STERILE NEUTRINOS

"The existence of hundreds of new particles may seem far fetched, but is in principle not impossible."
(Boyarski et al. 2018)

Antoniadis, Carreira, & Karchev. GRAPPA Student Seminar (2019)

MOTIVATION

Neutrinos

- Electrically neutral
- Only interact weakly
- Long-living
- Oscillate $\Rightarrow$ Massive $\Rightarrow$ DM candidate?

Neutrinos

- $\rho_\nu = n_\alpha \sum m_i \quad , \qquad n_\alpha = \frac{4}{6}\frac{\zeta(3)}{\pi^2}T_\nu^3$
- $T_\nu \simeq \left(\frac{4}{11}\right)^{\frac{1}{3}} T_\gamma \simeq 10^{-4} eV$
- DM candidates $\Rightarrow \sum m_i \simeq 11.5 eV$
- But $\sum m_i < 0.12 eV$

Neutrinos

- $m_\nu << T_\nu$

  $\Rightarrow$ Neutrinos decouple relativistic

  $\Rightarrow$ No time for large structure formation

- Hot DM

Neutrinos

- $\sum m_i < 0.12eV$

- Hot DM

$\Longrightarrow$ Not a viable DM candidate

The SM does not contain a viable DM candidate *“particles that are, from the point of view of ordinary weak interactions,* **sterile**, *i.e. practically unobservable, since they have the “incorrect” helicity”*

(Bruno Pontecorvo, 1967)

Sterile neutrinos

- With a mass of a few keV, sterile neutrinos could make up all DM
- Could also solve the neutrino mass problem

Sterile neutrinos

- $$\mathcal{L} = \mathcal{L}_{SM} + \underbrace{i\overline{\nu_{Ri}}\partial\!\!\!/\nu_{Ri}}_{\text{Kinetic}} - \left[\underbrace{\frac{1}{2}\overline{\nu^c_{Ri}}(M)_{ij}\nu_{Rj}}_{\text{Majorana}} - \underbrace{Y_{ai}\overline{l_{La}}\epsilon\phi^*\nu_{Ri}}_{\text{Interactions}} + h.c.\right]$$

- At low energies,

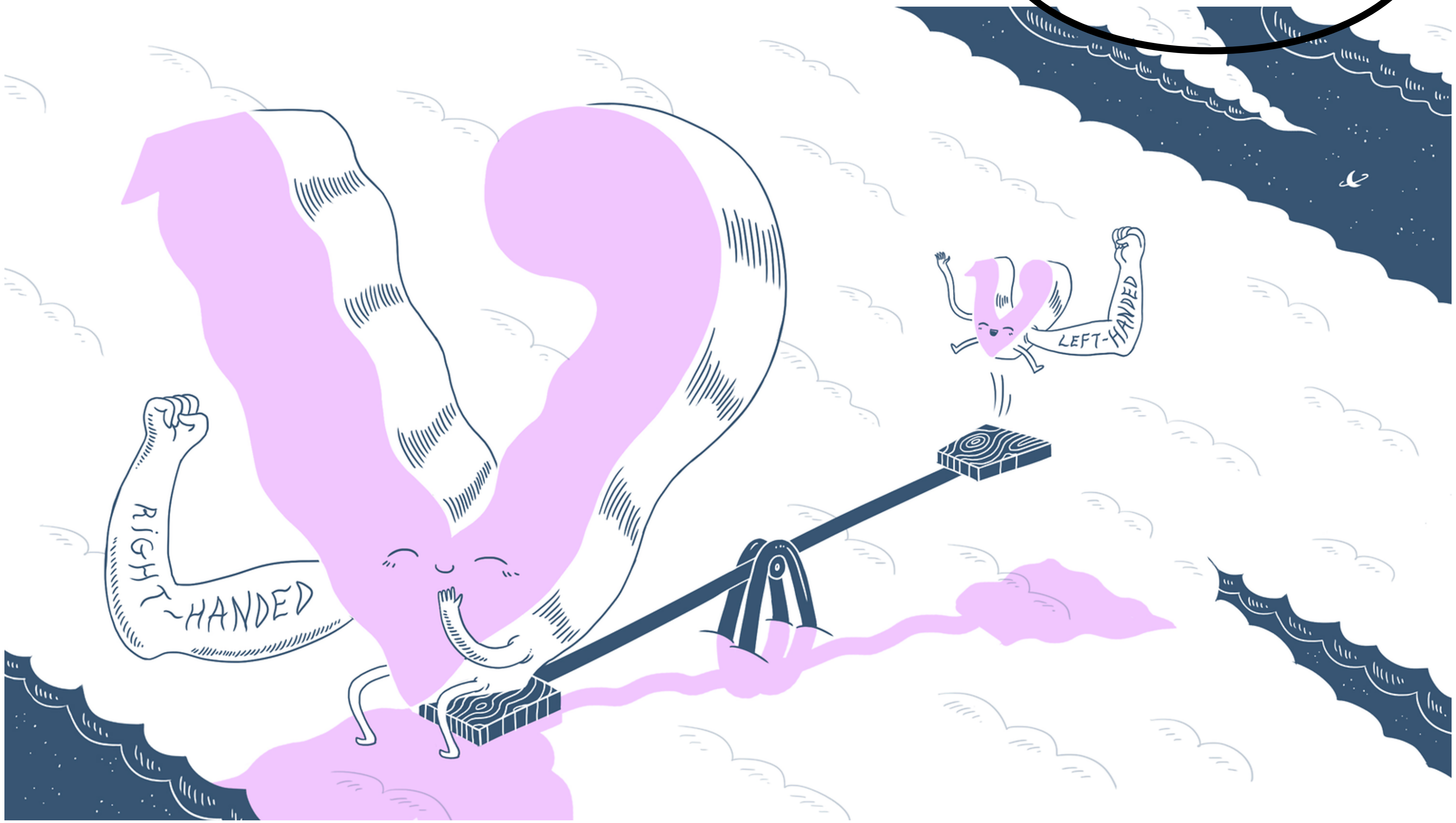
$$\Longrightarrow \; \mathcal{L}_{eff} = \mathcal{L}_{SM} + \frac{1}{2}\overline{l_L}\tilde{\phi}Y M_M^{-1} Y^T \tilde{\phi}^T l_L^c$$

