SIGNALS OF STERILE NEUTRINO DARK MATTER IN DWARF SPHEROIDAL GALAXIES

Mark Lovell
MPIA

Barolo Astroparticle Meeting, 05/09/2017

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AKA LIFE ON THE EDGE!

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WHY STERILE NEUTRINOS?

BECAUSE PARTICLE PHYSICS

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νMSM MODEL OF STERILE NEUTRINOS

M. Lovell, MPIA; BAM 05/09/17

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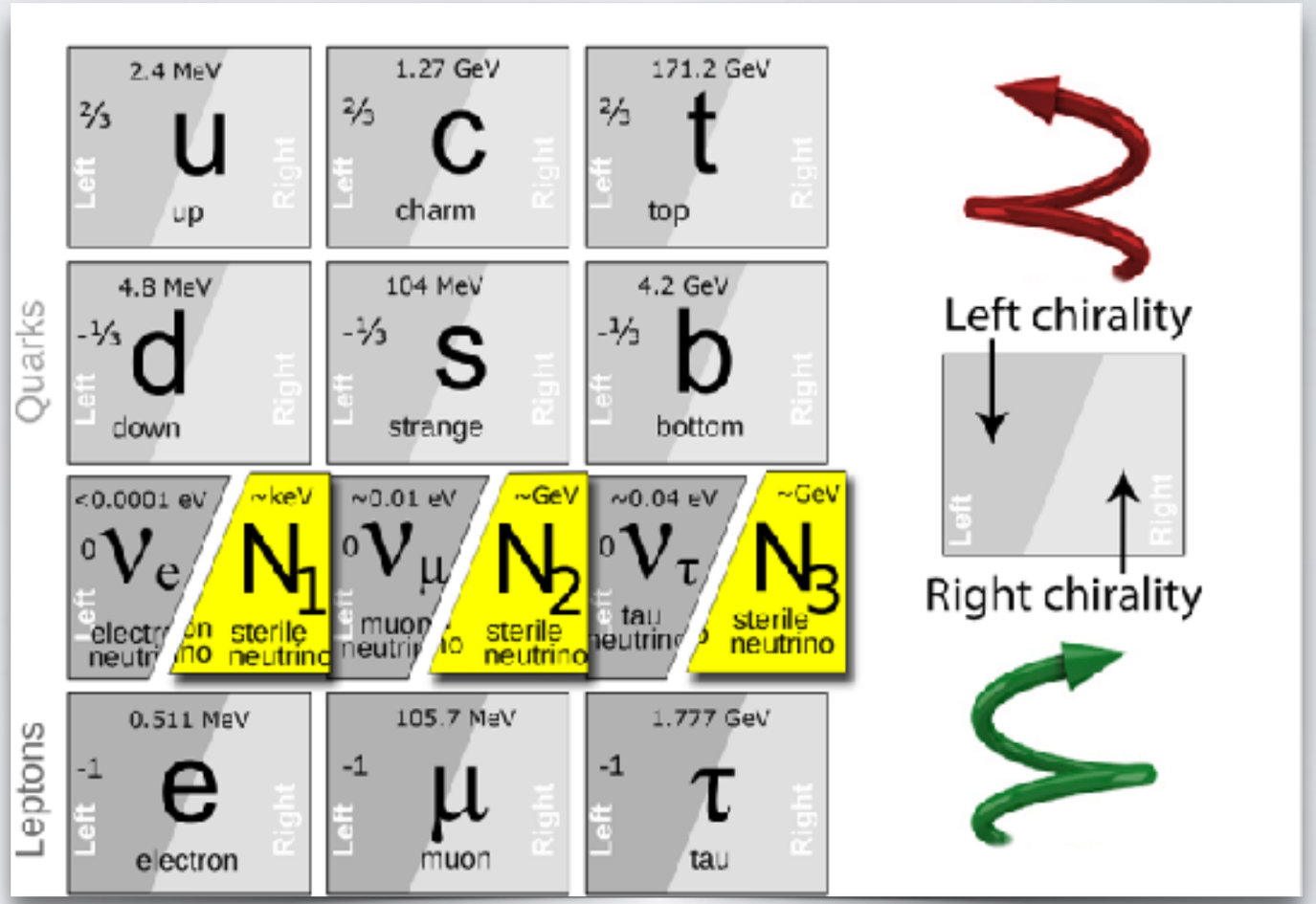

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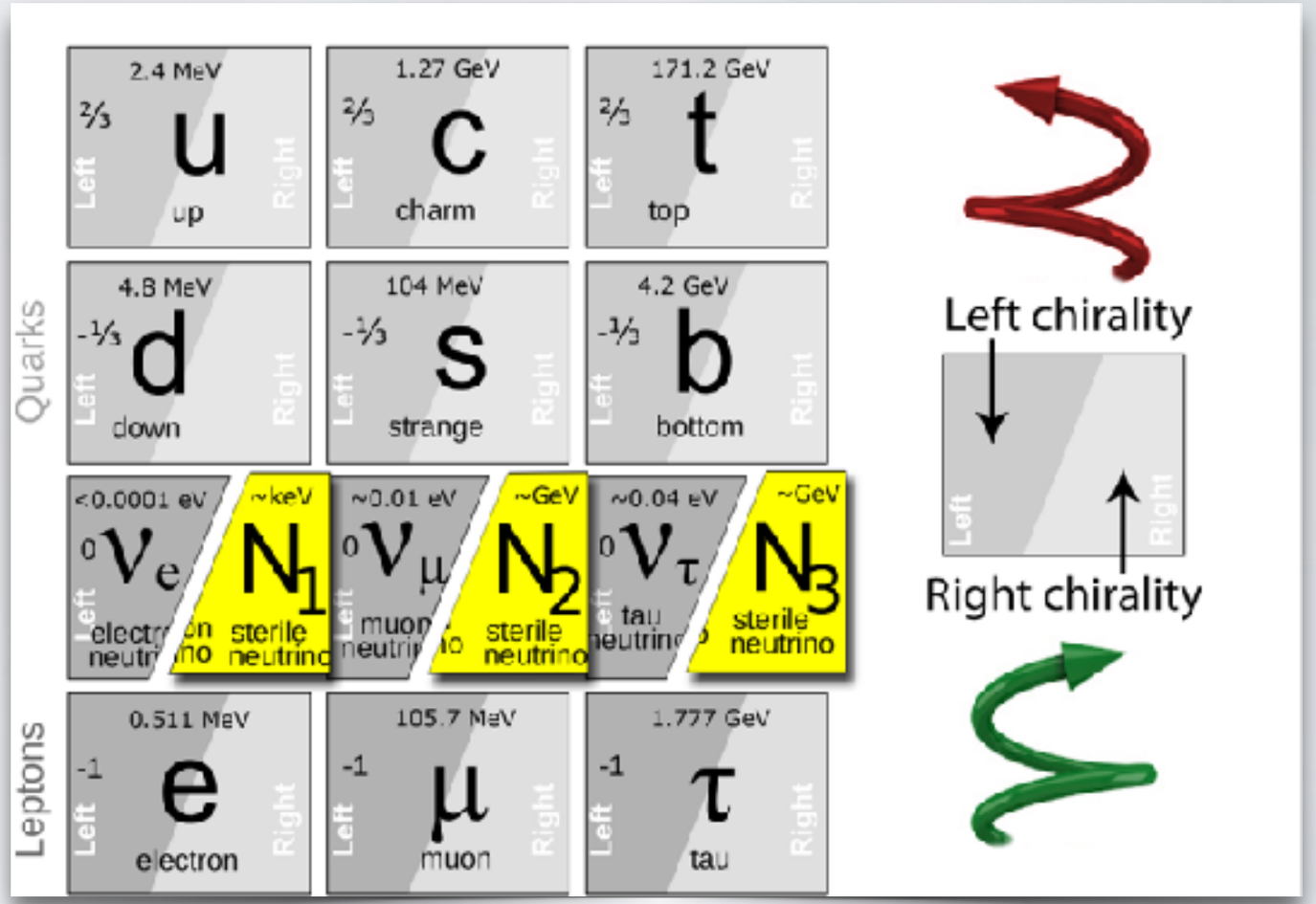

Solves multiple particle physics problems, inc. dark matter

TESTABLE IN MULTIPLE WAYS

M. Lovell, MPIA; BAM 05/09/17

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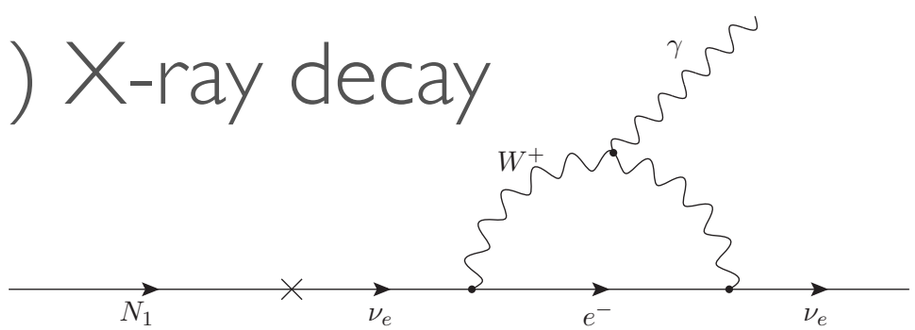
1) X-ray decay



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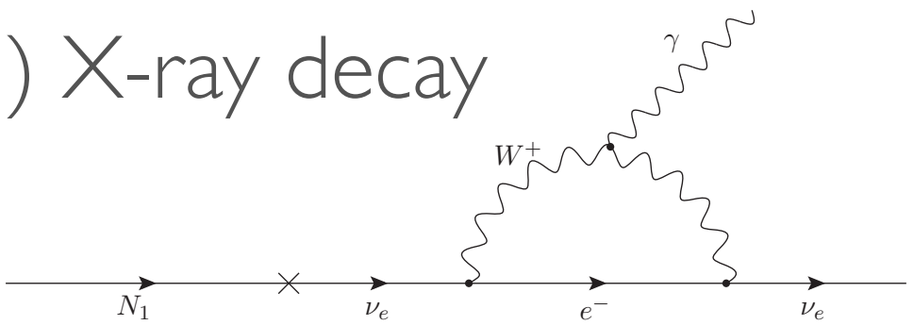

2) Experiment

SHiP
Search for Hidden Particles

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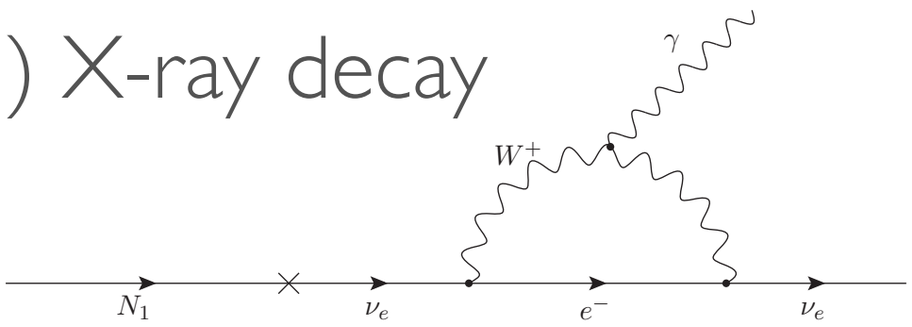

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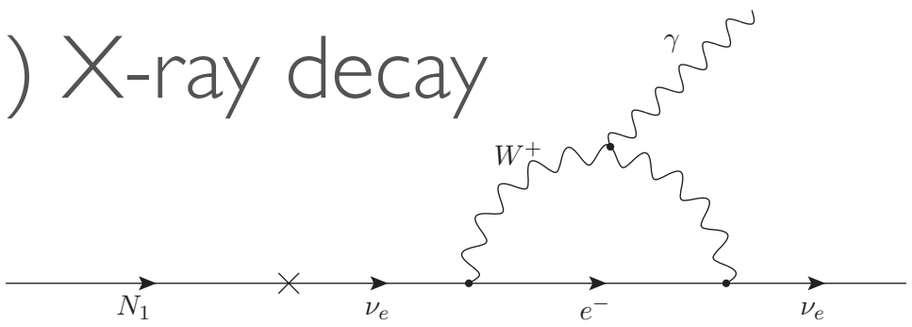

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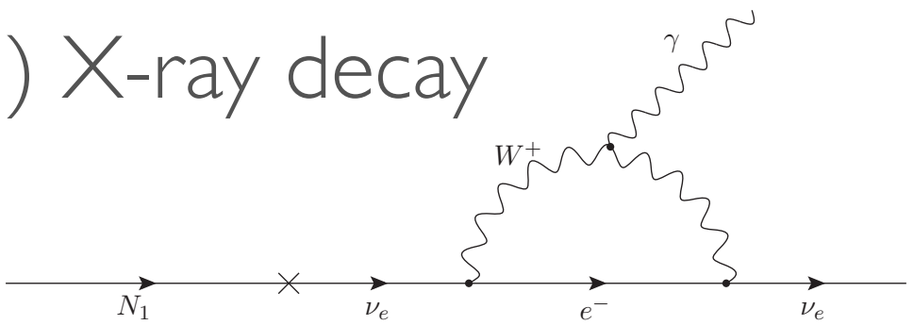

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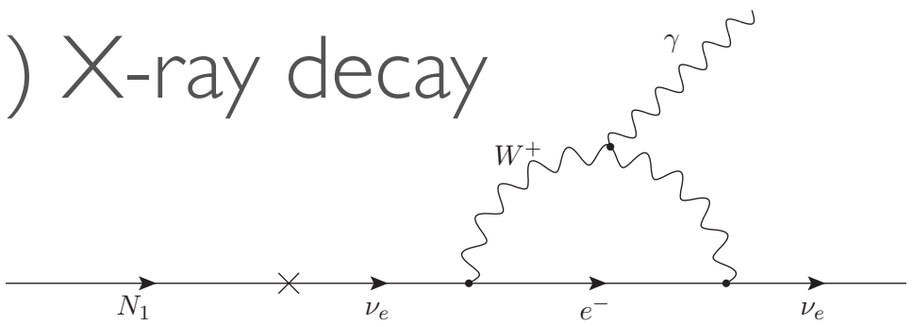

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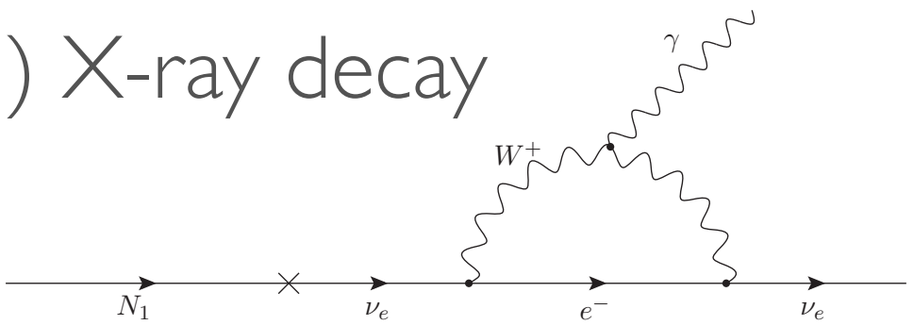

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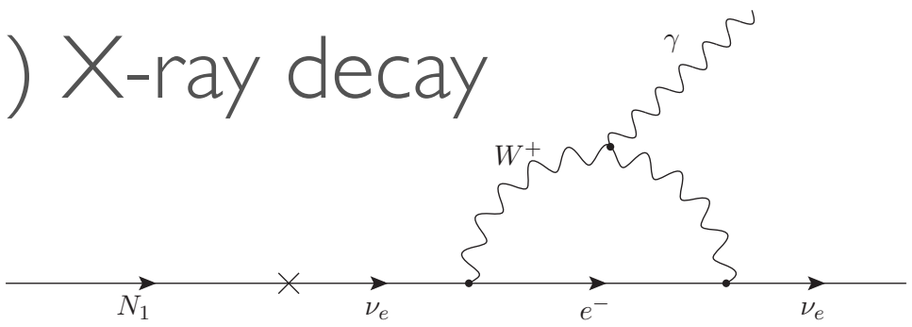

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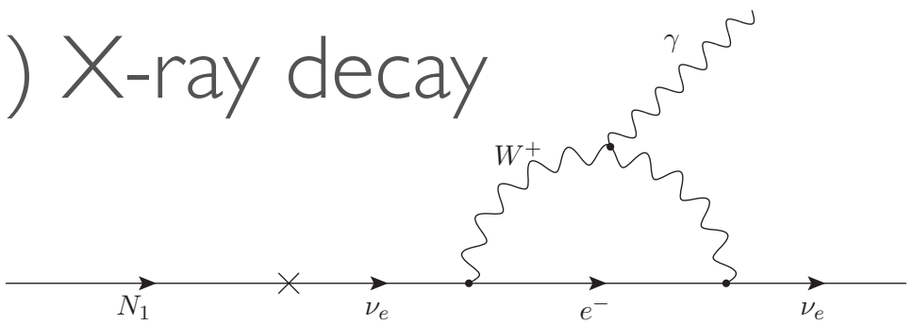

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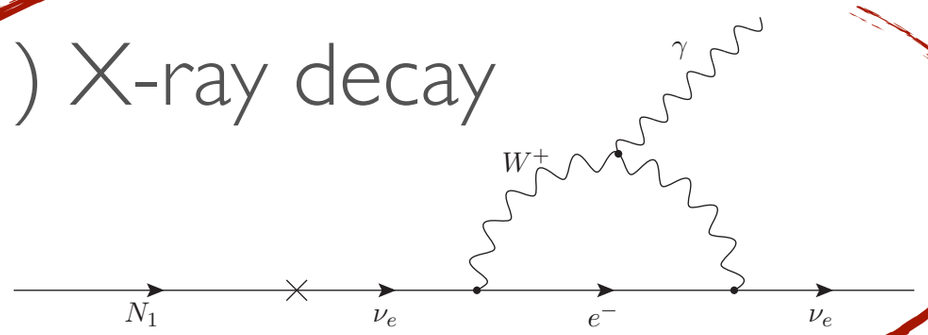

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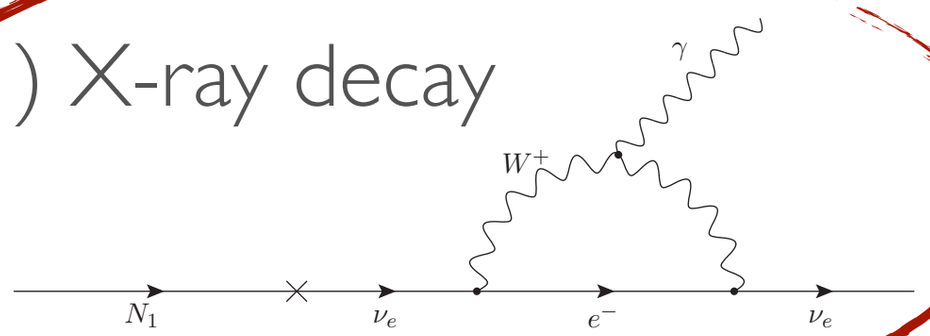

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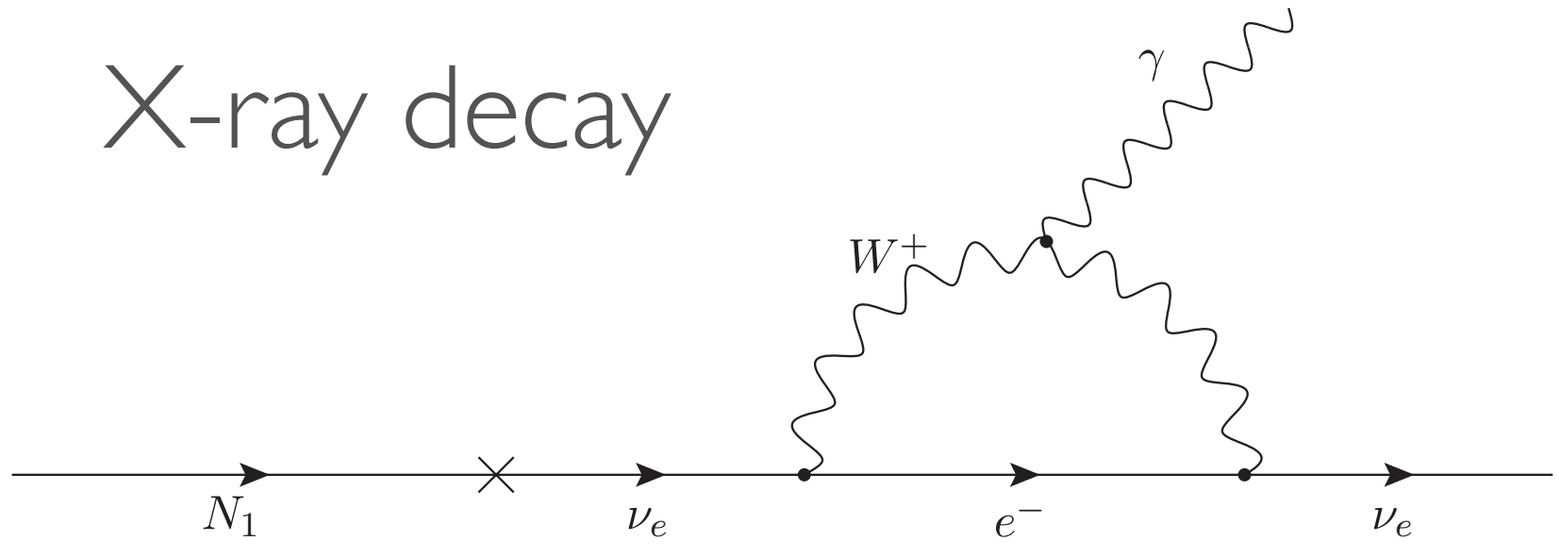

