Sterile Neutrinos as Dark Matter: NOT warm BUT non-thermal

Alexander Merle

MPP Munich

Germany

MAX-PLANCK-GESELLSCHAFT

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, JCAP **1604** (2016) 003, JCAP **1701** (2017) 025, JCAP **1611** (2016) 038, 1609.04671 [hep-ex], Astrophys. J. **836** (2017) 61 , 1704.07838 [astro-ph], ...

Erice 2017 Workshop, 19 September 2017

A White Paper on keV Sterile Neutrino Dark Matter

Editors: M. Drewes[1], T. Lasserre[2], A. Merle[3], S. Mertens[4]

Authors: R. Adhi... T. Araki[57]
...ov[64]
...ouvea[62]
... P. Di Bari[32]
...Dorrer[81] M. Durero[3] O. Dragoun[71]
...ewes... Ch.E. Düllmann[81,83] K. Eberhardt[81] S. Eliseev[86]
C. Enss[50] N.W. Evans[53] A. Faessler[85] P. Filianin[86] V. Fischer[3]
...ischmann[50] J.A. Formaggio[20] J. Franse[16] F.M. Fraenkle[7]
...Fuller[75] L. Gastaldo[50] A. Garzilli[16] C. Giunti[22]
...[21] M.C. Gonzalez-Garcia[19]
...en[69] S. Hannestad[34]
...[80] T. Houdy[2,4]
A. Huber... ...son[87]
T. Jeltema[76] S. Kemp...
V. Kornoukhov[42] T. Lachenmai... ...[66,67]
T. Lasserre[1,2,3,4] J. Lesgourgues[15] D. Lhuil...
W. Liao[79] A.W. Long[90] M. Maltoni[26] G. Mangano...
N.E. Mavromatos[44] N. Menci[58] A. Merle[5] S. Mertens[6,7]

It's finally published!!!
JCAP 1701 (2017) 025

About 150 authors in total,
~10% among us in Erice!

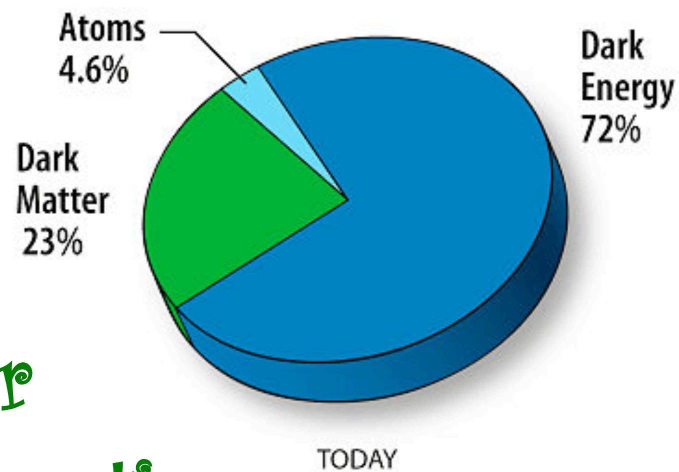
Contents:

1. To WIMP or not to WIMP

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 called "non-standard"!!!

1. To WIMP or not to WIMP

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...**

➔ ***let us think the unthinkable...***

WHAT IF DARK MATTER IS NOT A WIMP?!?

2. Sterile neutrinos

*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 (value 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**

NB: NO constraint from oscillations!!!

2. Sterile neutrinos

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 due to tiny coupling)
  ➔ **warm/cold/non-thermal?** (interesting for structure and/or galaxy formation)

- 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**

3. Non-thermal production mechanisms

3. Non-thermal production mechanisms

Non-thermal... *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**
$T \gg m$	$T \sim m$	$T \ll m$

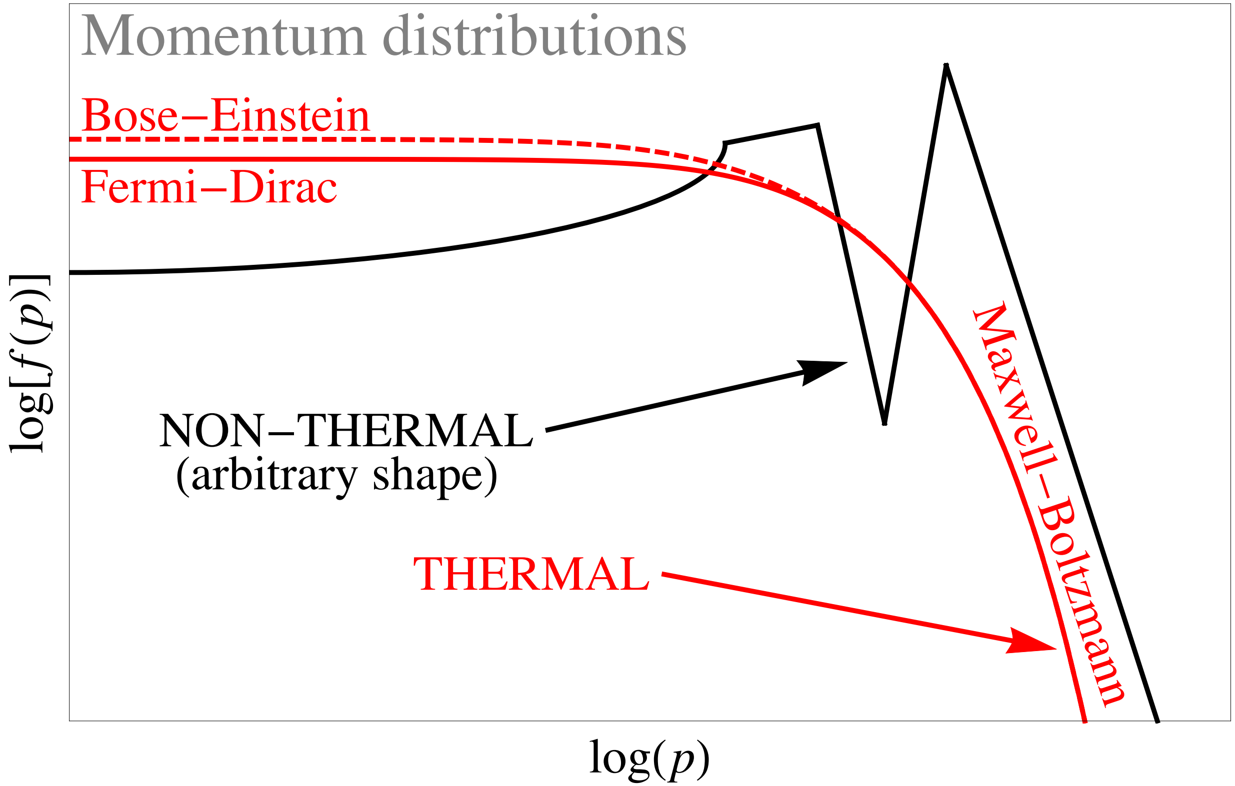
NON-THERMAL

$f(p)$ arbitrary

with:

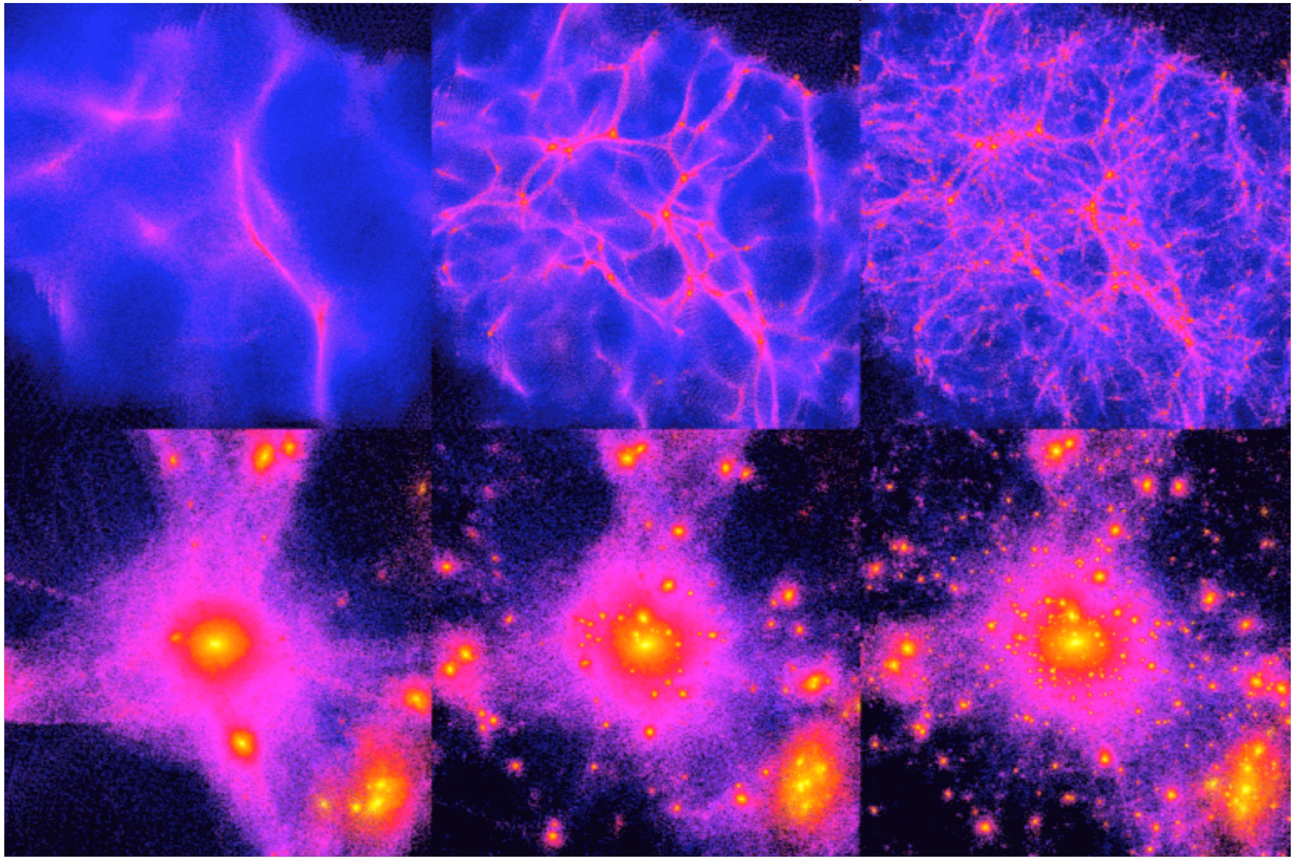
$$\int_{p=0}^{\infty} p^2 f(p) dp < \infty$$

T not defined **!!!**



3. Non-thermal production mechanisms

But what about structure formation?!?



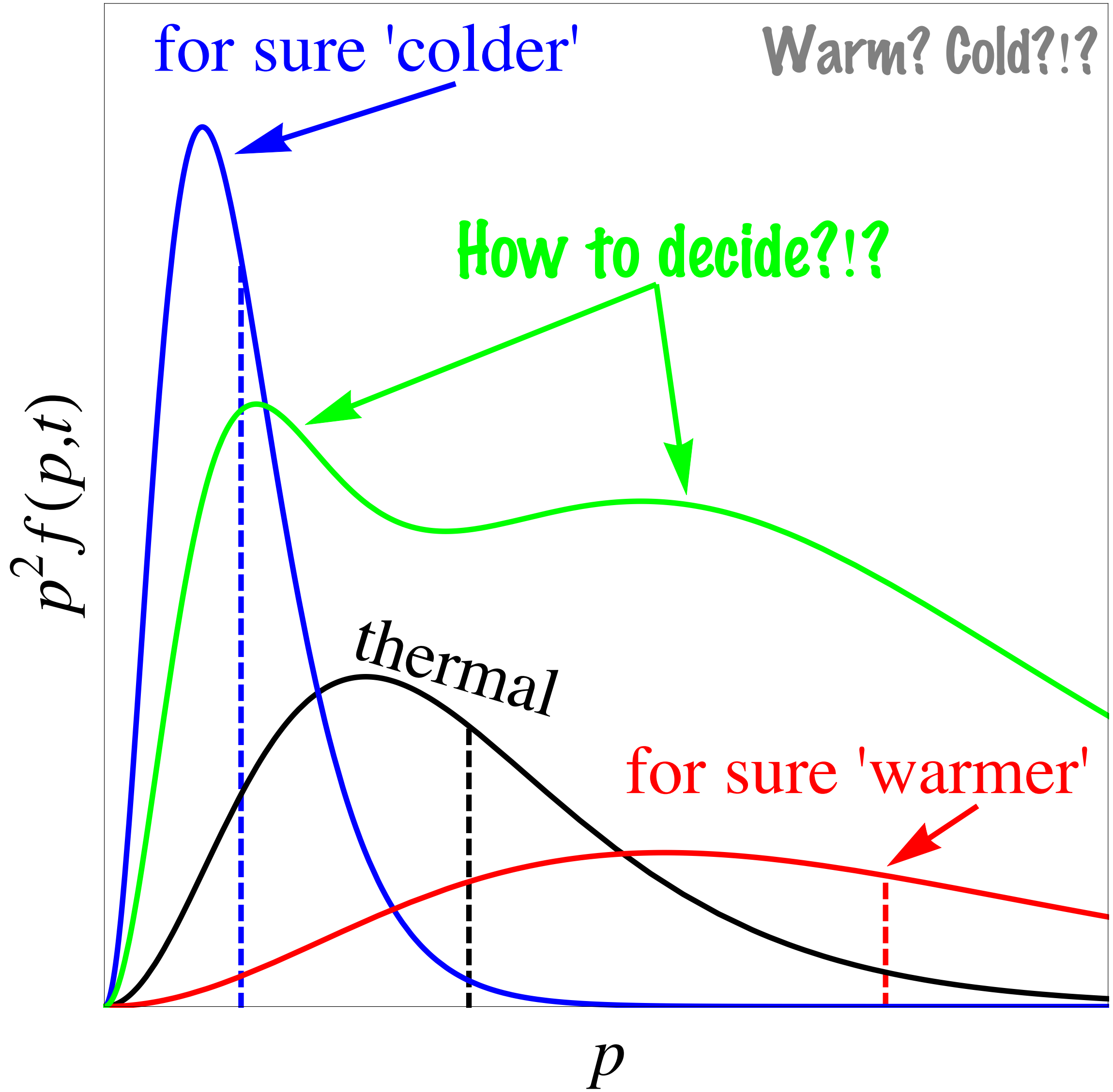
HOT WARM COLD

[http://www.ctac.uzh.ch/gallery/]

More involved for non-thermal spectra!!!

3. Non-thermal production mechanisms

PROBLEM: HOW TO COMPARE TO THE THERMAL CASE?



- ➔ Warm Dark Matter is an INSUFFICIENT DESCRIPTION!
- ➔ non-thermal spectra are more complicated!
- ➔ will become clear by the end of my talk

4. Production of Sterile Neutrinos

4. Production of Sterile Neutrinos

4 main mechanisms for sterile neutrinos:

Non-resonant transitions

First: Langacker

DM: Dodelson & Widrow

Idea: active-sterile mixings gradually produce ν_s

Resonant transitions

First: Enquist, Kainulainen

DM: Shi & Fuller, Abazajian, Shaposhnikov, Laine, ...

Idea: "MSW"-enhancement of active-sterile transitions

Decay production

ν_s-DM: Kusenko, **AM**, Boyanovsky, Shaposhnikov, ...

Idea: other new particle is produced and decays into ν_s

Diluted thermal production

ν_s-DM: Bezrukov, Lindner, Nemevsek, Senjanovic, **AM**,...

Idea: produce entropy to dilute thermal over-abundance

4. Production of Sterile Neutrinos

4 main mechanisms for sterile neutrinos:

Non-resonant transitions

First: Langacker

DM: Dodelson & Widrow

Idea: active-sterile mixi...

gradu...

Resonant transitions

First: Enquist, Kai... ...en

DM: S... ...ian,

... ...

...hancement

...tive-sterile transitions

...tion

ν_s-DM: Kusenko, **AM**, Boyanovsky, Shaposhnikov, ...

Idea: other new particle is produced and decays into ν_s

Diluted thermal production

ν_s-DM: Bezrukov, Lindner, Nemevsek, Senjanovic, **AM**,...

Idea: produce entropy to dilute thermal over-abundance

BUT: When confronted with data...

WHICH MECHANISMS SURVIVE?!?

4. Production of Sterile Neutrinos

4 main mechanisms for sterile neutrinos:

Non-resonant transitions

First: Langacker

DM: Dodelson & Widrow

Idea: active-sterile mixings gradually produce ν_s

R… ransitions

…inulainen

… Abazajian,

…v, Laine, …

…w"-enhancement

of active-sterile transitions

EXCLUDED BY STRUCTURE FORMATION (TOO "HOT" DM)

Decay production

ν_s-DM: Kusenko, **AM**, Boyanovsky, Shaposhnikov, …

Idea: other new particle is produced and decays into ν_s

Diluted thermal production

ν_s-DM: Bezrukov, Lindner, Nemevsek, Senjanovic, **AM**,…

Idea: produce entropy to dilute thermal over-abundance

4. Production of Sterile Neutrinos

4 main m… for sterile neutrinos:

STRONGLY PUSHED BY STRUCTURE FORMATION (TOO "WARM")

Non-resona…

First: Langack…

DM: Dodelson…

Idea: active-st… …mixings gradually produce ν_s

Resonant transitions

First: Enquist, Kainulainen

…M: Shi & Fuller, Abazajian, Shaposhnikov, Laine, ...

Idea: "MSW"-enhancement of active-sterile transitions

Decay production

ν_s-DM: Kusenko, **AM**, Boyanovsky, Shaposhnikov, ...

Idea: other new particle is produced and decays into ν_s

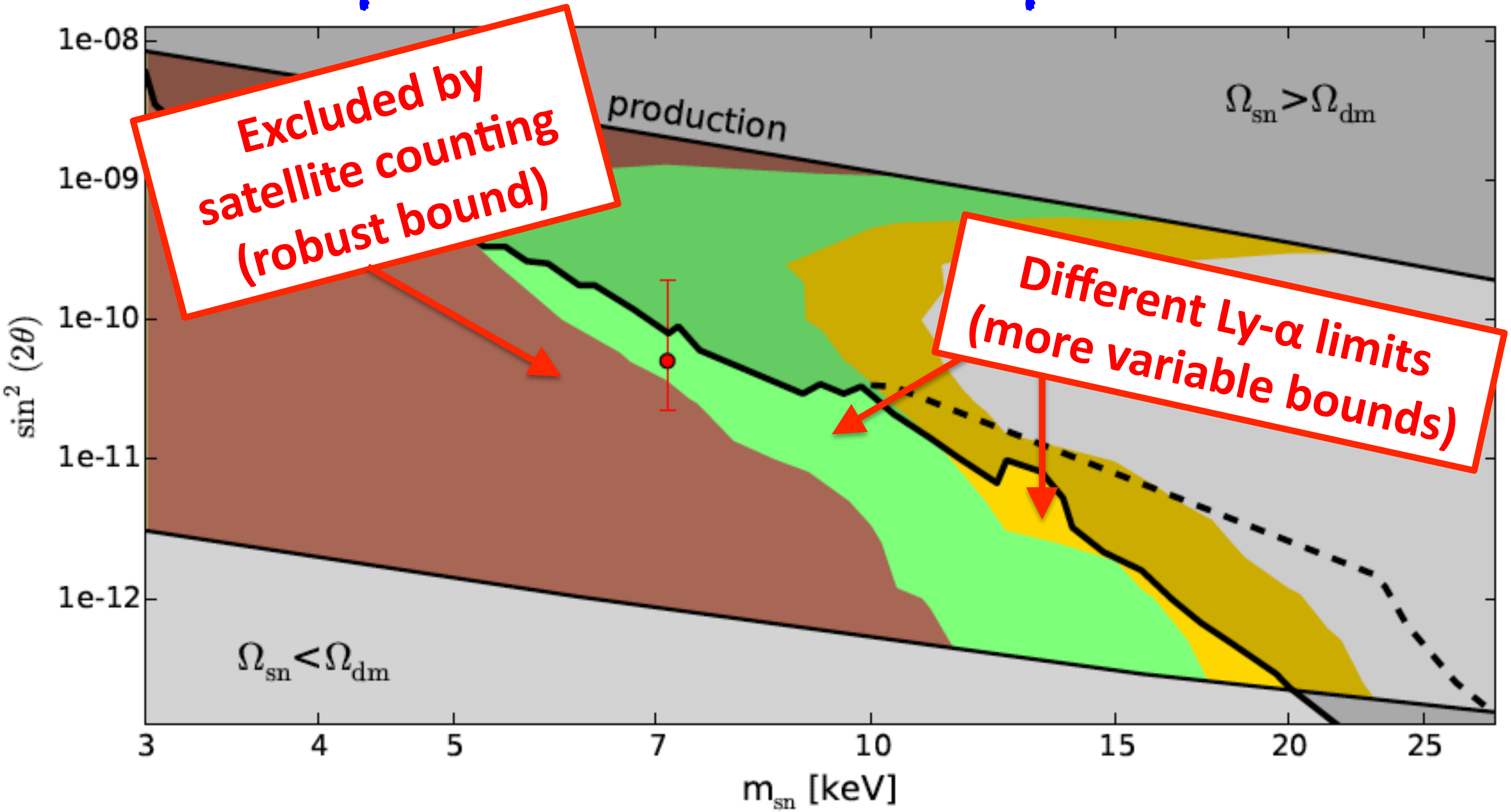
Diluted thermal production

ν_s-DM: Bezrukov, Lindner, Nemevsek, Senjanovic, **AM**,...

