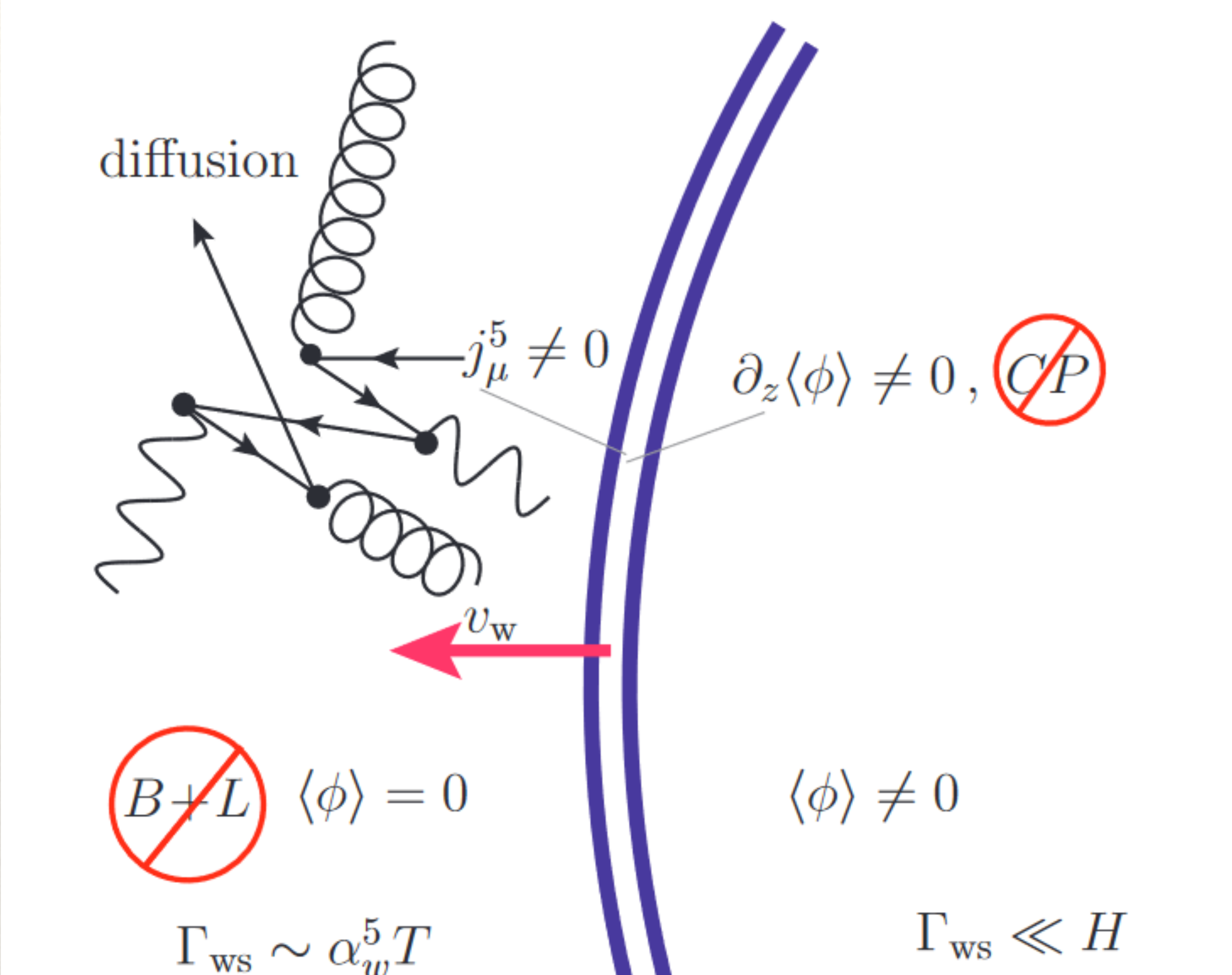
- collider searches for new scalars
- GW signature from phase transition

EWBG: CP violation

- asymmetry generated in diffusion in front of bubble wall
- preserved from washout when wall passes by
- needs new CP violation that can be observed in electric dipole moment measurements

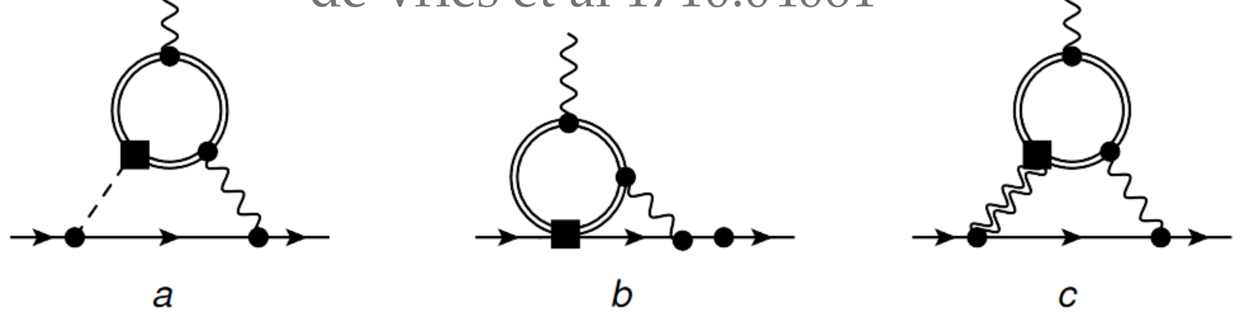
Signatures

- collider searches for new scalars
- GW signature from phase transition
- EDMs



Garbrecht 1812.02651

de Vries et al 1710.04061



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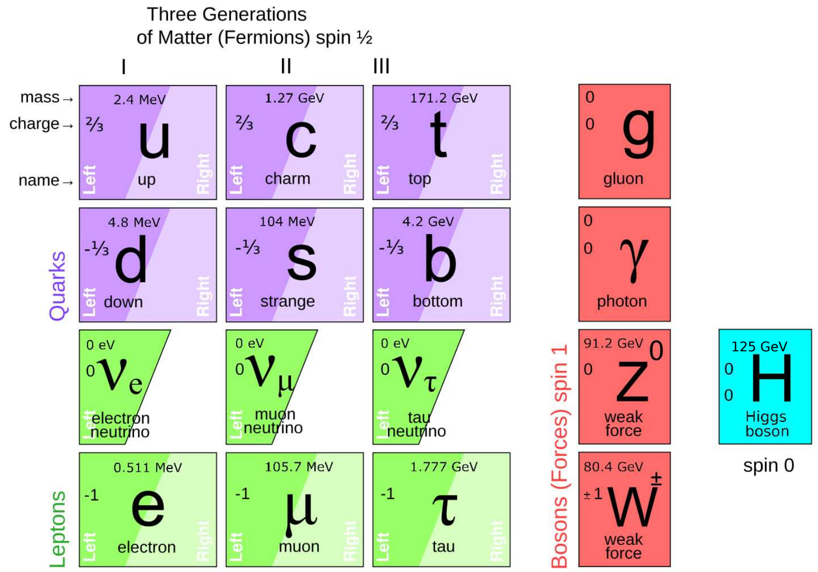
Where does the asymmetry come from?

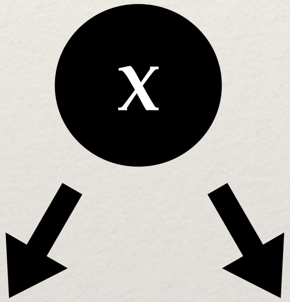
Leptogenesis

Fukugita/Yanagida



- Decaying particle could be heavy neutrino *N*
- Conveniently also explains neutrino masses! ("seesaw mechanism")
- Evidence for CP violation in neutrino oscillations

Decay of a heavy particle?

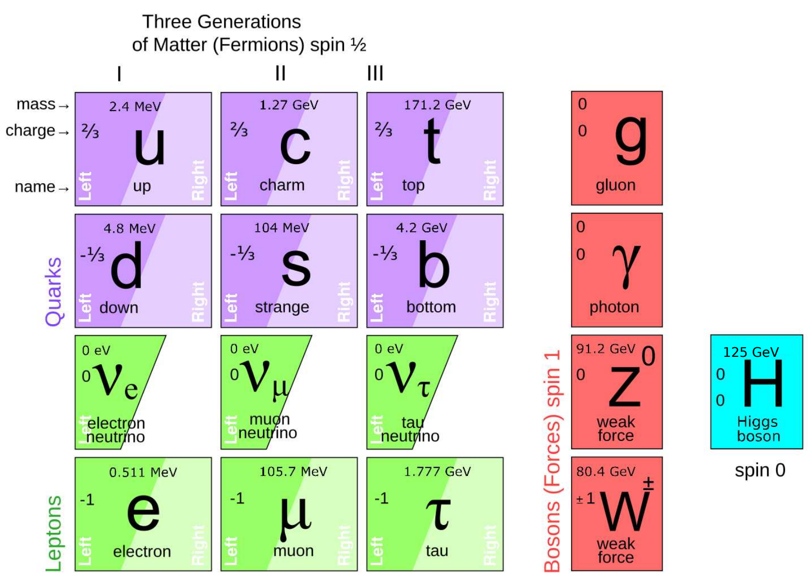


Matter Antimatter

GUT baryogengesis,
leptogenesis,
…

The Seesaw Mechanism (type I)

$$\mathcal{L} = \mathcal{L}_{SM} + i\bar{\nu}_R \partial\!\!\!/ \nu_R - \bar{L}_L F \nu_R \tilde{H} - \tilde{H}^\dagger \bar{\nu}_R F^\dagger L$$
$$- \frac{1}{2}(\bar{\nu^c}_R M_M \nu_R + \bar{\nu}_R M_M^\dagger \nu_R^c)$$



 # massive SM neutrinos ≤ # RH neutrino flavours

- minimal model with $m_{\text{lightest}} = 0$ has two RHN
- if all SM neutrinos are massive, three RHN flavours are needed

three light neutrinos mostly "active" SU(2) doublet
$\nu \simeq U_\nu(\nu_L + \theta \nu_R^c)$
with masses $\boldsymbol{m_\nu \simeq \theta M_M \theta^T = v^2 F M_M^{-1} F^T}$

three heavy mostly singlet neutrinos
$N \simeq \nu_R + \theta^T \nu_L^c$
with masses $\boldsymbol{M_N \simeq M_M}$

Minkowski 79, Gell-Mann/Ramond/Slansky 79, Mohapatra/Senjanovic 79, Yanagida 80, Schechter/Valle 80

Thermal Leptogenesis

Basic idea

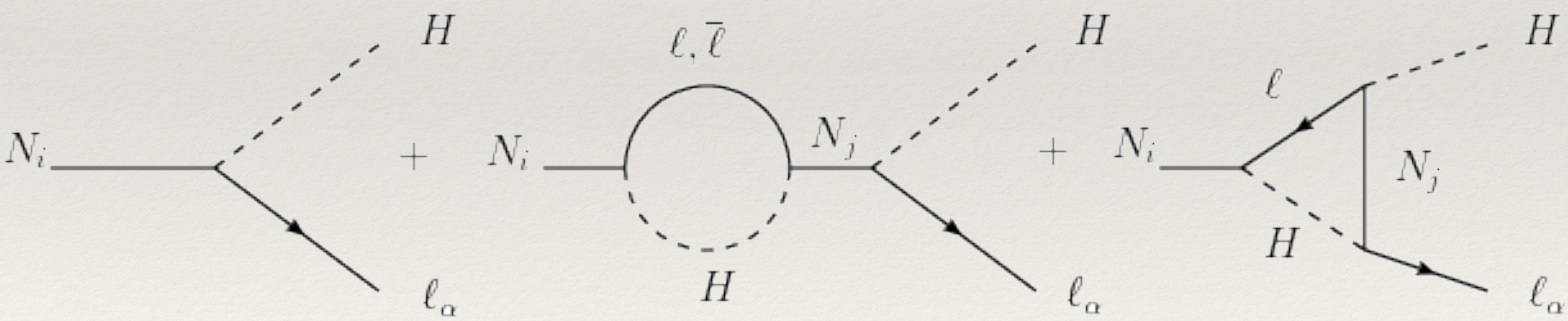
- ***N* are around in the early universe**
- ***N* interactions are CP violating**
- ***N* may preferably decay into matter**

CP violating parameter ϵ

$$\epsilon = \frac{\Gamma_{N\to\ell H} - \Gamma_{N\to\bar{\ell}H^*}}{\Gamma_{N\to\ell H} + \Gamma_{N\to\bar{\ell}H^*}}$$

final asymmetry

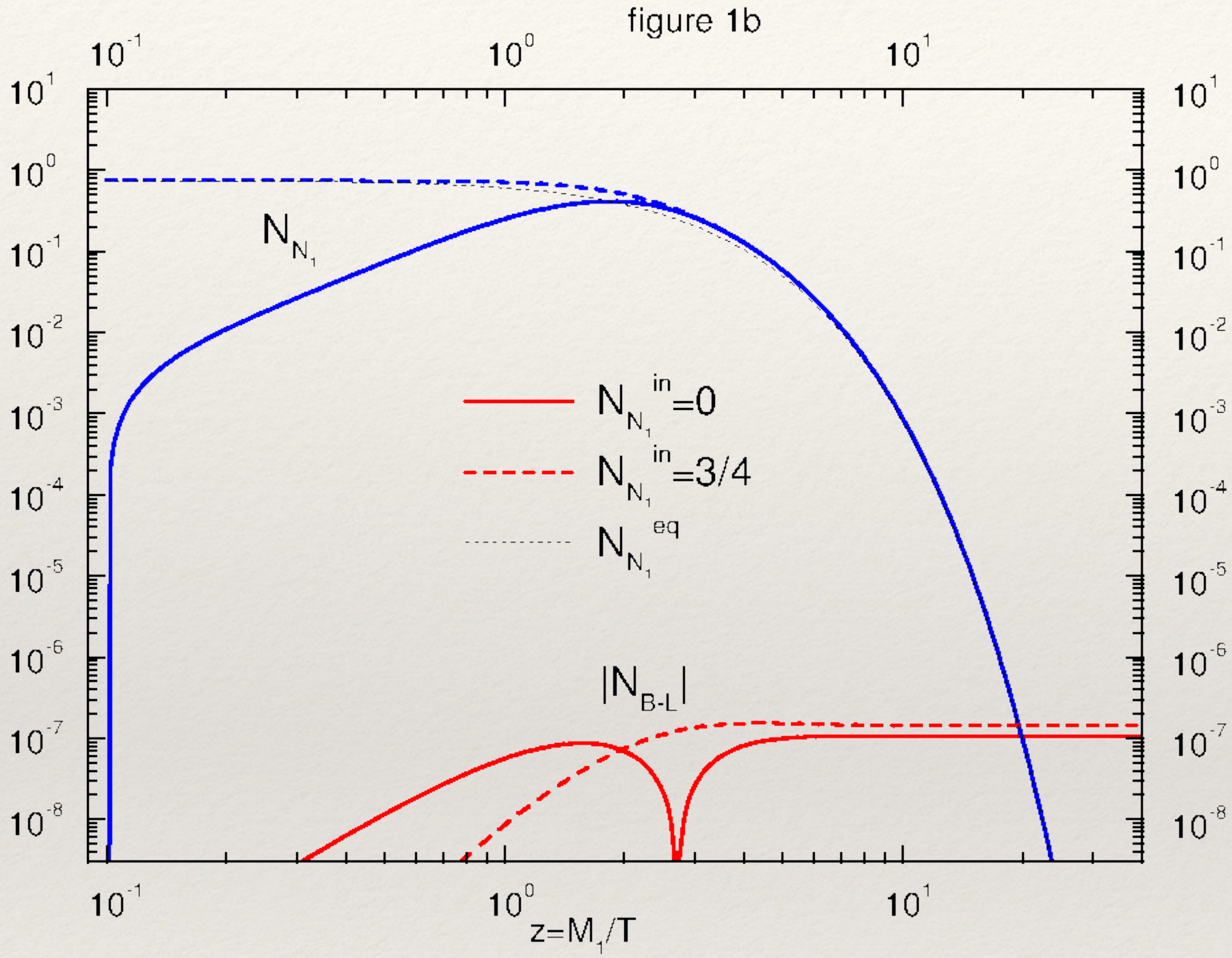
$$Y_{B-L} \;\propto\; \epsilon/g_*$$



asymmetry arises from quantum interference in the plasma

⇒ we derive quantum kinetic equations from first principles

Boltzmann Equations



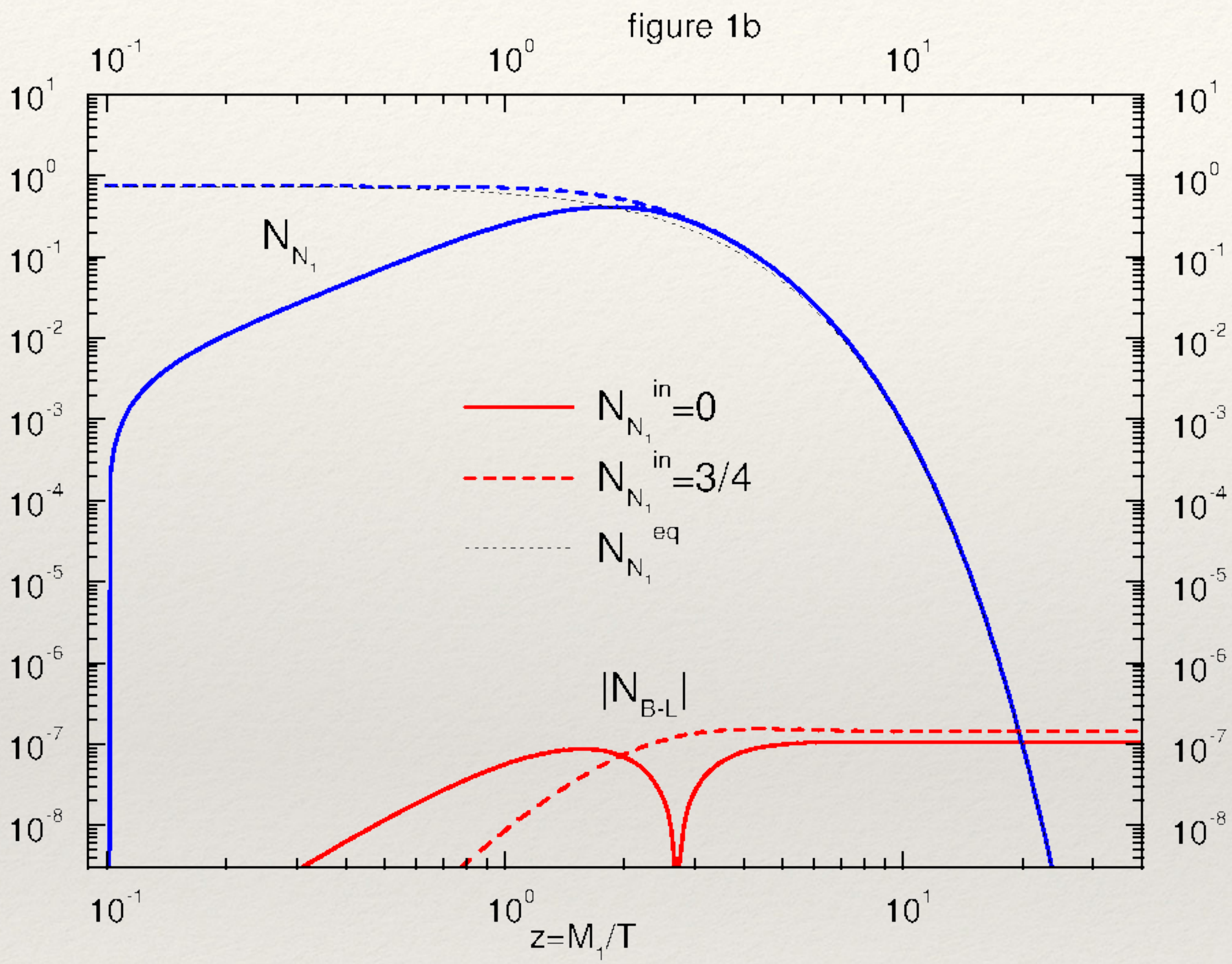
Buchmuller / Di Bari / Plumacher 0205349

$$xH\frac{d\mathrm{Y}_N}{dx} = -\Gamma_N(\mathrm{Y}_N - \mathrm{Y}_N^{\mathrm{eq}}) \qquad x = M/T$$

$$xH\frac{d\mathrm{Y}_{\mathrm{B-L}}}{dx} = \epsilon\Gamma_N(\mathrm{Y}_N - \mathrm{Y}_N^{\mathrm{eq}}) - c_W\Gamma_N\mathrm{Y}_{\mathrm{B-L}}$$

"source" "washout"

High Scale Leptogenesis



Buchmuller / Di Bari / Plumacher 0205349

"Vanilla leptogenesis" requires

$M > 10^9$ GeV **Davidson/Ibarra 0202239**

$$xH\frac{dY_N}{dx} = -\Gamma_N(Y_N - Y_N^{eq}) \qquad x = M/T$$

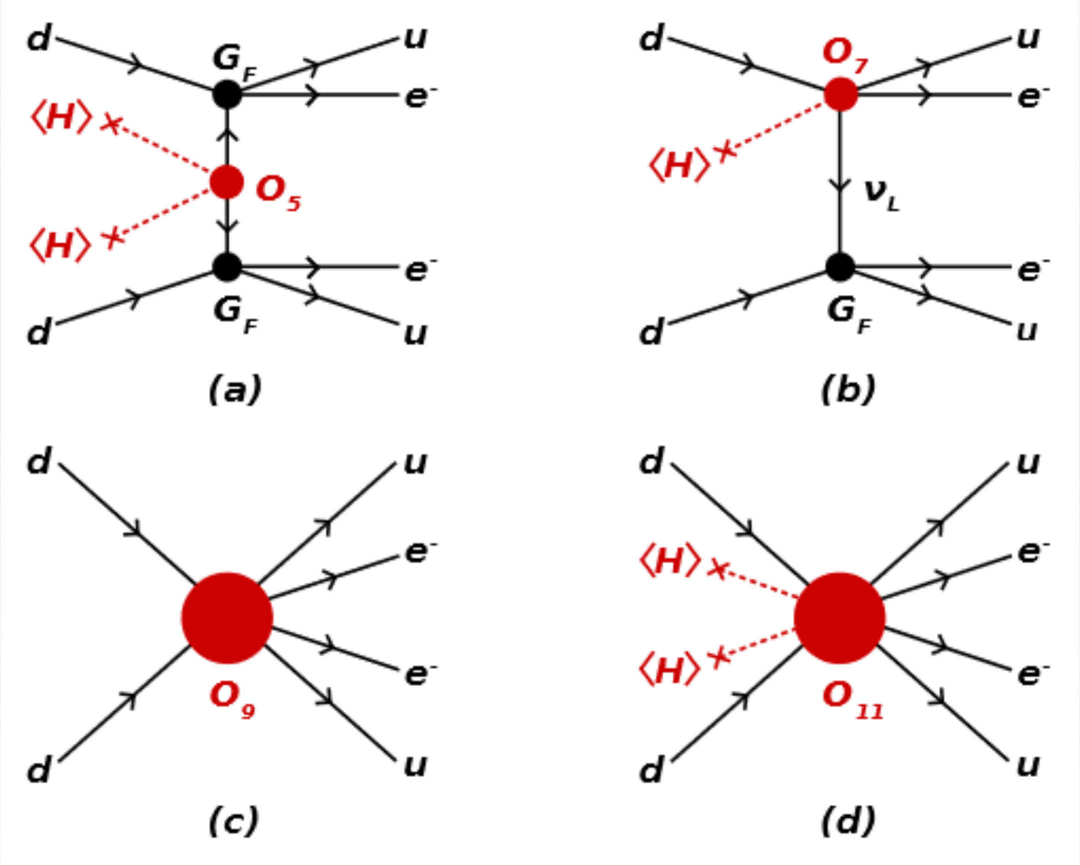
$$xH\frac{dY_{B-L}}{dx} = \epsilon\Gamma_N(Y_N - Y_N^{eq}) - c_W\Gamma_N Y_{B-L}$$

"source" "washout"

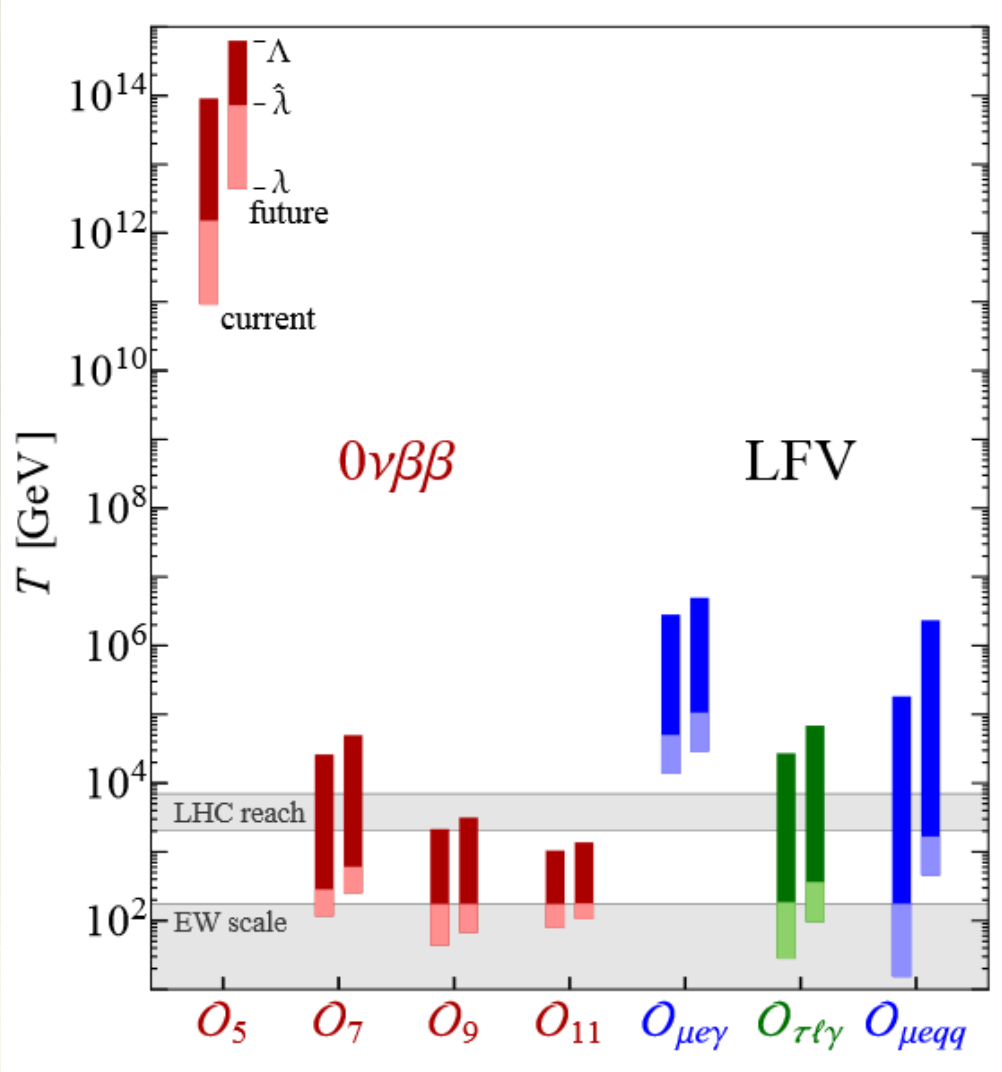
Falsifying High Scale Leptogenesis

- LNV at the TeV scale would wash out L generated at high scale
- electroweak sphalerons above ~130 GeV imply B also washed out
- discovery of low scale LNV can rule out high scale leptogenesis!