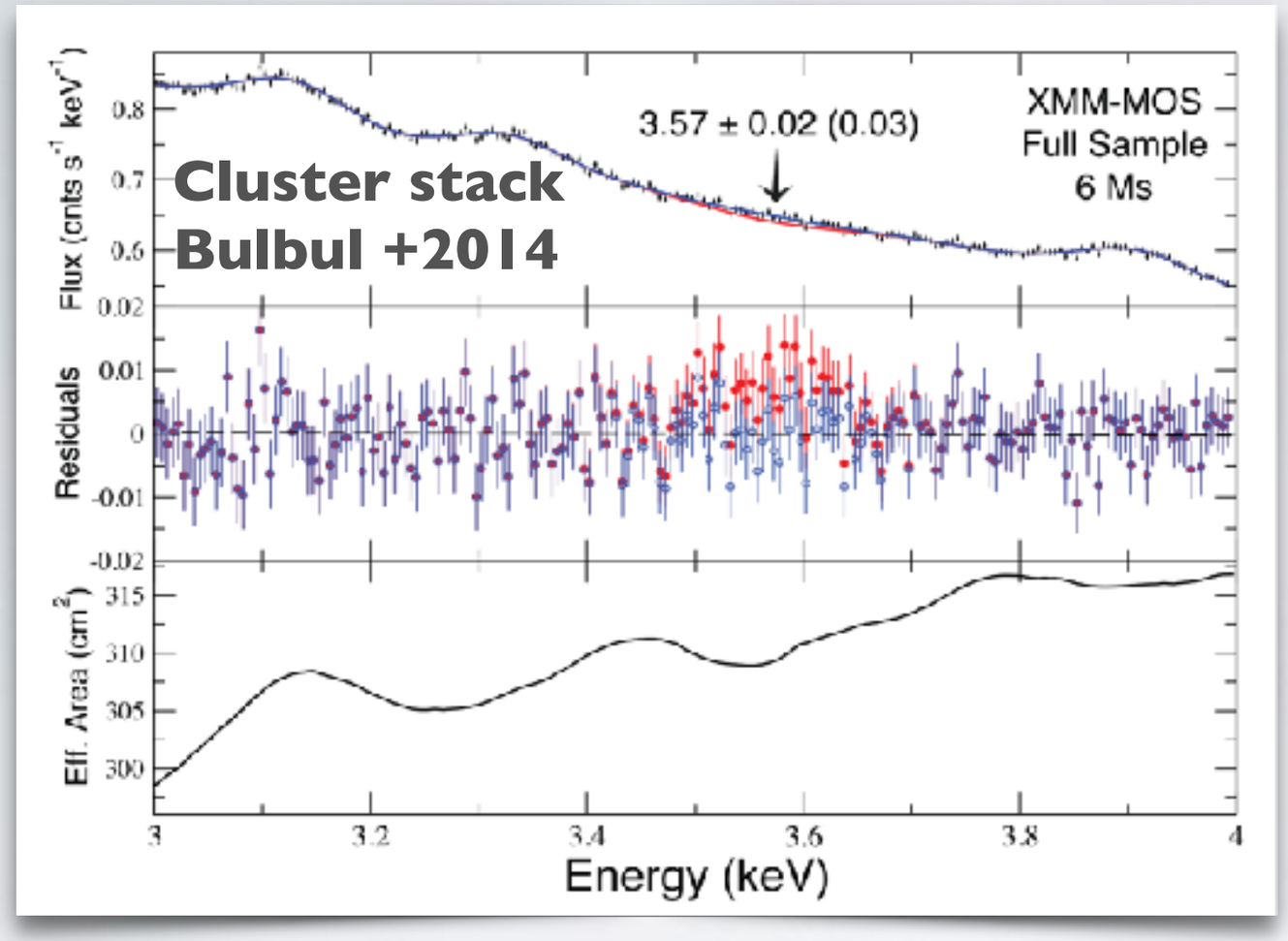

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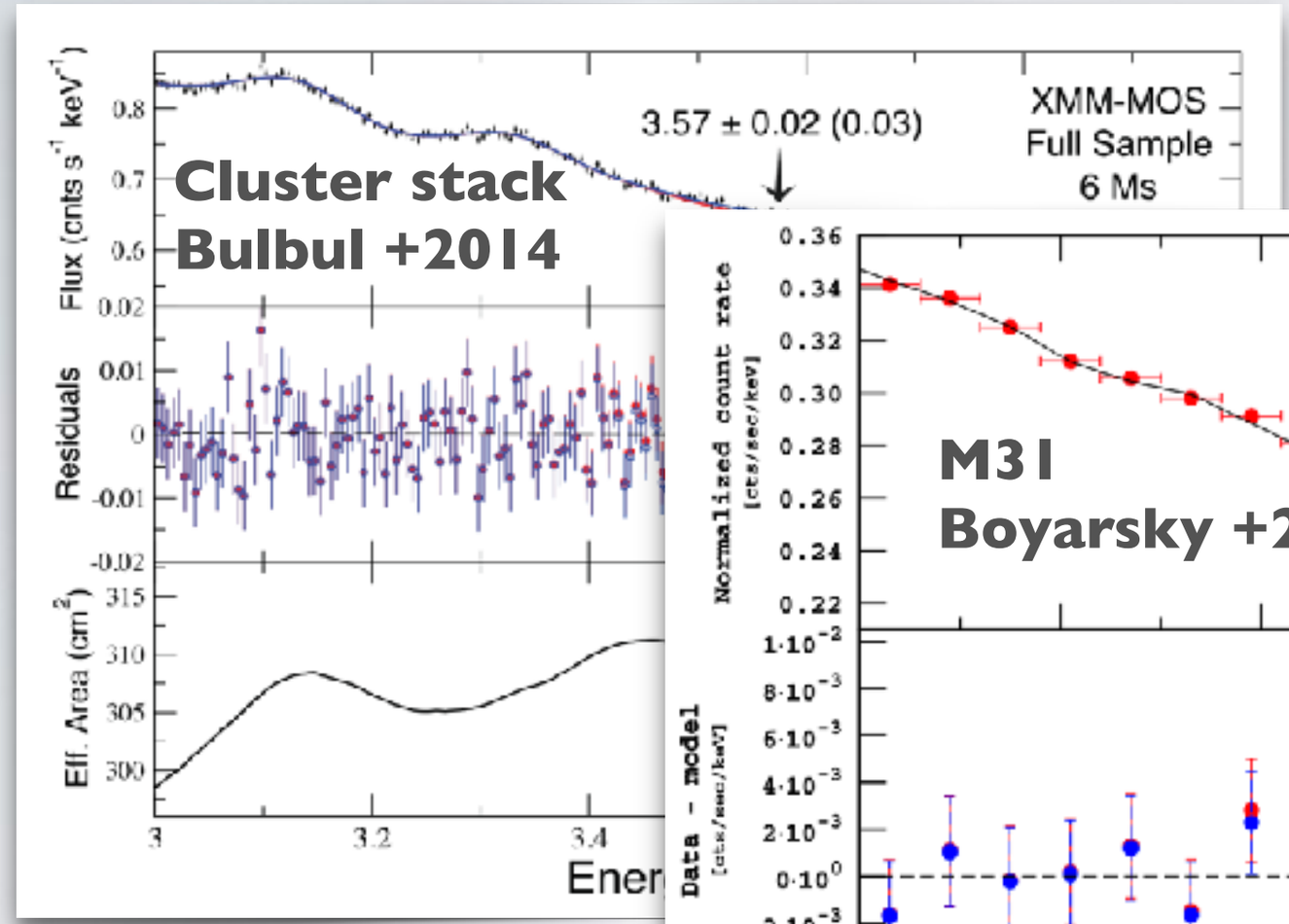
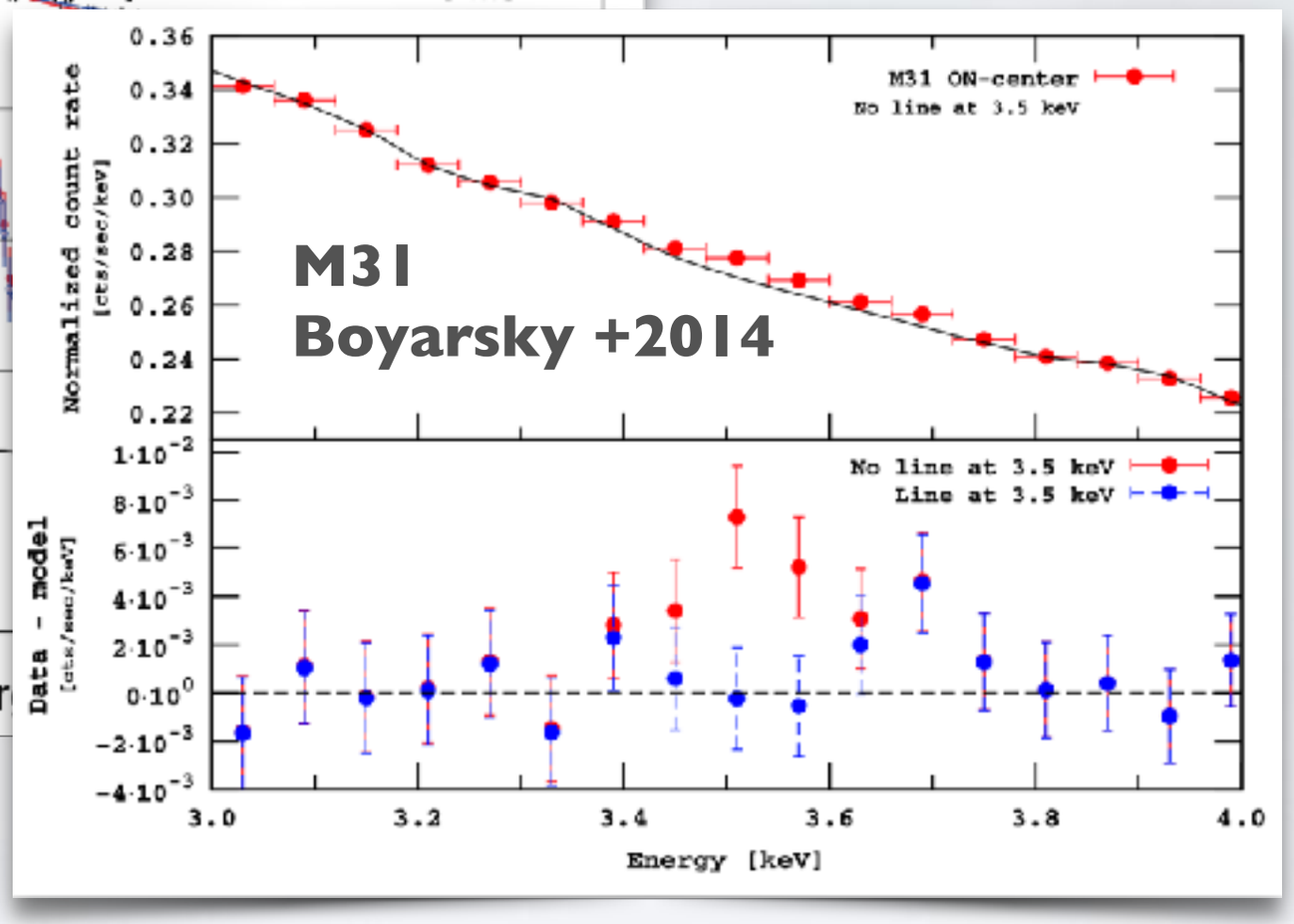
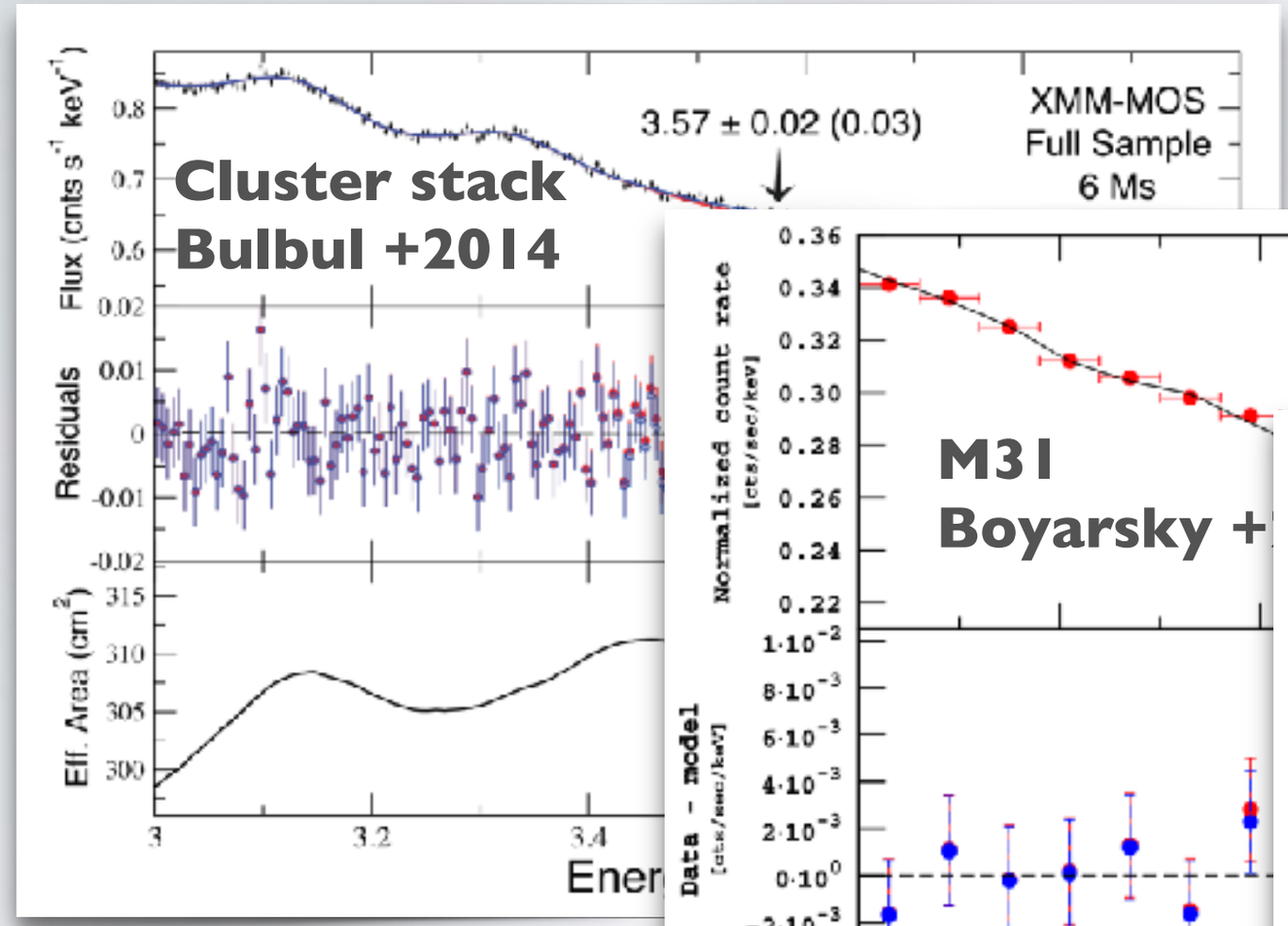
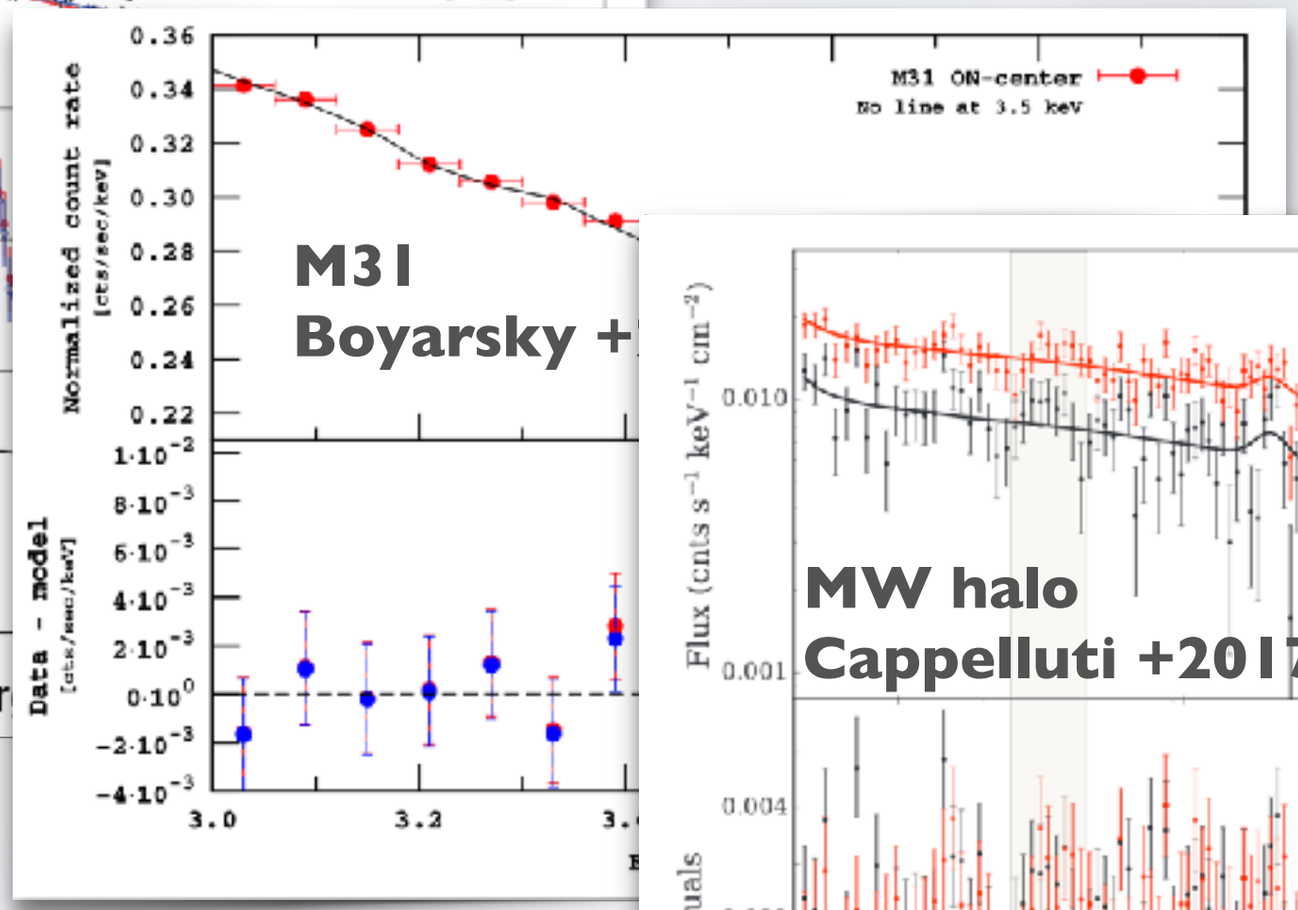
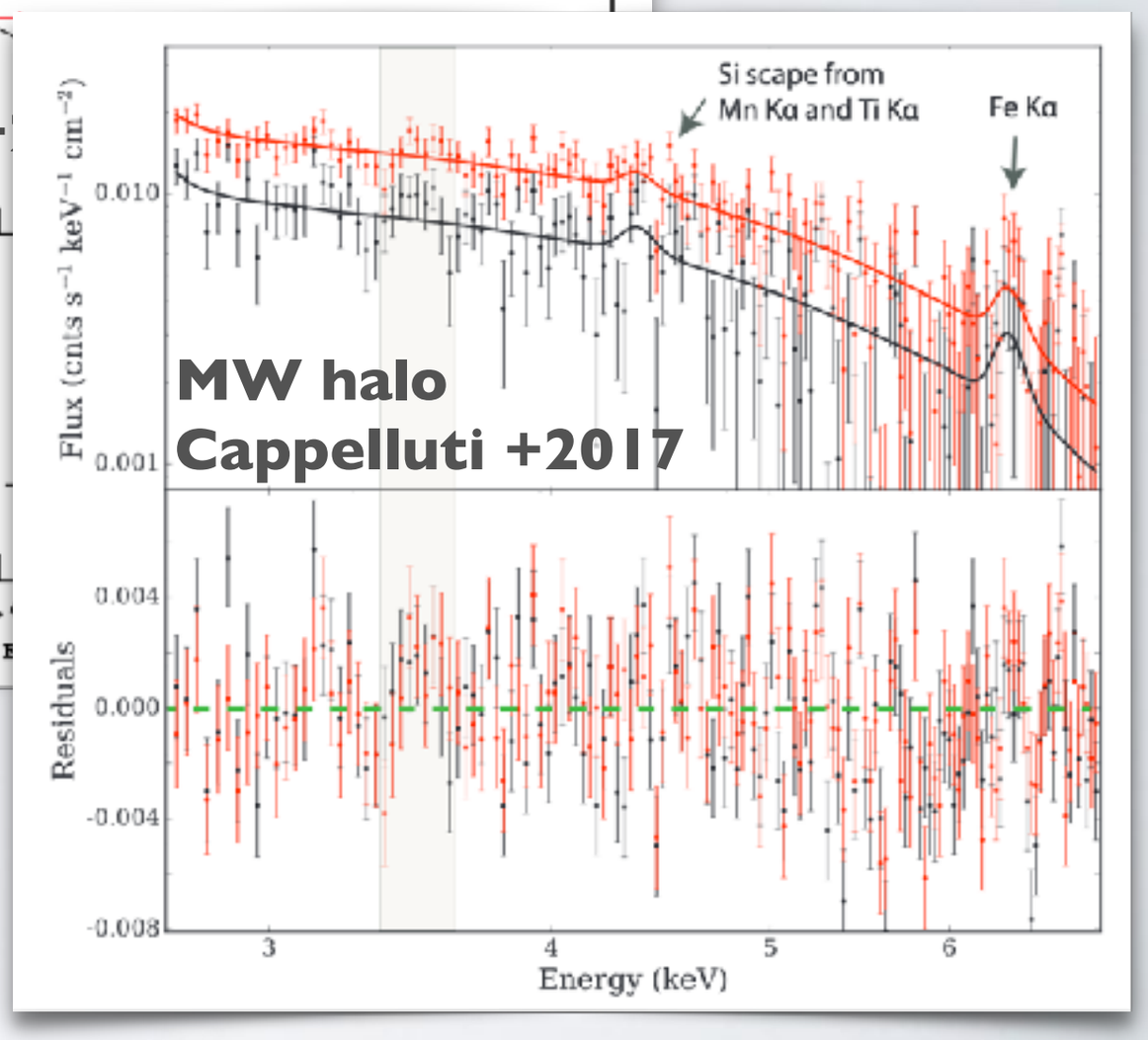

Cluster stack
Bulbul +2014
3.57 ± 0.02 (0.03)
XMM-MOS
Full Sample
6 Ms
Flux (cnts s^{-1} keV^{-1})
Residuals
Eff. Area (cm^2)
Ener


M31
Boyarsky +2014
M31 ON-center
No line at 3.5 keV
Normalized count rate [cts/sec/keV]
No line at 3.5 keV
Line at 3.5 keV
Data - model [cts/sec/keV]
Energy [keV]







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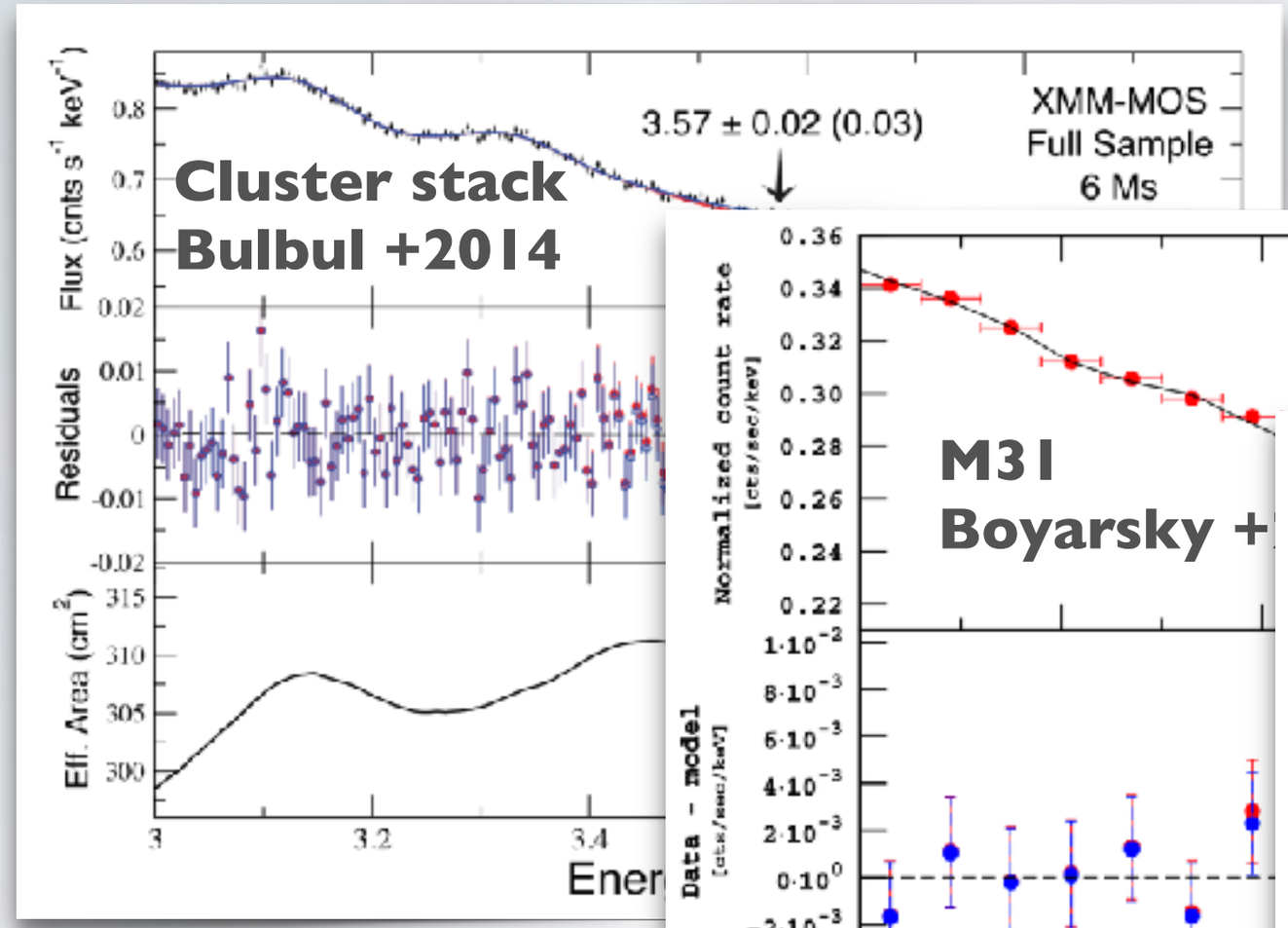
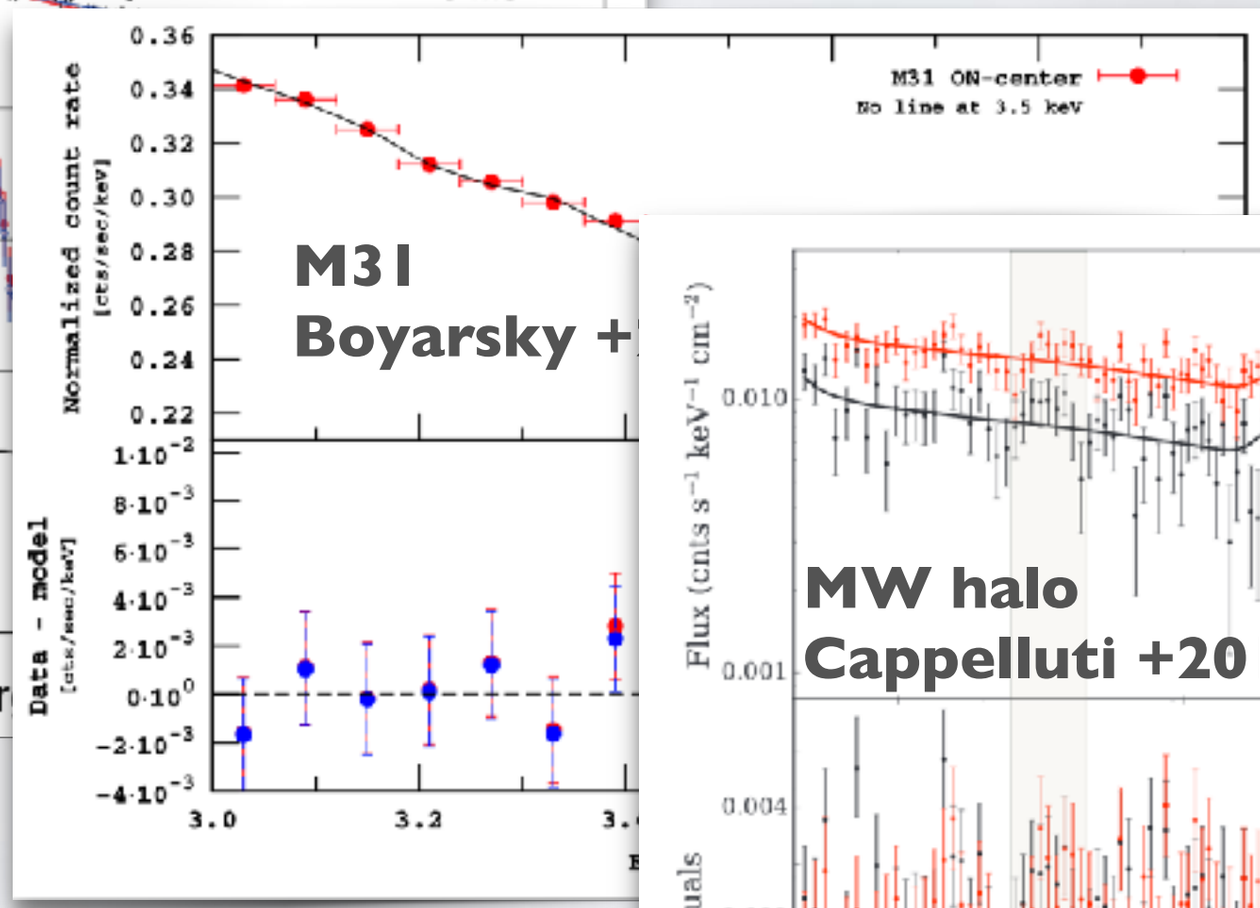
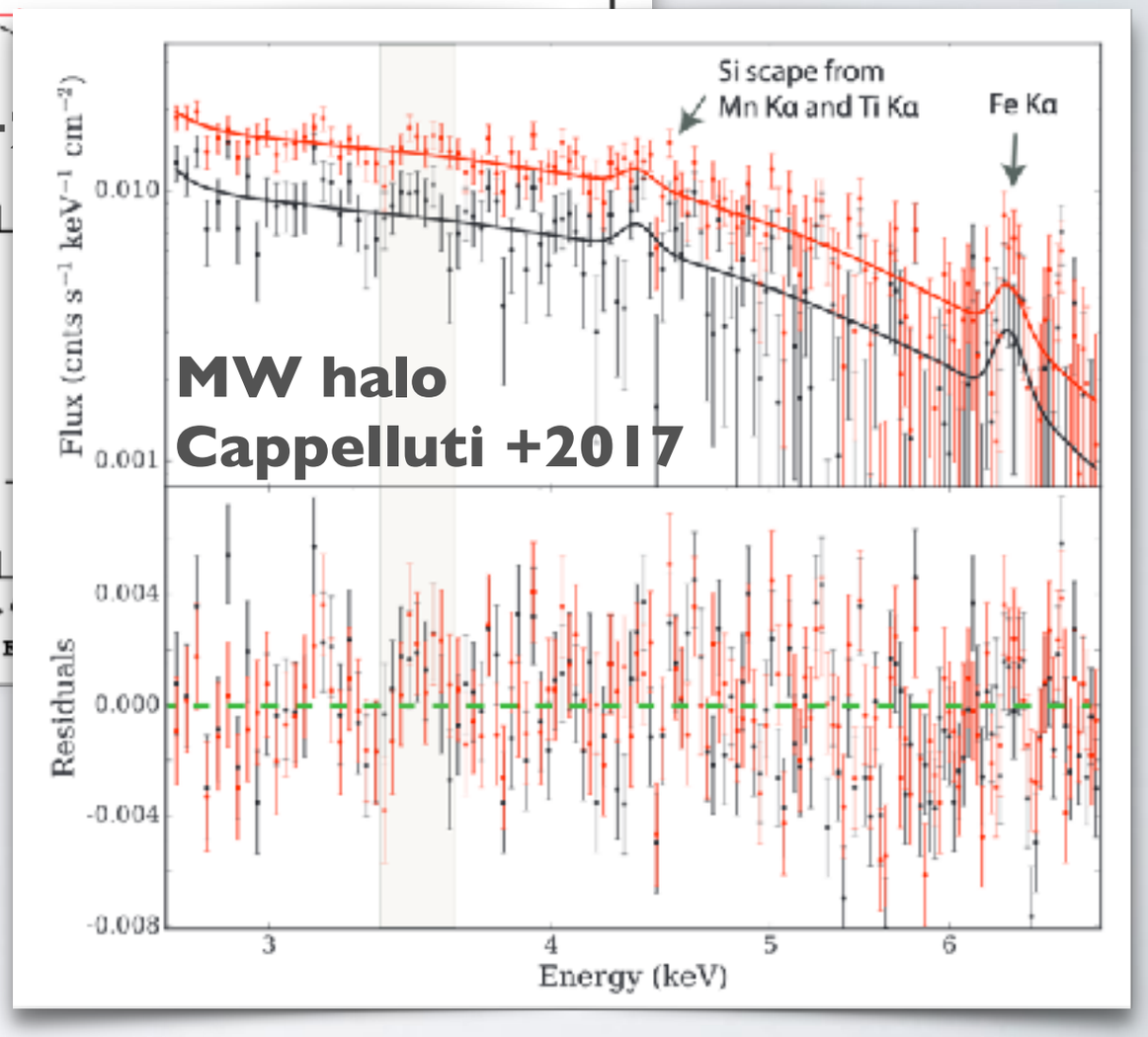
Position => mass = 7.1keV







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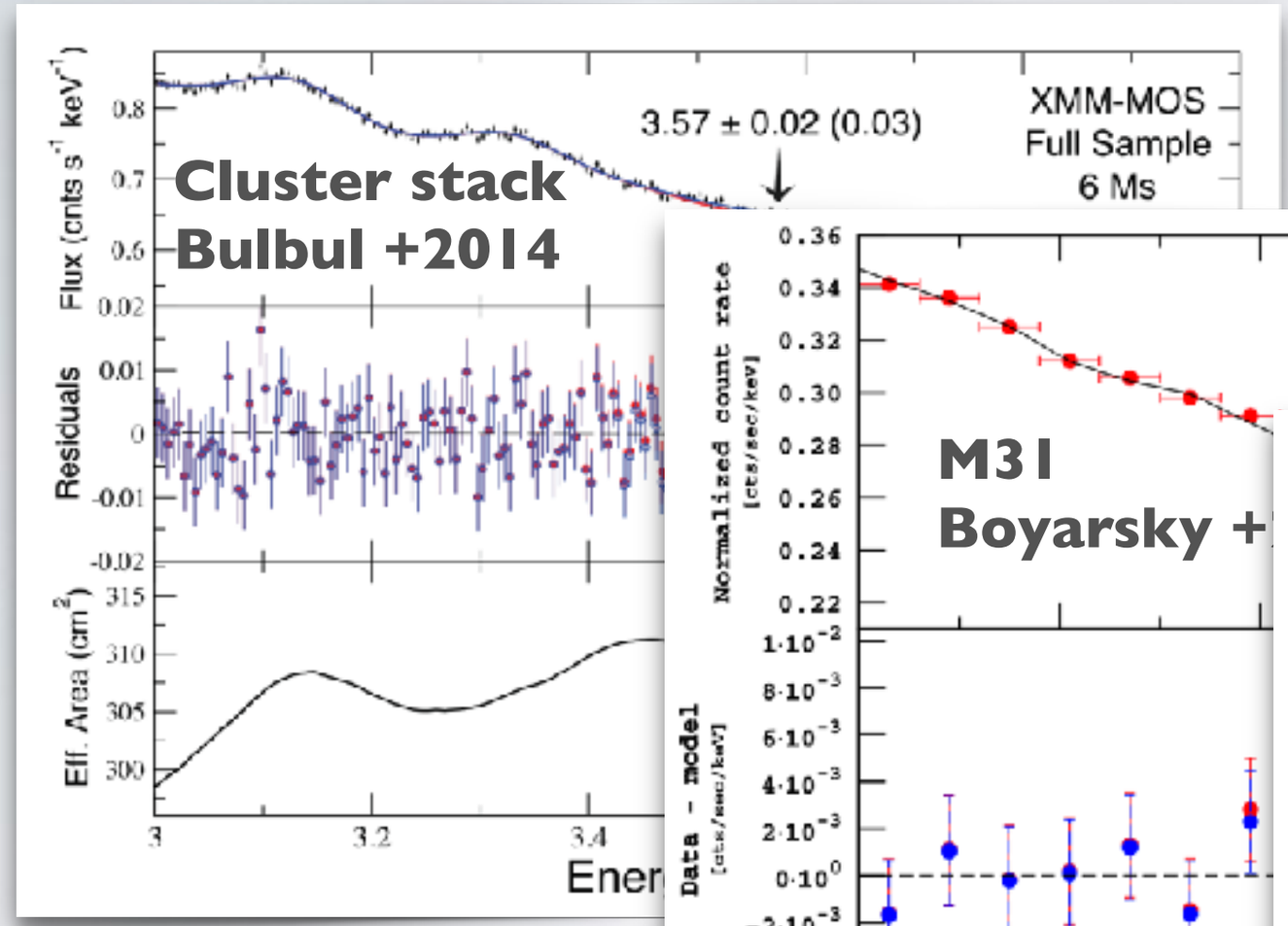

