keV Sterile Neutrino Dark Matter: Models & Production

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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, 1602.04816,...

Energy Ladder of the Universe, Mainz, 08-06-2016

A White Paper on keV Sterile Neutrino Dark Matter

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- Shoun Zhou

It's out!!! (Finally...)

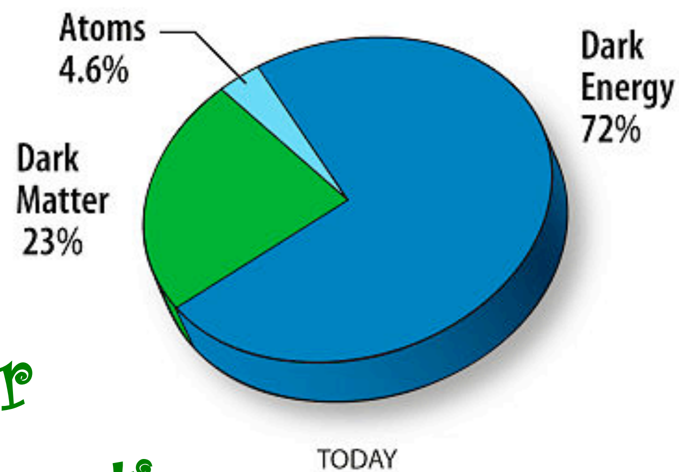
Contents:

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**

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LET'S START WITH THAT!

- **typically, this i**[...]**atter:** $N_1 \longrightarrow \nu+\gamma$
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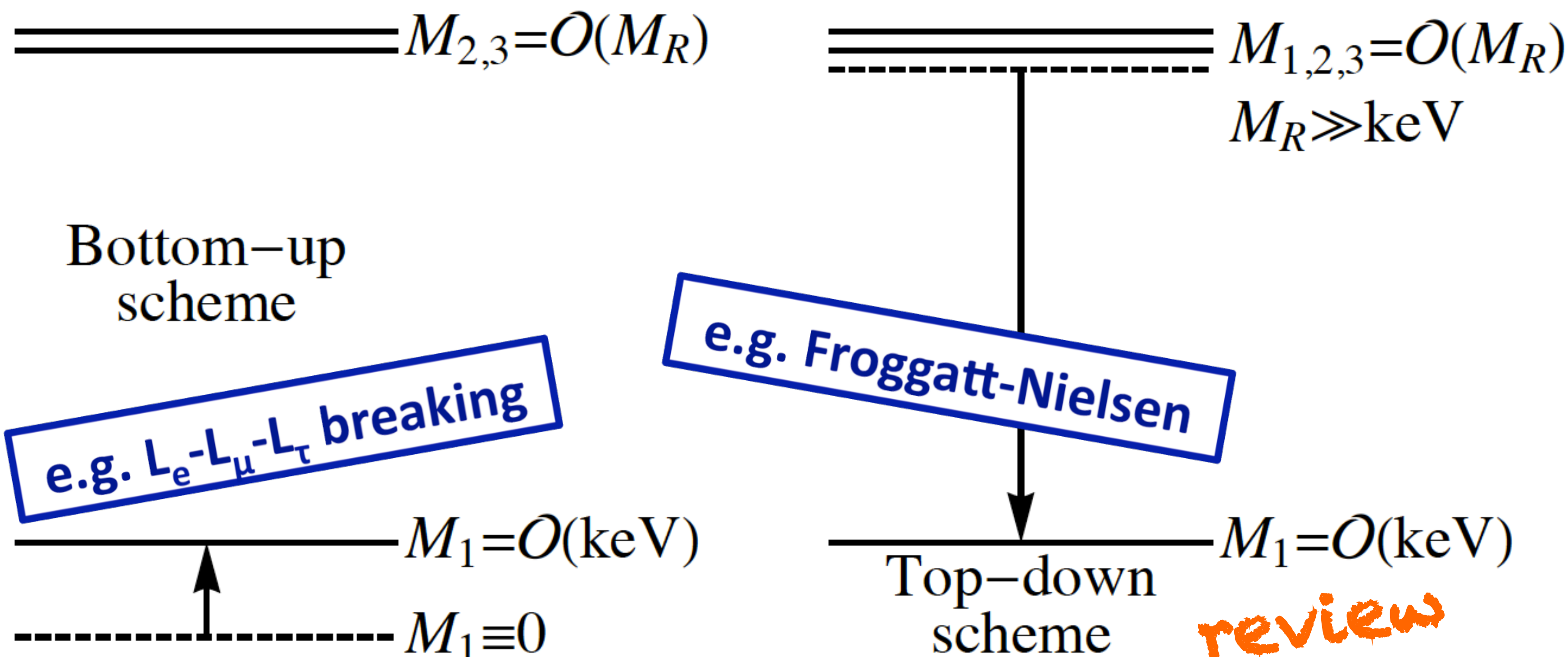
  ➔ **concrete models can be tested using light neutrinos**

2. Sterile neutrinos

Generic ideas to motivate light steriles:



[**AM**: Int. J. Mod. Phys. **D22** (2013) 1330020] ← review article

➔ **Most models fall into one or the other category!**

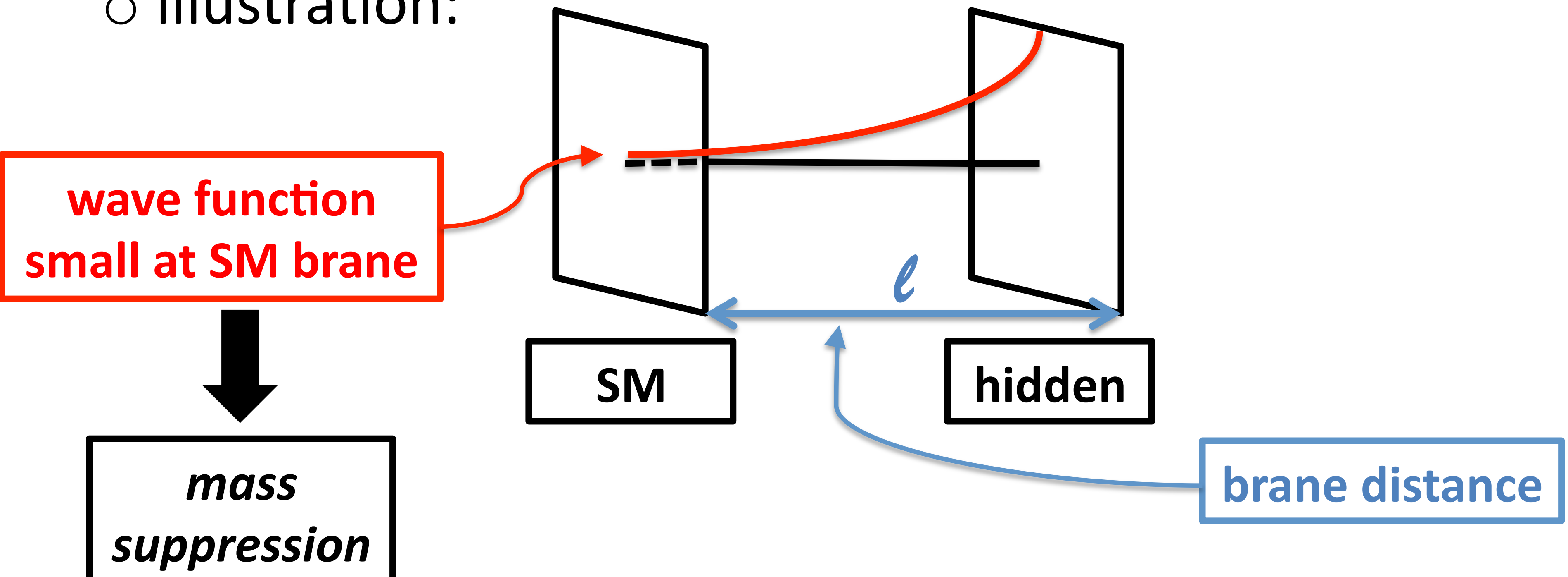
additional advantage: \`t Hooft naturalness tends to keep M_1 small!!!

2. Sterile neutrinos

Example 1: Extra dimensions

- Models based on the **Split Seesaw** mechanism:
  - *idea*: brane-splitting in etxra dimensions is known to lead to mass scale suppressions
  - ***this can be used to get a keV mass***

    [Kusenko, Takahashi, Yanagida: Phys. Lett. **B693** (2010) 144]
  - illustration:



2. Sterile neutrinos

Example 1: Extra dimensions

- Models based on the **Split Seesaw** mechanism:
  - 5D-action: $$S = \int d^4x \int_0^l dy\ M_0\ (i\overline{\Psi}\Gamma^A\partial_A\Psi - m\overline{\Psi}\Psi)$$

    ➔ Fourier-expanded fields: $\Psi_{L,R}(x^\mu, y) = \sum_n \psi^{(n)}_{L,R}(x^\mu)\ f^{(n)}_{L,R}(y)$
  - integrating out the 5th dimension leads to the characteristic exponential suppressions:

additional seesaw

5D mass (large)

effective 4D mass (TINY!!!)

$$M_i = \kappa_i \frac{v_{B-L}}{M_0} \frac{2m_i}{e^{2m_i l} - 1}$$

$e^{-2m_i l} << 1$ for $m_i l >> 1$ ➔ **STRONG SUPPRESSION!!!**

2. Sterile neutrinos

Example 2: Broken symmetry

- Model based on a $\boldsymbol{Q_6}$ symmetry (=double cover of D_3):
  [Araki, Li: Phys. Rev. **D85** (2012) 065016]
  - assignment: singlet N_1, doublet (N_2,N_3) + flavons
  - RH neutrino mass matrix:

$$M_R = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & M_a \\ 0 & M_a & 0 \end{pmatrix} + \frac{1}{\Lambda^2} \begin{pmatrix} M_c s_x s_y & 0 & 0 \\ 0 & M_b d_2^2 & 0 \\ 0 & 0 & M_b d_1^2 \end{pmatrix}$$

leading mass: $(M_1,M_2,M_3) = (0,M_a,M_a)$

subleading correction: $M_1 = \frac{s_x\, s_y}{\Lambda^2} M_c$

$M_{2,3} = M_a \pm M_b(d_1^2+d_2^2)/\Lambda^2$

2. Sterile neutrinos

Example 2: Broken symmetry

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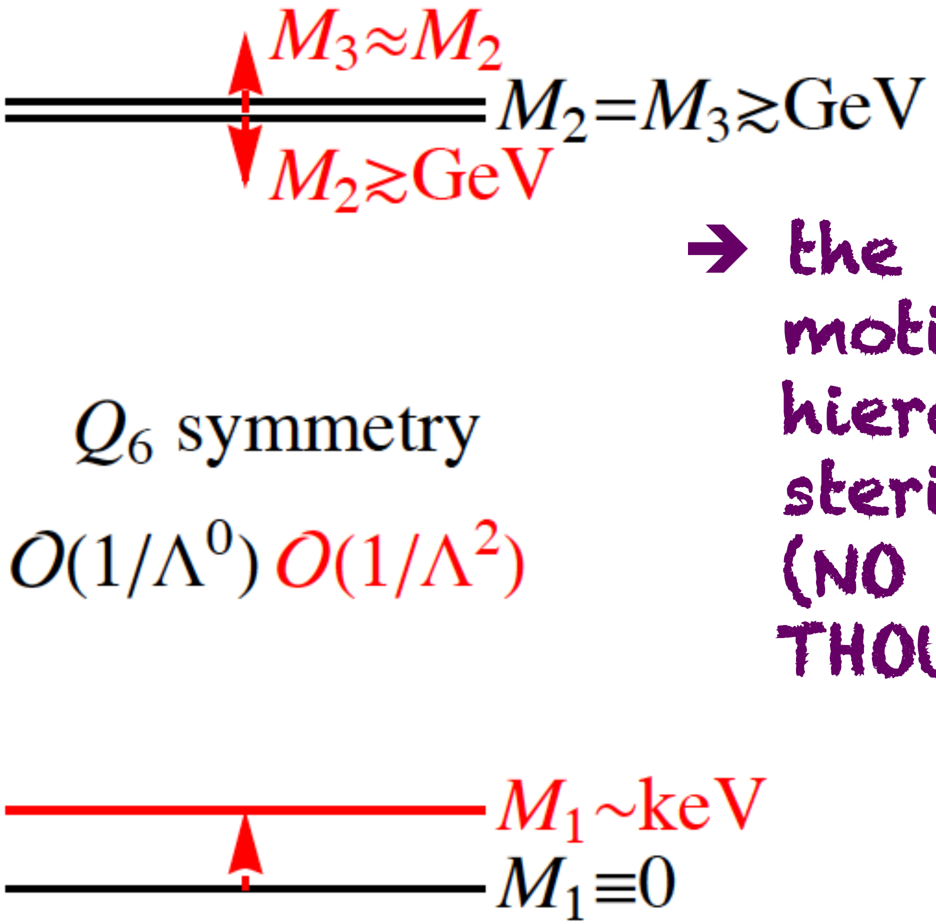
  - mass shifting scheme:



→ the broken symmetry motivates a certain hierarchy between the sterile neutrino masses (NO ABSOLUTE SCALE, THOUGH!!!)

3. Non-thermal production mechanisms

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NB: In reality we don‘t know the spectrum of Dark Matter very well!!

NON-THERMAL SPECTRA HAVE TO BE INVESTIGATED IF WE WANT A COMPLETE PICTURE!!!

