keV Sterile Neutrino 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, JCAP 1604 (2016) 003, 1602.04816 [hep-ph], 1609.01289[hep-ph], 1609.04671 [hep-ex], ...

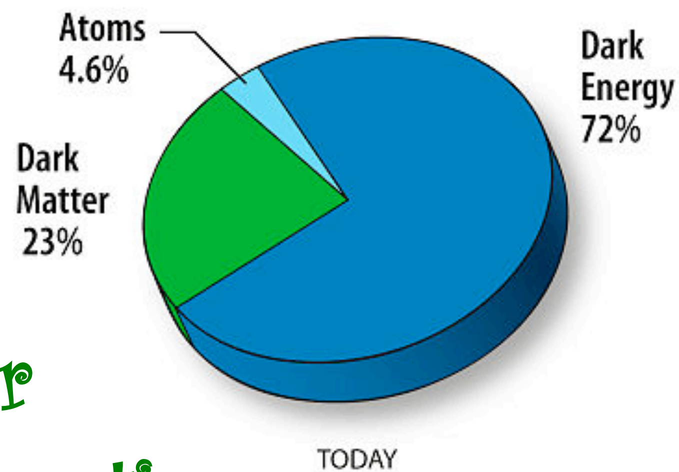
DESY Theory Workshop 2016, Hamburg, 28-09-2016

1. Introduction

What do we actually know about Dark Matter?!?

KNOWN ☺

- abundance
- rough distribution
- important for structure formation



UNKNOWN ☹

- identity
- production mechanism
- exact velocity spectrum

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

1. Introduction

*A **sterile neutrino** is a well-motivated alternative and **TESTABLE** 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**

X-ray photon

Smoking gun: $N_1 \longrightarrow \nu + \boxed{\gamma}$ **(detection claimed but disputed)**

2. 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** $T \ll m$

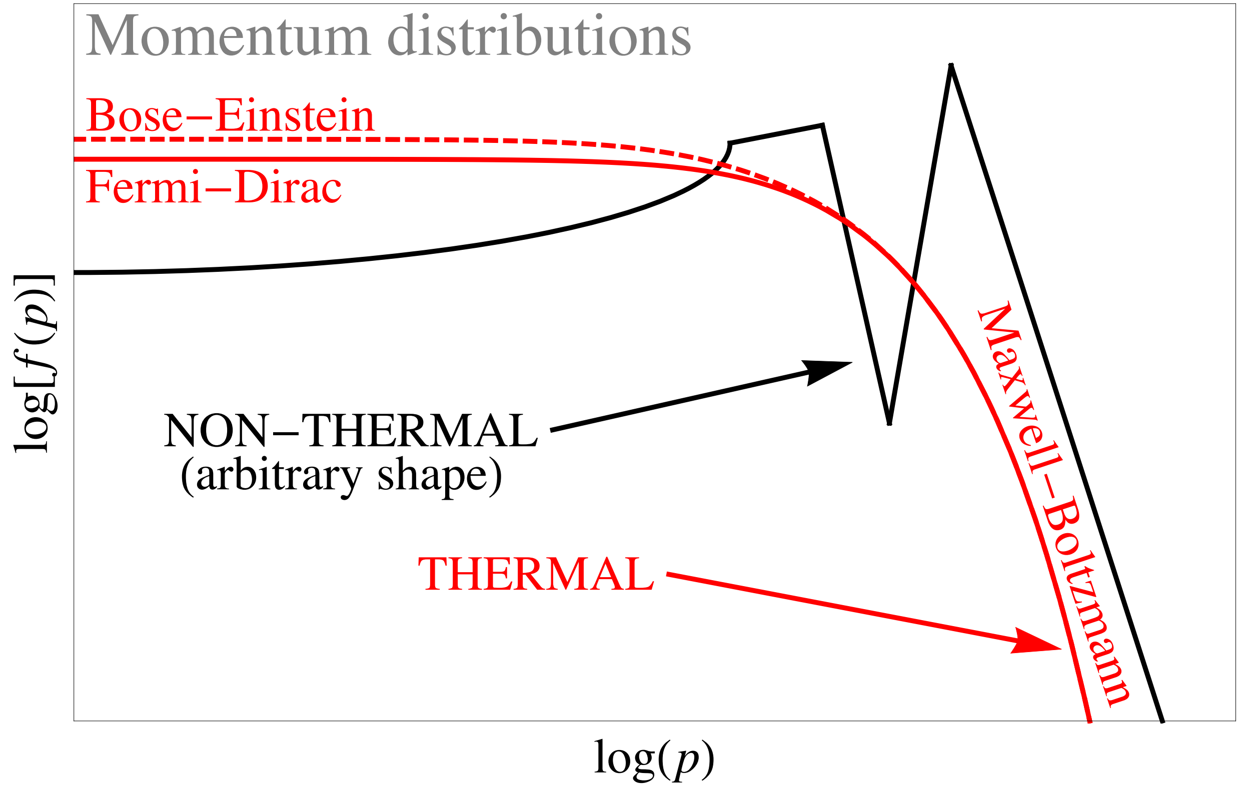
NON-THERMAL

$f(p)$ arbitrary

with:

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

T not defined**!!!**



2. Non-thermal production mechanisms

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

2. Non-thermal production mechanisms

4 main mechanisms for sterile neutrinos:

Non-resonant transitions

First: Langacker

DM: Dodelson & Wi

<u>Idea</u>: active-sterile n

gradually prod

✖ EXCLUDED

STRUCTURE FORMATION

✖ THREATENED

Resonant transitions

uist, Kainulainen

Fuller, Abazajian,

oshnikov, Laine, ...

W"-enhancement

of active-sterile transitions

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

ν_s-DM: Bezrukov, Lindner,

Nemevsel **AM**,...

<u>Idea</u>: proc to

dilute the

abundance

BBN

✖ PUSHED

2. Non-thermal production mechanisms

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...,

...

...ons

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

3. Decay production

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

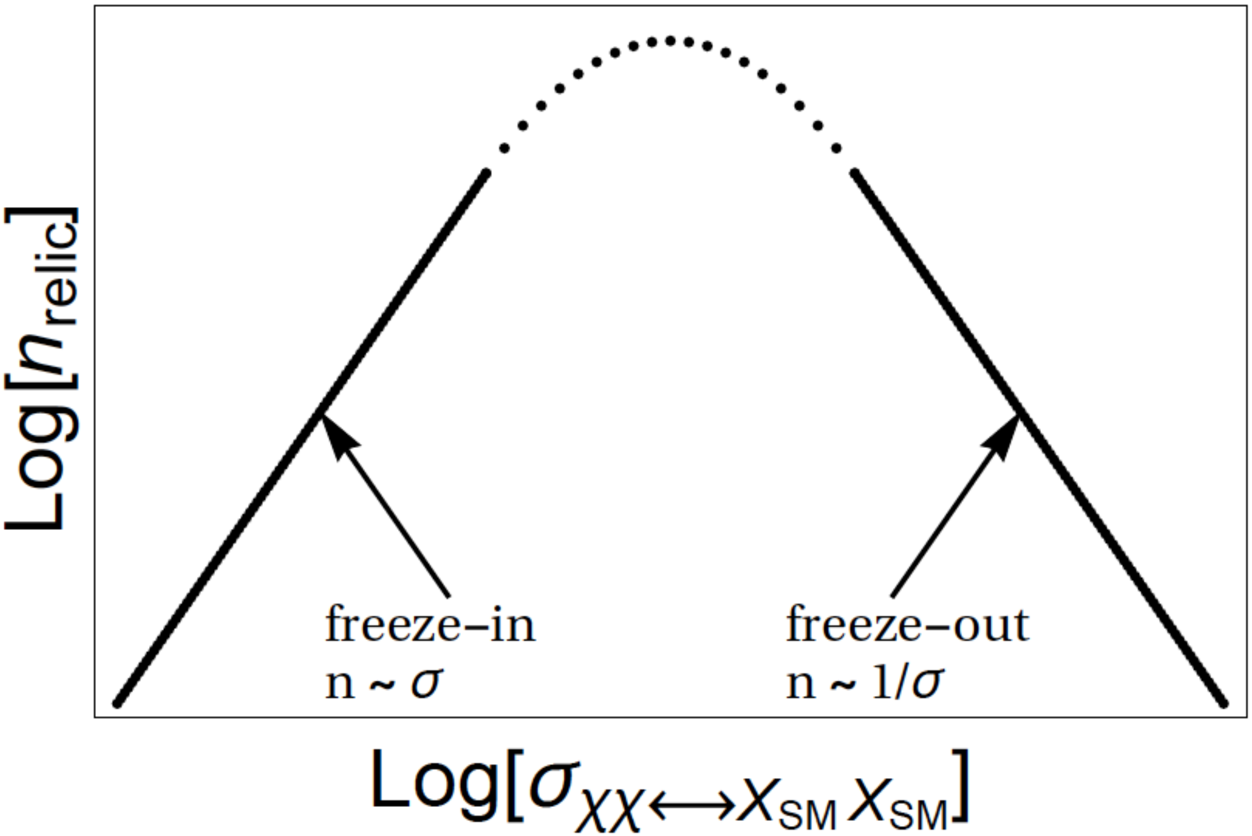
- **decaying inflaton**
  [Asaka *et al.*: Phys. Lett. **B638** (2006) 401]
  [Anisimov *et al.*: Phys. Lett. **B671** (2009) 211]
  [Bezrukov, Gorbunov: JHEP **1005** (2010) 010]
- **singlet scalar that freezes out**
  [Kusenko: Phys. Rev. Lett. **97** (2006) 241301; Kusenko, Petraki: Phys. Rev. **D77** (2008) 065014]
  [Frigerio, Yaguna: Eur. Phys. J. **C75** (2015), 1]
  [**AM**, Schneider: Phys. Lett. **B749** (2015) 283; **AM**, Totzauer: JCAP **1506** (2015) 011]
- **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: 1609.01289]
  [Klasen, Yaguna: JCAP 1311 (2013) 039]
- **other particle that decays**
  [Lello, Boyanovsky: Phys. Rev. **D91** (2015) 063502]
  [Lello, Boyanovsky: 1508.04077]

3. 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



→ momentum distribution of the scalar translates into that of sterile neutrinos

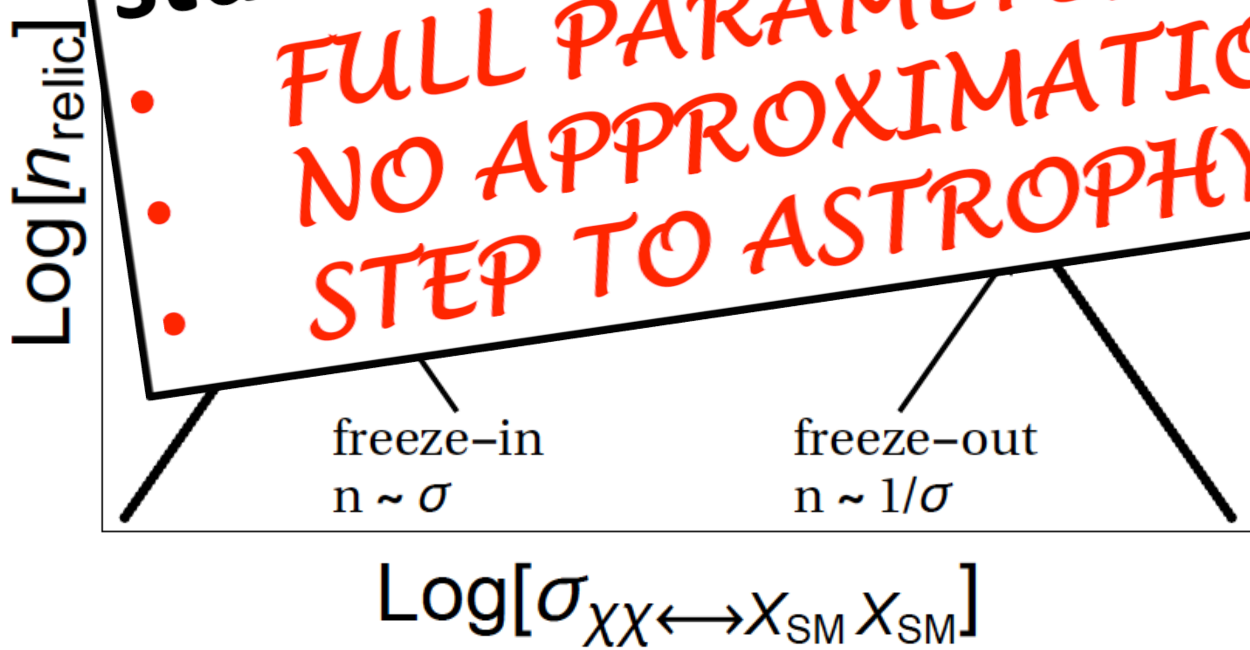
3. Decay production

• **SINGLET SCALAR "S" FREEZES IN OR OUT ... Y**

[Kusenko: Phys. Rev. Lett. **97** (2006) ... 4]
[**AM**, Niro, S...

NEW in 1609.01289, with Ph.D. student Max Totzauer and M.Sc. student Johannes König:

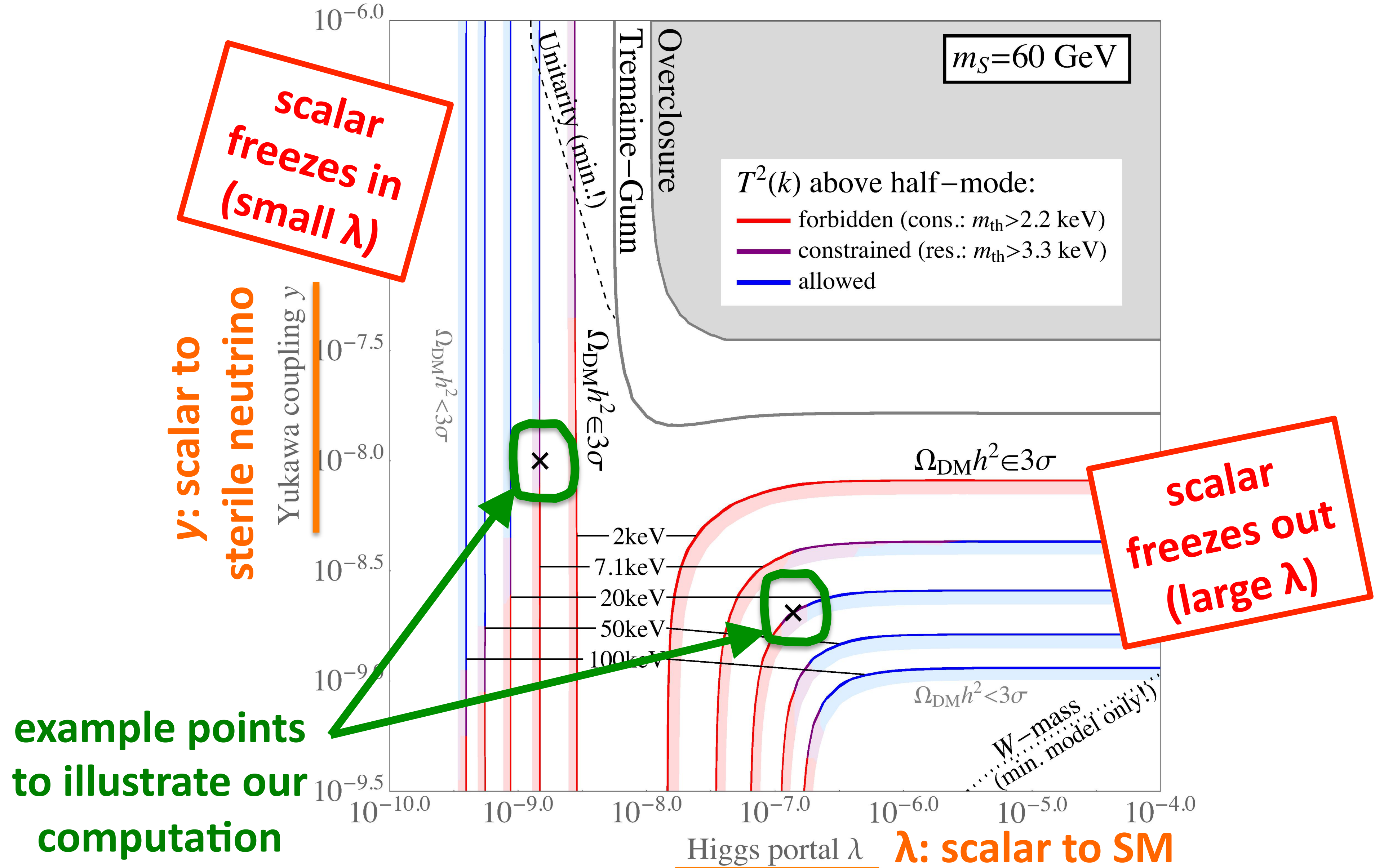
- FULL PARAMETER SPACE
- NO APPROXIMATIONS
- STEP TO ASTROPHYSICS MADE



...ates into that of sterile neutrinos

3. Decay production

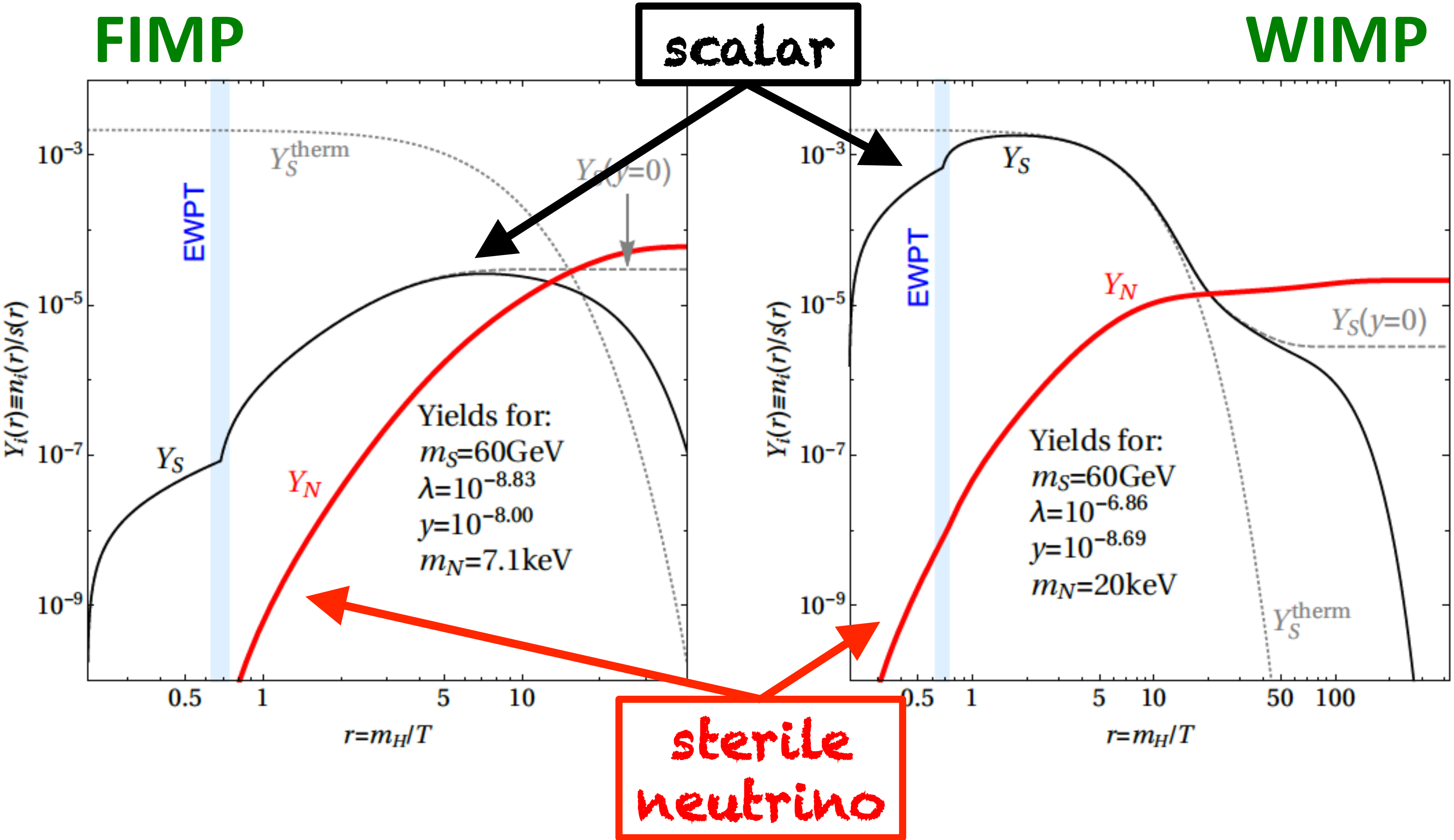
[König, **AM**, Totzauer: 1609.01289]