Deppisch/Harz 1312.4447



Deppisch et al 1503.04825, 1711.10432



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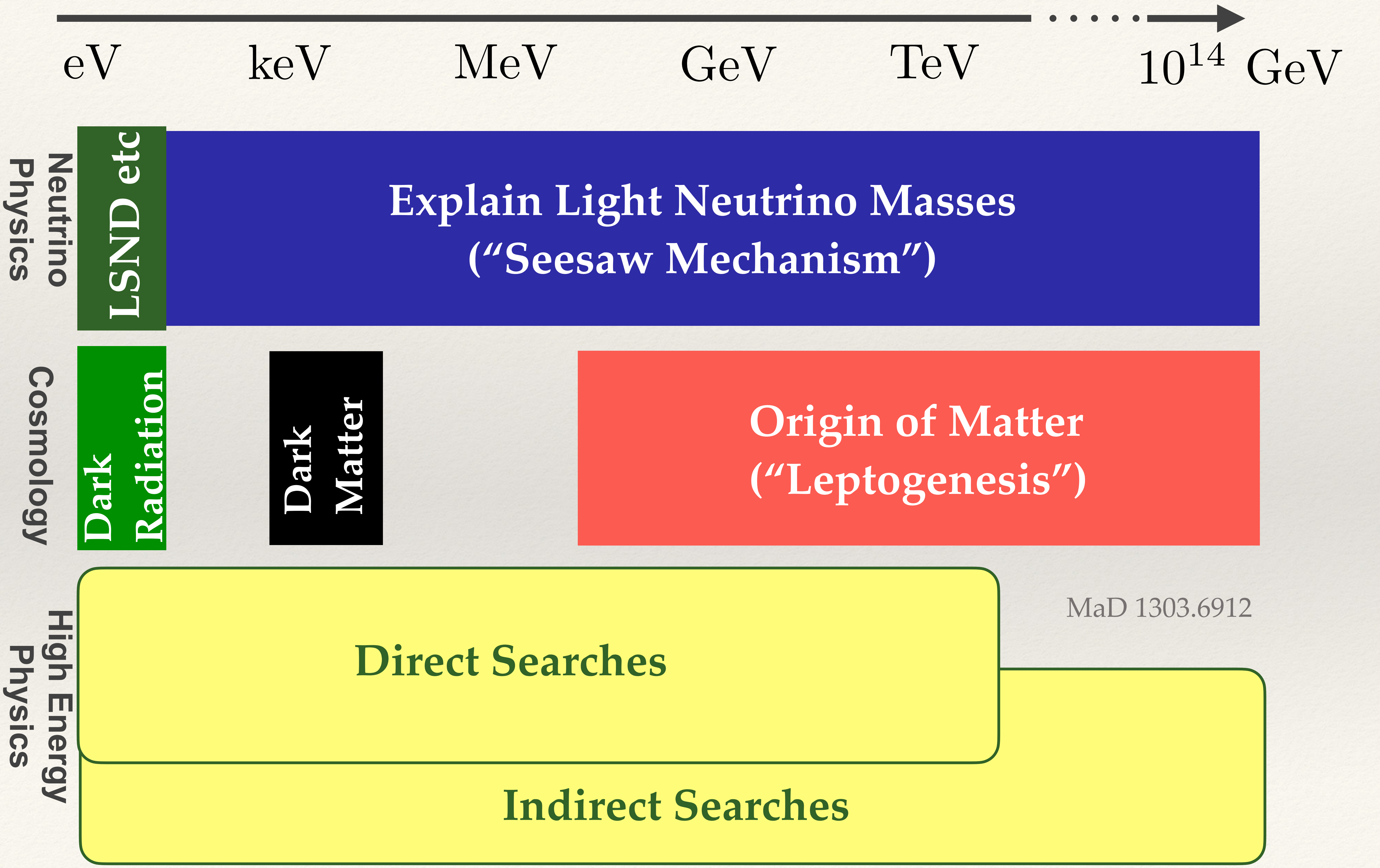
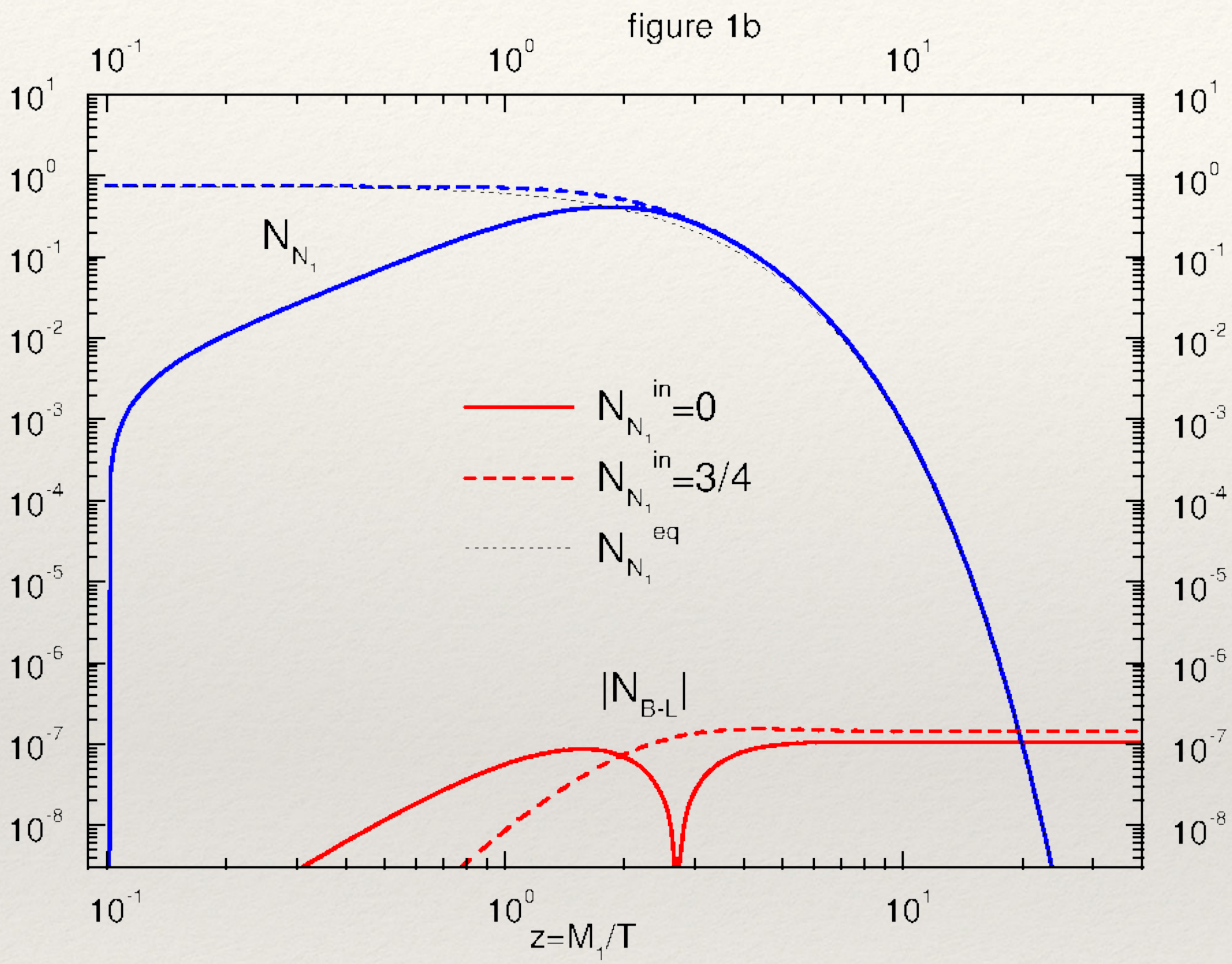
Right Handed Neutrino Mass Scale



Leptogenesis with small M?



Buchmuller / Di Bari / Plumacher 0205349

"Vanilla leptogenesis" requires $M > 10^9$ GeV Davidson/Ibarra 0202239

Flavour effects can reduce this by few orders e.g. Dev et al 1711.02861

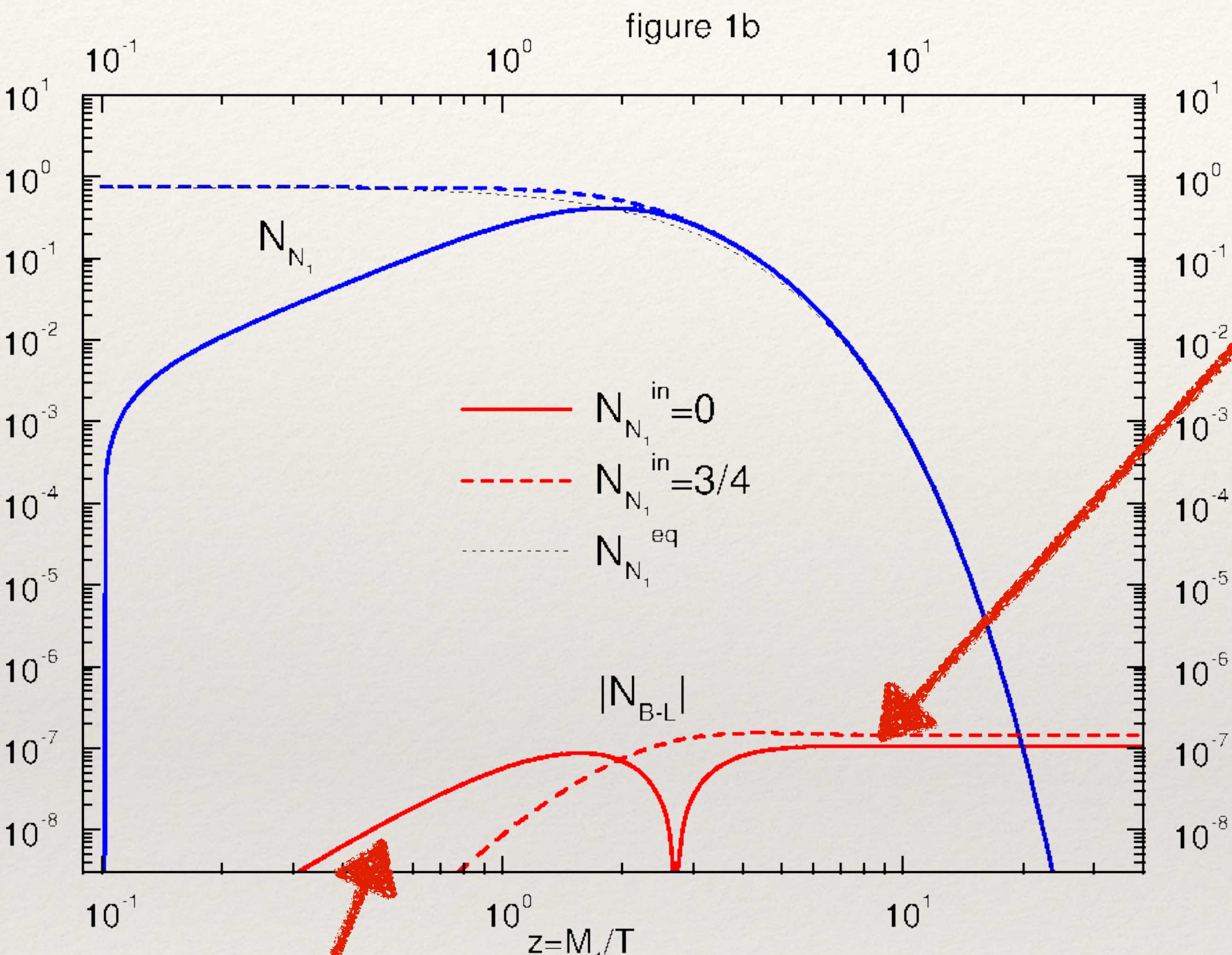
Resonant enhancement by Γ / ΔM permits M < TeV e.g. Dev et al 1711.02863

$$xH\frac{dY_N}{dx} = -\Gamma_N(Y_N - Y_N^{eq}) \qquad x = M/T$$

$$xH\frac{dY_{B-L}}{dx} = \epsilon\Gamma_N(Y_N - Y_N^{eq}) - c_W\Gamma_N Y_{B-L}$$

"source" "washout"

Leptogenesis with small M?



asymmetry generated during N decay ("freeze-out scenario")

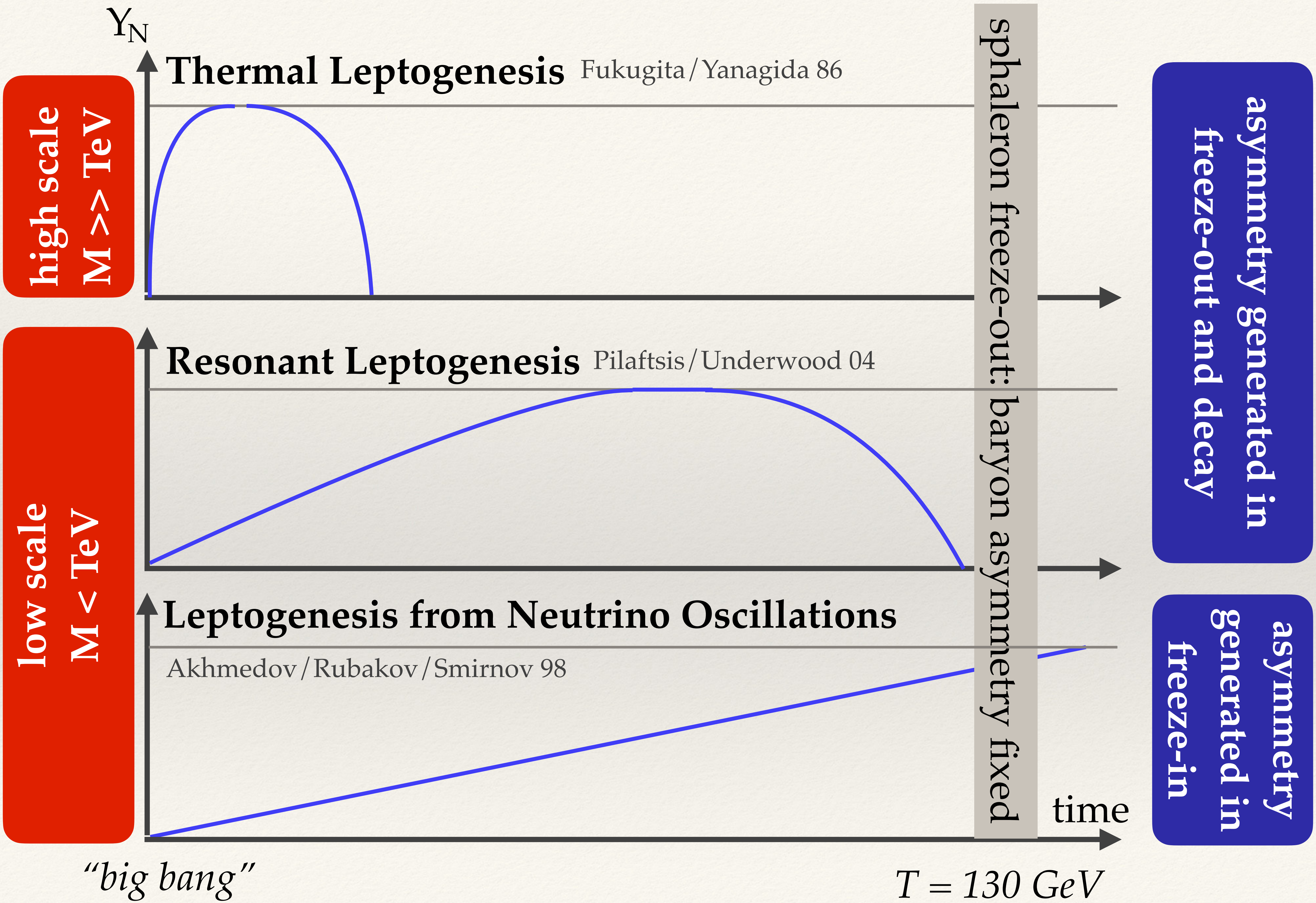
asymmetry generated during N production ("freeze-in scenario")

Sakharov's nonequilibrium condition can be fulfilled in two ways.

$$xH\frac{dY_N}{dx} = -\Gamma_N(Y_N - Y_N^{eq}) \qquad x = M/T$$

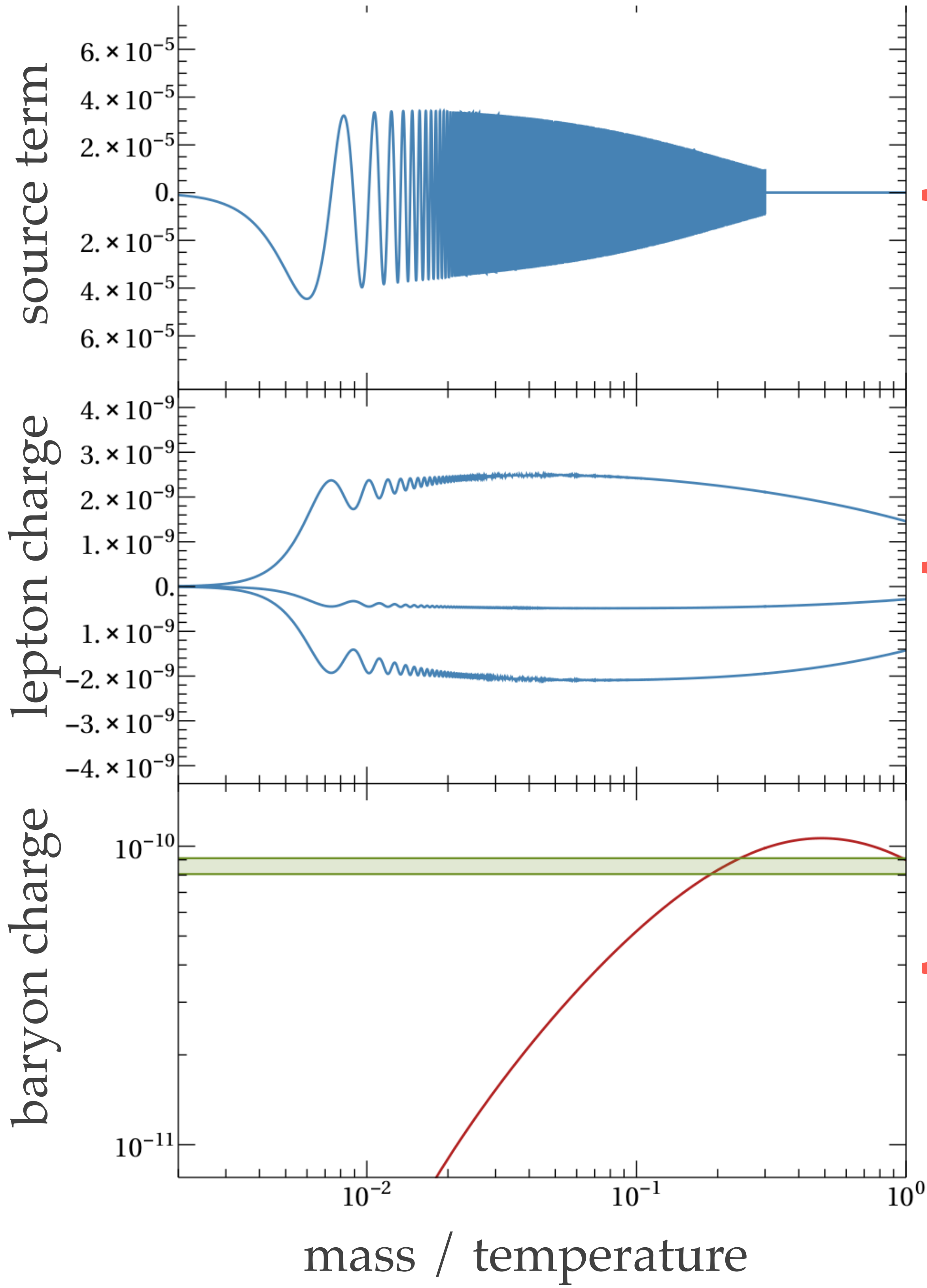
$$xH\frac{dY_{B-L}}{dx} = \epsilon\Gamma_N(Y_N - Y_N^{eq}) - c_W\Gamma_N Y_{B-L}$$

"source" "washout"



high scale
M >> TeV
low scale
M < TeV
Y_N
Thermal Leptogenesis
Fukugita/Yanagida 86
Resonant Leptogenesis
Pilaftsis/Underwood 04
Leptogenesis from Neutrino Oscillations
Akhmedov/Rubakov/Smirnov 98
sphaleron freeze-out: baryon asymmetry fixed
time
"big bang"
T = 130 GeV
asymmetry generated in freeze-out and decay
asymmetry generated in freeze-in

Freeze-In Leptogenesis



Heavy Neutrinos undergo CP violating oscillations during heat production.

This induces asymmetries in the SM lepton flavours.

Sphalerons partly transfer the asymmetries into a baryon number.

