Marco Drewes, Université catholique de Louvain

Sterile neutrinos as Dark Matter candidates

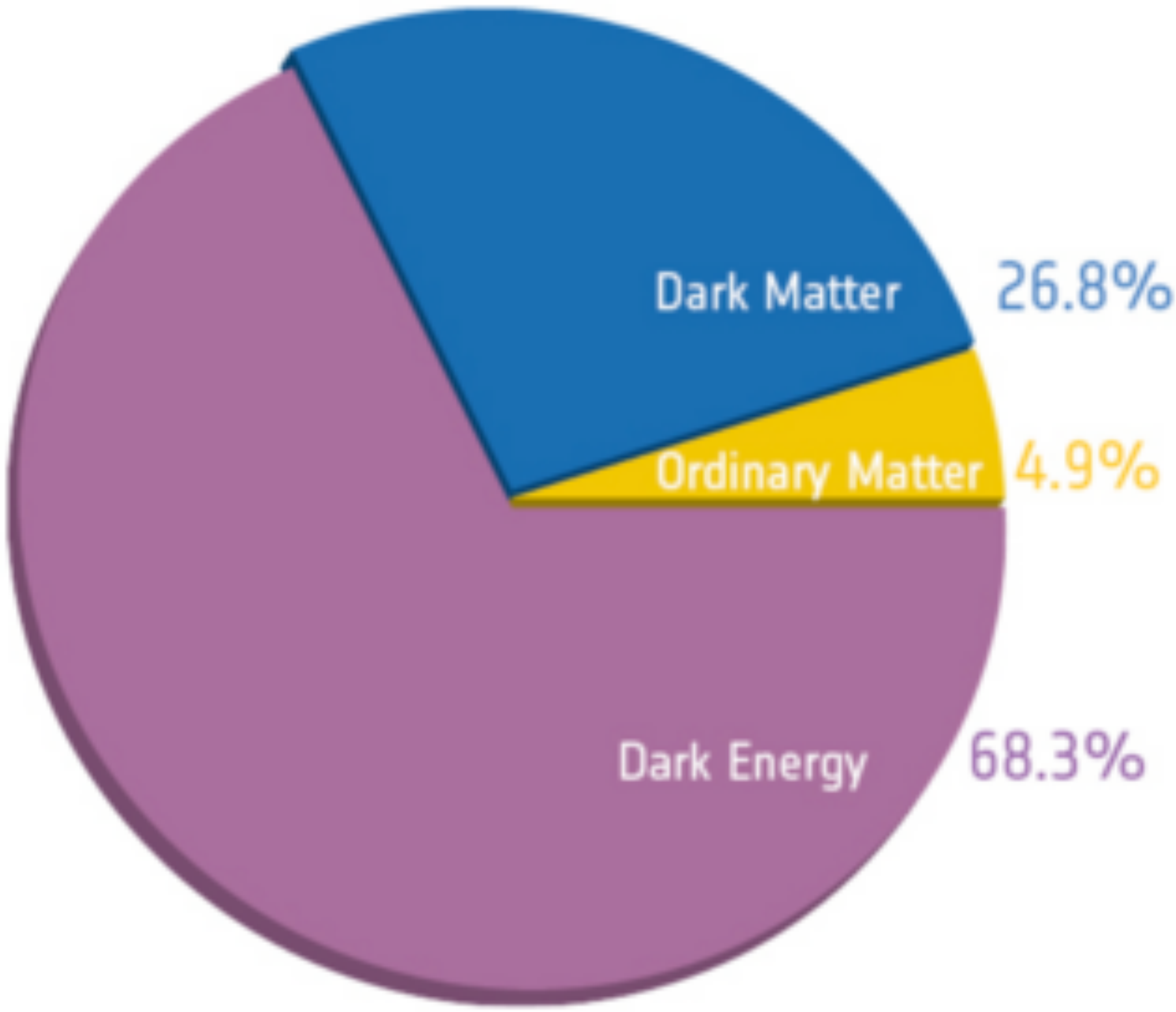
21. 10. 2020

University of Helsinki
& University of Jyväskylä

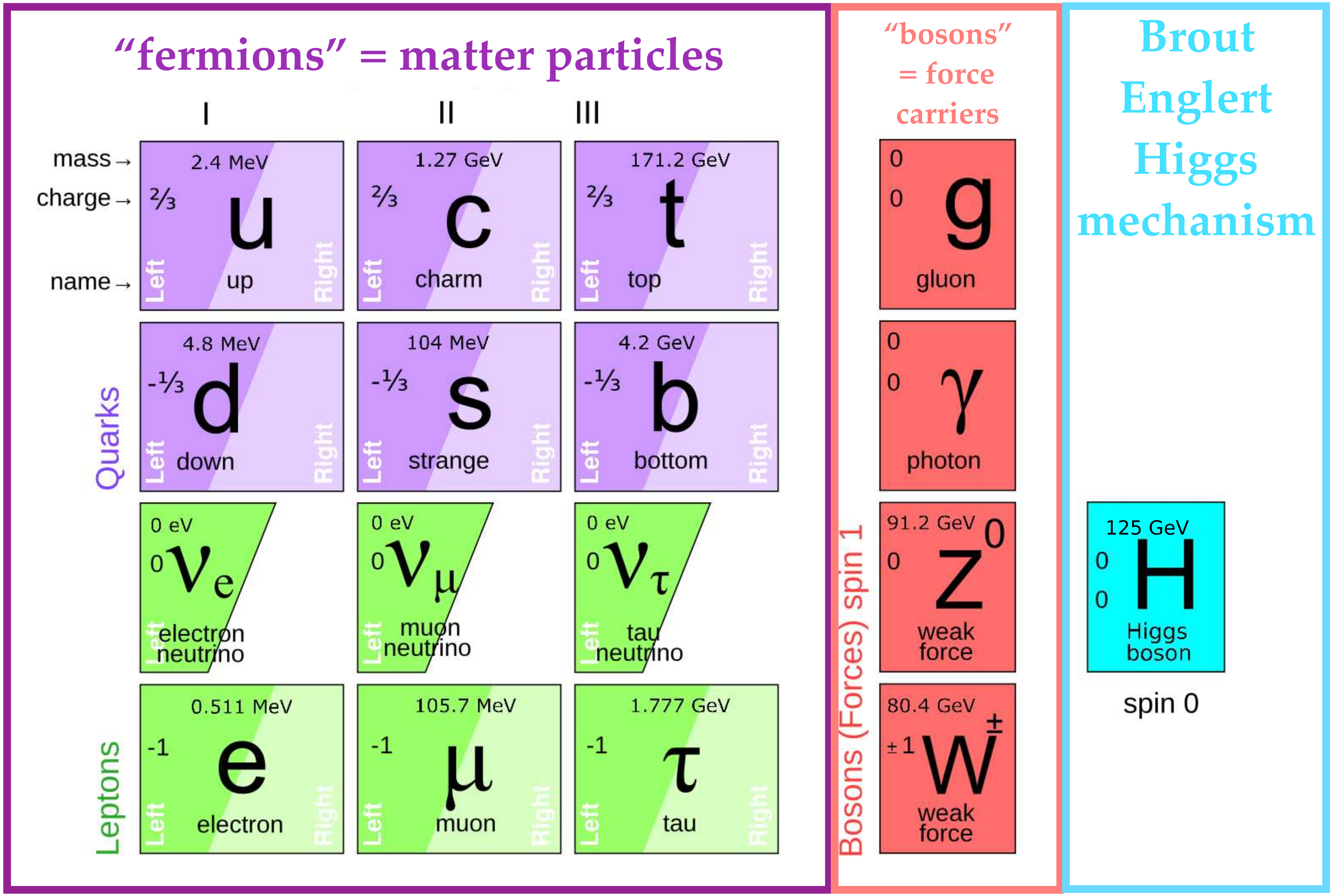
Finnland

mostly based on 1602.04816, 1807.07938

The Dark Matter Puzzle



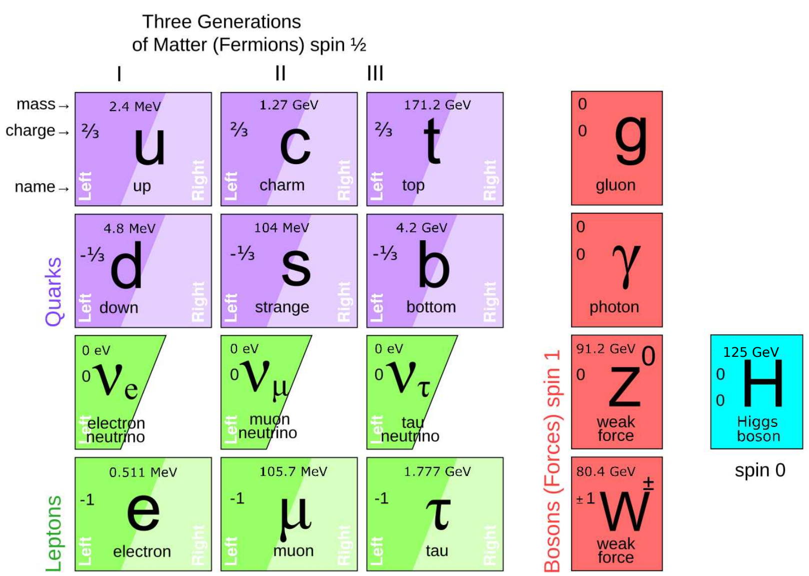
The Standard Model of Particle Physics



The "periodic table" of elementary particles

The Seesaw Mechanism (type I)

$$\mathcal{L}_{SM} \;+\; i\bar{\nu}_R \partial\!\!\!/ \nu_R - \bar{\ell}_L Y \nu_R \tilde{H} - \tilde{H}^\dagger \bar{\nu_R} Y^\dagger \ell_L$$
$$- \frac{1}{2}\left(\bar{\nu^c_R} M_M \nu_R + \bar{\nu_R} M_M^\dagger \nu^c_R \right) .$$

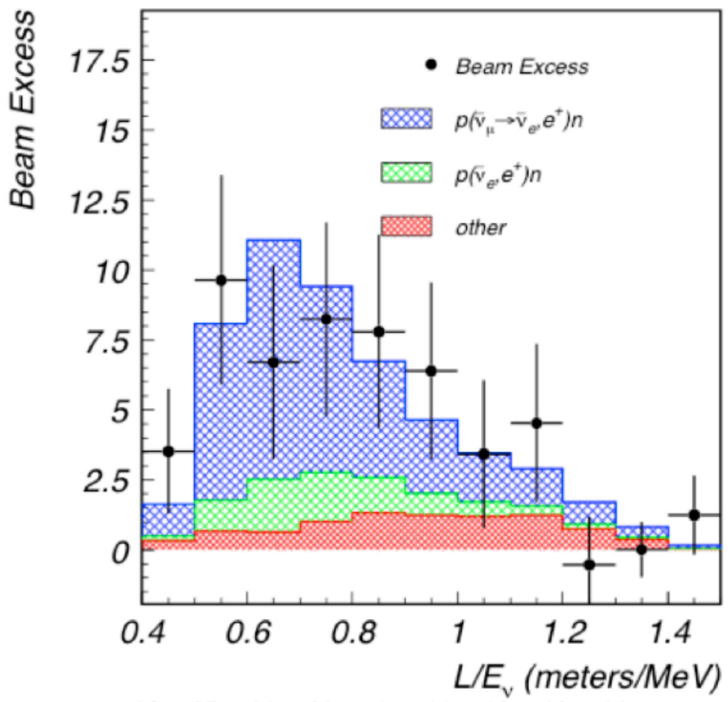


three light neutrinos mostly "active" SU(2) doublet
$\nu \simeq U_\nu(\nu_L + \theta \nu_R^c)$
with masses $m_\nu \simeq -\theta M_M \theta^T = -v^2 Y M_M^{-1} Y^T$

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

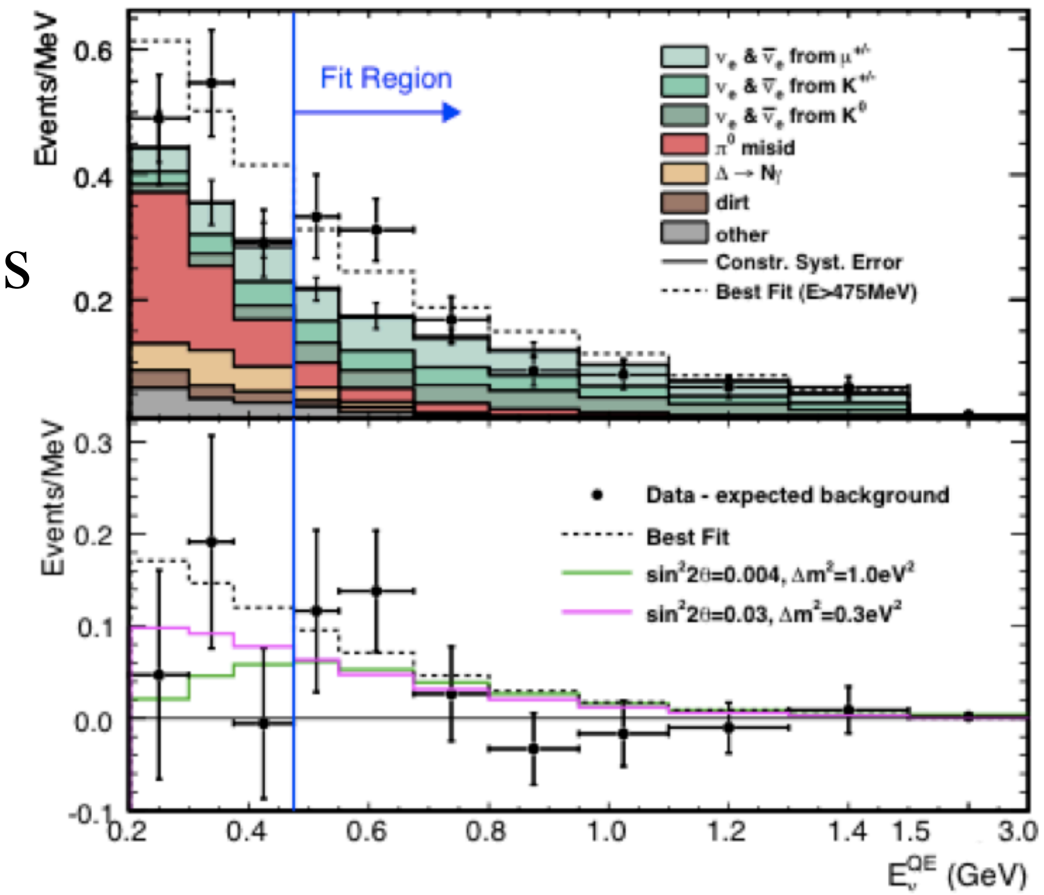
Minkowski 79, Gell-Mann/Ramond/
Slansky 79, Mohapatra/Senjanovic 79,
Yanagida 80, Schechter/Valle 80

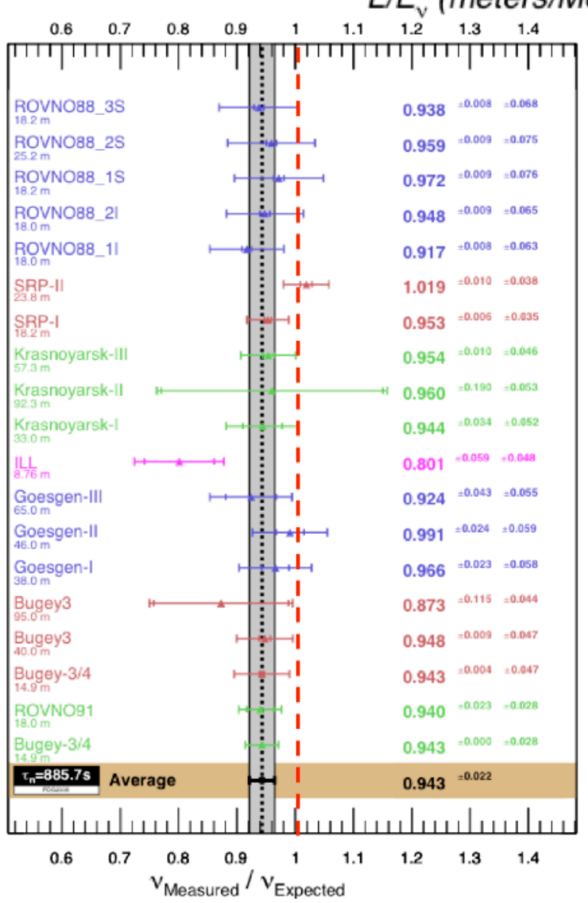
Have we seen it?



LSND: excess of electron antineutrinos

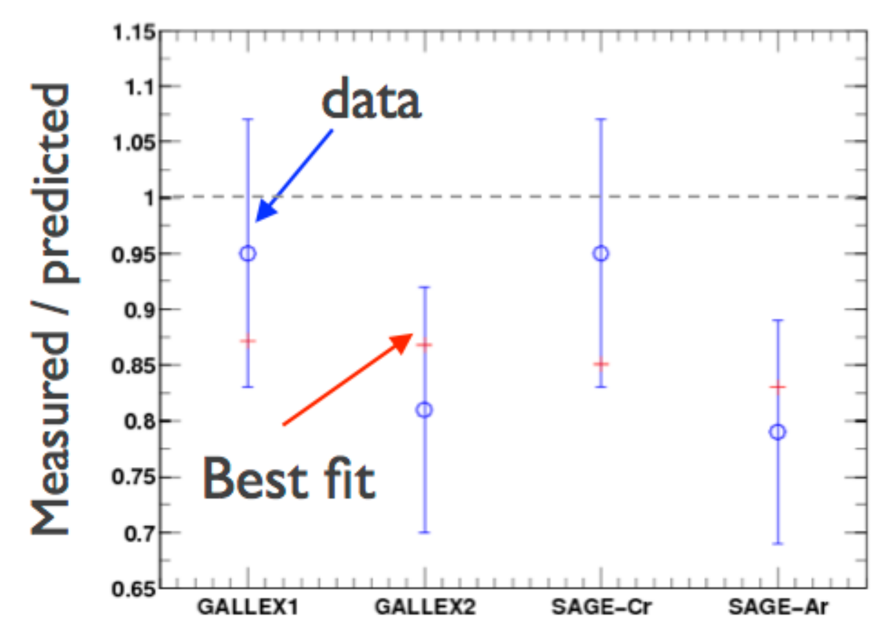
MiniBoone: extra electron (anti)neutrinos at low energy



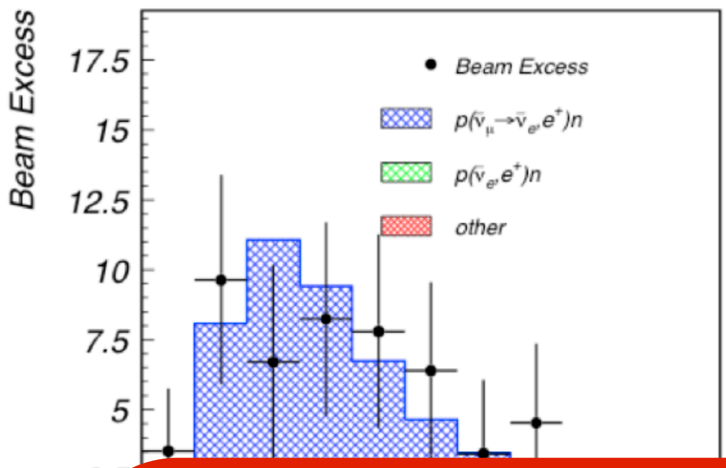


Reactor anomaly: too few neutrinos from reactors?

GALLEX/ SAGE: missing electron neutrinos

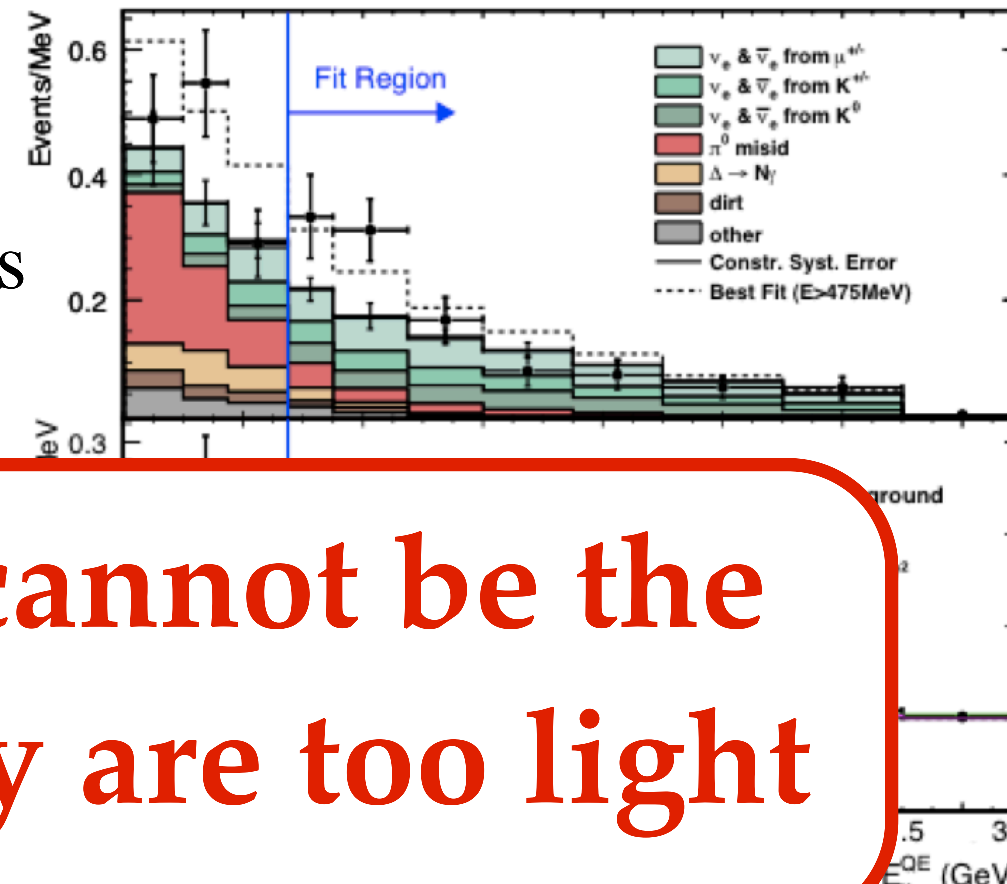


Have we seen it?