3. Decay production

[König, **AM**, Totzauer: 1609.01289]

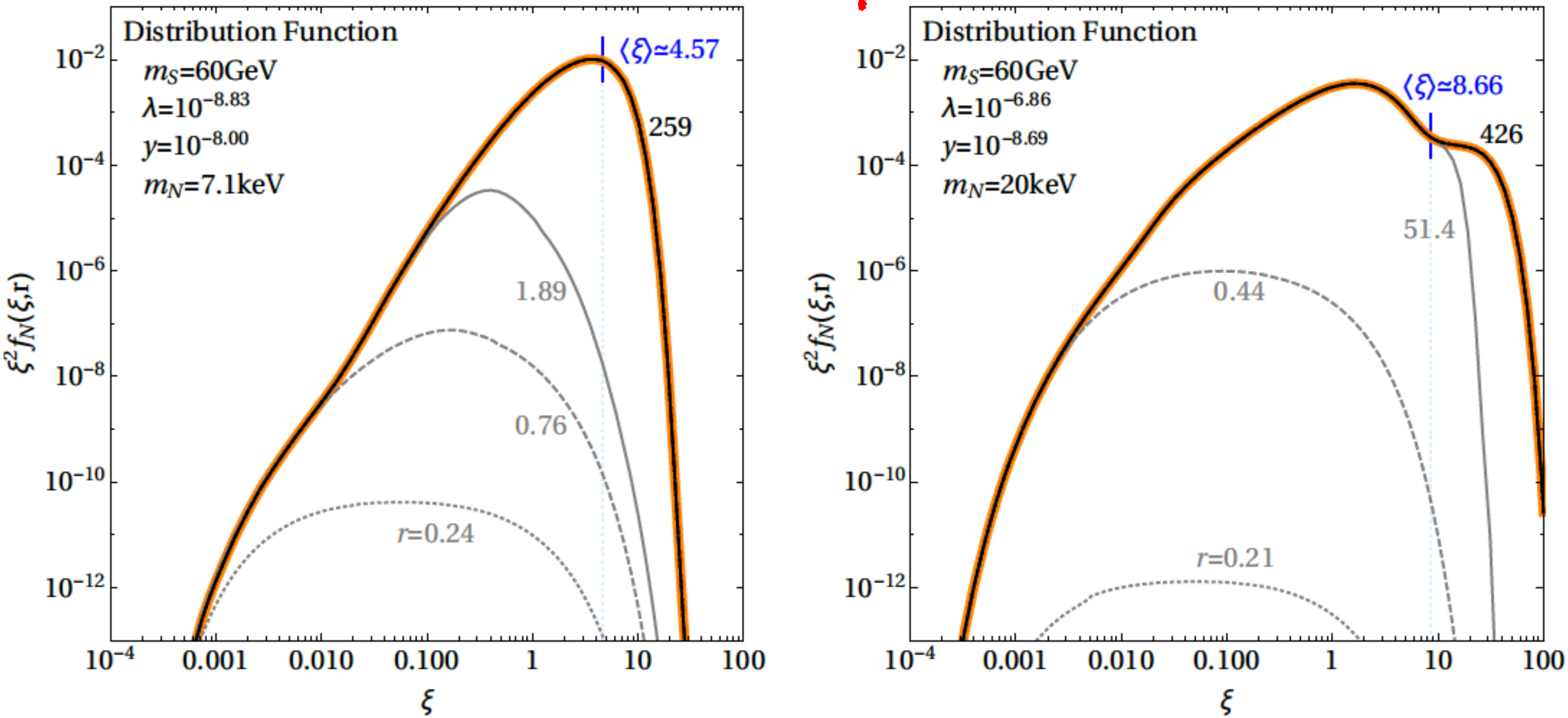
Example: Abundance/Yield by 2-step process



3. Decay production

[König, **AM**, Totzauer: 1609.01289]

Distribution functions computed for each case:



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

ξ = momentum variable that includes redshift

3. Decay production

[König, **AM**, Totzauer: 1609.01289]

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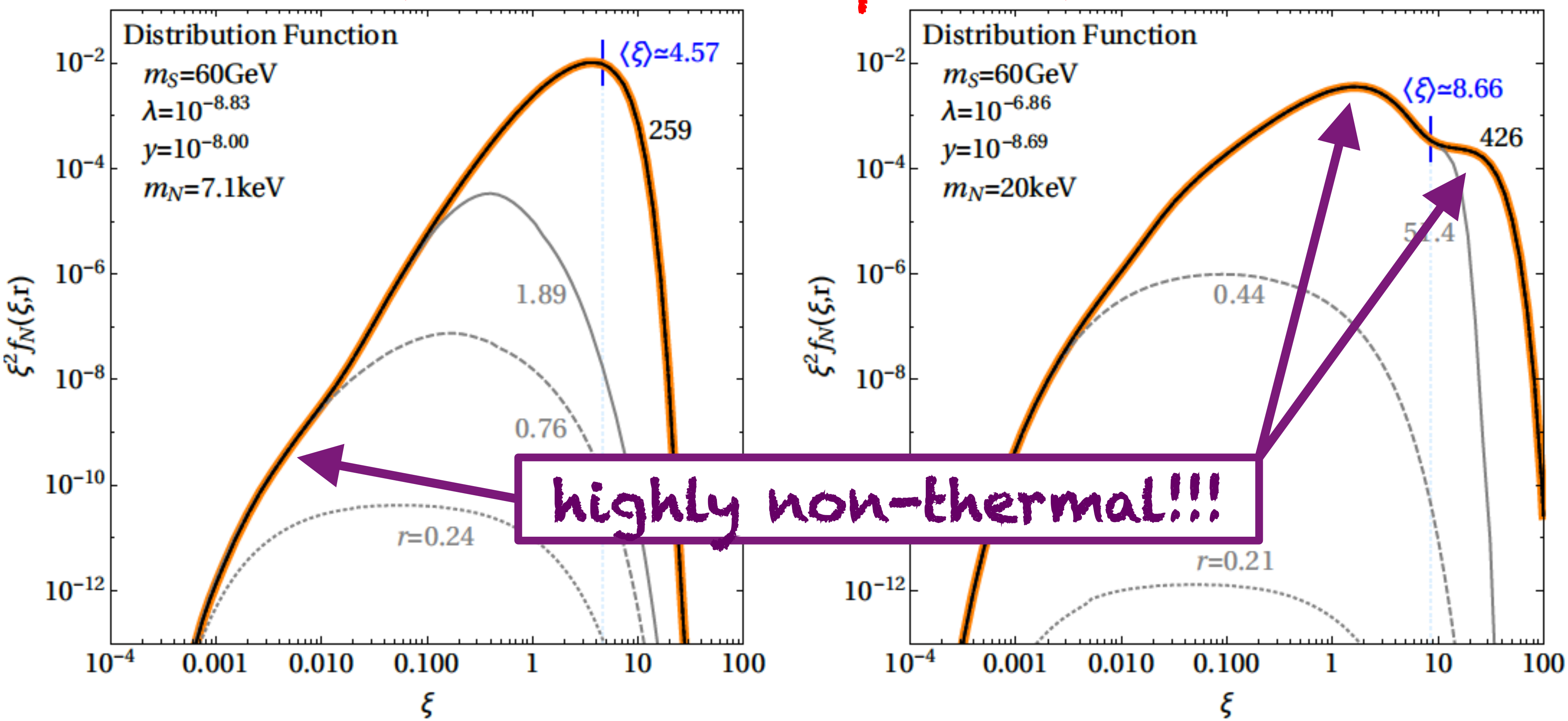

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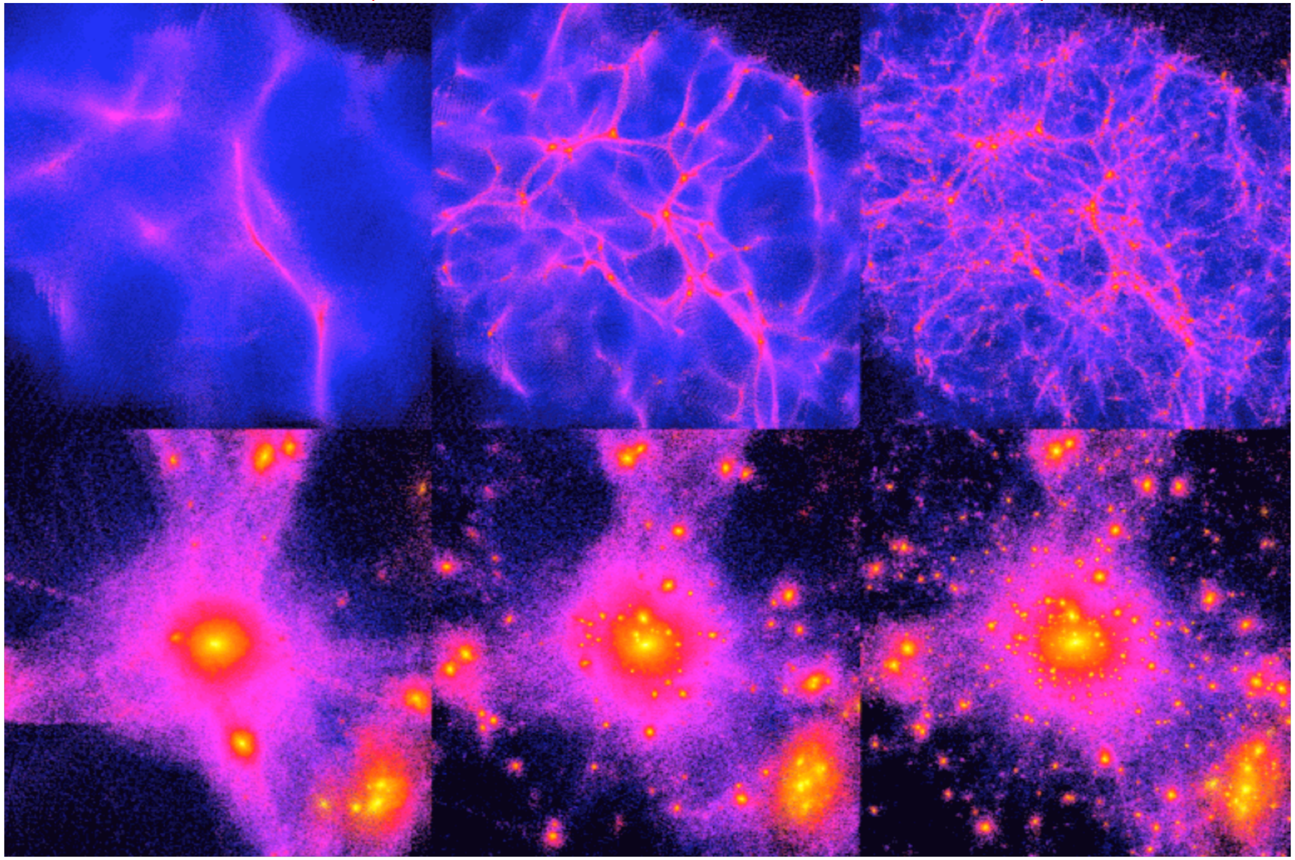
ξ = momentum variable that includes redshift

3. Decay production

Apply bounds from structure formation!!!



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

HOT WARM COLD

We exploit the explicit non-thermal spectra to compute the transfer functions!!!

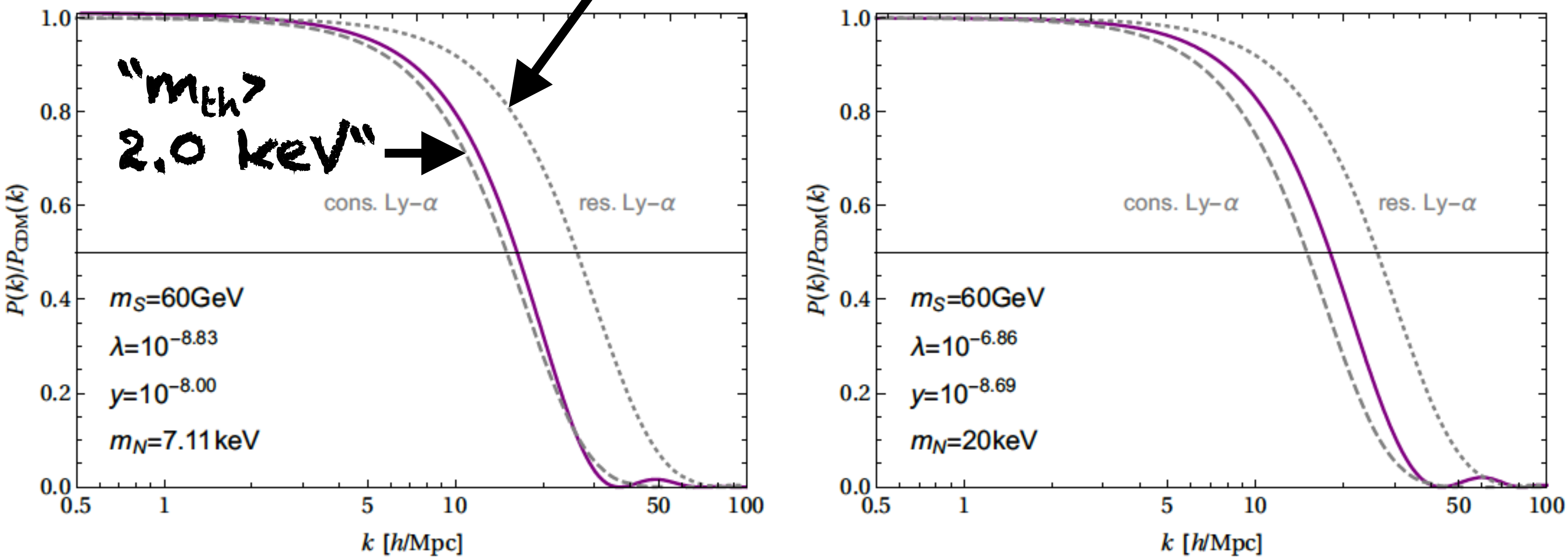
3. Decay production

[König, **AM**, Totzauer: 1609.01289]

Example: Structure formation/Ly-alpha data

FIMP **WIMP**

"m_{th}>3.3 keV"



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

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

3. Decay production

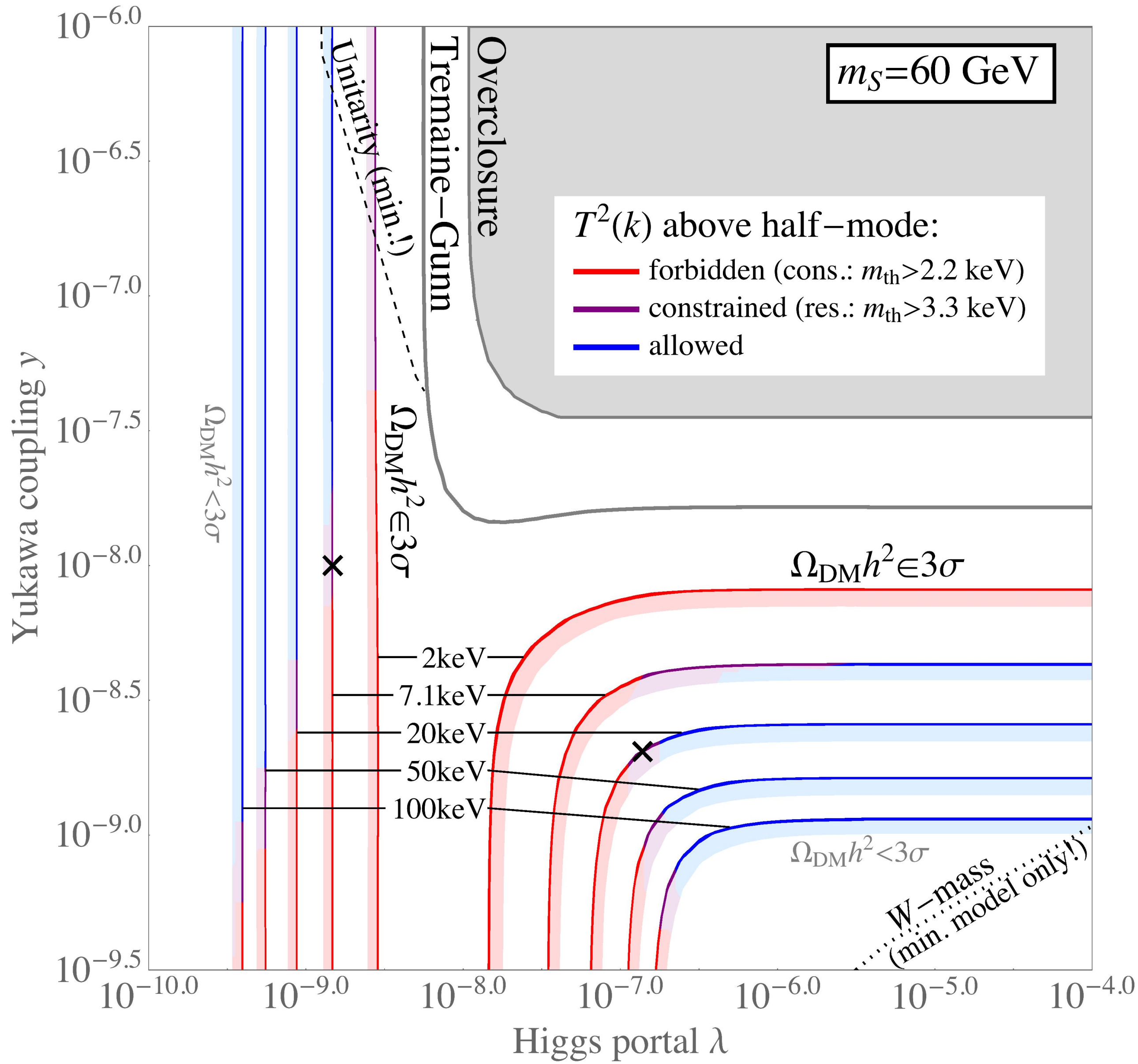
[König, **AM**, Totzauer: 1609.01289]

