# Sterile Neutrinos as Dark Matter

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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,...

Prospects in Low Mass DM, MPP Munich, 30-11-2015

# *Contents:*

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1. To WIMP or not to WIMP
2. Sterile neutrinos
3. Non-thermal DM prod
4. Active-ste ions
5. production
6. To line or no to line
7. Conclusions

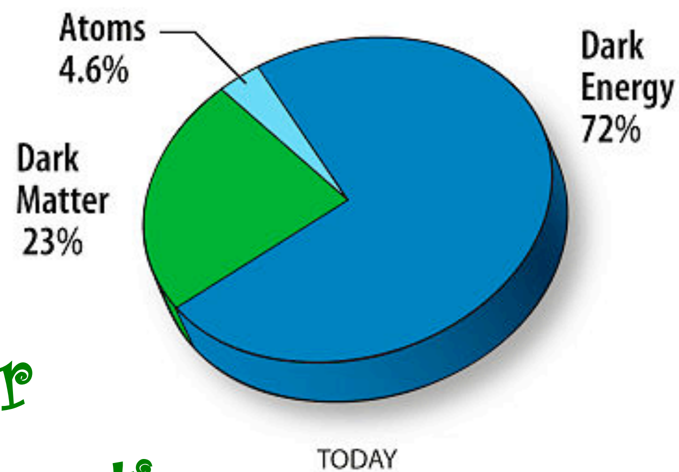
**My agenda looks longer than it is!! ;-)**

# 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...**

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

# 2. Sterile neutrinos

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

• **ordinary ("active") neutrino $\nu_a$: known elementary particle with very small mass and only weak interactions**

• **sterile neutrino $\nu_s$: may have a larger mass (value theoretically not predicted) and does not at all participate in standard interactions (BUT: small mixing with $\nu_a$)**

• **thus: if produced in the right amounts and with a suitable velocity spectrum, $\nu_s$ 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

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**Dark Matter:**

## THE STANDARD LORE

**Dark Matter is in equilibrium with everything in the early Universe and then "freezes out".**

→ **THERMAL SPECTRUM**

**NON-THERMAL?!?**

**Non-standard, exotic, unnecessary,...**

# 3. Non-thermal production mechanisms

**Dark Matter:**

## THE STANDARD LORE

Dark Matt

AL

M

**BUT: In reality we don't know the spectrum of Dark Matter very well at all!!**

**WHY NOT GOING NON-THERMAL?!?**

NON-THERMAL?!?

Non-standard, exotic, unnecessary,...

# 3. Non-thermal production mechanisms

**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 |
|---|---|---|
| $T \gg m$ | $T \sim m$ | $T \ll m$ |

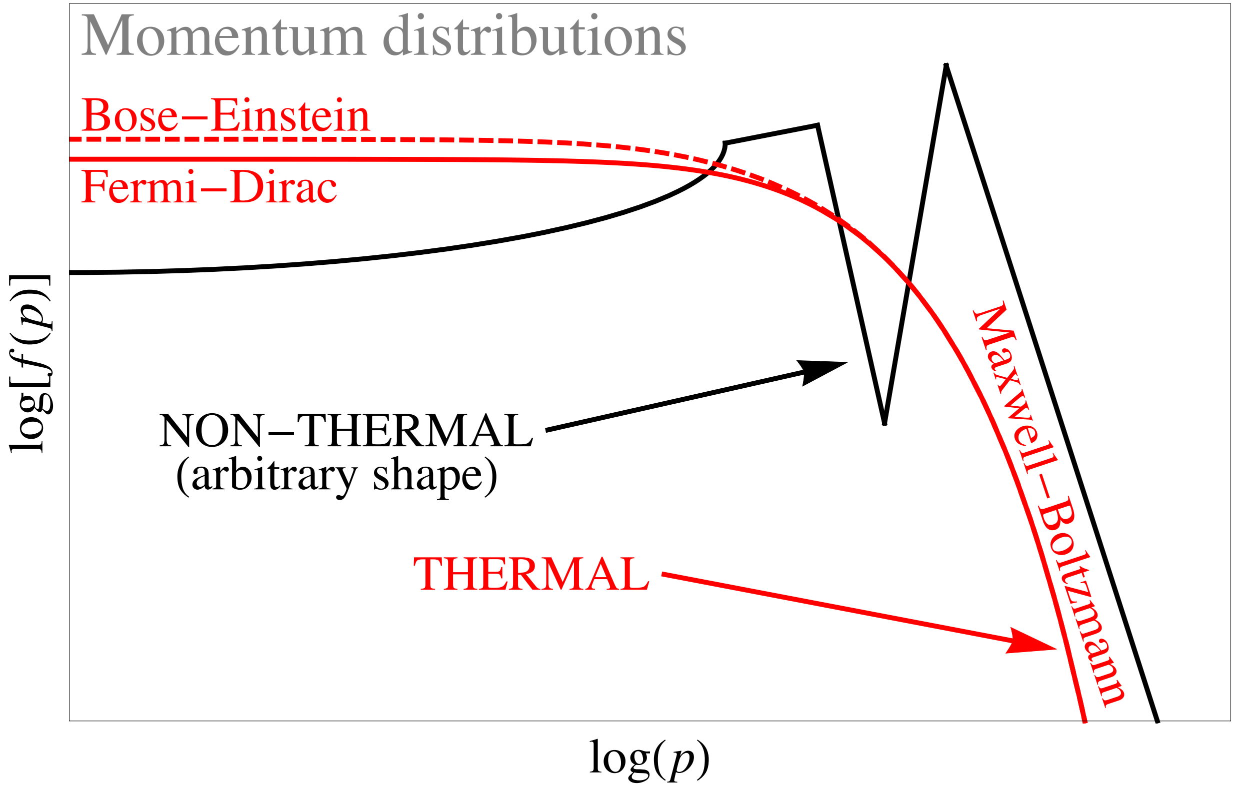
**NON-THERMAL**

$f(p)$ arbitrary

**with:**

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

$T$ not defined **!!!**



# 3. Non-thermal production mechanisms

For sterile neutrinos, all but the last mechanism produce a non-thermal shape:

**$\nu_a$-$\nu_s$ 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], ...

**Particle decays** [Asaka *et al.*: Phys. Lett. **B638** (2006) 401], [Anisimov *et al.*: Phys. Lett. **B671** (2009) 211], [Bezrukov, Gorbunov: JHEP **1005** (2010) 010], [Kusenko, Petraki: Phys. Rev. **D77** (2008) 065014], [**AM**, Niro, Schmidt: JCAP **1403** (2013) 028], [Frigerio, Yaguna: Eur. Phys. J. **C75** (2015) 31], [Adulpravitchai, Schmidt: JHEP **1501** (2015) 006], [**AM**, Totzauer: JCAP **1506** (2015) 011], [**AM**, Schneider: Phys. Lett. **B749** (2015) 283], [Lello, Boyanovsky: Phys. Rev. **D91** (2015) 063502], [Matsui, Nojiri: Phys. Rev. **D92** (2015) 025045], [Lello, Boyanovsky: 1508.04077], ...

**Diluted thermal overproduction** [Bezrukov *et al.*: Phys. Rev. **D81** (2010) 085032], [King, **AM**: JCAP **1208** (2012) 016], [Nemevsek *et al.*: JCAP **1207** (2012) 006], [Patwardhan *et al.*: 1507.01977], ...

# 3. Non-thermal production mechanisms

For sterile neutrinos, all but the last mechanism produce a non-thermal shape:

**PRACTICALLY EXCLUDED!!!**

~~**$\nu_a$-$\nu_s$ transitions** [Dodelson, Widrow: Phys. Rev. Lett. **72** (1994) 17]~~

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**OKAY!!!**

**Diluted thermal overproduction** [Bezrukov *et al.*: Phys. Rev. **D81** (2010) 085032], [King, **AM**: JCAP **1208** (2012) 016], [Nemevsek *et al.*: JCAP **1207** (2012) 006], [Patwardh...]

**BARELY ALLOWED...**

# 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!**

# 4. Active-Sterile Transitions

Simplest idea:

- **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")

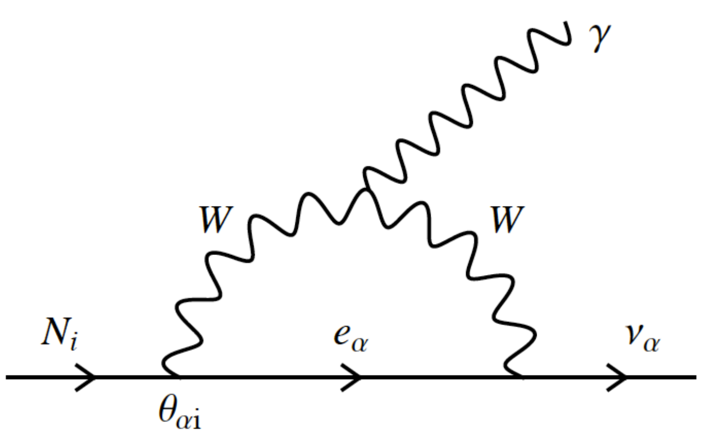
... these are the "standard" options

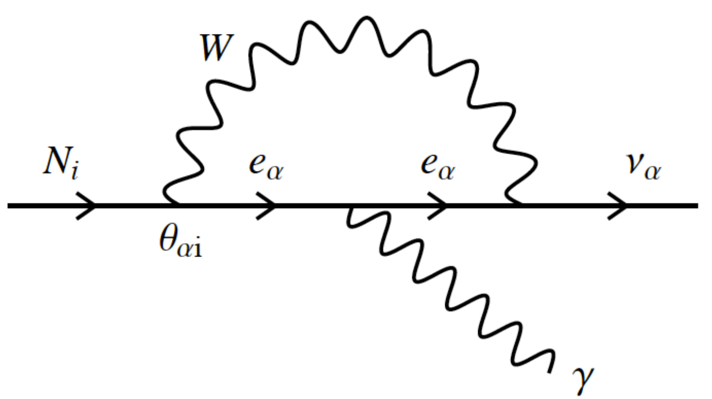
# The Dodelson-Widrow mechanism

**It could all be sooo simple...:**

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

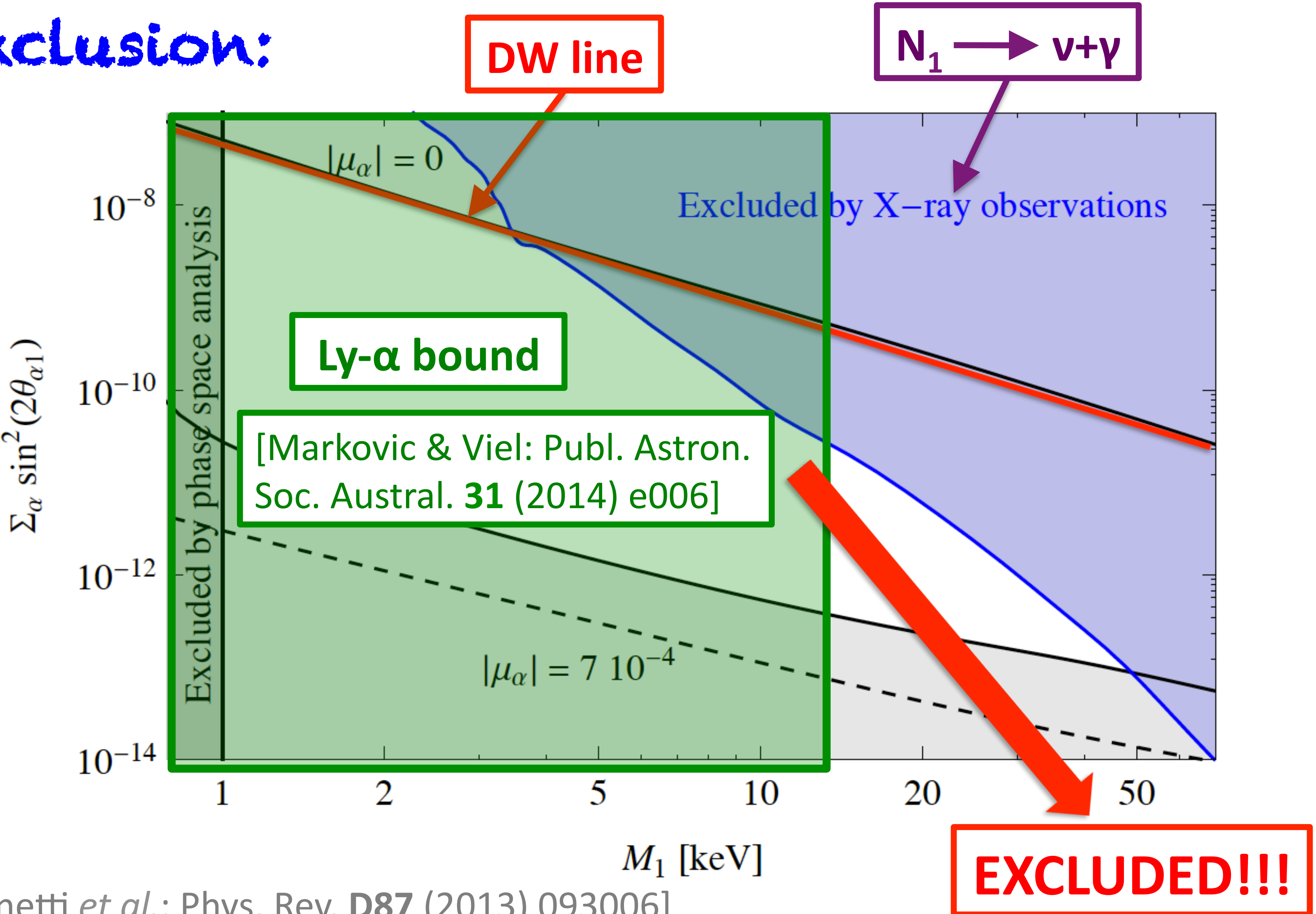
- **slow non-resonant "oscillations" of active into sterile neutrinos can gradually produce the DM from the thermal plasma (just like "freeze-in") ➔ *nice & simple***
- **this mechanism produces relatively hot DM ➔ large mass $M_1$ needed, BUT decay into X-rays scales like $M_1^5$:**



