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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)

$$\mathcal{L} = \mathcal{L}_{SM} + i\bar{\nu}_R \partial^\mu \nu_R - \bar{L}_L F \nu_R \tilde{H} - \tilde{H}^\dagger \bar{\nu}_R F^\dagger L$$

$$-\frac{1}{2}(\bar{\nu}^c_R M_M \nu_R + \bar{\nu}_R M_M^\dagger \nu_R^c)$$

Three Generations of Matter (Fermions) spin 1/2			
mass →	I	II	III
charge →	2/3 u up	2/3 c charm	2/3 t top
name →	Left u up	Left c charm	Left t top
Quarks	Right	Right	Right
mass →	2.4 MeV	1.27 GeV	171.2 GeV
charge →	2/3	2/3	2/3
name →	Left d down	Left s strange	Left b bottom
Leptons	Right	Right	Right
mass →	4.8 MeV	104 MeV	4.2 GeV
charge →	-1/3	-1/3	-1/3
name →	Left d down	Left s strange	Left b bottom
Bosons (Forces) spin 1			
mass →	0 eV	0 eV	0 eV
charge →	0	0	0
name →	ν _e electron neutrino	ν _μ muon neutrino	ν _τ tau neutrino
Leptons	Right	Right	Right
mass →	0 eV	0 eV	0 eV
charge →	0	0	0
name →	Left e electron	Left μ muon	Left τ tau
Leptons	Right	Right	Right
mass →	0.511 MeV	105.7 MeV	1.777 GeV
charge →	-1	-1	-1
name →	Left e electron	Left μ muon	Left τ tau
Bosons (Forces) spin 0			
mass →	91.2 GeV	0	125 GeV
charge →	0	0	0
name →	Left Z weak force	Left H Higgs boson	Left W weak force
Leptons	Right	Right	Right
mass →	80.4 GeV	0	0
charge →	+1	0	0
name →	Left W weak force	Left H Higgs boson	Left W weak force

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



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

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...)

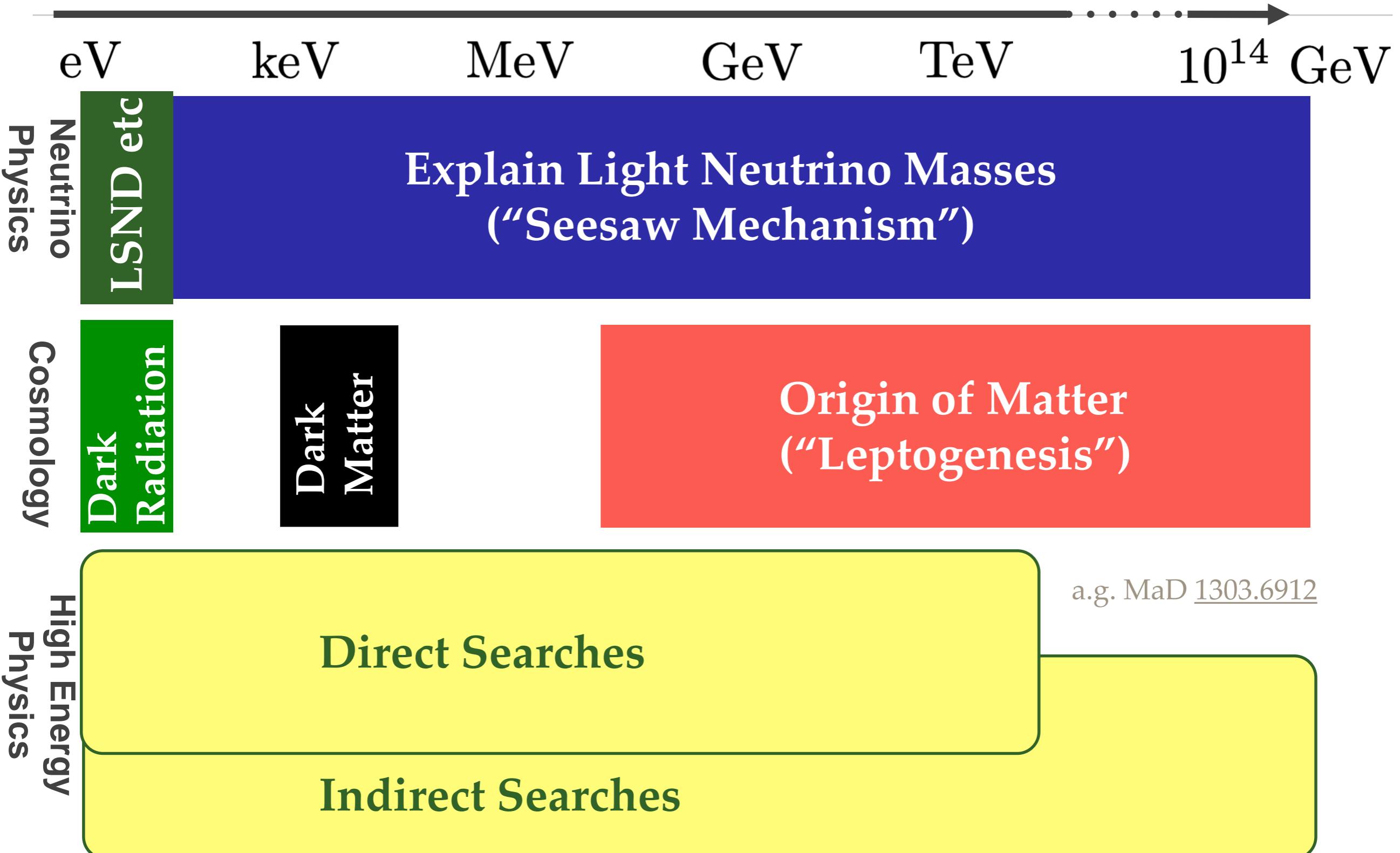
- can use generic EFT description for models with $M < \text{TeV} < \Lambda$
- need full dark sector description if $M, \Lambda < \text{TeV}$

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 Neutrino Mass Models](#)

Heavy Neutrino Mass Scale



Heavy Neutrino Mass Scale

nuclear
decay spectra



fixed target
experiments



b factories



far detectors



ATLAS/CMS



future colliders



D
R

High Energy
Physics

Direct Searches

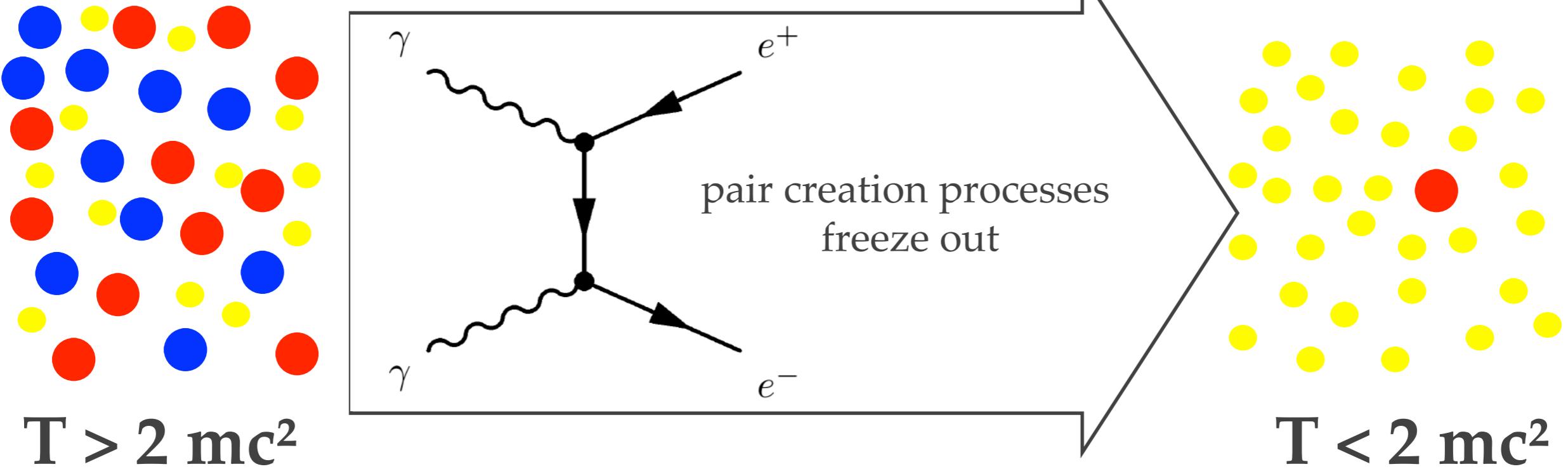
Indirect Searches

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](#)



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

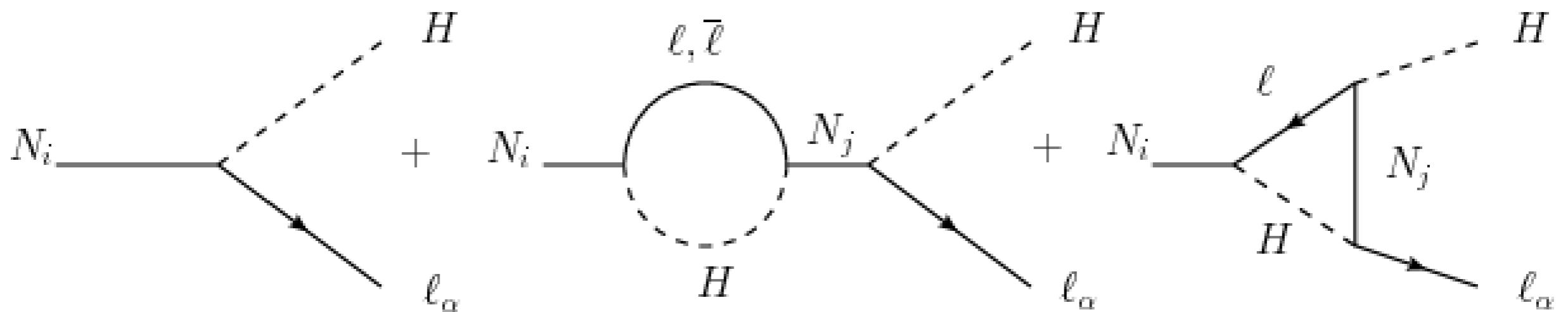
- N are around in the early universe
- N interactions are CP violating
- N may preferably decay into matter

CP violating parameter ϵ

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

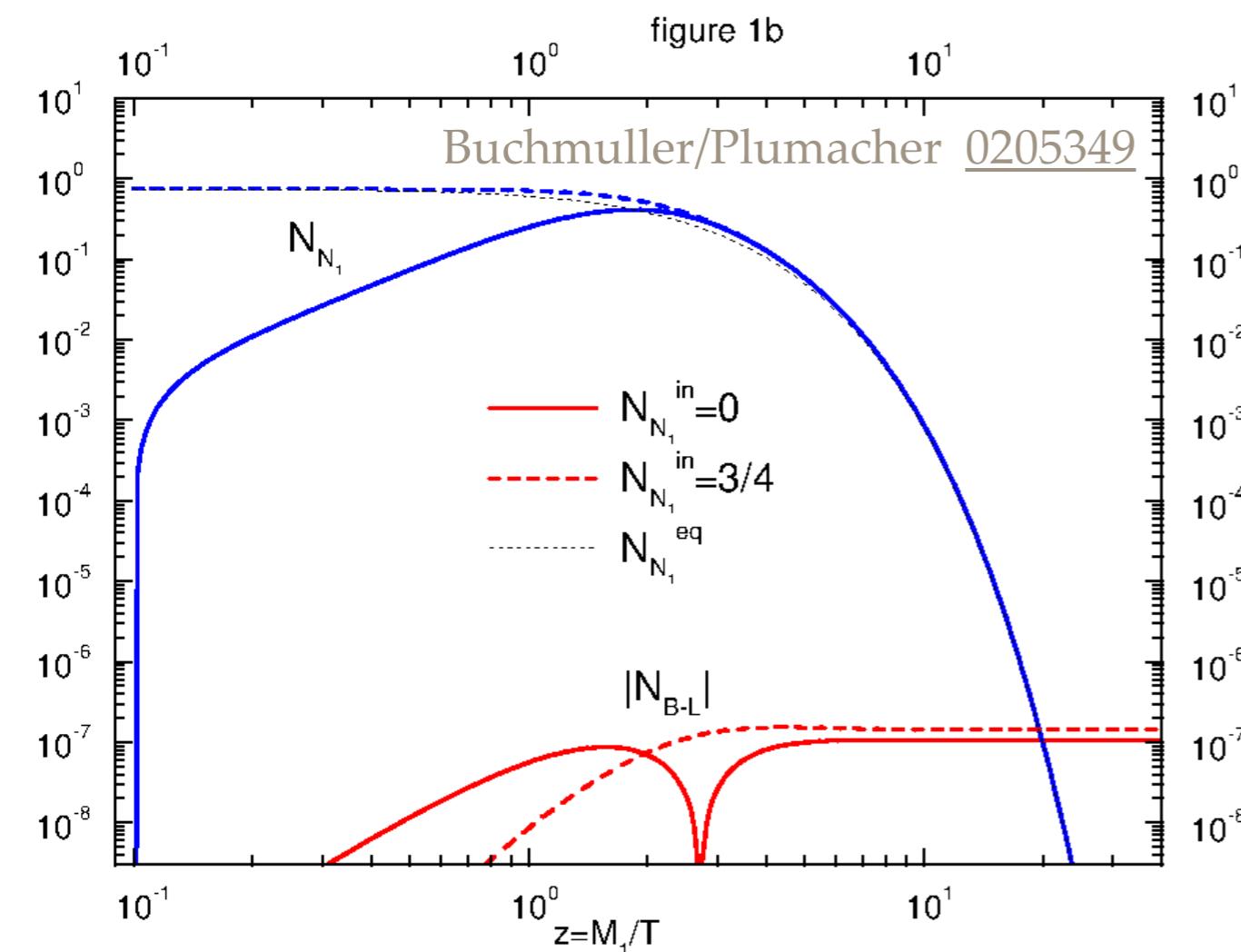
final asymmetry

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



asymmetry arises from quantum interference in the plasma

Boltzmann Equation



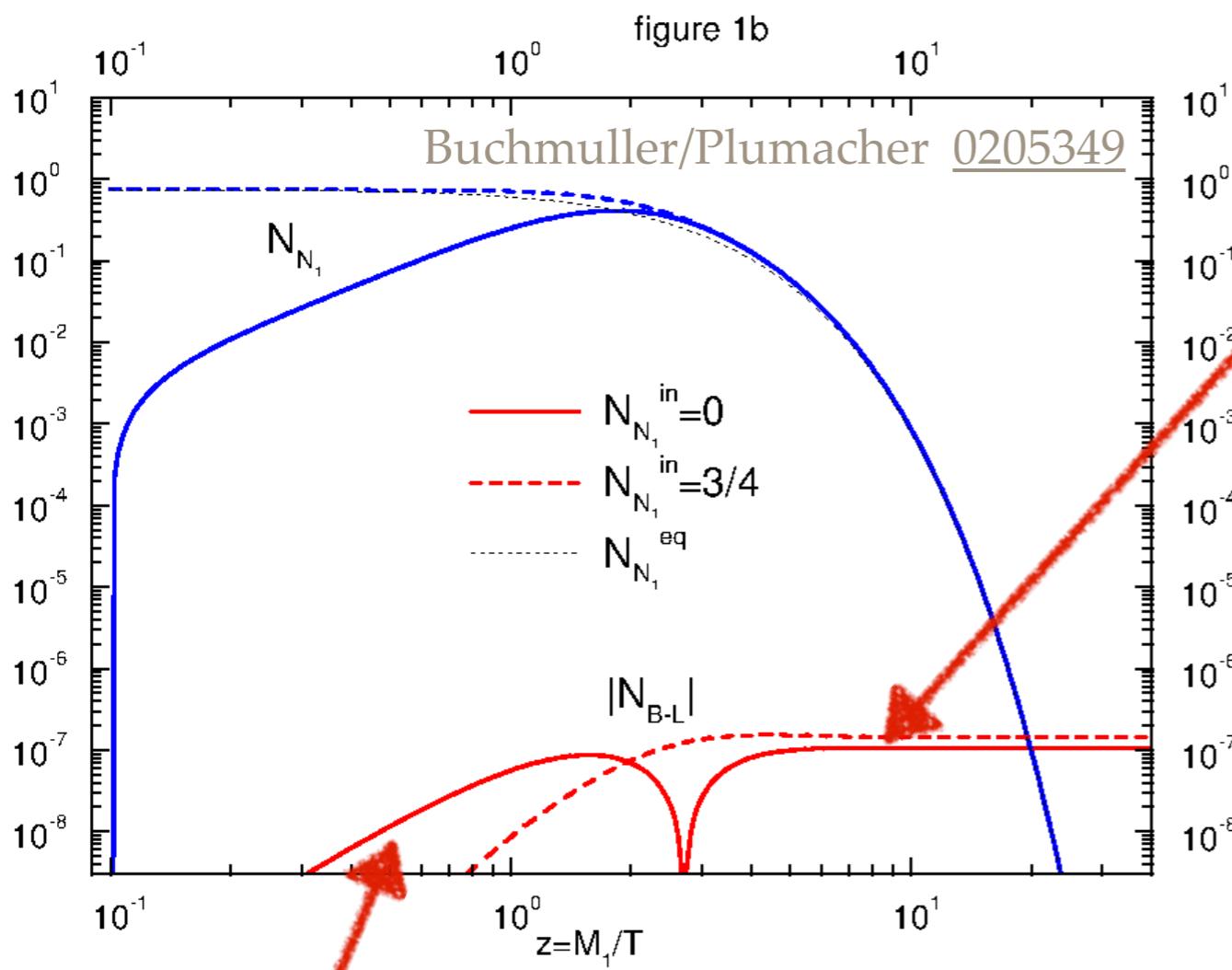
Sakharov's nonequilibrium condition can be fulfilled in two ways.

