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Heavy Sterile Neutrinos: From Cosmology to Experiment

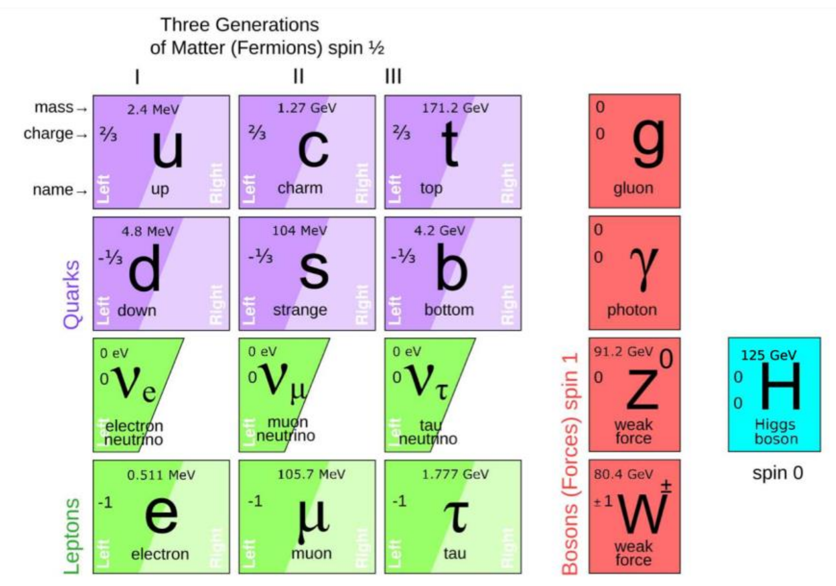
13. 01. 2022

IAS Program on High Energy Physics (HEP2022)

HKUST, Hong Kong, China

The Seesaw Mechanism (type I)

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



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

Minimal vs Non-minimal Scenarios

minimal = literally only add RH neutrinos

- generic EFT description of models with $M < \text{TeV} \ll \Lambda$
- can even be UV complete in the sense $\Lambda = M_P$ (Shaposhnikov 07)
- … or at least up to the scale of inflation (Bezrukov/Shaposhnikov 14)

non-minimal = anything else (gauge extensions, extended scalar sector, RHN as "portal" to dark sector…)

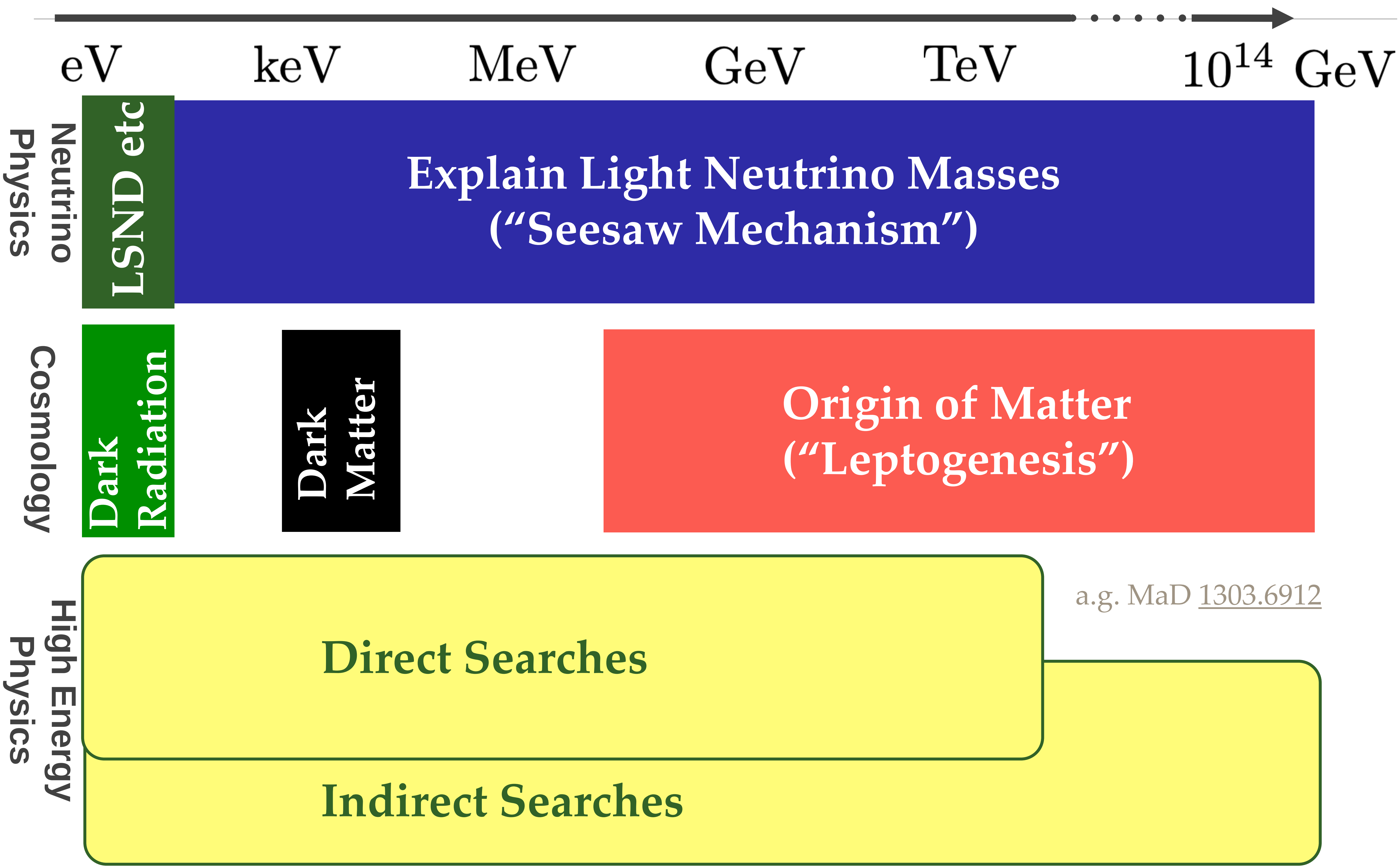
- can use generic EFT description for models with $M < \text{TeV} < \Lambda$
- need full dark sector description if $M, \Lambda < \text{TeV}$

recently growing interest in non-minimal "bottom up" approaches driven by the DM puzzle, MiniBooNE anomaly etc…

For a collection of references see e.g.

- reviews Deppisch/Dev/Pilaftsis 1502.06541, Cai/Han/Ruiz 1711.02180
- physics case papers for MATHUSLA (1806.07396) and SHiP (1504.04855)
- CERN PBC Working Group Report 1901.09966
- Snowmass LoIs on Opportunities and signatures of non-minimal Heavy Neutral Leptons and Testable Neutrio Mass Models

Heavy Neutrino Mass Scale



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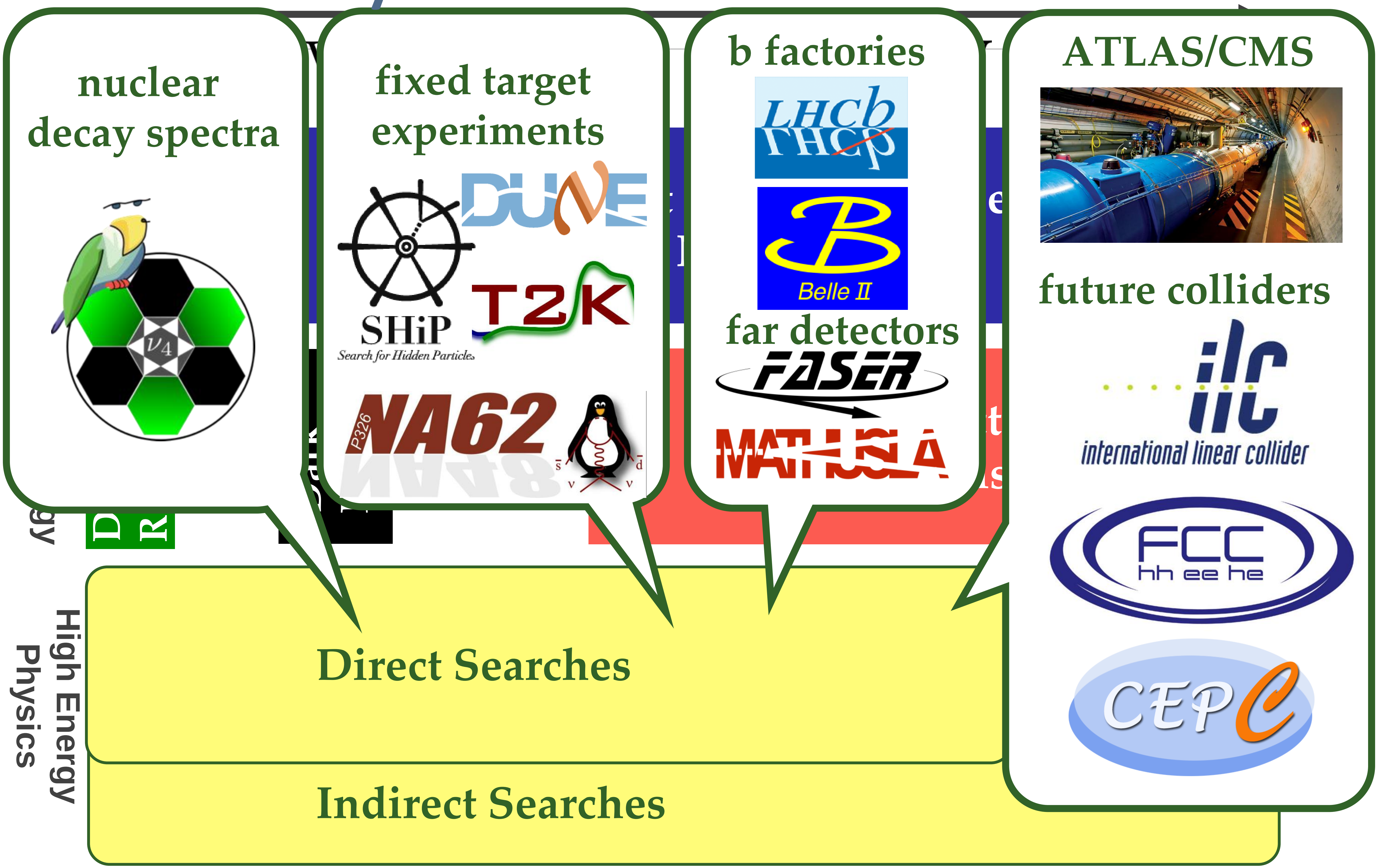
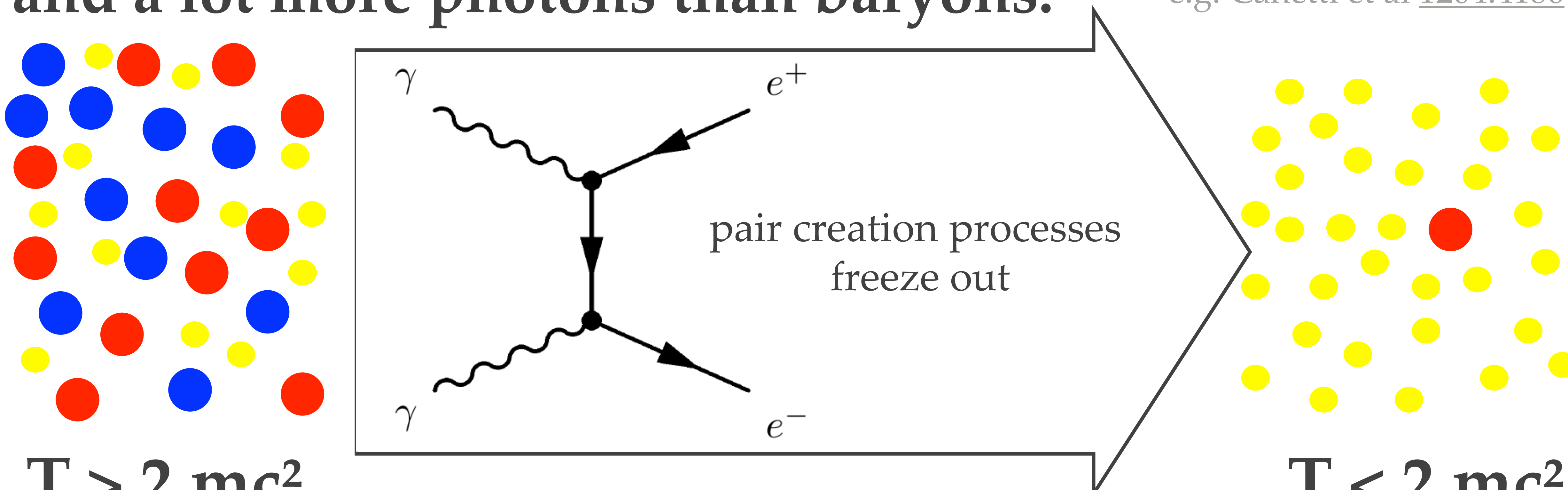


Low Scale Leptogenesis

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)

Thermal Leptogenesis

Basic idea

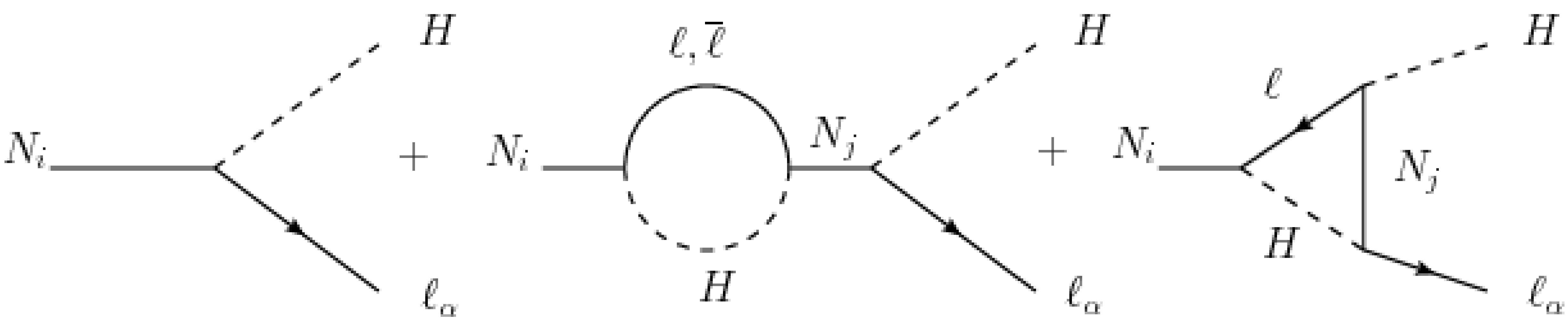
- ***N* are around in the early universe**
- ***N* interactions are CP violating**
- ***N* may preferably decay into matter**