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 $T \gg m$ **WARM/COOL** $T \sim m$ **COLD** $T \ll m$

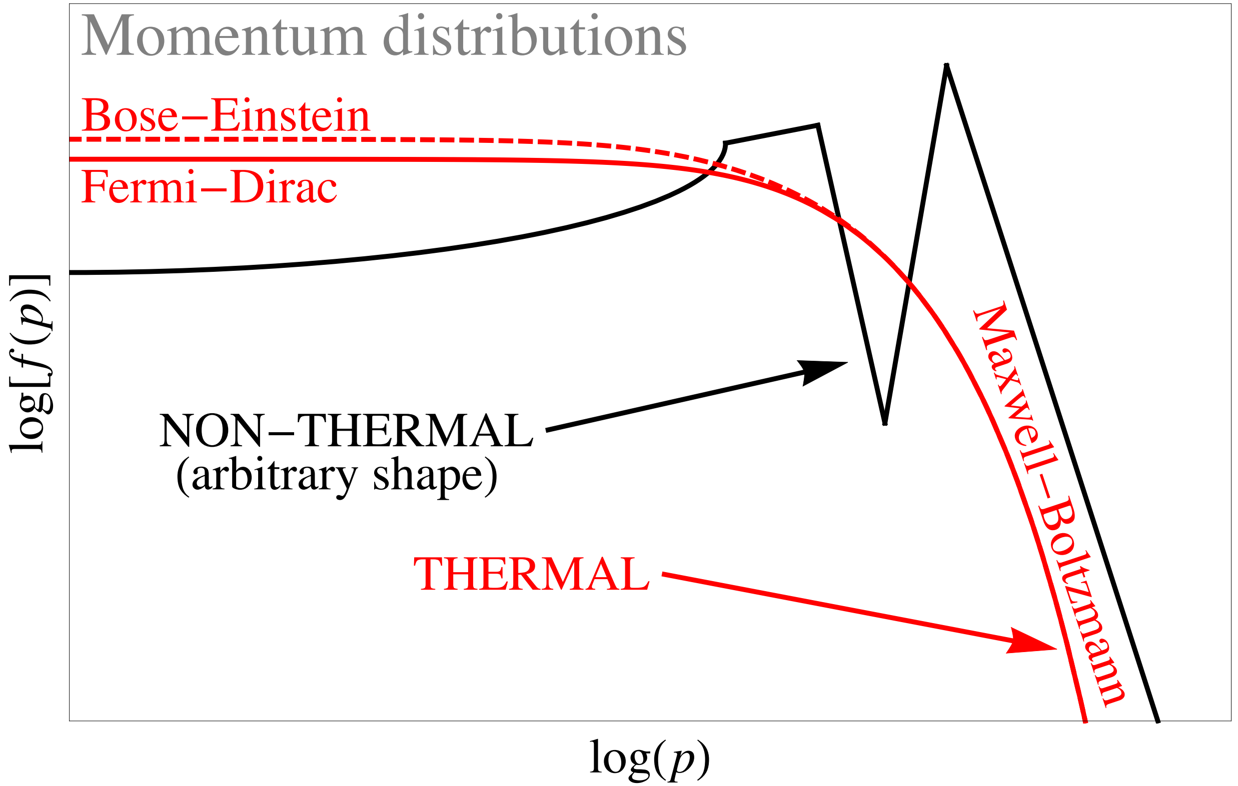
NON-THERMAL

$f(p)$ arbitrary

with:

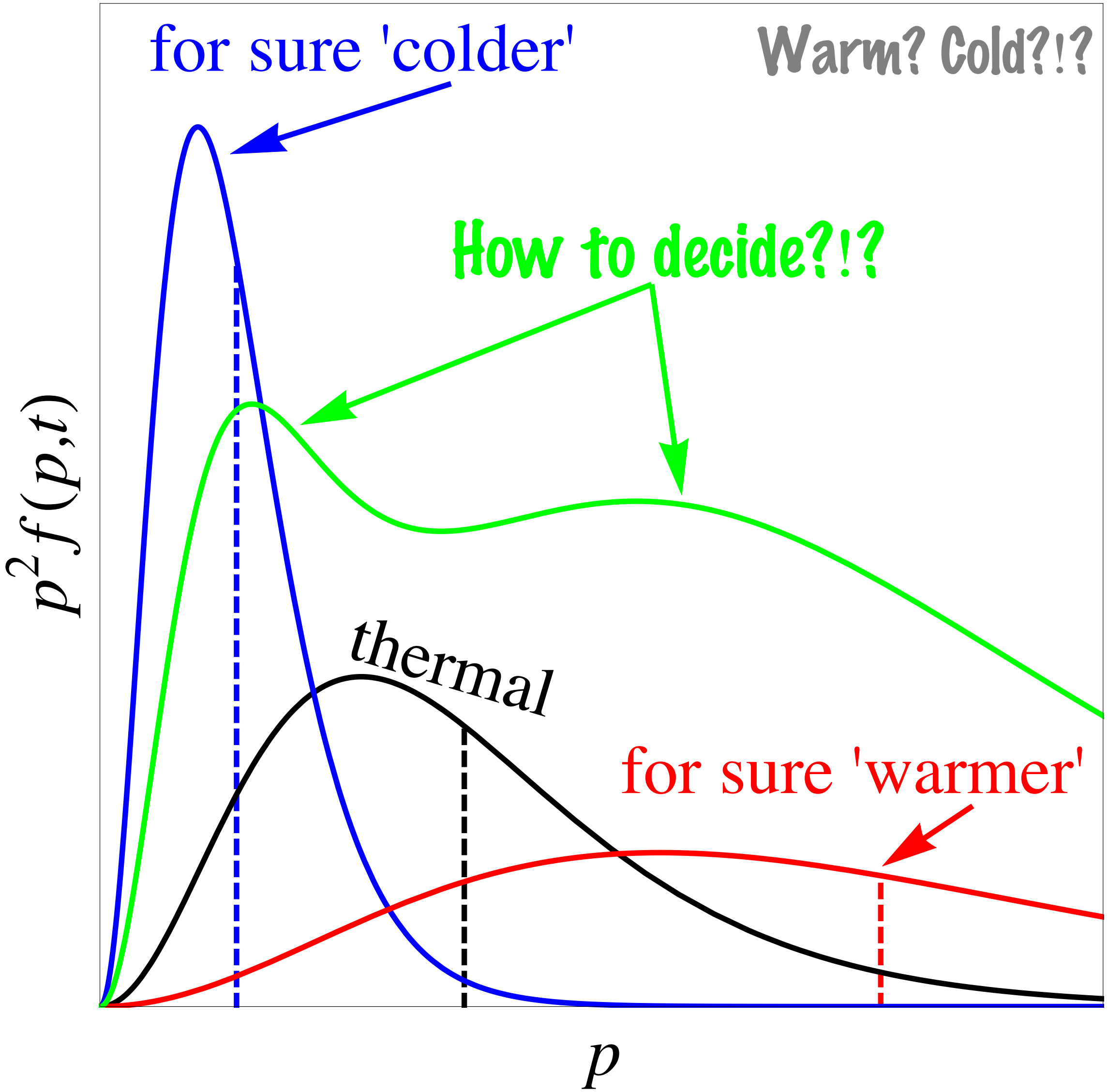
$$\int_{p=0}^{\infty} p^2 f(p) dp < \infty$$

T not defined **!!!**



3. Non-thermal production mechanisms

PROBLEM: HOW TO COMPARE TO THE THERMAL CASE?



- ➔ I will tell you later in this talk!!
- ➔ for now, let's look at the concrete case of sterile neutrinos
- ➔ see talk by Rouzbeh Allahverdi

4. Production of Sterile Neutrinos

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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

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…, …

…hancement

…tive-sterile transitions

BUT: When confronted with data…

WHICH MECHANISMS SURVIVE?!?

…ction

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...v, Laine, ...

...w"-enhancement

of active-sterile transitions

EXCLUDED BY STRUCTURE FORMATION (TOO "HOT" DM)

Decay production

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4. Producti[…]f Sterile Neutrinos

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AT LEAST PUSHED BY STRUCTURE FORMATION (RELATIVELY “WARM“)

Non-resona[…]

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D...

ν_s-DI...

Boya... ...vsky, Shaposhnikov, ...

Idea: other new particle is produced and decays into ν_s

STRONGLY PUSHED BY BBN REQUIREMENTS

Diluted thermal production

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

Idea: produce entropy to dilute thermal over-abundance

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4 main mechanisms for sterile neutrinos:

Non-resonant transitions

First: Langacker

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<u>Idea</u>: active-sterile mixings gradually produce

Resonant transitions

First: Enquist, Kainulainen

DM: Shi & Fuller,

OKAY FOR A SIGNIFICANT PART OF THE PARAMETER SPACE

(BUT: partially just like CDM)

Decay production

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

<u>Idea</u>: other new particle is produced and decays into ν_s

Diluted thermal production

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4. *Example 1*: Active-Sterile Transitions

<u>Simplest idea:</u>

- **sterile neutrinos are not entirely sterile**

  → ***their small mixing with active neutrinos connect them to the Standard Model***

- **Why not using this to efficiently produce them?!?**

  → ***non-resonant active-sterile transitions*** ("Dodelson-Widrow")

  → ***resonant active-sterile transitions*** ("Shi-Fuller")

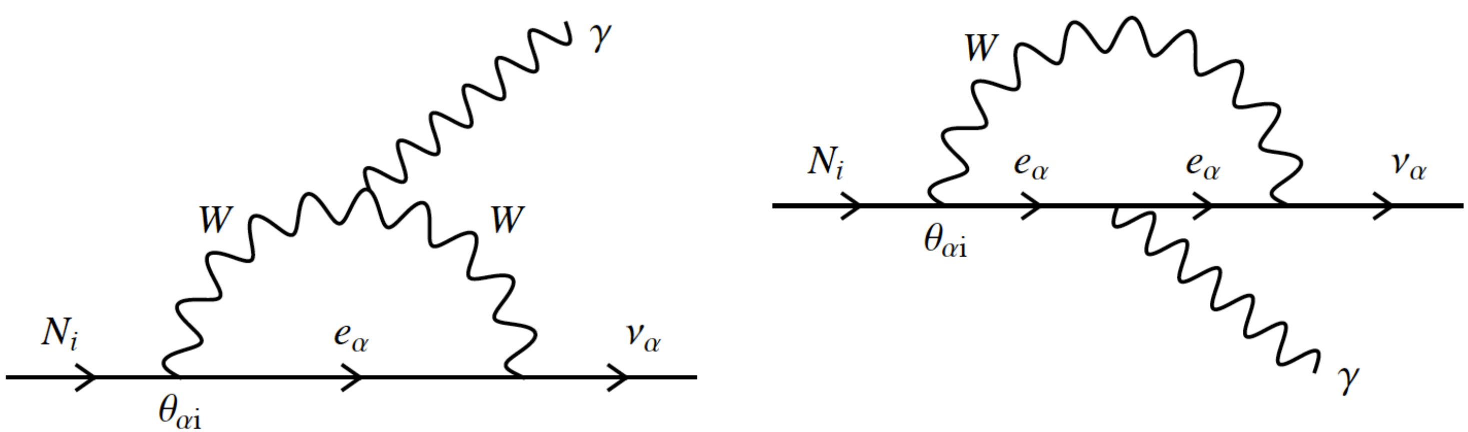
... these are the "standard" options

The Dodelson-Widrow mechanism

It could all be sooo simple...:

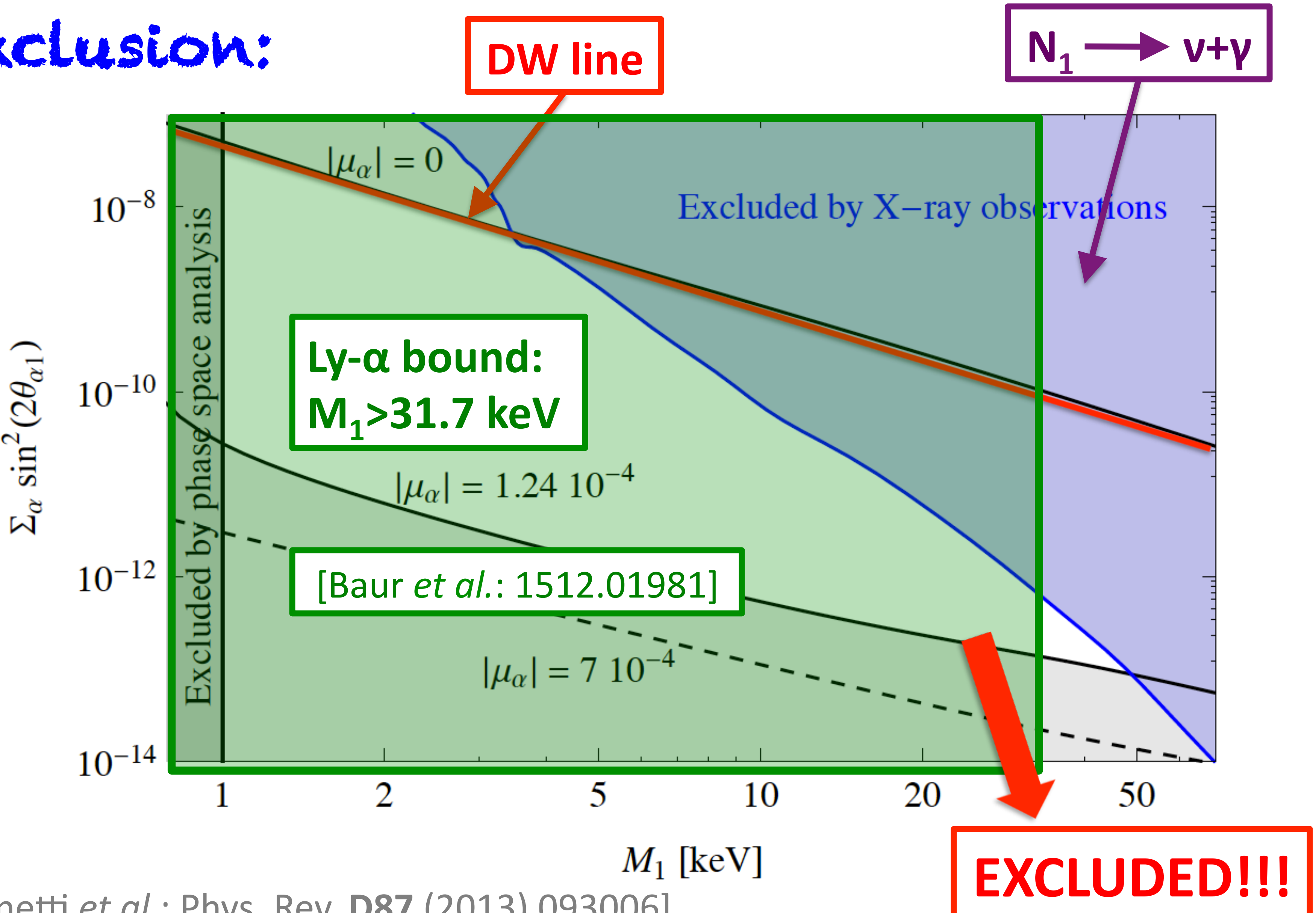
[Dodelson, Widrow: Phys. Rev. Lett. **72** (1994) 17]

- 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:



The Dodelson-Widrow mechanism

Exclusion:



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

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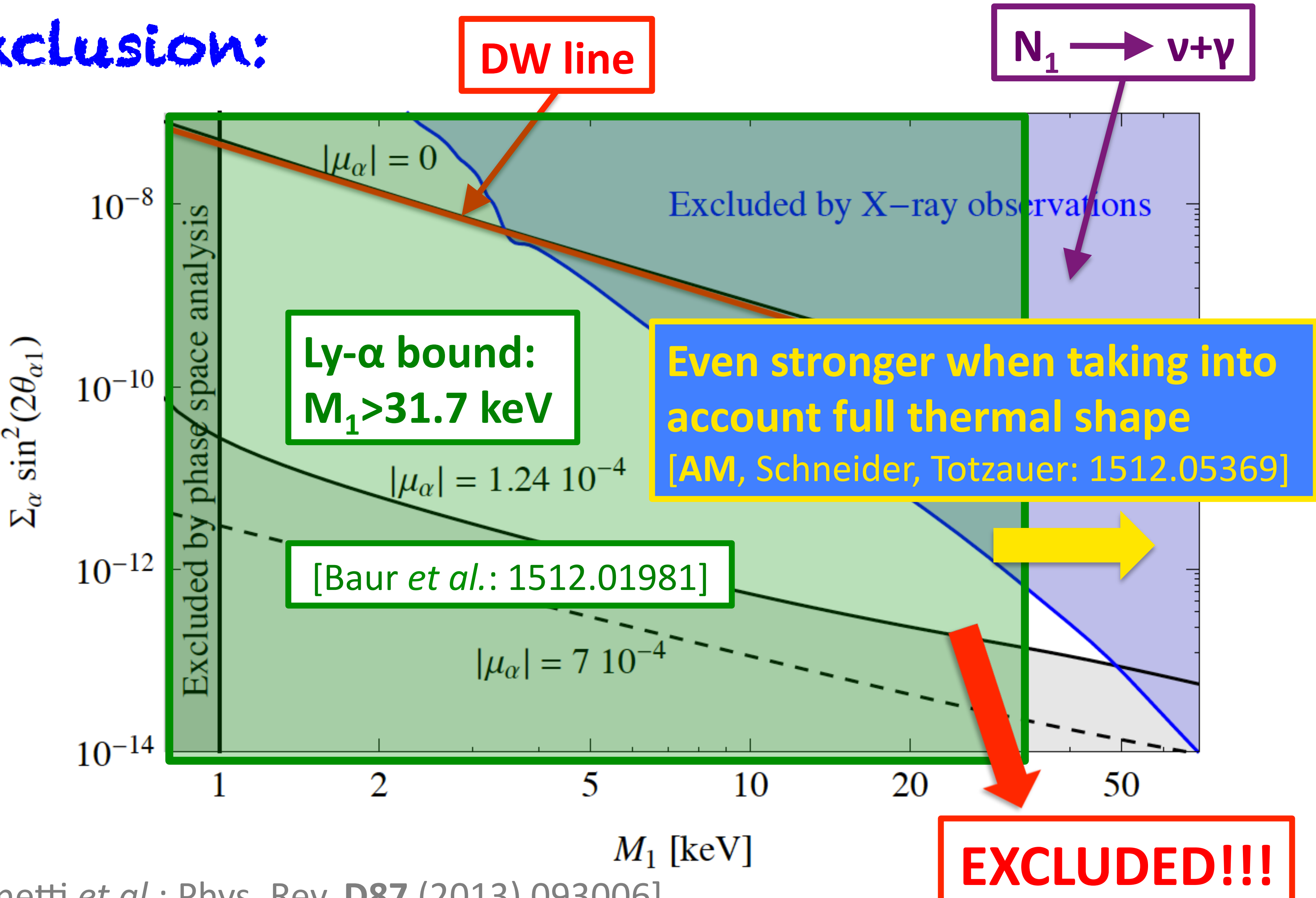
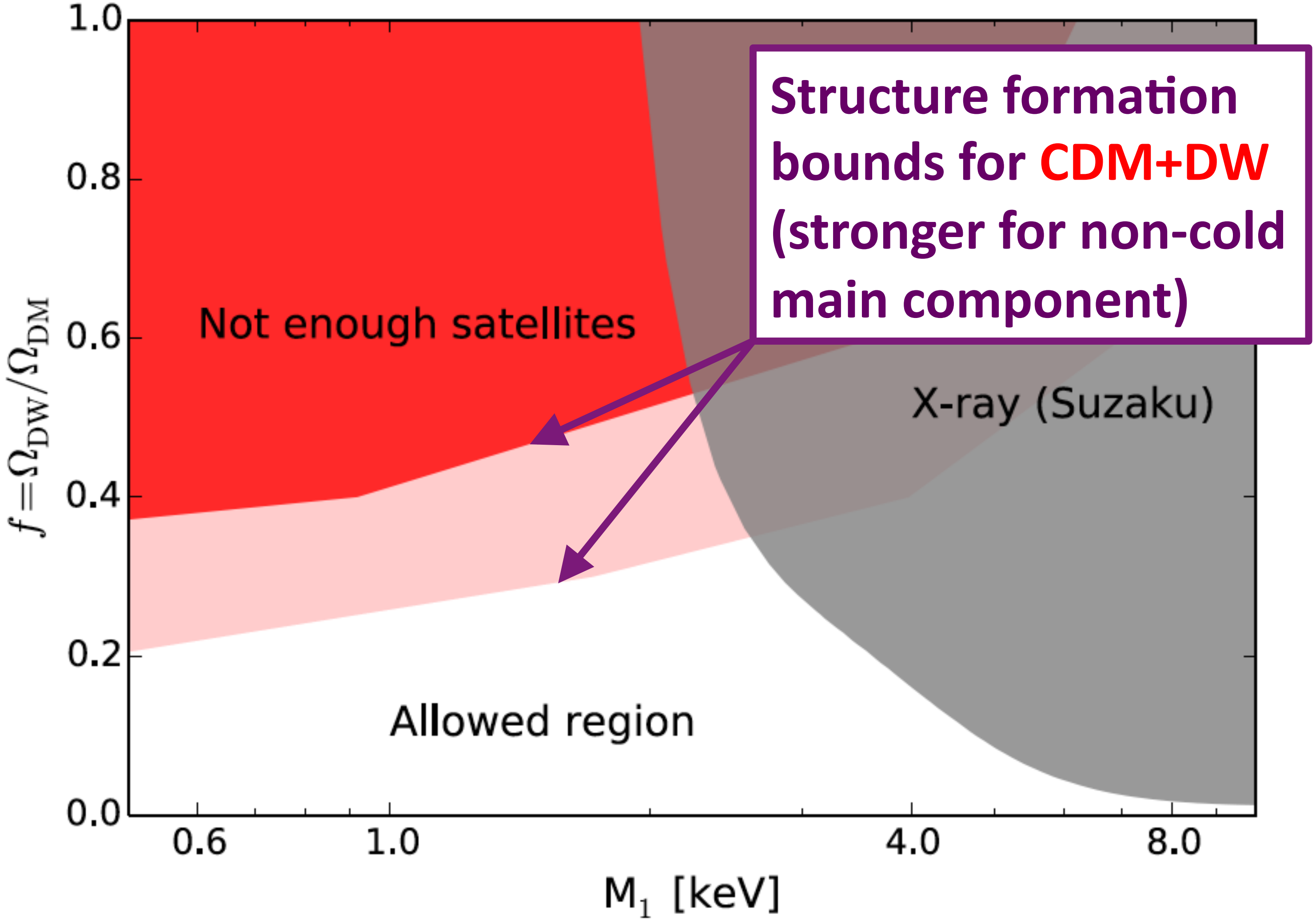


[Canetti *et al.*: Phys. Rev. **D87** (2013) 093006]

The Dodelson-Widrow mechanism

DW could still produce part of the DM:



[**AM**, Schneider, Totzauer: 1512.05369 [hep-ph]]

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**

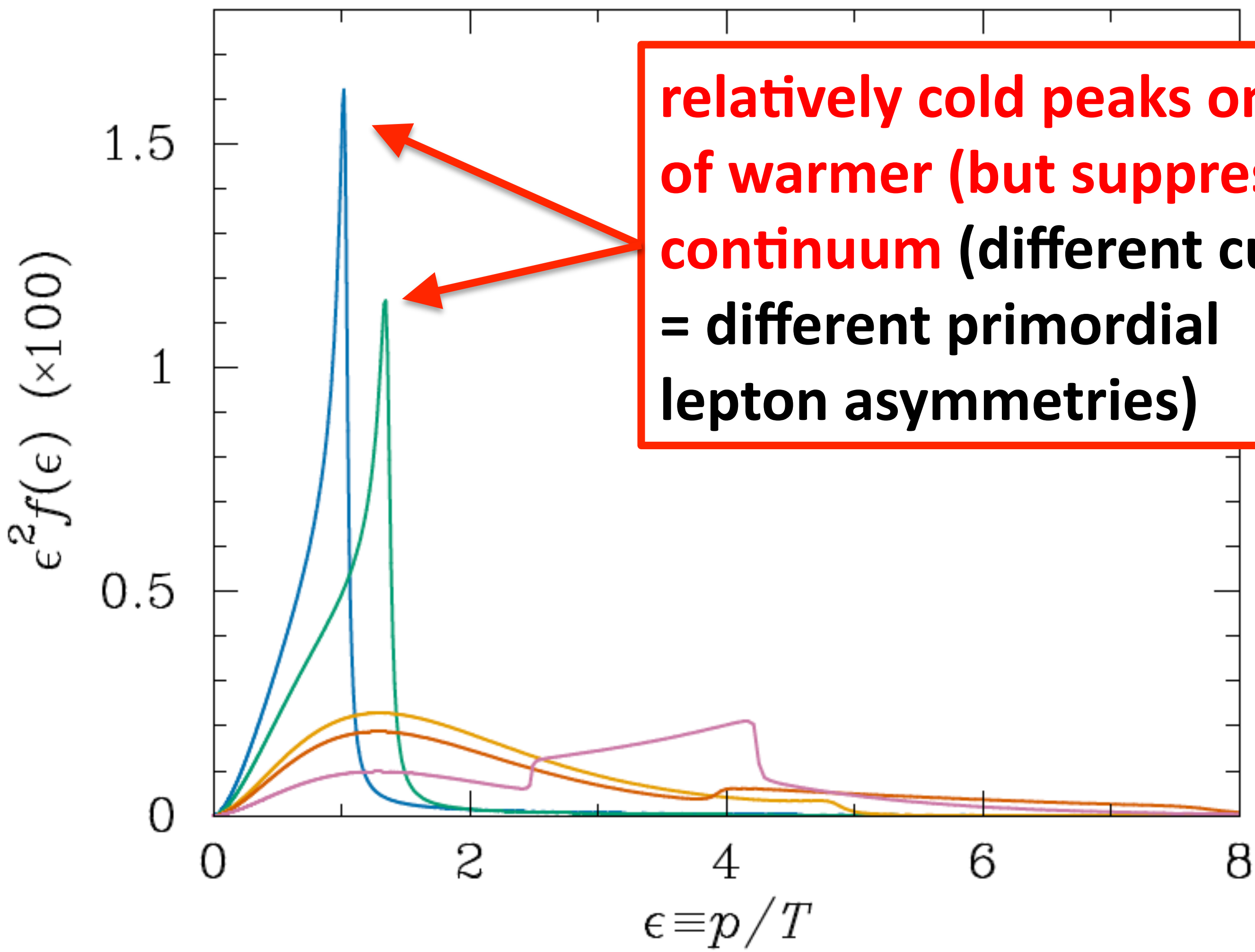
- **this would produce a large amount of ν_s at a specific (momentum-dependent) resonance temperature**
  ➔ *cooler spectrum*

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

The Shi-Fuller mechanism

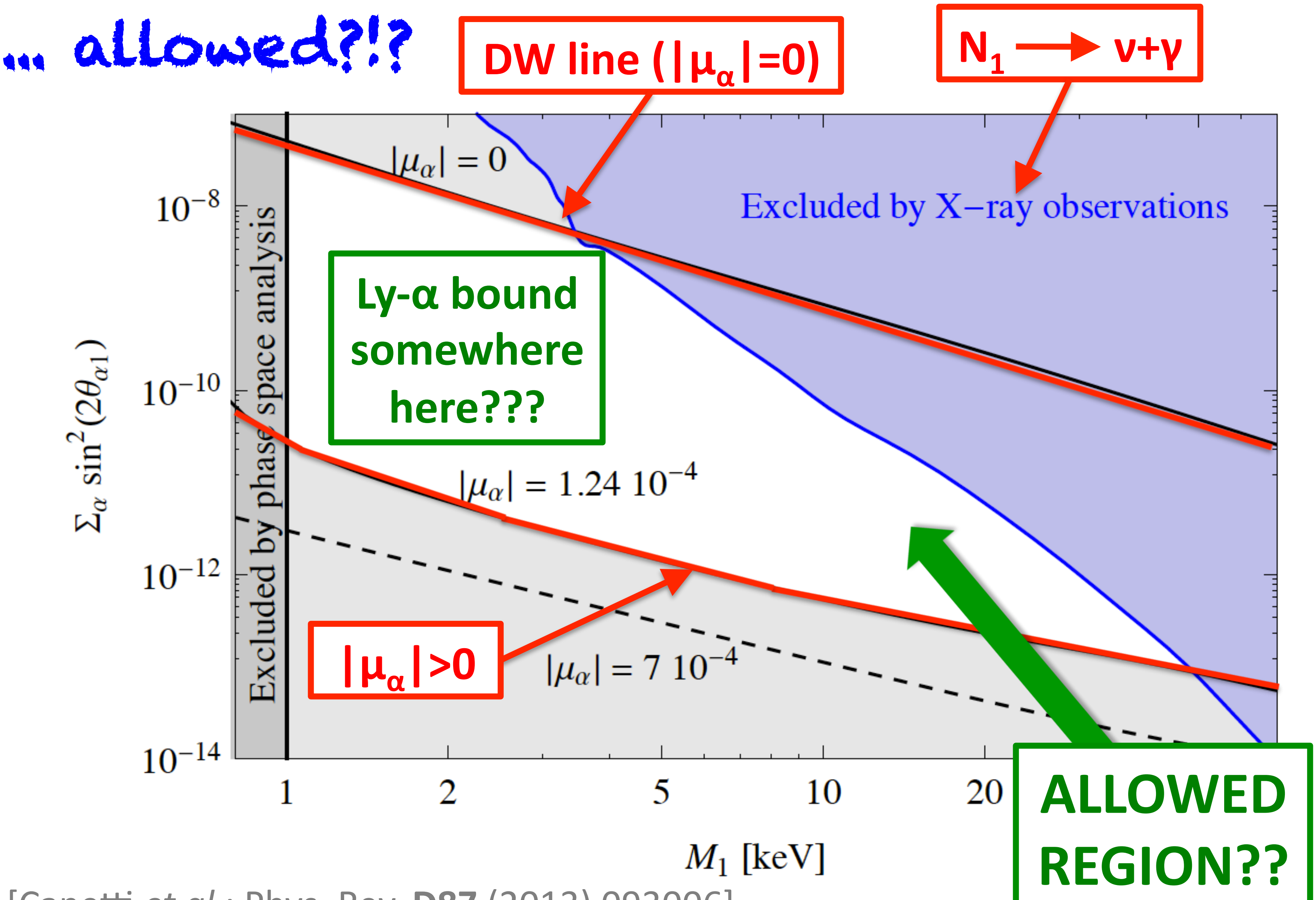
This produces to non-trivial spectra:

[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



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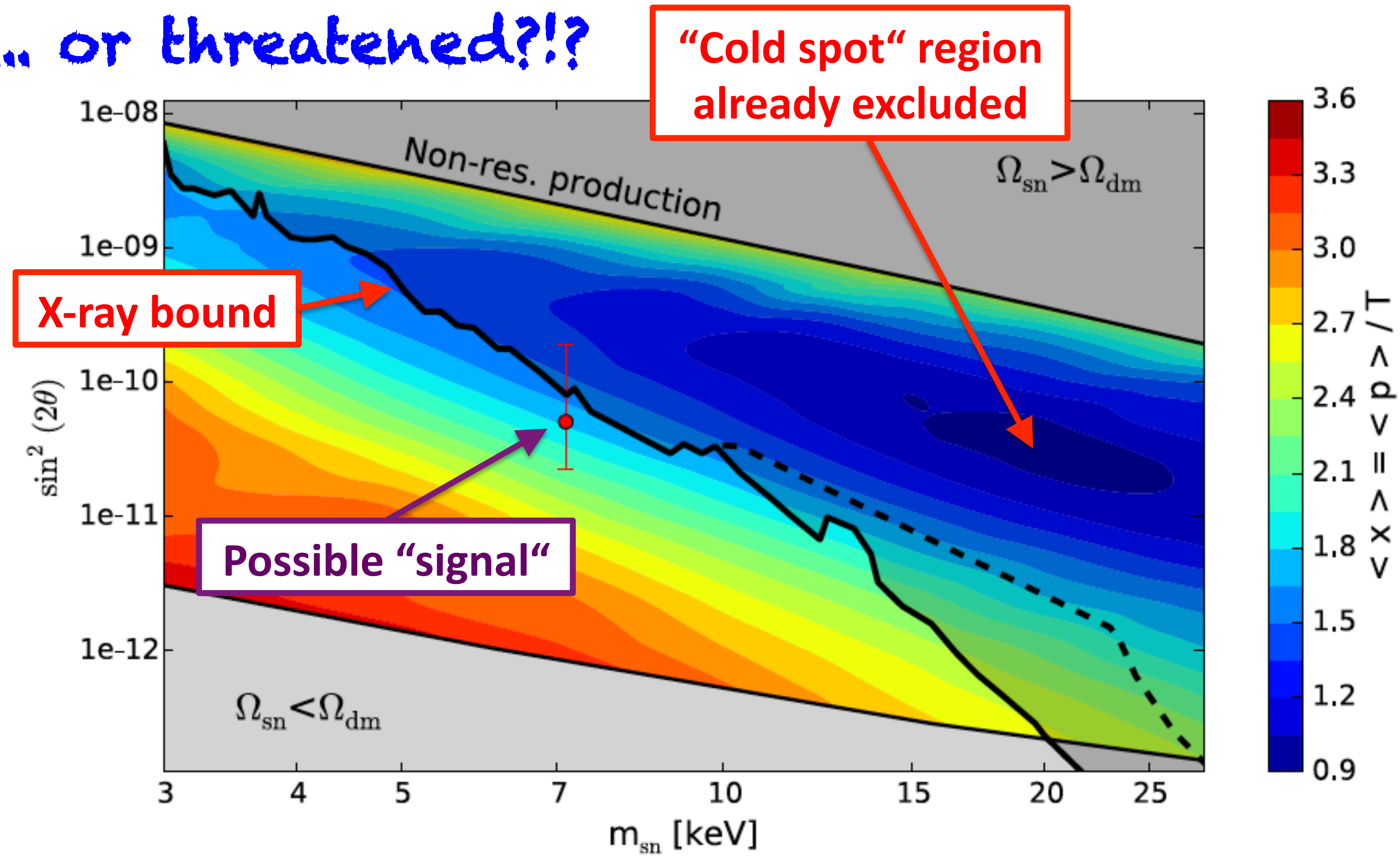
The Shi-Fuller mechanism

... or threatened?!?