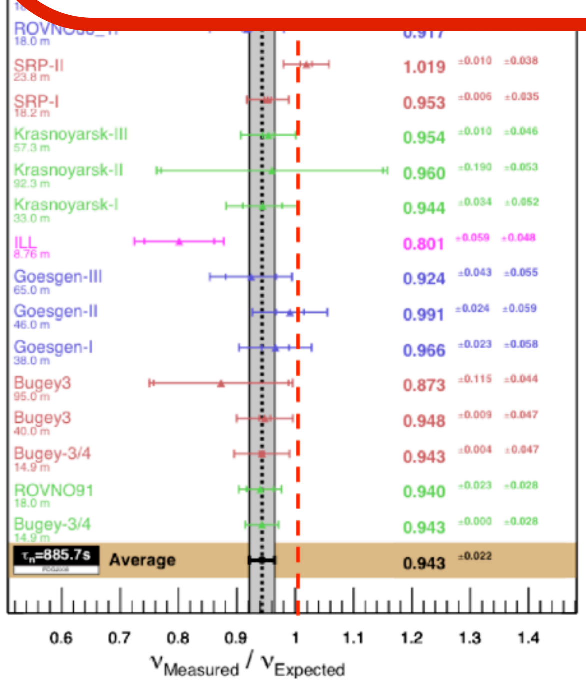


LSND: excess of electron

MiniBoone: extra electron (anti)neutrinos at low energy

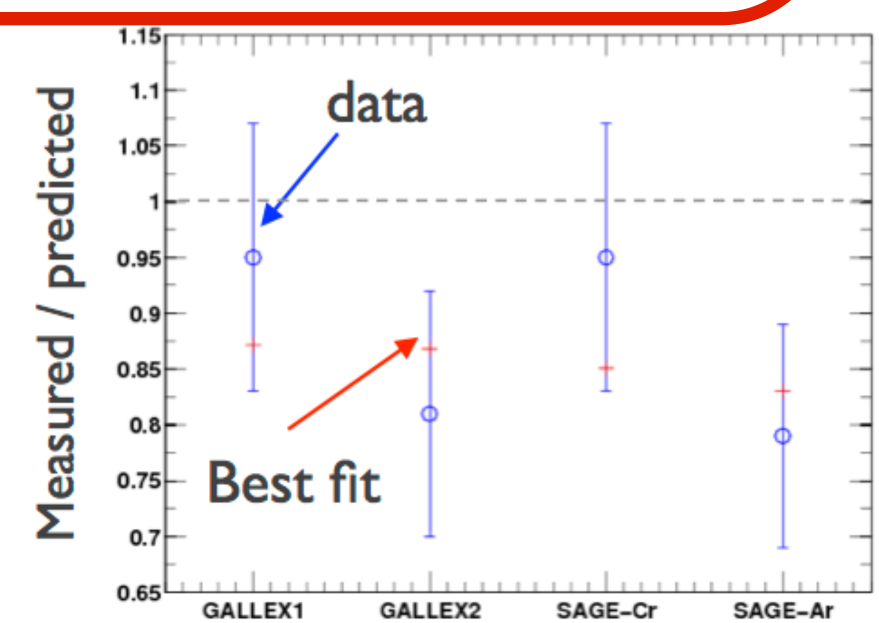


These sterile neutrinos cannot be the Dark Matter because they are too light



anomaly: too few neutrinos from reactors?

GALLEX/ SAGE: missing electron neutrinos



Overview

- introduction
- model independent bounds

    phase space density

    indirect detection (x-ray)

    nuclear β decay spectra

- model dependent bounds

    minimal model (νMSM)

    DM from scalar decay

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Phase Space Bounds

Model independent bound:

Fermions must respect Pauli's principle and have velocities below the escape velocity

$$M \geq 0.18 \text{ keV at } 68\% \text{ CL}$$
$$M \geq 0.13 \text{ keV at } 95\% \text{ CL}$$

Model dependent bound:

This must hold throughout the history of the universe

$$M \geq 2.80 \text{ keV at } 68\% \text{ CL}$$
$$M \geq 1.74 \text{ keV at } 95\% \text{ CL}$$

Updated numbers from Alvey et al 2010.03572

How heavy do they have to be?

velocity distribution for DM particles:

$$F_X(\mathbf{v}) = \frac{1}{\left(\sqrt{2\,\pi}\,M_X\,\sigma_X\right)^3}\exp\left(-\frac{\mathbf{v}^2}{2\,\sigma_X^2}\right),$$

the maximum number density must be consistent with Pauli principle

$$f_X^{\max}(\mathbf{v},\mathbf{x}) = \frac{\rho_X(\mathbf{x})}{M_X}F_X(0) \qquad f_F^{\mathrm{crit}} \equiv \frac{g_X}{(2\,\pi)^3},$$

$$\frac{(2\,\pi)^{3/8}}{g_X^{1/4}}\left(\frac{\rho_X}{\sigma_X^3}\right)^{1/4} \leq M_X$$

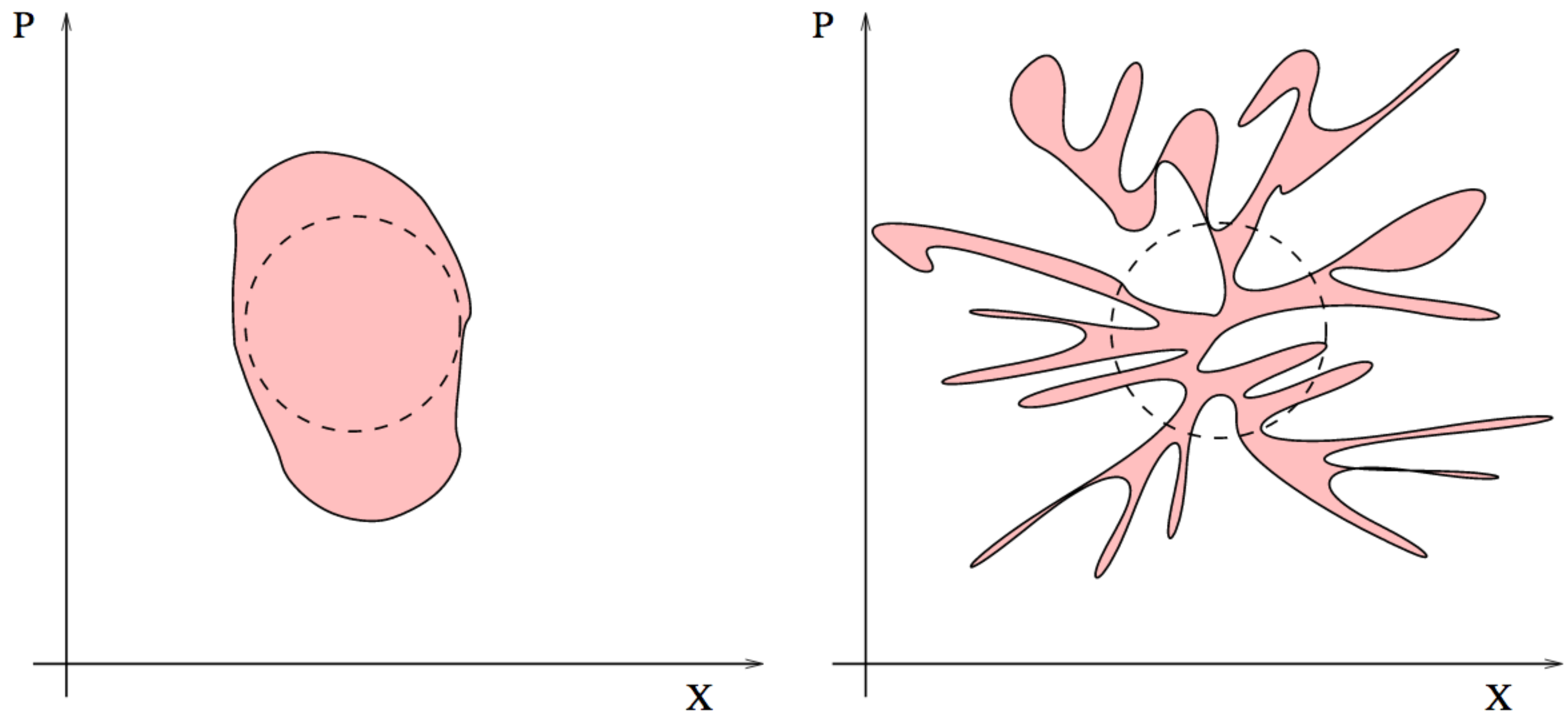
Pauli limit on fermionic Dark Matter mass

for milky way:

$$M_X \gtrsim 25\,\mathrm{eV}$$

DM Phase Space Density

Liouville's theorem: phase space volume constant



But coarse grained phase space density decreases in dense regions

$$\tilde{f}(\mathbf{k}, \mathbf{x}, t) \leq \max_k f_i(\mathbf{k})\,,$$

Tremaine Gunn Bound

Astronomical data constraints the quantity

$$Q \equiv \frac{\rho_0}{\langle \mathbf{v}_{\parallel}^2 \rangle^{3/2}}$$

For spheroidal dwarf galaxies:

$$\langle \mathbf{v}_{\parallel}^2 \rangle = \langle \mathbf{v}^2 \rangle / 3, \qquad \rho_0 = M_X \, n_X \qquad \langle \mathbf{p}^2 \rangle = M_X^2 \langle \mathbf{v}^2 \rangle$$

Combining the equations

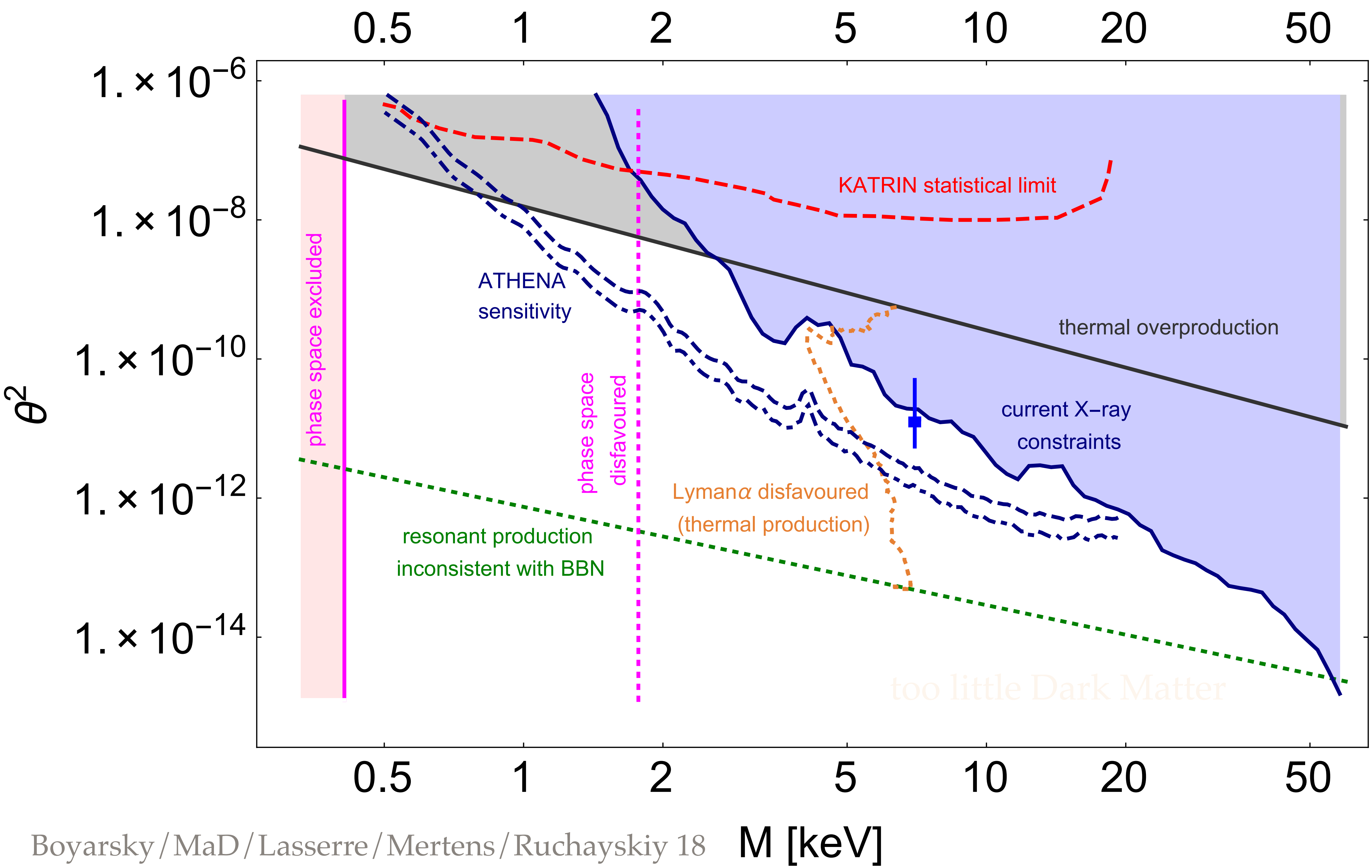
$$Q = 3^{3/2} \, M_X^4 \, \frac{n}{\langle \mathbf{p}^2 \rangle^{3/2}} \simeq 3^{3/2} \, M_X^4 \, \tilde{f}(\mathbf{p}, \mathbf{X}, t_0)$$

using coarse grained phase space distribution

Tremaine Gunn bound

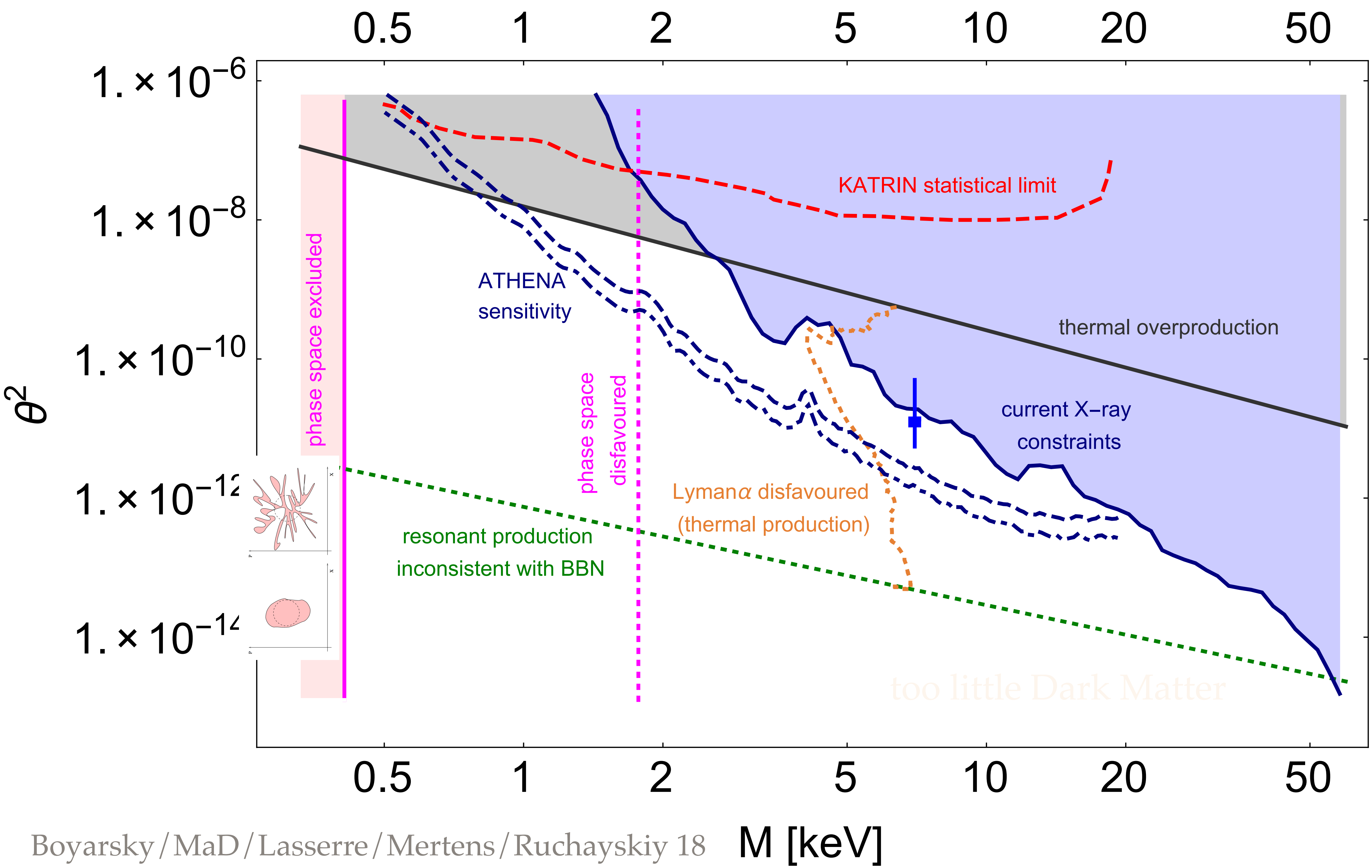
$$M_X \gtrsim \left(\frac{Q}{3^{3/2} \max \tilde{f}_i} \right)^{1/4}$$

Sterile Neutrino Dark Matter



Boyarsky/MaD/Lasserre/Mertens/Ruchayskiy 18

Sterile Neutrino Dark Matter



Boyarsky/MaD/Lasserre/Mertens/Ruchayskiy 18

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Dark Matter Decay

primary decay channel $N \to 3\nu$

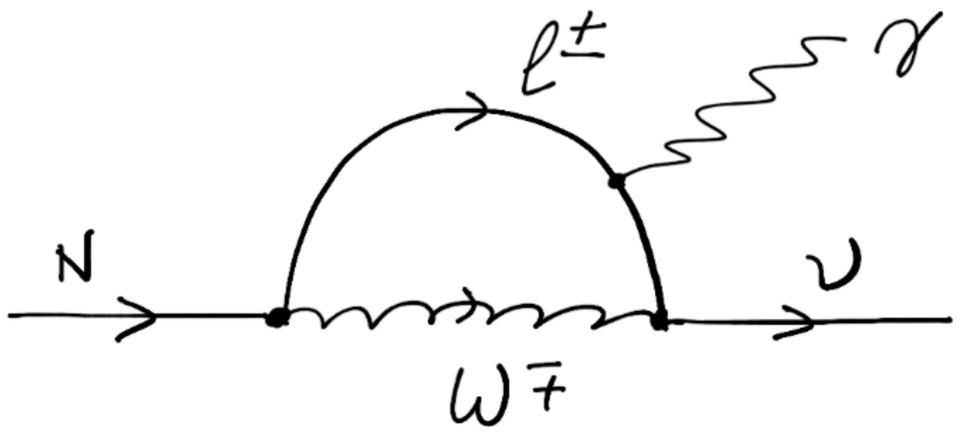
$$\Gamma_{N\to 3\nu} = \frac{G_F^2 M^5}{96\pi^3} \sum_\alpha |\theta_\alpha|^2 \approx \frac{1}{1.5 \times 10^{14}\,\mathrm{sec}} \left(\frac{M}{10\,\mathrm{keV}}\right)^5 \sum_\alpha |\theta_\alpha|^2$$