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

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

"source" "washout"

Freeze-in and freeze-out



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

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

Sakharov's nonequilibrium
condition can be fulfilled in
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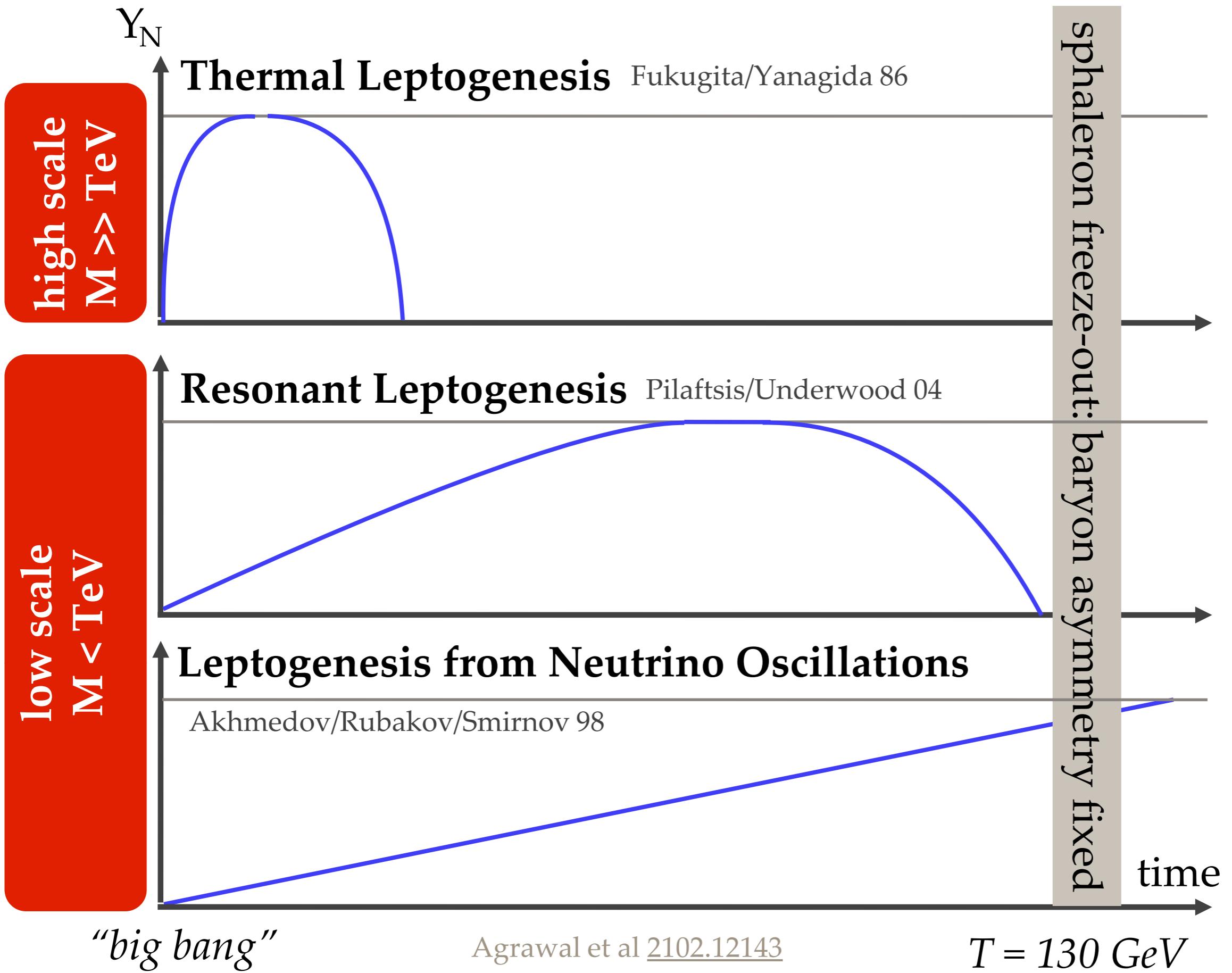
$$xH \frac{dY_N}{dx} = -\Gamma_N(Y_N - Y_N^{eq}) \quad x = M/T$$

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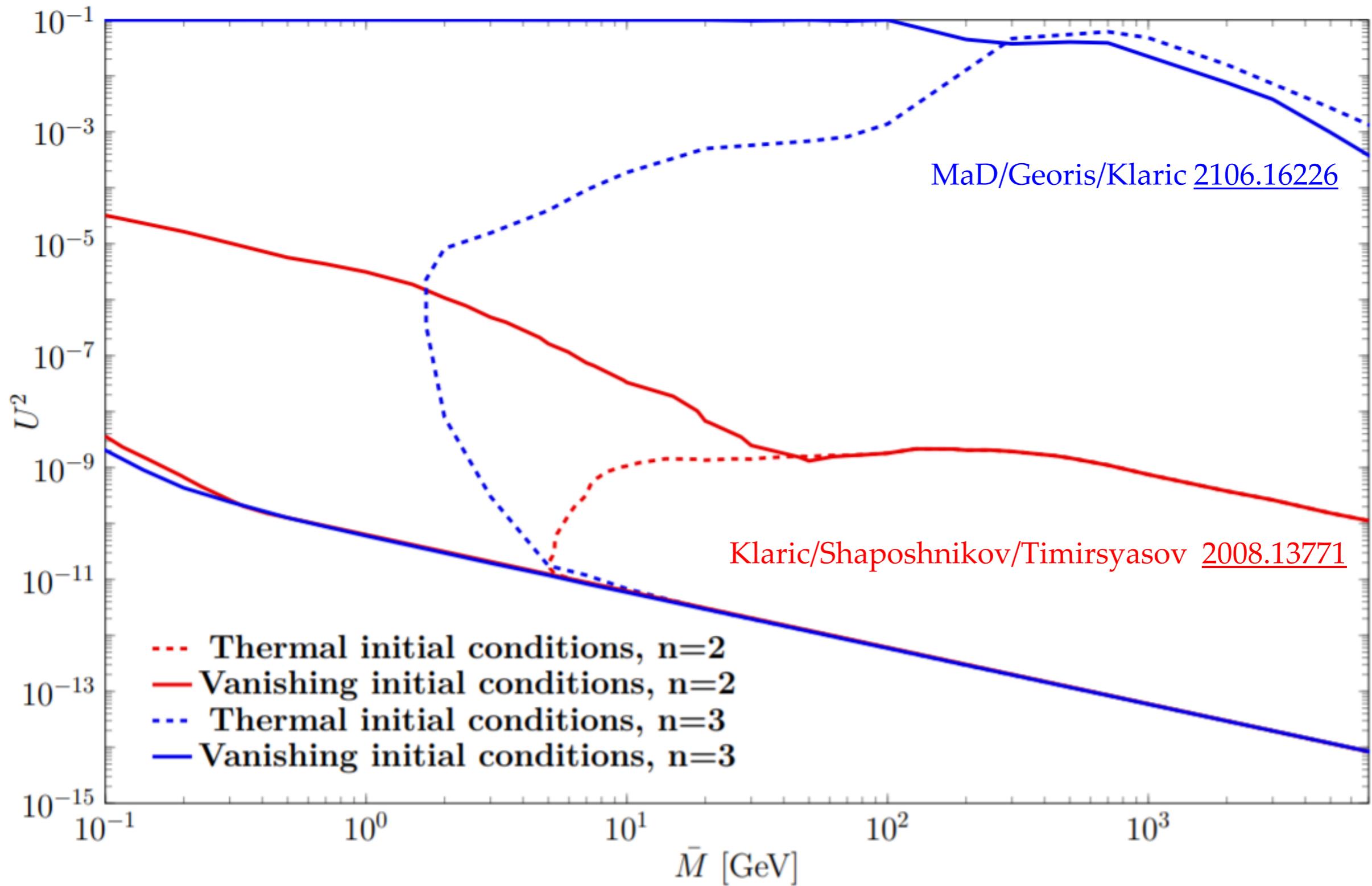
"source" "washout"

asymmetry generated in
freeze-out and decay

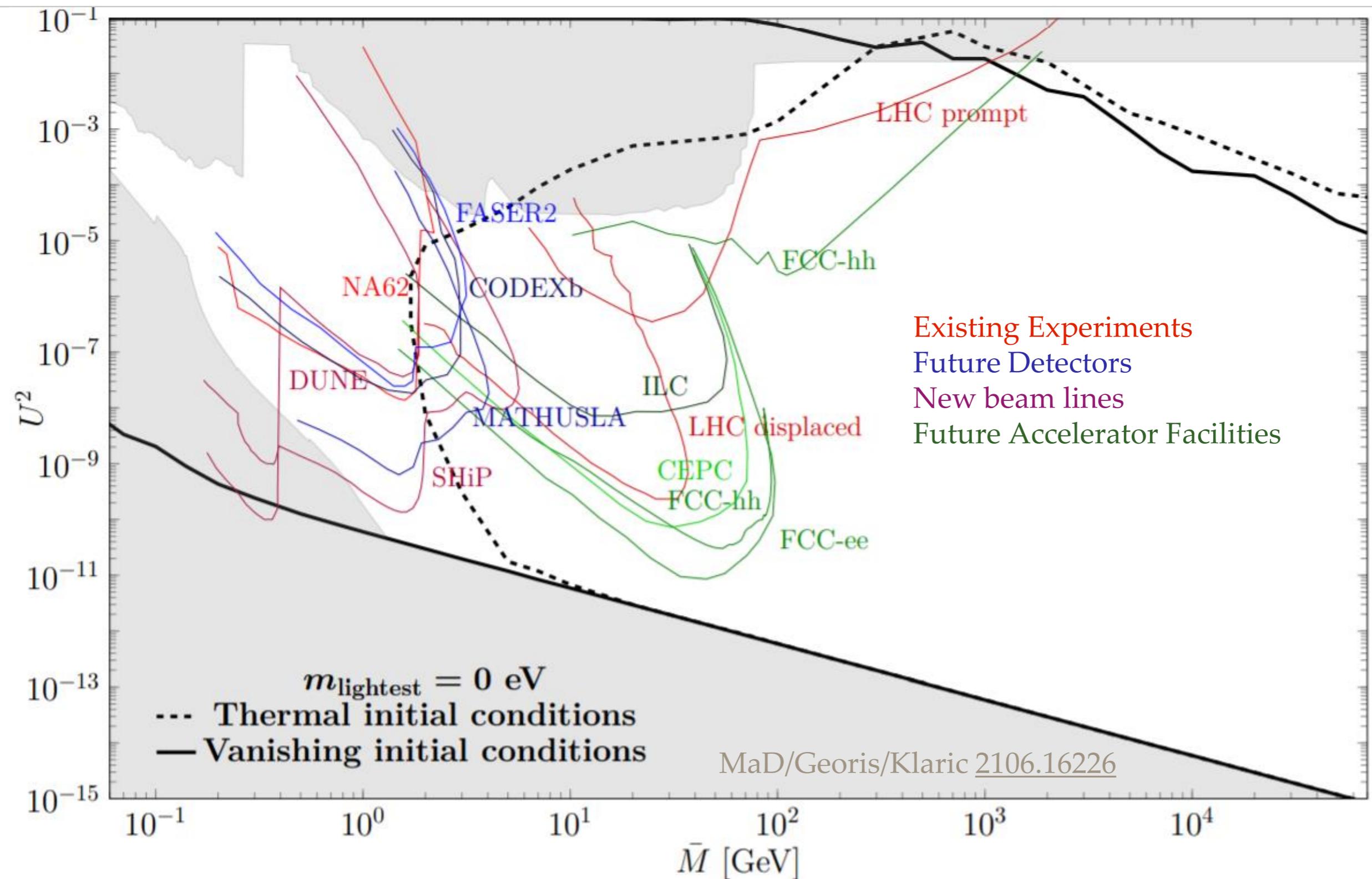
asymmetry
generated in
freeze-in



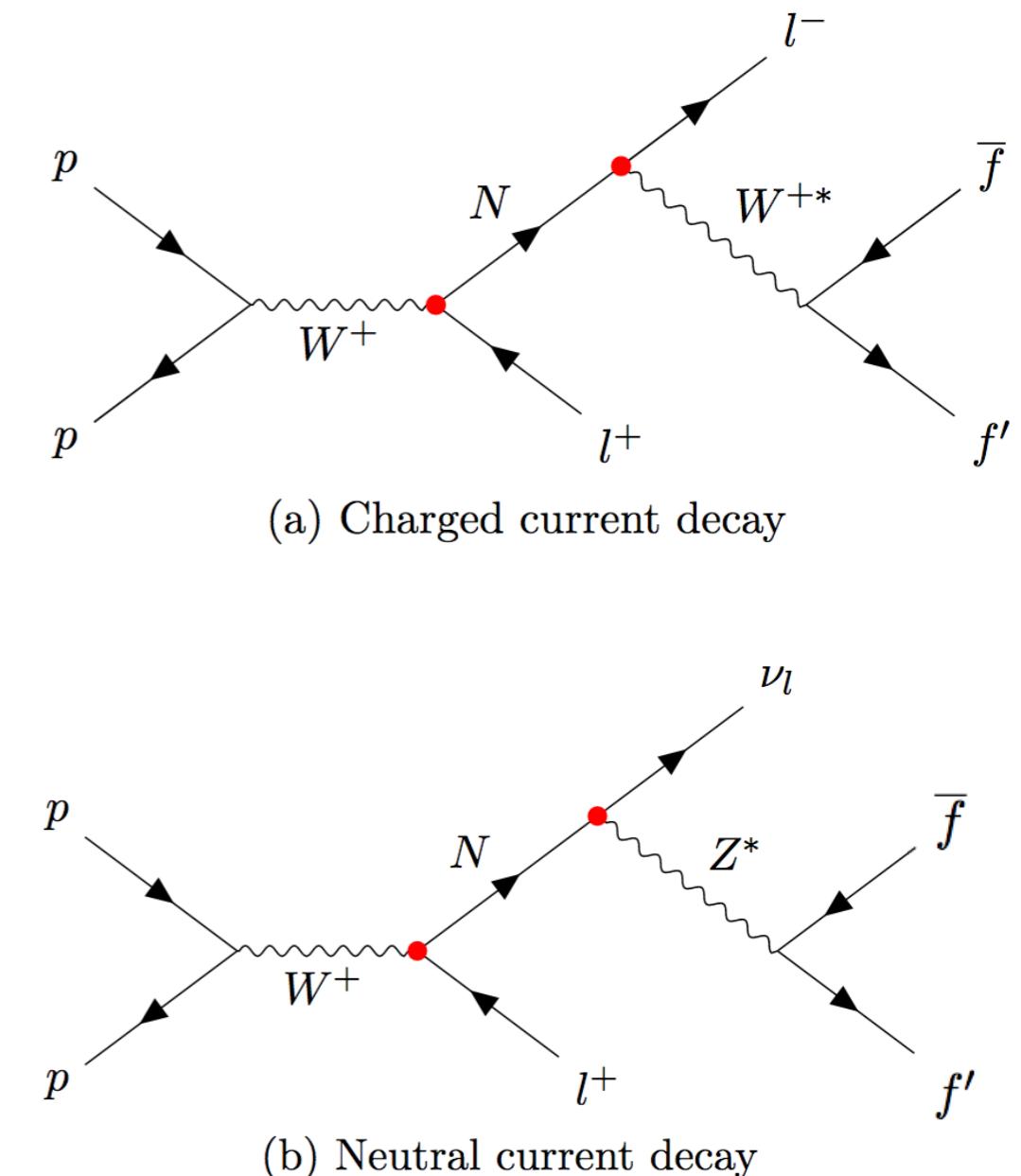
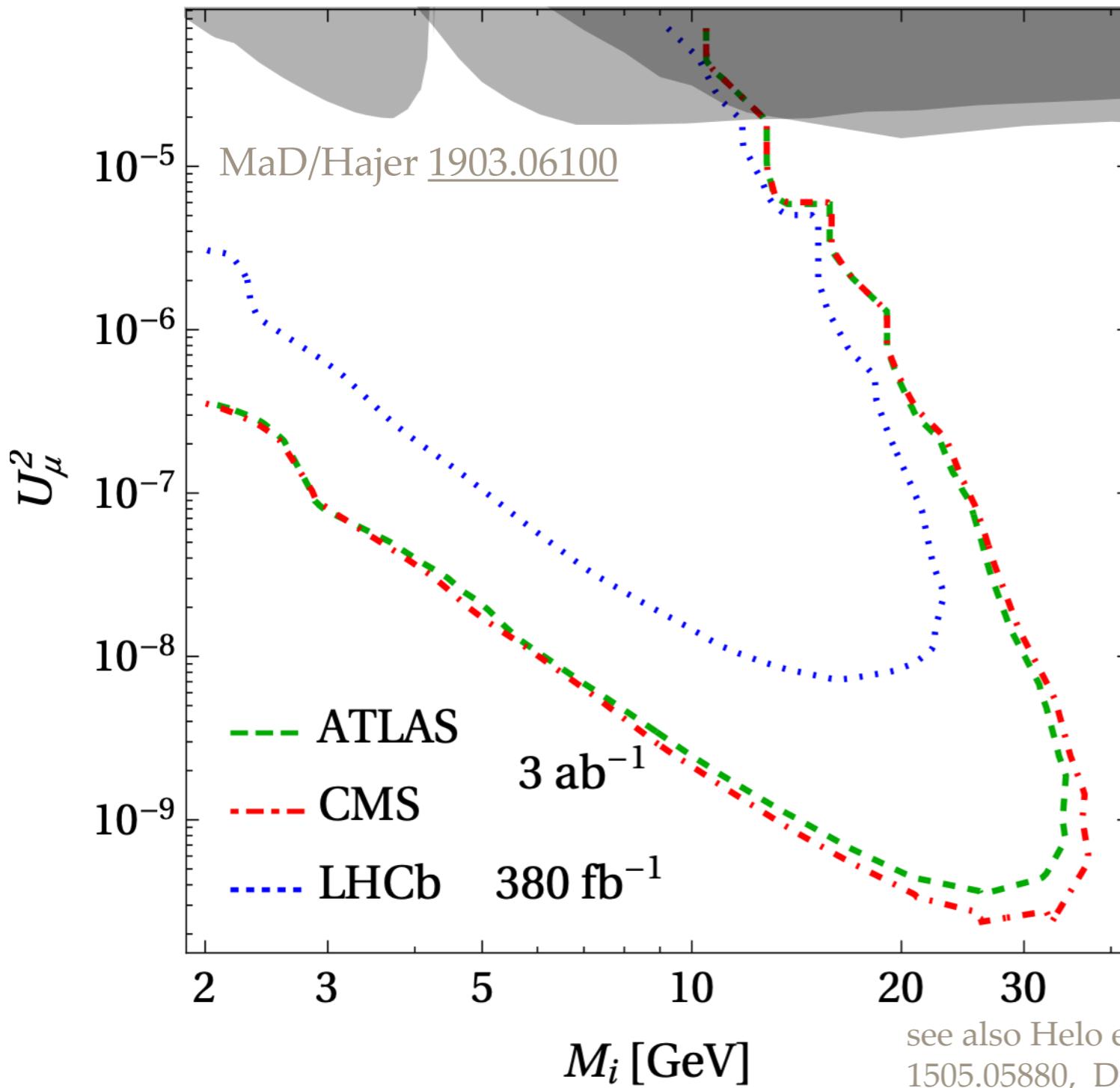
Leptogenesis with 3 HNLs vs 2 HNLs