Quantitative Description

- Start from 2PI effective action in the Schwinger-Keldysh formalism
- Derive Markovian quantum kinetic equations in a series of controlled approximations („density matrix equations")

$$\frac{dR_N}{dt} = -i\left[\langle H\rangle, R_N\right] - \frac{1}{2}\langle\gamma^{(0)}\rangle\left\{F^\dagger F, R_N - I\right\} - \frac{1}{2}\langle\gamma^{(1b)}\rangle\left\{F^\dagger \mu F, R_N\right\} + \langle\gamma^{(1a)}\rangle F^\dagger \mu F +$$
$$- \frac{1}{2}\langle\widetilde{\gamma}^{(0)}\rangle\left\{M_M F^T F^* M_M, R_N - I\right\} + \frac{1}{2}\langle\widetilde{\gamma}^{(1b)}\rangle\left\{M_M F^T \mu F^* M_M, R_N\right\} +$$
$$- \langle\widetilde{\gamma}^{(1a)}\rangle M_M F^T \mu F^* M_M\,,$$

$$\frac{d\mu_{\Delta_a}}{dt} = -\frac{9\,\zeta(3)}{2N_D\,\pi^2}\Big\{\langle\gamma^{(0)}\rangle\left(F R_N F^\dagger - F^* R_{\bar{N}} F^T\right) - 2\langle\gamma^{(1a)}\rangle \mu F F^\dagger +$$
$$+ \langle\gamma^{(1b)}\rangle \mu\left(F R_N F^\dagger + F^* R_{\bar{N}} F^T\right)$$
$$+ \langle\widetilde{\gamma}^{(0)}\rangle\left(F^* M_M R_{\bar{N}} M_M F^T - F M_M R_N M_M F^\dagger\right) - 2\langle\widetilde{\gamma}^{(1a)}\rangle \mu F^* M_M^2 F^T$$
$$+ \langle\widetilde{\gamma}^{(1b)}\rangle \mu\left(F^* M_M R_{\bar{N}} M_M F^T + F M_M R_N M_M F^\dagger\right)\Big\}_{aa}\,,$$

Quantitative Description

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neutrino effective Hamiltonian ***H***

$$\frac{dR_N}{dt} = -i\,[\langle H\rangle, R_N] - \frac{1}{2}\langle\gamma^{(0)}\rangle\left\{F^\dagger F, R_N - I\right\} - \frac{1}{2}\langle\gamma^{(1b)}\rangle\left\{F^\dagger \mu F, R_N\right\} + \langle\gamma^{(1a)}\rangle F^\dagger \mu F +$$
$$- \frac{1}{2}\langle\widetilde{\gamma}^{(0)}\rangle\left\{M_M F^T F^* M_M, R_N - I\right\} + \frac{1}{2}\langle\widetilde{\gamma}^{(1b)}\rangle\left\{M_M F^T \mu F^* M_M, R_N\right\} +$$
$$- \langle\widetilde{\gamma}^{(1a)}\rangle M_M F^T \mu F^* M_M\,,$$

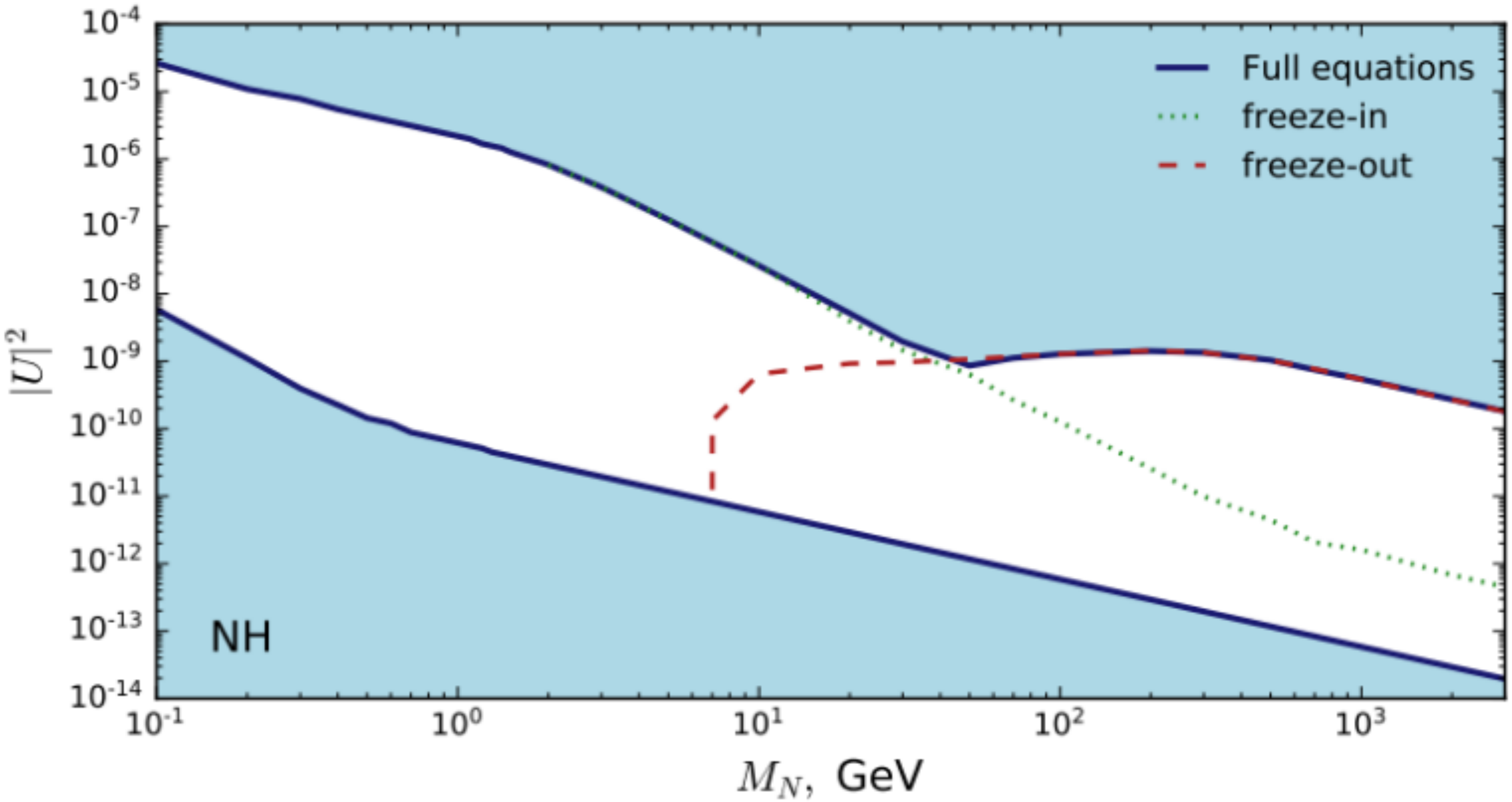
neutrino density matrix ***R***

lepton chemical potentials ***μ***

$$\frac{d\mu_{\Delta_a}}{dt} = -\frac{9\zeta(3)}{2N_D\,\pi^2}\Big\{\langle\gamma^{(0)}\rangle\left(F R_N F^\dagger - F^* R_{\bar{N}} F^T\right) - 2\langle\gamma^{(1a)}\rangle \mu F F^\dagger +$$
$$+ \langle\gamma^{(1b)}\rangle\mu\left(F R_N F^\dagger + F^* R_{\bar{N}} F^T\right)$$
$$+\langle\widetilde{\gamma}^{(0)}\rangle\left(F^* M_M R_{\bar{N}} M_M F^T - F M_M R_N M_M F^\dagger\right) - 2\langle\widetilde{\gamma}^{(1a)}\rangle \mu F^* M_M^2 F^T$$
$$+\langle\widetilde{\gamma}^{(1b)}\rangle\mu\left(F^* M_M R_{\bar{N}} M_M F^T + F M_M R_N M_M F^\dagger\right)\Big\}_{aa}\,,$$

Remaining terms: heavy neutrino mass ***M***, coupling ***F*** and thermal transport coefficients ***γ***

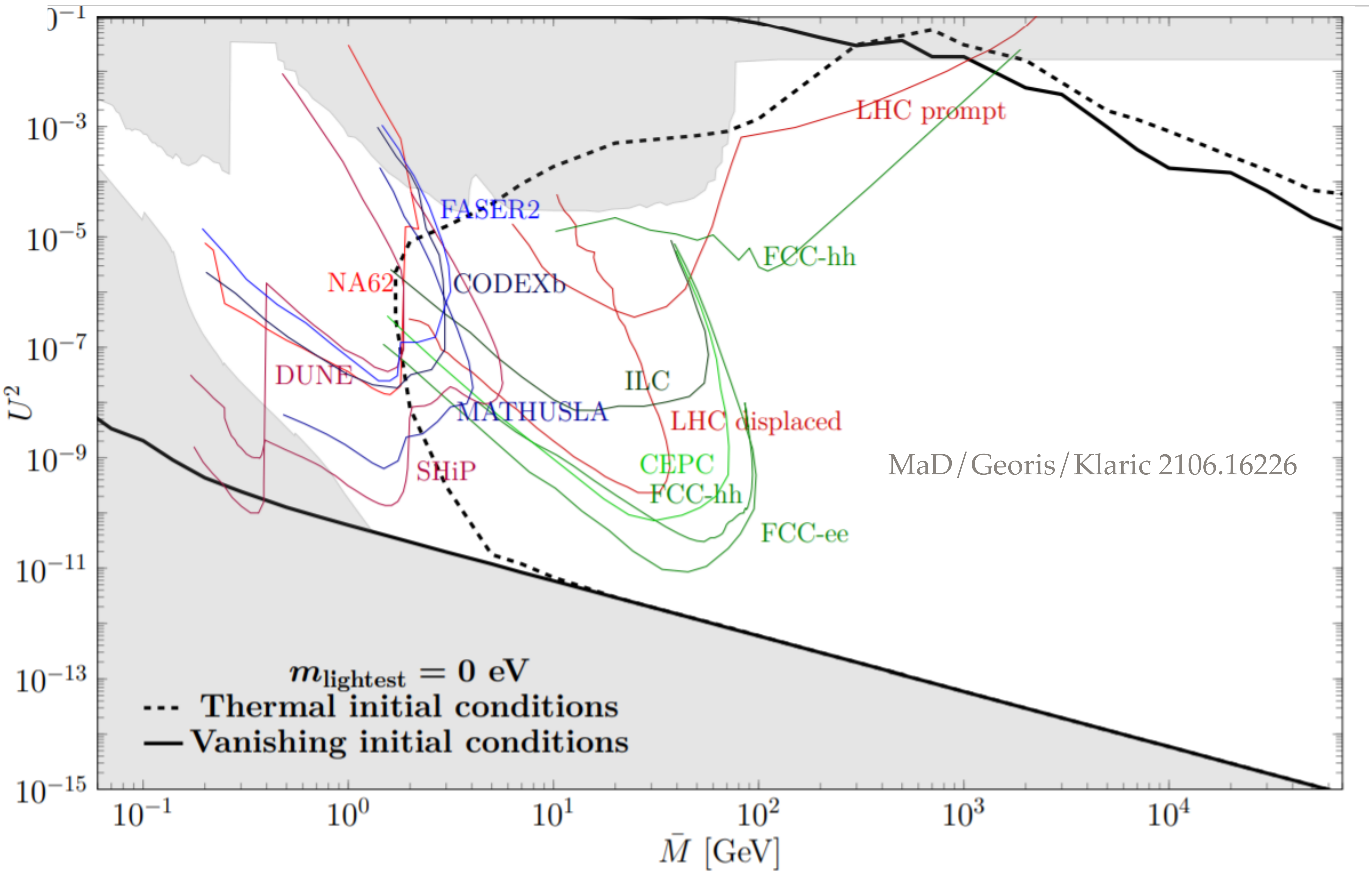
Leptogenesis with 2 RH Neutrinos



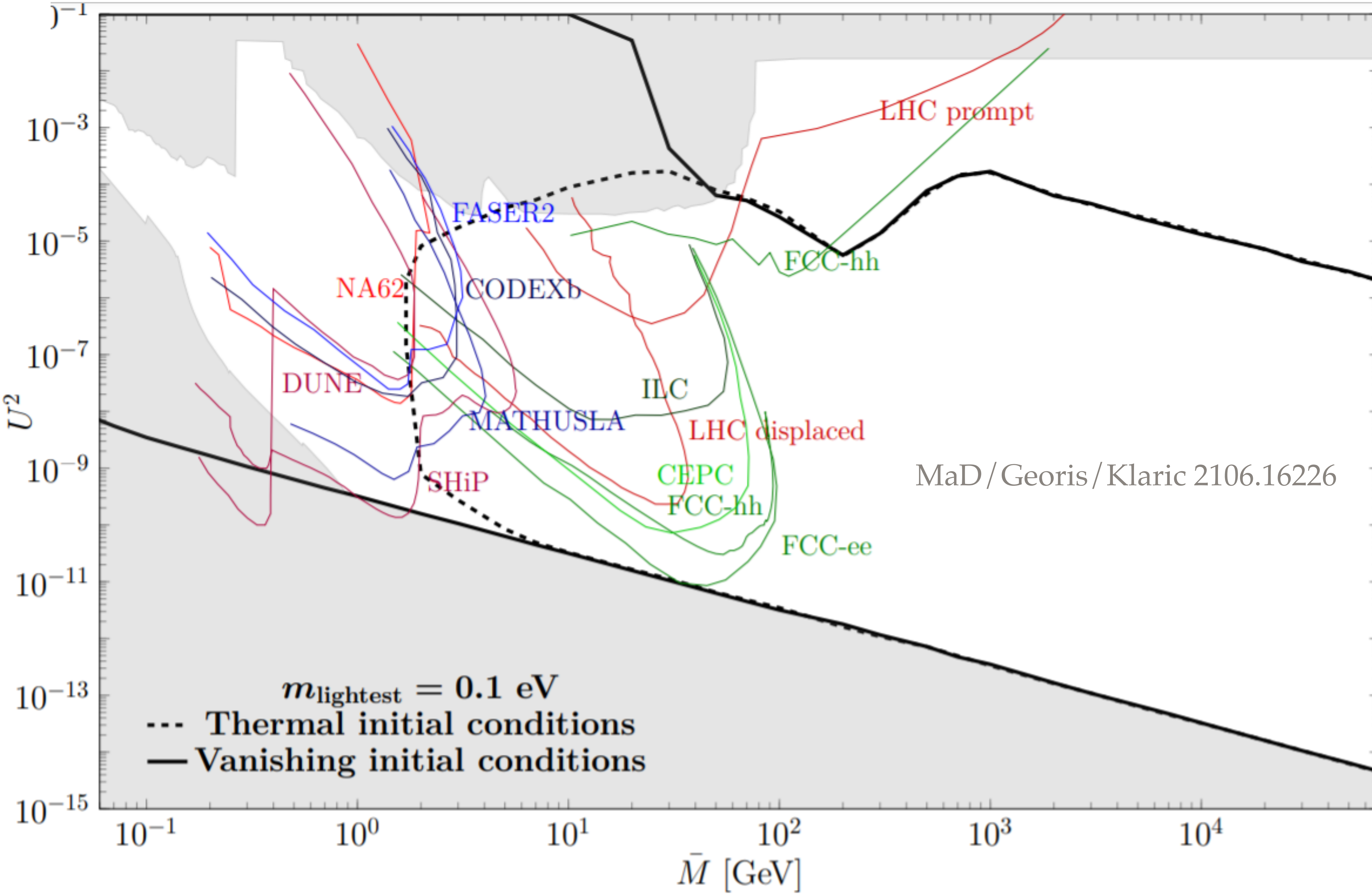
The region in which the freeze-out scenario ("resonant leptogenesis") and freeze-in scenario ("ARS leptogenesis") work overlap!

Klaric/Shaposhnikov/Timirsyasov 2008.13771

Leptogenesis with 3 RH Neutrinos



Leptogenesis with 3 RH Neutrinos



Overview

Part I:
General Considerations

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Falsifyable Barygenesis Scenarios

- electroweak baryogenesis
- high scale leptogenesis
- low scale leptogenesis

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How to test Low Scale Leptogenesis?

- discovering heavy neutrinos
- the mixing pattern
- the Majorana mass
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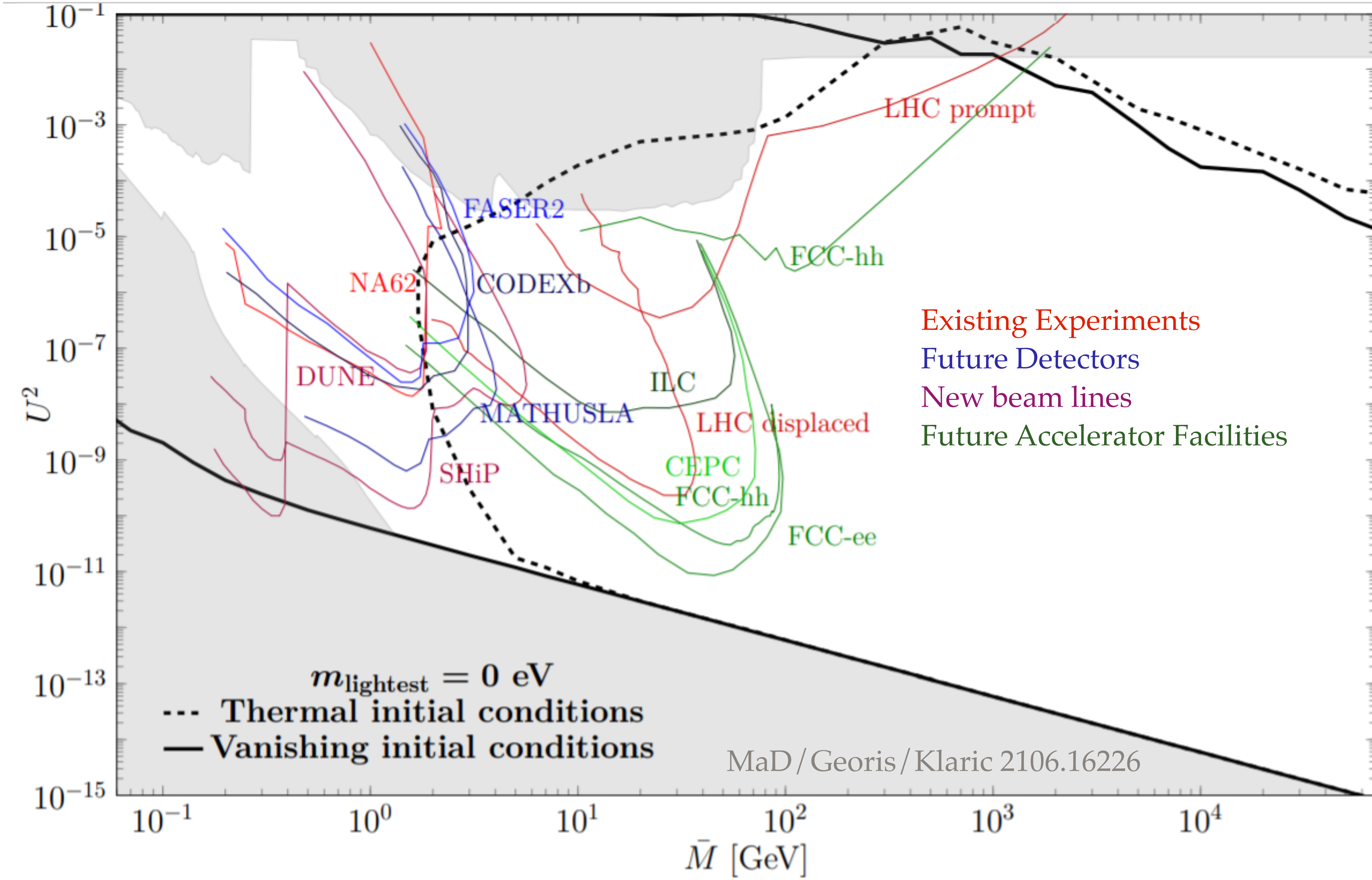
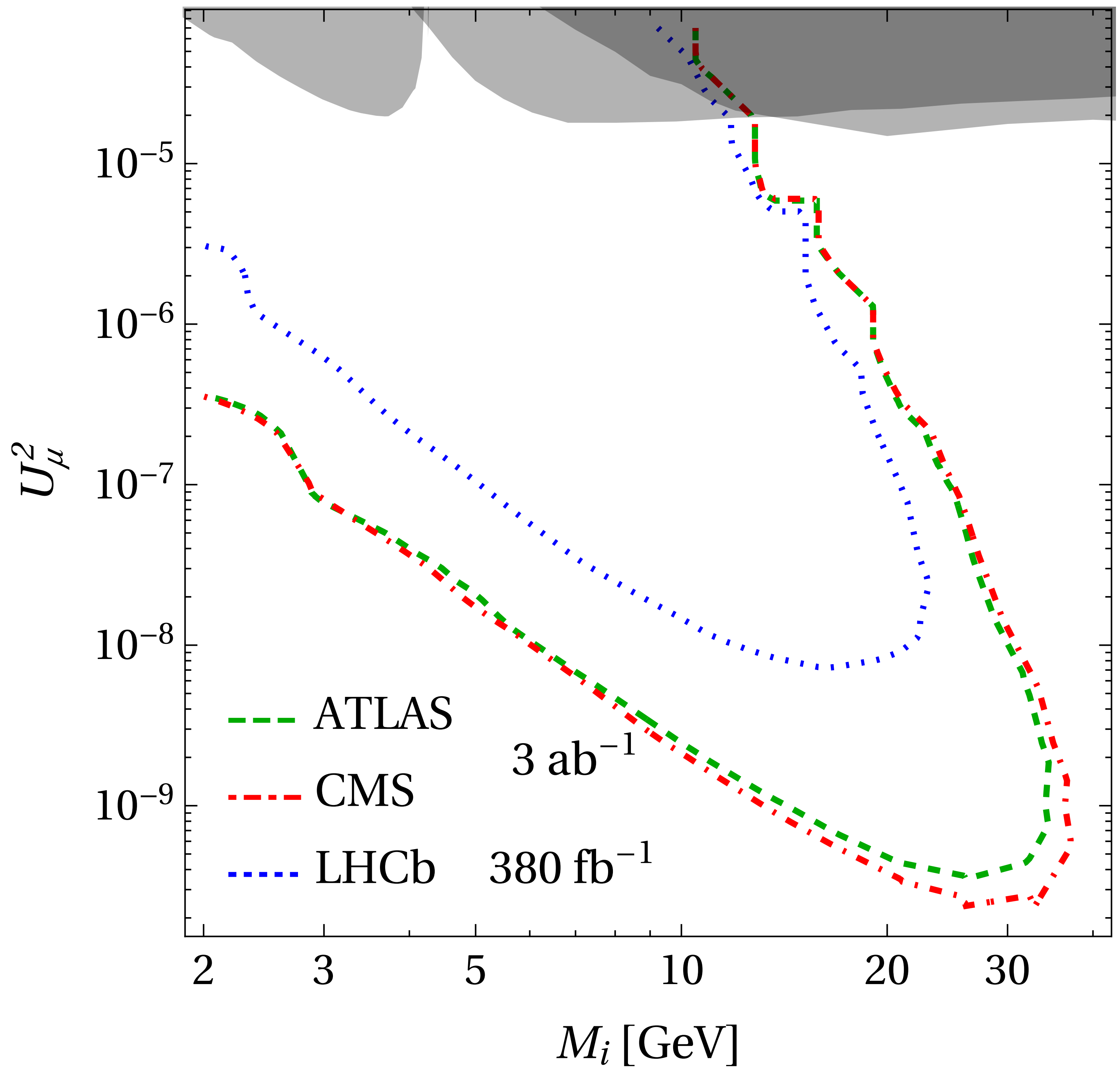
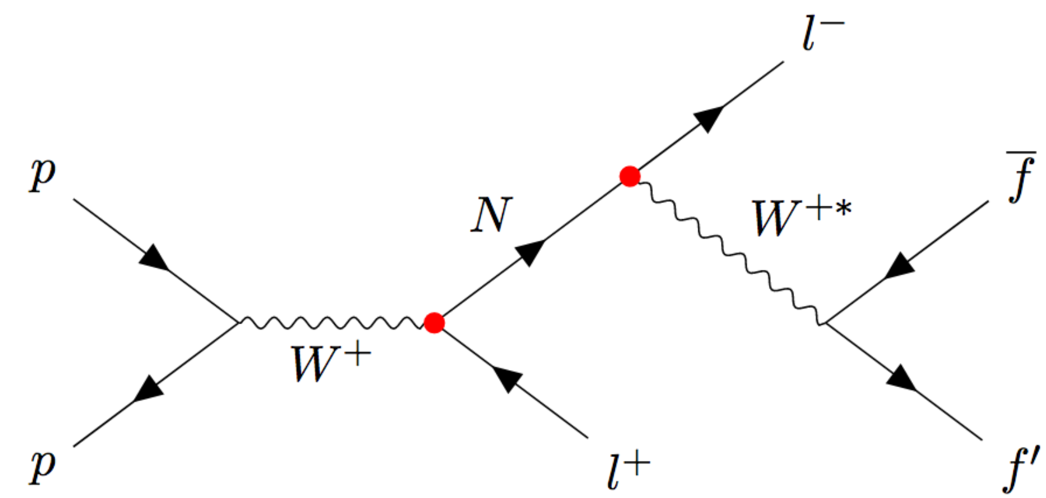
Leptogenesis with 3 RH Neutrinos

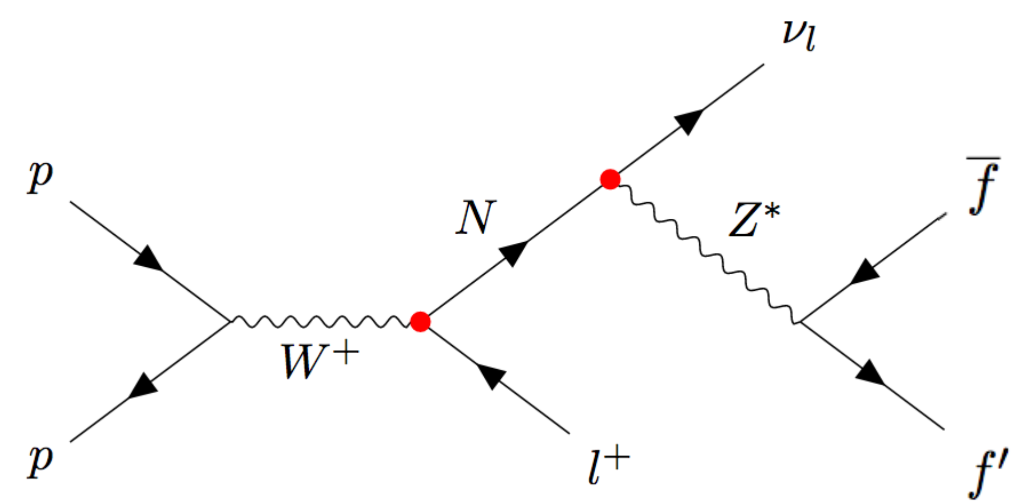


HL-LHC Displaced Vertex Search





(a) Charged current decay



(b) Neutral current decay

MaD/Hajer 1903.06100

see also Helo et al 1312.2900, Izaguirre/Shuve 1504.02470, Gago et al 1505.05880, Dib/Kim 1509.05981, Cottin et al 1806.05191, Abada et al 1807.10024, Boiarska et al 1902.04535, Liu et al 1904.01020 , Dib et al 1903.04905 , Cvetic et al 1805.00070, 1905.03097, …

What can we learn?