Idea: produce entropy to dilute thermal over-abundance

Resonant production (“standard“)

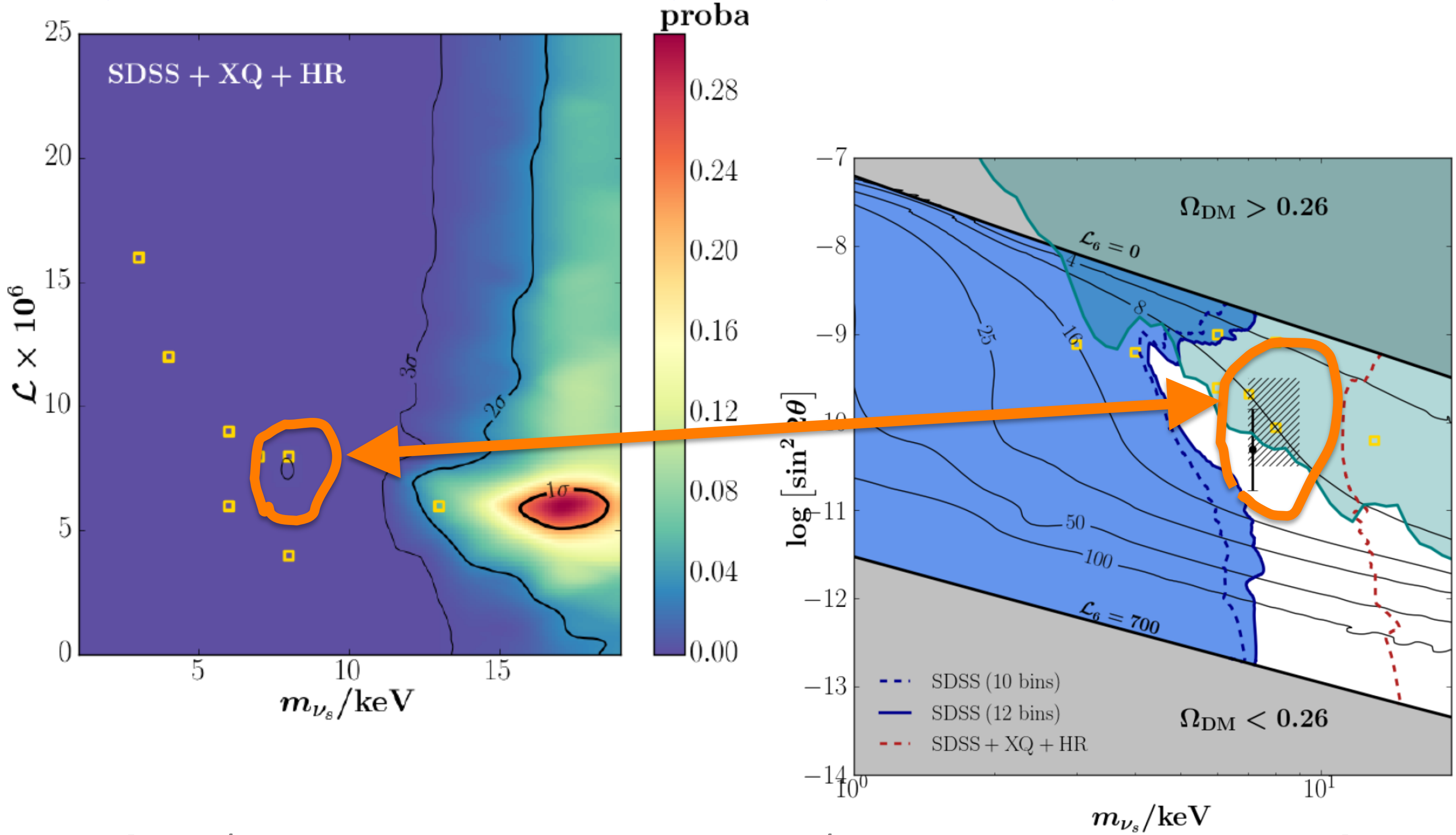
Resonant production under pressure!!



[e.g. Schneider: JCAP **1604** (2016) 059]

Resonant production (“standard“)

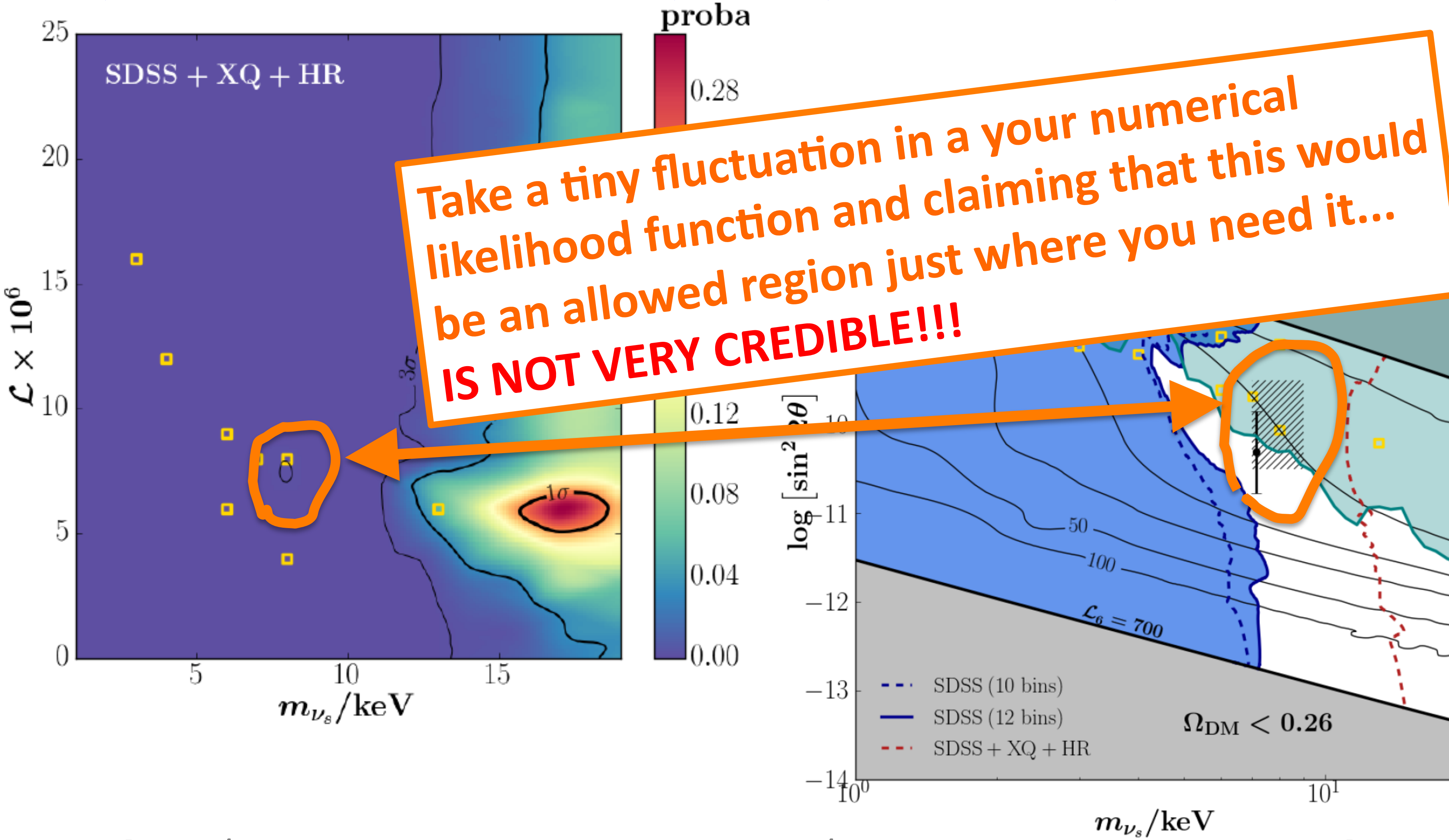
Thus, better be skeptical if somebody tries too hard to rescue this mechanism....



[Baur/Palanque-Dellabrouille + Boyarsky/Ruchayskiy *et al.*: 1706.03118]

Resonant production ("standard")

Thus, better be skeptical if somebody tries too hard to rescue this mechanism….



Take a tiny fluctuation in a your numerical likelihood function and claiming that this would be an allowed region just where you need it…

IS NOT VERY CREDIBLE!!!

[Baur/Palanque-Dellabrouille + Boyarsky/Ruchayskiy *et al.*: 1706.03118]

4. Production of Sterile Neutrinos

4 main mechanisms for sterile neutrinos:

Non-resonant transitions

First: Langacker

DM: Dodelson & Widrow

Idea: active-sterile mixings gradually produce ν_s

Resonant transitions

First: Enquist, Kainulainen

DM: Shi & Fuller, Abazajian, Shaposhnikov, Laine, ...

Idea: "MSW"-enhancement of active-sterile transitions

D

ν_s-D

Boya vsky, Shaposhnikov, ...

Idea: other new particle is produced and decays into ν_s

Possible, but BBN bound is non-trivial to fulfill!!

Diluted thermal production

ν_s-DM: Bezrukov, Lindner, Nemevsek, Senjanovic, **AM**,...

Idea: produce entropy to dilute thermal over-abundance

4. Production of Sterile Neutrinos

4 main mechanisms for sterile neutrinos:

Non-resonant transitions

First: Langacker

DM: Dodelson & Widrow

Idea: active-sterile mixings
gradually p

Resonant transitions

First: Enquist, Kainulainen

DM: Shi & Fuller, Aba

OKAY FOR A SIGNIFICANT PART OF THE PARAMETER SPACE

(BUT: partially "boring", i.e. like CDM)

Decay prod

ν_s-DM: Kusenko, **AM**, Boyanovsky, Shaposhnikov, ...

Idea: other new particle is produced and decays into ν_s

Diluted thermal production

ν_s-DM: Bezrukov, Lindner, Nemevsek, Senjanovic, **AM**,...

Idea: produce entropy to dilute thermal over-abundance

4. Production of Sterile Neutrinos

4 main mechanisms for sterile neutrinos:

Non-resonant transitions

DM: Dodelso…

Idea: active-sterile mixings … gradually p…

Resonant transitions

First: Enquist, Kainulainen

…M: Shi & Fuller, Aba…,

…ons

Decay prod…

ν_s-DM: Kusenko, **AM**, Boyanovsky, Shaposhnikov, …

Idea: other new particle is produced and decays into ν_s

…iluted thermal production

ν_s-DM: Bezrukov, Lindner, Nemevsek, Senjanovic, **AM**,…

Idea: produce entropy to dilute thermal over-abundance

… LET US DISCUSS A WORKING EXAMPLE

OKAY FOR A SIGN… …T OF THE PARAMETER SPA…

(BUT: partially "boring", i.e. like CDM)

4. *The one that works*: Decay production

4. *The one that works*: Decay production

Scalar (or other) decays: e.g. $S \rightarrow N_1 N_1$

- **decaying inflaton**
  [Asaka *et al.*: Phys. Lett. **B638** (2006) 401]
  [Anisimov *et al.*: Phys. Lett. **B671** (2009) 211]
  [Bezrukov, Gorbunov: JHEP **1005** (2010) 010]
- **singlet scalar that freezes out**
  [Kusenko: Phys. Rev. Lett. **97** (2006) 241301; Kusenko, Petraki: Phys. Rev. **D77** (2008) 065014]
  [Frigerio, Yaguna: Eur. Phys. J. **C75** (2015), 1]
  [**AM**, Schneider: Phys. Lett. **B749** (2015) 283; **AM**, Totzauer: JCAP **1506** (2015) 011]
- **singlet scalar that freezes in**
  [**AM**, Niro, Schmidt: JCAP **1403** (2013) 028]
  [Adulpravitchai, Schmidt: JHEP **1501** (2015) 006]
  [**AM**, Schneider: Phys. Lett. **B749** (2015) 283; **AM**, Totzauer: JCAP **1506** (2015) 011]
  [König, **AM**, Totzauer: JCAP 1611 (2016) 038]
  [Klasen, Yaguna: JCAP 1311 (2013) 039]
- **other particle that decays**
  [Lello, Boyanovsky: Phys. Rev. **D91** (2015) 063502]
  [Lello, Boyanovsky: JCAP **1606** (2016) 011]

4. *The one that works*: Decay production

- **SINGLET SCALAR "S" FREEZES IN OR OUT BEFORE DECAY**

[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]

Two-step process:

scalar S must be produced before it can decay

4. *The one that works*: Decay production

- **SINGLET SCALAR "S" FREEZES IN OR OUT BEFORE DECAY**

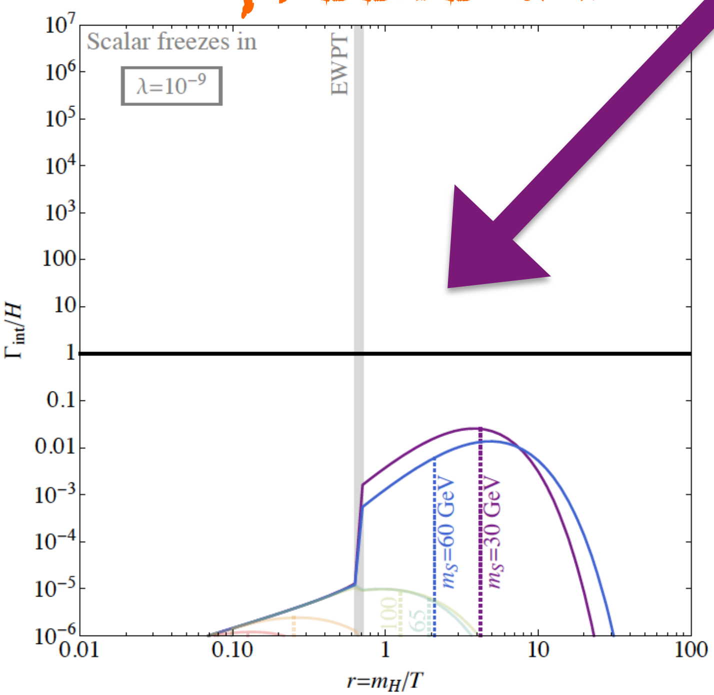
[Kusenko: Phys. Rev. Lett. **97** (2006) 241301; Kusenko, Petraki: Phys. Rev. **D77** (2008) 065014]
[**AM**, Niro, Schmidt: JCAP **1403** (2013) 028; **AM**, Totzauer: JCAP **1506** (2015) 011]

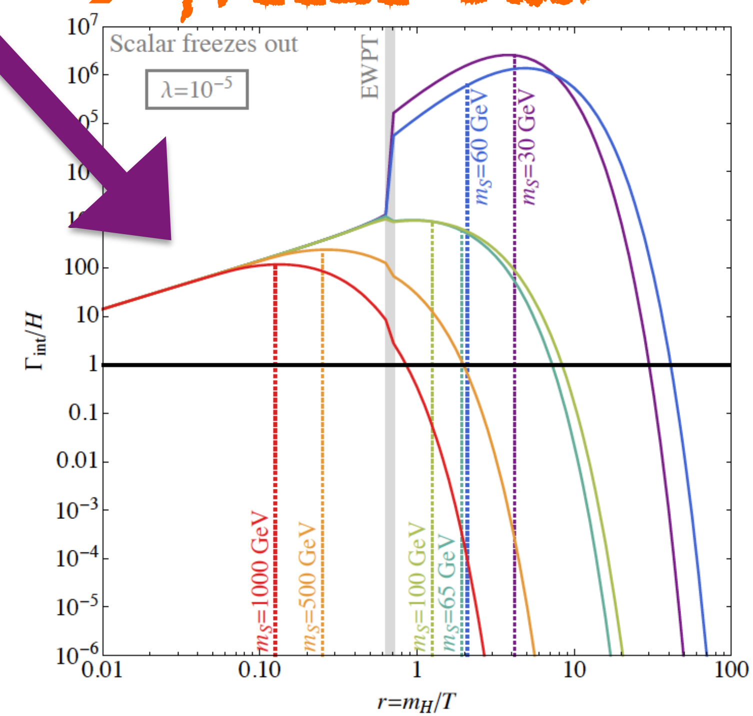
Two-step process:

scalar S must be produced before it can decay

small coupling to SM → freeze-in!

large coupling to SM → freeze-out!





4. *The one that works*: Decay production

- **SINGLET SCALAR "S" FREEZES IN OR OUT BEFORE DECAY**

[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]

Two-step process:

scalar S must be produced before it can decay

→ solution: distribution of scalar translates directly into distribution of sterile neutrinos

$$f_N(x,r) = \int_0^r \mathrm{d}r' \, 2\mathcal{C}_\Gamma \frac{r'^2}{x^2} \int_{\hat{x}_{\min}}^{\infty} \mathrm{d}\hat{x} \, \frac{\hat{x}}{\sqrt{\hat{x}^2 + r'^2}} f_S(\hat{x}, r')$$

$$\hat{x}_{\min} = \| x - r^2/(4x) \| .$$

$x = p/T$
$r = m_S/T$

direct translation

4. *The one that works*: Decay production

- **SINGLET SCALAR "S" FREEZES IN OR OUT BEFORE DECAY**

[Kusenko: Phys. Rev. Lett. **97** (2006) 241301; Kusenko, ... 4]
[**AM**, Niro, Schmidt: JCAP **1403** (2014) ...

We set the bar high in JCAP 1611 (2016) 038 (König, AM, Totzauer):

