Constraining DM models with extremely distant galaxies

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with:

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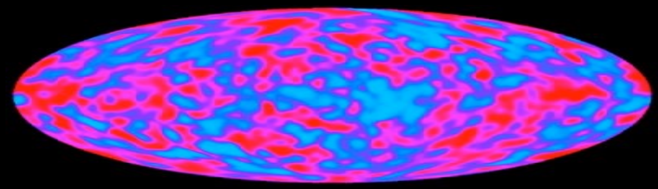
M. Totzauer, A. Lamastra

The Nature of DM determines the shape of the power spectrum P(k) and hence of the variance $\sigma^2(M)$

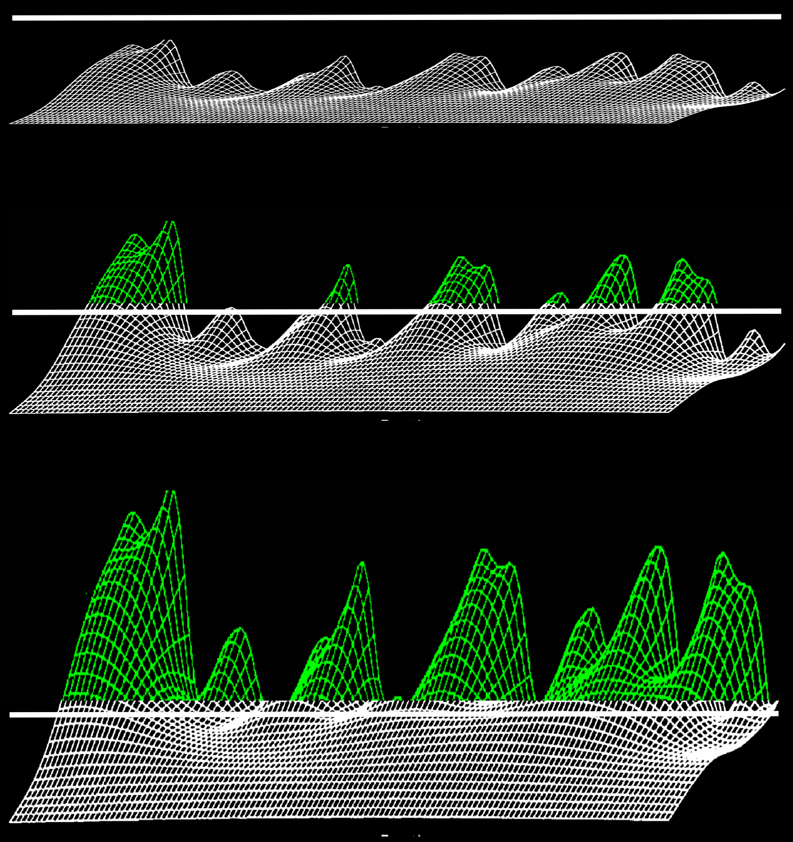


Mean (square) value of perturbations of size R(~1/k) enclosing a mass M

$$P(k) = \frac{1}{V} \langle |\delta_k|^2 \rangle$$

$$\sigma_M^2 = \frac{1}{(2\pi)^3 V} \int^{M \leftrightarrow k} dk\, k^2\, P(k)$$

$$\sigma_M^2 \leftrightarrow P(k)$$



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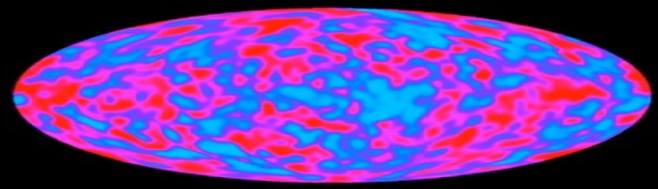

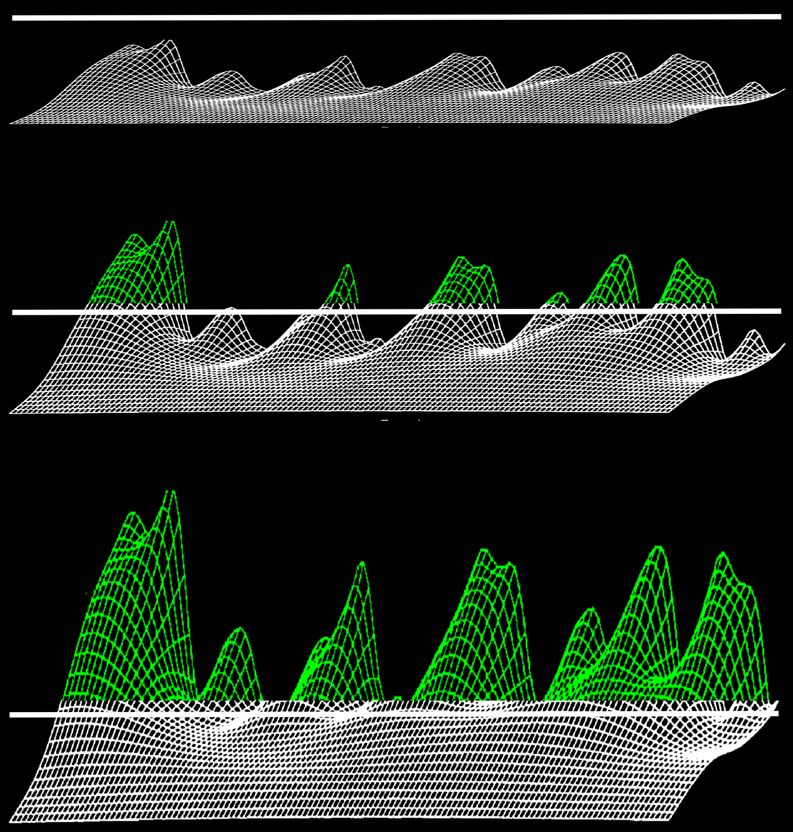

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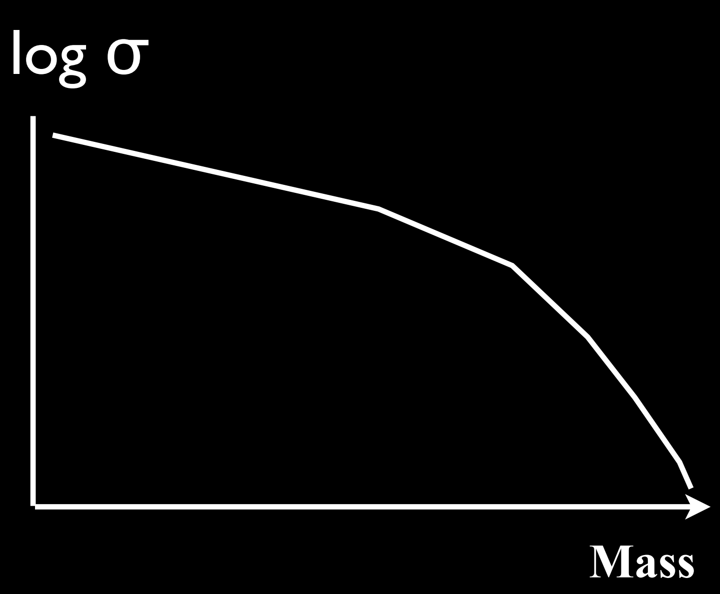
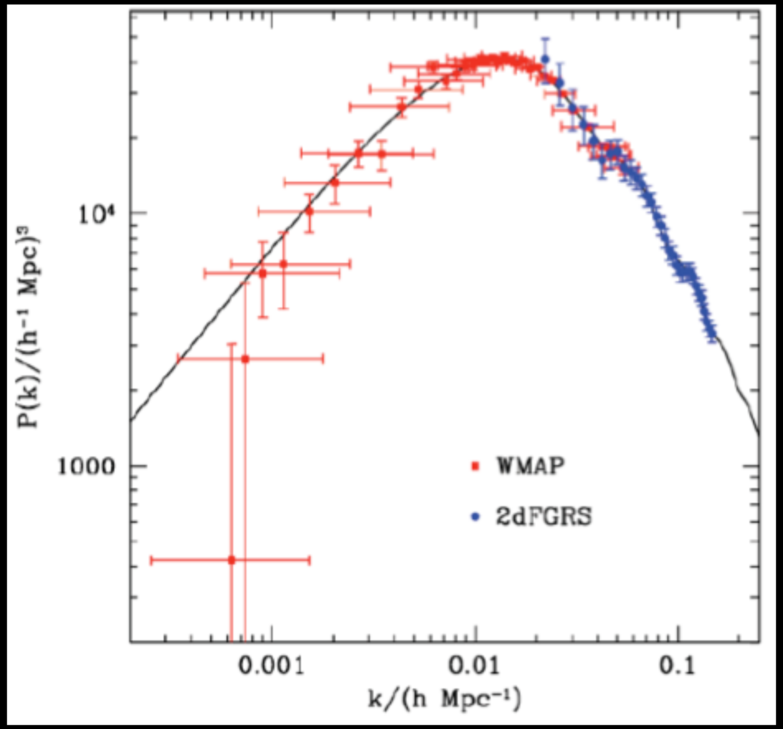
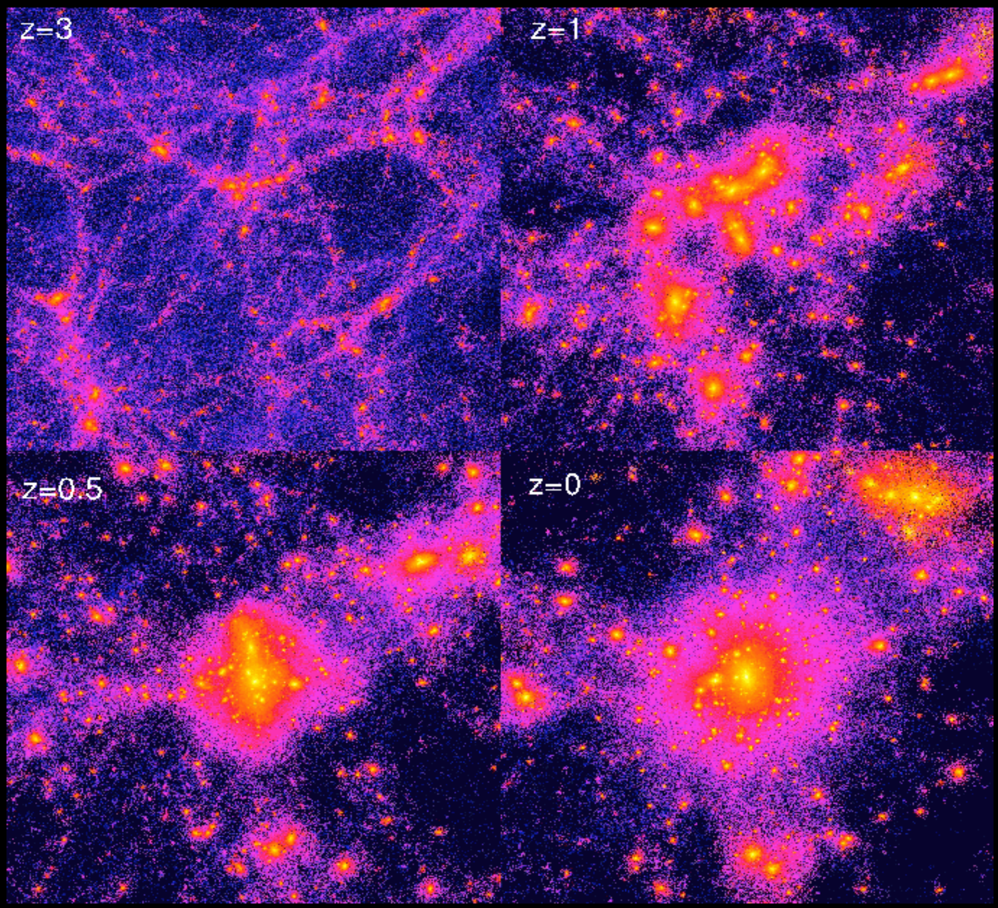
E.g. CDM generally assumes DM to be constituted by thermal relics with low velocity dispersion. Low-mass perturbations are not dissipated.

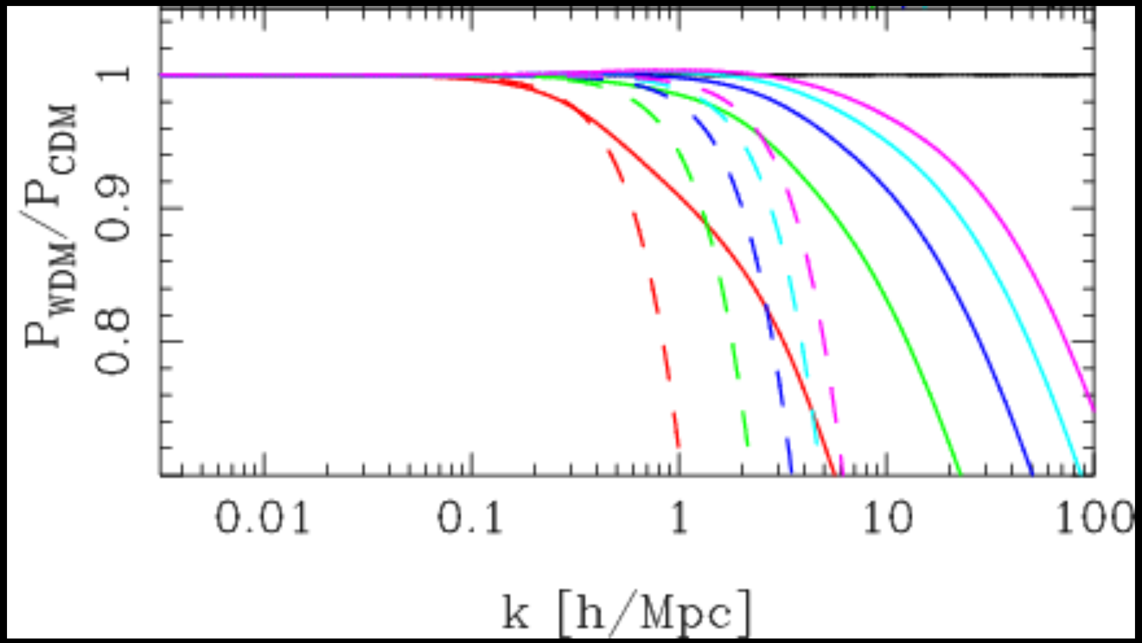


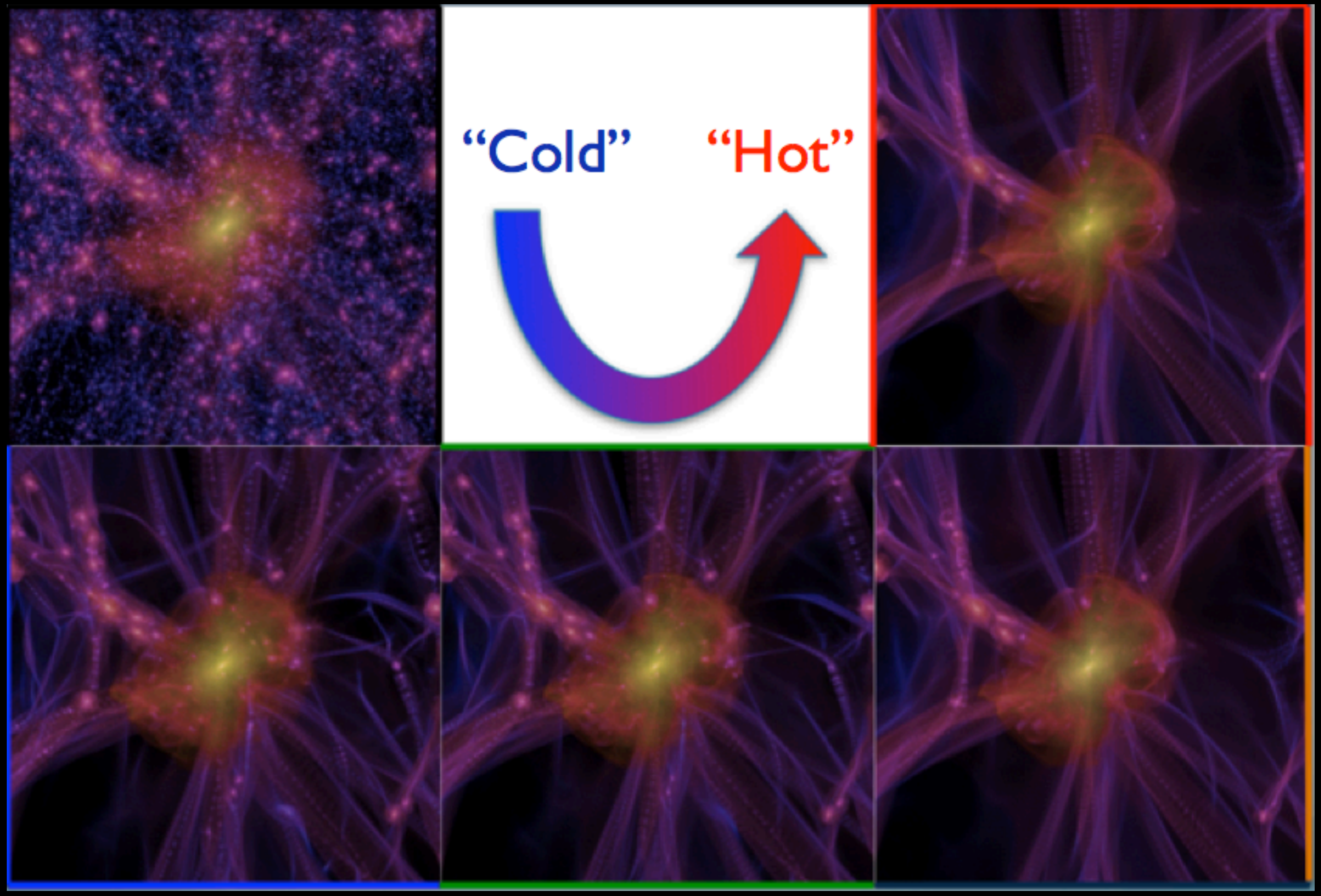


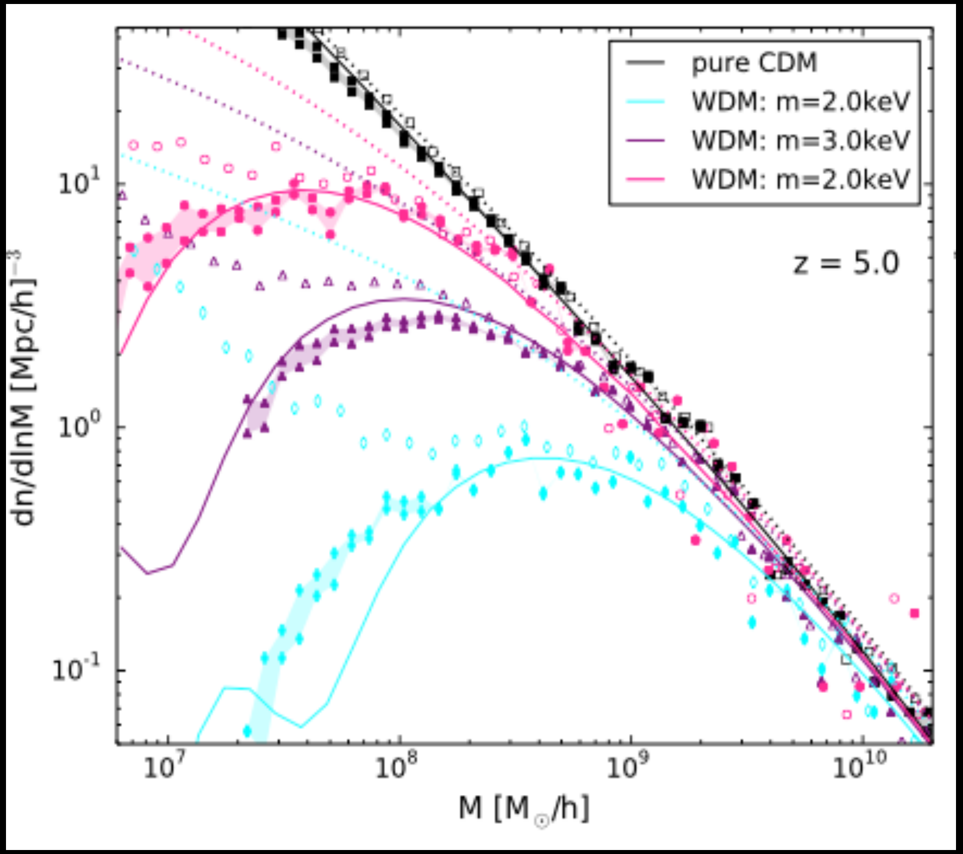


Thermal WDM The simplest case. Small-scale perturbations smoothed by free-streaming