Dirac vs Majorana

- **LNV vs LFV decay rates** e.g. Anamiati/Hirsch/Nardi 1607.05641
- **Angular distribution** e.g. Arbelaez et al 1712.08704 , Balantekin/Gouvea/Kayser 1808.10518
- **Flavour mixing pattern** e.g. Dib/Kim/Wang/Zhang 1605.01123

CP properties

e.g. Cvetic / Dib / Kim / Saa 1503.01358

Mass spectrum

e.g. Antusch / Fischer 1709.03797

Test seesaw mechanism and leptogenesis

Hernandez /Kekic / Lopez-Pavon / Racker / Savaldo 1606.06719,
MaD / Garbrecht / Gueter / Klaric 1609.09069
Antusch/Cazzato/MaD/Fischer/Garbrecht/Gueter/Klaric 1710.03744

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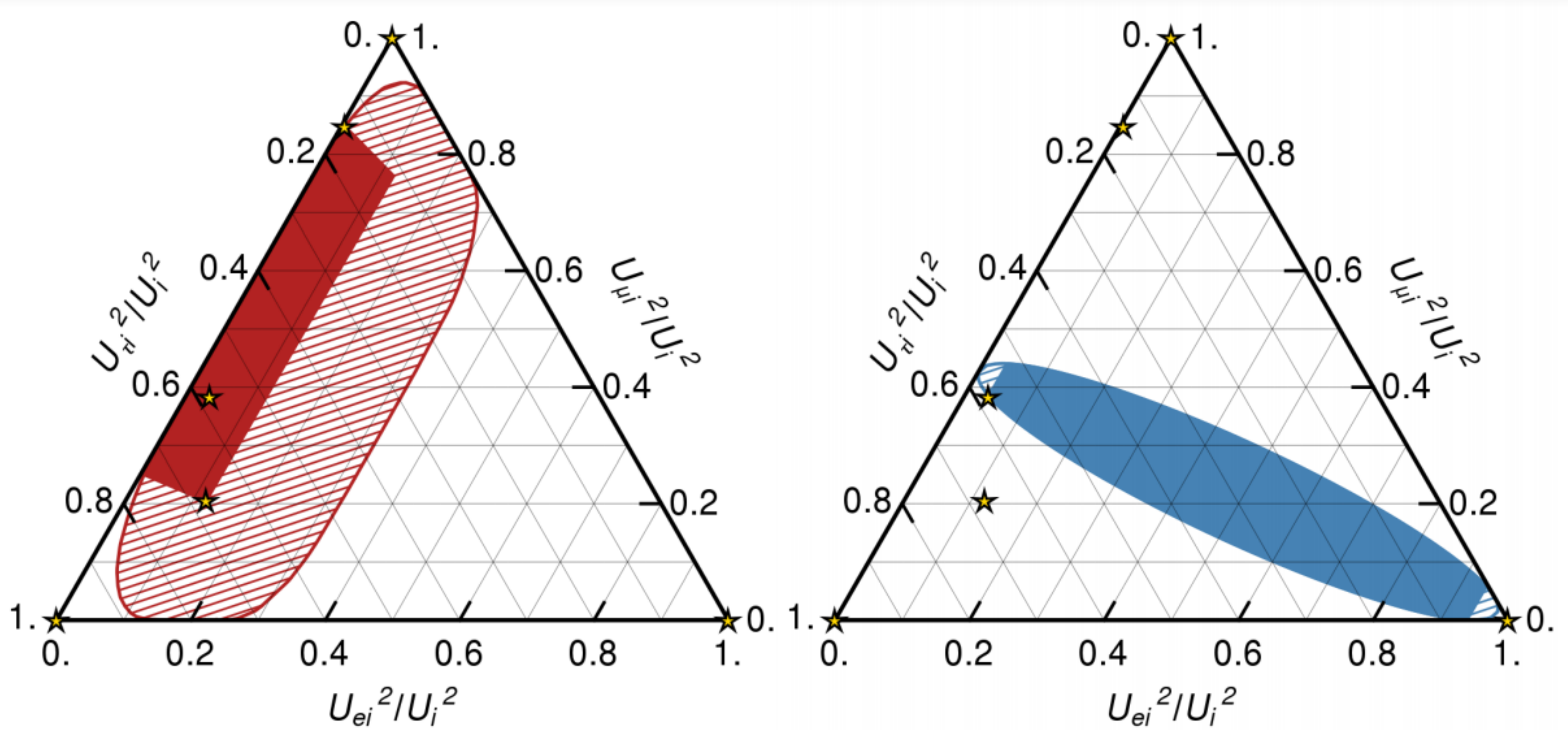
Most Minimal Scenario (2HNL)

- This minimal scenario is very predictive
- In particular, the flavour mixing pattern is strongly constrained: important for experimental sensitivity 1606.06719, 1609.09069, 1704.08721, 1801.04207

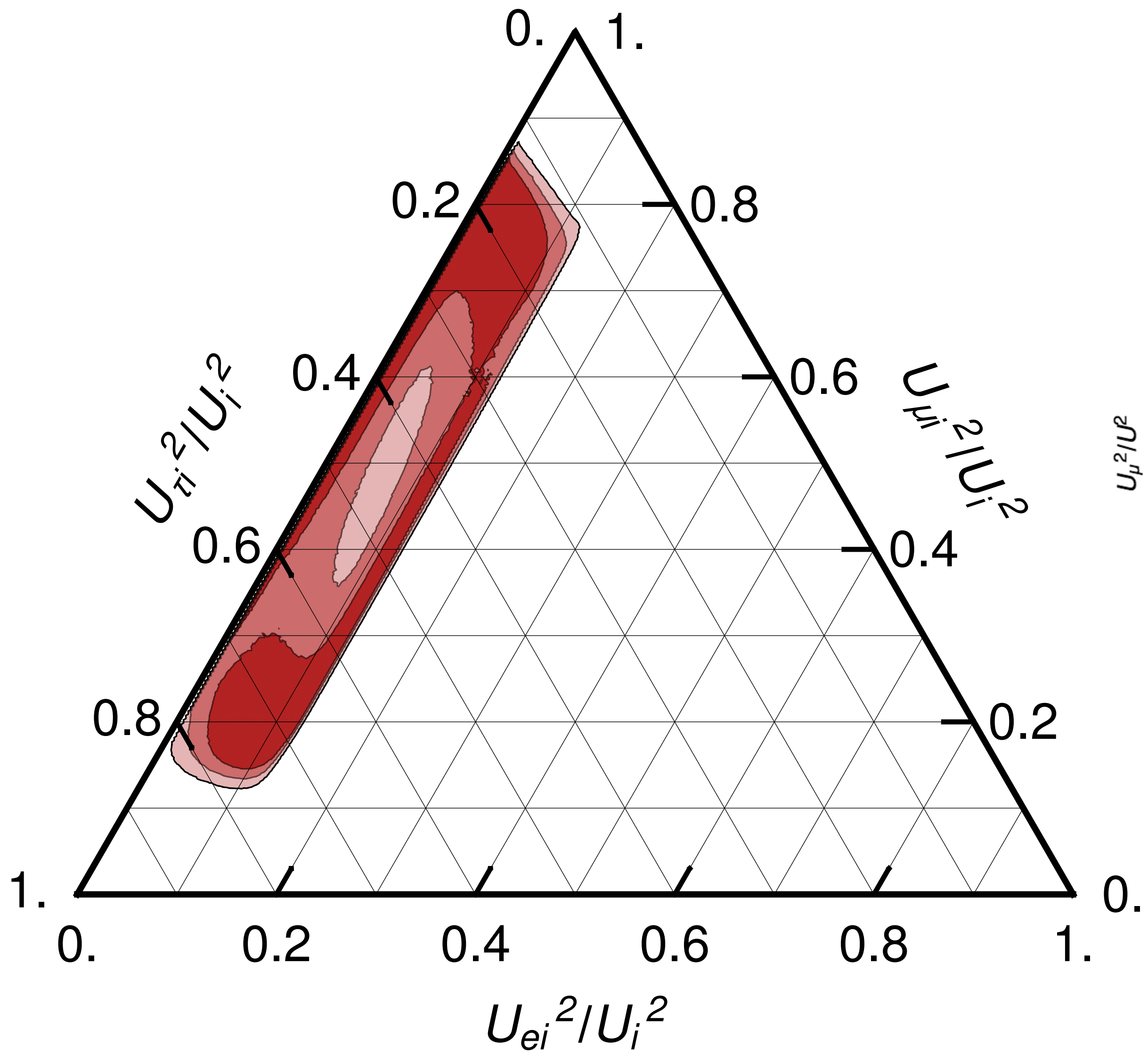


(a) Normal ordering.

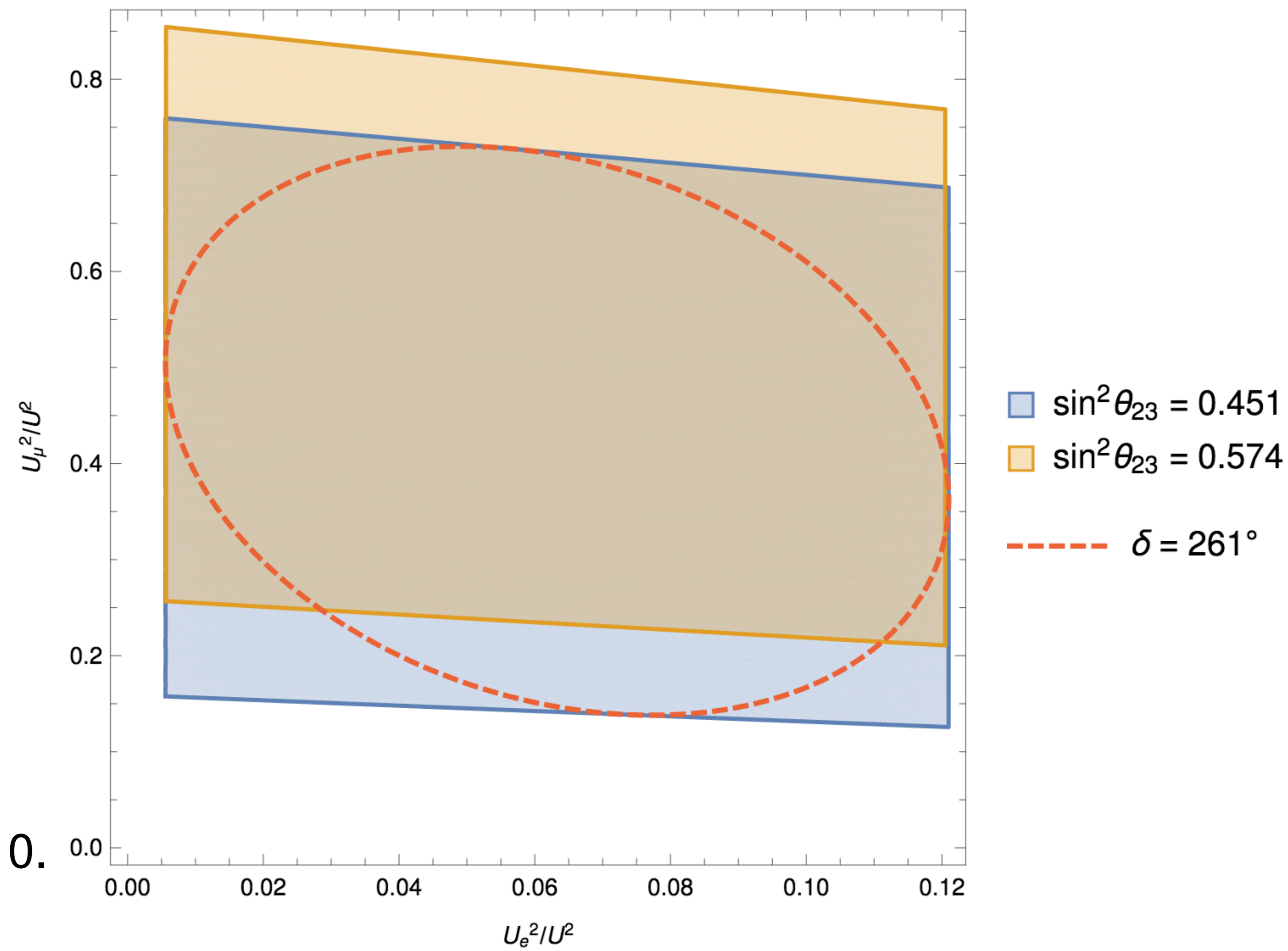
(b) Inverted ordering.

plot from 1801.04207

Constraints from ν-Oscillation Data in Model with 2 Heavy Neutrinos



normal neutrino mass ordering



normal neutrino mass ordering

coloured areas: consistent with ν-oscillation data at 1σ, 2σ and 3σ

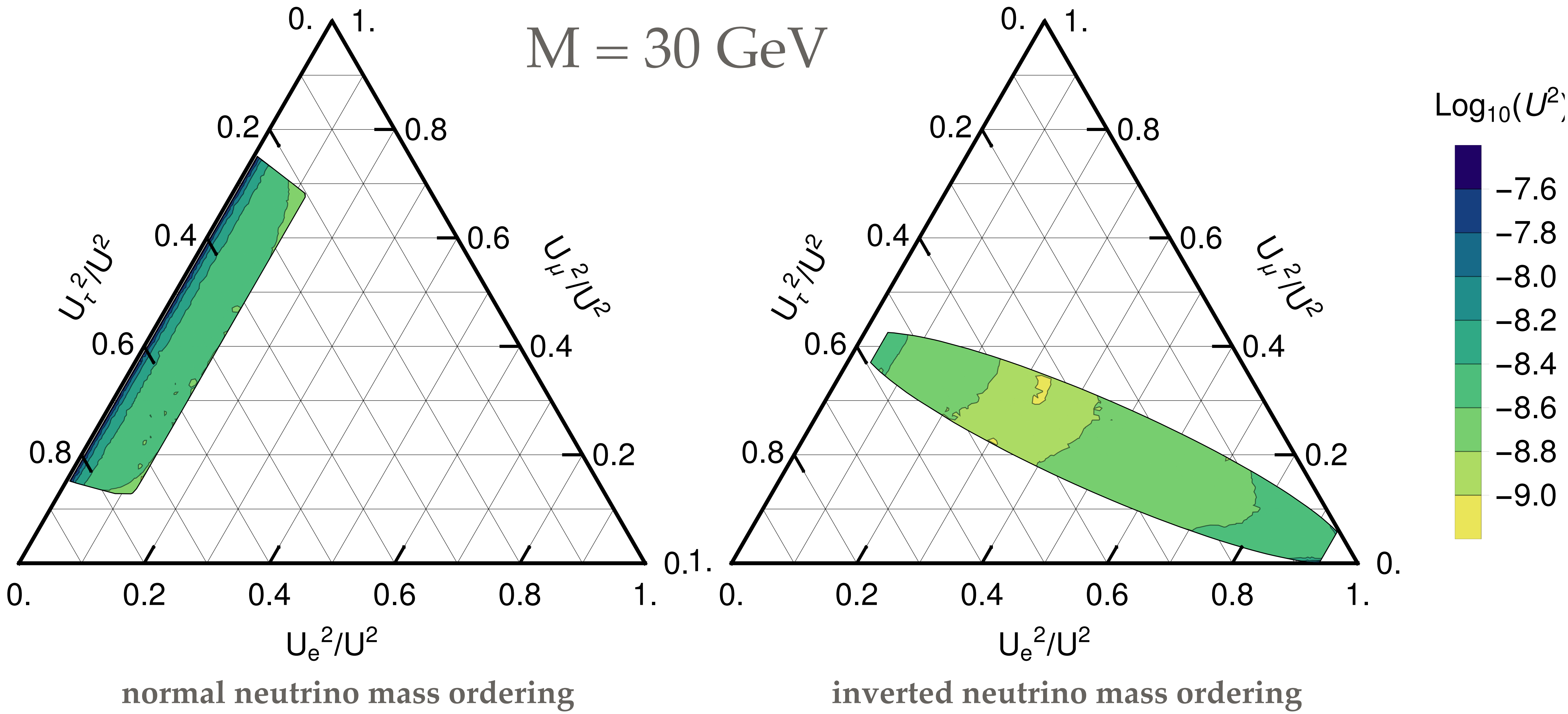
MaD/Hajer/Klaric/Lafranchi 1801.04207

can measure Majorana phase α!

MaD et al 1609.09069

cf. also Caputo et al 1611.05000

Constraints from Leptogenesis in Model with 2 Heavy Neutrinos



plots from Antusch / Cazzato / MaD / Fischer / Garbrecht / Gueter / Klaric 1710.03744

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Neutrino masses vs collider searches

neutrino masses m_i are small (sub eV)

→ **active-sterile mixing angle θ must be small**

Problem!

Solution → **approximate B-L conservation**

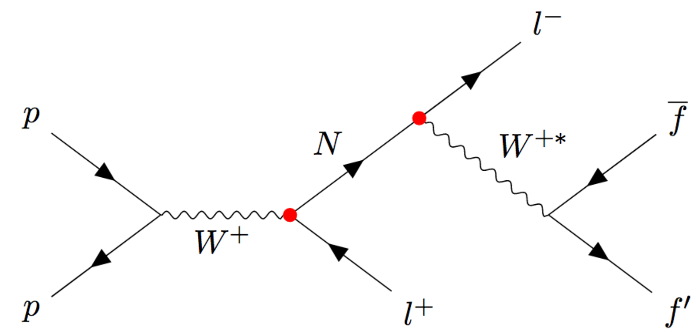
Shaposhnikov 0605047
Kersten/Smirnov 0705.3221

colliders rely on branching ratio

→ **active-sterile mixing angle θ must be large**

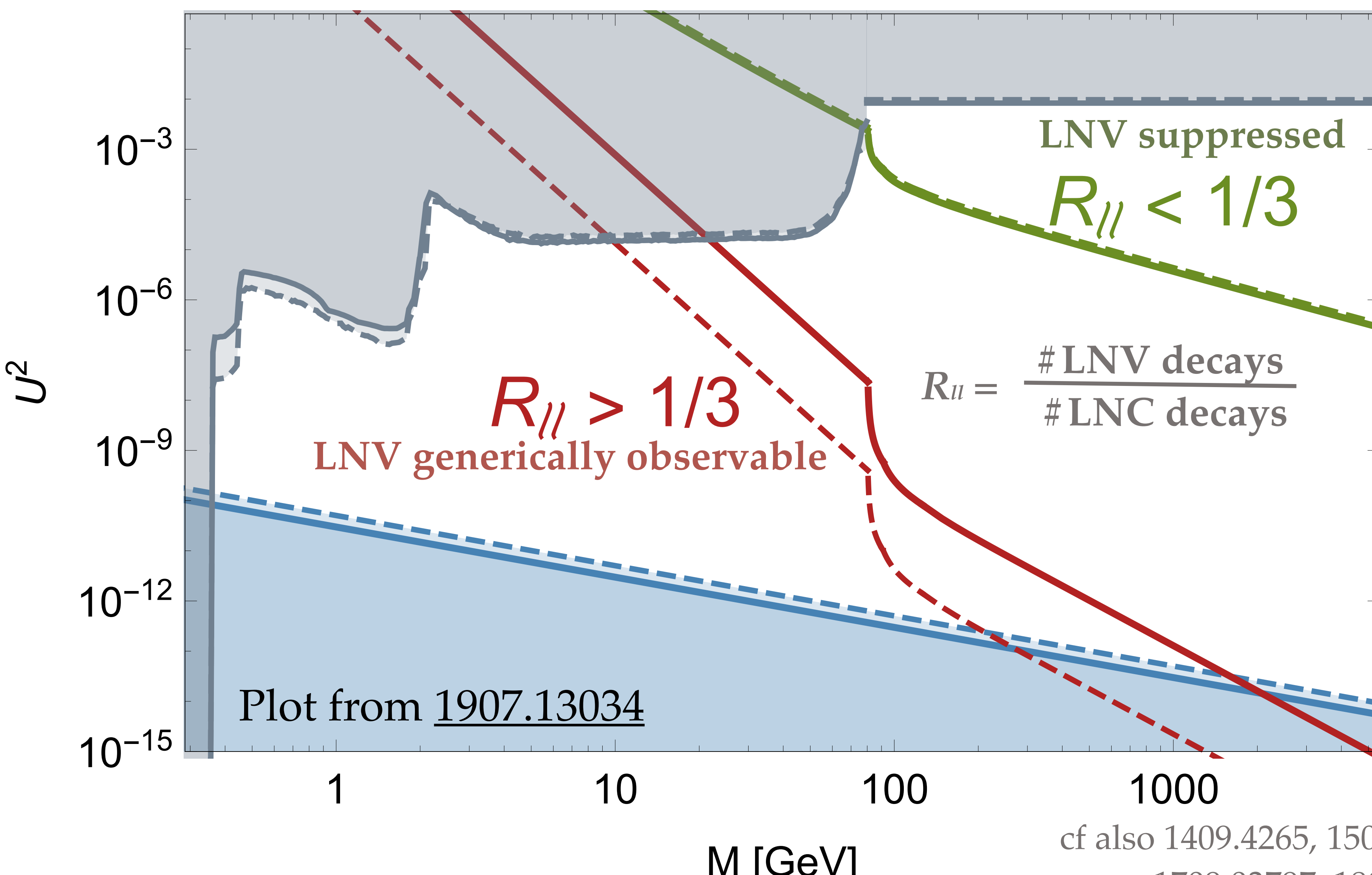
Can LNV be observed?

B-L symmetry: destructive interference amongst contributions from different HNL flavour



(a) Charged current decay

But: B-L is broken to generate neutrino mass.
Is this enough???



HNL oscillations destroy coherence and make LNV observable!