# The Dodelson-Widrow mechanism

**Exclusion:**




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

# *The Shi-Fuller mechanism*

**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**

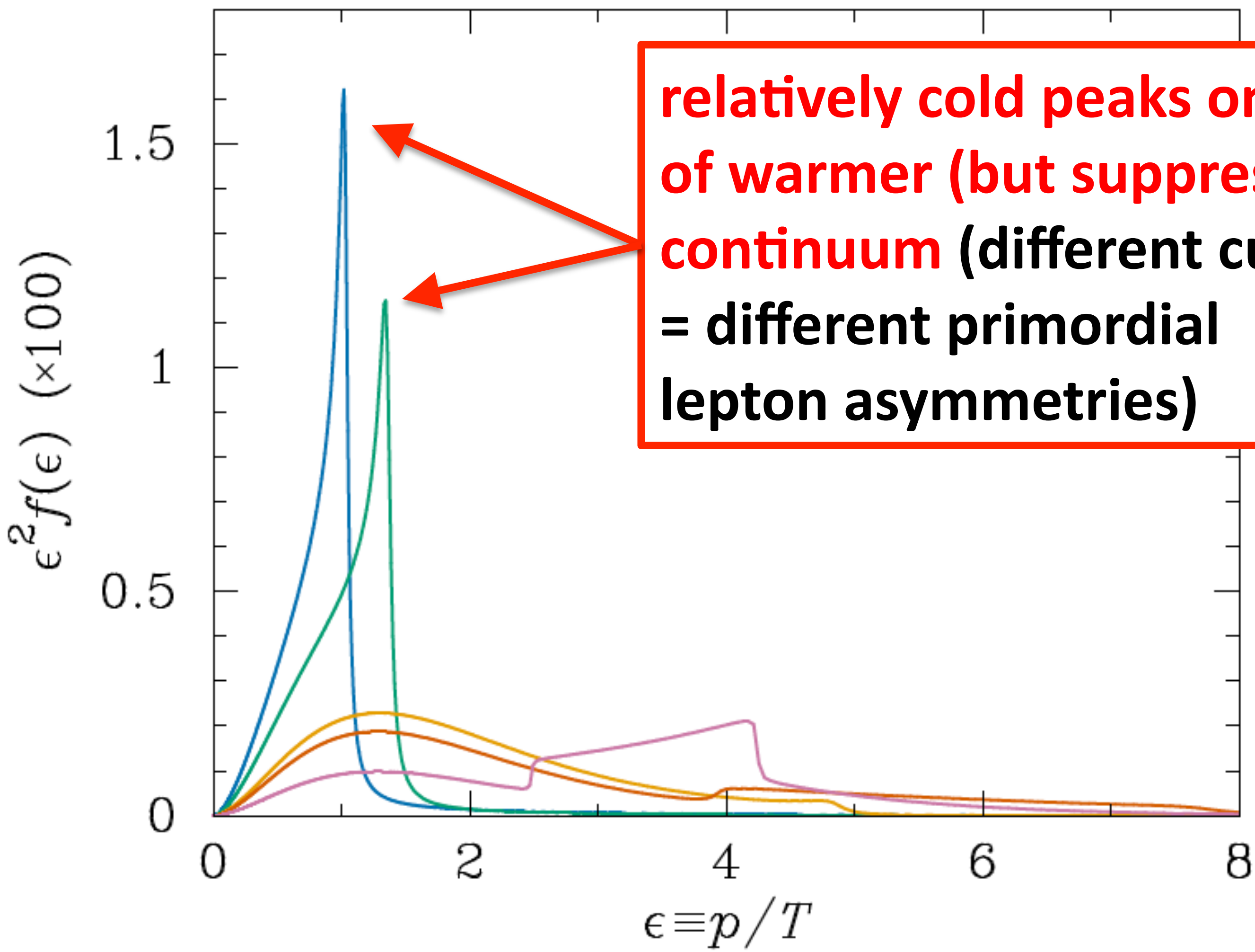
- **this would produce a large amount of $\nu_s$ at a specific (momentum-dependent) resonance temperature**
  **➔ *cooler spectrum***

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

# *The Shi-Fuller mechanism*

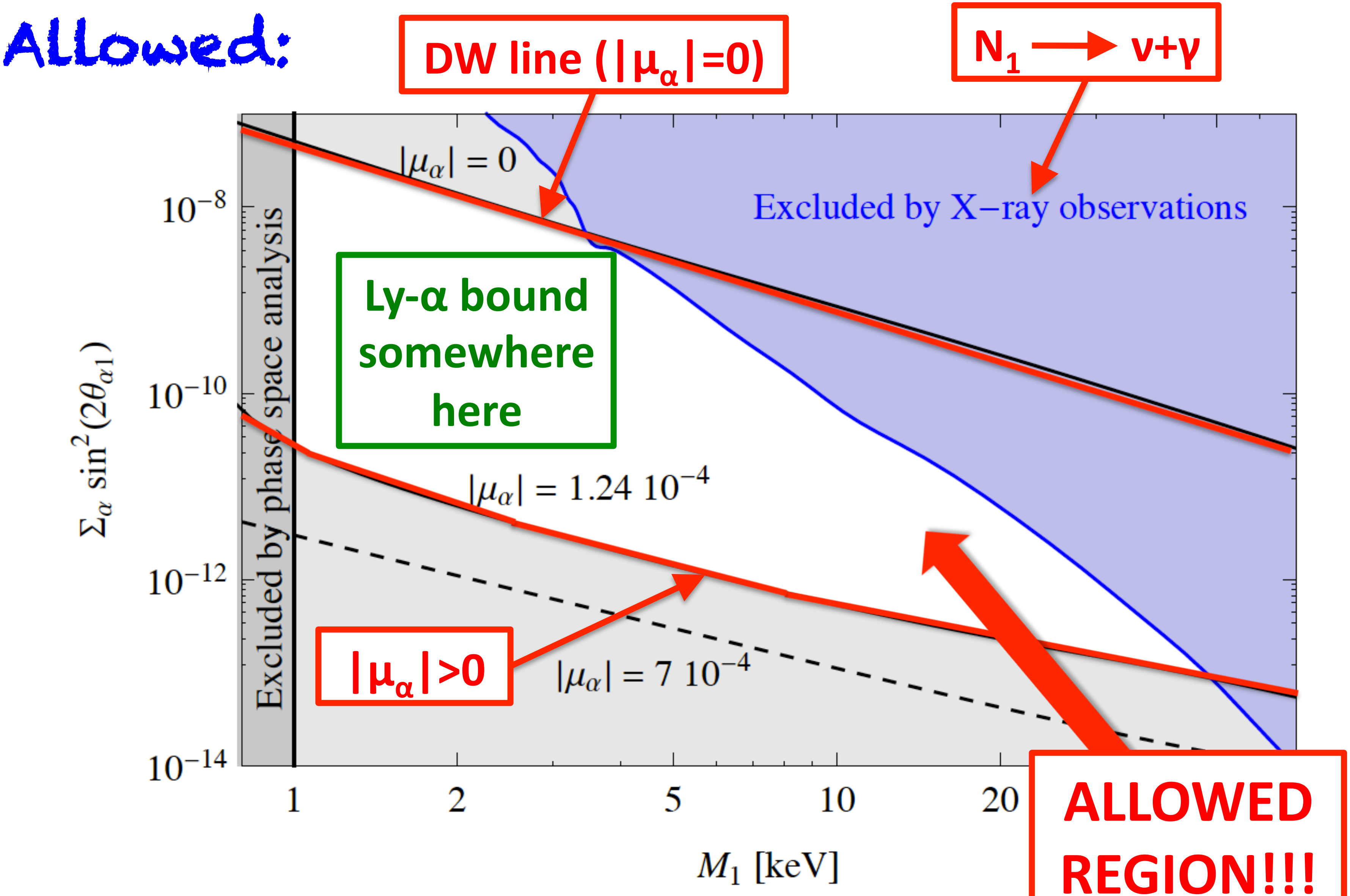
**This produces to non-trivial spectra:**

[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




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

# 5. 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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  [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]

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

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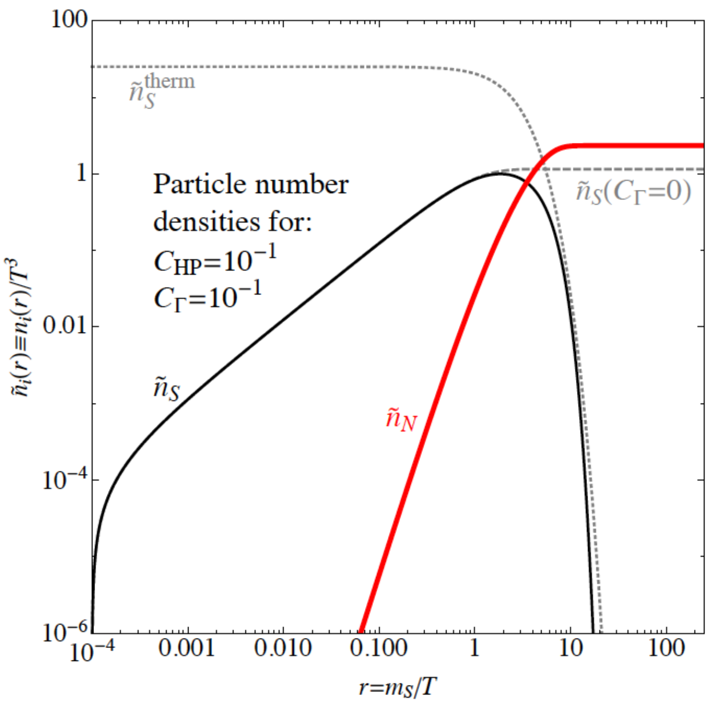
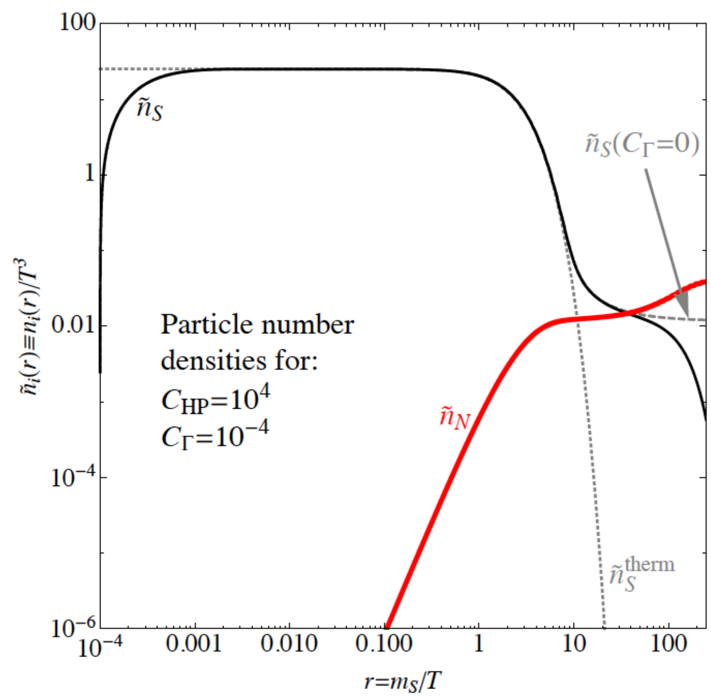
Two-step process: scalar S must be produced before decaying → many possibilities, e.g.:

S freezes-in and decays afterwards

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

Abundance



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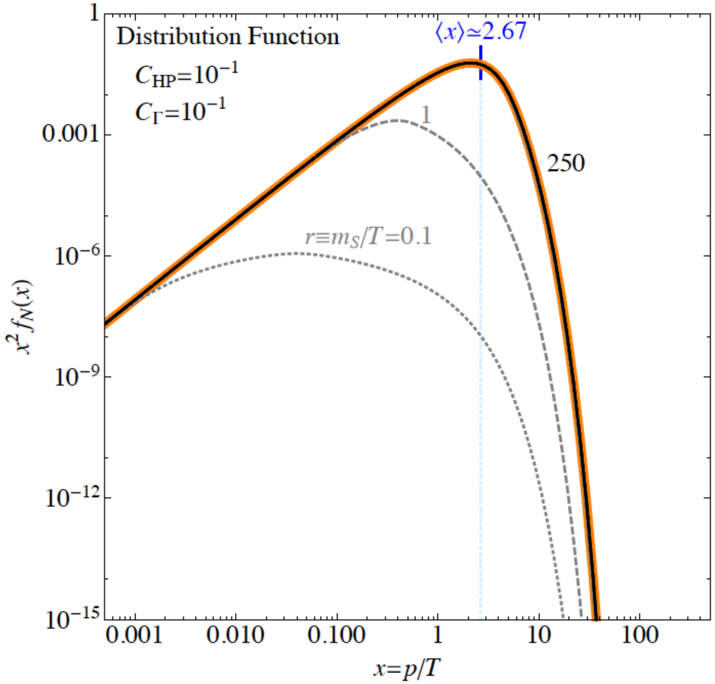
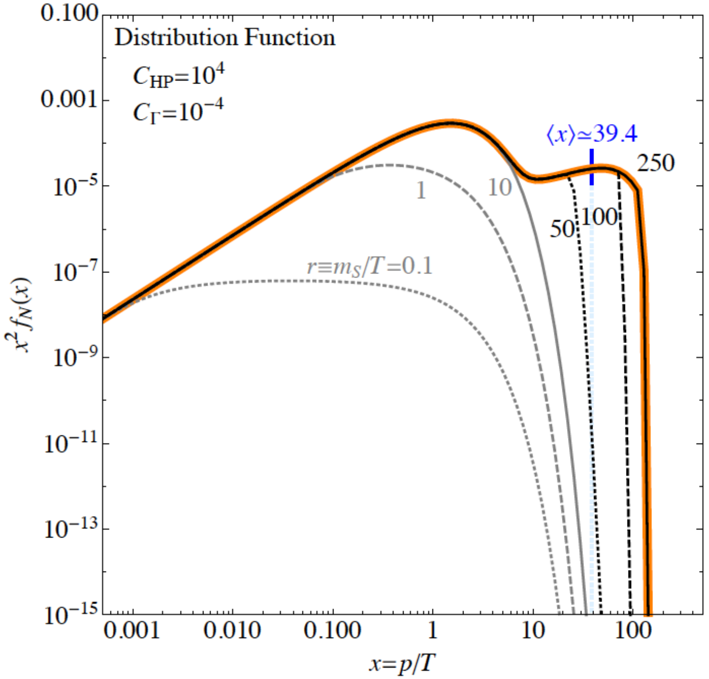
Distribution function