1 parameter: the particle mass m_X in the range. m_X = 1 - 5 keV







Thermal WDM

The simplest case. Small-scale perturbations smoothed by free-streaming

1 parameter: the particle mass m_X in the range. $m_X = 1 - 5$ keV

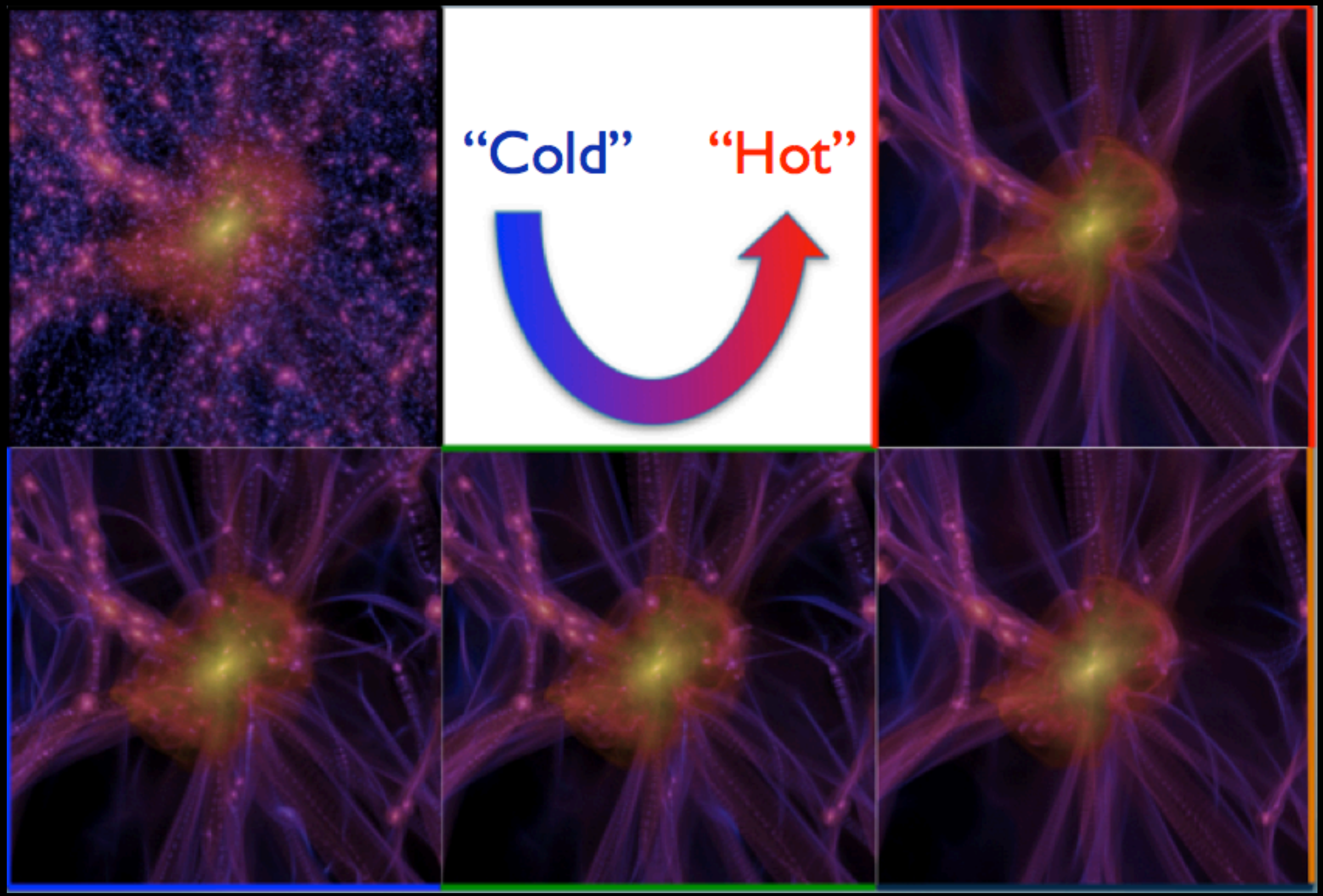
Constraints on m_X

from comparing the observed abundance of small-scale clumps (dwarf galaxies, Lyman-α absorbers) to the predicted abundance of low-mass DM clumps

This involves modelling the baryon physics to relate the observed structures to DM

Lower limits on m_X from abundance of sub-structures

$m_X \geq 1.5$ keV Polisensky & Ri-cotti 2011; Lovell et al. 2012, 2015 Horiuchi et al. 2014, Belokurov et al. 2010



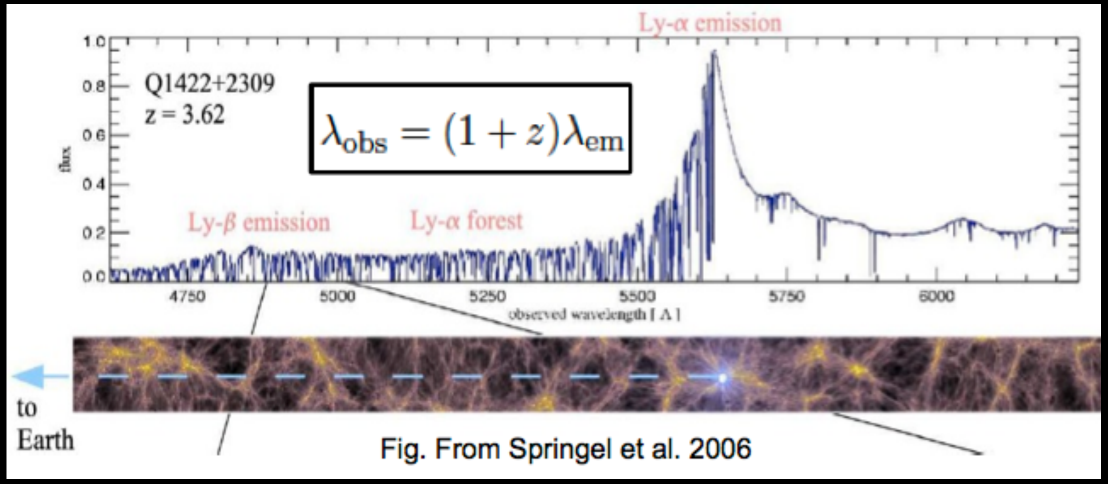


Fig. From Springel et al. 2006

Lyman-α absorbers yield $m_X > 3$keV

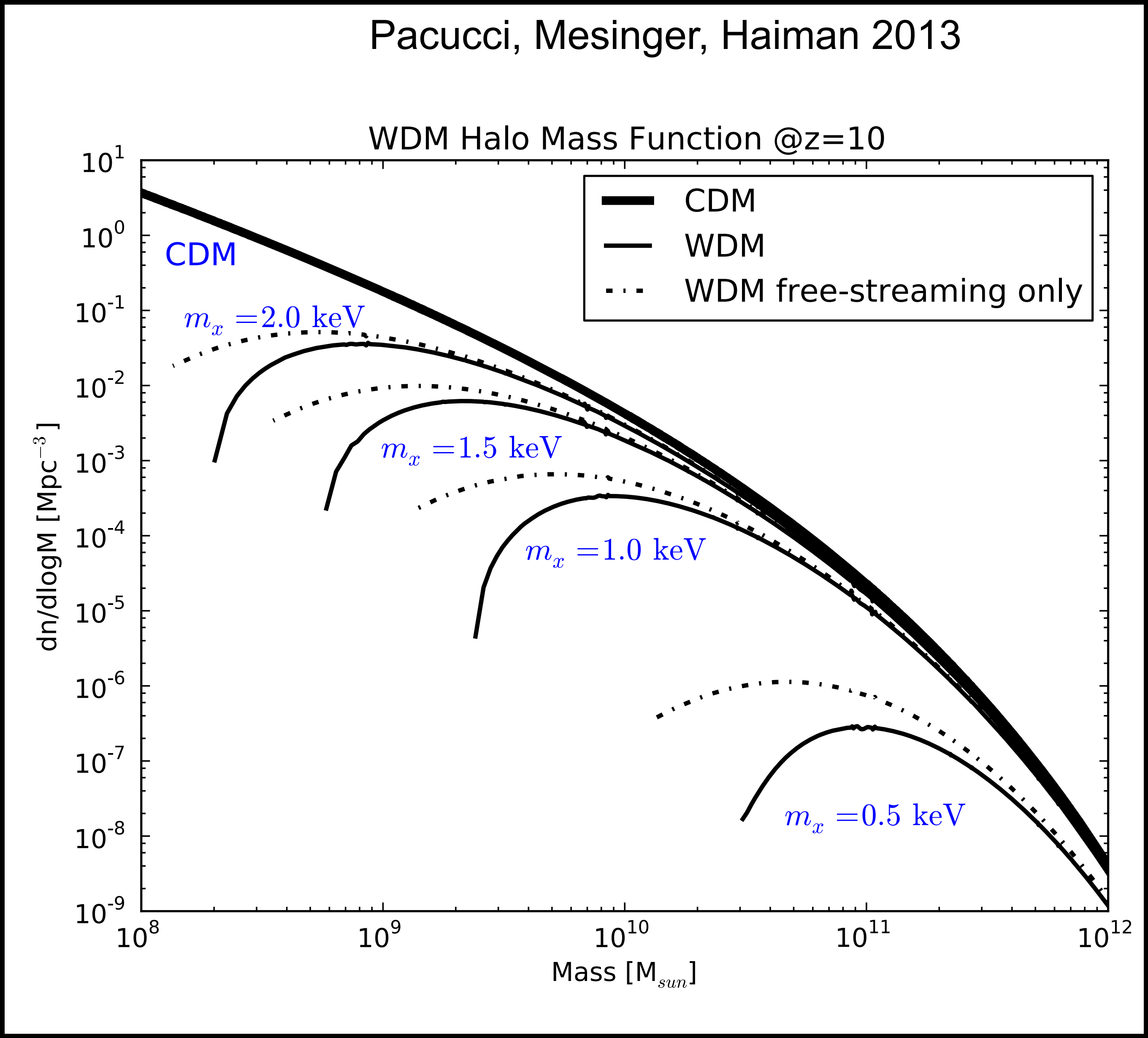
when compared to hydro simulations (intergalactic gas physics)
Viel+2005, 2013

Constraints on m_x from the abundance of low-mass galaxies: getting rid of degeneracy with astrophysics of gas and stars

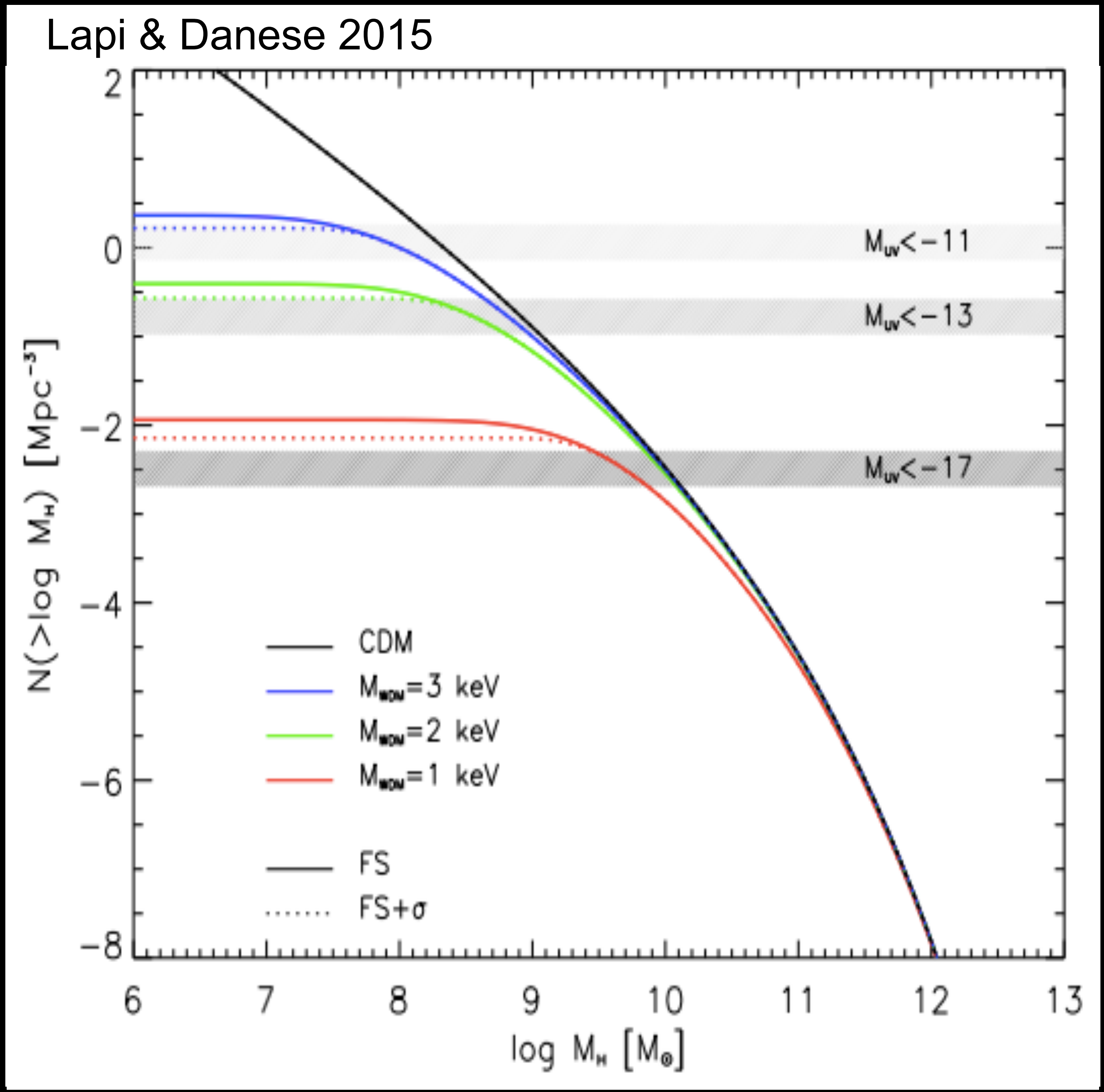
WDM mass functions exhibit a down turn at masses close to the half-mode mass
Correspondingly, the number density of halos per Mpc^3 saturates to a maximum value at small M

Observe galaxy density larger than such a maximum value would rule out the corresponding WDM particle mass independently of L/M relation

Differential Halo Mass function



Cumulative Halo Mass function (number / Mpc^3)



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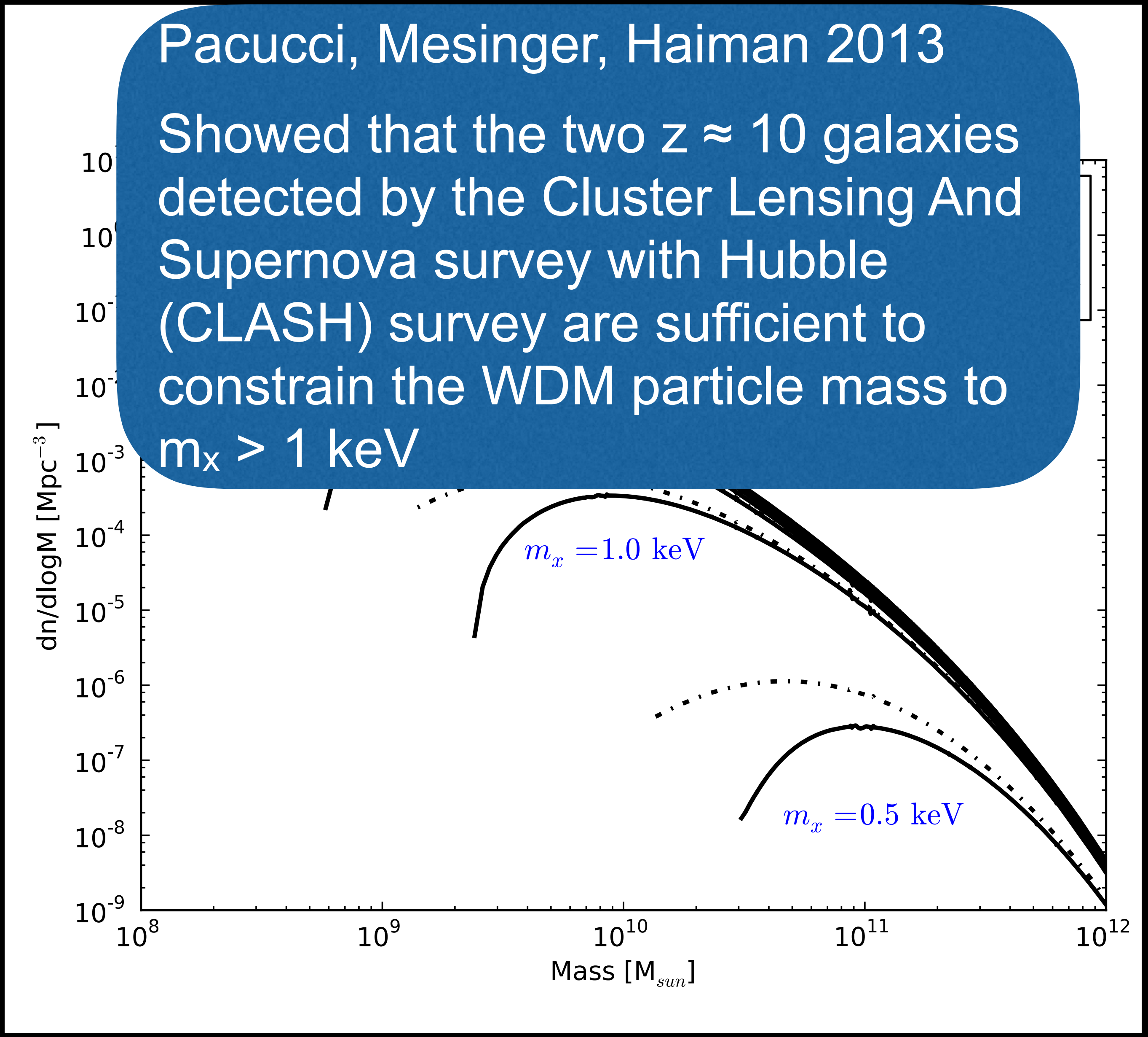