Sterile neutrinos

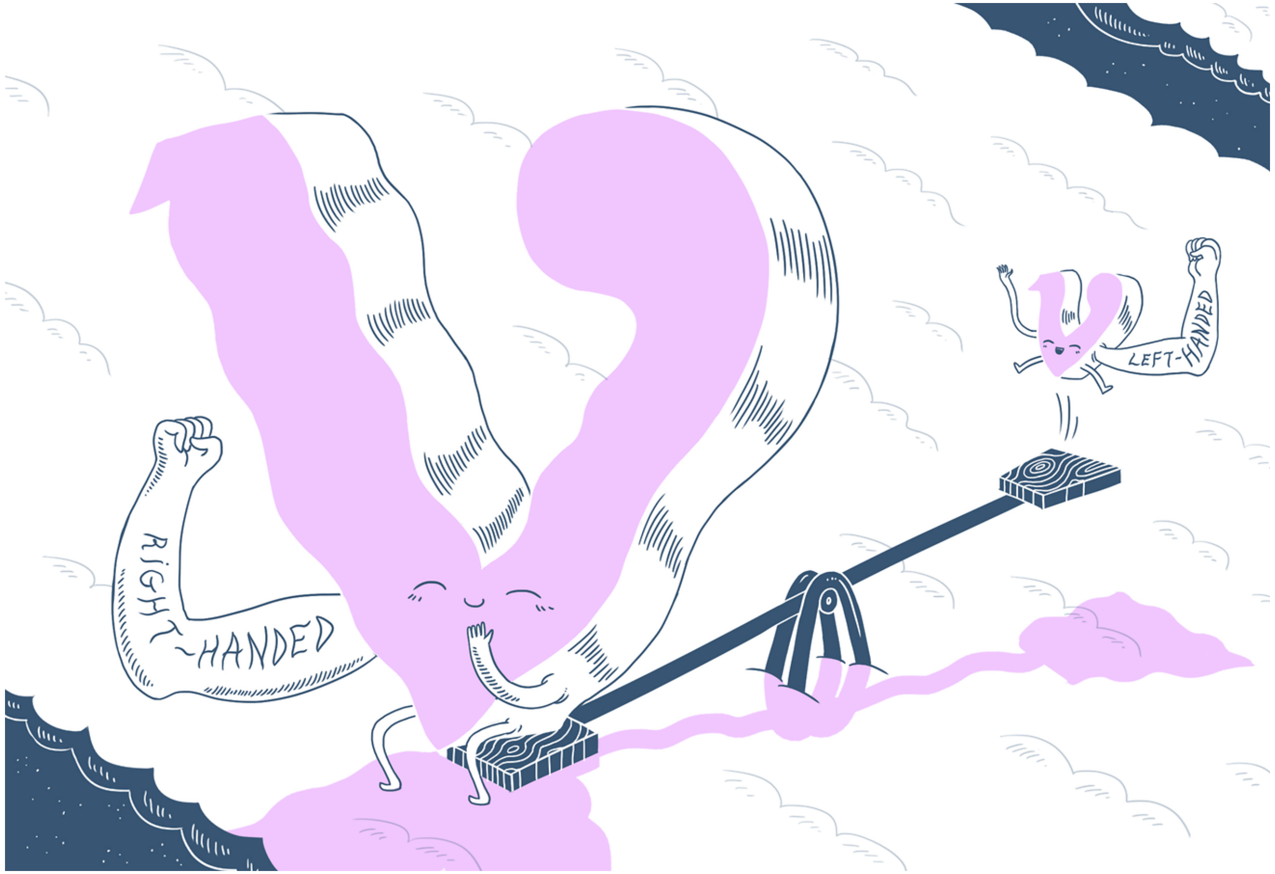
- $\mathcal{L}_{eff} = \mathcal{L}_{SM} + \frac{1}{2}\overline{l_L}\tilde{\phi} Y M_M^{-1} Y^T \tilde{\phi}^T l_L^c$
- The Higgs mechanism then generates a Majorana mass term of the form $\frac{1}{2}\overline{\nu_L} m_\nu \nu_L^c$
- With $m_\nu = -v^2 Y M_M^{-1} Y^T \Rightarrow$ Seesaw mechanism

Seesaw mechanism

$$m_\nu = -v^2 Y M_M^{-1} Y^T$$



Seesaw mechanism



$$m_\nu = -v^2 Y M_M^{-1} Y^T$$

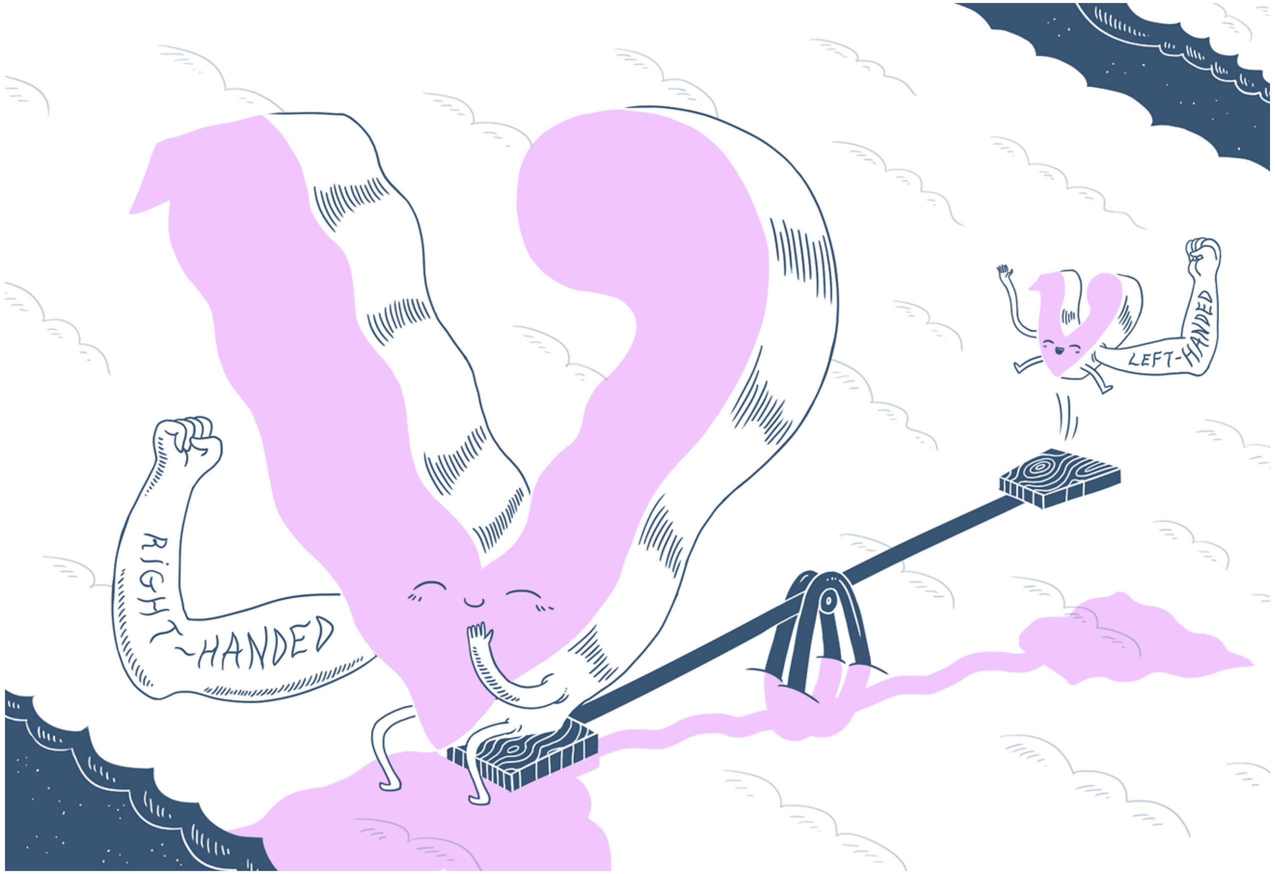
$$m_\nu \simeq 0.1 eV$$

$$Y \simeq 1$$

$$\Downarrow$$

$$M_N \simeq \text{GUT scale}$$

Seesaw mechanism



$$m_\nu = -v^2 Y M_M^{-1} Y^T$$

$$m_\nu \simeq 0.1 eV$$

$$Y << 1$$

$$\Downarrow$$

$$M_N \simeq keV \text{ scale}$$

(Dark Matter)