[Schneider: JCAP **1604** (2016) 059] ➔ *based on Kevork's software* (1507.06655)

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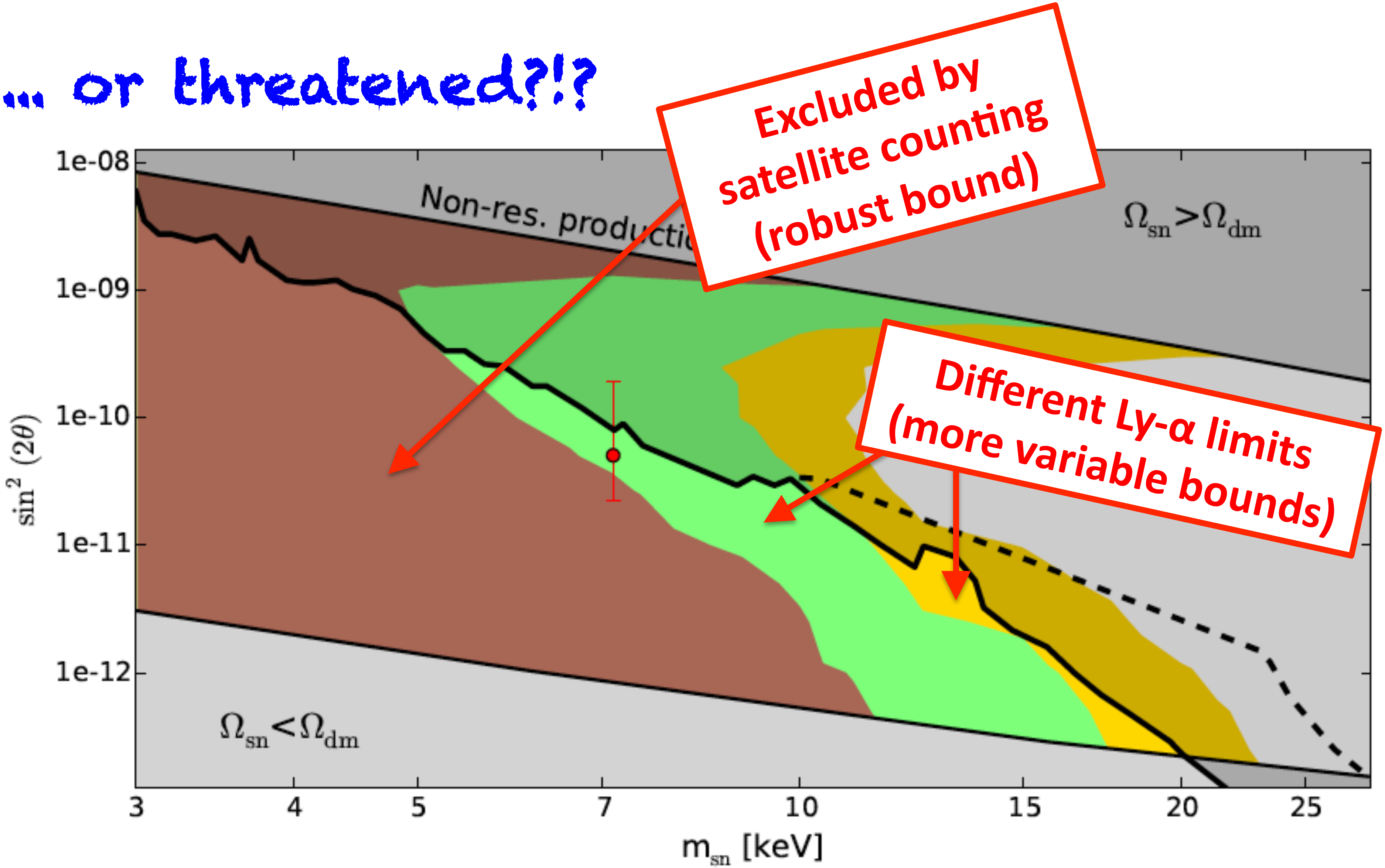

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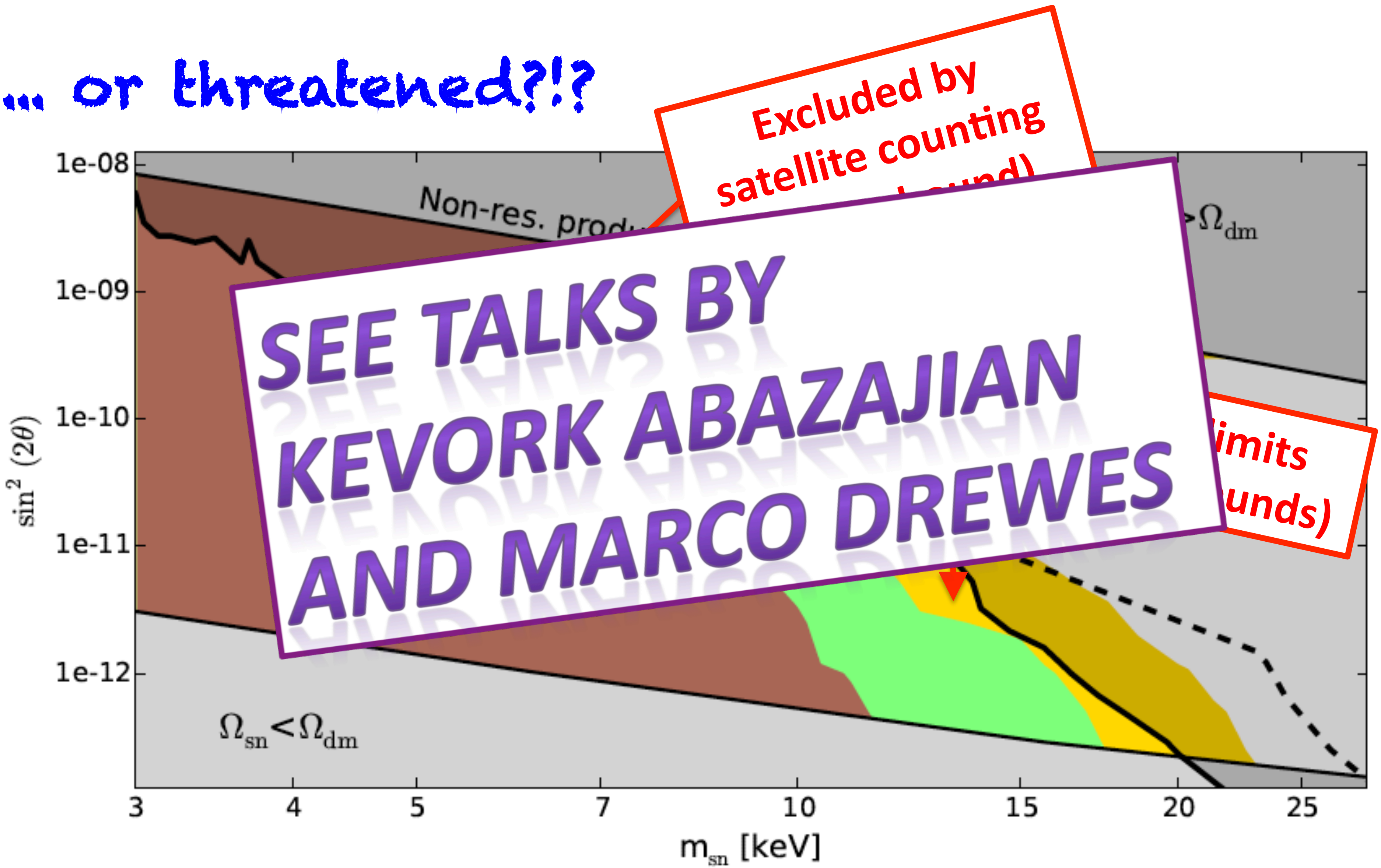

[Schneider: JCAP **1604** (2016) 059] ➔ *based on Kevork's software* (1507.06655)

4. *Example 2*: Decay production

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E.g. scalar 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]
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  [**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]
  [Klasen, Yaguna: JCAP 1311 (2013) 039]
- **other particle that decays**
  [Lello, Boyanovsky: Phys. Rev. **D91** (2015) 063502]
  [Lello, Boyanovsky: 1508.04077]

4. *Example 2*: 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

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Two-step process:
scalar S must be produced before it can decay
→ TWO crucial quantities (in convenient units):

$$\begin{cases} \text{the effective decay width:} & \mathcal{C}_\Gamma \equiv \frac{M_0}{m_S}\frac{\Gamma}{m_S} \\ \text{the effective (squared) Higgs portal:} & \mathcal{C}_{\rm HP} \equiv \frac{M_0}{m_S}\frac{\lambda^2}{16\pi^3} \end{cases}$$

→ C_Γ: "rate of scalar decay"
→ C_{HP}: "coupling strength to SM particles"

For sufficiently high temperatures, where the production happens, m_S drops out of quantities which are not dimensionful (in particular the DM abundance only depends on M_1/m_S)!!!

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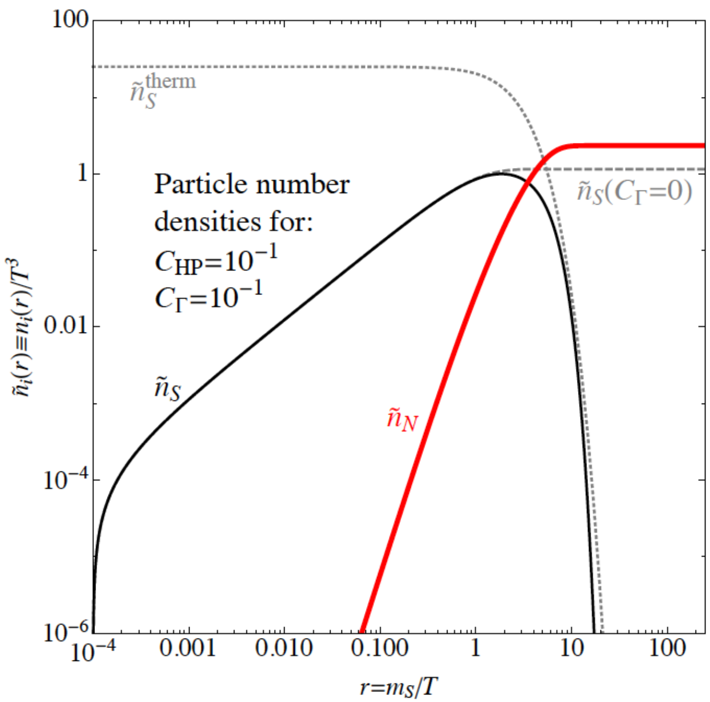
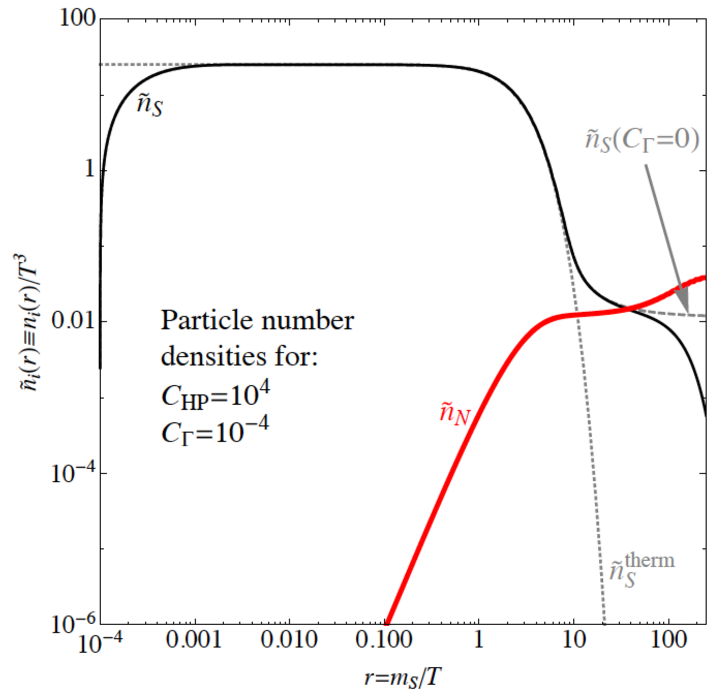
Two-step process:
scalar S must be produced before it can decay

S freezes-in and decays afterwards

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



Abundance



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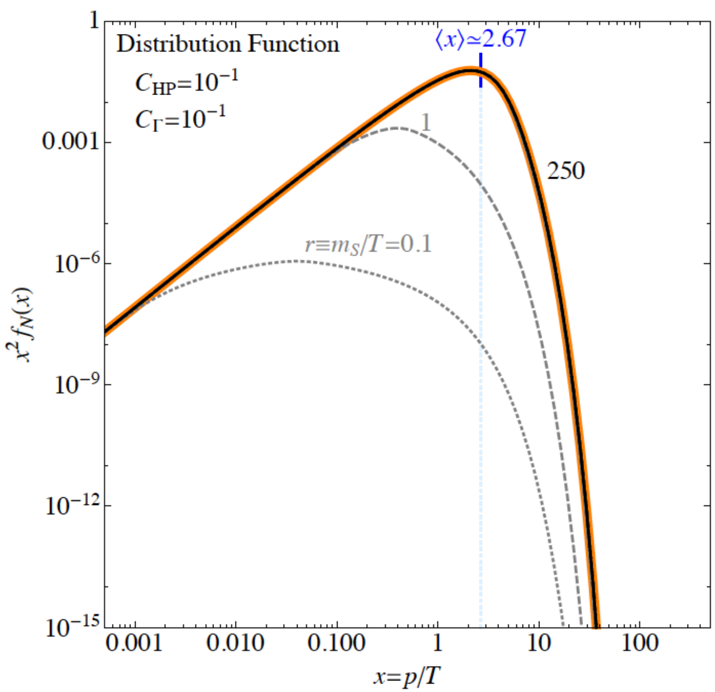
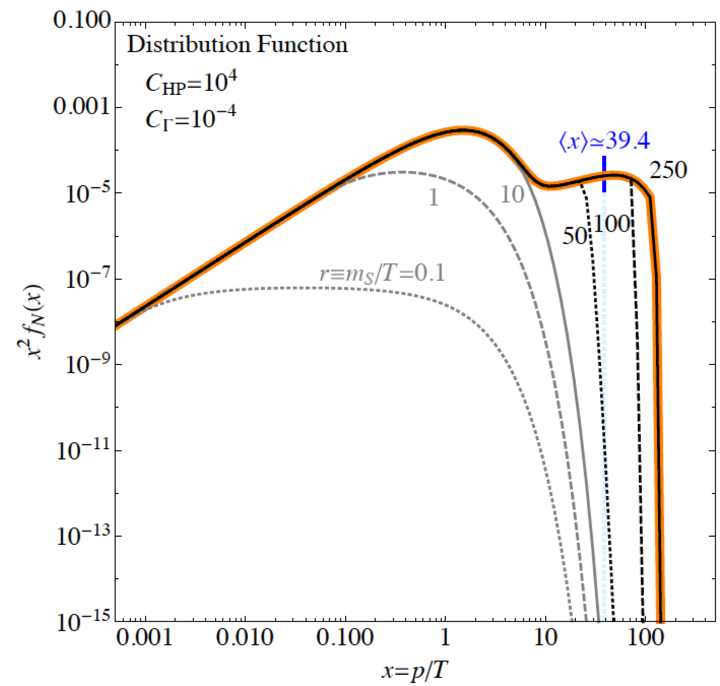