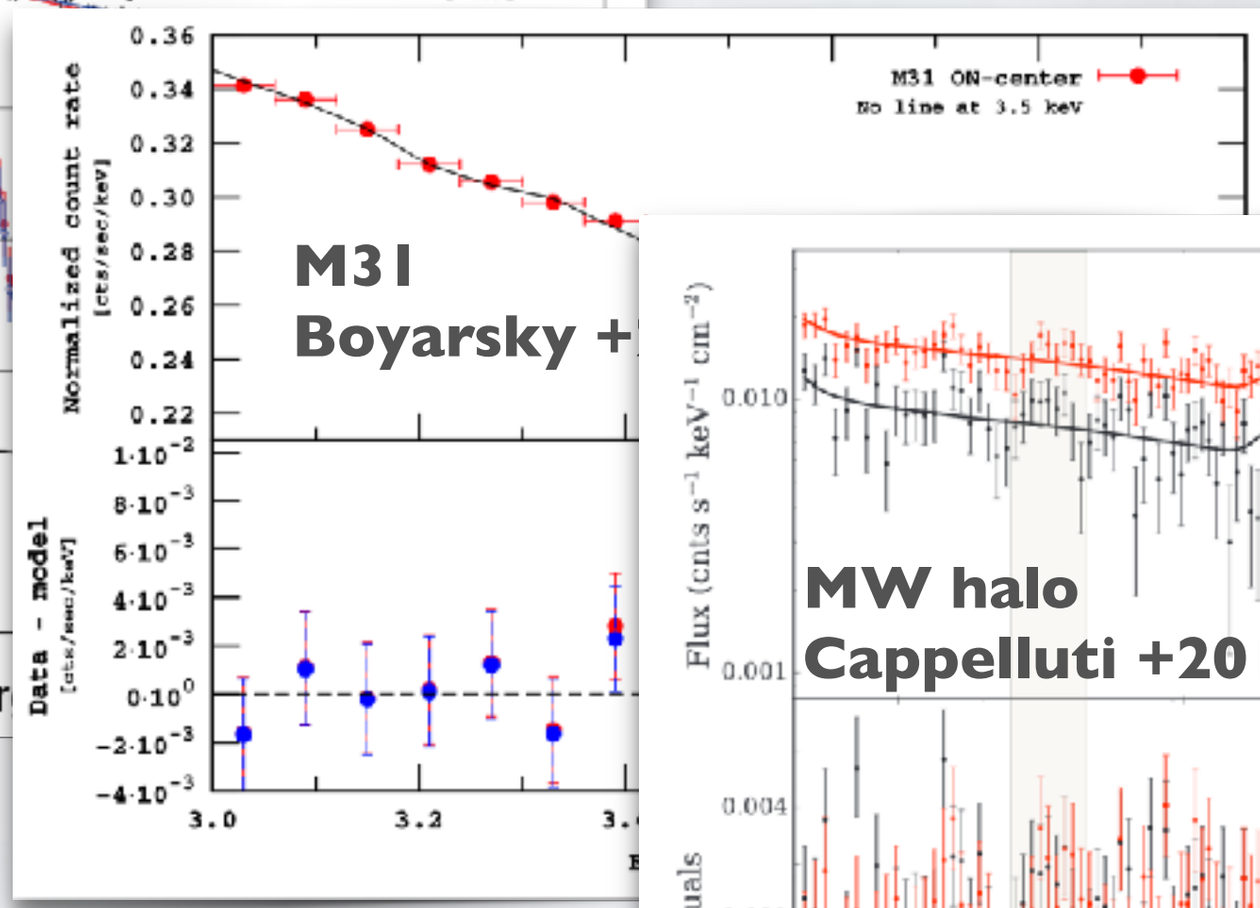

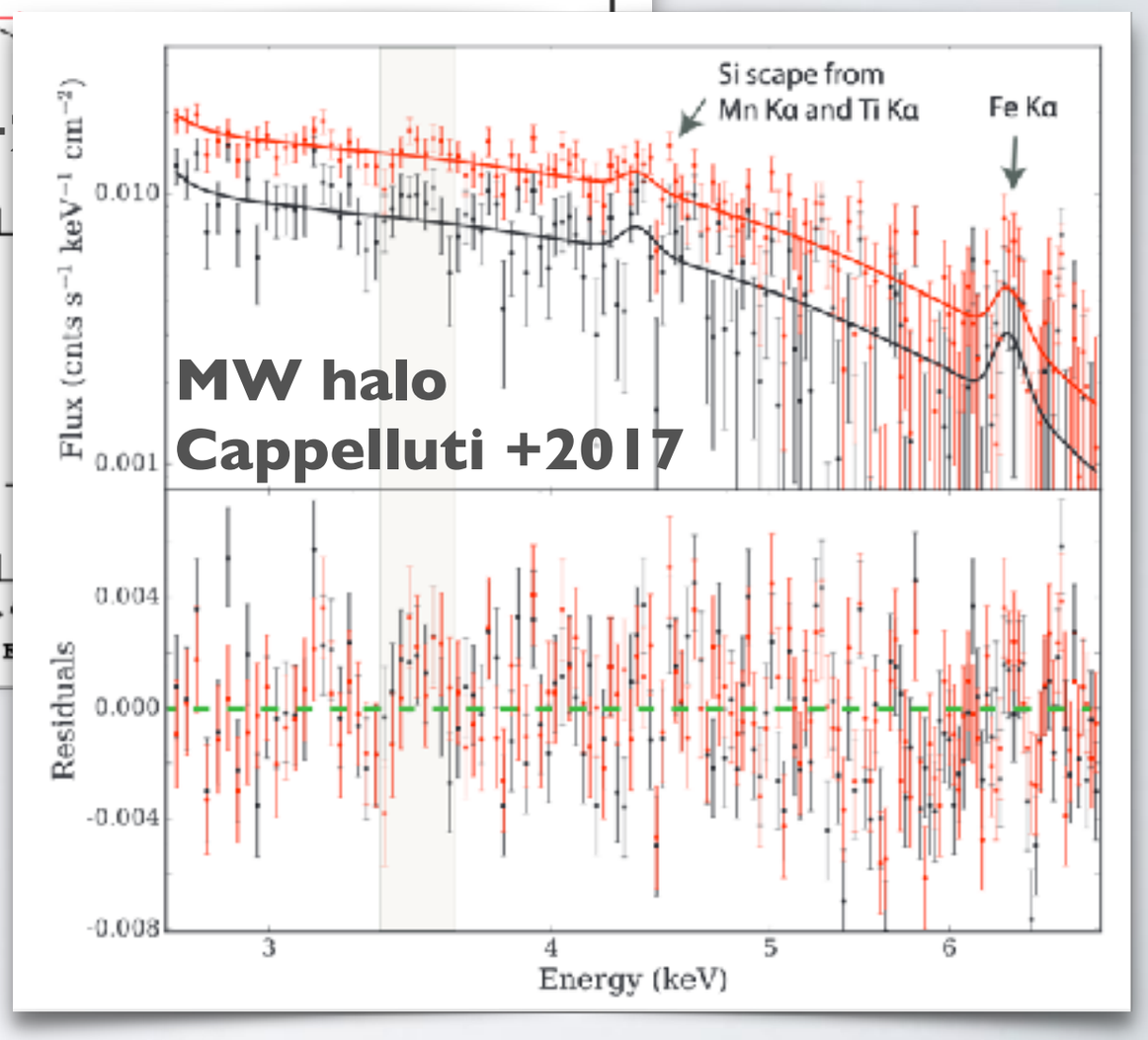

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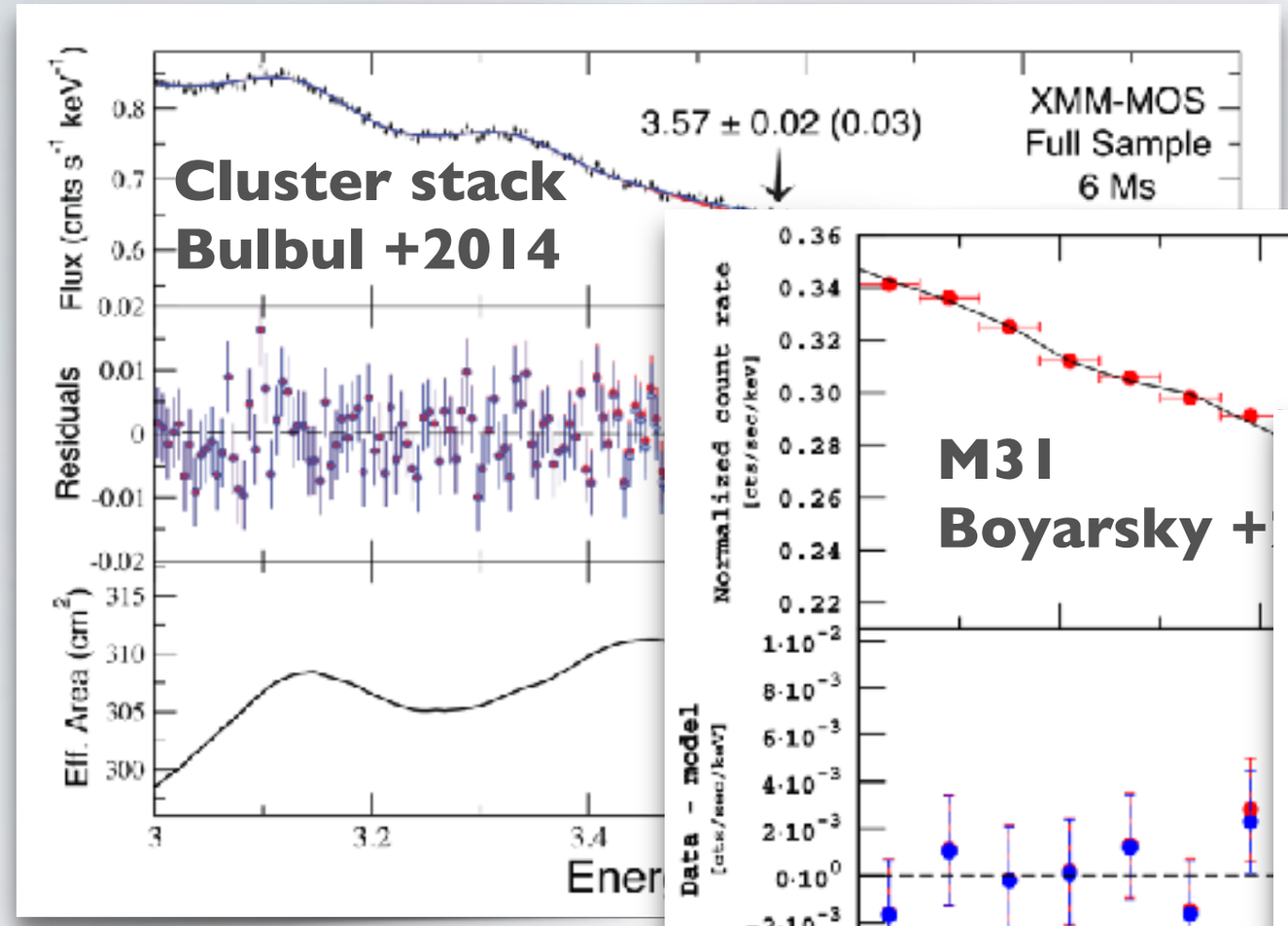
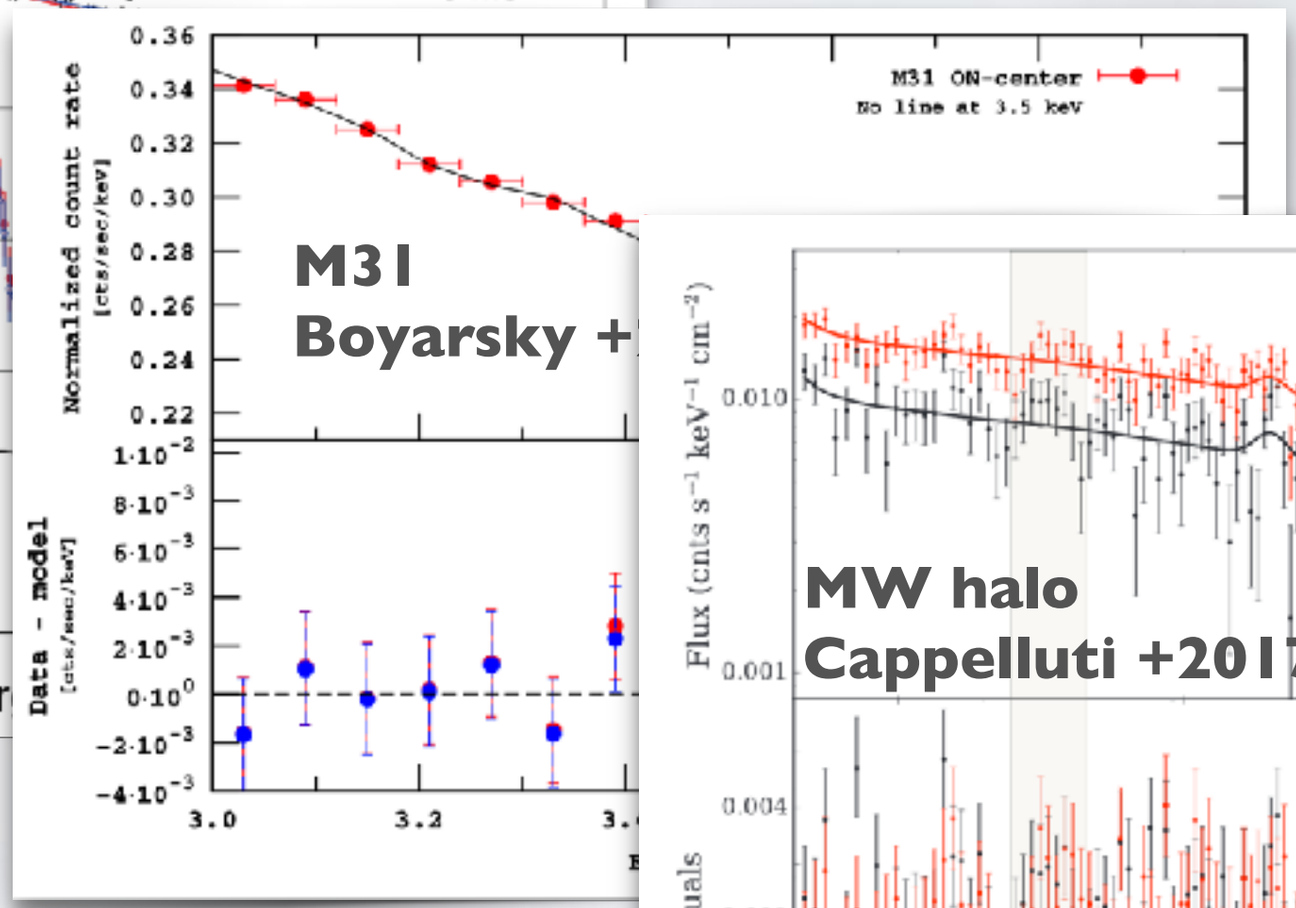
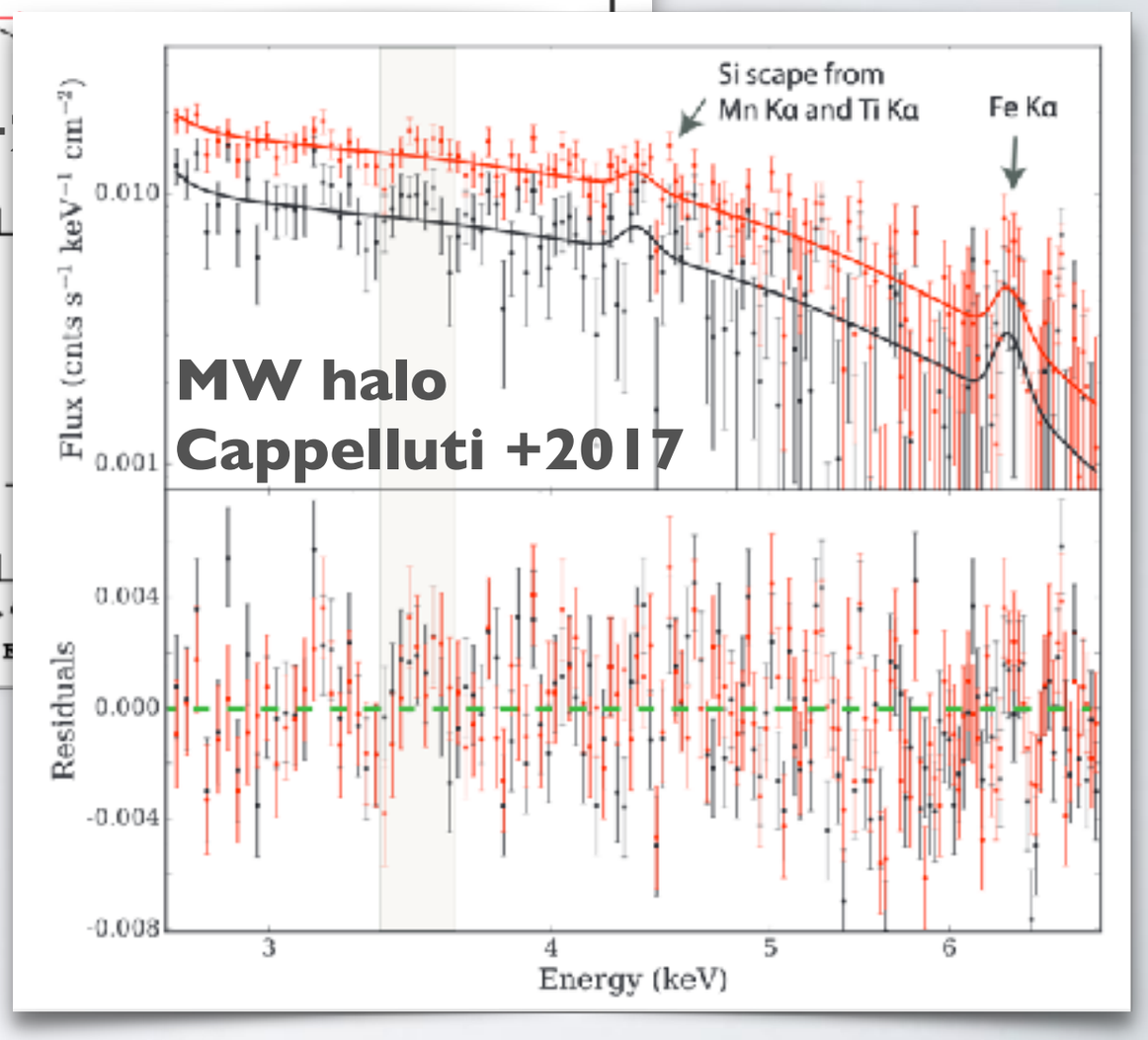
$\sin^2(2\theta) = [2,20]\times10^{-11}$







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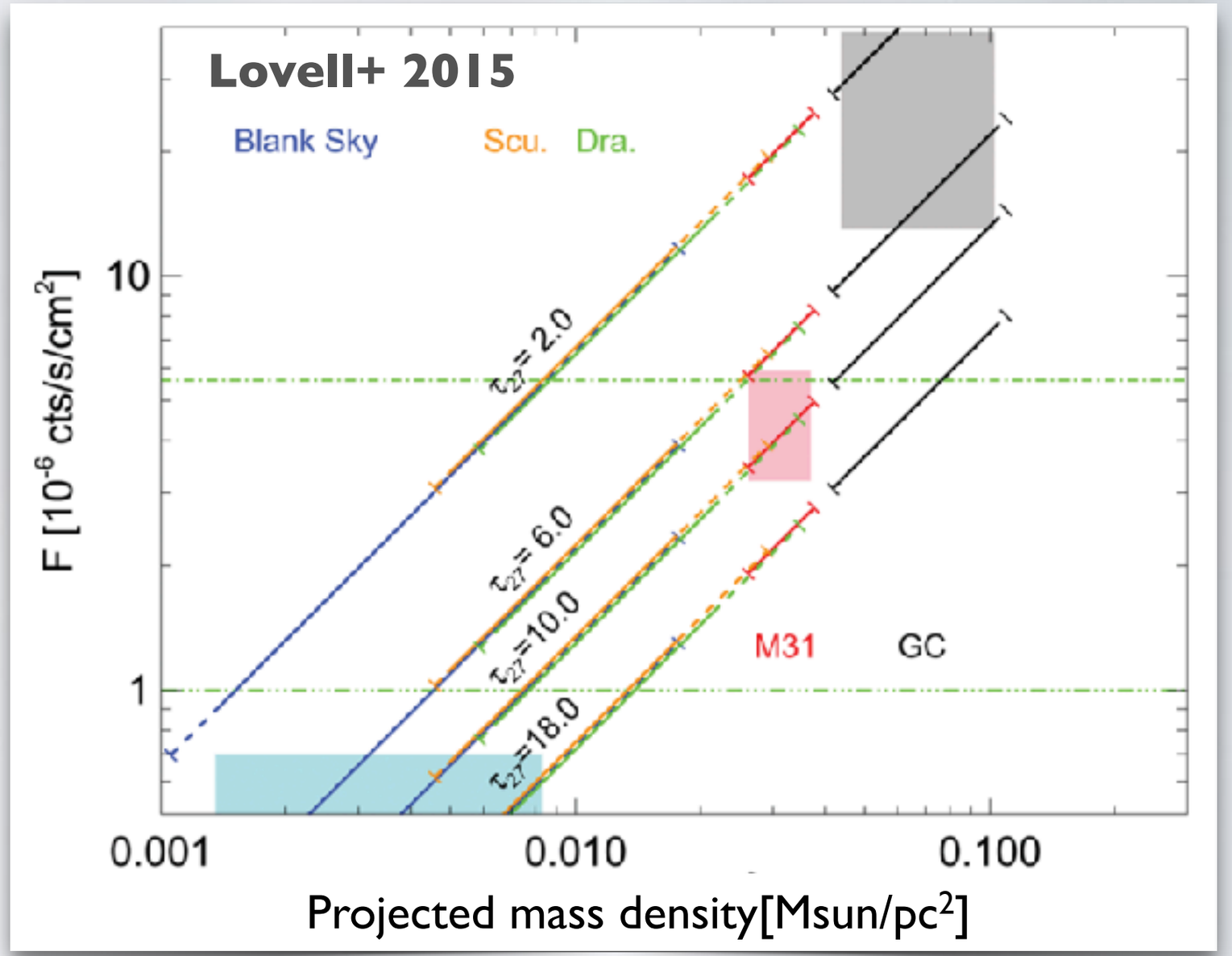

M. Lovell, MPIA; BAM 05/09/17

Awarded 1.4Ms for Draco on XMM-Newton (PI: A. Boyarsky)

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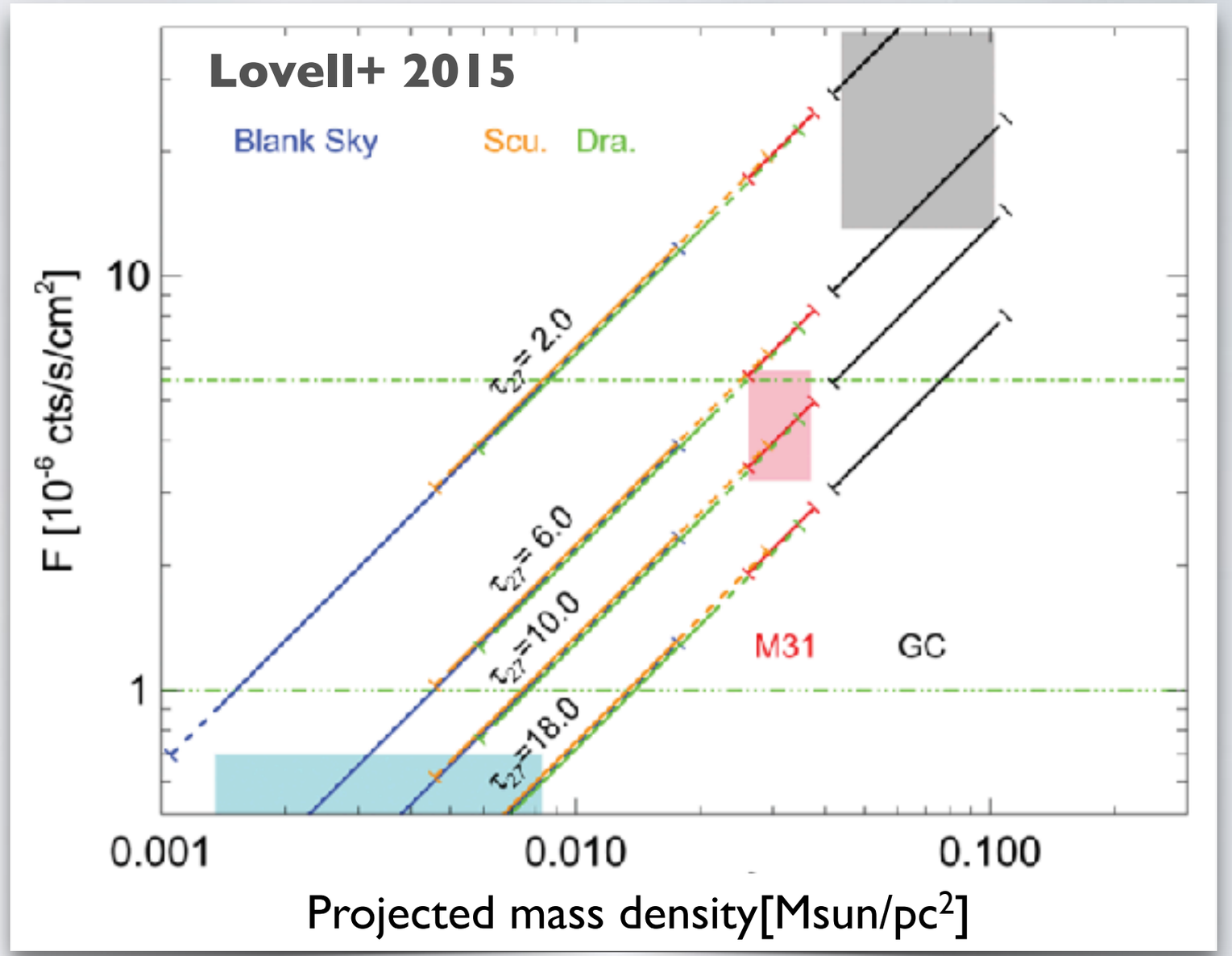

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RESULT …

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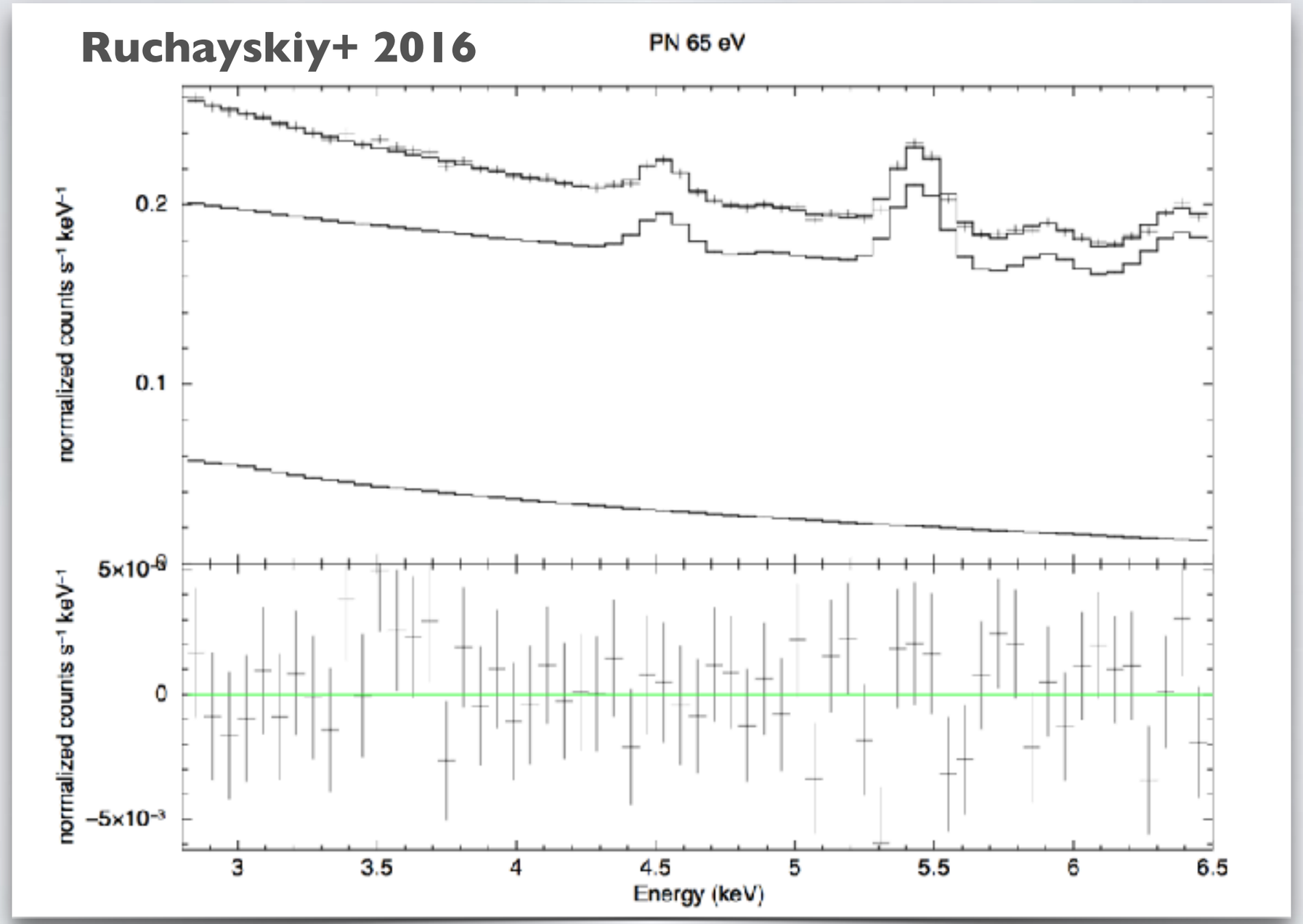
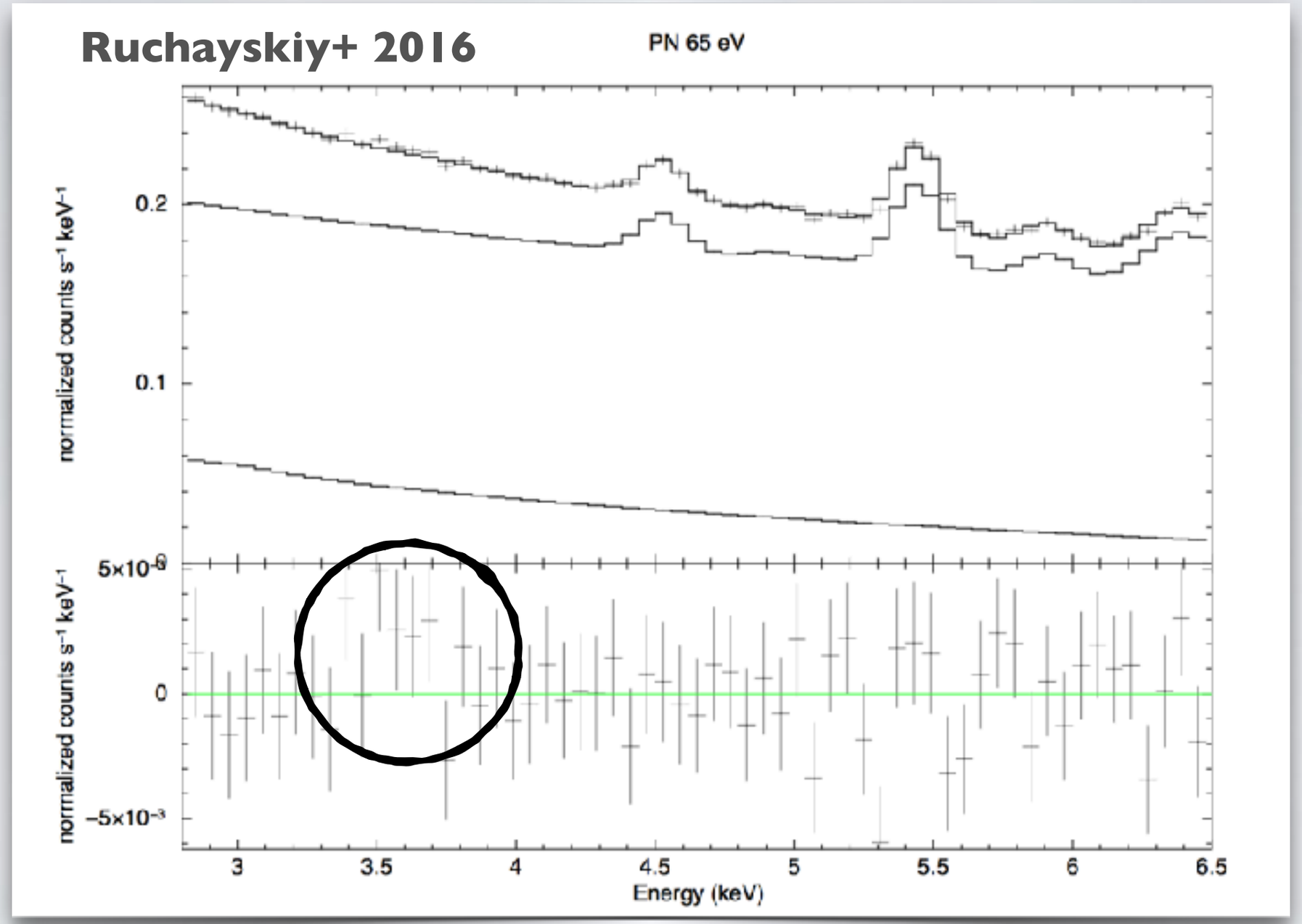

Ruchayskiy+ 2016
PN 65 eV
normalized counts s⁻¹ keV⁻¹
0.2
0.1
5×10⁻³
0
−5×10⁻³
normalized counts s⁻¹ keV⁻¹
3
3.5
4
4.5
5
5.5
6
6.5
Energy (keV)