Leptogenesis with 3 RH Neutrinos



HL-LHC Displaced Vertex Search



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](#)

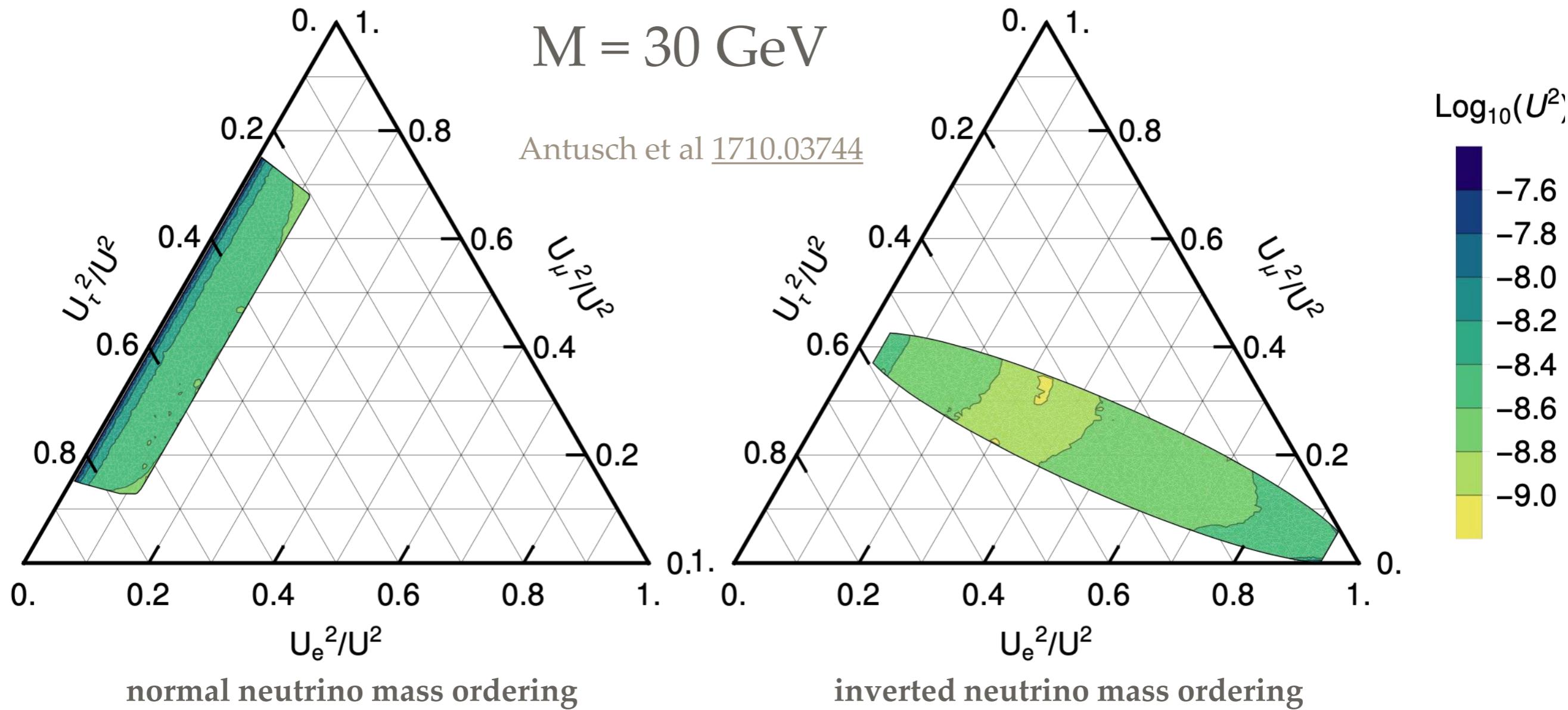
Test seesaw mechanism and leptogenesis

Hernandez / Kekic / Lopez-Pavon / Racker / Savaldo [1606.06719](#),

MaD / Garbrecht / Gueter / Klaric [1609.09069](#)

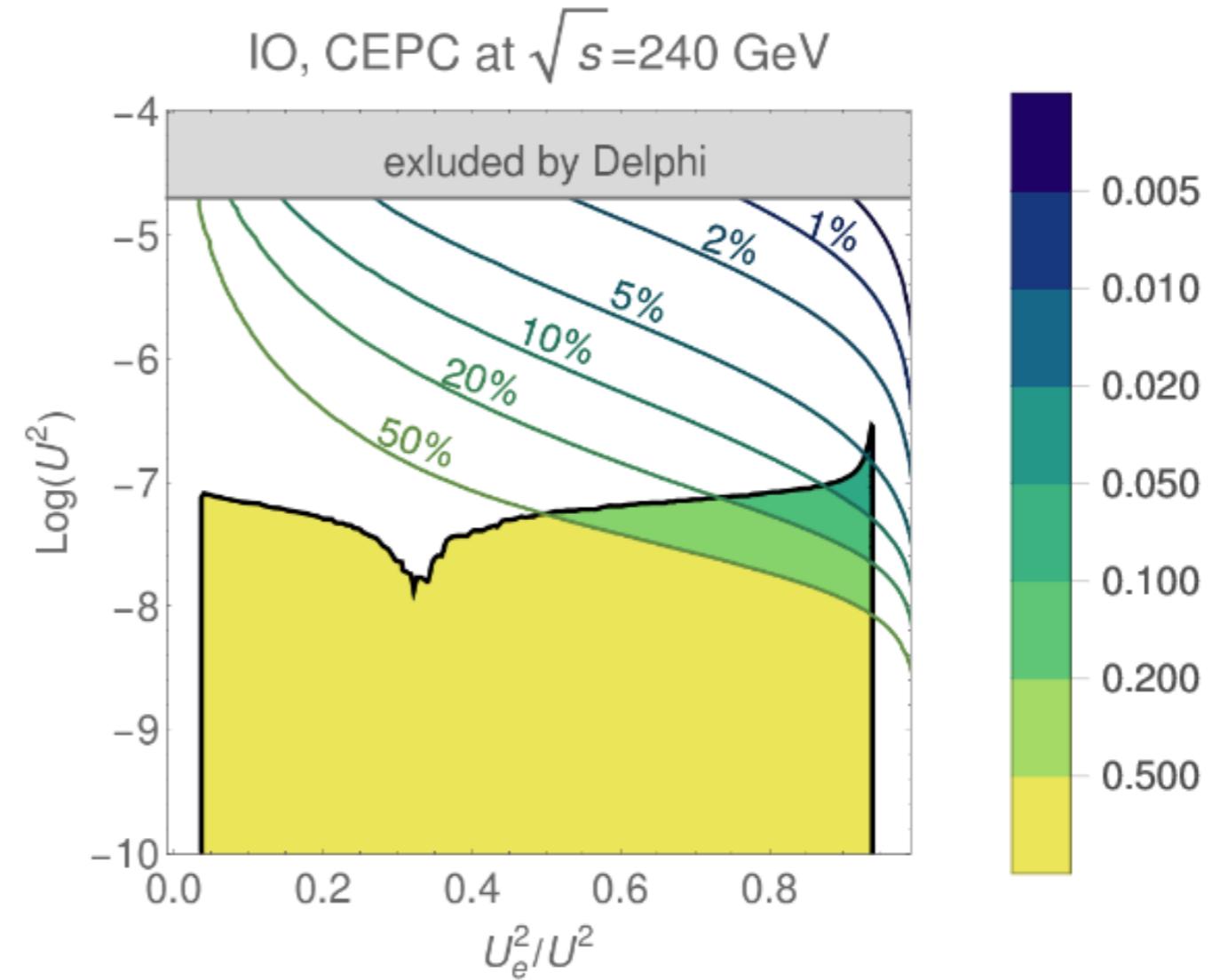
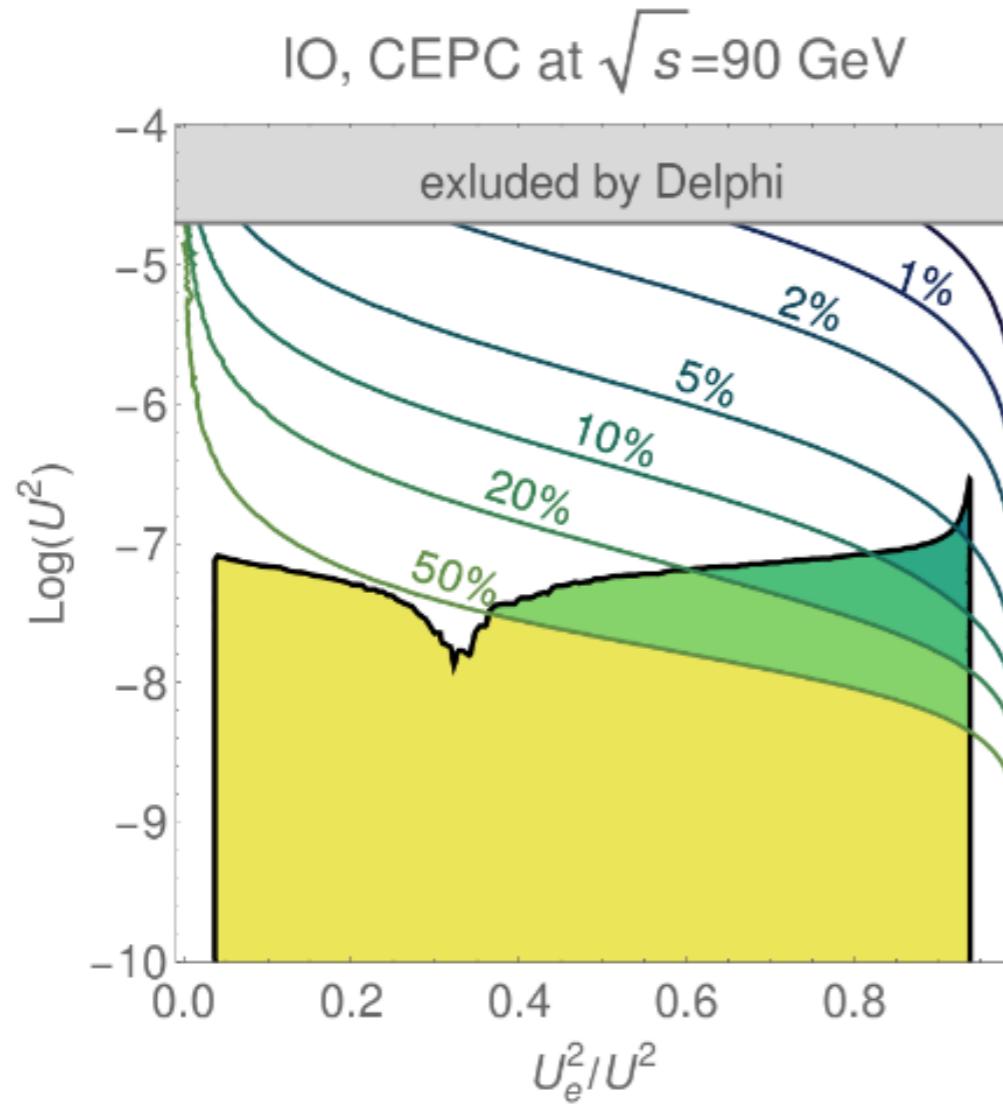
Antusch/Cazzato/MaD/Fischer/Garbrecht/Gueter/Klaric [1710.03744](#)

Constraints from Leptogenesis in Model with 2 Heavy Neutrinos



Large U^2 require strong hierarchies in couplings to SM generations

How well can this be measured?



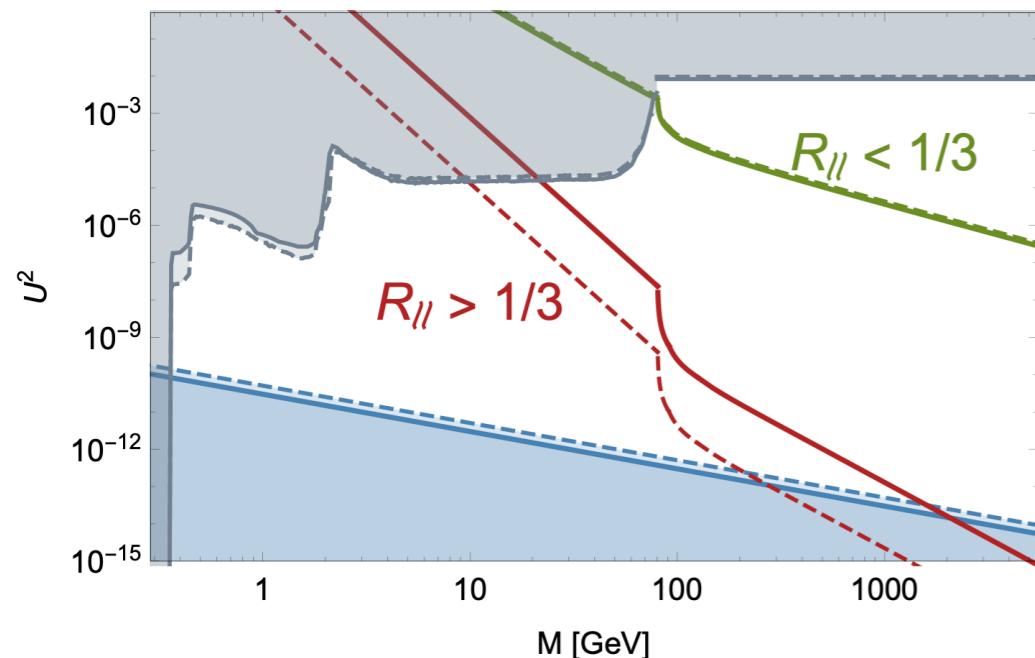
Plots were made for $0.1/\text{ab}$ at Z pole, nowadays expect 16/ab,
⇒ an order of magnitude better accuracy possible!
⇒ **With a bit of luck, CEPC can make percent level measurement**

How to measure ΔM ?

ratio of LNV to LNC decays
is sensitive to ΔM

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

Anamiati et al [1607.05641](#)