CP violating parameter ϵ

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

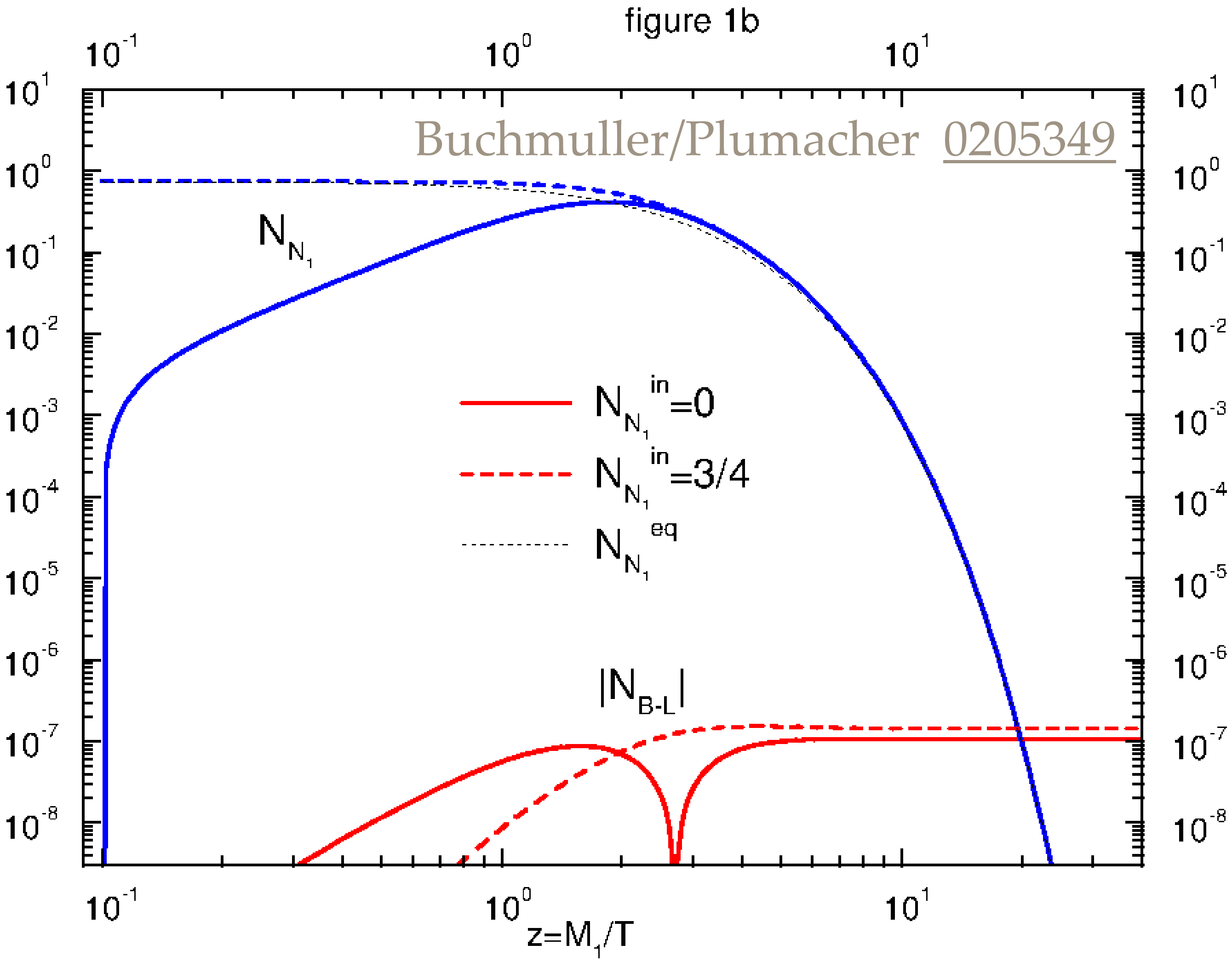
final asymmetry

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



asymmetry arises from quantum interference in the plasma

Boltzmann Equation



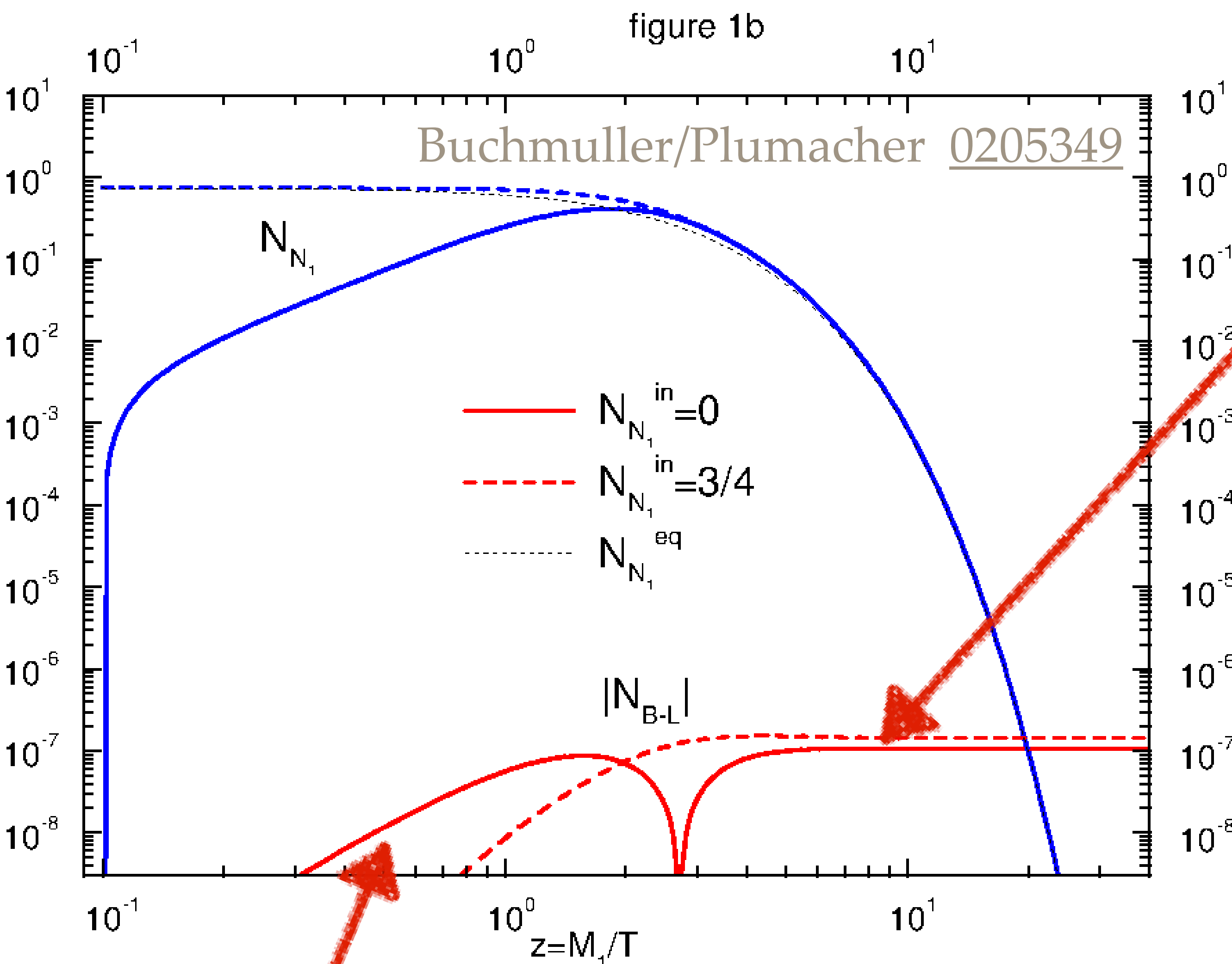
Sakharov's nonequilibrium condition can be fulfilled in two ways.

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

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

"source" "washout"

Freeze-in and freeze-out



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

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

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

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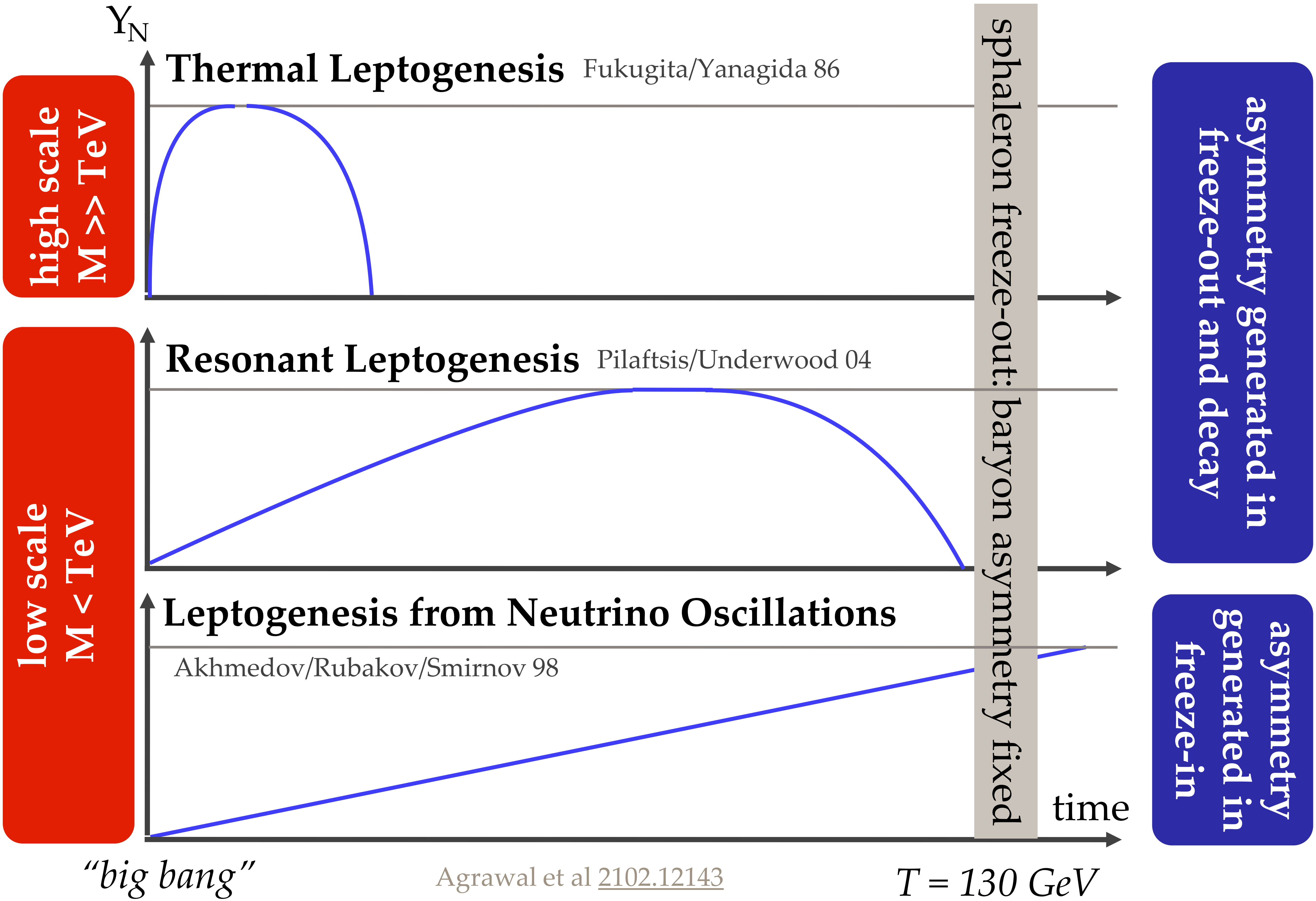
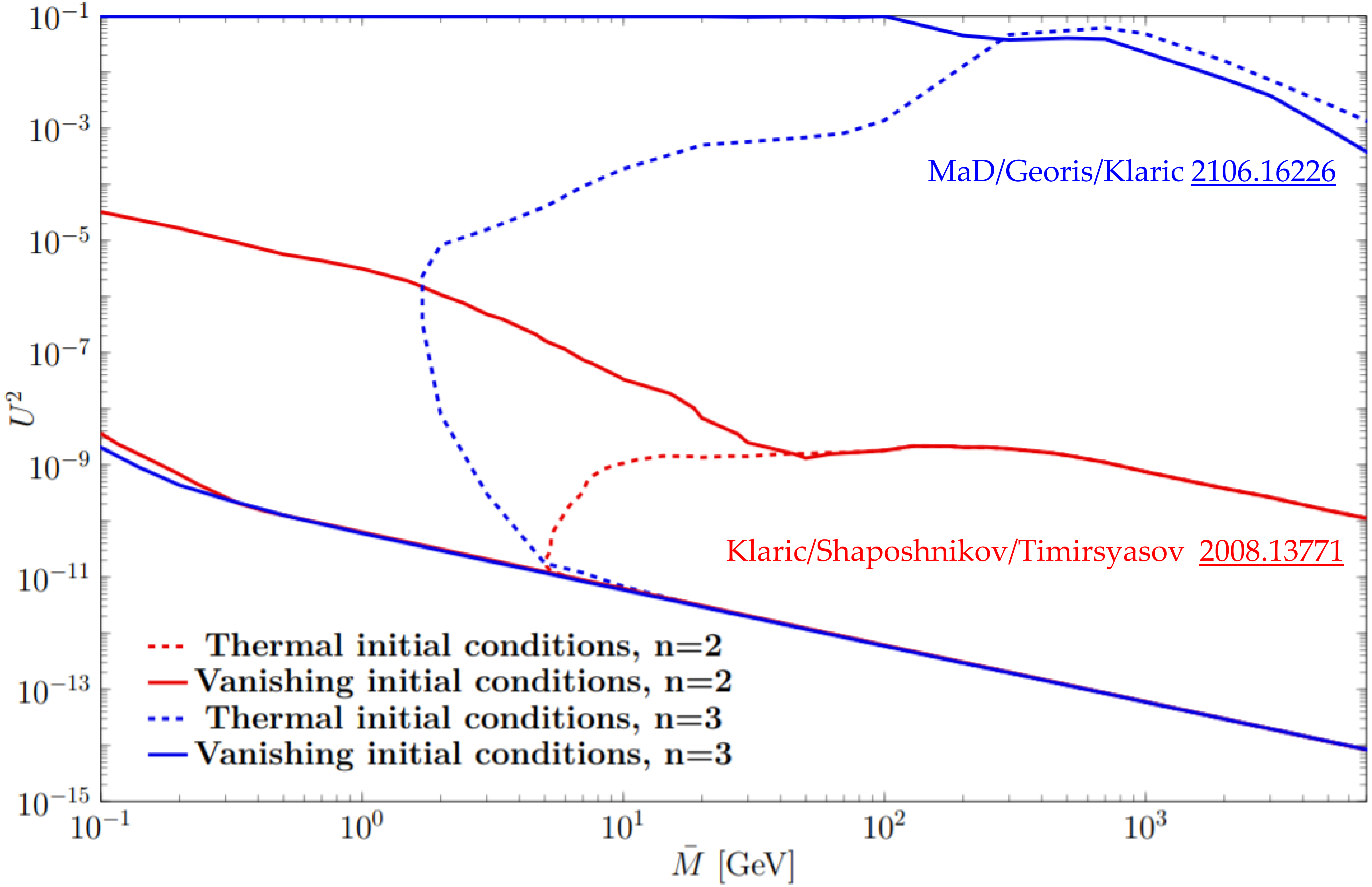
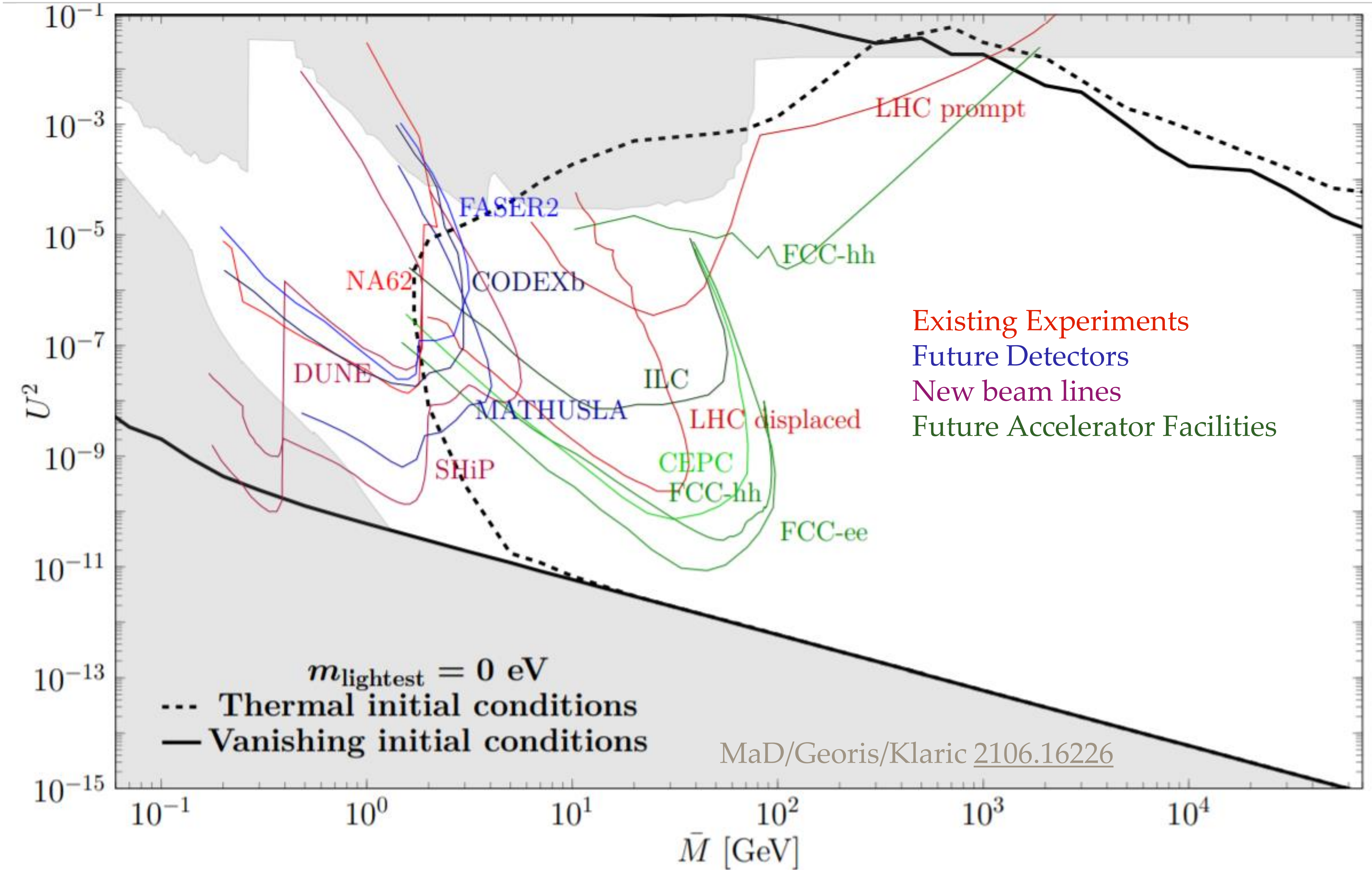


Y_N
Thermal Leptogenesis
Fukugita/Yanagida 86
high scale
M >> TeV
Resonant Leptogenesis
Pilaftsis/Underwood 04
low scale
M < TeV
Leptogenesis from Neutrino Oscillations
Akhmedov/Rubakov/Smirnov 98
sphaleron freeze-out: baryon asymmetry fixed
asymmetry generated in freeze-out and decay
asymmetry generated in freeze-in
time
"big bang"
Agrawal et al 2102.12143
T = 130 GeV