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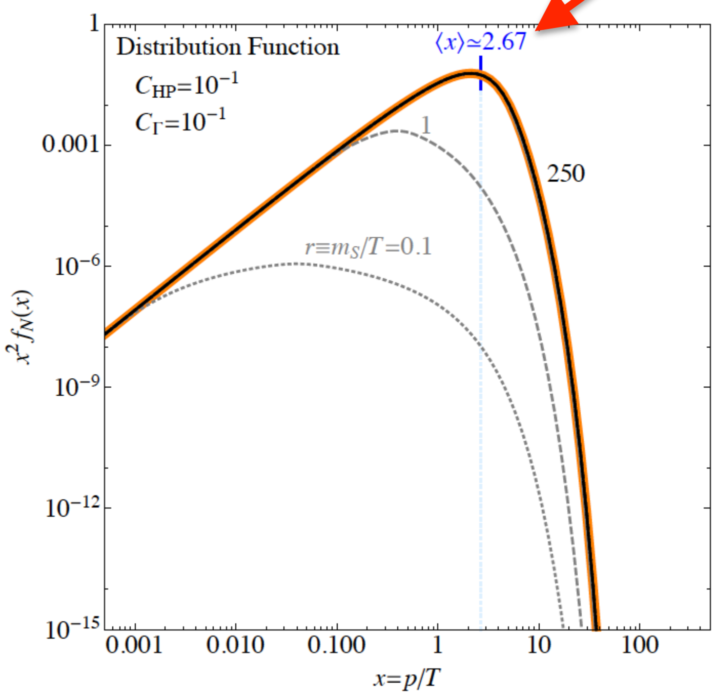
Two-step process: scalar S must be produced before decaying → many possibilities, e.g.:

S freezes-in and decays afterwards

colder

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

warmer

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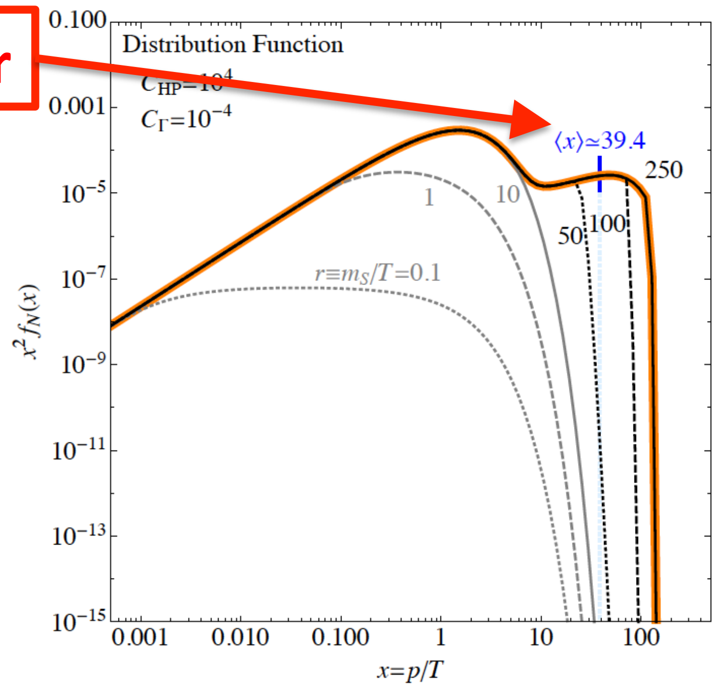

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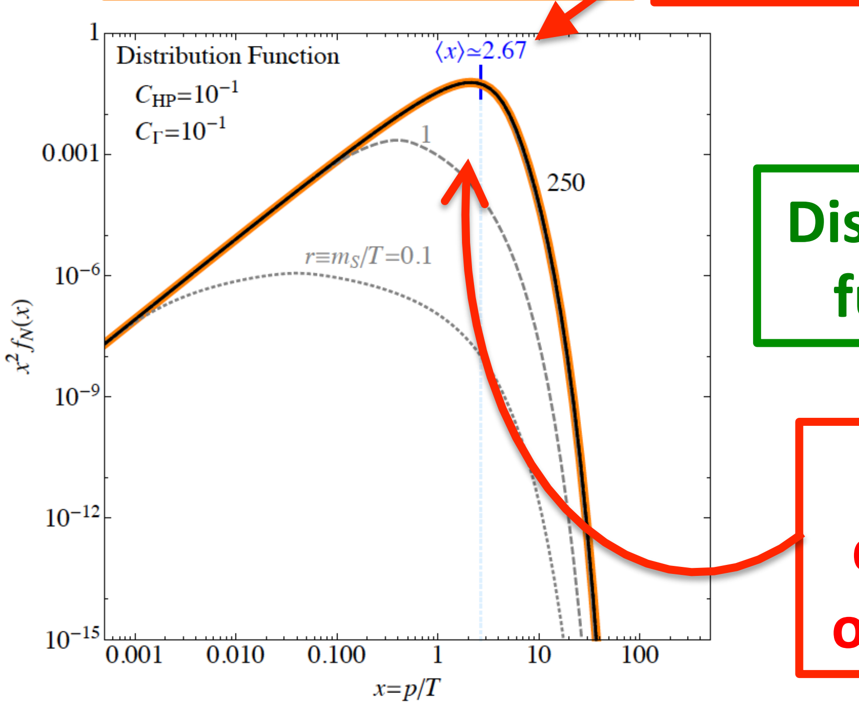
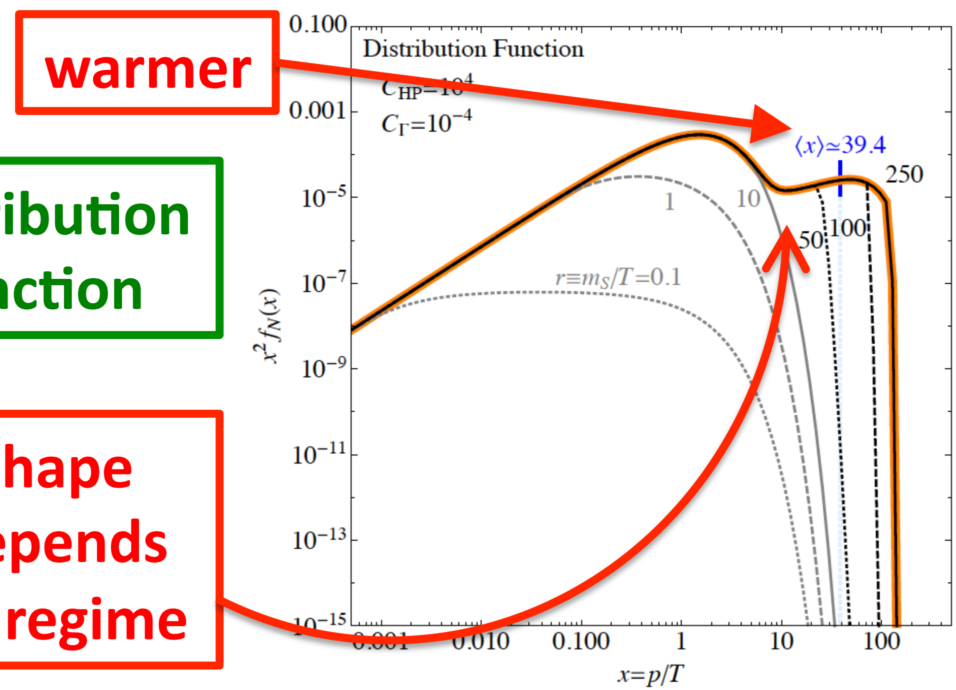
Two-step process: scalar S must be produced before decaying → many possibilities, e.g.:

**S freezes-in and decays afterwards**

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



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

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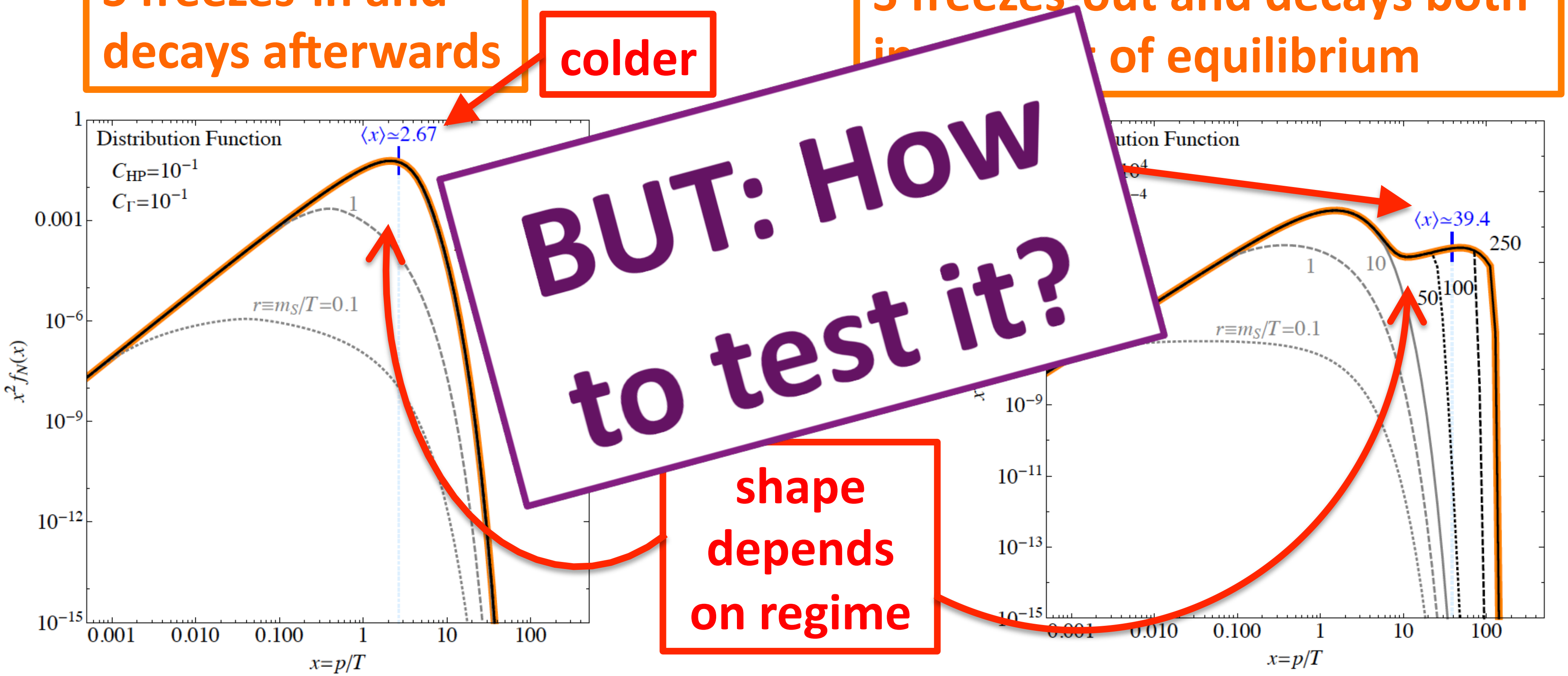
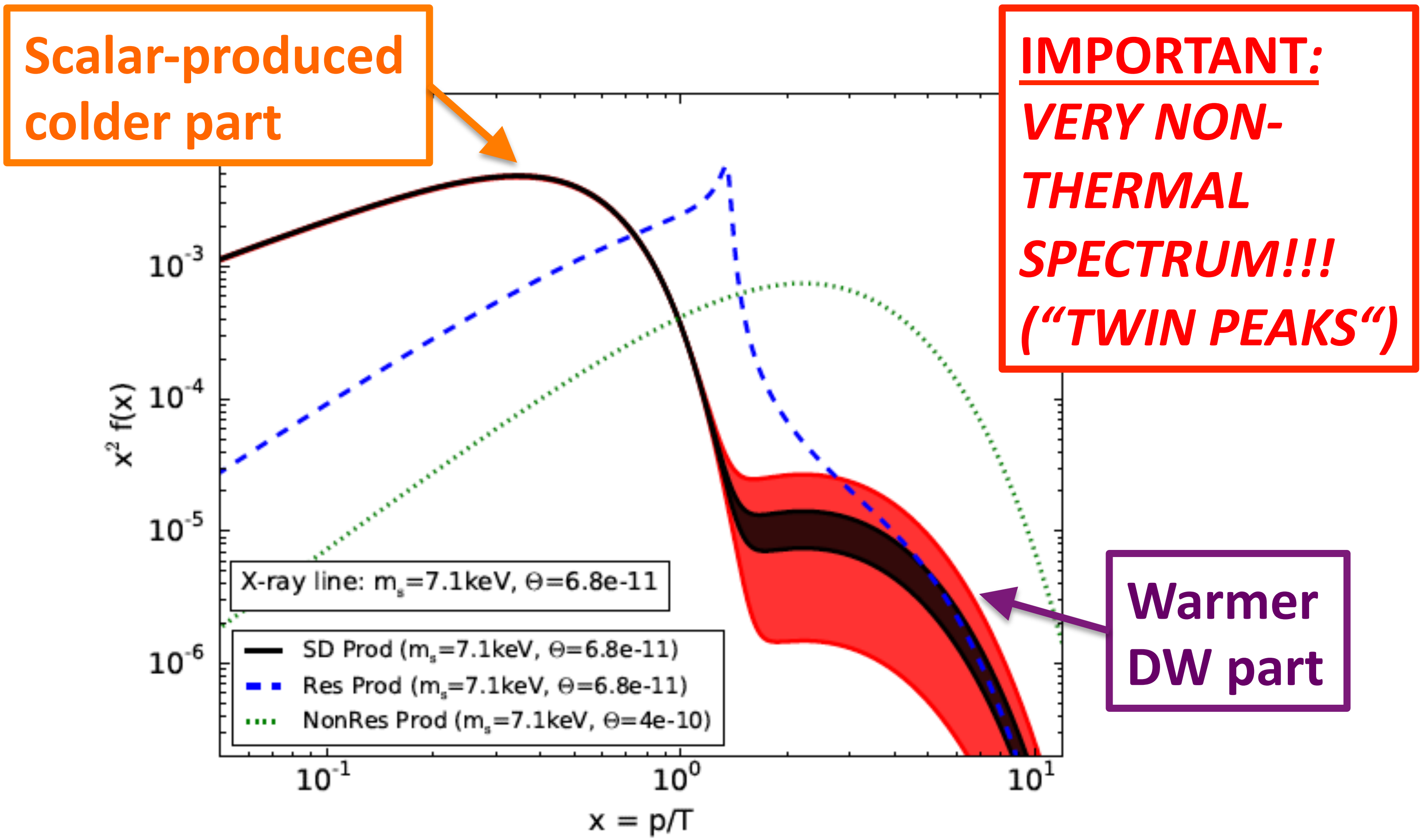