- FULL PARAMETER SPACE
- NO APPROXIMATIONS
- STEP TO ASTROPHYSICS MADE

f_N ... $\sqrt{x^2 + r'^2} f_S(x, r')$

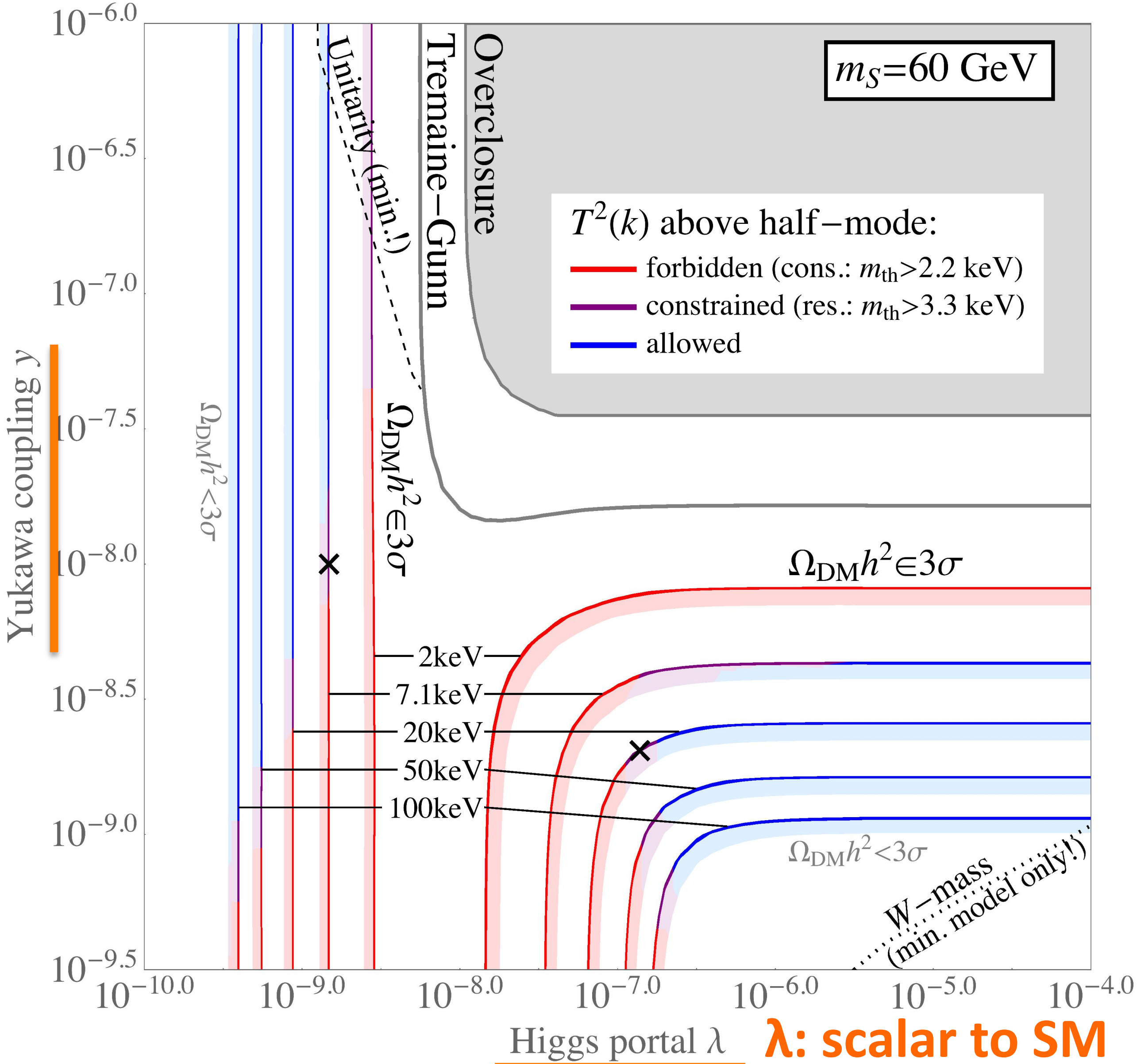
$$x_{\min} = \|x - r^2/(4x)\|.$$

$x = p/T$
$r = m_S/T$

direct translation

4. *The one that works*: Decay production

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

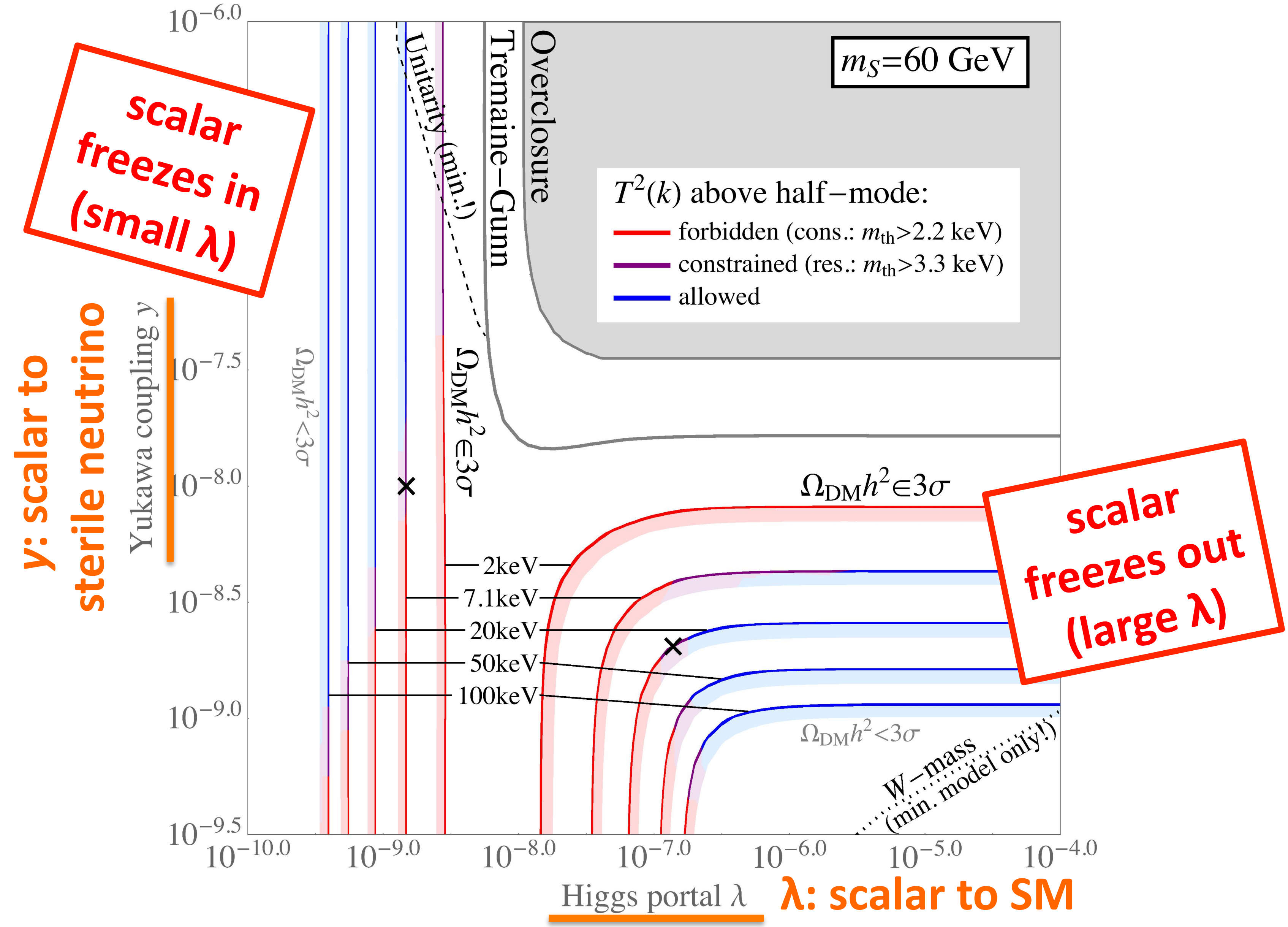


y: scalar to sterile neutrino

λ: scalar to SM

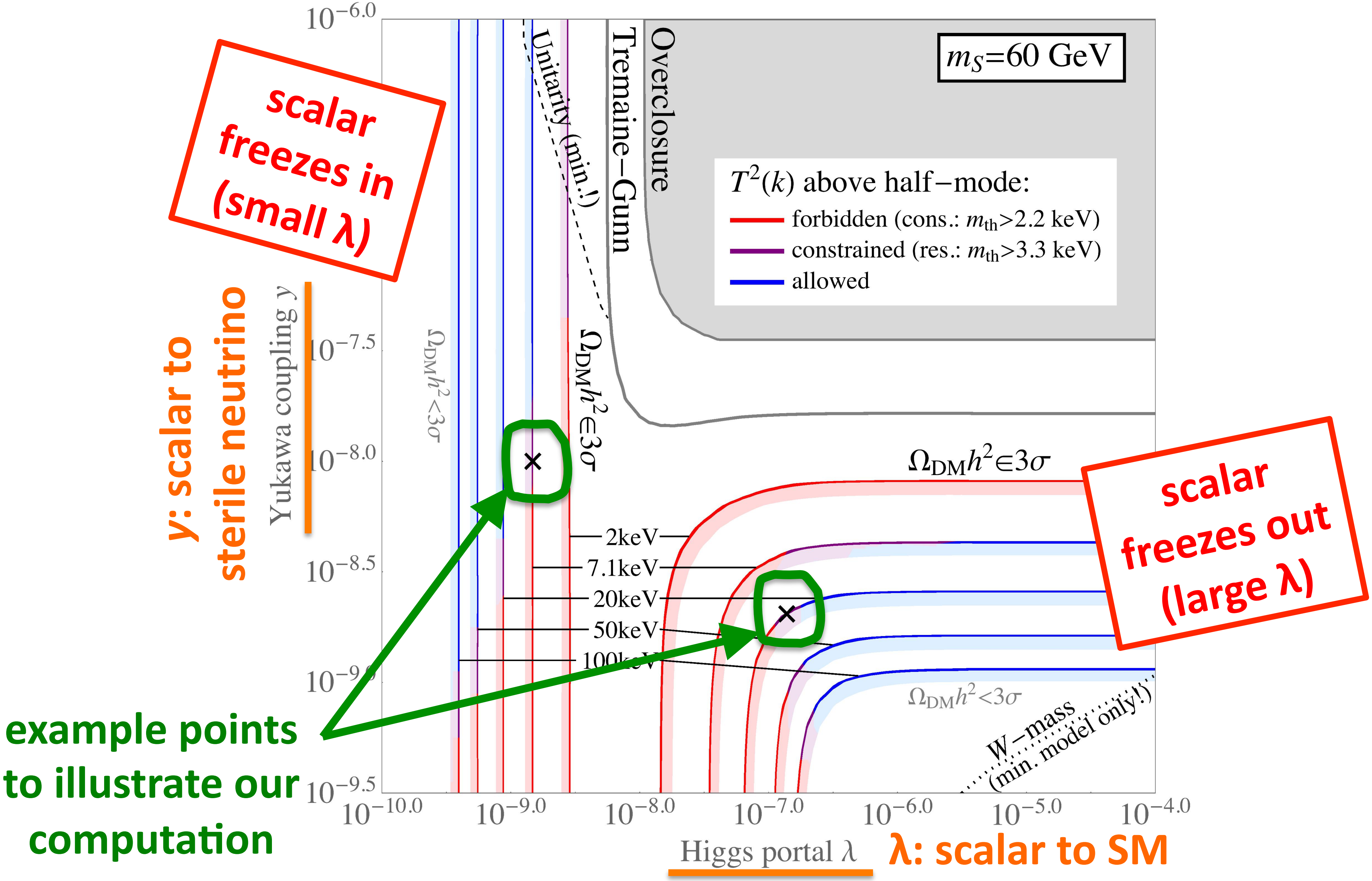
4. *The one that works*: Decay production

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



4. *The one that works*: Decay production

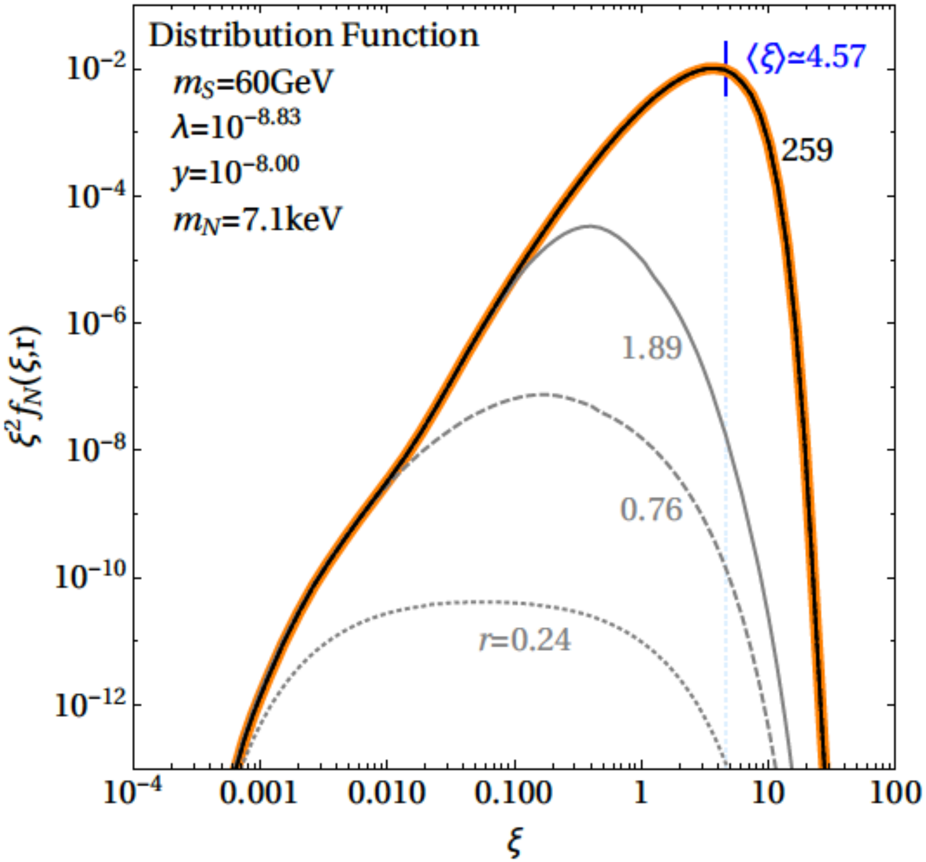
[König, **AM**, Totzauer: JCAP **1611** (2016) 038]

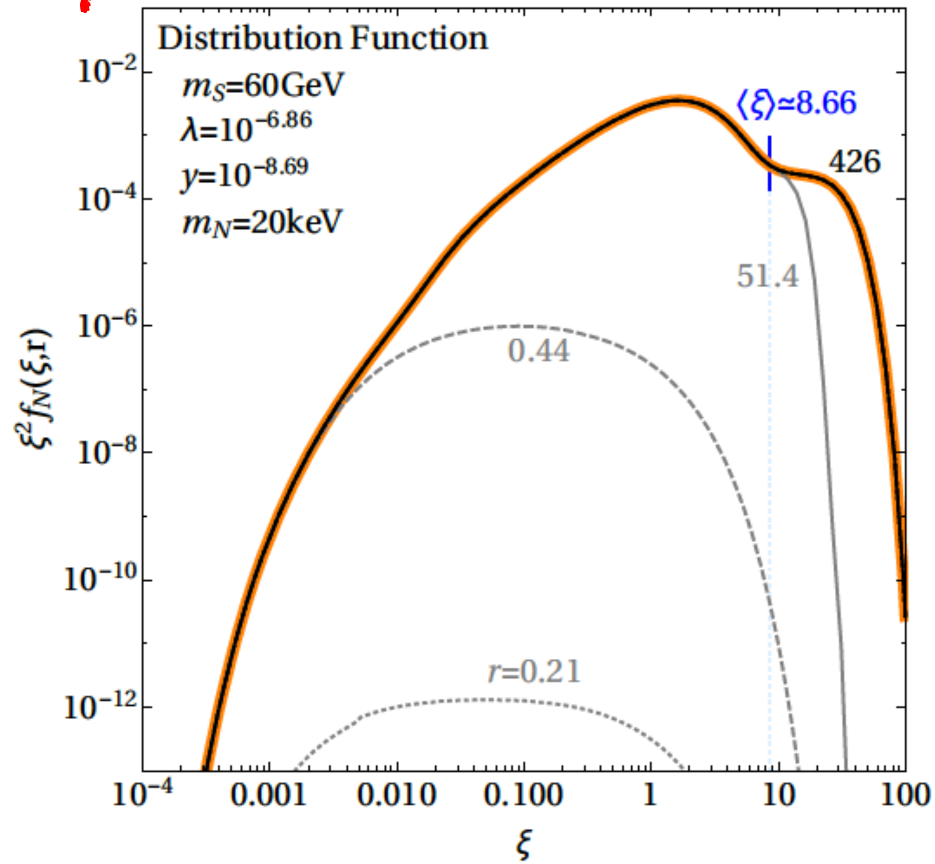


4. *The one that works*: Decay production

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

Distribution functions computed for each case:





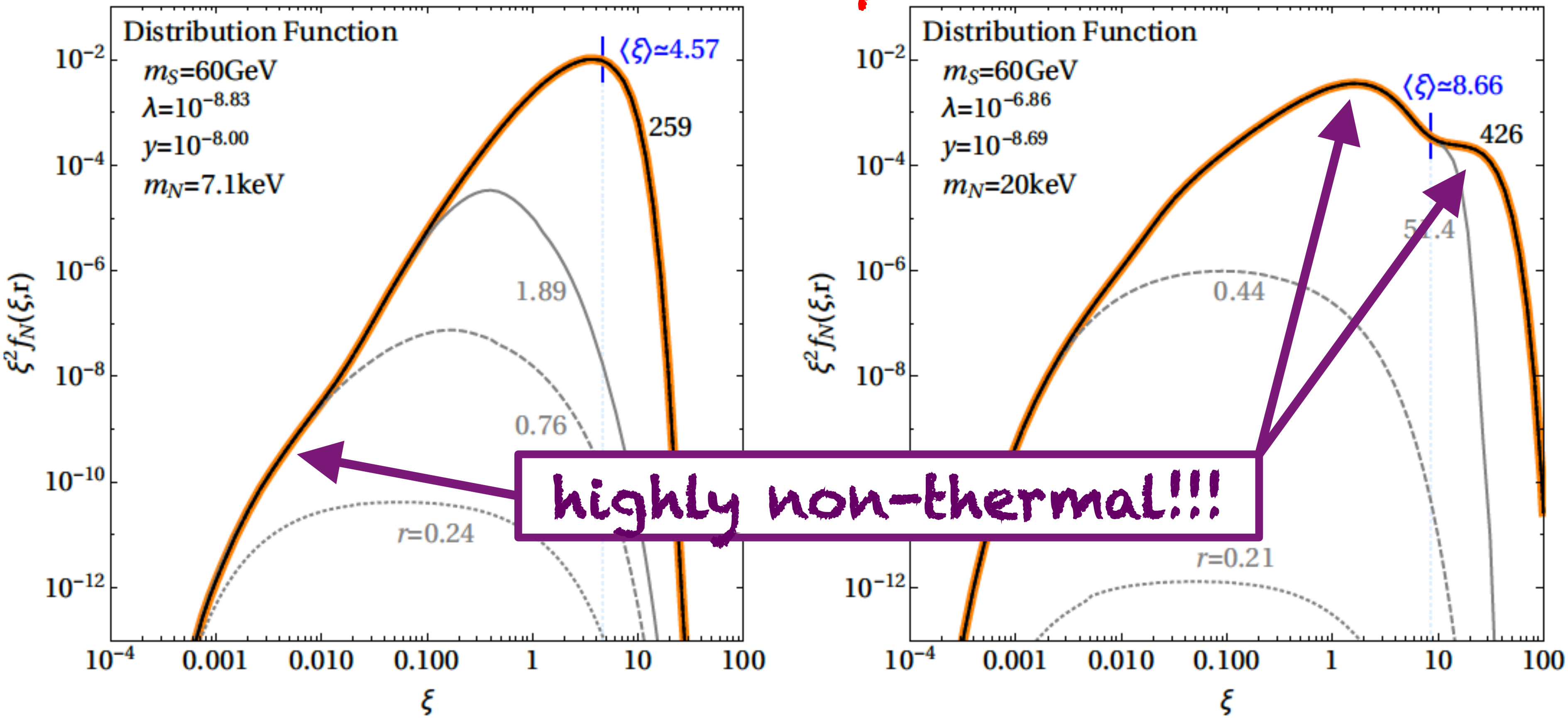
$$\xi = \frac{1}{T_0}\frac{a(t)}{a(t(T_0))}\,p = \left(\frac{g_s(T_0)}{g_s(T)}\right)^{1/3}\frac{p}{T}$$

ξ = momentum variable that includes redshift

4. *The one that works*: Decay production

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

Distribution functions computed for each case:



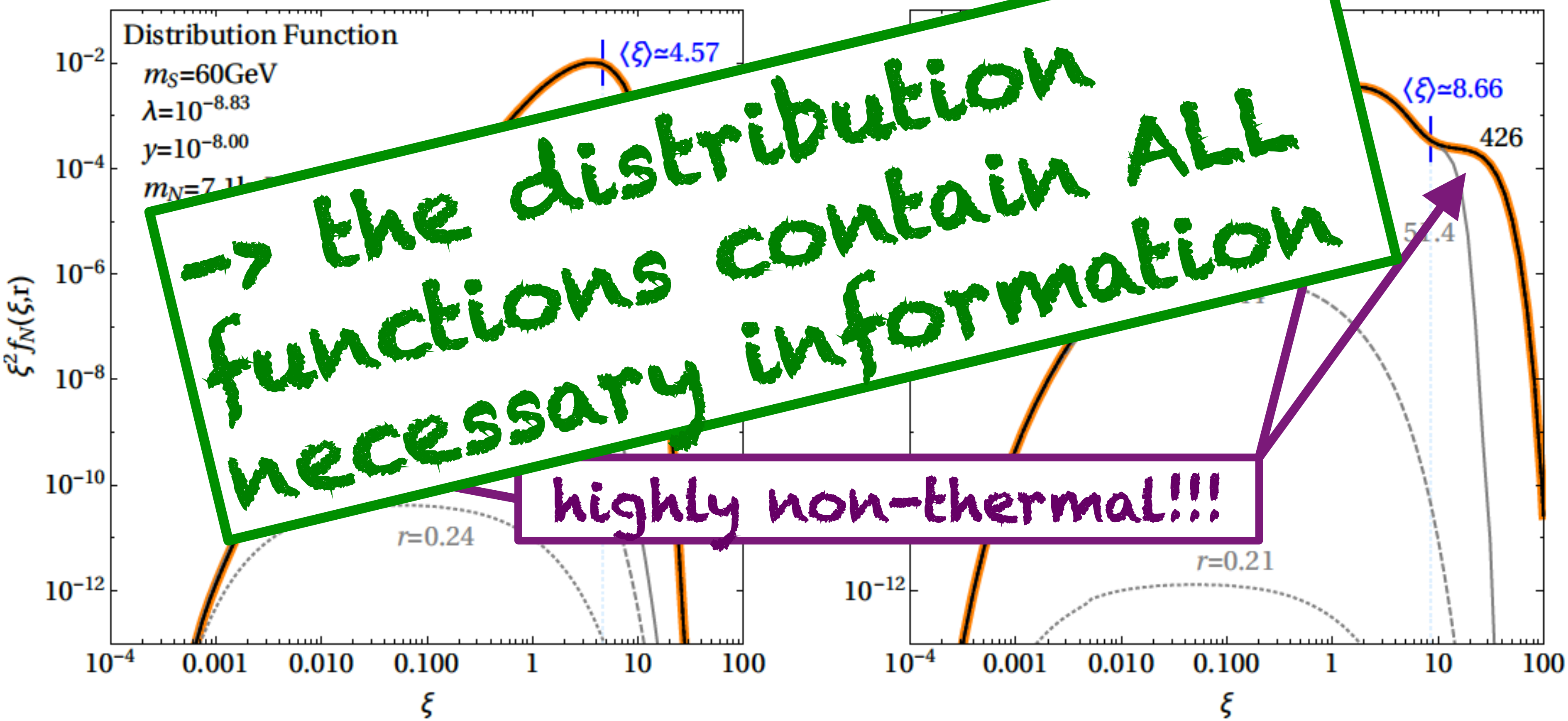
$$\xi = \frac{1}{T_0}\frac{a(t)}{a(t(T_0))}\,p = \left(\frac{g_s(T_0)}{g_s(T)}\right)^{1/3}\frac{p}{T}$$

ξ = momentum variable that includes redshift

4. *The one that works*: Decay production

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

Distribution functions computed for … case:



-> the distribution functions contain ALL necessary information

highly non-thermal!!!

