Production of Sterile Neutrino Dark Matter

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Germany

Based on:

JCAP **1506** (2015) 011, Phys. Lett. **B749** (2015) 283, Int. J. Mod. Phys. **D22** (2013) 1330020, JCAP **1403** (2014) 028, JCAP **1107** (2011) 023, Phys. Rev. **D88** (2013) 113004,...

HAP Dark Matter 2015, Karlsruhe, Germany, 21-09-2015

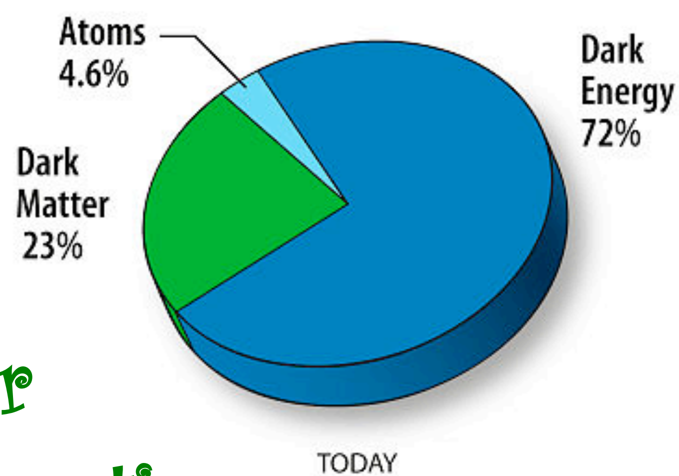
Contents:

1. Introduction

What do we actually know about Dark Matter?!?

KNOWN ☺

- abundance
- rough distribution
- important for structure formation



UNKNOWN ☹

- identity
- production mechanism
- exact velocity spectrum

THUS: We should be careful not to overlook possibilities just because they are "non-standard"!!!

1. Introduction

Maybe our most natural guess for the identity of DM is a yet unknown elementary particle:

- **historically most natural possibility: WIMP**
  - ↳ **because:**
    - **- weak interaction known → "NATURAL"**
    - **- stable WIMPs are predicted in particular by SUSY and by extra dimensions → "THEORY MOTIVATION"**
    - **- comparatively good detection prospects → "EXPERIMENTAL INTEREST"**
- **BUT: unfortunately no clear detection so far...**

→ we should seriously think about alternatives, which may become "standard" at some point

1. Introduction

*What is a **sterile neutrino** and why could it be a good Dark Matter candidate?!?*

- **ordinary ("active") neutrino ν_a: known elementary particle with very small mass and only weak interactions**

- **sterile neutrino ν_s: may have a larger mass (theoretically not predicted) and does not at all participate in standard interactions (BUT: small mixing with ν_a)**

- **thus: if produced in the right amounts and with a suitable velocity spectrum, ν_s could act as DM if they are sufficiently stable**

→ *Let's try...*

1. Introduction

Indeed, a sterile neutrino with a (typical) mass of a few keV may act as DM, but...

- needs non-standard production mechanism (ordinary thermal freeze-out does not work)

  ➔ WARM/COLD/NON-THERMAL (*depending on the details of the production process!!!*)

- typically, this is decaying Dark Matter: $N_1 \longrightarrow \nu+\gamma$

  ➔ MONOENERGETIC X-RAY SIGNAL e.g. from galaxies

- strong connection to ordinary neutrinos

  ➔ CONCRETE MODELS CAN BE TESTED USING LIGHT NEUTRINOS

2. DM-Production in General

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Dark Matter: ***What does this mean?!?***

THERMAL

$$f(p) = \frac{1}{\exp\left(\frac{\sqrt{p^2+m^2}}{T}\right) \pm 1}$$

HOT **WARM/COOL** **COLD**

$T \gg m$ $T \sim m$ $T \ll m$

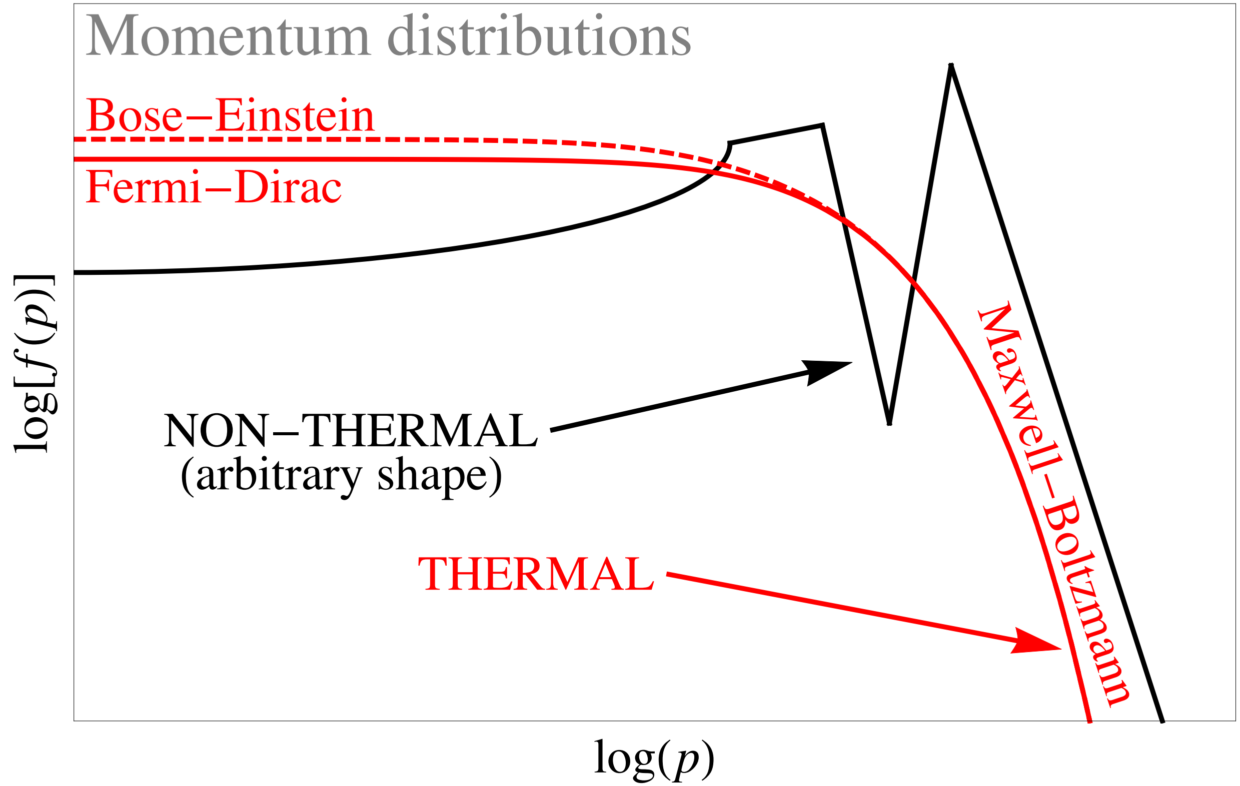
NON-THERMAL

$f(p)$ arbitrary

with:

$$\int_{p=0}^{\infty} p^2 f(p) dp < \infty$$

T not defined **!!!**



2. DM-Production in General

Four different mechanisms to produce sterile neutrino DM are often discussed:

ν_a-ν_s transitions [Dodelson, Widrow: Phys. Rev. Lett. **72** (1994) 17]

Resonant transitions [Shi, Fuller: Phys. Rev. Lett. **82** (1999) 2832], [Canetti *et al.*: Phys. Rev. **D87** (2013) 093006], [Venumadhav *et al.*: 1507.06655], ...

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OKAY!!!

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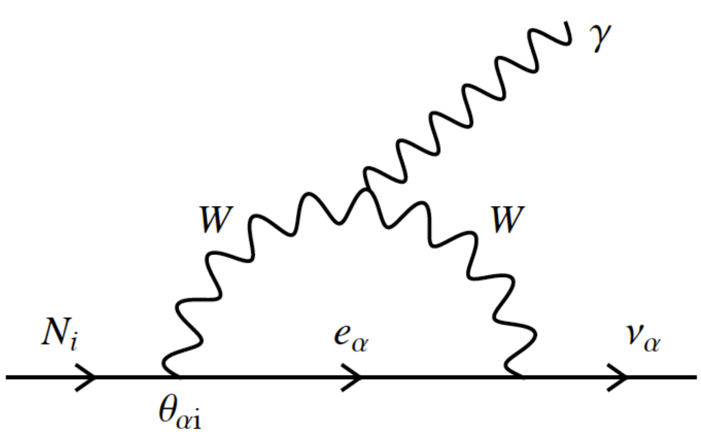
BARELY ALLOWED...

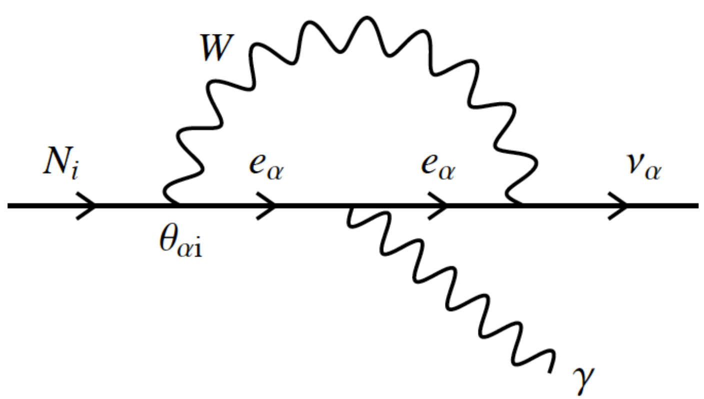
3. The Dodelson-Widrow mechanism

It could all be sooo simple...:

[Dodelson, Widrow: Phys. Rev. Lett. **72** (1994) 17]

- **slow non-resonant "oscillations" of active into sterile neutrinos can gradually produce the DM from the thermal plasma (just like "freeze-in") → *nice & simple***
- **this mechanism produces relatively hot DM → large mass M_1 needed, BUT decay into X-rays scales like M_1^5:**