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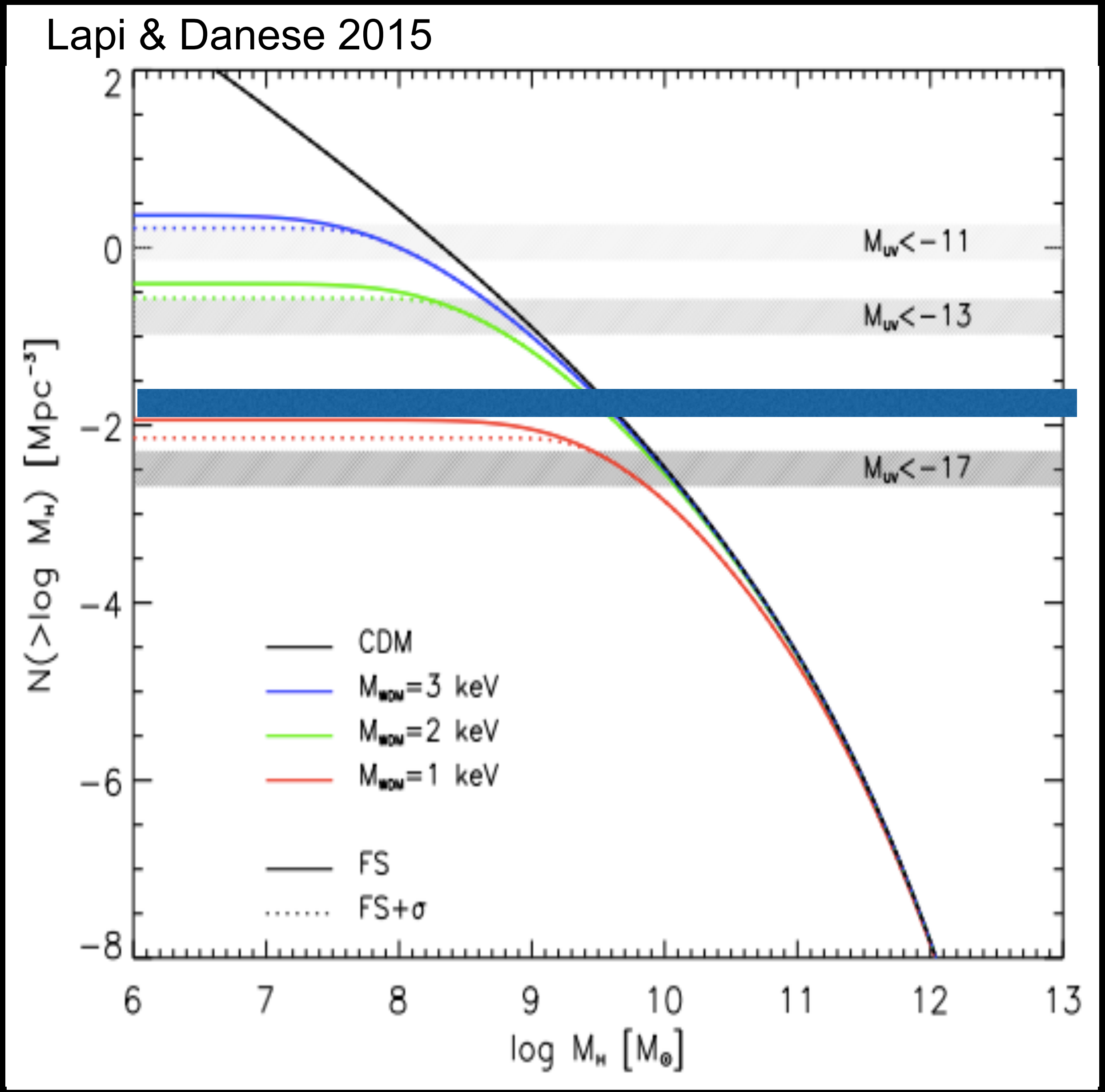
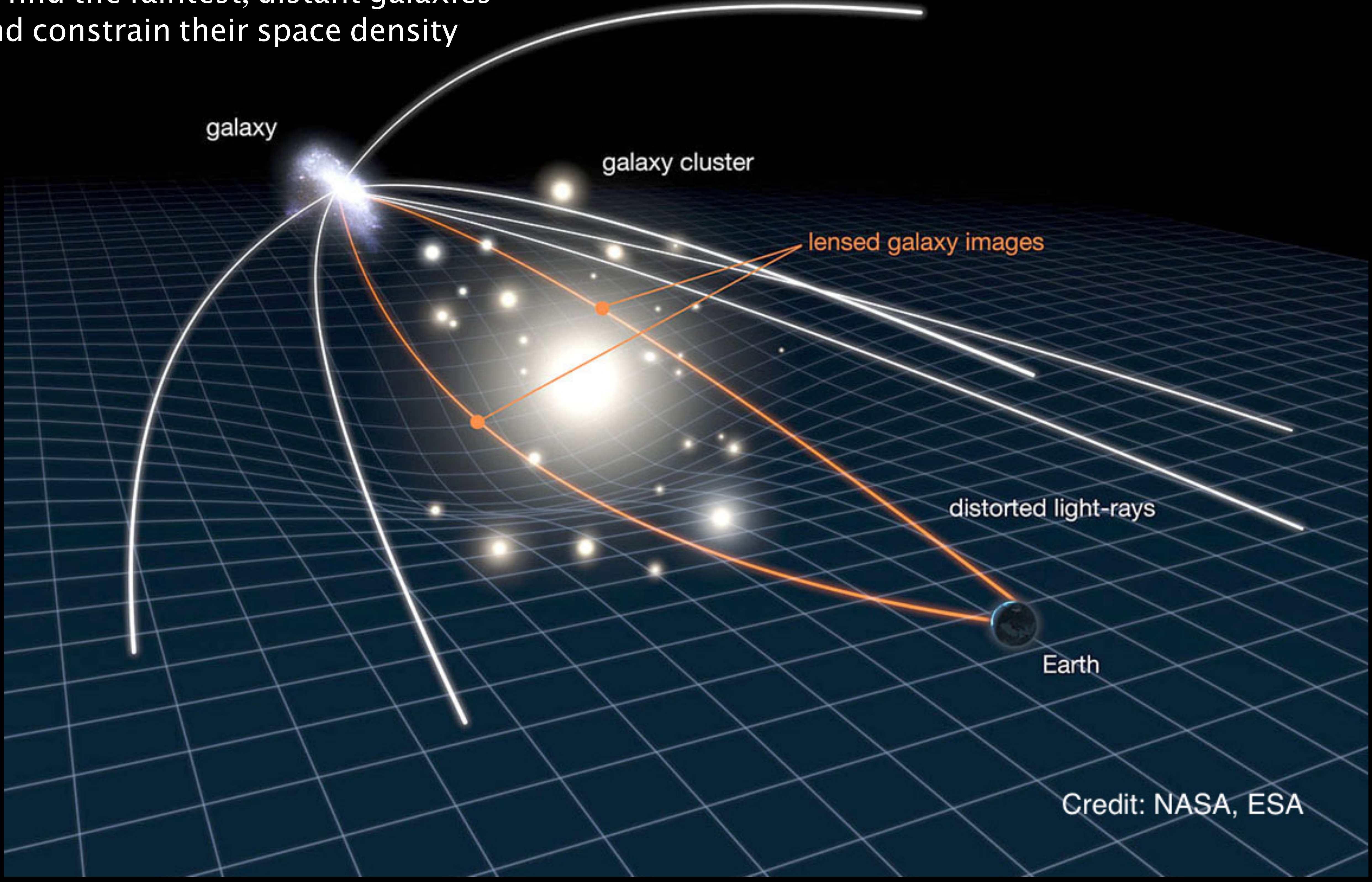


Finding the faintest galaxies

Gravitational lensing is the tool we need
to find the faintest, distant galaxies
and constrain their space density



The Hubble Frontier Fields survey

HST Treasury program

Deep multi-band survey of 6 strong lensing clusters.

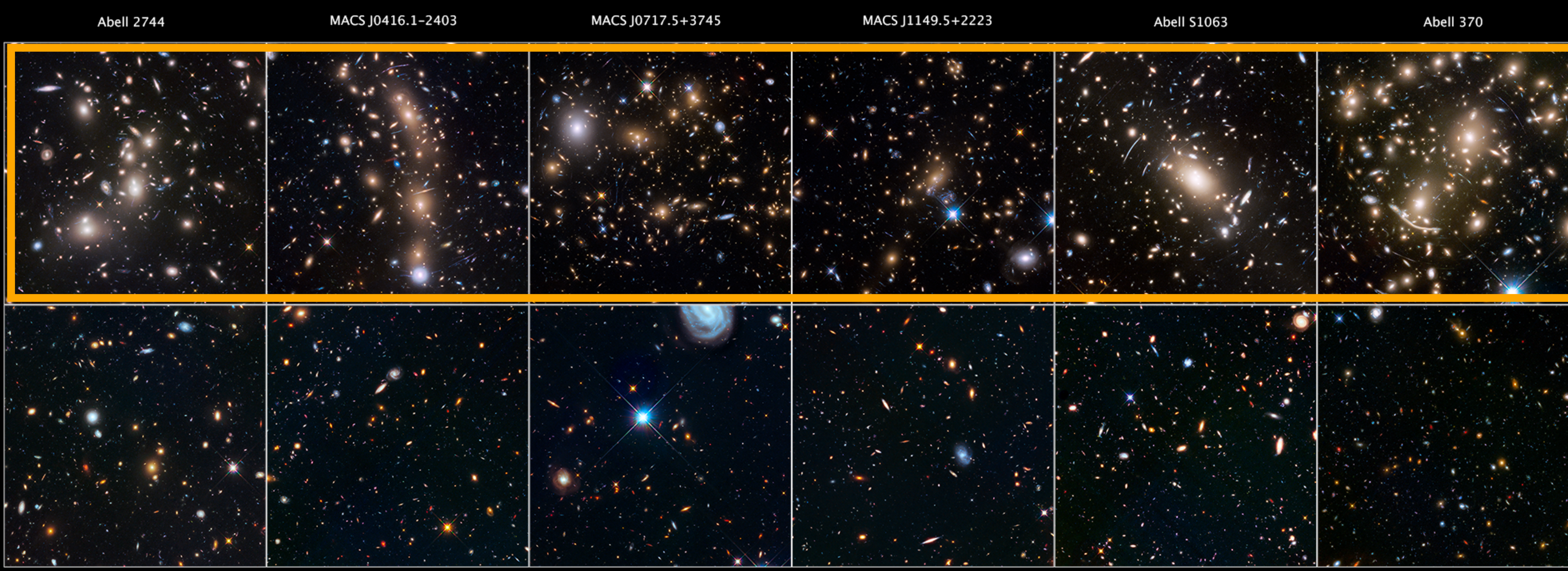
Designed to reach to the faintest high-redshift galaxies thanks to the combined power of ultra-deep space observations and lensing magnification

The Frontier Fields Goals

Using Director's Discretionary (DD) observing time, HST is undertaking a revolutionary deep field observing program to peer deeper into the Universe than ever before and provide a first glimpse of JWST's universe.

These Frontier Fields will combine the power of HST with the natural gravitational telescopes of high-magnification clusters of galaxies. Using both the Wide Field Camera 3 and Advanced Camera for Surveys in parallel, HST will produce the deepest observations of clusters and their lensed galaxies ever obtained, and the second-deepest observations of blank fields (located near the clusters). These images will reveal distant galaxy populations ~10-100 times fainter than any previously observed, improve our statistical understanding of galaxies during the epoch of reionization, and provide unprecedented measurements of the dark matter within massive clusters.

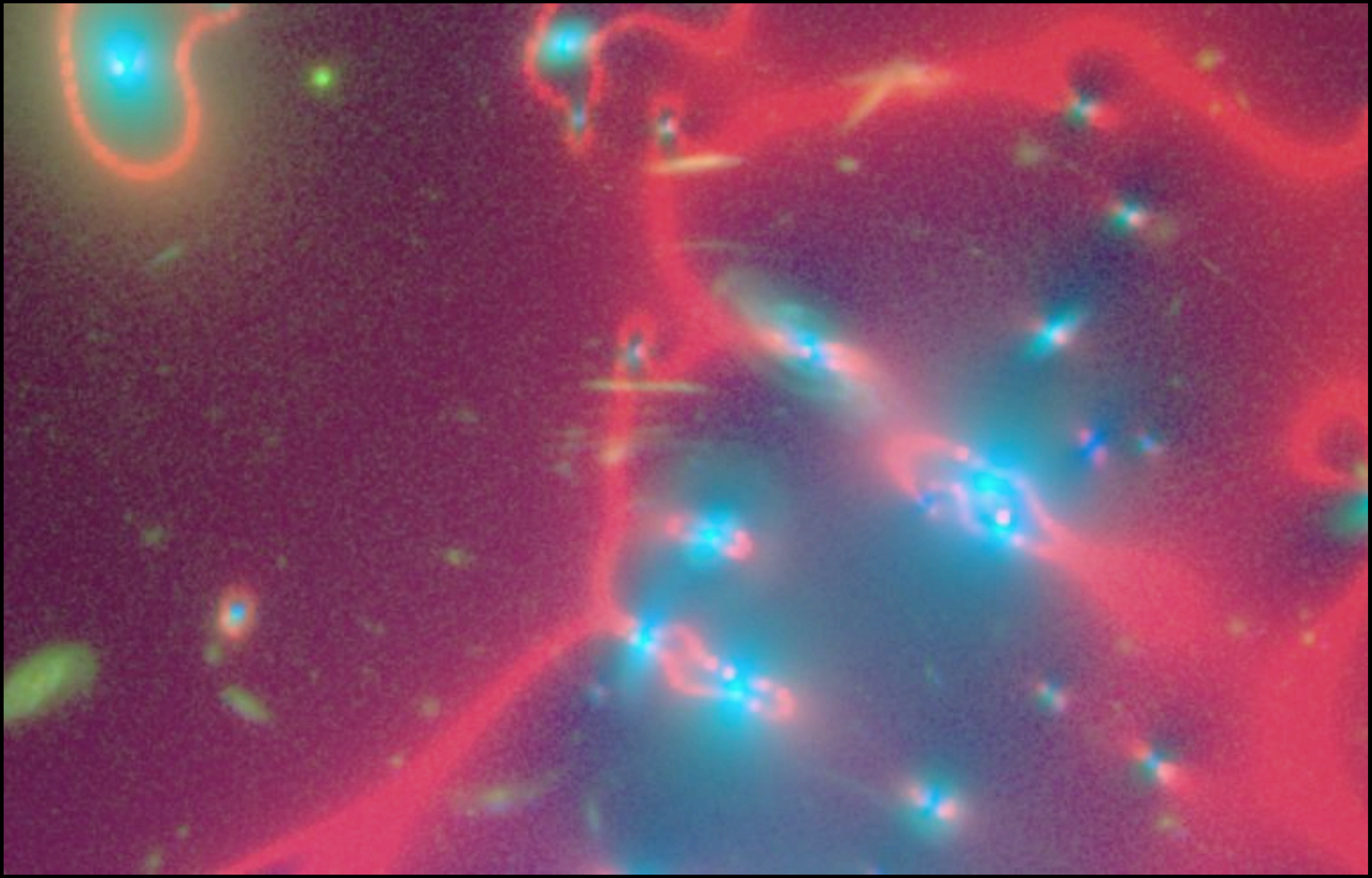
This program is based upon the 2012 recommendations from the Hubble Deep Fields Initiative Science Working group: SWG Report 2012



Clusters as lensing telescopes

slide by Jennifer Lotz


Abell 2744
Cluster
slide by Jennifer Lotz



background galaxies are magnified by factors up to ~10-20, providing the deepest yet view of the universe

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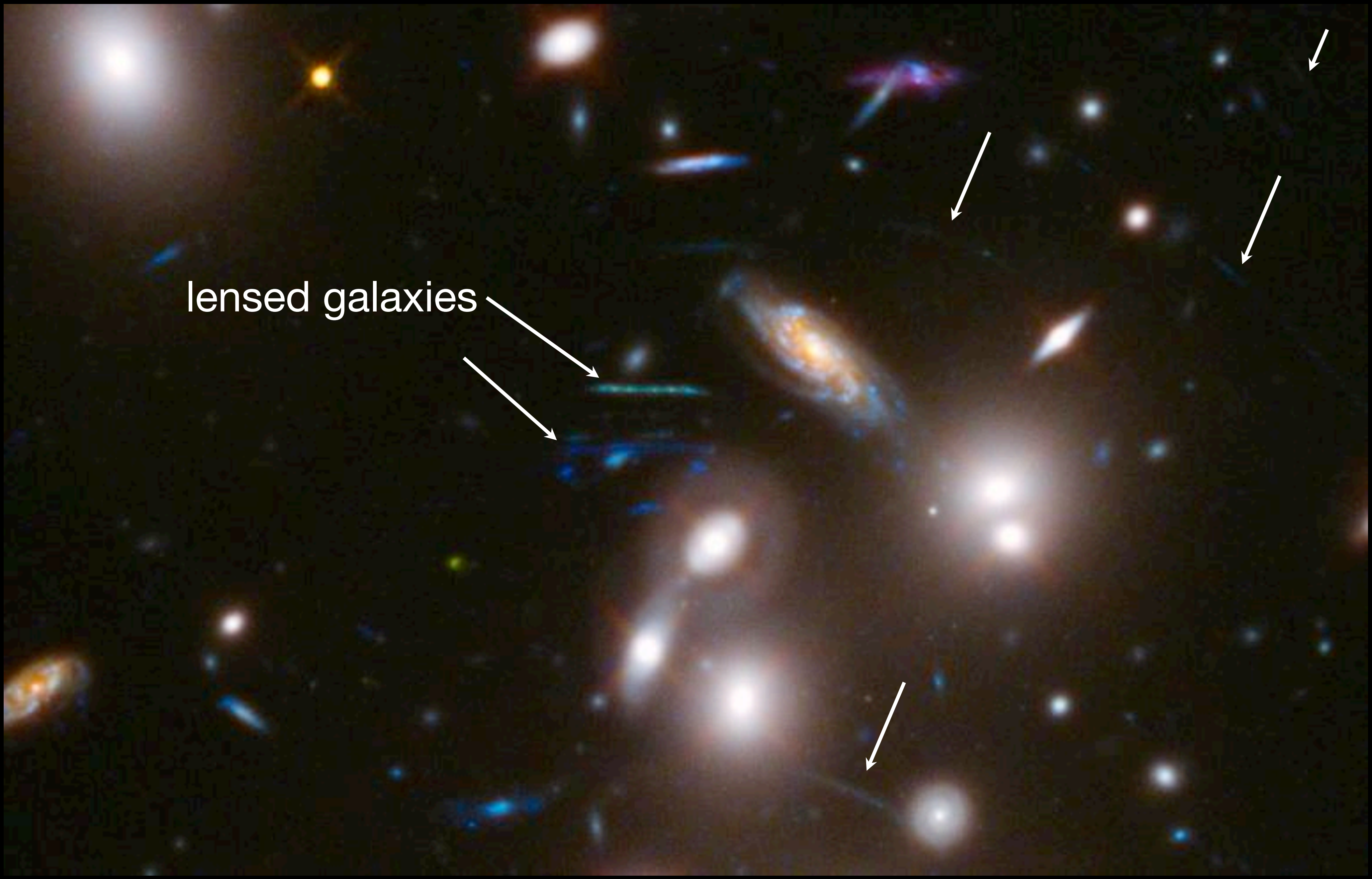