# 5. Decay production

- <u>*Cold Dark Matter is not perfect*</u>: **NON-THERMAL DM CAN BE VERY INTERESTING FOR STRUCTURE FORMATION**

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



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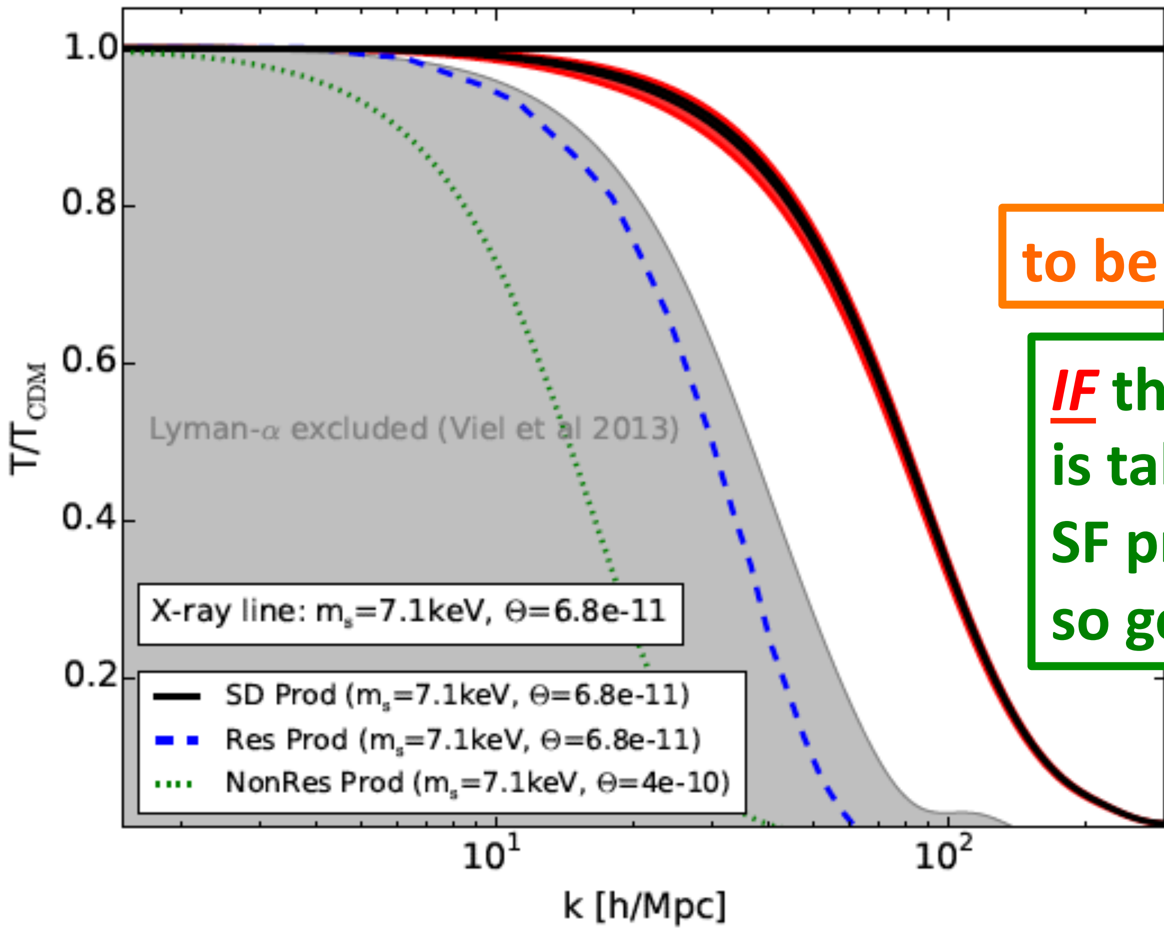


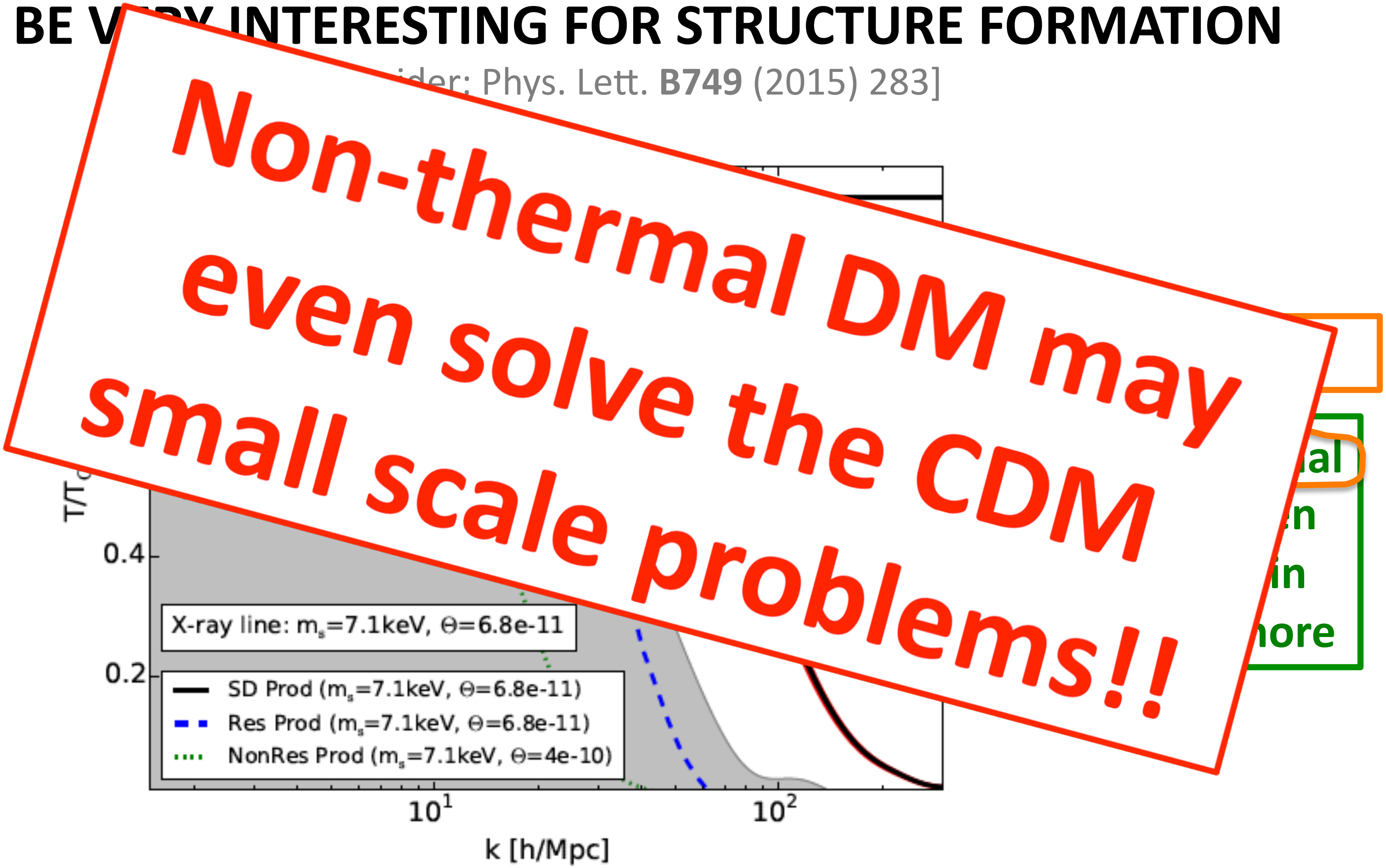

**to be discussed in a minute**

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

# 5. Decay production

- *Cold Dark Matter is not perfect*: **NON-THERMAL DM CAN BE V[...] INTERESTING FOR STRUCTURE FORMATION**

[...]ider; Phys. Lett. **B749** (2015) 283]



# 5. Decay production

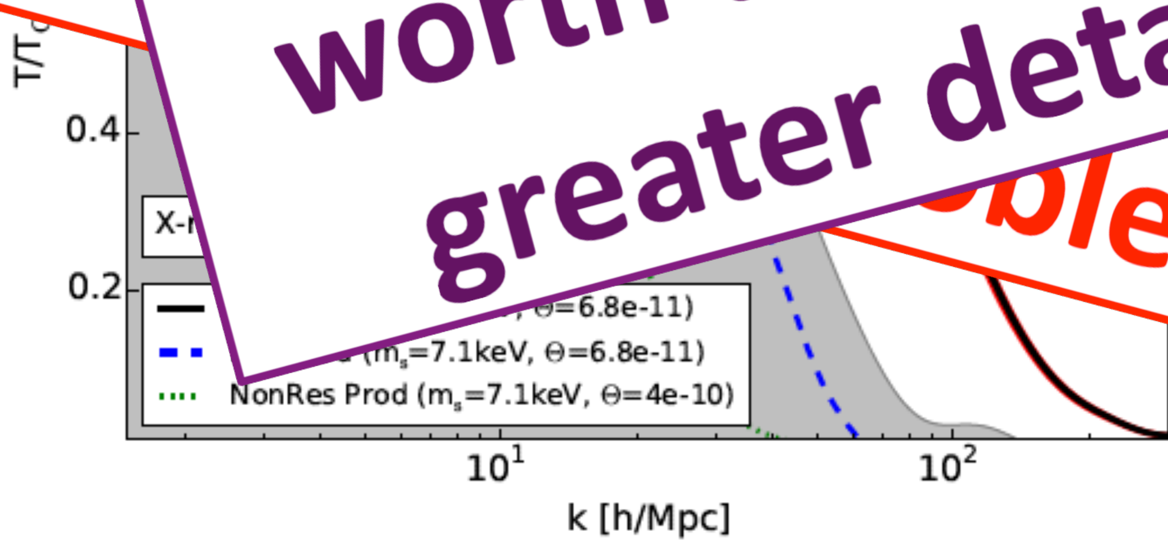
- *Cold Dark Matter is not perfect*: **NON-THERMAL DM CAN BE V... INTERESTING FOR STRUCTURE FORMATION**

...ider: Phys. Lett. **B749** (2015) 283]

**Non-th...**

**...blems!!**

**Decay production worth to study in greater detail!**



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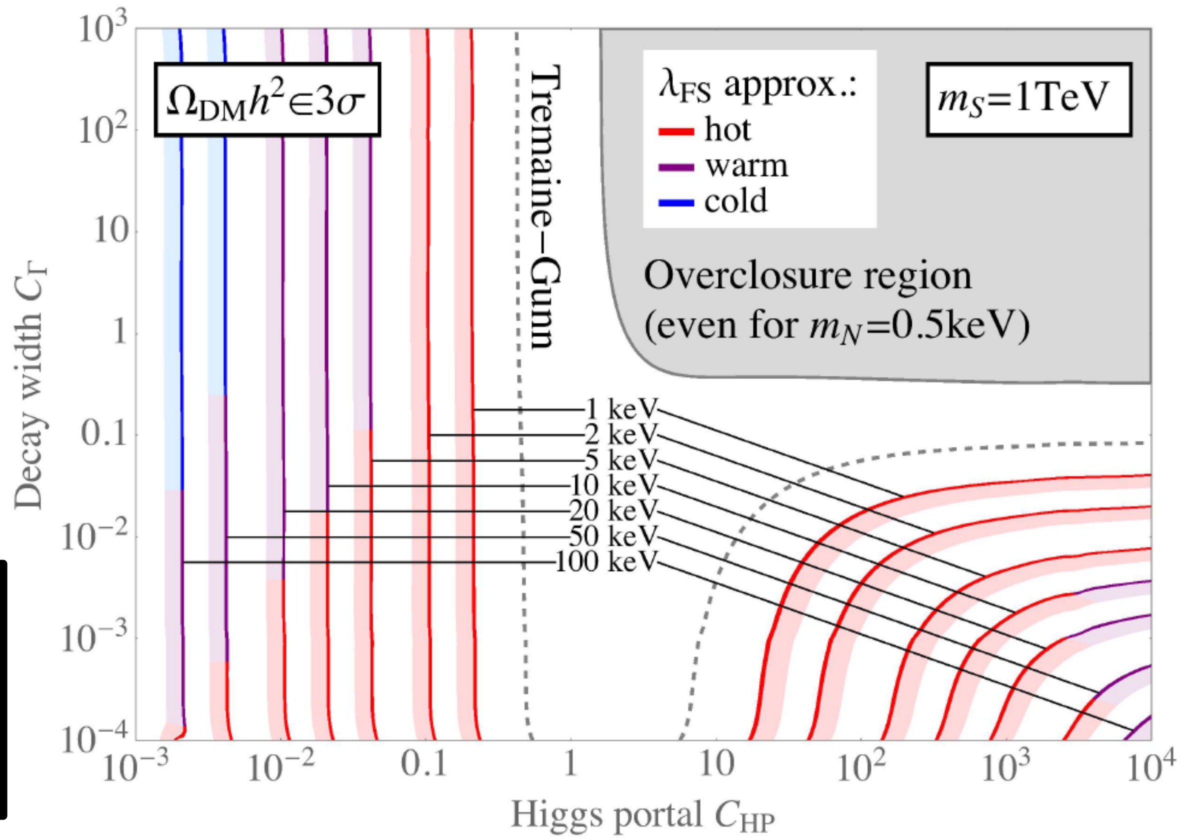
[**AM**, Niro, Schmidt: JCAP **1403** (2013) 028; **AM**, Totzauer: JCAP **1506** (2015) 011]

**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 effective parameters ($C_\Gamma$,$C_{\rm HP}$)**

➔ **STRUCTURE FORMATION STUDY OUT SOON!**

[**AM**, Schneider, Totzauer: 1512.XXXXX]