***Allowed regions from Ly-α data*:**

Coservative ✖
Restrictive ✖

Coservative ✓
Restrictive ✖

Coservative ✓
Restrictive ✓



4. Wrap-up

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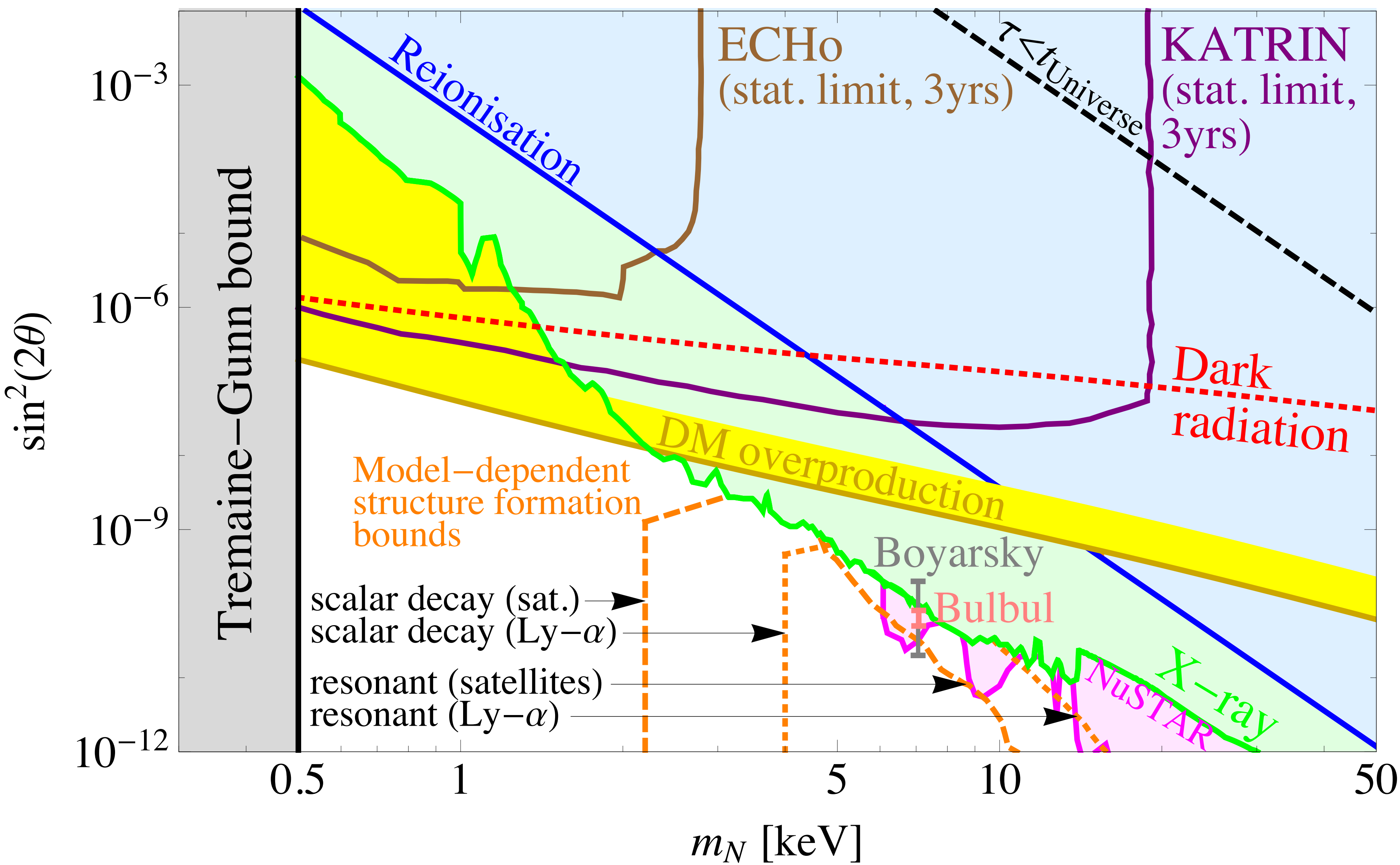
Summary of all constraints (from keV-WP):



4. Wrap-up

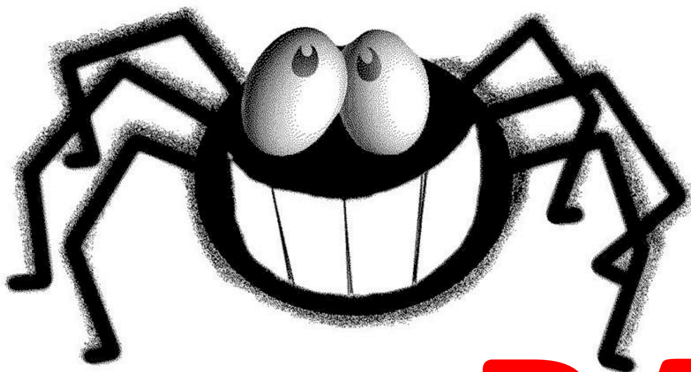
- **sterile neutrino DM: works, and we are in fact closing in on possible production mechanisms**

- **technical challenges: build bridges to our astro-friends, to truly confront models with data**

- **experiments & observations: challenging on the ground (although new ideas are around!!!), but in any case good for X-ray astronomy**

THANK YOU!!!

(much more material in the back-up slides)



[www.bobinoz.com/blog/17893/dont-let-fear-of-spiders-stop-you-from-moving-to-australia]

BACK-UP SLIDES

[www.hoax-slayer.com/beanie-baby-spider-eggs-hatching.shtml]

A White Paper on keV Sterile Neutrino Dark Matter

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

Authors: R. Adhikari[61] M. Agostini[84] N. Anh Ky[39,73] T. Araki[57]
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P.S. Bhupal Dev[31] D. Borah[35] A. Boyarsky[45] A. de Gouvea[62]
C.A. de S. Pires[37] H.J. de Vega[†9] A.G. Dias[36] P. Di Bari[32]
Z. Djurcic[21] K. Dolde[7] H. Dorrer[81] M. Durero[3] O. Dragoun[71]
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A. Fleischmann[50] J.A. Formaggio[20] J. Franse[16] ...
C.S. Frenk[63] G. Fuller[75] L. Gastaldo[50] A. ...
F. Glück[7,66] M.C. Goodman[21] M.C. ...
D. Gorbunov[65,72] J. Hamann[40] ...
J. Heeck[11] S.H. Hansen... ... Houdy[2,4]
A. Huber[7] D. Iak... ... R. Jacobsson[87]
T. Jeltema[76] ... Korzeczek[7,2]
V. Kornouk... ... M. Laine[74] P. Langacker[66,67]
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N.E. Mavroma...os[44] N. Menci[58] A. Merle[5] S. Mertens[6,7]

It's out!!! (and close to acceptance)

A White Paper on keV Sterile Neutrino Dark Matter

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

T. Lasserre
parallel yesterday

A. Merle
THIS TALK

...dhikari[61] M. Agostini[84] N. An... ...raki[57]
... M. Bahr[70] J. Behren...
P.S. ... D. Borah[35] A. Boyar... ...ouvea[62]
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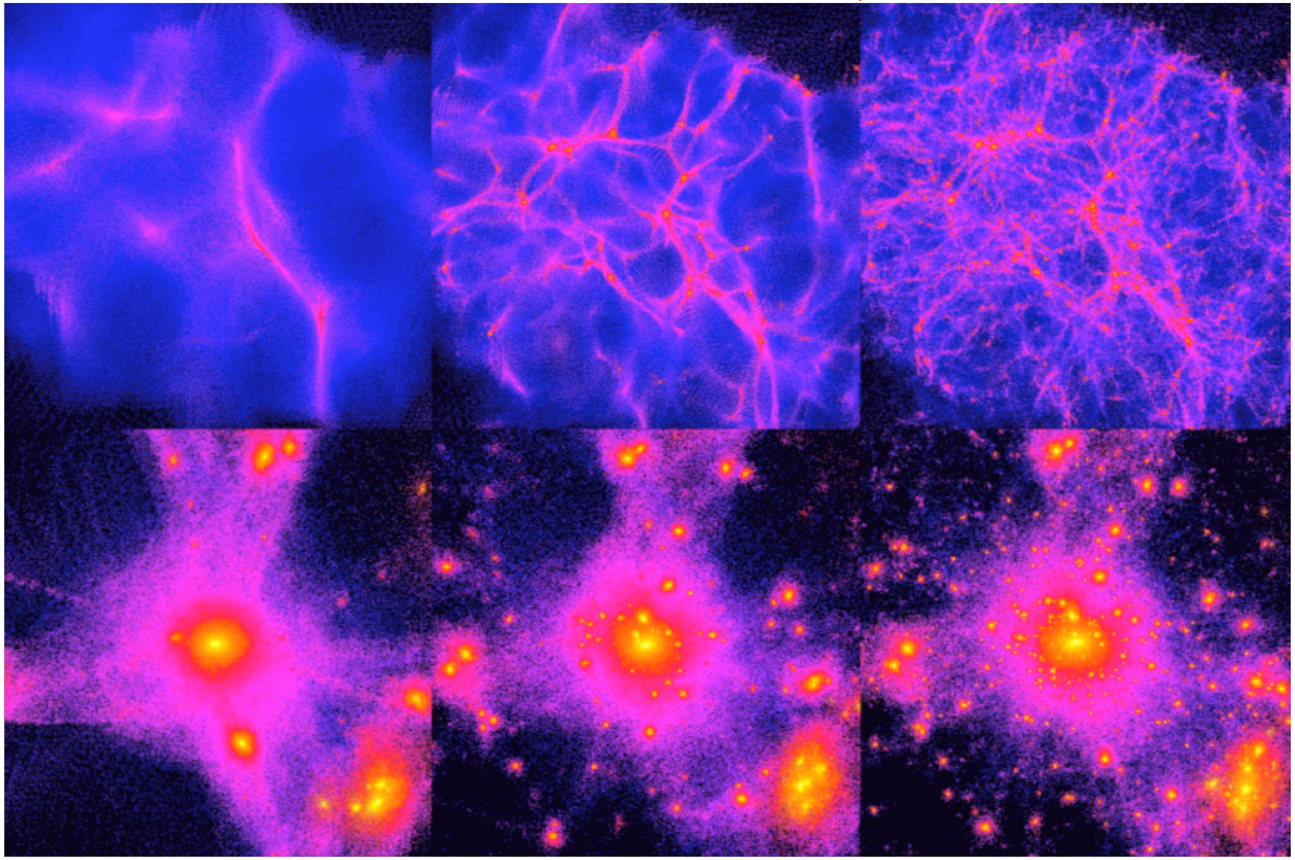
A. Schneider:
parallel today

It's out!!! (and close to acceptance)

3. Non-thermal production mechanisms

But what about structure formation?!?



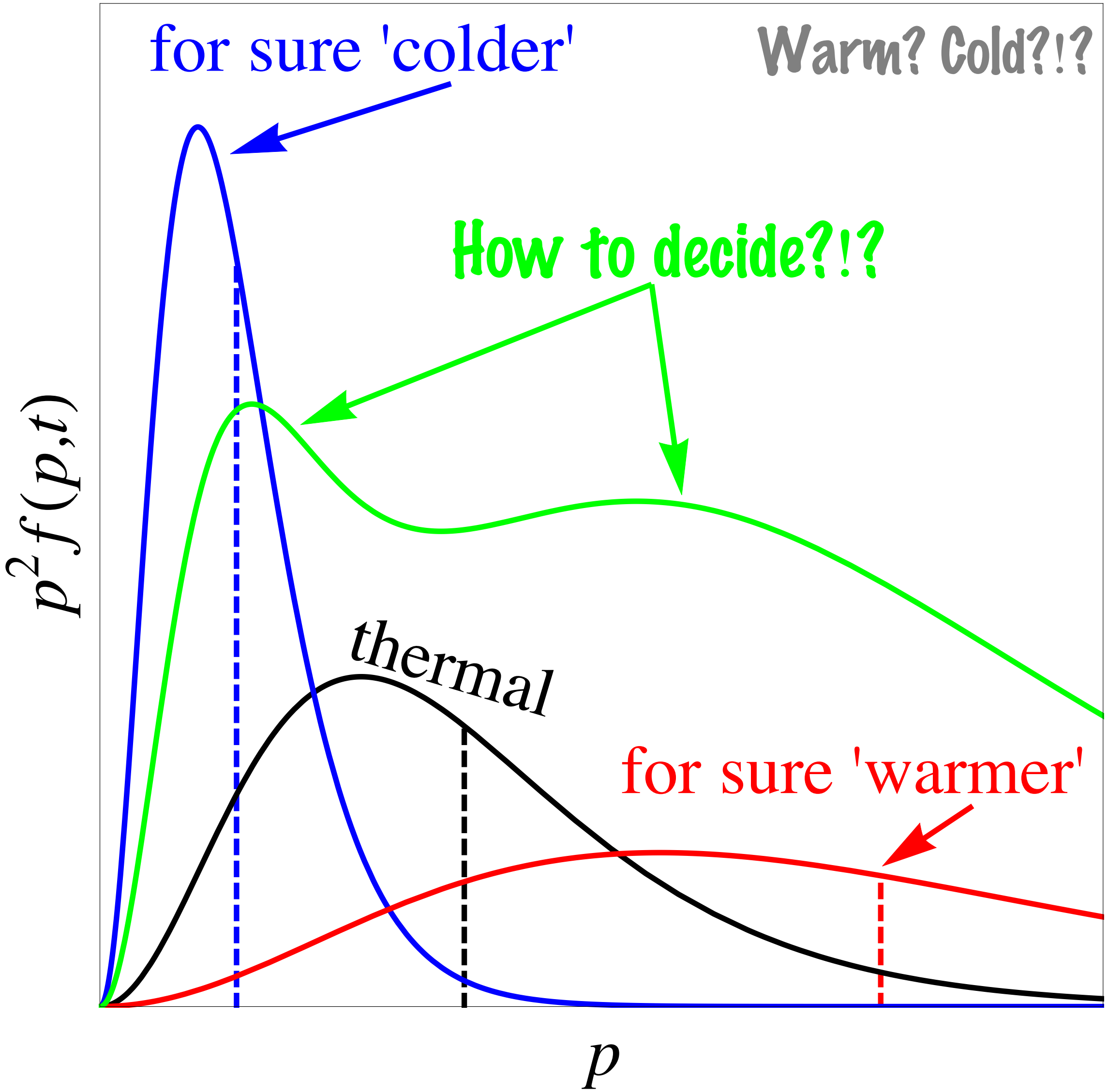
[http://www.ctac.uzh.ch/gallery/]

HOT WARM COLD

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!

→ see talk by Aurel Schneider (afternoon)

3. The Dodelson-Widrow mechanism

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

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

[**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]

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

- 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,...]

3. The Dodelson-Widrow mechanism

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

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

[**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:

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

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

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

3. The Dodelson-Widrow mechanism

Explicit counterexample:

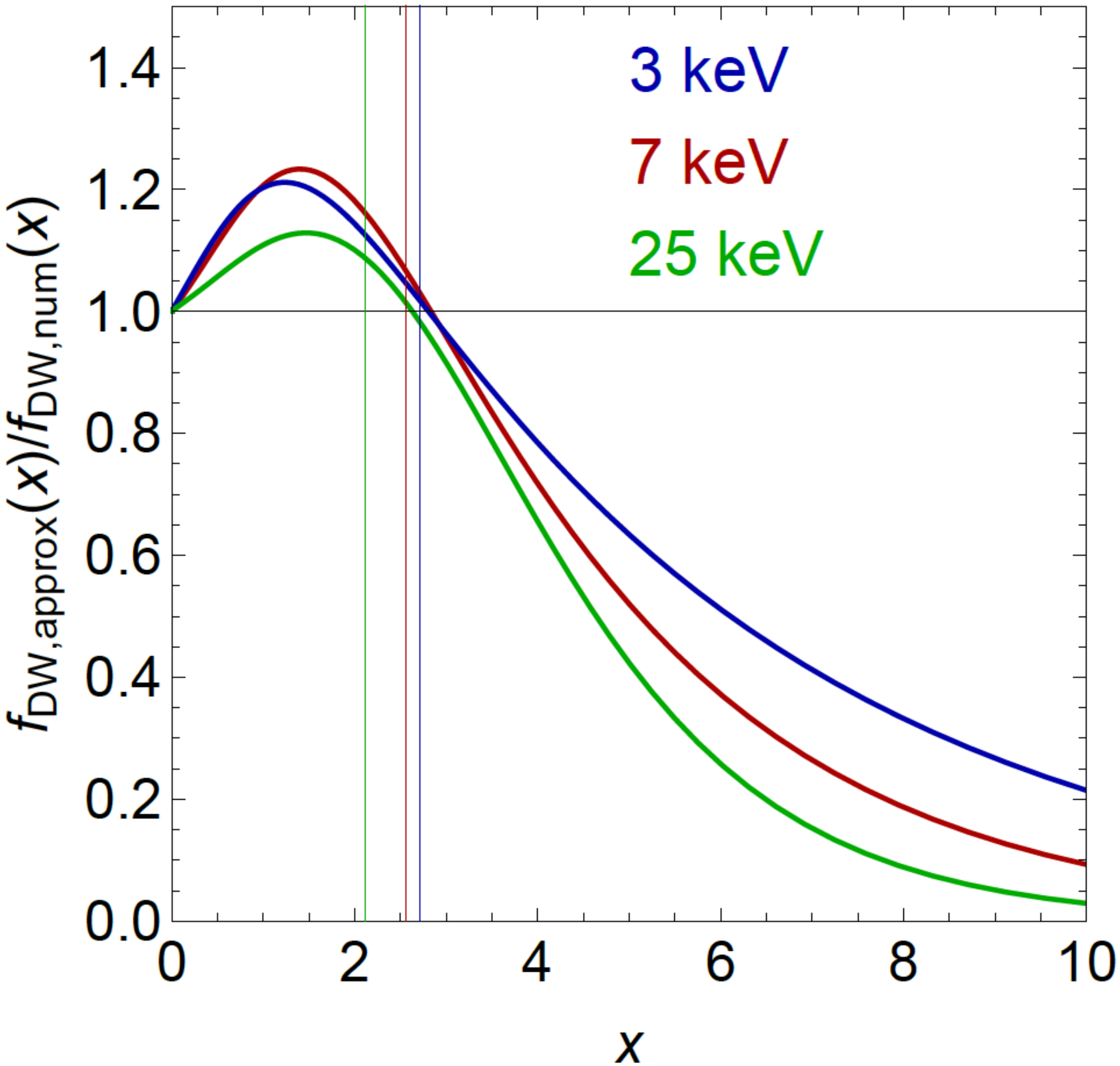
[**AM**, Schneider, Totzauer: JCAP **1604** (2016) 003]

(thermal shape + suppression)

÷

(exact result)

≠1



3. The Dodelson-Widrow mechanism

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

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

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

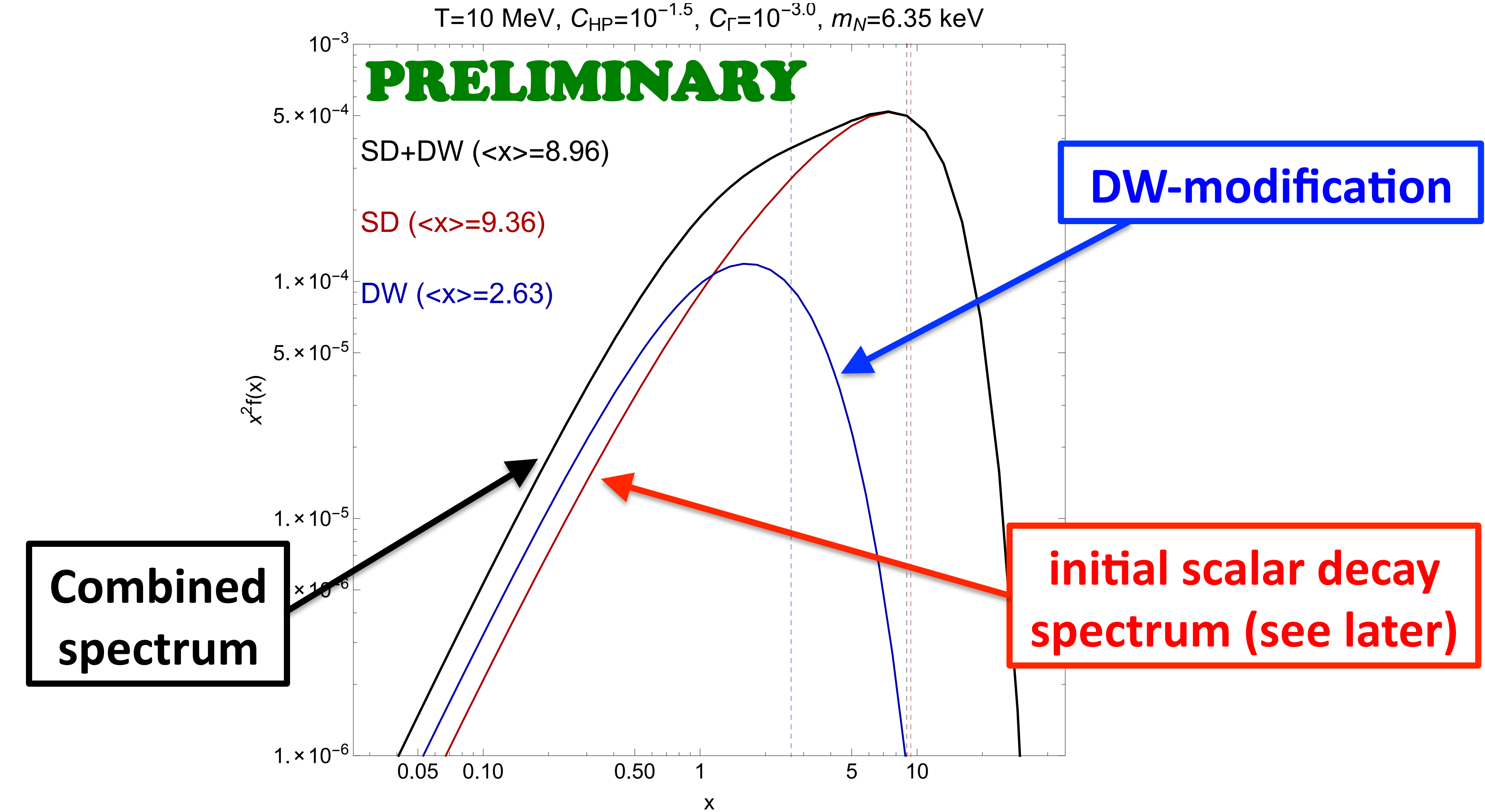
2nd prejudice:

DW always produces a too hot spectrum

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

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

3. The Dodelson-Widrow mechanism



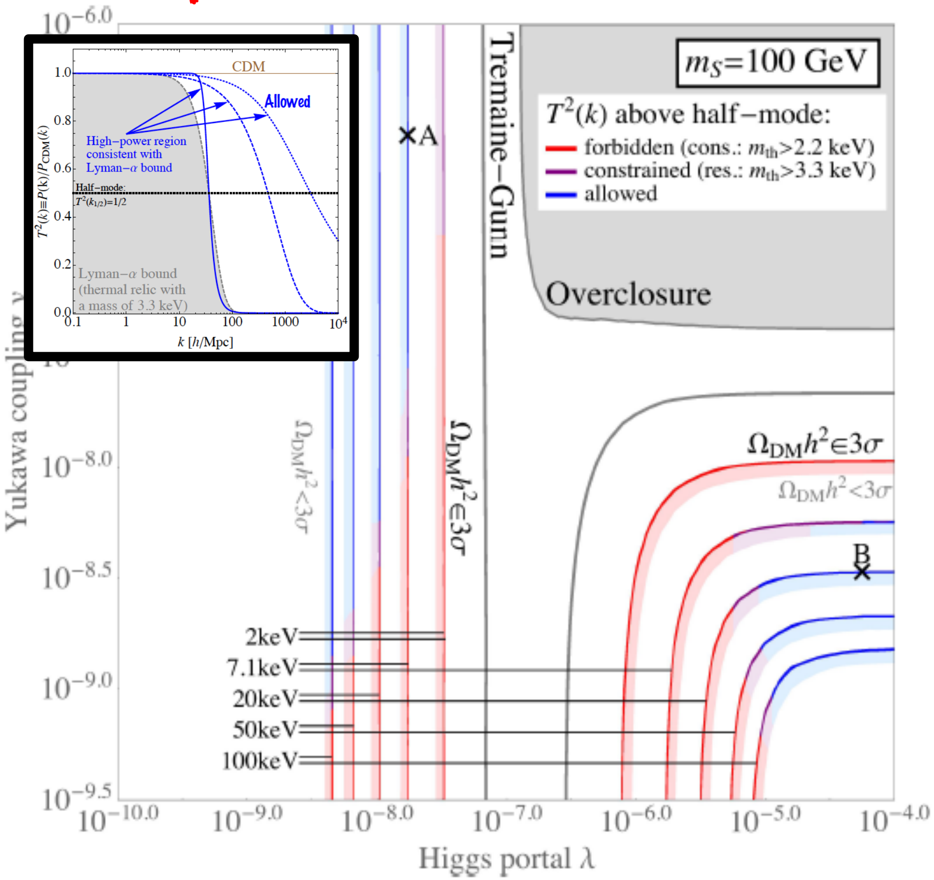
may shift the average momentum to LOWER values ("DW-cooling")

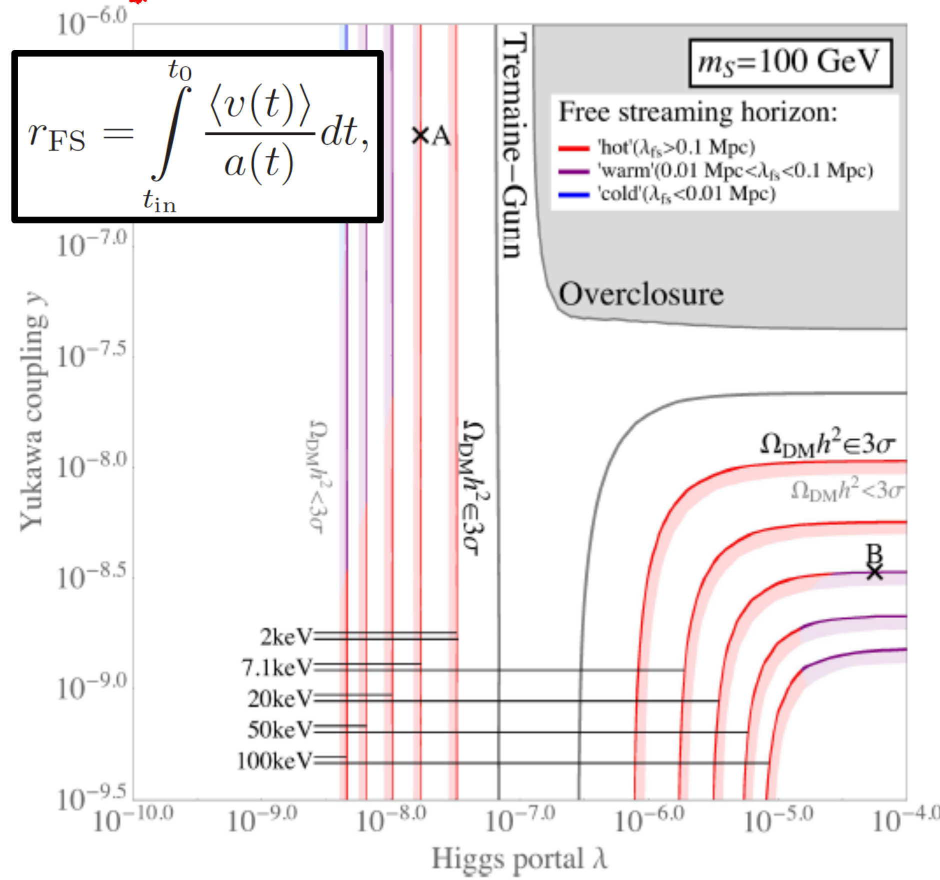
BUT: *SMALL EFFECT*!!! (DW-part can at most be a ~25% modification)

4. *Example 2*: Decay production

[König, **AM**, Totzauer: 1609.01289]

Comparison: Half-mode analysis vs. free streaming





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

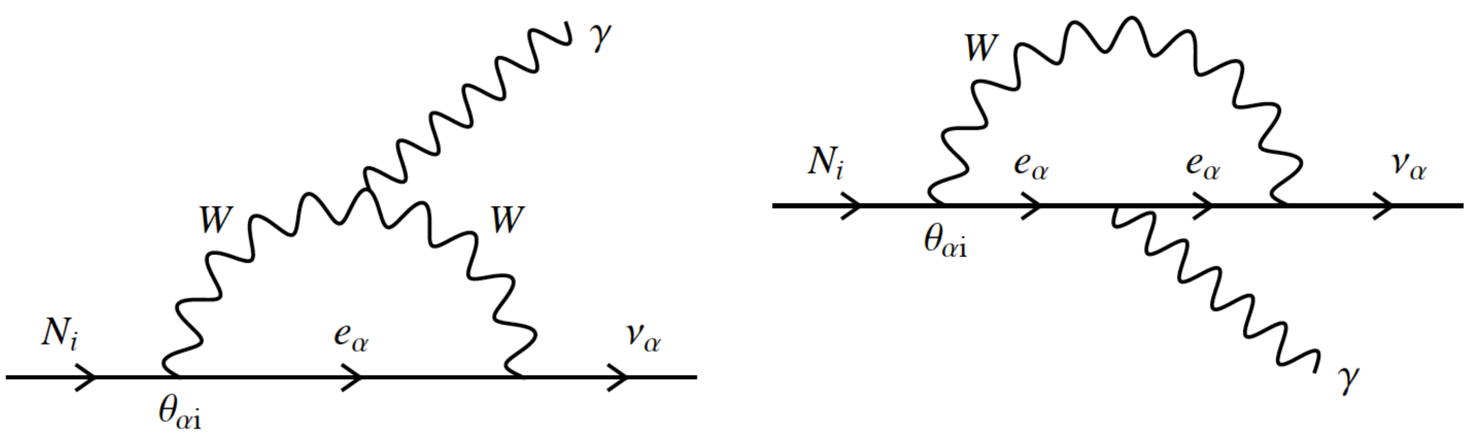
4. *Example 1*: Active-Sterile Transitions

It could all be sooo simple...:

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

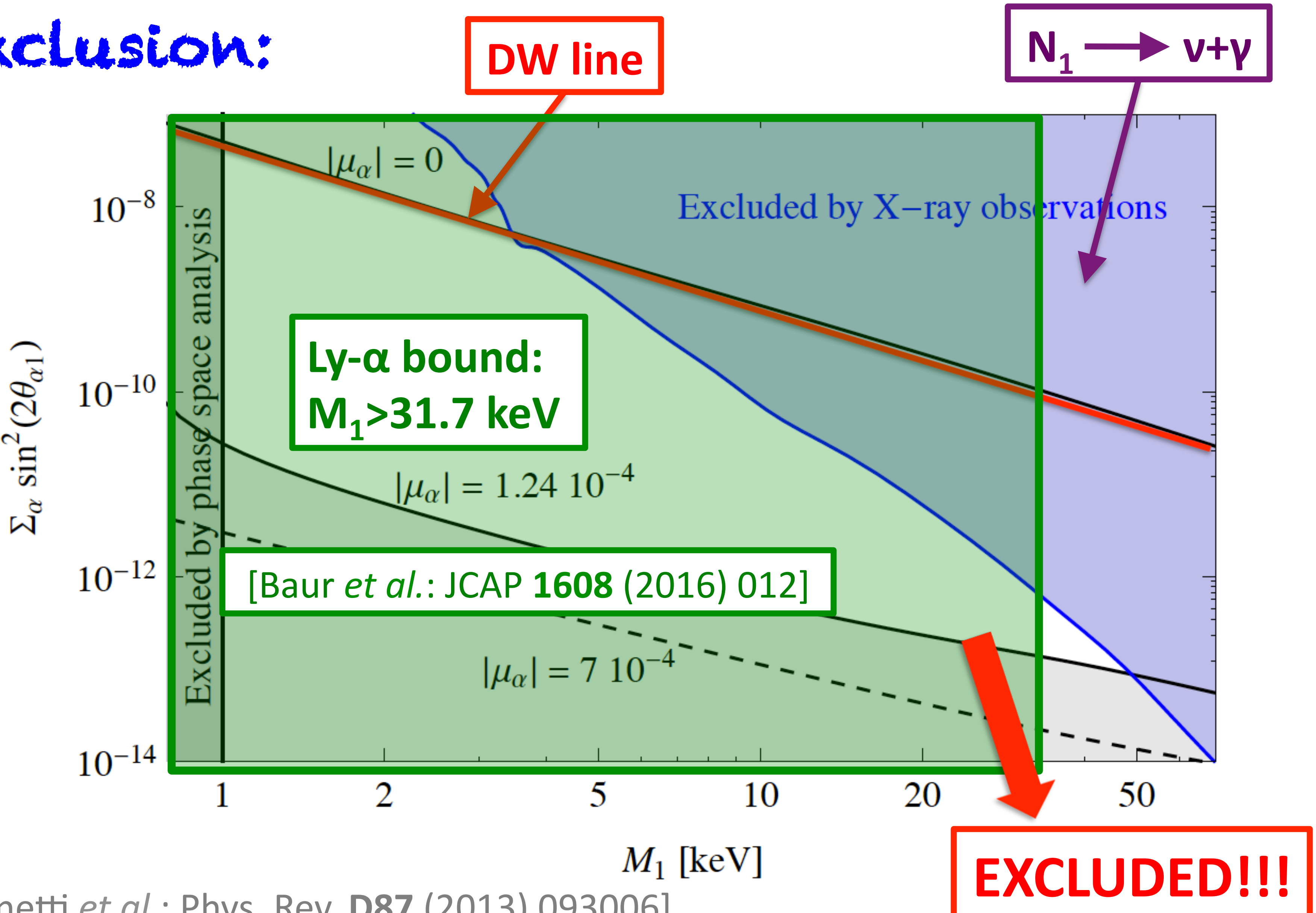
- **slow non-resonant "oscillations" of active into sterile neutrinos can gradually produce the DM from the thermal plasma (just like "freeze-in") ➔ *nice & simple***

- **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

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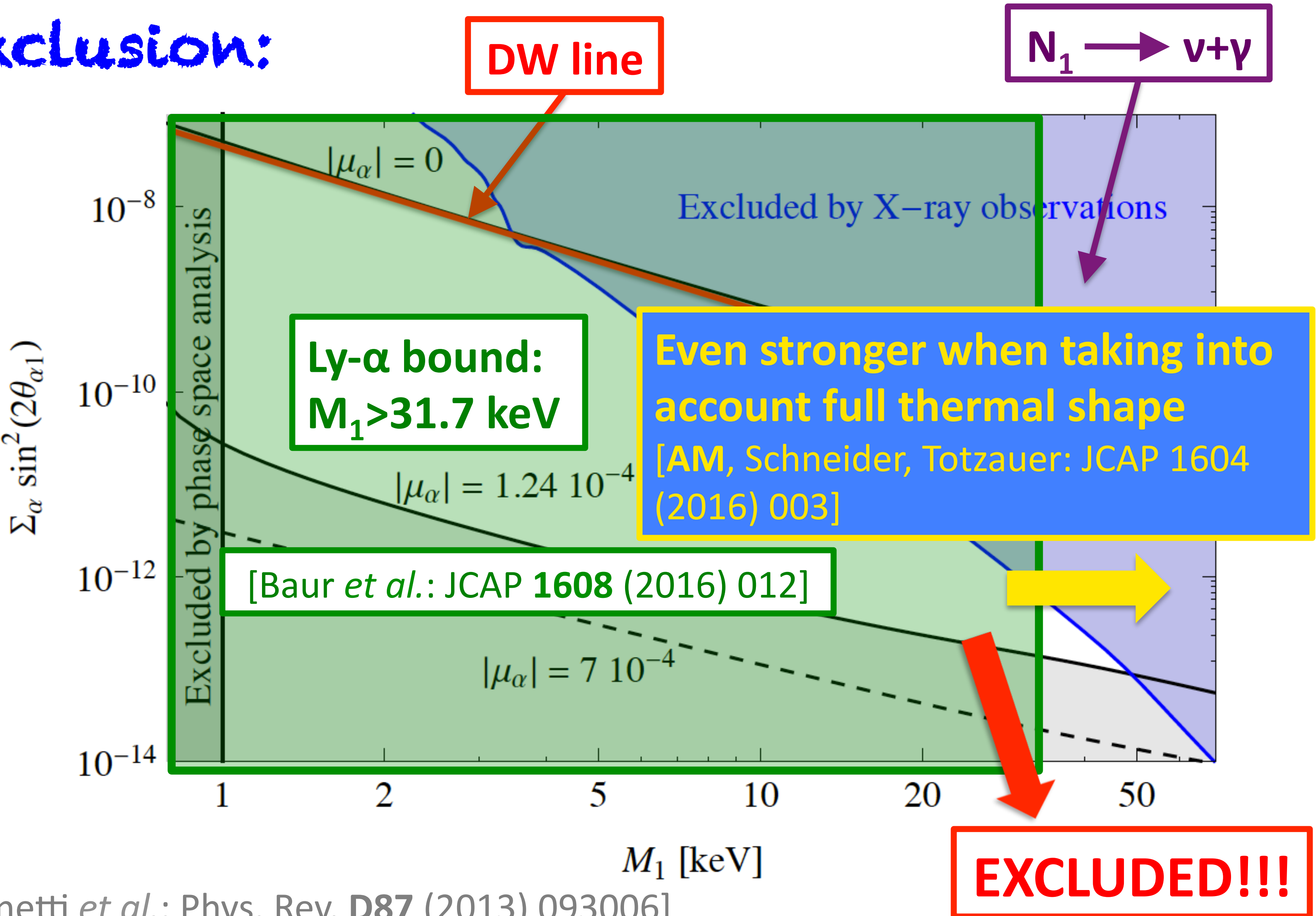


[Canetti *et al.*: Phys. Rev. **D87** (2013) 093006]

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**

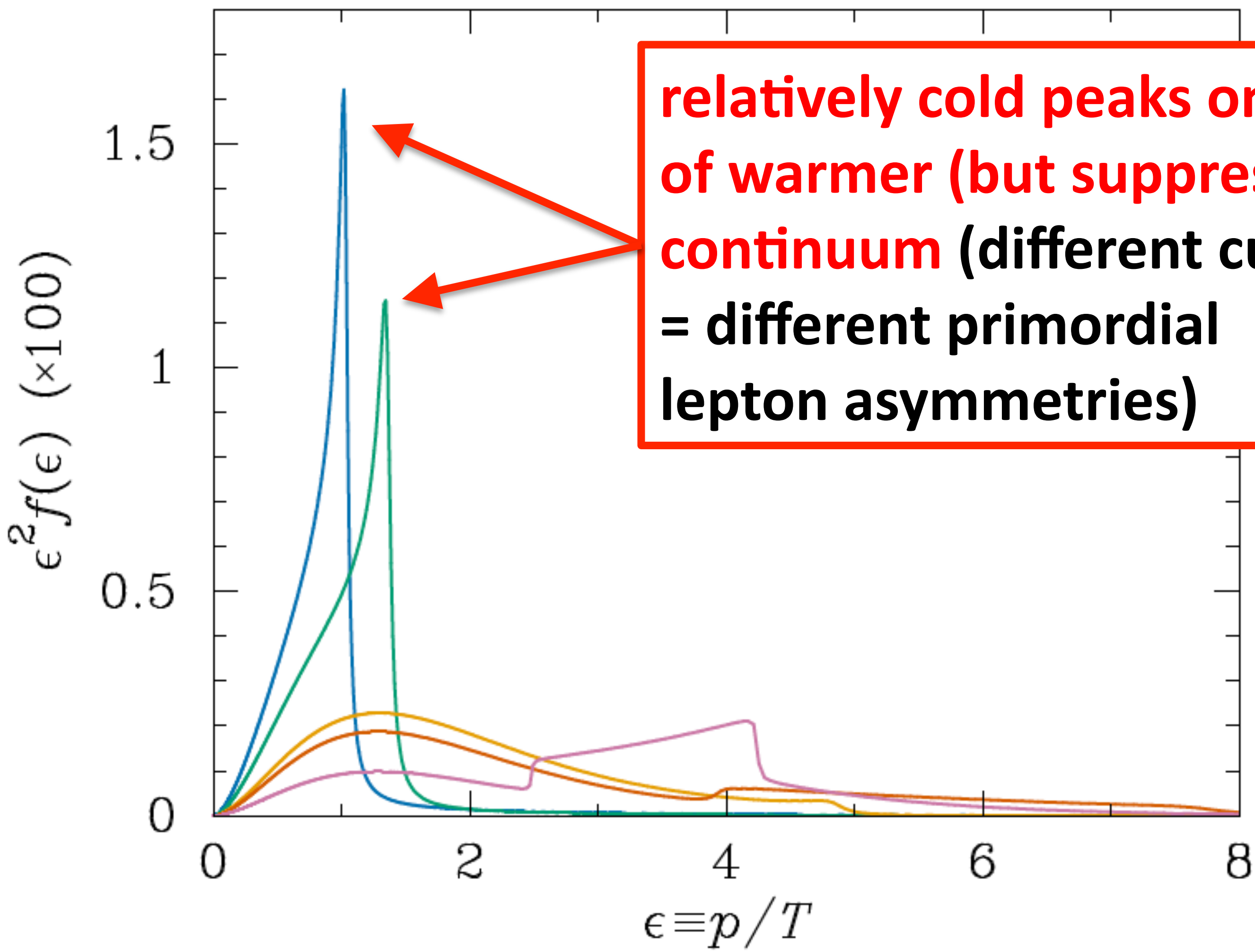
- **this would produce a large amount of ν_s at a specific (momentum-dependent) resonance temperature**
  ➔ *cooler spectrum*