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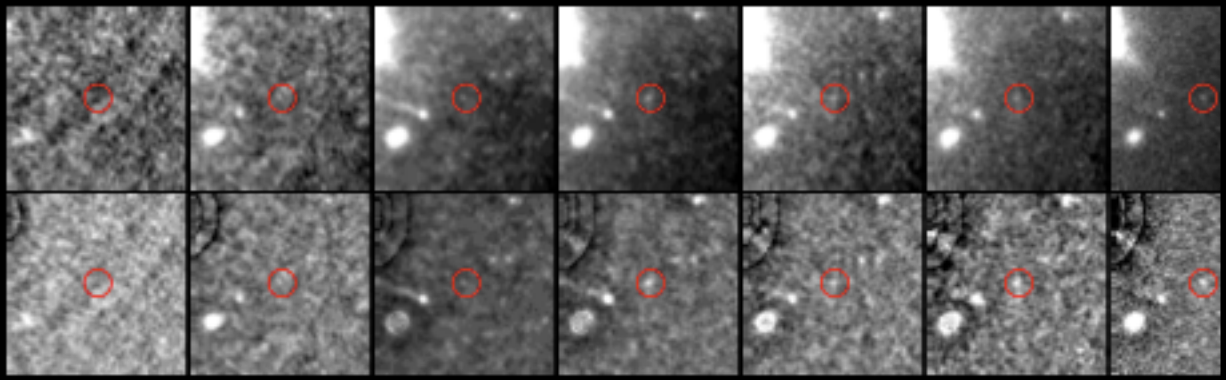
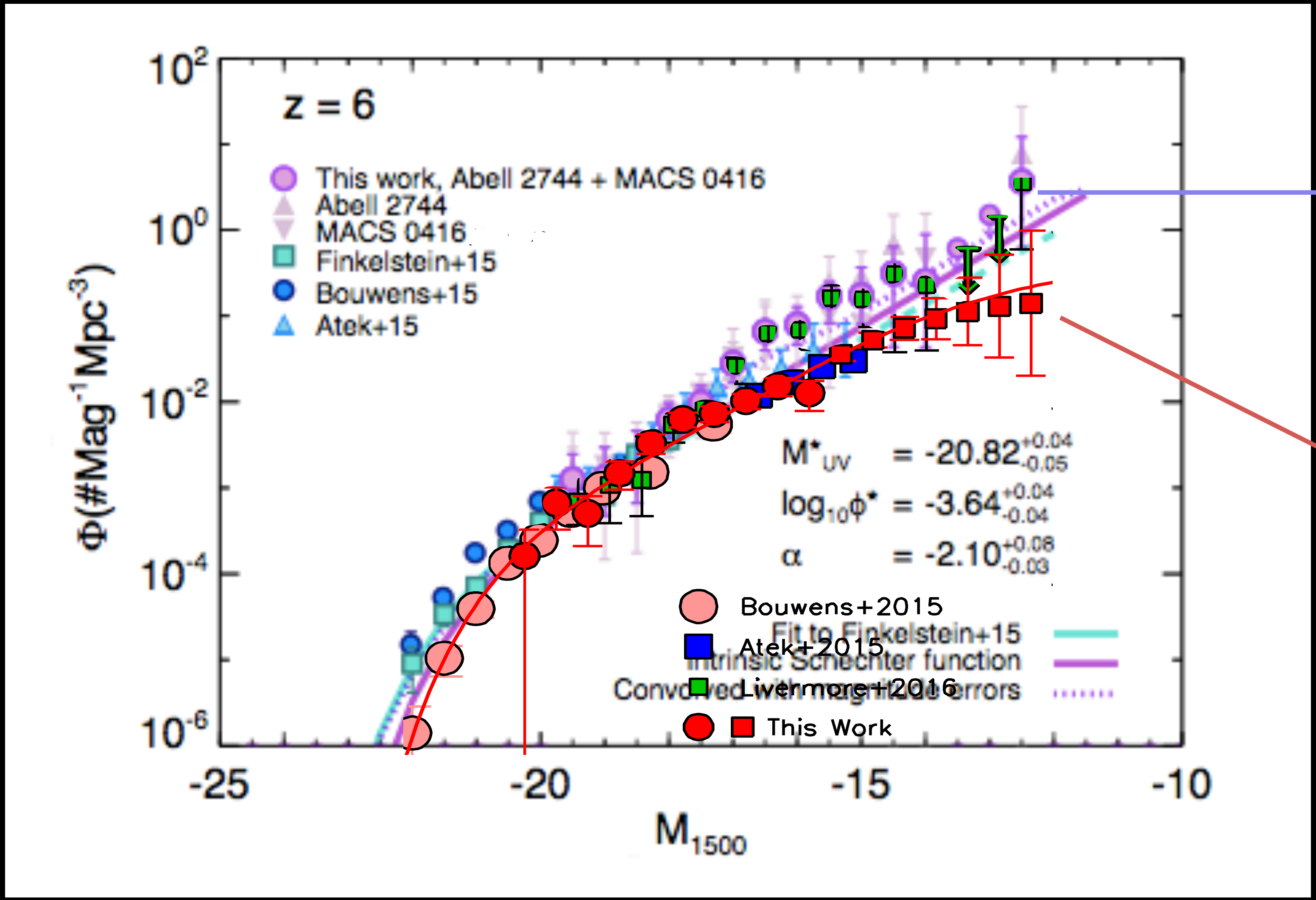
Luminosity Functions of z=6 Galaxies in the Hubble Frontier Fields: Based on 2 HFF lensing clusters 164 galaxies at z=6



Postage stamp image of a2744 z6 3341, from the z ~ 6 sample detected in the Abell 2744 cluster field. The circle shows a 0.4" aperture. This galaxy is magnified by a factor ~ 20×, giving it an intrinsic UV magnitude of MUV = −14.54, but was not detected in previous studies due to the bright foreground object close to the line of sight (top row). It is easily detected in the wavelet-subtracted images (lower row

Integrated number densities of galaxies (#/Mpc³) down to the faints magnitude: correspond to



Livermore et al. 2017

Best fit	log Φ_{obs}=0.54
1σ	log Φ_{obs}=0.26
2σ	log Φ_{obs}=0.01
3σ	log Φ_{obs}=—0.36

Bouwens et al. 2017

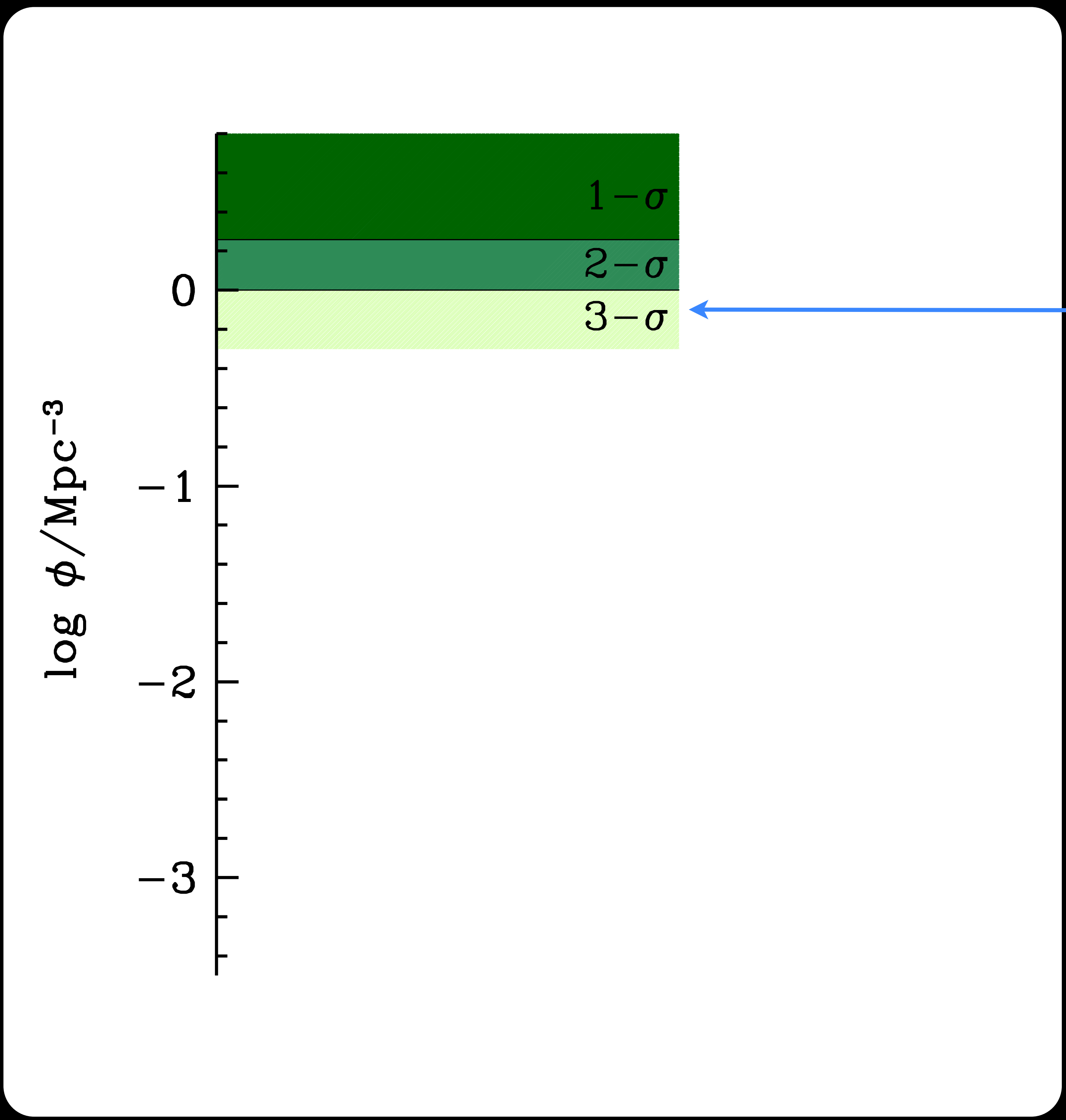
Best fit	log Φ_{obs}=-0.25
1σ	log Φ_{obs}=-0.47
2σ	log Φ_{obs}=-0.62
3σ	log Φ_{obs}=-0.9

HFF constraints on thermal WDM models

Based on 2 HFF lensing clusters Abell 2744 and MACS 0416

Menci, Grazian, Castellano & Sanchez 2016

1. Starting from observed luminosity function, we run 10^7 Monte Carlo extractions of galaxies according to the observed distribution and with an uncertainty provided by the observed error bars.



2. Compute the total nuber density of galaxies down to the faintest magn bin: # of galaxies/Mpc^3 at different confidence levels:

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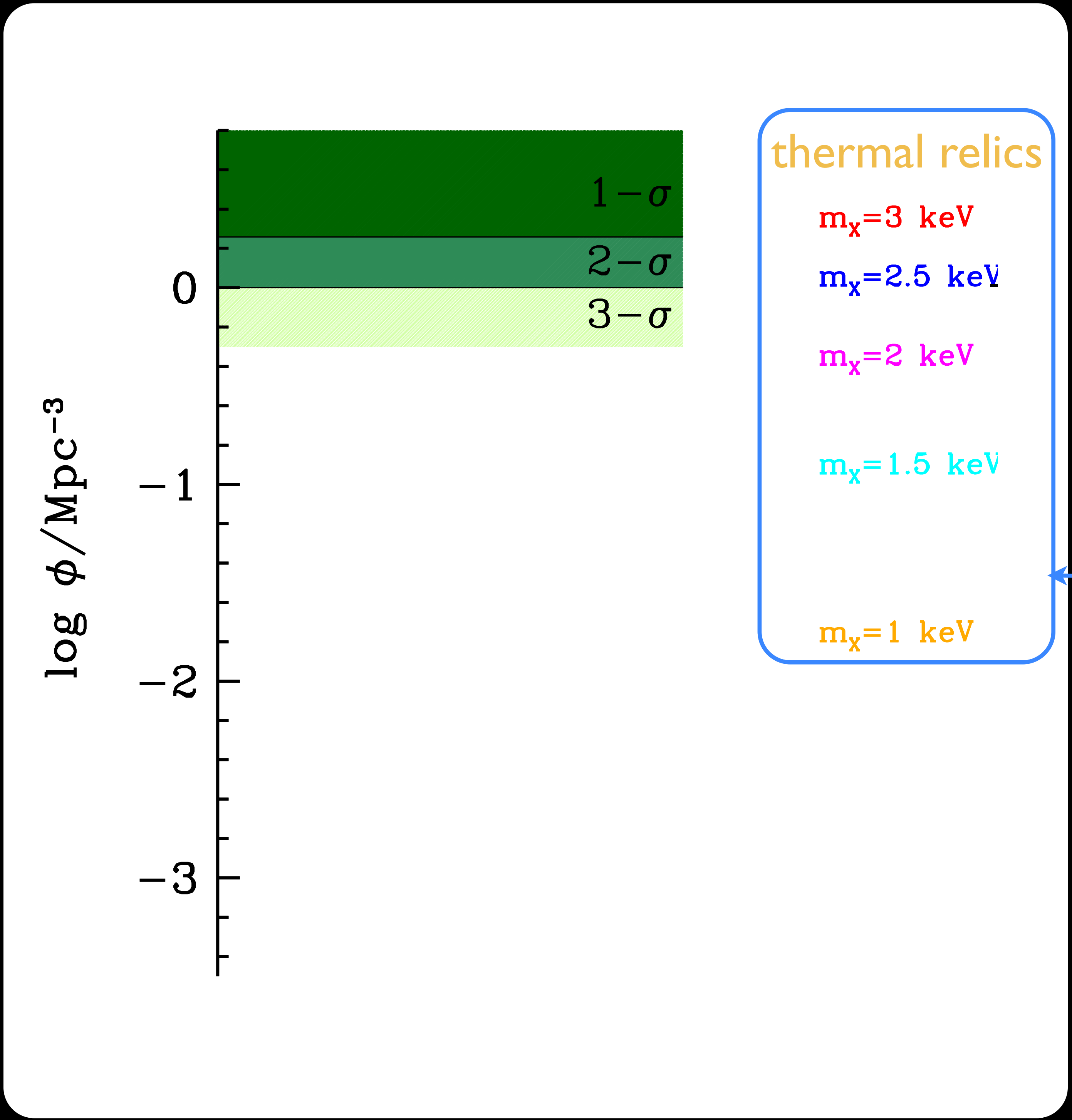

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HFF constraints on thermal WDM models

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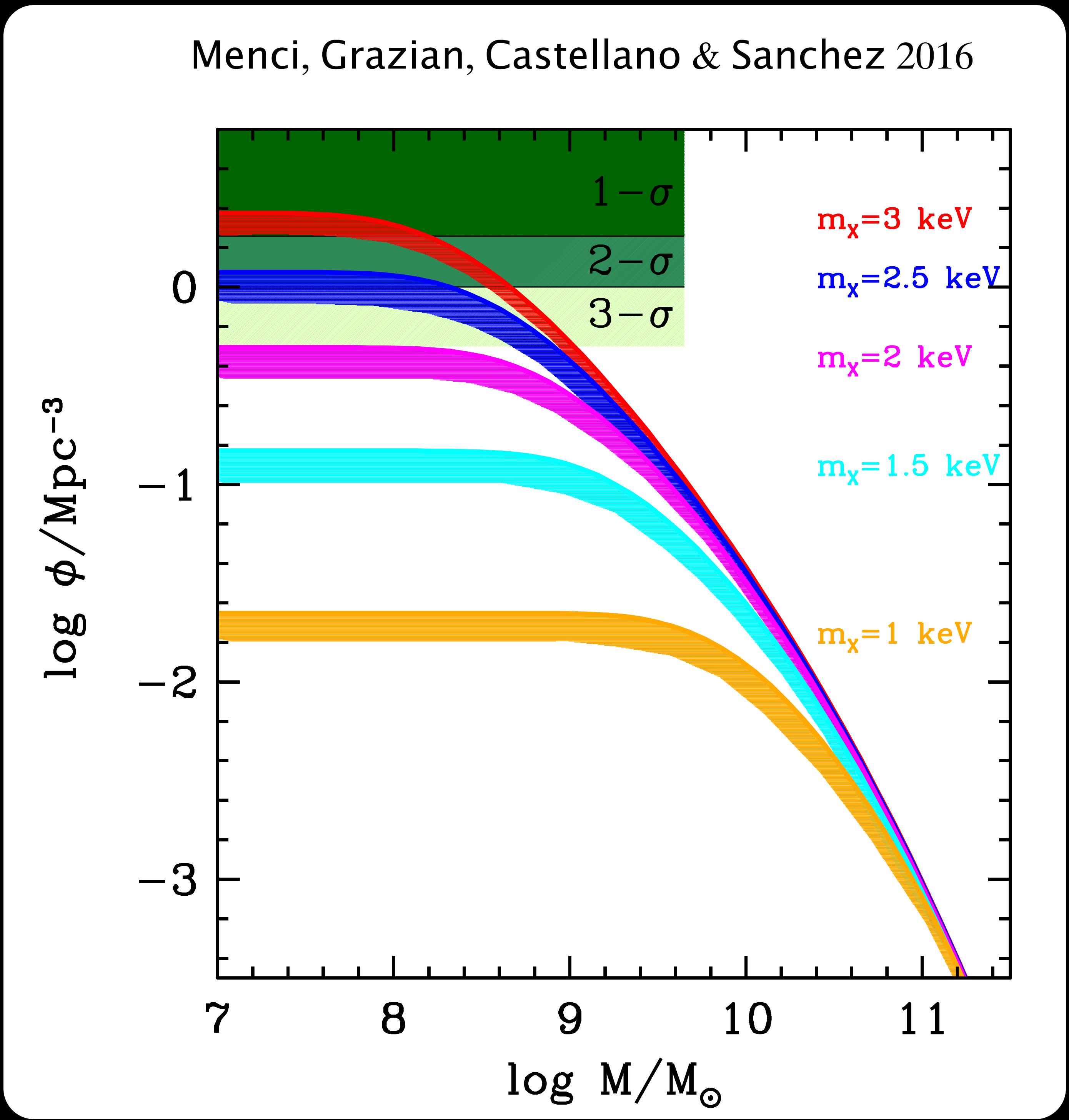
thermal relics



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\# of galaxies/Mpc^3
at different confidence levels:

3. Assume a Power Spectrum
P(m_X, production model)

4. Compute the associated WDM cumulative mass function and the corresponding maximum number density $\tilde{\Phi}$ (m_X, production model)

5. Allowed WDM models are those with
$\Phi_{obs} \leq \tilde{\Phi}$ (m_X, production model)
observed galaxies cannot outnumber the DM halos

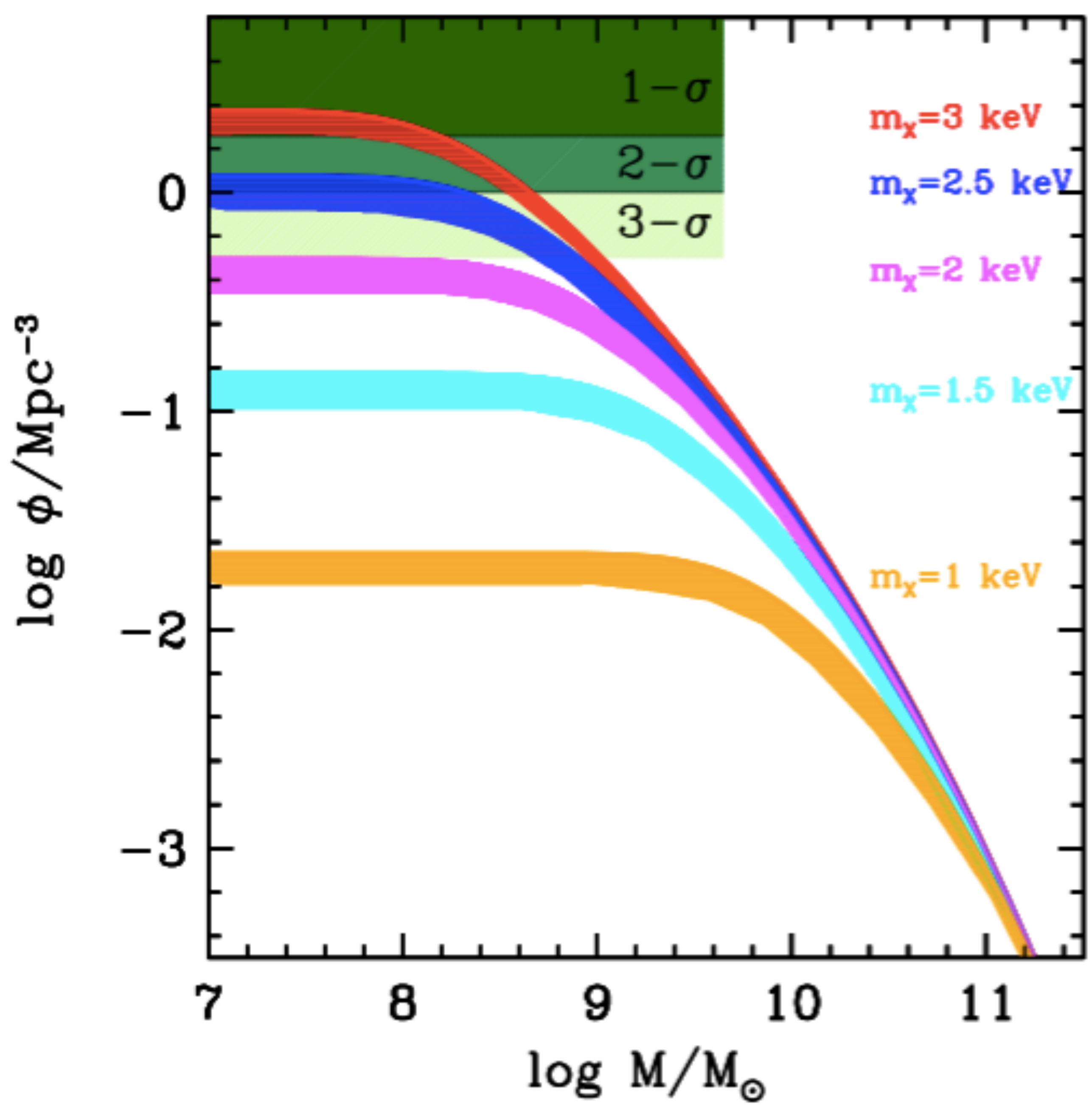
HFF constraints on thermal WDM models

$m_X > 3$ keV (1σ) $m_X > 2.4$ keV (2σ)
(comparing with Livermore et al)