RESULT …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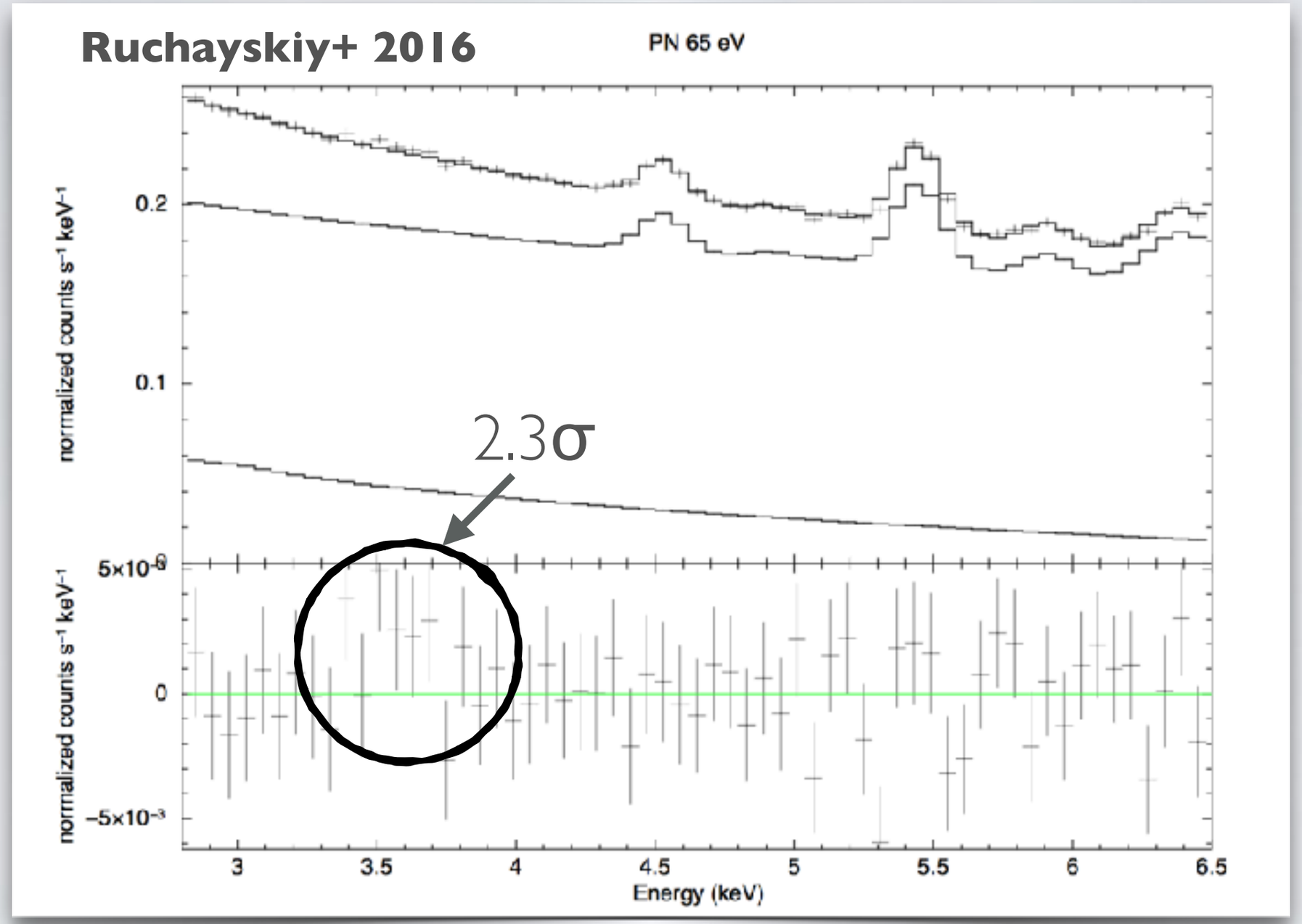
Ruchayskiy+ 2016
PN 65 eV
normalized counts s⁻¹ keV⁻¹
0.2
0.1
2.3σ
5×10⁻³
0
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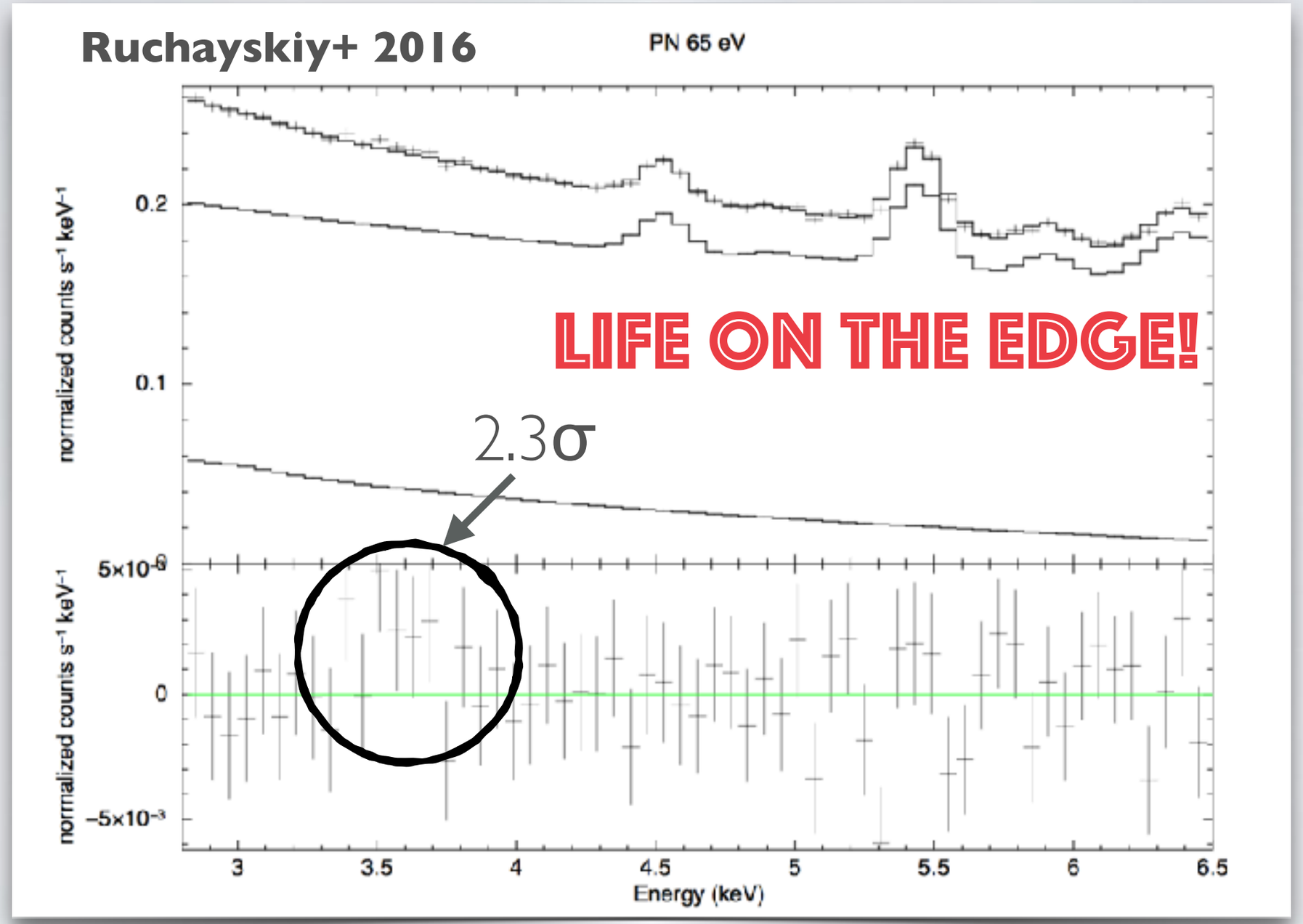
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LIFE ON THE EDGE!
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0.2
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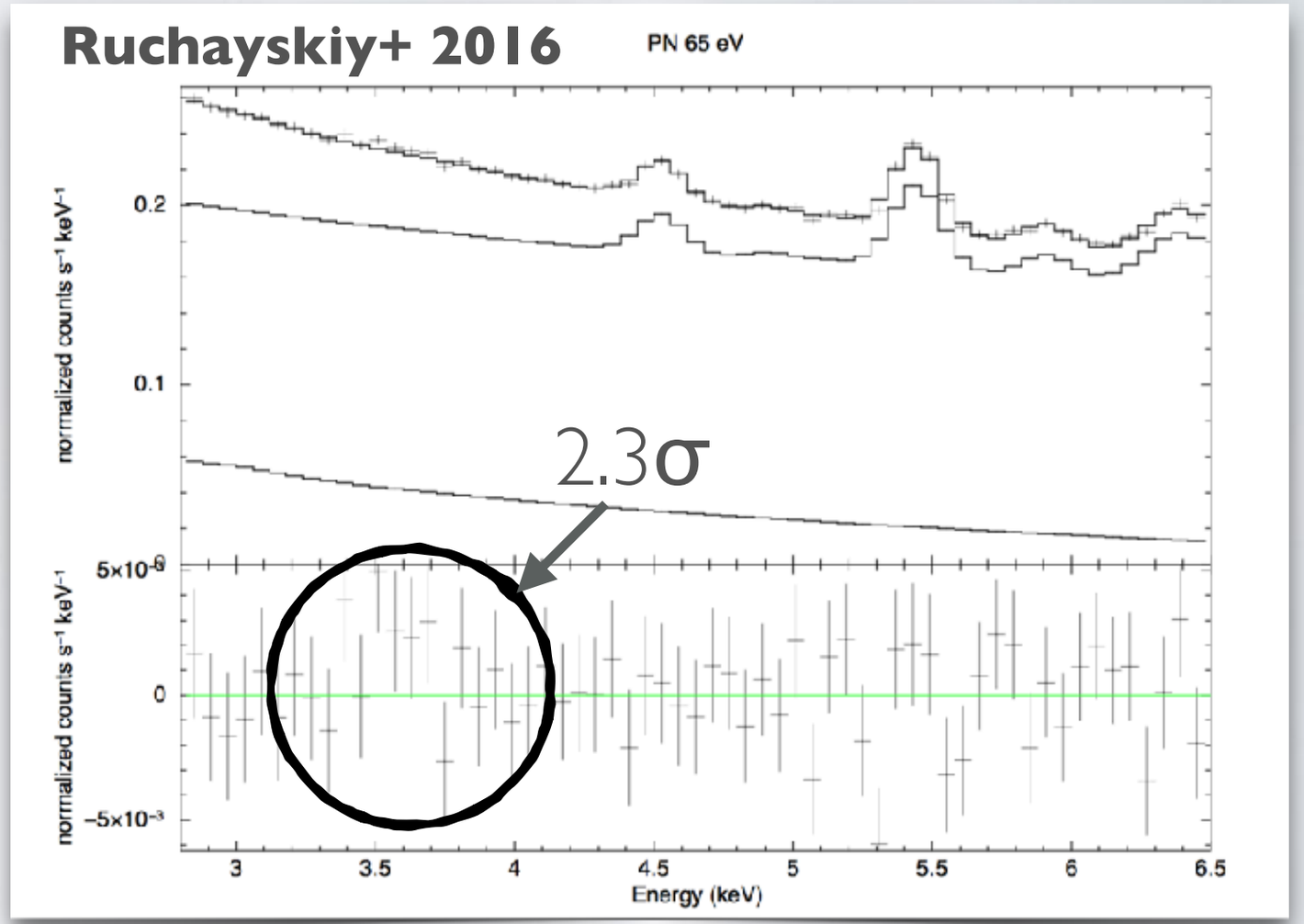
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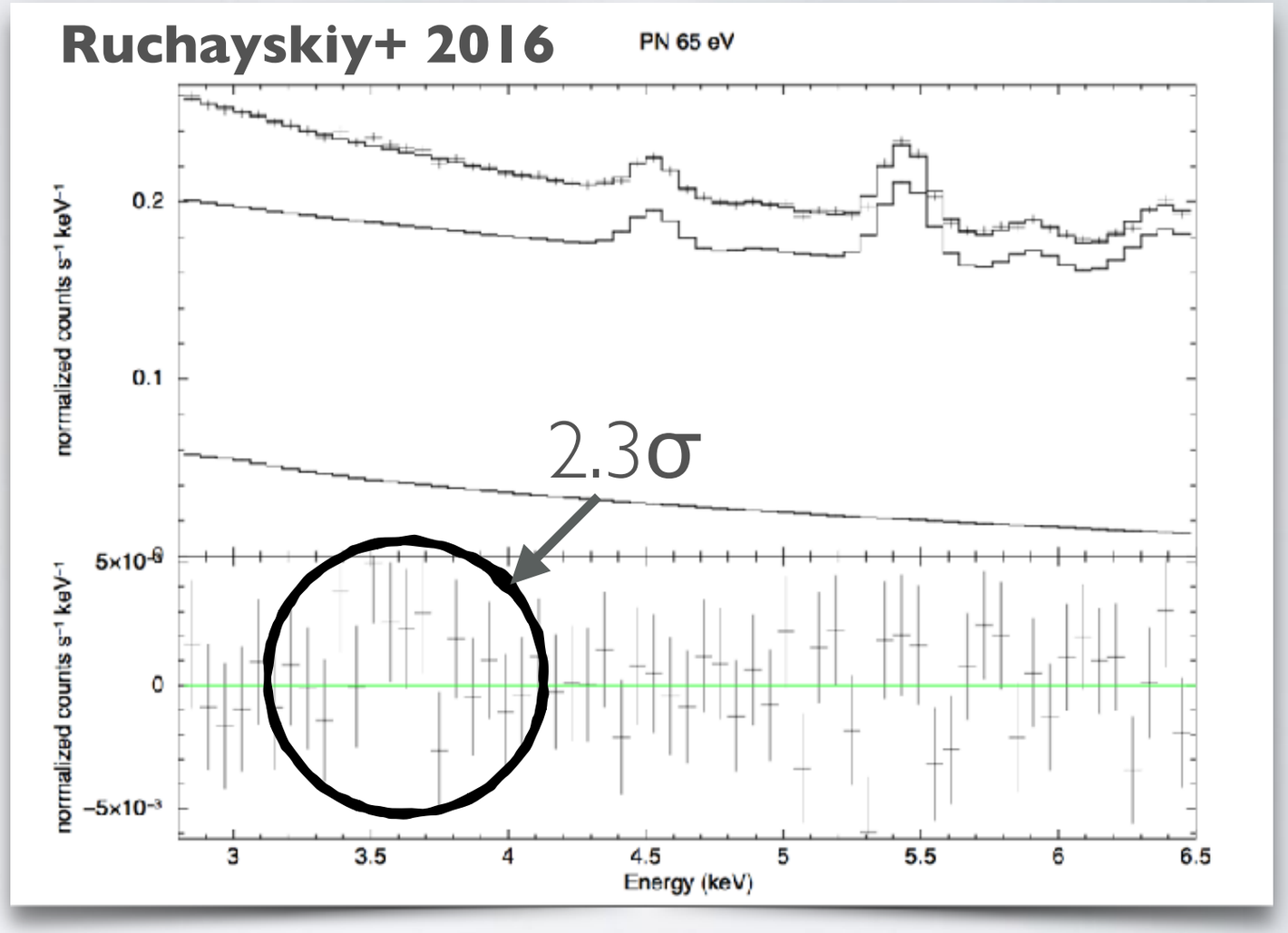
- Predicted 3.5keV signal from Draco



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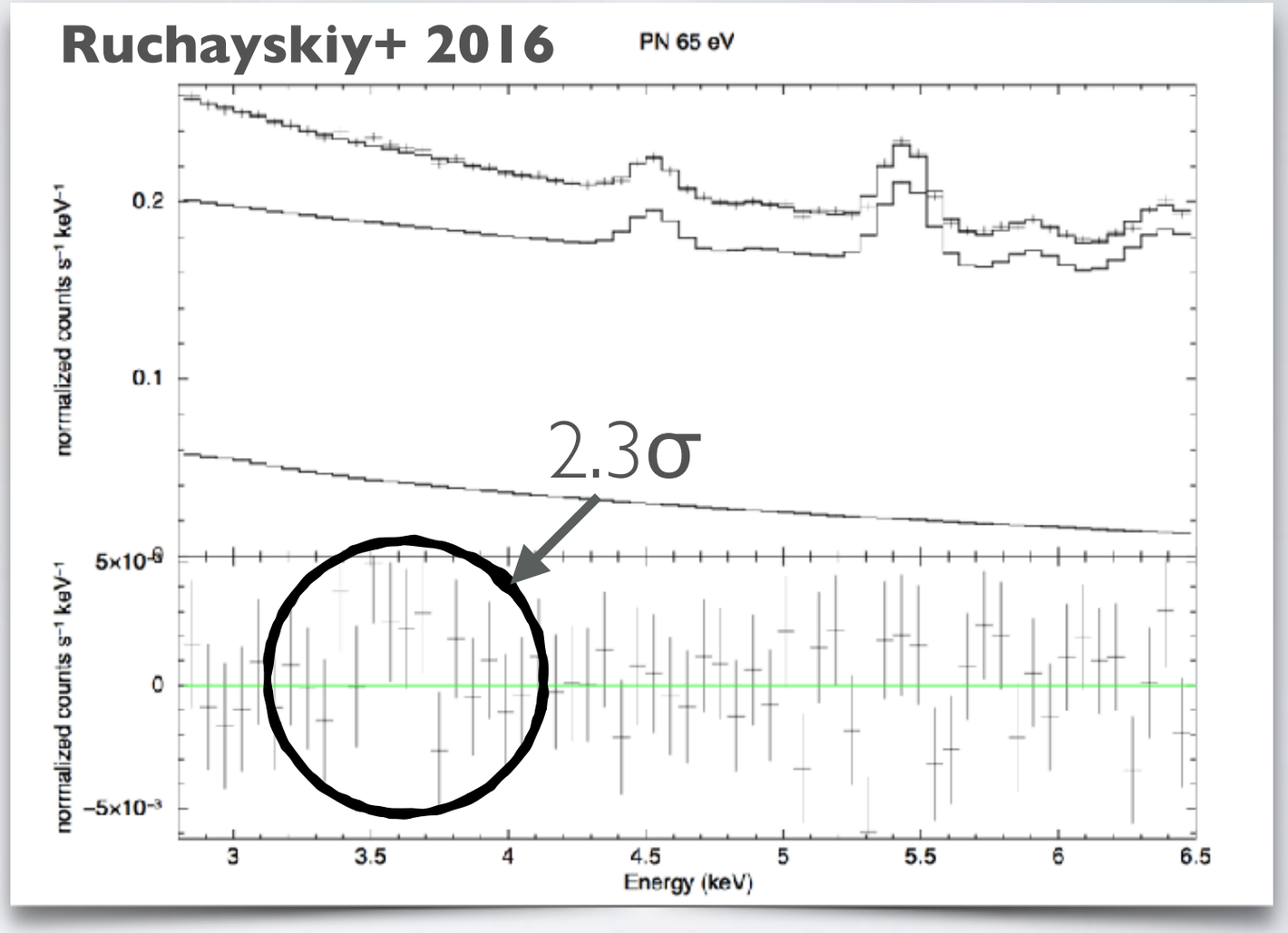
- 2.3σ 'detection'



WDM — Theory

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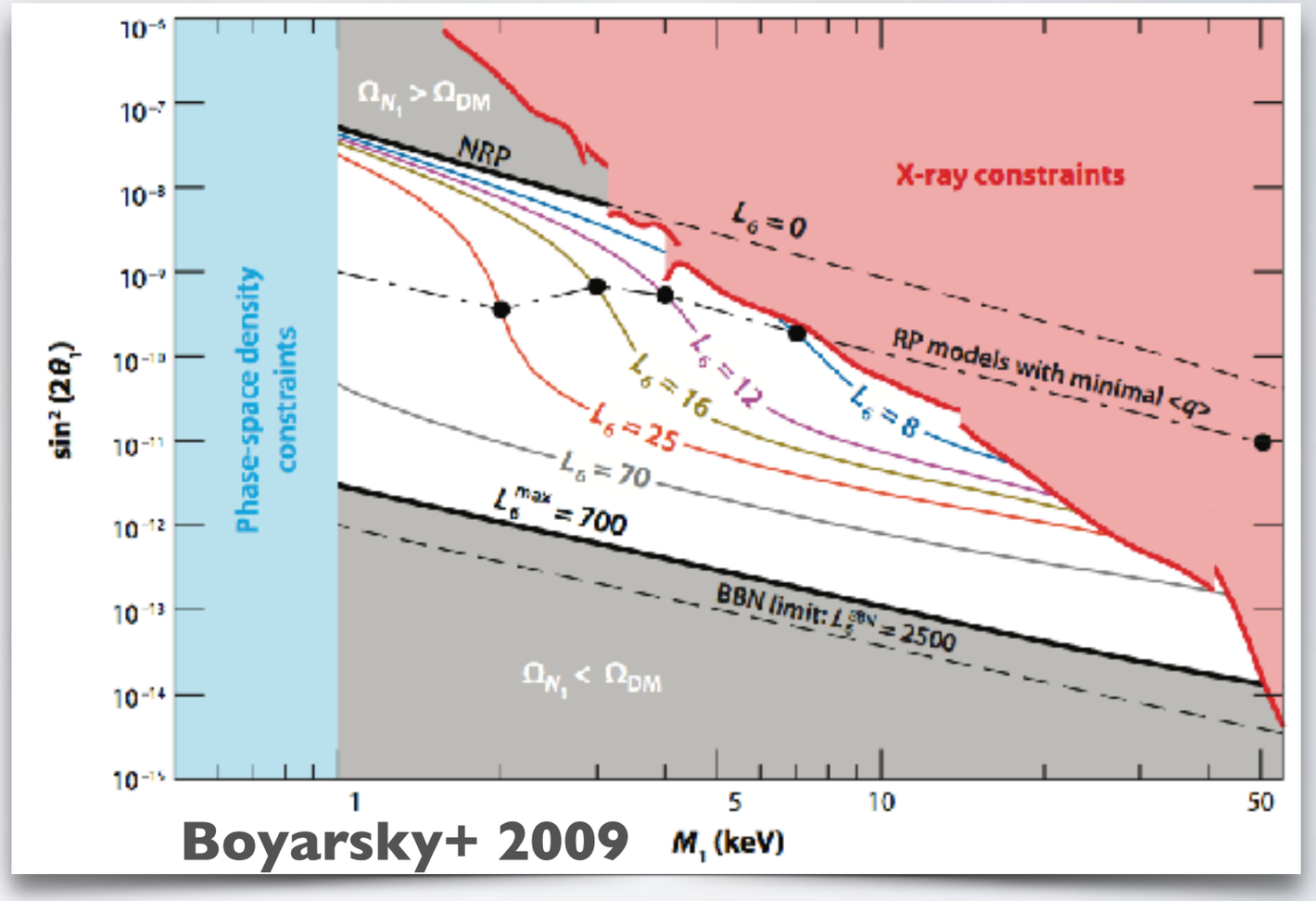
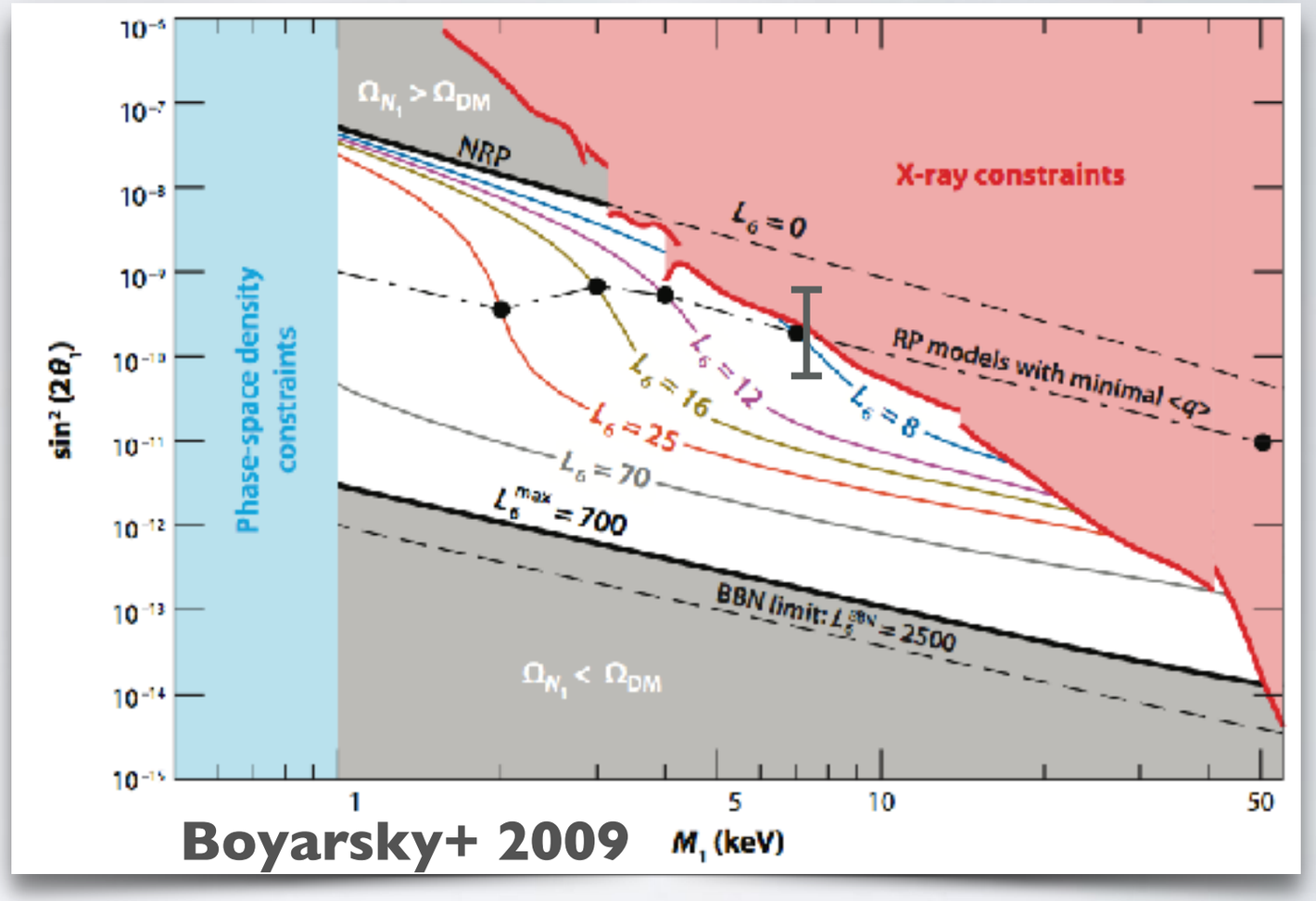
STERILE NEUTRINOS & WDM



Boyarsky+ 2009

M. Lovell, MPIA; BAM 05/09/17

STERILE NEUTRINOS & WDM



Boyarsky+ 2009

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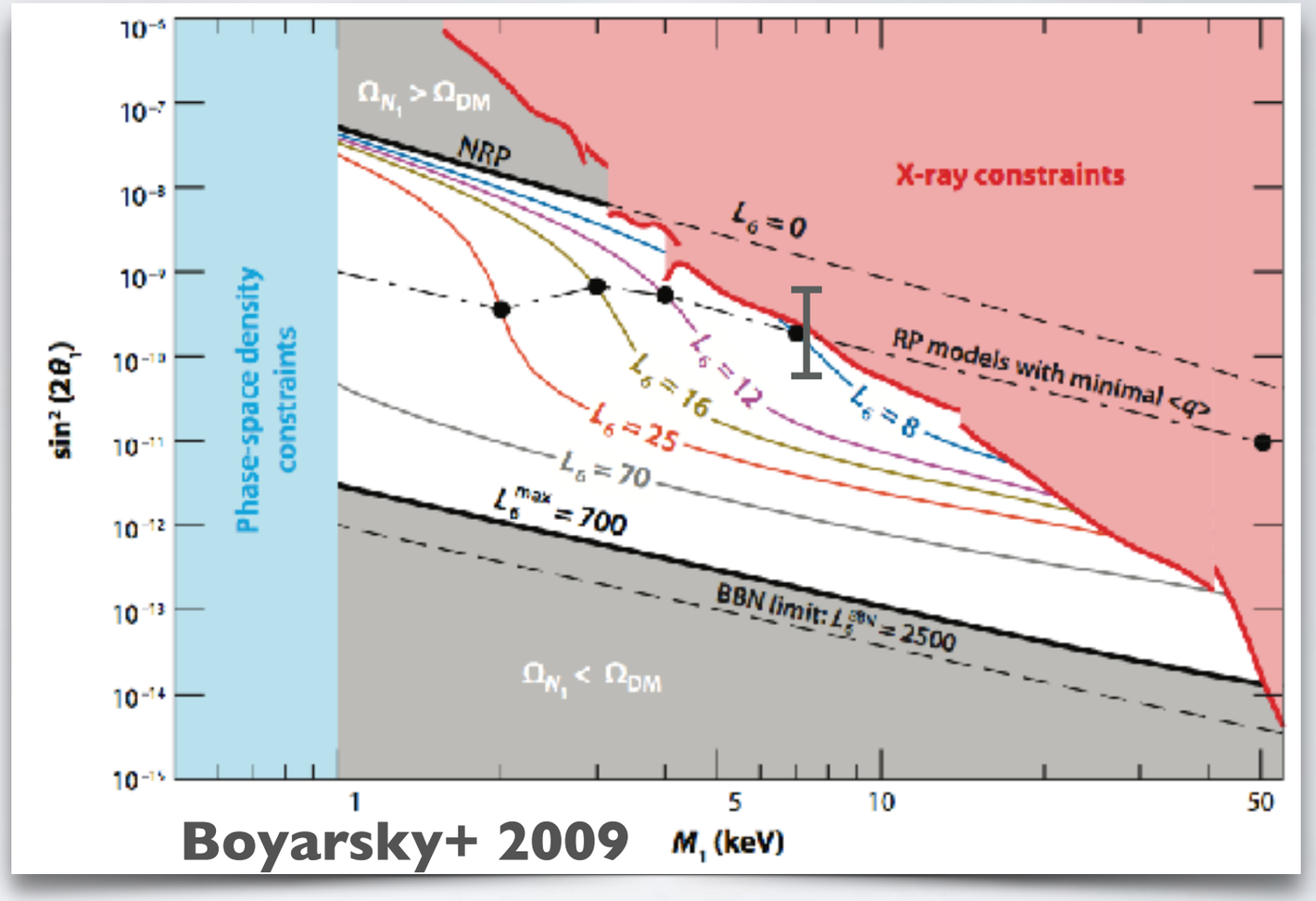
STERILE NEUTRINOS & WDM

- Require lepton asymmetry to obtain correct DM abundance — resonant production



Boyarsky+ 2009

M. Lovell, MPIA; BAM 05/09/17

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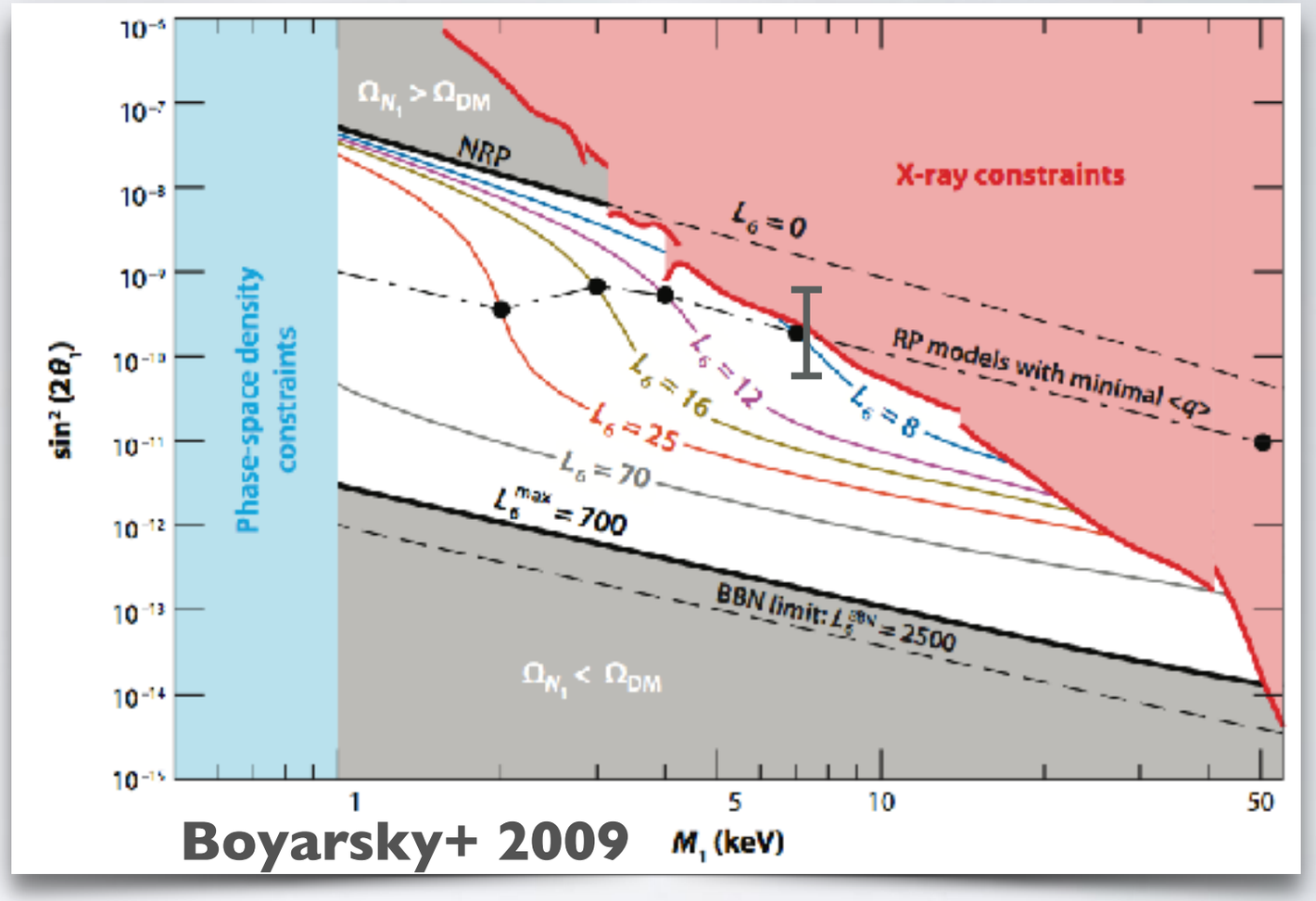