Distribution function



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Two-step process:
scalar S must be produced before it can decay

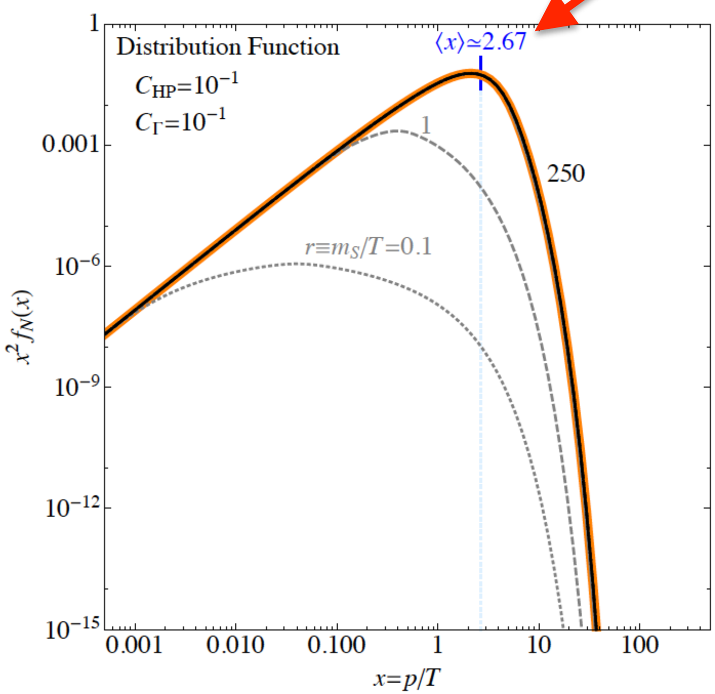
S freezes-in and decays afterwards

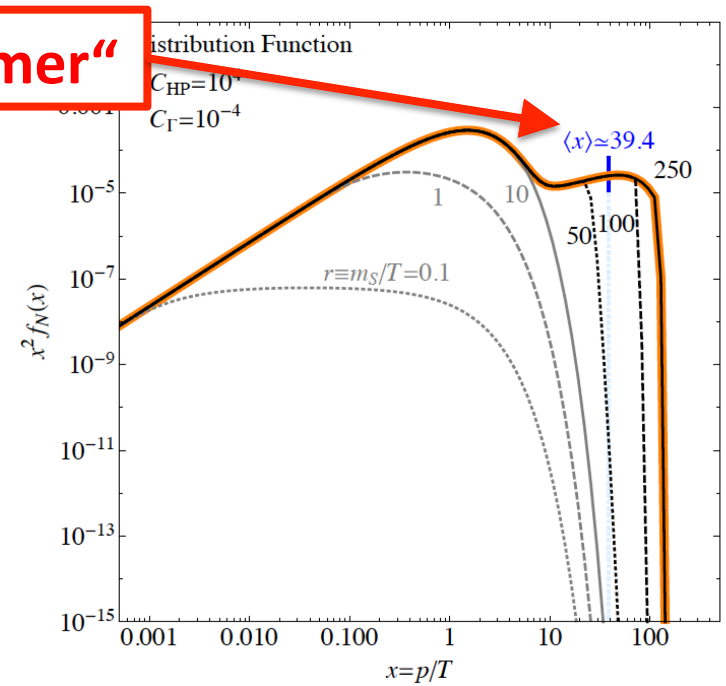
"colder"

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

"warmer"

Distribution function





4. *Example 2*: 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]

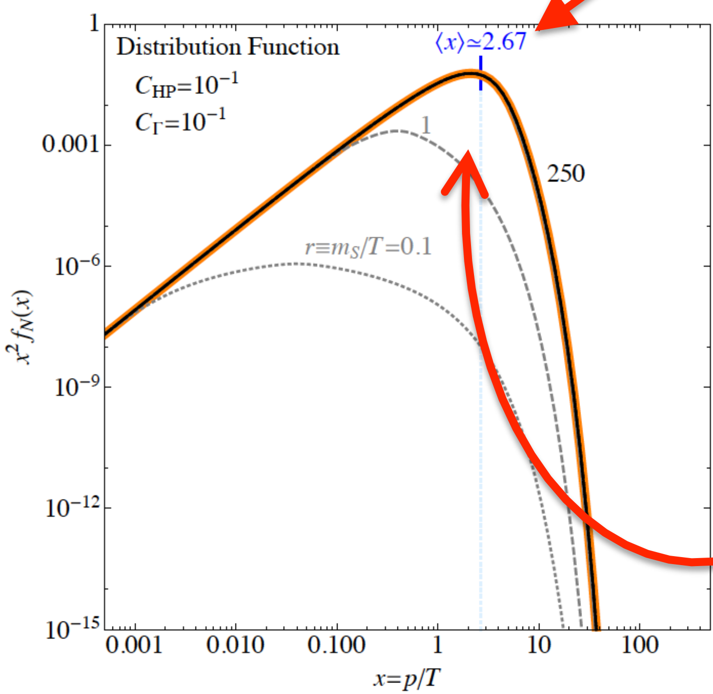
Two-step process:
scalar S must be produced before it can decay

S freezes-in and decays afterwards

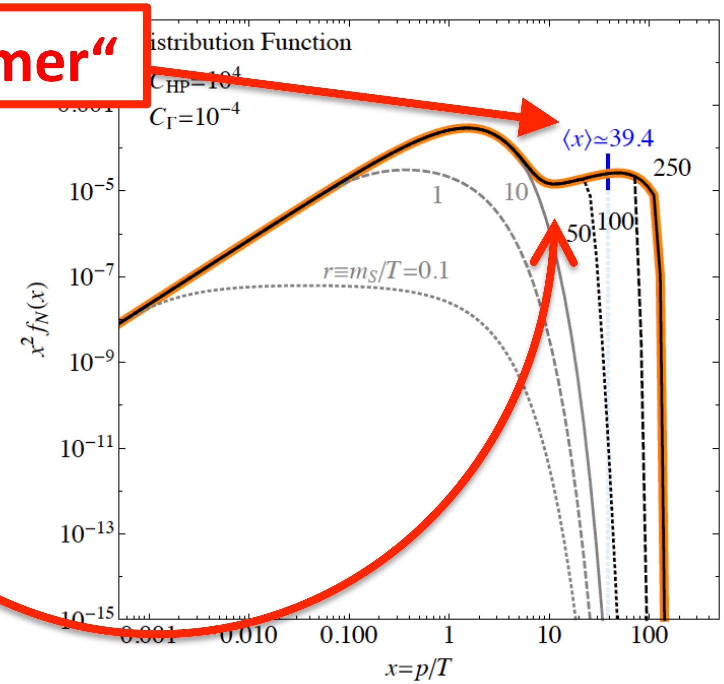
“colder“

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

“warmer“

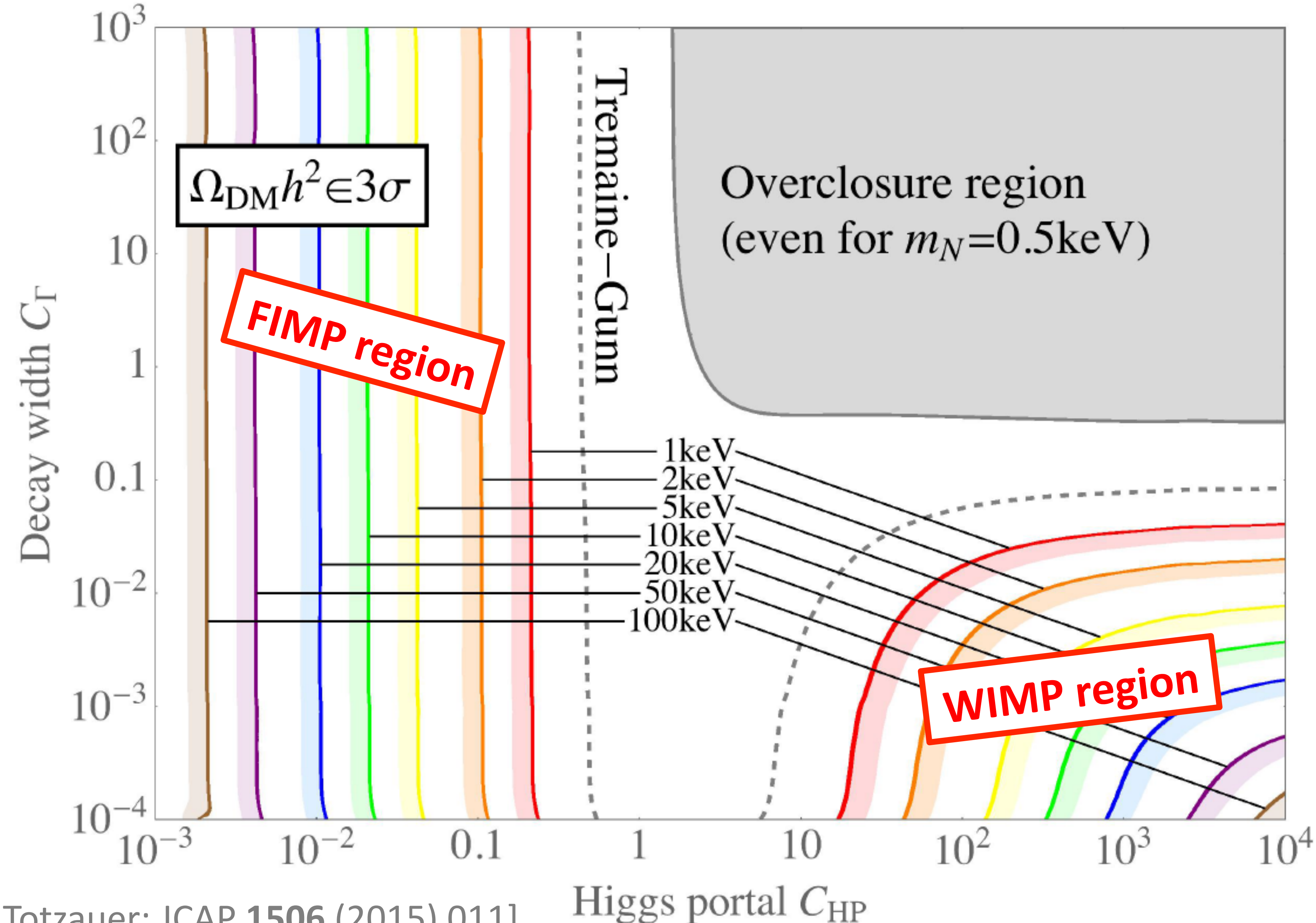


Distribution function



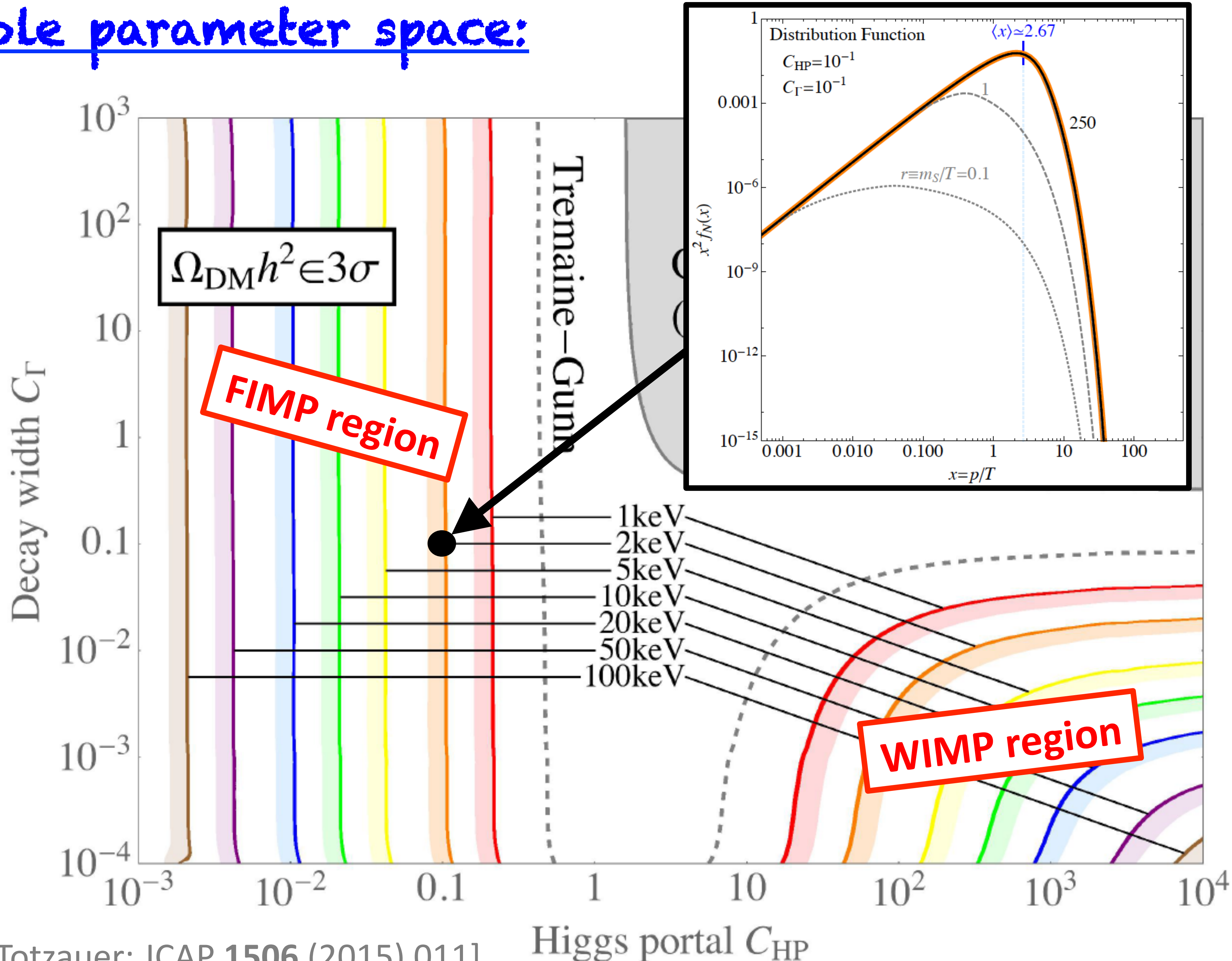
shape depends on regime

Whole parameter space:



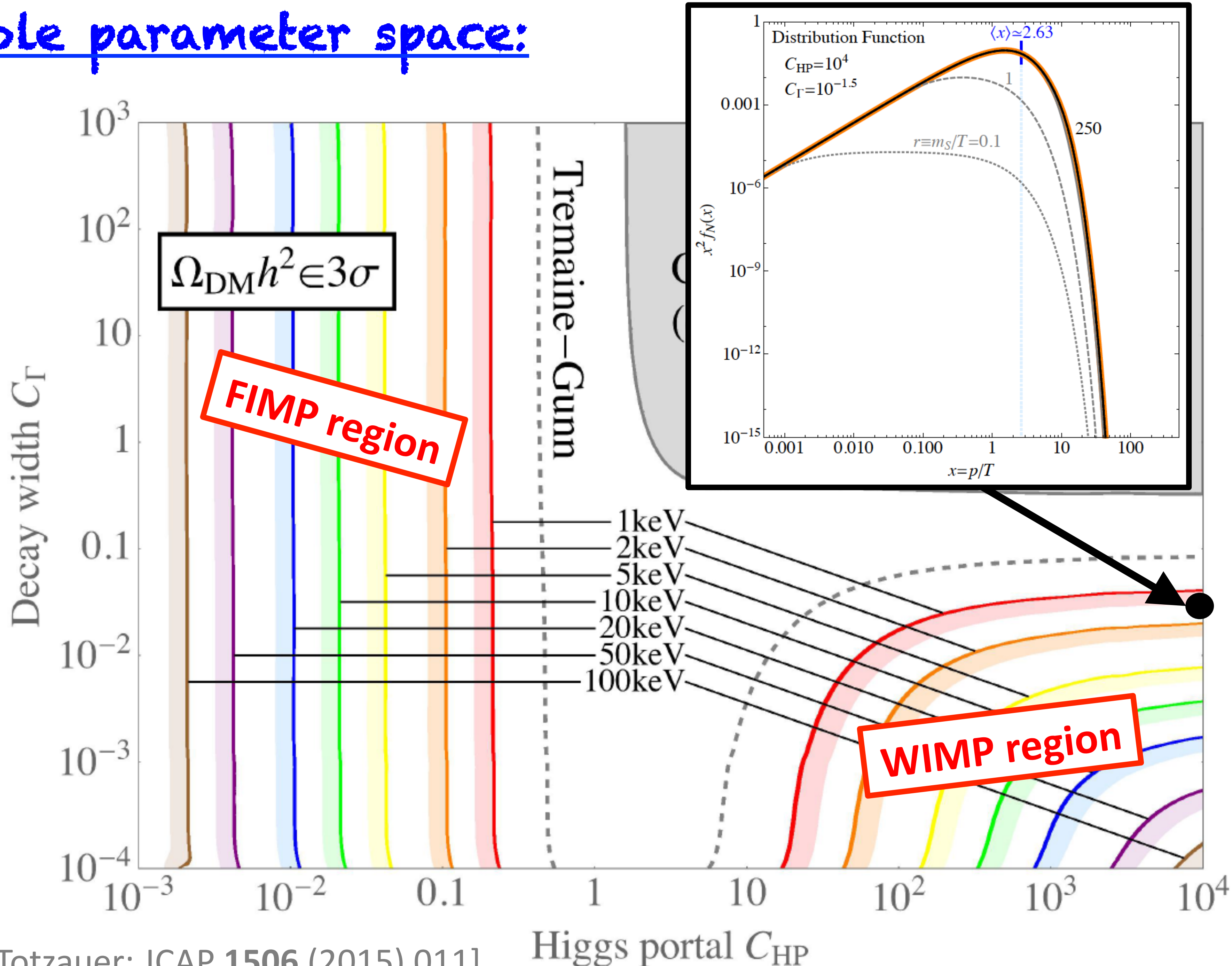
[**AM**, Totzauer: JCAP **1506** (2015) 011]

Whole parameter space:



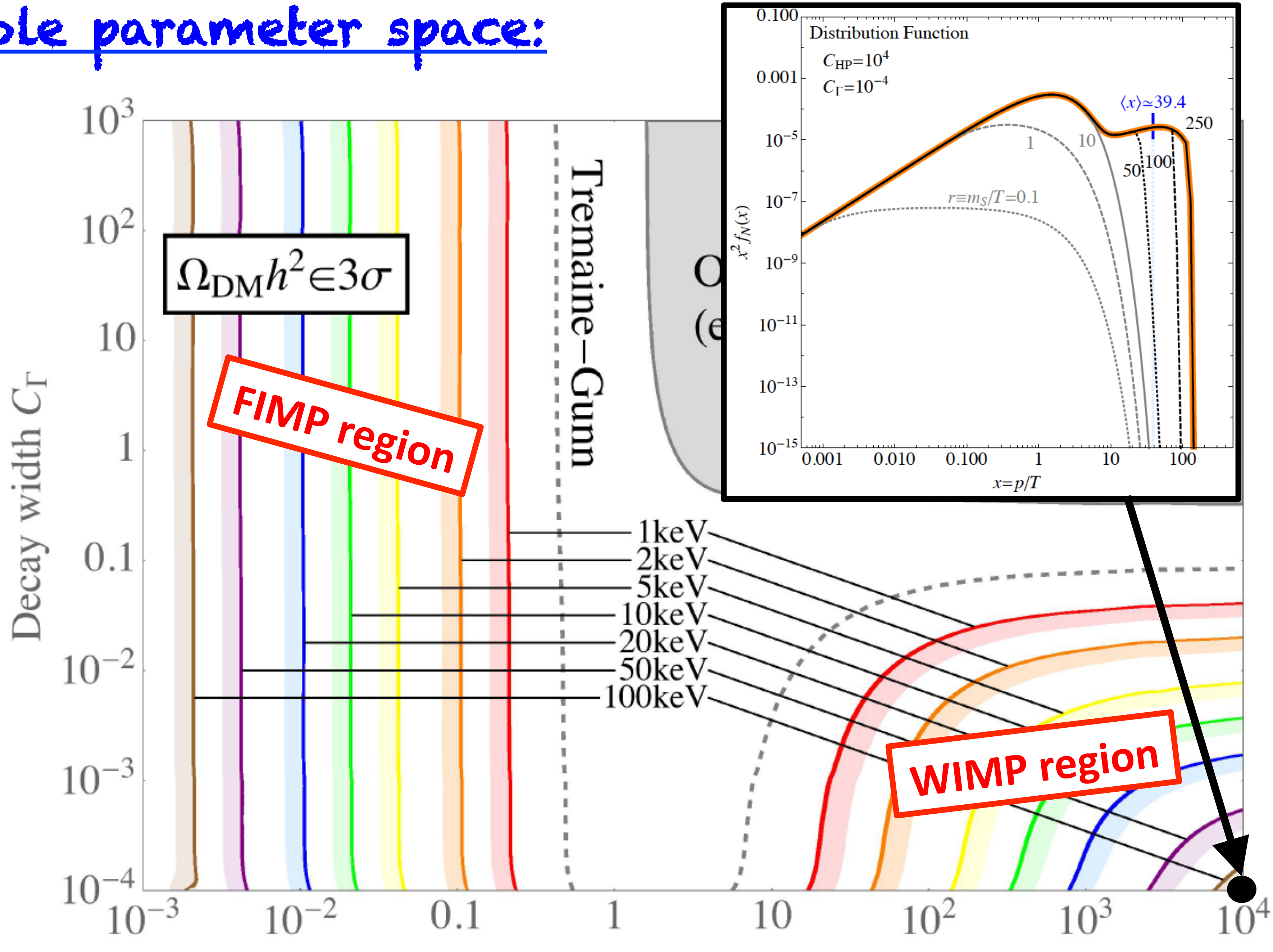
[**AM**, Totzauer: JCAP **1506** (2015) 011]

Whole parameter space:



[**AM**, Totzauer: JCAP **1506** (2015) 011]

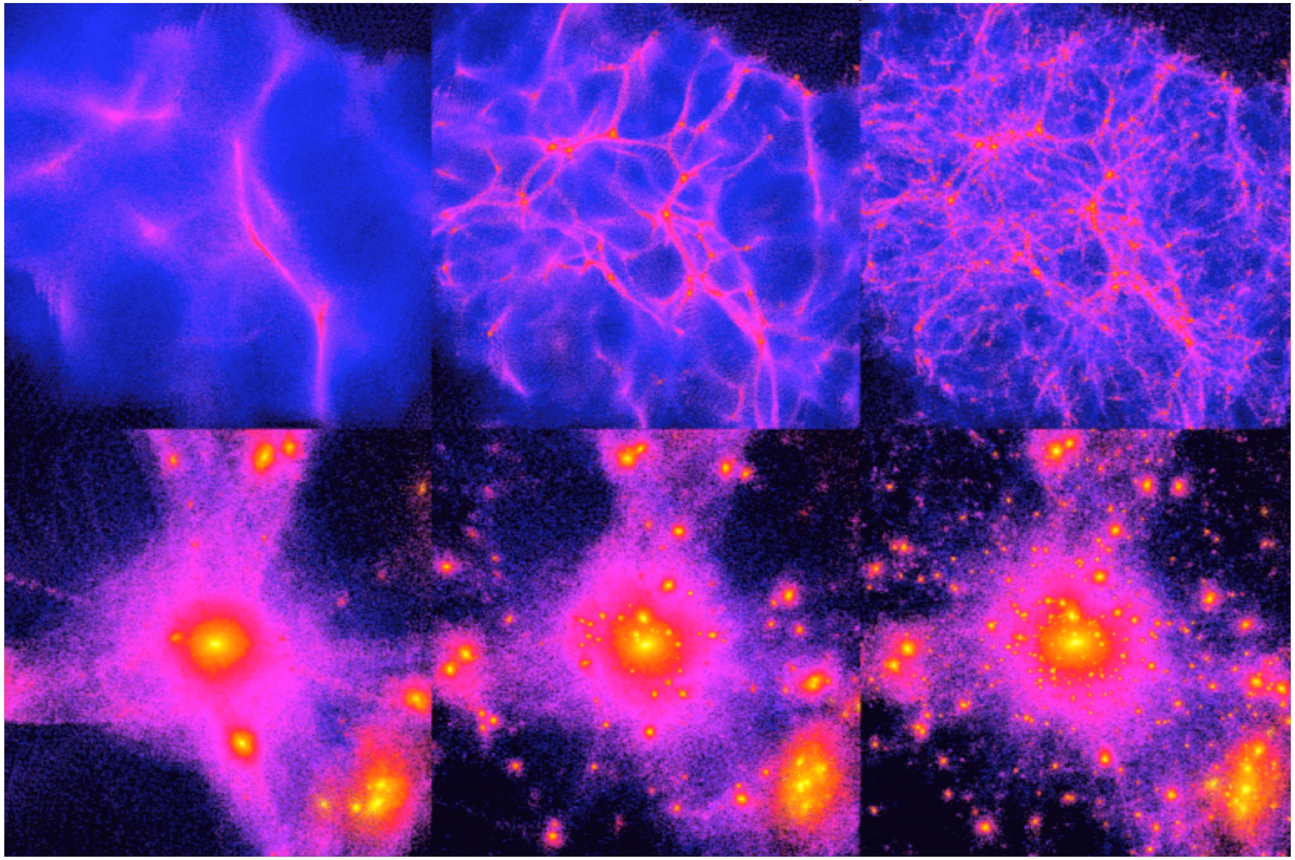
Whole parameter space:



[**AM**, Totzauer: JCAP **1506** (2015) 011]

5. Structure Formation

But what about structure formation?!?



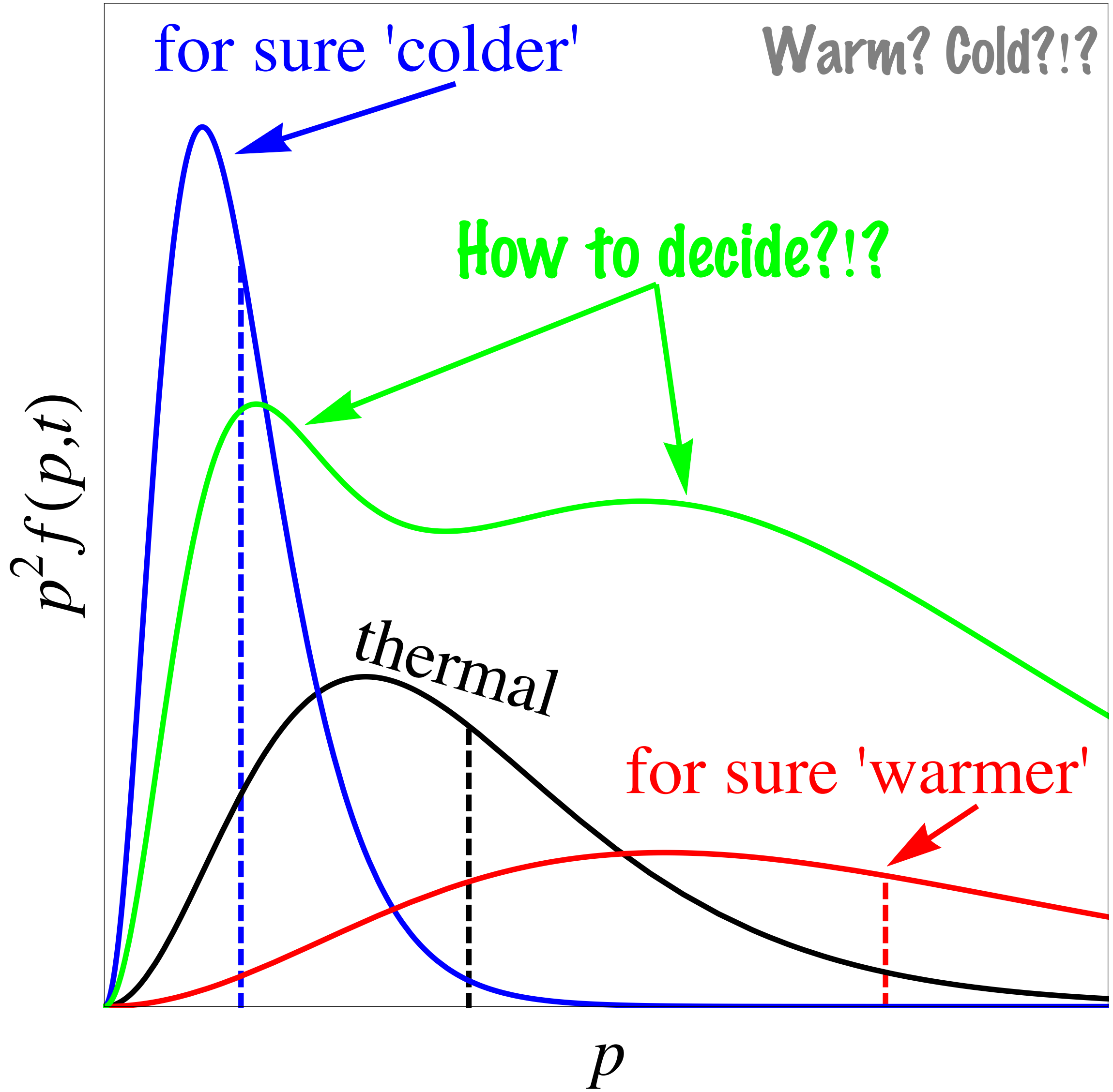
HOT WARM COLD

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

With non-thermal spectra…?!?