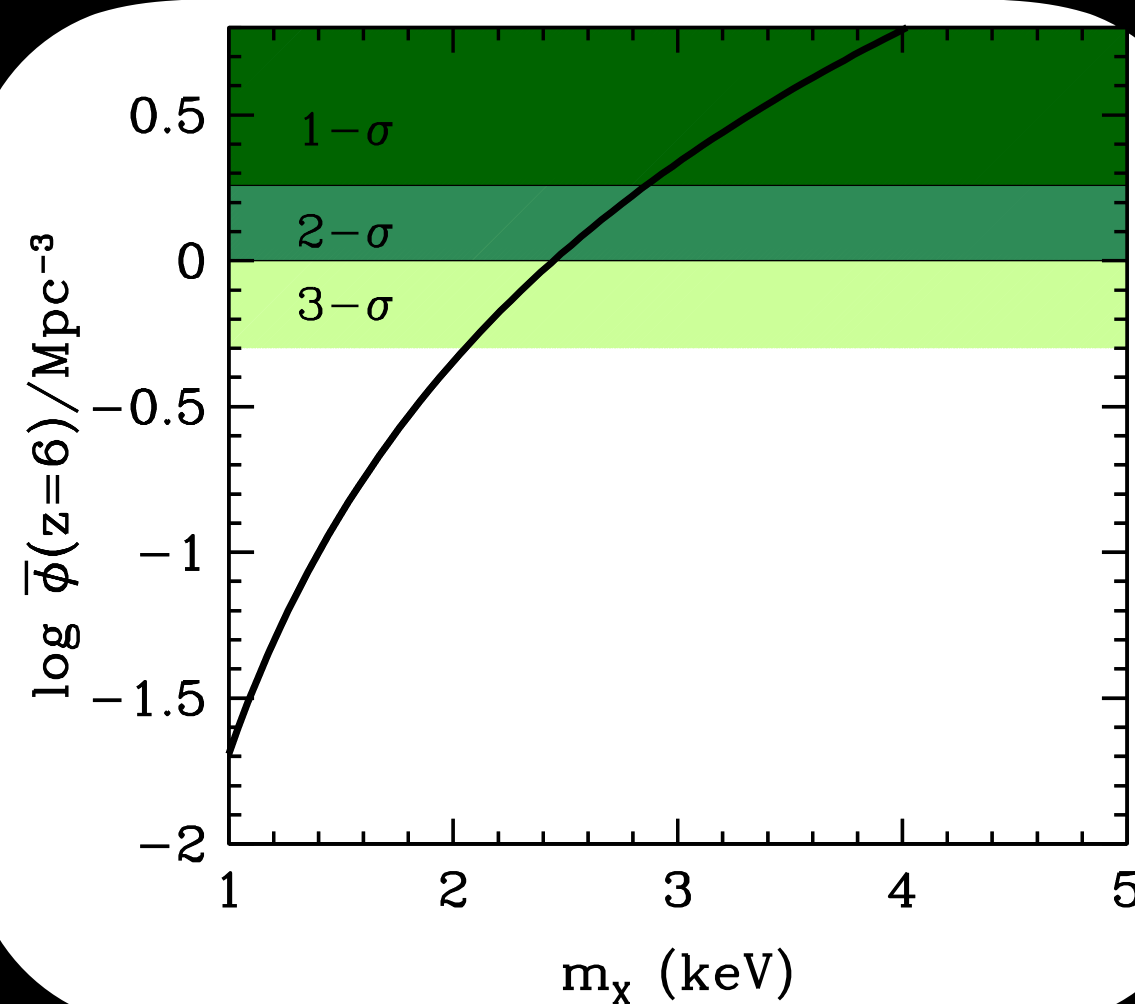
$m_X > 2.5$ keV (1σ) $m_X > 2.$ keV (2σ)
(comparing with Bouwens et al)

The tighter limits derived so far independently of baryon physics visible galaxies cannot outnumber their host DM halos

Menci, Grazian, Castellano & Sanchez 2016



Very Conservative: The observed galaxies cannot outnumber their host DM halo, whose density saturates to a max. value depending on m_X



Sterile Neutrino WDM   Production from Active–Sterile Transitions

Strong physical motivation: the most natural extension of SM to include mass terms for active neutrinos.

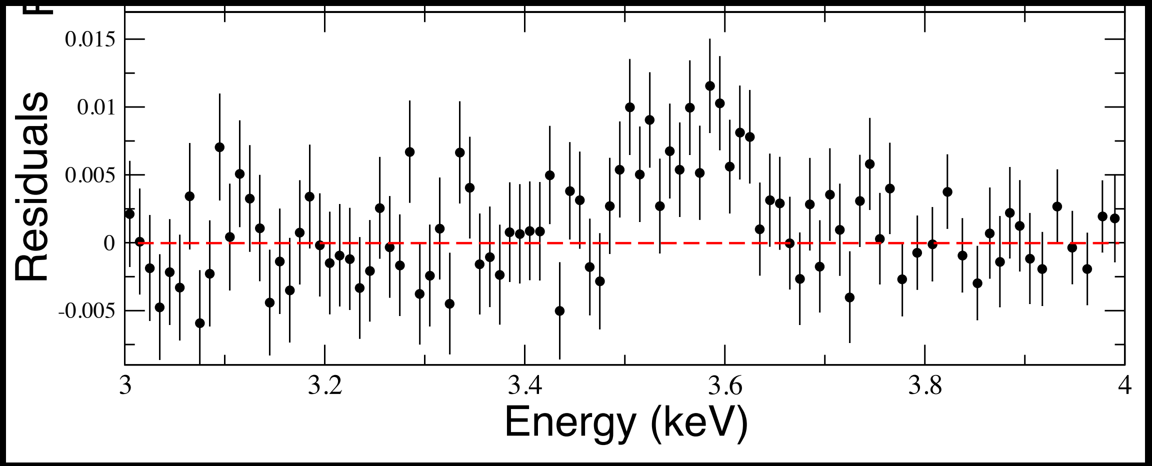
2 parameters: neutrino mass m_ν
mixing with active neutrinos $sin^2(2\theta)$
(oscillation probability)

Not completely Dark !

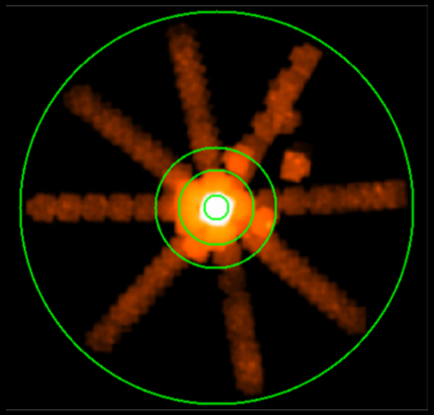
Stacked XMM spectra (MOS and PN) of 73 bright galaxy

Detected a very weak line at *E* = 3.55–3.57 keV rest-frame energy: IF due to WDM corresponds to the decay of

$m_\nu \approx 7$ keV



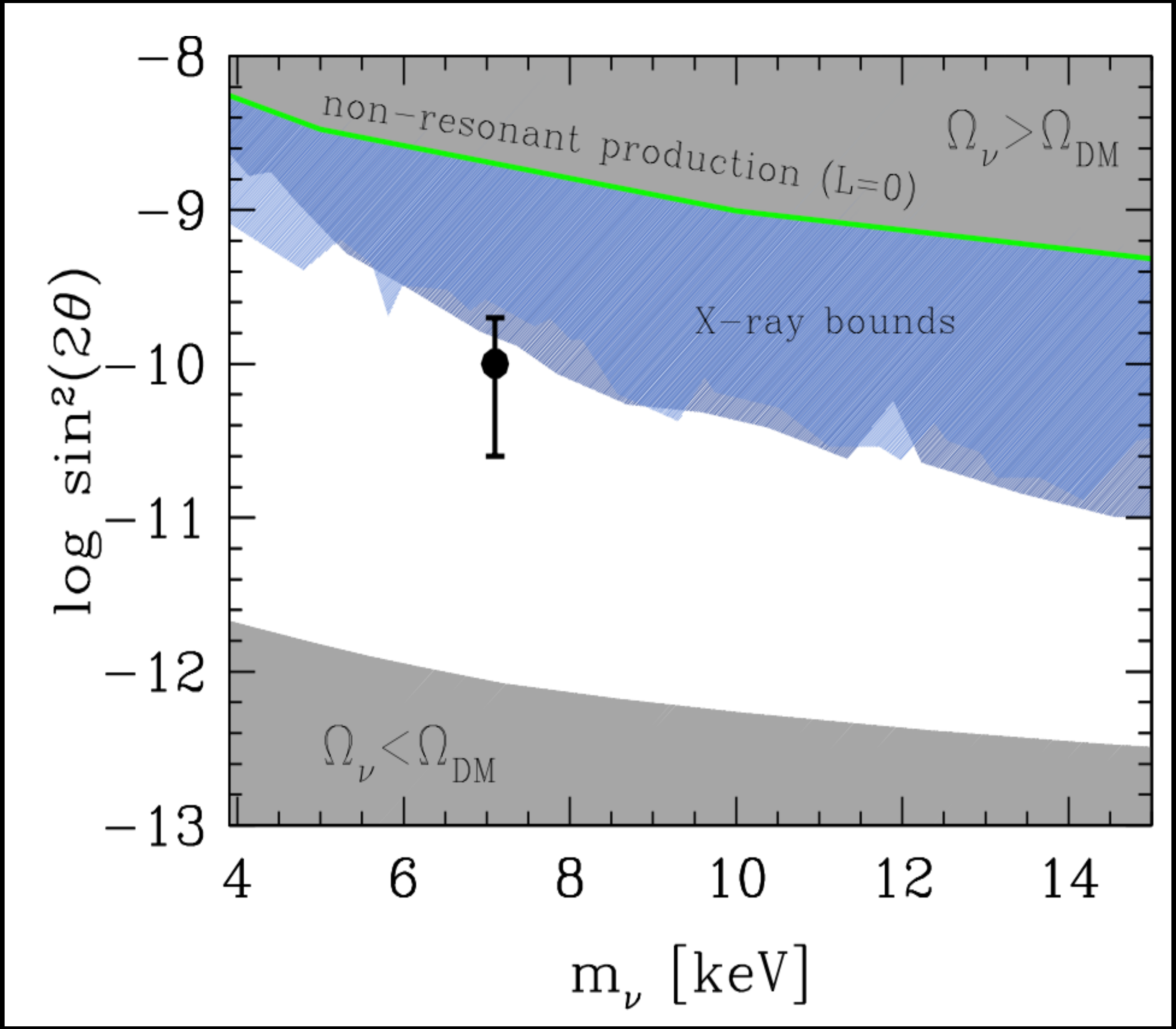
X-ray line reported in stacked observations of X-ray clusters with the XMM-Newton X-ray Space telescope with both CCD instruments (Bulbul et al. 2014). Consistent line in XMM-Newton observations of M31, Galactic Center (Boyarsky et al. 2015) and M31, Draco (Ruchayskiy 2015), Perseus Cluster (Boyarsky et al. 2014) + 9 individual clusters (Iakubovskyi 2016). Signal from Milky Way detected also by NuSTar (Nerenov et al. 2016)



The radial distribution of the signal is consistent with a decay origin (Franse et al. 2016)

Sterile Neutrino WDM   Production from Active-Sterile Transitions

Exploring the Parameter Space of
Sterile Neutrino Models
based on resonant production



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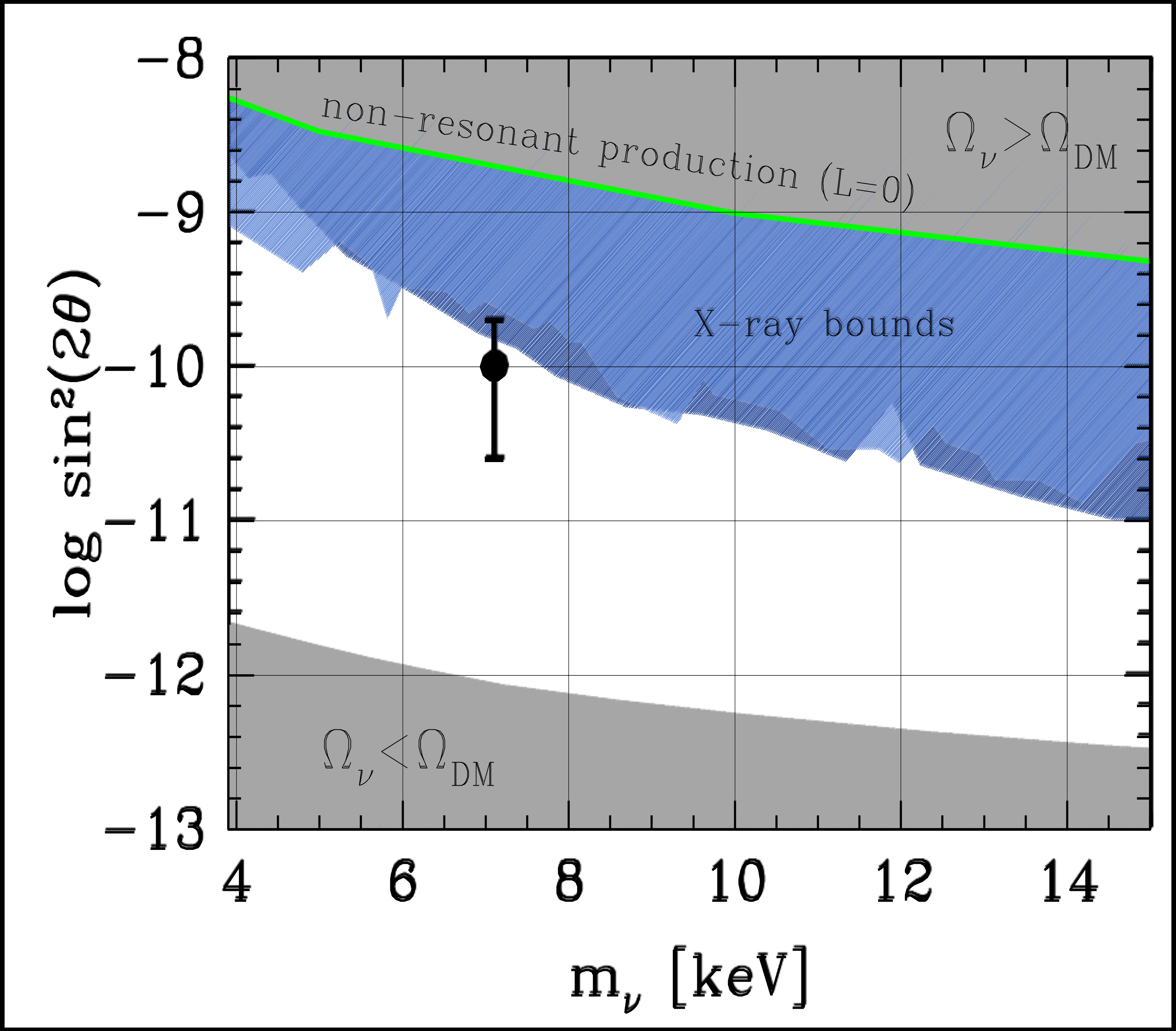
Grid of Values for

m_ν $sin^2(2\theta)$



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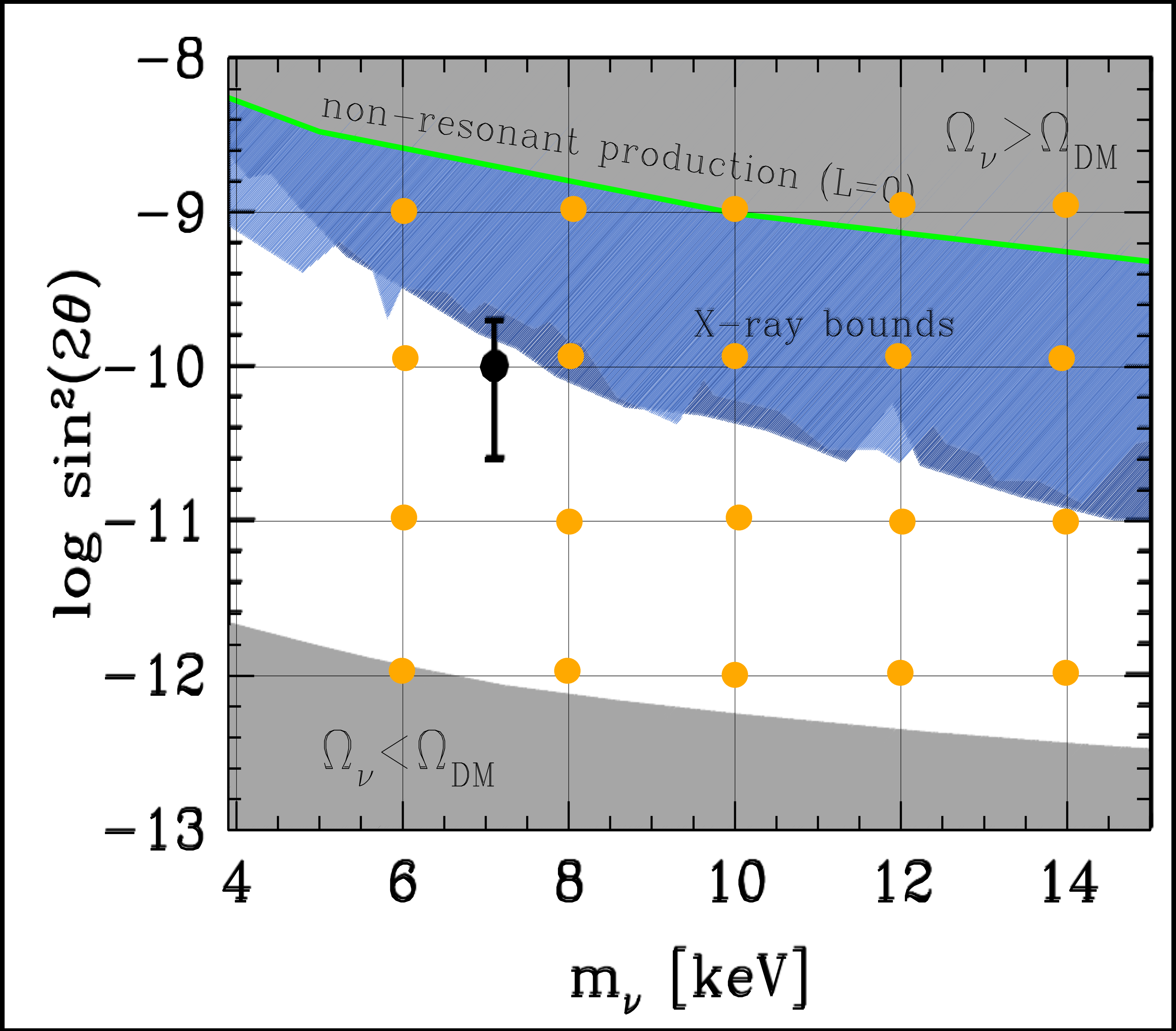