lifetime must be longer than the age of the universe

$$\theta^2 < 3.3 \times 10^{-4} \left(\frac{10\,\mathrm{keV}}{M}\right)^5$$

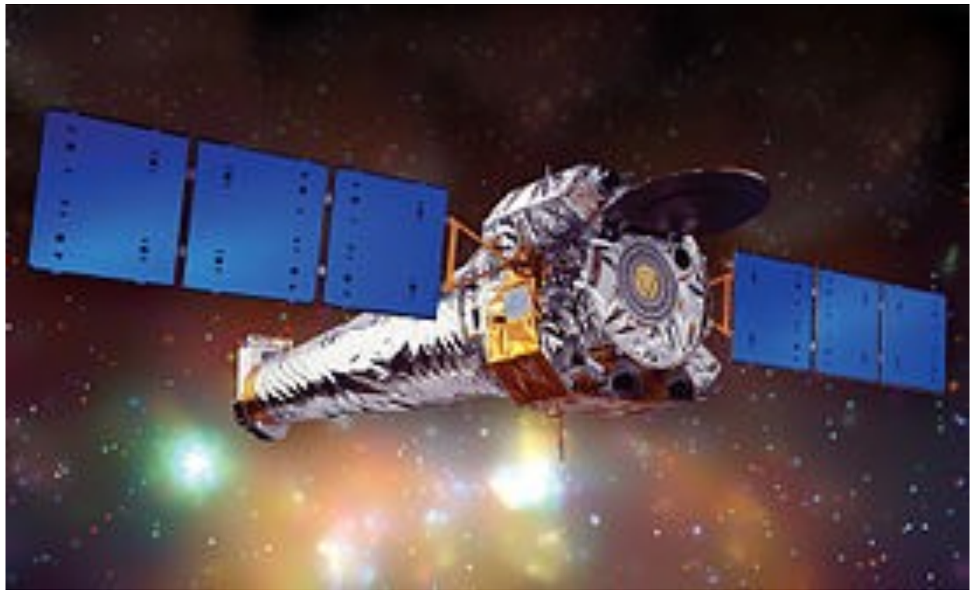
Indirect DM Searches

loop level decay into photons

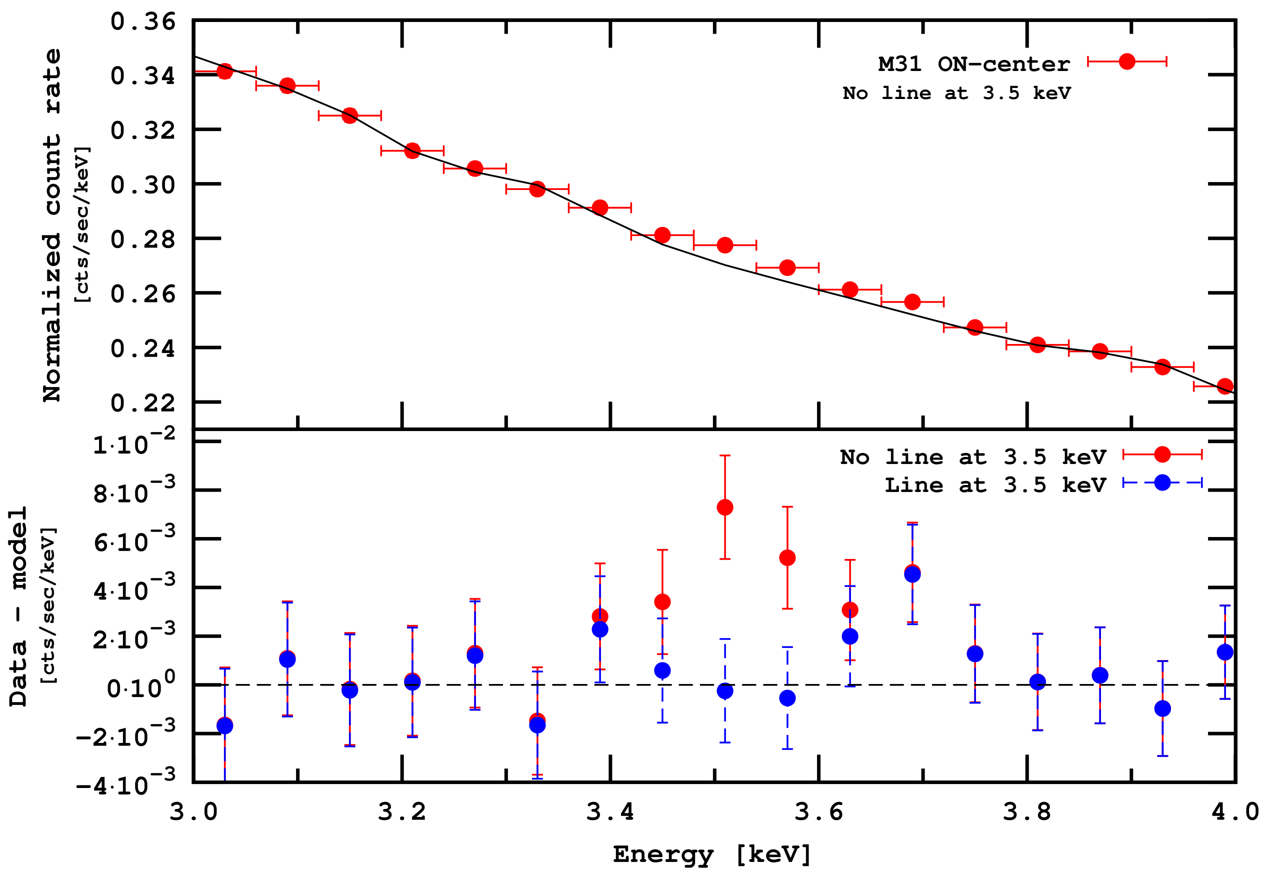


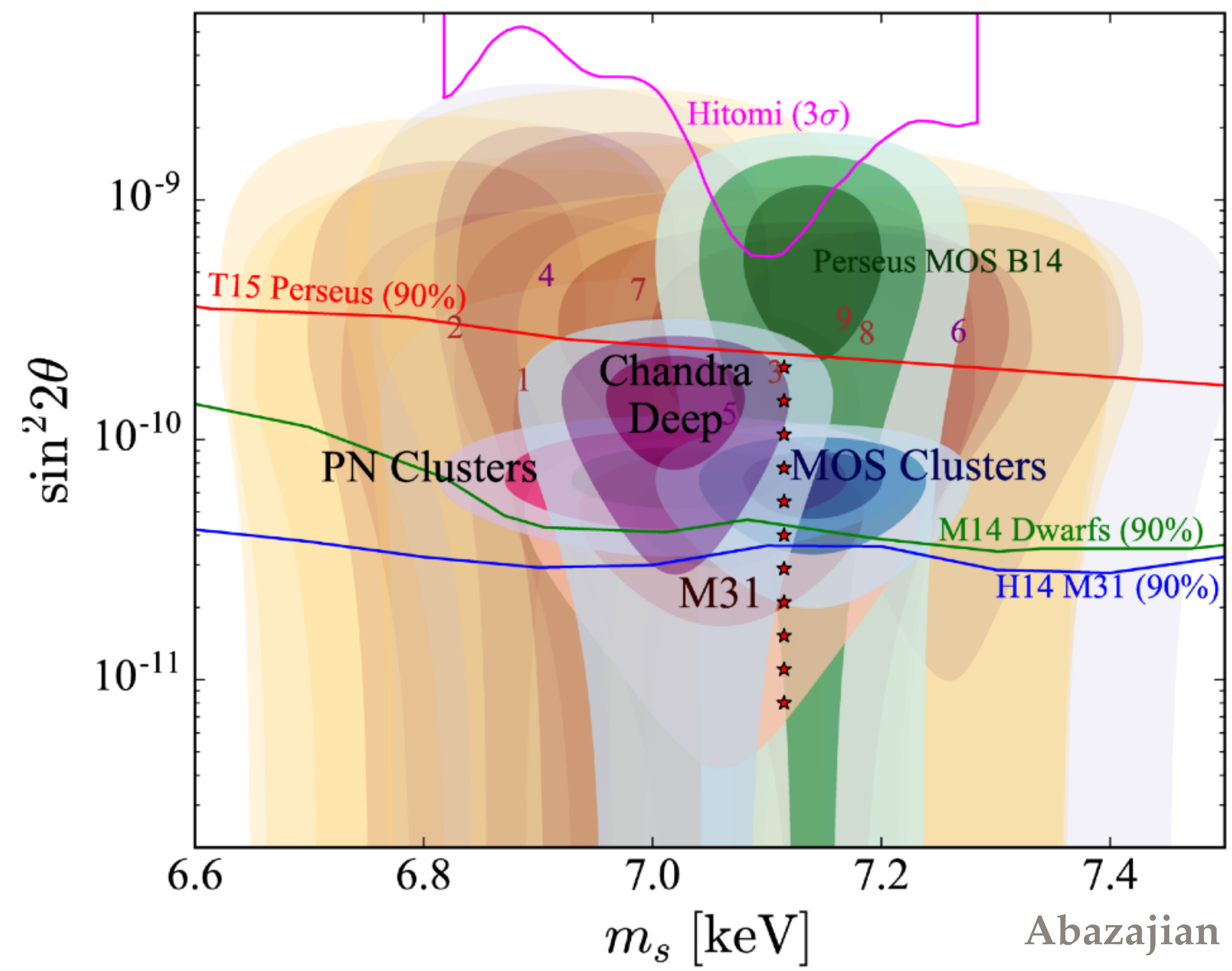
$$\Gamma_{N\to\gamma\nu} = \frac{9\,\alpha\,G_F^2}{256\pi^4}\theta^2 M^5 = 5.5\times 10^{-22}\theta^2\left[\frac{M}{1\,\mathrm{keV}}\right]^5 \mathrm{sec}^{-1}\,.$$

One can search for an emission line!



Has the line been seen?





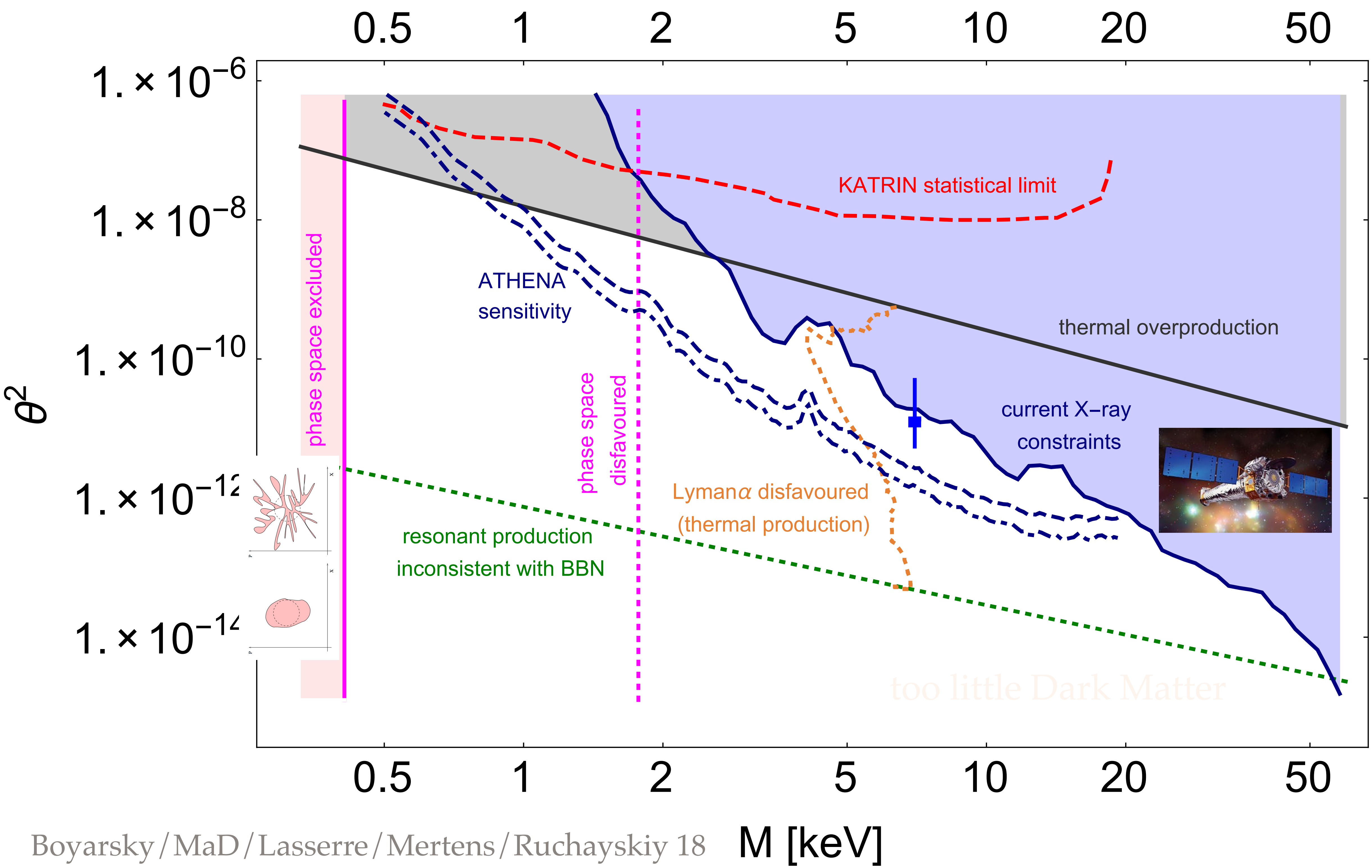
Abazajian 16

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

Situation unclear…

…need better spectral resolution (XRISM, ATHENA+ will help)

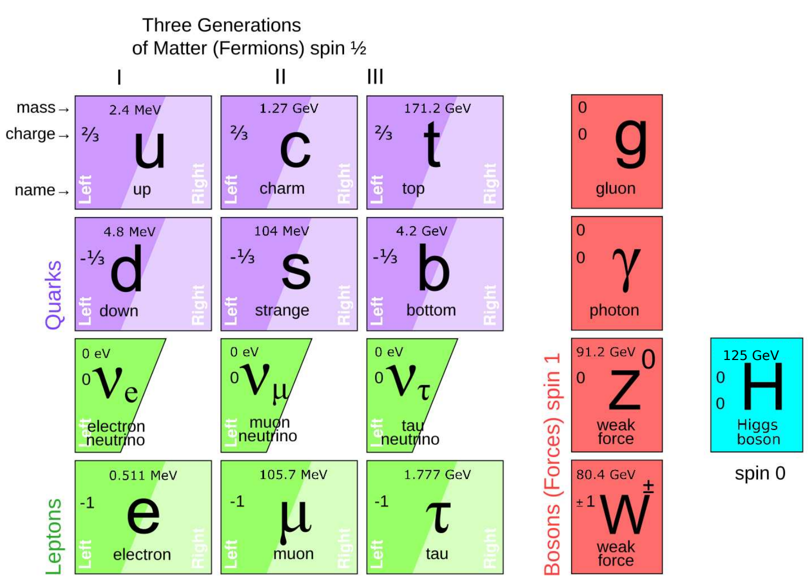
Sterile Neutrino Dark Matter



Boyarsky/MaD/Lasserre/Mertens/Ruchayskiy 18

The Seesaw Mechanism (type I)

$$\mathcal{L}_{SM} + i\bar{\nu}_R \partial\!\!\!/ \nu_R - \bar{\ell_L} Y \nu_R \tilde{H} - \tilde{H}^\dagger \bar{\nu_R} Y^\dagger \ell_L - \frac{1}{2}\left(\bar{\nu^c_R} M_M \nu_R + \bar{\nu_R} M_M^\dagger \nu^c_R\right) .$$



- A sterile neutrino that is DM makes no measurable contribution to the seesaw
- Simple check: $m_\nu \sim \theta^2 M < 10^{-7}$ **eV**
- But with three RHN the two siblings can do the seesaw… and leptogenesis…

three light neutrinos mostly "active" SU(2) doublet

$\nu \simeq U_\nu(\nu_L + \theta\nu^c_R)$

with masses $m_\nu \simeq -\theta M_M \theta^T = -v^2 Y M_M^{-1} Y^T$

three heavy mostly singlet neutrinos

$N \simeq \nu_R + \theta^T \nu^c_L$

with masses $M_N \simeq M_M$

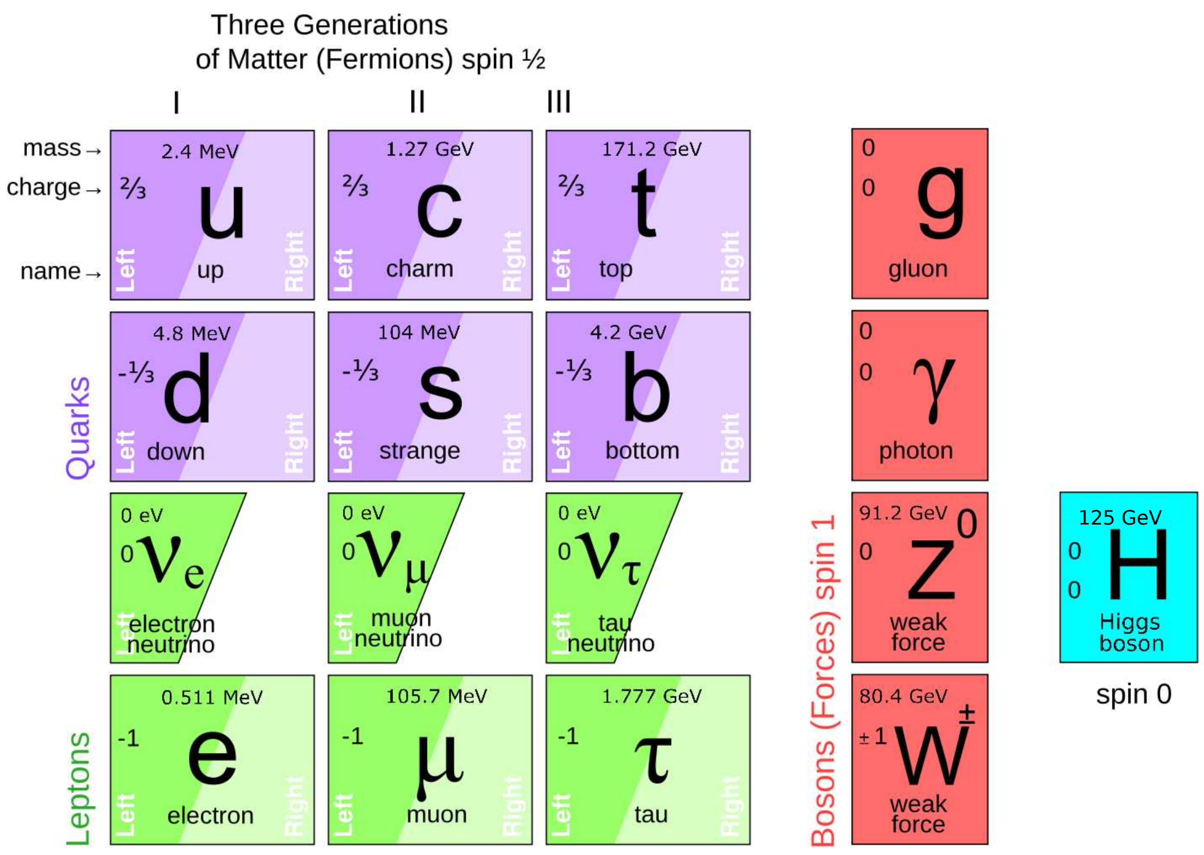
Minkowski 79, Gell-Mann/Ramond/Slansky 79, Mohapatra/Senjanovic 79, Yanagida 80, Schechter/Valle 80

A Minimal Model: The νMSM

Pure Type I seesaw with RH Neutrinos below EW scale

Asaka/Shaposhnikov 0503065, 0505013

- **two RH Neutrinos have degenerate ~GeV masses**
  seesaw + leptogenesis
- **one has a ~keV mass and feeble couplings**
  Dark Matter candidate



Could in principle be complete EFT up to the Planck scale

Bezrukov et al 1205.2893

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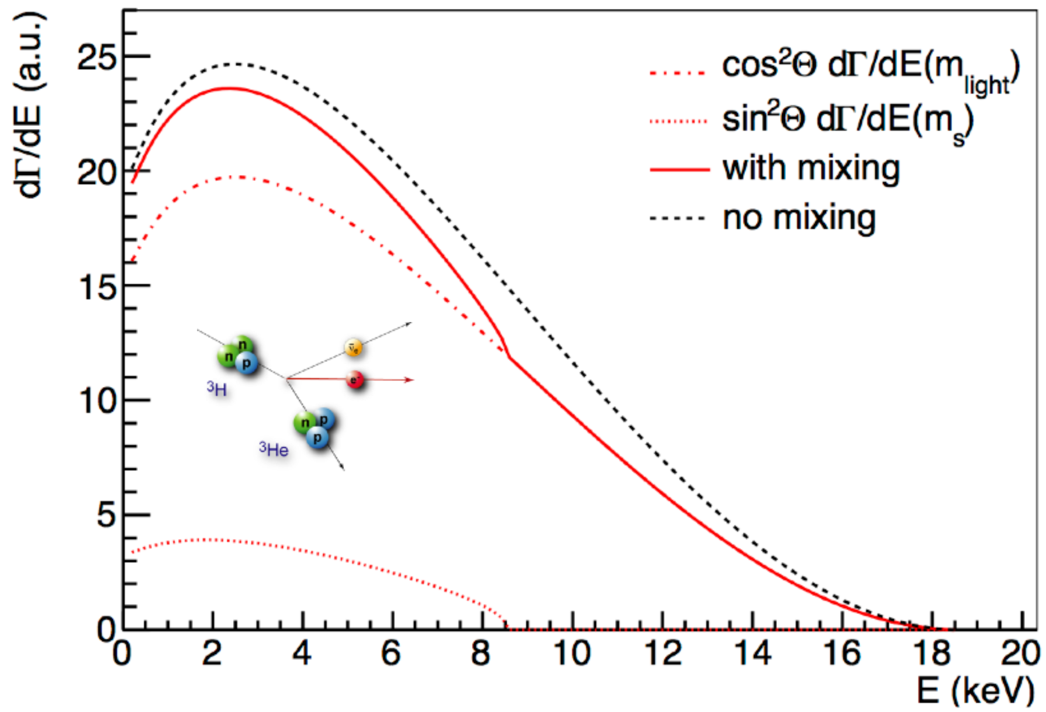
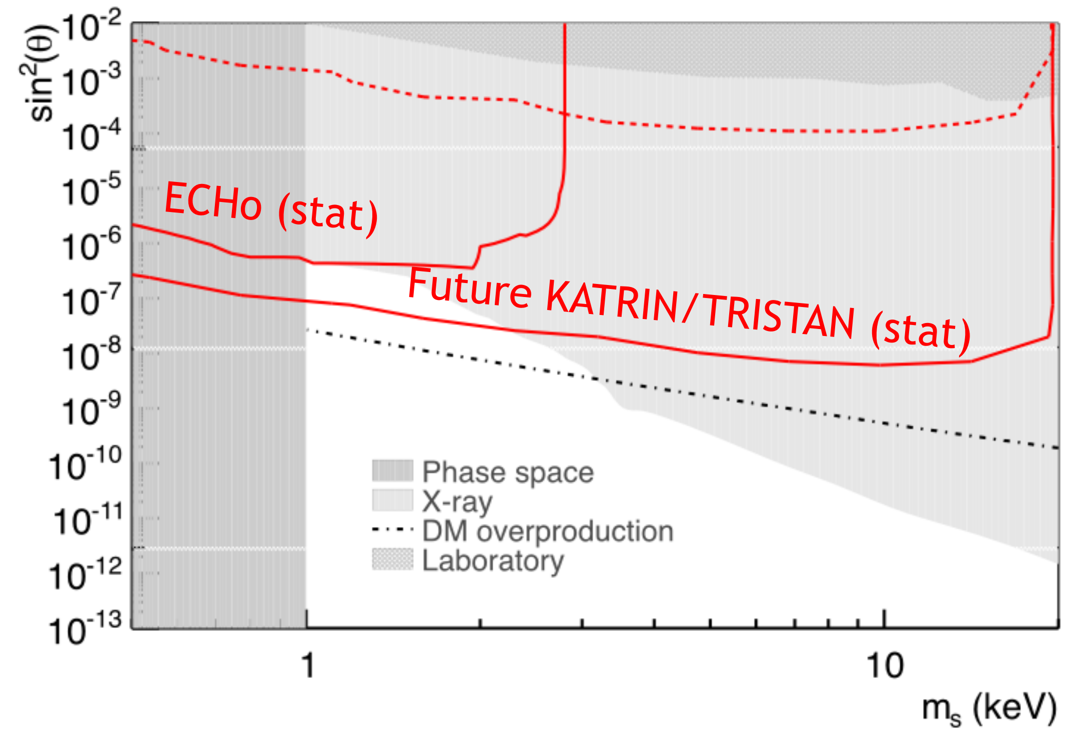
KATRIN/TRISTAN & keV Sterile Neutrinos

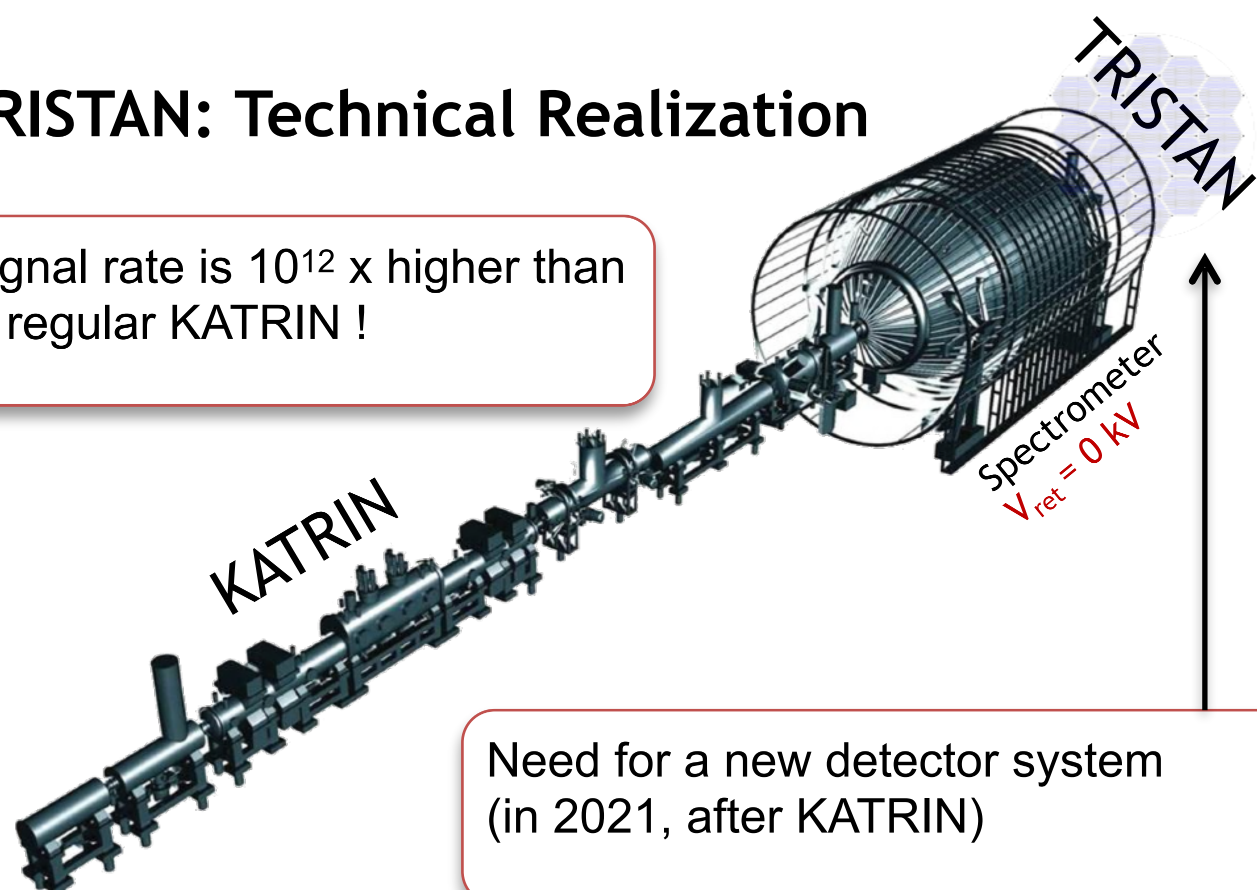
Imprint of keV Neutrinos on Tritium β-spectrun



Statistical Sensitivity



TRISTAN: Technical Realization



Signal rate is 10^{12} x higher than in regular KATRIN !

Need for a new detector system (in 2021, after KATRIN)

Novel Silicon Detector System (R&D)

- Handling high rates (10^9 cts/s)
  - >10 000 pixels
- 300 eV energy resolution & 1 keV threshold
  - Thin deadlayer (~10 nm)
- 1 mm pixels with <0.2 pF capacity
  - Multi-drift-ring design (SDD)
- Minimize systematics (ppm-level)
  - Low ADC non-linearity read-out, etc...