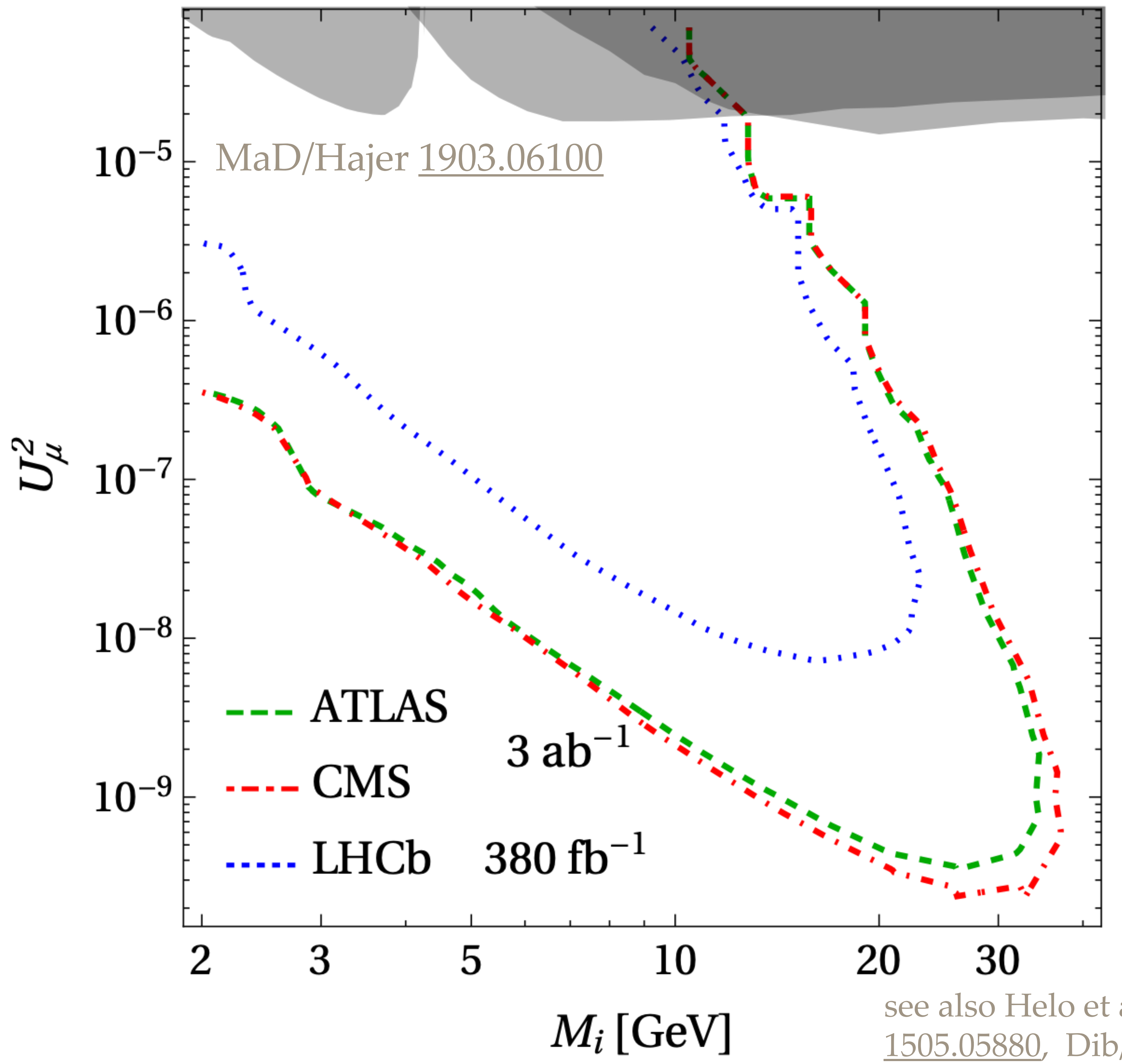
Leptogenesis with 3 HNLs vs 2 HNLs

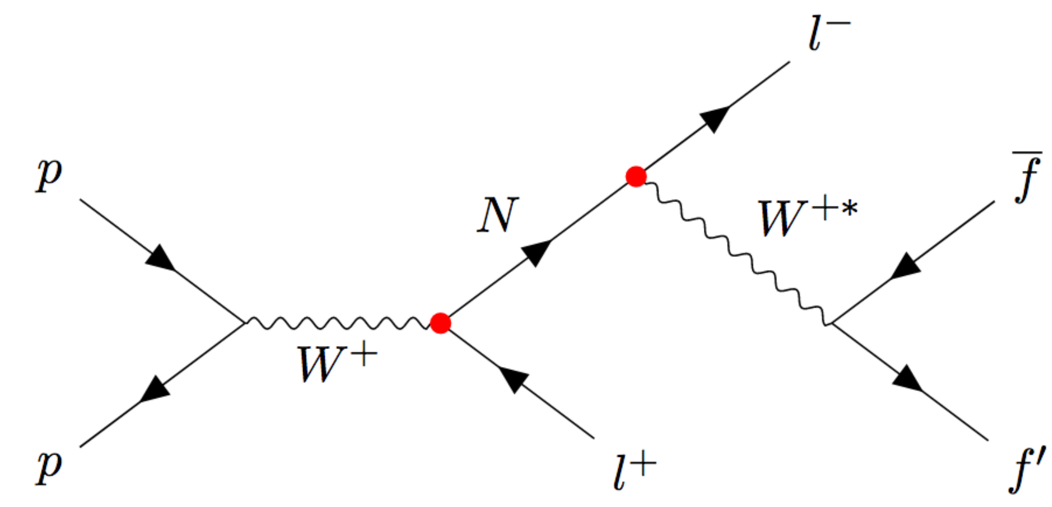


Leptogenesis with 3 RH Neutrinos

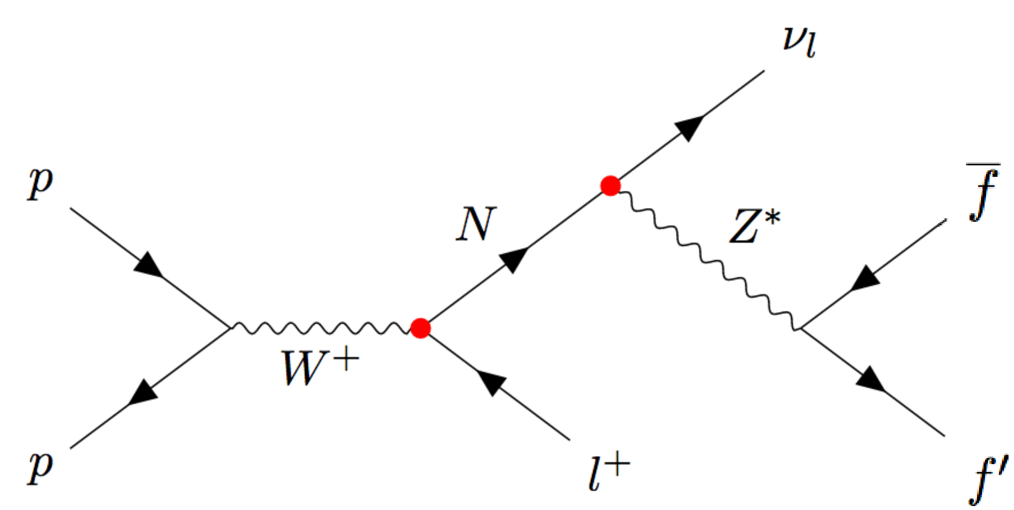


HL-LHC Displaced Vertex Search





(a) Charged current decay



(b) Neutral current decay

see also Helo et al 1312.2900, Izaguirre/Shuve 1504.02470, Gago et al 1505.05880, Dib/Kim 1509.05981, Antusch et al 1612.02728, 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

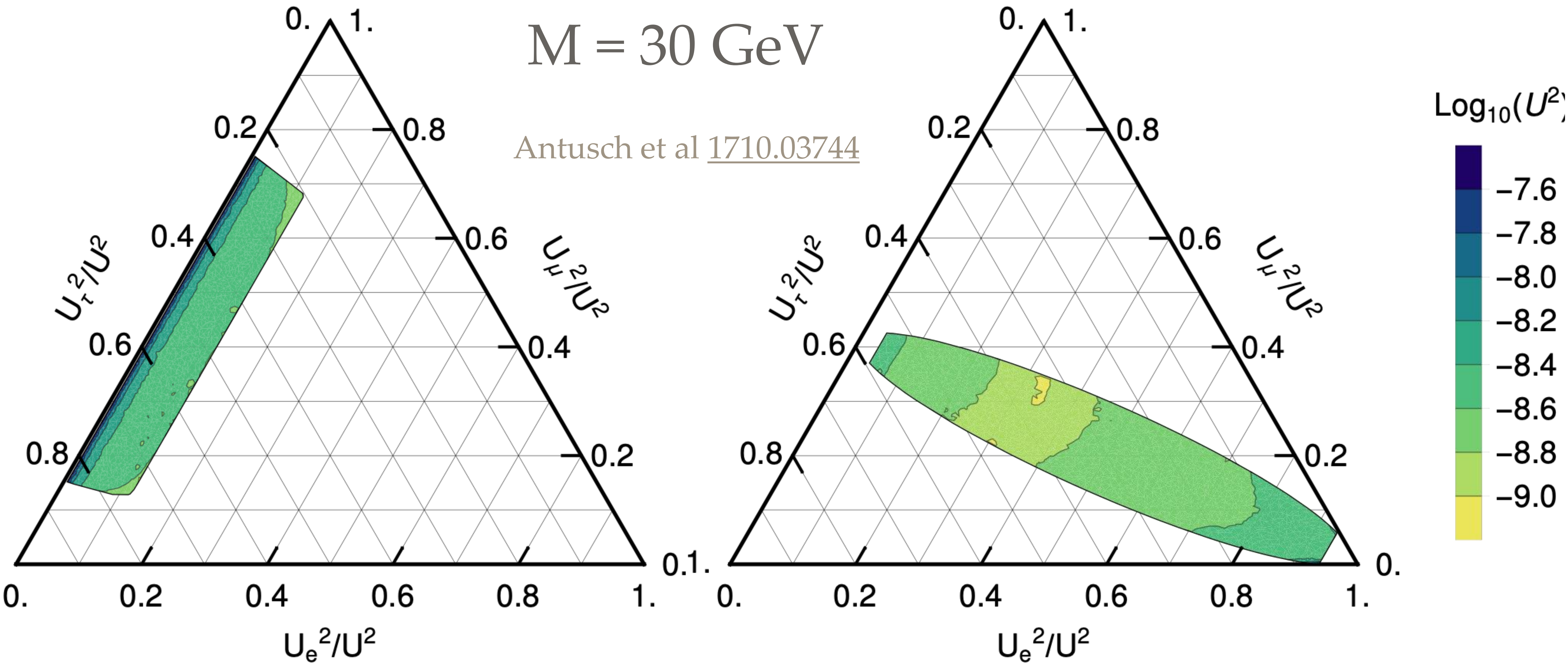
Test seesaw mechanism and leptogenesis

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

Constraints from Leptogenesis in Model with 2 Heavy Neutrinos

M = 30 GeV

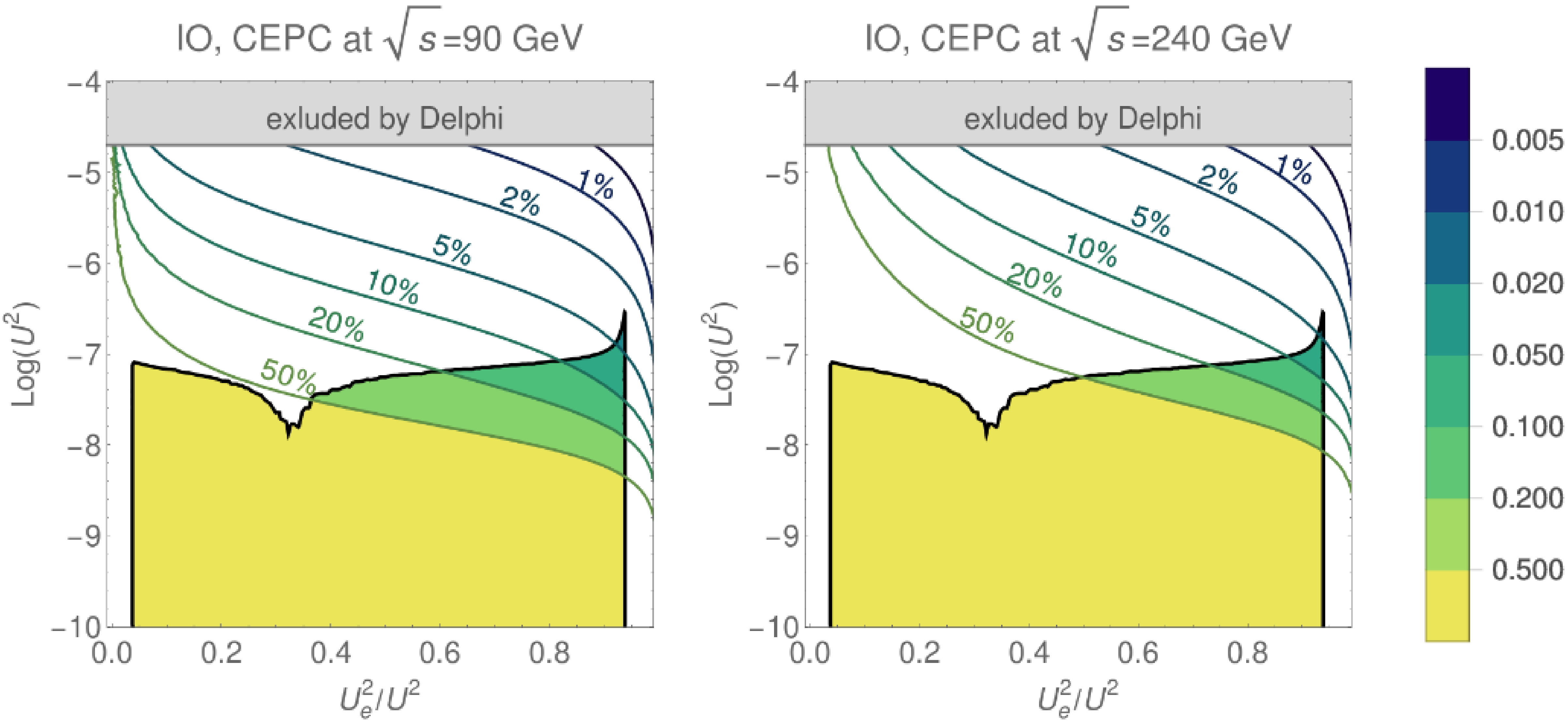
Antusch et al 1710.03744



normal neutrino mass ordering | **inverted neutrino mass ordering**

Large U² require strong hierarchies in couplings to SM generations

How well can this be measured?



Plots were made for 0.1/ab at Z pole, nowadays expect 16/ab,
⇒ an order of magnitude better accuracy possible!
⇒ **With a bit of luck, CEPC can make percent level measurement**

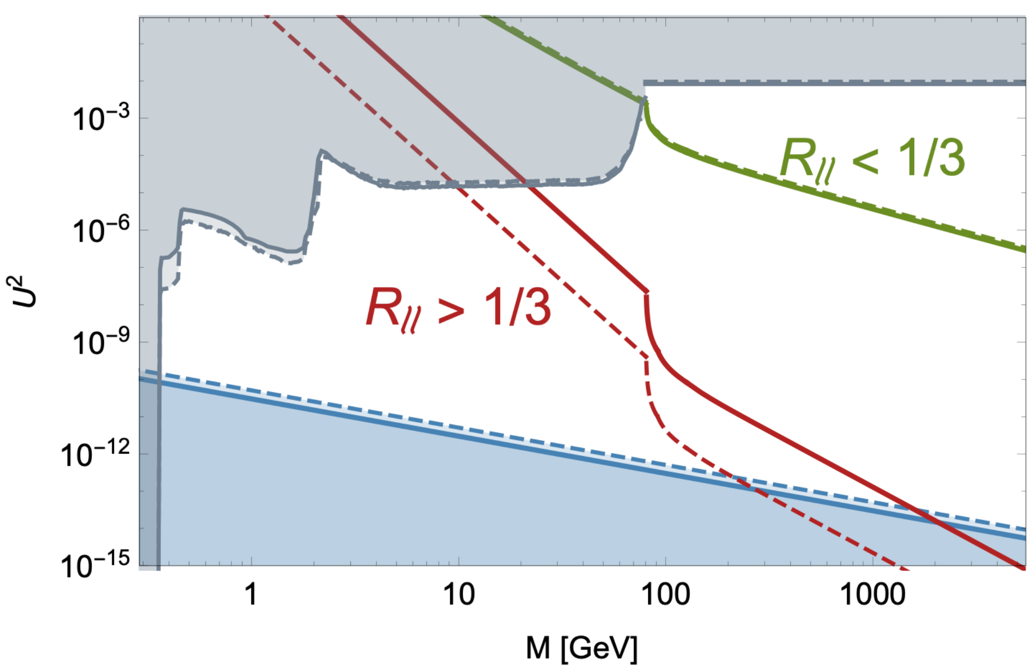
Antusch et al 1710.03744

How to measure ΔM?