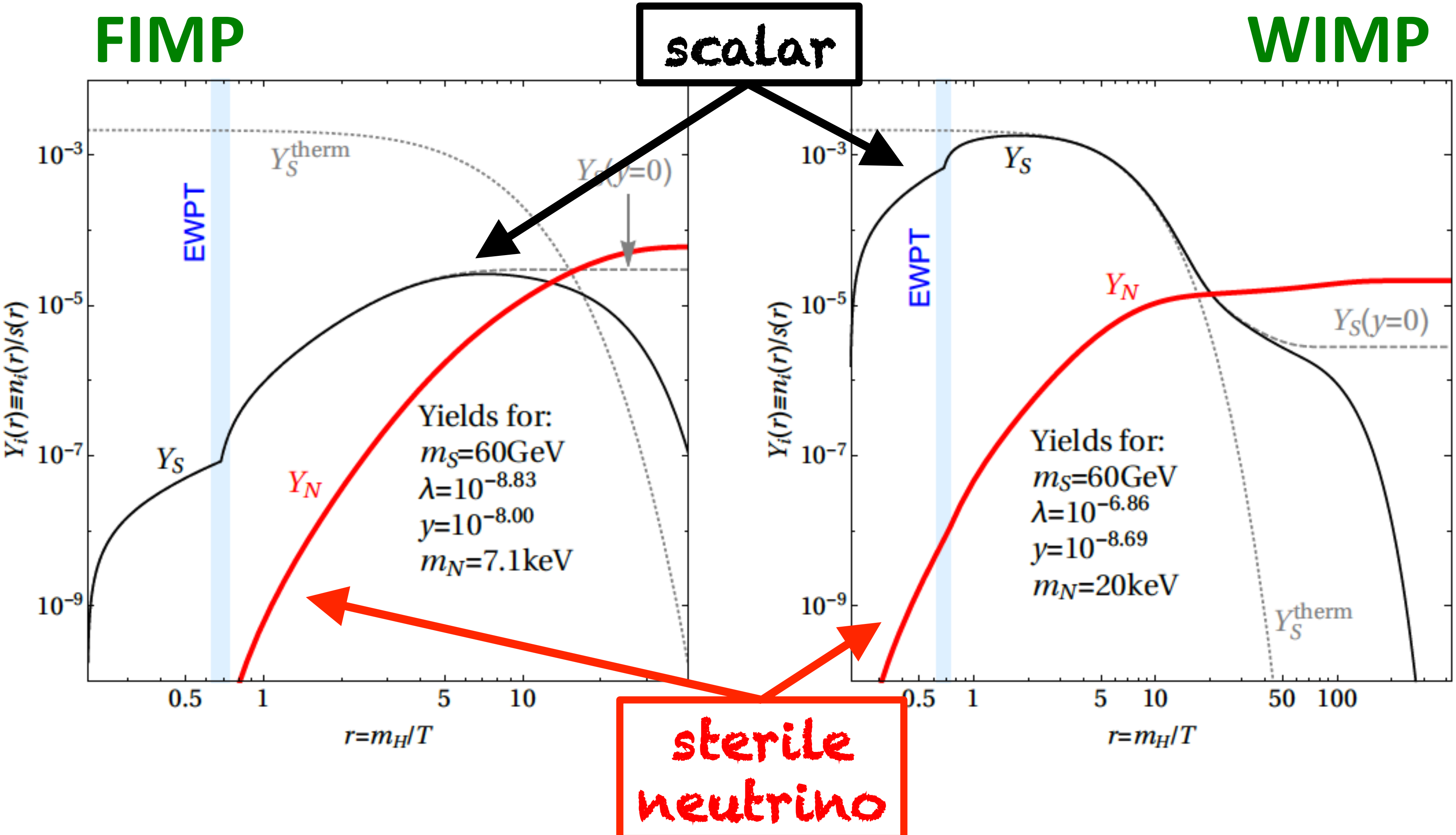
$$\xi = \frac{1}{T_0}\frac{a(t)}{a(t(T_0))}\,p = \left(\frac{g_s(T_0)}{g_s(T)}\right)^{1/3}\frac{p}{T}$$

ξ = momentum variable that includes redshift

4. *The one that works*: Decay production

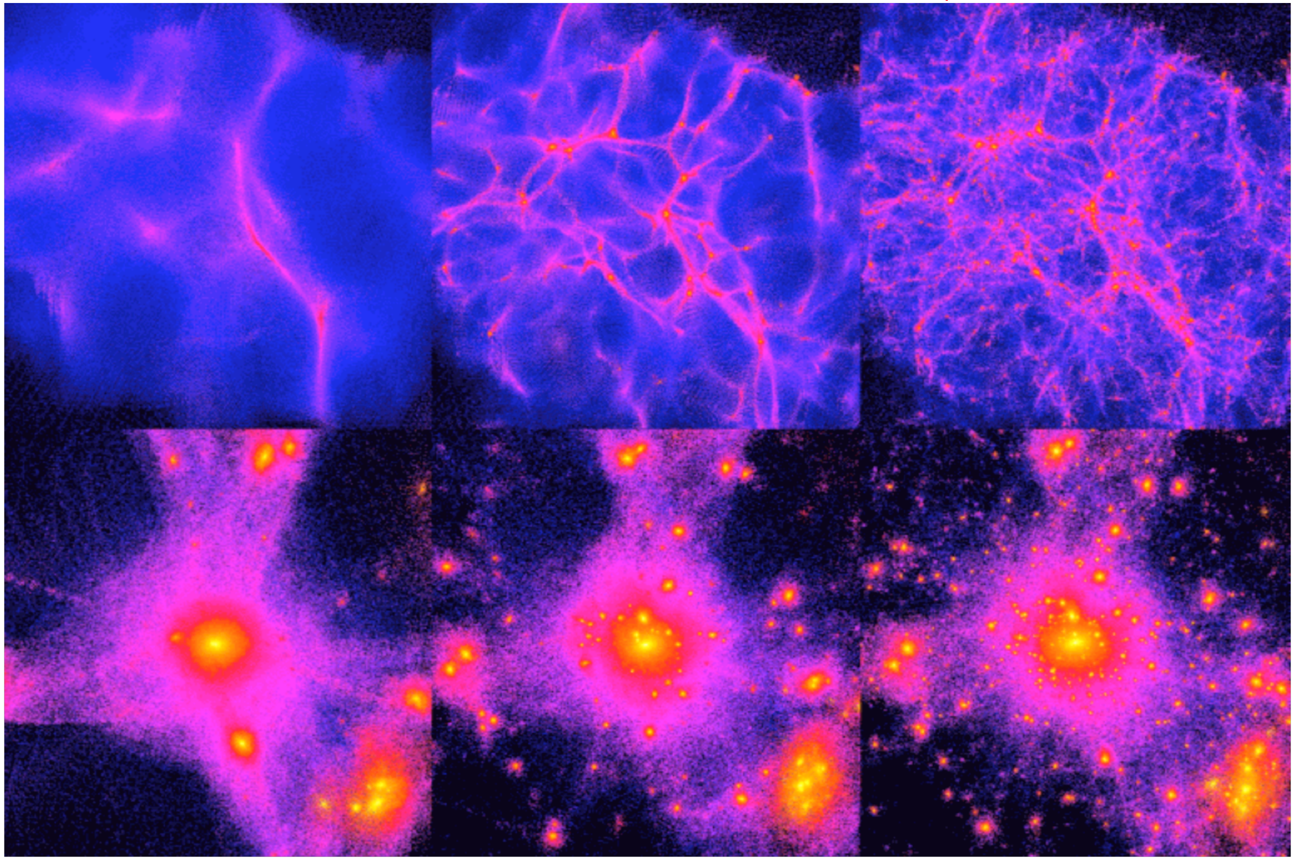
[König, **AM**, Totzauer: JCAP **1611** (2016) 038]

Example: Abundance/Yield by 2-step process



5. Structure Formation

Sooo, what about structure formation...?!?



[http://www.ctac.uzh.ch/gallery/]

HOT **WARM** **COLD**

... with non-thermal spectra!!!

-> We will see that now!!

5. Structure Formation

- **SINGLET SCALAR “S“ FREEZES IN OR OUT BEFORE DECAY**

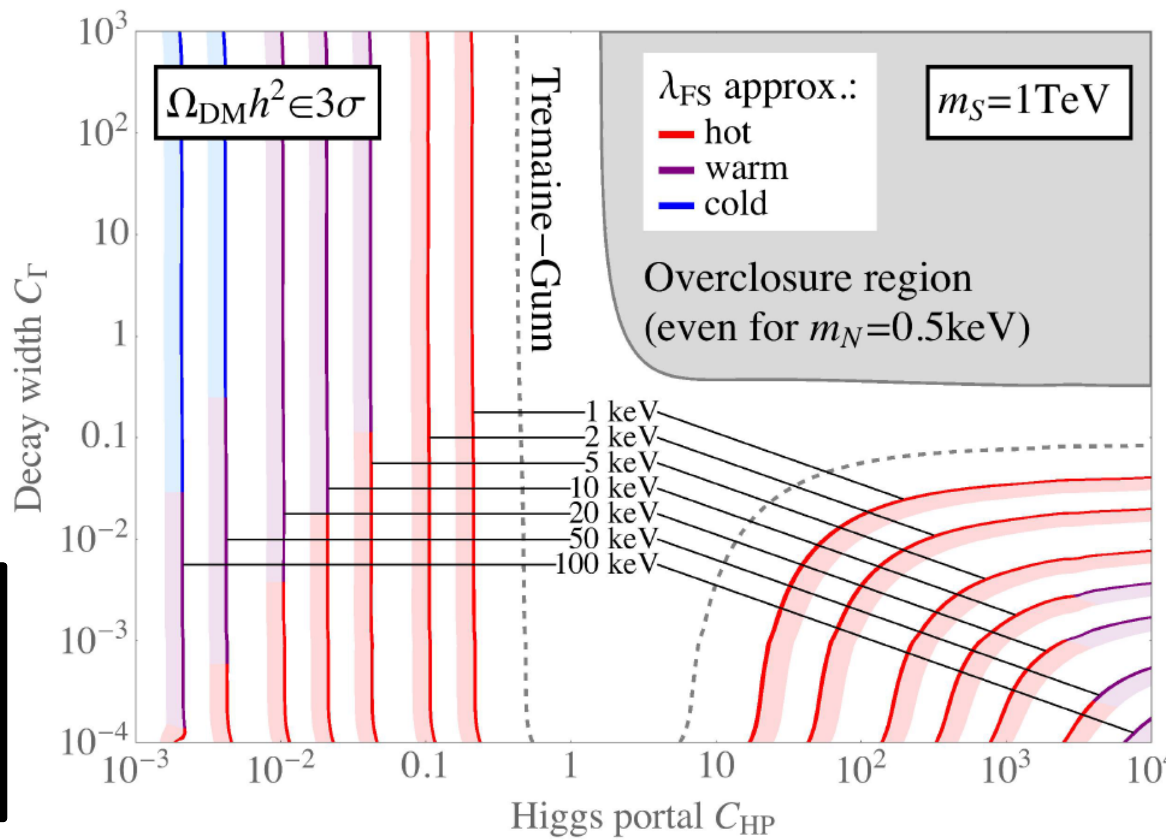
[Kusenko: Phys. Rev. Lett. **97** (2006) 241301; Kusenko, Petraki: Phys. Rev. **D77** (2008) 065014]
[**AM**, Niro, Schmidt: JCAP **1403** (2013) 028; **AM**, Totzauer: JCAP **1506** (2015) 011]

→ “Standard treatment“: FREE STREAMING

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**



5. Structure Formation

- **SINGLET SCALAR “S“ FREEZES IN OR OUT BEF… ECAY**

[Kusenko: Phys. Rev. Lett. **97** (2006) 241301; Kusenko, Pet… 065014]
[**AM**, Niro, Schmidt: JCAP **1403** (2013) 028; **AM** …

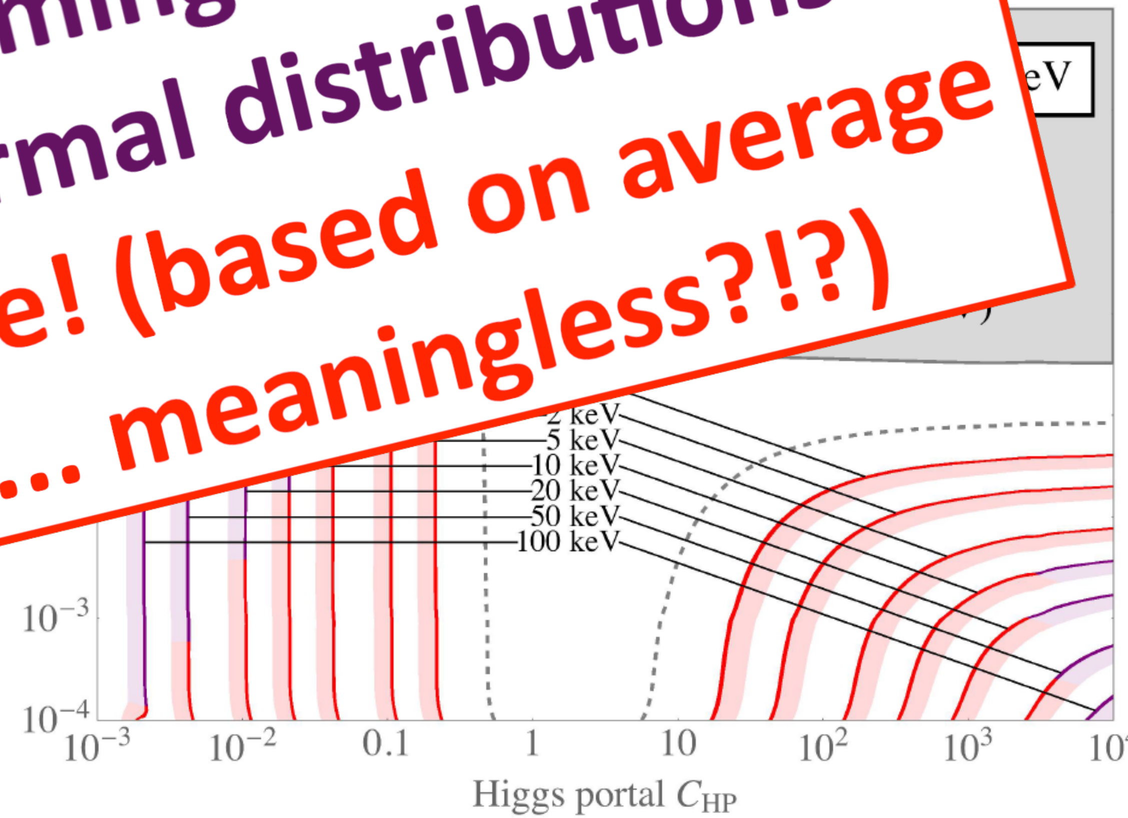
➔ “Stand…

Fr…

r…

Problem: INSUFFICIENT!!!!!

- **free-streaming is inspired from thermal distributions**
- **too crude! (based on average velocity… meaningless?!?)**

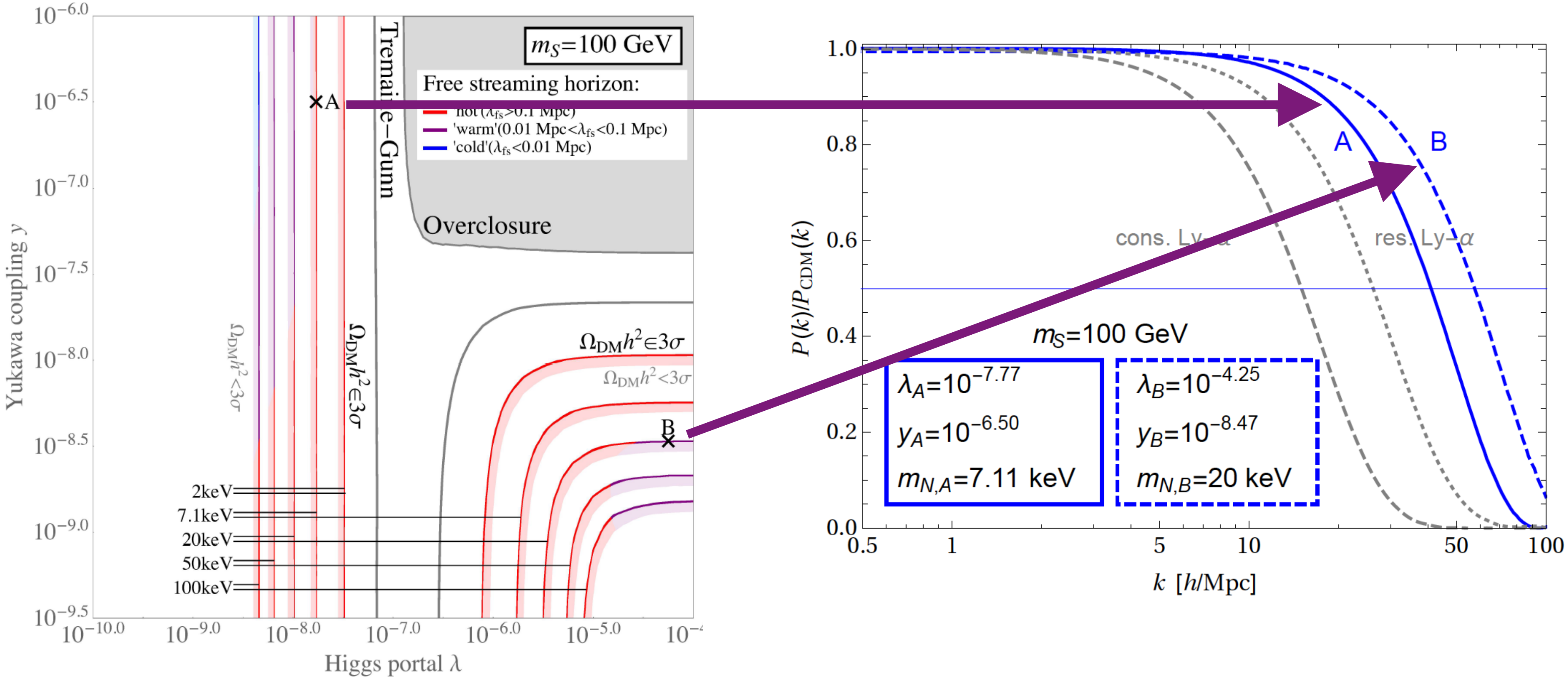


Decides … whether the keV sterile neutrinos are **HOT**, **WARM**, or **COLD**

5. Structure Formation

- **HOW FREE STREAMING CAN FAIL:**

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

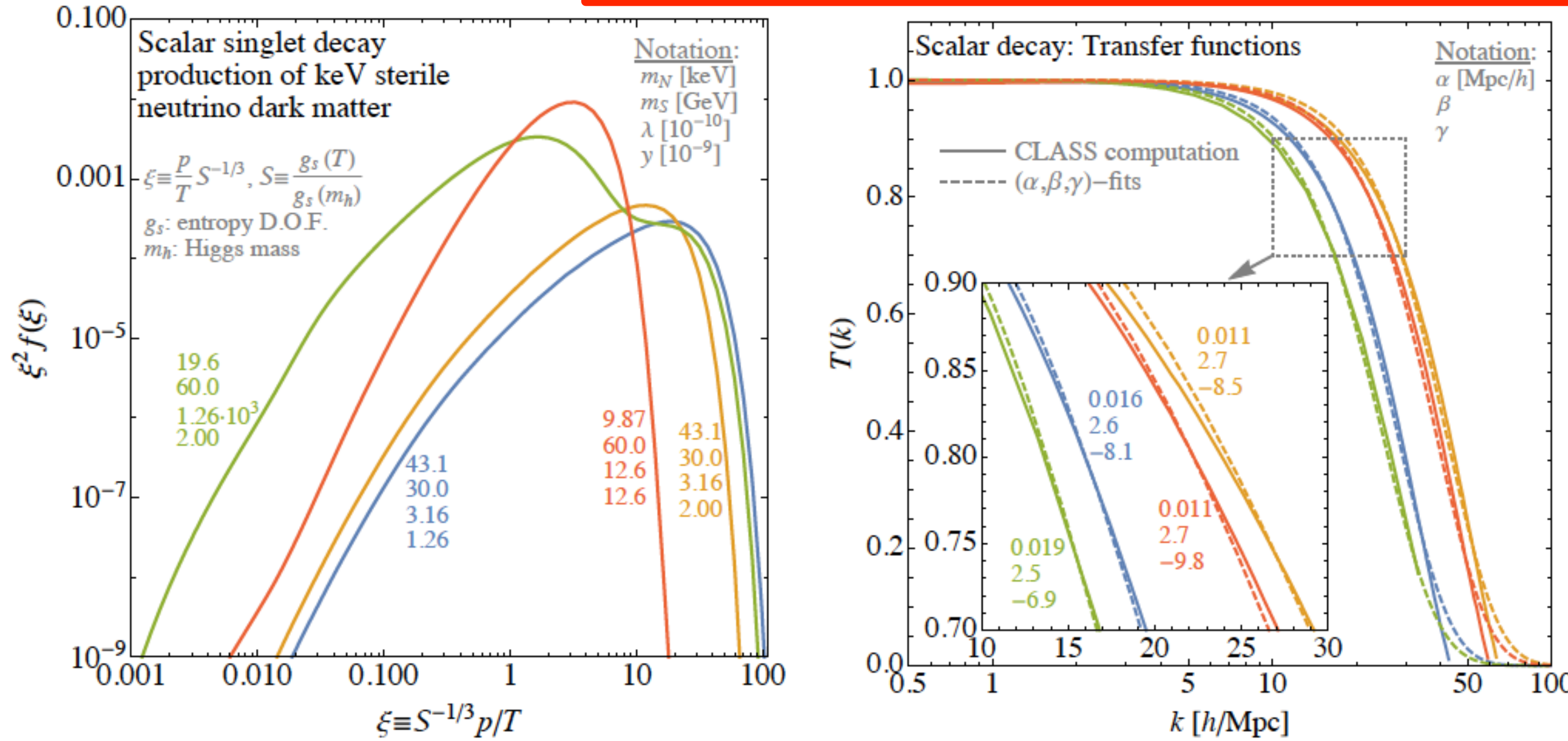


Points that fail according to a free-streaming analysis can actually be in full agreement with data....