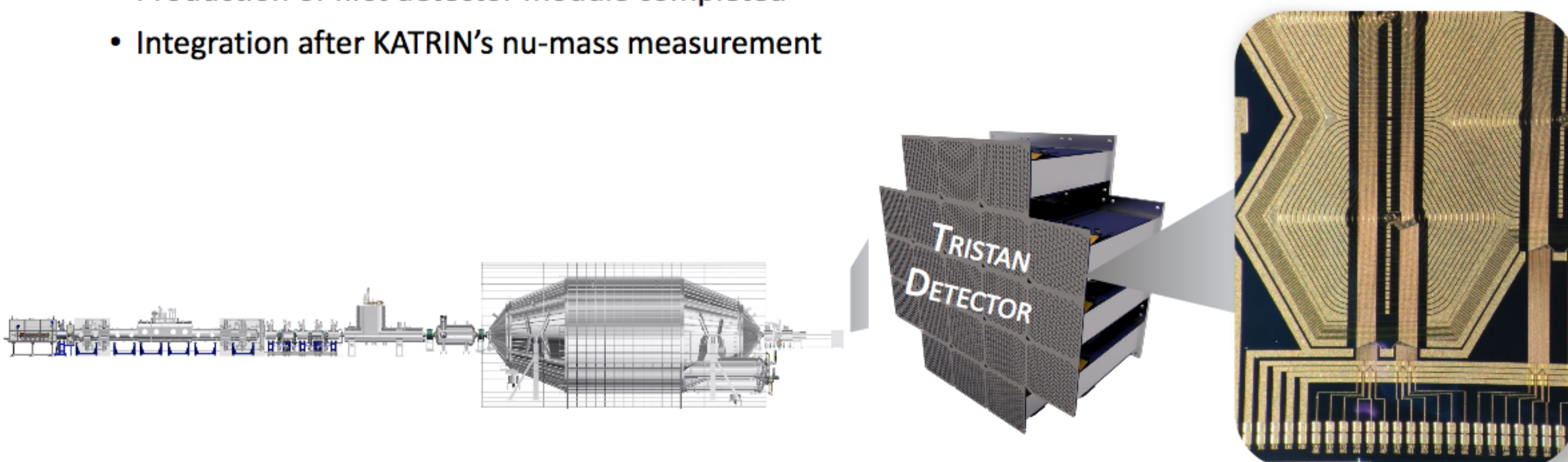
contact: smertens@lbl.gov

Detector is under way…

Search for sterile neutrinos with a

Novel detector system for KATRIN

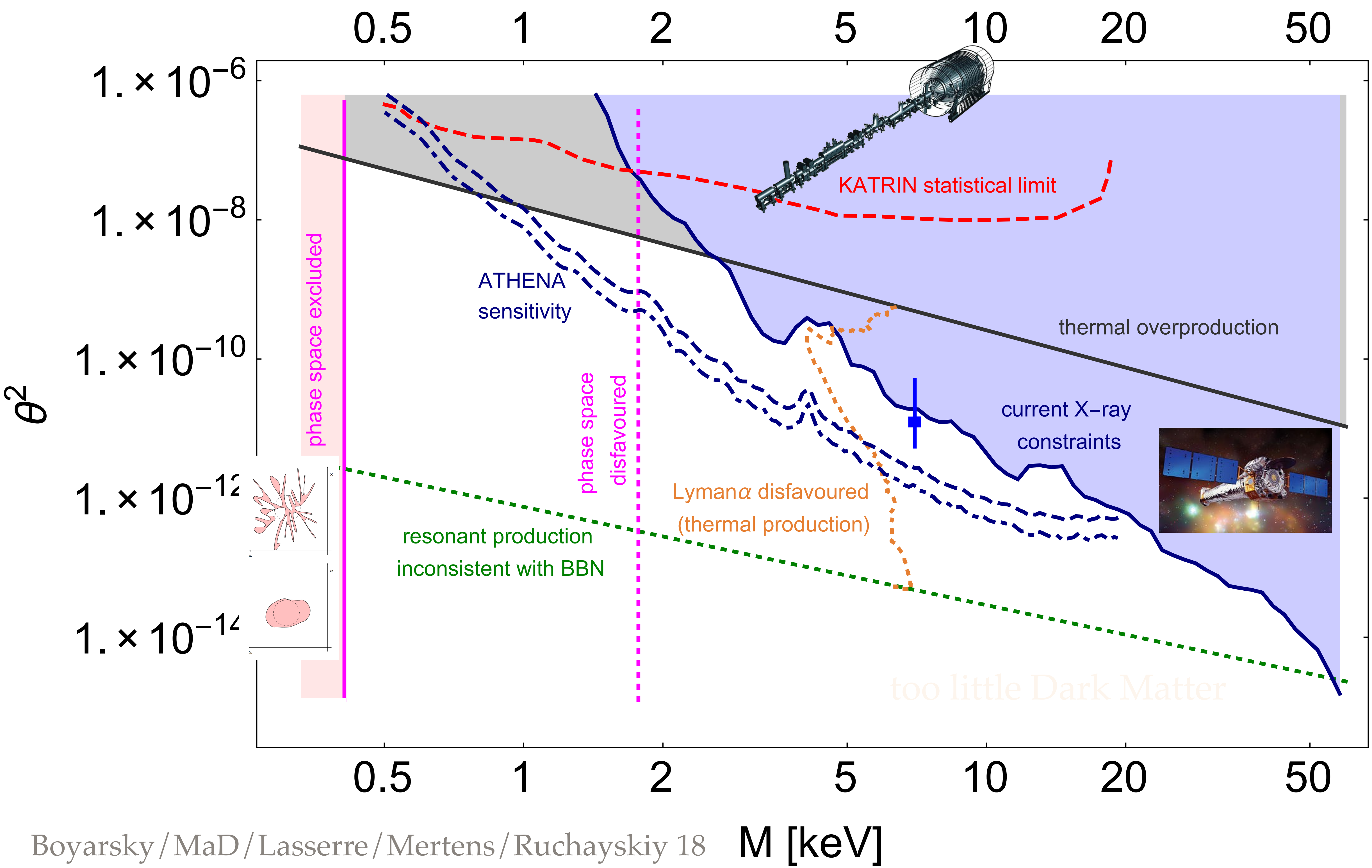
- 3500-pixel silicon drift detector (SDD) focal plane array
- Excellent performance (noise, resolution, linearity) of first prototypes demonstrated
- Production of first detector module completed
- Integration after KATRIN's nu-mass measurement



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

Slide by Susanne Mertens

Sterile Neutrino Dark Matter



Boyarsky/MaD/Lasserre/Mertens/Ruchayskiy 18

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How to make Sterile Neutrino DM?

- **Thermal production via their mixing θ**
  - happens unavoidably for $\theta \neq 0$ Barbieri/Dolgov 91, Dodelson/Widrow 94
  - never reach equilibrium for realistic θ ("freeze in DM", "FIMP DM") $\Rightarrow$ non-thermal spectrum!
  - can be resonantly enhanced by MSW effect Shi/Fuller 99
- **Non-thermal production in the decay of heavy particles**
  - inflaton or other scalar Kusenko 06, Shaposhnikov/Tkachev 06, Bezrukov/Gorbunov 09, Kusenko/Petraki 07, ...
  - can occur when scalar is in equilibrium or during scalar production ("freeze in") see e.g. Merle/Totzauer 15
  - charged scalar Boyanovsky 08, Frigerio/Yaguna 14, leptophilic Higgs Adulpravitchai/Schmidt 15, fermion Abada 14 or vector particles Shuve/Yavin 14
- **Thermal production via (gauge) interactions at high energies**
  very difficult to dilute Bezrukov/Hettmansperger/Lindner, ...
  [I won’t talk about this]

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Production through Mixing

Consider system with one active and one sterile neutrino

$$|\nu_a\rangle = \cos\theta\,|\nu_1\rangle + \sin\theta\,|\nu_2\rangle,$$
$$|\nu_s\rangle = -\sin\theta\,|\nu_1\rangle + \cos\theta\,|\nu_2\rangle.$$

In the primordial plasma there is an effective mixing angle

$$|\nu_a\rangle = \cos\theta_m(t)\;|\nu_1(t)\rangle + \sin\theta_m(t)\;|\nu_2(t)\rangle,$$
$$|\nu_s\rangle = -\sin\theta_m(t)\;|\nu_1(t)\rangle + \cos\theta_m(t)\;|\nu_2(t)\rangle$$

Thermal production rate $\Gamma_N \sim G_F^2 T^5 \sin^2(2\theta_m)$

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

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

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

Non-resonant Production

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

The active-sterile mass splitting enters via

$$\Delta(p) = \Delta m^2/(2p)$$

And the "matter potentials" are

$$V_T \simeq -G_{\rm eff}^2 T^4 p \qquad G_{\rm eff}^2 \sim 10^2 G_F^2$$

$$V_D \simeq 0$$

Thermal production rate peaks at T ~ 0.1 - 1 GeV

$$\Gamma_N \sim G_F^2 T^5 \sin^2(2\theta_m)$$

Non-resonant Production

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

vacuum mixing angle smaller than 10-6 (X -ray searches)

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The active-sterile mass splitting enters via

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at high T the matter potential suppresses the effective mixing angle

And the "matter potentials" are

$$V_T \simeq - G_{\text{eff}}^2 T^4 p \qquad G_{\text{eff}}^2 \sim 10^2 G_F^2$$

$$V_D \simeq 0$$

Thermal production rate peaks at T ~ 0.1 - 1 GeV

$$\Gamma_N \sim G_F^2 T^5 \sin^2(2\theta_m)$$

Non-resonant Production

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

The active-sterile mass splitting enters via

$$\Delta(p) = \Delta m^2/(2p)$$

at low T the light neutrino flux is too low

And the "matter potentials" are

$$V_T \simeq - G_{\rm eff}^2 T^4 p \qquad G_{\rm eff}^2 \sim 10^2 G_F^2$$

$$V_D \simeq 0$$

Thermal production rate peaks at T ~ 0.1 - 1 GeV

$$\Gamma_N \sim G_F^2 T^5 \sin^2(2\theta_m)$$

Resonant Production

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

The active-sterile mass splitting enters via

$$\Delta(p) = \Delta m^2/(2p)$$

resonance condition

$$\Delta(p)\cos(2\theta) - V_D - V_T = 0$$

resonance condition strongly depends on lepton asymmetries

$$M^2 - 2\frac{4\sqrt{2}\zeta(3)}{\pi^2}G_F l_\nu p T^3 + 2G_{\text{eff}}^2 p^2 T^4 = 0, \quad l_\nu \equiv (n_\nu - n_{\bar{\nu}})/n_\gamma.$$

Resonance Condition

resonance for mode with $x \equiv p/T$ occurs at

$$x_{res} = \frac{G_F}{G_{\rm eff}^2 T^2} \frac{4\zeta(3)}{\sqrt{2}\pi^2} l_\nu \left[1 \pm \sqrt{1 - \frac{1}{2} \frac{M^2}{T^2} \frac{G_{\rm eff}^2}{G_F^2} \frac{\pi^4}{8\zeta(3)^2} \frac{1}{l_\nu^2}} \right]$$

resonance requires a lepton asymmetry

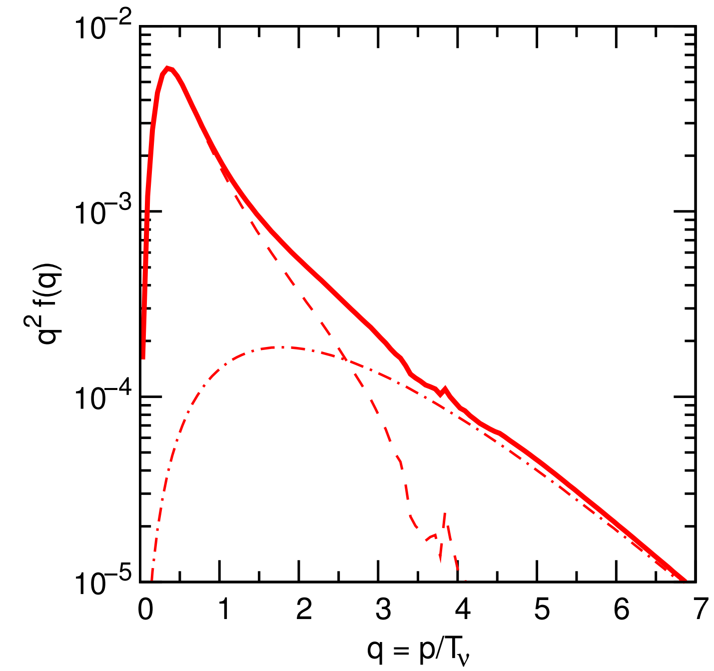
$$|l_\nu| > \frac{1}{2} \frac{M}{T} \frac{G_{\rm eff}}{G_F} \frac{\pi^2}{2\zeta(3)},$$

this is several orders of magnitude larger than the baryon asymmetry!
(but well below the observational bound)

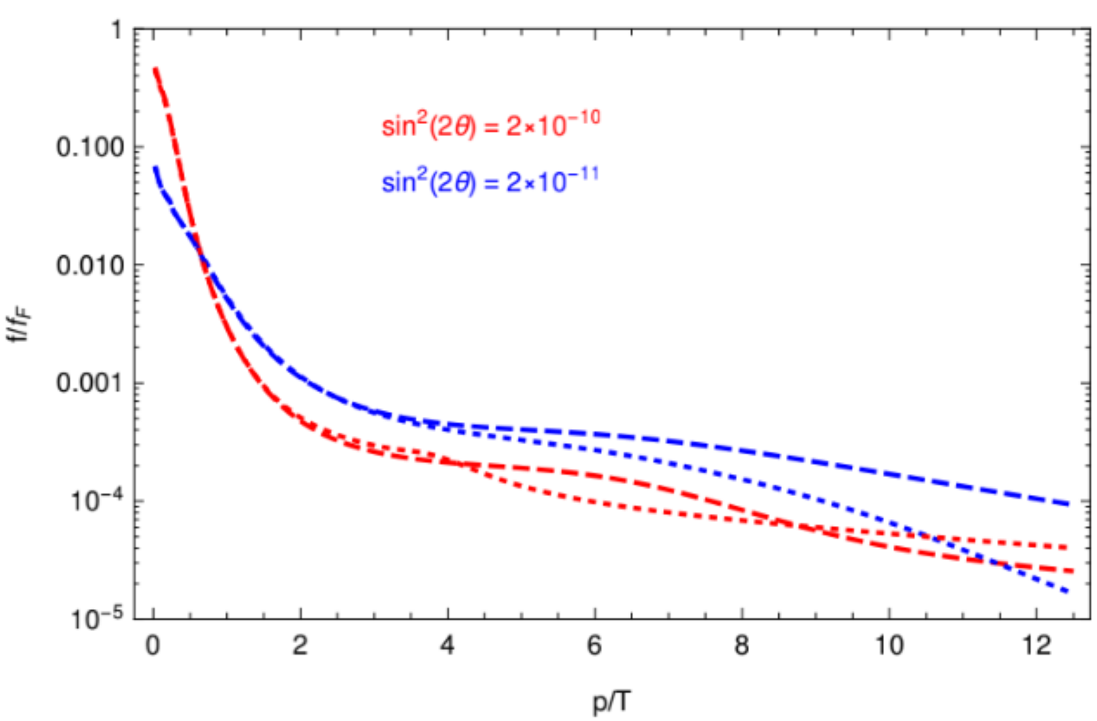
DM Spectrum

DM momentum distribution has two components:

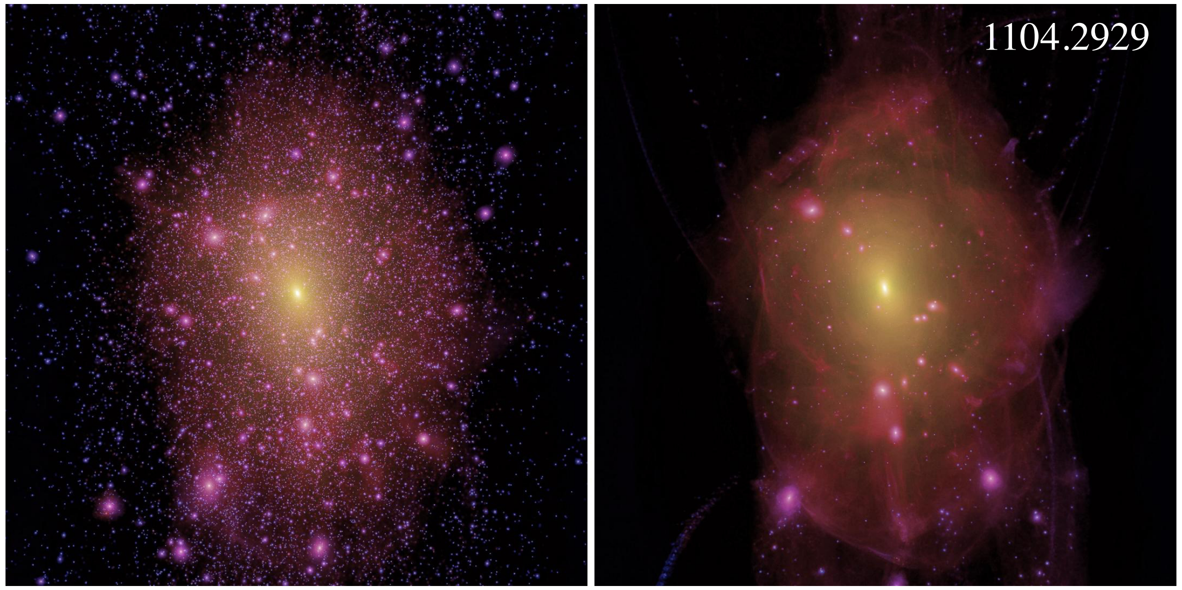
- A “warm” part from the non-resonant production
- A “cold” part from the resonant production



Updated spectra:



input for structure formation simulation

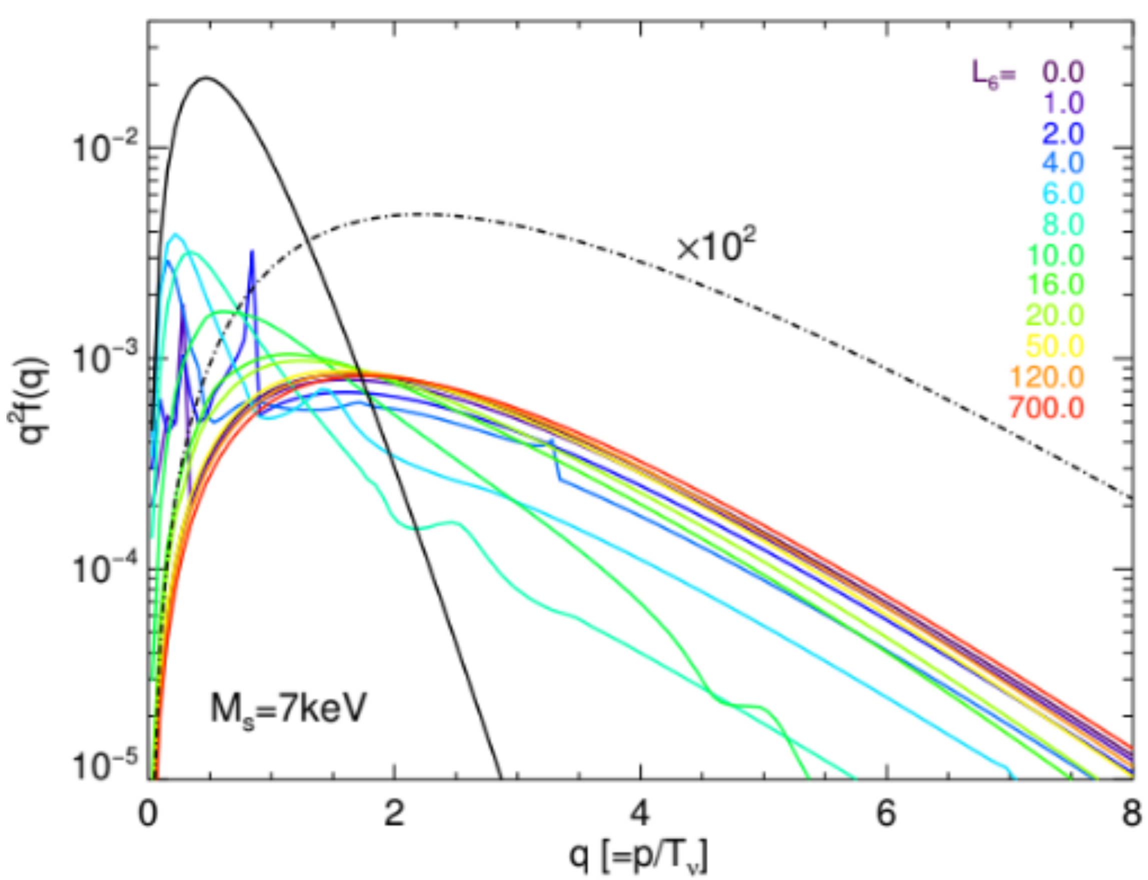


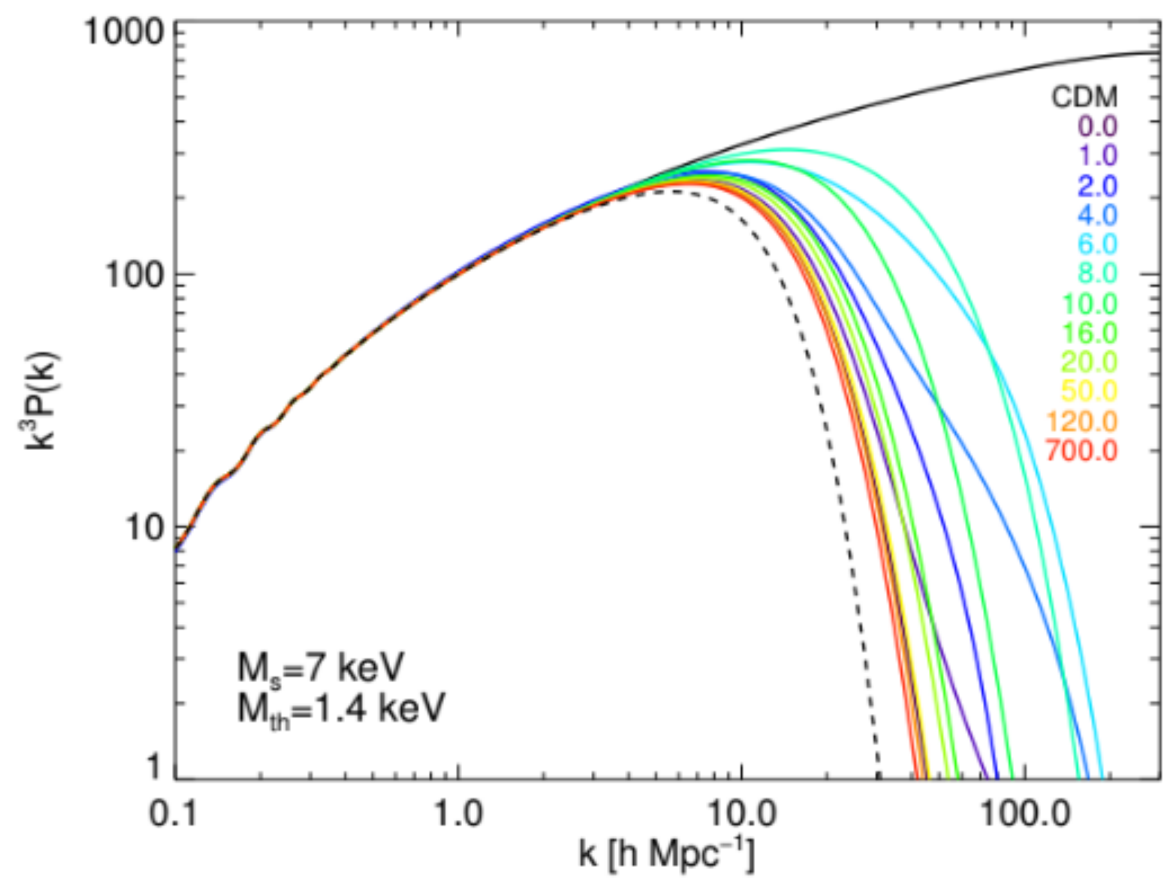
Structure Formation

DM free streaming length

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

affects matter power spectrum



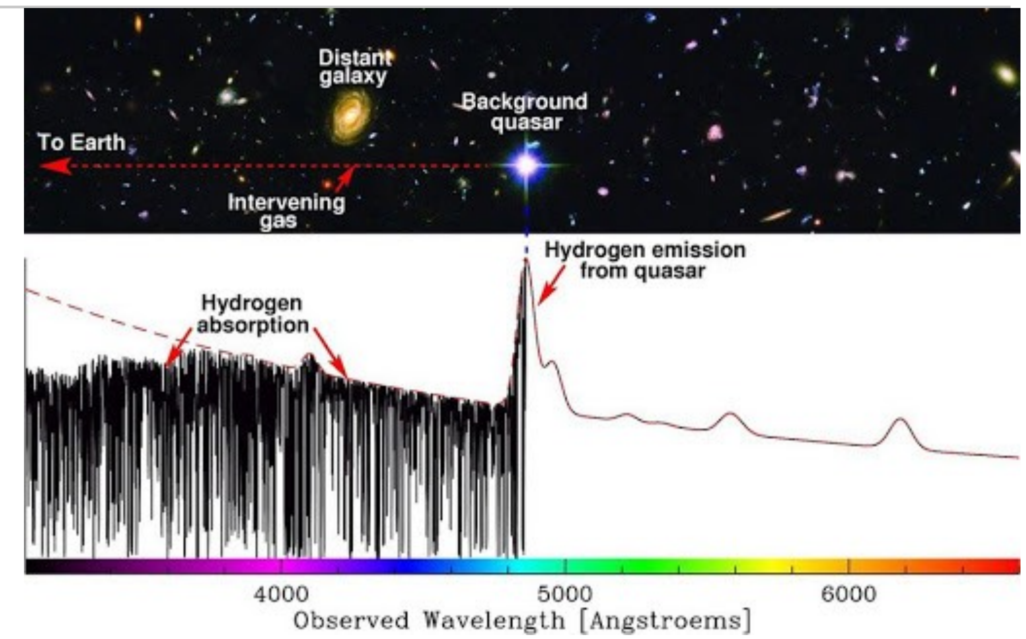


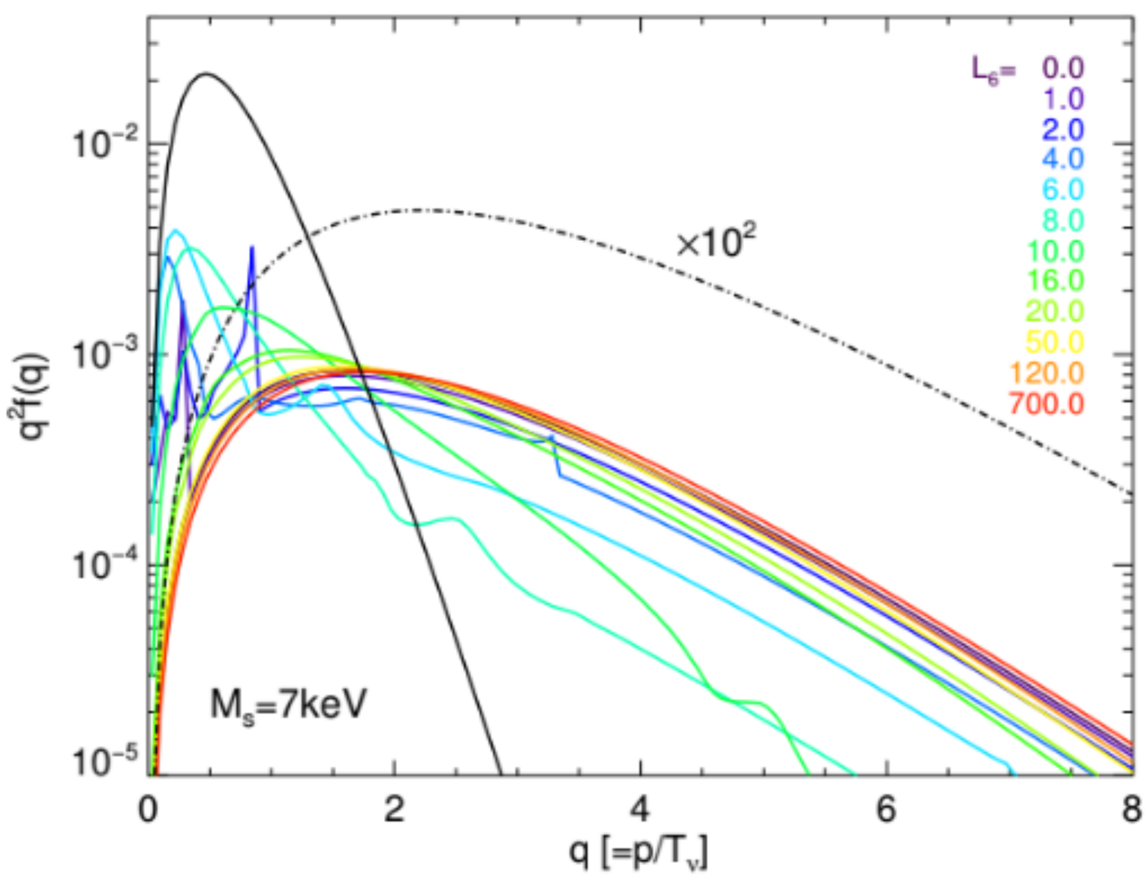
Structure Formation

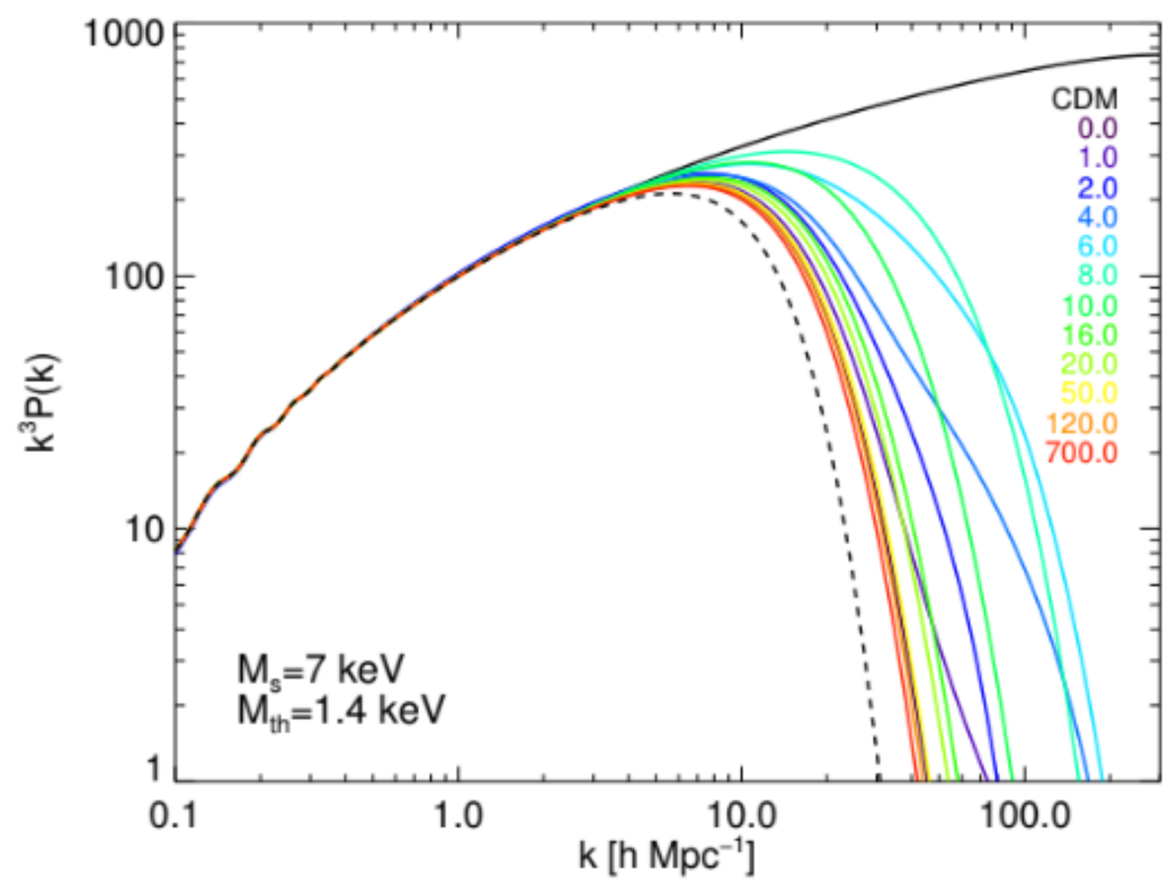
DM free streaming length

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

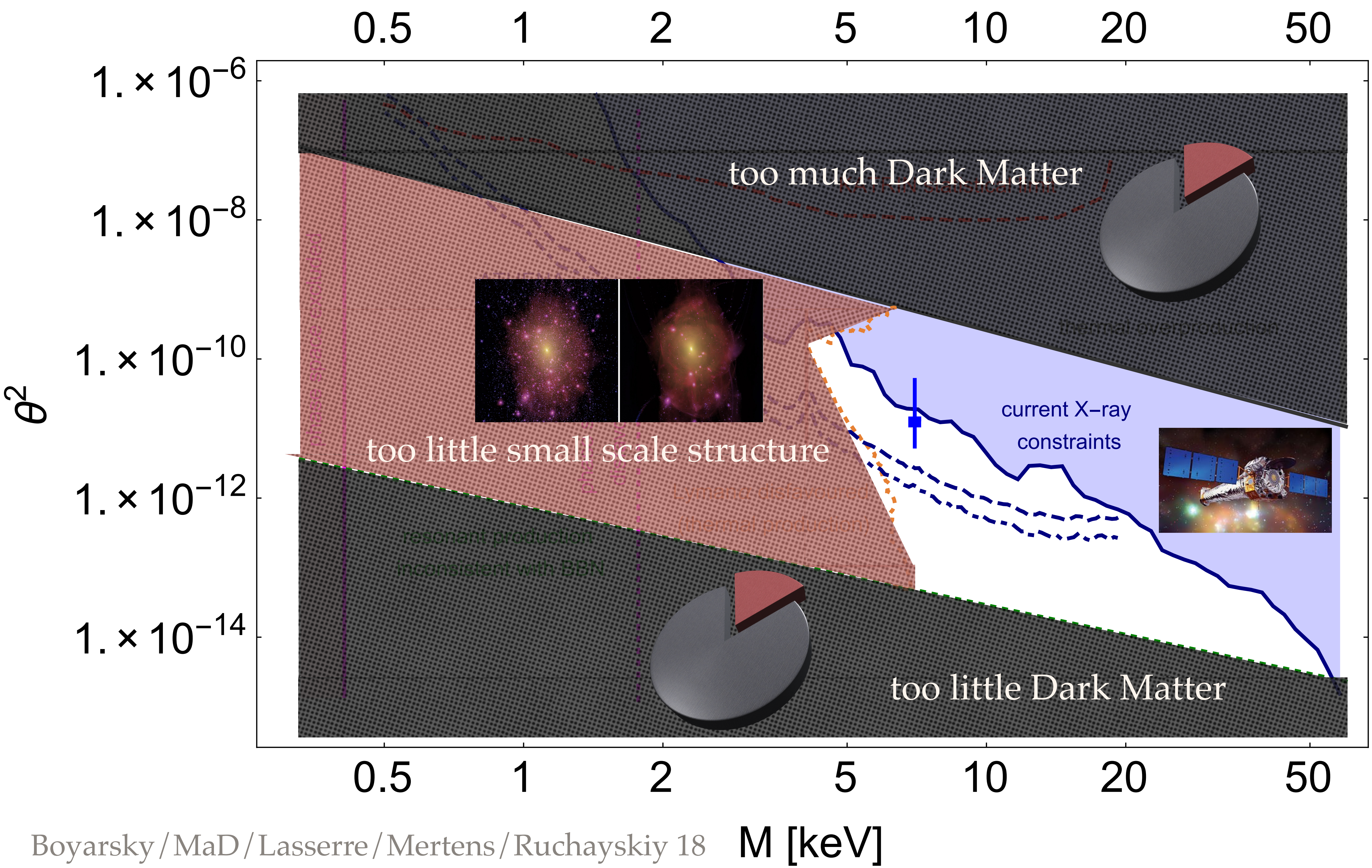
affects matter power spectrum





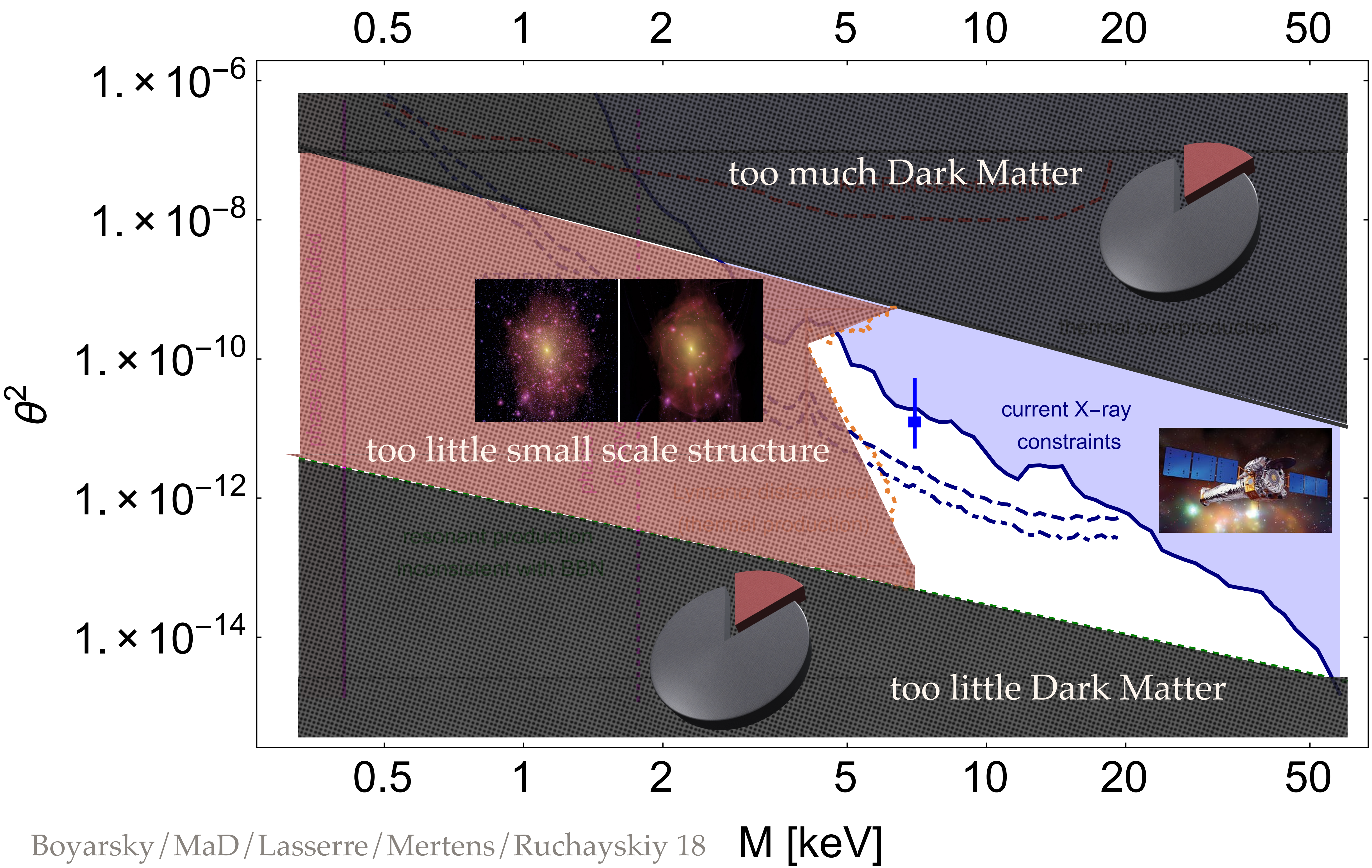


Sterile Neutrino Dark Matter



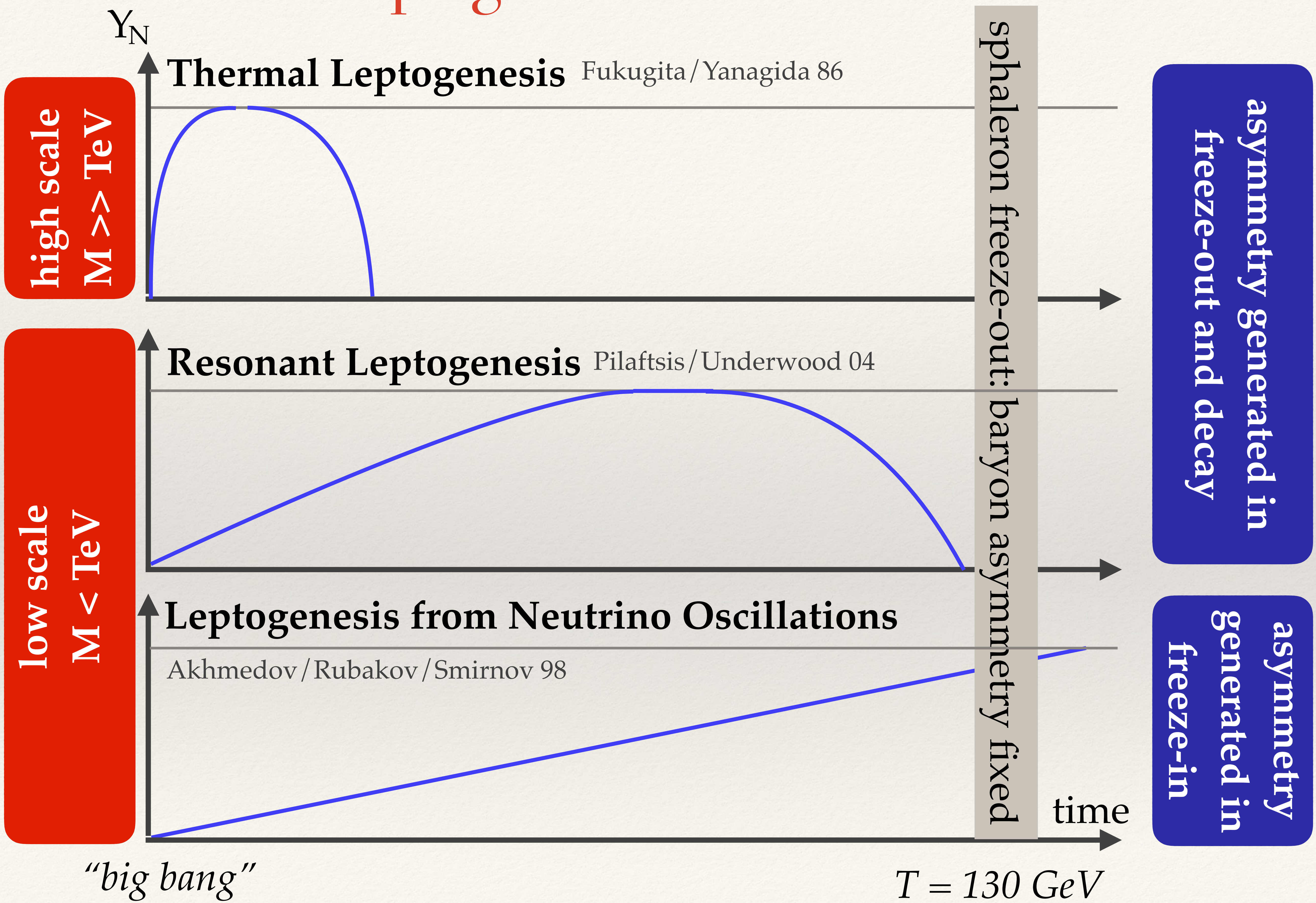
Boyarsky/MaD/Lasserre/Mertens/Ruchayskiy 18