ratio of LNV to LNC decays
is sensitive to ΔM

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

Anamiati et al 1607.05641



MaD/Klaric/Klose 1907.13034

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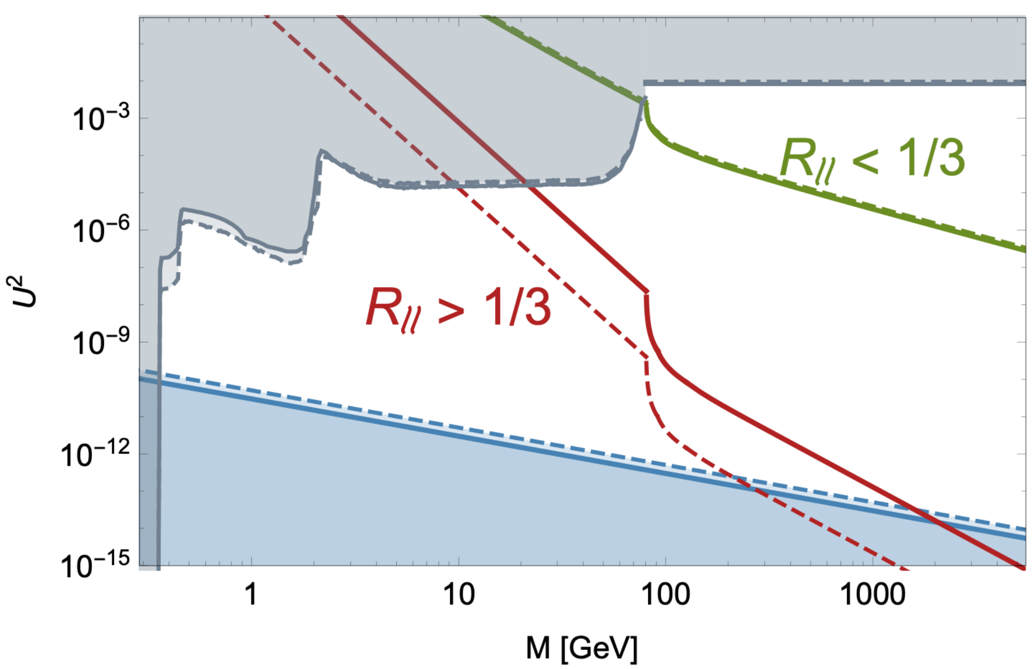
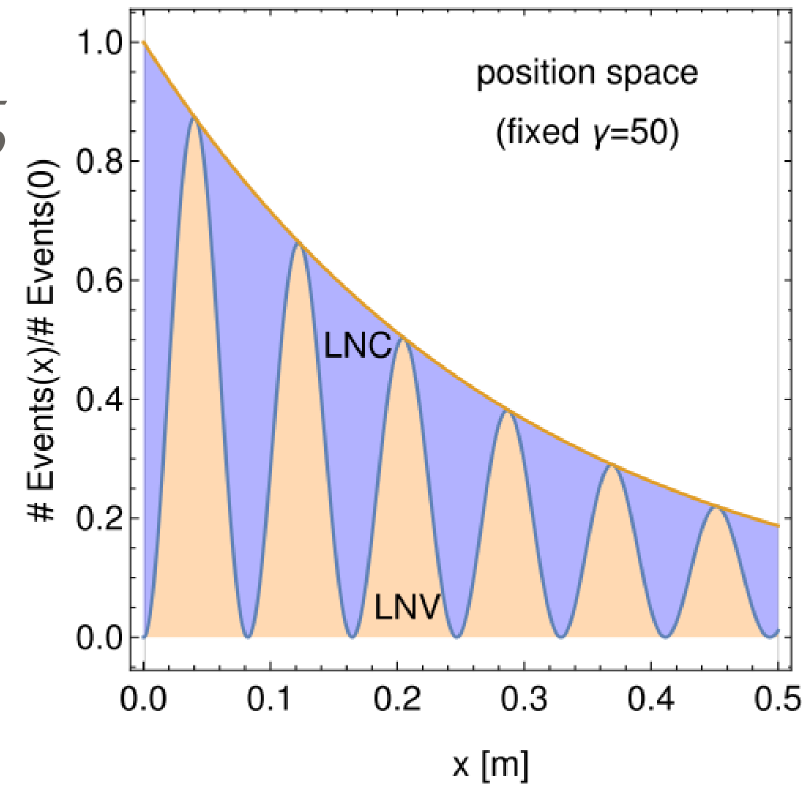
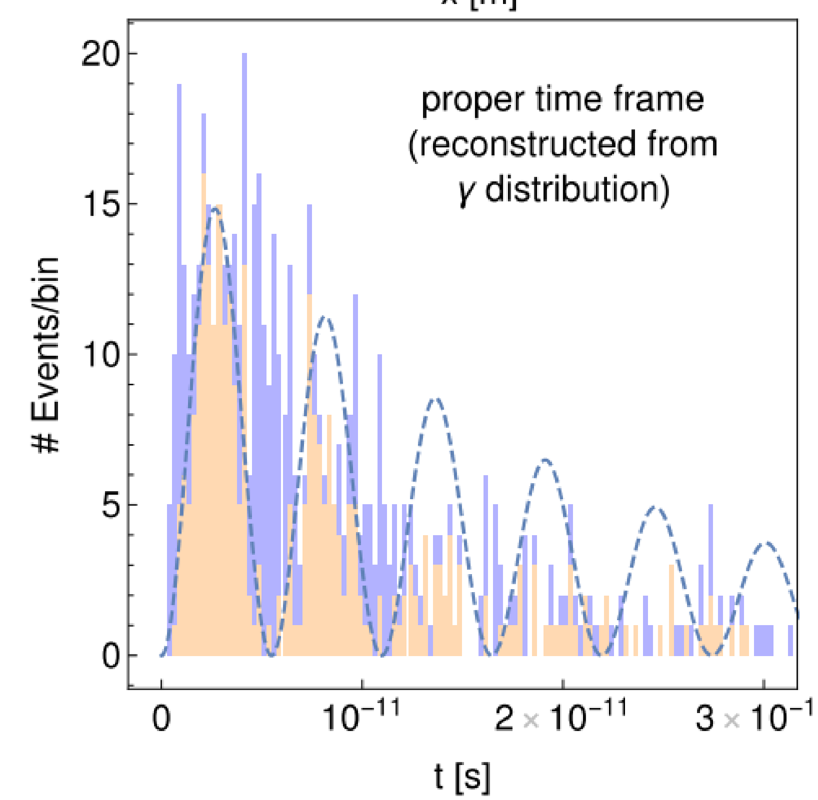


MaD/Klaric/Klose 1907.13034

spatially resolving this ratio gives more information!

Antusch et al 1709.03797





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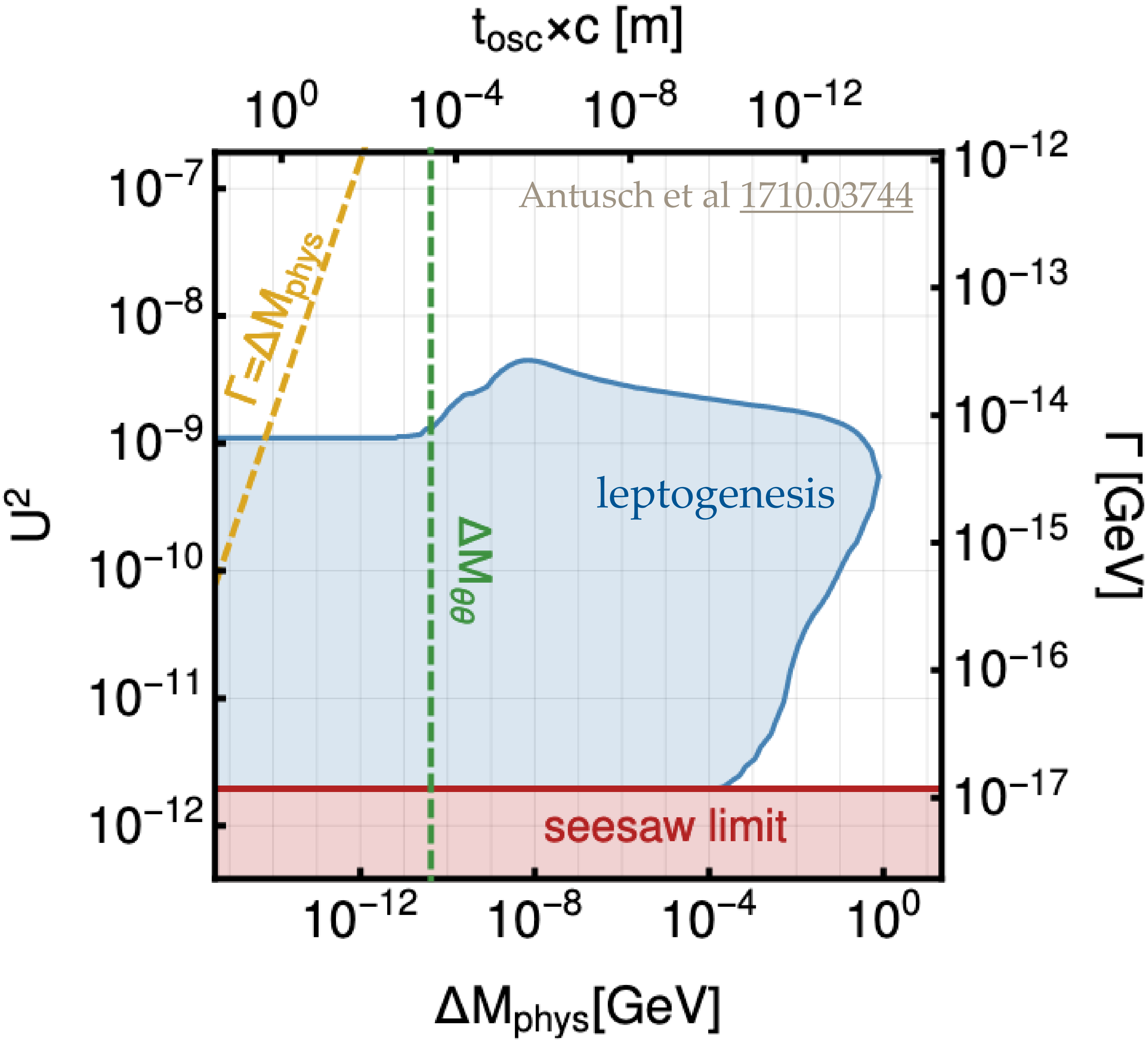

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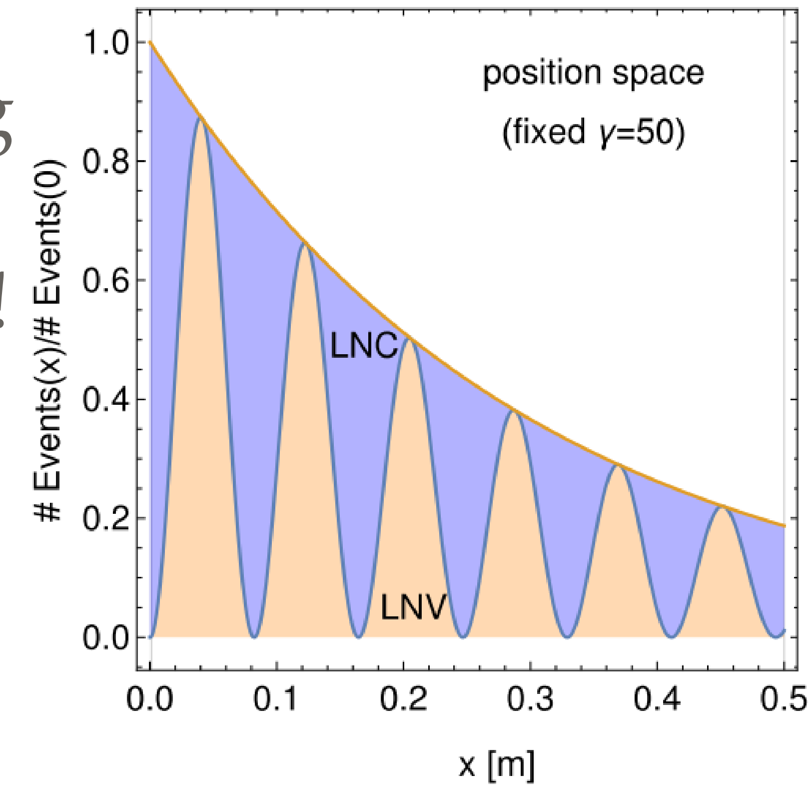

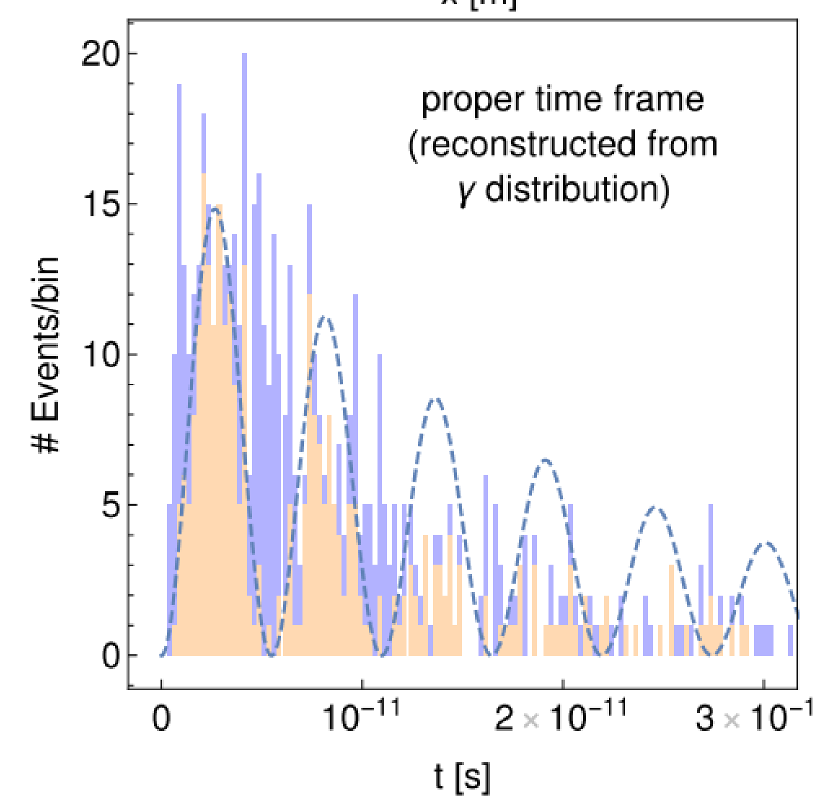

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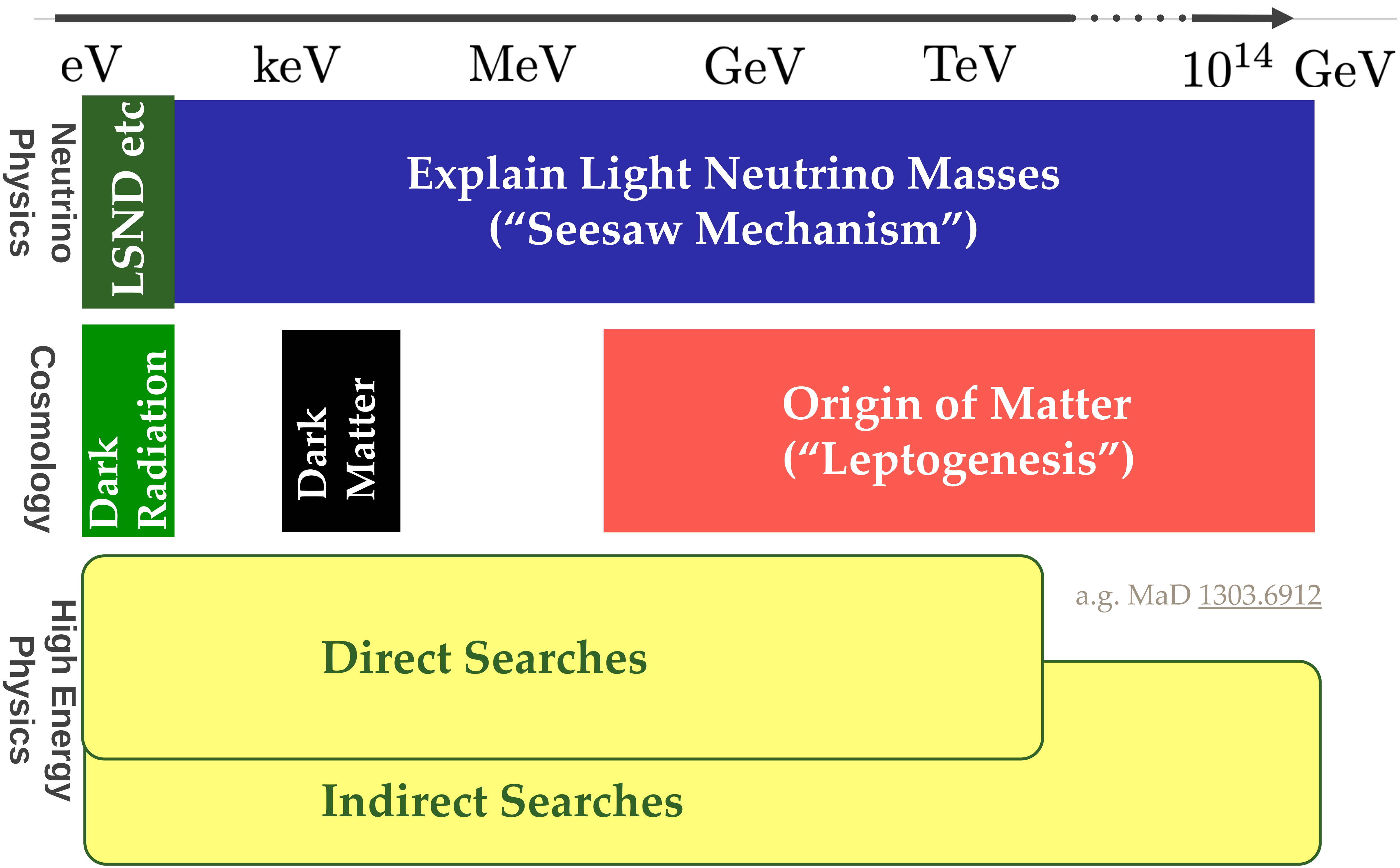

Sterile Neutrino DM

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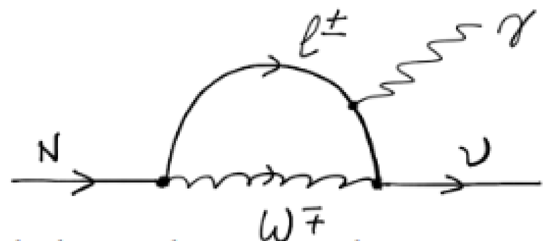
Indirect searches

- radiative decay $N \to \nu\gamma$ gives emission line at $M/2$



- 3.5 keV excess observed, but disputed
- new missions (XRISM, ATHENA, Lynx…)

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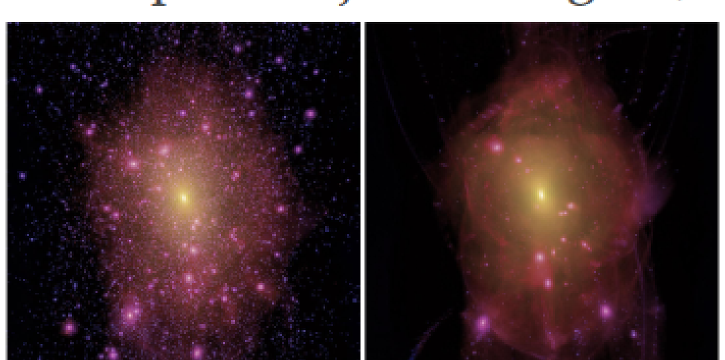