# 6. *To Line Or Not To Line*

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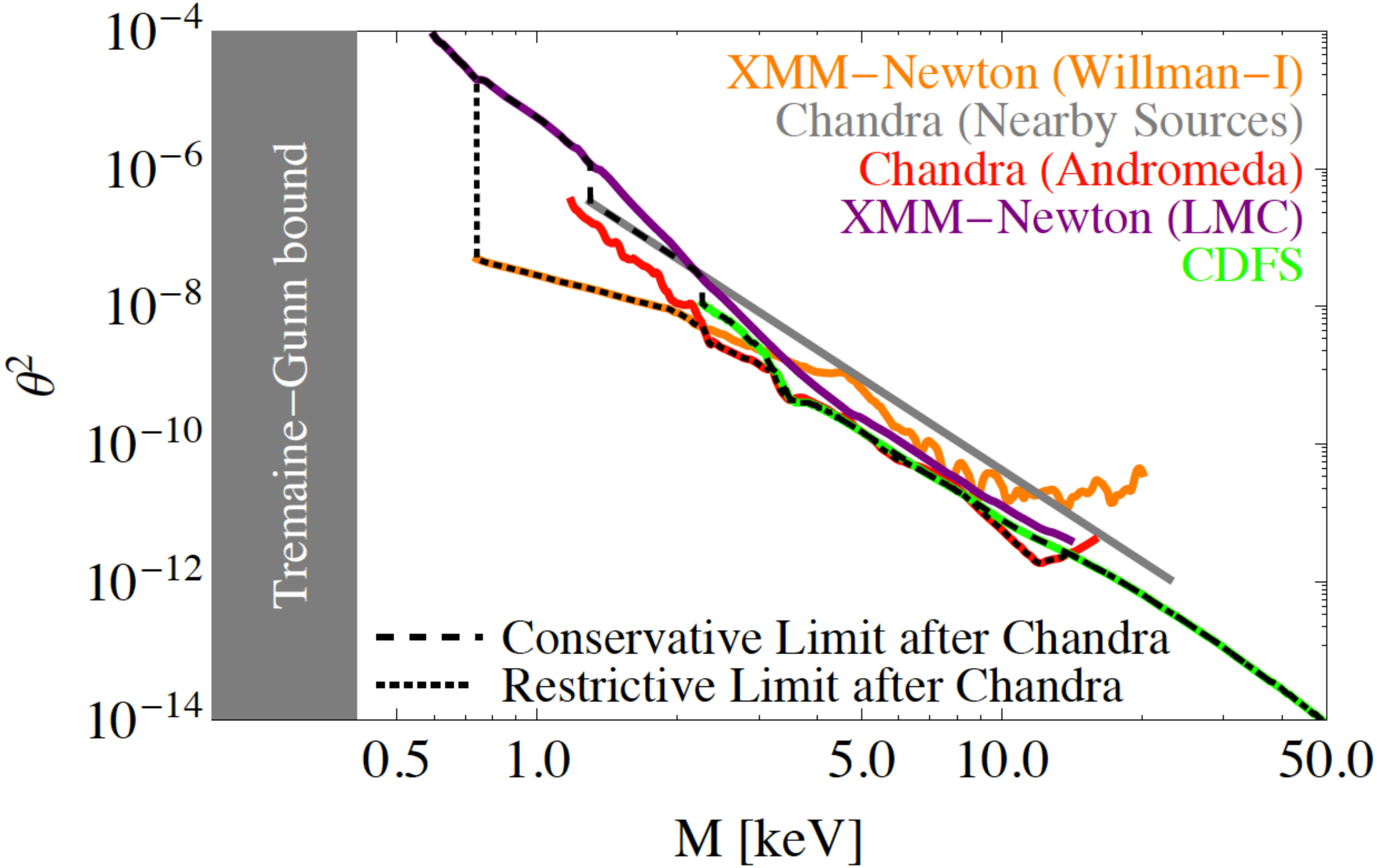
Up to February 2014 we only had bounds:

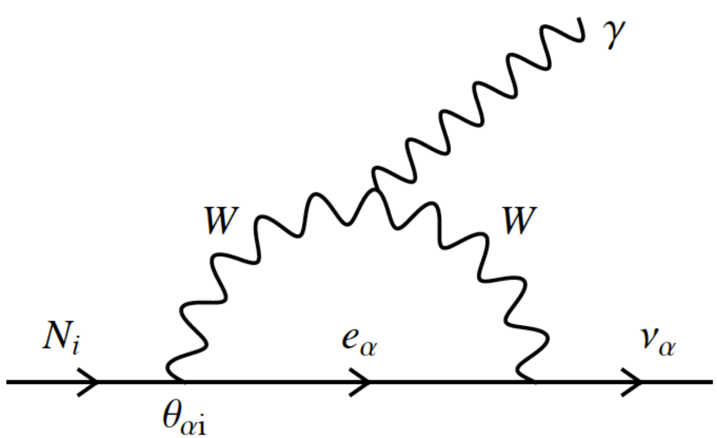


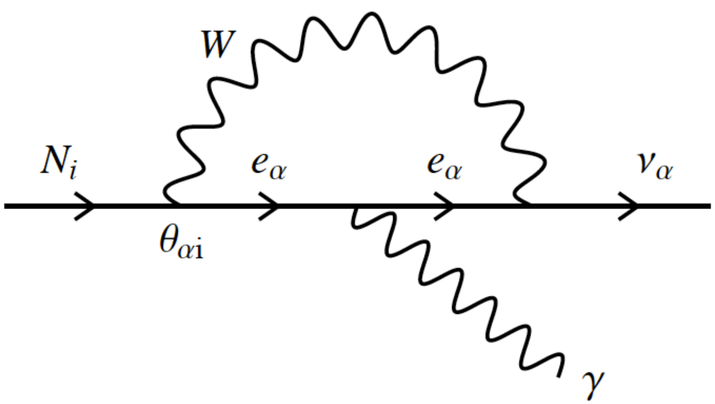

[**AM**, Niro: Phys. Rev. **D88** (2013) 11, 113004]

# 6. *To Line Or Not To Line*

Do we now have a signal?!?

- ***a possible hint***: the "3.5" keV line (**ACTUALLY**: 3.6 keV, at least according to the first paper)
  - stacked XMM-Newton spectrum of 73 galaxy clusters + division into 3 subsamples (e.g. Perseus cluster only):
    **$m_s \approx 7.1$ keV & $\sin^2(2\theta) \approx 7\times10^{-11}$** [Bulbul *et al.*: Astrophys. J. **789** (2014) 13]
  - XMM-Newton spectrum of Perseus cluster & Andromeda galaxy:
    **$m_s = 7.06\pm0.05$ keV & $\sin^2(2\theta) = (2.2\text{-}20)\times10^{-11}$** [Boyarsky *et al.*: Phys. Rev. Lett. **113** (2014) 251301]

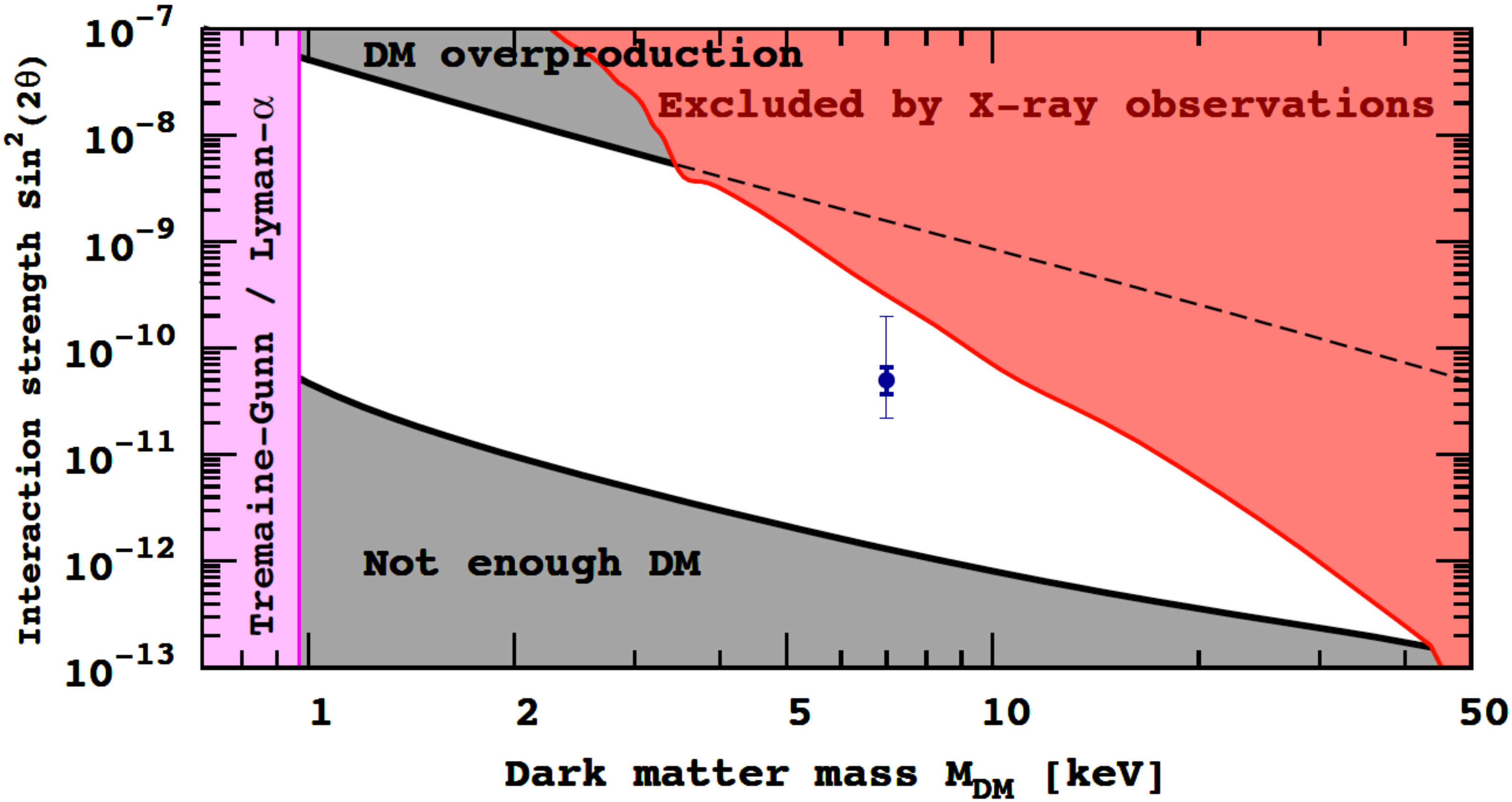


# 6. *To Line Or Not To Line*

Do we now have a signal?!?

- ***resulting region:***




[Boyarsky *et al.*: 1402.4119]

# 6. *To Line Or Not To Line*

**BUT:** Not everybody agrees...

... little "war" on the arXiv:

*Main arguments on the "con"-side:*

- **signal not seen in all data sets** [e.g. Jeltema, Profumo: Mon. Not. Roy. Astron. Soc. **450** (2015) 2143; Malyshev, Neronov, Eckert: Phys. Rev. **D90** (2014) 103506; Riemer-Sorensen: 1405.7943]
- **wrong use of atomic data** [e.g. Jeltema, Profumo: Mon. Not. Roy. Astron. Soc. **450** (2015) 2143]
- **signal does not correctly follow DW-profile** [e.g. Carlson, Jeltema, Profumo: JCAP **1502** (2015) 009]

**ON THE OTHER HAND:**

***COUNTER-ARGUMENTS EXIST FOR ALL OF THEM...***

# 6. *To Line Or Not To Line*

My personal take on this:

**THE STATISTICS OF SIGNAL IS BAD!!!**

→ CLEAR:

will depend on analysis method

weak position from the very beginning

→ ALSO CLEAR:

*no need to argue at this stage…*

… let's just wait for Astro-H or LOFT (beginning of 2016 is not too far)!!!

# 7. Conclusions

# 7. 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!

- *back-up slides available*:
  TERRESTRIAL EXPERIMENTS
  MODEL BUILDING
  DETAILS ON DM PRODUCTION


THANK YOU!!!

# ADVERTISEMENT


***<u>Workshop on keV sterile neutrino Dark Matter</u>*:**

- **at IAS Garching**
- **7 – 9 December 2015**

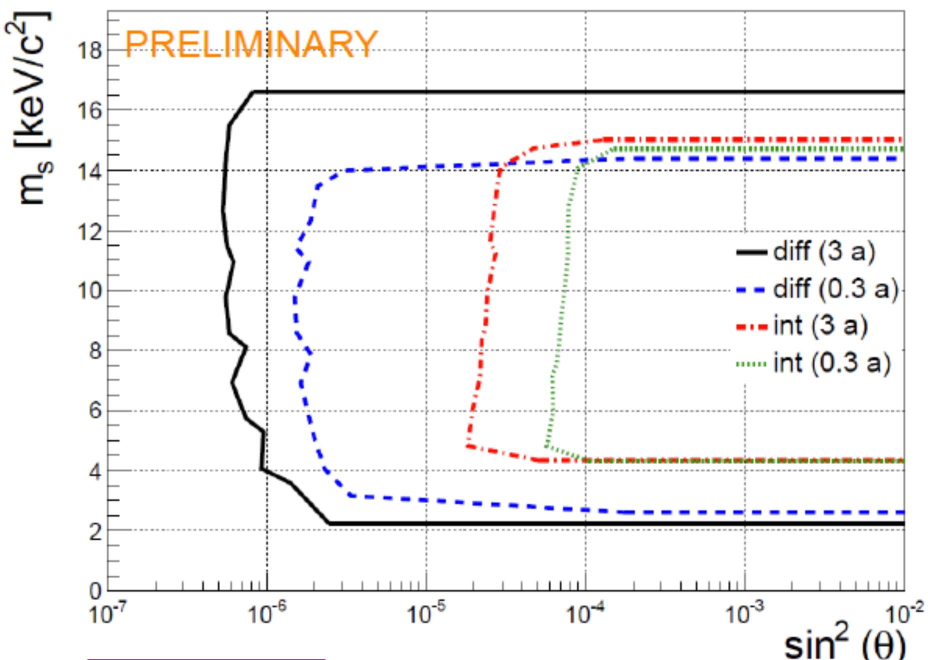
ν-Dark

# BACK-UP SLIDES

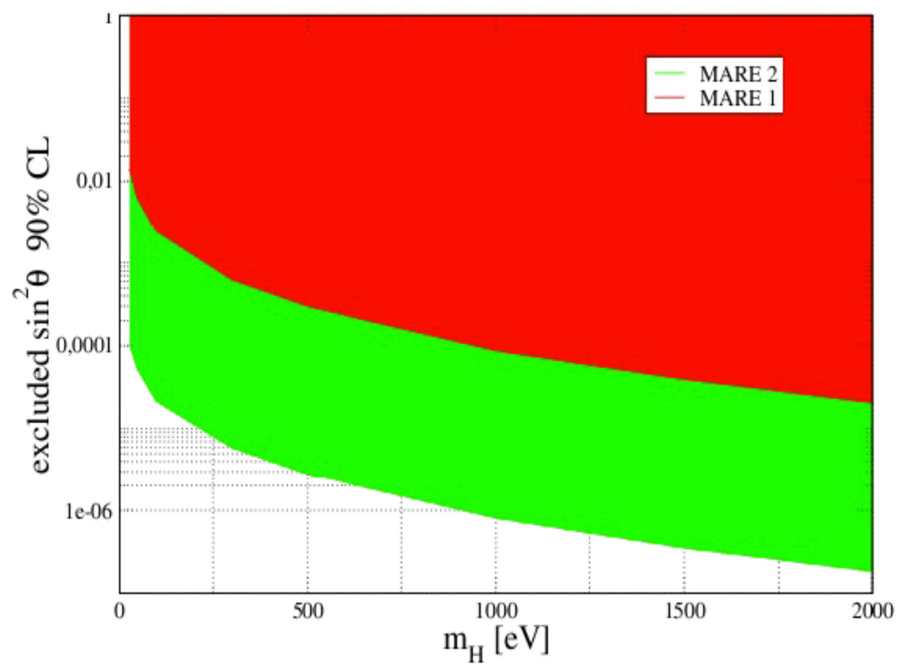
# 8. BACK-UP: Terrestrial Experiments

There are several Earth-based experiments attempting to measure something...