Anamiati et al 1607.05641

$$\mathcal{R}_{\ell\ell} = \frac{\Delta M^2_{\rm phys}}{2\Gamma_N^2 + \Delta M^2_{\rm phys}}$$

Does neutrino osc. data allow for this without fine tuning? It depends

MaD / Klaric / Klose 1907.13034

cf also 1409.4265, 1505.04749, 1605.01123, 1709.06553, 1703.01934, 1709.03797, 1805.00070, 1810.07210, 1905.03097, 1904.05367

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Full Testability of the νMSM

- Neutrino Minimal Standard Model (νMSM): example for a simple UV complete scenario Asaka/Shaposhnikov 0503065 , 0505013
- Effective theory for νMSM collider/fixed target pheno: Type I seesaw with two RH Neutrinos below EW scale

[observational constraints on DM candidate (cf. e.g. 1602.04816, 1807.07938) imply that it must have very feeble couplings]

$$F = \frac{1}{v} U_\nu \sqrt{m_\nu^{\mathrm{diag}}} \mathcal{R} \sqrt{M^{\mathrm{diag}}}$$ Casas/Ibarra 01

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Higgs vev v

light neutrino mixing angles

light neutrino mass splittings

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Casas/Ibarra 01

Dirac phase δ
Majorana phase α

lightest ν mass (almost) vanishes

complex angle ω

N-mass M and splitting ΔM

Full Testability of the νMSM

- Effective theory for νMSM collider / fixed target pheno:

Type I seesaw with two RH Neutrinos below EW scale

Unknown parameters:

M, Δ*M*, Reω, Imω, δ, *α*

Higgs vev v

light neutrino mixing angles

light neutrino mass splittings

$$F = \frac{1}{v} U_\nu \sqrt{m_\nu^{\rm diag}} \mathcal{R} \sqrt{M^{\rm diag}}$$

Casas / Ibarra 01

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Majorana phase α

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complex angle ω

N-mass *M* and splitting Δ*M*

Full Testability of the νMSM

heavy neutrino masses

size of N_1 and N_2 couplings relative to each other

overall N_i coupling strength

DUNE, NOvA, T2K, HyperK…

Unknown parameters:

M, ΔM, Reω, Imω, δ, α

N_i flavour mixing pattern

Higgs vev v

light neutrino mixing angles

light neutrino mass splittings

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Dirac phase δ
Majorana phase α

lightest ν mass (almost) vanishes

complex angle ω

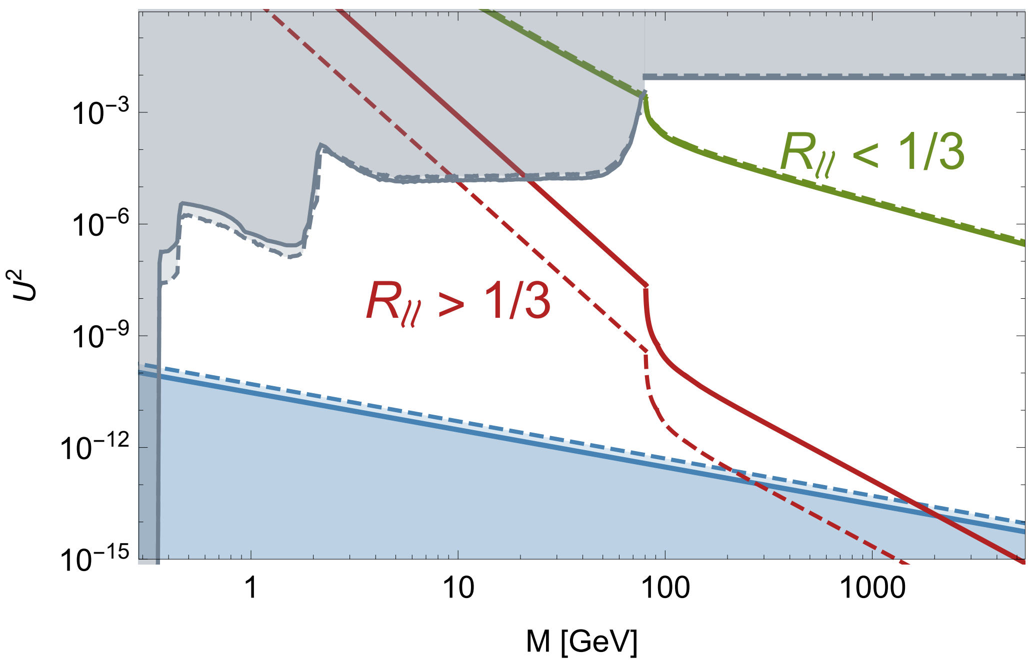
N-mass M and splitting ΔM

How to measure ΔM?

ratio of LNV to LNC decays is sensitive to ΔM

$$\mathcal{R}_{\ell\ell} = \frac{\Delta M_{\rm phys}^2}{2\Gamma_N^2 + \Delta M_{\rm phys}^2}$$

Anamiati et al 1607.05641



MaD/Klaric/Klose 1907.13034

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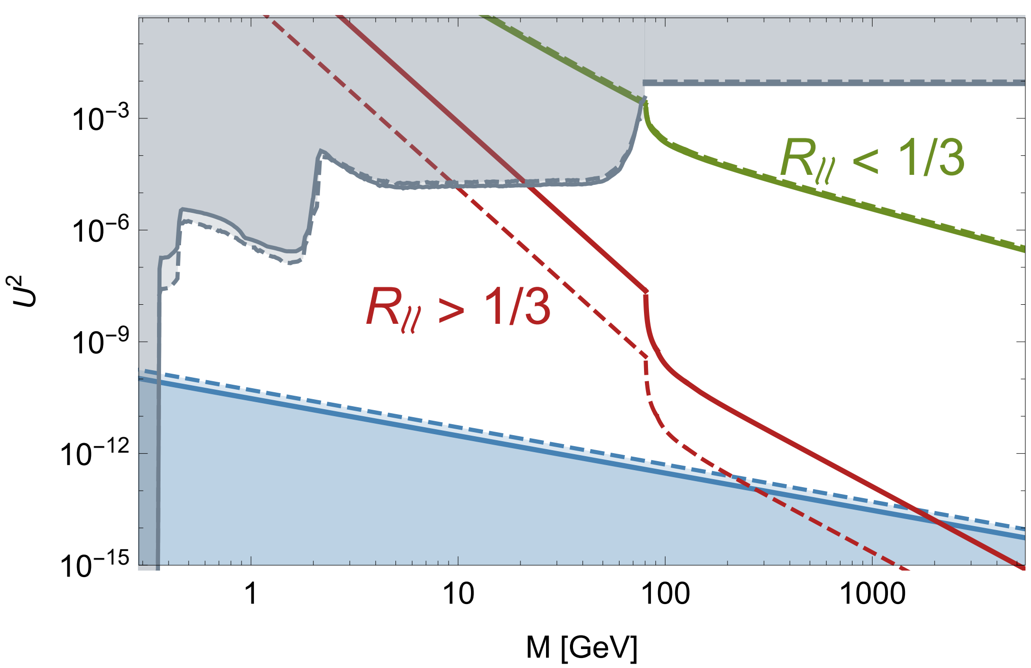
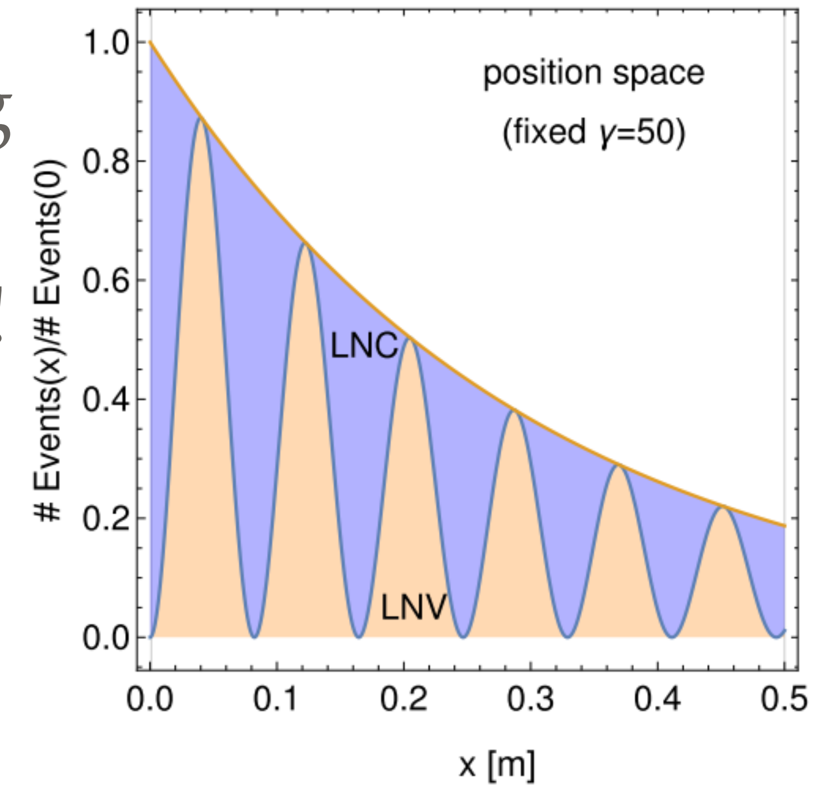
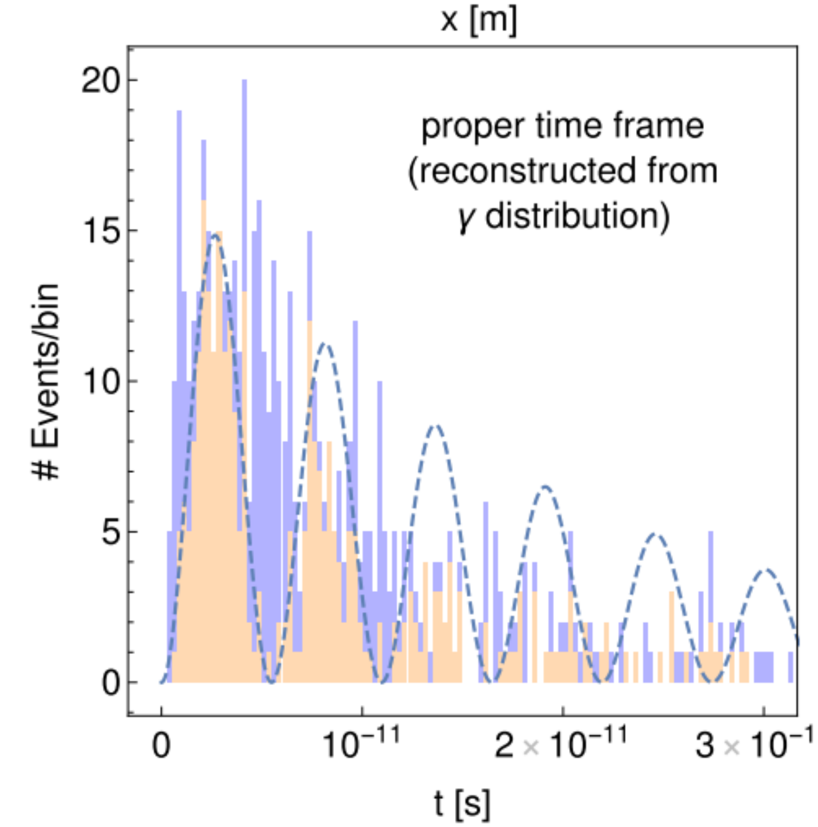


MaD/Klaric/Klose 1907.13034

spatially resolving this ratio gives more information!

Antusch et al 1709.03797





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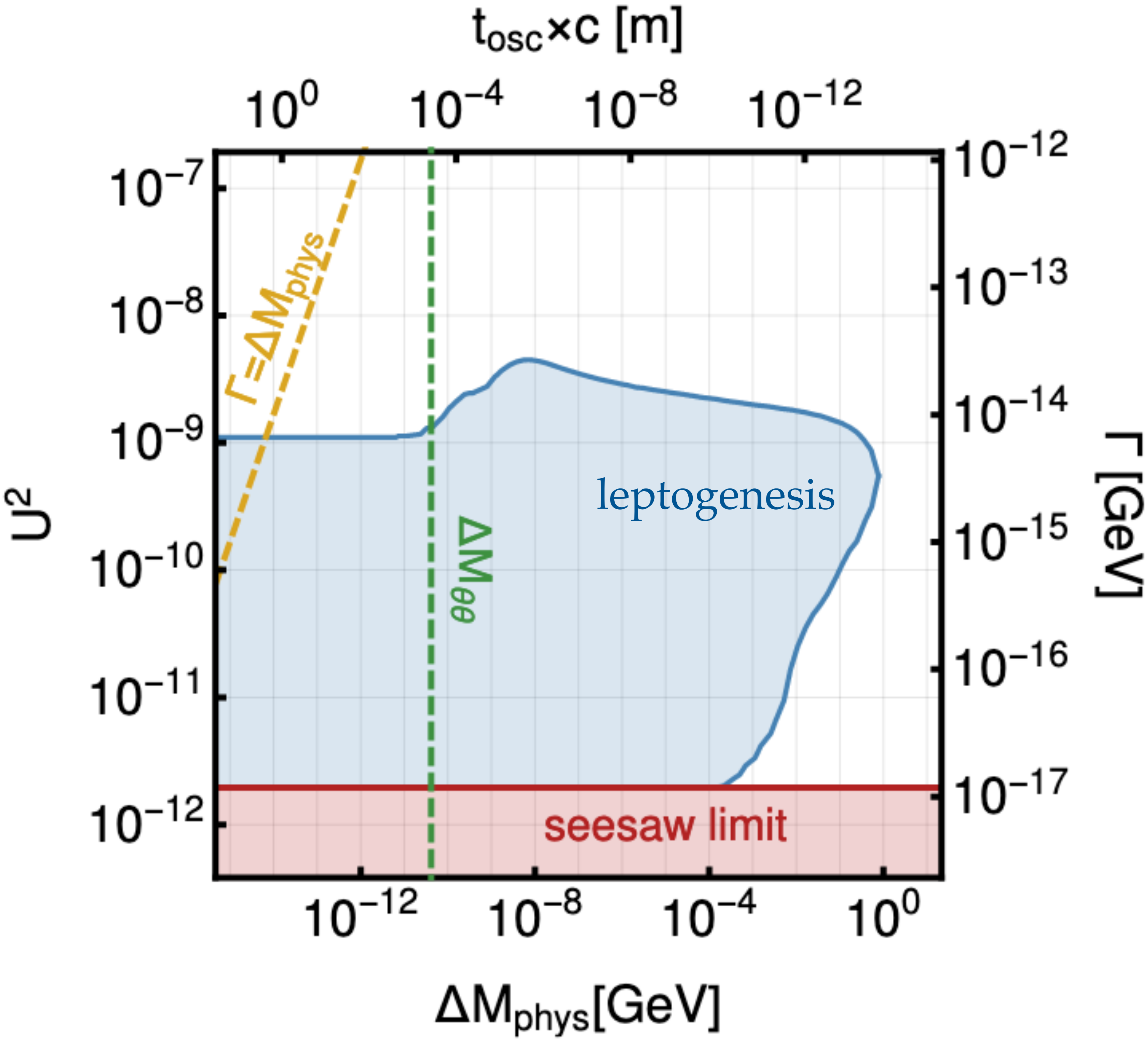
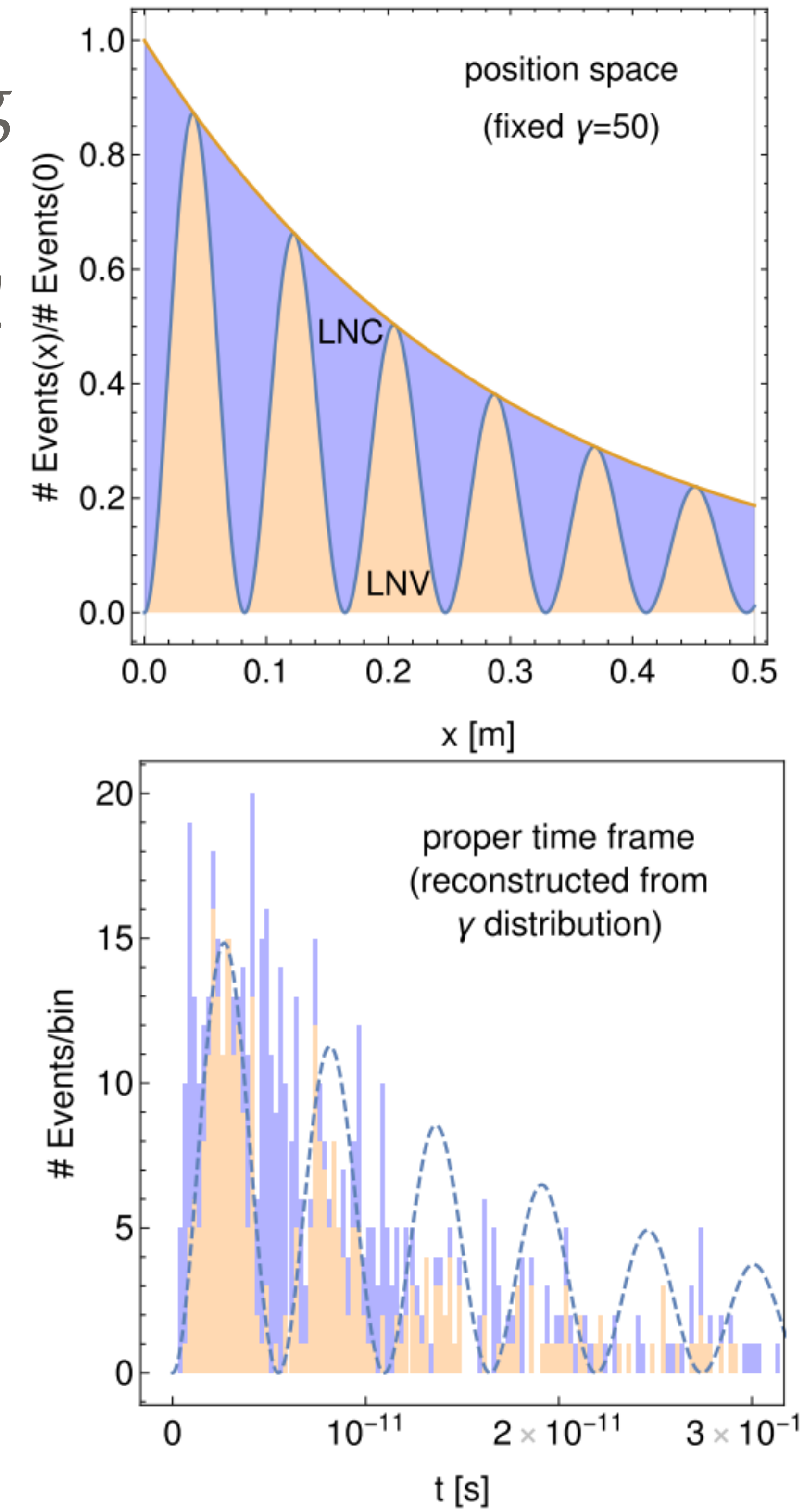
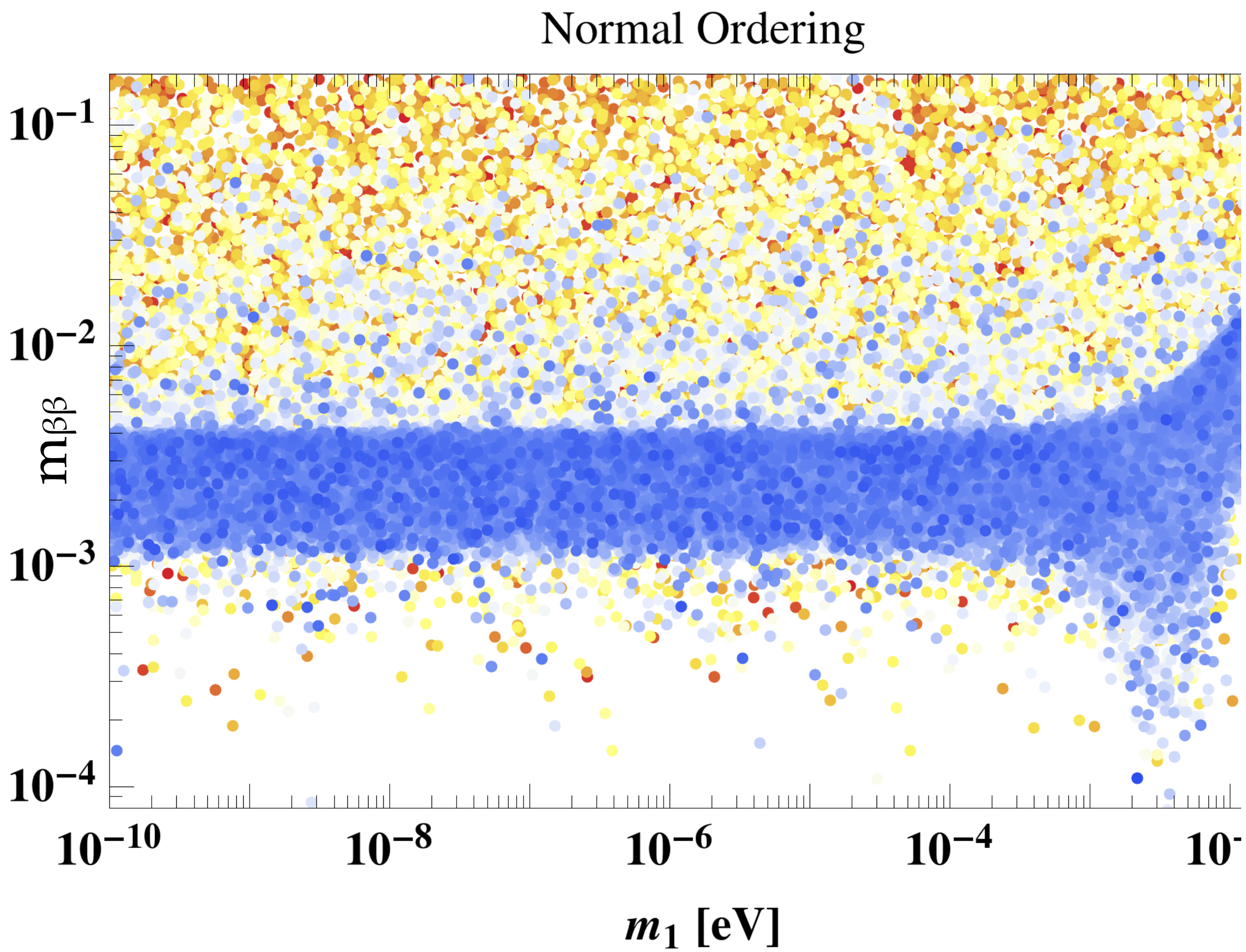




The 0νββ Connection

Heavy neutrino exchange can dominate 0νββ…
…even in the leptogenesis region
⇒ additional probe of Reω !

Bezrukov 0505247
Blennow et al 1005.3240
Lopez Pavon et al 1209.5342
MaD / Eijima 1606.06221
Hernandez et al 1606.06719
Asaka et al 1606.06686
Abada et al 1810.12463



Abada et al 1810.12463

- **colourful points: can explain baryon asymmetry and neutrino mass**
- **colour code measures the degree of fine tuning**
- **points outside the standard 0νββ band are possible…**
- **…..observing a non-standard value provides a probe of RH neutrino properties!**

Full Testability of the νMSM

heavy neutrino masses

size of N_1 and N_2 couplings relative to each other

overall N_i coupling strength

DUNE, NOvA, T2K, HyperK…

N_i flavour mixing pattern

Unknown parameters:

M, ΔM, $\mathrm{Re}\,\omega$, $\mathrm{Im}\,\omega$, δ, α

- In principle all parameters can be measured
  ⇒ fully testable model of neutrino masses and baryogenesis
- This requires a combination of collider/fixed target experiment data and ν-osc. data (and possibly 0νββ)
  ⇒ poster child example for synergy between collider and long baseline programs! cf. Hernandez et al 1606.06719, MaD et al 1609.09069

The Quest for the Origin of Matter - A Multi Frontier Problem!