5. Structure Formation

• **WAY OUT** (***VALID FOR ANY NON-THERMAL MODEL ON THE MARKET, AT LEAST SO FAR***):

Generalised TF $$T(k) = [1 + (\alpha k)^{\beta}]^{\gamma}$$



[Murgia, **AM**, Viel, Totzauer, Schneider: 1704.07838 [astro-ph]]

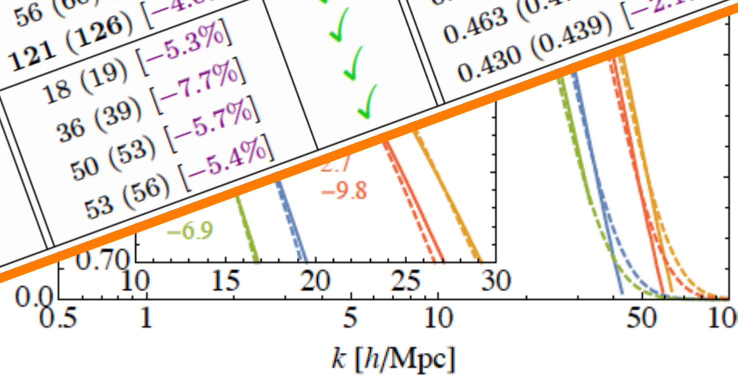
CLASS: www.class-code.net: Lesgourgues & Tram

5. Structure Formatio

• **WAY OUT** (***VALID FOR ANY NON-*** … ***DEL ON THE MARKET, AT LEAST SO*** …

Generalised … $]\gamma$

	α	β	γ	$k_{1/2}$ [h/Mpc]	$N_{\rm sub}^{\rm fit}$ ($N_{\rm sub}^{\rm true}$) [%]	Agree?	$\delta A_{\rm fit}$ ($\delta A_{\rm true}$) [%]	Agree?
RP neutrinos	0.025	2.3	−2.6	17.276	38 (39) [−2.6%]	✓	0.555 (0.571) [−2.8%]	✓
	0.071	2.3	−1.0	9.828	15 (14) [+7.1%]	✓	0.743 (0.754) [−1.5%]	✓
	0.038	2.3	−4.4	8.604	5 (5) [±0.0%]	✓	0.799 (0.810) [−1.4%]	✓
	0.035	2.1	−1.5	15.073	35 (37) [−5.4%]	✓	0.599 (0.613) [−2.3%]	✓
Neutrinos from particle decay	0.016	2.6	−8.1	19.012	38 (42) [−9.5%]	✓	0.521 (0.535) [−2.6%]	✓
	0.011	2.7	−8.5	28.647	**91 (97)** [−6.2%]	✓	0.339 (0.360) [−5.8%]	✓
	0.019	2.5	−6.9	16.478	27 (28) [−3.6%]	✓	0.582 (0.576) [+1.0%]	✓
	0.011	2.7	−9.8	26.31	**79 (87)** [−9.2%]	✓	0.375 (0.390) [−3.8%]	✗
Mixed models	0.16	3.2	−0.4	6.743	9 (9) [±0.0%]	✓	0.823 (0.834) [−1.3%]	✓
	0.20	3.7	−0.18	7.931	28 (27) [+3.7%]	✓	0.738 (0.752) [−1.9%]	✓
	0.21	3.7	−0.1	11.36	60 (62) [−3.2%]	✓	0.596 (0.610) [−2.3%]	✓
	0.21	3.4	−0.053	33.251	**110 (114)** [−3.5%]	✓	0.365 (0.377) [−3.2%]	✓
Fuzzy DM	0.054	5.4	−2.3	13.116	8 (9) [−11.1%]	✓	0.691 (0.708) [−2.4%]	✓
	0.040	5.4	−2.1	18.106	21 (23) [−8.7%]	✓	0.543 (0.565) [−3.9%]	✓
	0.030	5.5	−1.9	25.016	56 (60) [−6.7%]	✓	0.376 (0.399) [−5.8%]	✗
	0.022	5.6	−1.7	34.590	**121 (126)** [−4.0%]	✓	0.228 (0.250) [−8.8%]	✓
ETHOS models	0.0072	1.1	−9.9	7.274	18 (19) [−5.3%]	✓	0.780 (0.788) [−1.0%]	✓
	0.013	2.1	−9.3	16.880	36 (39) [−7.7%]	✓	0.568 (0.581) [−2.2%]	✓
	0.014	2.9	−10.0	21.584	50 (53) [−5.7%]	✓	0.463 (0.477) [−2.9%]	✓
	0.016	3.4	−9.3	23.045	53 (56) [−5.4%]	✓	0.430 (0.439) [−2.1%]	✓



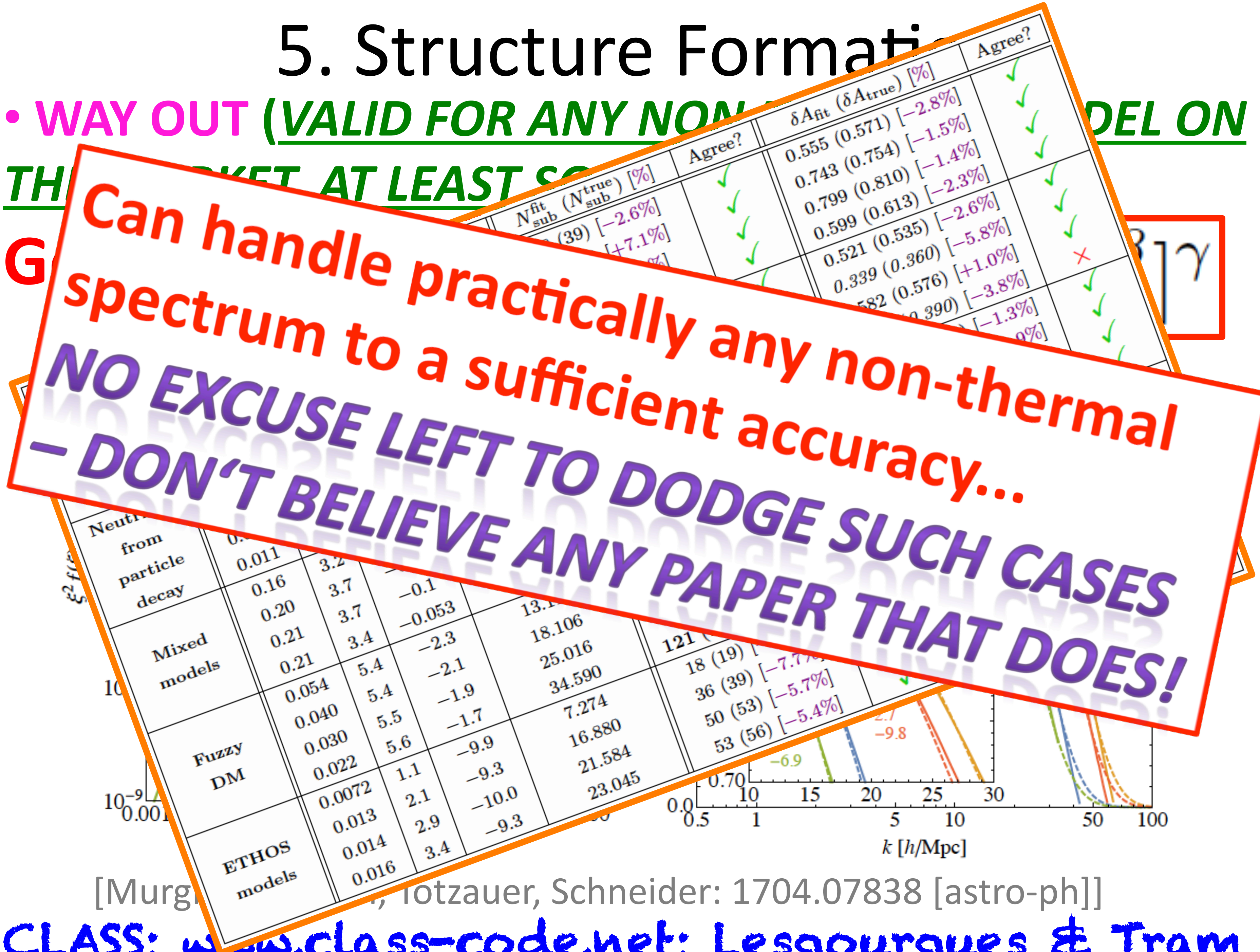
[Murg… …Totzauer, Schneider: 1704.07838 [astro-ph]]

CLASS: www.class-code.net: Lesgourgues & Tram

5. Structure Formati...

• WAY OUT (*VALID FOR ANY NON-... ...DEL ON THE ...RKET, AT LEAST SO...*

G...



[Murgi..., Totzauer, Schneider: 1704.07838 [astro-ph]]

CLASS: www.class-code.net: Lesgourgues & Tram

... and it confirms our **half-mode analysis**:

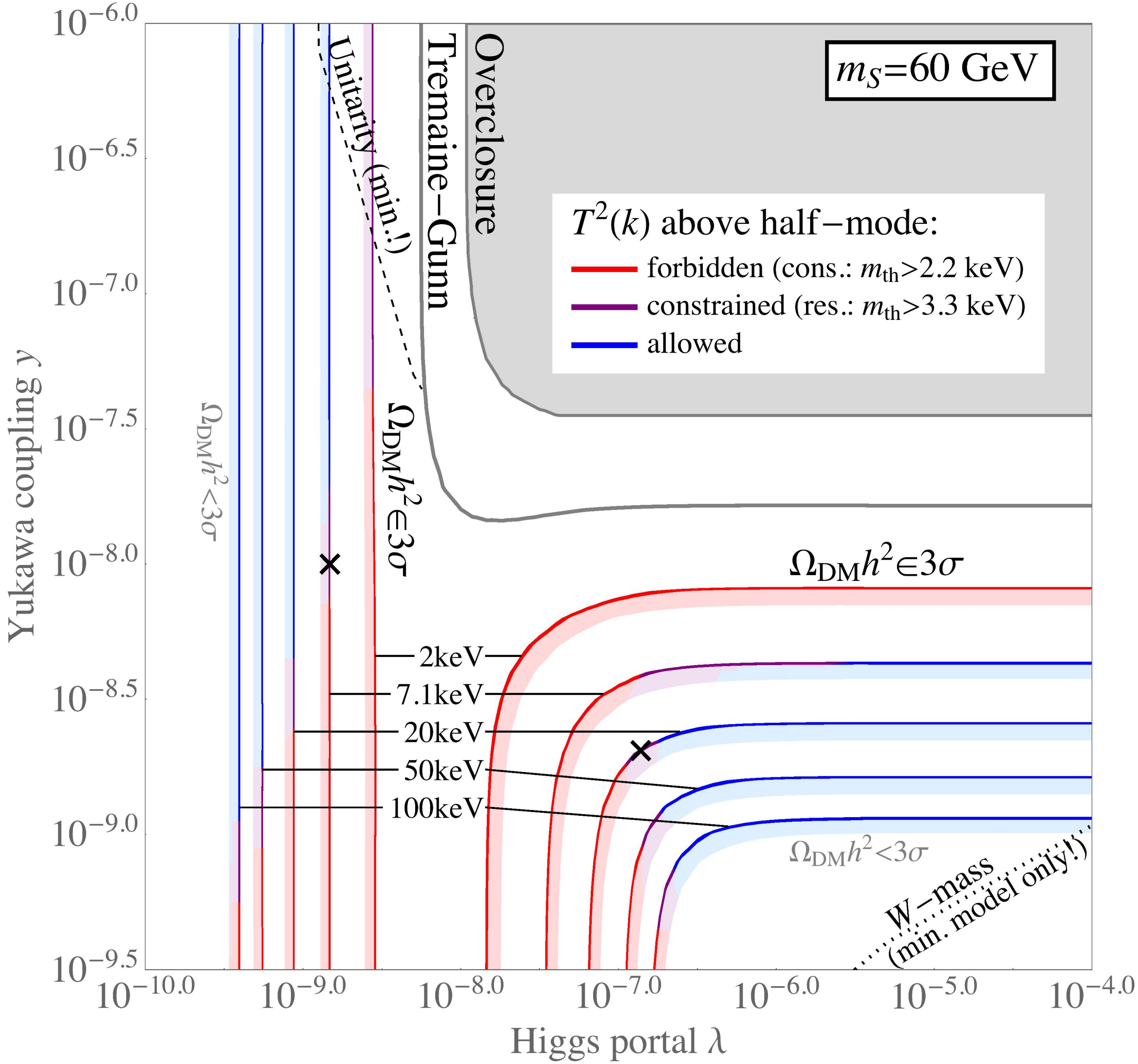
[König, **AM**, Totzauer: JCAP **1611** (2016) 038]

***Allowed regions from Ly-α data*:**

Coservative ✖
Restrictive ✖

Coservative ✓
Restrictive ✖

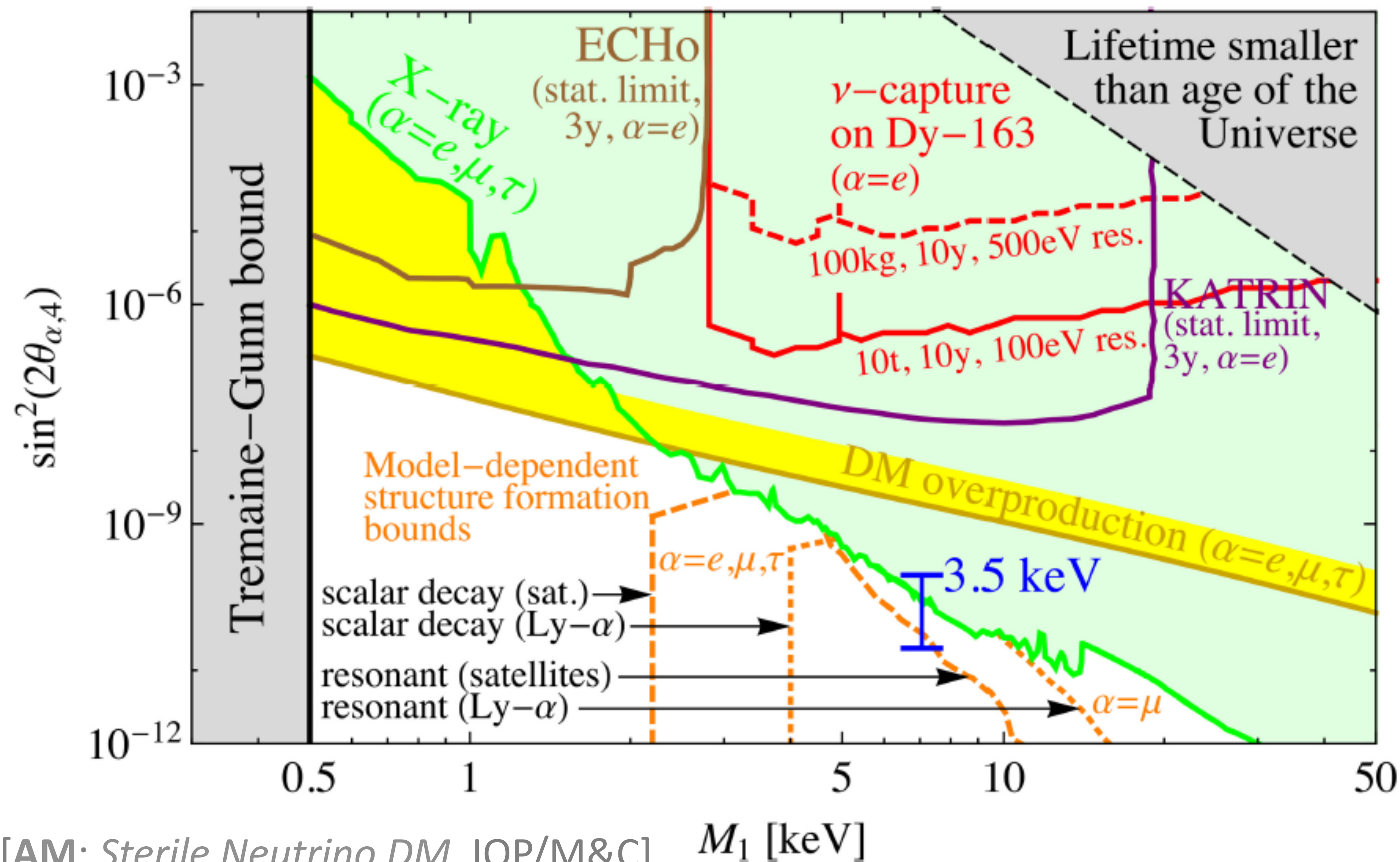
Coservative ✓
Restrictive ✓



6. Where to go from here?!?

6. Where to go from here?!?

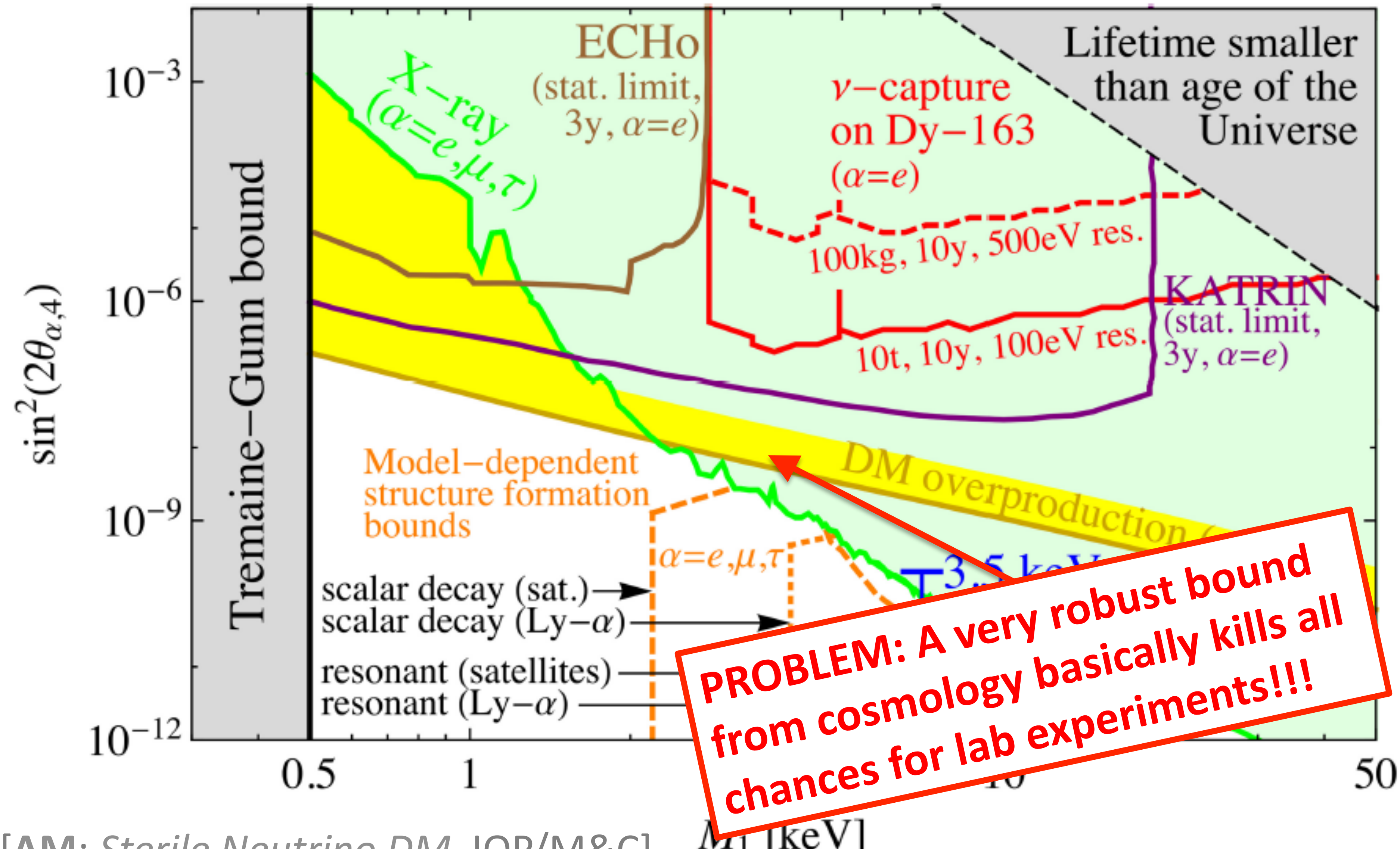
Summary of all constraints:



[**AM**: *Sterile Neutrino DM*, IOP/M&C]

6. Where to go from here?!?

Summary of all constraints:



[**AM**: *Sterile Neutrino DM*, IOP/M&C]

This elephant can‘t be hidden:

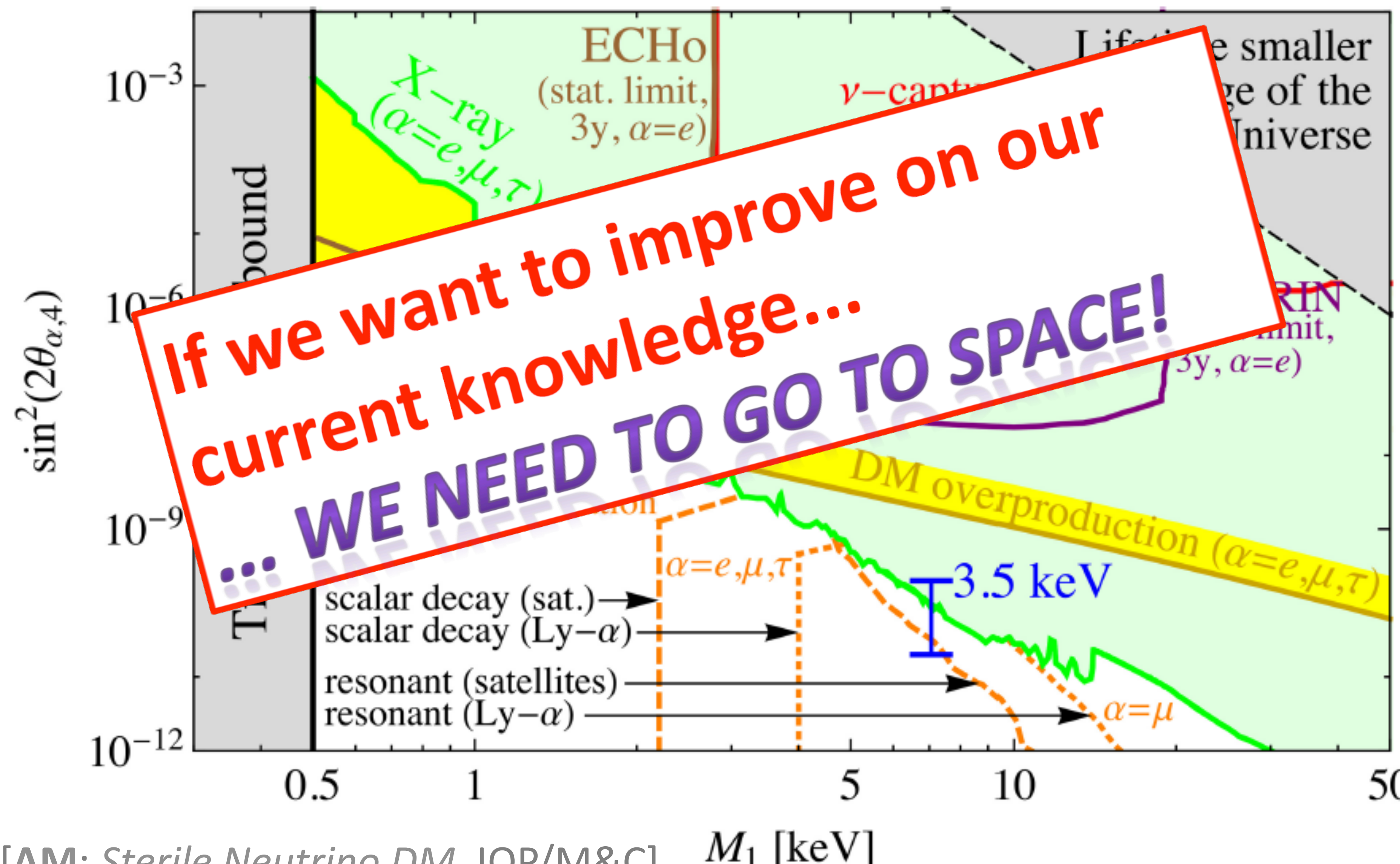
[JCAP **1706** (2017) 051] **claims that keV sterile neutrino interactions can be made *T*-dependent**, so that one can actually **detect them in kinematical experiments without spoiling DM production and early Universe cosmology**.