- **β *decays***: can produce $\nu_s$ if mass < Q-value




KATRIN [Korzeczek: Meudon `14]



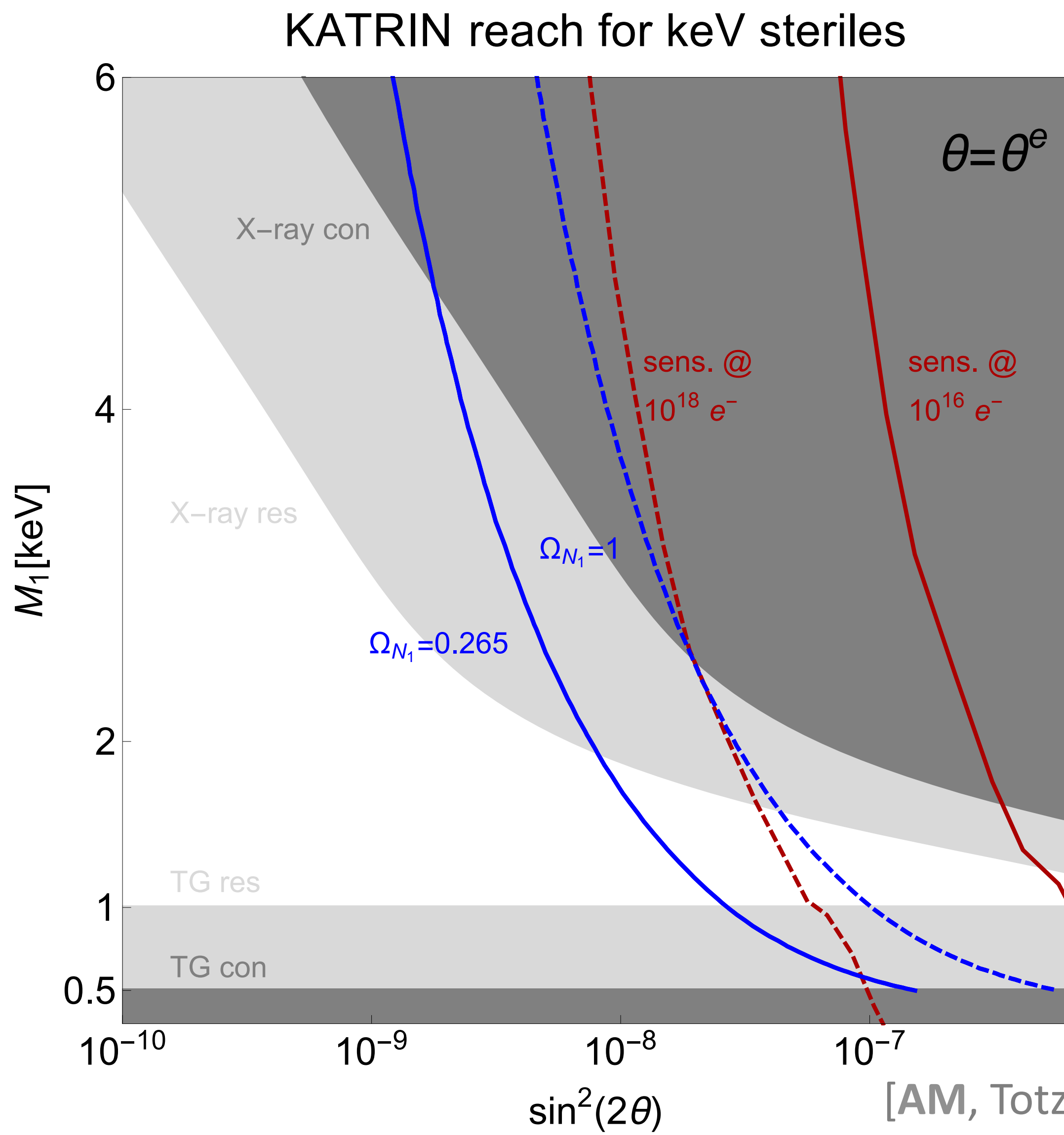

MARE [Ferri: Meudon `13]

➔ *upgrade to TRISTAN*

# 8. BACK-UP: Terrestrial Experiments

BUT: KATRIN/TRISTAN IS ONLY STICKING IN THE DARK!!!

- ➔ *only sensitive if sterie neutrinos mix with electrons*
- ➔ *even then, there is ZERO parameter space left which would still be allowed*

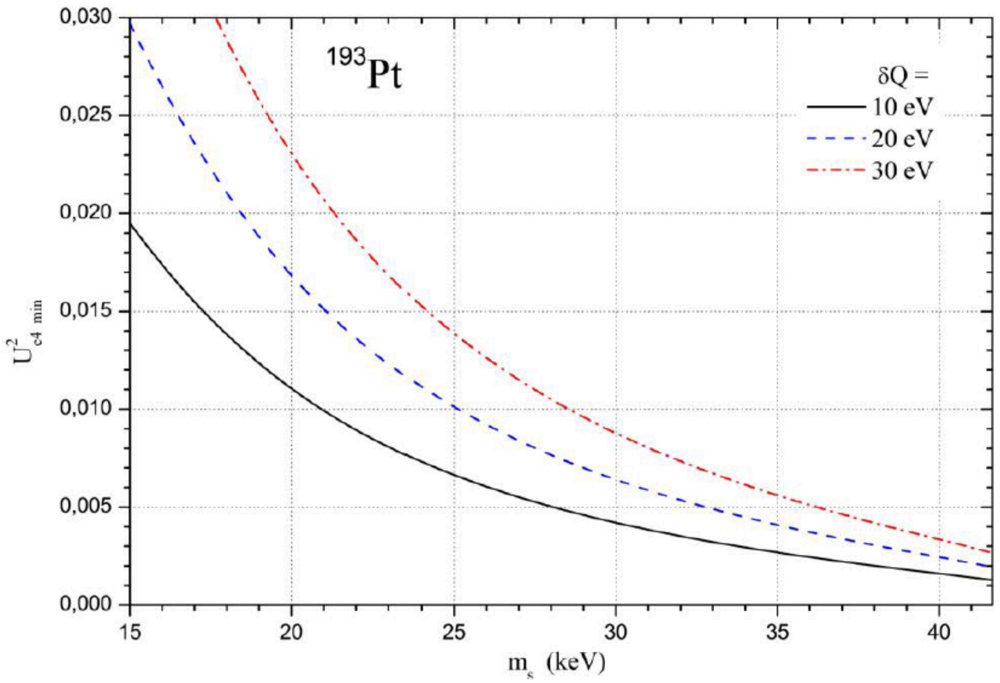



[AM, Totzauer]

# 8. BACK-UP: Terrestrial Experiments

**Other experiments unfortunately can't do any better....**

- **electron capture**: alternative process



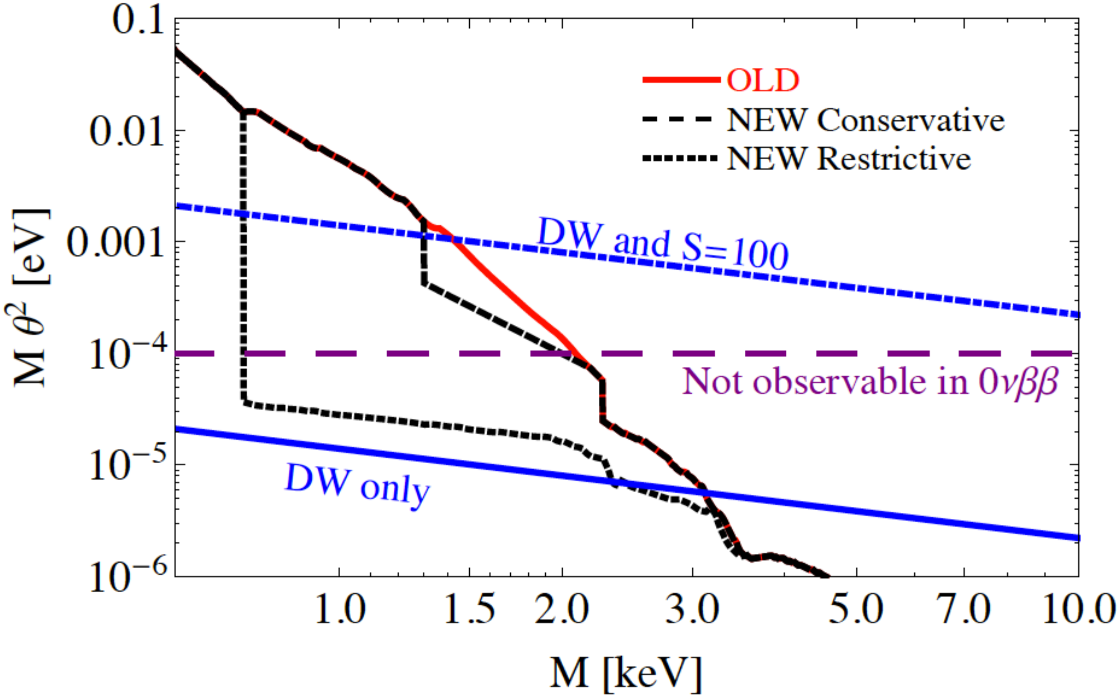

[Filianin *et al.*: 1402.4400]

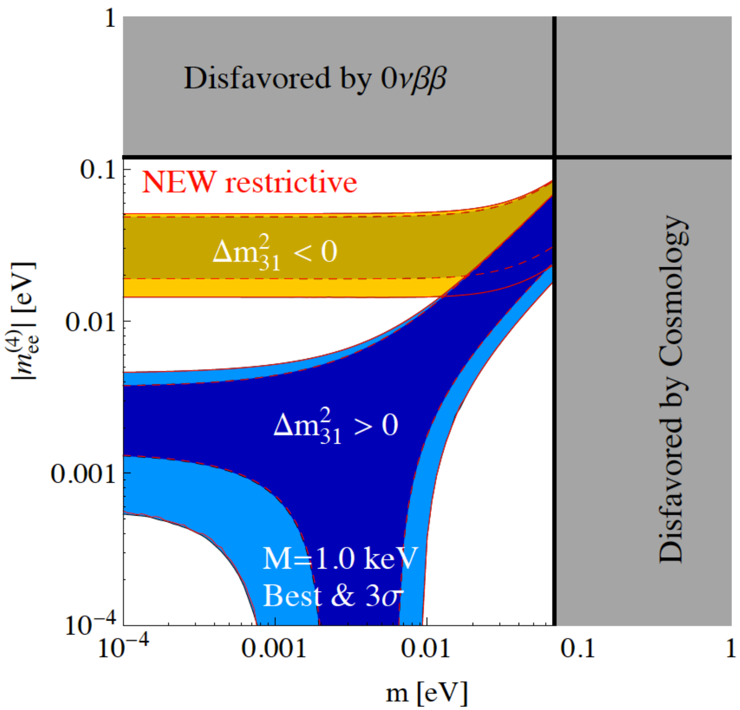
- ***combine techniques to go beyond rate measurements***
- ***e.g.: cryogenic micro-calorimetry → de-excitation spectrum (perturbed by $\nu_s$) & Penning traps → Q-value***
- ***other proposals: Holmes, ECHo, ...***

***→ complementary approach, but does it help?***

# 8. BACK-UP: Terrestrial Experiments

But many do not seem ideal for this...