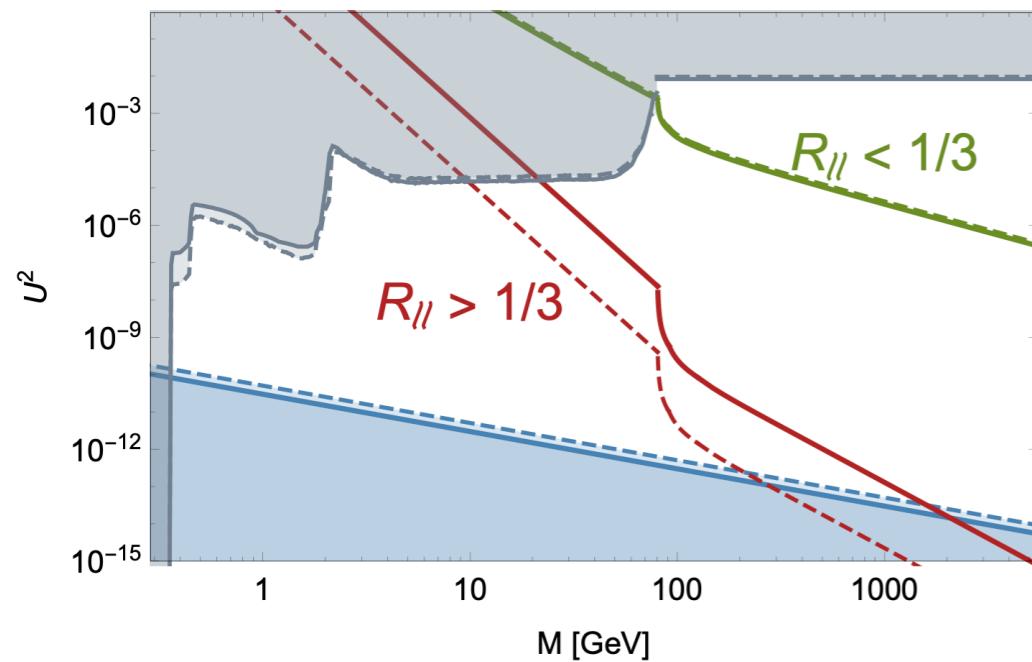
MaD/Klaric/Klose [1907.13034](#)

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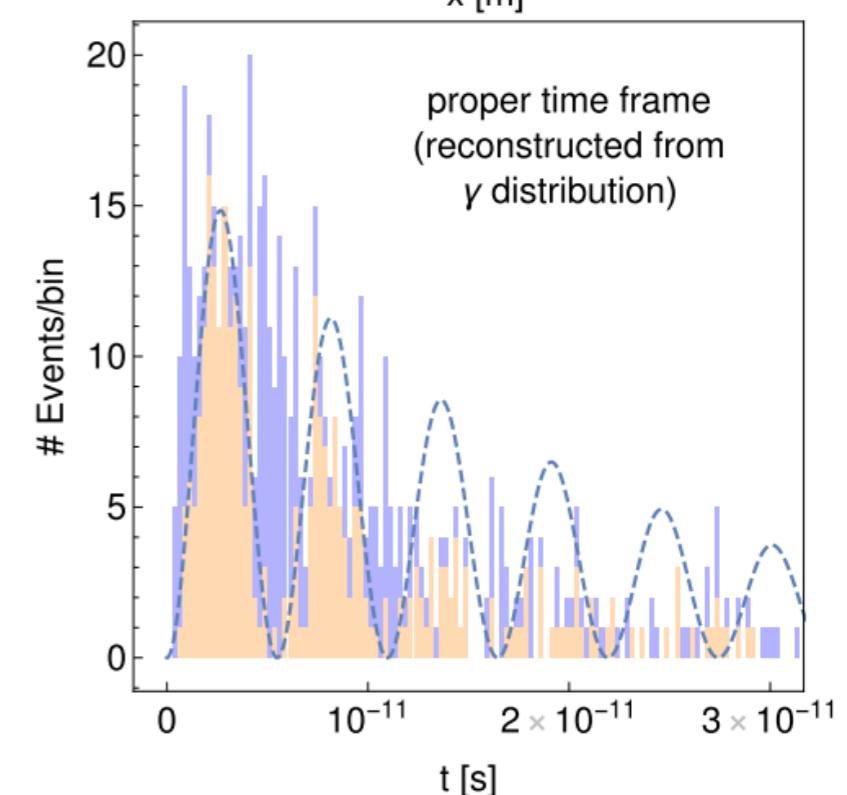
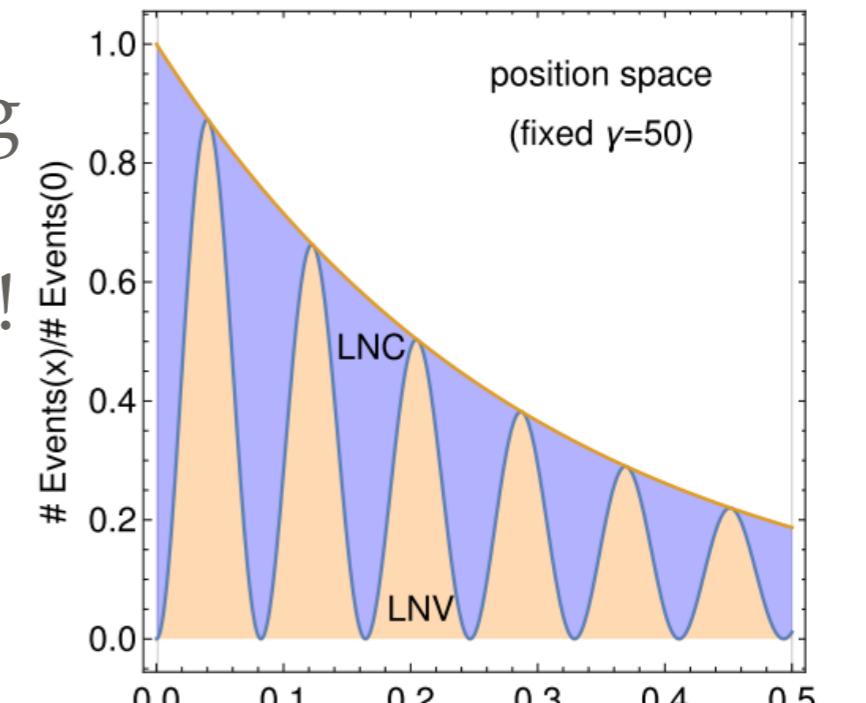
Anamiati et al [1607.05641](#)



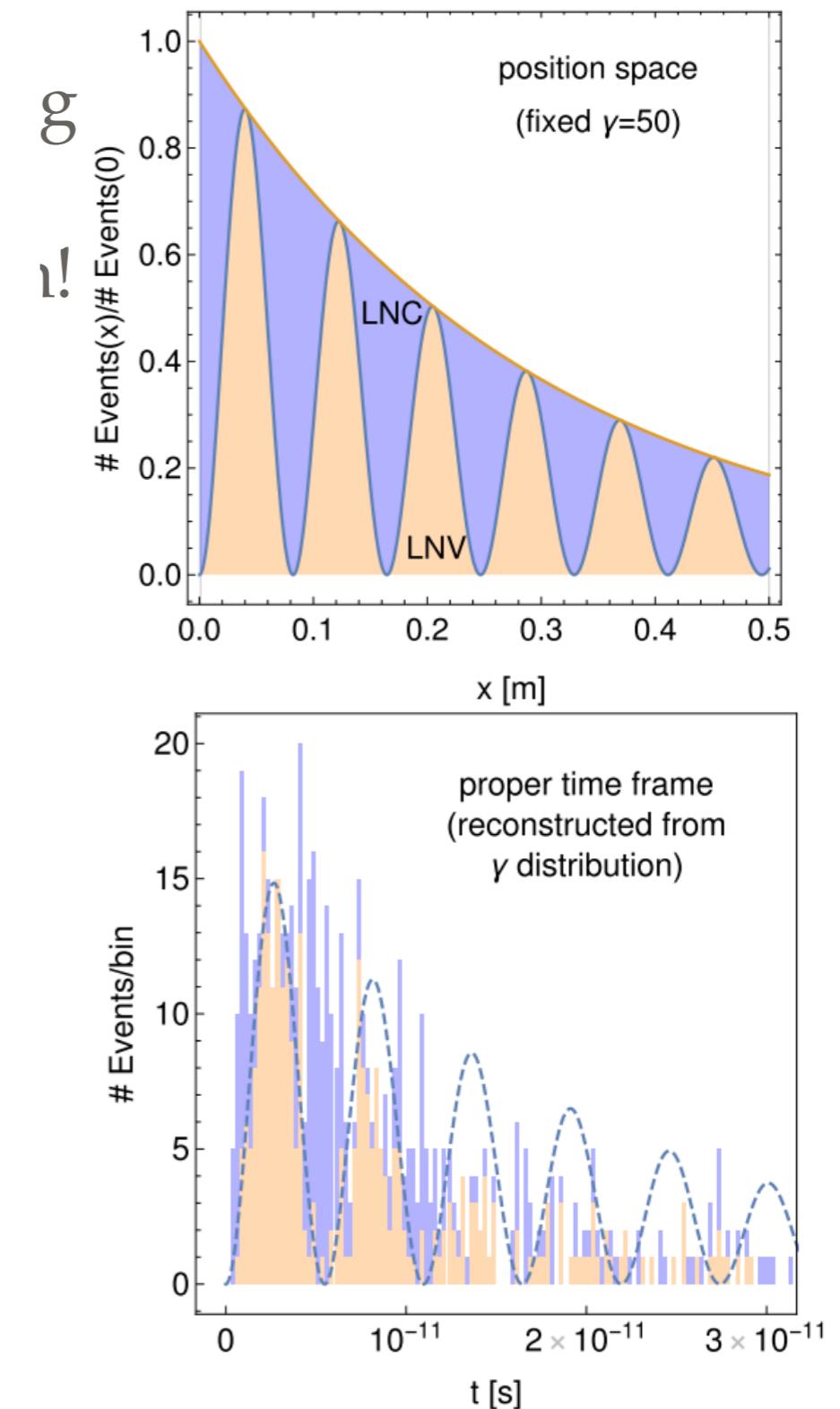
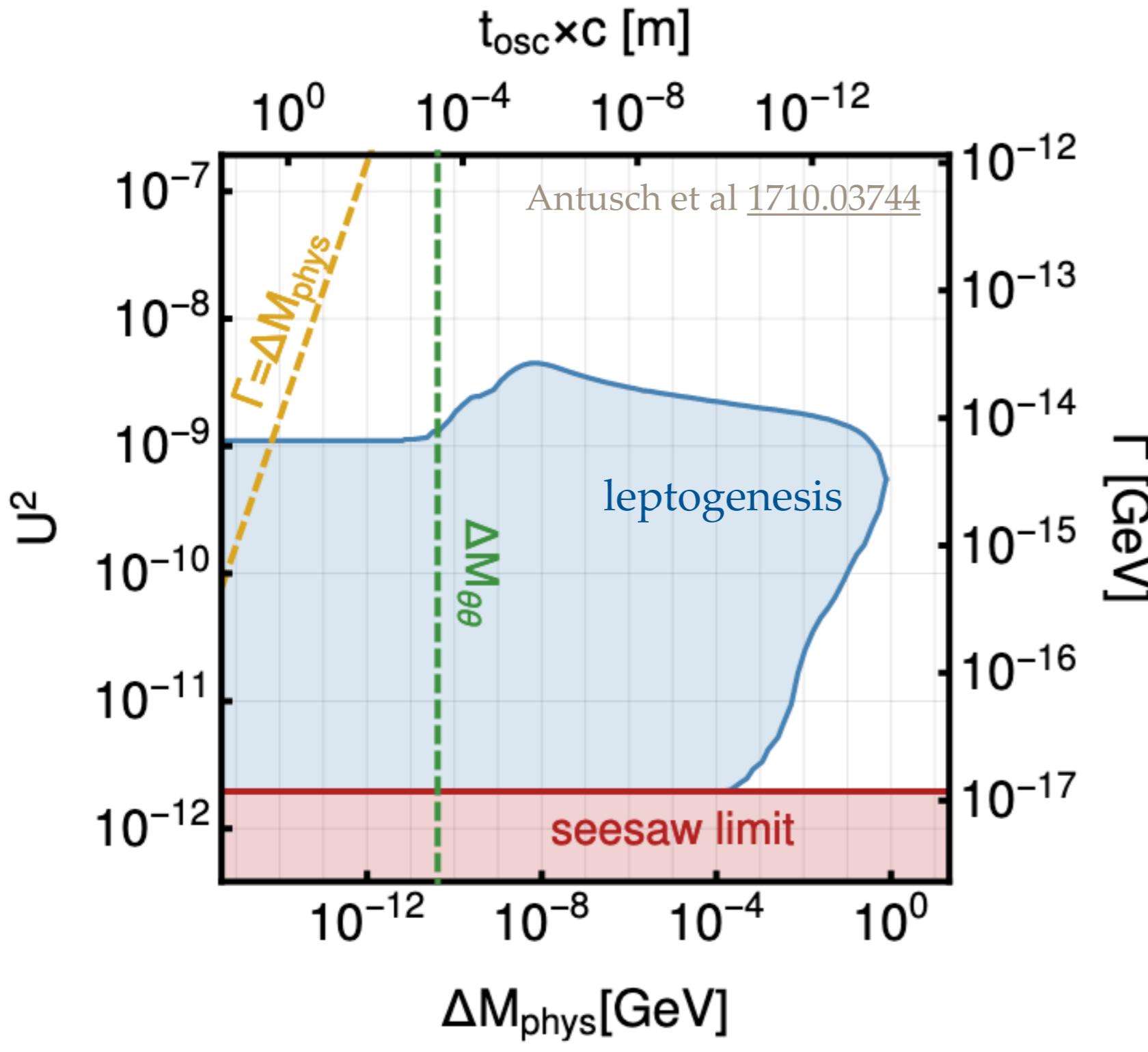
MaD/Klaric/Klose [1907.13034](#)

spatially resolving
this ratio gives
more information!

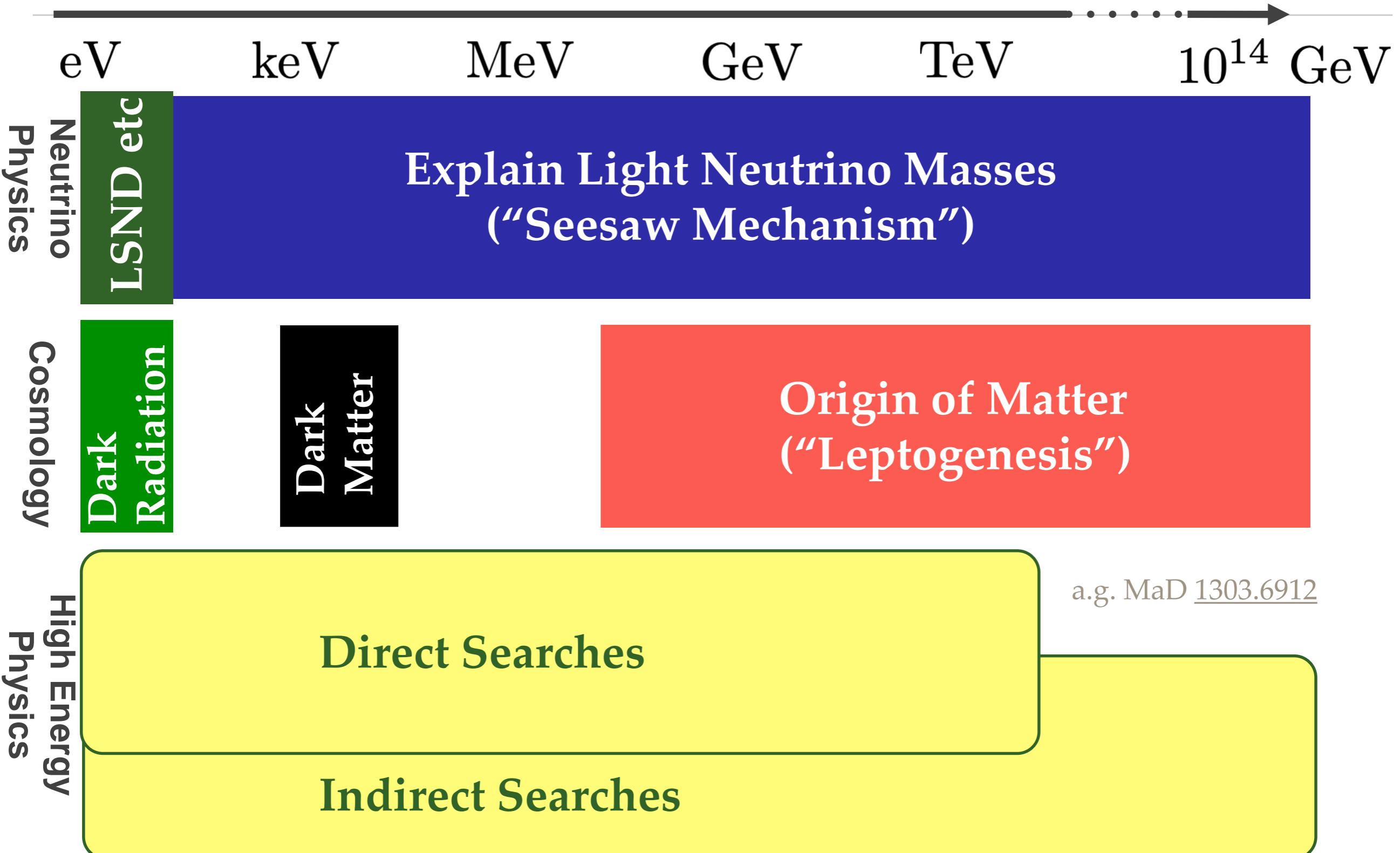
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How to measure ΔM ?