Indirect probes at accelerators rare decays, EWPD, lepton universality)

new detectors (FASER, Codex-b, MATHUSLA, Al3X, ANUBIS

Collider searches for heavy neutrinos

absolute neutrino mass searches (KATRIN ect.)

non-accelerator searches (TRISTAN…)

neutrinoless double β decay

fixed target experiments (SHiP, NA62, DUNE, T2K..)

neutrino oscillation experiments DUNE, Hyper-K

X-ray searches: SRG/eROSITA, SRG/ART-XC, ATHNEA, XRISM, Lynx…

CMB and LSS : absolute neutrino mass

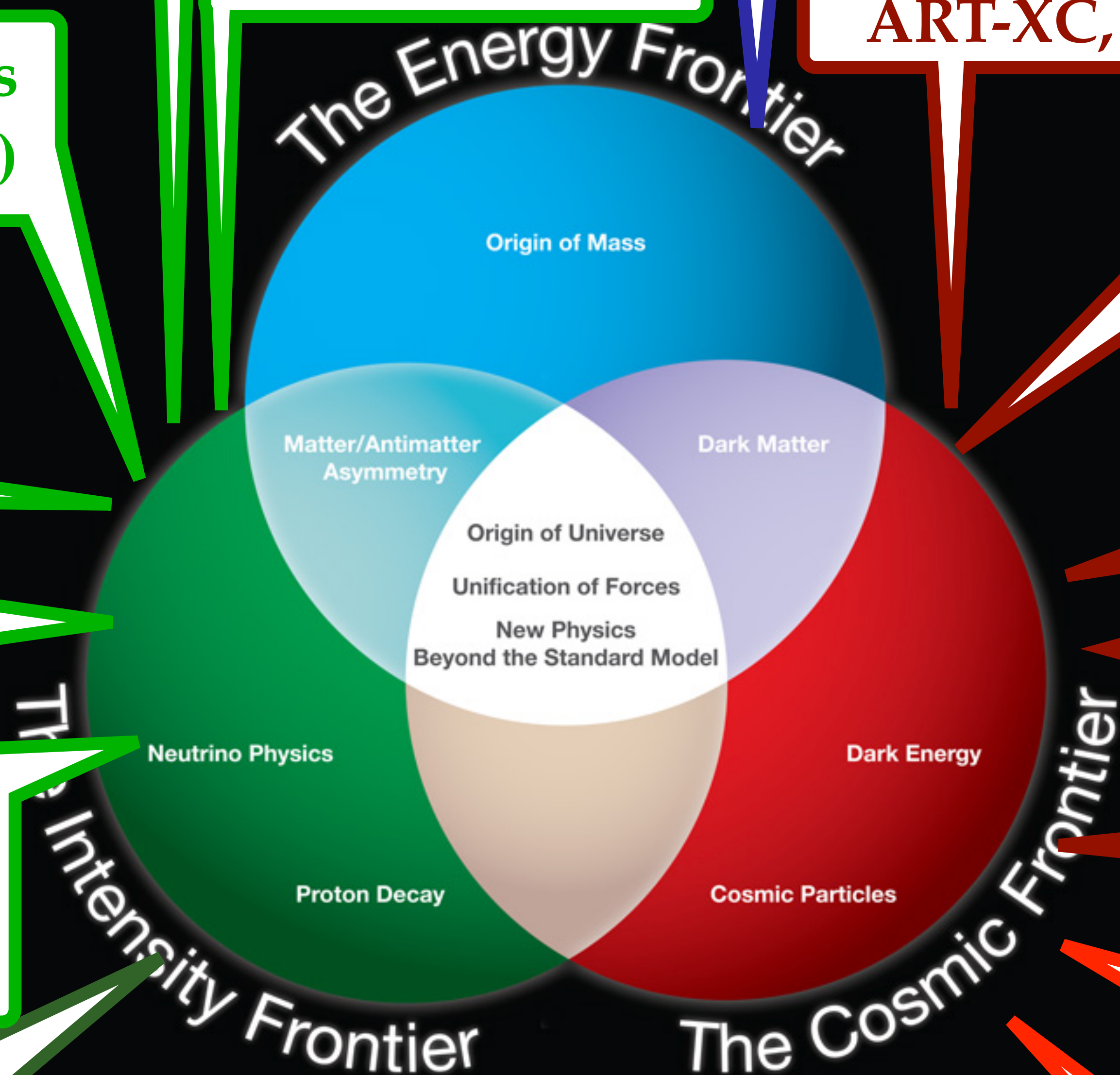
astrophysics: supernovae etc.

Structure formation: simulation, observation

IGM temperature: WDM vs CDM

Theory: leptogenesis parameter region

Theory: Sterile neutrino DM production



RF, NF, EF, CF, TF

Backup Slides

B-L Symmetry

B-L Symmetric Limit

express Lagrangian in terms of the Dirac spinor $\psi_N = (\nu_{R\mathrm{s}} + \nu^c_{R\mathrm{w}})$.

$$\mathcal{L} = \mathcal{L}_{\mathrm{SM}} + \overline{\psi_N}(\mathrm{i}\partial\!\!\!/ - \bar{M})\psi_N + \overline{\nu_{R3}}\mathrm{i}\partial\!\!\!/\nu_{R3} - F^*_a \overline{\psi_N}\phi^T\varepsilon^\dagger \ell_{La} - F_a \bar{\ell}_{La}\varepsilon\phi^*\psi_N$$
$$-\epsilon^*_a F^*_a \overline{\psi^c_N}\phi^T\varepsilon^\dagger\ell_{La} - \epsilon_a F_a \bar{\ell}_{La}\varepsilon\phi^*\psi^c_N - \epsilon'_a F_a \overline{\ell_{La}}\varepsilon\phi^*\nu_{R3} - \epsilon'^*_a F^*_a \overline{\nu_{R3}}\phi^T\varepsilon^\dagger\ell_{La}$$
$$-\mu\bar{M}\frac{1}{2}\left(\overline{\psi^c_N}\psi_N + \overline{\psi_N}\psi^c_N\right) - \mu'\bar{M}\overline{\nu^c_{R3}}\nu_{R3}\,,$$

charge assignment in Lagrangian

spinor	$\bar{L}$-charge
$\nu_{R\mathrm{s}} \equiv \frac{1}{\sqrt{2}}(\nu_{R1} + i\nu_{R2})$	$+1$
$\nu_{R\mathrm{w}} \equiv \frac{1}{\sqrt{2}}(\nu_{R1} - i\nu_{R2})$	-1
ν_{R3}	0

approximately conserved charges in leptogenesis

spinors	$\widetilde{L}$-charge
$P_+N_i, \quad \bar{N}_iP_+$	$+1$
$P_-N_i, \quad \bar{N}_iP_-$	-1

νMSM from B-L Symmetry

$$M_M = \begin{pmatrix} \bar{M}(1-\mu) & 0 & 0 \\ 0 & \bar{M}(1+\mu) & 0 \\ 0 & 0 & M' \end{pmatrix}$$

$$F = \begin{pmatrix} F_e(1+\epsilon_e) & iF_e(1-\epsilon_e) & F_e\epsilon'_e \\ F_\mu(1+\epsilon_\mu) & iF_\mu(1-\epsilon_\mu) & F_\mu\epsilon'_\mu \\ F_\tau(1+\epsilon_\tau) & iF_\tau(1-\epsilon_\tau) & F_\tau\epsilon'_\tau \end{pmatrix},$$

Shaposhnikov 06
Kersten/Smirnov 07

***B-L* violating parameters**

$\mu, \ \epsilon, \ \epsilon'$

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No hierarchy problem
Vacuum metastable

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Shaposhnikov 06
Kersten/Smirnov 07

light ν masses: pseudo Dirac pair; feebly coupled sterile neutrino

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leptogenesis:
mass degeneracy for free for pseudo Dirac

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Shaposhnikov 06
Kersten/Smirnov 07

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leptogenesis:

mass degeneracy for free for pseudo Dirac

No hierarchy problem

Vacuum metastable

Dark Matter:

lighter (keV) mass

feeble coupling

$$F = \begin{pmatrix} F_e(1+\epsilon_e) & iF_e(1-\epsilon_e) & F_e\epsilon'_e \\ F_\mu(1+\epsilon_\mu) & iF_\mu(1-\epsilon_\mu) & F_\mu\epsilon'_\mu \\ F_\tau(1+\epsilon_\tau) & iF_\tau(1-\epsilon_\tau) & F_\tau\epsilon'_\tau \end{pmatrix},$$

Shaposhnikov 06

Kersten/Smirnov 07

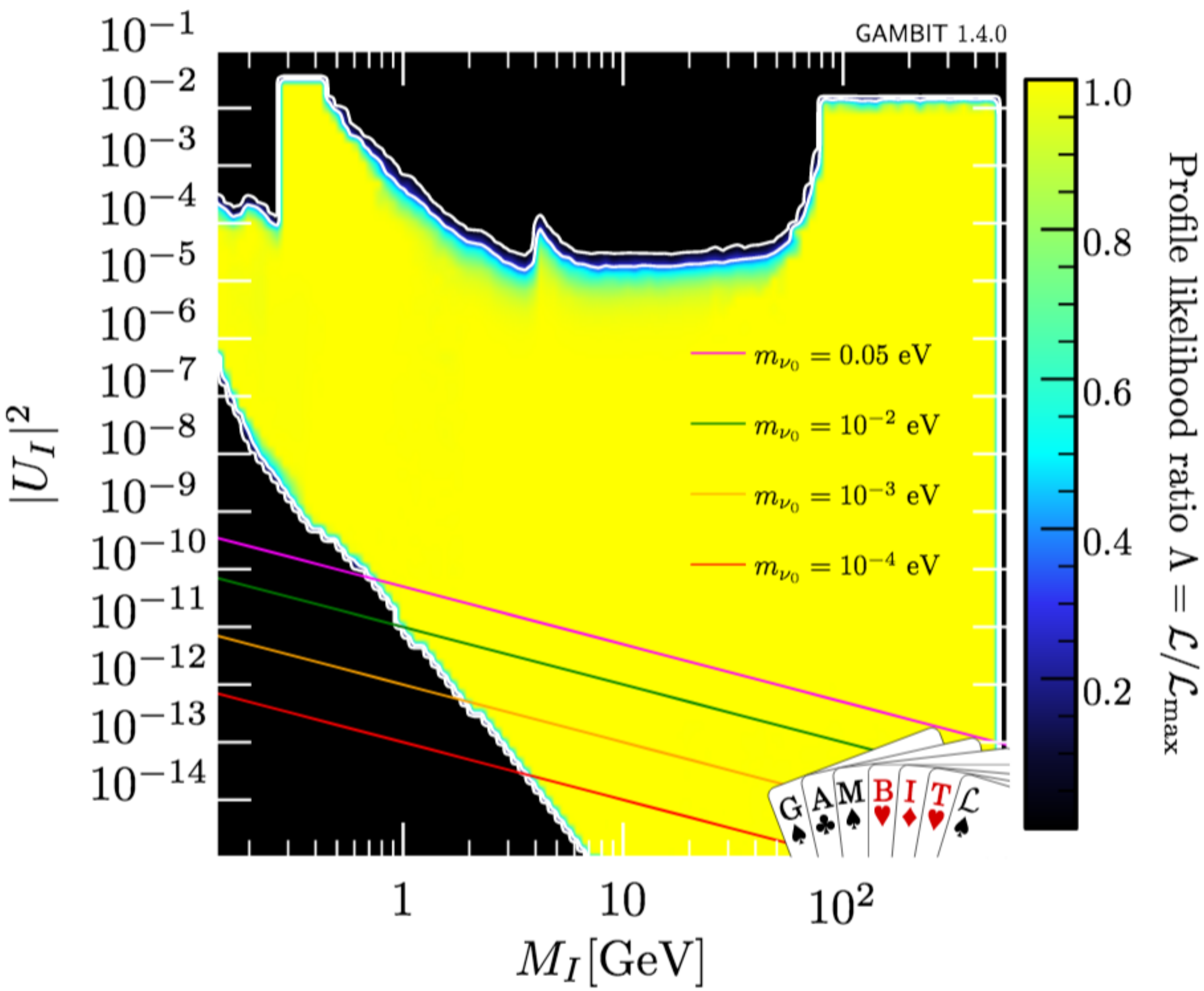
light ν masses: pseudo Dirac pair; feebly coupled sterile neutrino

B-L **violating parameters**

$\mu, \ \epsilon, \ \epsilon'$

Global Constraints for 3 RHN

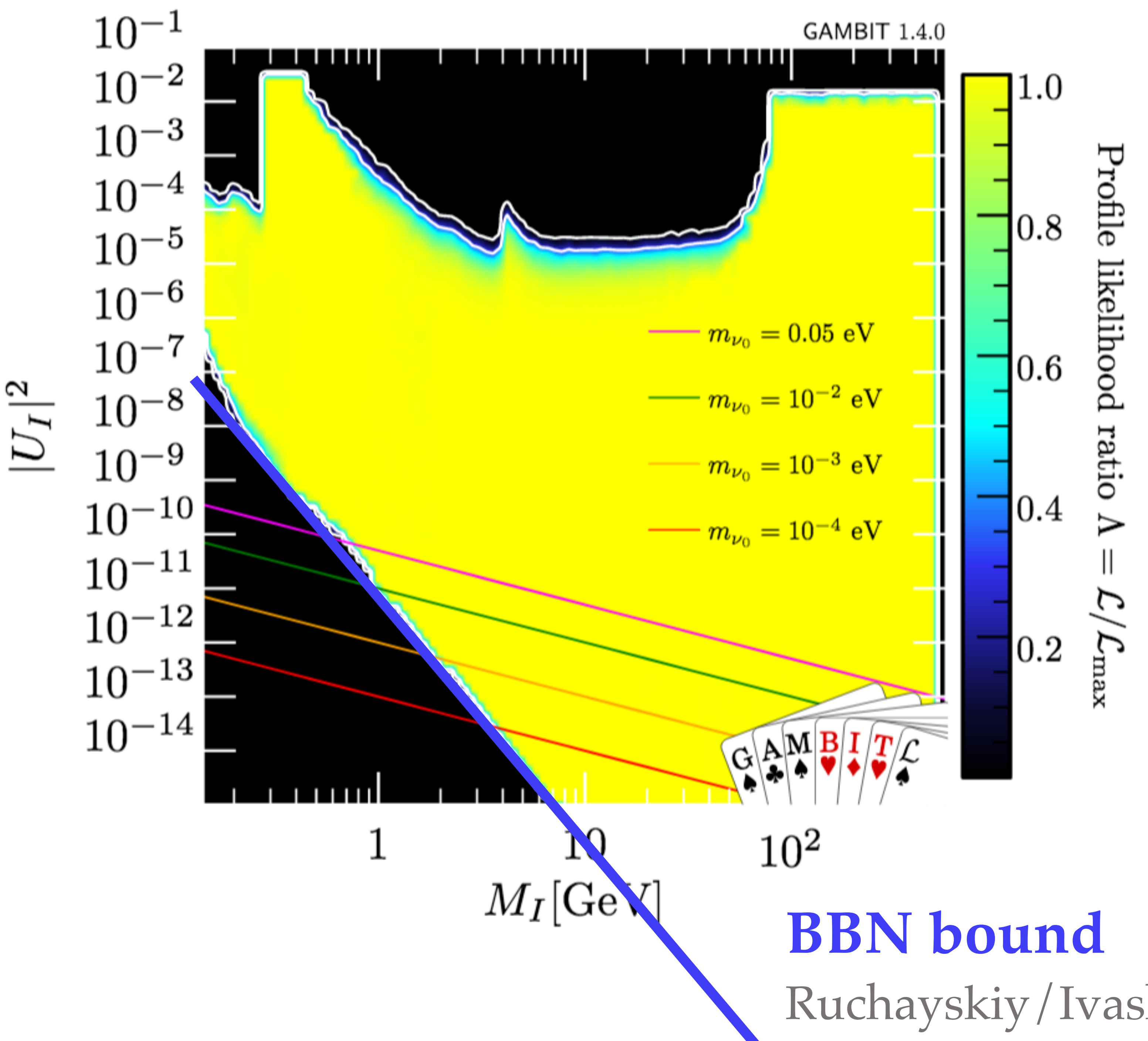
Global Constraints: Total Mixing



3 heavy neutrinos, normal ordering of light neutrino masses

Chrzaszcz et al 1908.02302

Global Constraints: Total Mixing



3 heavy neutrinos, normal ordering of light neutrino masses

Chrzaszcz et al 1908.02302

Ruchayskiy/Ivashko 1202.2841

Hernandez/Lopez-Pavon 1406.2961

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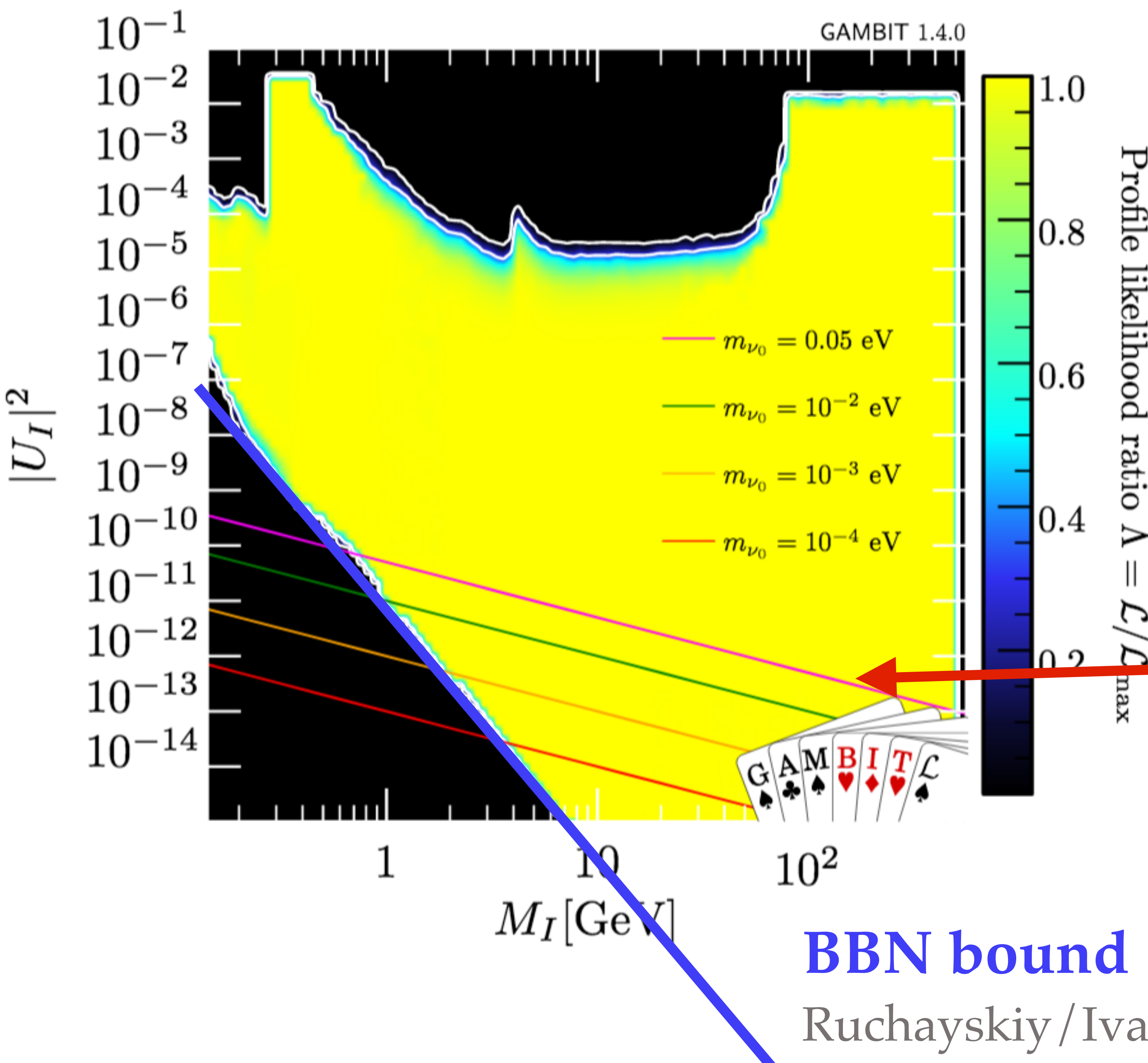