BUT: Their arguments rely, to quite some extend, on incorrect assumptions and/or oversimplifications…

- **DW-distribution of thermal shape:**
  disproved [**AM**, Schneider, Totzauer: JCAP **1604** (2016) 003]
- **abundance-calculation unrealiable:**
  successive error due to incorrect shape
- **hidden scalar sector very sketchy:**
  no actual computation of the decisive scalar production
- **crucial phase transition not actually computed:**
  again, only very sketchy estimates are presented

6. Where to go from here?!?

Summary of all constraints:



[**AM**: *Sterile Neutrino DM*, IOP/M&C]

6. Where to go from here?!?

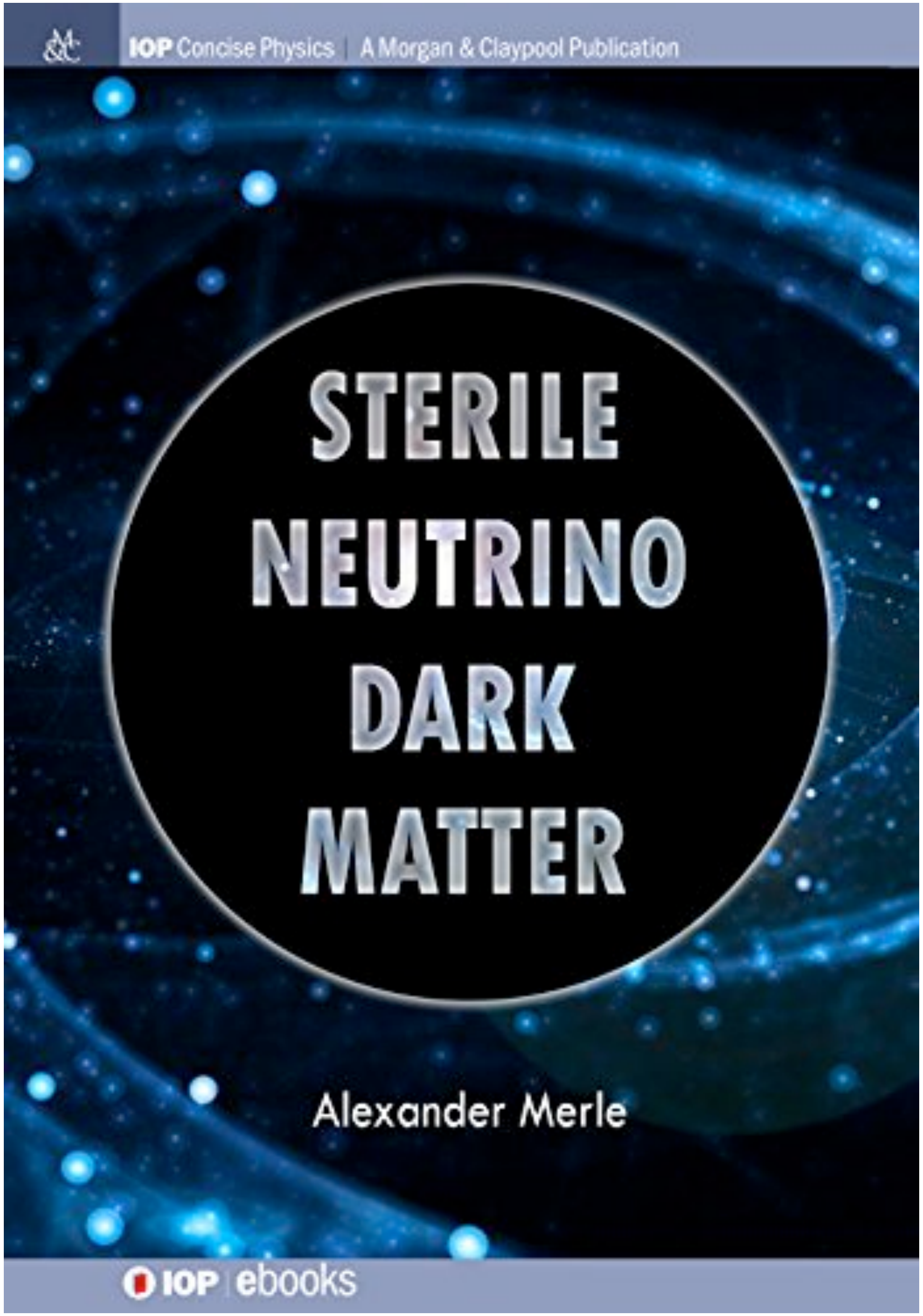
THREE ROADS LOOK PROMISING:

- **X-ray observations from $N_1 \rightarrow \nu + \gamma$ decay**
  -> would be good but will take time given that Hitomi (Astro-H) went to the happy hunting ground
- **new astrophysical signatures to constrain structure formation at smaller scales**
  -> e.g. high-redshift galaxies provide strong support for Lyman-α limits
- **seriously including non-thermal DM into high-resolution *N*-body simulations**
  -> we have shown that this is possible with less effort than anticipated


THANK YOU!!!

And if you want to know more…

… YOU MAY WANNA CHECK OUT MY NEW BOOK!!



BACK-UP SLIDES

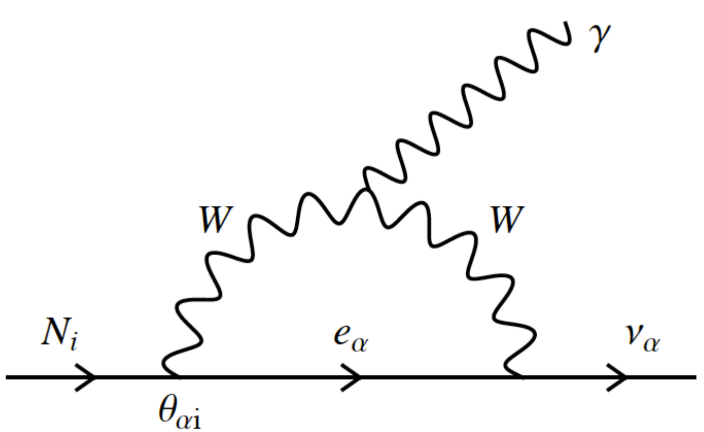
4. *Example A*: Active-Sterile Transitions

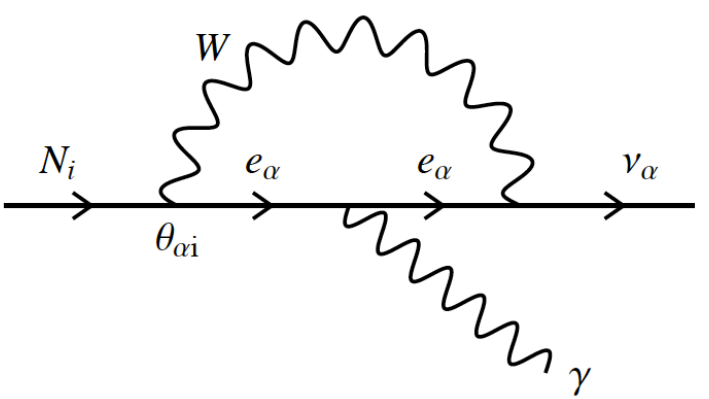
It could all be sooo simple...:

[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***

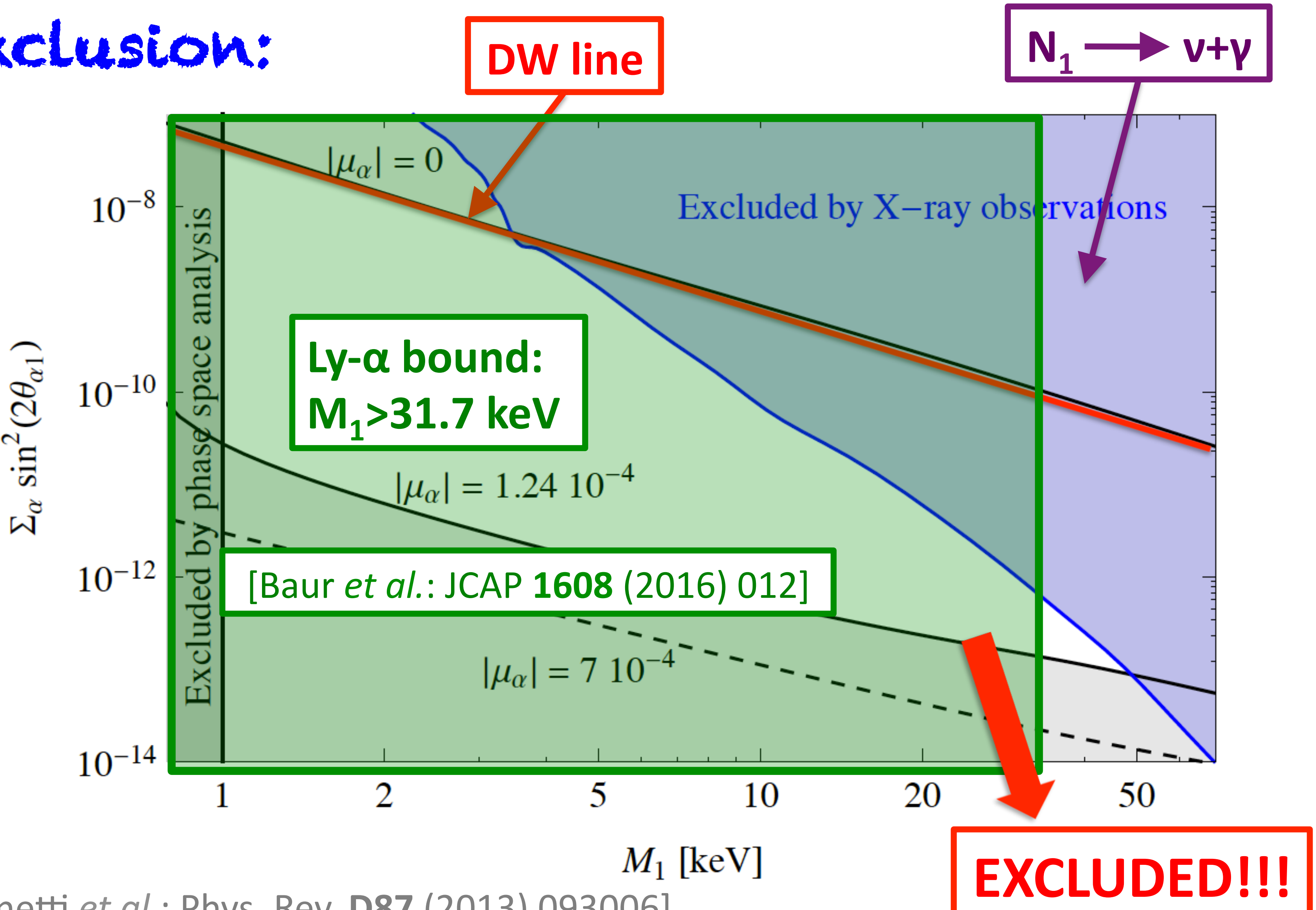
- **this mechanism produces relatively hot DM → large mass M_1 needed, BUT decay into X-rays scales like M_1^5:**





The Dodelson-Widrow mechanism

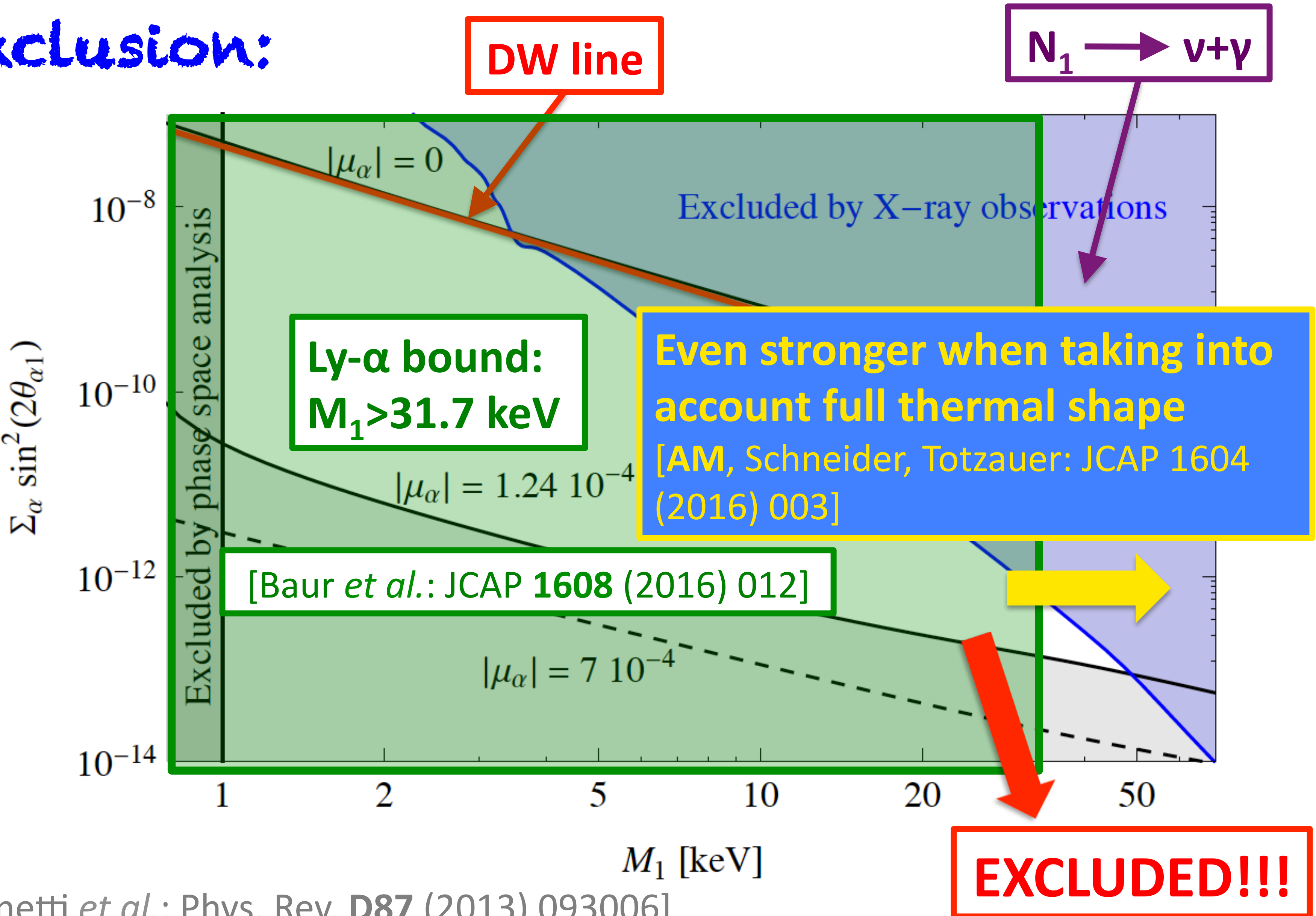
Exclusion:



[Canetti *et al.*: Phys. Rev. **D87** (2013) 093006]

The Dodelson-Widrow mechanism

Exclusion:



[Canetti *et al.*: Phys. Rev. **D87** (2013) 093006]

The Shi-Fuller mechanism

Is there 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**

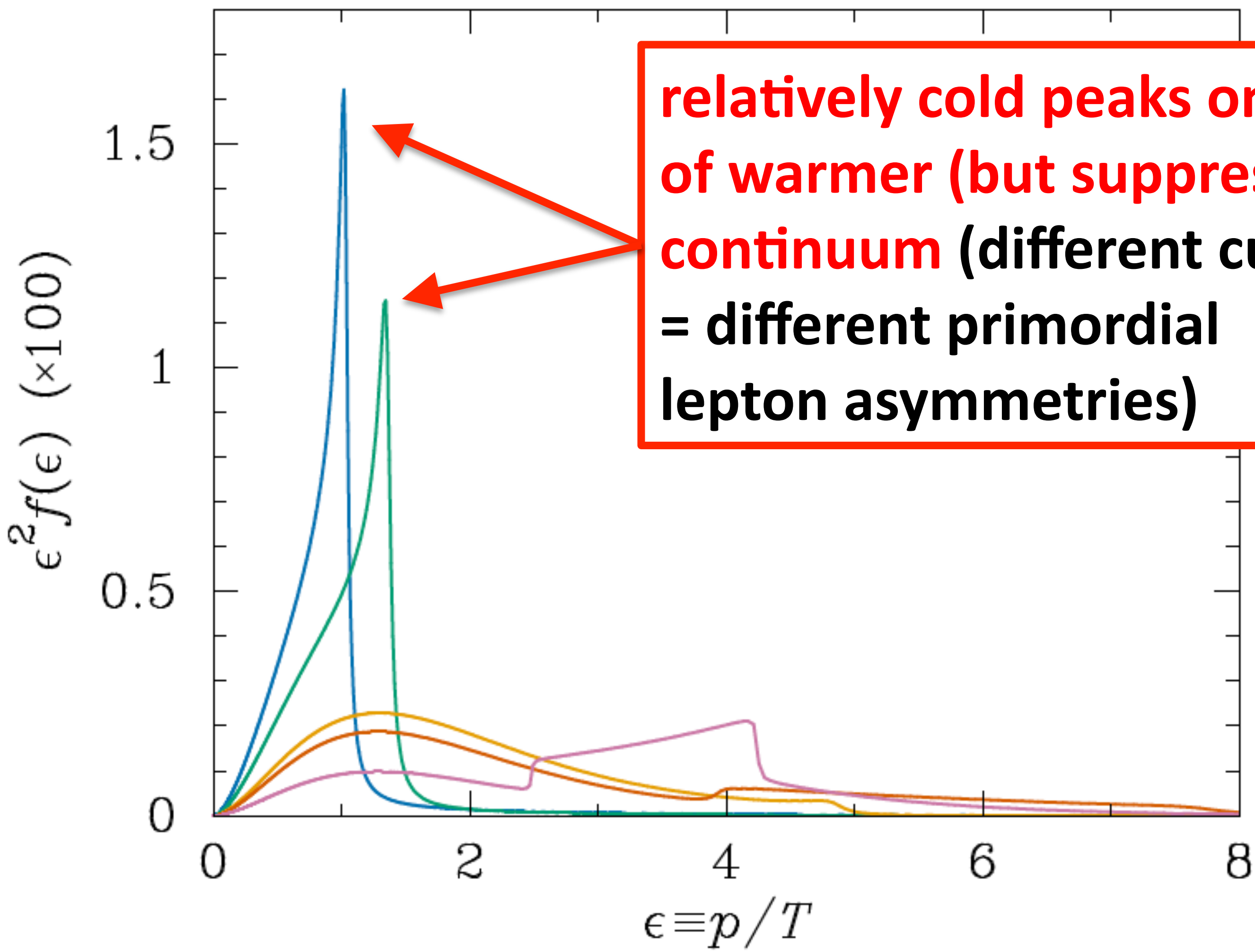
- **this would produce a large amount of ν_s at a specific (momentum-dependent) resonance temperature**
  ➔ *cooler spectrum*