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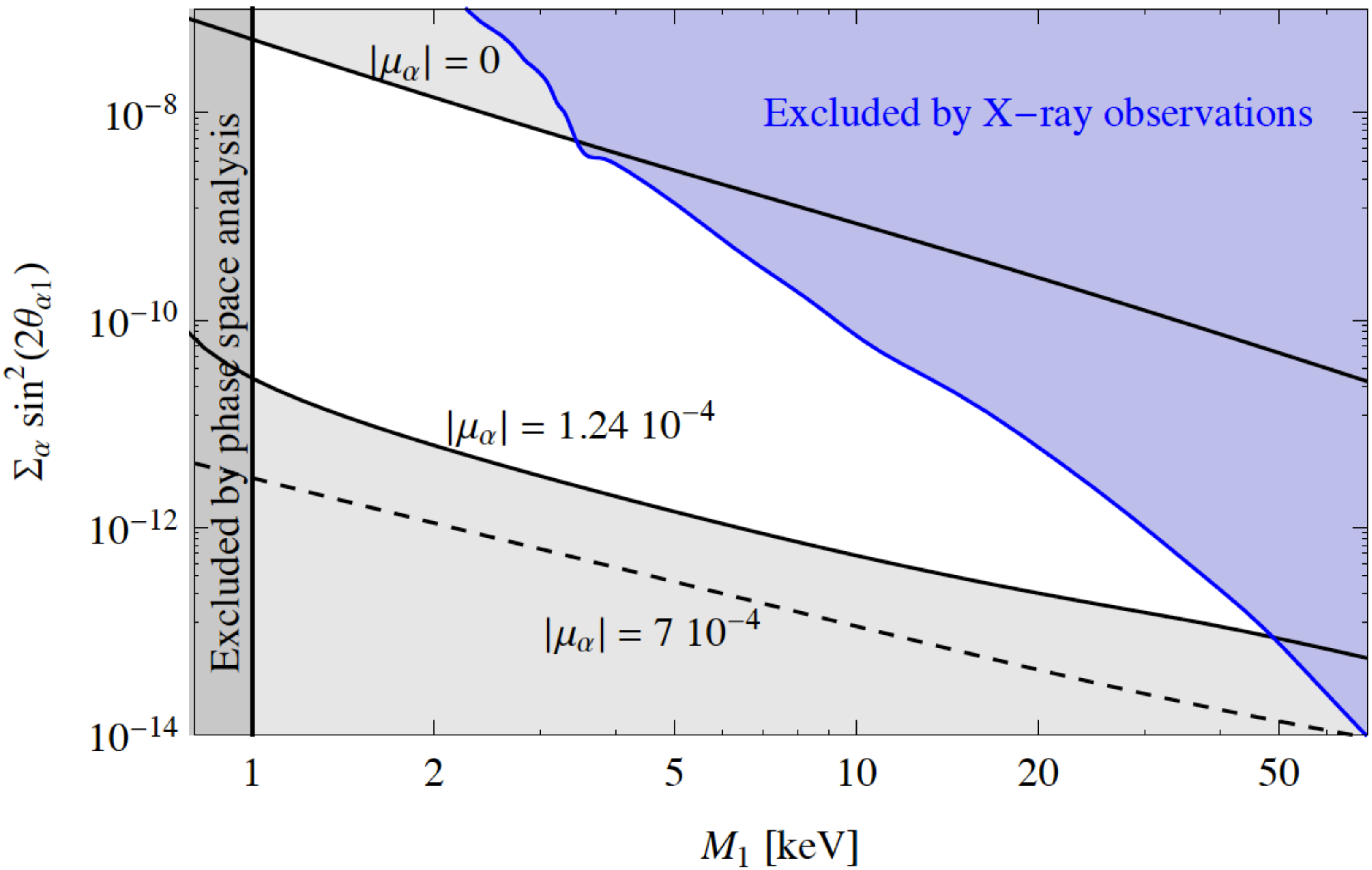

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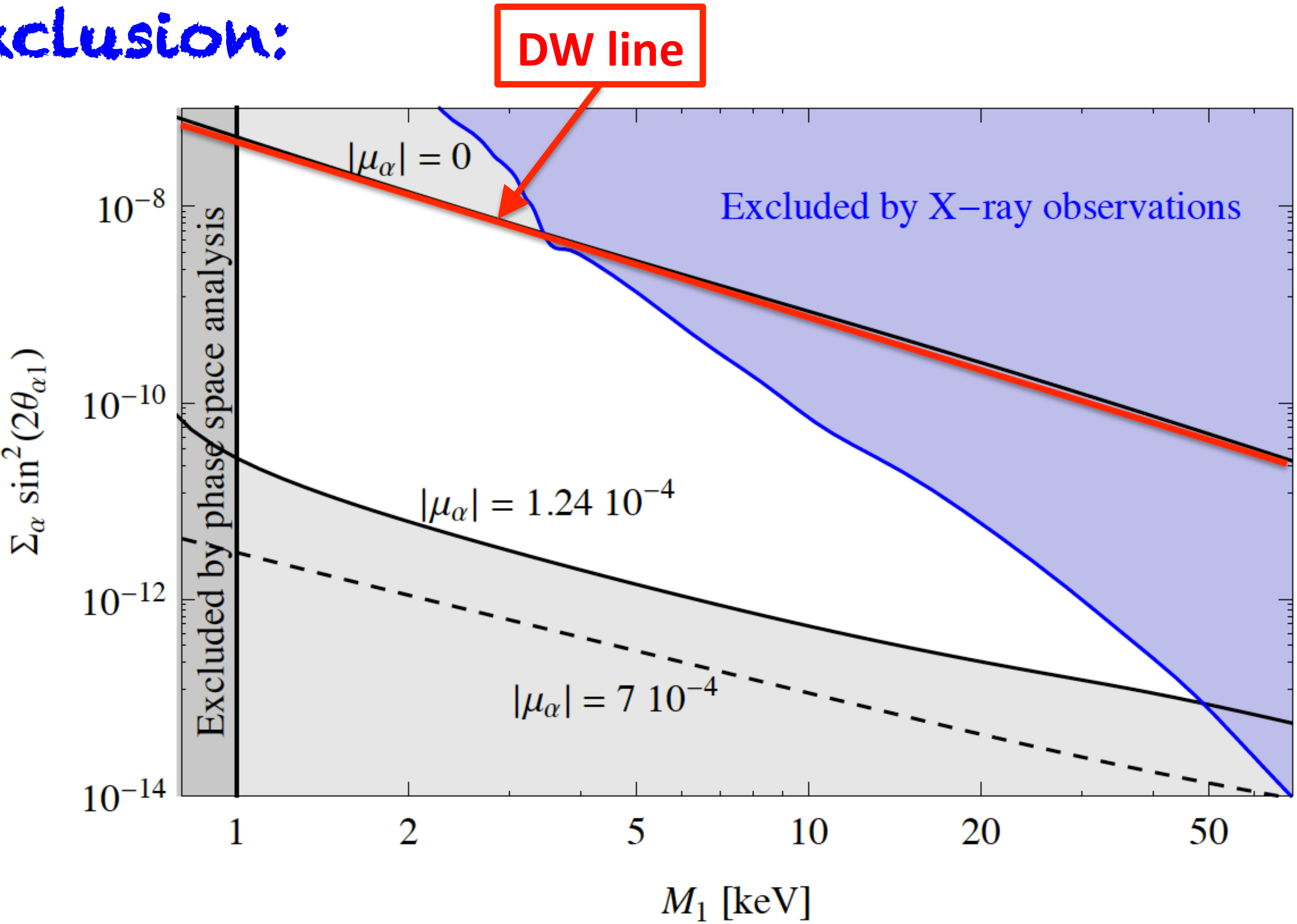

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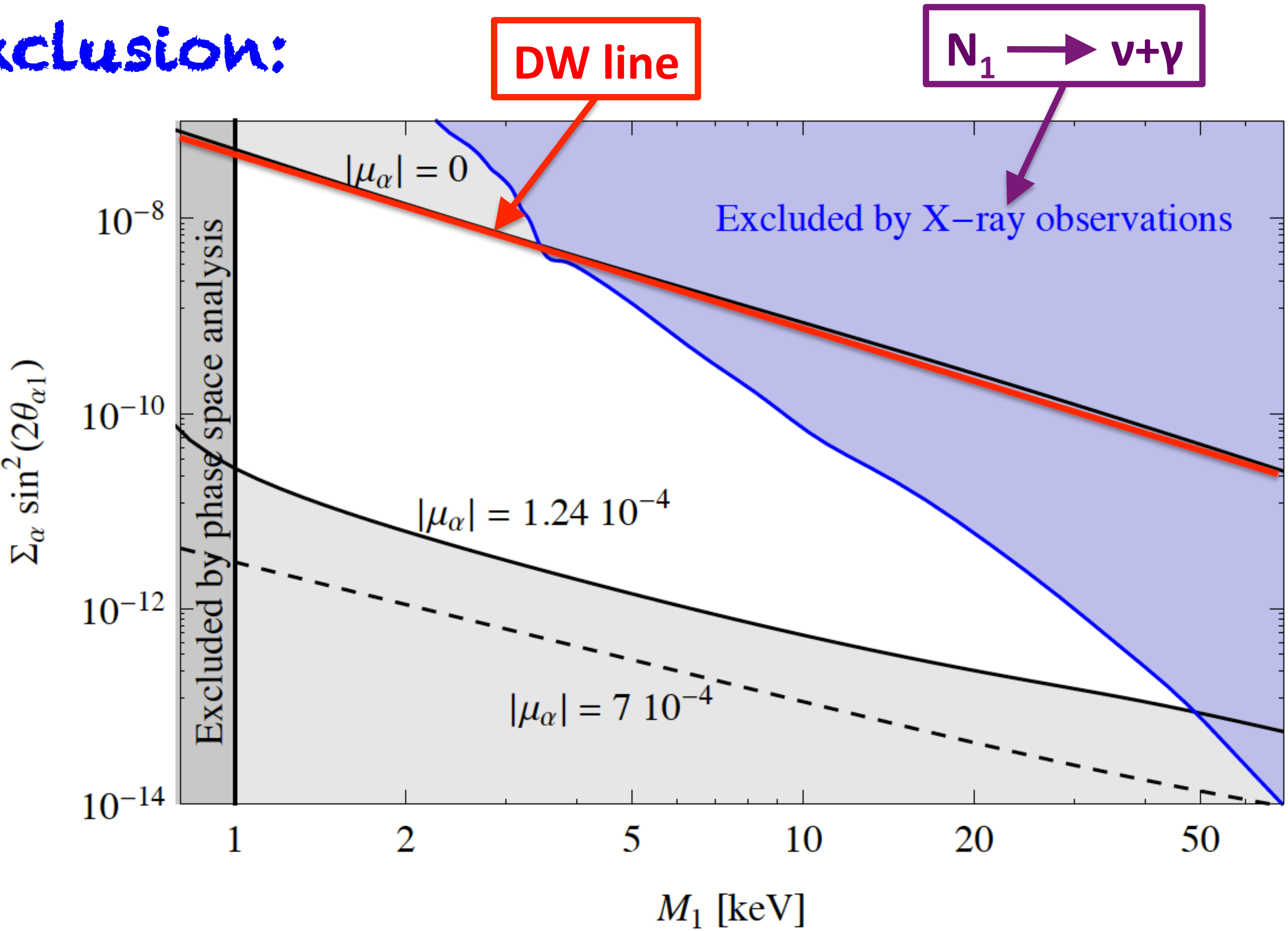