3 heavy neutrinos, normal ordering of light neutrino masses

Seesaw bounds

MaD 1904.11959

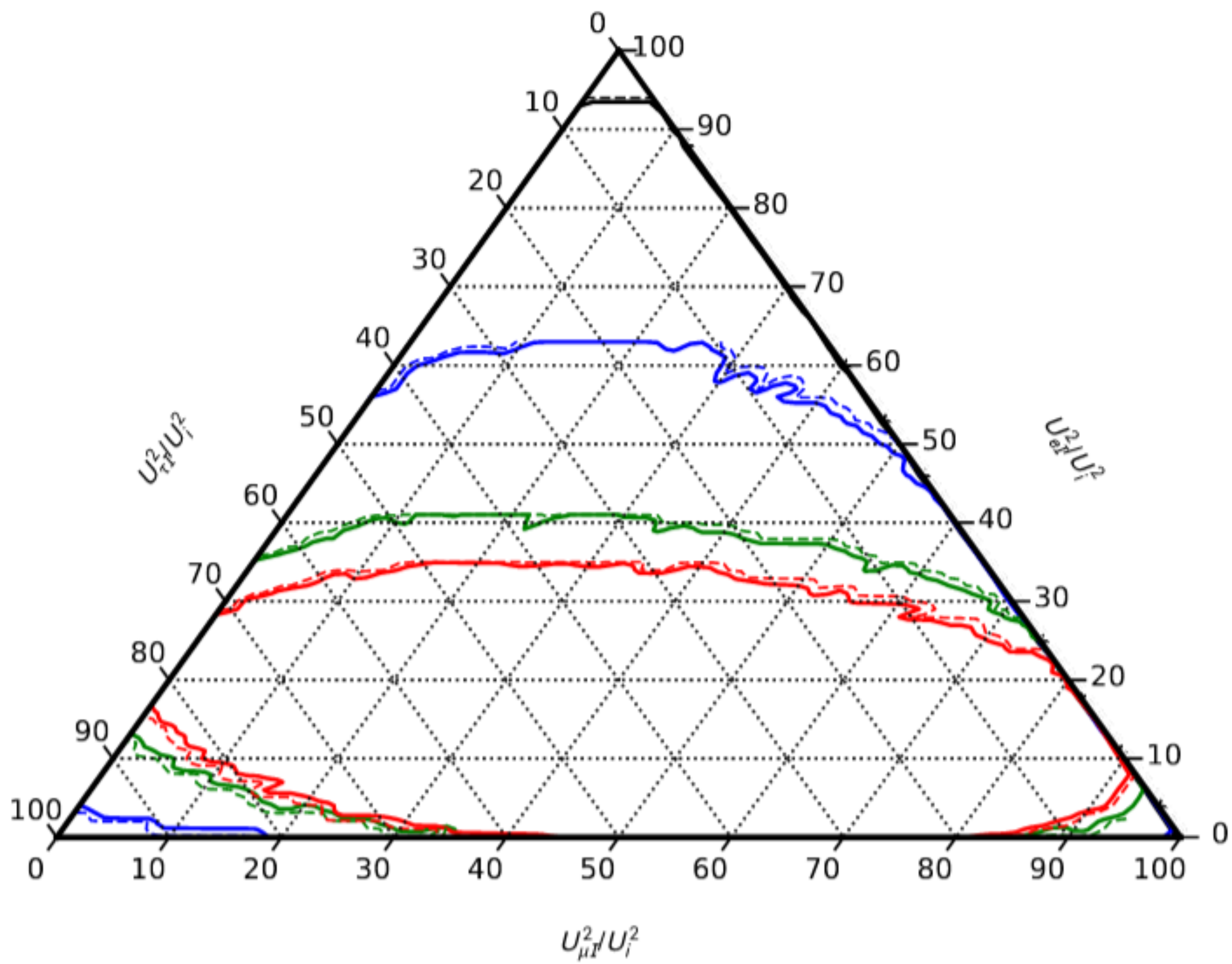
Chrzaszcz et al 1908.02302

BBN bound

Ruchayskiy/Ivashko 1202.2841

Hernandez/Lopez-Pavon 1406.2961

Constraints from ν-Oscillation Data in Model with 3 Heavy Neutrinos



normal ordering

$m_{\text{lightest}} < 10$ meV

$m_{\text{lightest}} < 1$ meV

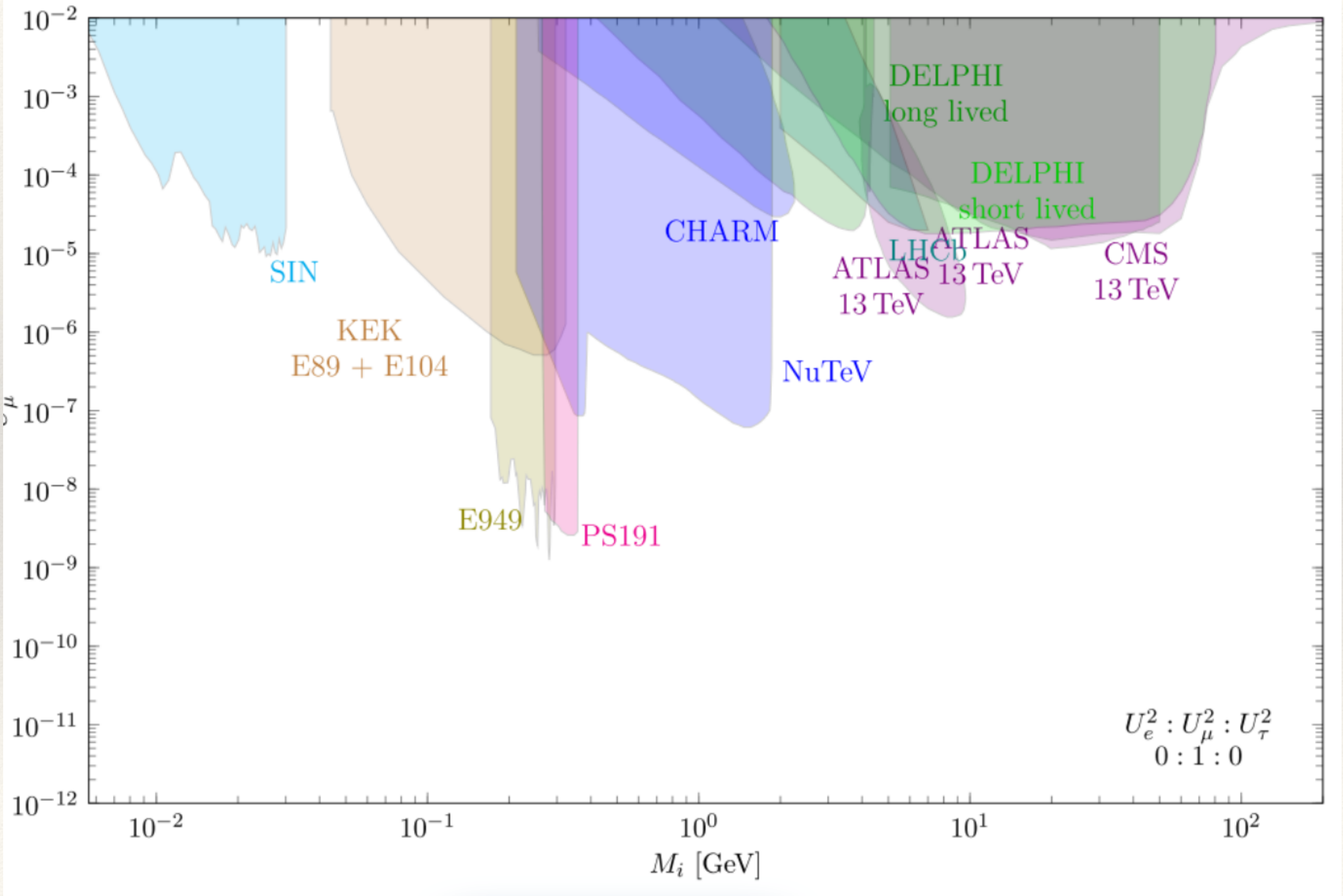
$m_{\text{lightest}} < 0.1$ meV

$m_{\text{lightest}} < 0.01$ meV

Chrzaszcz et al 1908.02302

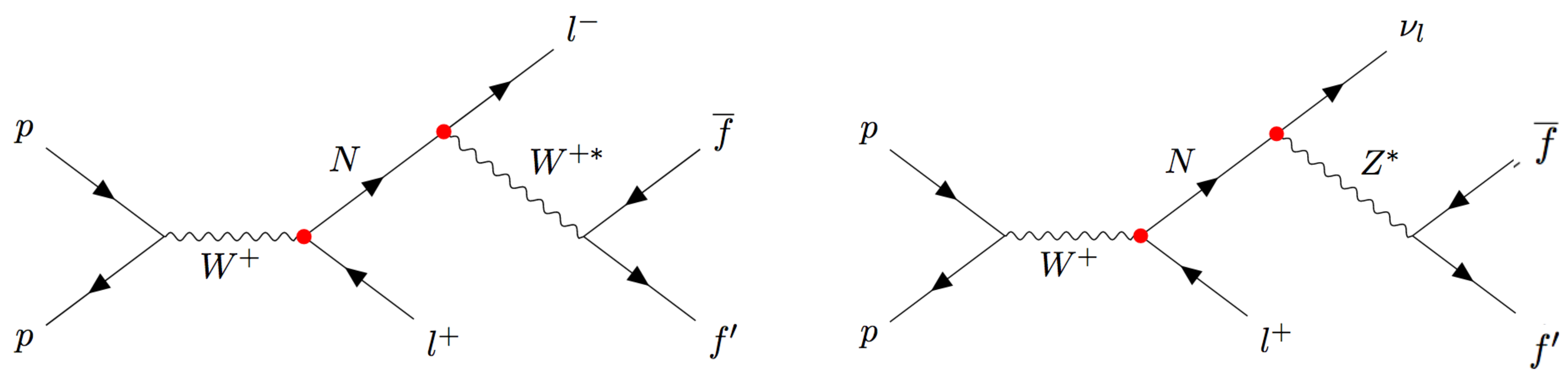
LHC Searches

Current Direct Search Constraints



LHC Signatures

- Most searches to date focus on production via s-channel exchange go weak gauge bosons
- At higher energies t-channel Wγ-fusion becomes important
  Dev et al 1308.2209



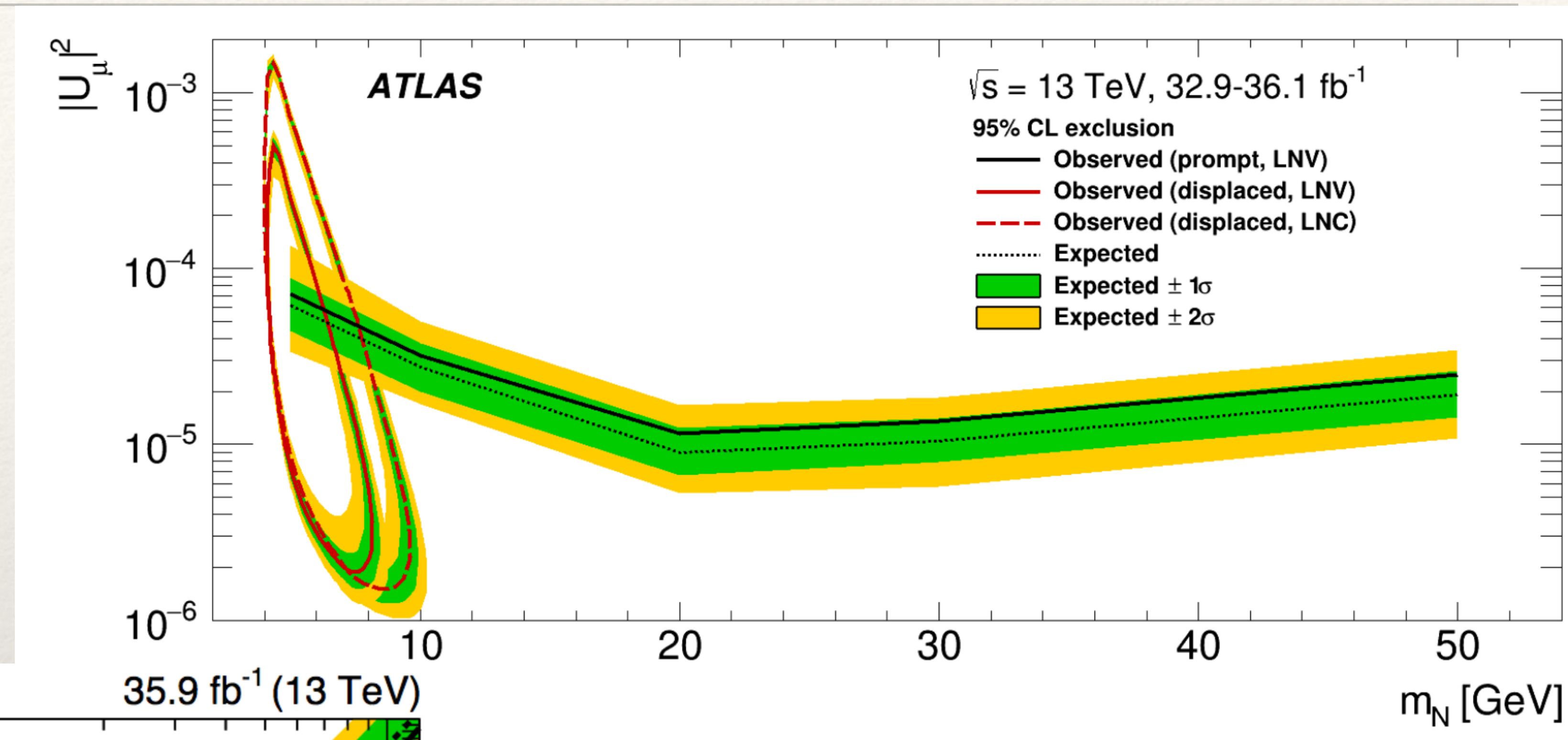
(a) Charged current decay (b) Neutral current decay

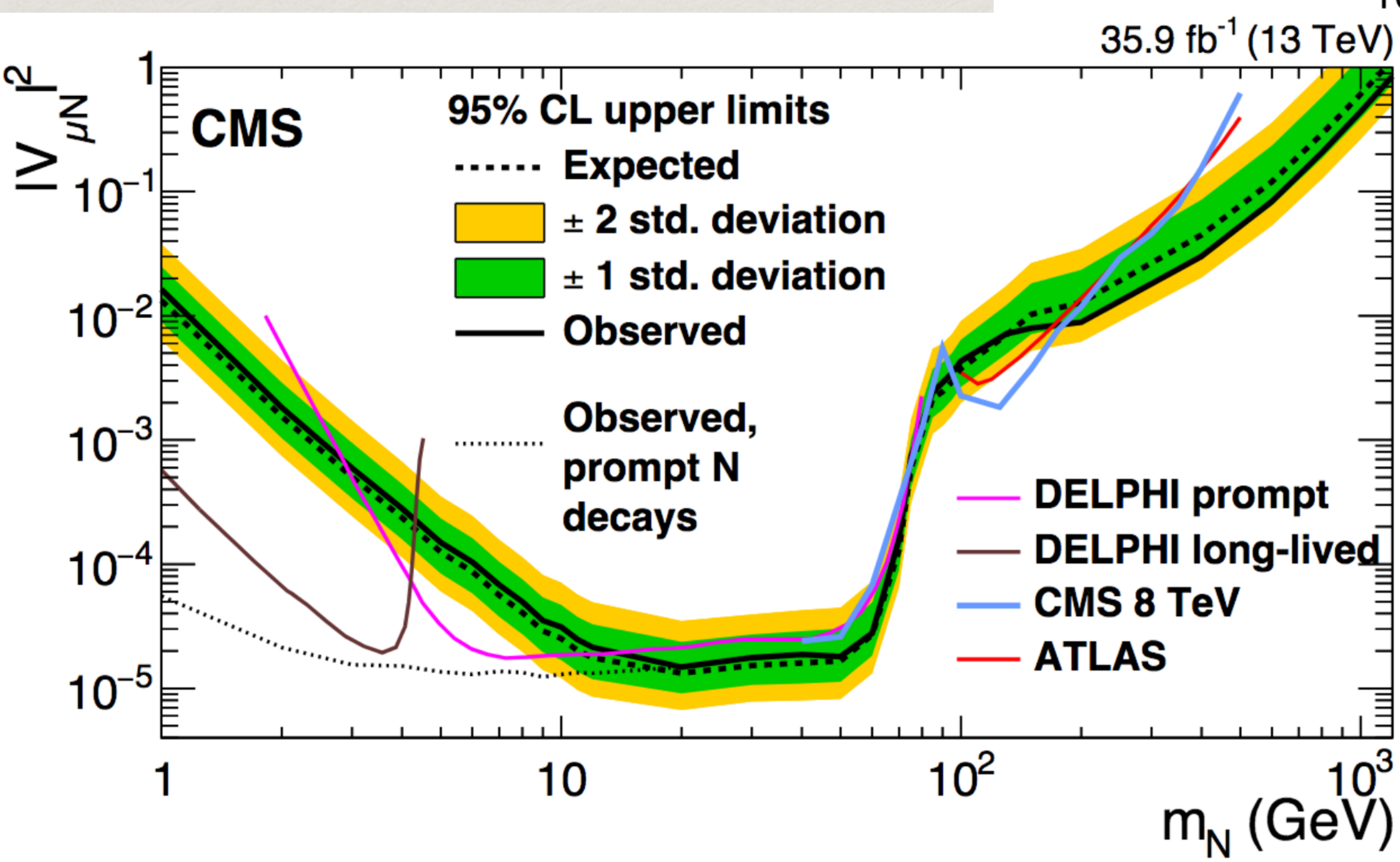
Many final states:

The heavy neutrino can decay **leptonically or semileptonically**, into **mesons or jets**, **prompt or displaced**, with **LFV** and/or **LNV**

Recent LHC Results

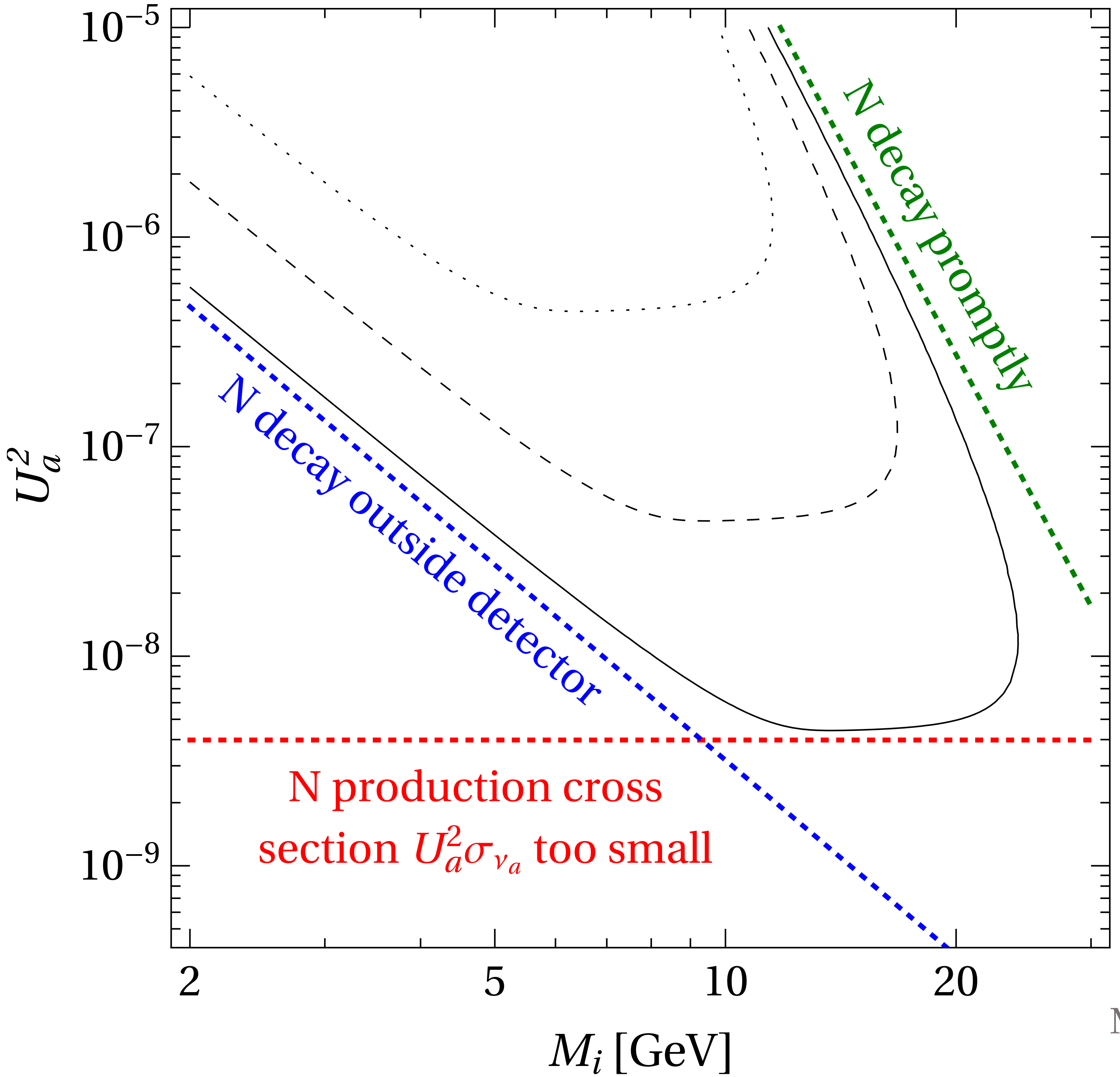
ATLAS trilepton search
prompt and displaced
LNV or LNC
1905.09787





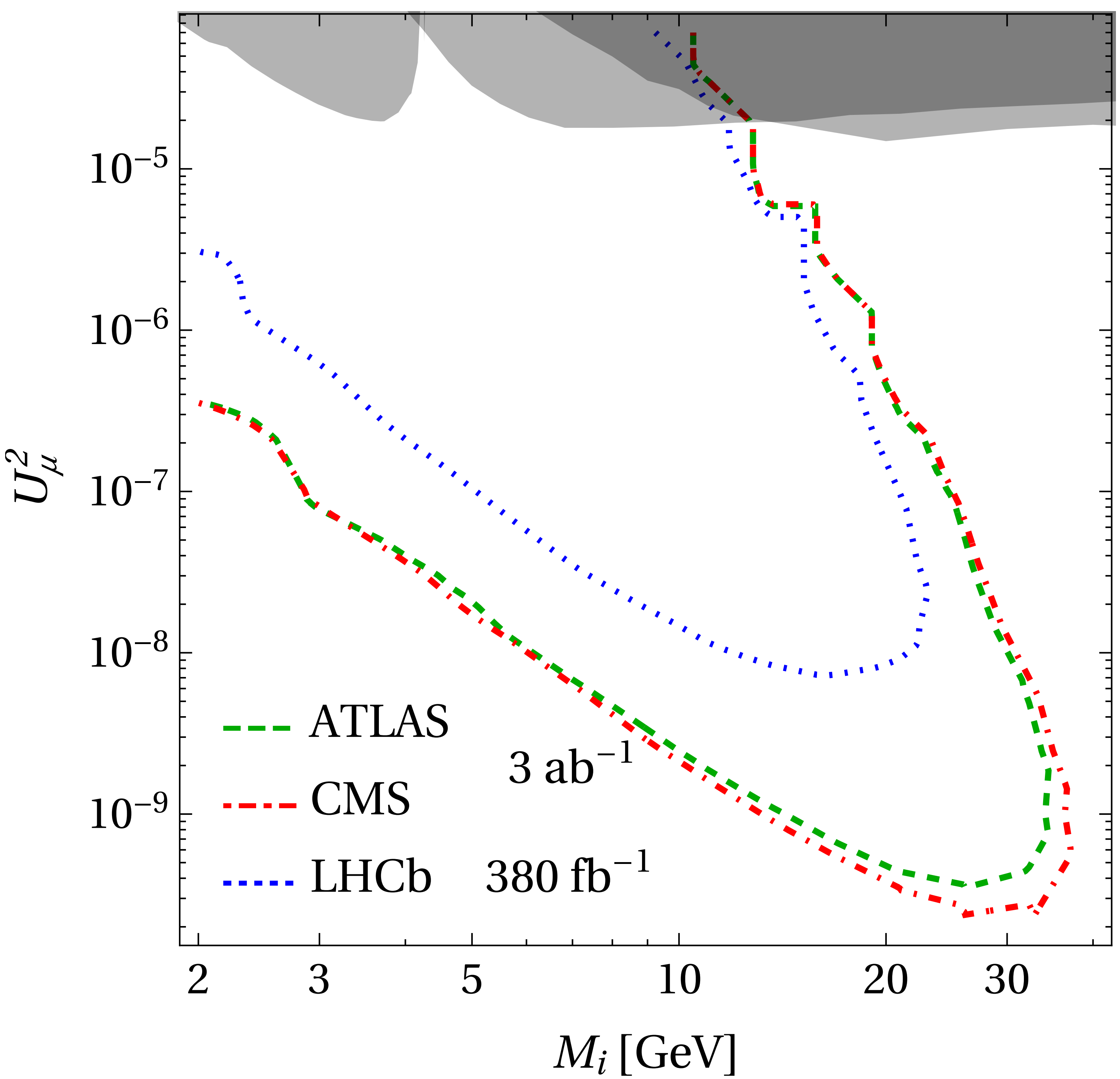
CMS trilepton search
prompt decays only
LNV or LNC
1802.02965

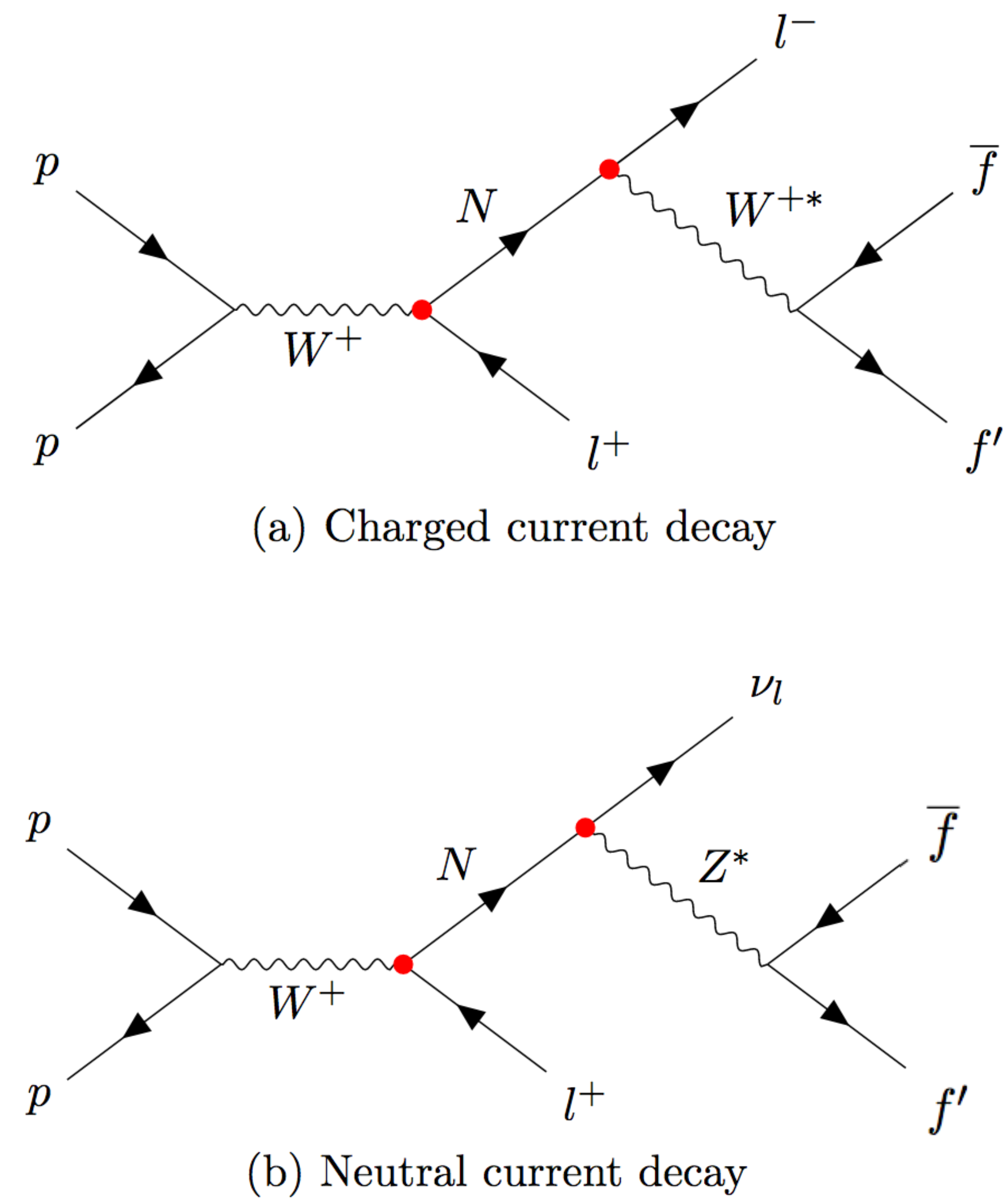
Displaced Vertex Sensitivity Region



MaD / Hajer 1903.06100

HL-LHC Displaced Vertex Search



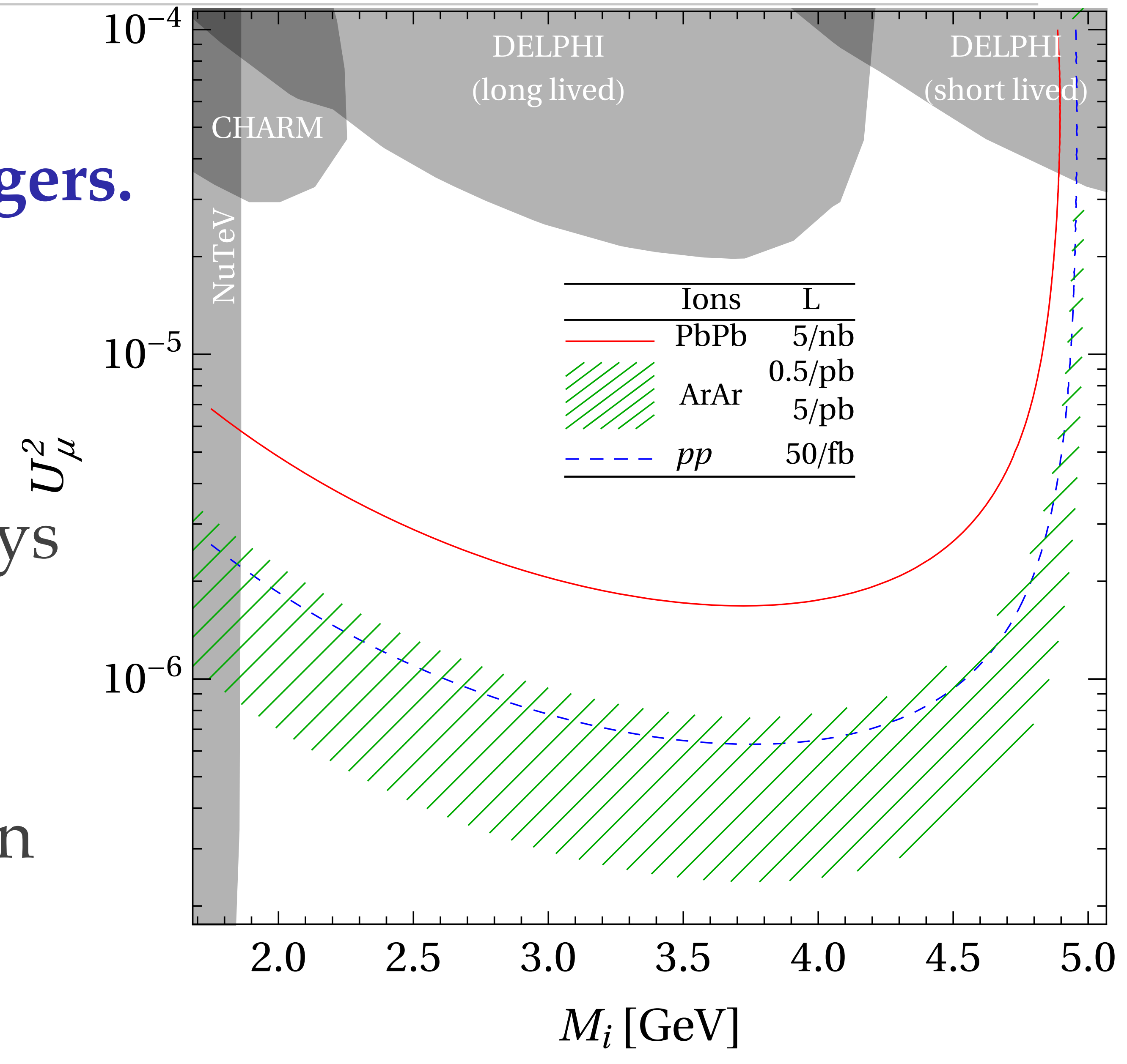


MaD / Hajer 1903.06100

A Heavy Metal Path to New Physics

In heavy ion runs: use very low triggers. Allows to search for low p_T events!