PRODUCTION MECHANISMS

Thermal Production via Mixing ("freeze in")

Non-resonant Production

Resonant Production

Thermal Production via New Gauge Interactions ("freeze out")

Non-thermal Production in the decay of heavier particles

Thermal production via mixing ("freeze in")

- Weak interaction
- Active-sterile mixing (seesaw model)

$$|\nu_a\rangle = \cos\theta\,|\nu_1\rangle + \sin\theta|\nu_2\rangle$$

$$|\nu_s\rangle = -\sin\theta\,|\nu_1\rangle + \cos\theta|\nu_2\rangle$$

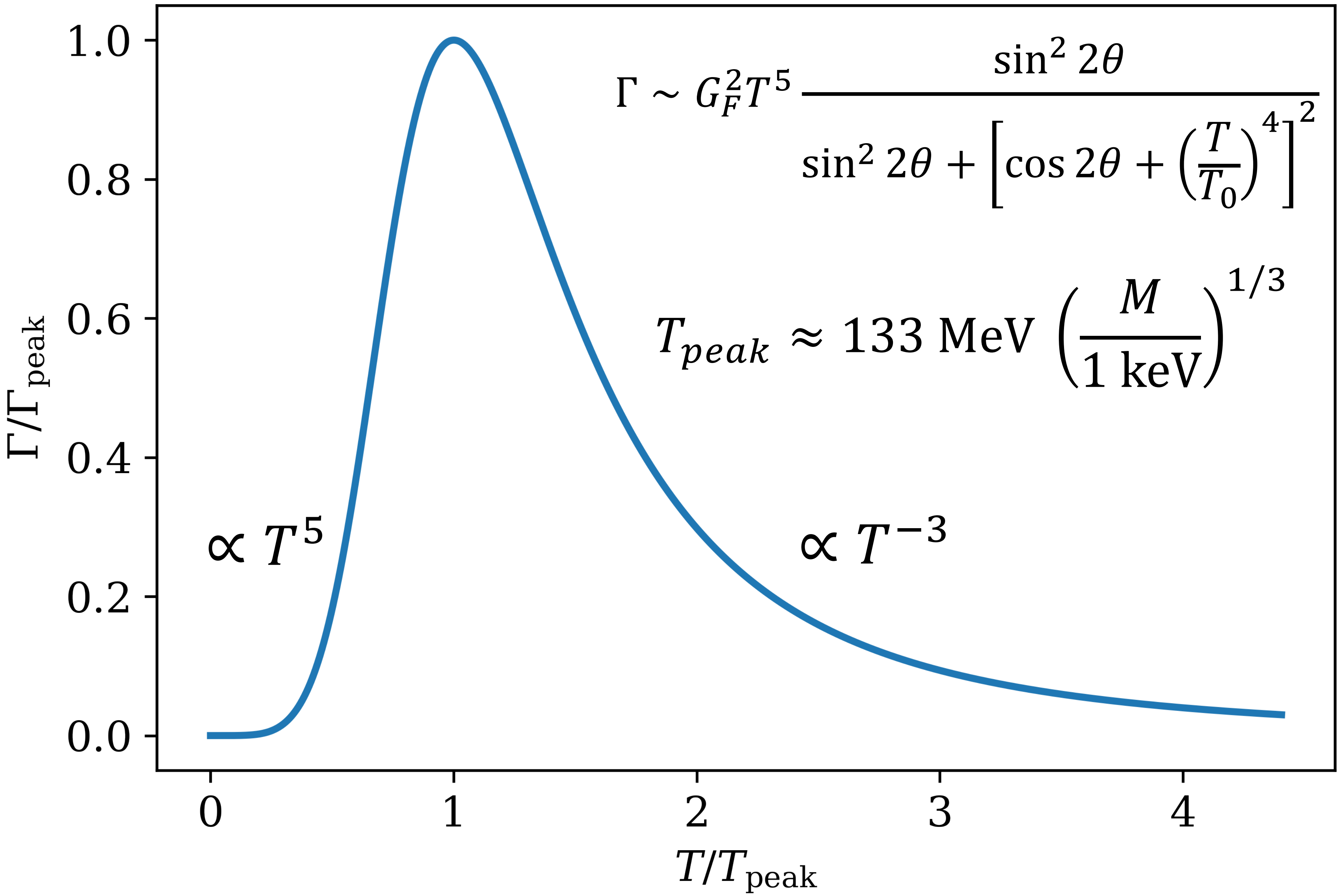
Non-resonant production

- Coherent oscillations between active and sterile states
- Decoherent scatterings
  - *Destroy the coherence of the quantum state*
  - *Force it into weak interaction*

$$|\nu_a\rangle = \cos\theta_m(t)\,|\nu_1(t)\rangle + \sin\theta_m(t)|\nu_2(t)\rangle$$

$$|\nu_s\rangle = -\sin\theta_m(t)\,|\nu_1(t)\rangle + \cos\theta_m(t)|\nu_2(t)\rangle$$

$$\Gamma \sim G_F^2 T^5 \frac{\sin^2 2\theta}{\sin^2 2\theta + \left[\cos 2\theta + \left(\frac{T}{T_0}\right)^4\right]^2}$$



$\Gamma \sim G_F^2 T^5 \dfrac{\sin^2 2\theta}{\sin^2 2\theta + \left[\cos 2\theta + \left(\frac{T}{T_0}\right)^4\right]^2}$
$T_{peak} \approx 133\ \mathrm{MeV} \left(\dfrac{M}{1\ \mathrm{keV}}\right)^{1/3}$
$\propto T^5$
$\propto T^{-3}$
$\Gamma/\Gamma_{\rm peak}$
$T/T_{\rm peak}$
1.0
0.8
0.6
0.4
0.2
0.0
0
1
2
3
4