Heavy Neutrino Mass Scale

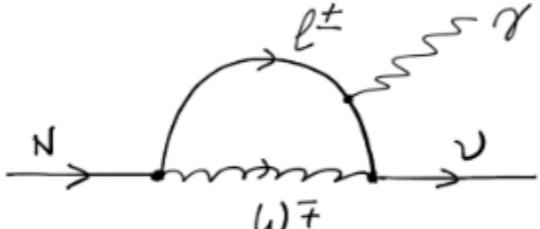
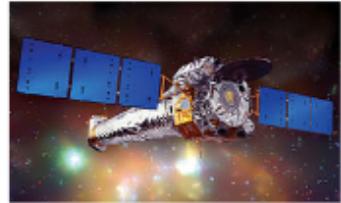


Sterile Neutrino DM

How to find Sterile Neutrino DM?

Indirect searches

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

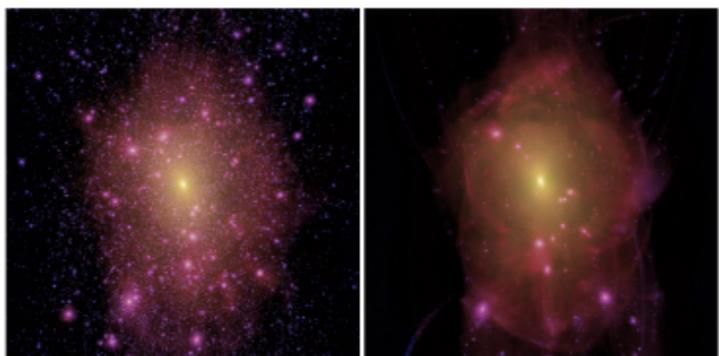


- 3.5 keV excess observed, but disputed
- new missions (XRISM, ATHENA, Lynx...)

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)
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Production mechanisms

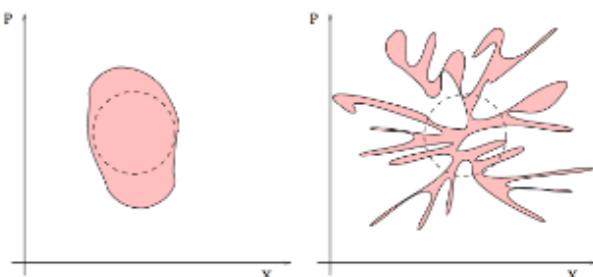
Three known production mechanisms:

- thermal production through mixing-suppressed weak interaction (resonant or non-resonant)
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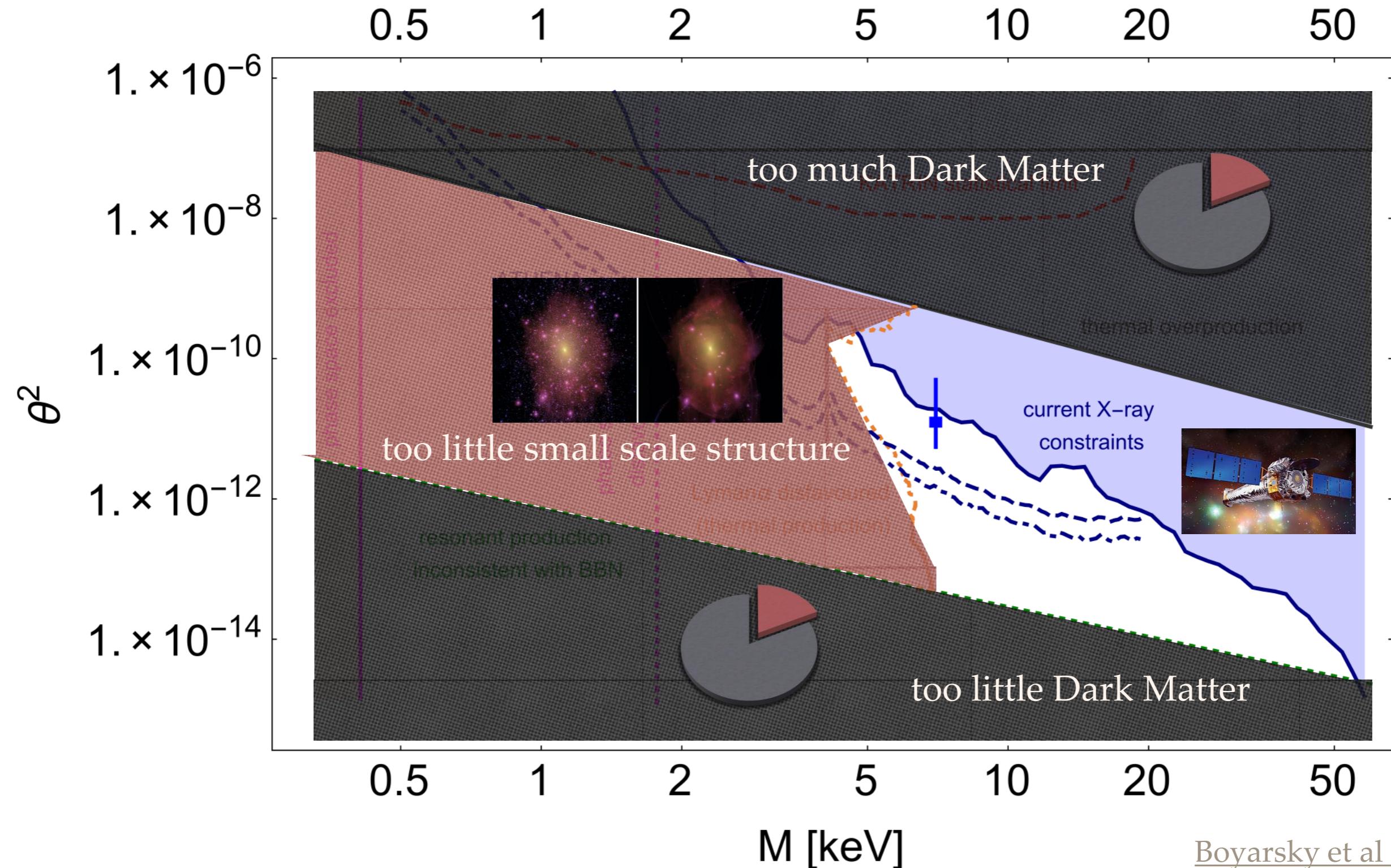
Three Generations of Matter (from lightest spin 0 to heaviest spin 1)			
mass charge	I: u II: c III: t	I: d II: s III: b	I: g II: γ III: Z
name	u: up quark d: down quark	s: strange quark V_c : charm lepton	e: electron V_μ : muon lepton
spin	0	1/2	1/2
Quarks	u, d, s, b	c, t	g, γ , Z
Leptons	ν_u , ν_d , ν_s , ν_b	ν_c , ν_t	ν_e , ν_μ , ν_τ

Phase space

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



Sterile Neutrino Dark Matter



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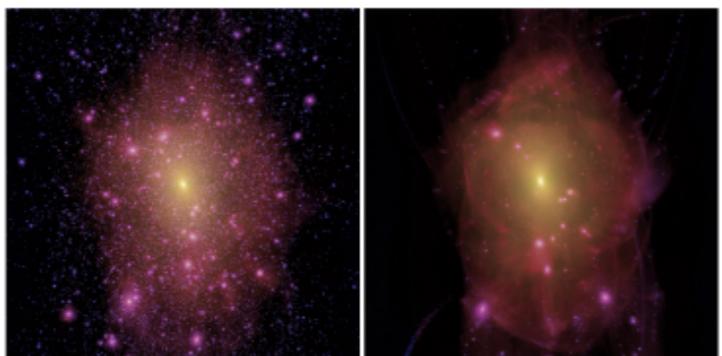


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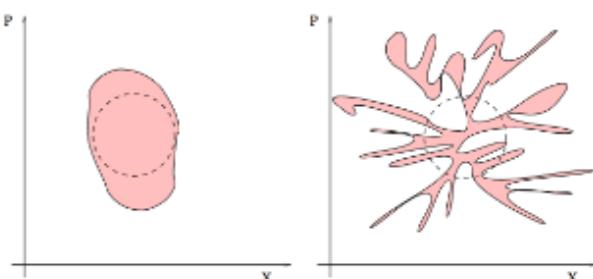
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Three Generations of Matter (from lightest spin 0 to heaviest spin 1)			
mass charge	I: u d e	II: c s v _e	III: t b v _μ
name	u: up quark	c: charm quark	t: top quark
mass	~2.3 MeV	~1.5 GeV	~173 GeV
charge	+2/3	+2/3	+2/3

Quarks	Leptons	Gauge	Others
u: up quark	e: electron	W: weak boson	H: Higgs boson
d: down quark	v _e : electron neutrino	Z: Z boson	
c: charm quark	v _μ : muon neutrino		
s: strange quark	v _τ : tau neutrino		
t: top quark	μ: muon		
b: bottom quark	τ: tau		

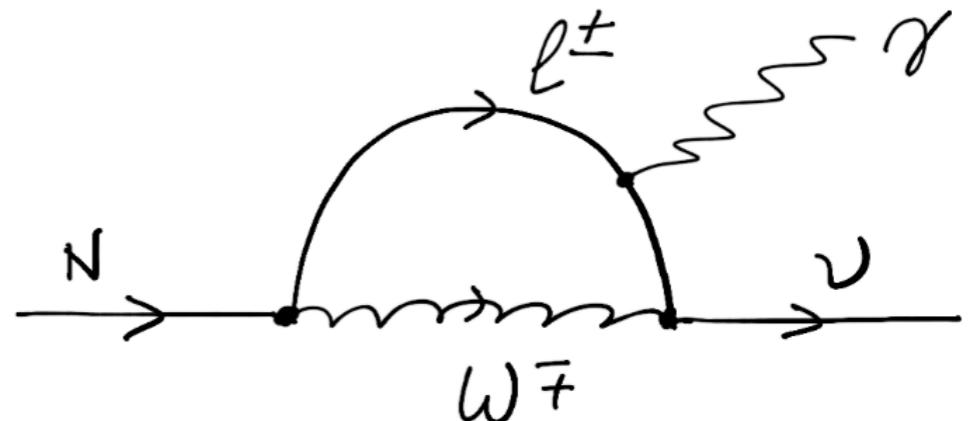
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Indirect DM Searches

loop level decay into photons

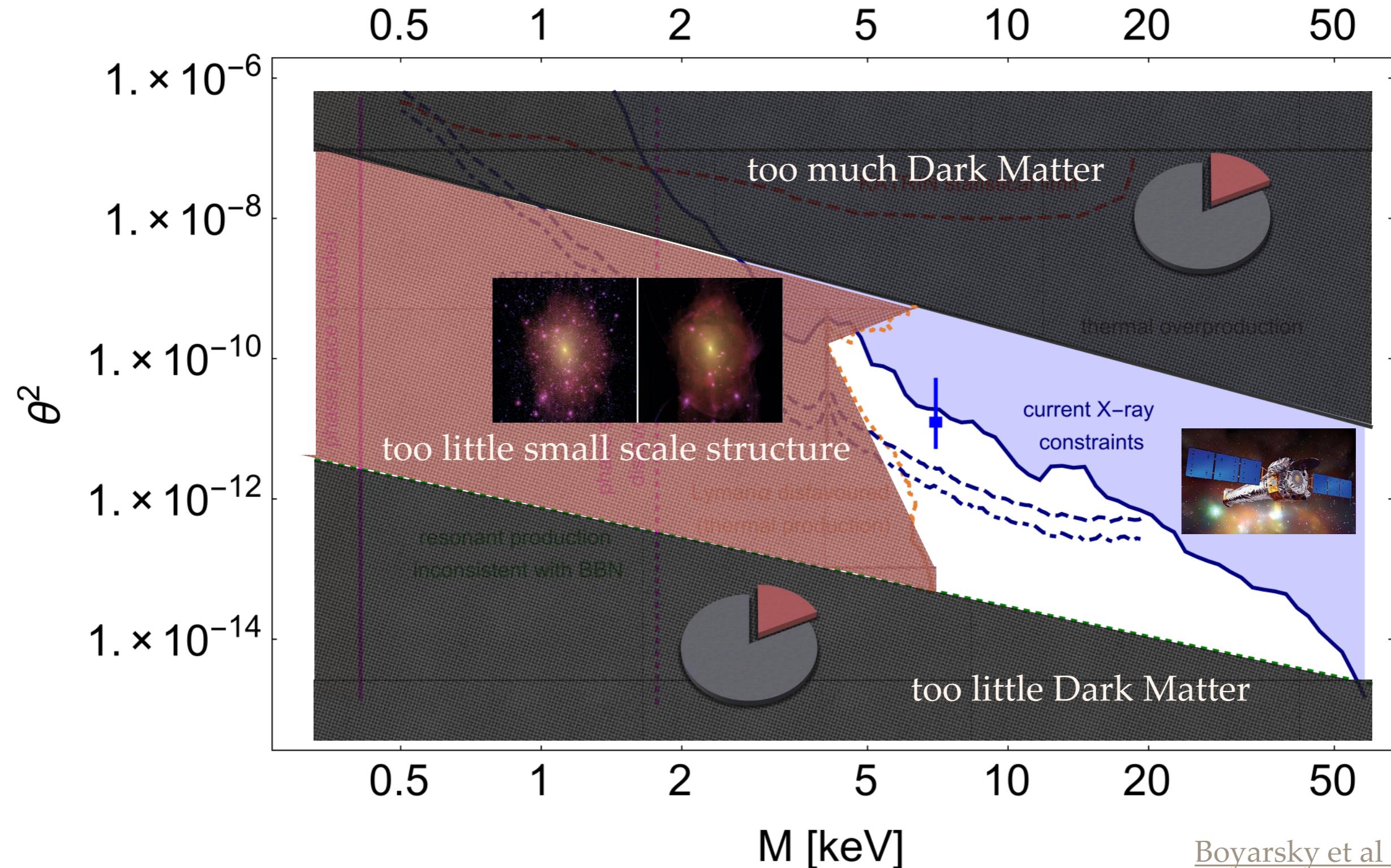


$$\Gamma_{N \rightarrow \gamma \nu} = \frac{9 \alpha G_F^2}{256 \pi^4} \theta^2 M^5 = 5.5 \times 10^{-22} \theta^2 \left[\frac{M}{1 \text{ keV}} \right]^5 \text{ sec}^{-1}.$$

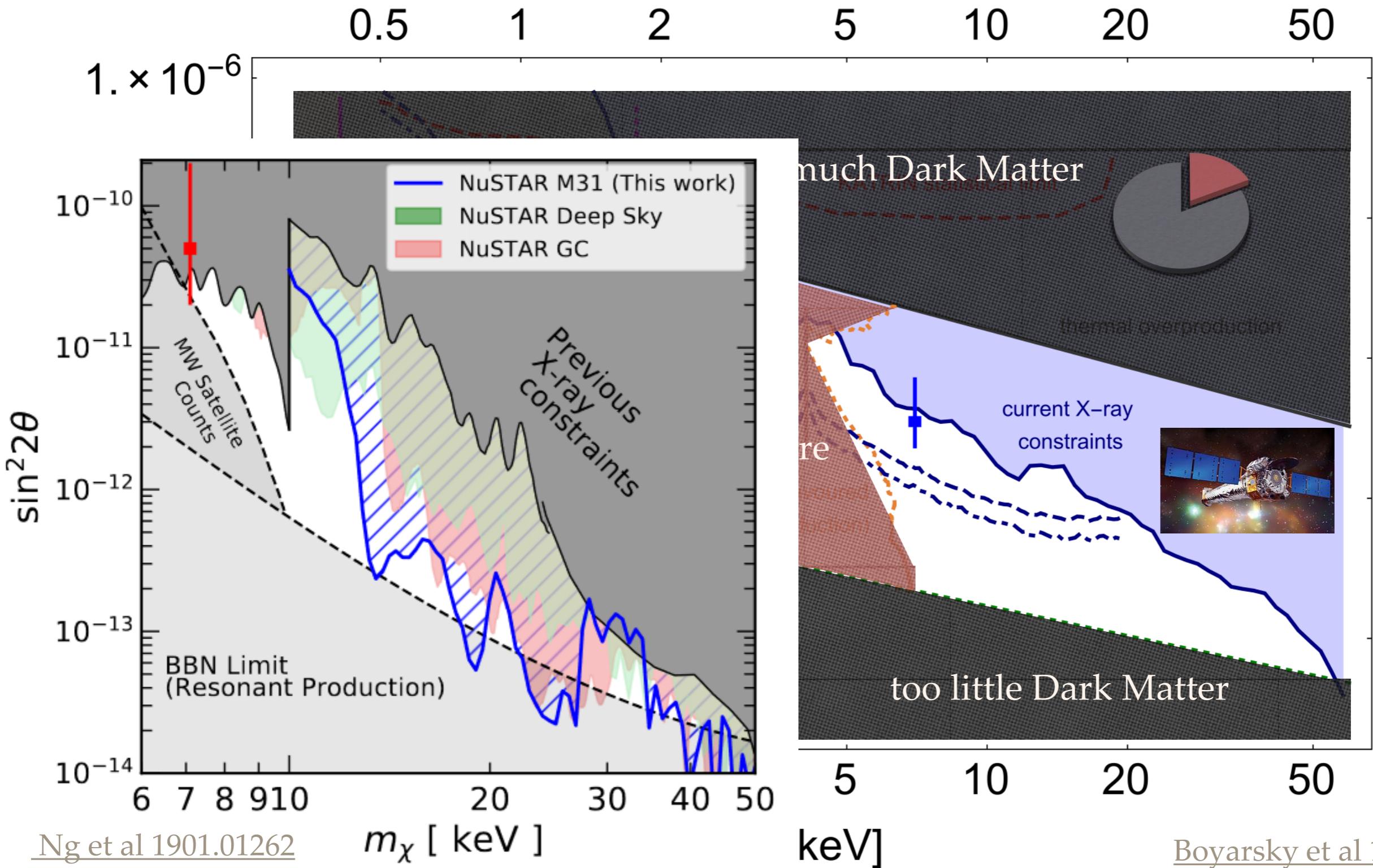
One can search for an emission line!