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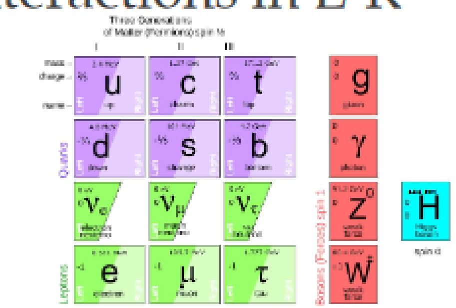
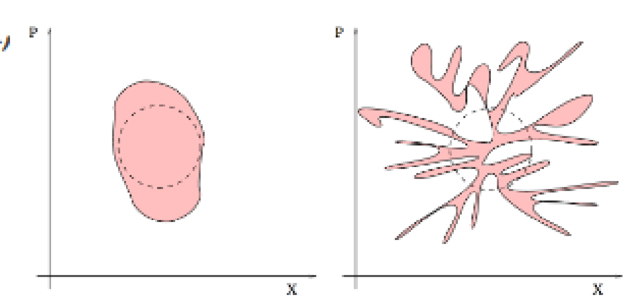
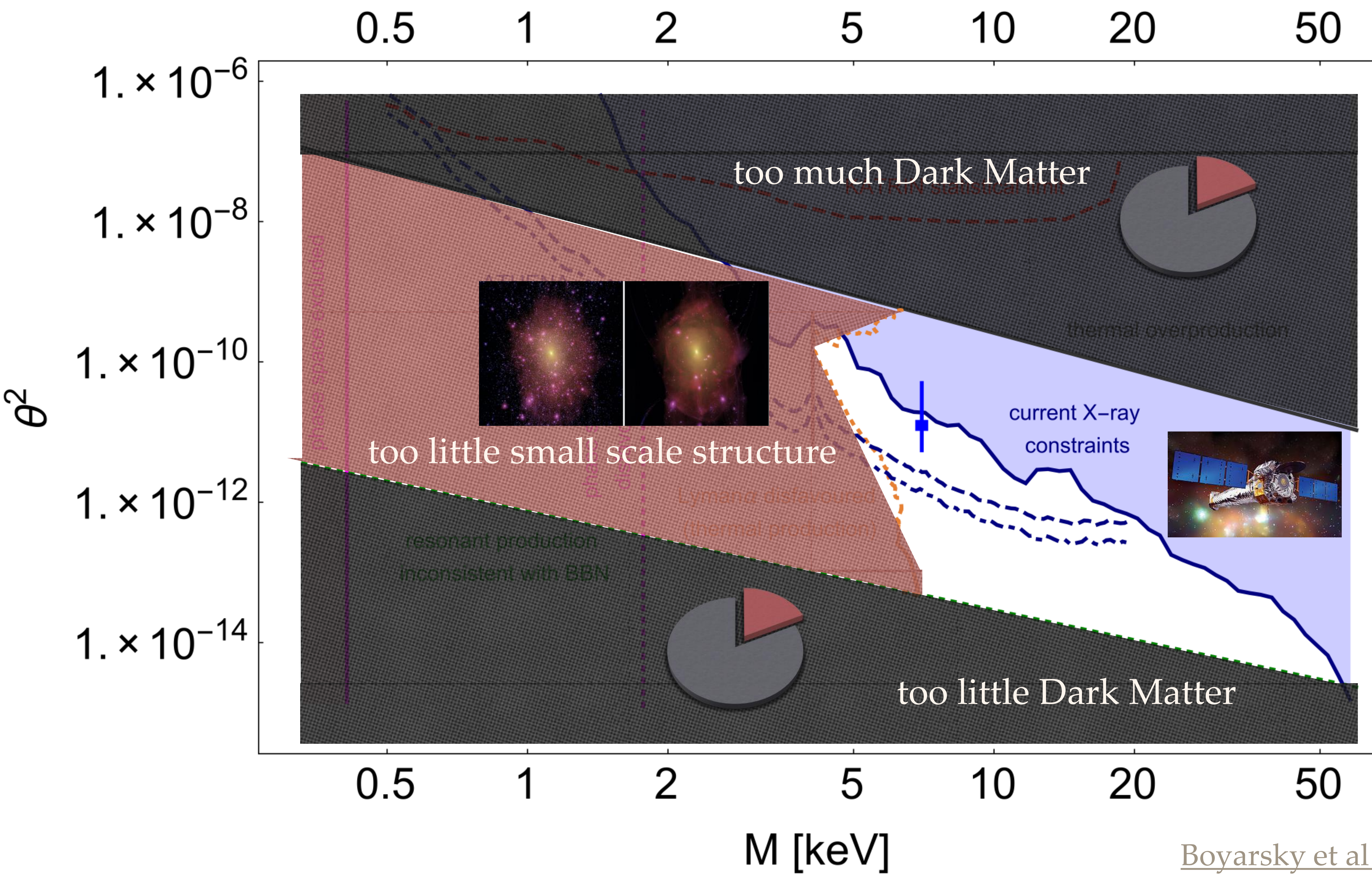


Phase space

- fermions are subject to Pauli principle
  $M > 25$ eV
- applying this throughout the history of the universe yields Temaine-Gunn bound
- Tremaine-Gunn bound depends on production mechanism, excludes $M < 0.5$ keV disfavours $M < 2$ keV



Sterile Neutrino Dark Matter



Boyarsky et al 1807.07938

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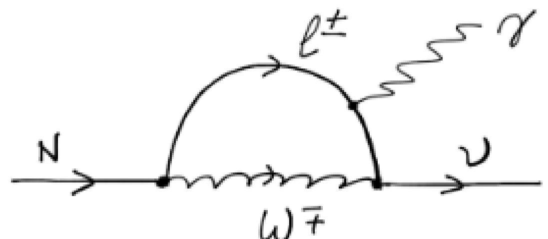

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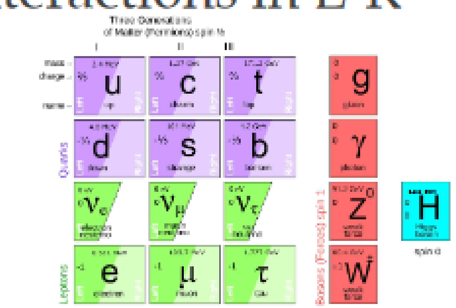

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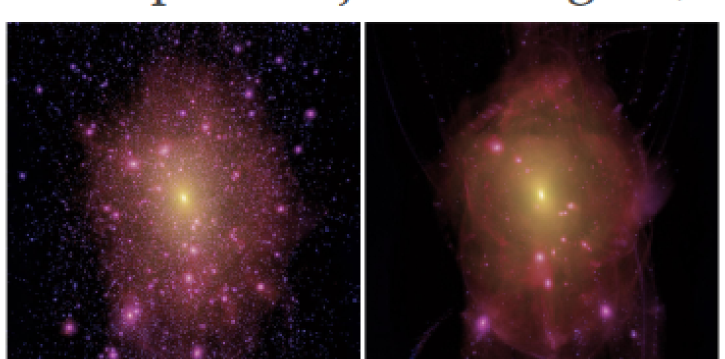

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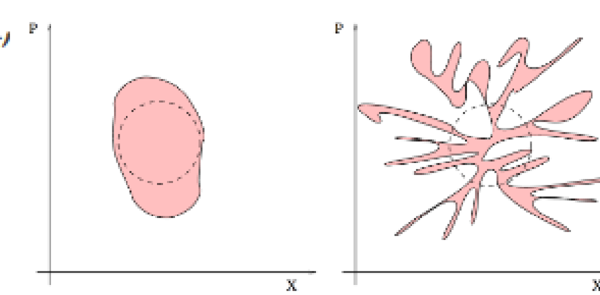
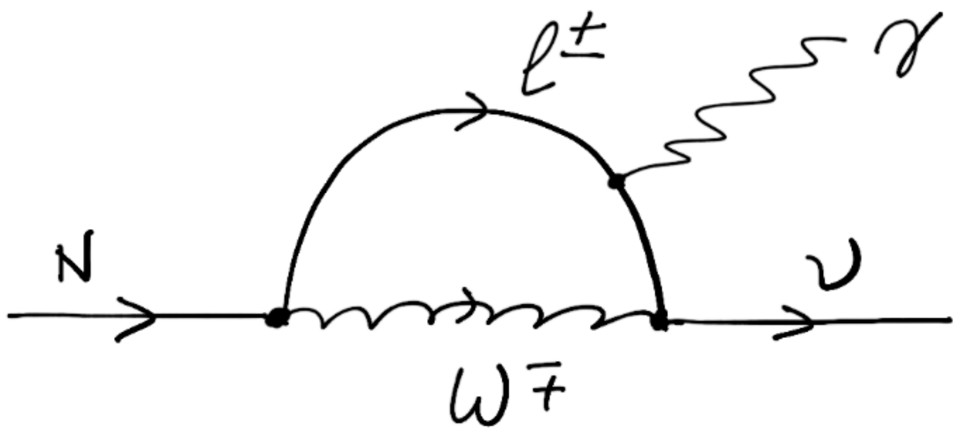


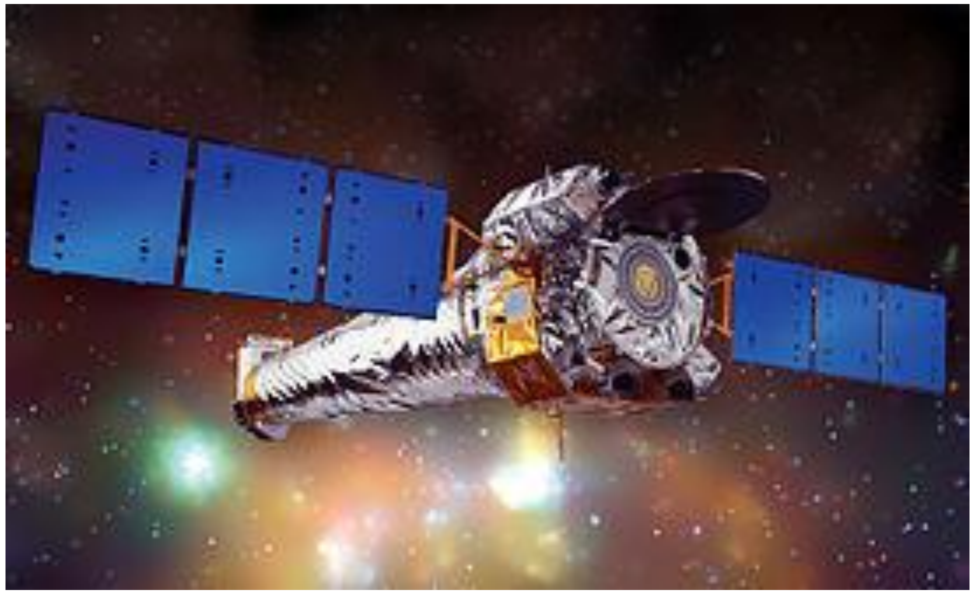
Indirect DM Searches

loop level decay into photons

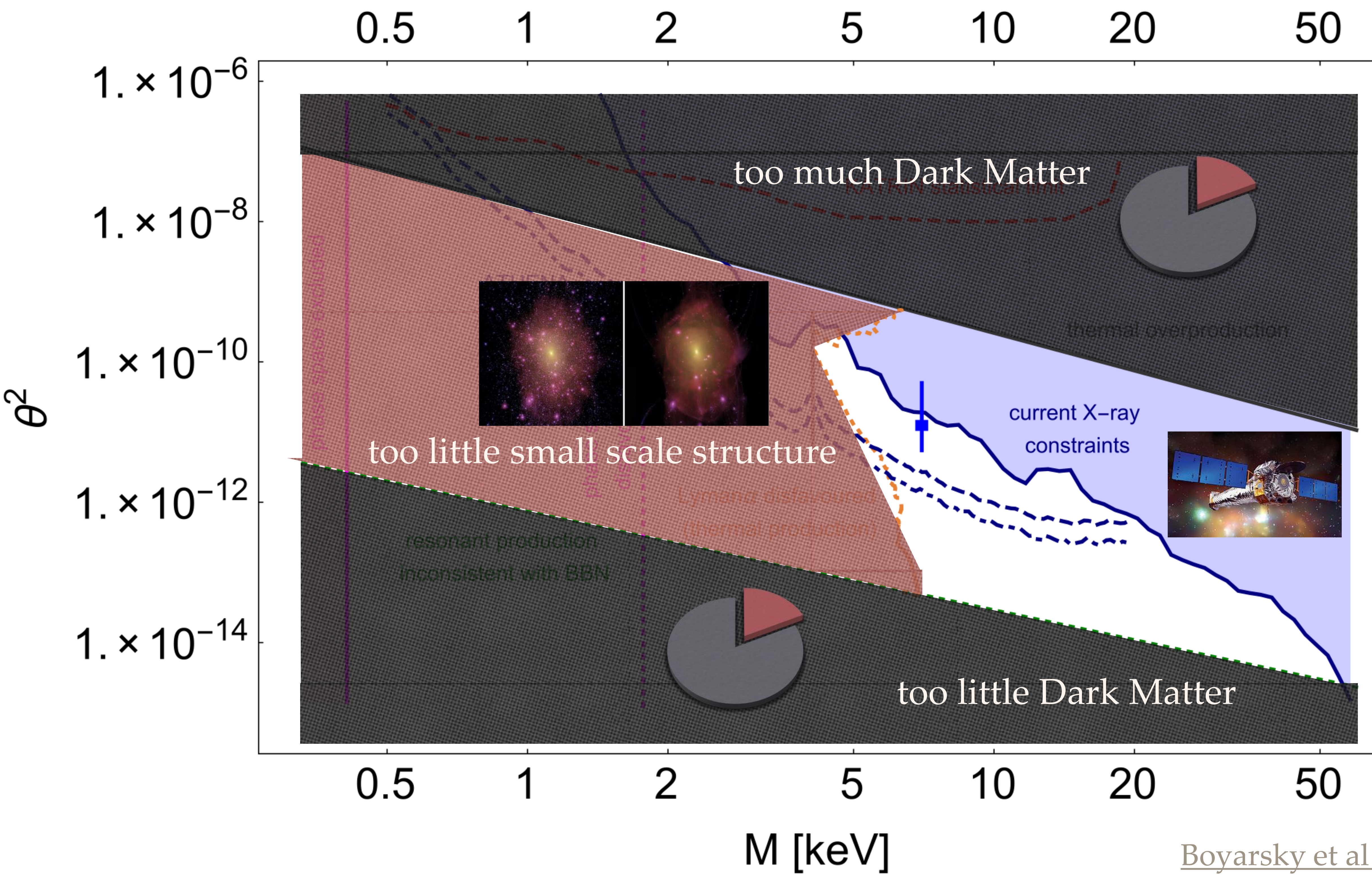


$$\Gamma_{N\to\gamma\nu} = \frac{9\,\alpha\,G_F^2}{256\pi^4}\theta^2 M^5 = 5.5\times 10^{-22}\theta^2\left[\frac{M}{1\,\mathrm{keV}}\right]^5\ \mathrm{sec}^{-1}\,.$$

One can search for an emission line!