- HNLs with masses below 5 GeV can be produced in B meson decays
- Searches at CMS and ATLAS are difficult because of the low transverse momentum (more than 99% of them have below 25 GeV)
- Low triggers in heavy ion runs allow to collect this data



MaD/Giammanco/Hajer/Lucente 1812.07688, 1905.09828

Sterile Neutrino Dark Matter

Heavy "Sterile" Neutrino Dark Matter

Dark Matter Particles are

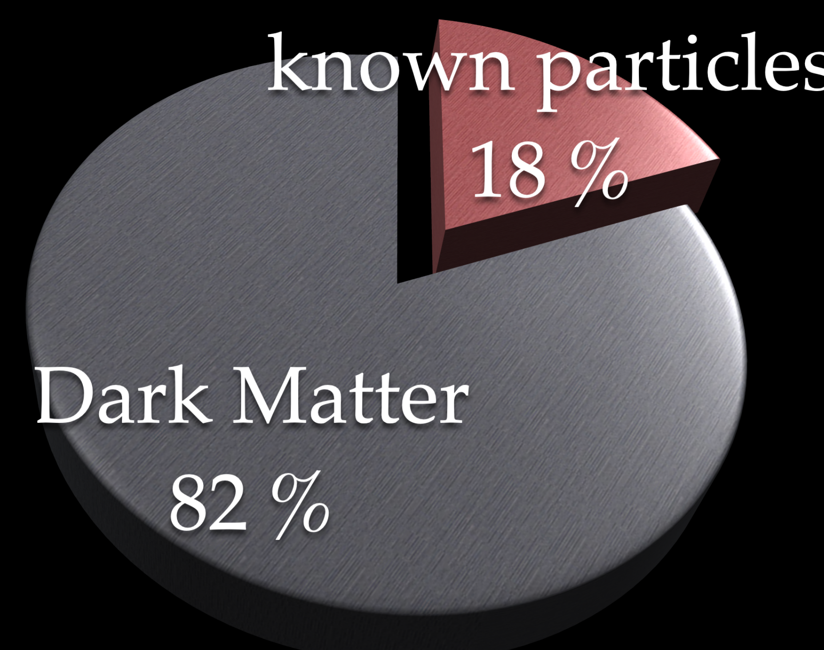
- heavy
- long lived
- neutral
- feebly interacting

Neutrinos are the only known particles that fulfil three conditions…

…but they are too light

❖ **What is the Dark Matter made of?**

It makes up most of the mass in the universe.



Heavy "Sterile" Neutrino Dark Matter

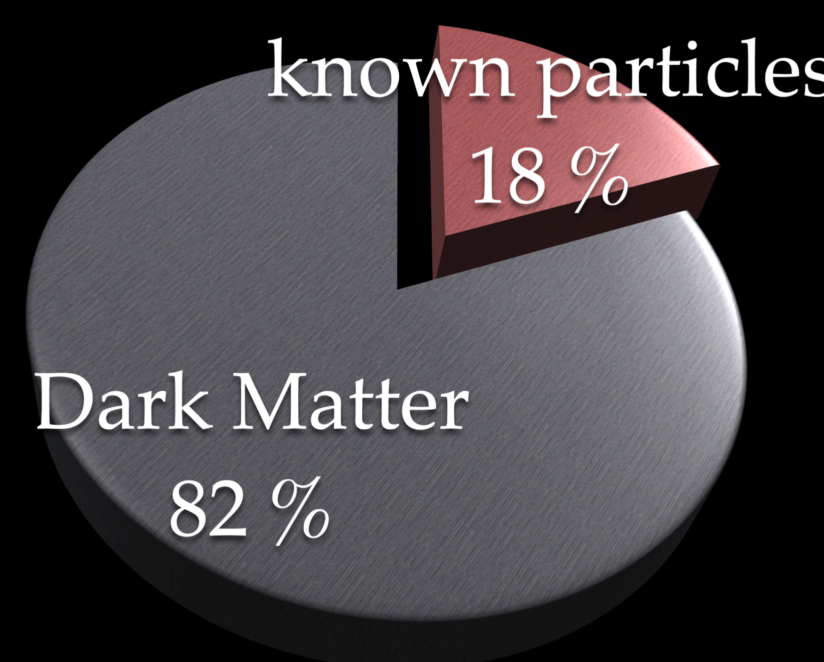
Dark Matter Particles are

- heavy
- long lived
- neutral
- feebly interacting

heavy sterile neutrinos can fulfil all conditions!

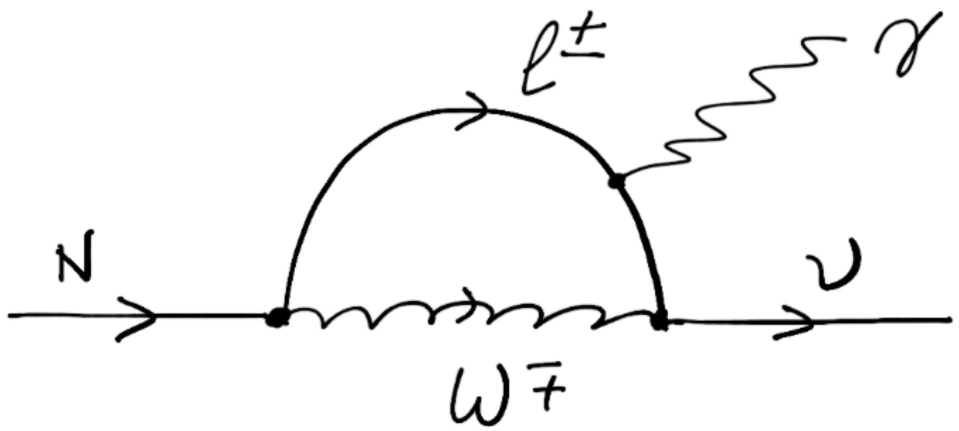
❖ What is the Dark Matter made of?

It makes up most of the mass in the universe.



Indirect Dark Matter Searches

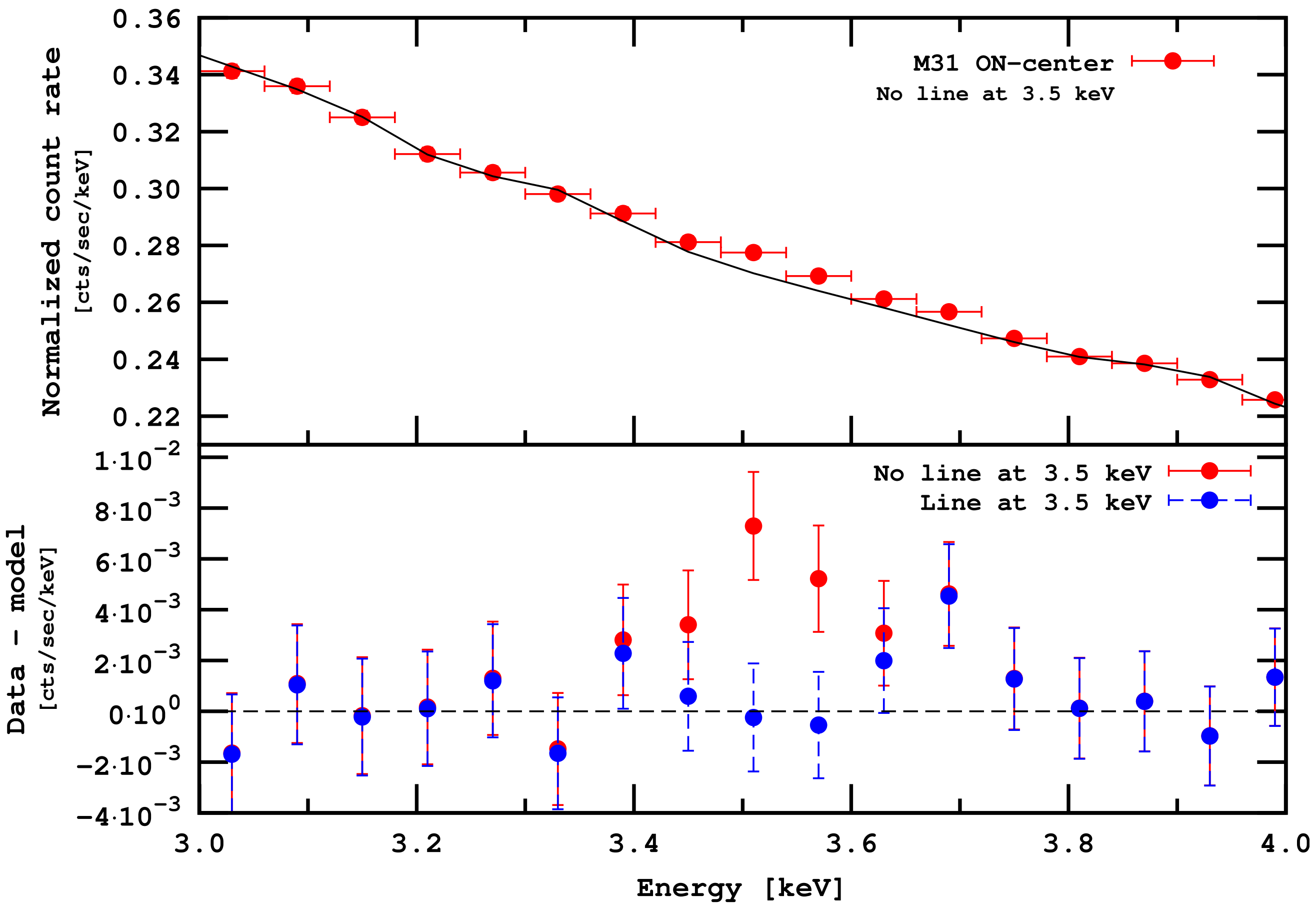
loop level decay into photons



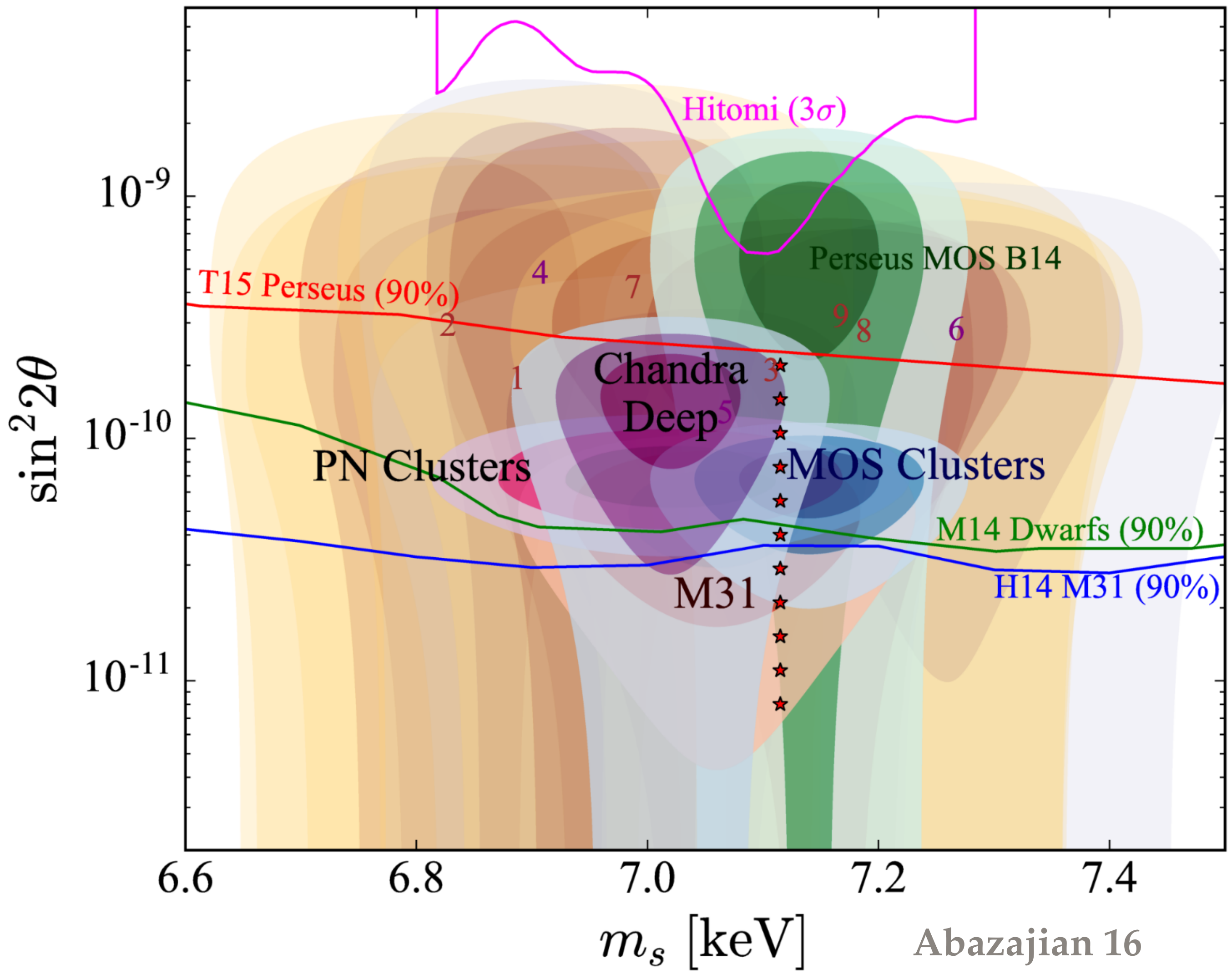
$$\Gamma_{N\to\gamma\nu} = \frac{9\,\alpha\,G_F^2}{256\pi^4}\theta^2 M^5 = 5.5\times 10^{-22}\theta^2\left[\frac{M}{1\,\mathrm{keV}}\right]^5\ \mathrm{sec}^{-1}\,.$$

One can search for an emission line!

Has the line been seen?



Boyarsky/Ruchayskiy/Iakubovskyi/Franse 2014
see also Bulbul/Markevitch/Foster/Smith/Loewenstein/Randall 2014

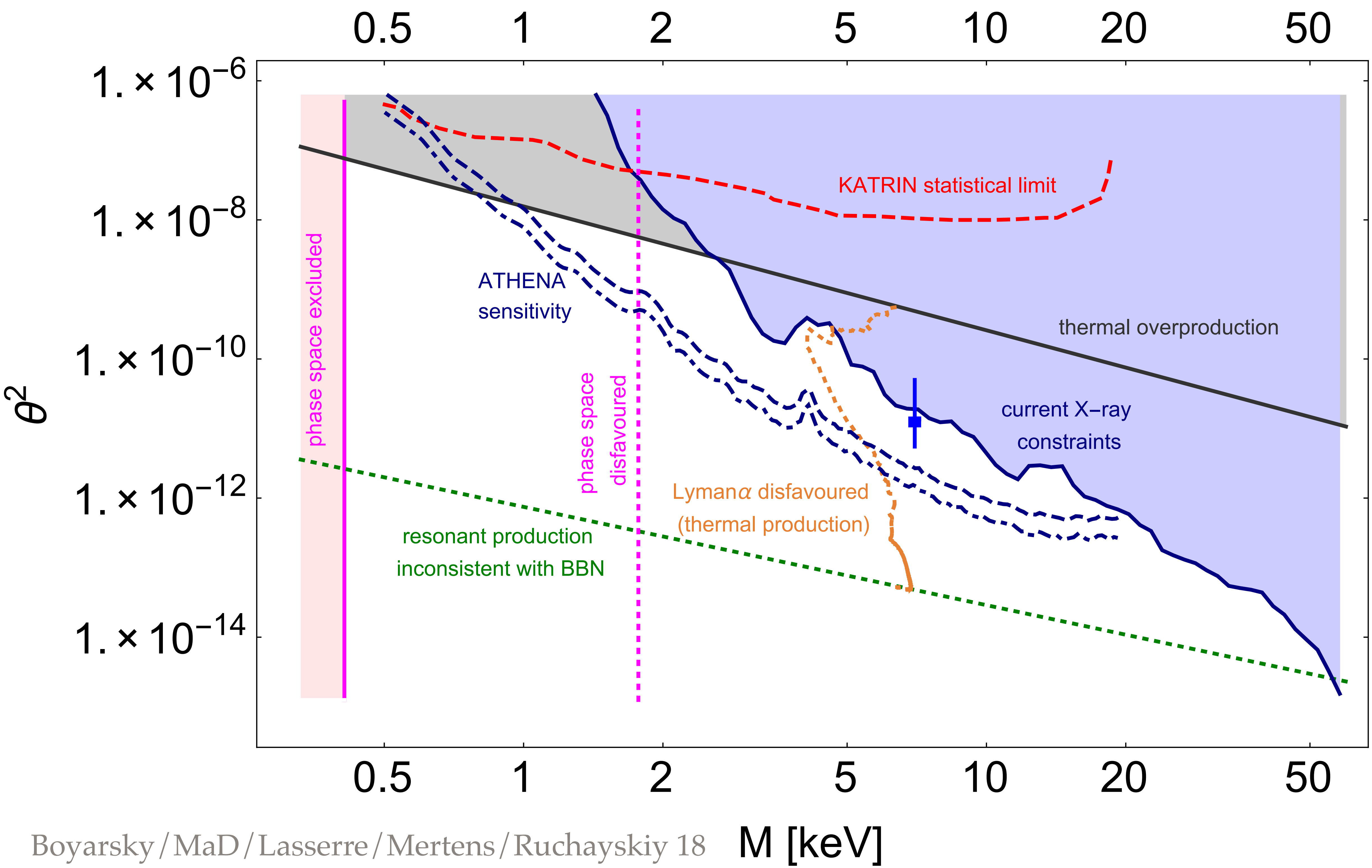


Abazajian 16

Situation unclear…

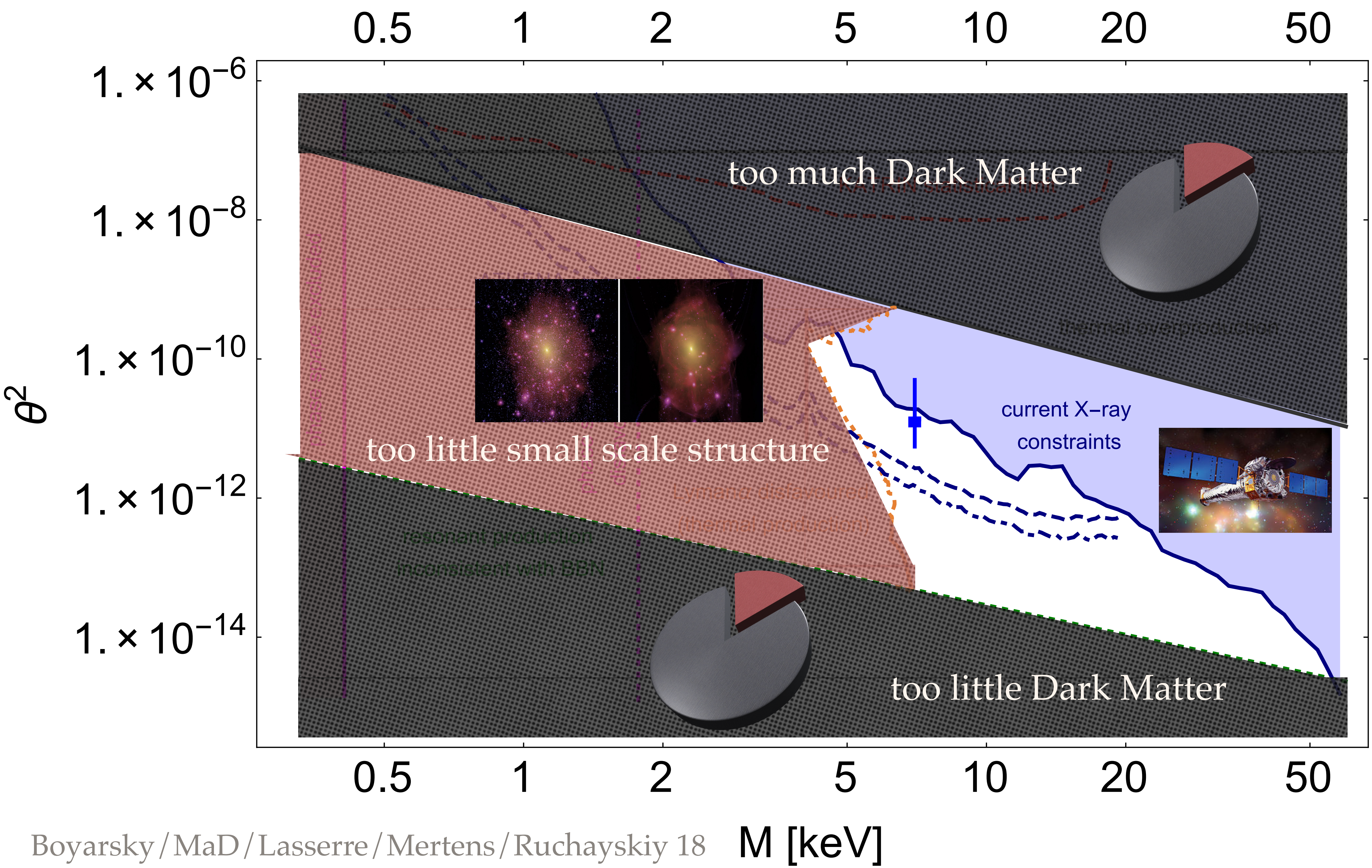
need better spectral resolution (XARM and ATHENA will help)

Sterile Neutrino Dark Matter



Boyarsky/MaD/Lasserre/Mertens/Ruchayskiy 18

Sterile Neutrino Dark Matter



Boyarsky/MaD/Lasserre/Mertens/Ruchayskiy 18