Resonant production

- Lepton asymmetries

$$l_{\nu_a} \equiv (n_{\nu_a} - n_{\overline{\nu}_a})/n_\gamma$$

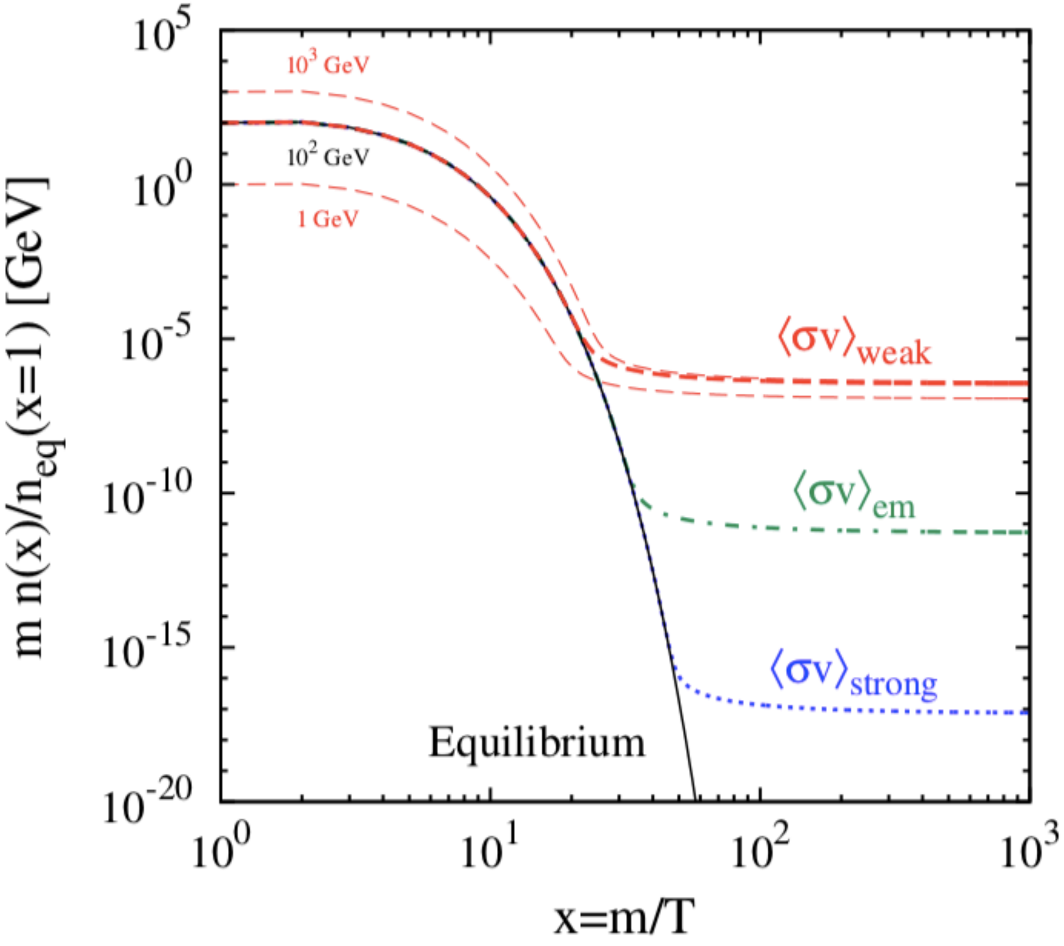
- Mikheyev–Smirnov–Wolfenstein (MSW) effect
  - *Enhances the transition between two kinds of neutrinos in a changing lepton density*
- Disfavoured by constraints from Lyman-α forest, dwarf galaxy number counts and X-ray data
- Uncertain how large lepton asymmetries could be generated

New gauge interactions ("freeze-out")

$$\Gamma_N = G_F^2\, T^5 \left(\frac{m_W}{m_{W_R}}\right)^4$$

$$m_{W_R} > 1\ \mathrm{TeV}$$

Steigman et al. 2012

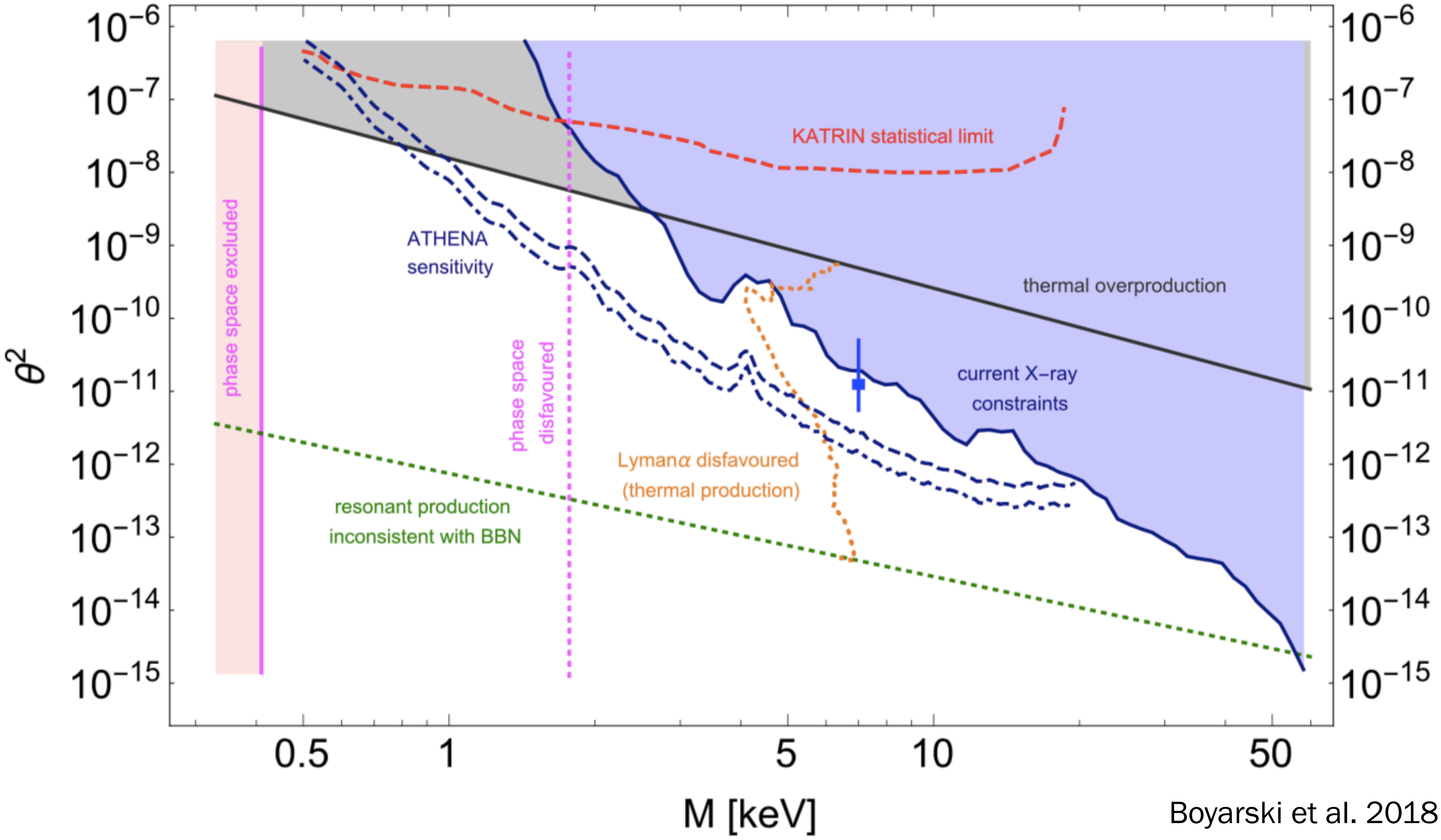


$$\Omega_N/\Omega_{DM} = \frac{1}{S}\left(\frac{10.75}{g_{*S}(t_f)}\right)\left(\frac{M}{\mathrm{keV}}\right) \times 100$$