[Bezrukov: Phys. Rev. **D72** (2005) 071303]

[Asaka *et al.*: JHEP **1104** (2011) 011]

[**AM**, Niro: Phys. Rev. **D88** (2013) 113004]

➔ ***essentially no effect due to strong X-ray bound*** ☹

# 8. BACK-UP: Model Building Aspects

# 8. BACK-UP: Model Building Aspects

## *Simple framework:* νMSM

[Asaka, Blanchet, Shaposhnikov: Phys. Lett. **B631** (2005) 151]

- **SM + 3 RH neutrinos** at (keV, GeV-ε, GeV+ε)

➔ can accommodate for ν-oscillations, BAU, and WDM

- provides fundamental connections between two clear signs for BSM physics: **neutrinos & Dark Matter**
- very **minimalistic extension of the SM**: only singlet (RH) neutrinos and lepton number violation
- *BUT:* **keV mass not explained**

  **GeV-degeneracy not explained**

  **$\nu$-mixing pattern not explained**

  **hardly testable**

➔ **MODEL BUILDING NEEDED!!!**

# 8. BACK-UP: Model Building Aspects

- ***<u>Differences to “ordinary“ model building</u>***:
  - we need an explanation for the keV scale:
    - not considered to be “fundamental“
    - need some mechanism

# 8. BACK-UP: Model Building Aspects

- ***Differences to "ordinary" model building***:
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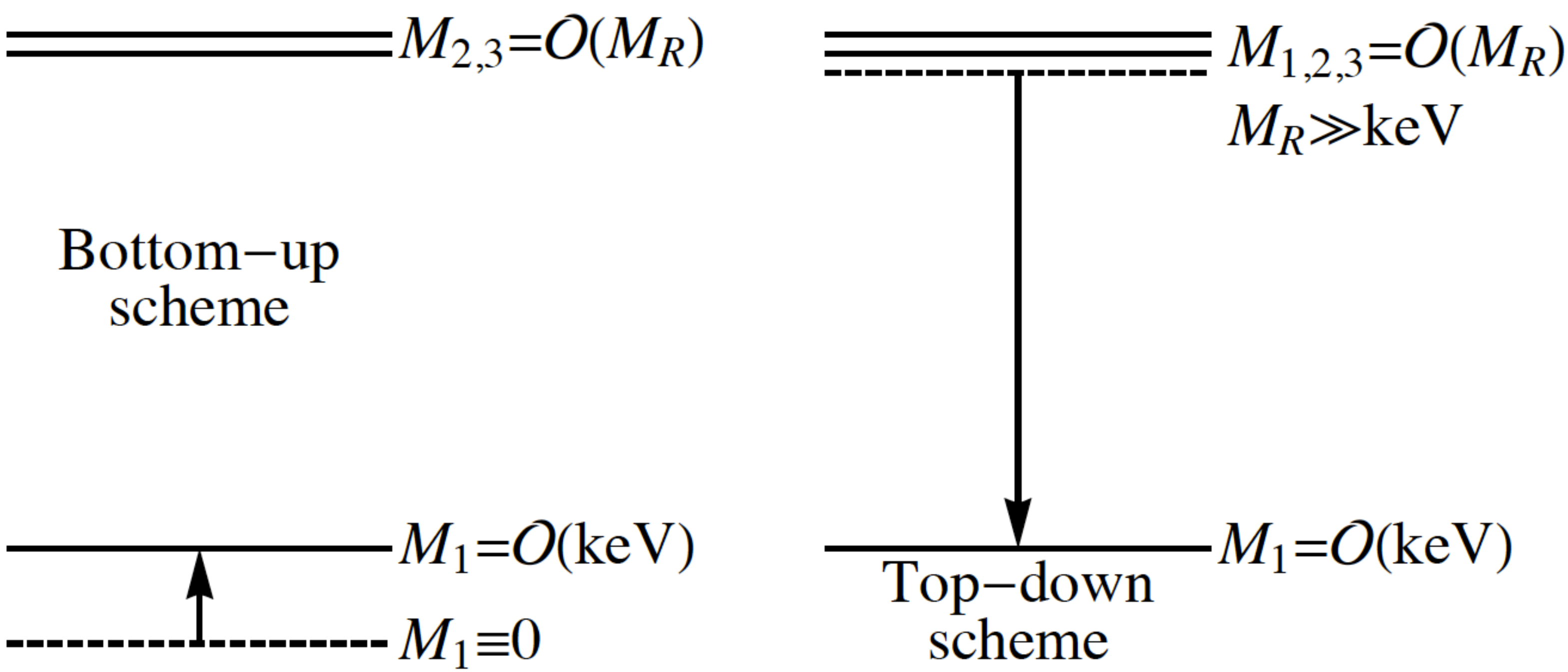
    - not considered to be "fundamental"
    - need some mechanism ➔ two generic schemes:




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

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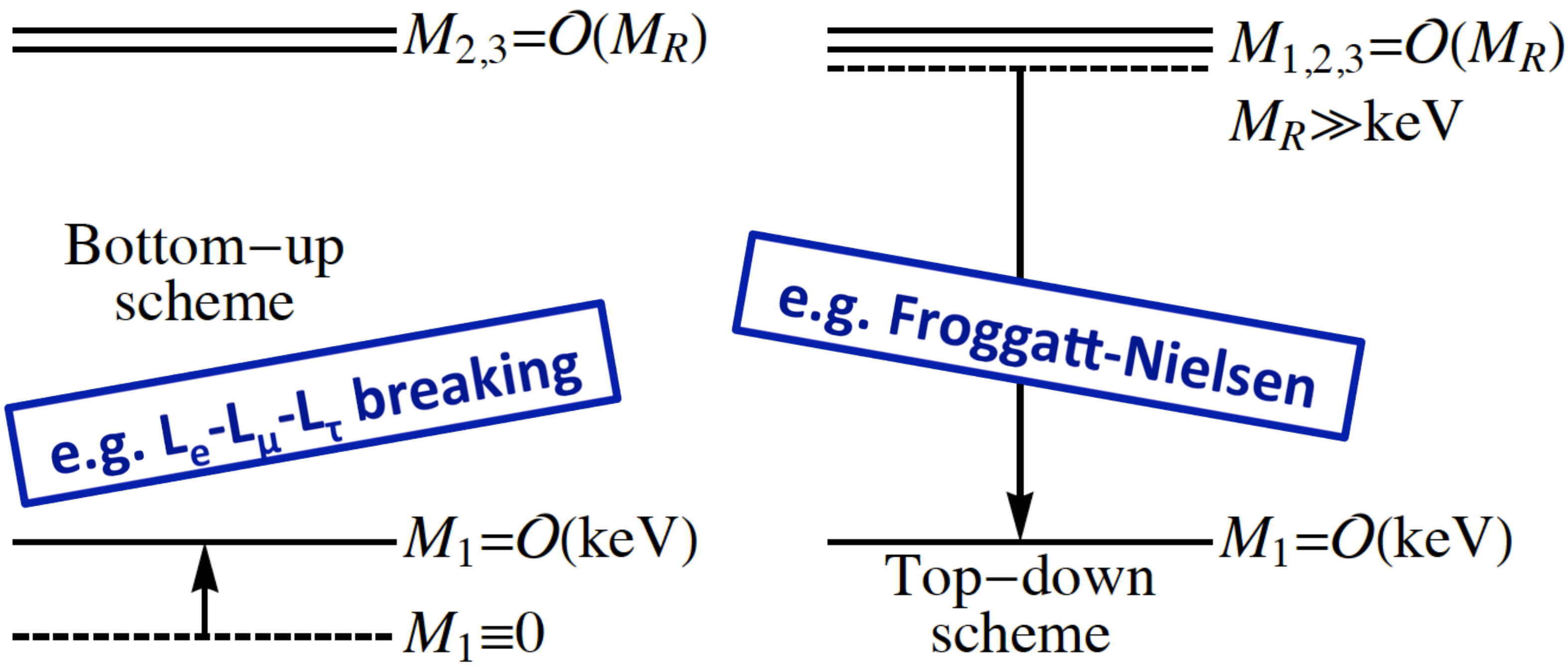


[AM: Int. J. Mod. Phys. **D22** (2013) 1330020]

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

# 8. BACK-UP: Model Building Aspects

Example

- Model based on a flavour symmetry: $\mathcal{F}=L_e-L_\mu-L_\tau$
  - original: [Petcov: Phys. Lett. **B110** (1982) 245]
  - 2 RH neutrinos: [Grimus, Lavoura: JHEP **0009** (2000) 007]
  - 3 RH neutrinos:

    [Barbieri, Hall, Tucker-Smith, Strumia, Weiner: JHEP **9812** (1998) 017]

    [Mohapatra: Phys. Rev. **D64** (2001) 091301]
  - *application to keV sterile neutrinos*:

    [Shaposhnikov: Nucl. Phys. **B763** (2007) 49]

    [Lindner, **AM**, Niro: JCAP **1101** (2011) 034]
  - general features:
    - ***symmetry*** → patterns: $(0,m,m)$ & $(0,M,M)$
    - ***broken*** → small mass, degeneracy lifted

# 8. BACK-UP: Model Building Aspects

Example

- Model based on a flavour symmetry: $\mathcal{F}$=$\mathbf{L_e}$-$\mathbf{L_\mu}$-$\mathbf{L_\tau}$
  - charge assignment under global U(1) [or: $Z_4$]:

| | $L_{eL}$ | $L_{\mu L}$ | $L_{\tau L}$ | $e_R$ | $\mu_R$ | $\tau_R$ | $N_{1R}$ | $N_{2R}$ | $N_{3R}$ | $\phi$ | $\Delta$ |
|---|---|---|---|---|---|---|---|---|---|---|---|
| $\mathcal{F}$ | $1$ | $-1$ | $-1$ | $1$ | $-1$ | $-1$ | $1$ | $-1$ | $-1$ | $0$ | $0$ |

  - then, only symmetry preserving terms are allowed:

$$\mathcal{L}_{\rm mass} = -\frac{1}{2}\overline{\Psi^C}\mathcal{M}_\nu\Psi + h.c.$$

with: $\Psi \equiv \left((\nu_{eL})^C, (\nu_{\mu L})^C, (\nu_{\tau L})^C, N_{1R}, N_{2R}, N_{3R}\right)^T$

➔ mass matrix:

$$\mathcal{M}_\nu = \left(\begin{array}{ccc|ccc} 0 & m_L^{e\mu} & m_L^{e\tau} & m_D^{e1} & 0 & 0 \\ m_L^{e\mu} & 0 & 0 & 0 & m_D^{\mu 2} & m_D^{\mu 3} \\ m_L^{e\tau} & 0 & 0 & 0 & m_D^{\tau 2} & m_D^{\tau 3} \\ \hline m_D^{e1} & 0 & 0 & 0 & M_R^{12} & M_R^{13} \\ 0 & m_D^{\mu 2} & m_D^{\tau 2} & M_R^{12} & 0 & 0 \\ 0 & m_D^{\mu 3} & m_D^{\tau 3} & M_R^{13} & 0 & 0 \end{array}\right)$$

# 8. BACK-UP: Model Building Aspects

Example

- Model based on a flavour symmetry: $\mathcal{F}$=**L$_e$-L$_\mu$-L$_\tau$**
  - eigenvalues of $\mathcal{M}_\nu$ (***with μ-τ symmetry!!***):
    - light neutrinos: $(\lambda_+,\lambda_-,0)$
    - heavy neutrinos: $(\Lambda_+,\Lambda_-,0)$
    - with: $\lambda_\pm = \pm\sqrt{2}\left[m_L - \frac{m_D^2}{M_R}\right]$ $\Lambda_\pm = \pm\sqrt{2}M_R$
  - mass patterns:
    - light ν's: $(0,\lambda_+,\lambda_-)$ ➔ okay up to degeneracy
    - heavy N's: $(0,\Lambda_+,\Lambda_-)$ ➔ 0 << *M*, but still 0≠keV
  - WAY OUT: **broken symmetry**
    - ➔ will remedy the above issues
    - ➔ important: no matter how the breaking is achieved, the results will always look similar

# 8. BACK-UP: Model Building Aspects

Example

- Model based on a flavour symmetry: $\mathcal{F}$=**L$_e$-L$_\mu$-L$_\tau$**
  - pragmatic: *soft breaking* [Lindner, **AM**, Niro: JCAP **1101** (2011) 034]
  - we assumed ***small*** breaking terms and worked out their consequences:

  ➔ new mass matrix:

$$\left(\begin{array}{ccc|ccc} s_L^{ee} & m_L^{e\mu} & m_L^{e\tau} & m_D^{e1} & 0 & 0 \\ m_L^{e\mu} & s_L^{\mu\mu} & 0 & 0 & m_D^{\mu 2} & m_D^{\mu 3} \\ m_L^{e\tau} & 0 & s_L^{\tau\tau} & 0 & m_D^{\tau 2} & m_D^{\tau 3} \\ \hline m_D^{e1} & 0 & 0 & S_R^{11} & M_R^{12} & M_R^{13} \\ 0 & m_D^{\mu 2} & m_D^{\tau 2} & M_R^{12} & S_R^{22} & 0 \\ 0 & m_D^{\mu 3} & m_D^{\tau 3} & M_R^{13} & 0 & S_R^{33} \end{array}\right)$$

  ➔ new eigenvalues: $\Lambda_s = S \quad \Lambda'_\pm = S \pm \sqrt{2} M_R$

$$\lambda_s = s \qquad \lambda'_\pm = s \pm \sqrt{2}\left[m_L - \frac{m_D^2}{M_R}\right] + \frac{5 m_D^2 S}{4 M_R^2}$$

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**natural assumption: like p-n isospin symmetry**

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**keV neutrino**

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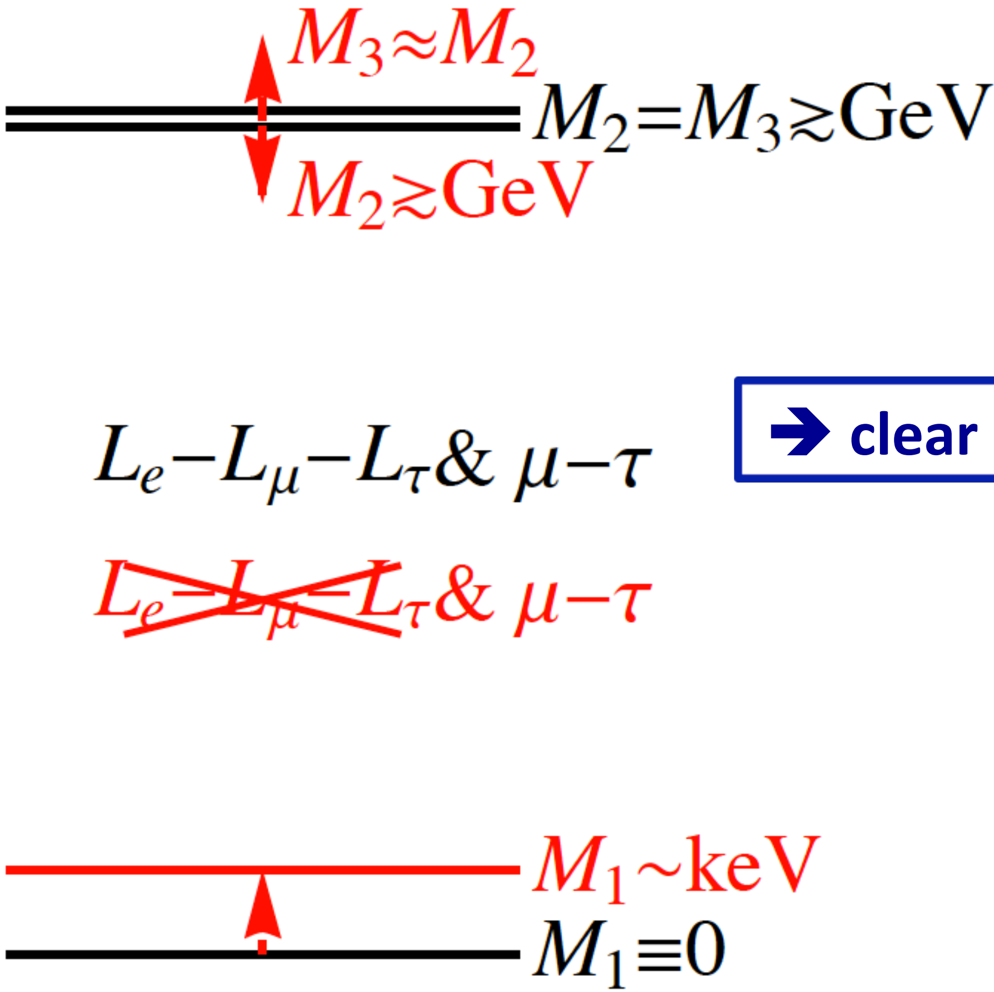
$$\lambda_s = s \qquad \lambda'_\pm = s \pm \sqrt{2}\left[m_L - \ldots\right] \ldots \frac{\ldots S}{\ldots M_R^2}$$