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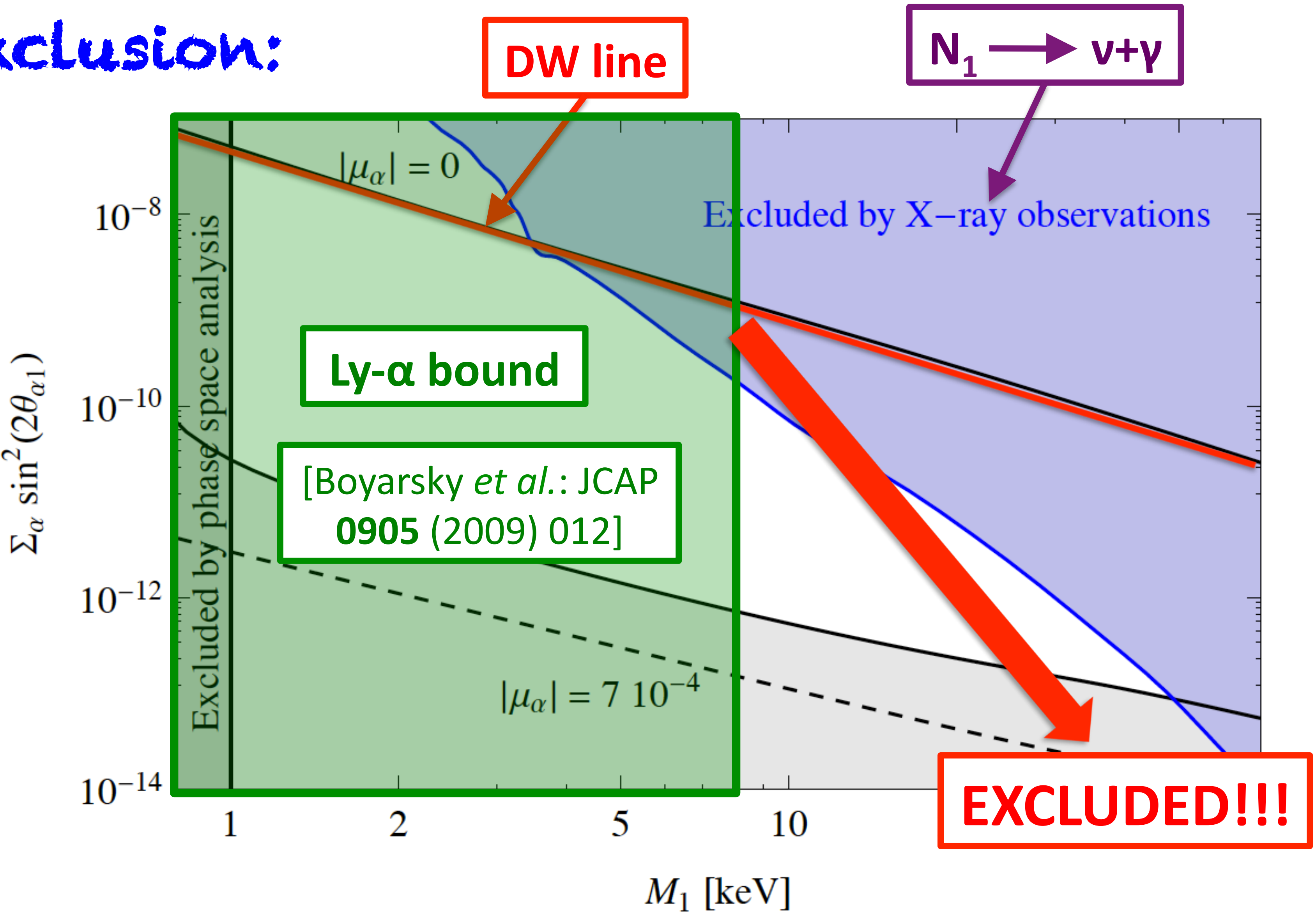

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BUT: Is this really the end of the story?!?

NO!!! We have disproved two common prejudices...

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1st prejudice:

DW produces spectrum with thermal shape

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1st prejudice:

DW produces spectrum with thermal shape

- appears as approximation in the original papers:

[Dodelson, Widrow: Phys. Rev. Lett. **72** (1994) 17; DW & Colombi: Astrophys. J. **458** (1996) 1]

$$f(q) = \frac{\beta_{\rm DW}}{\exp(q/T_{\rm DW}) + 1}$$

- used in structure/galaxy formation computations:

[Viel *et al.*: Phys. Rev. **D71** (2005) 063534; Herpich *et al.*: Mon. Not. Roy. Astron. Soc. **442** (2014) 176; Menci, Fiore, Lamastra: Mon. Not. Roy. Astron. Soc. **421** (2012) 2384; Lovell *et al.*: Mon. Not. Roy. Astron. Soc. **439** (2014) 300,...]

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1st prejudice:

DW produces spectrum with thermal shape

- in reality, even if g_S is taken constant, which it is NOT during DW production:

$$f_N^{\mathrm{DW}}(T_{\mathrm{f}}, p) \approx \frac{1}{\exp\left(\frac{p}{T_{\mathrm{f}}}\left(\frac{\langle g_S\rangle}{g_S(T_{\mathrm{f}})}\right)^{1/3}\right)+1} \int_{T_{\mathrm{ini}}}^{T_{\mathrm{f}}} \mathrm{d}T_2\, h\left(T_2, \frac{T_2}{T_{\mathrm{f}}}\left(\frac{g_S(T_2)}{g_S(T_{\mathrm{f}})}\right)^{1/3} p\right)$$

This function *h* (contains active-sterile mixing, mass difference, etc.) and the whole integral needs to vary SLOWLY with the momentum *p*!

➔ *not the case in reality...* ➔ NO THERMAL SHAPE!!!

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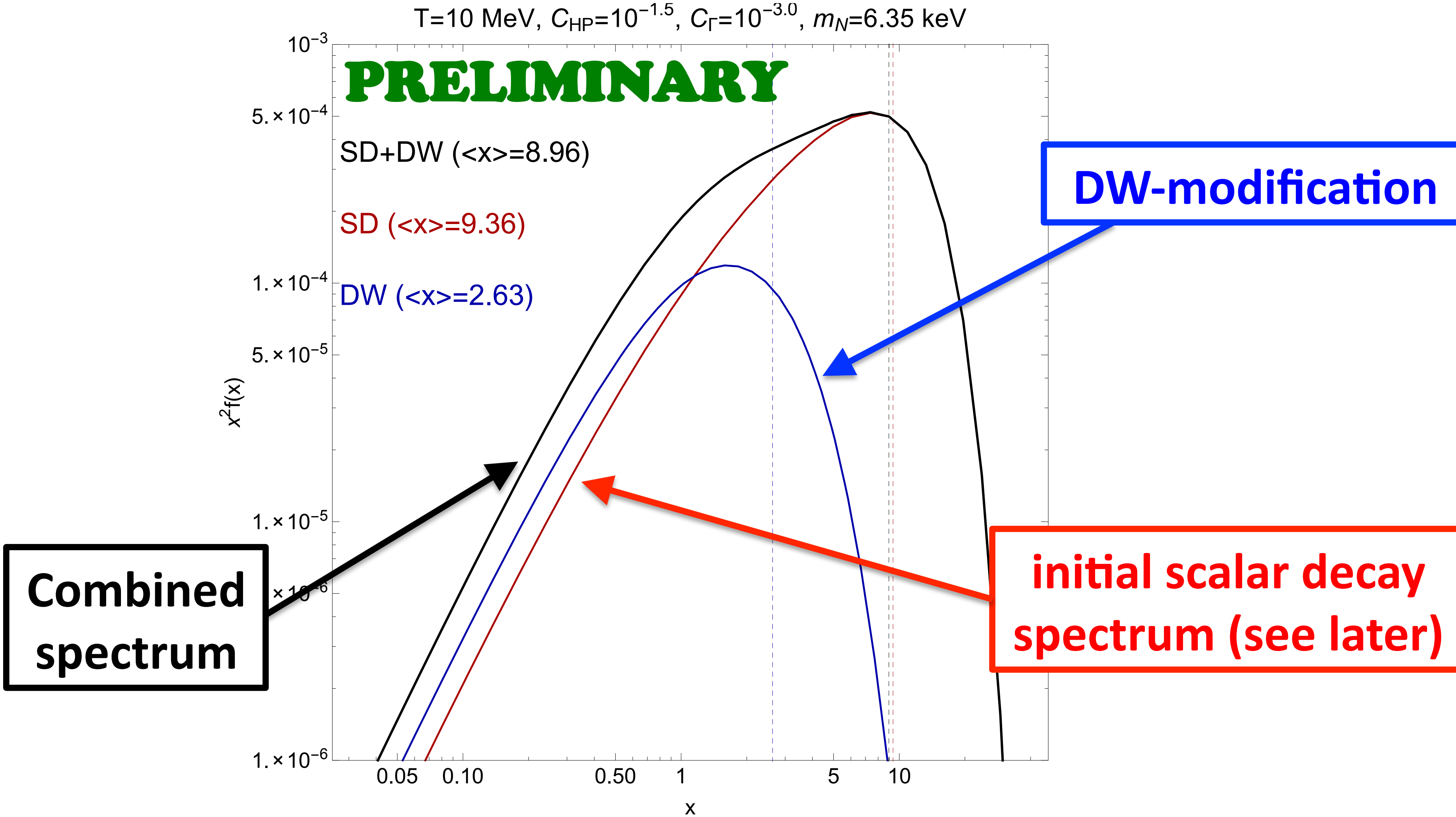
2nd prejudice:

DW always produces a too hot spectrum

- ***different for non-zero initial abundance: if DM is already present <u>before</u> DW sets in, the spectrum may experience non-trivial modifications***

- ***example: scalar decay production + <u>SUBSEQUENT</u> modification by the Dodelson-Widrow mechanism***

3. The Dodelson-Widrow mechanism



may shift the average momentum to <u>LOWER</u> values ("DW-cooling")

BUT: <u>*SMALL EFFECT*</u>!!! (DW-part can at most be a ~25% modification)

4. The Shi-Fuller mechanism

Maybe there is a good way out!

[Shi, Fuller: Phys. Rev. Lett. **82** (1999) 2832]

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Maybe there is a good way out!