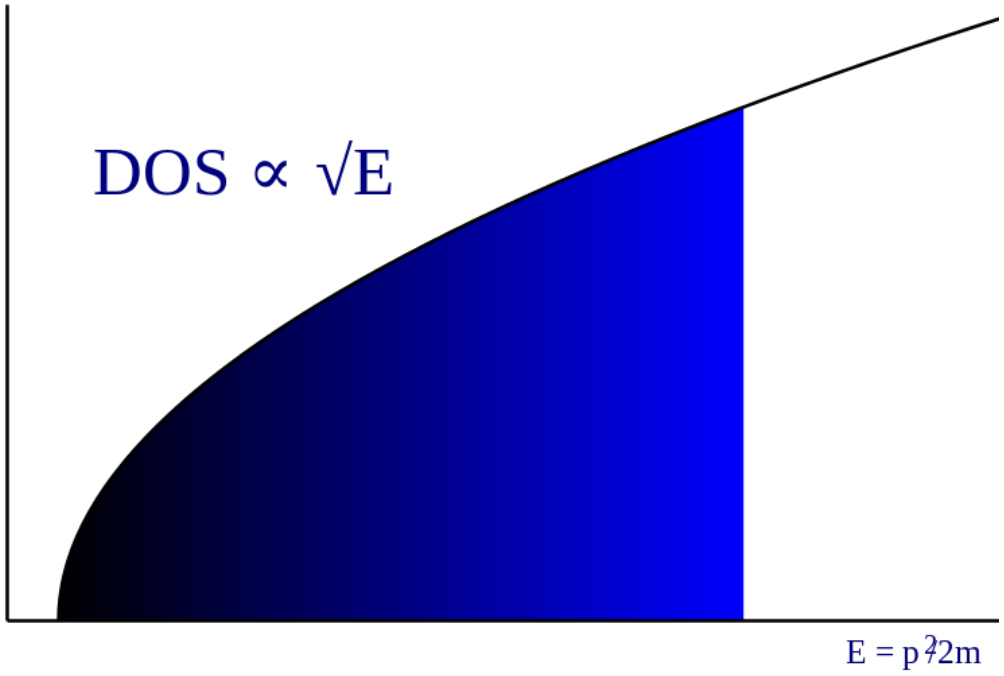
Non-thermal Production in the decay of heavier particles

- Decay far from thermal equilibrium
- Decay of a heavier parent particle
- Sterile neutrino in keV scale
- highly relativistic
- Possible decays of pions, the Higgs boson, W bosons