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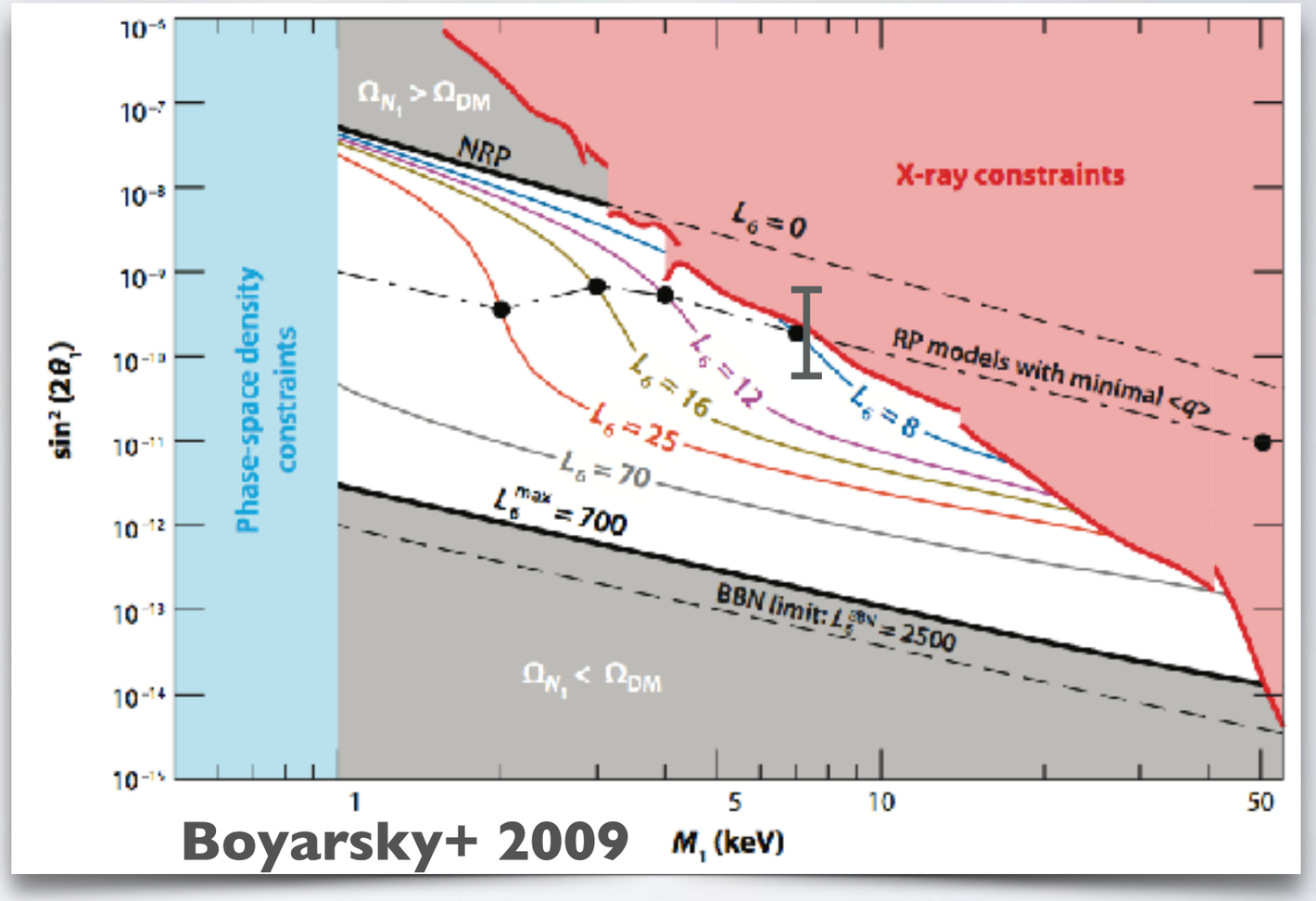

M. Lovell, MPIA; BAM 05/09/17

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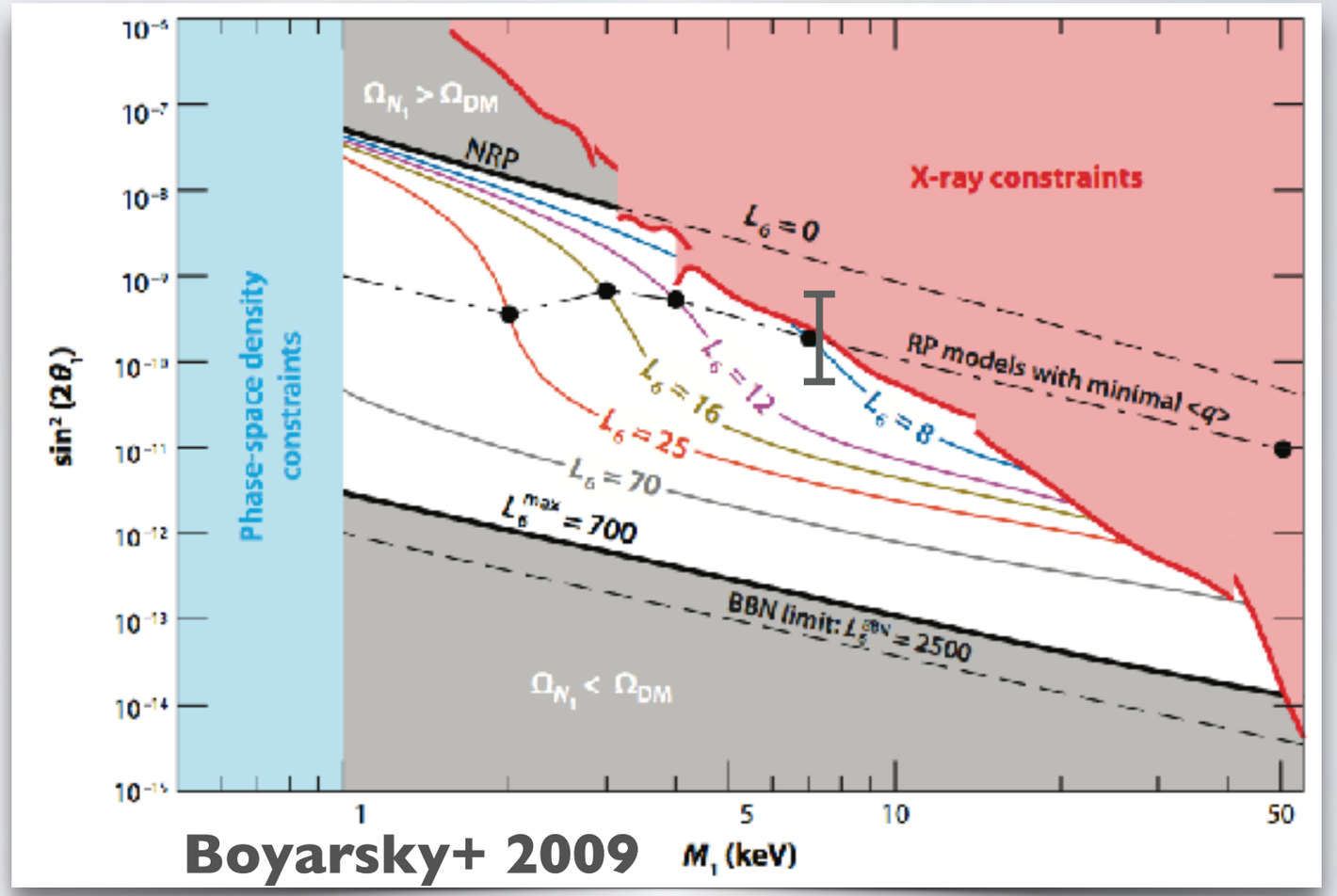
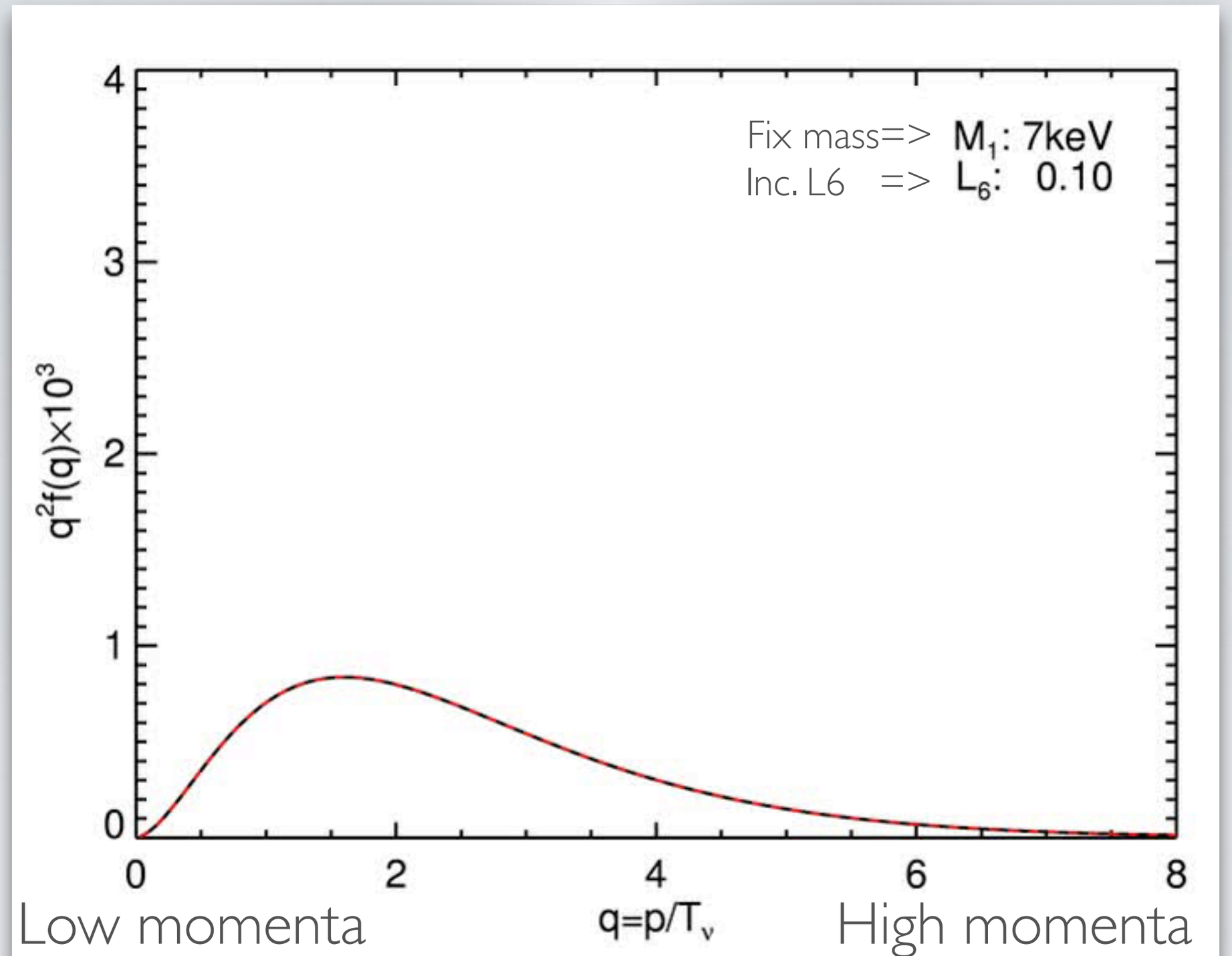
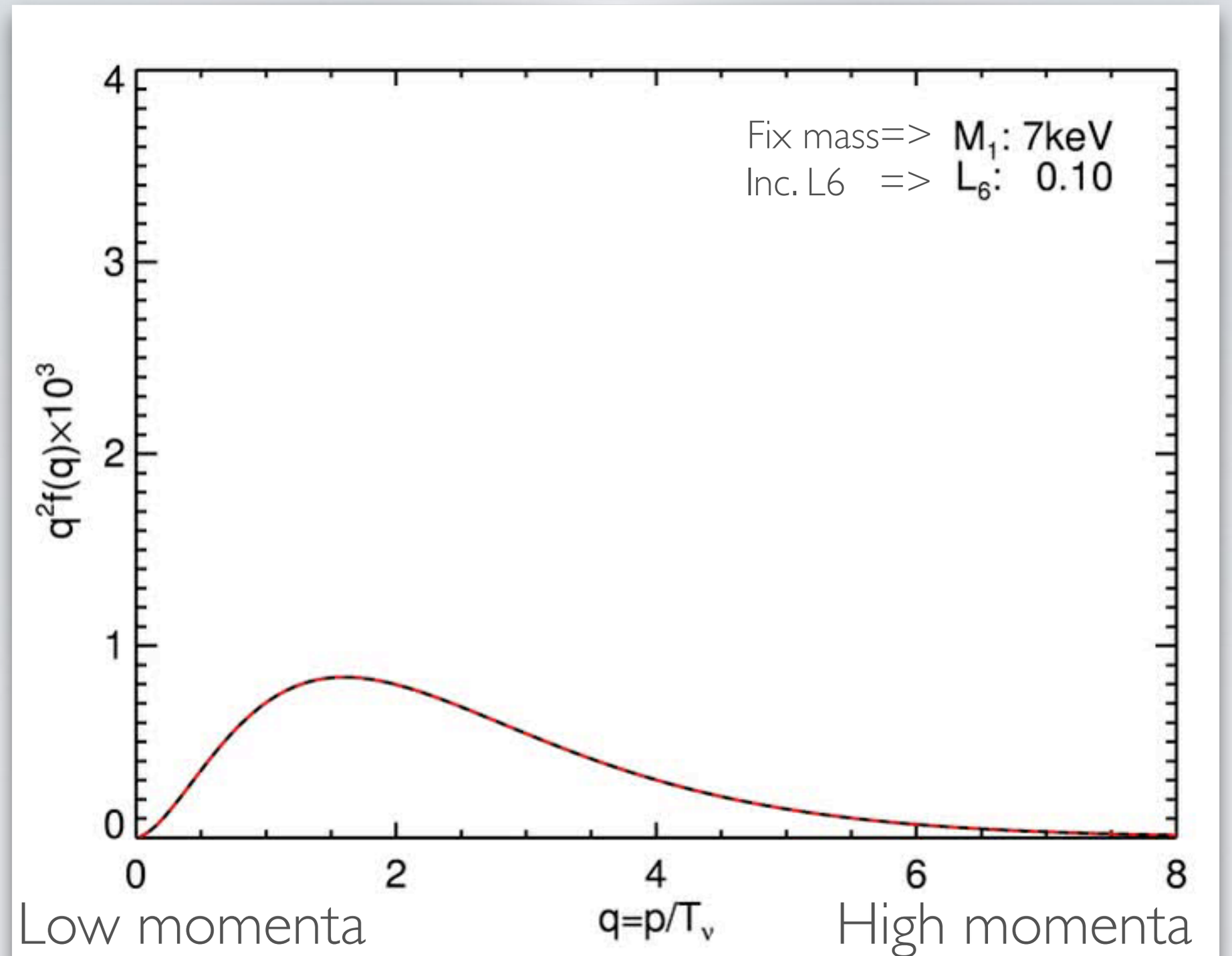


X-ray measured properties specify momentum / kinematics



Low momenta

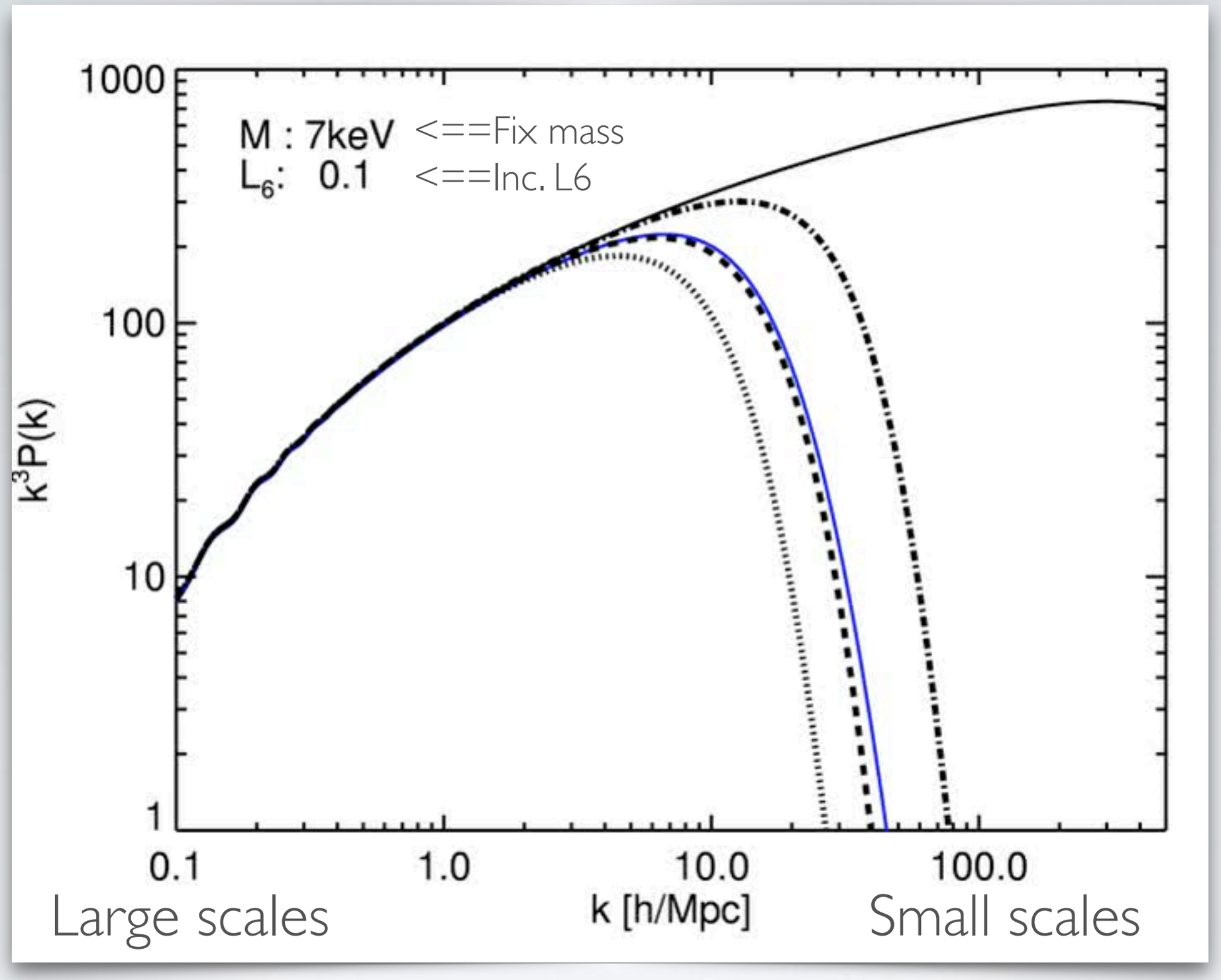
High momenta



Low momenta

High momenta

LINEAR MATTER POWER SPECTRUM



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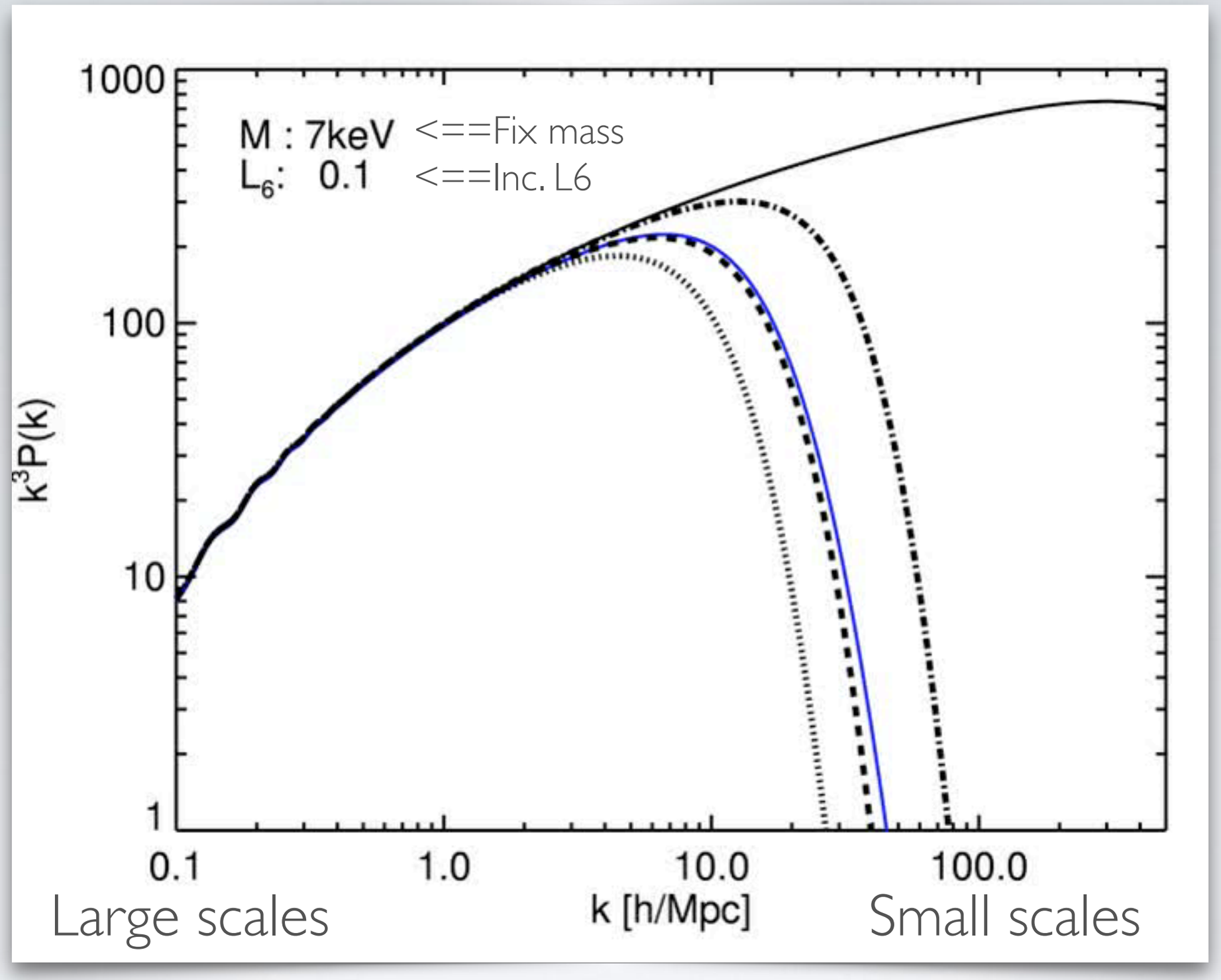
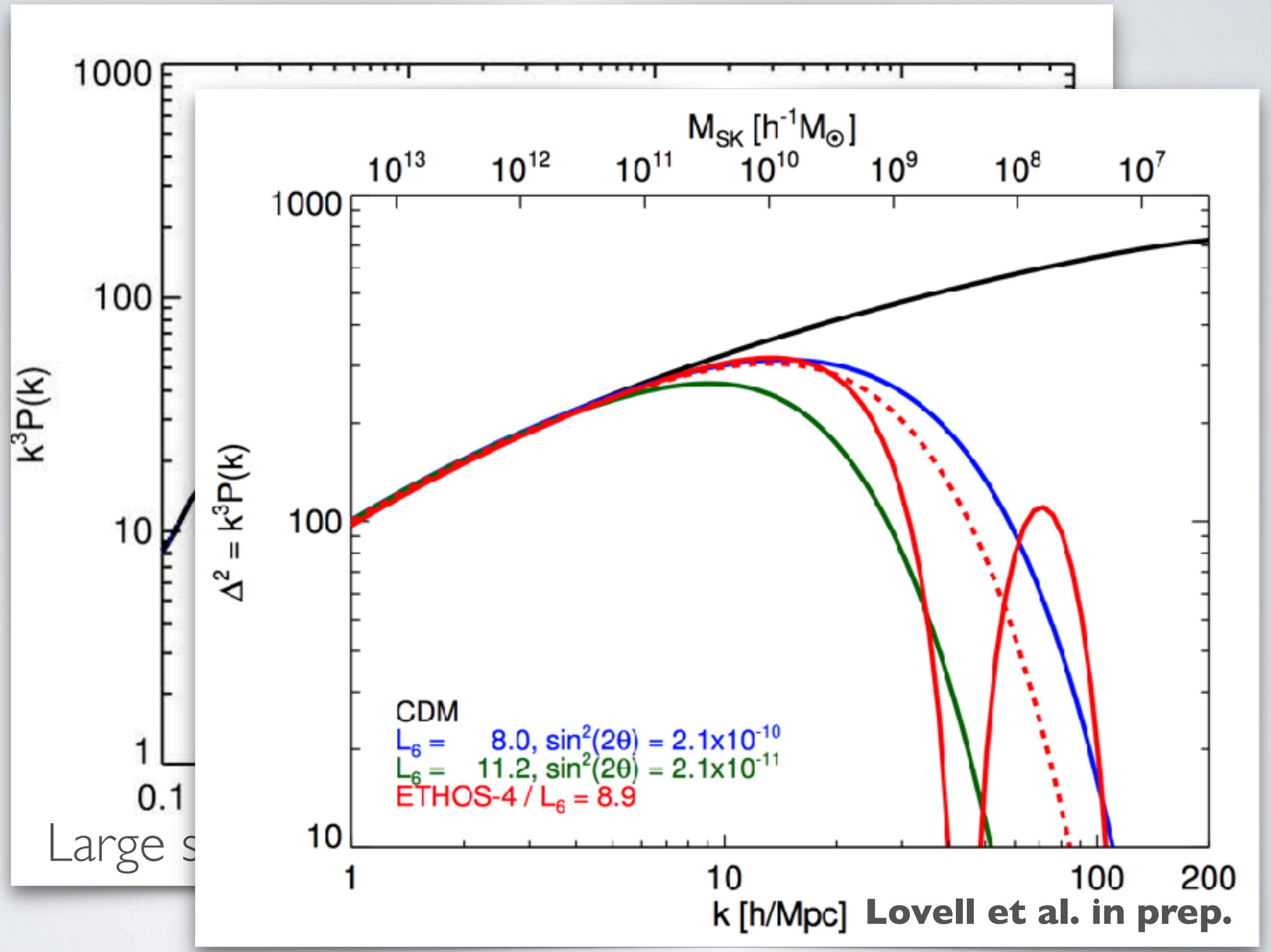


LINEAR MATTER POWER SPECTRUM



WDM — Methods

M. Lovell, MPIA; BAM 05/09/17

Hydro-simulations

WDM — Methods

Hydro-simulations

Semi-analytics

WDM — Methods

Hydro-simulations

M. Lovell, MPIA; BAM 05/09/17

Hydro-simulations

From APOSTLE simulations of Local Groups analogues:

Hydro-simulations

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Hydro-simulations

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- EAGLE model of galaxy formation: starformation, supernova feedback, reionisation

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- Detect galaxies $M^* > 10^5 M_{sun}$

Semi-analytics

M. Lovell, MPIA; BAM 05/09/17

Semi-analytics

Build merger trees using extended Press-Schechter (EPS) methods:

Semi-analytics

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Semi-analytics

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  - Calibrated against COCO CDM/WDM DMO simulations
- Resolve galaxies M_V<-2

WDM — Structure

M. Lovell, MPIA; BAM 05/09/17

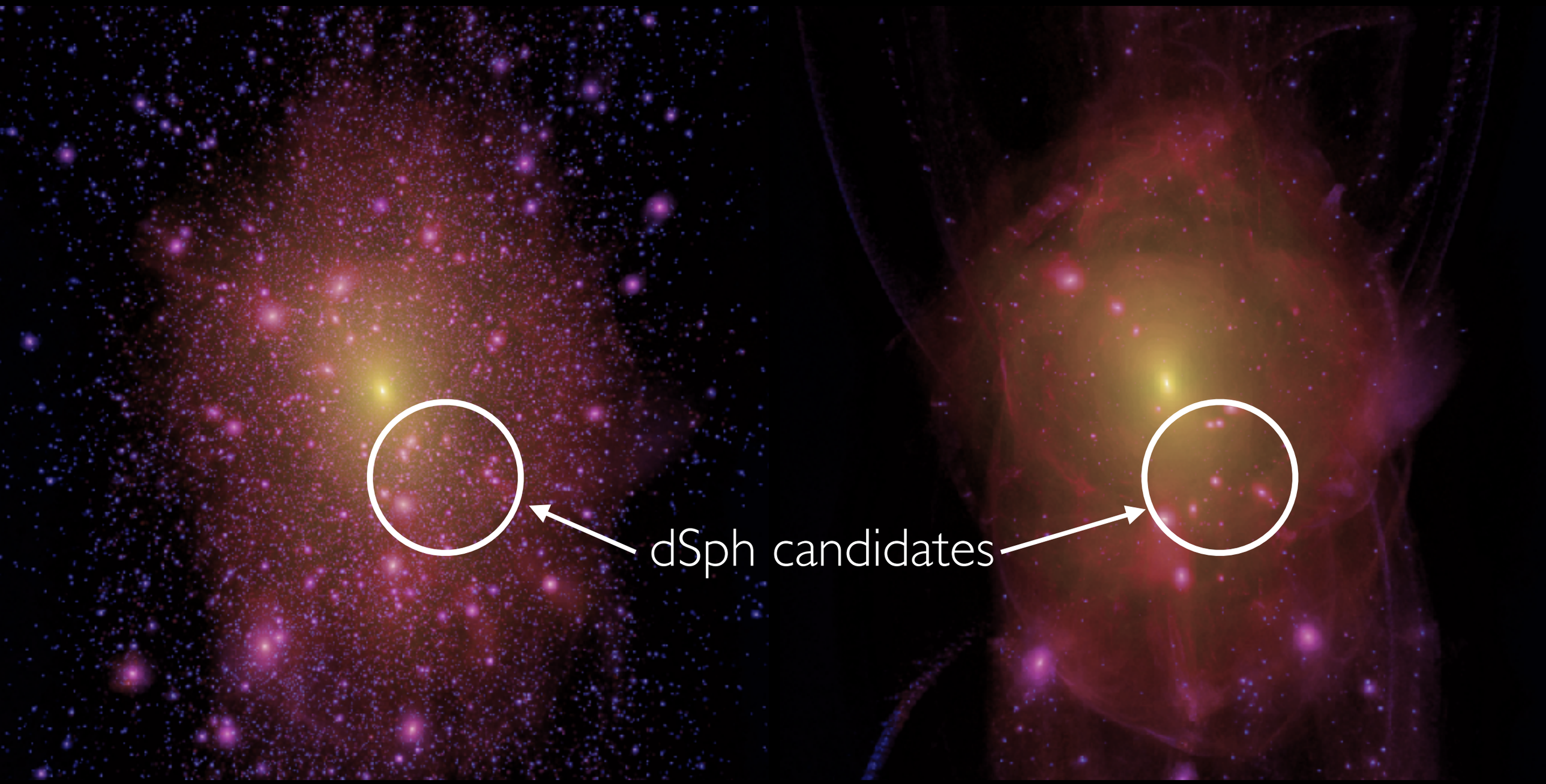
CDM

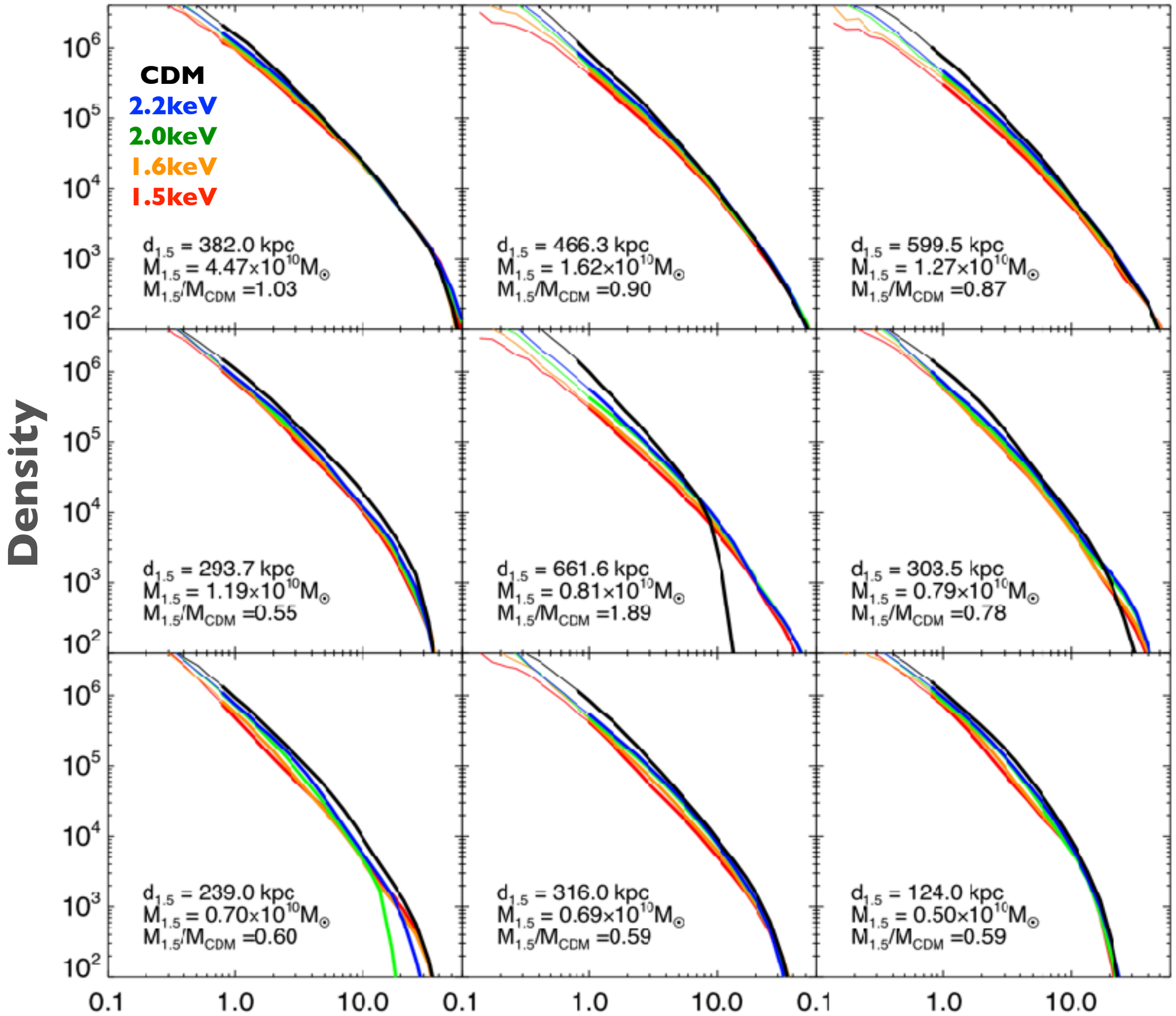
WDM (1.5keV thermal relic)