[Shi, Fuller: Phys. Rev. Lett. **82** (1999) 2832]

- **just like for ordinary neutrinos in the Sun, active-sterile neutrino transitions could be resonantly enhanced by a sizeable lepton number asymmetry $|\mu_\alpha|$ present in the early Universe**

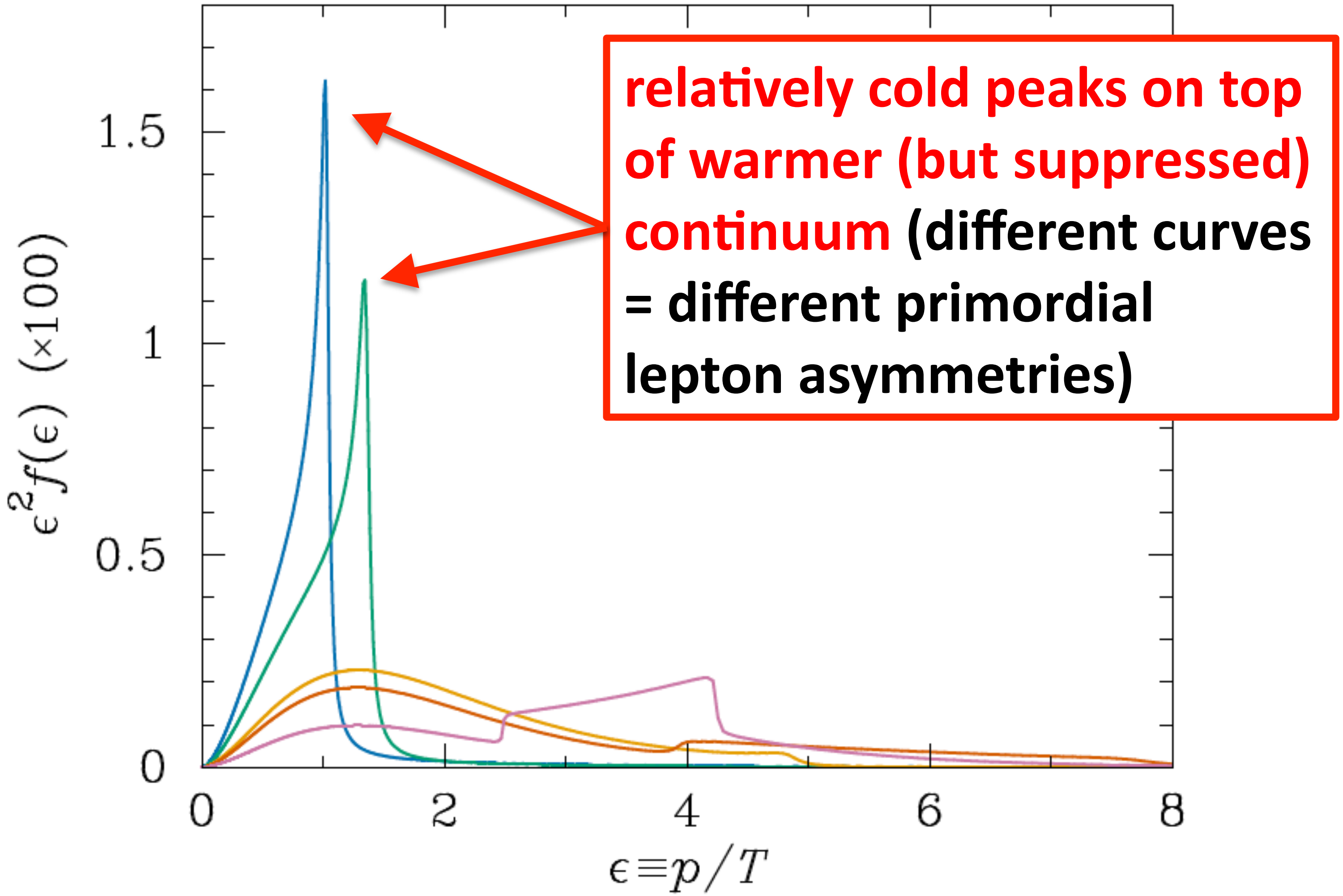
- **this would produce a large amount of ν_s at a specific (momentum-dependent) resonance temperature**
  ➔ ***cooler spectrum***

- **BUT:** ***the origin of such a primordial lepton number asymmetry is unclear...***

4. The Shi-Fuller mechanism

This produces to non-trivial spectra:

[Abazajian: Phys. Rev. Lett. **112** (2014) 161303]



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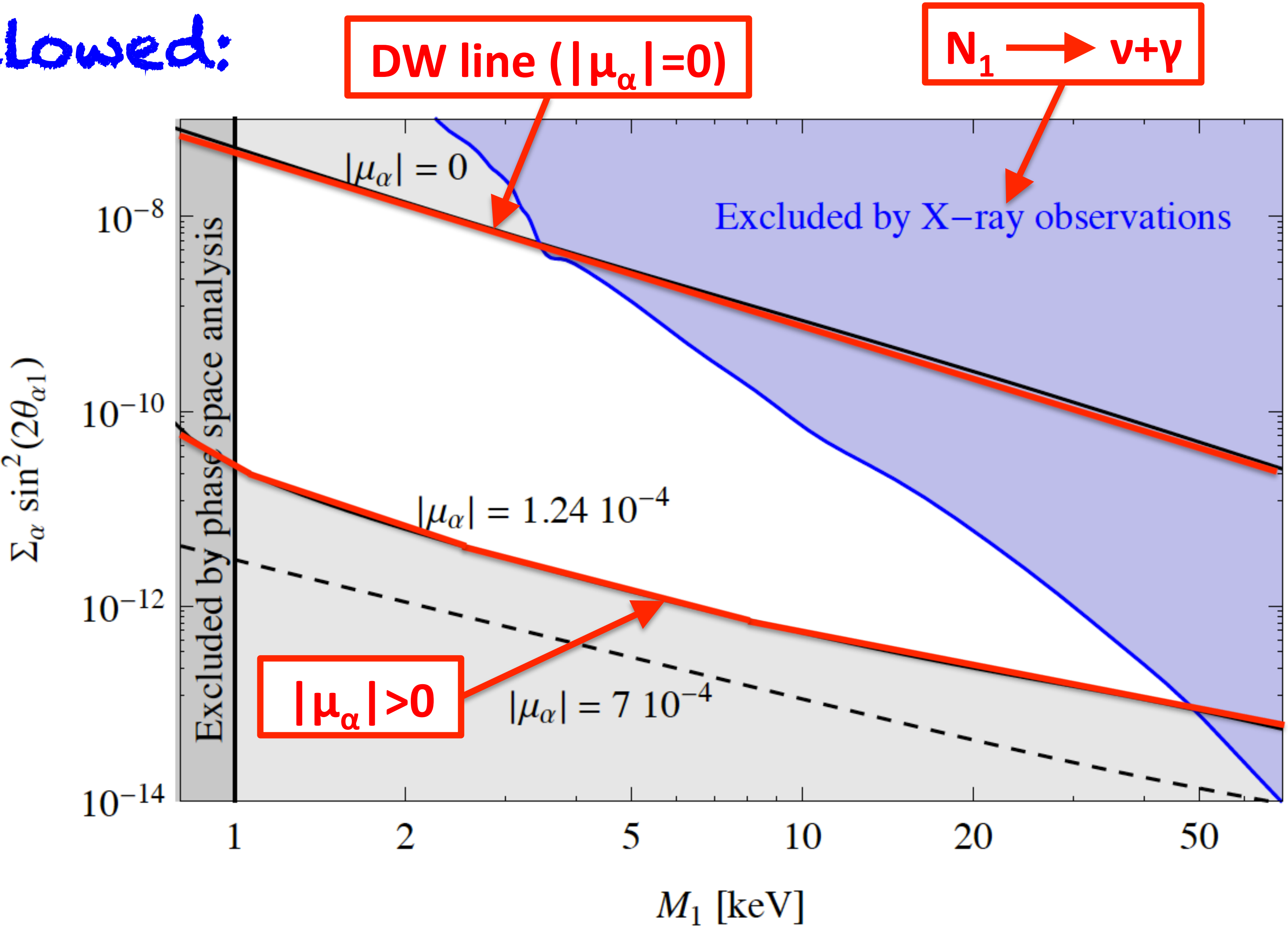
Allowed:



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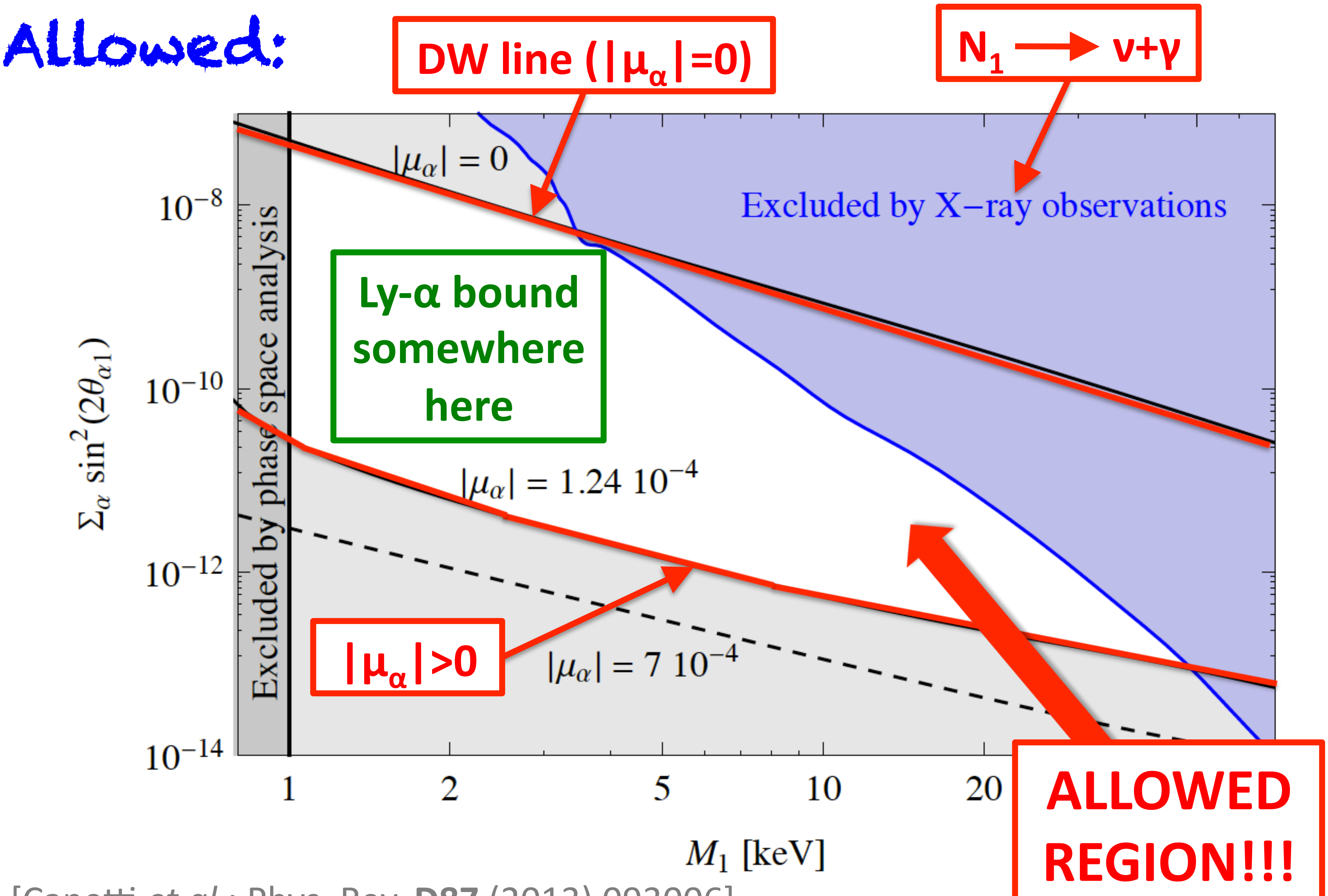