OBSERVATIONAL EVIDENCE



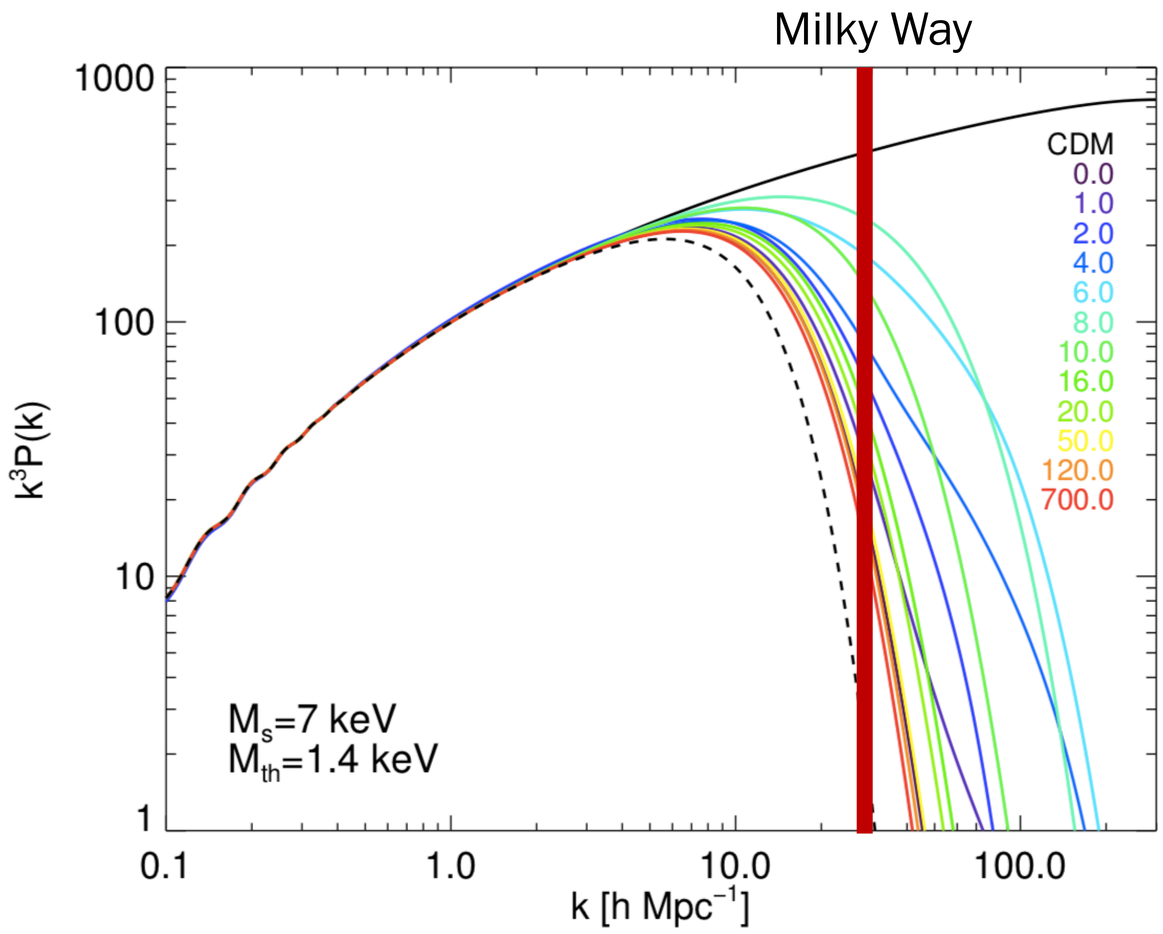
Boyarski et al. 2018



$$M_{DM} > \frac{9\pi\hbar^3}{4\sqrt{2}G_N^{3/2}} \frac{1}{\sqrt{M_{halo}R^3}}$$

$$\approx 100 \text{ eV}$$

Phase space saturation



Boyarski et al. 2018

Warm dark matter

Lensing

- Lensing applicable at low z
- CDM/WDM difference most pronounced at high-z

Lensing

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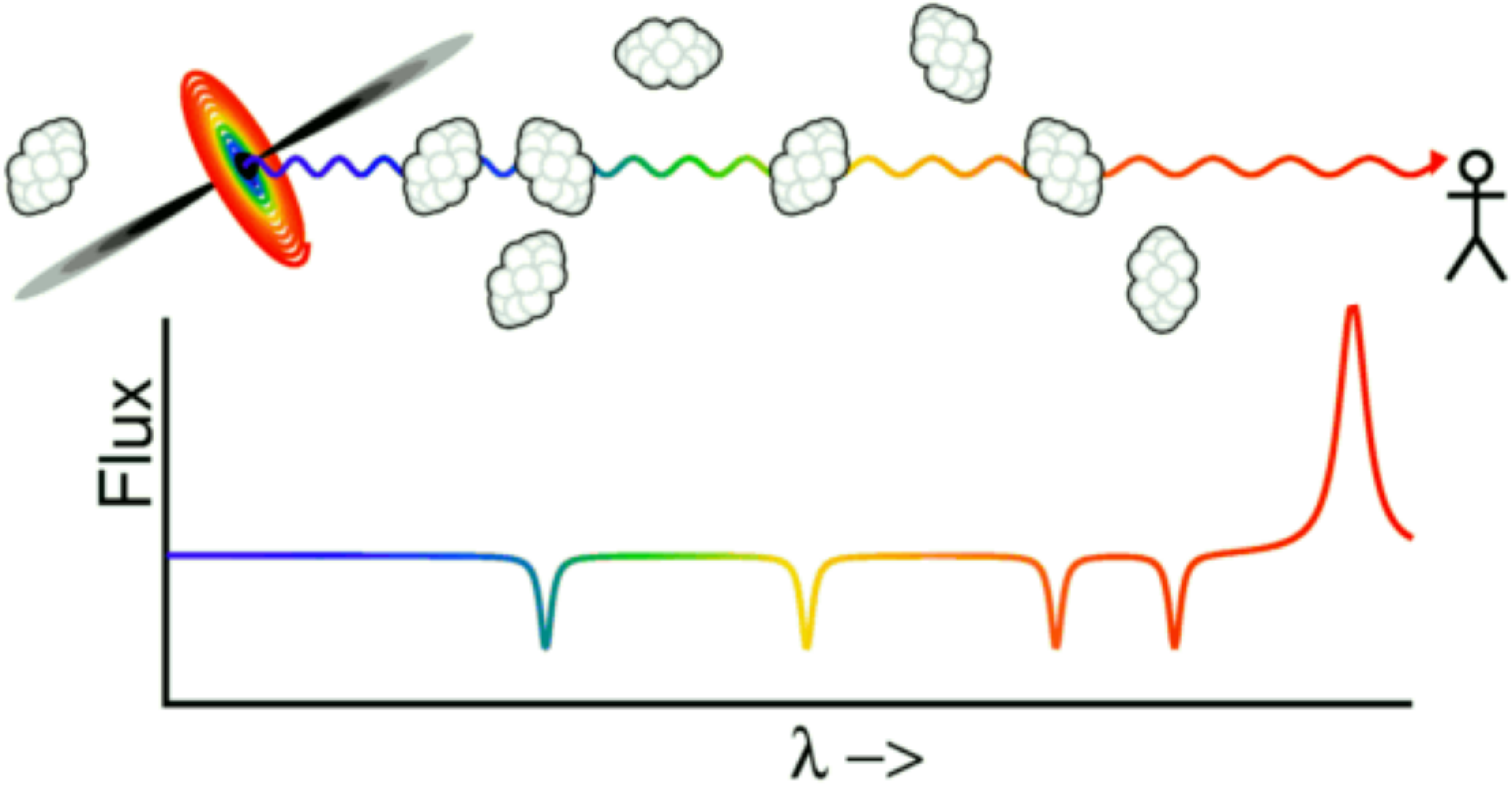
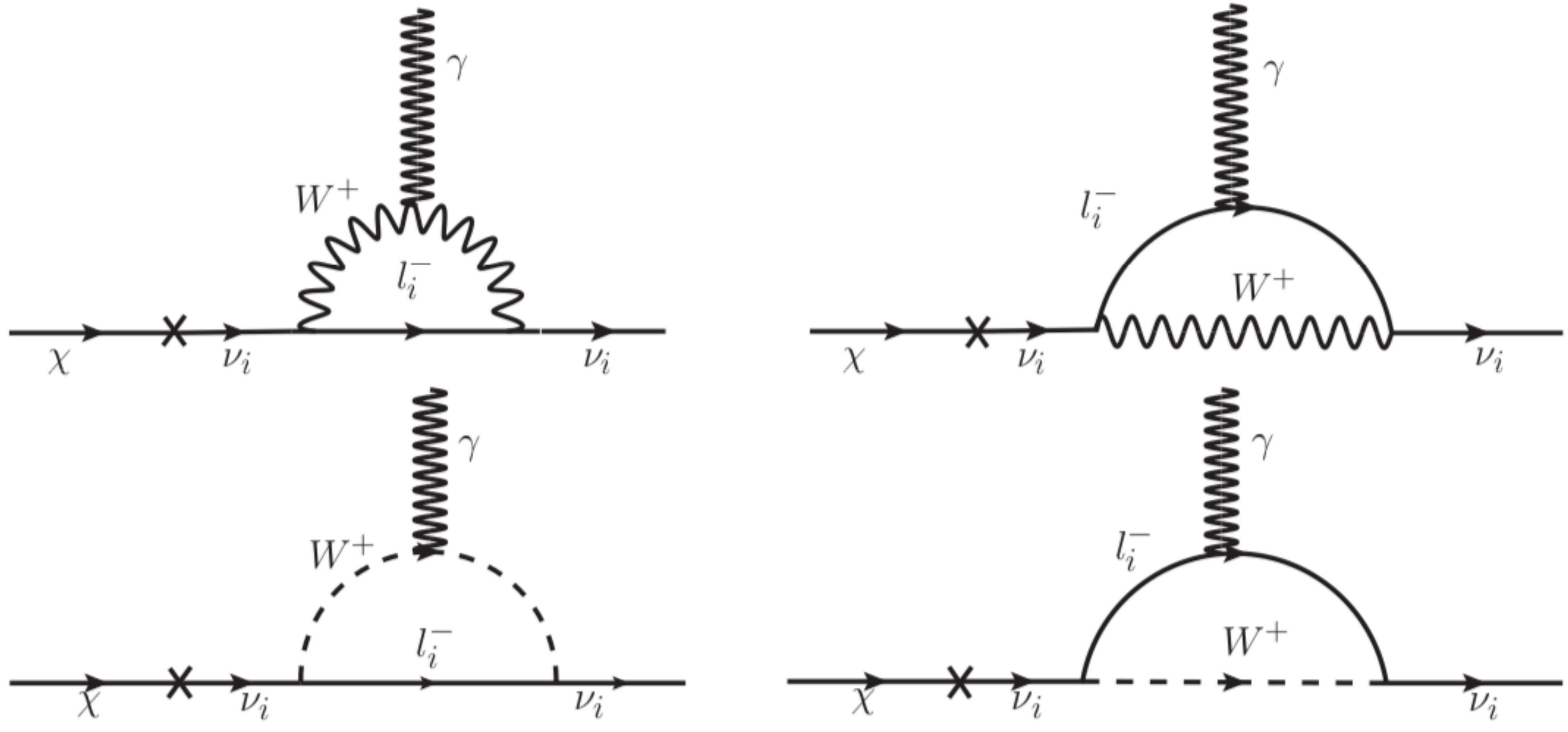
Counting haloes