1.5Mpc

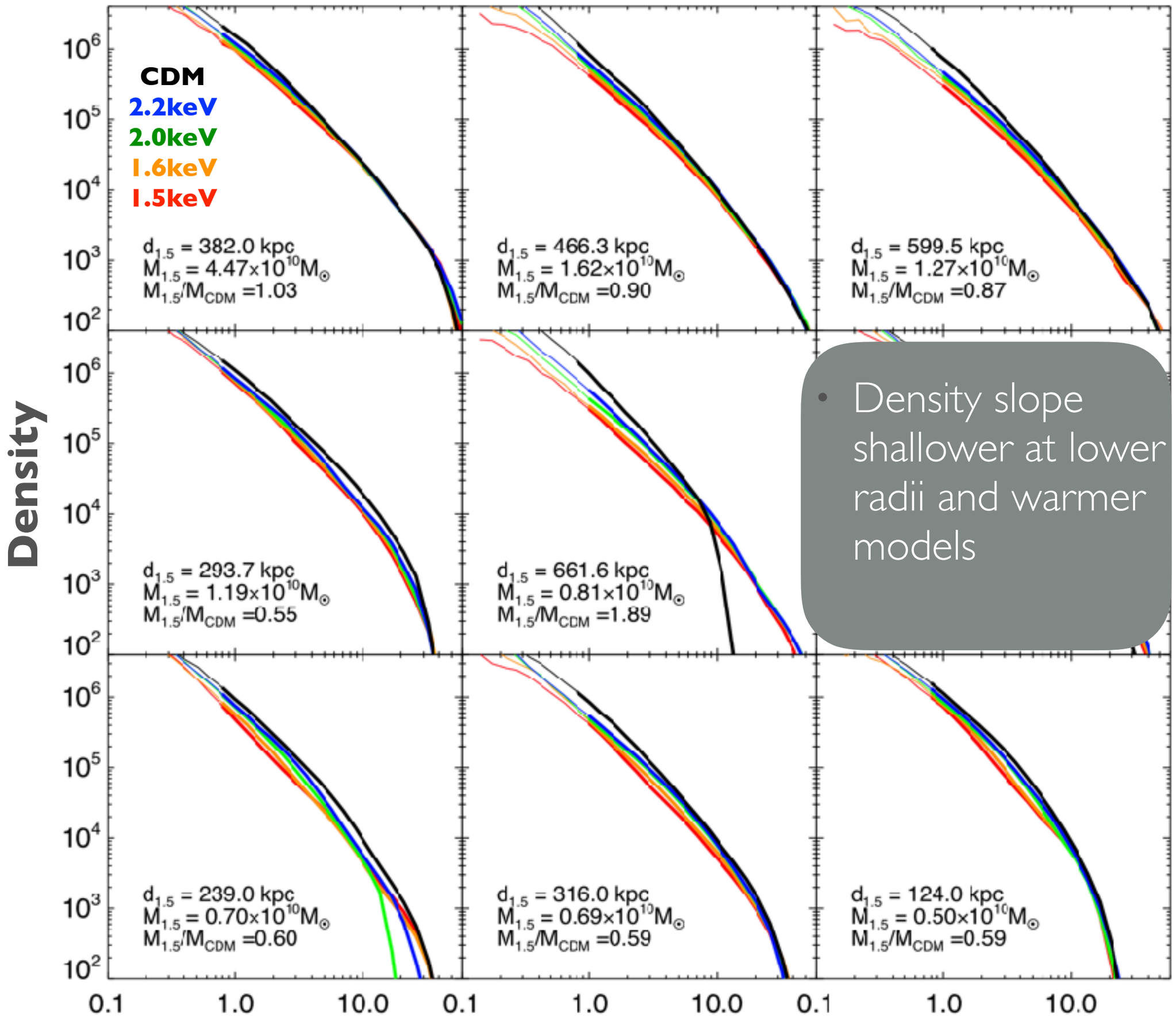
CDM

WDM (1.5keV thermal relic)





See also Bozek et al. 2016



- Density slope shallower at lower radii and warmer models

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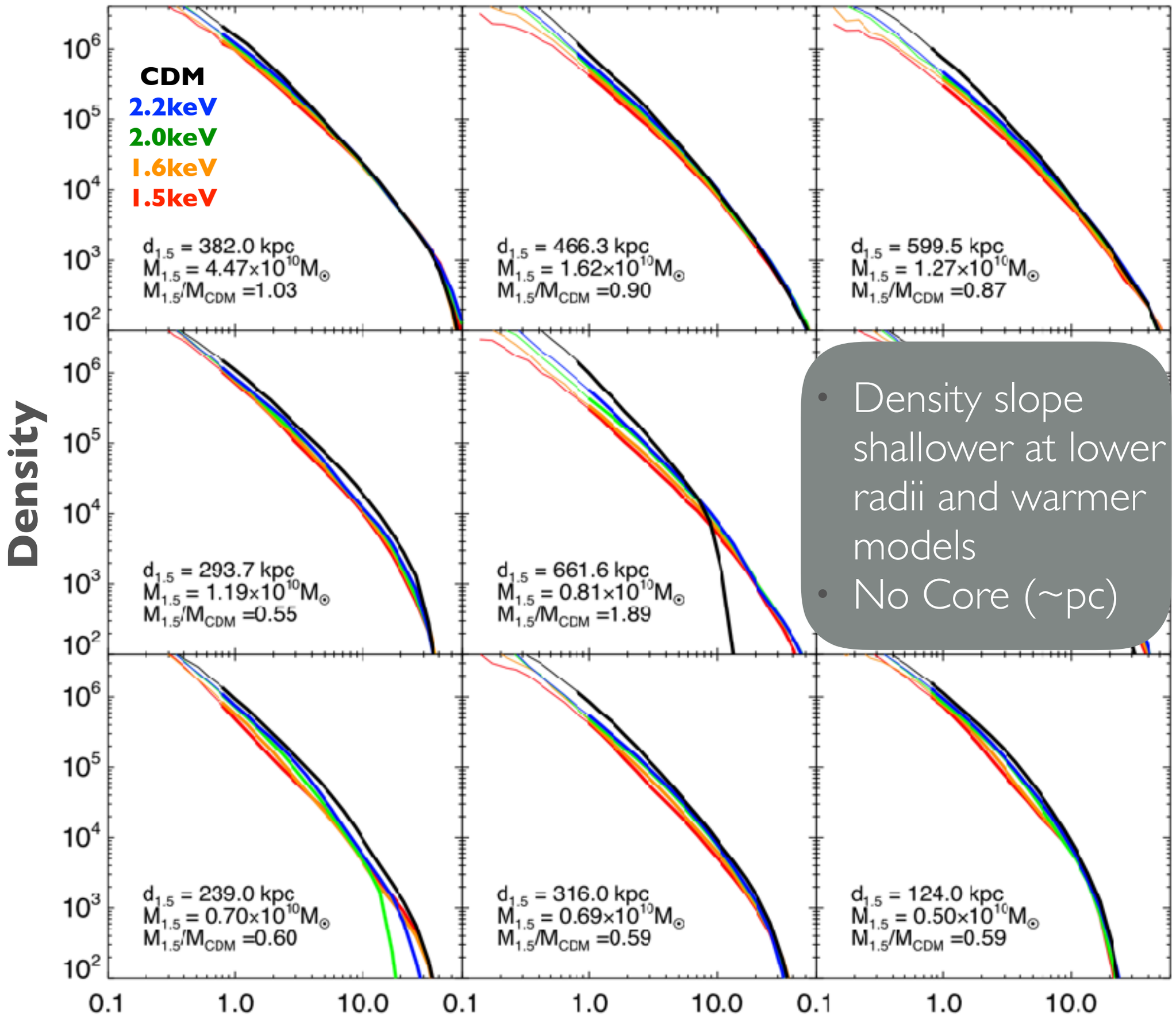
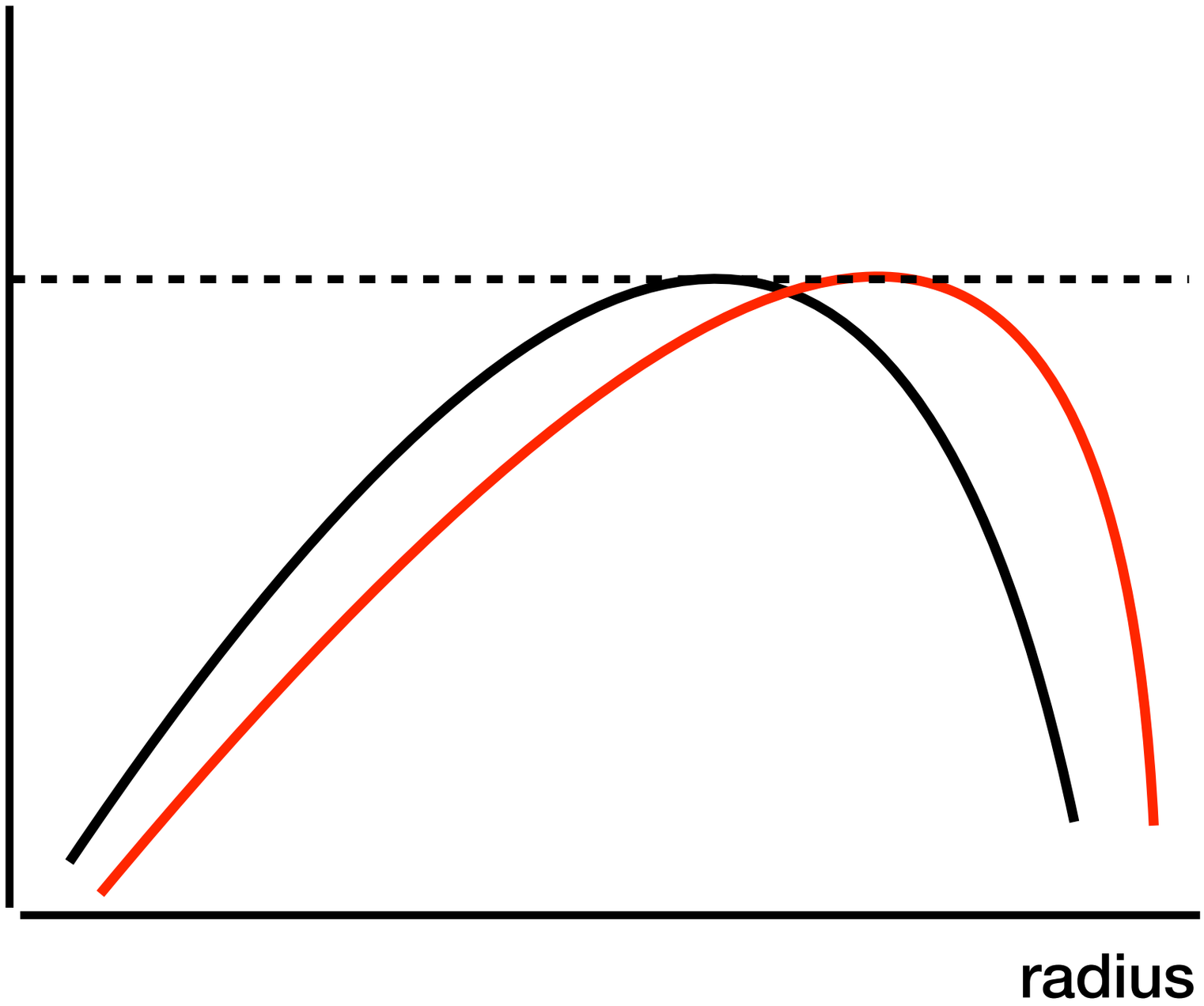


- Density slope shallower at lower radii and warmer models
- No Core (~pc)

See also Bozek et al. 2016

$V_c = \sqrt{GM(<r)/r}$



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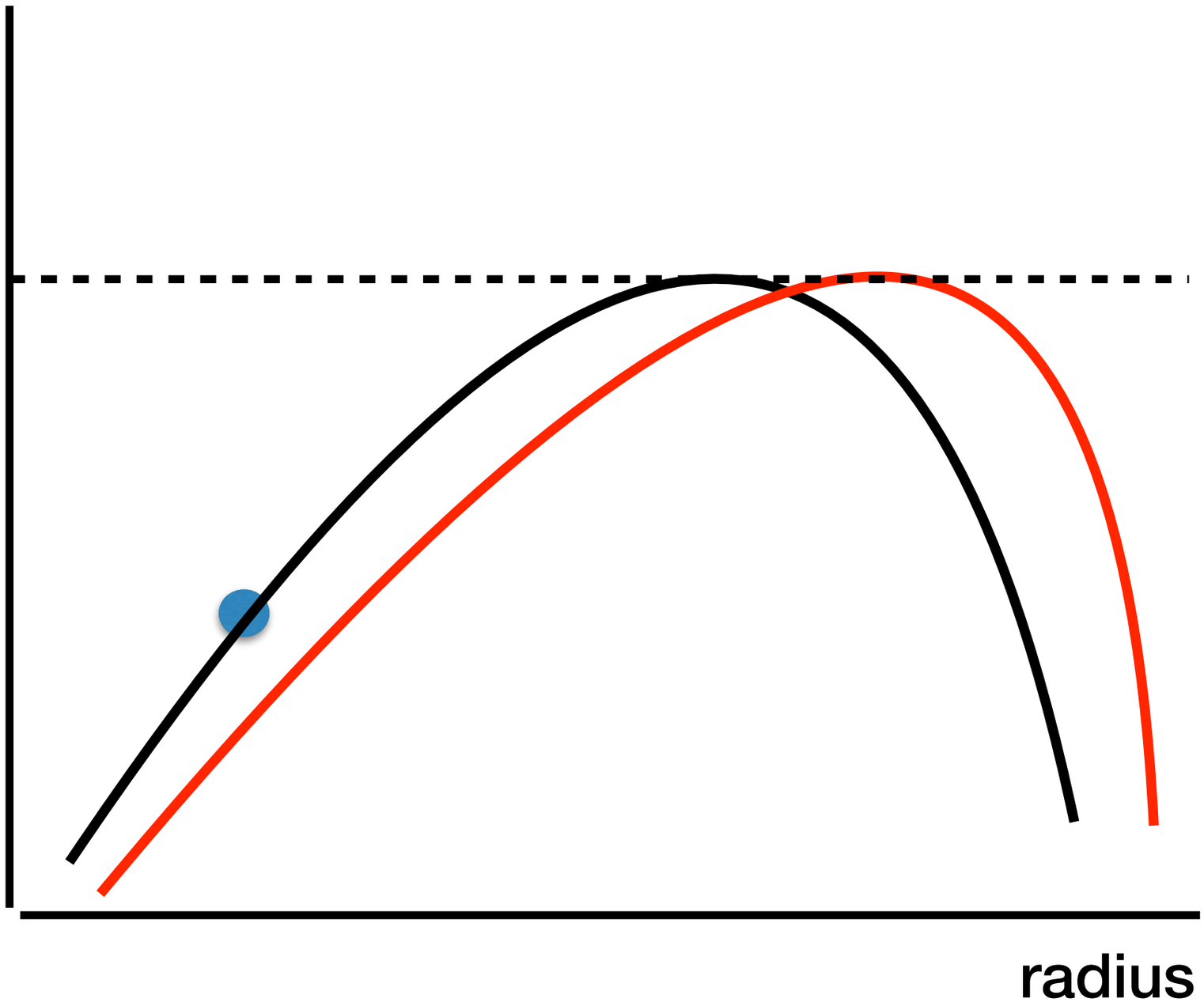
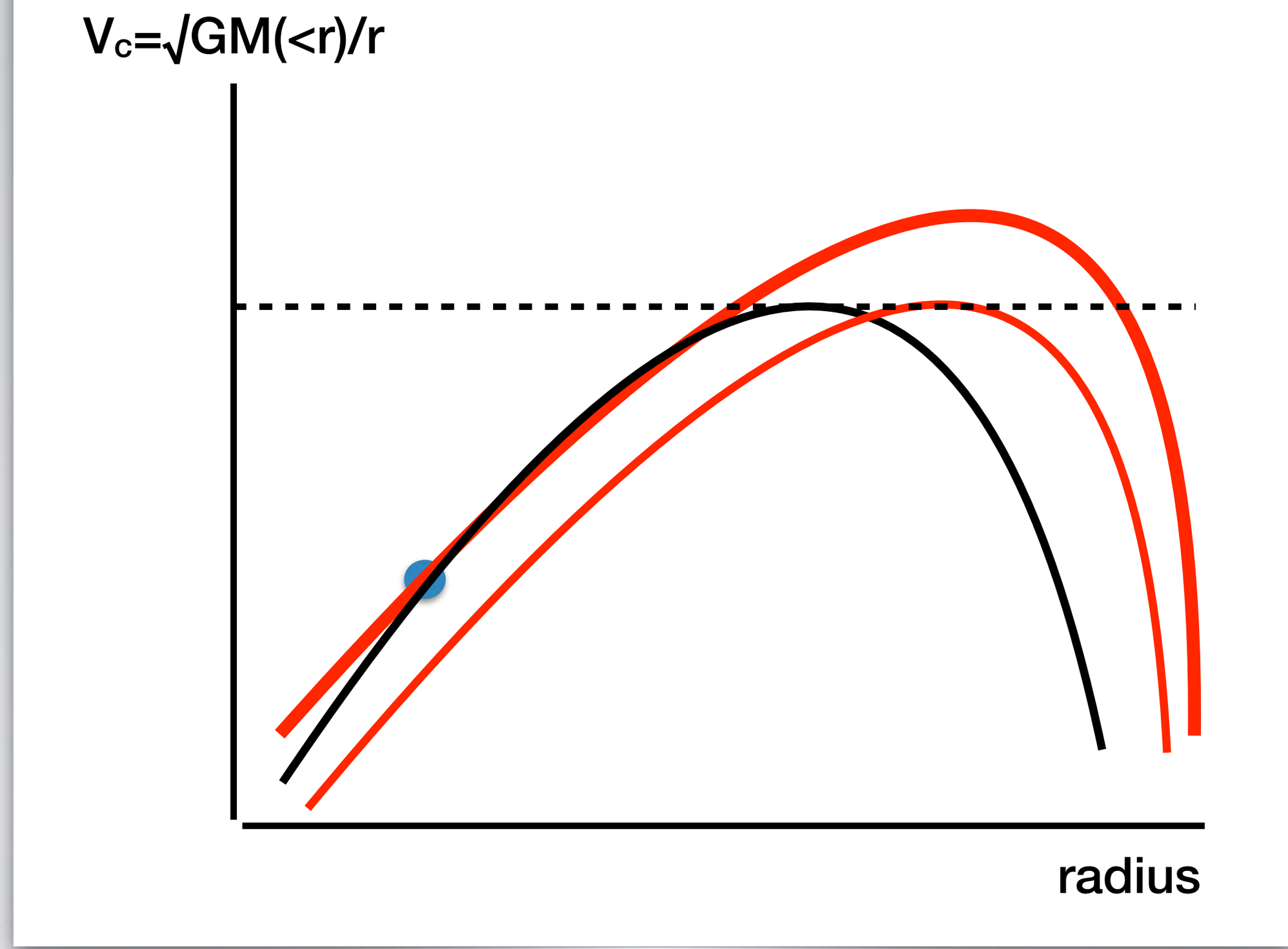
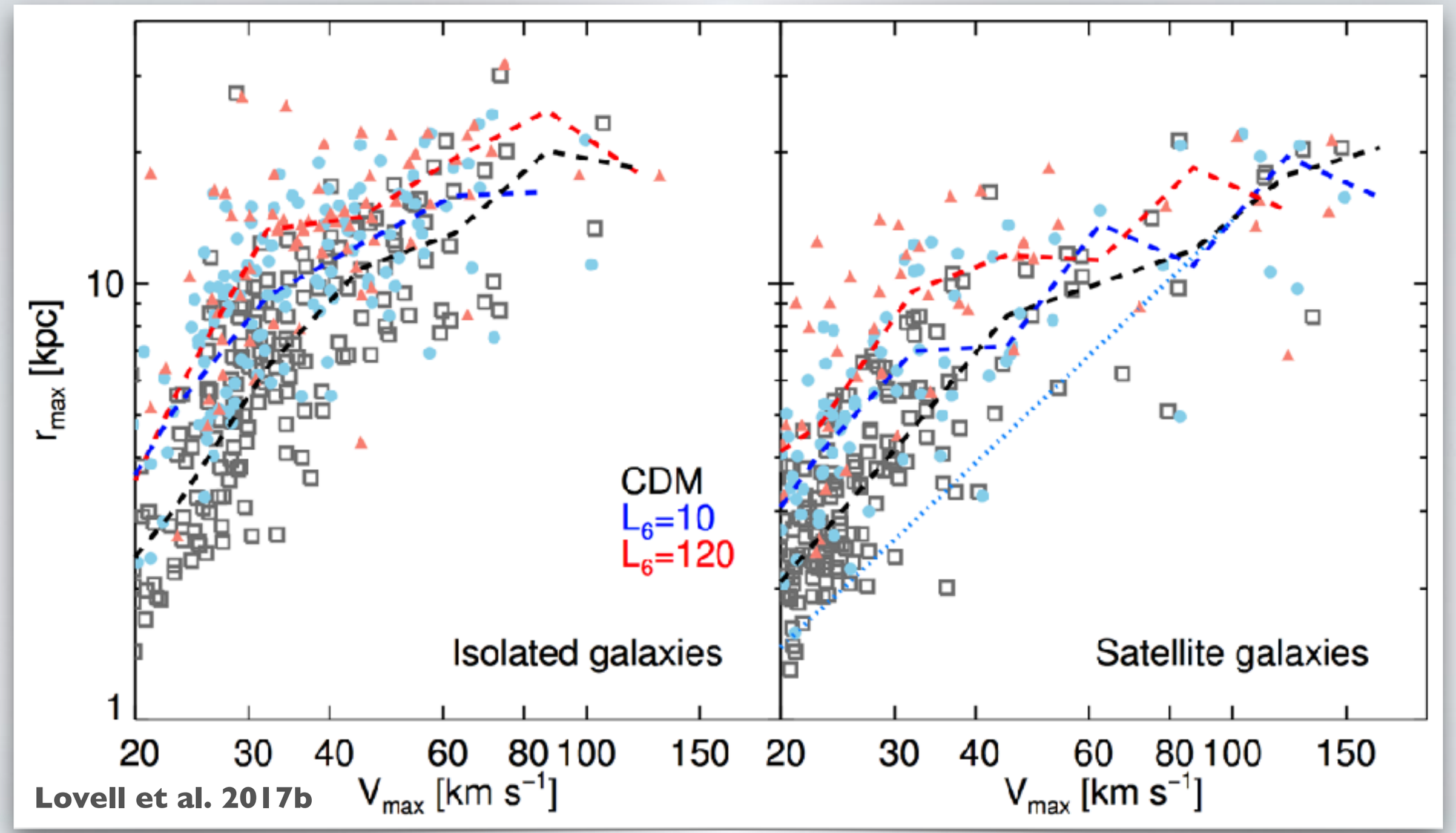
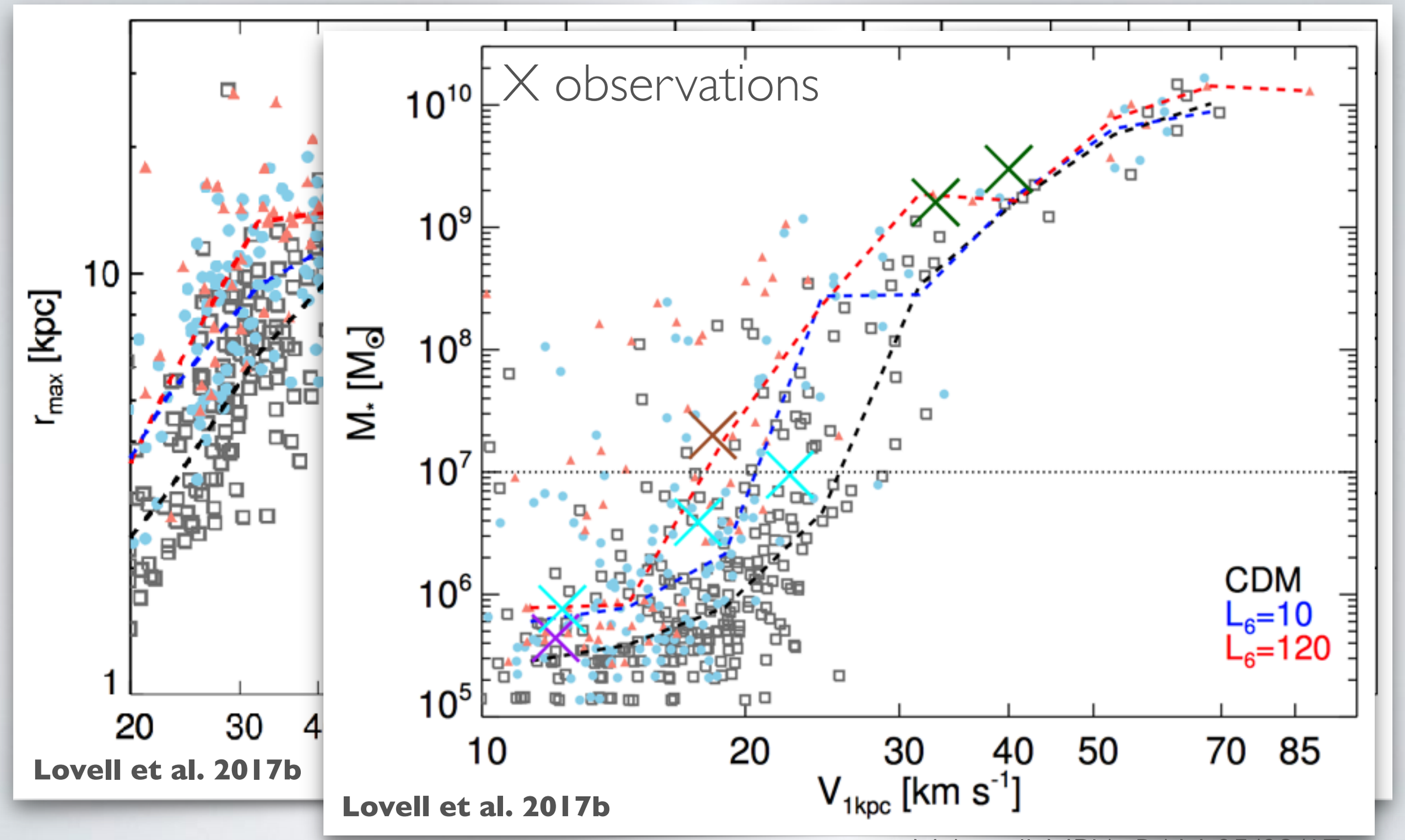