**small splitting**

# 8. BACK-UP: Model Building Aspects

Example

- Model based on a flavour symmetry: $\mathcal{F}$=$L_e$-$L_\mu$-$L_\tau$
  - mass shifting scheme:




➔ **clear bottom-up type scheme**

# 8. BACK-UP: Model Building Aspects

Example

- Model based on a flavour symmetry: $\mathcal{F}$=$L_e$-$L_\mu$-$L_\tau$
  - mixings also require soft breaking:

$$\mathcal{M}_l \mathcal{M}_l^\dagger \simeq \begin{pmatrix} m_e^2 + m_\mu^2 \lambda^2 & m_\mu^2 \lambda & 0 \\ m_\mu^2 \lambda & m_\mu^2 & 0 \\ 0 & 0 & m_\tau^2 \end{pmatrix}$$

$$\tan^2\theta_{12} \simeq 1 - 2\sqrt{2}\lambda + 4\lambda^4 - 2\sqrt{2}\lambda^3 \quad \rightarrow \quad \theta_{12} \simeq 33.4^\circ$$

$$|U_{e3}| \simeq \frac{\lambda}{\sqrt{2}} \quad \rightarrow \quad \theta_{13} \simeq 8^\circ\,,$$

$$\sin^2 2\theta_{23} \simeq 1 - 4\lambda^4 \quad \rightarrow \quad \theta_{23} \simeq 45^\circ\,.$$

$\lambda=\theta_{12}-\pi/4$

- prediction for the masses (under assumptions):

$$|m_1| = 0.0486 \text{ eV}, \; |m_2| = 0.0494 \text{ eV}, \text{ and } |m_3| = 0.0004 \text{ eV}$$

# *The Dodelson-Widrow mechanism*

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

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

[**AM**, Schneider, Totzauer: 1511.XXXXX]

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***- 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:***

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

**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!!!**

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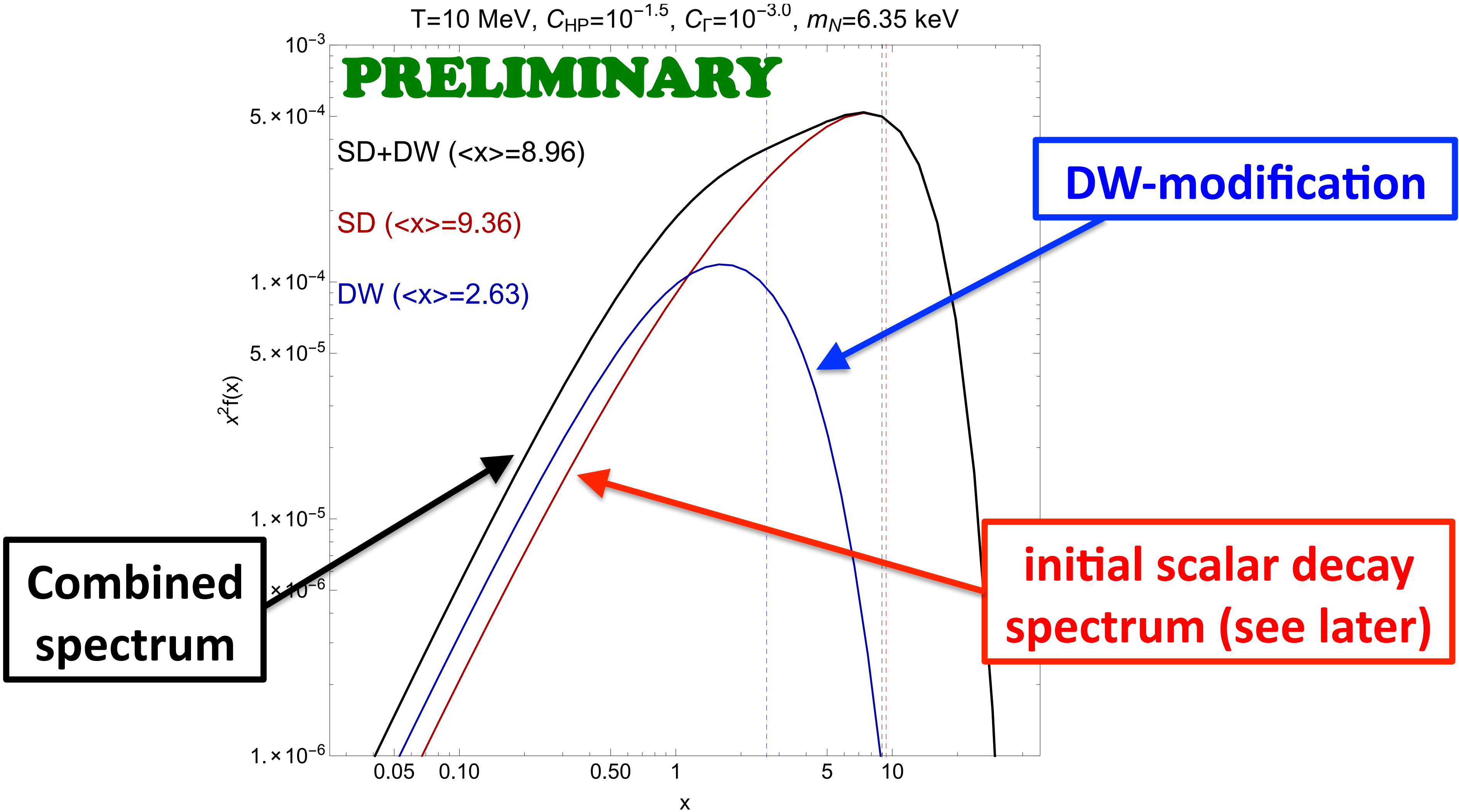
**DW always produces a too hot spectrum**

***- 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***

# The Dodelson-Widrow mechanism

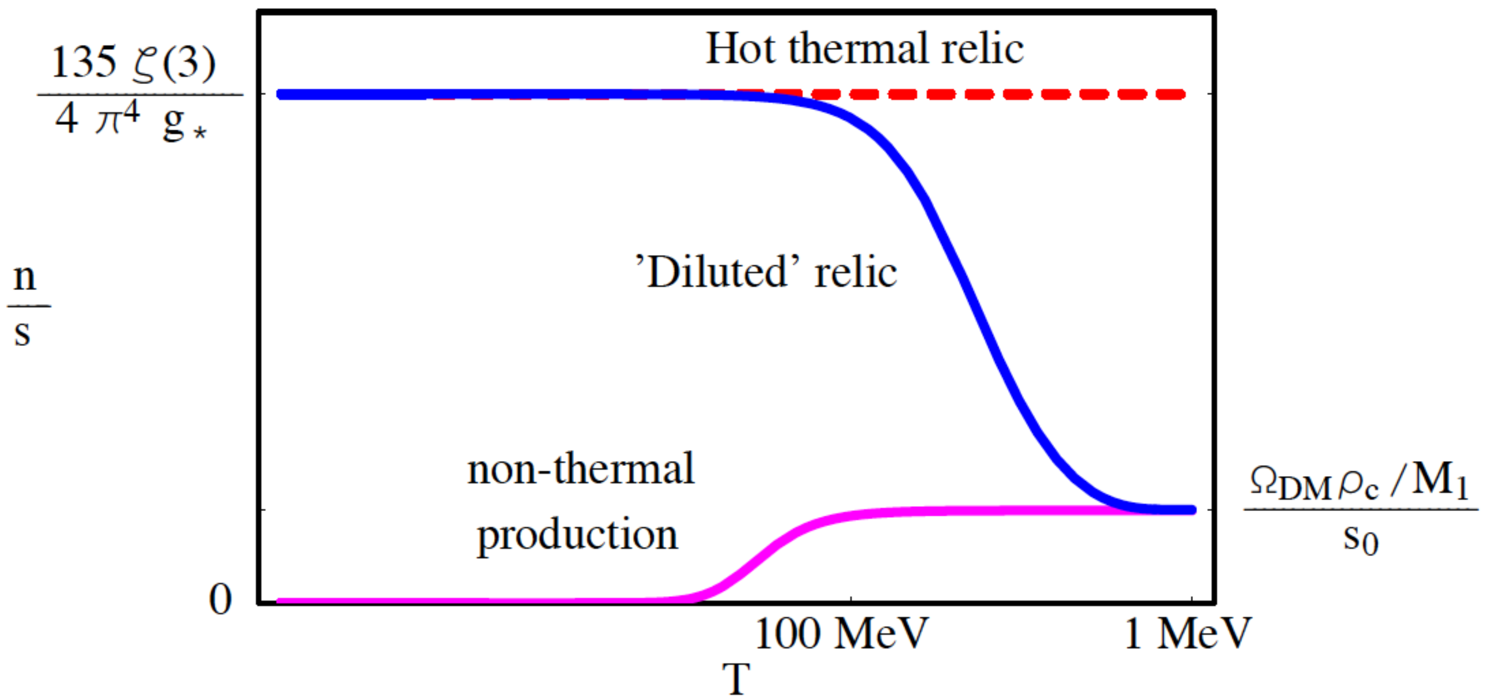



*may shift the average momentum to LOWER values ("DW-cooling")*

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

# Diluted Thermal Production

- *Beyond the SM*: **sterile neutrino may be charged or have other interactions sufficiently stron to equilibrate it**
  ➔ ***overproduction unless diluted by entropy production***

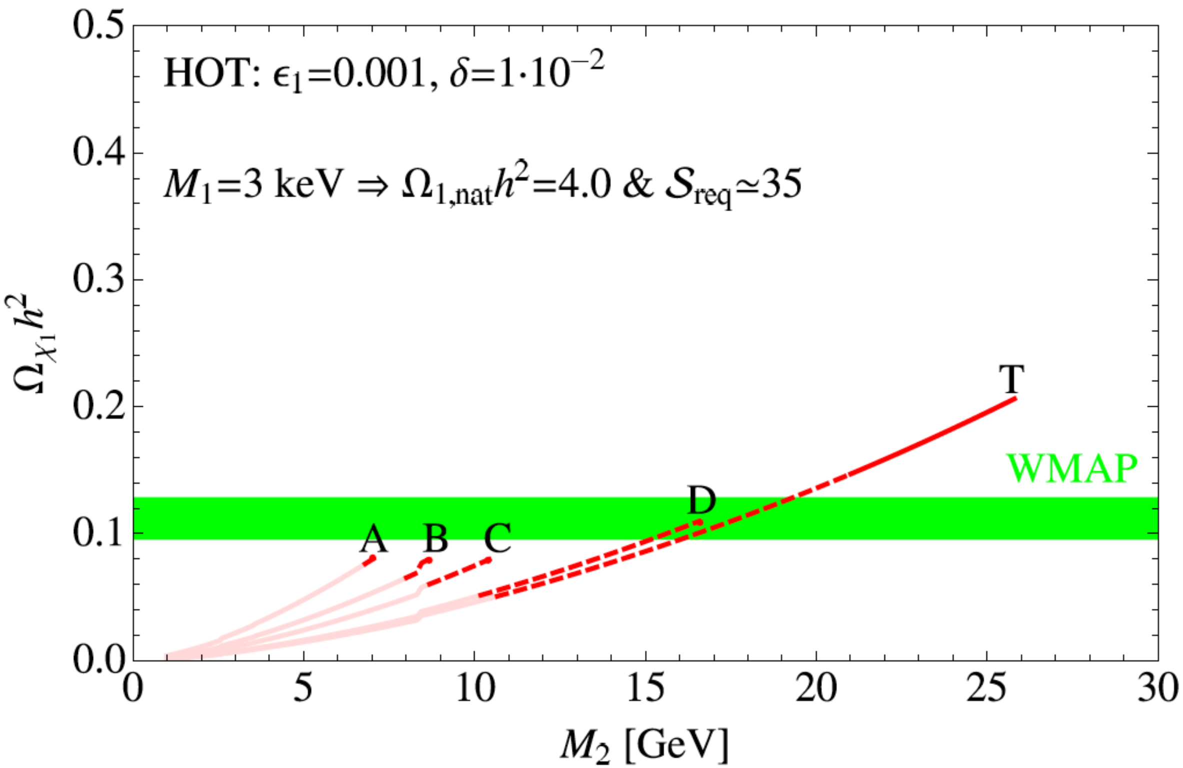



[Bezrukov, Hettmansperger, Lindner: Phys. Rev. **D81** (2010) 085032]
[King, **AM**: JCAP **1208** (2012) 016]
[Nemevsek, Senjanovic, Zhang: JCAP **1207** (2012) 006]

# Diluted Thermal Production

- ***requirement 1***: **the diluter has to decay slowly enough to maximise entropy production**
- ***requirement 2***: **the diluter has to decay fast enough not to disturb big bang nucleosynthesis**

➔ ***hardly any viable parameter space left*** ☹




[King, **AM**:
JCAP **1208** (2012) 016]