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5. Decay Production

E.g. scalar decays: e.g. $S \rightarrow N_1 N_1$

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- **other particle that decays**
  [Lello, Boyanovsky: Phys. Rev. **D91** (2015) 063502]
  [Lello, Boyanovsky: 1508.04077]

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- ***EXAMPLE*: SINGLET SCALAR "S" FREEZES IN OR OUT**

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Two-step process: scalar S must be produced before decaying → many possibilities, e.g.:

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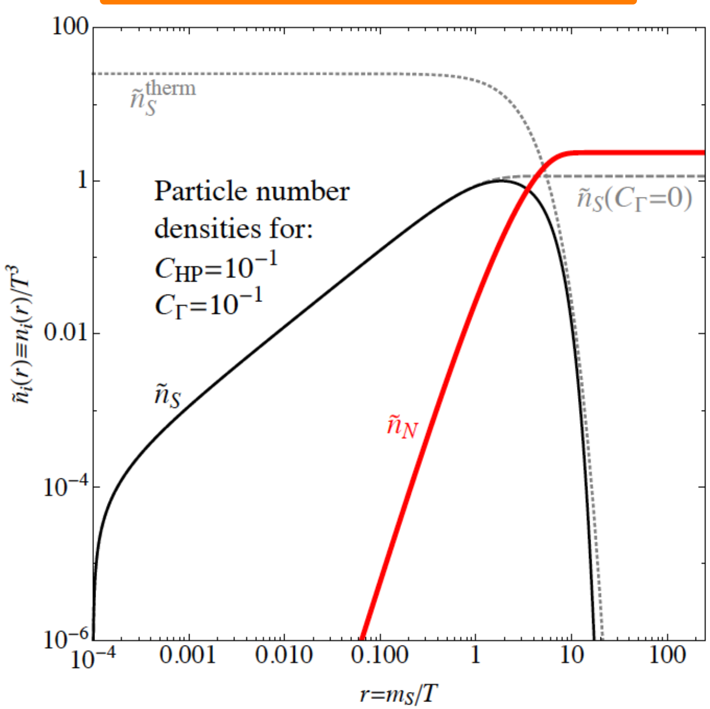
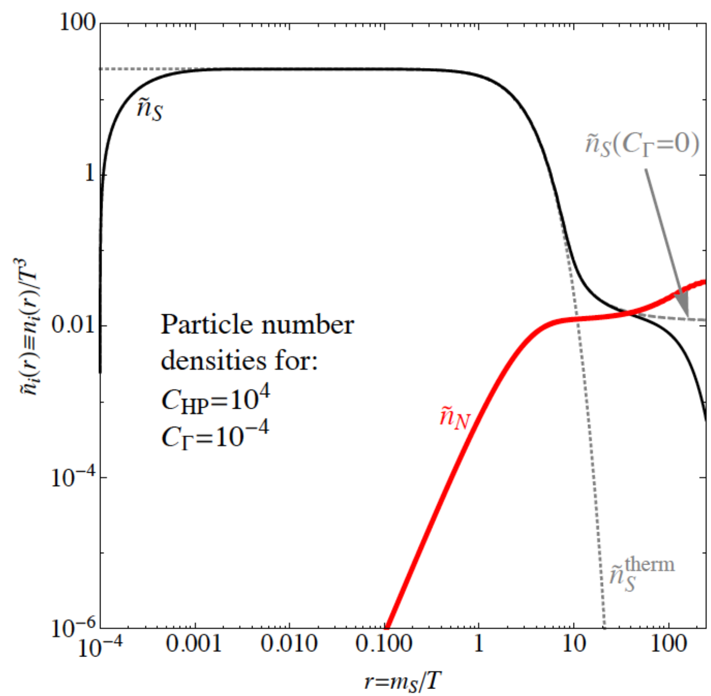
Two-step process: scalar S must be produced before decaying → many possibilities, e.g.:

S freezes-in and decays afterwards

S freezes-out and decays both in and out of equilibrium



Abundance



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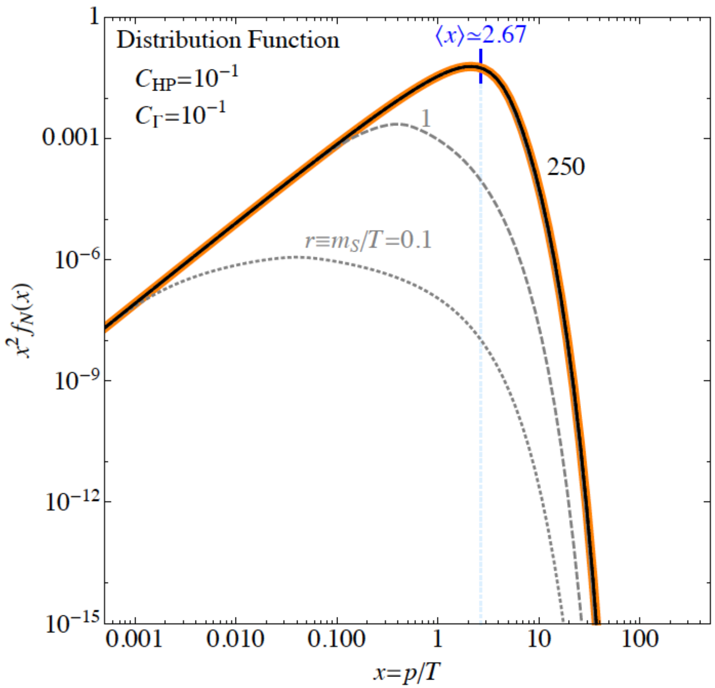
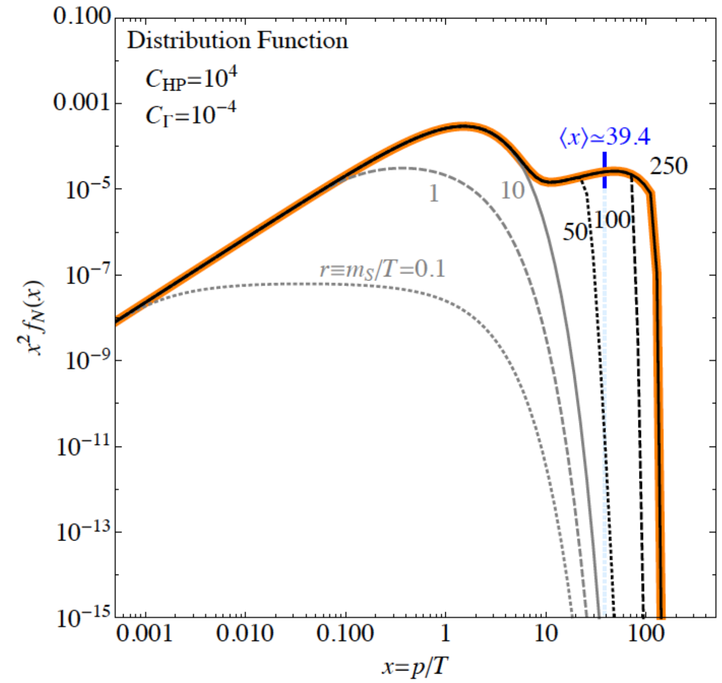


Distribution function



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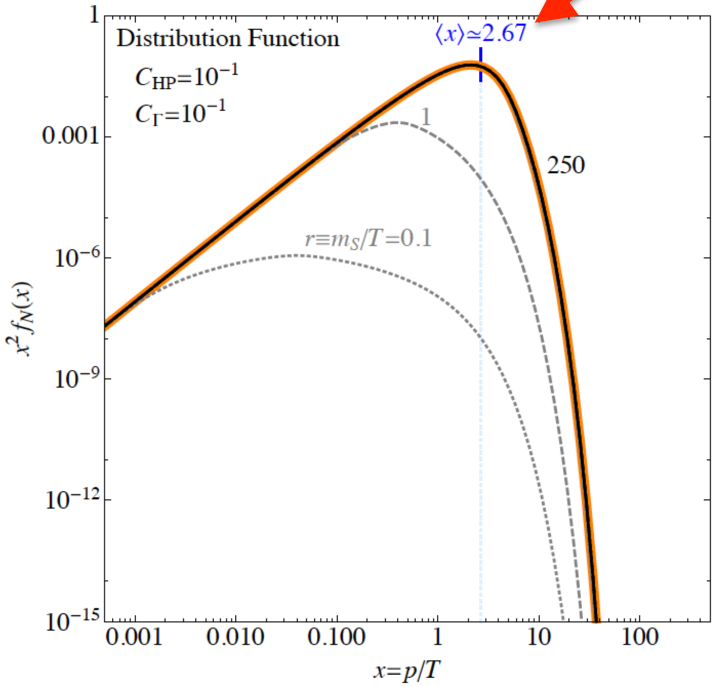
Two-step process: scalar S must be produced before decaying → many possibilities, e.g.:

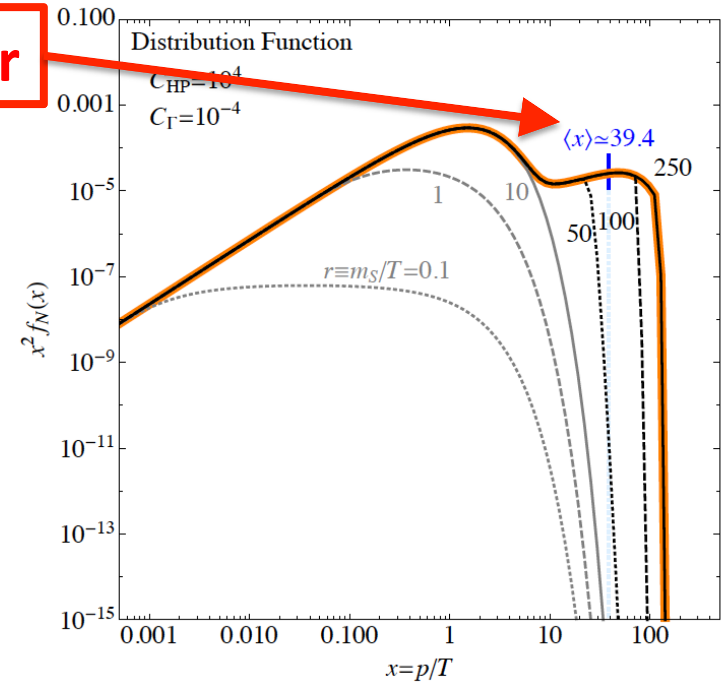
S freezes-in and decays afterwards

colder

S freezes-out and decays both in and out of equilibrium



warmer



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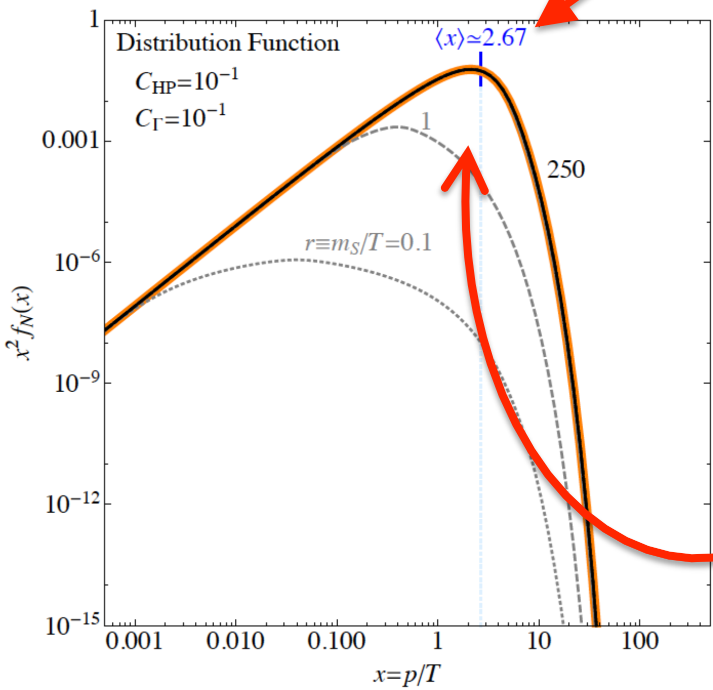

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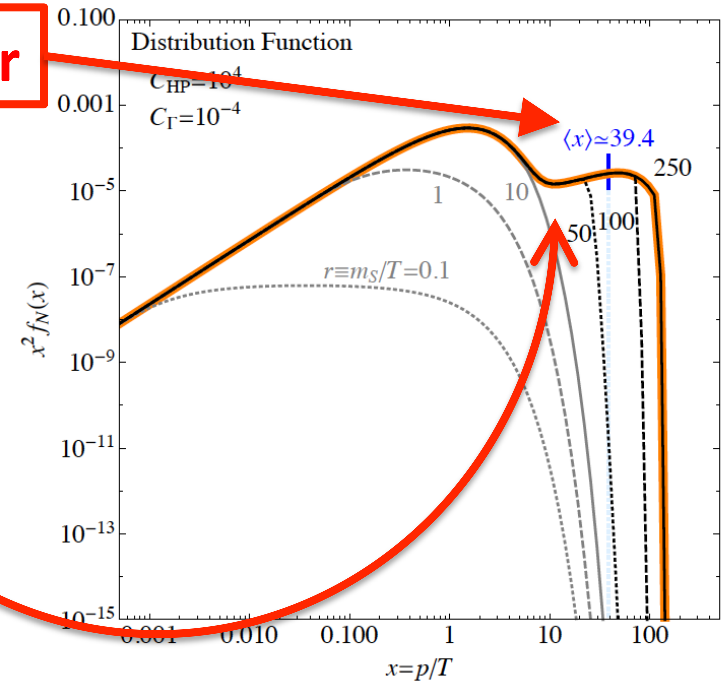

shape depends on regime

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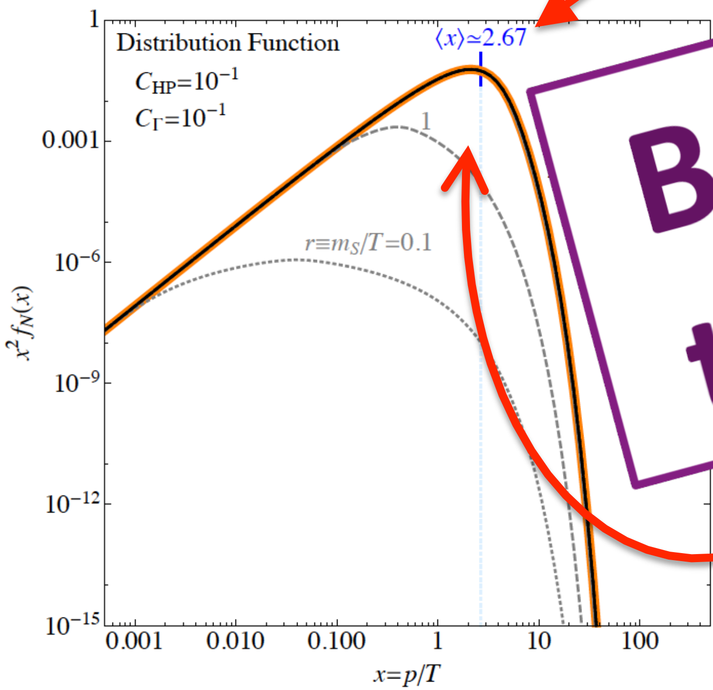
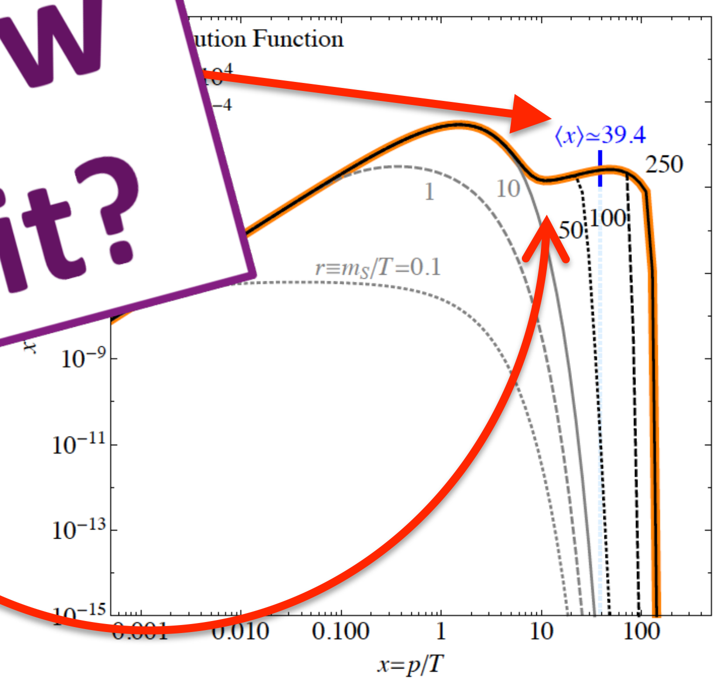


BUT: How to test it?



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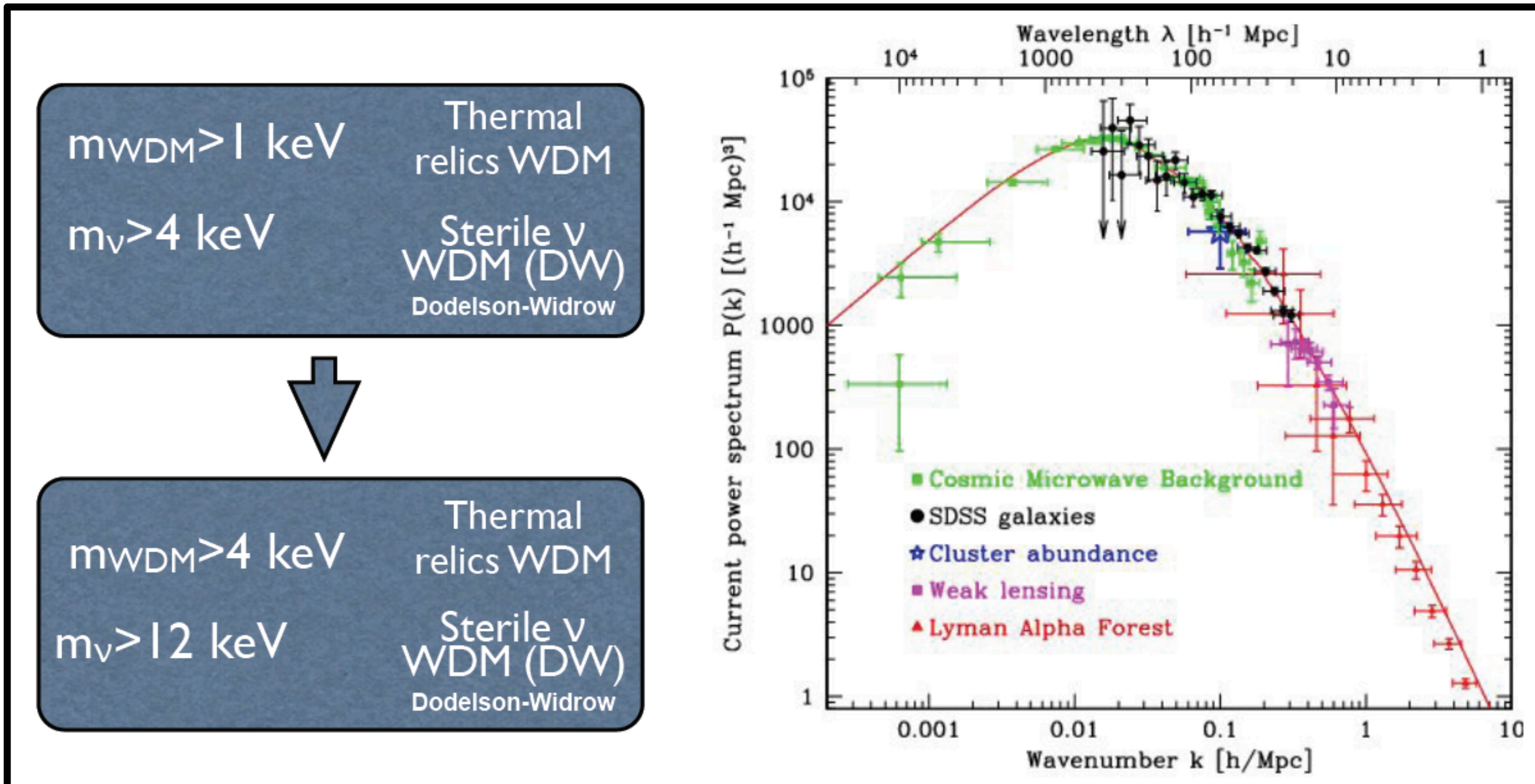

(Partial slide shamelessly stolen from N. Menci, Vulcano 2014, 20-05-2014)