Sterile Neutrino Dark Matter



Boyarsky et al 1807.07938

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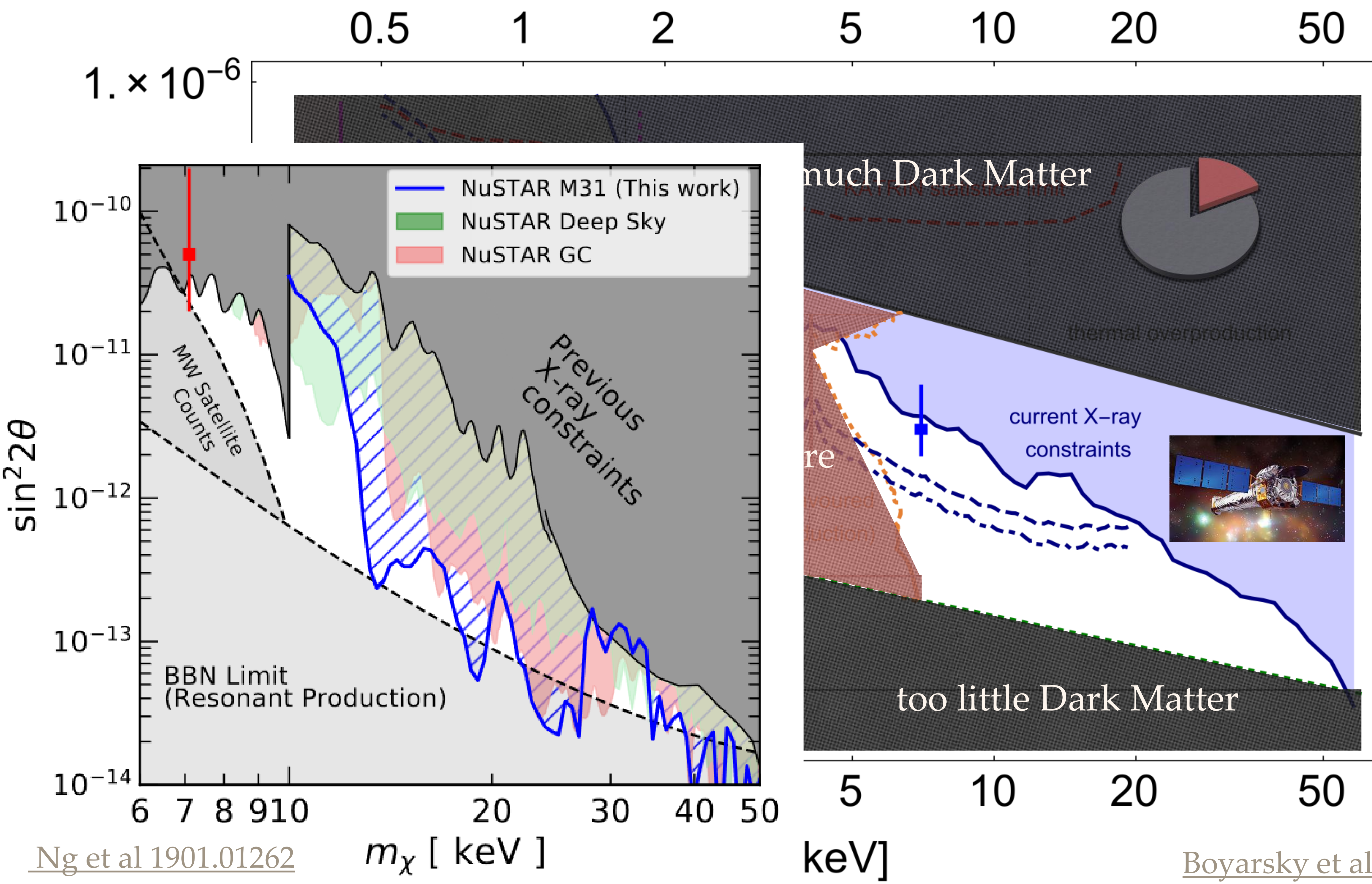
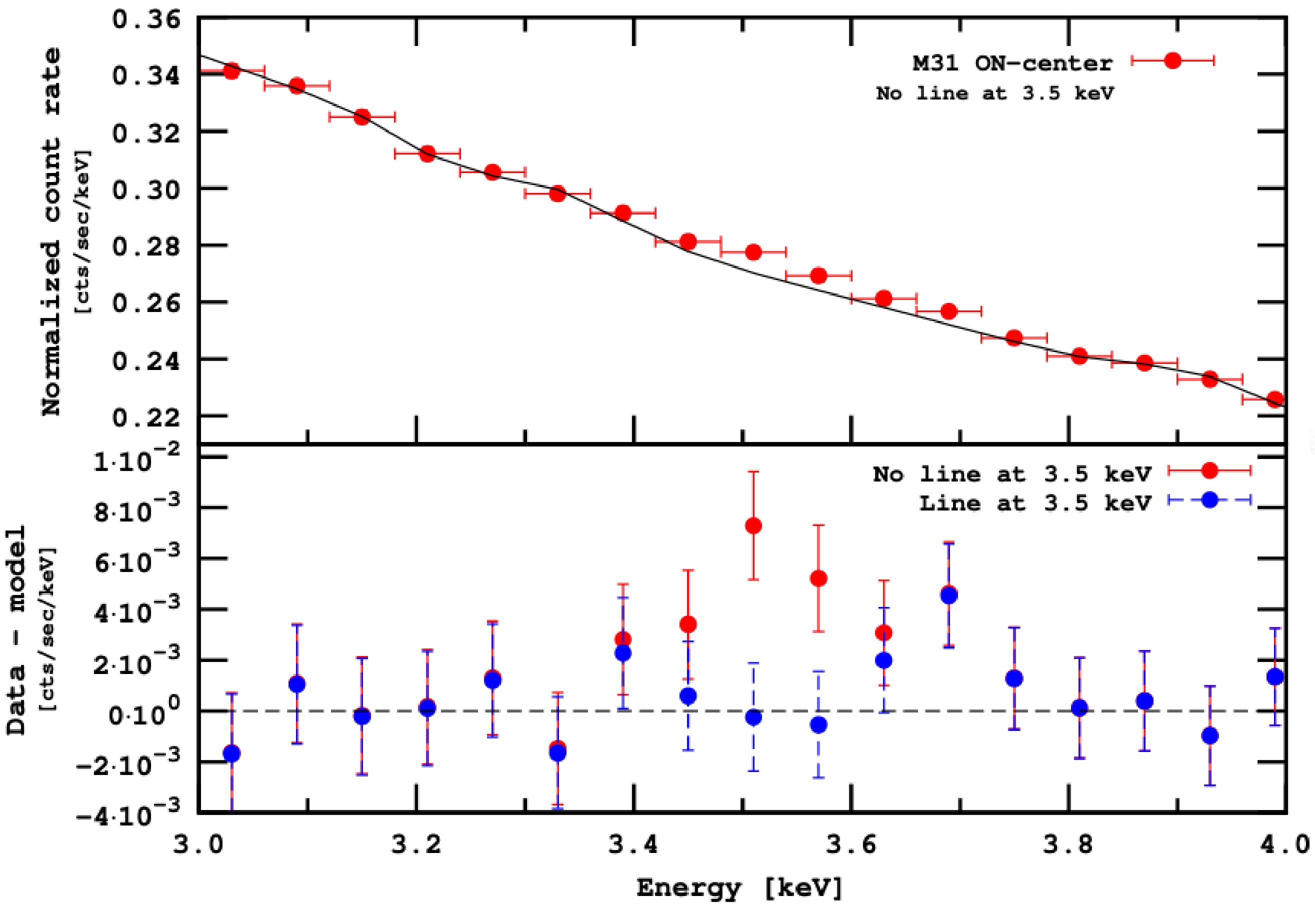


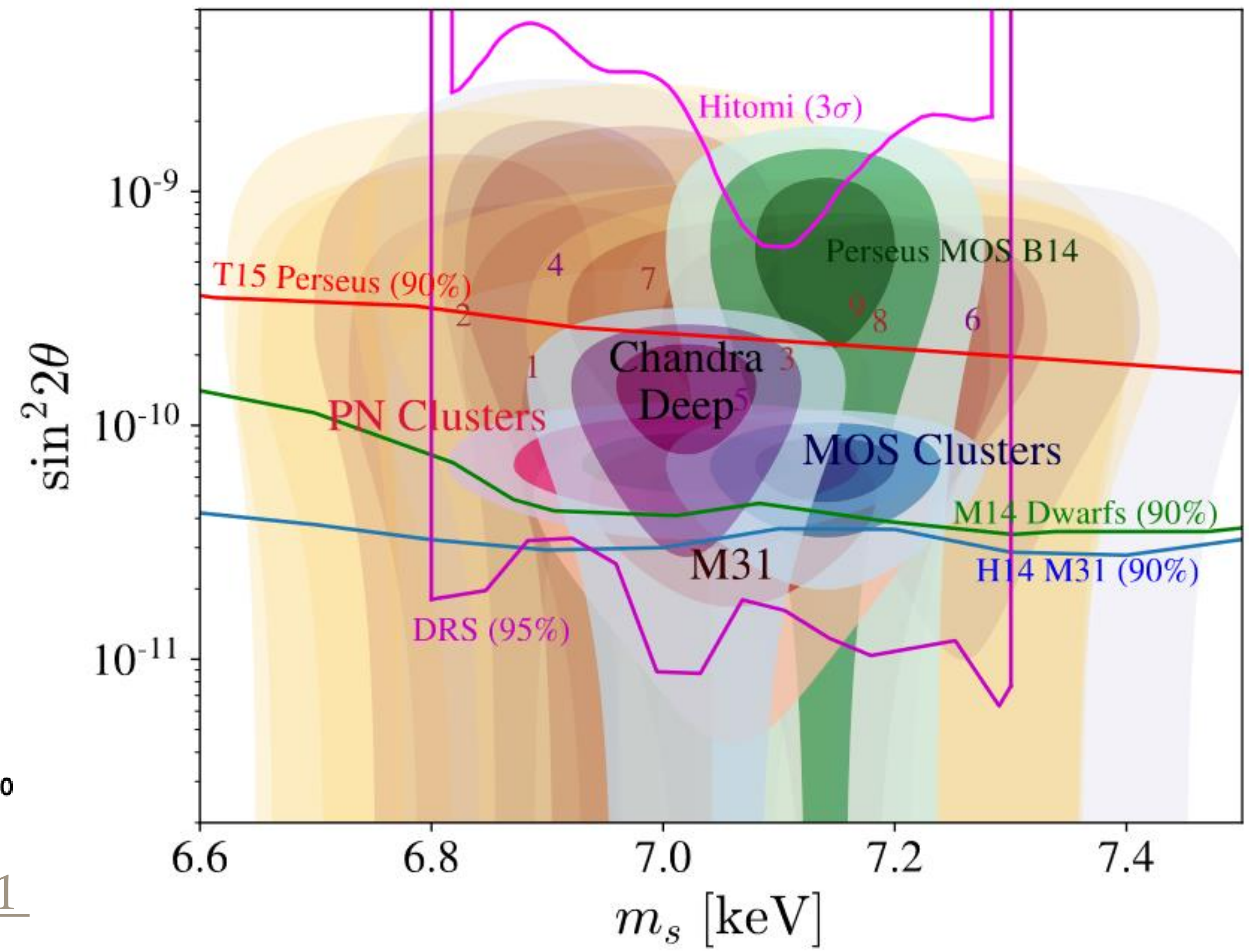
Ng et al 1901.01262

Boyarsky et al 1807.07938

Has the line been seen?



Boyarsky et al 1402.4119 Bulbul et al 1402.2301



Abazajian 2004.06170

Situation unclear…

need better spectral resolution (XARM and ATHENA will help)

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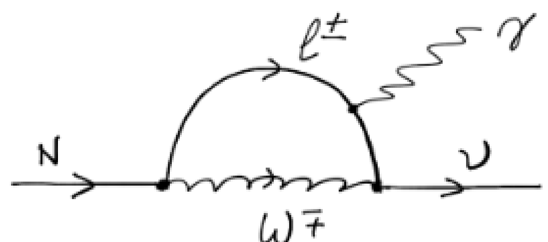

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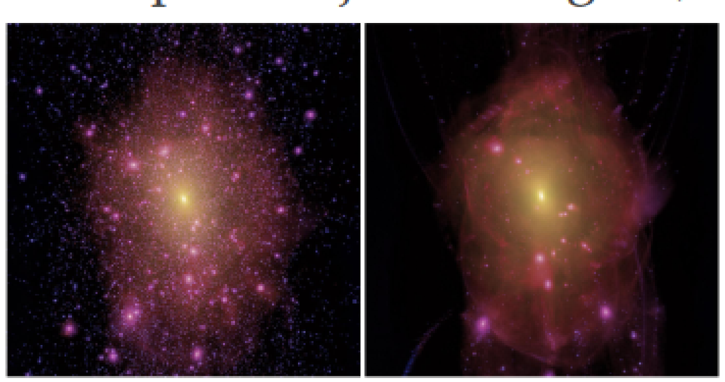

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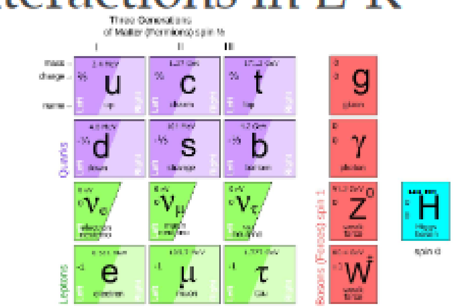

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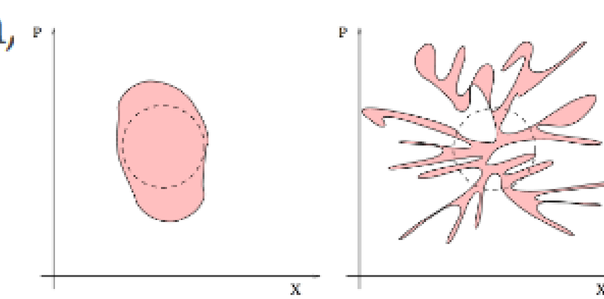

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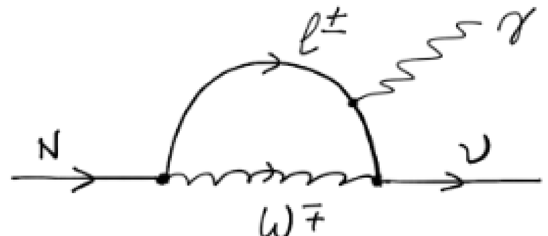

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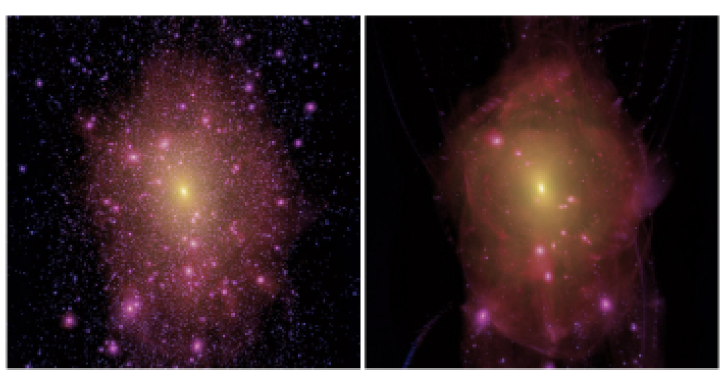

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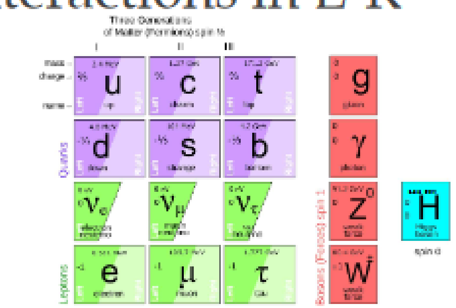
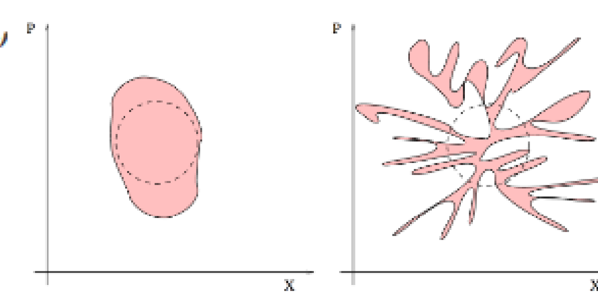
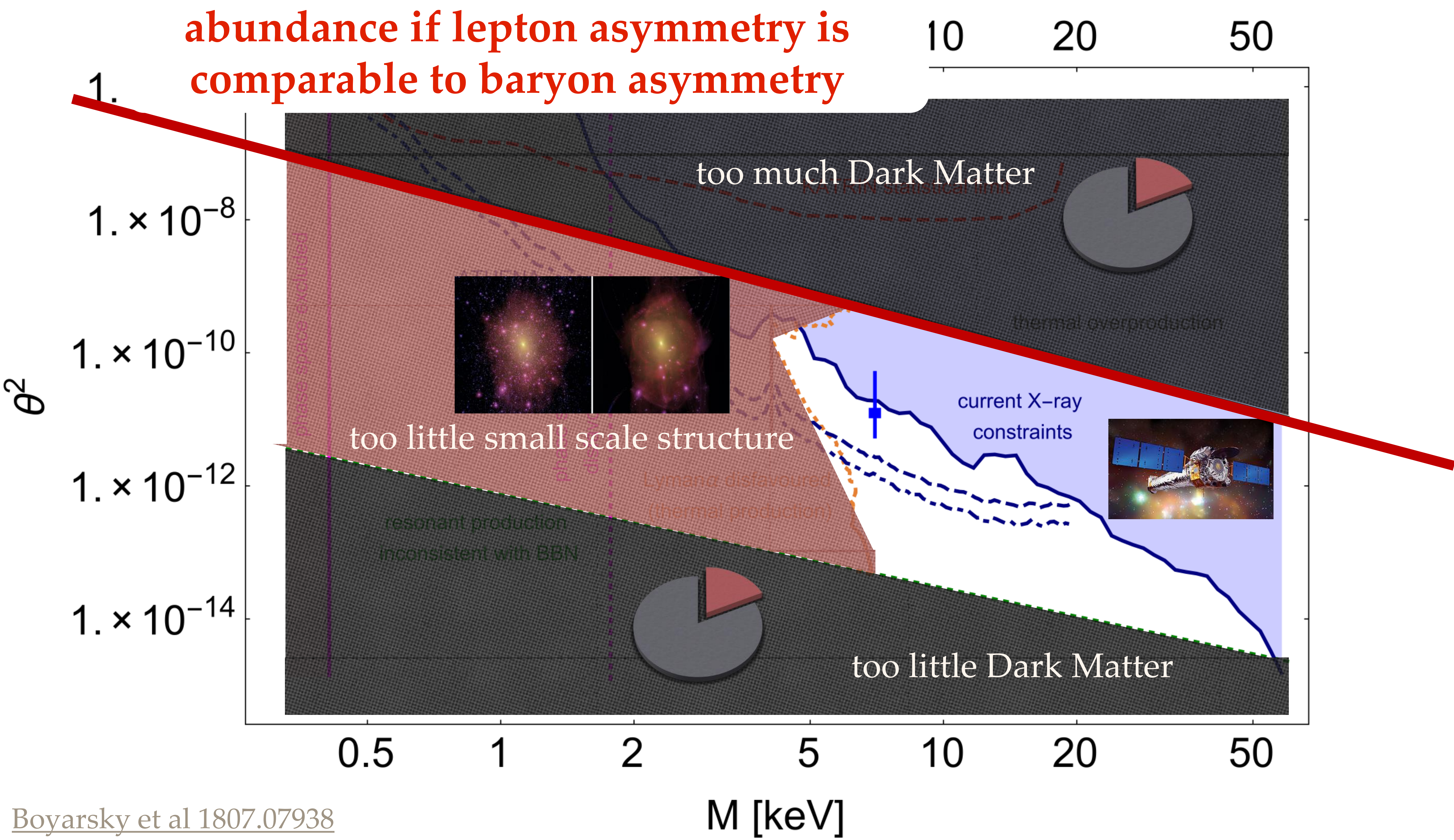


Phase space

- fermions are subject to Pauli principle
  $M > 25$ eV
- applying this throughout the history of the universe yields Temaine-Gunn bound
- Tremaine-Gunn bound depends on production mechanism, excludes $M < 0.5$ keV disfavours $M < 2$ keV



Sterile Neutrino Dark Matter



Boyarsky et al 1807.07938

Effective Mixing Angle

$$\sin^2(2\theta_m) = \frac{\Delta^2(p)\sin^2(2\theta)}{\Delta^2(p)\sin^2(2\theta) + [\Delta(p)\cos(2\theta) - V_D - V_T]^2}.$$

The active-sterile mass splitting enters via $\Delta(p) = \Delta m^2/(2p)$

And the "matter potentials" are

$$V_T \simeq -\frac{8}{3}\sqrt{2}G_F\left[\frac{\rho_\nu}{m_Z^2} + \frac{\rho_\ell}{m_W^2}\right]E_\nu$$

$$V_D \simeq 2\sqrt{2}G_F n_\gamma l_\nu = 2\sqrt{2}G_F\frac{2\zeta(3)}{\pi^2}T^3 l_\nu,$$

- **In matter-antimatter symmetric universe:** abundance determeined by M and θ alone, phase space distribution roughly thermal

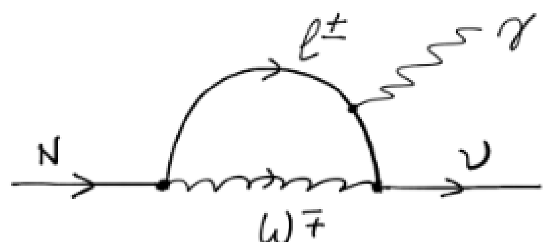
  Dodelson/Widrow 9303287
- **In presence of large lepton asymmetry l_ν:** MSW-like resonant enhancement of DM abundance, cooler spectrum

  Shi/Fuller 9810076

How to find Sterile Neutrino DM?