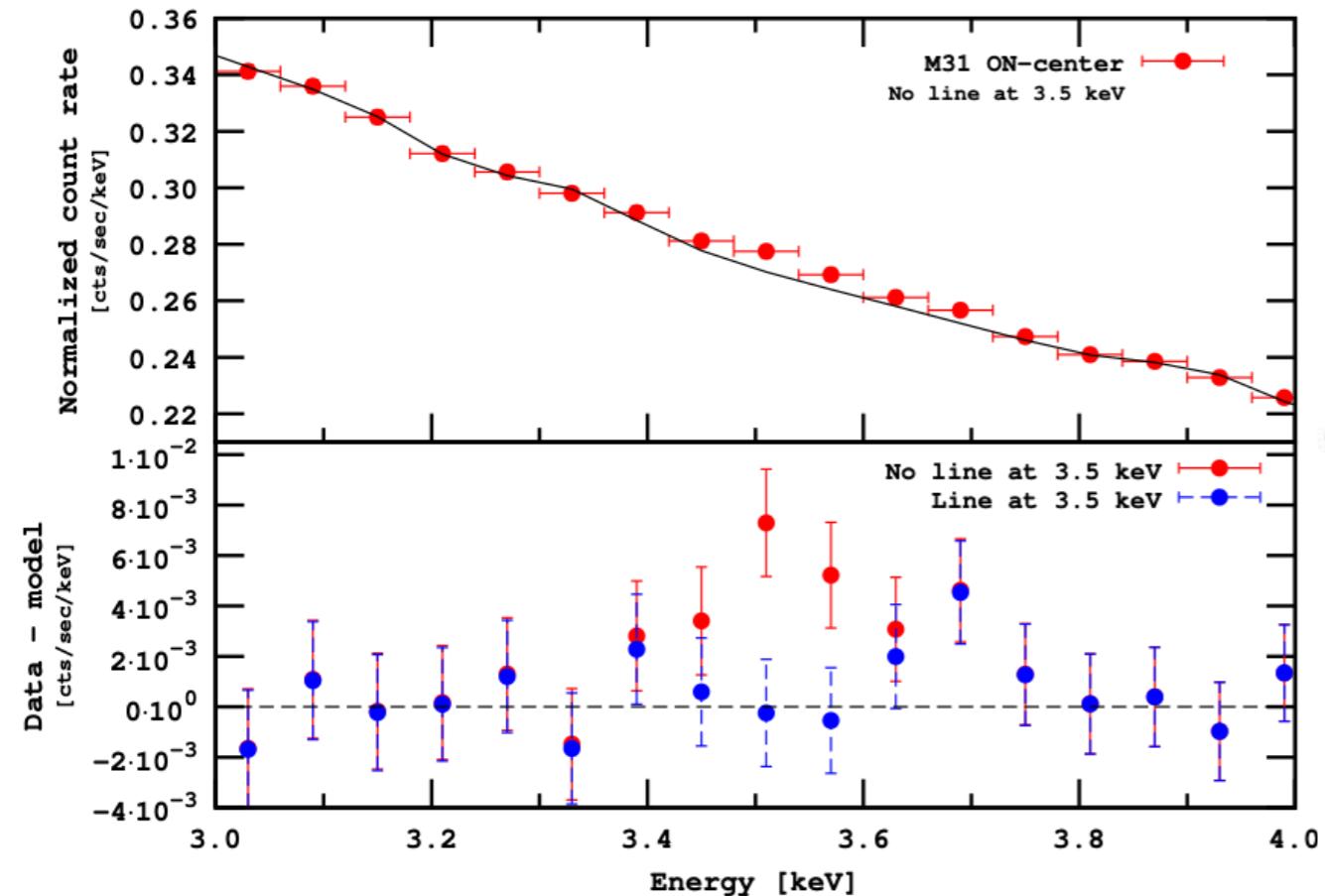
Sterile Neutrino Dark Matter



Sterile Neutrino Dark Matter

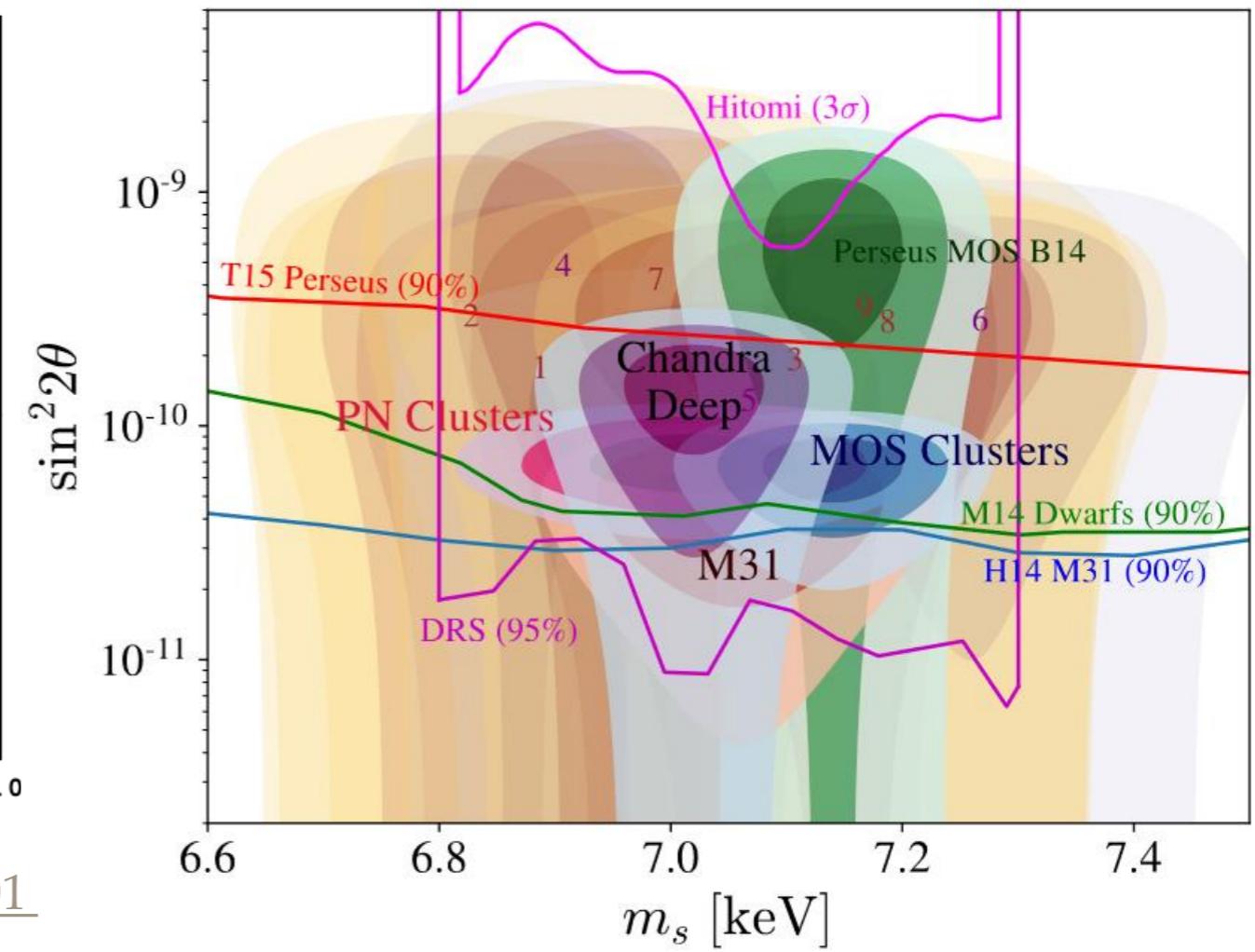


Has the line been seen?



Boyarsky et al [1402.4119](#)

Bulbul et al [1402.2301](#)



Abazajian [2004.06170](#)

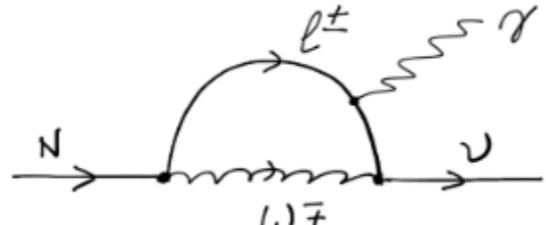
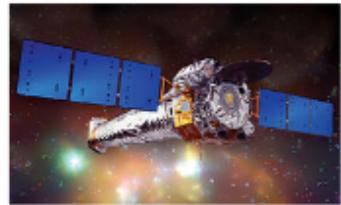
Situation unclear...

need better spectral resolution (XARM and ATHENA will help)

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Indirect searches

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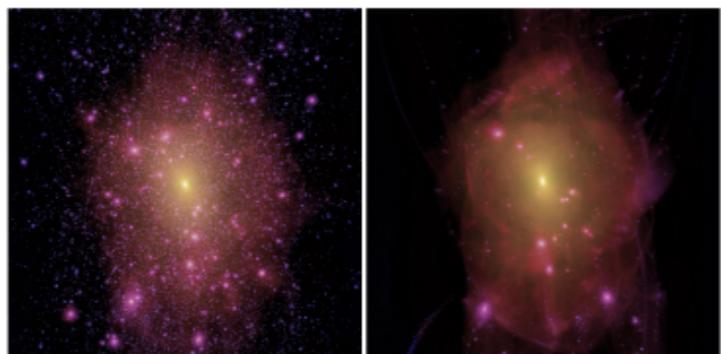


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Production mechanisms

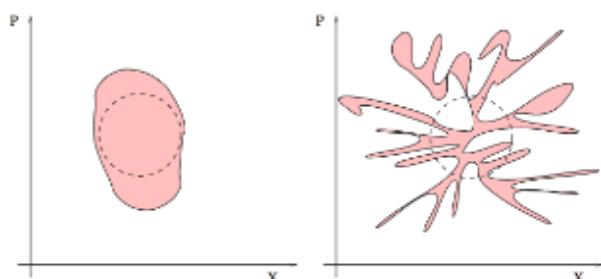
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Fundamental particles of Matter (three-loop spin 0)					
mass	charge	name	mass	charge	name
2.3 MeV	+2/3	u	0.5 GeV	-1/3	c
1.7 GeV	+2/3	d	1.7-2.6 GeV	-1/3	t
0.5 GeV	0	e	0.2 GeV	0	s
0.5 GeV	0	v _e	0.2 GeV	0	v _s
0.5 GeV	0	μ	0.5 GeV	0	b
0.5 GeV	0	τ	0.5 GeV	0	W
0	0	g	0	0	Z
0	0	γ	0	0	H

Phase space

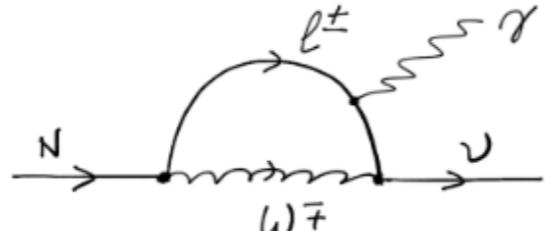
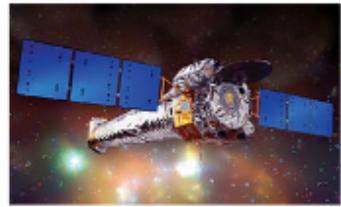
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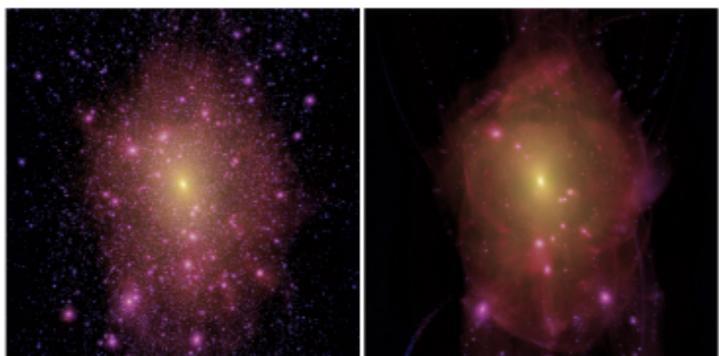


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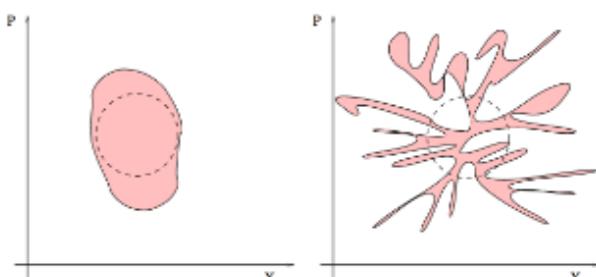
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Fundamental particles of matter (three-loop spin 0)			
I	II	III	IV
mass: 0.5 keV charge: 0 name: u type: up quark	mass: 0.5 keV charge: 0 name: c type: charm quark	mass: 17-20 GeV charge: 0 name: t type: top quark	mass: 0.5 keV charge: 0 name: g type: gluon
mass: 0.5 keV charge: -1 name: d type: down quark	mass: 0.5 keV charge: -1 name: s type: strange quark	mass: 17-20 GeV charge: -1 name: b type: bottom quark	mass: 0.5 keV charge: 0 name: γ type: photon
mass: 0.5 keV charge: 0 name: e type: electron	mass: 0.5 keV charge: 0 name: ν_e type: electron neutrino	mass: 0.5 keV charge: 0 name: μ type: muon	mass: 0.5 keV charge: 0 name: ν_μ type: muon neutrino
mass: 0.5 keV charge: 0 name: τ type: tauon	mass: 0.5 keV charge: 0 name: ν_τ type: tauon neutrino	mass: 0.5 keV charge: 0 name: Z^0 type: Z boson	mass: 0.5 keV charge: 0 name: H type: Higgs boson

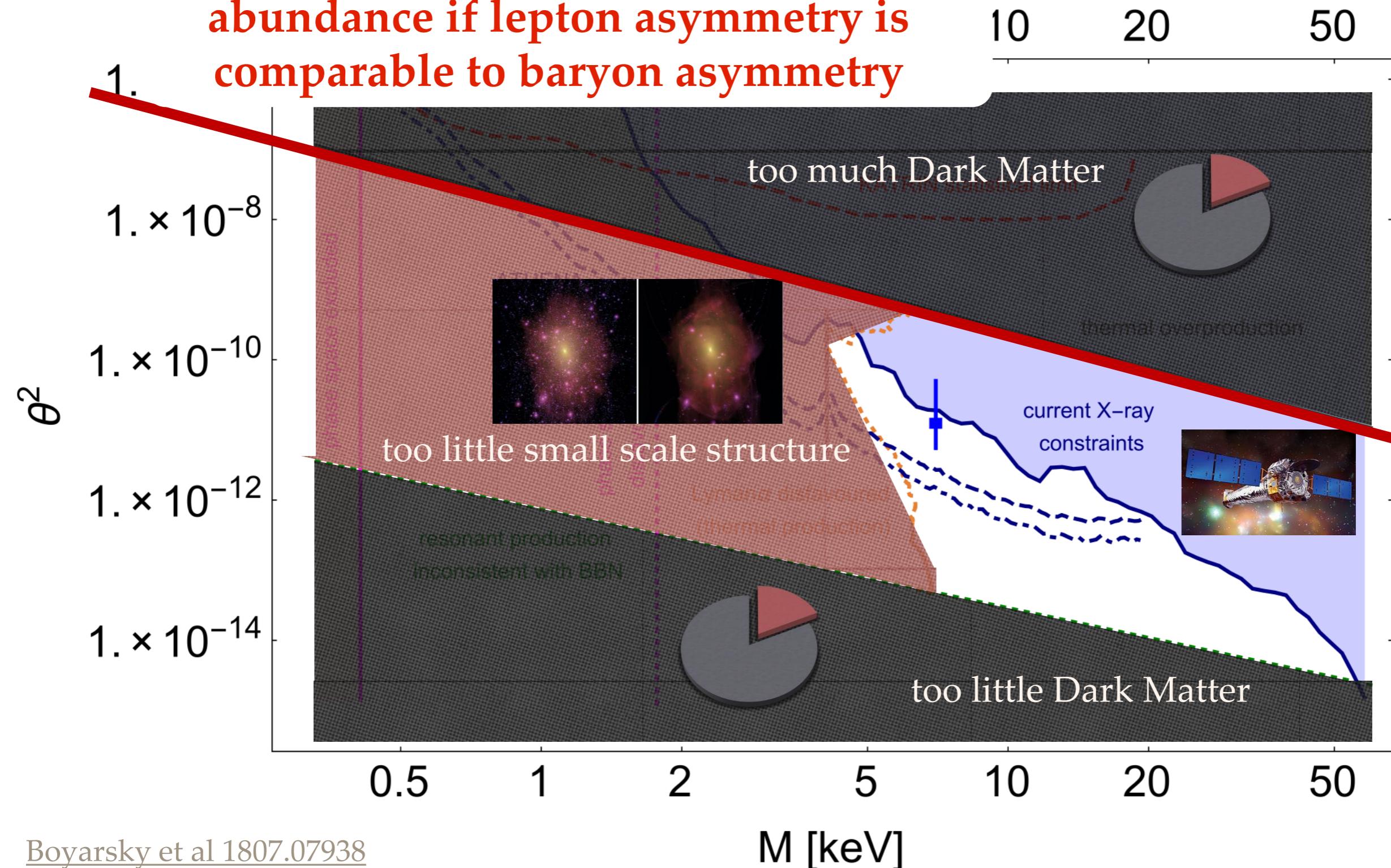
Phase space

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



Sterile Neutrino Dark Matter

abundance if lepton asymmetry is comparable to baryon asymmetry



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 determined by M and θ alone, phase space distribution roughly thermal
- **In presence of large lepton asymmetry l_ν :** MSW-like resonant enhancement of DM abundance, cooler spectrum

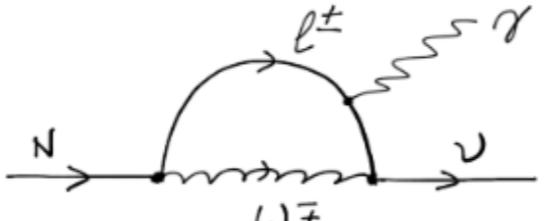
Dodelson/Widrow [9303287](#)

Shi/Fuller [9810076](#)

How to find Sterile Neutrino DM?