Sterile Neutrino Dark Matter

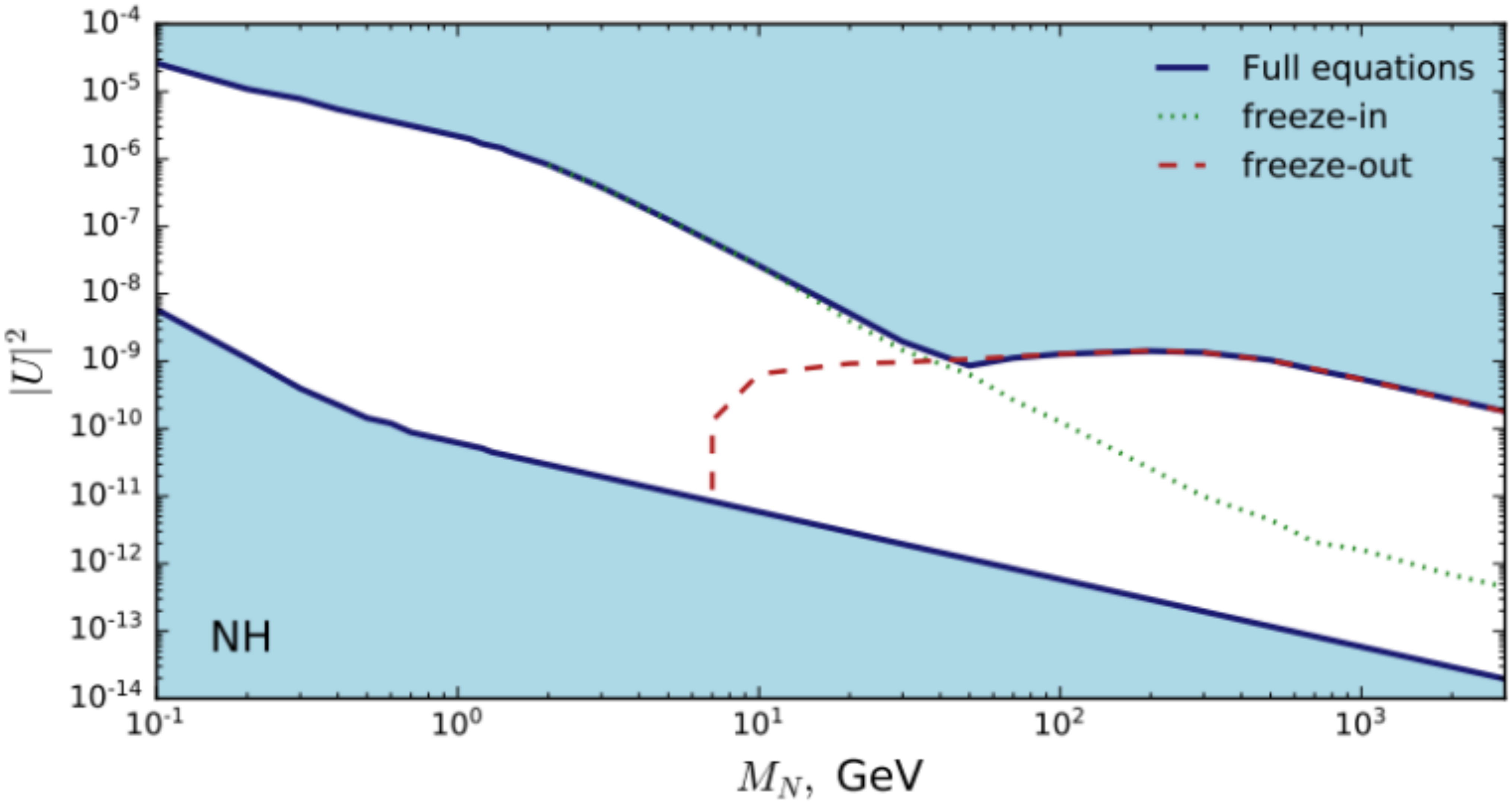


Boyarsky/MaD/Lasserre/Mertens/Ruchayskiy 18

Leptogenesis Senarios



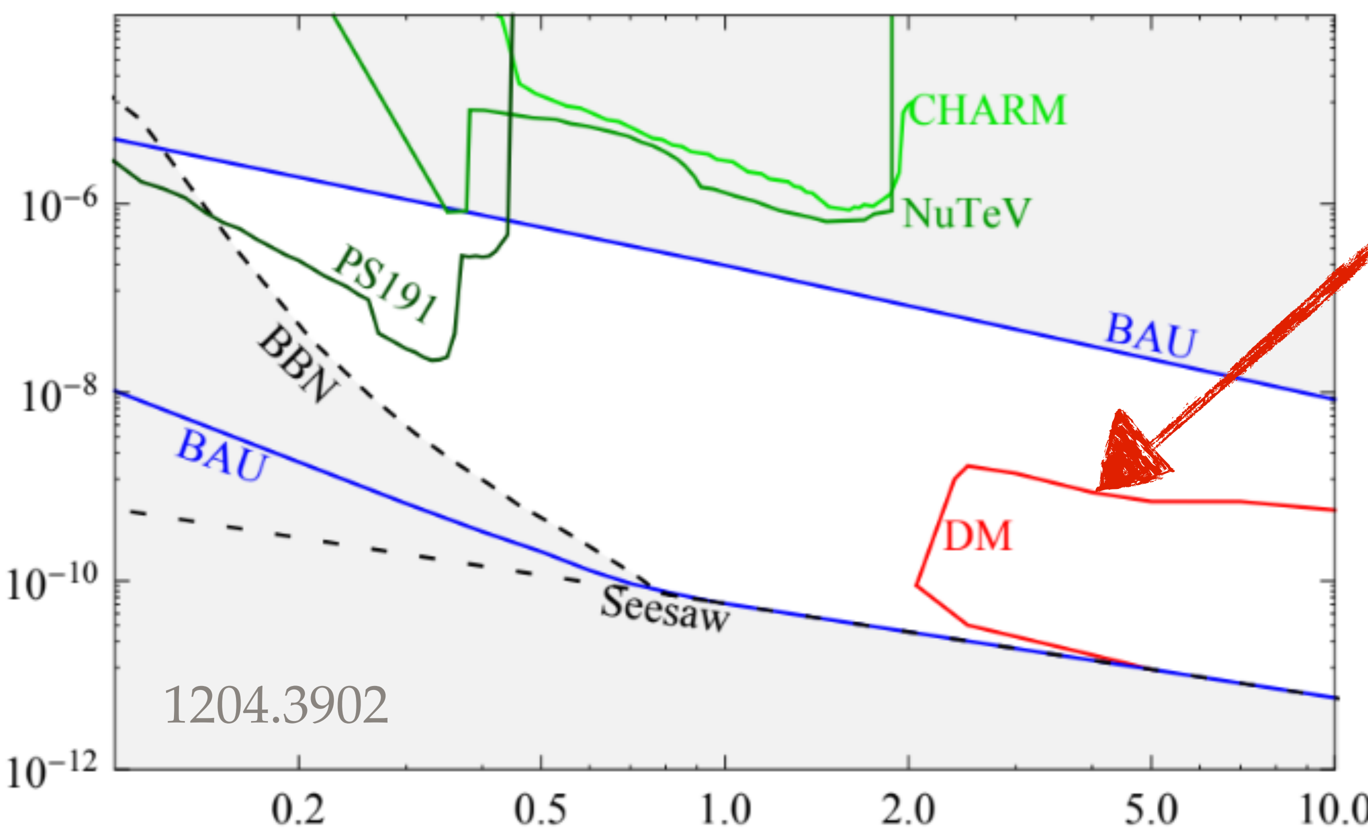
Leptogenesis with 2RHN



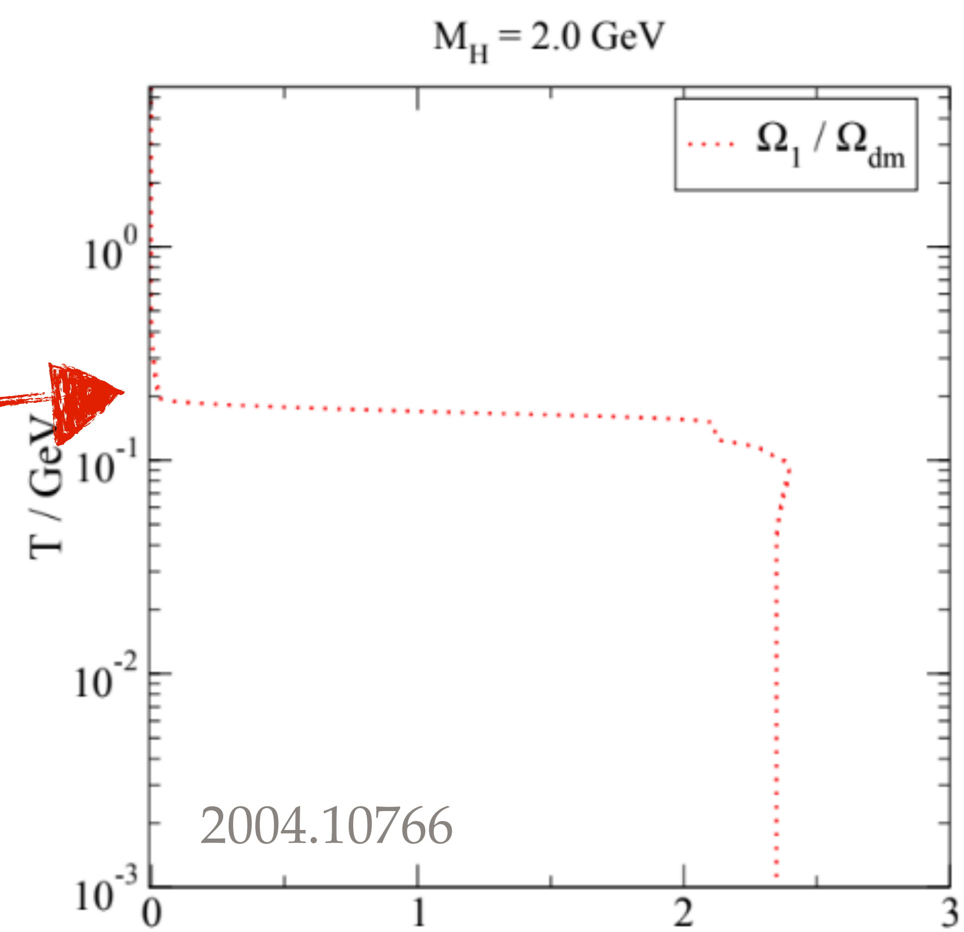
The region in which the freeze-out scenario ("resonant leptogenesis") and freeze-in scenario ("ARS leptogenesis") work overlap!

Klaric/Shaposhnikov/Timirsyasov 2008.13771

How to make a large lepton asymmetry?



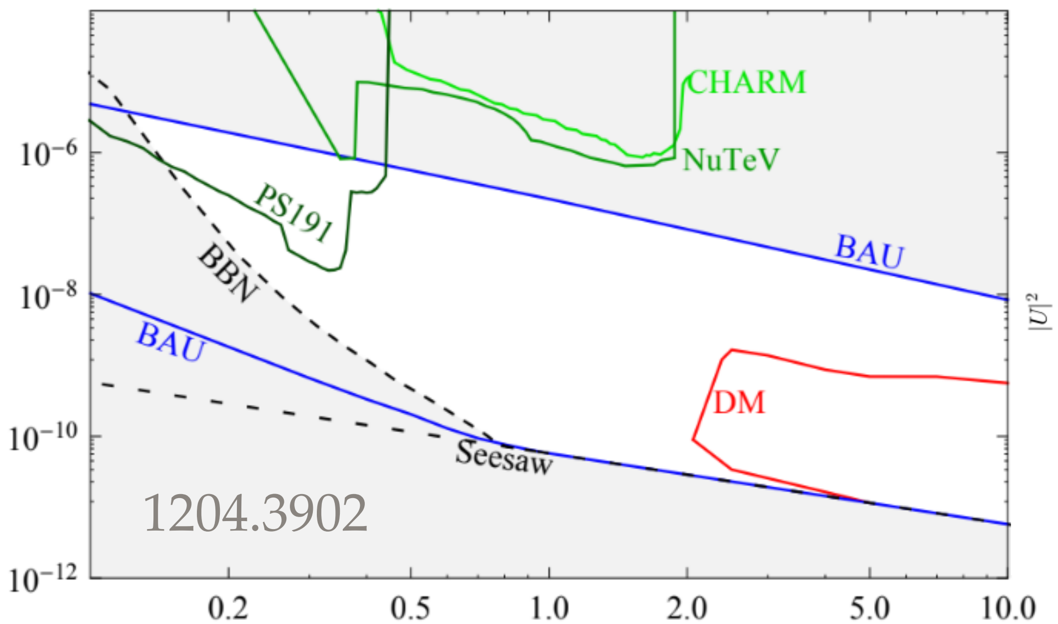
- We showed a long time ago that the asymmetry needed for resonant DM production can be generated in the νMSM from the late time decay of the heavier N
- But our analysis contained a number of simplifications

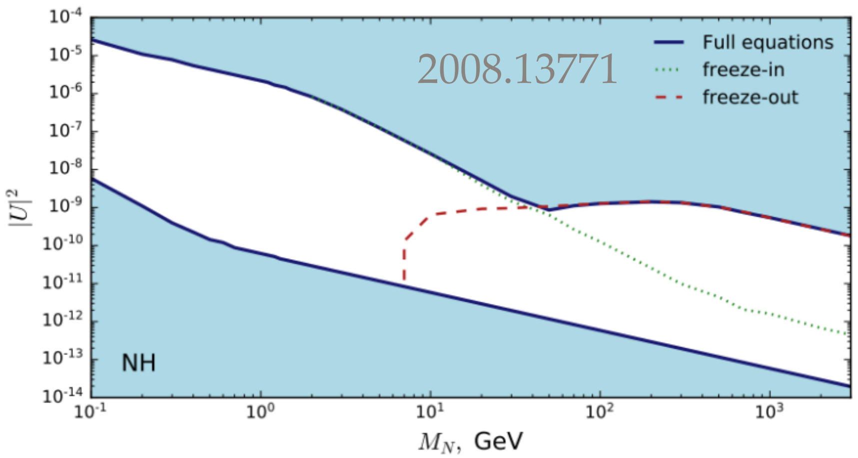


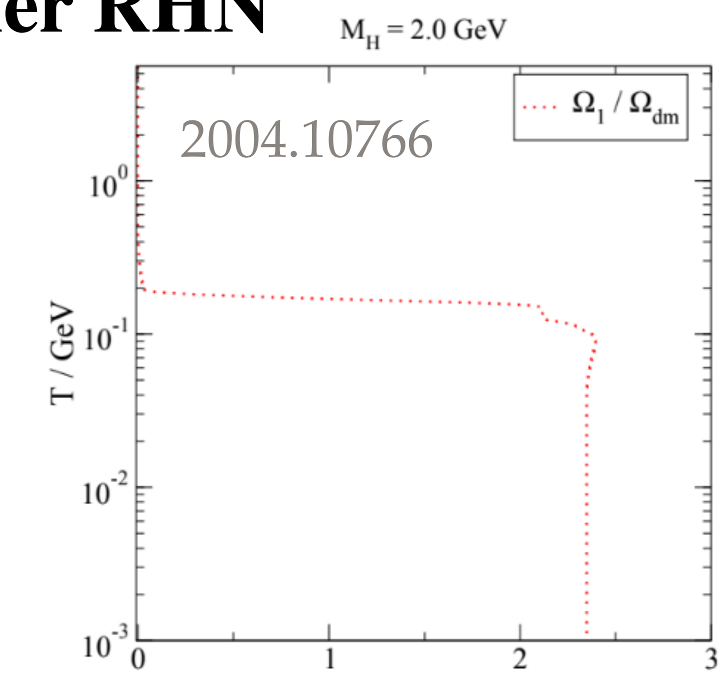
- Recently Mikko Laine's group confirmed our claim with a more sophisticated treatment
- But no full parameter space scan has been done

Complementarity in the νMSM

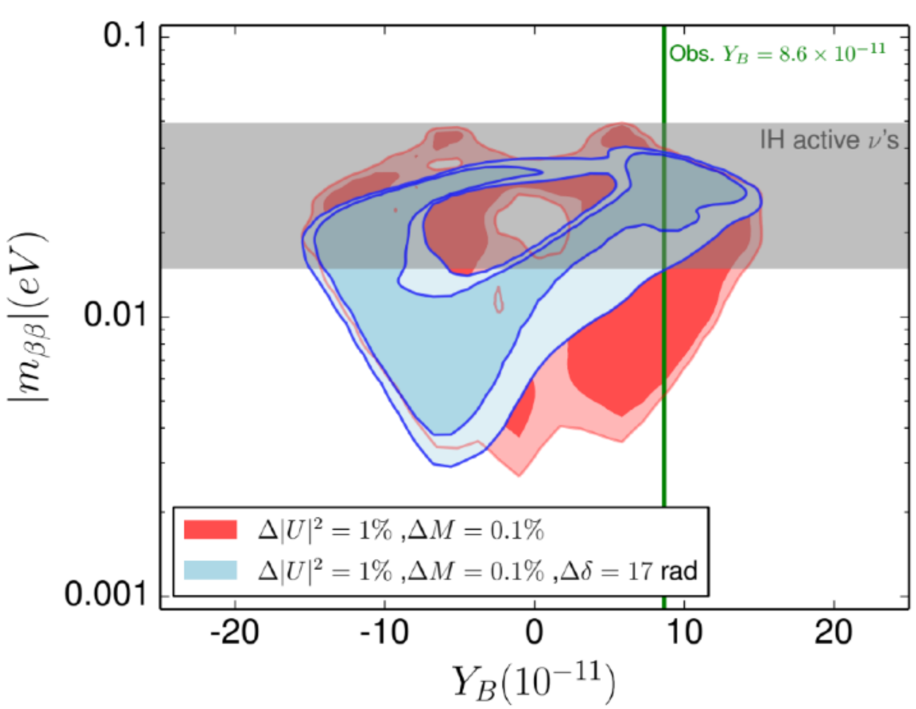
Resonant production relies on properties of the two heavier RHN



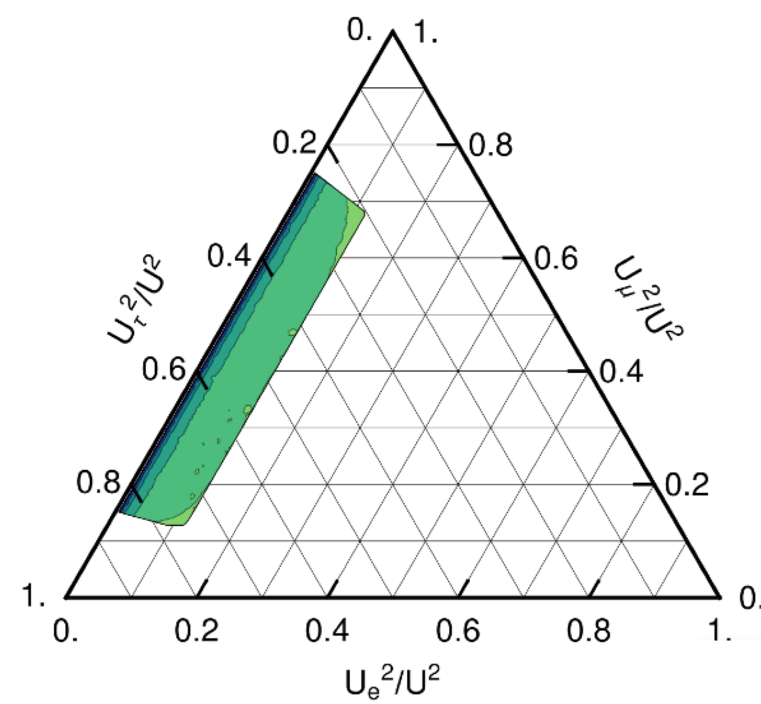




Their properties can be constrained by combining data from many sources



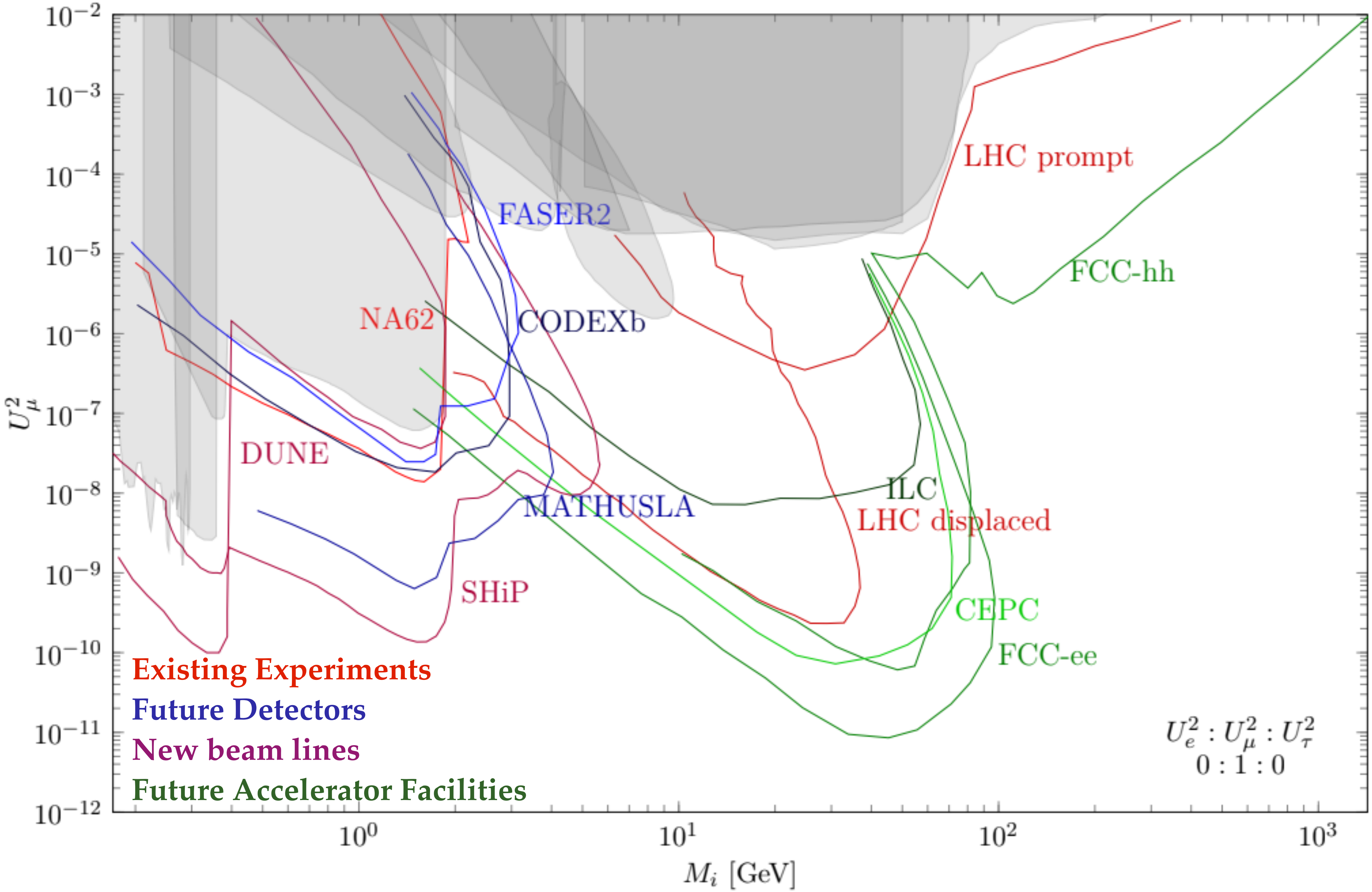
1606.06719



More cross-frontier studies needed!

1710.03744 1609.09069

Accelerator-based Heavy Neutrino Searches



Complementarity in the νMSM

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

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

Collider searches for heavy neutrinos

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

absolute neutrino mass searches (KATRIN ect.)

CMB and LSS : absolute neutrino mass

non-accelerator searches (TRISTAN…)

astrophysics: supernovae etc.

neutrinoless double β decay

Structure formation: simulation, observation

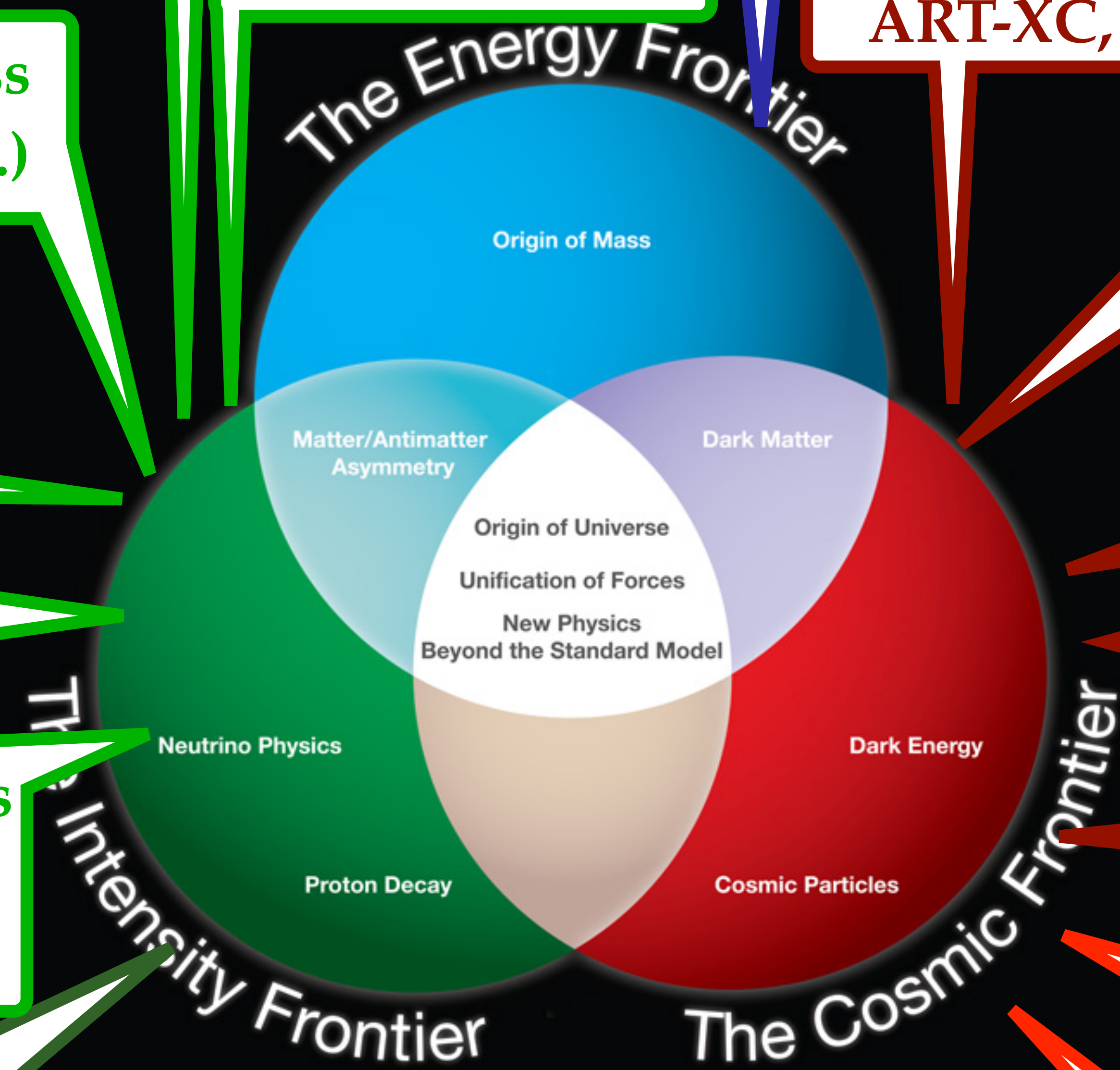
fixed target experiments (SHiP, NA62, DUNE, T2K..)