Indirect searches

- radiative decay $N \to \nu\gamma$ gives emission line at $M/2$

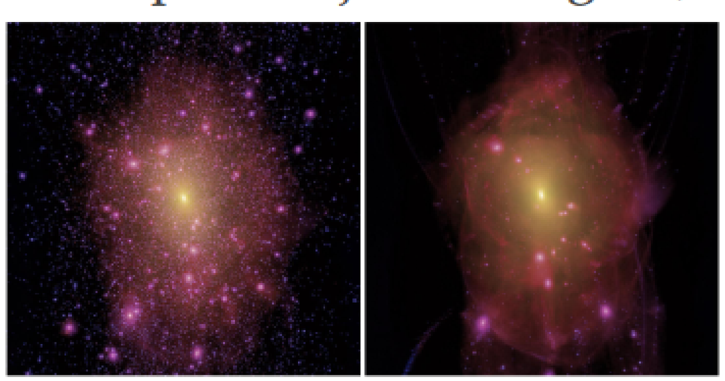


- 3.5 keV excess observed, but disputed
- new missions (XRISM, ATHENA, Lynx…)

Structure formation

Free streaming of DM affects formation of structures at sub-Mpc lengths

- matter power spectrum (Lyman α forest, 21 cm astronomy, weak lensing)
- # collapsed structures (dwarf galaxy counts, reionisation history; collapsed objects at high-z)
- matter distribution within collapsed objects

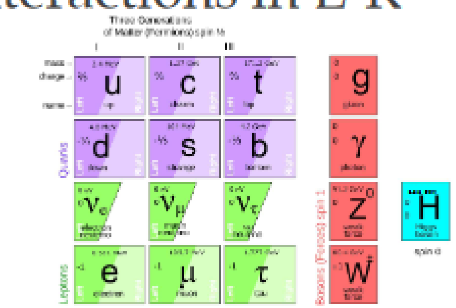


- uncertainties: baryonic feedback, IGM temperature…

Production mechanisms

Three known production mechanisms:

- thermal production through mixing-suppressed weak interaction (resonant or non-resonant)
- thermal production through new interactions at high energies (e.g. gauge interactions in L-R symm. model)
- decay of heavy particle/field (e.g. inflaton during reheating)



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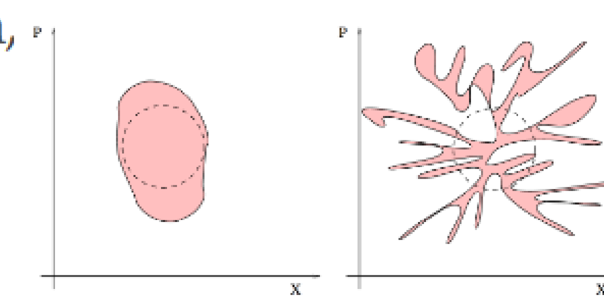
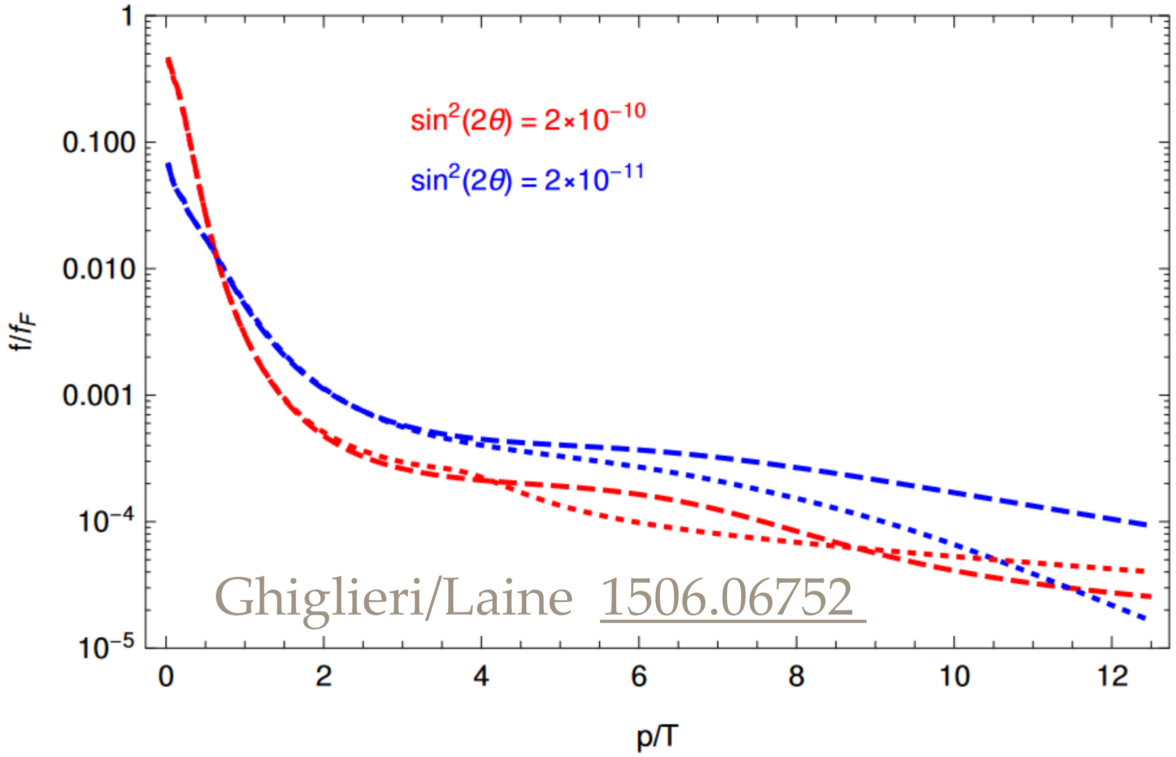


Structure Formation

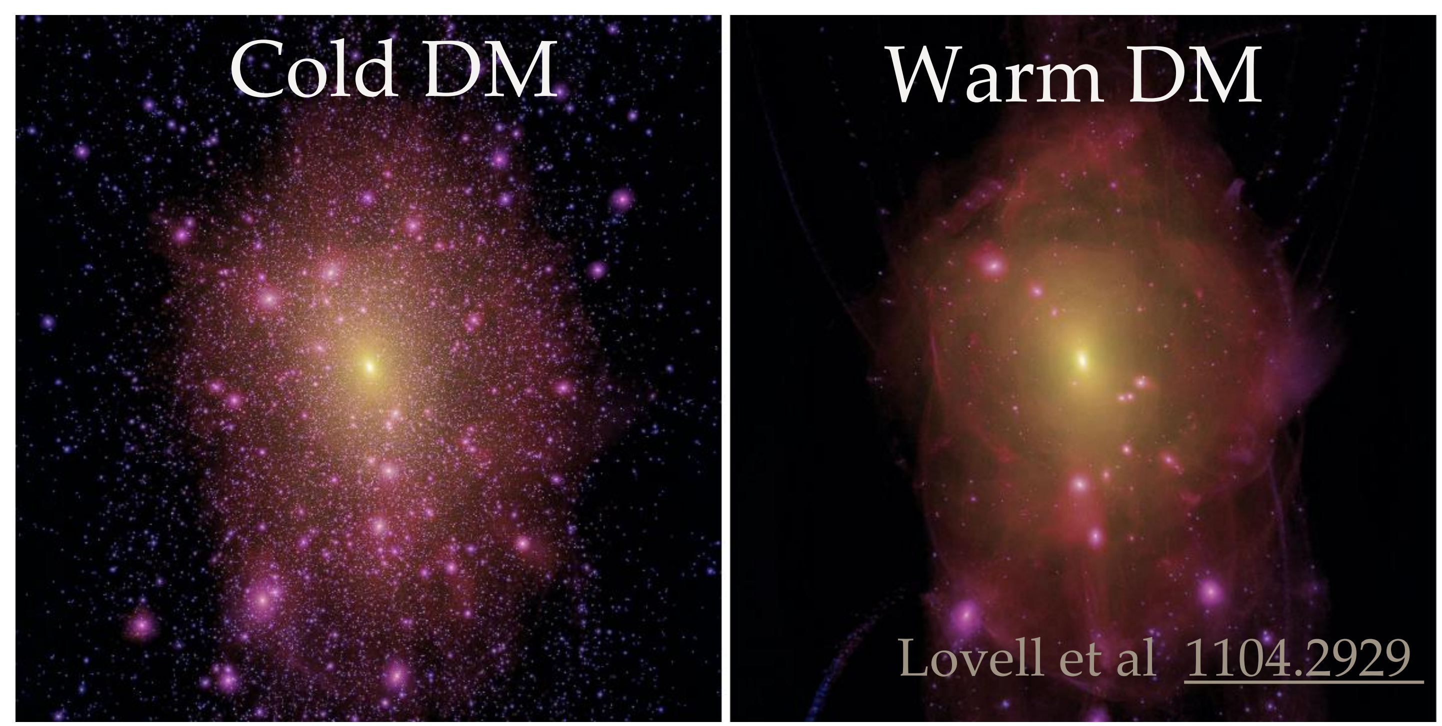
DM momentum distribution



DM free streaming length

$$\lambda_{\rm fs}(t) \equiv a(t)\int_{t_i}^{t} dt'\,\frac{v(t')}{a(t')} \approx 1\,{\rm Mpc}\,\frac{\rm keV}{M}\,\frac{\langle p_{\rm DM}\rangle}{\langle p_\nu\rangle}$$

- Free streaming leads to (relative) suppression of small scale structures (galactic to sub-galactic scales)
- Visible in dwarf galaxy counts, subhalo counts, Lyman forest, lensing, 21cm …



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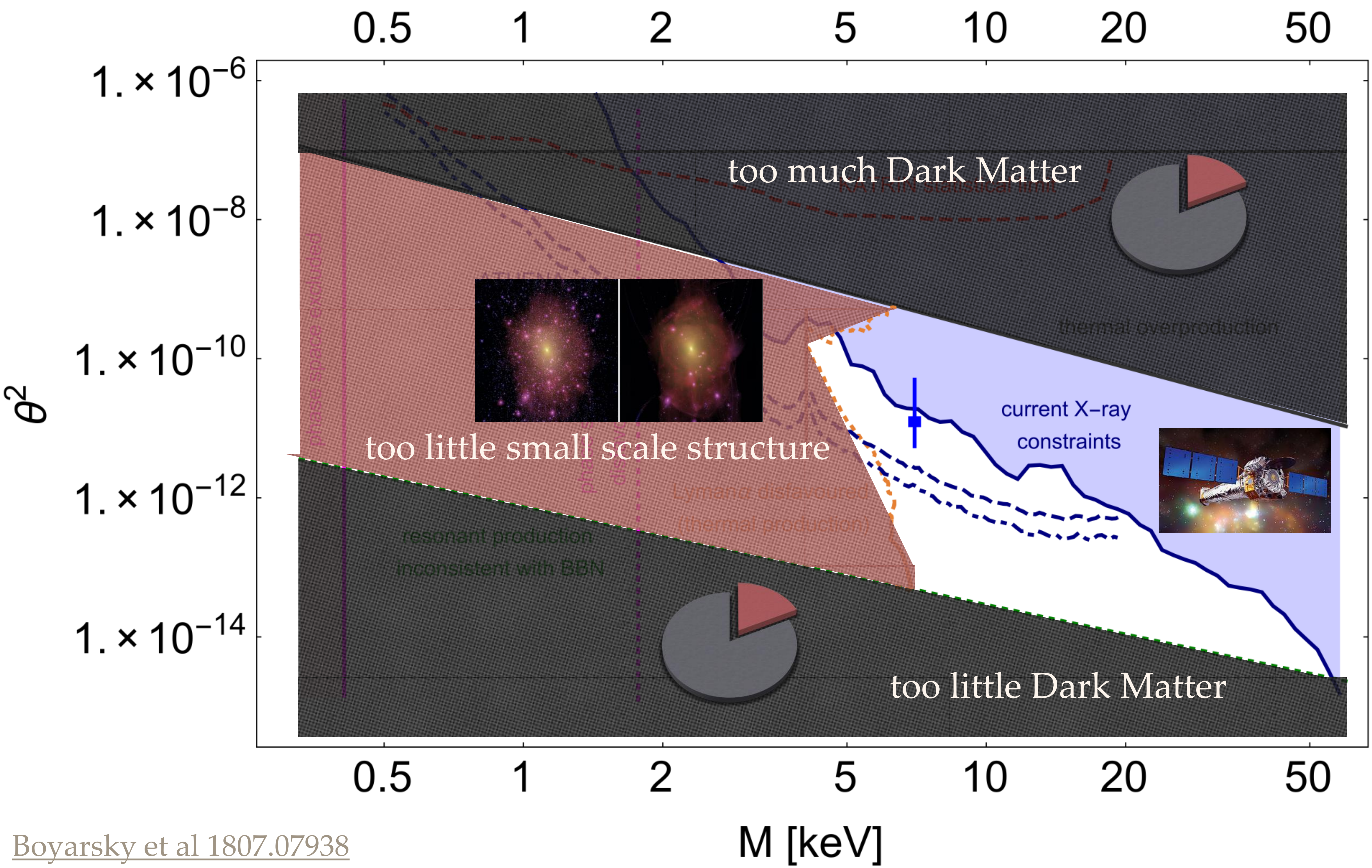

Boyarsky et al 1807.07938

Large Lepton Asymmetries

- Lepton asymmetries needed for resonant DM production at T ~ 200 MeV exceed observed baryon asymmetry by orders of magnitude
- Recall: at T > 130 GeV lepton and baryon asymmetries are kept in equilibrium by electroweak sphalerons
- How did the lepton asymmetry grow by orders of magnitude between T = 130 GeV and T = 200 MeV?

Cold DM Warm DM

Large Lepton Asymmetries

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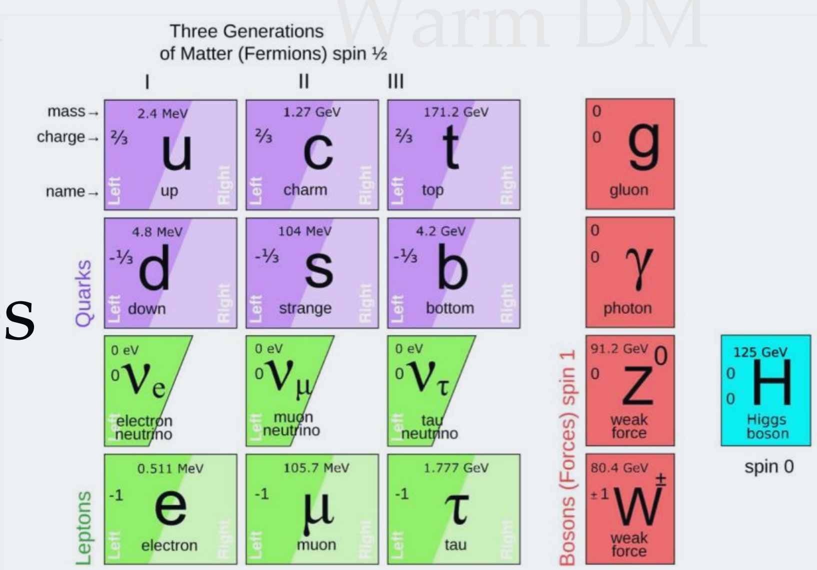
- How did the lepton asymmetry grow by orders of magnitude between T = 130 GeV and T = 200 MeV?