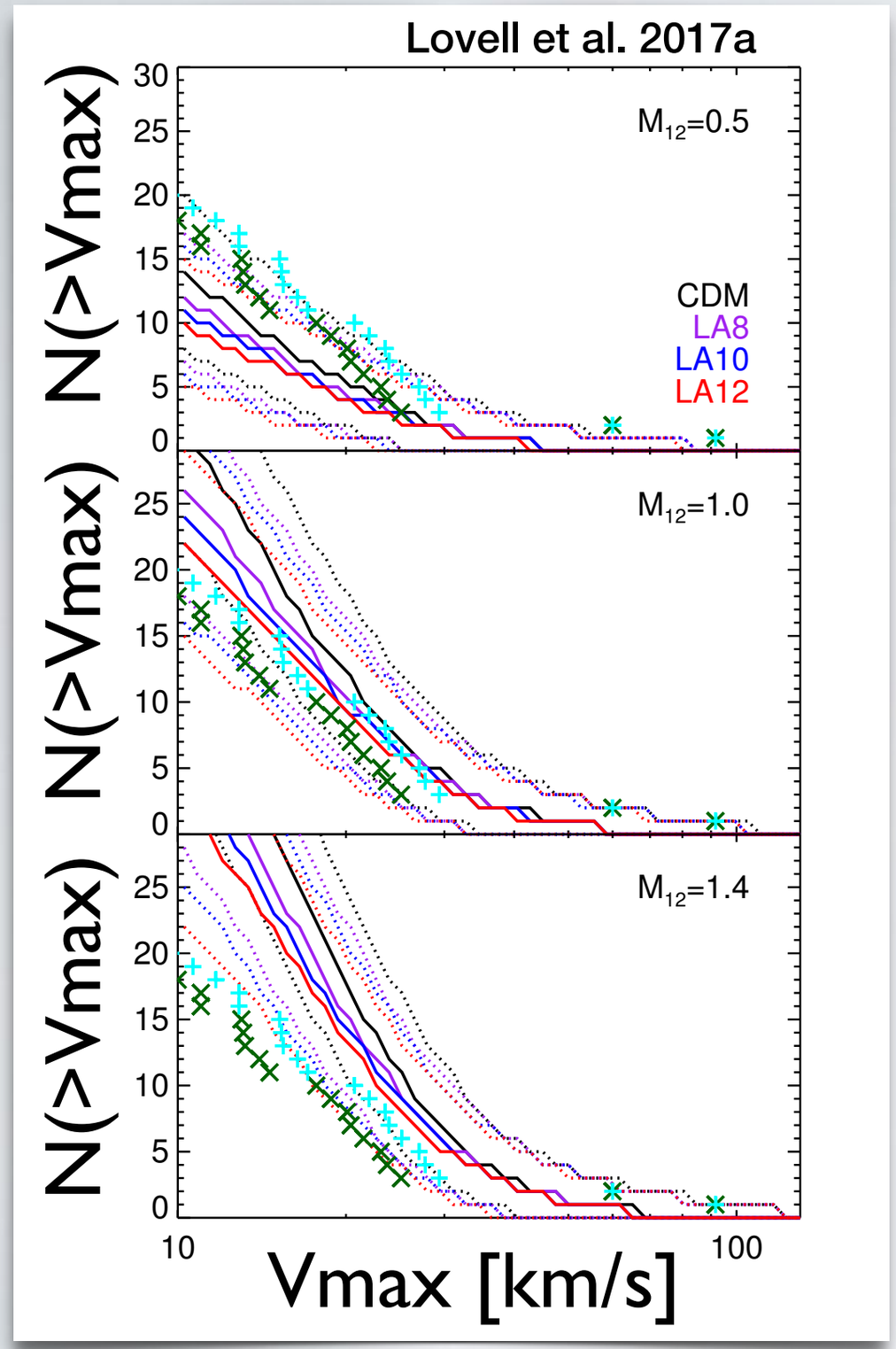

$V_c=\sqrt{GM(<r)/r}$
radius

Hydro-simulations



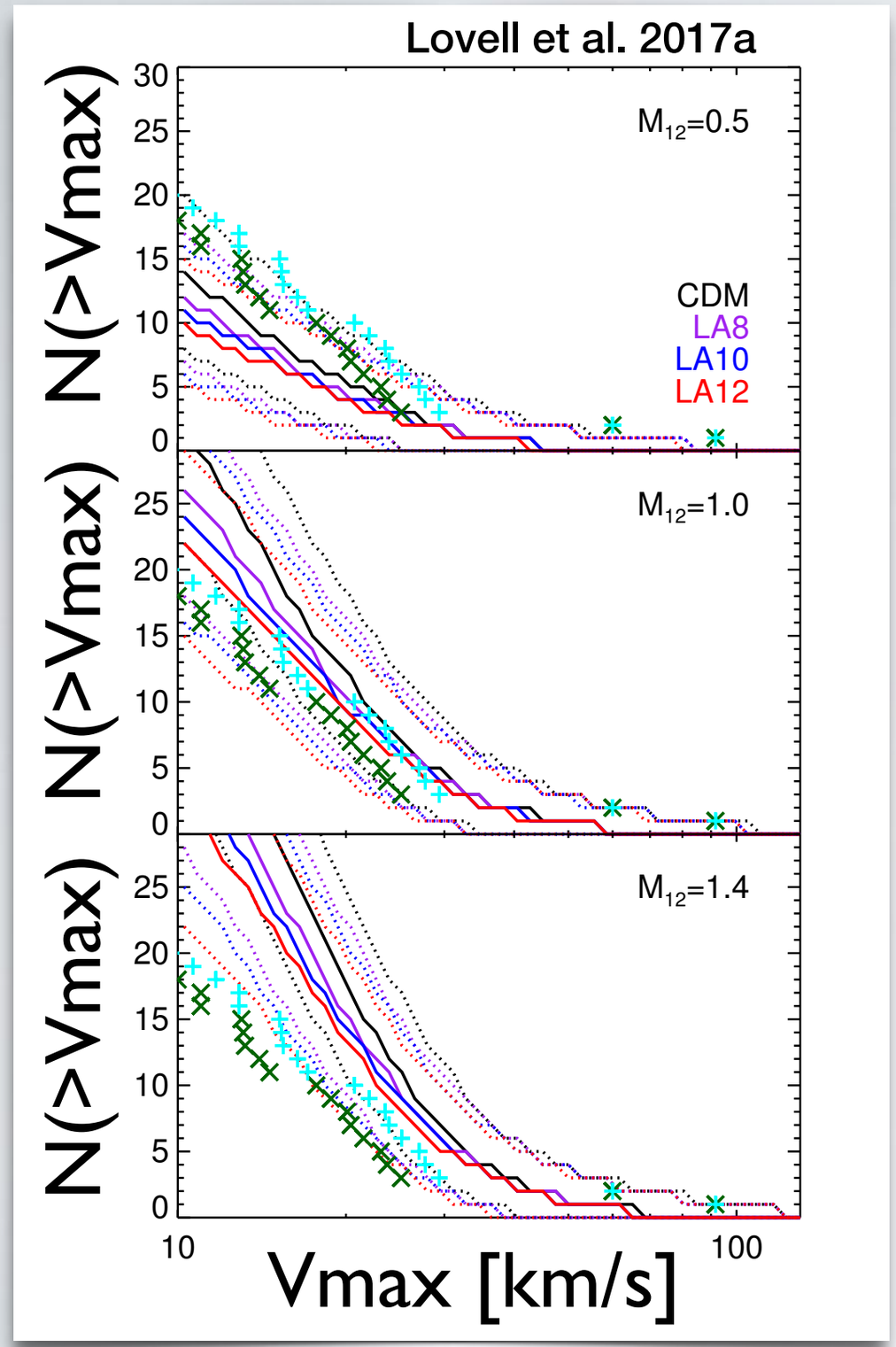
Hydro-simulations





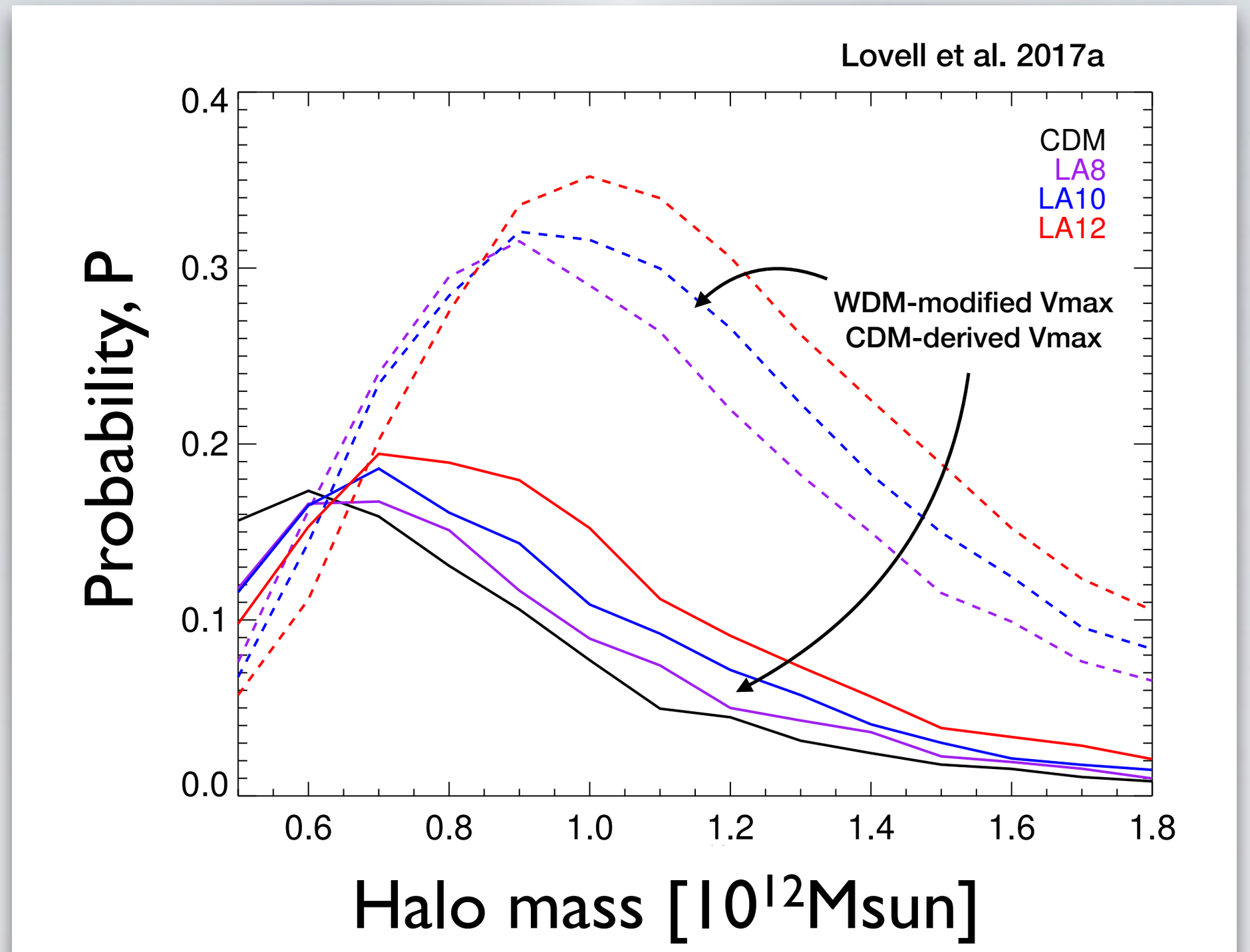
Semi-analytics

- Generate ~1000 x10 MW halo mass satellite populations using EPS methodology
- Predict z=0 Vmax functions with semi-analytic stripping model of Jiang & vd Bosch 2017
- Predict satellite luminosities with semi-analytic galaxy formation of Lacey et al. 2016 (Galform)
- Predict central density / Vmax suppression from hydrodynamical simulations of Sawala et al. 2016



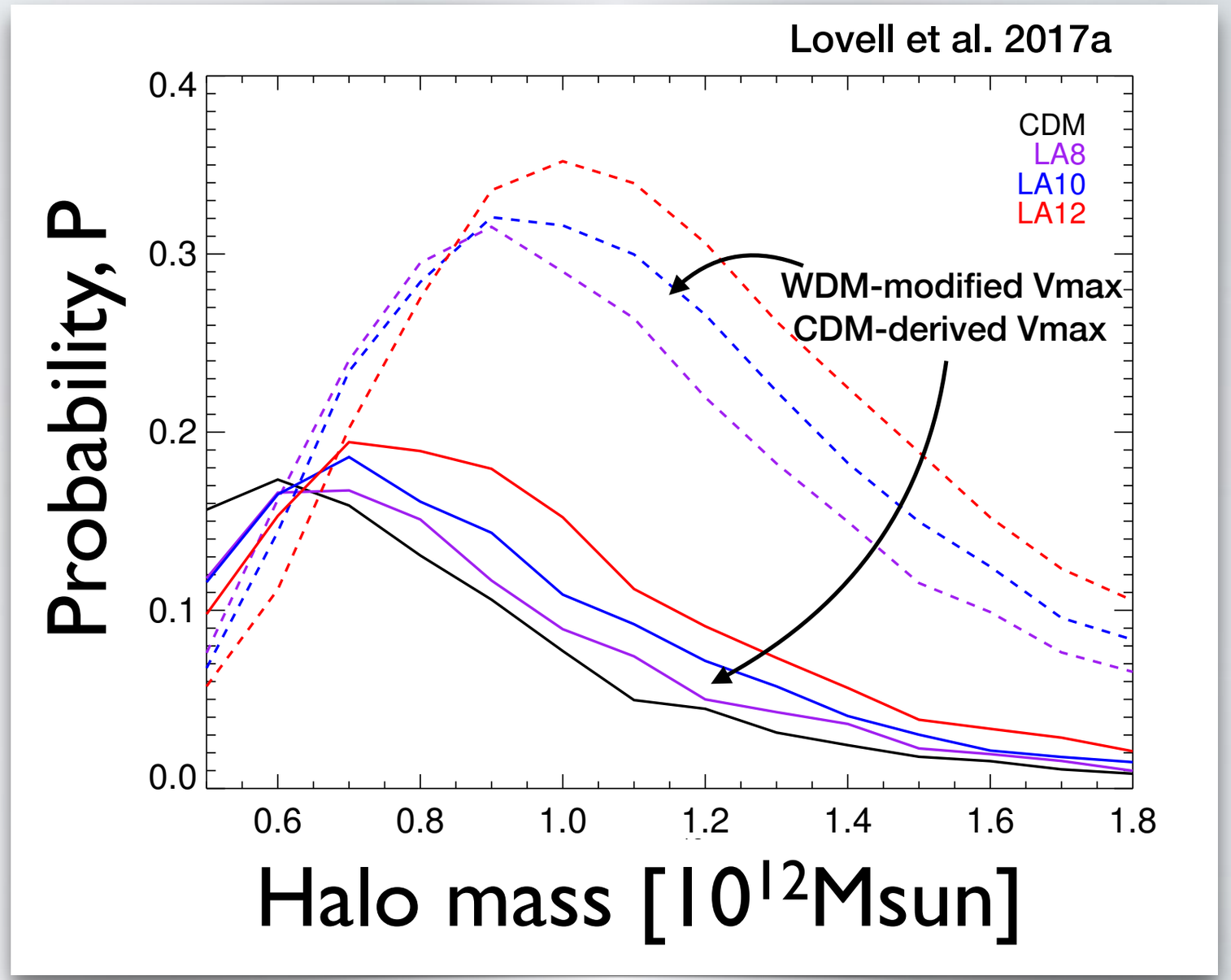
Semi-analytics

- Calculate probability of drawing the MW satellite Vmax function from theoretically obtained functions using method of Jiang & van den Bosch 2015
- Make ranked lists of nine most luminous satellites, rank by Vmax



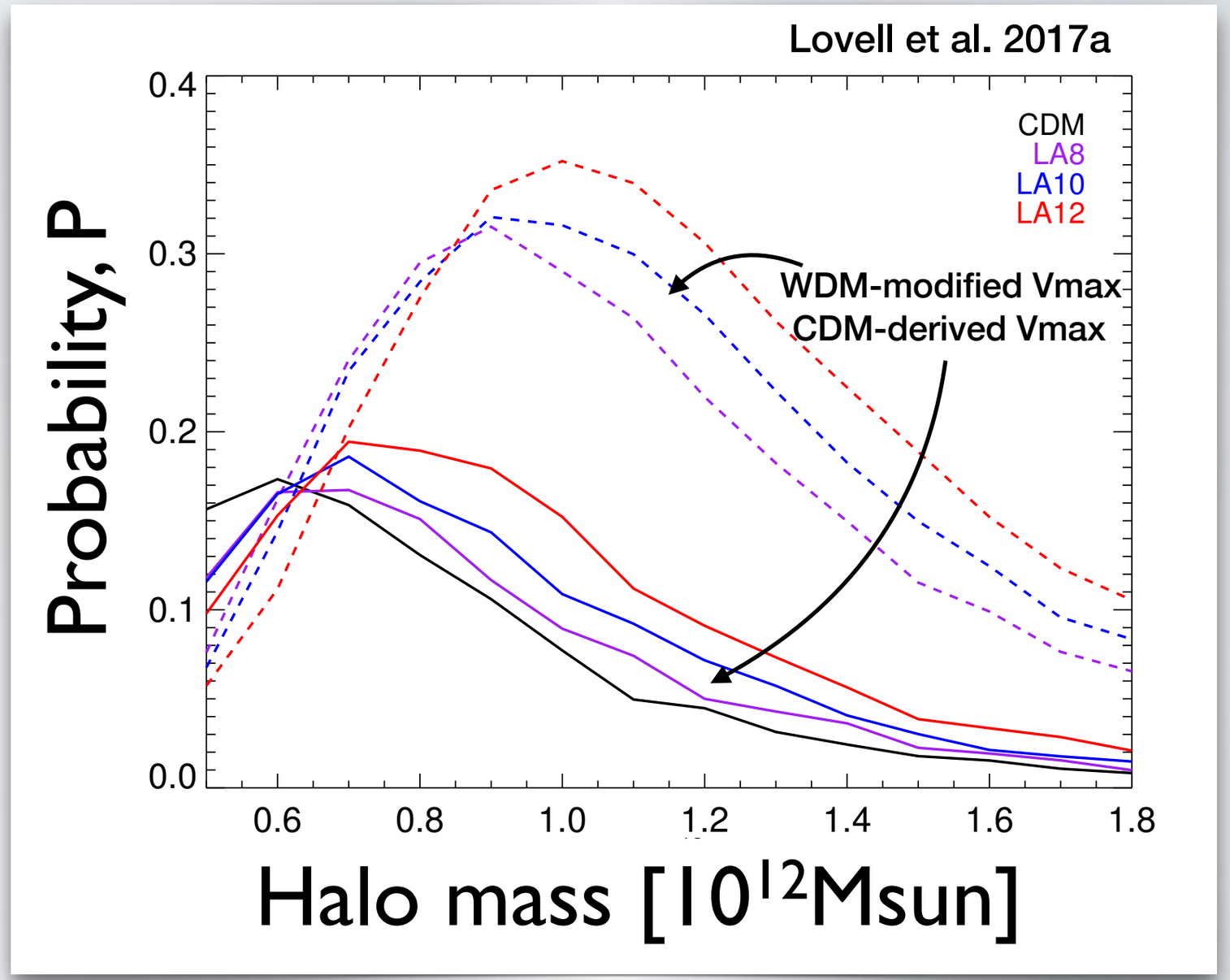
NB: not precision cosmology!

SUMMARY (2)


Lovell et al. 2017a
Probability, P
0.4
0.3
0.2
0.1
0.0
CDM
LA8
LA10
LA12
WDM-modified Vmax
CDM-derived Vmax
0.6
0.8
1.0
1.2
1.4
1.6
1.8
Halo mass [10^12Msun]

SUMMARY (2)

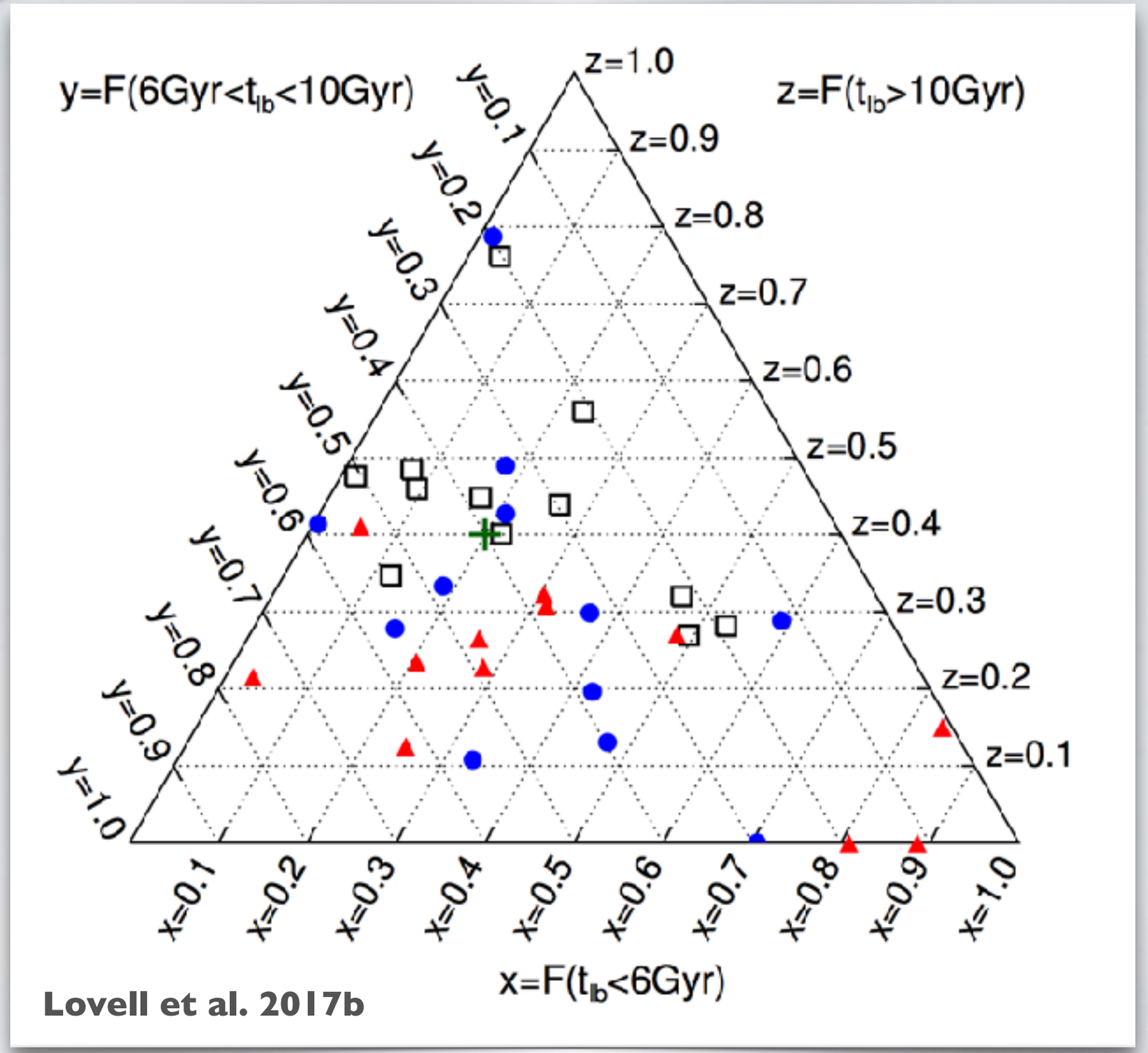
- WDM satellites densities do better than CDM given the baryon physics, prefer a more massive halo.



WDM — Age

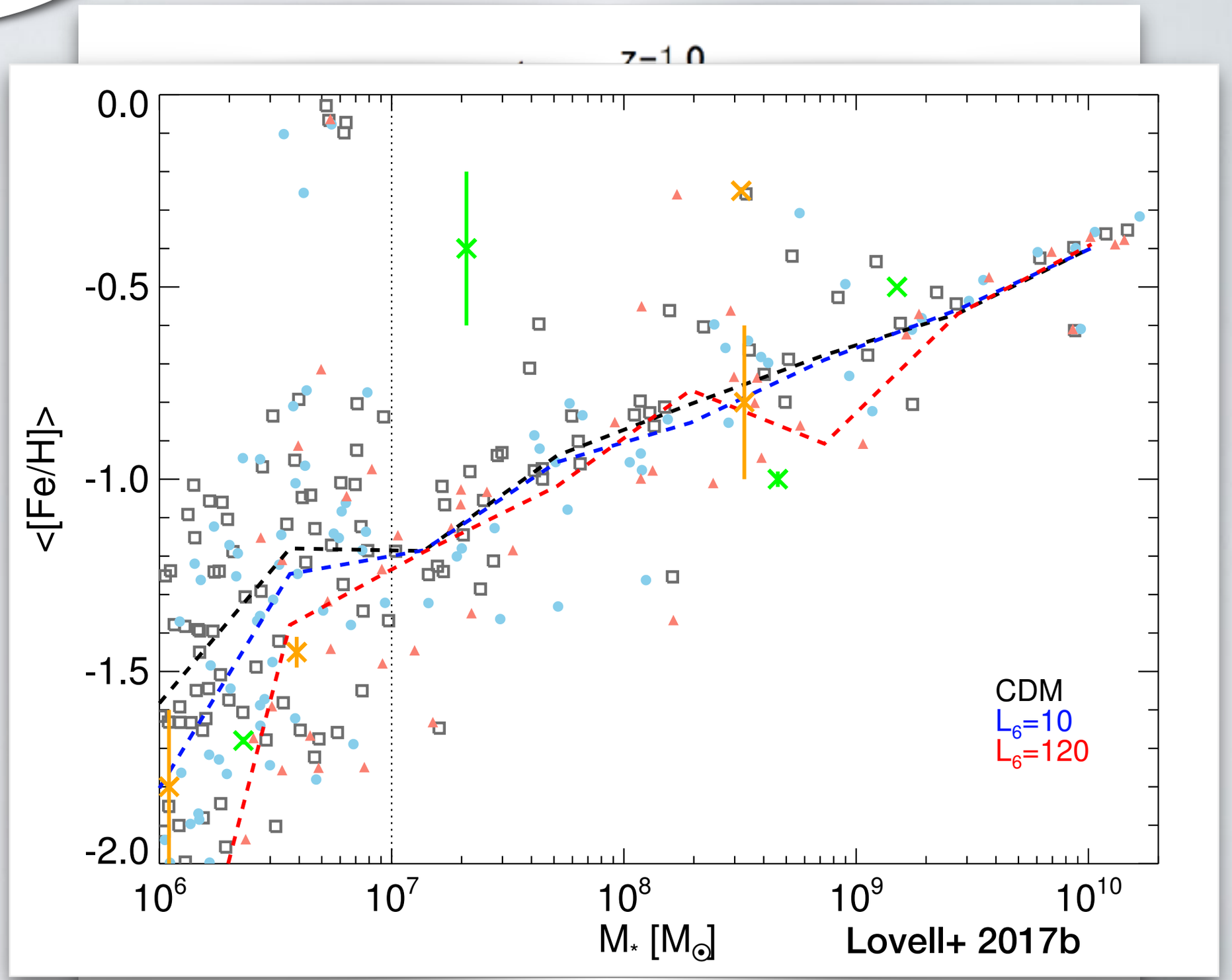
M. Lovell, MPIA; BAM 05/09/17

Hydro-simulations



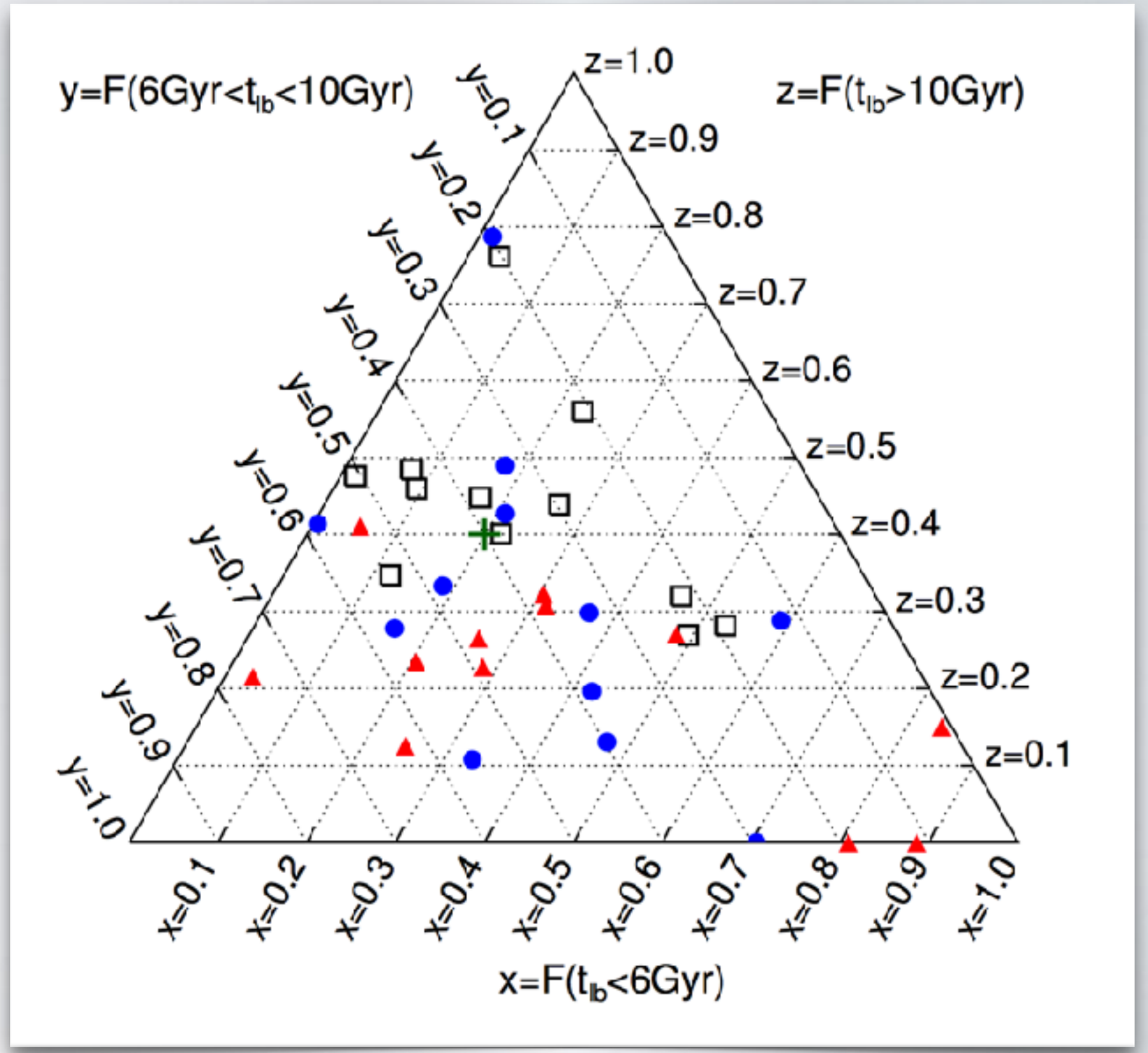
Lovell et al. 2017b

Hydro-simulations



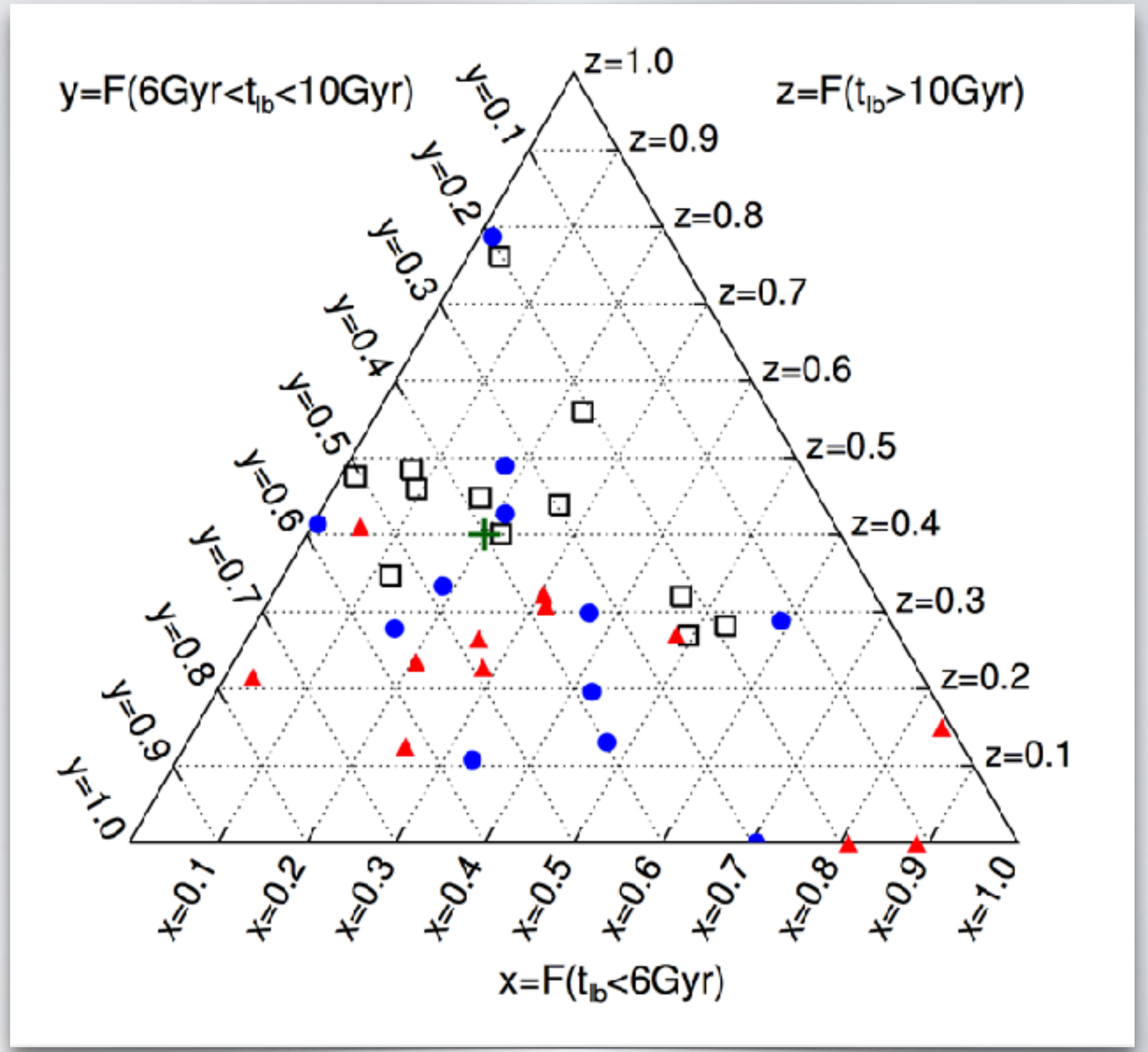
M. Lovell, MPIA; BAM 05/09/17

SUMMARY (3)


y=F(6Gyr<t_lb<10Gyr)
z=F(t_lb>10Gyr)
x=F(t_lb<6Gyr)
z=1.0
z=0.9
z=0.8
z=0.7
z=0.6
z=0.5
z=0.4
z=0.3
z=0.2
z=0.1
y=0.1
y=0.2
y=0.3
y=0.4
y=0.5
y=0.6
y=0.7
y=0.8
y=0.9
y=1.0
x=0.1
x=0.2
x=0.3
x=0.4
x=0.5
x=0.6
x=0.7
x=0.8
x=0.9
x=1.0