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

Example: Resonant production

This produces to non-thermal spectra:

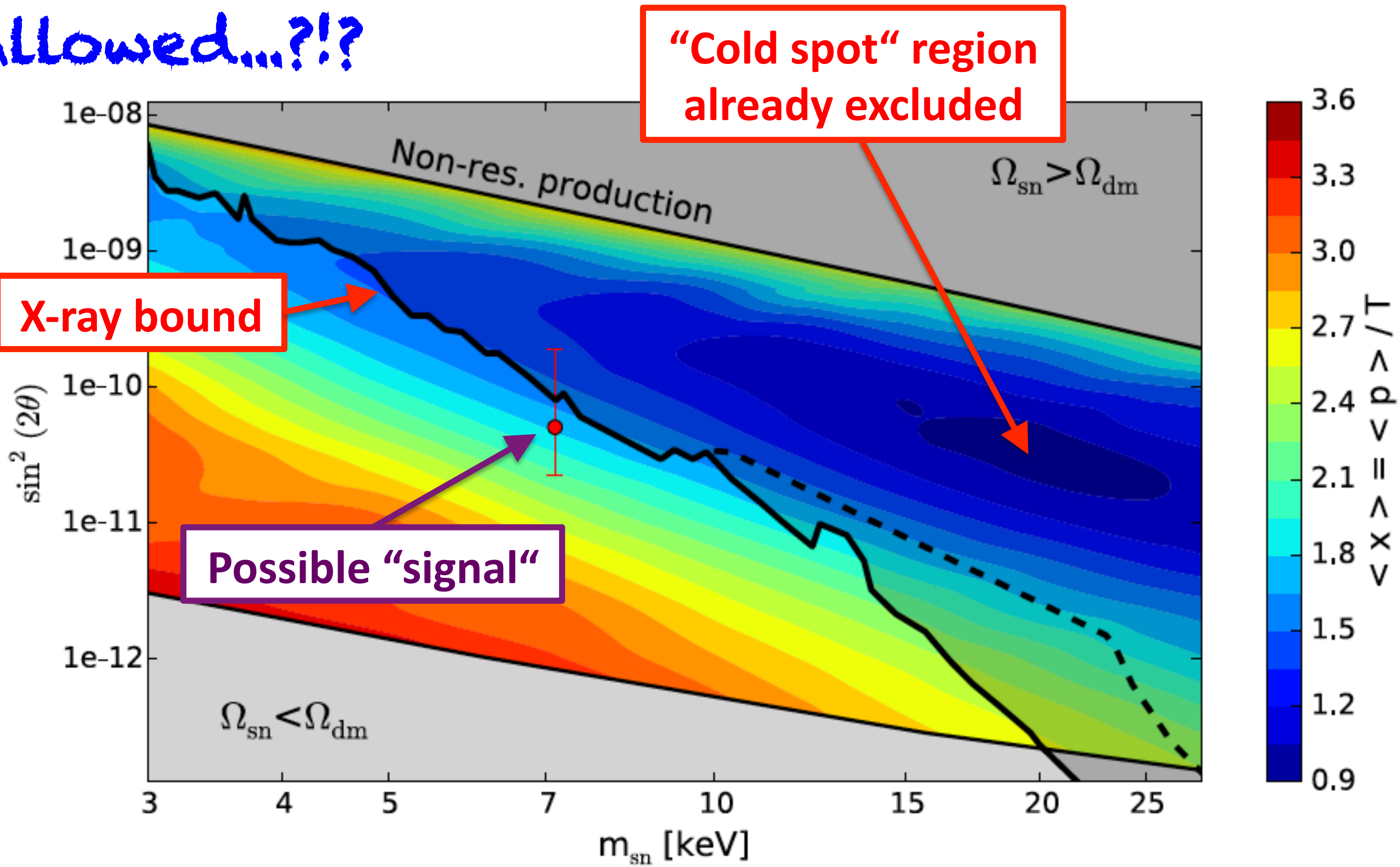
[Abazajian: Phys. Rev. Lett. **112** (2014) 161303]



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

The Shi-Fuller mechanism

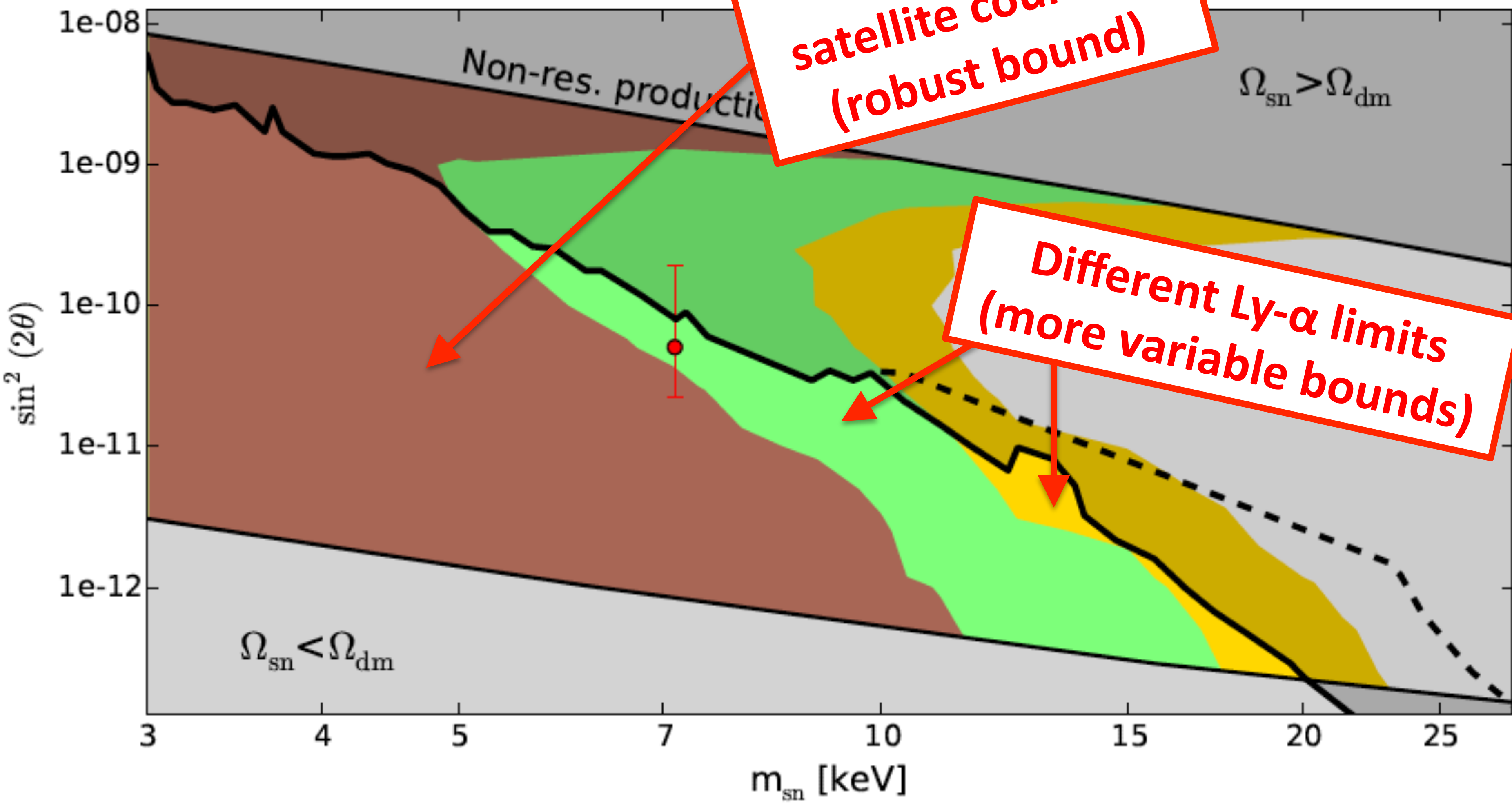
Allowed...?!?



[Schneider: JCAP **1604** (2016) 059] ➔ **see Talk by Aurel Schneider (today!!)**

Example: Resonant production

... or threatened?!?



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

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[Kusenko: Phys. Rev. Lett. **97** (2006) 241301; Kusenko, Petraki: Phys. Rev. **D77** (2008) 065014]
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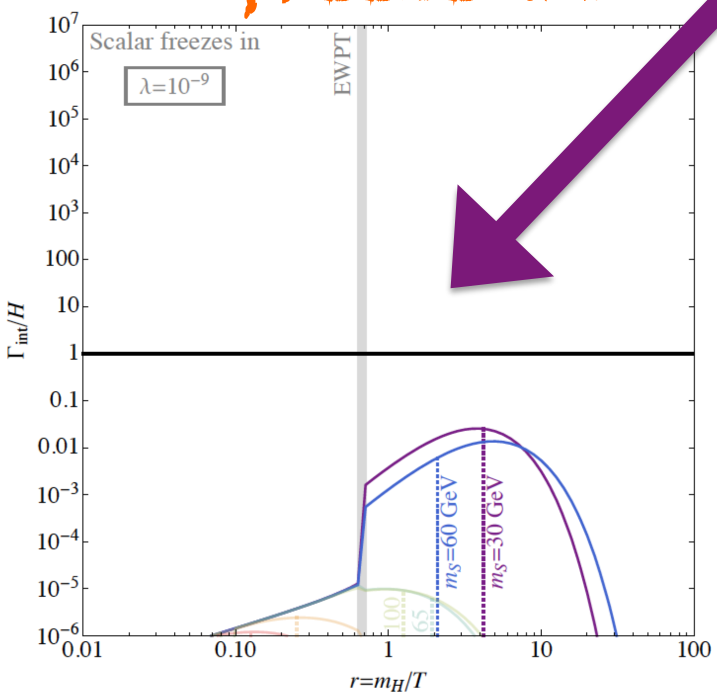
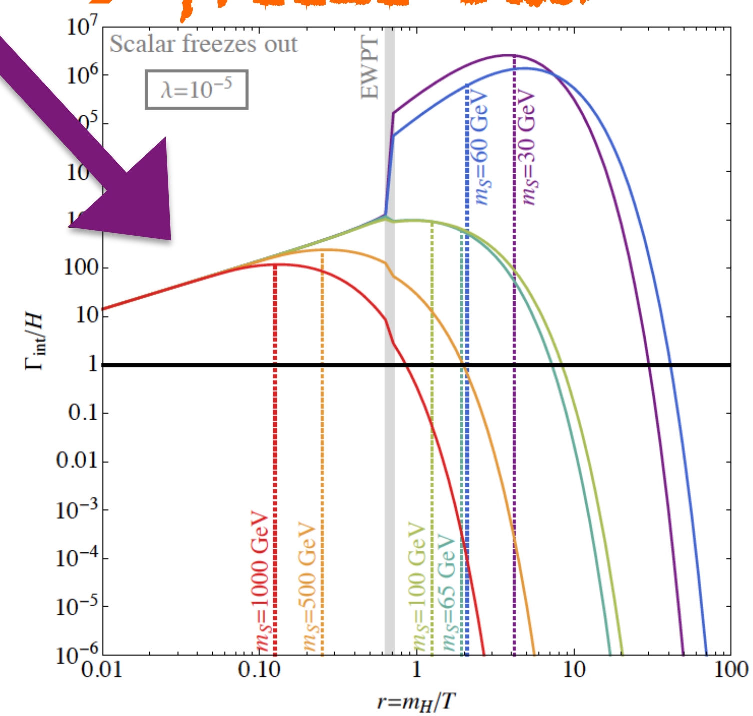
<u>Two-step process:</u>

scalar S must be produced before it can decay

small coupling to SM → freeze-in!

large coupling to SM → freeze-out!





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

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) ...4]
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Two-step proces...

sc...

→

NEW in 1609.01289:

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

$$f_N \ldots \int_{\hat{x}_{\min}} d\hat{x} \, \frac{\ldots}{\sqrt{\hat{x}^2 + r'^2}} f_S(\hat{x}, r')$$

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

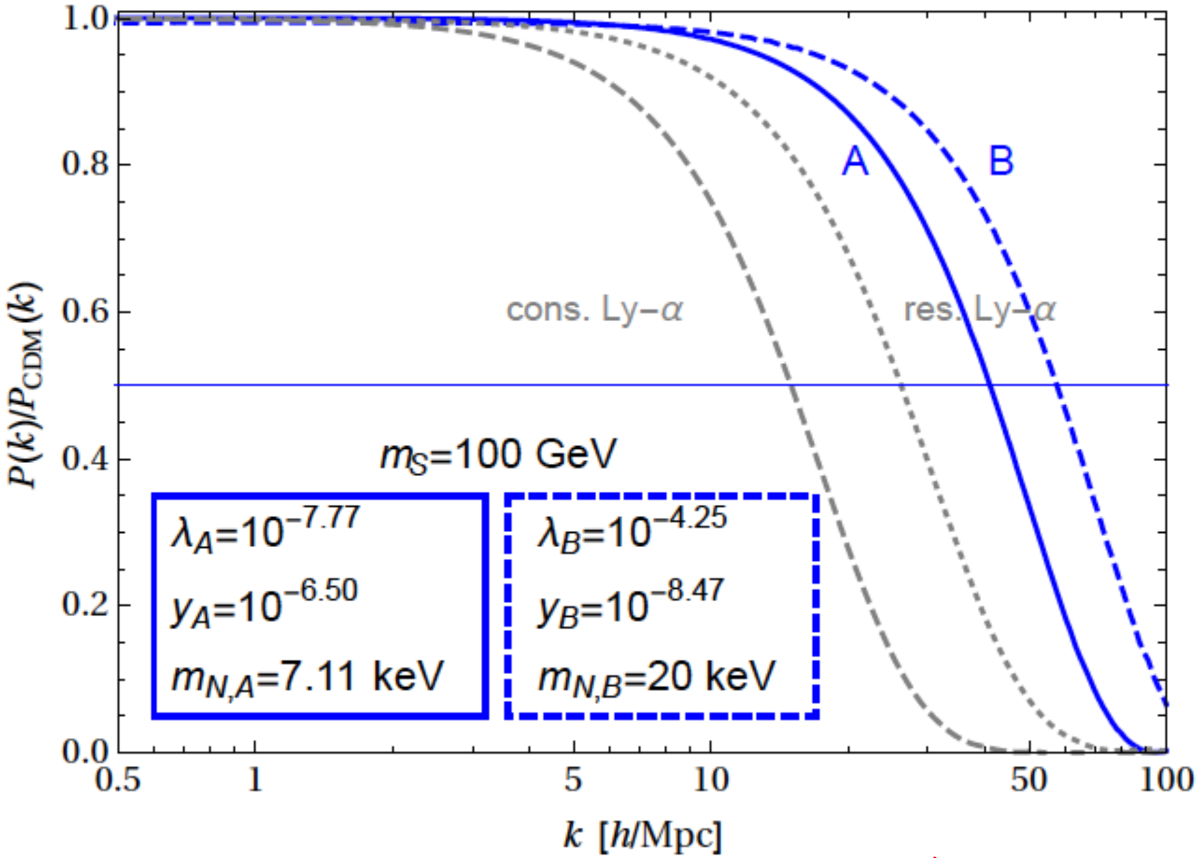
$x = p/T$
$r = m_S/T$

direct translation

4. *Example 2*: Decay production

[König, **AM**, Totzauer: 1609.01289]

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

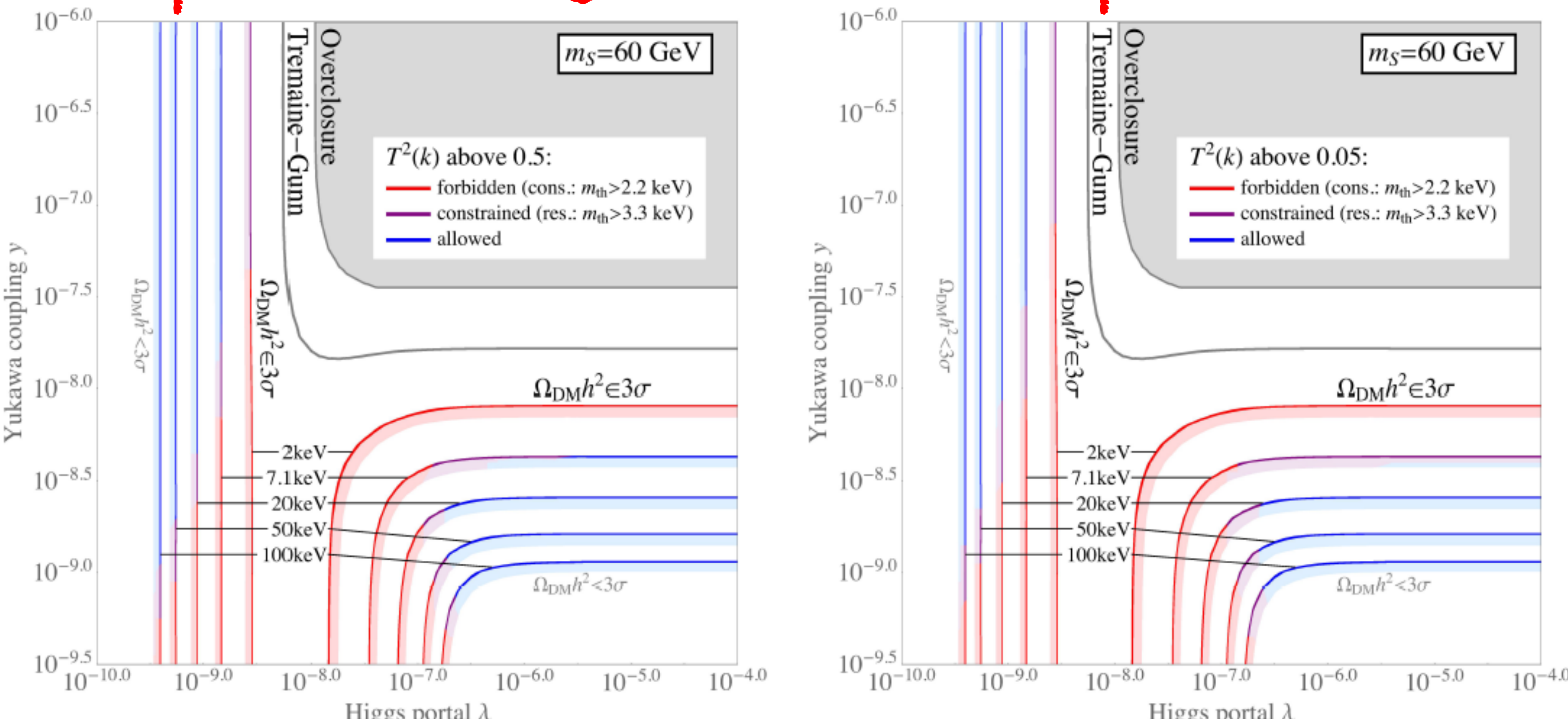


→ free-streaming cannot describe non-thermal distributions correctly!!!!