For each point in the grid
of parameter space

Compute Power Spectrum (solve Boltzmann equation) $P(k)$

Compute $\overline{\phi}$

Compare with HFF number density of galaxies at z=6
Allowed region: $\overline{\phi} \geq \phi_{obs}$

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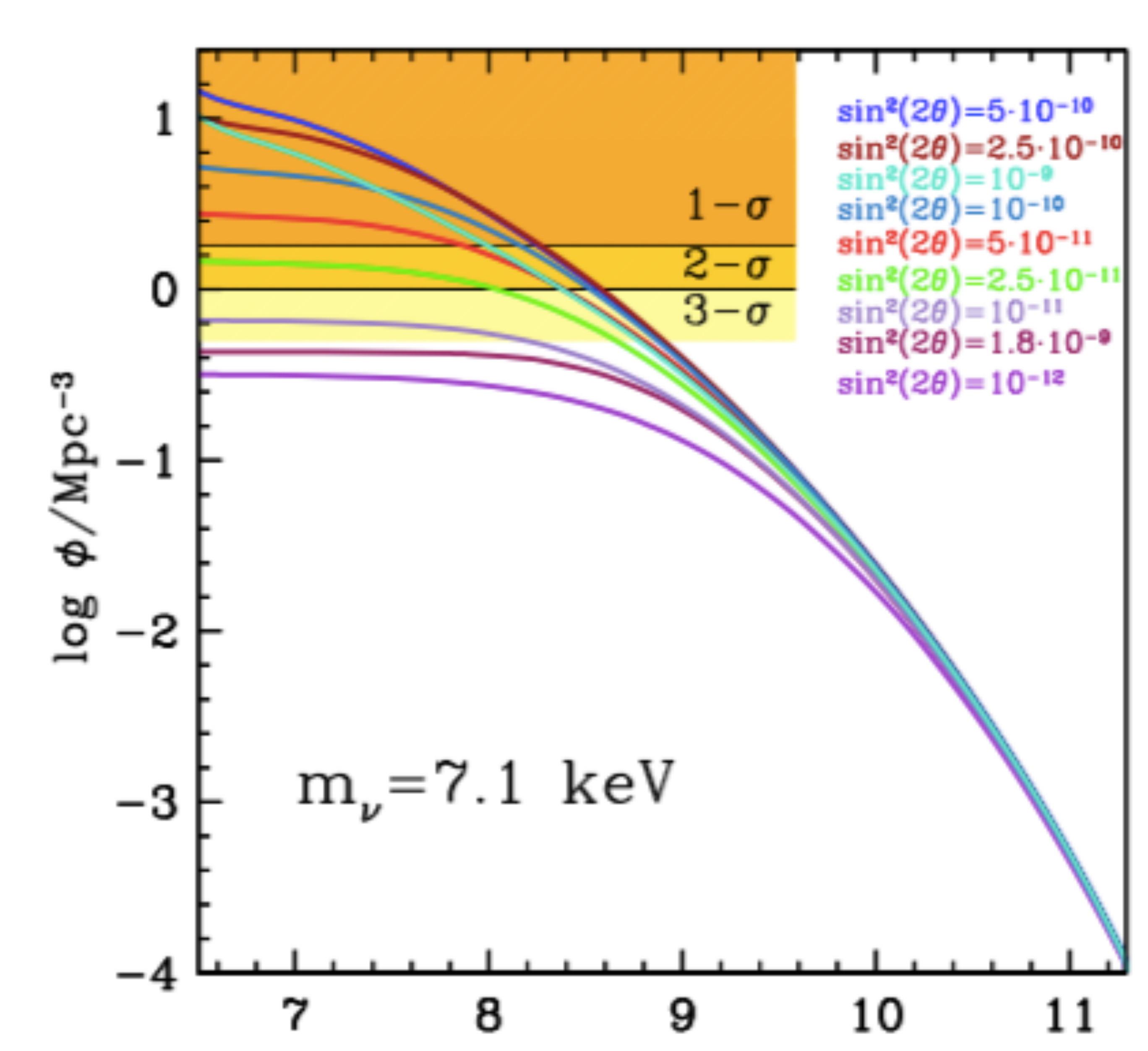

Menci et al. 2017

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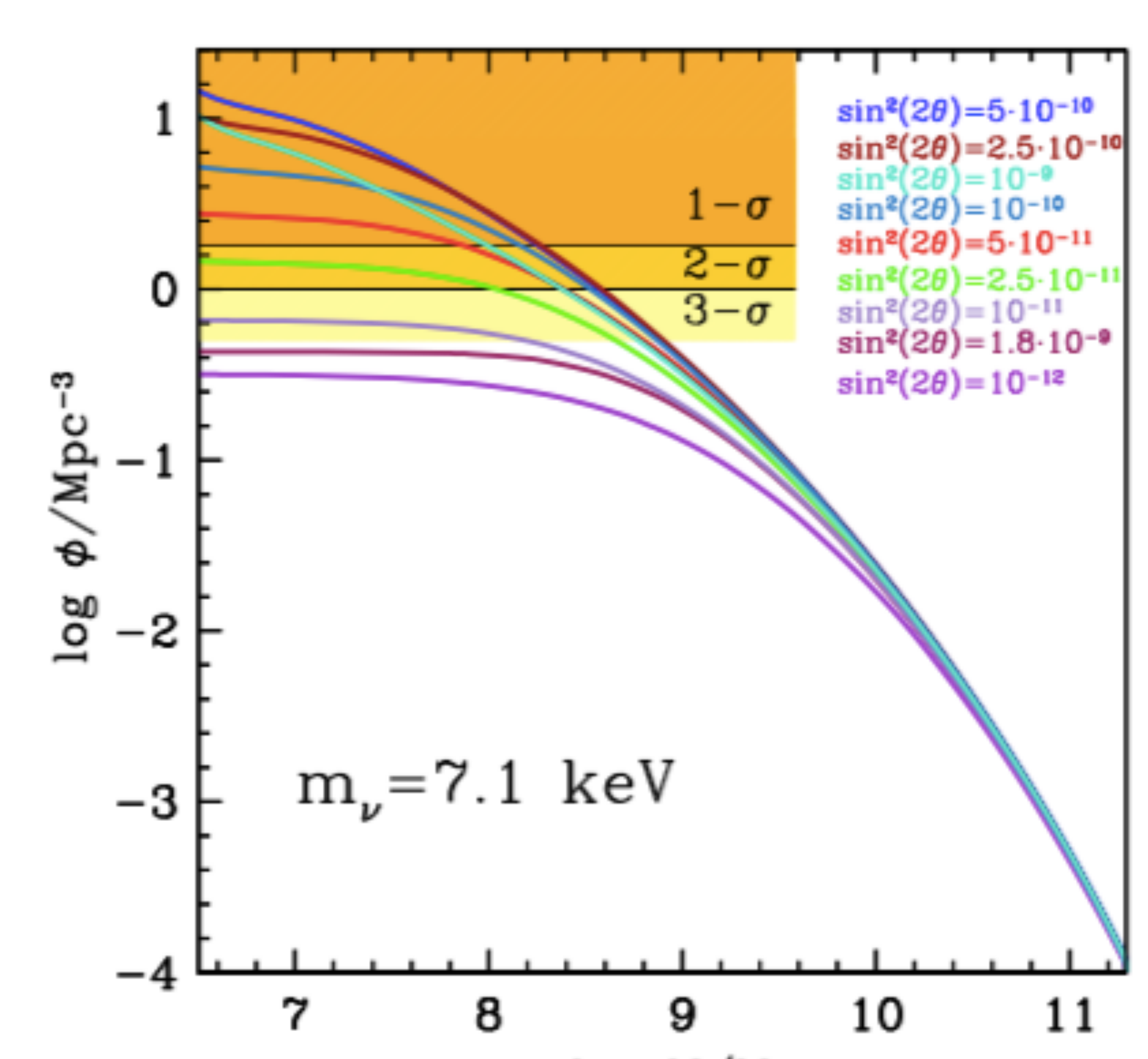

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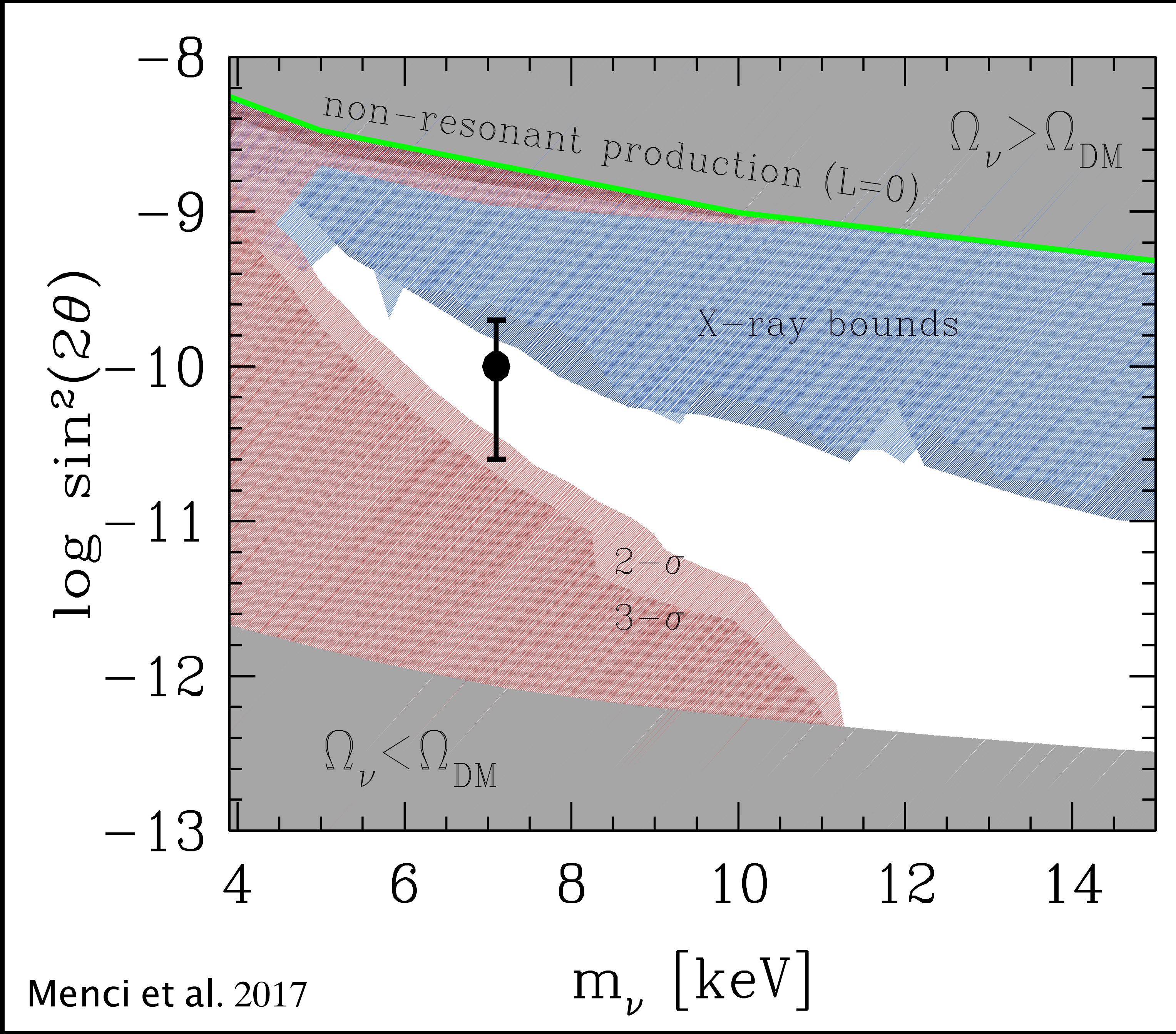

Sets lower bounds for mixing angle which are
Independent of baryon physics (L/M ratio) and of
the assumed density profile.

Unprecedented constraints on parameter space of
such models

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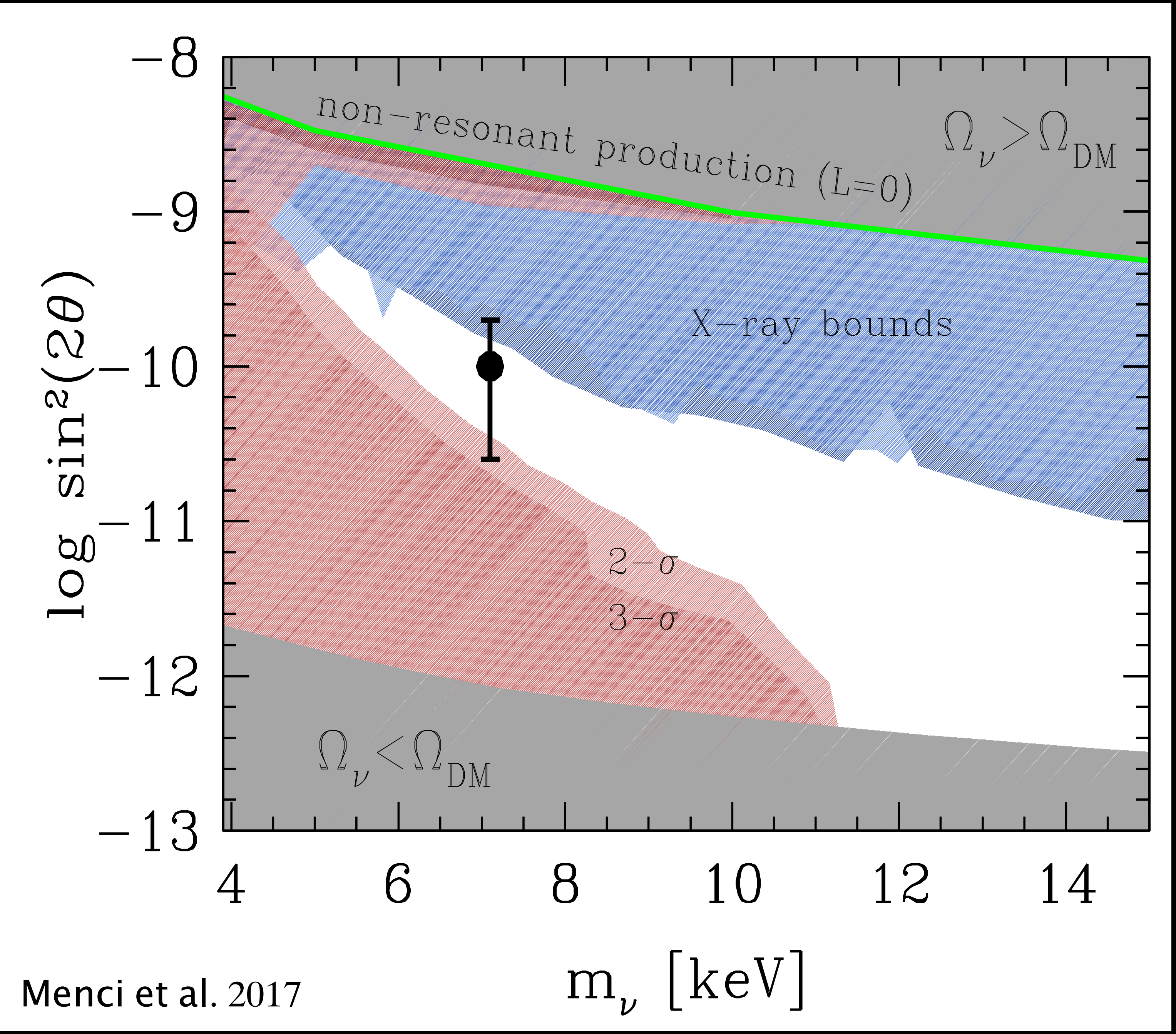

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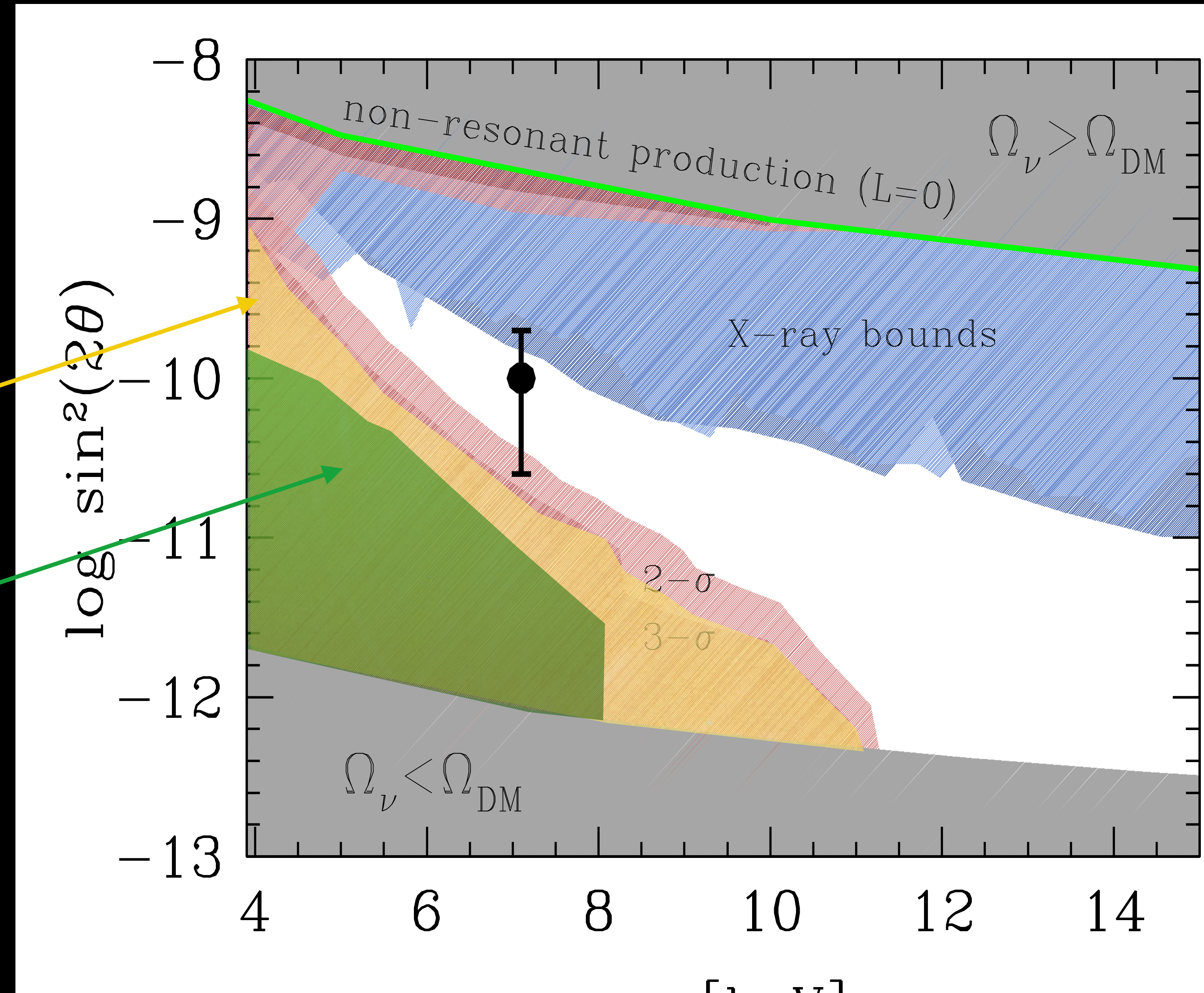
Schneider et al. 2016