One possibility: the Neutrino Minimal Standard Model (νMSM)

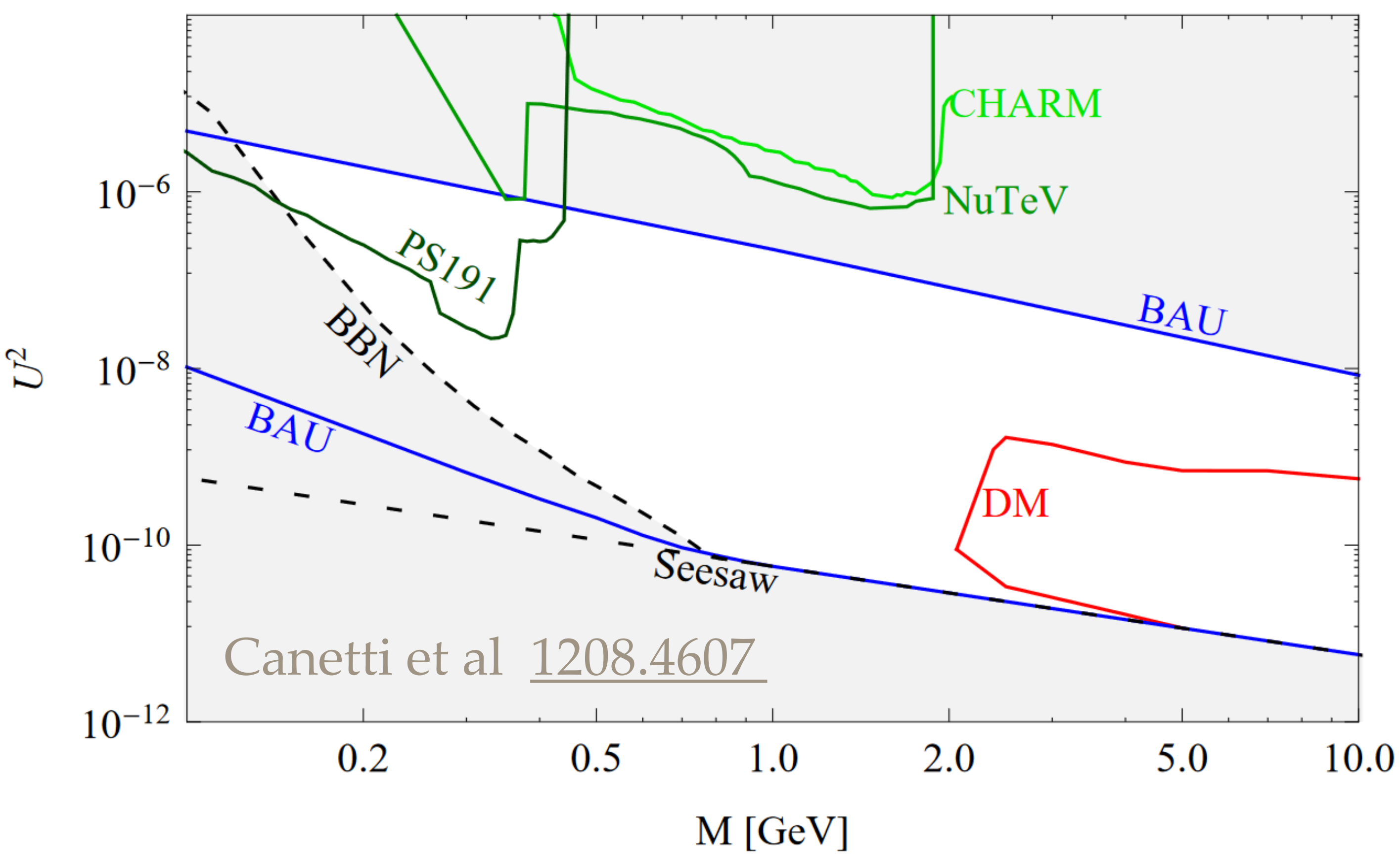
- one heavy neutrino is DM (keV mass) Asaka/Shaposhnikov 0505013
- the two others (GeV masses) generate baryon asymmetry during freeze-in at T > 130…

  …and generate additional lepton asymmetries during freeze-out and decay at T < 130 GeV
- late time lepton asymmetry causes resonant DM production Laine/Shaposhnikov 0804.4543



Can νMSM produce enough DM?

- Only parameter scan to date finds viable region!



DM production may be probed indirectly at colliders by discovering GeV scale heavy neutrinos that produced the large lepton asymmetry (which resonantly enhanced DM production…)

- Since then: considerable progress in computational methods

Biondini et al 1711.02864 Garbrecht 1812.02651

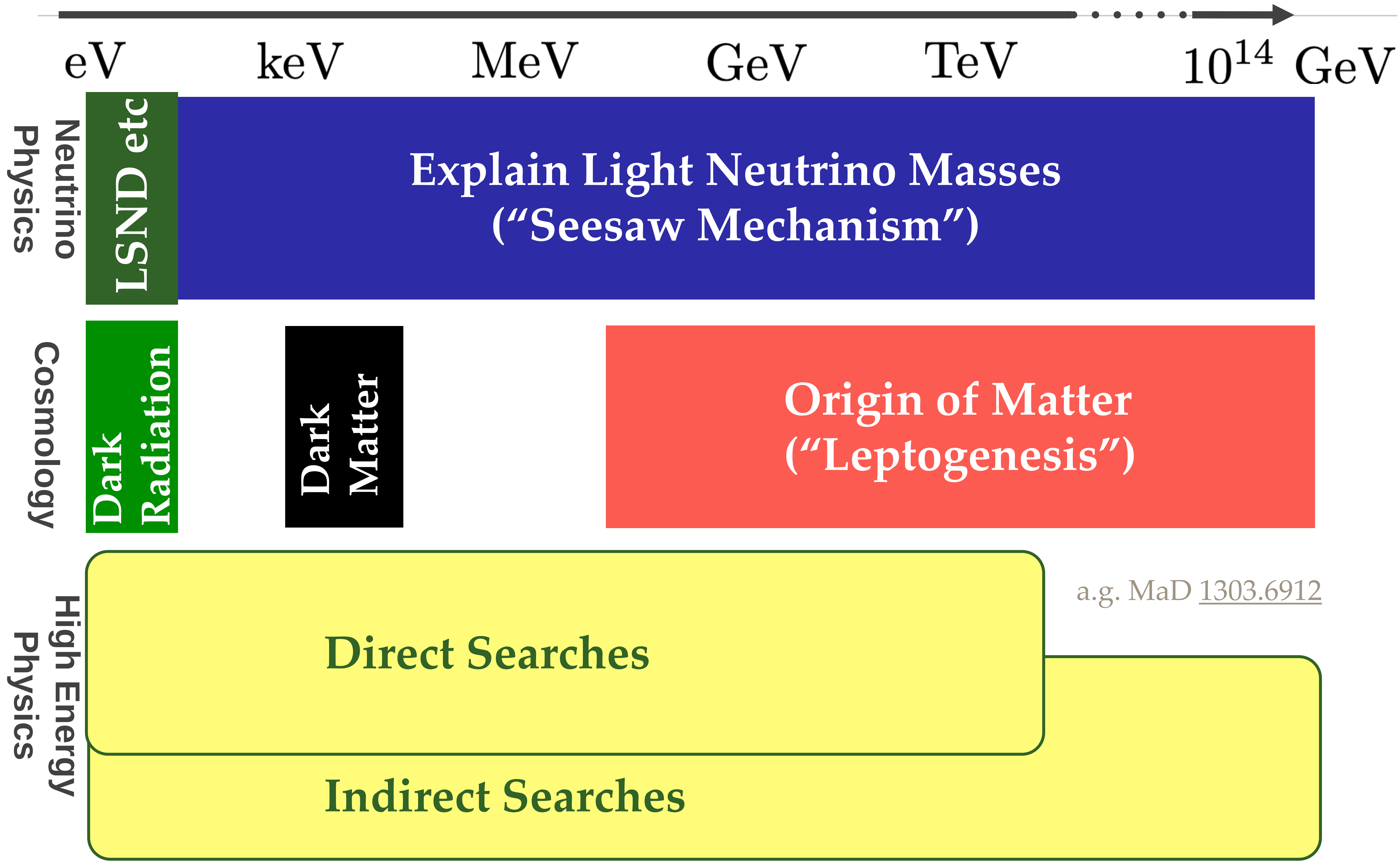
- Recent analysis confirms existence of viable region

Ghilieri/Laine 2004.10766

- Currently field of active research…

Eijima/Shaposhnikov./Timiryasov 2011.12637

Heavy Neutrinos in Particle Physics and Cosmology



The Hunt for RH Neutrinos: 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.)

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

CMB and LSS : absolute neutrino mass

non-accelerator searches (TRISTAN…)

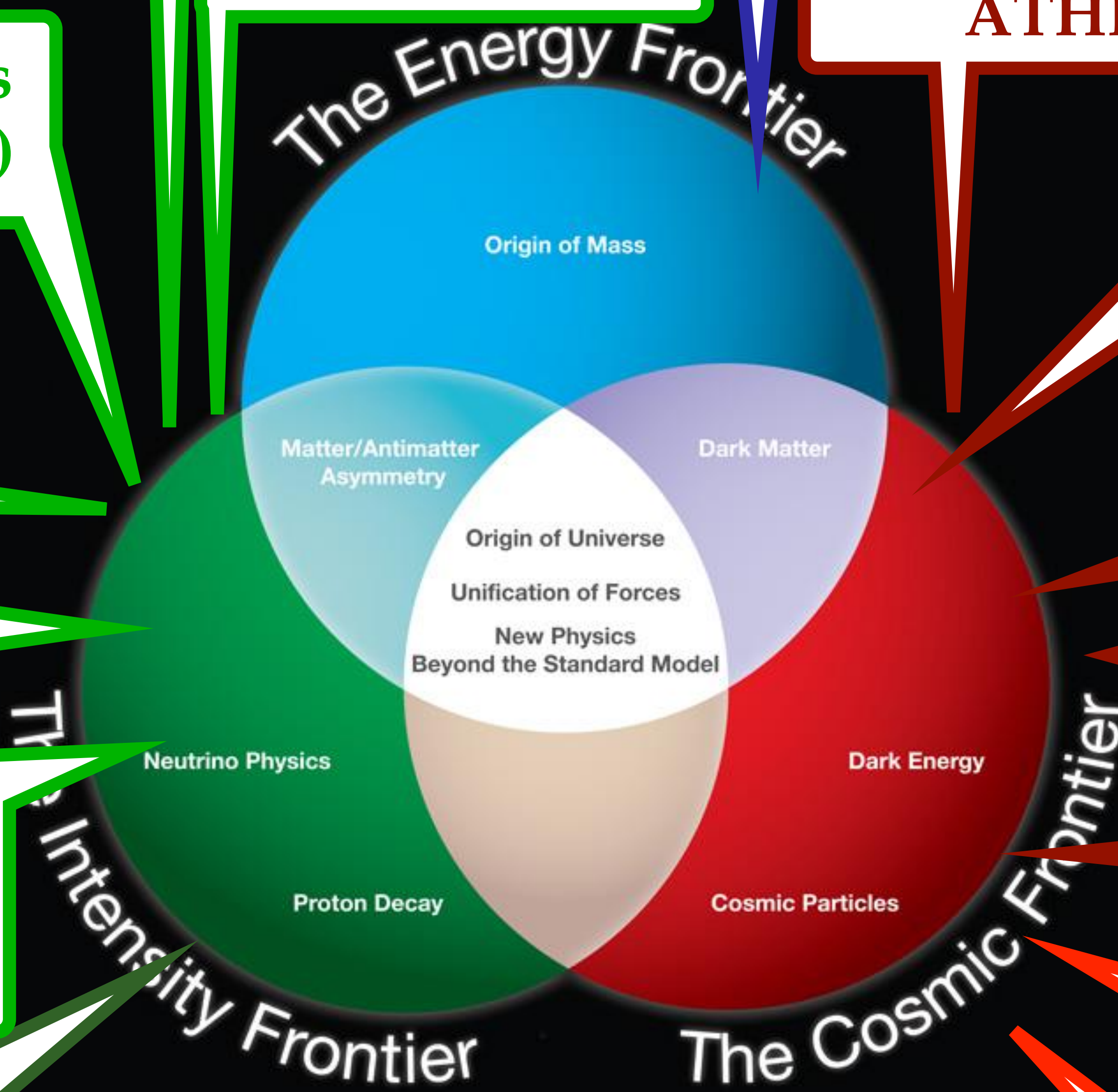
astrophysics: supernovae etc.

neutrinoless double β decay

Structure formation: simulation, observation

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

IGM temperature: WDM vs CDM



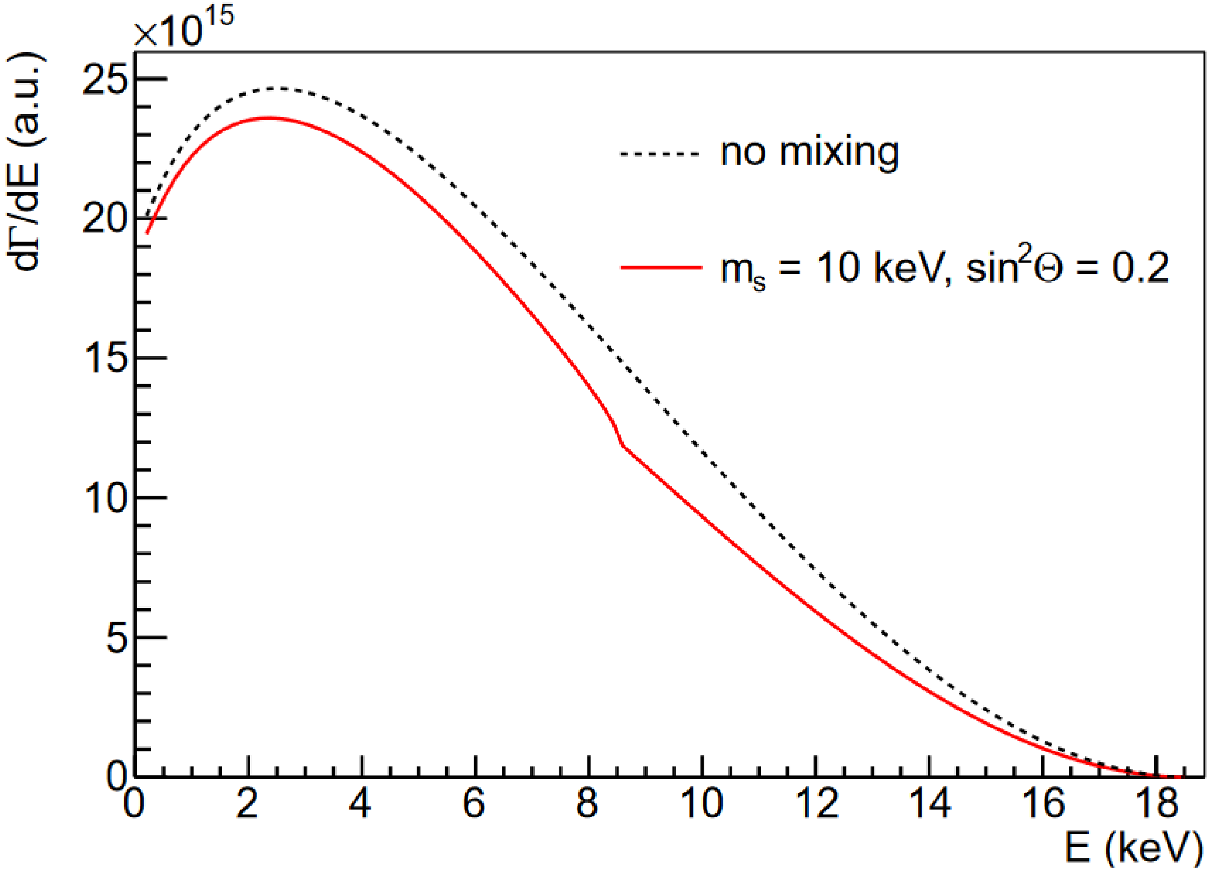
Theory: leptogenesis parameter region

neutrino oscillation experiments DUNE, Hyper-K

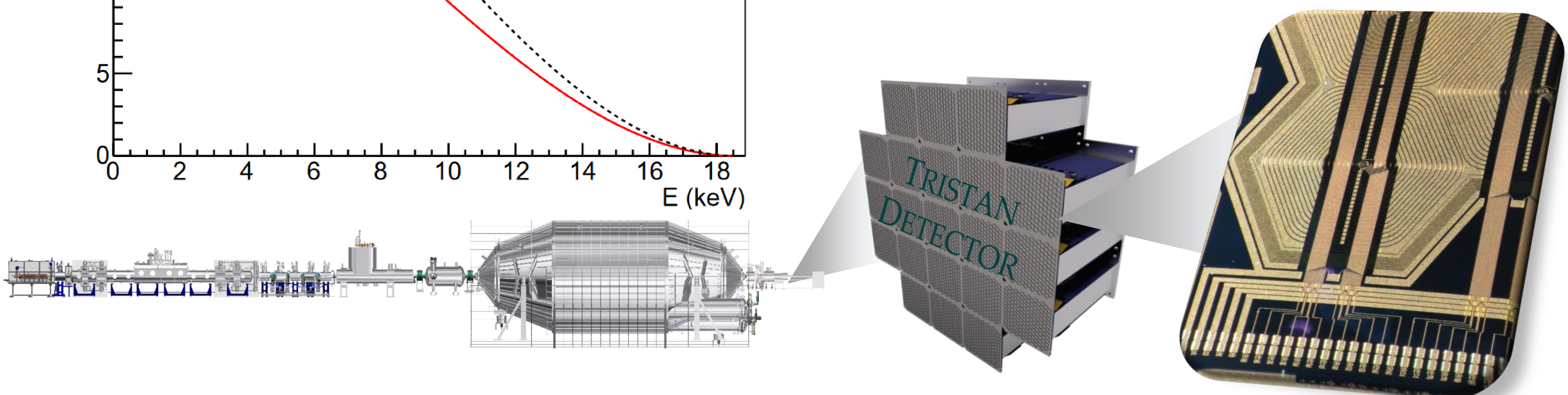
RF, NF, EF, CF, TF

Theory: Sterile neutrino DM production

Novel Detector System for KATRIN



Mertens et al. JCAP 1502 (2015)
Mertens et al. J. Phys. G46 (2019)



- keV mass sterile neutrinos can be discovered via their impact on β decay spectra
- This can e.g. be done with an upgrade to KATRIN