4. *Example 2*: Decay production

[König, **AM**, Totzauer: 1609.01289]

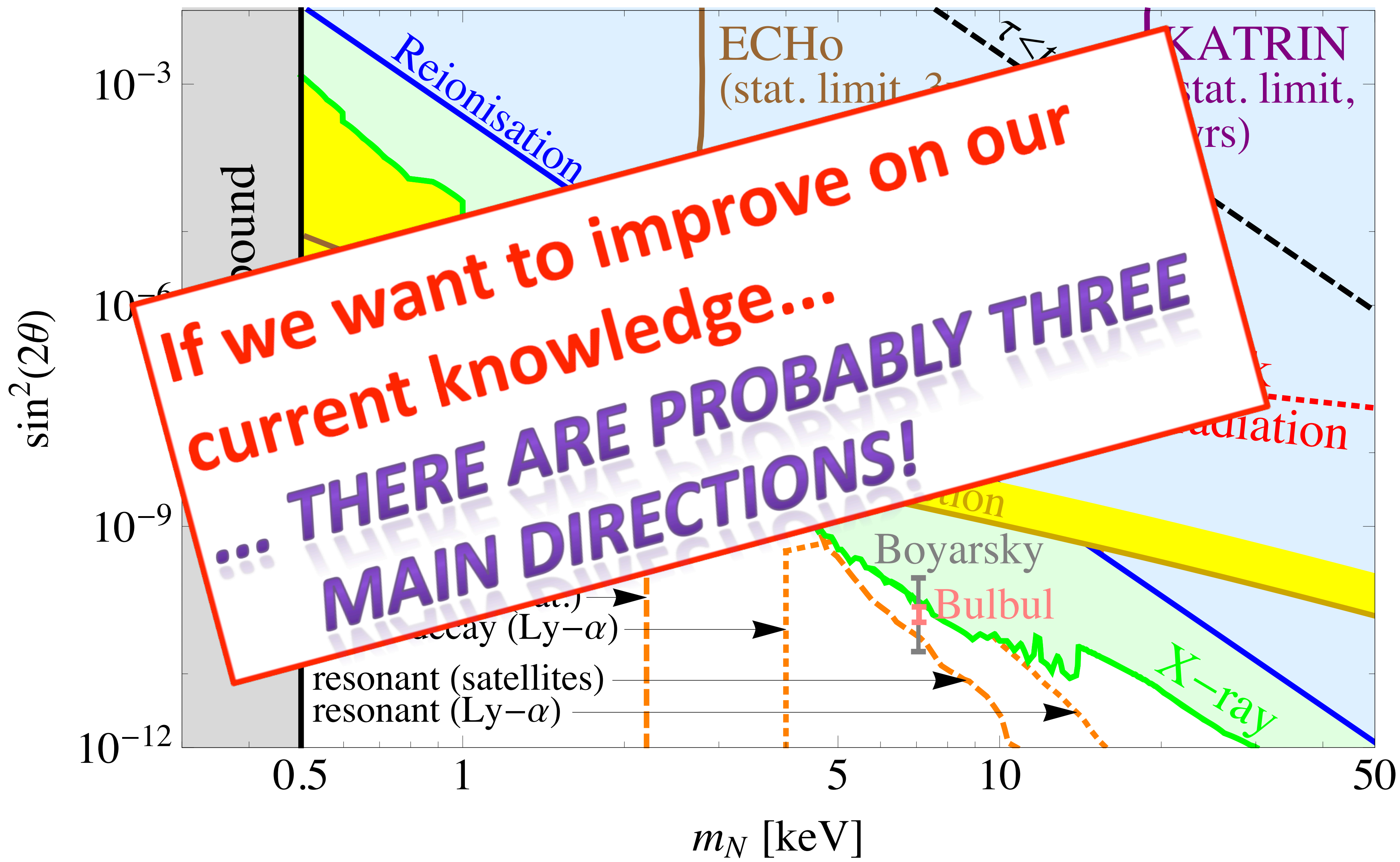
… whereas our analysis is very robust with respect to changes in the assumption:



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

5. Where to go from here?!?

Summary of all constraints (from keV-WP):



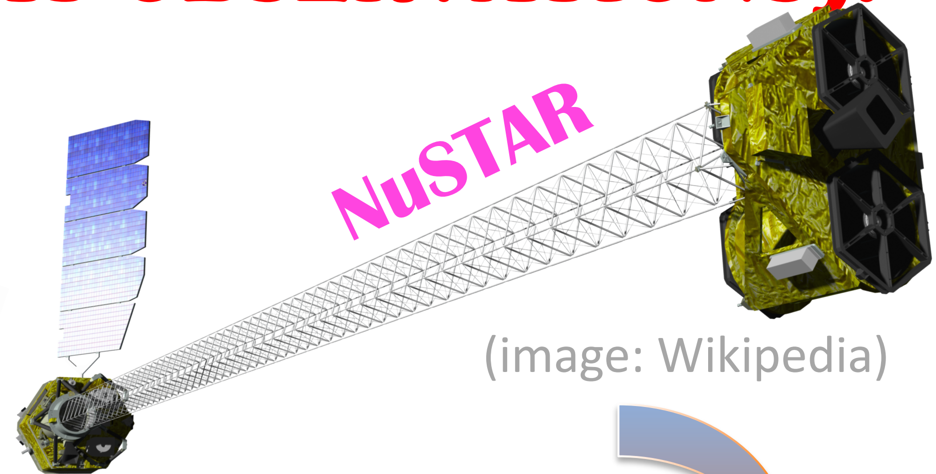
5. Where to go from here?!?

ASTROPHYSICS (X-RAY OBSERVATIONS):

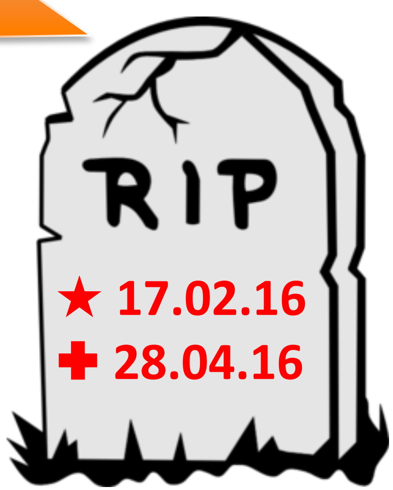
5. Where to go from here?!?

ASTROPHYSICS (X-RAY OBSERVATIONS):

(image: JAXA)



(image: Wikipedia)



(image: www.clker.com/cliparts/U/H/t/l/l/W/rip-tombstone-md.png)

Paper 1609.00667:

"(Almost) Closing the Sterile Neutrino Dark Matter Window"

➔ *Really?!?*

5. Where to go from here?!?

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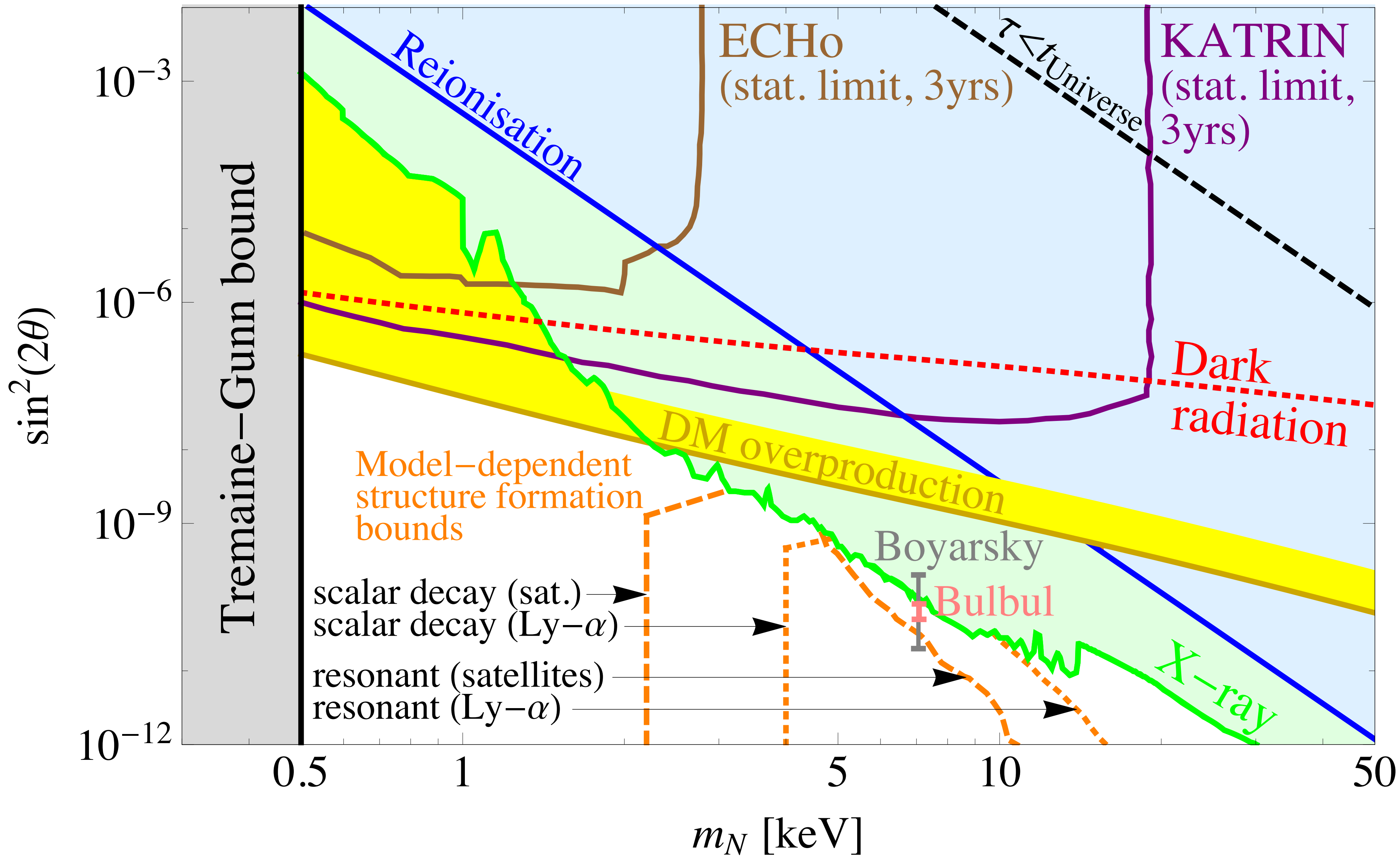

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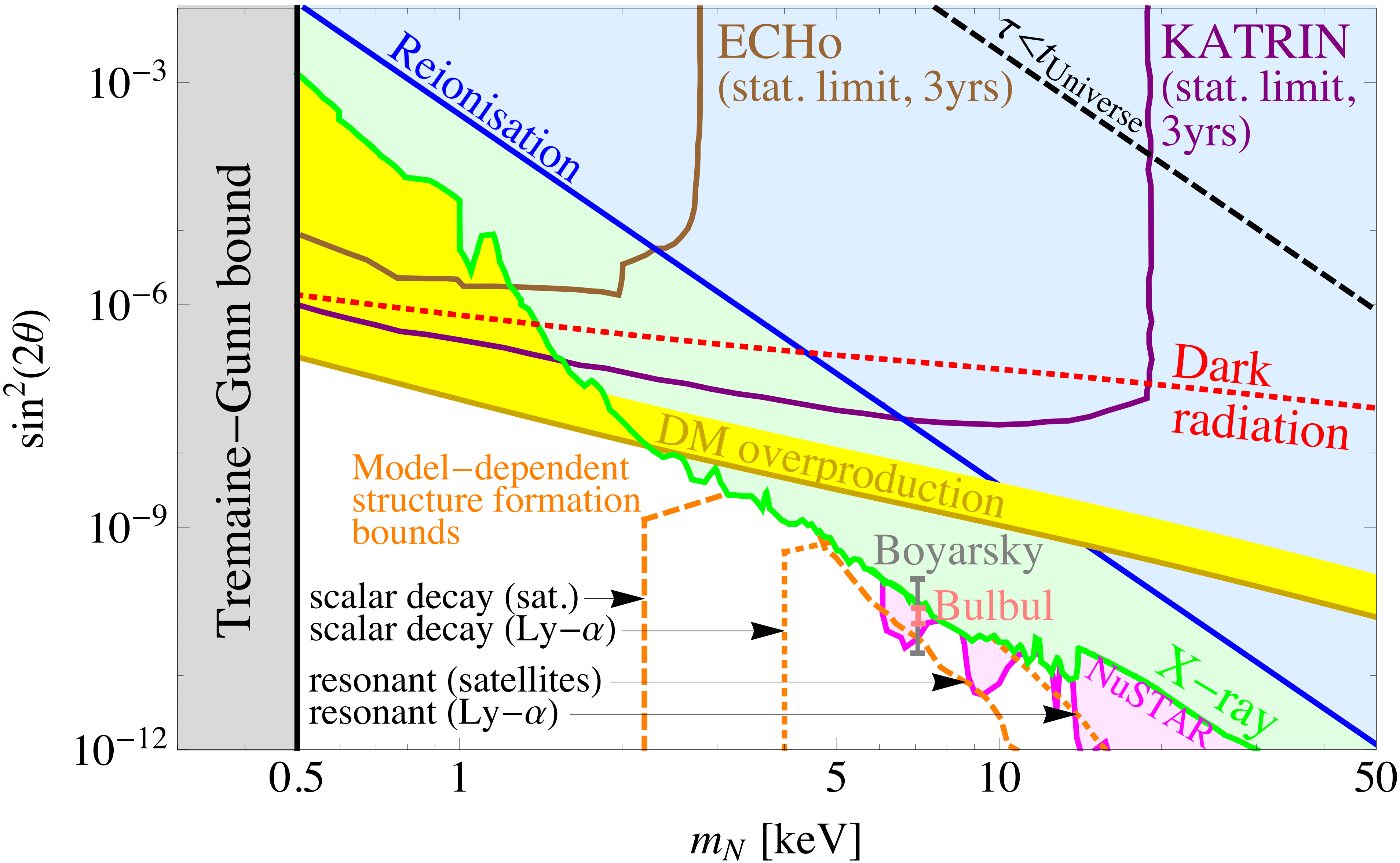

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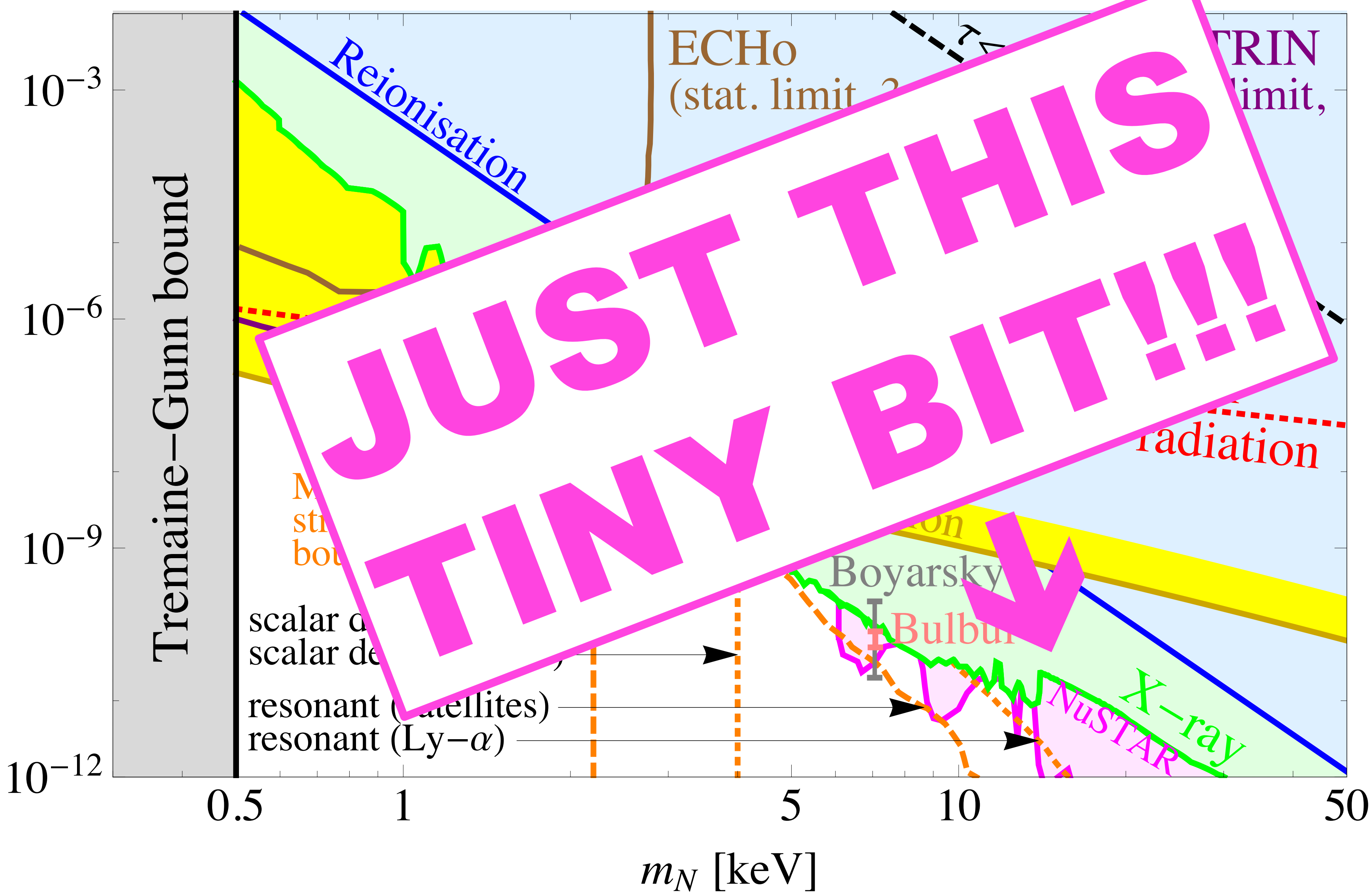

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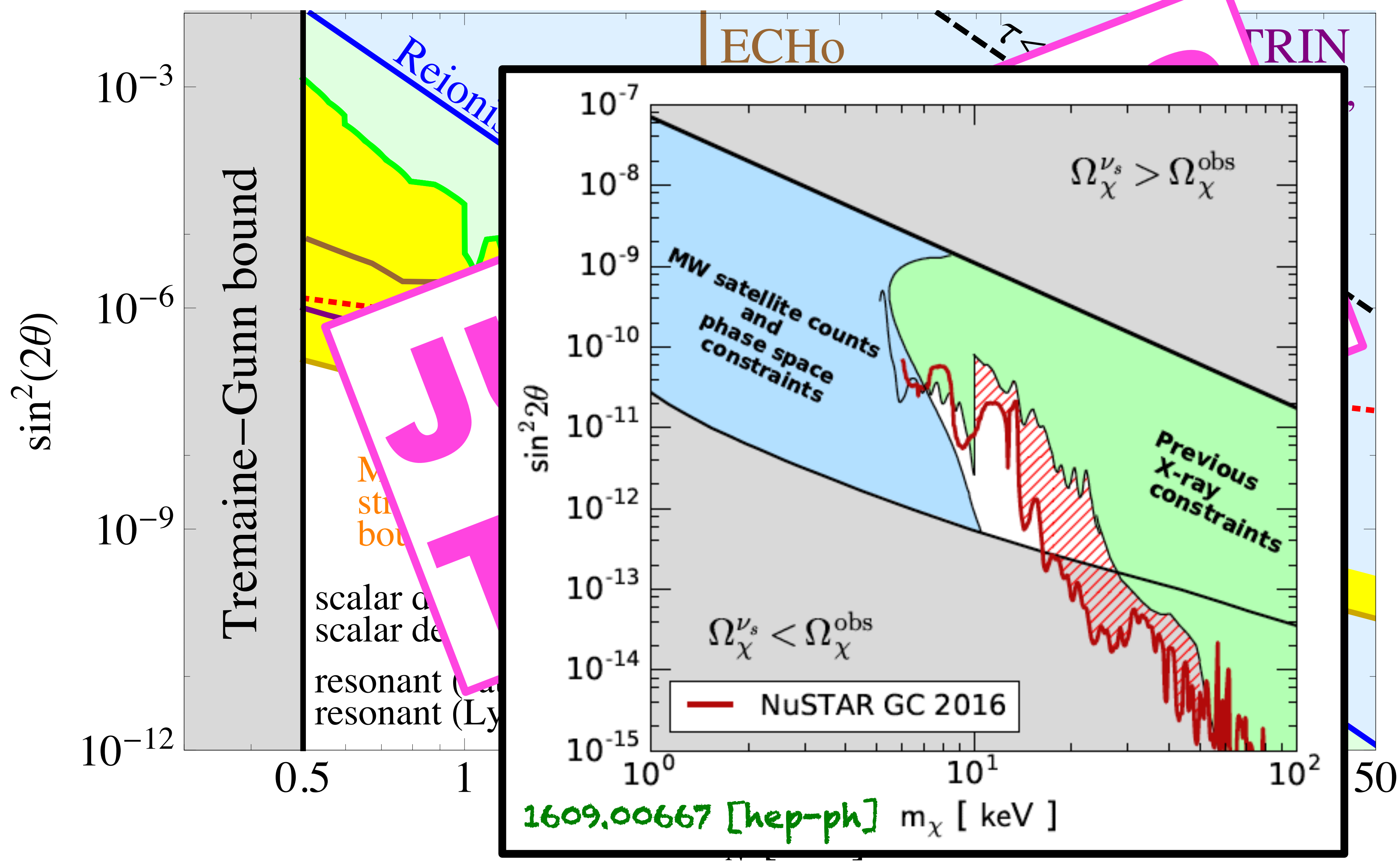