5. Structure Formation

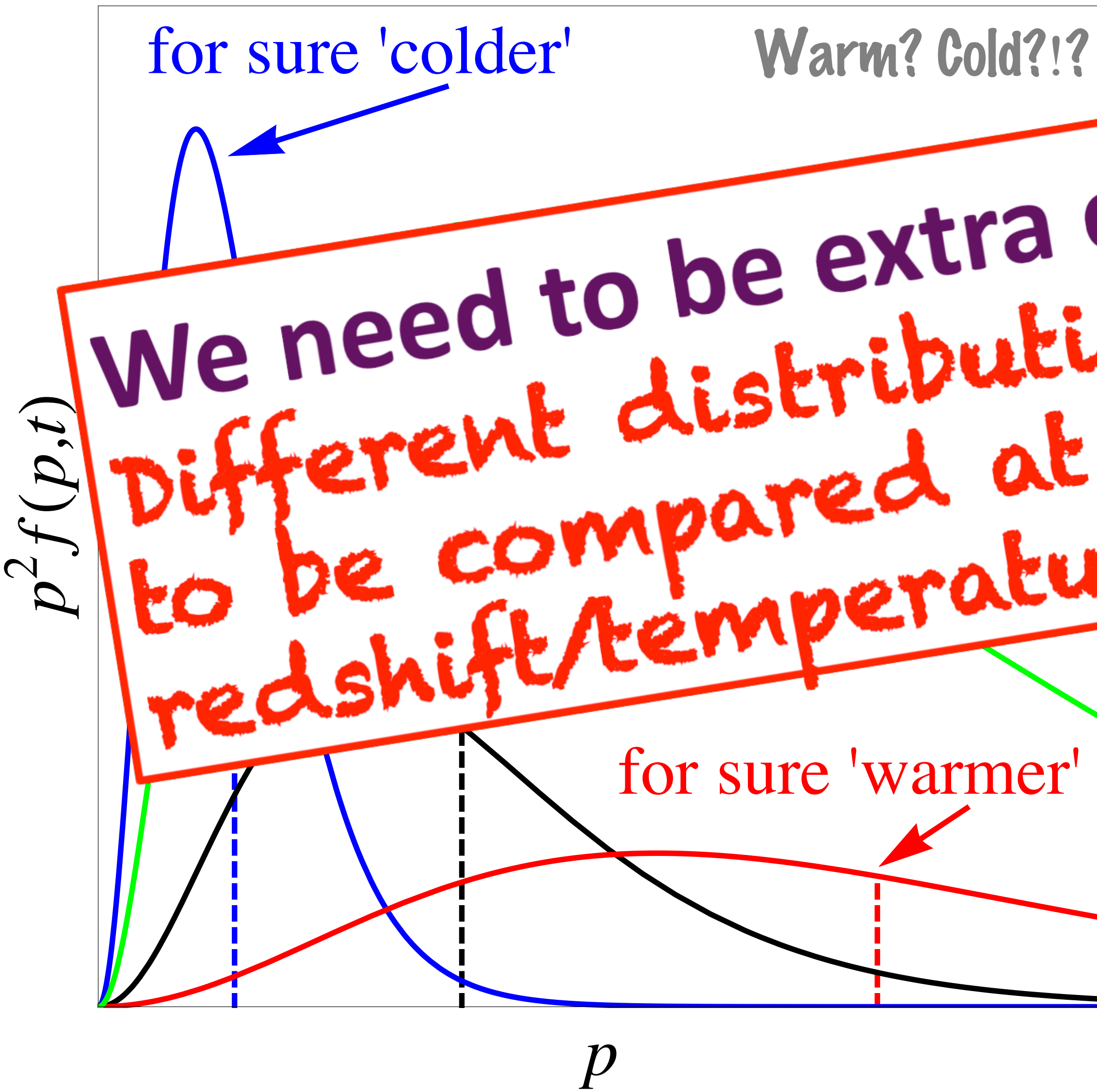
NOW WE ARE COMING BACK TO THIS ISSUE:



- ➔ How to decide which spectrum is warmer or cooler?!?
- ➔ ISSUE: average momentum is a bad measure
- ➔ GOAL: we have to find a way to decide if a spectrum is allowed, or not

5. Structure Formation

NOW WE ARE COMING BACK TO THIS ISSUE:



We need to be extra careful:

Different distributions have to be compared at <u>THE SAME</u> redshift/temperature!!!

→ How to ...cide ... rum ... or

... ge ... s ... easure

→ GOAL: we have to find a way to decide if a spectrum is allowed, or not

5. Structure Formation

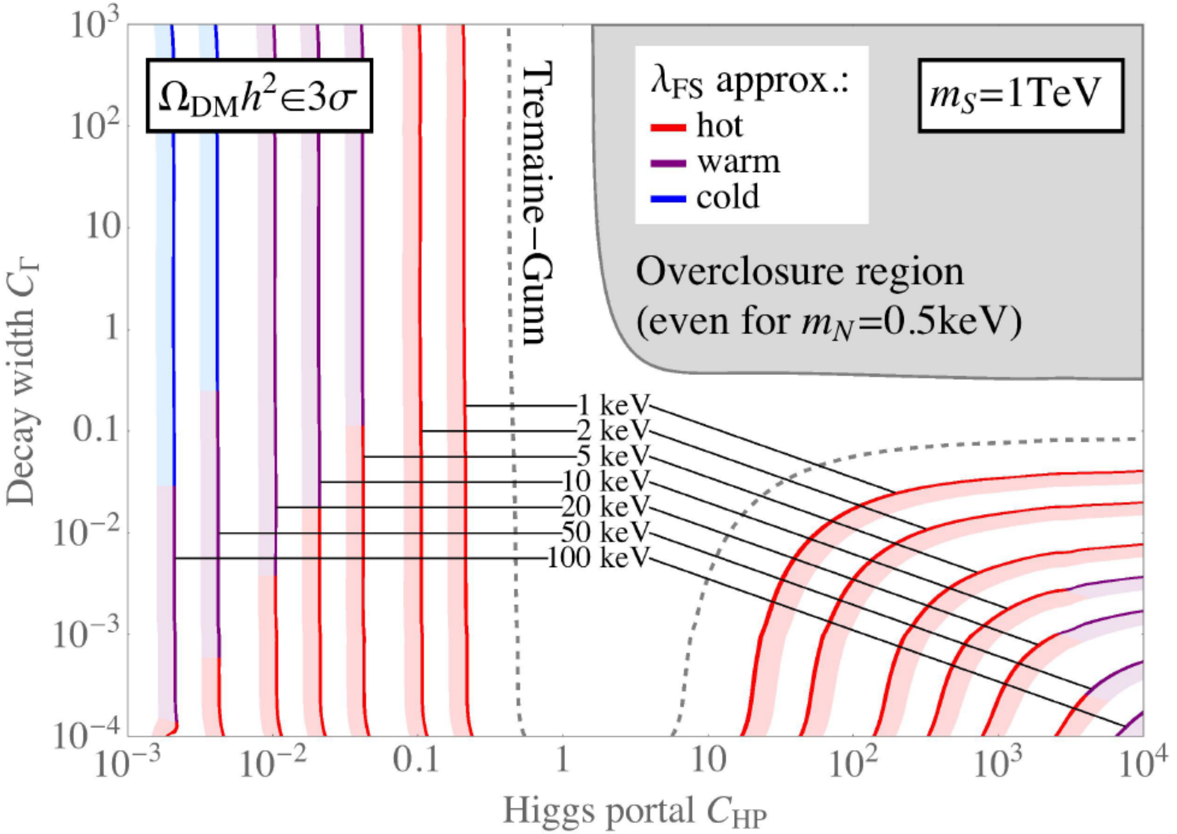
- **SINGLET SCALAR "S" FREEZES IN OR OUT BEFORE DECAY**

[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]

Free-streaming horizon

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

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



➔ **ALL possible depending on two effective parameters: effective decay widths C_Γ & effective Higgs portal $C_{\rm HP}$**

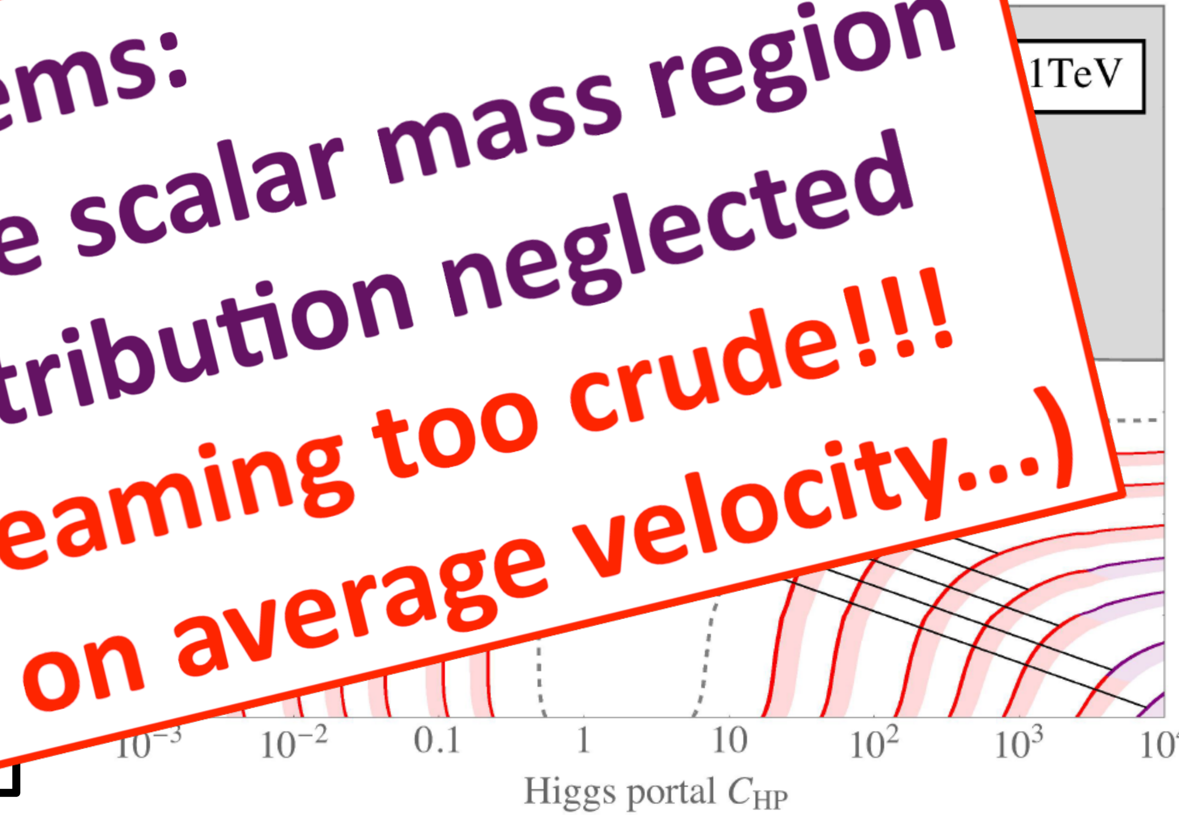
5. Structure Formation

- **SINGLET SCALAR "S" FREEZES IN OR OUT BEFO... ECAY**

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

Free-streaming ho...

Decid...
the ke...
are **HO**...



Three problems:

- **only large scalar mass region**
- **DW-contribution neglected**
- **free-streaming too crude!!! (based on average velocity...)**

➔ ALL possible depending on two effective parameters: effective decay widths C_Γ & effective Higgs portal C_{HP}

5. Structure Formation

- **ALL PROBLEMS SOLVED IN NEXT PAPER:**

  [König, **AM**, Totzauer: *Work in Progress*... 1607.XXXXX]

- DW-contribution already shown to be often negligible [**AM**, Schneider, Totzauer: JCAP **1604** (2016) 003]

- smaller scalar masses: technically involved (e.g. g_* not constant, more channels, Higgs freeze-out, ...) -> difficult but done

- much better estimate of structure formation properties, based on power spectra obtained with the CLASS code (Lesgourgues & Tram)...

... and even better ones to come!

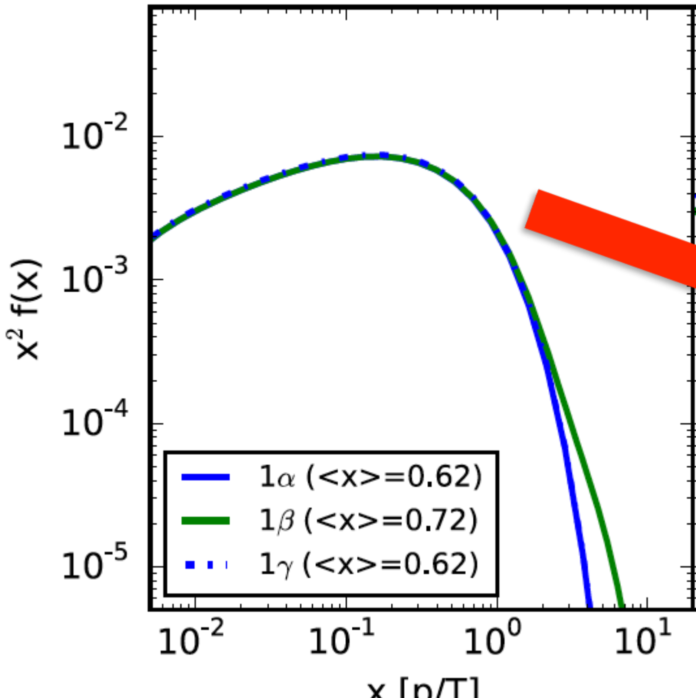
[König, **AM**, Schneider, Totzauer: *Work in Progress*]
[Menci, **AM**, Schneider, Viel: *Work in Progress*]

5. Structure Formation

- **ALL PROBLEMS SOLVED IN NEXT PAPER:**

  [König, **AM**, Totzauer: *Work in Progress*... 1607.XXXXX]

- we can use CLASS [www.class-code.net]
  -> authors: Julien Lesgourgues & Thomas Tram

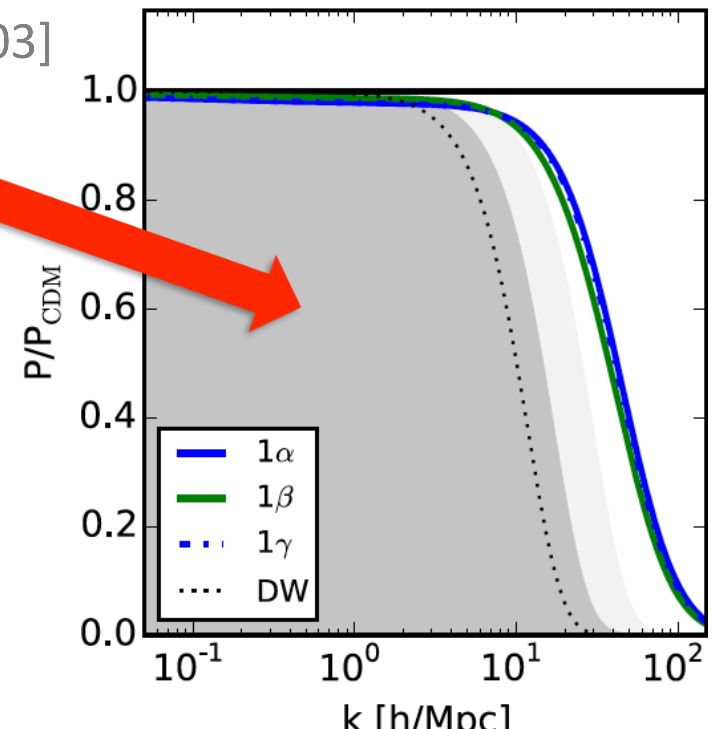


INPUT: momentum distribution f(p,T)