Indirect searches

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

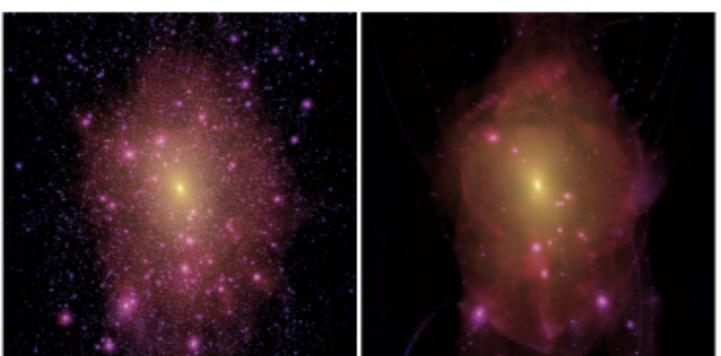


- 3.5 keV excess observed, but disputed
- new missions (XRISM, ATHENA, Lynx...)

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

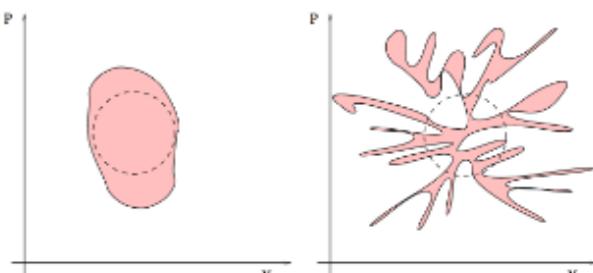
Three known production mechanisms:

- 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)

Three Generations of Matter (from lightest spin 0)			
I	II	III	
mass: 0.05	0.05	0.05	0.05
charge: +	0.05	0.05	0.05
name: u	c	t	g
quarks	down	up	gluon
mass: 0.15	0.15	0.15	0.15
charge: -	-0.15	-0.15	-0.15
name: d	s	b	gamma
quarks	up	down	photon
mass: 0.15	0.15	0.15	0.15
charge: 0	0.15	0.15	Z boson
name: e	v _e	v _e	Higgs
leptons	electron	neutrino	boson
mass: 0.15	0.15	0.15	0.15
charge: 0	0.15	0.15	W boson
name: mu	v _{mu}	v _{mu}	
leptons	muon	neutrino	
mass: 0.15	0.15	0.15	0.15
charge: 0	0.15	0.15	0.15
name: tau	v _{tau}	v _{tau}	
leptons	tau	neutrino	

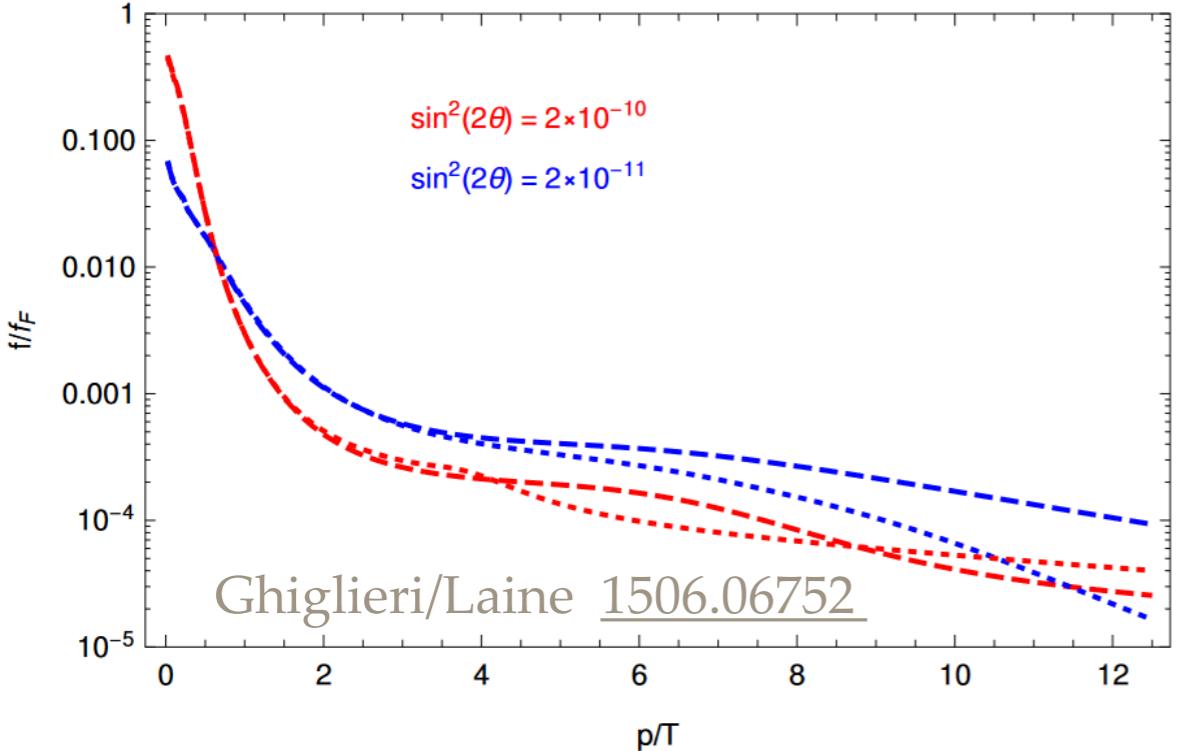
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Structure Formation

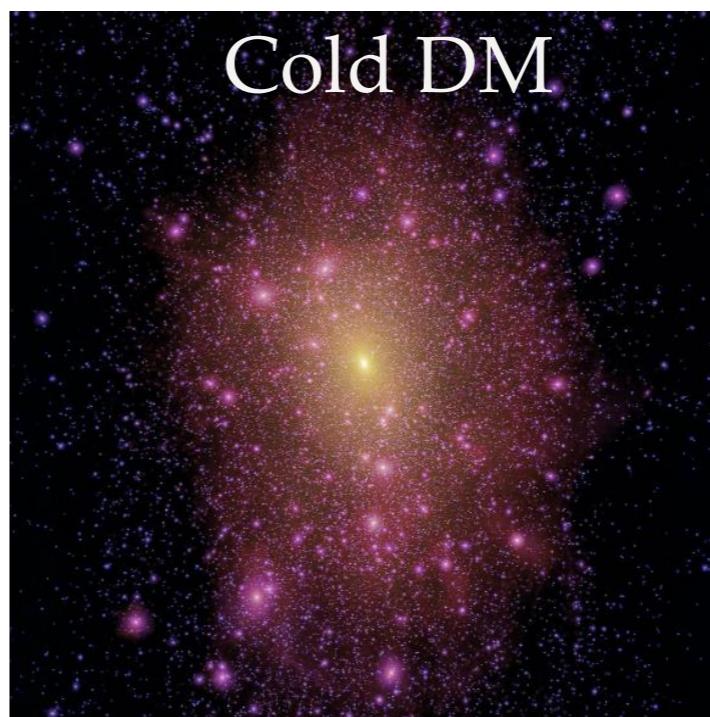
DM momentum distribution



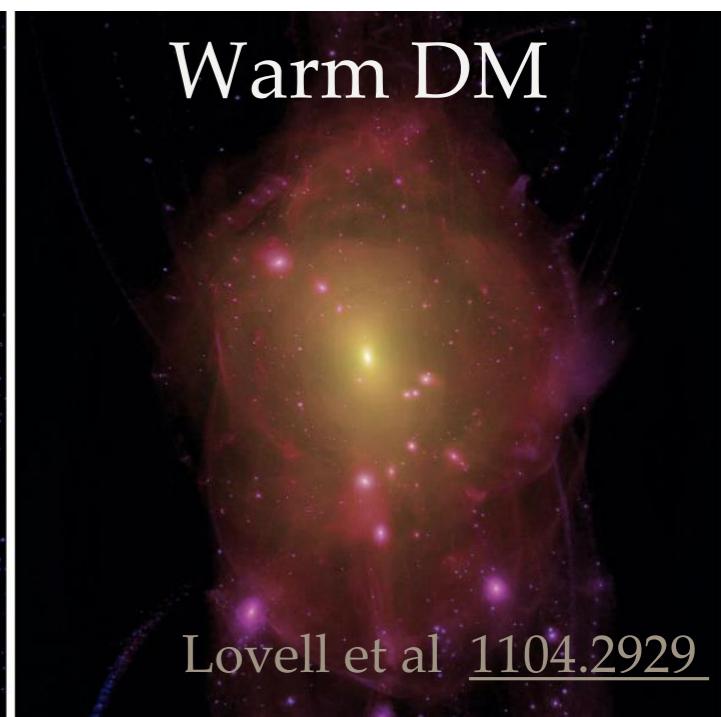
DM free streaming length

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

- 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 ...

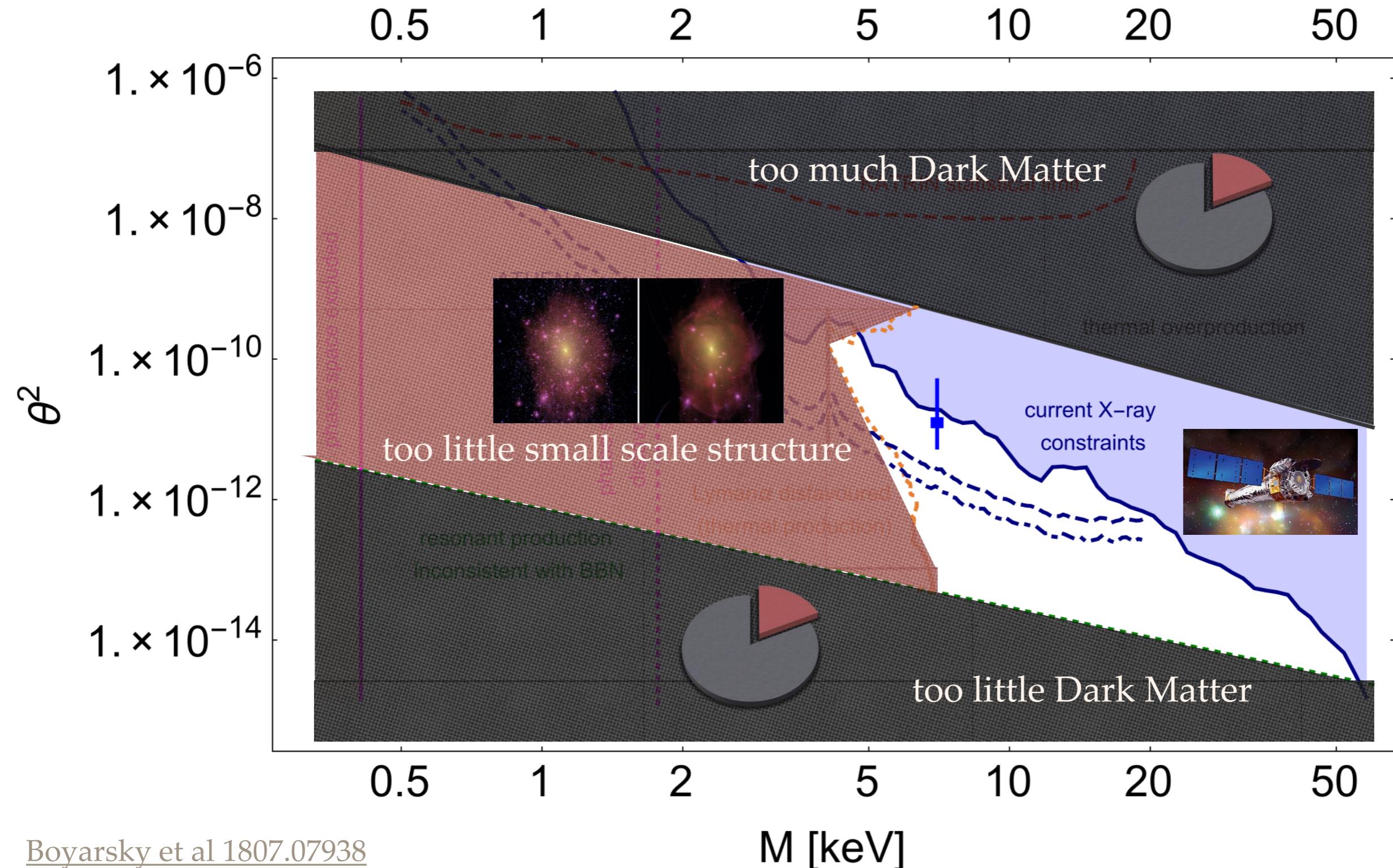


Cold DM



Warm DM
Lovell et al [1104.2929](#)

Sterile Neutrino Dark Matter



Large Lepton Asymmetries

- Lepton asymmetries needed for resonant DM production at $T \sim 200$ 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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- 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?

One possibility: the Neutrino Minimal Standard Model (vMSM)

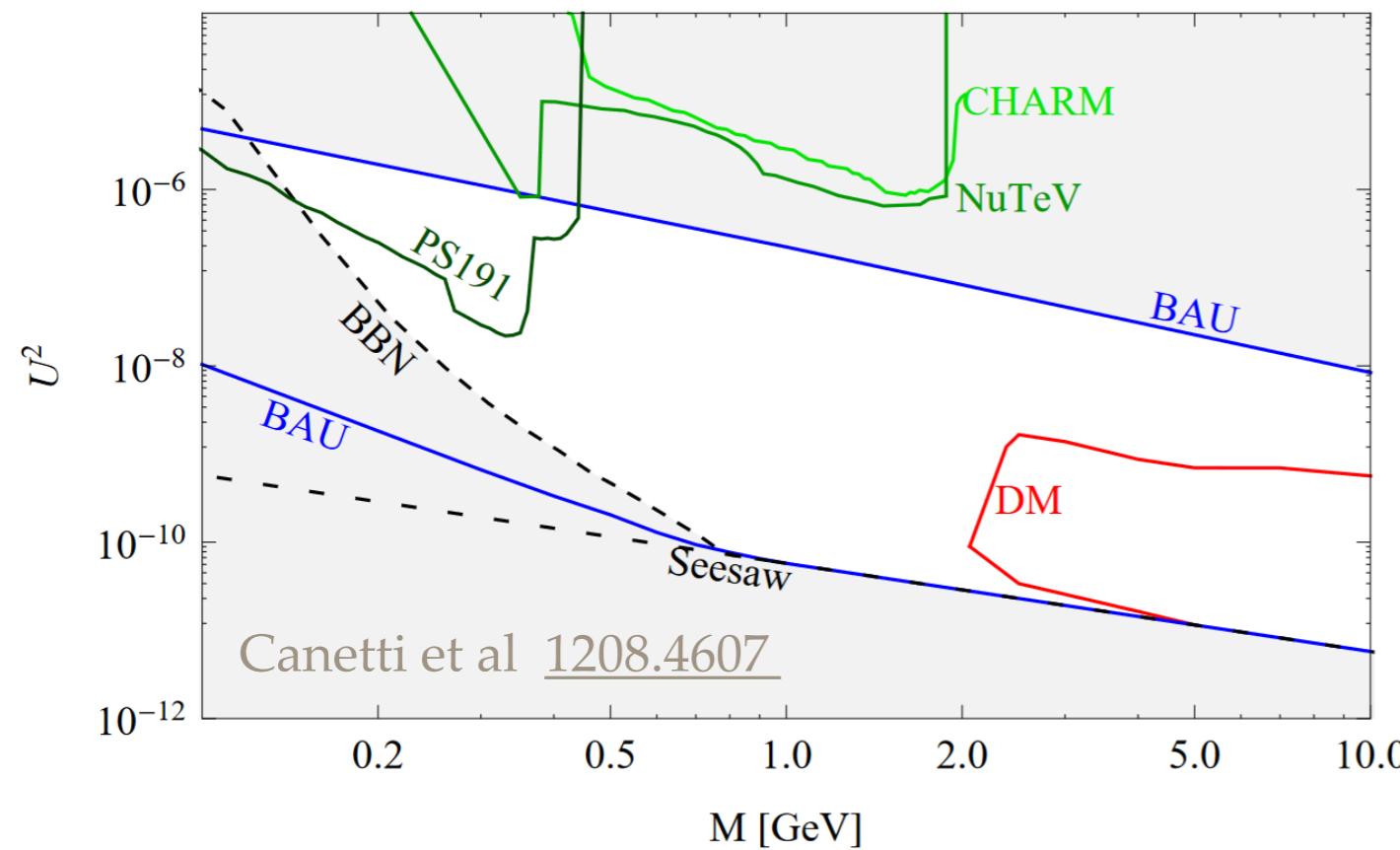
- one heavy neutrino is DM (keV mass)
- the two others (GeV masses) generate baryon asymmetry during freeze-in at $T > 130$...
...and generate additional lepton asymmetries during freeze-out and decay at $T < 130$ GeV
- late time lepton asymmetry causes resonant DM production

Three Generations of Matter (Fermions) spin $\frac{1}{2}$			Asaka/Shaposhnikov 0505013	
mass →	I	II	III	
charge →	$\frac{2}{3}$ u up	$\frac{2}{3}$ c charm	$\frac{2}{3}$ t top	
name →	Left d down	Left s strange	Left b bottom	Right g gluon
Quarks	Right	Right	Right	
	4.8 MeV	104 MeV	4.2 GeV	
	- $\frac{1}{3}$	- $\frac{1}{3}$	- $\frac{1}{3}$	
Leptons	Left	Left	Left	Right
	0 eV ${}^0\nu_e$ electron neutrino	0 eV ${}^0\nu_\mu$ muon neutrino	0 eV ${}^0\nu_\tau$ tau neutrino	
	Right	Right	Right	
Bosons (Forces) spin 1				
	0.511 MeV -1 e electron	105.7 MeV -1μ muon	1.777 GeV -1τ tau	125 GeV 0^0Z weak force
	Left	Left	Left	Right
				80.4 GeV $+1^0W$ weak force
				spin 0 125 GeV 0^0H Higgs boson

Laine/Shaposhnikov 0804.4543

Can vMSM produce enough DM?