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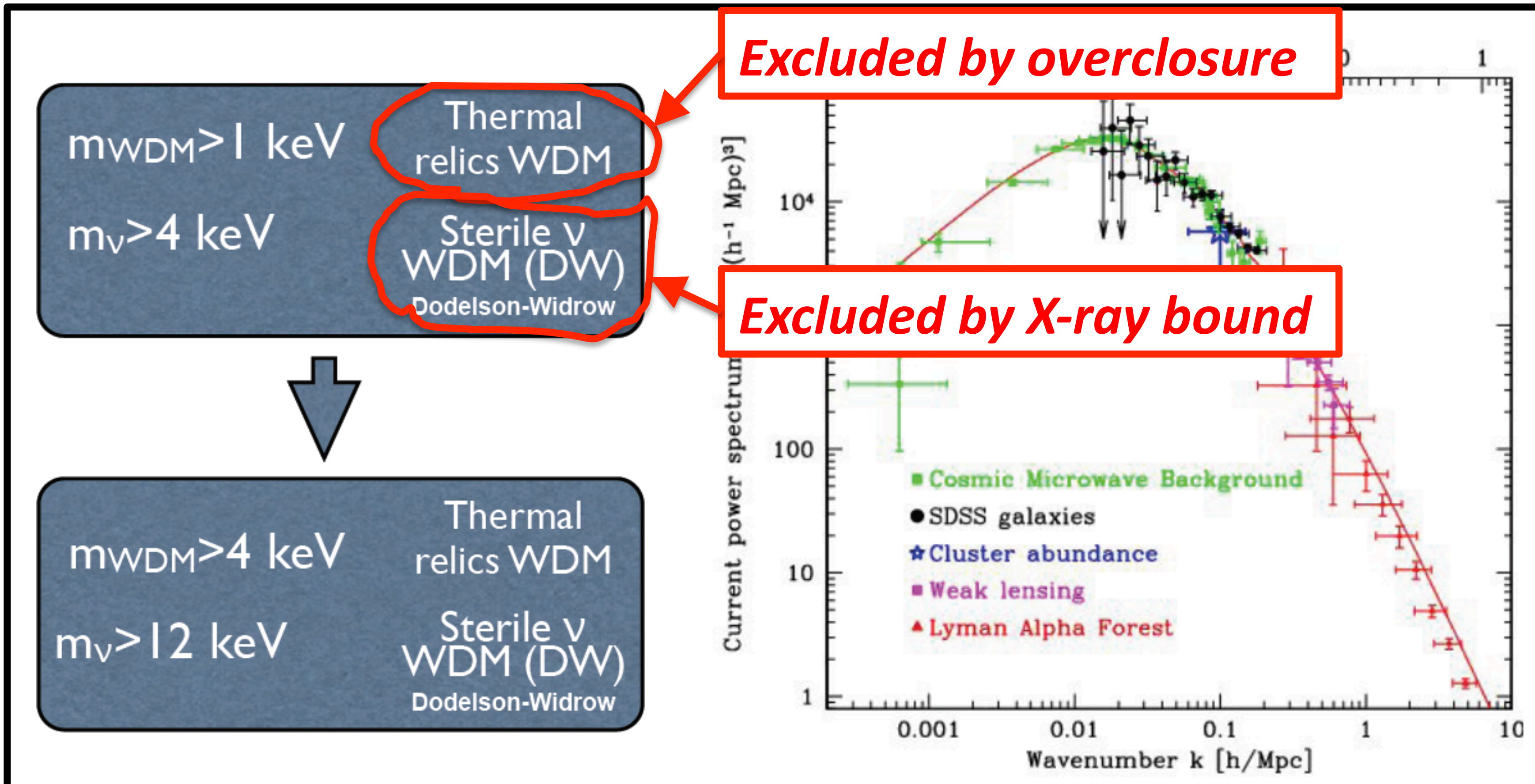
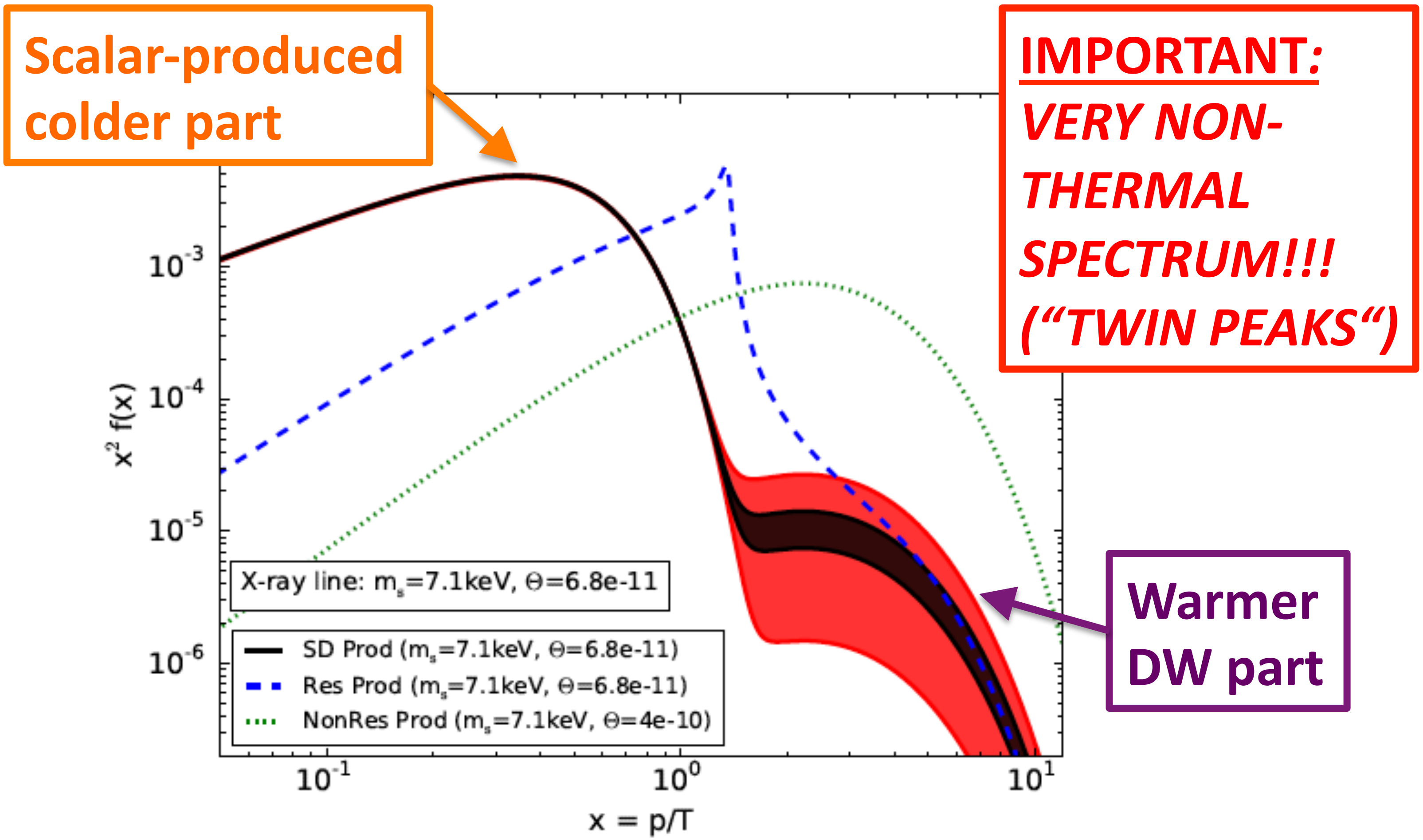


(Partial slide shamelessly stolen from N. Menci, Vulcano 2014, 20-05-2014)

5. Decay Production

• *SCRUTINY NEEDED*: **SCALAR PRODUCTION MAY EVEN YIELD BETTER AGREEMENT WITH STRUCTURE FORMATION**

[**AM**, Schneider: Phys. Lett. **B749** (2015) 283]



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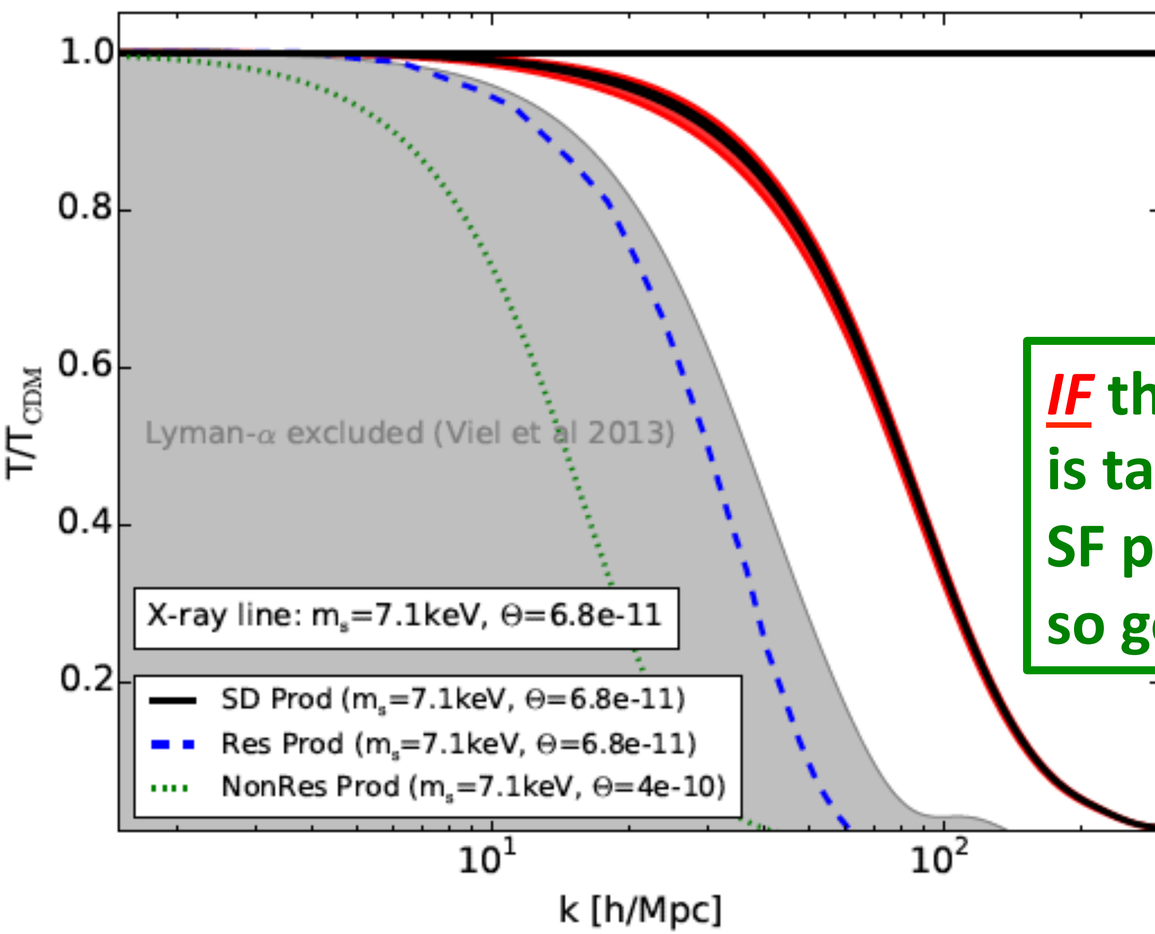

see next talk

IF the 3.5 keV line signal is taken seriously, then SF production is not in so good shape anymore