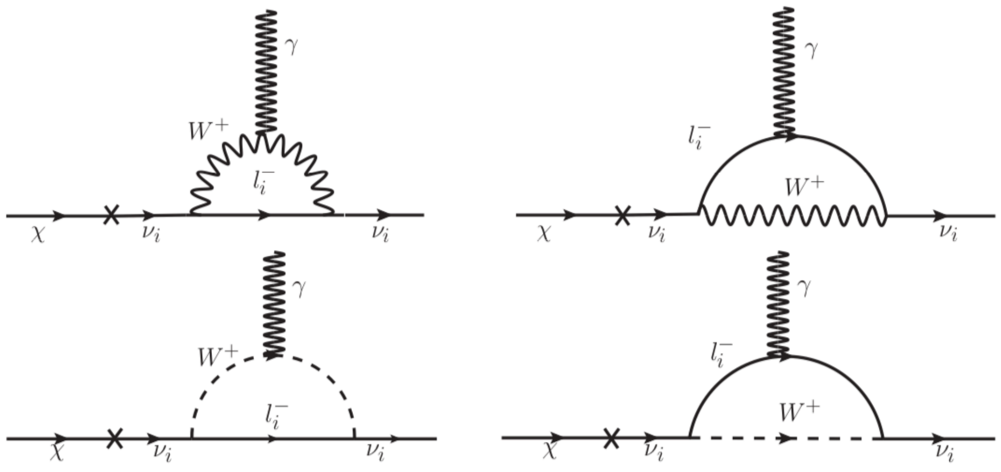
- Nonlinear structure formation
  - *realization variance (possibly larger than physical effects)*
- Small haloes countable only for very local universe (MW, Andromeda)
  - *Milky Way has fewer satellites than predicted*
- Baryonic structures may not trace DM
- Effects of pressure