IGM temperature: WDM vs CDM

Theory: leptogenesis parameter region

neutrino oscillation experiments DUNE, Hyper-K

Theory: Sterile neutrino DM production



RF, NF, EF, CF, TF

Overview

- introduction
- model independent bounds

  phase space density

  indirect detection (x-ray)

  nuclear β decay spectra

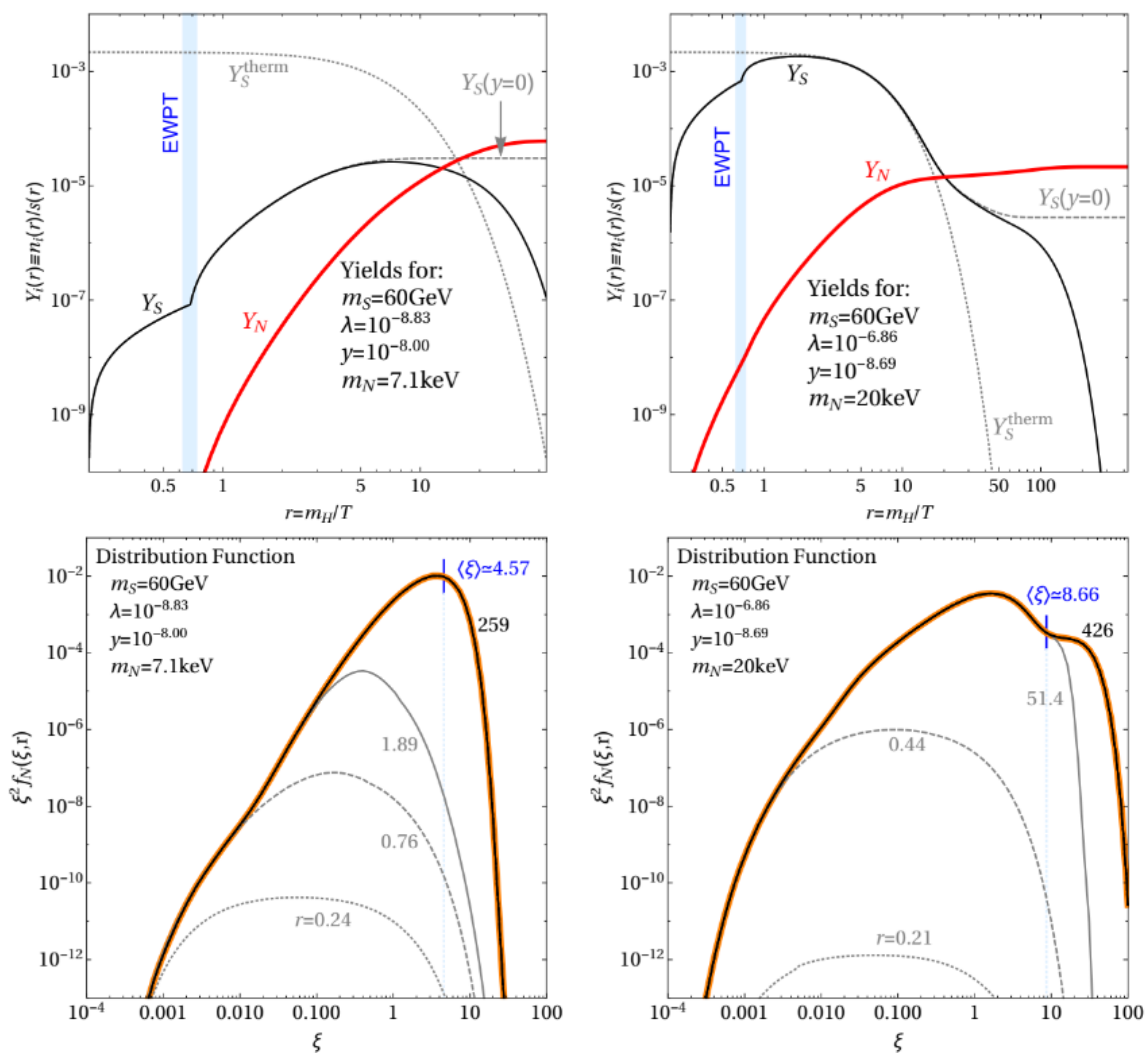
- model dependent bounds

  minimal model (νMSM)

  DM from scalar decay

Example I: DM from scalar singlet decay

consider scalar singlet model: $\mathcal{L} = \mathcal{L}_{\rm SM} + \left[\frac{i}{2}\overline{N}\partial\!\!\!/ N + \frac{1}{2}\left(\partial_\mu S\right)\left(\partial^\mu S\right) - \frac{y}{2} S\overline{N^c}N + \text{h.c.}\right] - V_{\rm scalar} + \mathcal{L}_\nu$



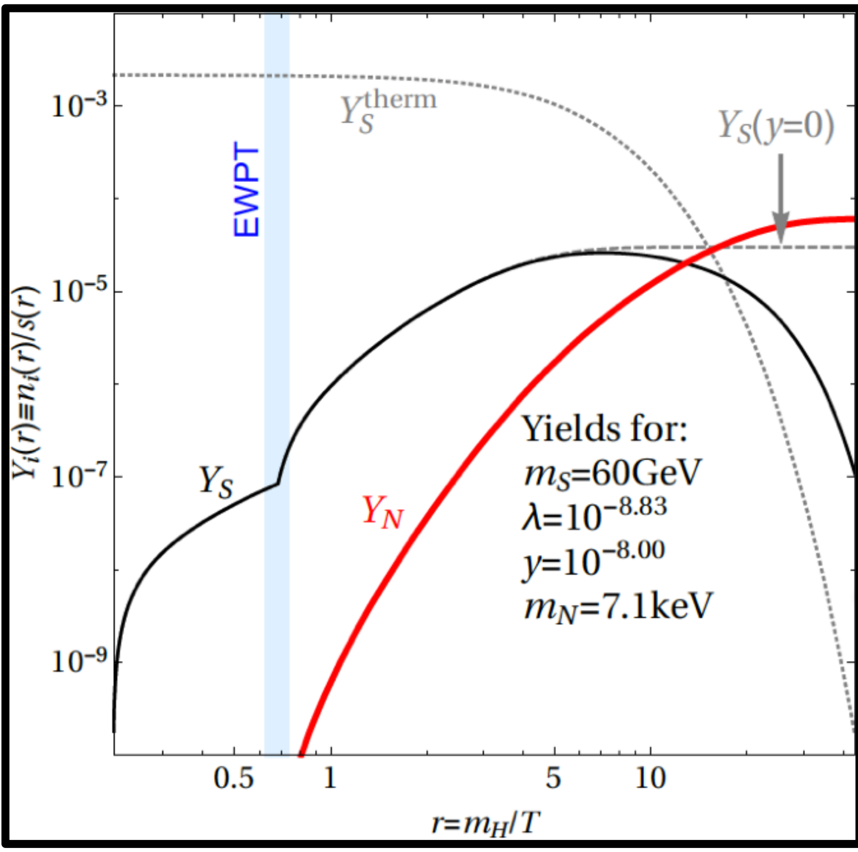
scalar potential:

$$V_{\rm scalar} = \frac{1}{2}m_S^2 S^2 + \frac{\lambda_S}{4}S^4 + 2\lambda\left(\Phi^\dagger\Phi\right)S^2$$

- **DM can be produced before scalar comes into equilibrium ("freeze in", left panel) or after ("freeze out", right panel)**
- **DM momentum distribution differs in both cases**

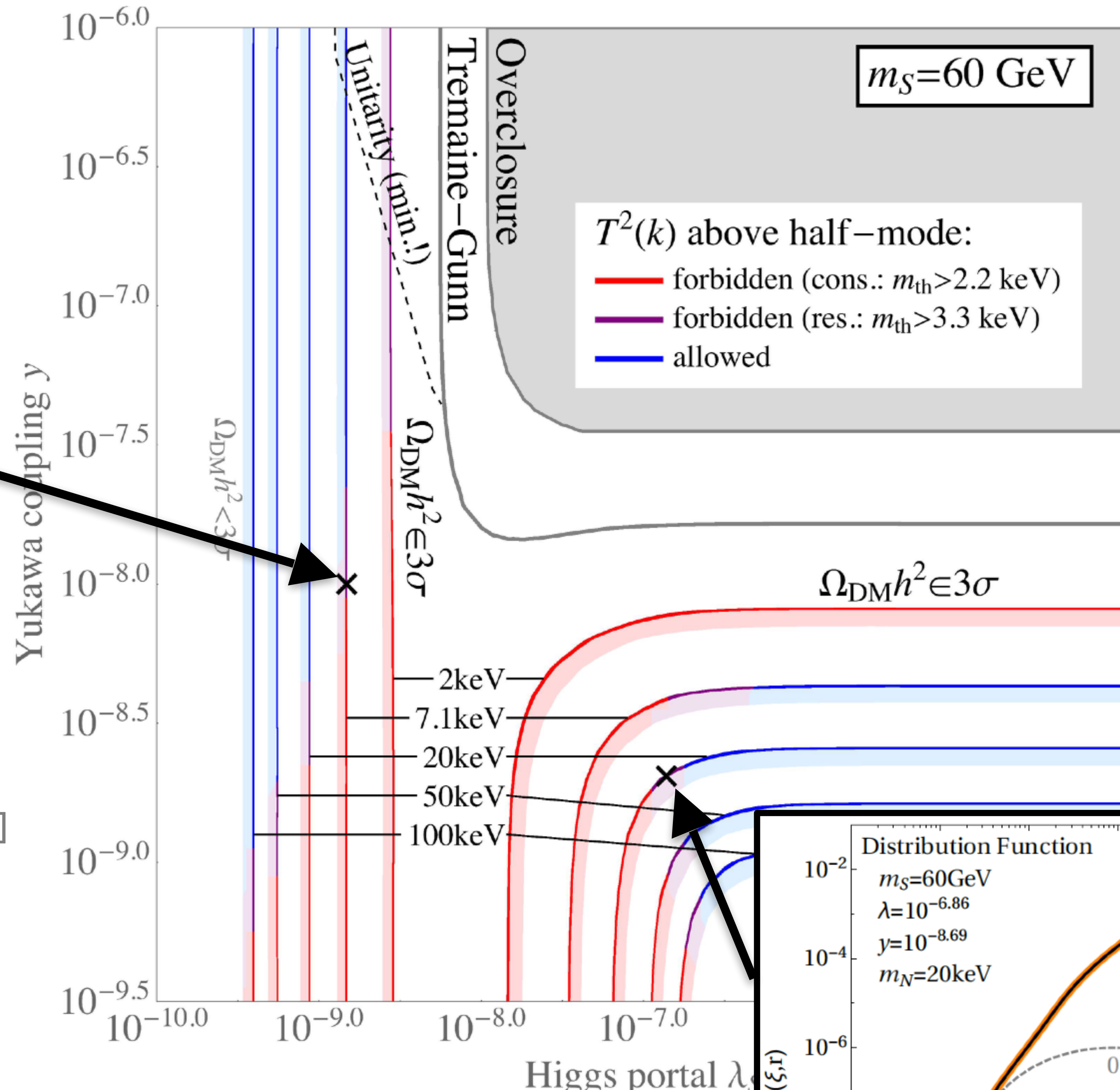
Konig / Merle / Totzauer 2004.10766

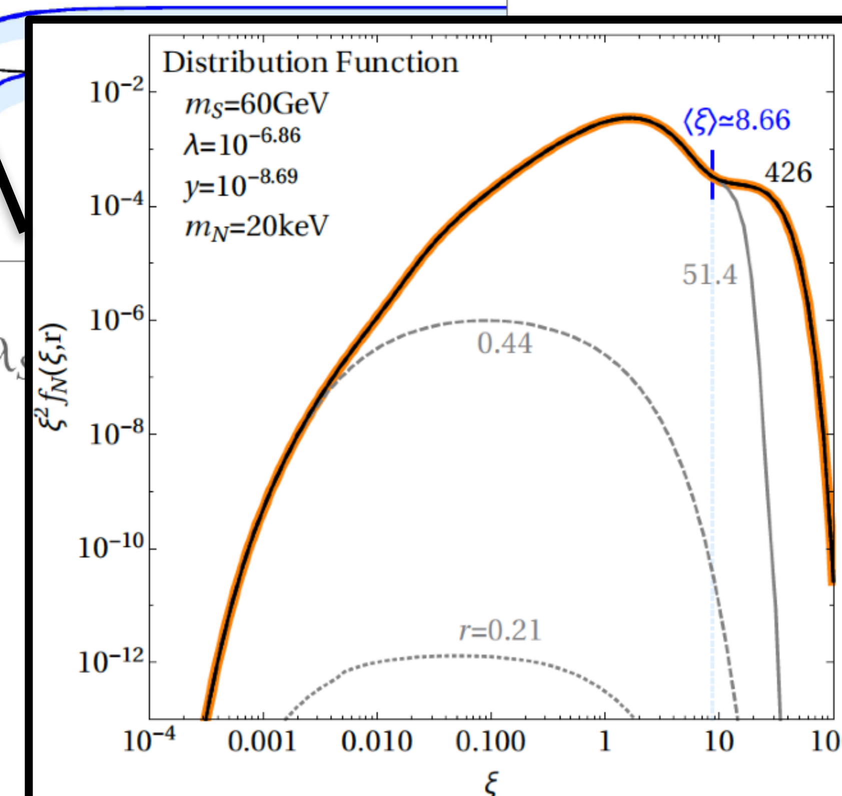
Example I: DM from scalar singlet decay



Scalar freezes in:

[Merle, Niro, Schmidt: JCAP **1403** (2014) 028]
[Merle, Totzauer: JCAP **1506** (2015) 011]
[König, Merle, Totzauer: JCAP 1611 (2016) 038]



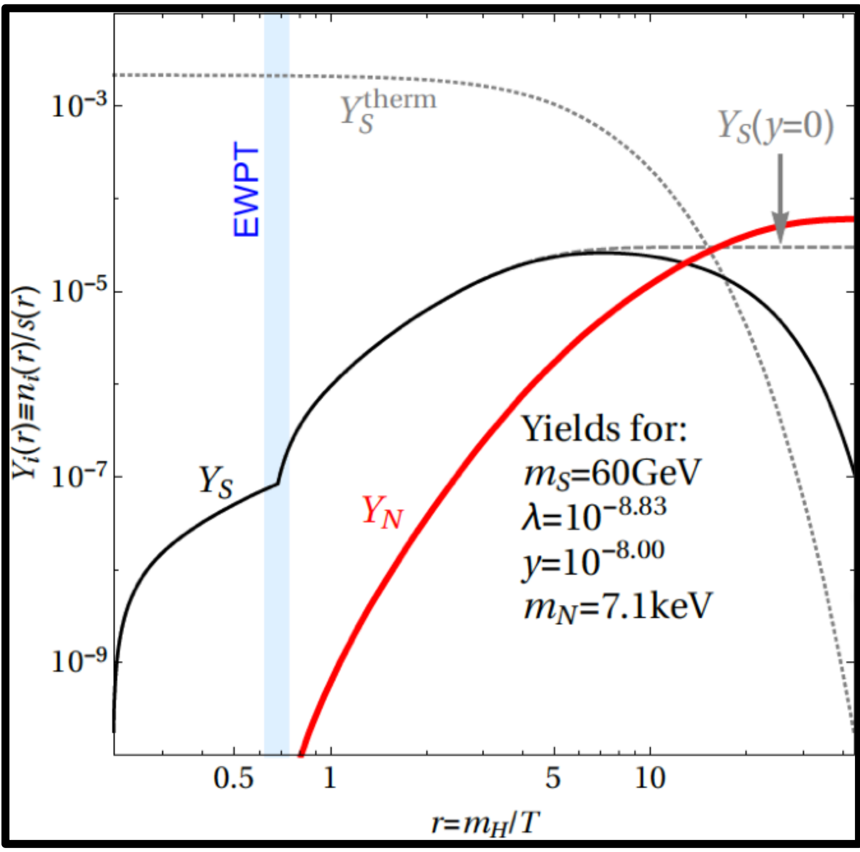


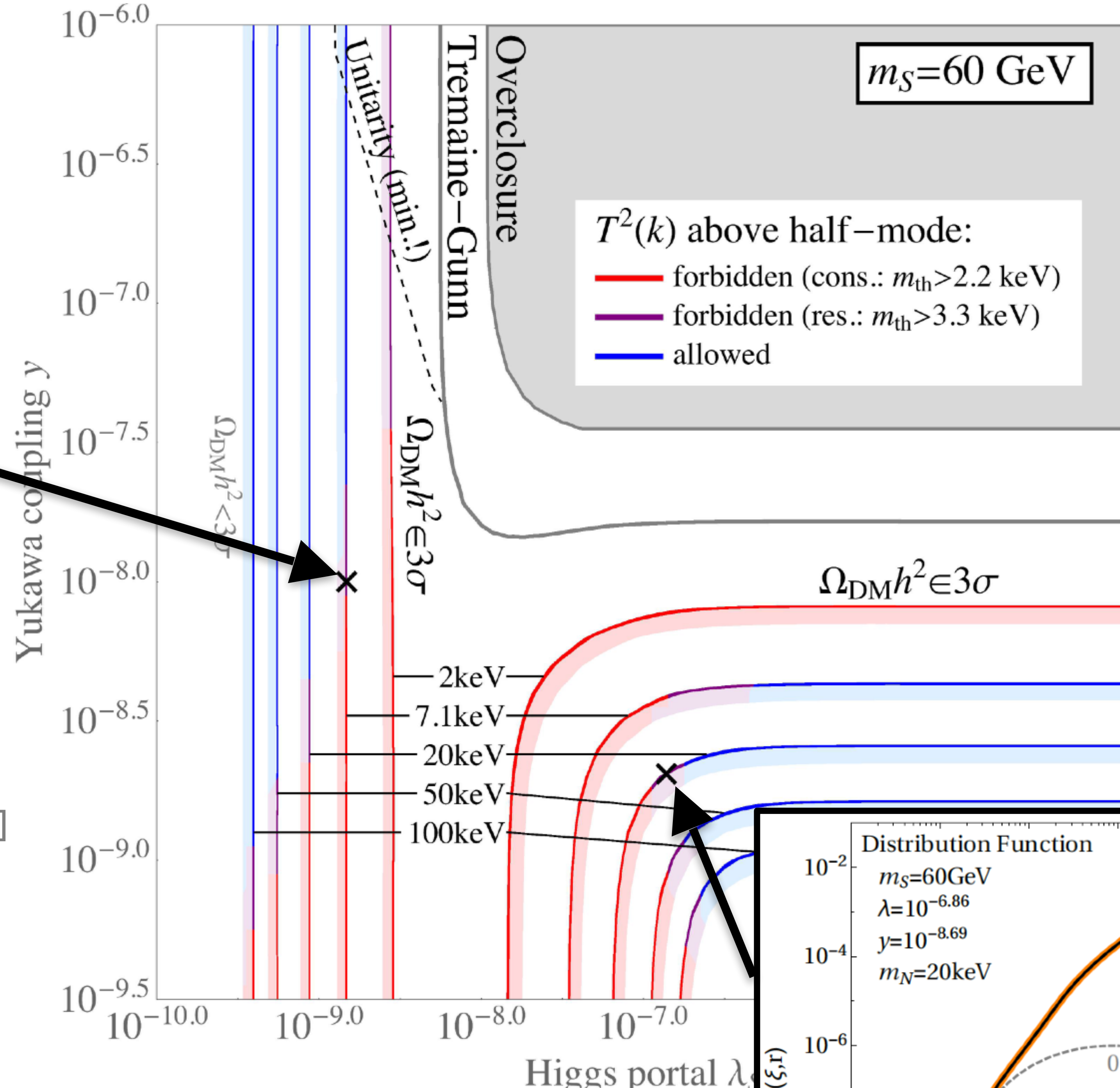
Scalar freezes out:

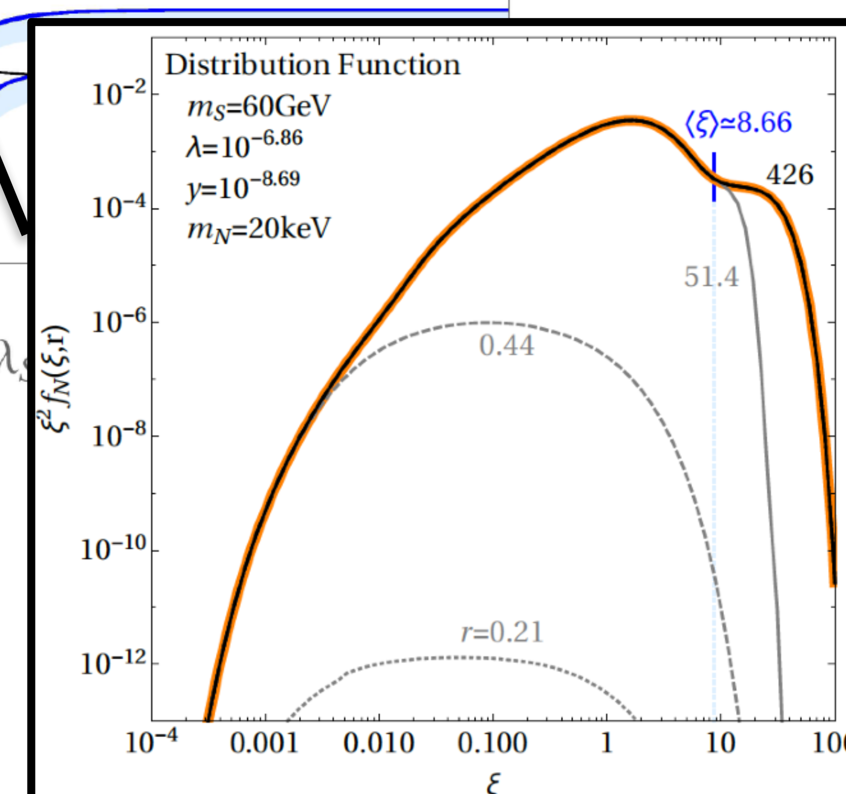
[M. Shaposhnikov, I. Tkachev,, Phys. Lett. **B639** (2006) 414-417]
[Kusenko: Phys. Rev. Lett. **97** (2006) 241301]
[Kusenko & Petraki: Phys. Rev. **D77** (2008) 045016]

Material by A. Merle

Example I: DM from scalar singlet decay







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[König, Merle, Totzauer: JCAP 1611 (2016) 038]

What about thermal corrections?
Usually small when scalar is singlet (except thermal mass from scalar self-coupling)

Scalar freezes out:

[M. Shaposhnikov, I. Tkachev,, Phys. Lett. **B639** (2006) 414-417]
[Kusenko: Phys. Rev. Lett. **97** (2006) 241301]
[Kusenko & Petraki: Phys. Rev. **D77** (2008) 045016]

Material by A. Merle

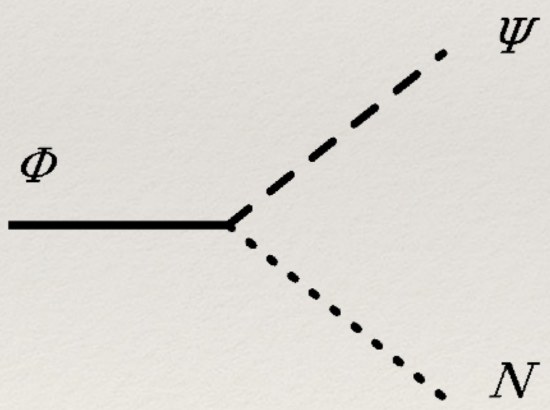
Example II: Leptophilic Higgs Model

new scalar Φ with Yukawa coupling $y\Phi\bar{\Psi}N$ to charged fermion Ψ and heavy neutrinos N