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

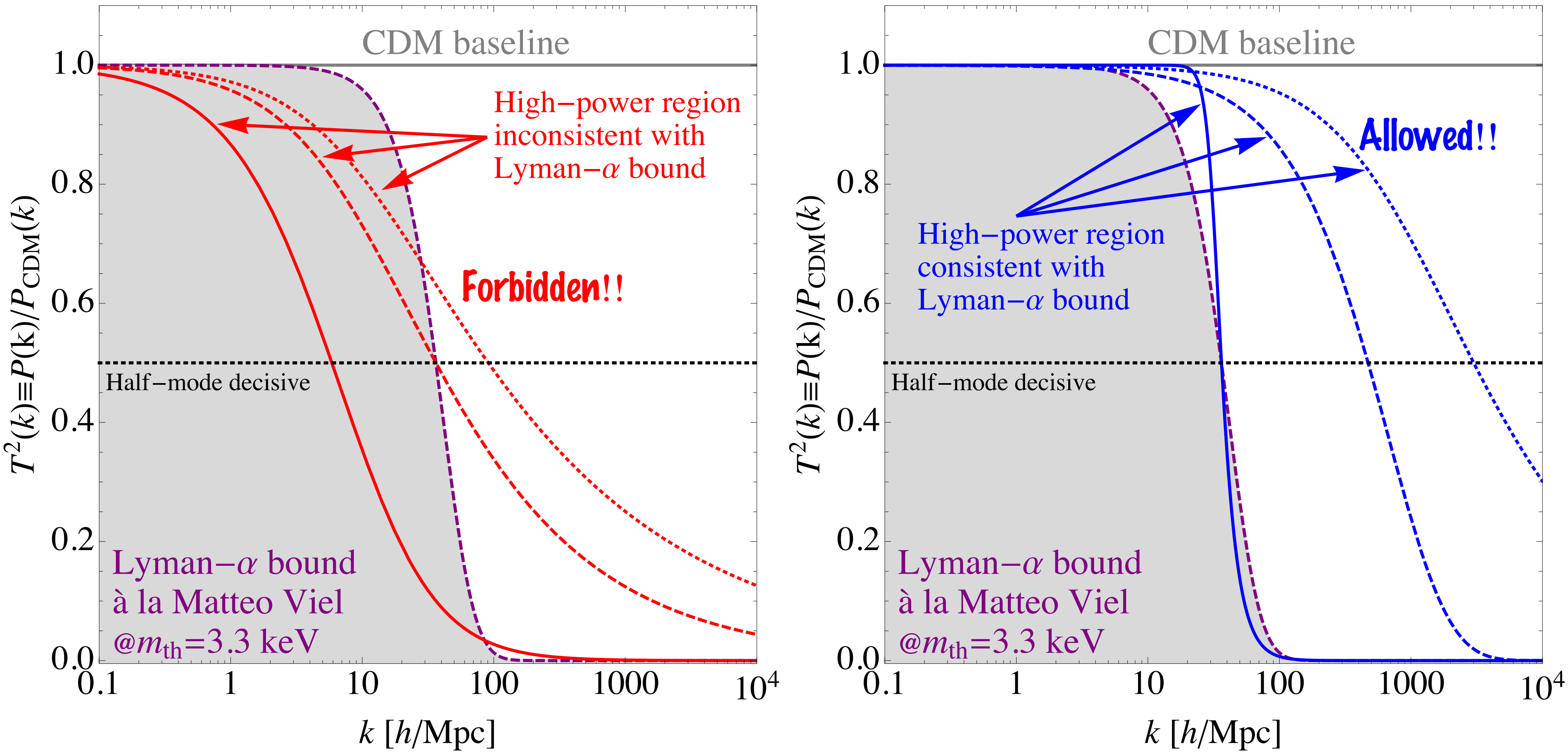
scalar decay +DW

OUTPUT: (squared) transfer function



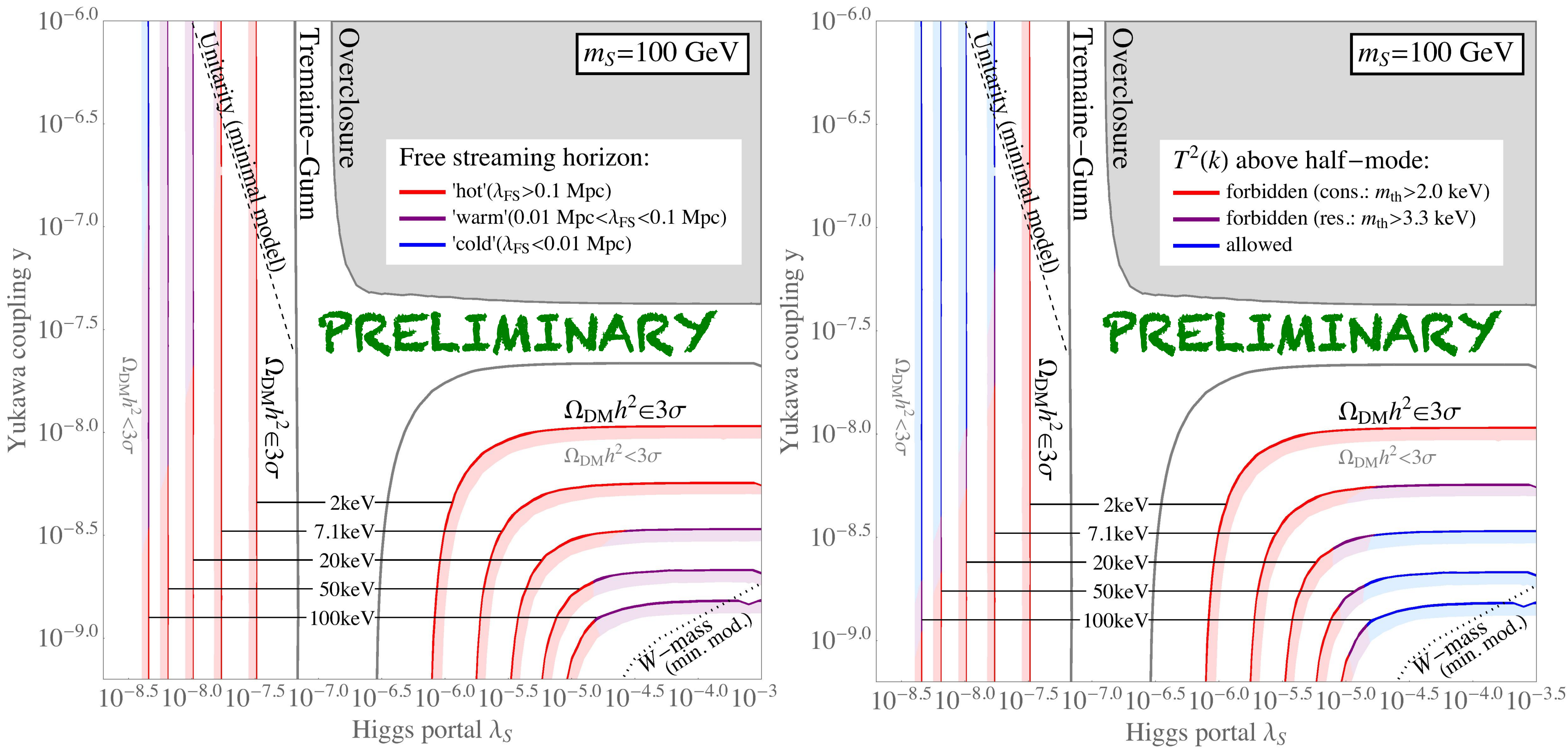
5. Structure Formation

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



5. Structure Formation

- YIELDS A MUCH MORE ACCURATE ESTIMATE:



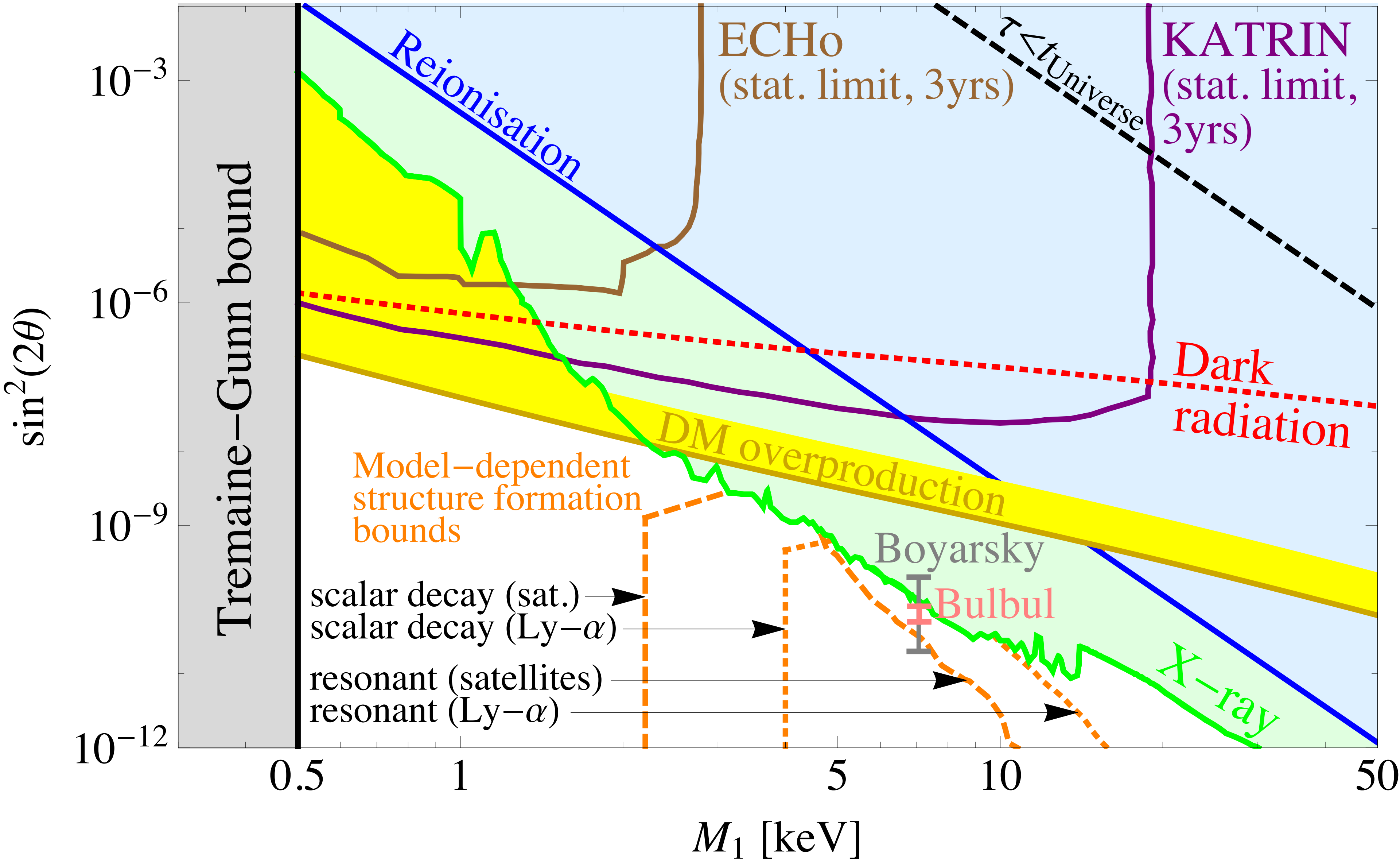
➔ FS-Horizon is actually too restrictive

➔ this method is as close as possible to a particle physicist's comfort zone

6. Conclusions

6. This is my take-home message...

Summary of all constraints (from keV-WP):



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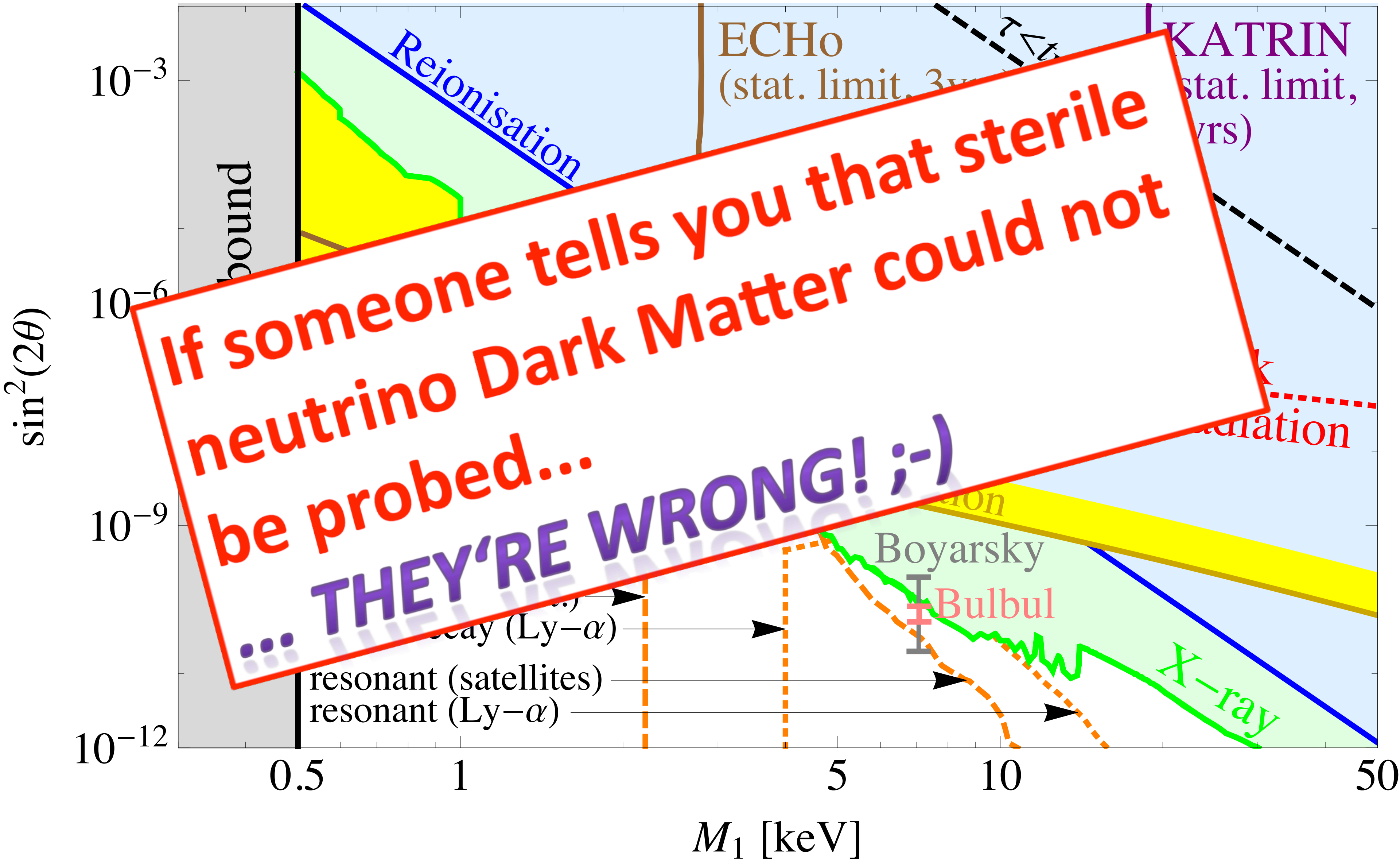


THANK YOU!!!