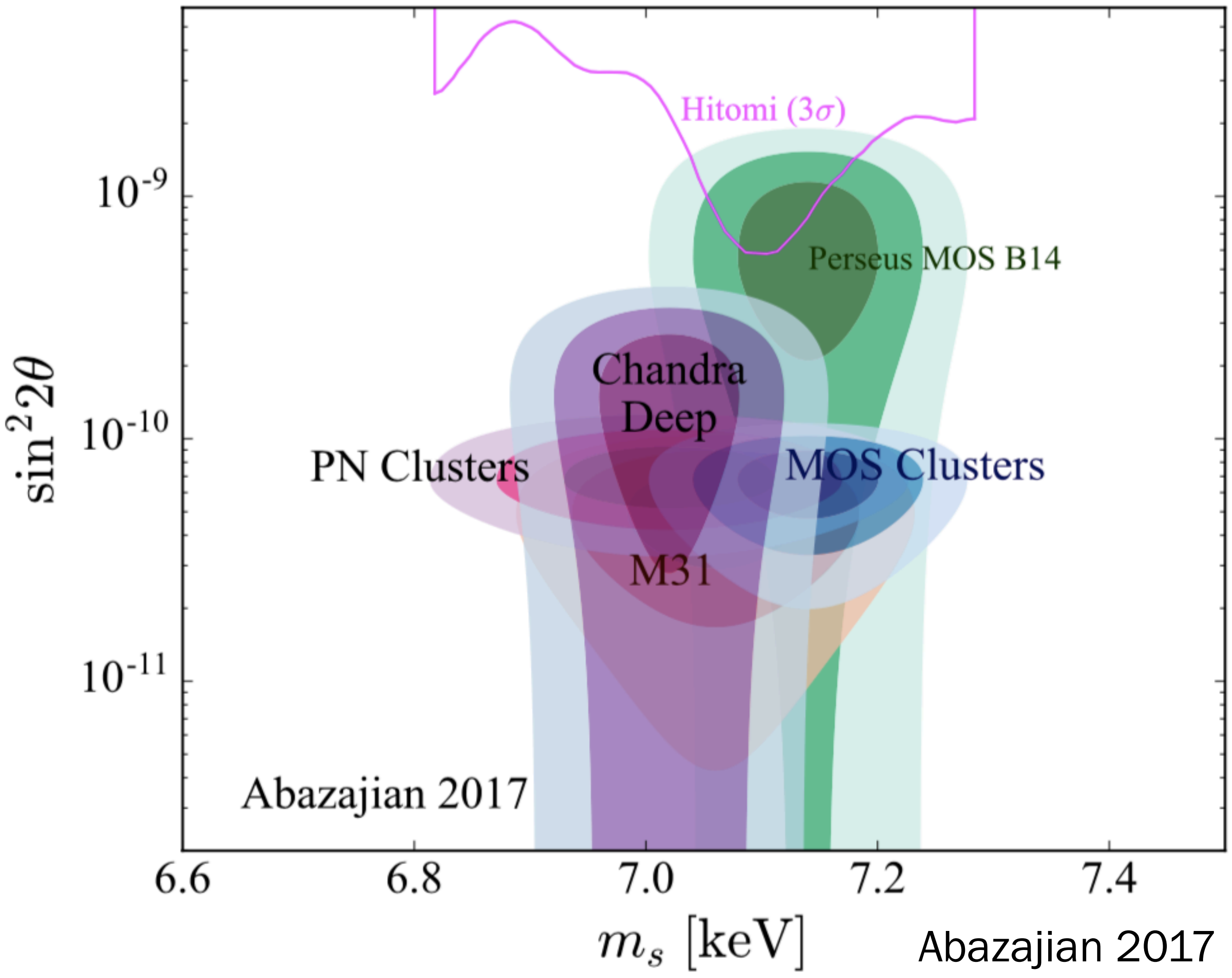


Lyman-α forest



Photon emission & the 3.5 keV line





Abazajian 2017

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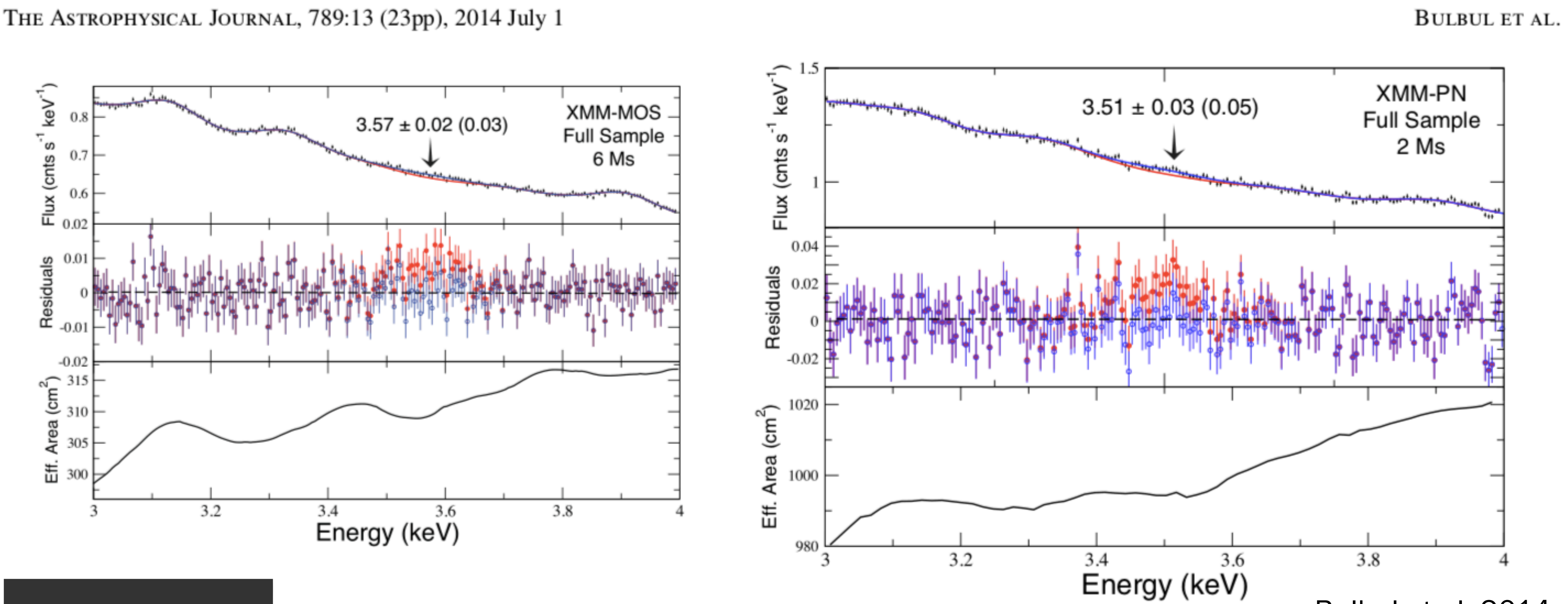

Bulbul et al. 2014

Significant?

A novel scenario for the possible X-ray line feature at ~3.5 keV:

Charge exchange with bare sulfur ions

Liyi Gu[1], Jelle Kaastra[1,2], A. J. J. Raassen[1,3], P. D. Mullen[4], R. S. Cumbee[4], D. Lyons[4], and P. C. Stancil[4]

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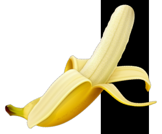
Dark matter searches going bananas: the contribution of Potassium (and Chlorine) to the 3.5 keV line

Tesla Jeltema[1⋆] and Stefano Profumo[1†]
[1]*Department of Physics and Santa Cruz Institute for Particle Physics University of California, Santa Cruz, CA 95064, USA*



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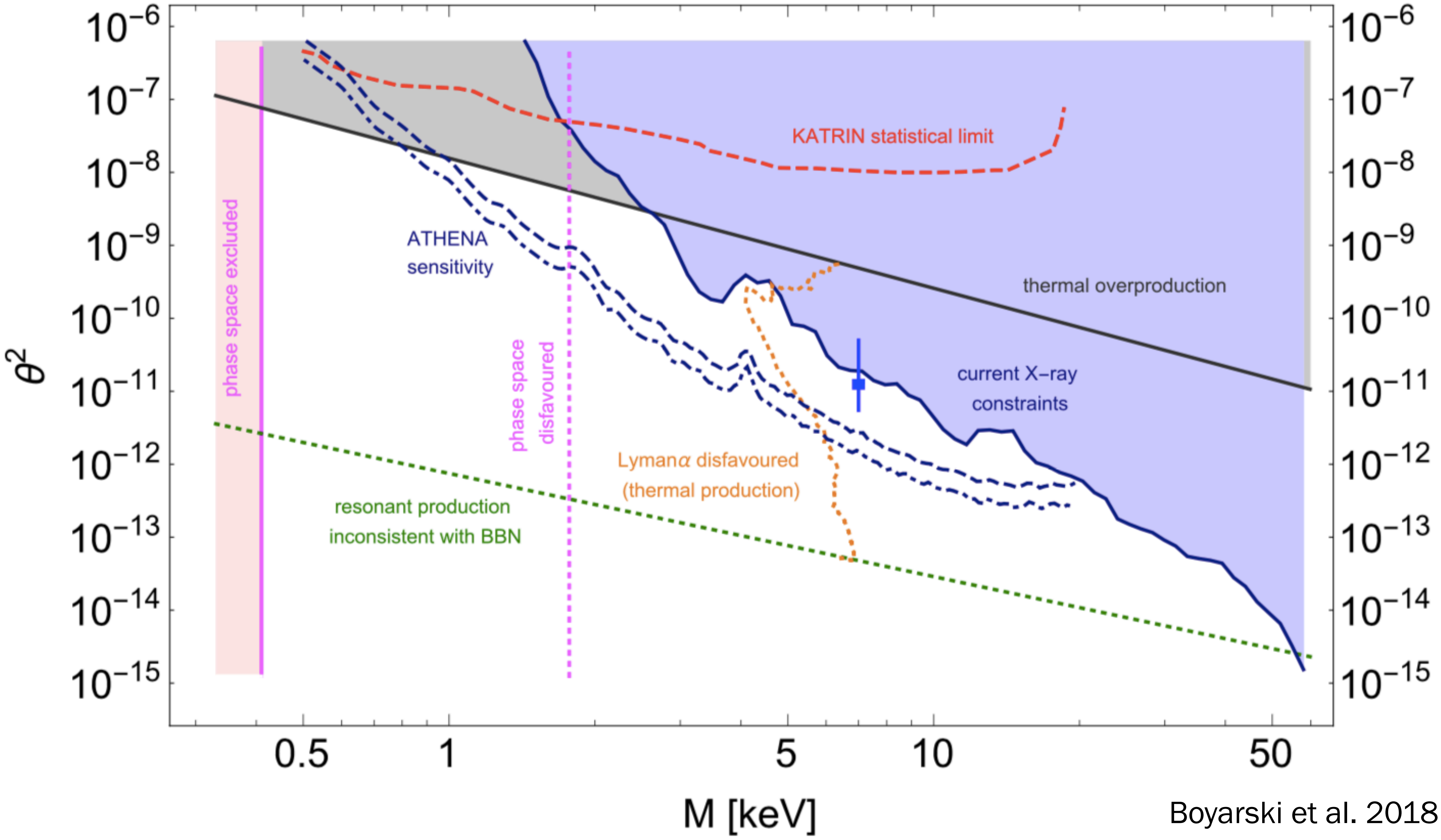
COMMENT ON "DARK MATTER SEARCHES GOING BANANAS: THE CONTRIBUTION OF POTASSIUM (AND CHLORINE) TO THE 3.5 KEV LINE"

Esra Bulbul (1), Maxim Markevitch (2), Adam R. Foster (1), Randall K. Smith (1), Michael Loewenstein (2), Scott W. Randall (1)
(1) Harvard-Smithsonian Center for Astrophysics, (2) NASA/GSFC

Draft version September 16, 2014



Boyarski et al. 2018


ν_e
ν_μ
ν_τ
?