N = *sterile neutrino Dark Matter*

Φ = *leptophilic Higgs*

Ψ = *charged lepton*



N can be produced in decays $\Phi \to \Psi N$

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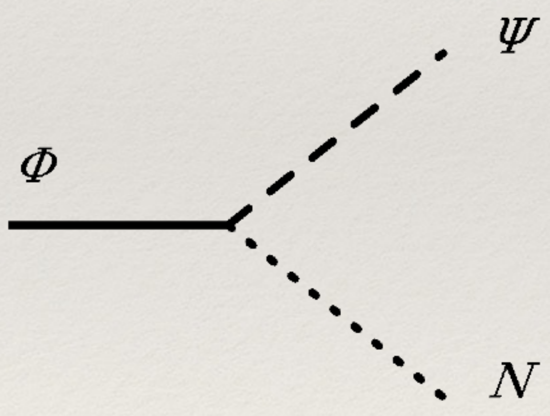

N can be produced in decays $\Phi \to \Psi N$

Decay occurs in the hot primordial plasma

- modified (quasi)particle dispersion relations
- quantum statistical effects
- scatterings of Φ in the plasma contribute to Dark Matter production

Example II: Leptophilic Higgs Model

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N = sterile neutrino Dark Matter

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Ψ = charged lepton

Decay rate in the medium MaD/Kang 16

$$\tilde{\Gamma}_{\Phi\mathbf{q}} \simeq \tilde{\Gamma}_0 \frac{M_\Phi}{m_\Phi} \frac{M_\Phi}{\Omega_{\Phi\mathbf{q}}} \left[\frac{T}{\mathbf{q}} \log\left[\frac{f_F\left(\frac{\Omega_{\Phi\mathbf{q}}-\mathbf{q}}{2}\right)}{f_F\left(\frac{\Omega_{\Phi\mathbf{q}}+\mathbf{q}}{2}\right)} \right] + \alpha \left[-1 + \frac{T}{\beta\mathbf{q}} \log\left[\frac{f_F\left(\beta\frac{(\Omega_{\Phi\mathbf{q}}-\mathbf{q})}{2}\right)}{f_F\left(\beta\frac{(\Omega_{\Phi\mathbf{q}}+\mathbf{q})}{2}\right)} \right] \right] \right].$$

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Φ = leptophilic Higgs

Ψ = charged lepton

enhancement from thermal Φ mass

suppression from time dilatation

suppression from Pauli blocking

$$\tilde{\Gamma}_{\Phi\mathbf{q}} \simeq \tilde{\Gamma}_0 \frac{M_\Phi}{m_\Phi}\frac{M_\Phi}{\Omega_{\Phi\mathbf{q}}}\left[\frac{T}{\mathbf{q}}\log\left[\frac{f_F\left(\frac{\Omega_{\Phi\mathbf{q}}-\mathbf{q}}{2}\right)}{f_F\left(\frac{\Omega_{\Phi\mathbf{q}}+\mathbf{q}}{2}\right)}\right]+\alpha\left[-1+\frac{T}{\beta\mathbf{q}}\log\left[\frac{f_F\left(\beta\frac{(\Omega_{\Phi\mathbf{q}}-\mathbf{q})}{2}\right)}{f_F\left(\beta\frac{(\Omega_{\Phi\mathbf{q}}+\mathbf{q})}{2}\right)}\right]\right]\right].$$

vacuum decay rate

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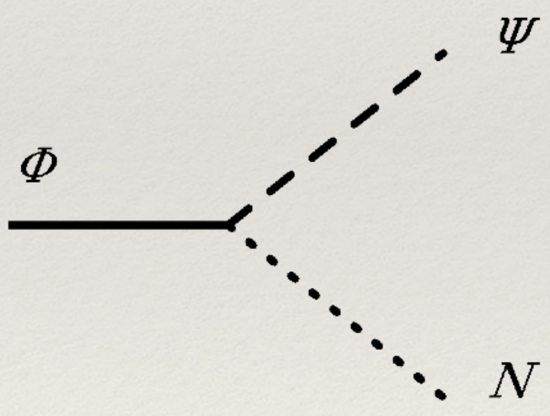

N can be produced in decays $\Phi \to \Psi N$

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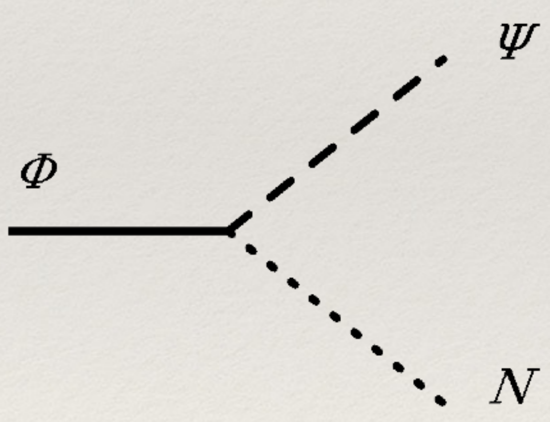
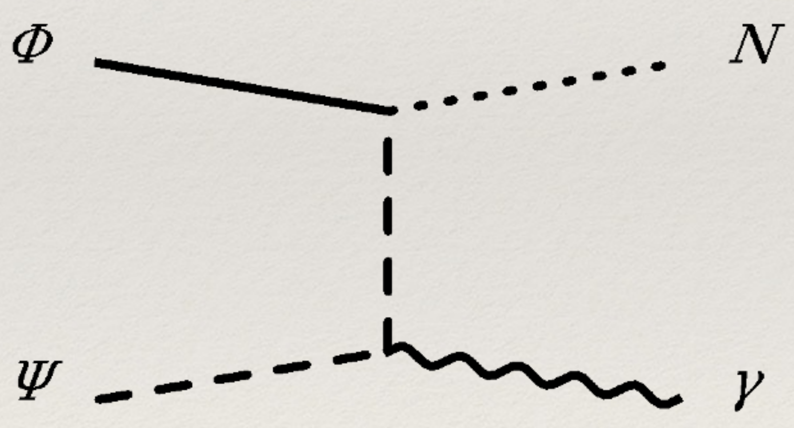


N can be produced in decays $\Phi \rightarrow \Psi N$



scatterings of Φ also contribute to the production

Example II: Leptophilic Higgs Model

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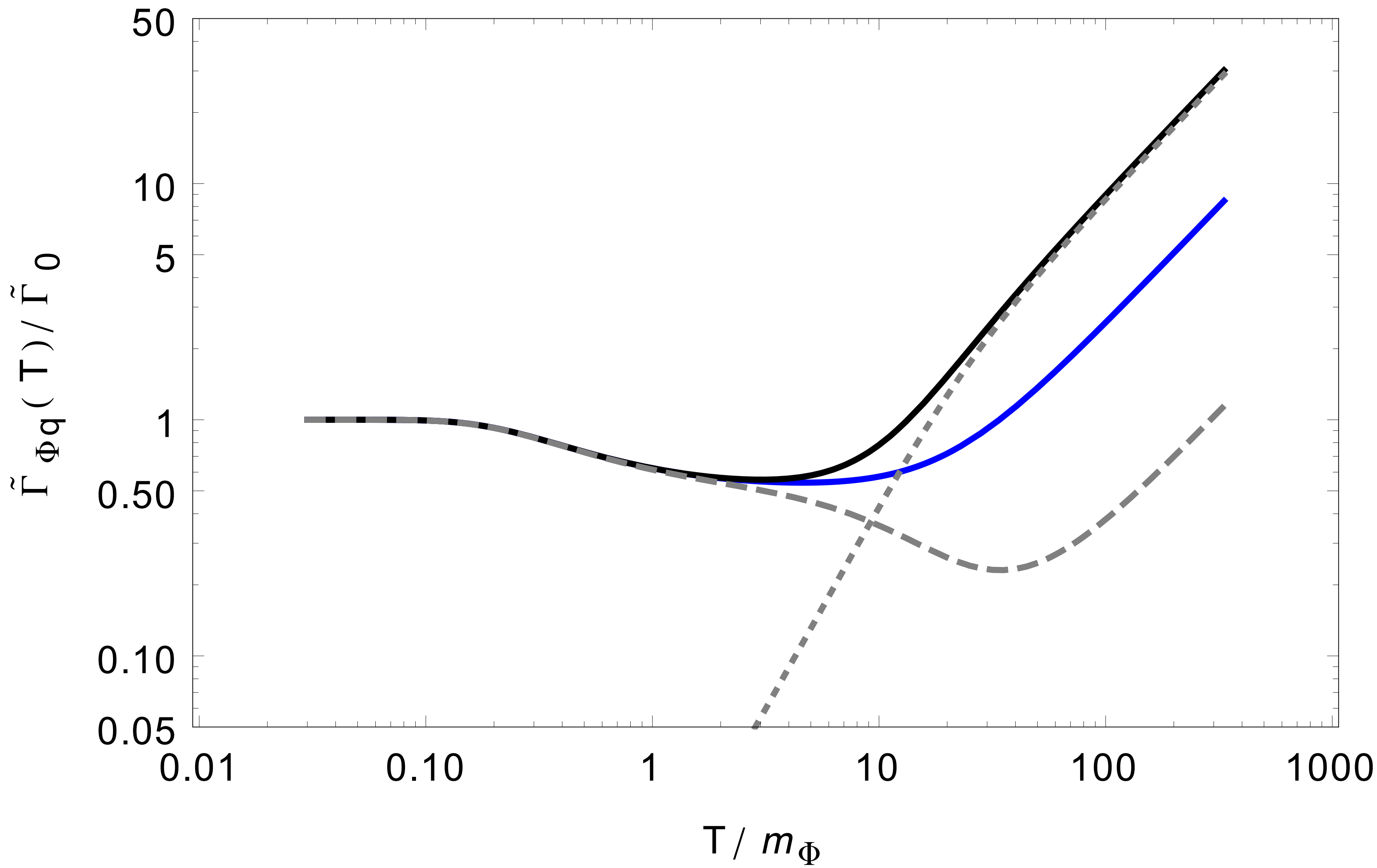
full production rate MaD/Kang 16



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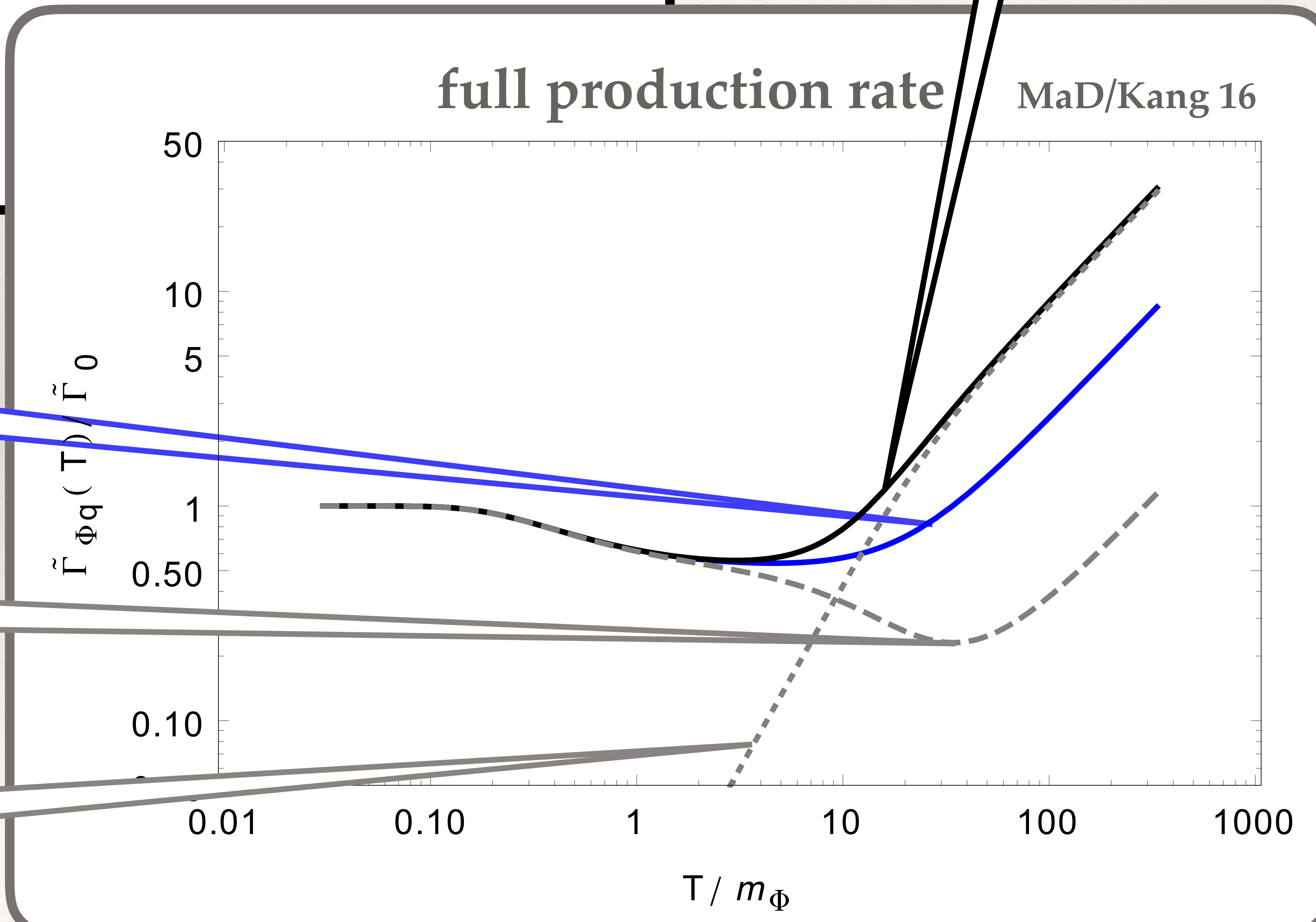

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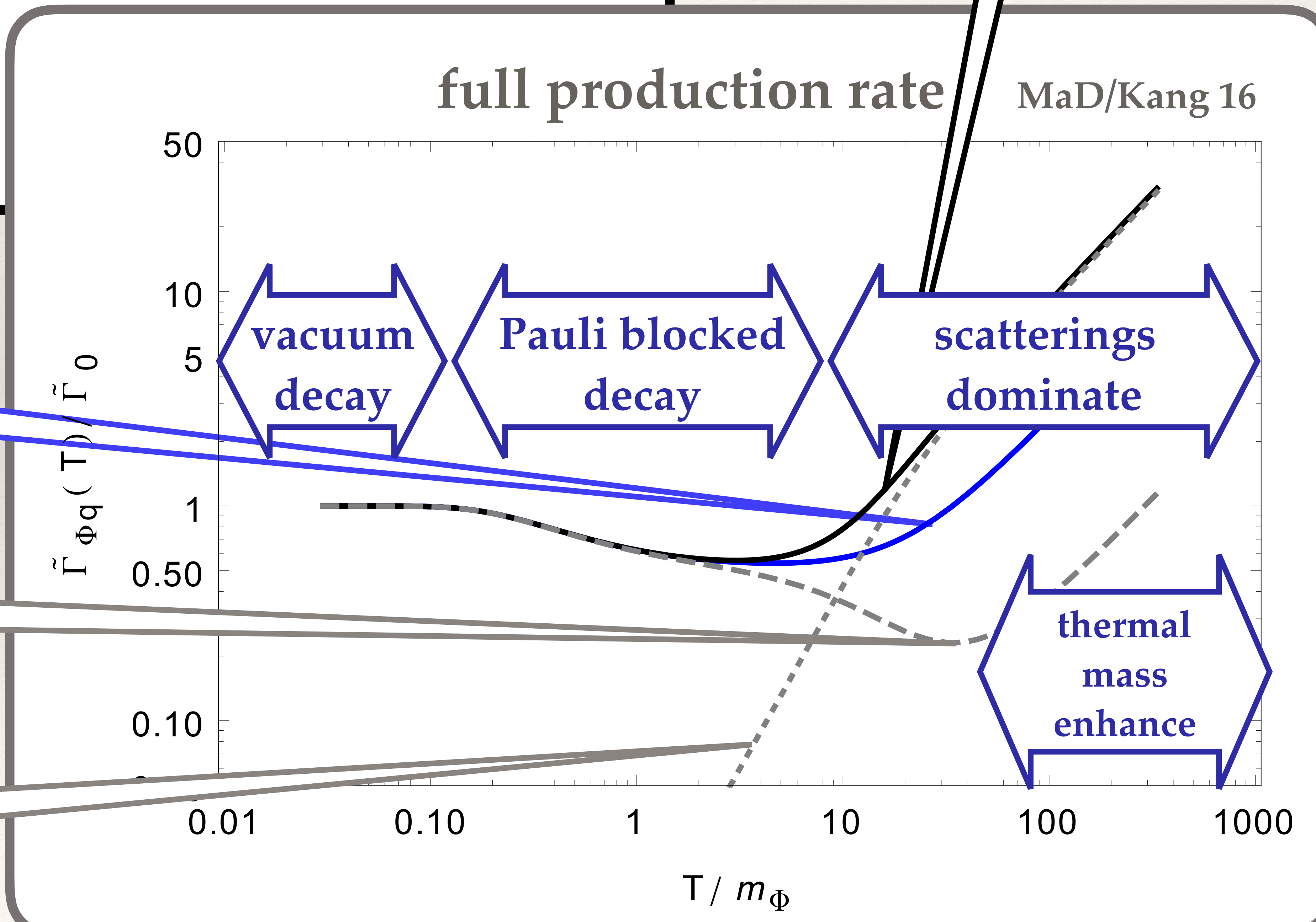
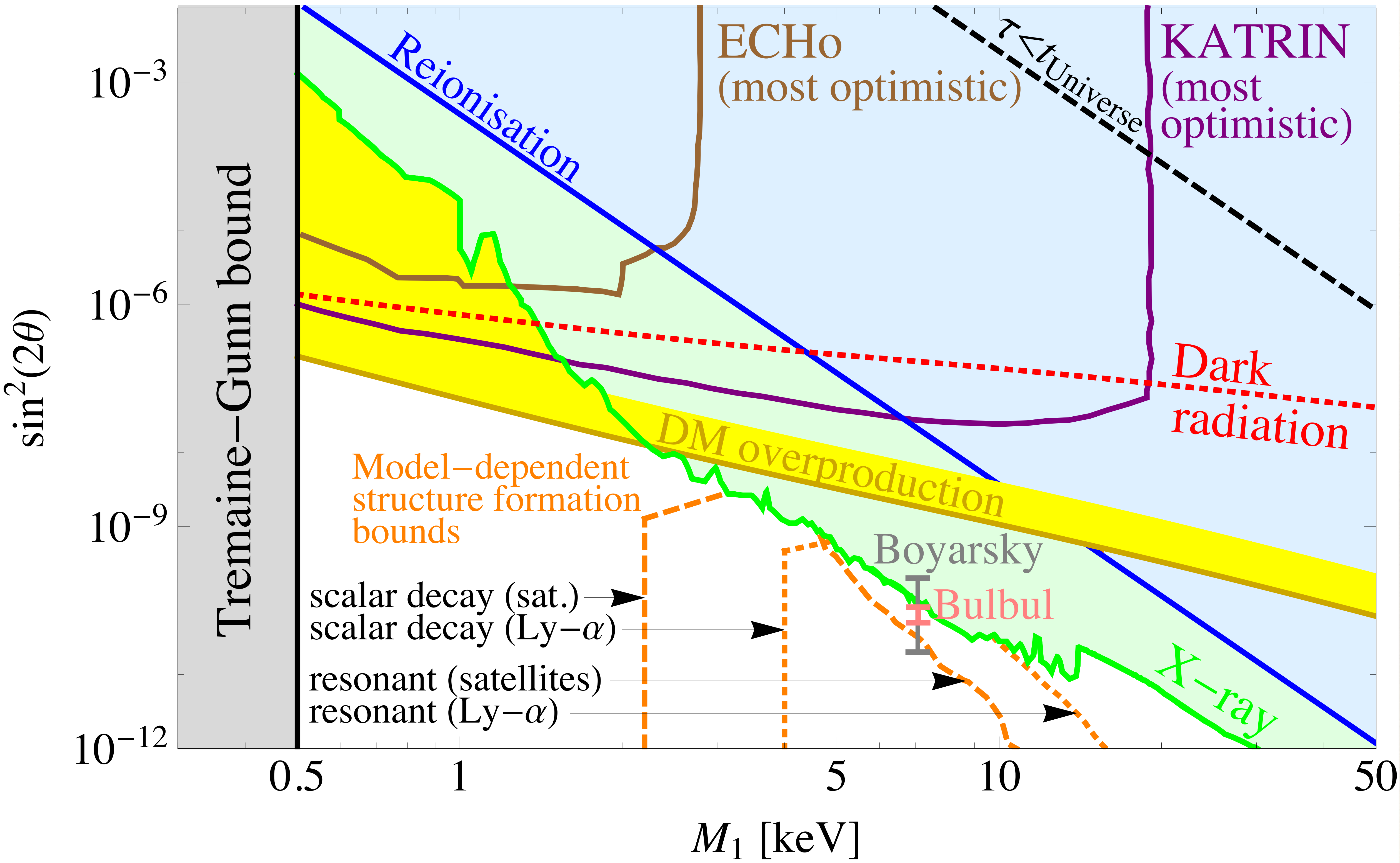


Heavy Neutrino Dark Matter Summary

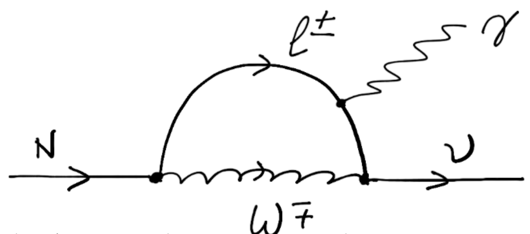


JCAP01(2017)025

Important Aspects of Sterile Neutrino DM

Indirect searches

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

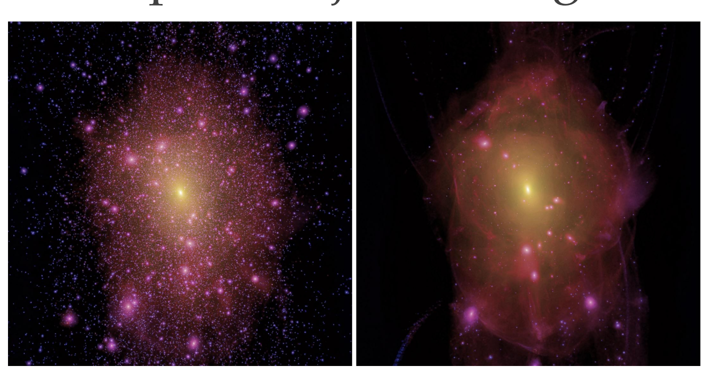


- 3.5 keV excess observed, but disputed
- new missions (XRISM, ATHENA, Lynx…)

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

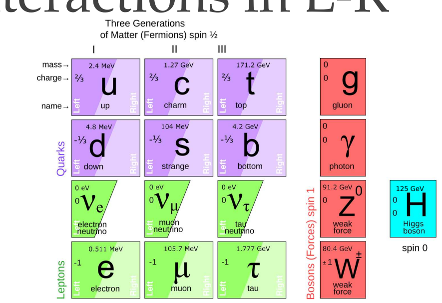


- uncertainties: baryonic feedback, IGM temperature…

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)



Phase space

- fermions are subject to Pauli principle

$$M > 25 \text{ eV}$$

- 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