Lovell et al. 2015



Menci et al. 2017

Limits from Milky Way satellites:

Depend on

assumed upper limit for MW mass

assumed lower limit for satellite masses (based on estimated L/M ratio or stellar velocity dispersion depending on assumed density profile)

assumed isotropic distribution to correct SDSS observations for limited sky coverage

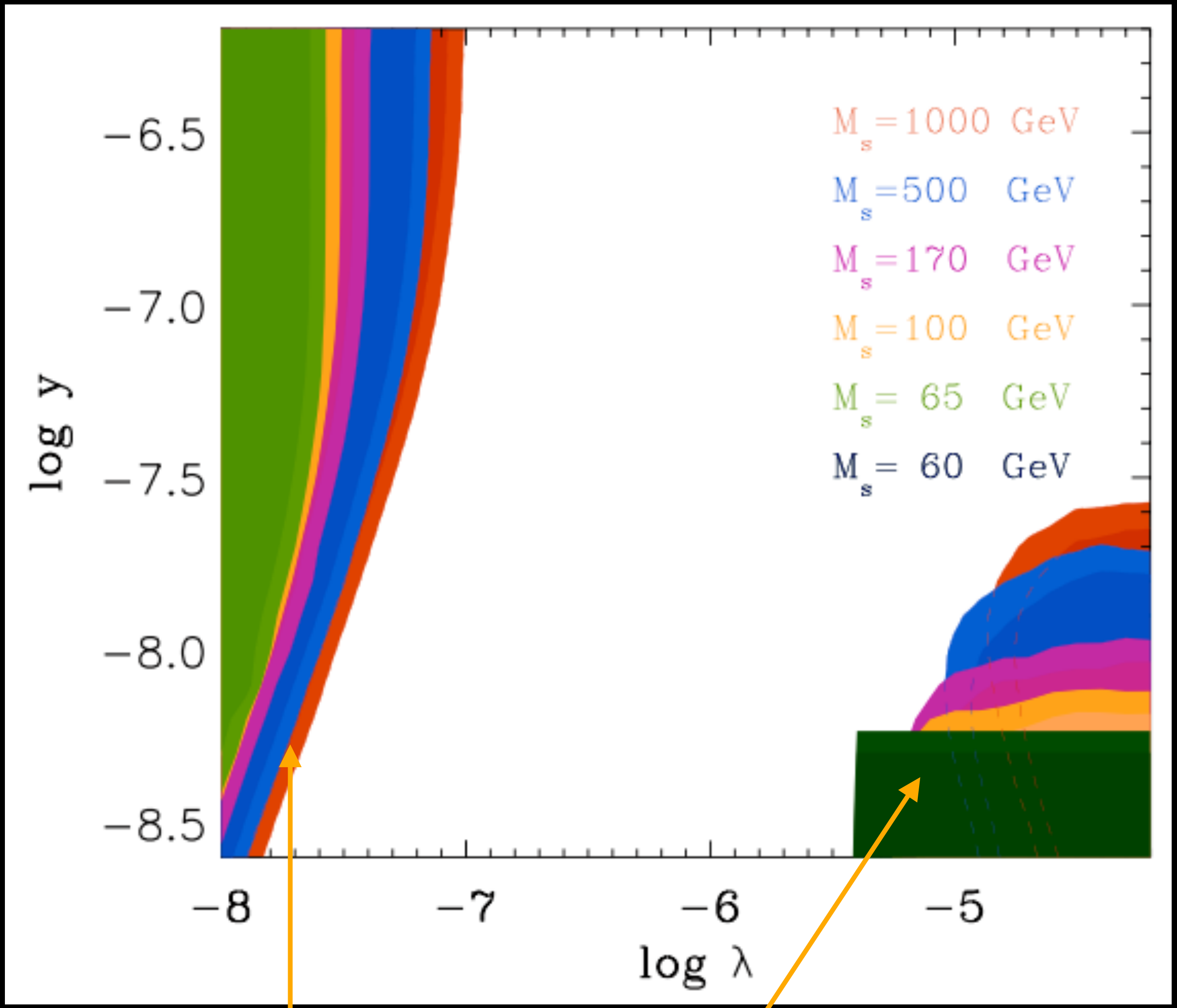
assumed halo-to-halo variance

Sets lower bounds for mixing angle which are Independent of baryon physics (L/M ratio) and of the assumed density profile.

Unprecedented constraints on parameter space of such models

Sterile neutrinos from scalar decay (Merle et al. 2013)

Exploring the full parameter space of Sterile Neutrino Models based on scalar decay



3 parameters

m_S mass of scalar
y coupling to scalar field
λ coupling to Higgs

Special Cases

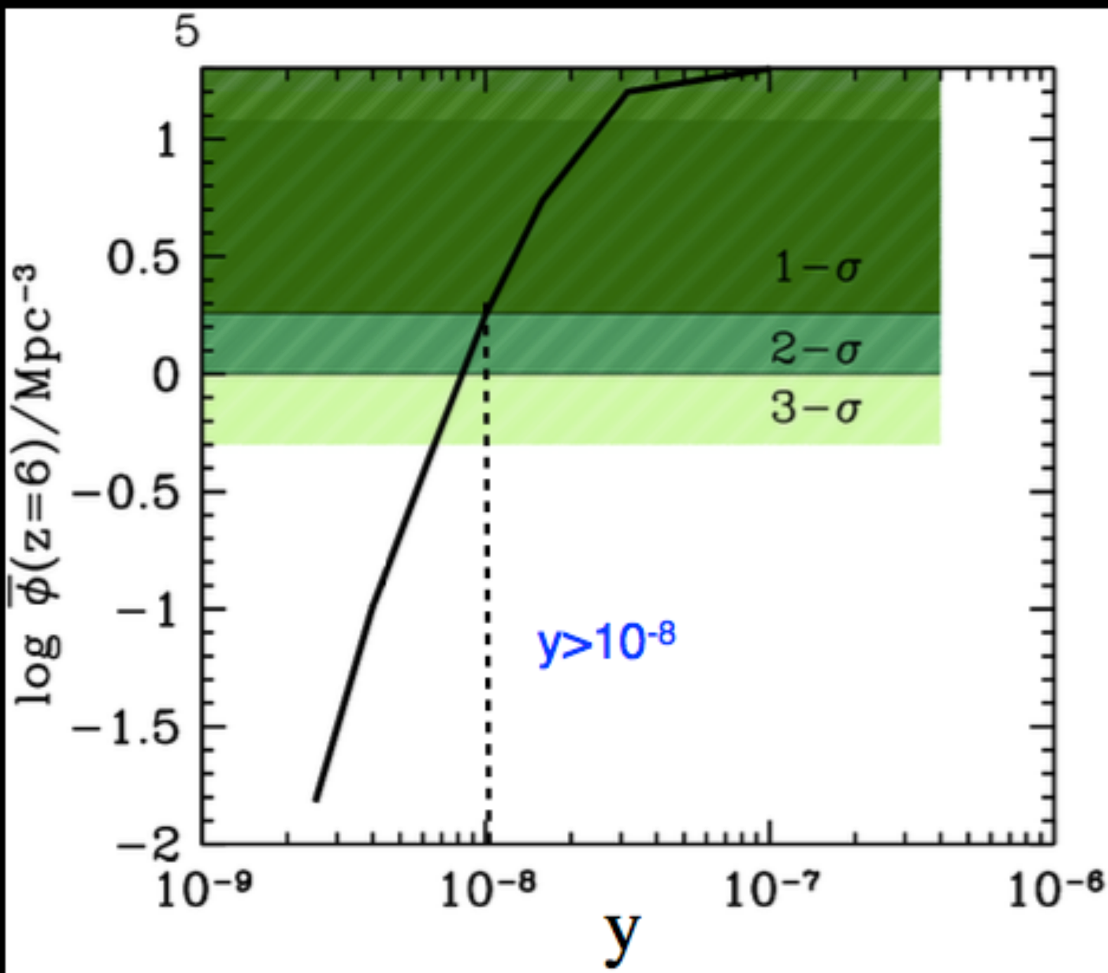
Small Higgs coupling $\lambda \ll 10^{-6}$
S is gradually produced, and sterile neutrino production follows.
Freeze-in limit. Model depend only on y

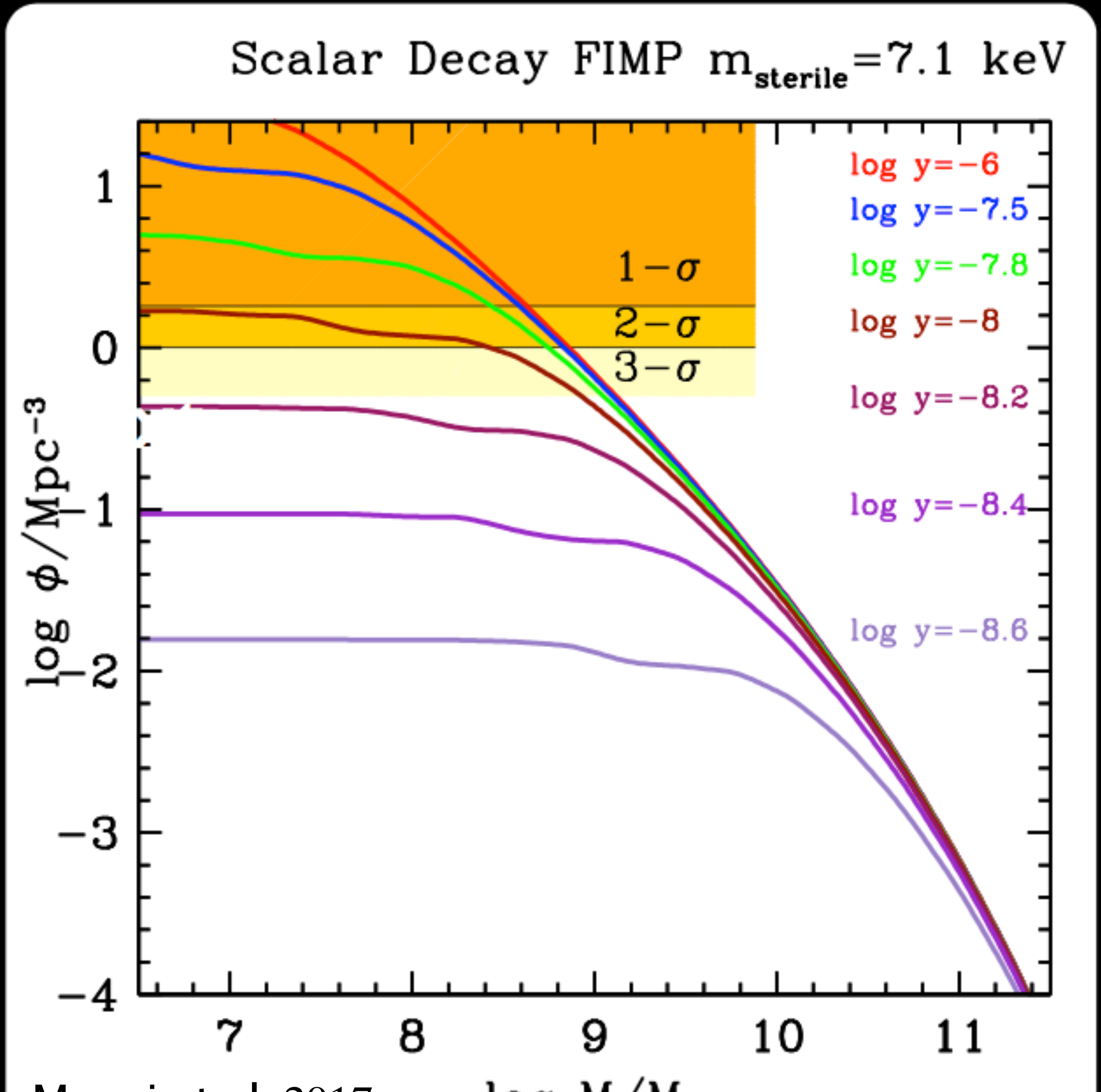
Strong Higgs coupling
S is abundantly produced at early times. Fast sterile neutrino production follows until freeze-out
Freeze-out limit

Sterile neutrinos from scalar decay (Merle et al. 2013)

Scalar field S coupled to the right-handed neutrino. The most general coupling is a Yukawa term with coupling strength y

$y>10^{-8}$ at 2-σ level for $m_{sterile}=7$ keV





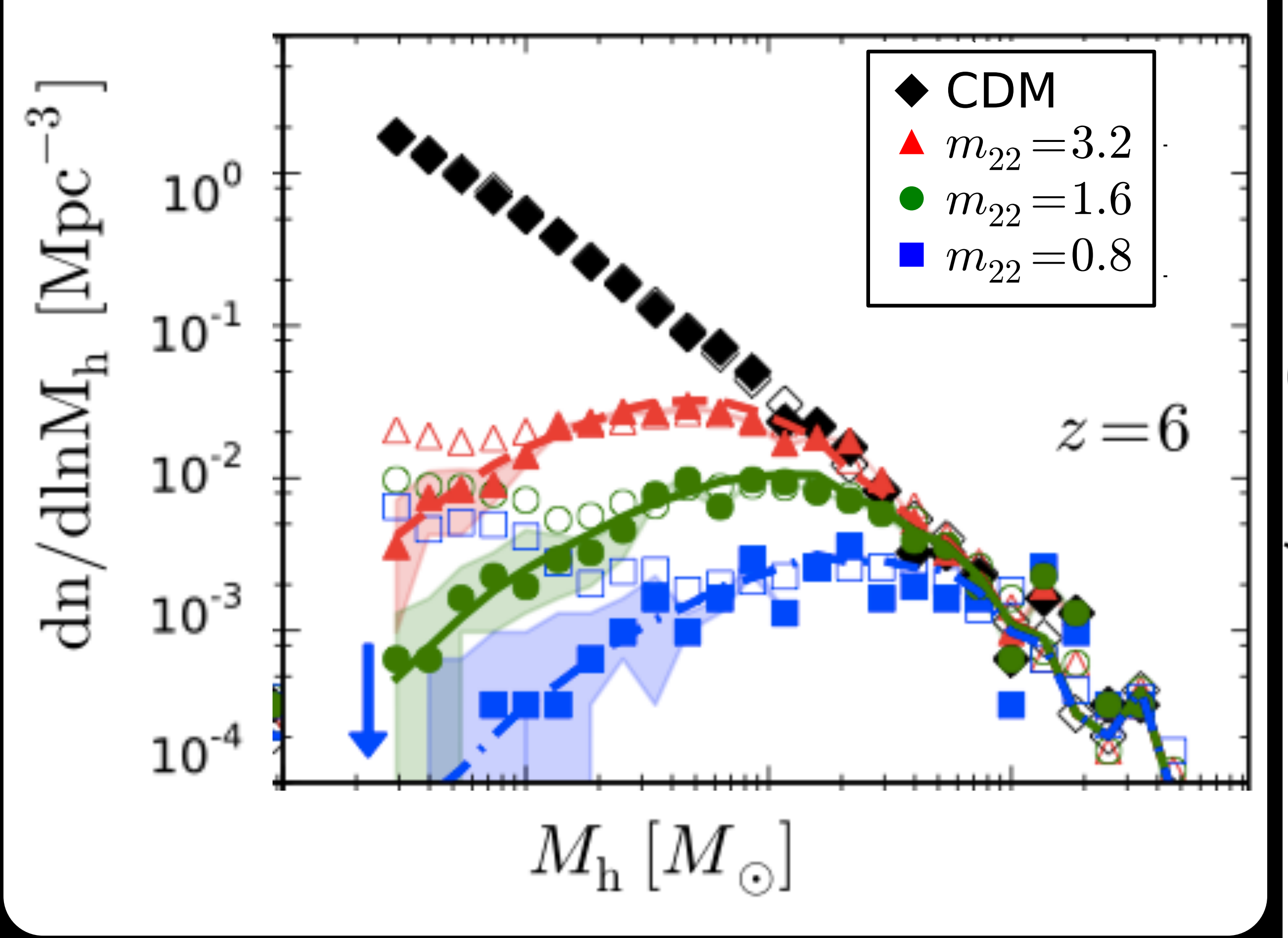
Menci et al. 2017

Scalar field S coupled to the right-handed neutrino. The most general coupling is a Yukawa term with coupling strength y

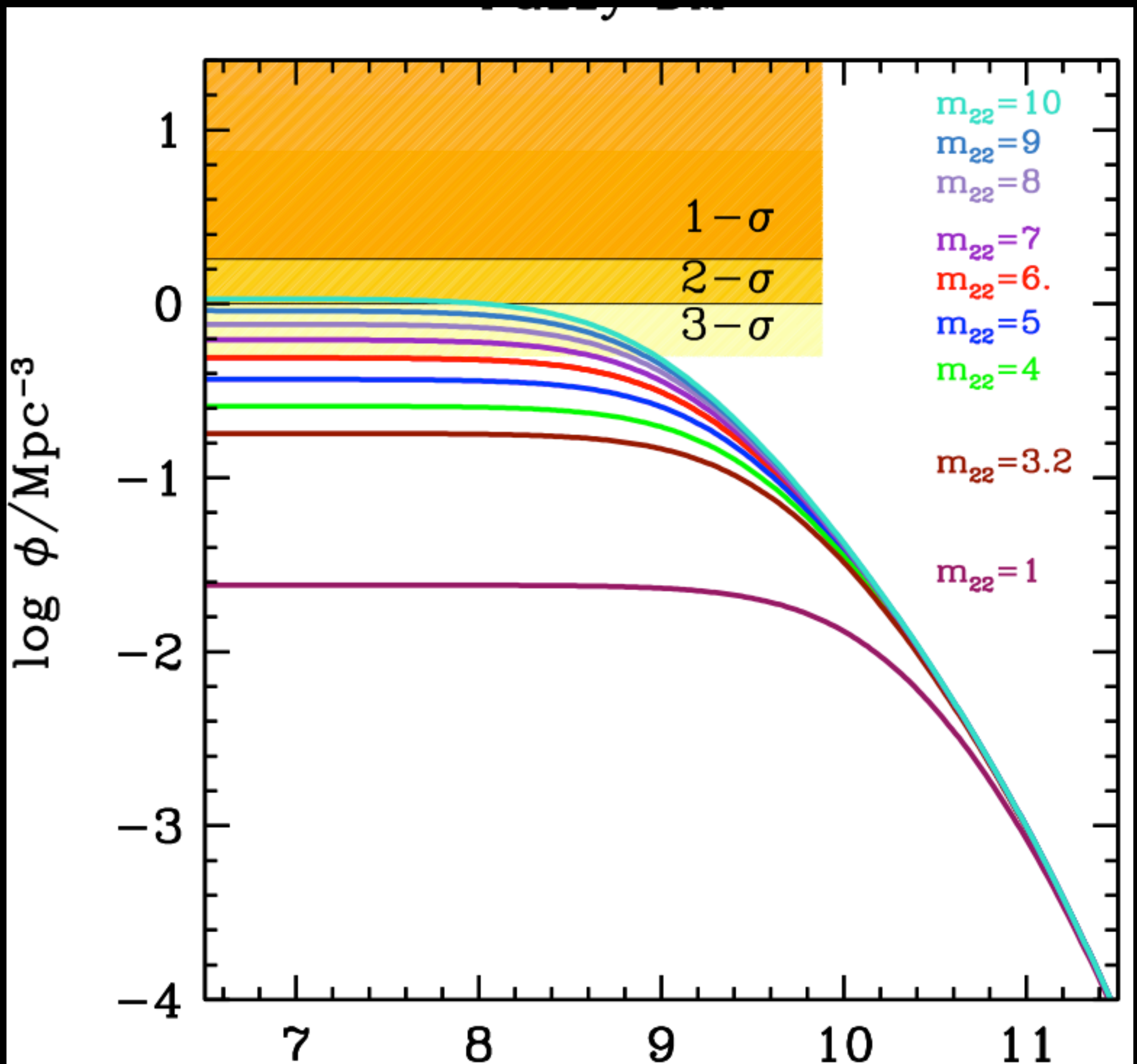
$$\mathcal{L} \supset -\frac{y}{2} S \overline{N^c} N, \qquad \lambda \ll 10^{-6}$$ Small Higgs coupling

Wave DM - Fuzzy Dm: Bose condensate of ultra-light axion $m_X \sim 10^{-22}$ ev. Such class of models is ruled out

matching observed abundance of z=6 galaxies requires $m_{22}>10$
Matching the dwarf profiles requires $m_{22}<1.2$



Schive et al. 2016



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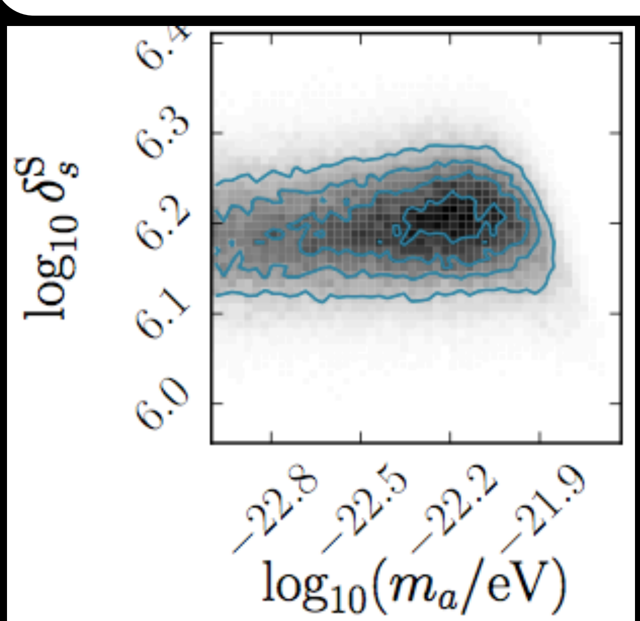


Marsch et al. 2015

Conclusions

The abundance of faint galaxies at z=5-7 down to MUV=-12.5 yields strong constraints on DM models with suppressed power spectra.