- Only parameter scan to date finds viable region!

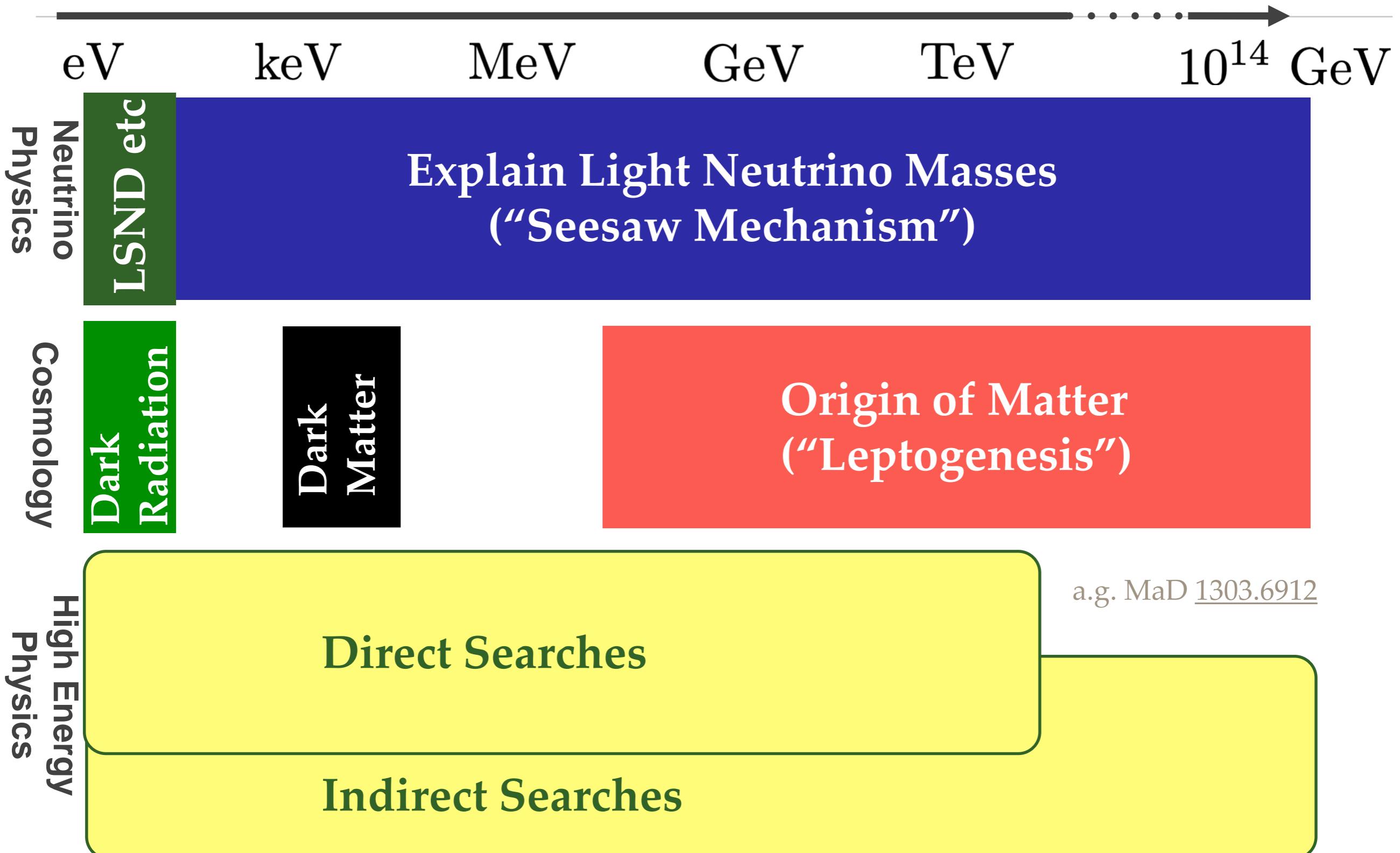


DM production may be probed indirectly at colliders by discovering GeV scale heavy neutrinos that produced the large lepton asymmetry (which resonantly enhanced DM production...)

Cold DM

- 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)

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

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

Collider searches for heavy neutrinos

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

CMB and LSS :
absolute neutrino mass

astrophysics:
supernovae etc.

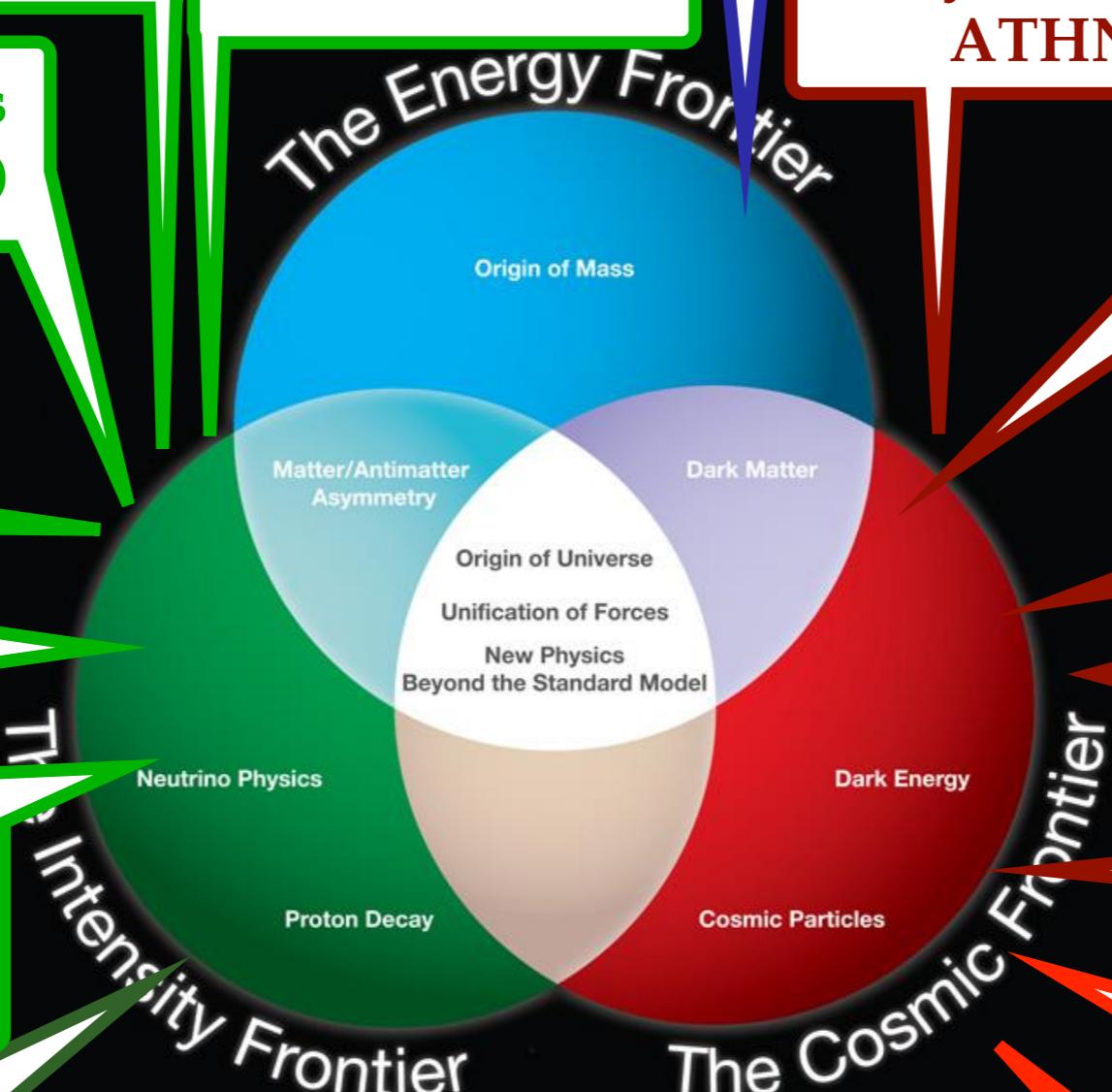
Structure formation:
simulation, observation

IGM temperature:
WDM vs CDM

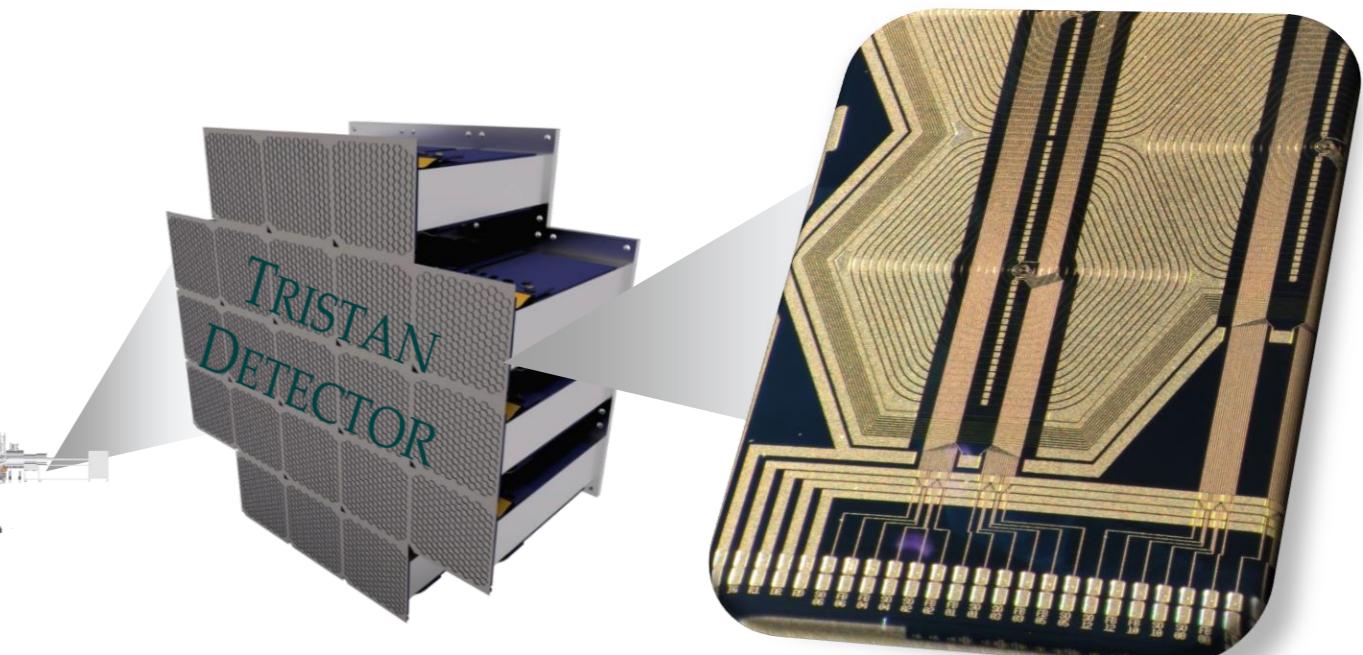
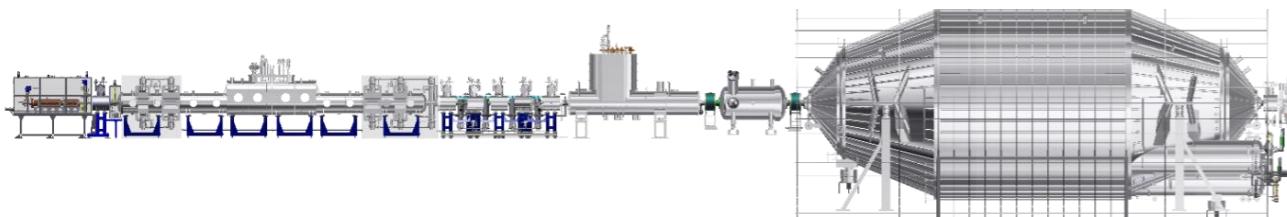
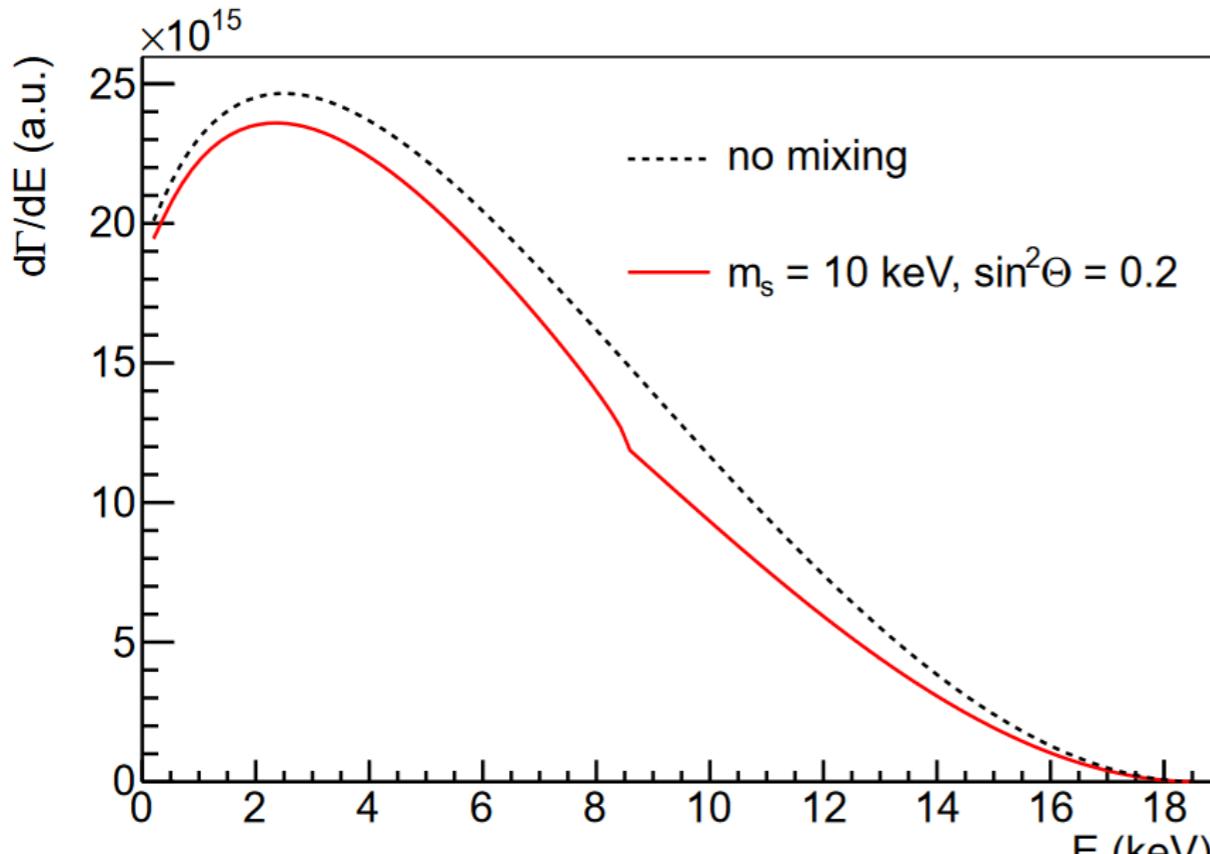
Theory: leptogenesis
parameter region

Theory: Sterile neutrino
DM production

RF, NF, EF, CF, TF



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