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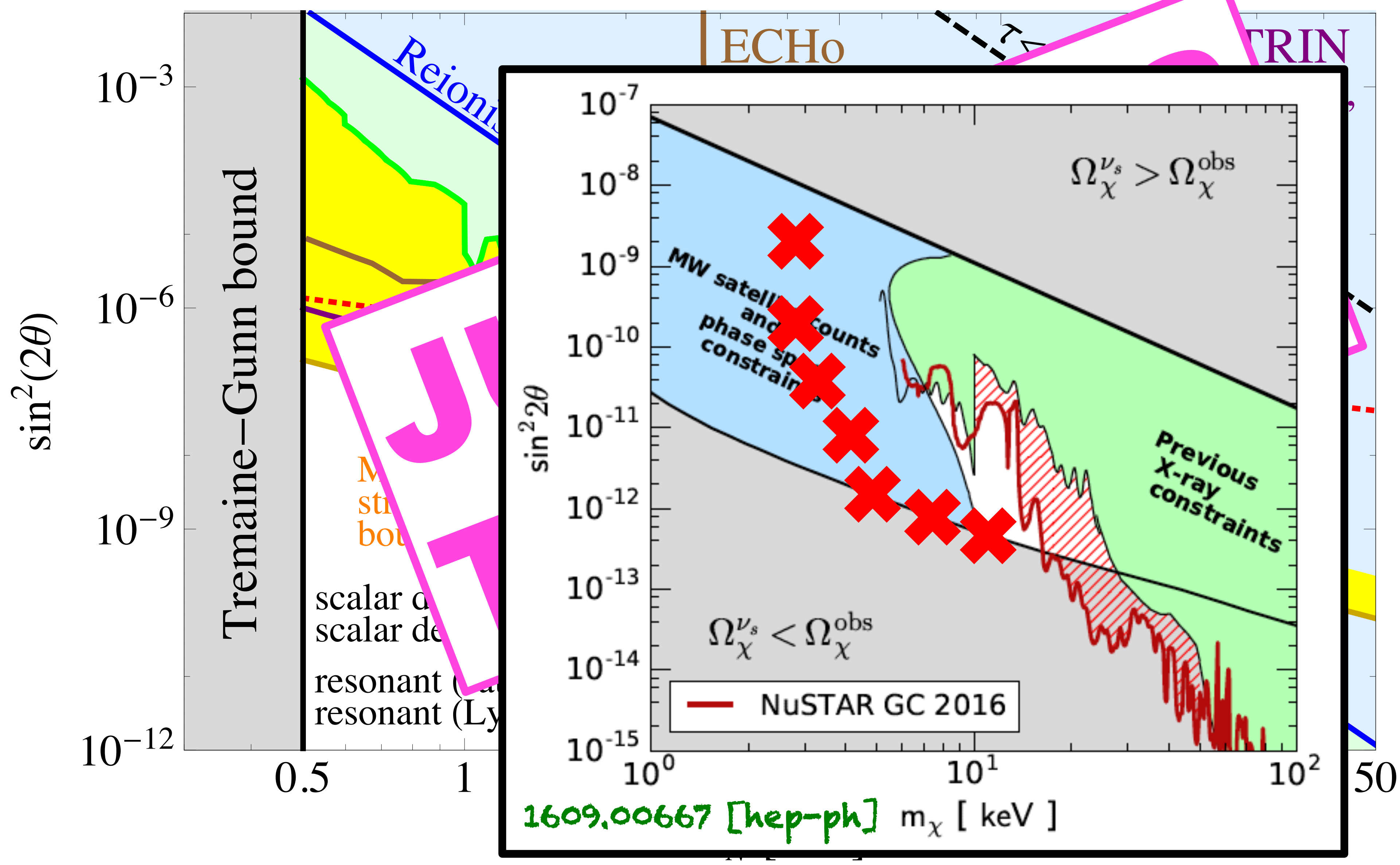

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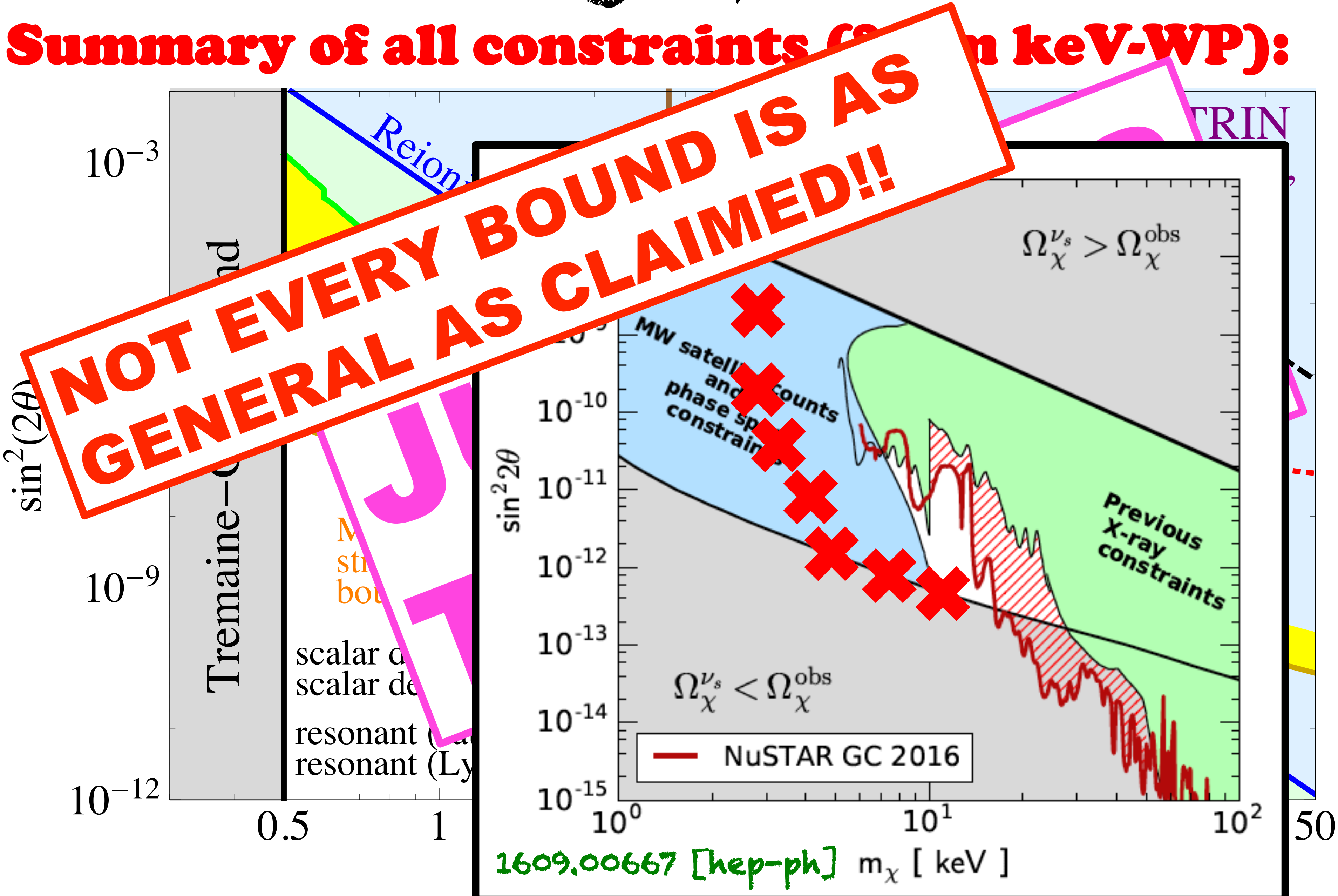

5. Where to go from here?!?

STRUCTURE ON DIFFERENT SCALES:

5. Where to go from here?!?

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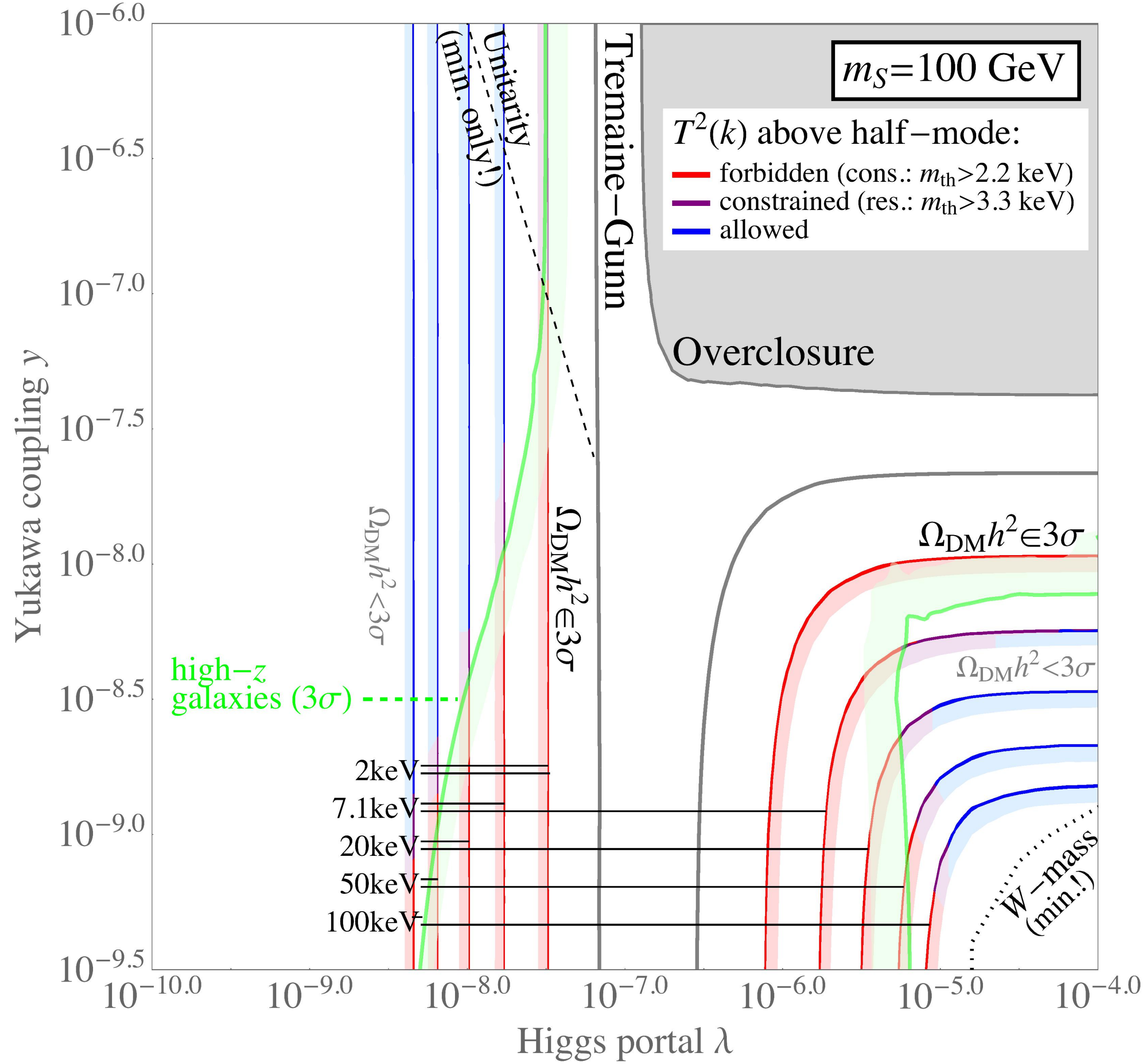
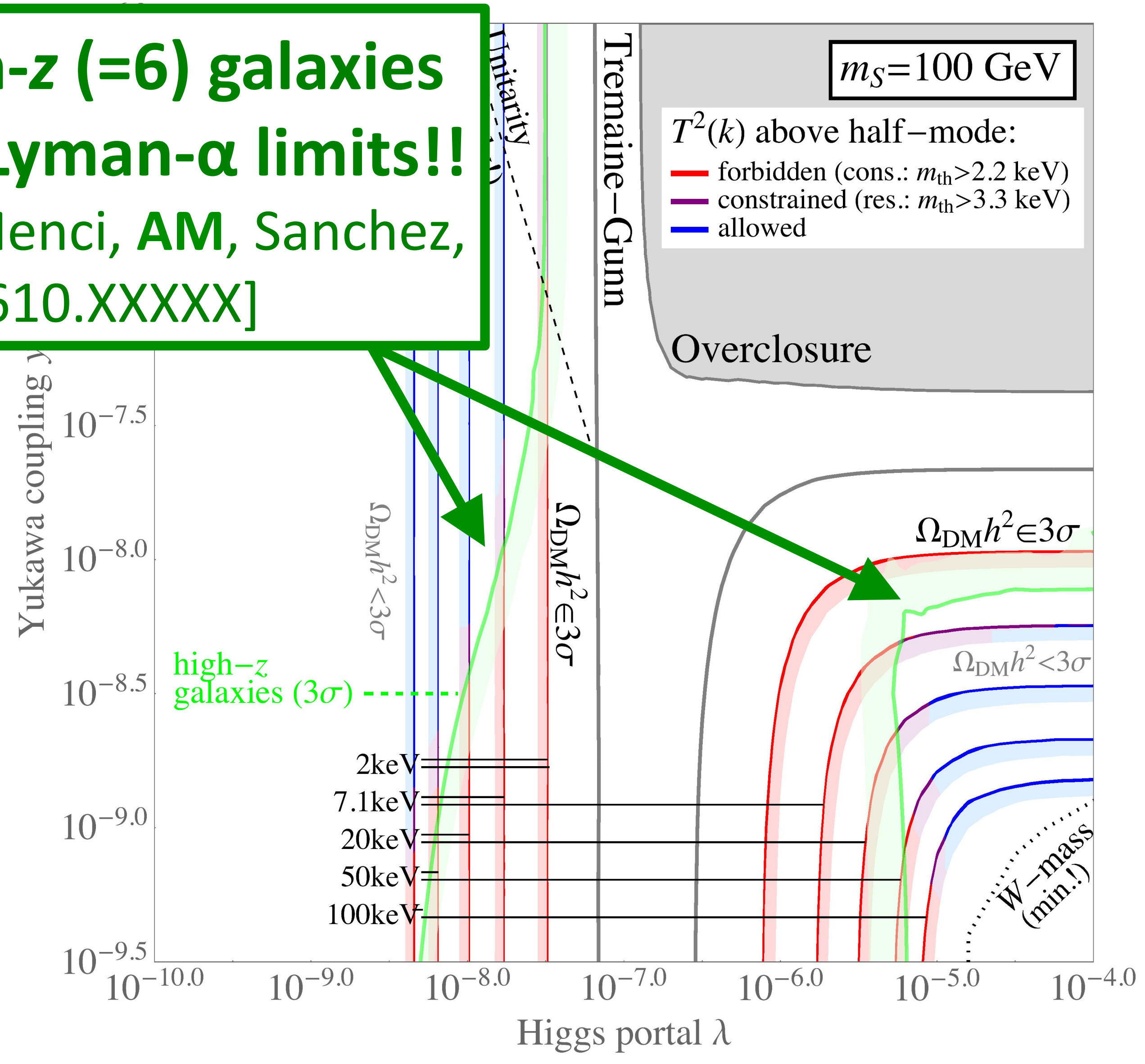


5. Where to go from here?!?

STRUCTURE ON DIFFERENT SCALES:

Abundance of high-z (=6) galaxies strongly backs up Lyman-α limits!!
[Castellano, Grazian, Menci, **AM**, Sanchez, Schneider, Totzauer: 1610.XXXXX]



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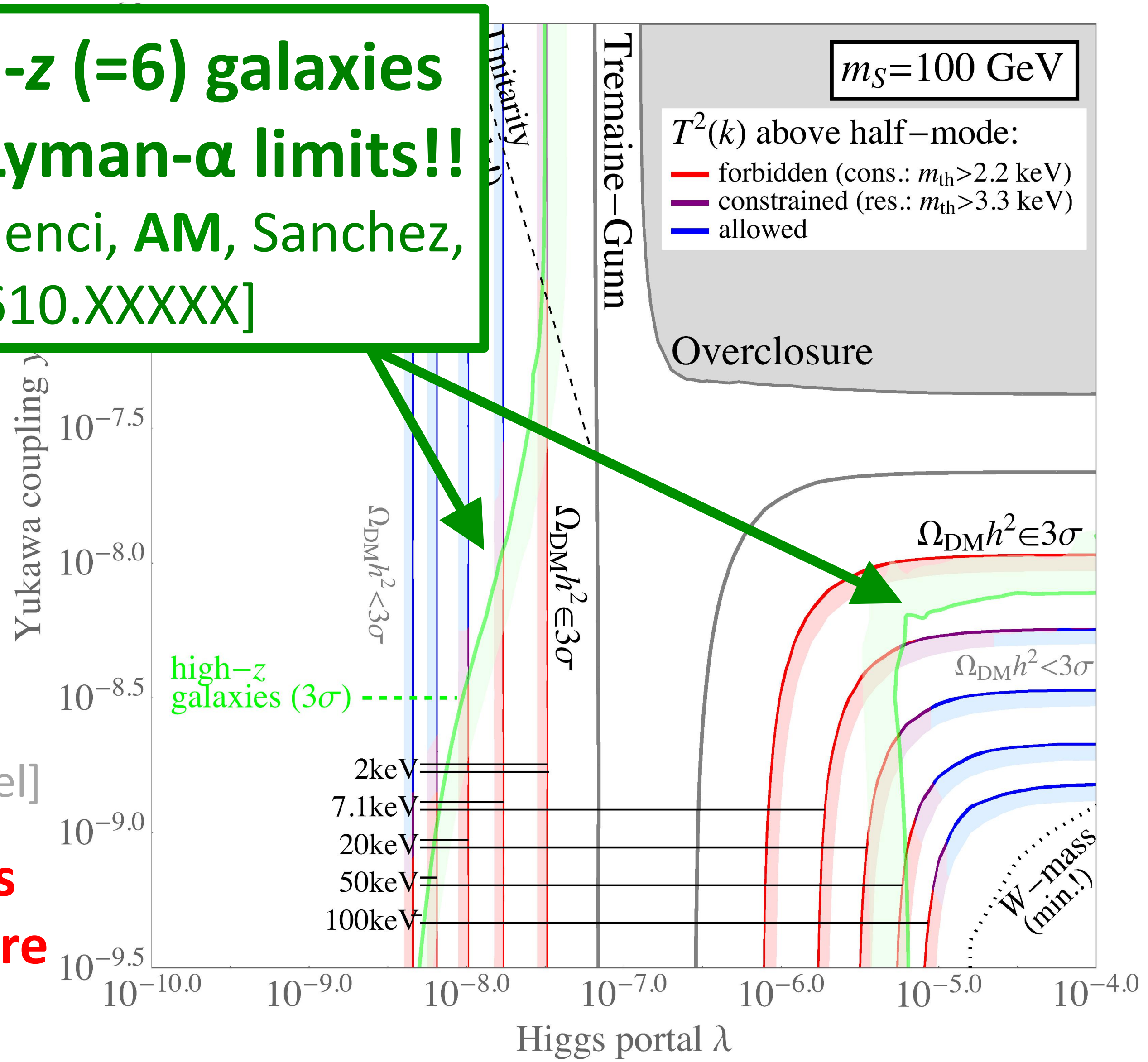


Further work in progress:

- **Ly-α bounds for non-thermal Dark Matter**
  [Menci, **AM**, Schneider, Viel]
- **approximate methods for non-linear structure**
  [**AM**, Schneider, Totzauer]

5. Where to go from here?!?

GROUND-BASED EXPERIMENTS:

5. Where to go from here?!?

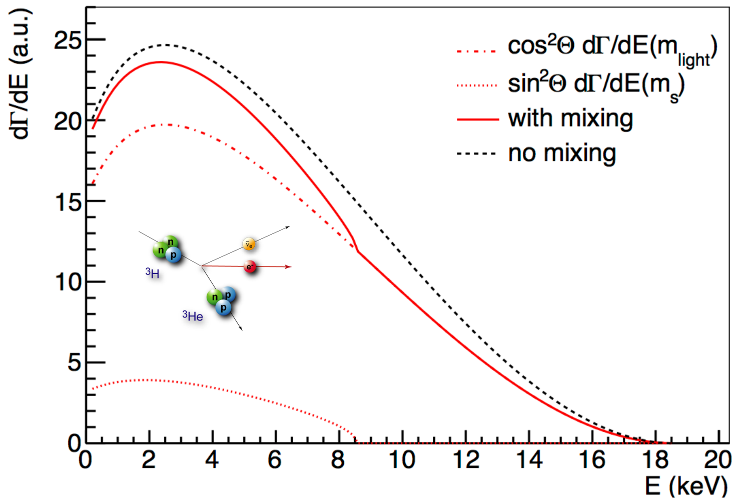
GROUND-BASED EXPERIMENTS:

two slides shamelessly stolen from
Susanne Mertens & Thierry Lasserre

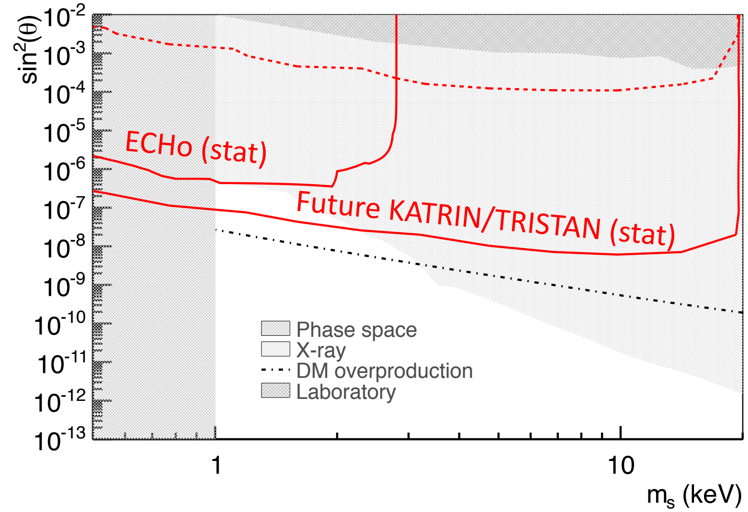
KATRIN/TRISTAN & keV Neutrinos

Slide from Susanne

Imprint of keV Neutrinos on Tritium β-spectrum

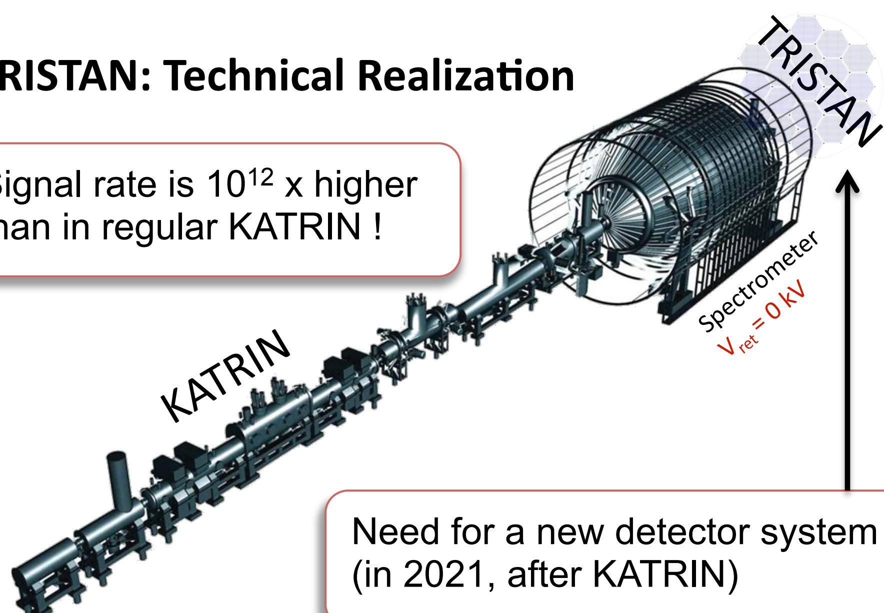


Statistical Sensitivity



TRISTAN: Technical Realization

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



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

Novel Silicon Detector System (R&D)

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

contact: smertens@lbl.gov

Direct Search for keV Neutrino Dark Matter with ^{163}Dy

Stimulated neutrino capture on stable dysprosium 163 if $m_4 > 2.8$ keV

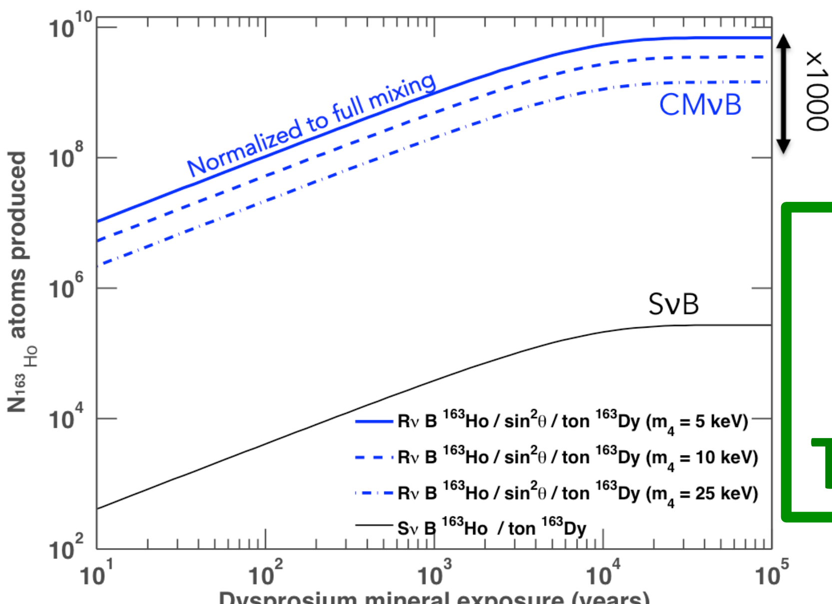
$$\nu_4(m_4 > 2.8\,\mathrm{keV}) + {}^{163}\mathrm{Dy}(\mathrm{gs}, 5/2^-) \rightarrow {}^{163}\mathrm{Dy}(\mathrm{gs}, 7/2^-) + e^-$$

I) Integral counting of ^{163}Ho atoms from Dy-based ore

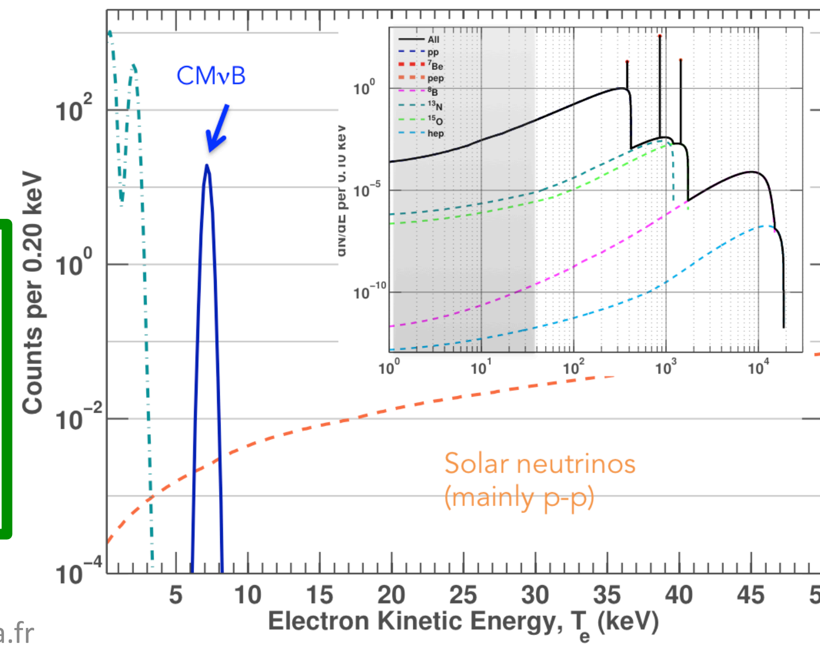
II) Real-time search in a Dy-based detector

kg-scale of ^{163}Dy $\rightarrow$ $\sin^2\theta \approx 10^{-6}$

ton-scale ^{163}Dy-detector $\rightarrow$ $\sin^2\theta \approx 10^{-9}$?



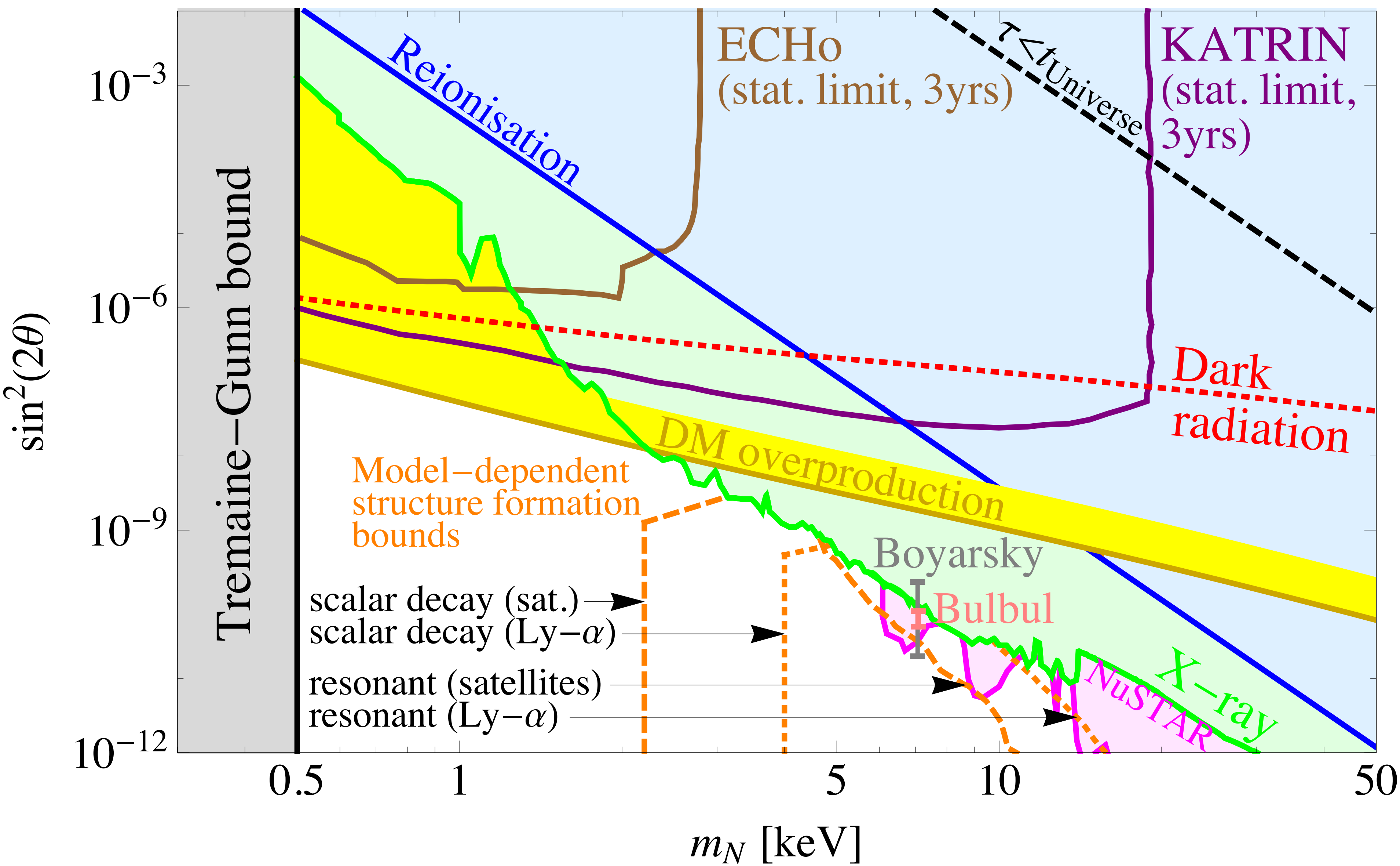
Slide from Thierry



thierry.lasserre@cea.fr

5. Where to go from here?!?

GROUND-BASED EXPERIMENTS:



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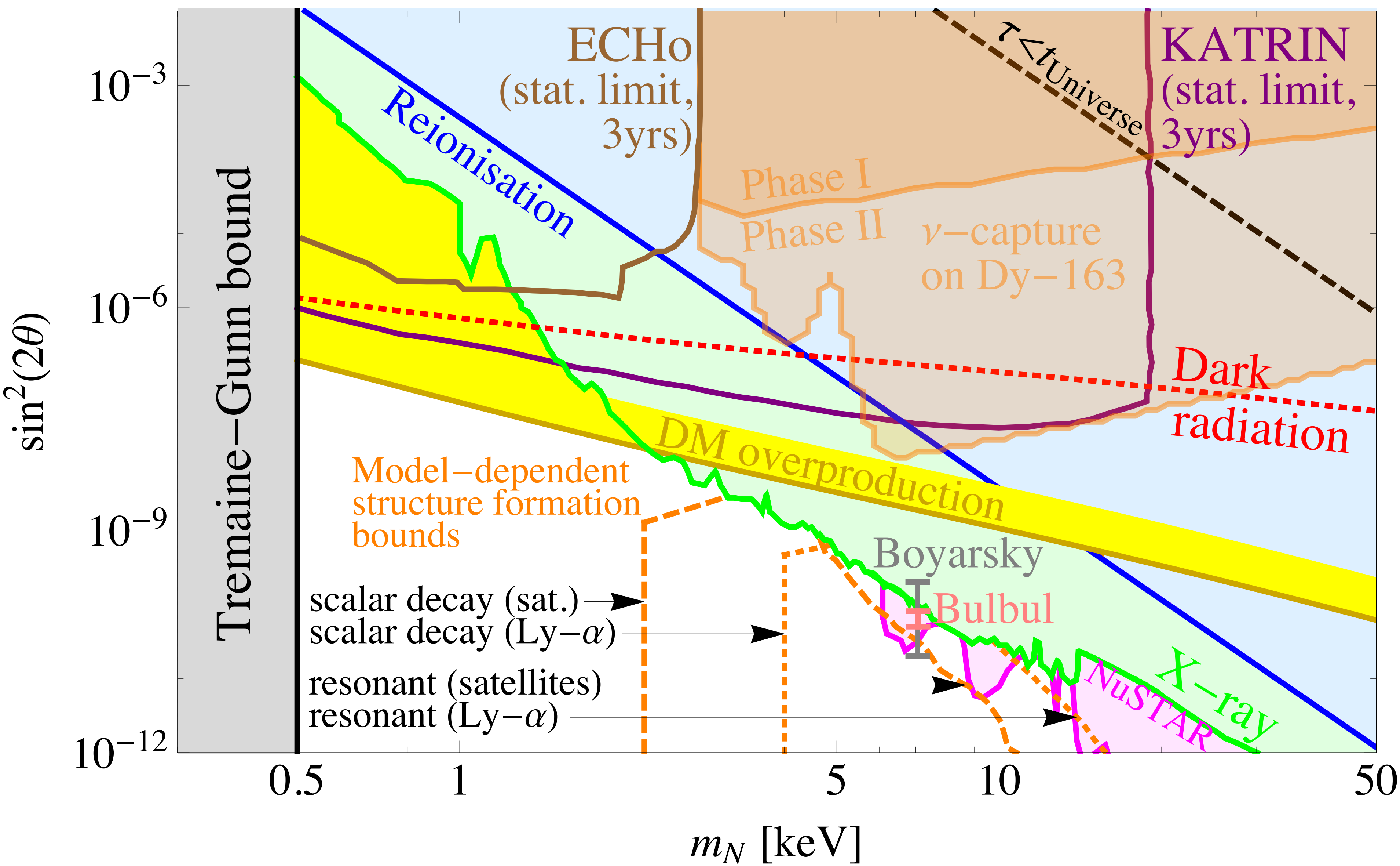

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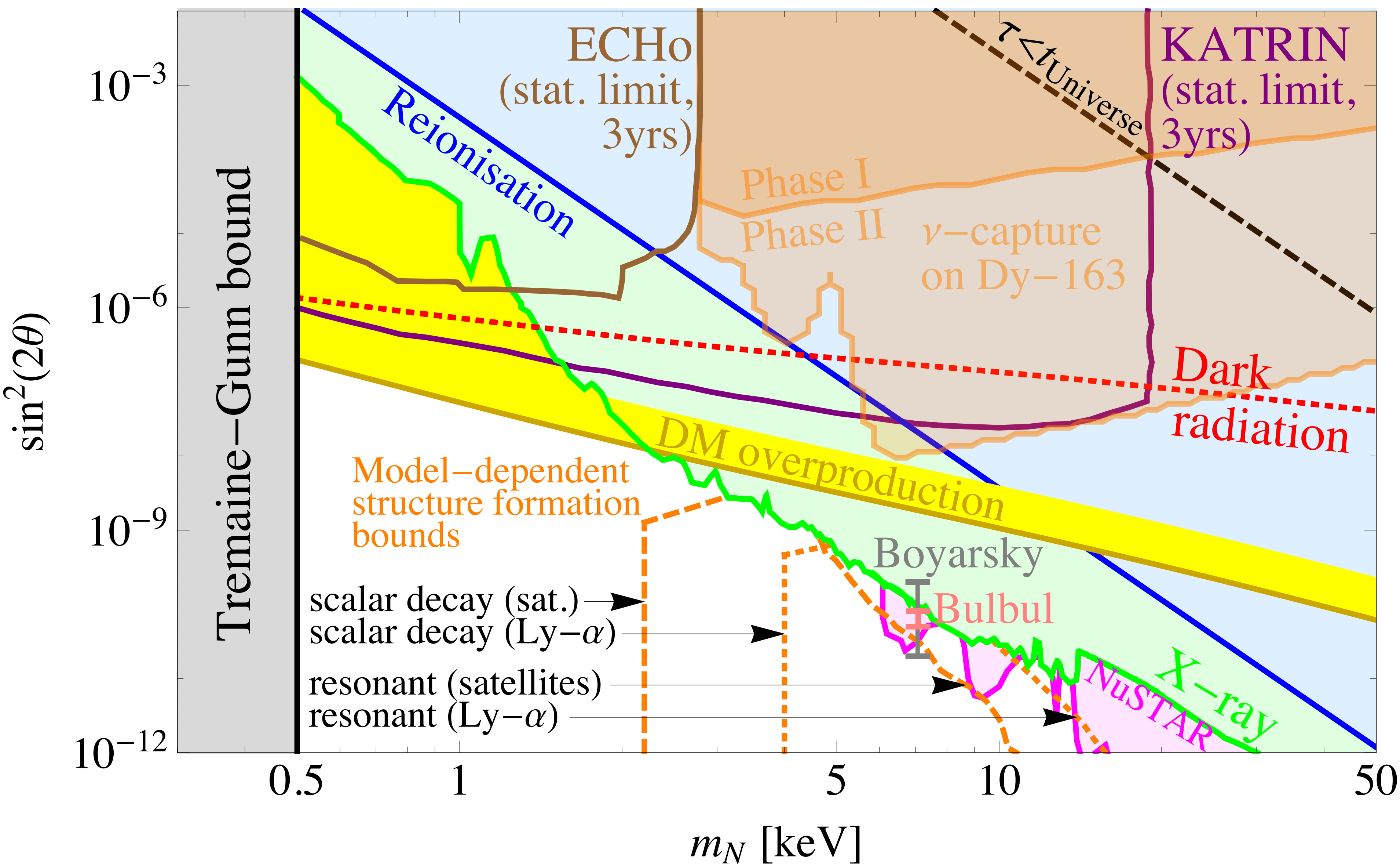

5. Where to go from here?!?

GROUND-BASED [...] MENTS:

- scalable!!
- benefits from SMALL mass!!
- detailed paper out soon