Strongest constraints derived so far independently of baryon physics

- **Thermal Relics:**
  m_X>2 kev (abundances in Bouwens et al. 2017) at 2-σ level
  m_X>2.4 keV (abundances in Livermore et al. 2017) at 2-σ level

- **Sterile neutrinos**

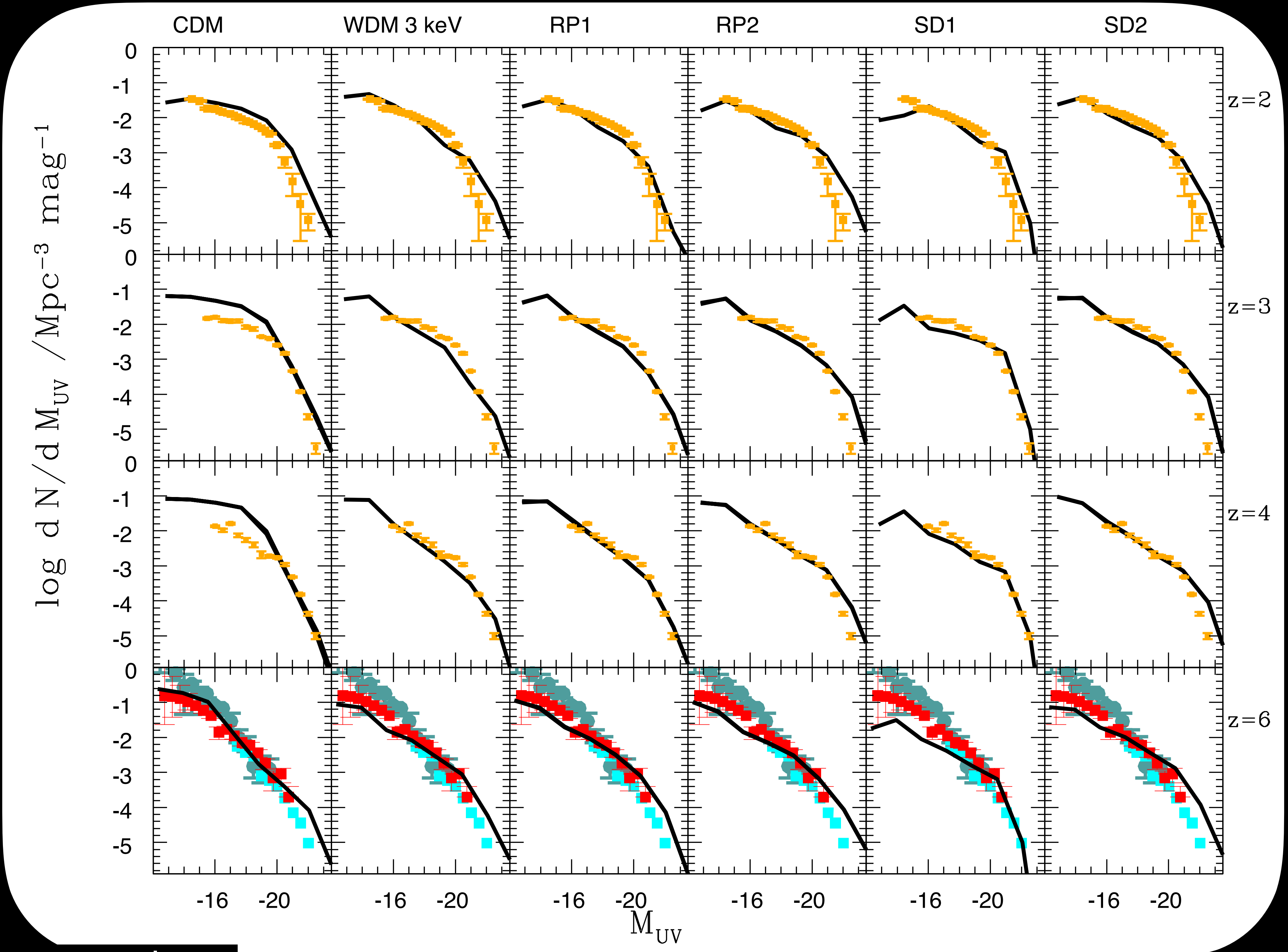
–Produced through Shi-Fuller mechanism (resonant production):
unprecedented lower limits for $\sin^2(2\vartheta)$ as a function of $m_{sterile}$.
E.g., for $m_{sterile}$=7 keV we obtain $-10.4 < \log \sin^2(2\vartheta) < -9.8$ at at 2-σ level

–Produced through scalar decay (for small Higgs portal coupling)
$y>10^{-8}$ at at 2-σ level

- **Fuzzy DM (condensate of ultra-light axions) are ruled out: $m_X > 10^{-21}$ eV**
  2-σ level

Constraints from maximum abundance of DM halos are MODEL INDEPENDENT but VERY CONSERVATIVE. The observed galaxies cannot outnumber their host DM halo,

If baryon physics is included in the models (e.g. through SAM models) the predicted abundance of luminous galaxies can provide tighter constraints



Menci et al. 2018

UV LF computed from the Rome Semi-analytic model

Feedback tuned so as to match the local stellar mass and the local LFs.

CDM
3 keV thermal model

4 sterile neutrino models Consistent with the tentative 3.5 keV line (2 based on resonant production, 2 based on scalar decay)

Observed abundance by Livermore disfavour all WDM and sterile N models.

Scalar decay models are Disfavoured by existing Measurements

The Nature of DM determines the shape of the power spectrum P(k)

CDM: Large power in at small scales yields Guo et al. 2011
- huge amount of small-scale structures Papastergis et al. 2011
- huge amount of sub-structure Kravtsov, Klypin, Gnedin 2004

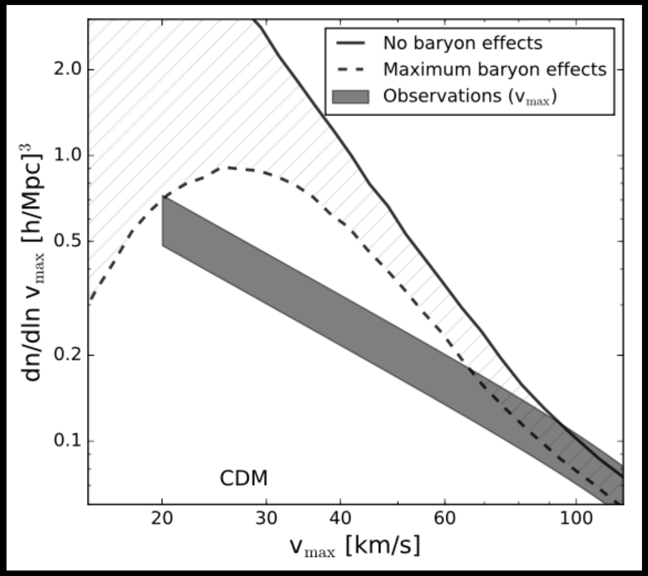
Predicted abundance of low-mass halos are much larger than the observed abundances of low-luminosity galaxies

$$N(L) = N(M)\left[\frac{dM}{dL}\right]$$

A Possible Solution: Baryon Physics
Suppress luminosity (star formation) in low-mass haloes
Heat - Expell Gas from shallow potential wells
- Enhanced SN feedback
- UV background

Even considering baryonic effects, the comparison with observed abundance of dwarf galaxy is critical

An Alternative Solution:
The problem is rooted in the power spectrum, i.e., in the assumed DM model: the actual DM Power Spectrum and Mass Function are suppressed with respect to CDM below mass scales $M \sim 10^8\ M_\odot - 10^9\ M_\odot$



Sterile Neutrino WDM   Production from Active-Sterile Transitions

Suppression of Power spectrum with respect to CDM

2 parameters: neutrino mass m_ν
mixing with active neutrinos
(oscillation probability)

Suppression of Power Spectrum is only approximately similar to thermal WDM with a rescaled mass

Approximate correspondence between thermal relic mass m_X and sterile neutrino mass m_ν (yielding the same power spectrum) depends on the assumed production mechanism
E.g. for the Shi-Fuller mechanism $m_\nu \approx 2.5\, m_X$

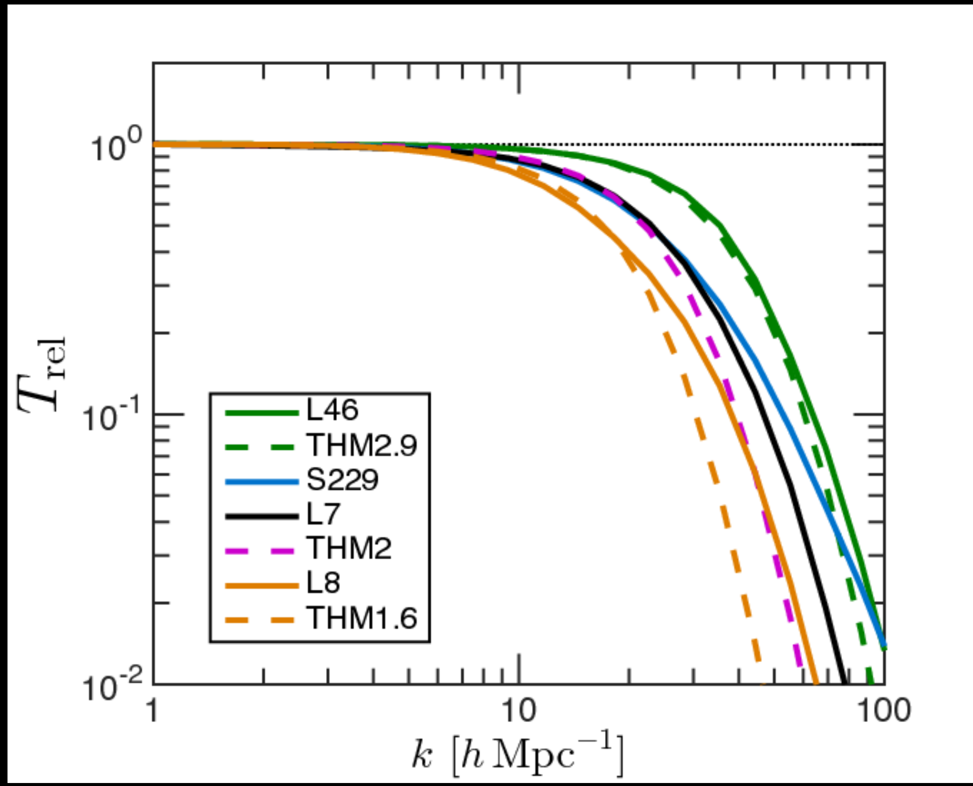
Deriving Power Spectra in the sterile neutrino case requires complete computations

For each couple of free parameters m_ν $sin^2(2\theta)$

- Solve the Boltzmen equation to get the momentum distrib.
  sterile-dm code (Venumadhav et al. 2016)

- Compute the Power Spectrum based on obtained f(p)
  Boltzmann solver CLASS (Blas et al. 2011; Lesgourgues & Tram 2011)

Suppression with respect to CDM



Bozek et al. 2015

Suppression of the power spectrum of resonantly-produced sterile neutrino models (solid lines) and their best-fit thermal equivalent model (dashed lines) relative to CDM.

The L7 model has an equivalent thermal WDM model of m=2 keV (THM2/dashed; magenta).

The shape and large-k behavior of the WD transfer functions vary among the sterile neutrino models and compared with their thermal equivalent models.

Sterile Neutrino WDM

Right-handed neutrino

Strong physical motivation: the most natural extension of SM to include mass terms for active neutrinos requires SNs

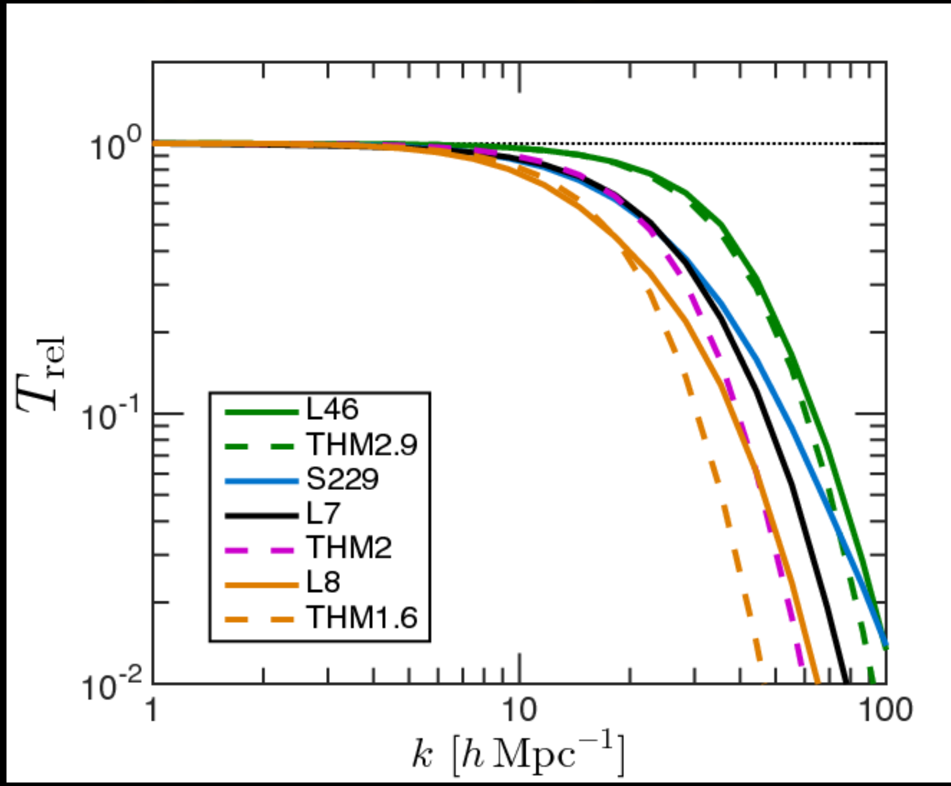
$$\mathcal{L}_{\rm Yuk} = h_d \overline{Q}_L \, d_R \, \Phi + h_u \overline{Q}_L \, u_R \, \tilde{\Phi} + h_e \overline{\ell}_L \, e_R \, \Phi + \text{H.c.}$$

If right-handed neutrinos exist, neutrinos get a mass through a Yukawa term $h_\nu \overline{\ell}_L \, \nu_R \, \tilde{\Phi} \Rightarrow m_D = h_\nu v$

$$\ell_L = \begin{pmatrix} \nu_L \\ e_L \end{pmatrix}$$

2 parameters: neutrino mass m_ν
mixing with active neutrinos $sin^2(2\theta)$
(oscillation probability)

Suppression with respect to CDM



are produced in primordial plasma through

- oscillations with null lepton asymmetry L=0
  Dodelson, Widrow; Abazajian, Fuller; Dolgov, Hansen;Asaka, Laine, Shaposhnikov et al.
- oscillations on resonance with lepton asymmetry
  Shi Fuller, Laine Shaposhnikov
- Decay of a scalar field
  Merle 2015
- production mechanisms which do not involve oscillations
  – inflaton decays directly into sterile neutrinos Shaposhnikov, Tkachev
  – Higgs physics: both mass and production AK, Petraki

→ 1 parameter m_ν
$m_\nu \;\; sin^2(2\theta)$ are related to produce the correct abundance

→ 2 parameters $m_\nu \;\; sin^2(2\theta)$
$sin^2(2\theta)$ and lepton asymmetry are related to produce the correct abundance

→ 3 parameters

m_S mass of scalar
y coupling to scalar field
λ coupling to Higgs

Sterile Neutrino WDM

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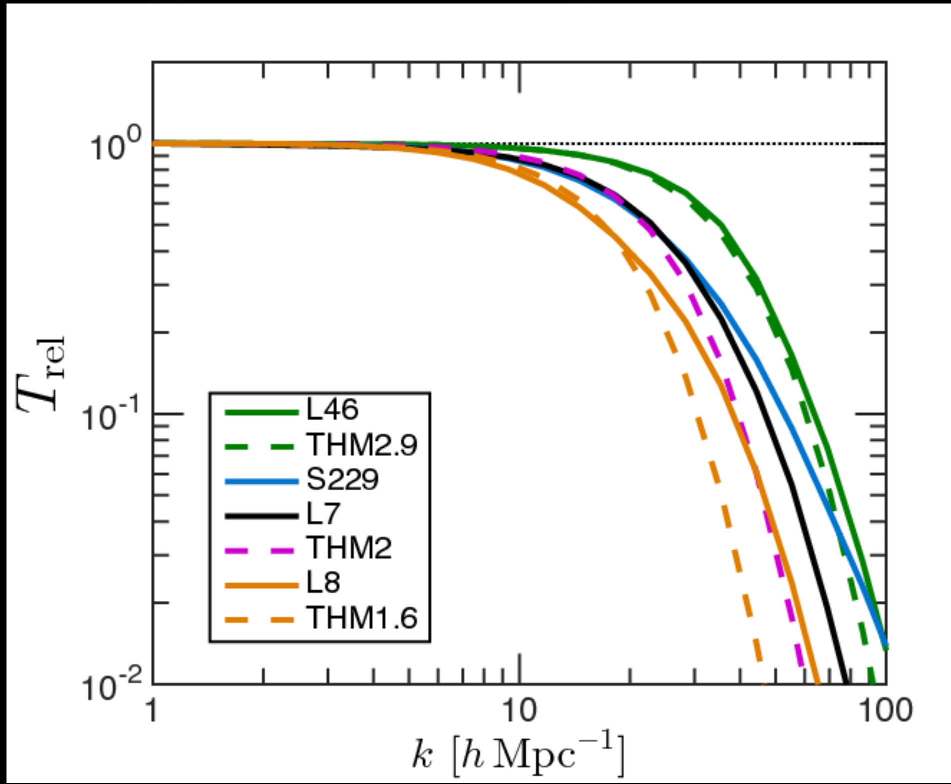

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