5. Decay Production

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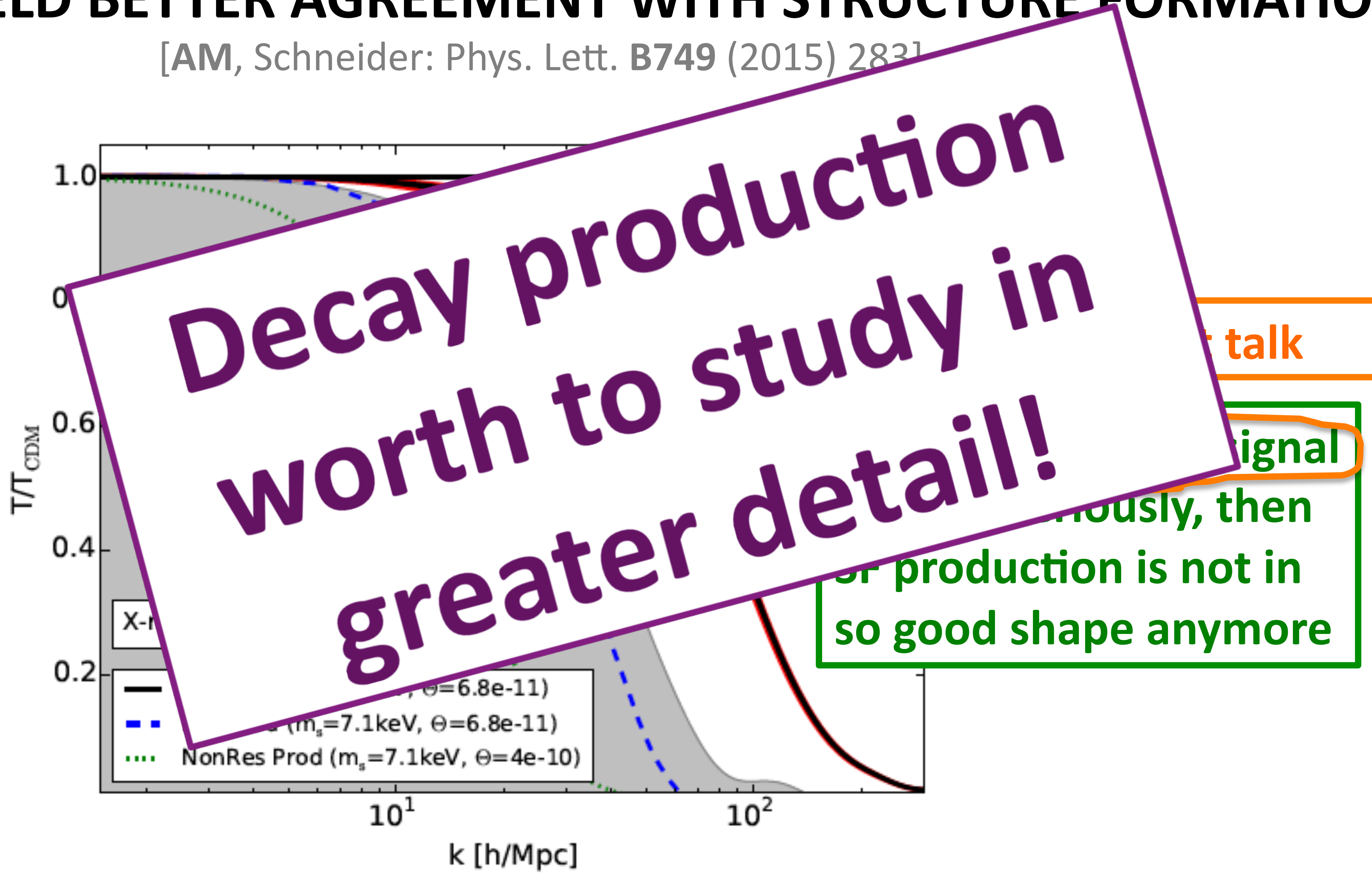


5. Decay Production

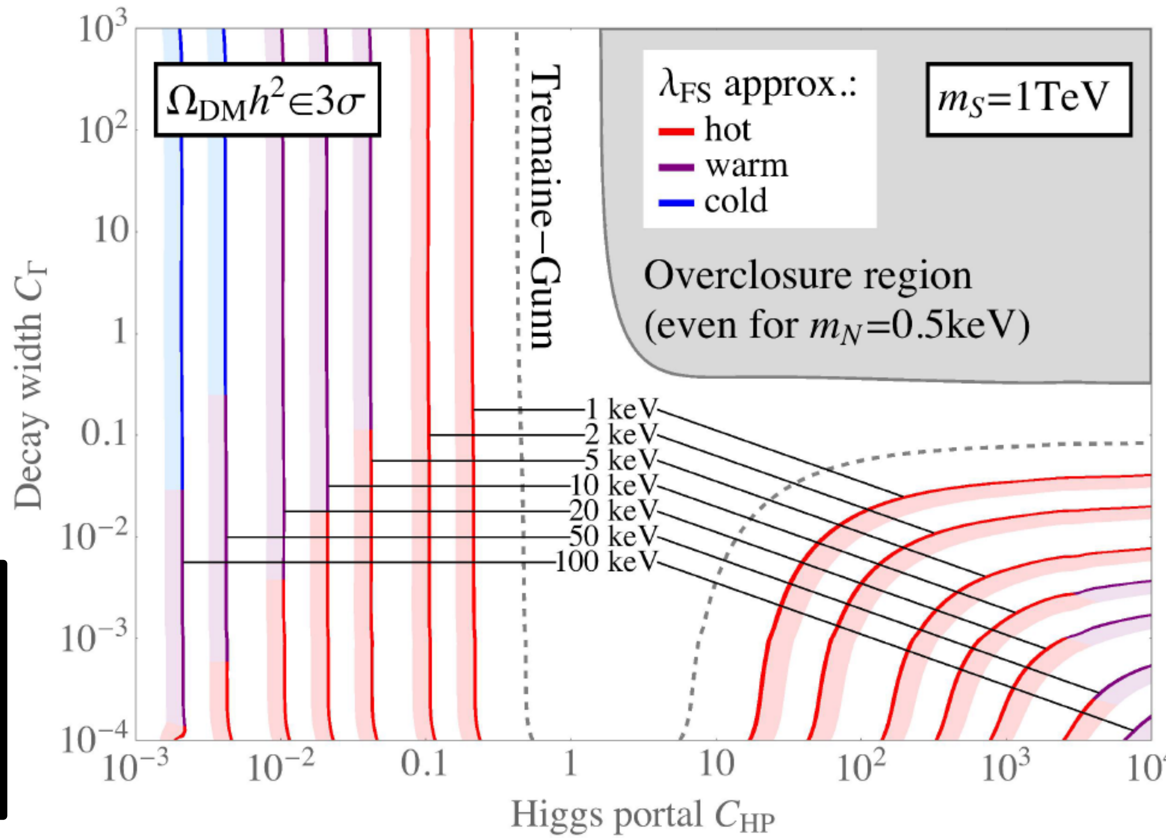
- ***EXAMPLE*: SINGLET SCALAR "S" FREEZES IN OR OUT**

[Kusenko: Phys. Rev. Lett. **97** (2006) 241301; Kusenko, Petraki: Phys. Rev. **D77** (2008) 065014]
[**AM**, Niro, Schmidt: JCAP **1403** (2013) 028; **AM**, Totzauer: JCAP **1506** (2015) 011]

Free-streaming horizon

$$r_{\mathrm{FS}} = \int_{t_{\mathrm{in}}}^{t_0} \frac{\langle v(t) \rangle}{a(t)} dt$$

Decides about whether the keV sterile neutrinos are **HOT**, **WARM**, or **COLD**



➔ ALL possible depending on effective parameters (C_Γ,C_{HP})

➔ DETAILED STUDY OUT SOON [**AM**, Schneider, Totzauer: 1510.XXXXX]

6. Conclusions

- **Dark Matter...** may be very different from WIMPS, only time will tell!
- **Production Mechanisms for sterile neutrinos...** are non-standard and need to be studied!
- **Active-sterile mixing...** does not work in the easiest setting, but resonances can help.
- **Decay production...** is a well motivated alternative and may even be advantegous!

6. Conclusions

- **Dark Matter...** may be very different from WIMPS, only time will tell!

- **Prod**... **eutrinos...** are no... ed!

- **Active-**... does not work in the easiest s... g, but resonances can help.

- **Decay production...** is a well motivated alternative and may even be advantegous!

Carlos, I think we can deliver the type of model you have just been asking for in your talk... ;-)


THANK YOU!!!

ADVERTISEMENT

Planning Page for the White Paper on keV Sterile Neutrino Dark Matter

This initiative was launched at the NIAPP Workshop "Neutrinos in Astro and Particle Physics" held at TU Munich on July 14-25 2014. Part of this workshop was devoted to review the evidence for and against - keV scale - sterile neutrino as a possible warm/cold Dark Matter candidate. At the cross road of particle physics, astrophysics, and cosmology, the observational constraints, the production mechanisms in the early Universe, and the experimental perspectives have been discussed. As an outcome of the workshop the participants proposed to gather the current status of this field in a white paper.

Outline and Section Editors

Editorial Committee: Marco Drewes, Thierry Lasserre, Alexander Merle, Susanne Mertens

I - Neutrinos in the Standard Model of Particle Physics and Beyond

(Section Editors: Carlo Giunti and André de Gouvea)

1. Current status of Neutrino Masses and Oscillations
2. Open questions in Neutrino Physics
   - 2.1 Neutrino Masses
   - 2.2 Neutrino Nature, Dirac or Majorana
   - 2.3 Neutrino Mass Hierarchy
   - 2.4 Neutrino CP violation
   - 2.5 Additional neutrino states
3. Sterile Neutrinos
   - 3.1 eV-scale
   - 3.2 keV-scale
   - 3.3 GeV, TeV, and >>TeV scales

II - Neutrinos in The Standard Model of Cosmology

(Section Editors: Julien Lesgourgues and Alessandro Miriz

1. Cosmological Concordance Model (J. Hamann, G.
2. Active neutrinos in Cosmology (J. Lesgourgues, S.
3. Sterile neutrinos in Cosmology
   - 3.1 eV-scale (M. Archidiacono, N. Saviano)
   - 3.2 KeV-scale (A. Boiarskyi, O. Ruchayskiy)
   - 3.3 Mev-scale (S. Pascoli)
   - 3.4 GeV-TeV (A. Ibarra)
   - 3.5 Leptogenesis (P. Di Bari)

The topic starts to be recognised by a larger community… a dedicated White Paper is on the way!