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

The Shi-Fuller mechanism

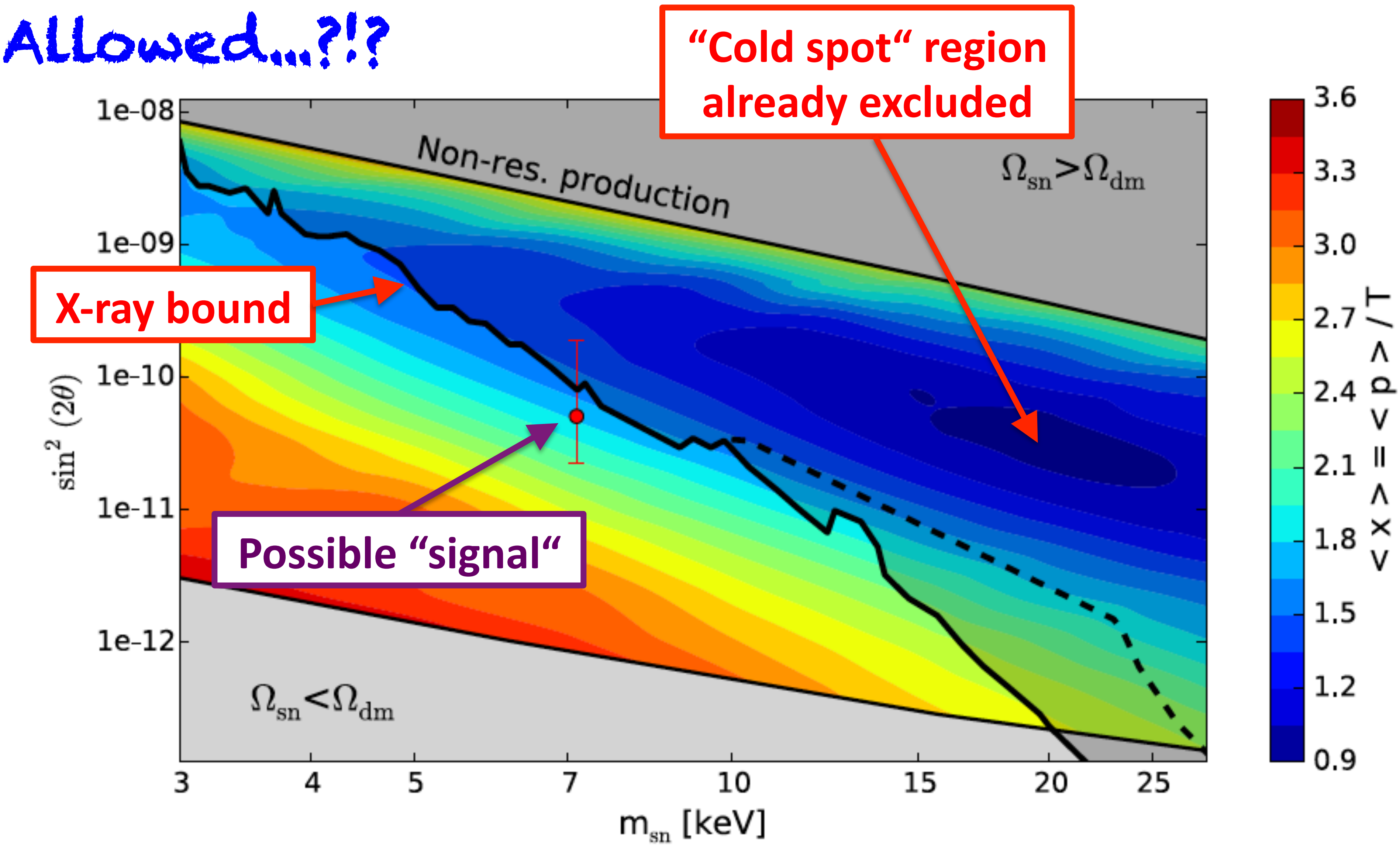
This produces to non-trivial spectra:

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



relatively cold peaks on top of warmer (but suppressed) continuum (different curves = different primordial lepton asymmetries)

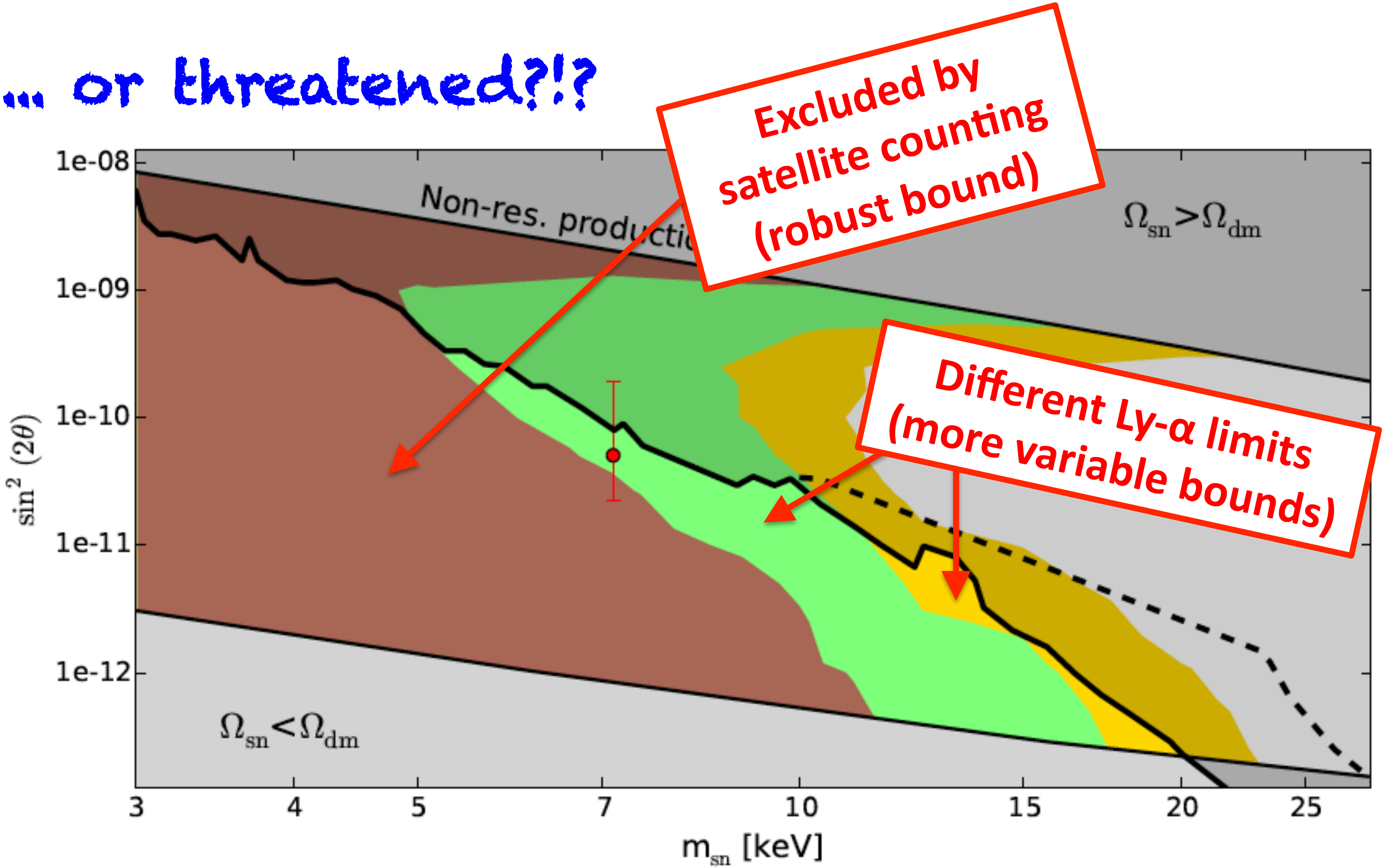
The Shi-Fuller mechanism



[Schneider: JCAP **1604** (2016) 059]

The Shi-Fuller mechanism

... or threatened?!?



[Schneider: JCAP **1604** (2016) 059]

4. *Example B*: DW with initial abundance

4. *Example B*: DW with initial abundance

BUT: DW is an unavoidable correction!!!

We have looked into this and, in passing, disproved two common prejudices about DW-production...

[**AM**, Schneider, Totzauer: JCAP **1604** (2016) 003]

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,...]

4. *Example B*: DW with initial abundance

We have found the FULL SOLUTION (semi-analytically)

[**AM**, Schneider, Totzauer: JCAP **1604** (2016) 003]

$$f_N(T_f, p) = \mathcal{S}(T_f, T_{ini}, T_f, p,) \left[f_{ini}\left(\frac{T_{ini}}{T_f} \left(\frac{g_S(T_{ini})}{g_S(T_f)} \right)^{1/3} p \right) + f_{DW}(T_f, T_{ini}, p) \right]$$

With:

$$\mathcal{S}(T_a, T_b, T_c, p) \equiv \exp\left[\int_{T_a}^{T_b} dT_2 \; h\left(T_2, \frac{T_2}{T_c} \left(\frac{g_S(T_2)}{g_S(T_c)} \right)^{1/3} p \right) \right]$$

$$f_{DW}(T_a, T_b, p) \equiv -\int_{T_a}^{T_b} dT_2 \mathcal{S}^{-1}(T_2, T_b, T_a, p)\,(h f_{th})\left(T_2, \frac{T_2}{T_f} \left(\frac{T_2}{T_f} \frac{g_S(T_2)}{g_S(T_f)} \right)^{1/3} p \right)$$

$$\mathcal{S}(T_f, T_{ini}, T_f, p)\, f_{DW}(T_f, T_{ini}, p) \stackrel{!}{=}$$

"Stop the clock"

$$\mathcal{S}(T_f, T_3, T_f, p) \left[\mathcal{S}\left(T_3, T_{ini}, T_3, \frac{T_3}{T_f} \left(\frac{g_S(T_3)}{g_S(T_f)} \right)^{1/3} p \right) f_{DW}\left(T_3, T_{ini}, \frac{T_3}{T_f} \left(\frac{g_S(T_3)}{g_S(T_f)} \right)^{1/3} p \right) + f_{DW}(T_f, T_3, p) \right],$$

CONSERVATION LAW

4. *Example B*: DW with initial abundance

We have found the FULL SOLUTION (semi-analytically)

[**AM**, Schneider, Totzauer: JCAP **1604** (2016) 003]

$$f_N(T_\mathrm{f}, p) = \mathcal{S}(T_\mathrm{f}, T_\mathrm{ini}, T_\mathrm{f}, p,) \left[f_\mathrm{ini}\left(\frac{T_\mathrm{ini}}{T_\mathrm{f}} \left(\frac{g_S(T_\mathrm{ini})}{g_S(T_\mathrm{f})} \right)^{1/3} p \right) + f_\mathrm{DW}(T_\mathrm{f}, T_\mathrm{ini}, p) \right]$$

coupling between both parts ($\mathcal{S}\approx 1$)

Redshifted initial distribution

DW-part

$$\ldots, p) \equiv \exp\left[\int^{T_b} \mathrm{d}T_2\, h \left(T_2, \frac{T_2}{T_c} \left(\frac{g_S(T_2)}{g_S(T_c)} \right)^{1/3} \ldots \right) \right]$$

$$f_\mathrm{DW}(T_a, \ldots) \ldots \int_{T_a} \ldots T_a, p)\, (h f_\mathrm{th}) \left(T_2, \frac{T_2}{T_\mathrm{f}} \left(\frac{T_2}{T_\mathrm{f}} \frac{g_S(T_2)}{g_S(T_\mathrm{f})} \right)^{1/3} p \right)$$

$$\mathcal{S}(T_\mathrm{f}, T_\mathrm{ini}, T_\mathrm{f}, p)\, f_\mathrm{DW}(T_\mathrm{f}, T_\mathrm{ini}, p) \overset{!}{=}$$

$$\mathcal{S}(T_\mathrm{f}, T_3, T_\mathrm{f}, p) \left[\mathcal{S}\left(T_3, T_\mathrm{ini}, T_3, \frac{T_3}{T_\mathrm{f}} \left(\frac{g_S(T_3)}{g_S(T_\mathrm{f})} \right)^{1/3} p \right) f_\mathrm{DW}\left(T_3, T_\mathrm{ini}, \frac{T_3}{T_\mathrm{f}} \left(\frac{g_S(T_3)}{g_S(T_\mathrm{f})} \right)^{1/3} p \right) + f_\mathrm{DW}(T_\mathrm{f}, T_3, p) \right],$$

"Stop the clock"

CONSERVATION LAW

4. *Example B*: DW with initial abundance

BUT: DW is an unavoidable correction!!!

We have looked into this and, in passing, disproved two common prejudices about DW-production...

[**AM**, Schneider, Totzauer: JCAP **1604** (2016) 003]

1st prejudice:

DW produces spectrum with thermal shape

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

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

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!!!**

4. *Example B*: DW with initial abundance

BUT: DW is an unavoidable correction!!!

We have looked into this and, in pass... ...oved two common prejudices ...

...6) 003]

1st preju...

D...

- i... ...OT

d...

$$f_N^{\mathrm{DW}} (\ldots (g_S(T_f)) \ldots) + 1 \int_{T_{\mathrm{ini}}} \mathrm{d}T_2\, h\left(T_2, \frac{T_2}{T_f}\left(\frac{g_S(T_2)}{g_S(T_f)}\right)^{1/3} p\right)$$

--> thus, all bounds based on the assumption of a thermal shape are, strictly speaking, wrong (how far from reality depends on the details...)

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!!!

4. *Example B*: DW with initial abundance

BUT: DW is an unavoidable correction!!!

We have looked into this and, in passing, disproved two common prejudices about DW-production...

[**AM**, Schneider, Totzauer: JCAP **1604** (2016) 003]

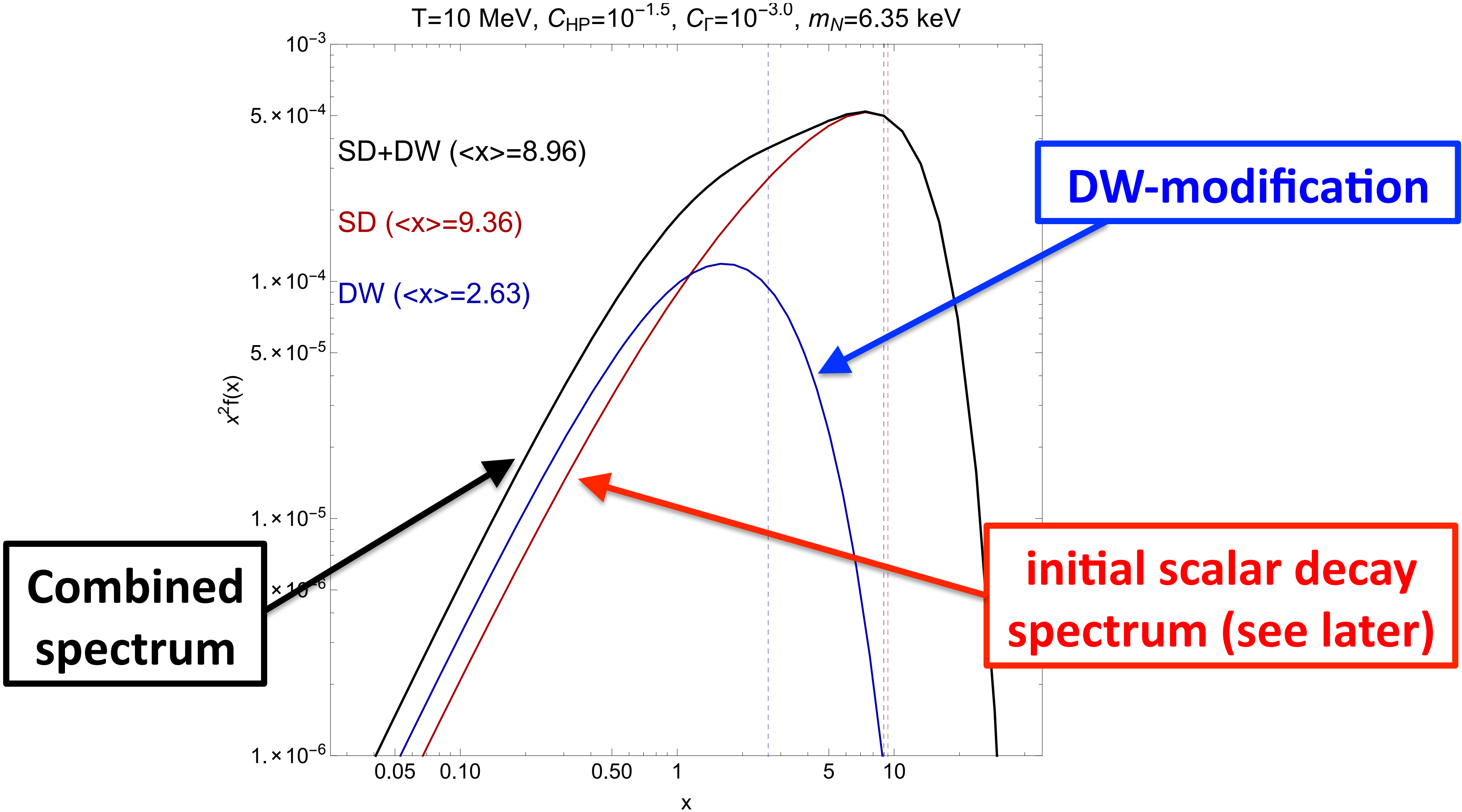
2nd prejudice:

DW always produces a too hot spectrum

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

- ***illustration: scalar decay production + SUBSEQUENT modification by the Dodelson-Widrow mechanism***

4. *Example B*: DW with initial abundance



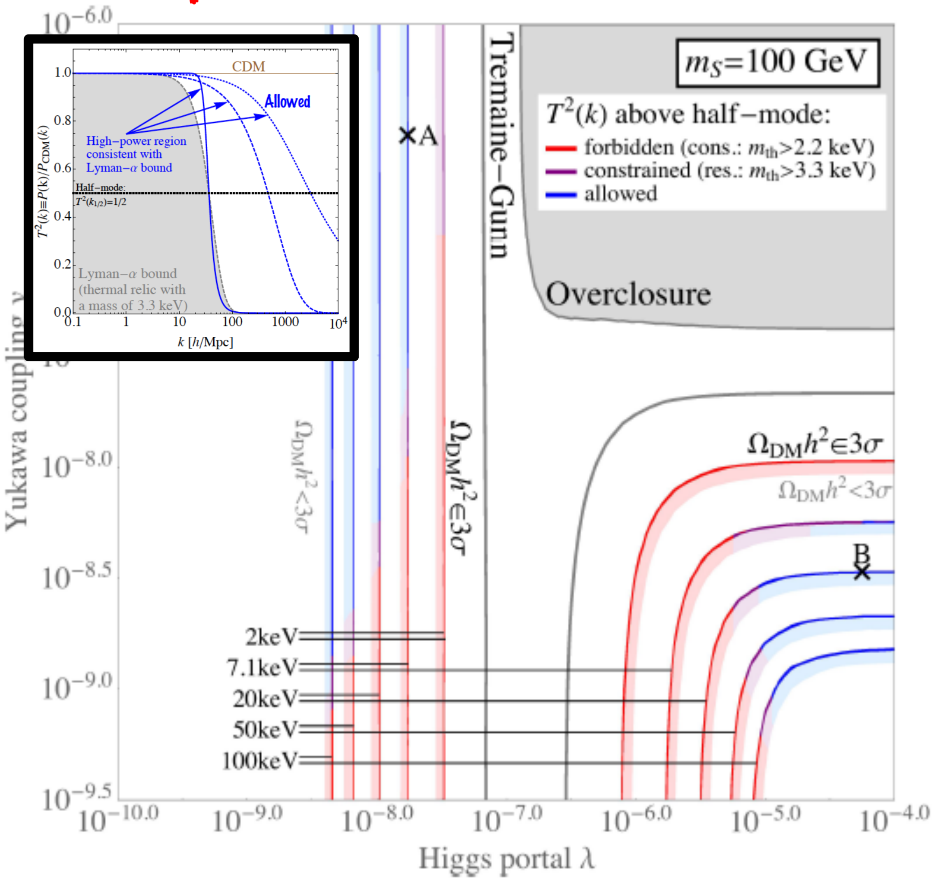
may shift the average momentum to LOWER values ("DW-cooling")

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

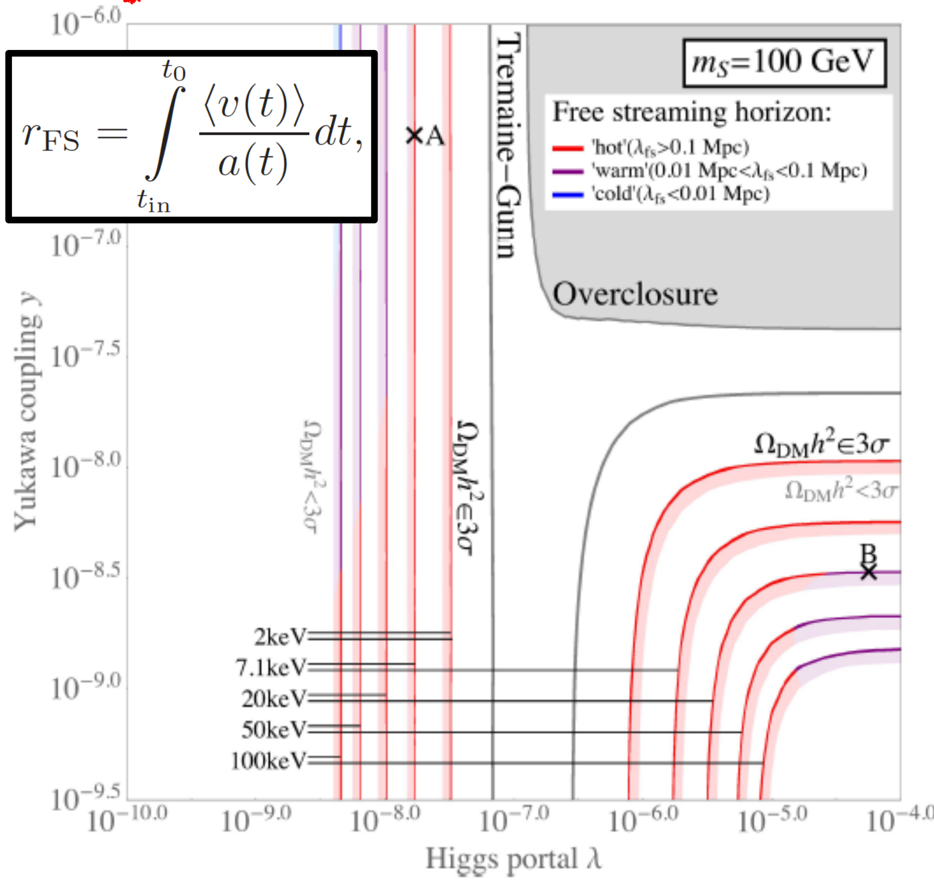
4. *Example 2*: Decay production

[König, **AM**, Totzauer: 1609.01289]

Comparison: Half-mode analysis vs. free streaming



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

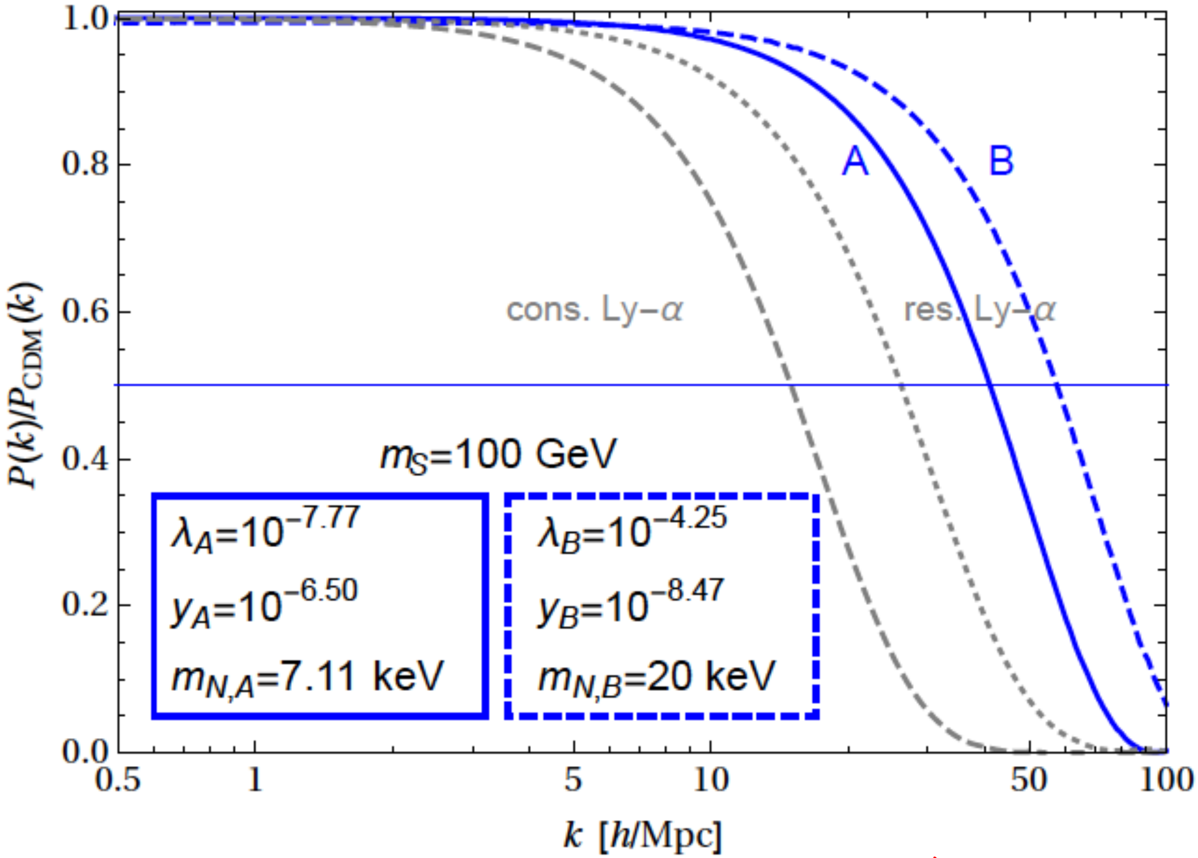


-> free-streaming would classify points A/B as "hot"/"warm" and discard at least one...

4. *Example 2*: Decay production

[König, **AM**, Totzauer: 1609.01289]

... while in reality both are not even touched by structure formation constraints!!!!

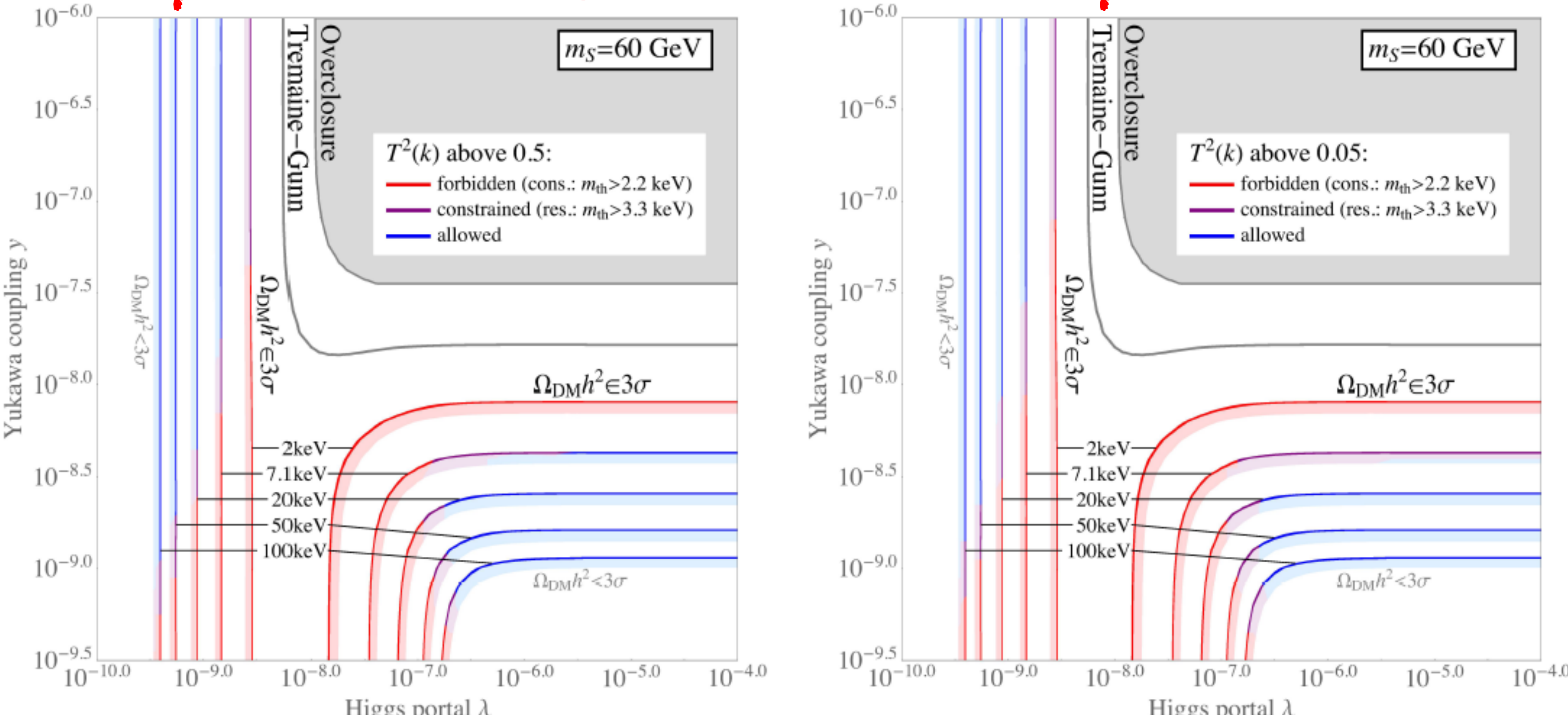


➔ free-streaming cannot describe non-thermal distributions correctly!!!!

4. *Example 2*: Decay production

[König, **AM**, Totzauer: 1609.01289]

... whereas our analysis is very robust with respect to changes in the assumption:



→ even a change of the referece point by one order of magnitude hardly affects our results!

4. *The one that works*: Decay production

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

- **TECHNICALITY:** **How to crack a coupled system of non-linear partial integro-differential equations in two variables?**

SCALAR

$$\hat{L} f_S(p,T) = \mathcal{D}(p,T) f_S(p,T) + \int_0^\infty \mathrm{d}p' \mathcal{K}^S(p,p',T) \left[f_S(p,T) f_S(p',T) - f_S^{\mathrm{eq}}(p,T) f_S^{\mathrm{eq}}(p',T) \right]$$

$$\hat{L} f_N(p,T) = \int_0^\infty \mathrm{d}p' \mathcal{K}^N(p,p',T) f_S(p',T)$$

$$\hat{L} = \frac{\partial}{\partial t} - H p \frac{\partial}{\partial p}$$

STERILE NEUTRINO

Liouville oerpator

-> extremely tricky if not appraoched in the correct way (no known type of integro-differential equation, like e.g. Volterra-type, because of integrals extending over the whole domain in the momentum p)

4. *The one that works*: Decay production

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

- **Our strategy:**
  - **family of new variables:**

$$\left.\begin{matrix} T \\ p \end{matrix}\right\} \rightarrow \left\{\begin{matrix} r(T,p) = r(T) \\ \xi(T,p) = f\left(\frac{a[t(T)]}{a[t(T_0)]}p\right) \end{matrix}\right\} \rightarrow \left\{\begin{matrix} r = m_0/T \\ \xi = \frac{p}{T}\left(\frac{g_s(T_0)}{g_s(T)}\right)^{1/3} \end{matrix}\right.$$

-> equations decoupled, numerics stabelised (m_0 & T_0!!)

  - **discretise the "momentum" ξ into fine slices, to turn the PDE into a system of ODEs:**

$$\frac{\mathrm{d}}{\mathrm{d}r} f_S^i(r) = \tilde{\mathcal{D}}^i(T) f_S^i(r) + \sum_{j=1,\ldots,M} \tilde{\mathcal{K}}^{ij}(r)\left[f_S^i(r) f_S^j(r) - f_S^{i,\mathrm{eq}}(r) f_S^{j,\mathrm{eq}}(r)\right]$$

  - **use a solver that is NOT list-based (like Mathematica), but matrix-based (like *ode15s* in Matlab) to exploit semi-analytical methods**

4. *The one that works*: Decay production

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

- **Our strategy:**
  - **family of new variables:**

$$\left.\begin{matrix} T \\ p \end{matrix}\right\} \to \left\{\begin{matrix} r(T,p) = r(T) \\ \xi(T,p) = f\left(\frac{a[t(T)]}{a[t(T_0)]}p\right) \end{matrix}\right\} \to \left\{ r = m_0/T \right.$$

-> equations dec...

... turn the PDE

THIS WAY, WE COULD SOLVE THE FULL SET OF EQUATIONS GOVERNING DARK MATTER PRODUCTION IN THE WHOLE PARAMETER SPACE

$$\ldots f_S^i(r) + \sum_{j=1,\ldots,M} \tilde{\mathcal{K}}^{ij}(r)\left[f_S^i(r)\, f_S^j(r) - f_S^{i,\mathrm{eq}}(r)\, f_S^{j,\mathrm{eq}}(r)\right]$$

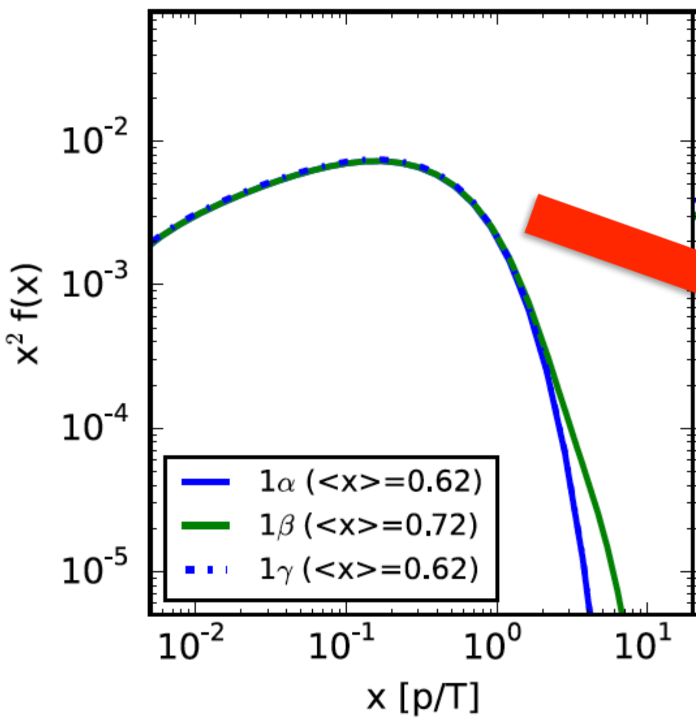
  - **use a solver that is NOT list-based (like Mathematica), but matrix-based (like *ode15s* in Matlab) to exploit semi-analytical methods**

5. Structure Formation

- **OUR PROPOSAL** (***for stupid particle guys only***):

Half-mode analysis [König, **AM**, Totzauer: JCAP 1611 (2016) 038]

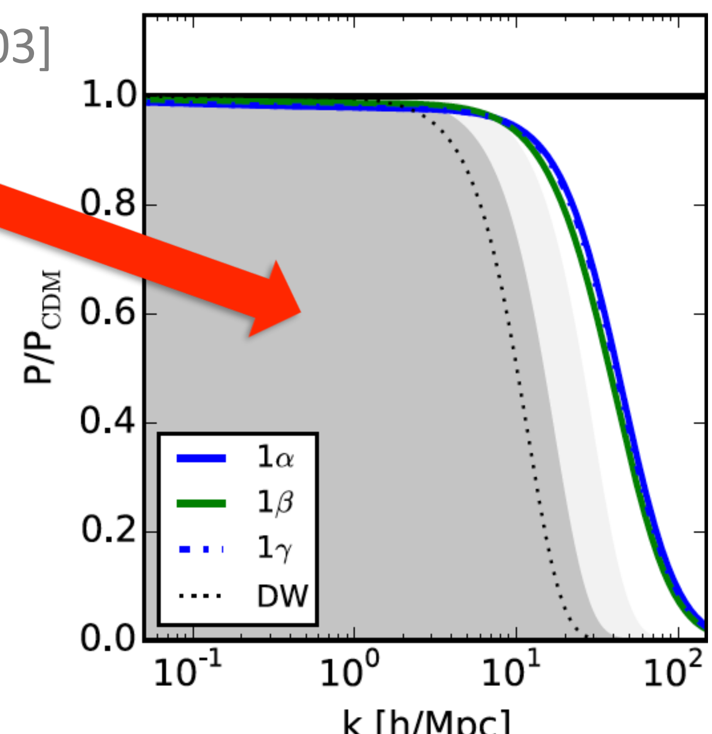
- Linear power spectrum with CLASS
  -> www.class-code.net: Lesgourgues & Tram



[**AM**, Schneider, Totzauer: JCAP **1604** (2016) 003]

OUTPUT: (squared) transfer function

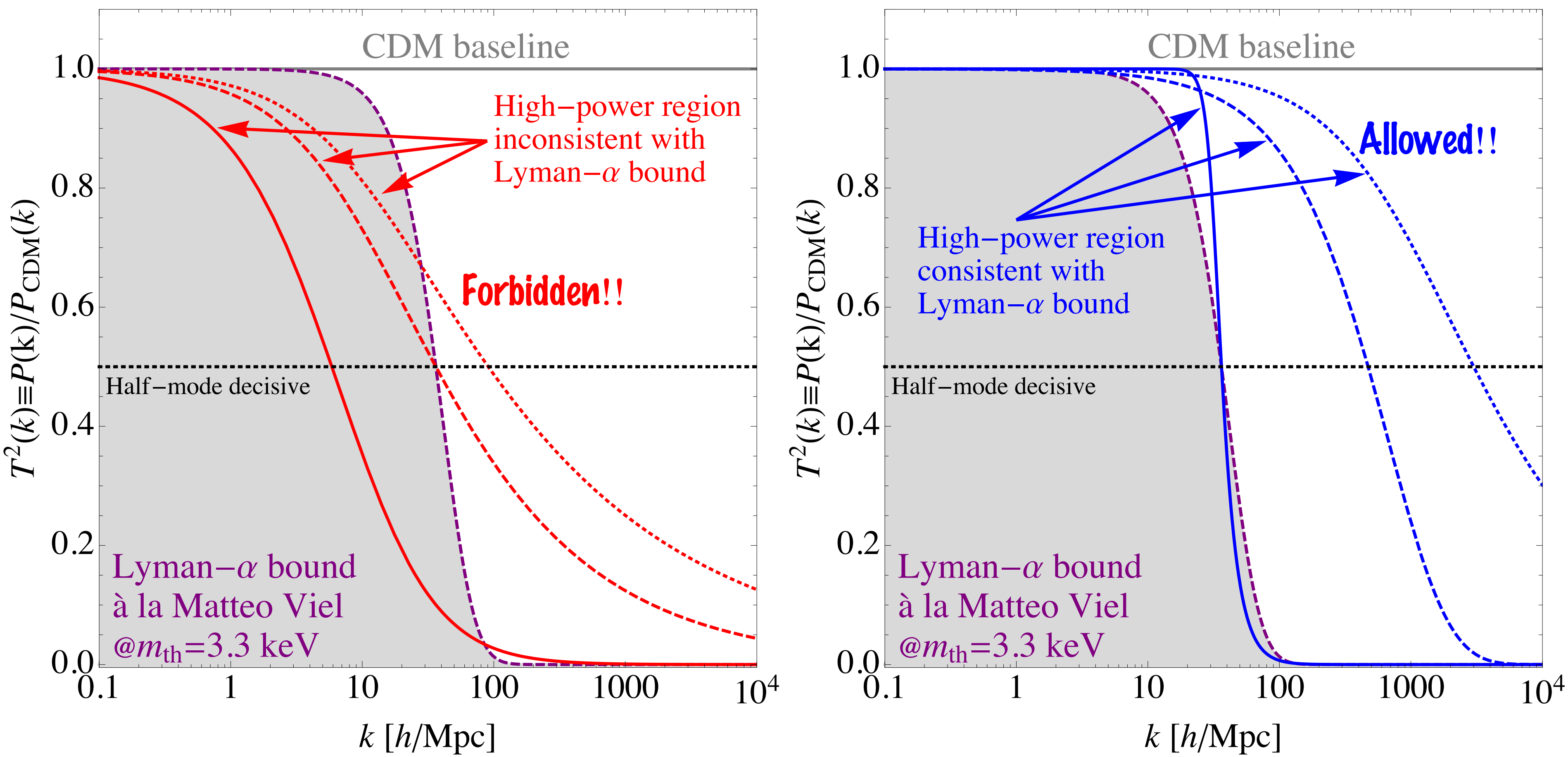
scalar decay +DW



INPUT: momentum distribution f(p,T)

5. Structure Formation

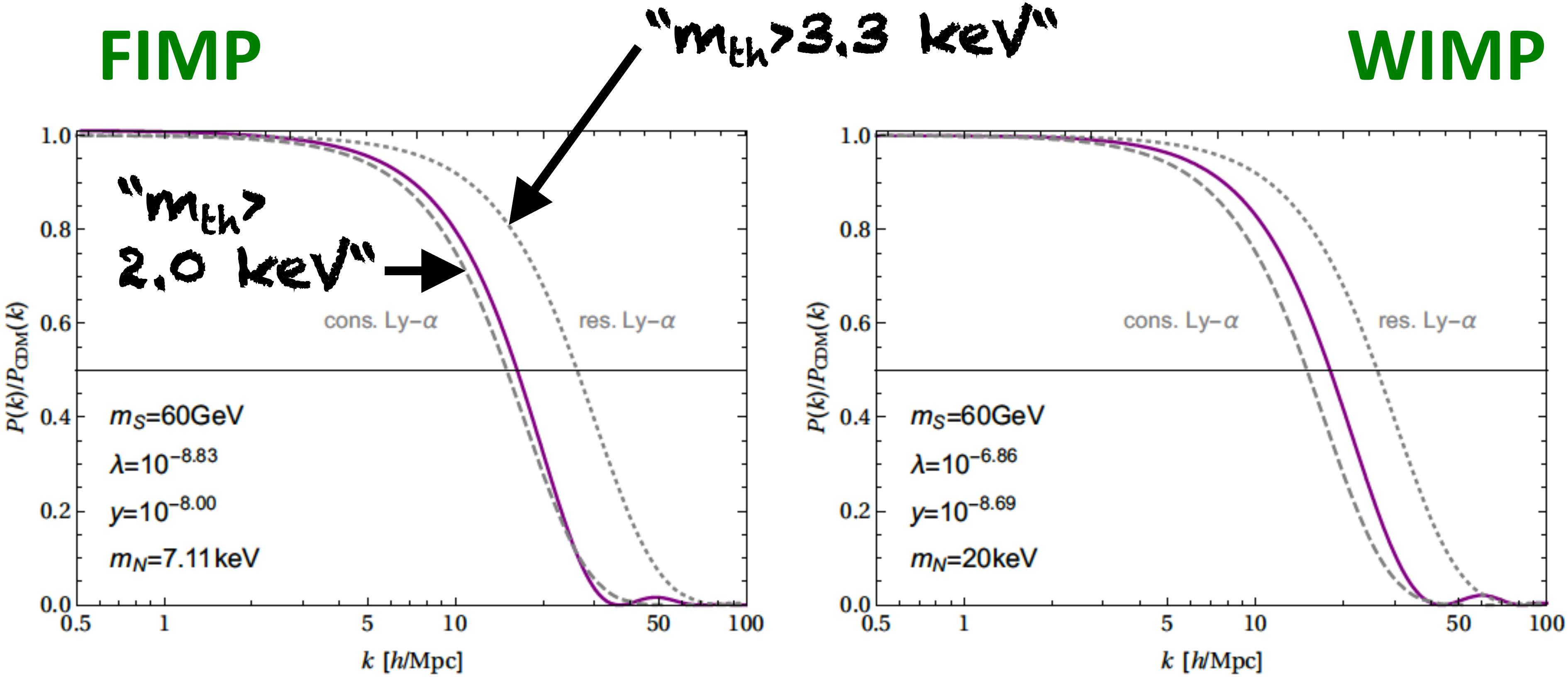
- use half-mode crossing, instead of free streaming: WORKS FOR ANY DISTRIBUTION, NO MATTER HOW NON-THERMAL!!



Applied to Decay production

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

Ly-alpha limits on the two example points:



-> both agree with conservative Ly-alpha bound but violate restrictive one

(NB: thermal relic mass ≠ physical mass!!!)

Applied to Decay production

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

Allowed regions from Ly-α data:

Coservative ✖
Restrictive ✖

Coservative ✓
Restrictive ✖

Coservative ✓
Restrictive ✓