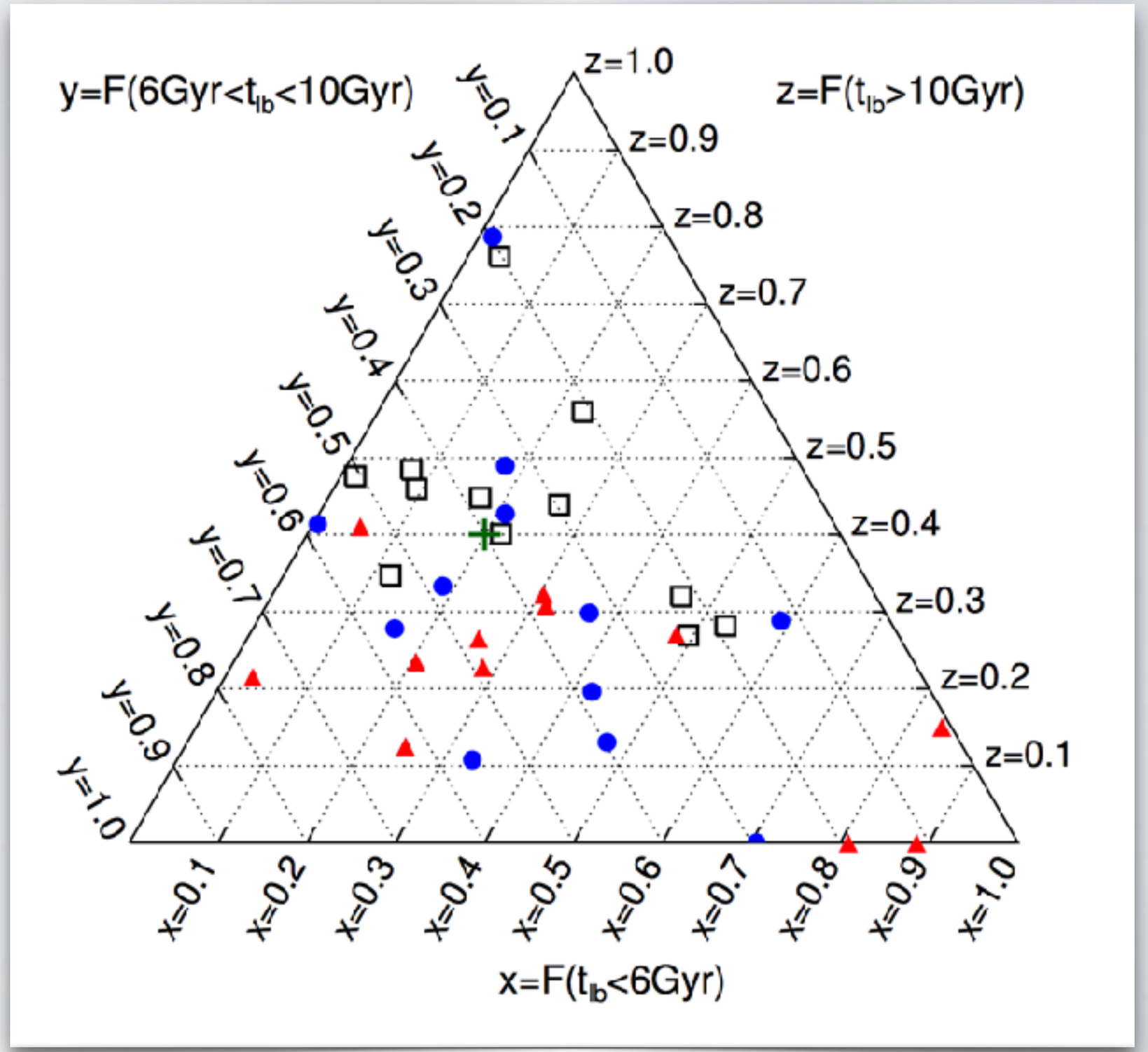
SUMMARY (3)

- MW-M31 systems younger in warmer models



SUMMARY (3)

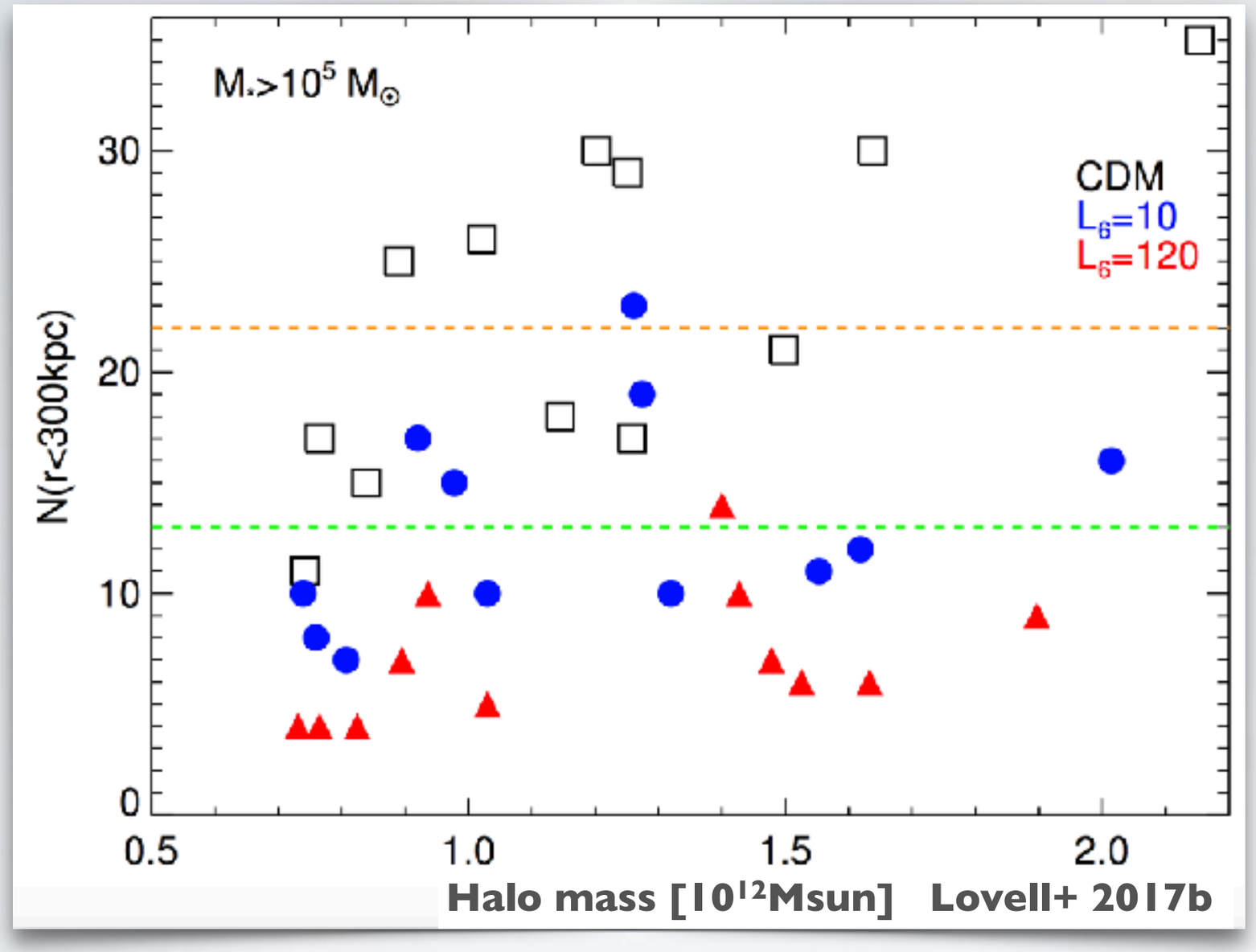
- MW-M31 systems younger in warmer models
- Difficult to measure observationally



WDM — Abundance

M. Lovell, MPIA; BAM 05/09/17

Hydro-simulations

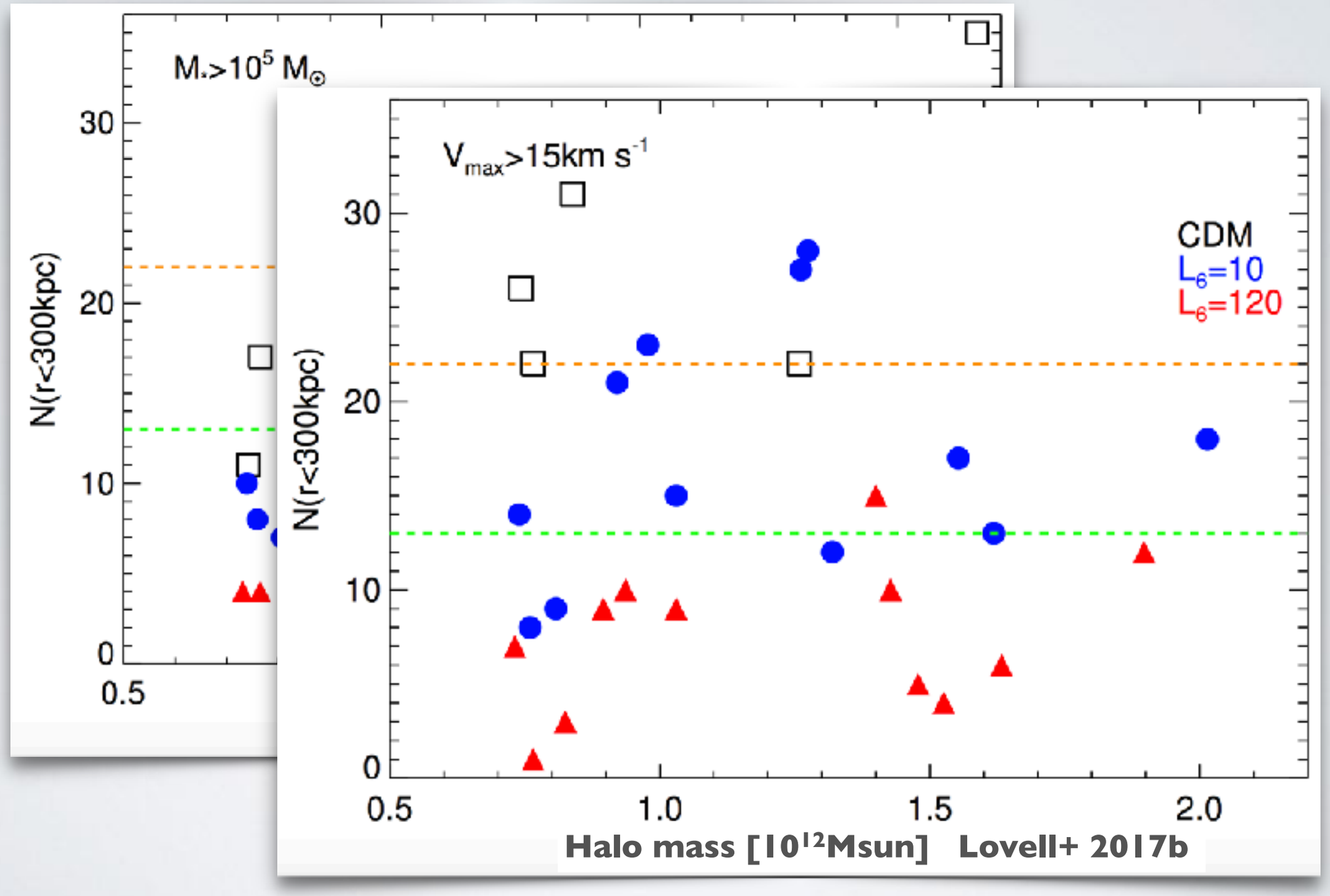


<=N M31 sats

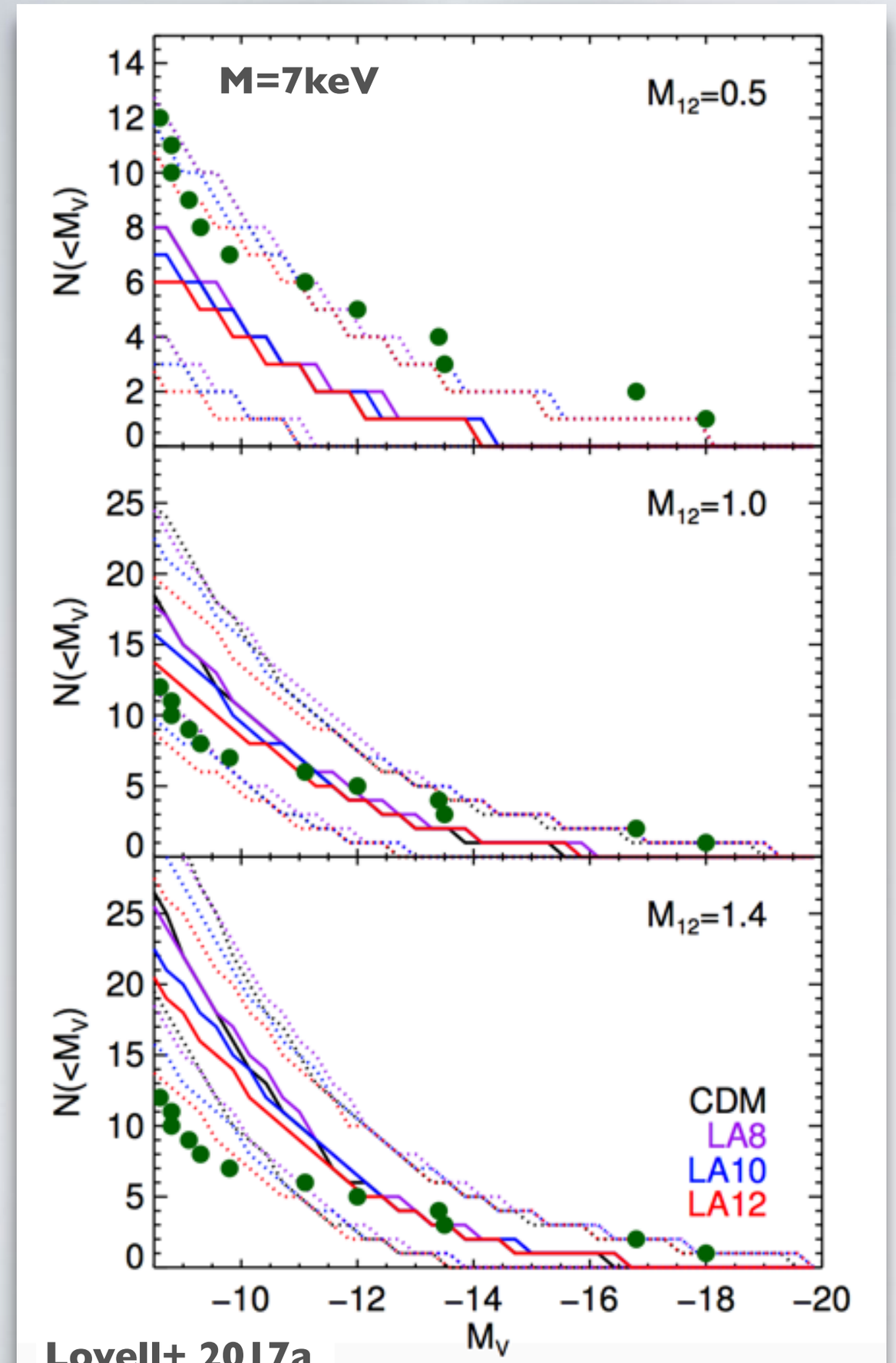
<=N MW sats

M. Lovell, MPIA; BAM 05/09/17

Hydro-simulations

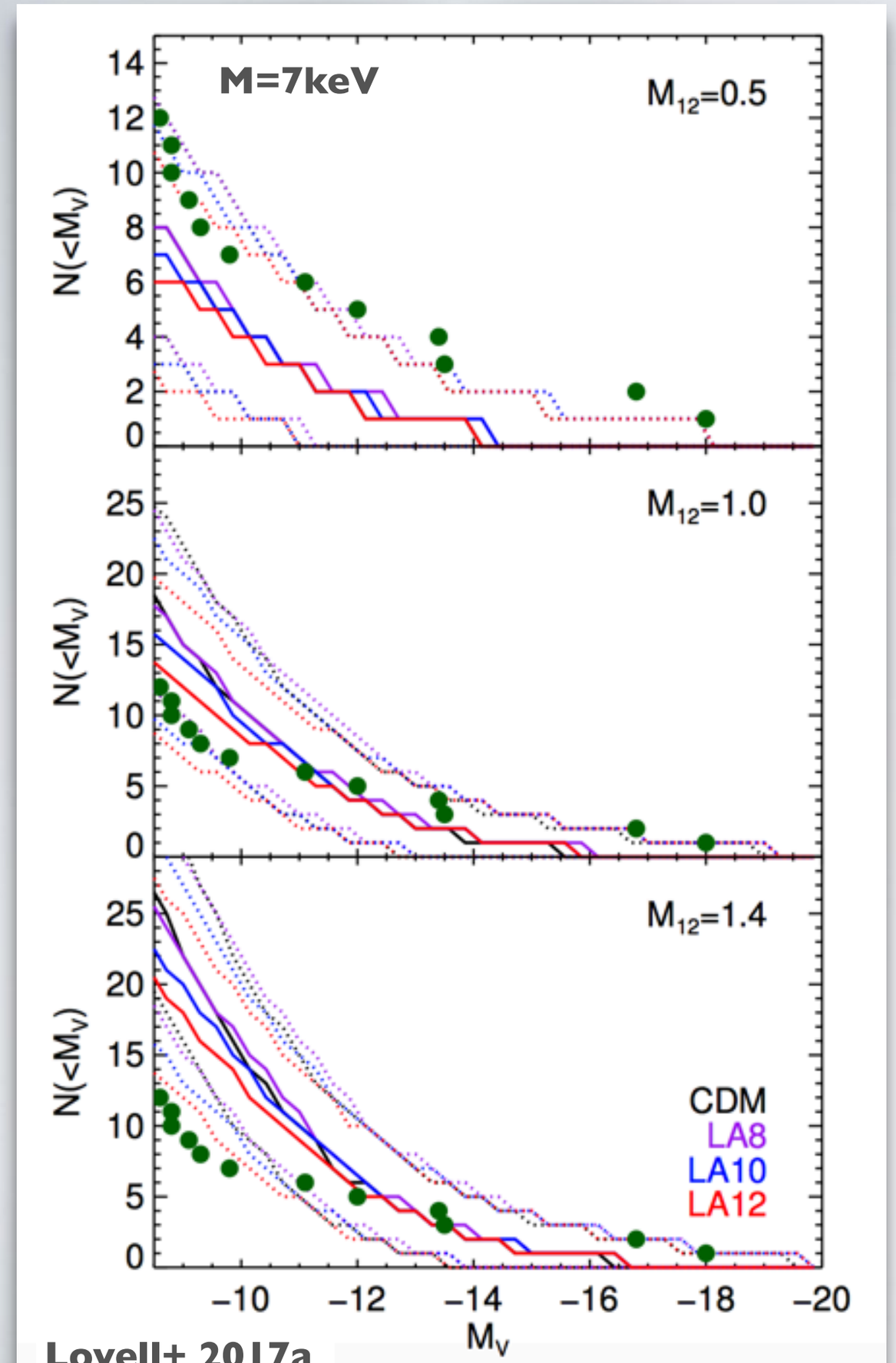


M. Lovell, MPIA; BAM 05/09/17



Semi-analytics

M. Lovell, MPIA; BAM 05/09/17

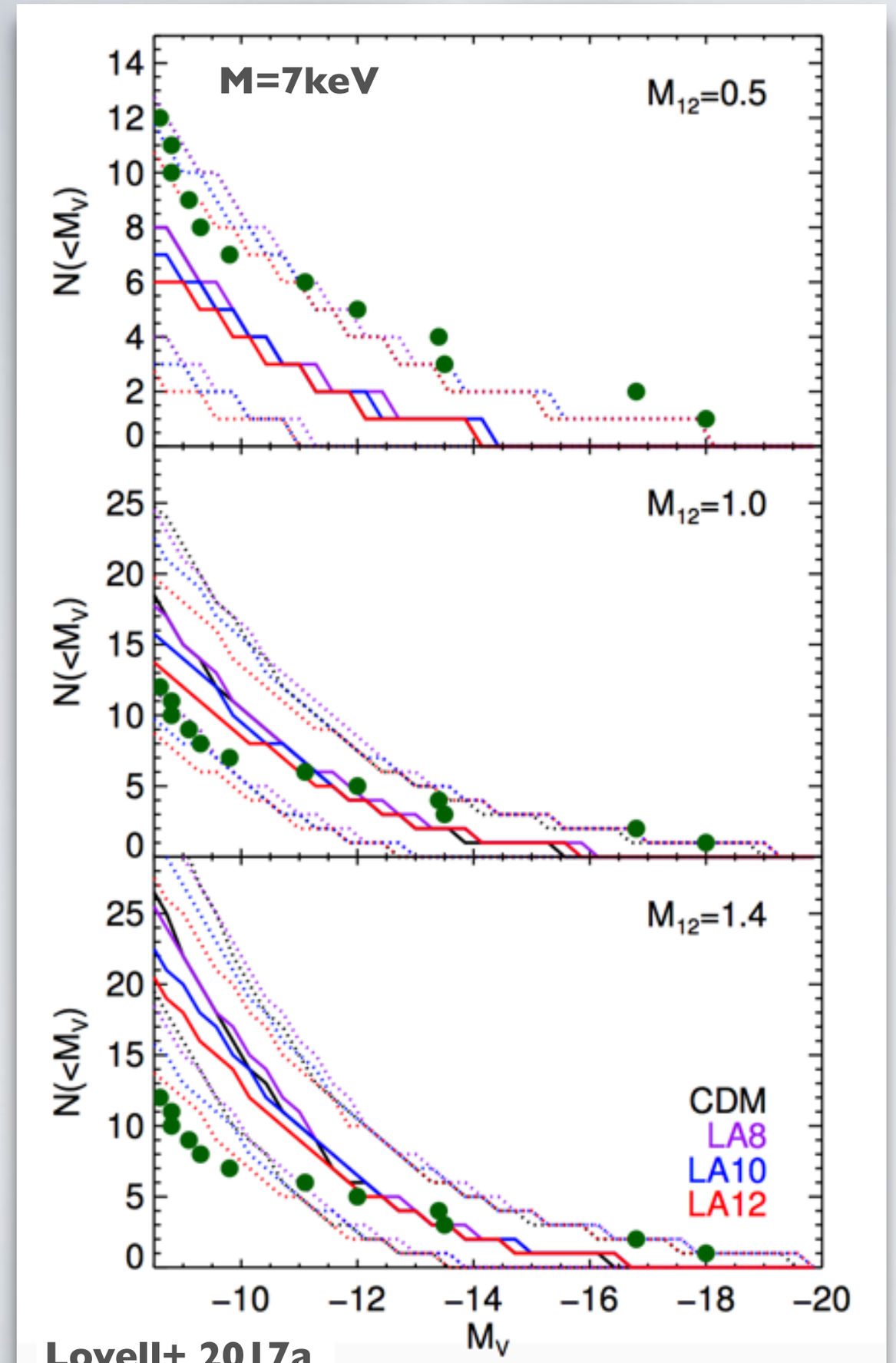


Lovell+ 2017a

Semi-analytics

Predict luminosity functions for ~200 realisations of a M-L6 pair,

M. Lovell, MPIA; BAM 05/09/17



Lovell+ 2017a

Semi-analytics

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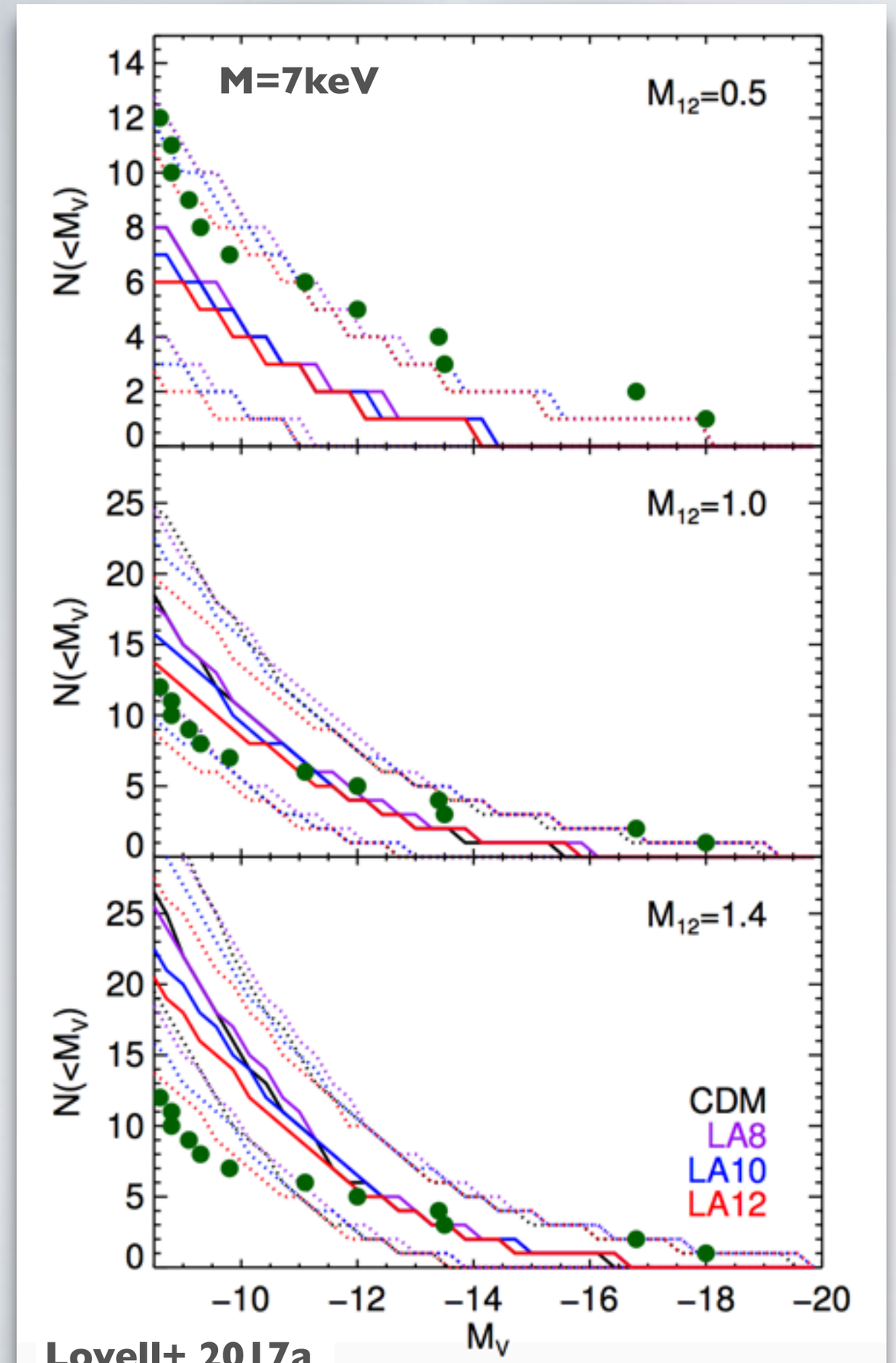
M. Lovell, MPIA; BAM 05/09/17



Lovell+ 2017a

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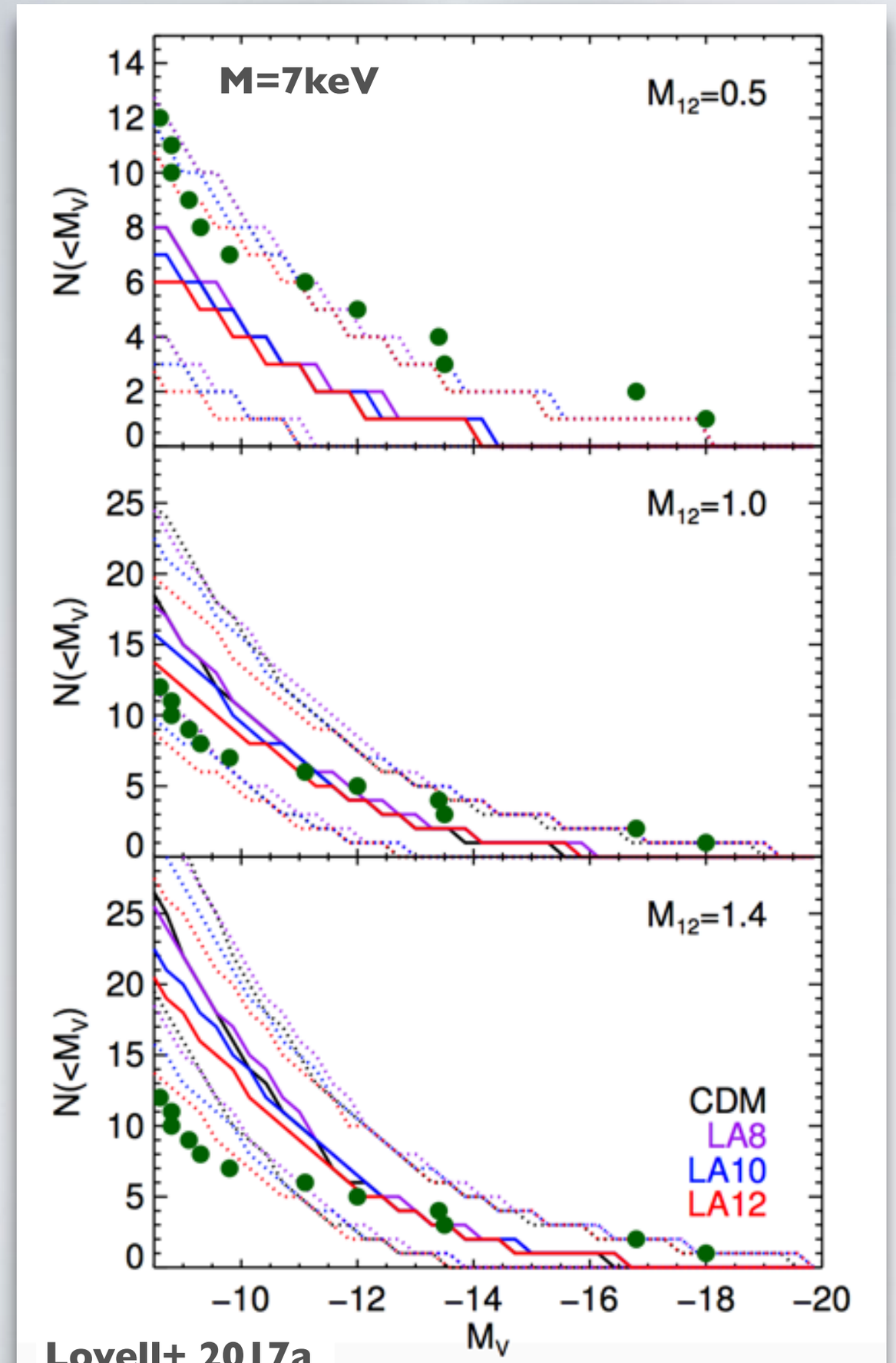


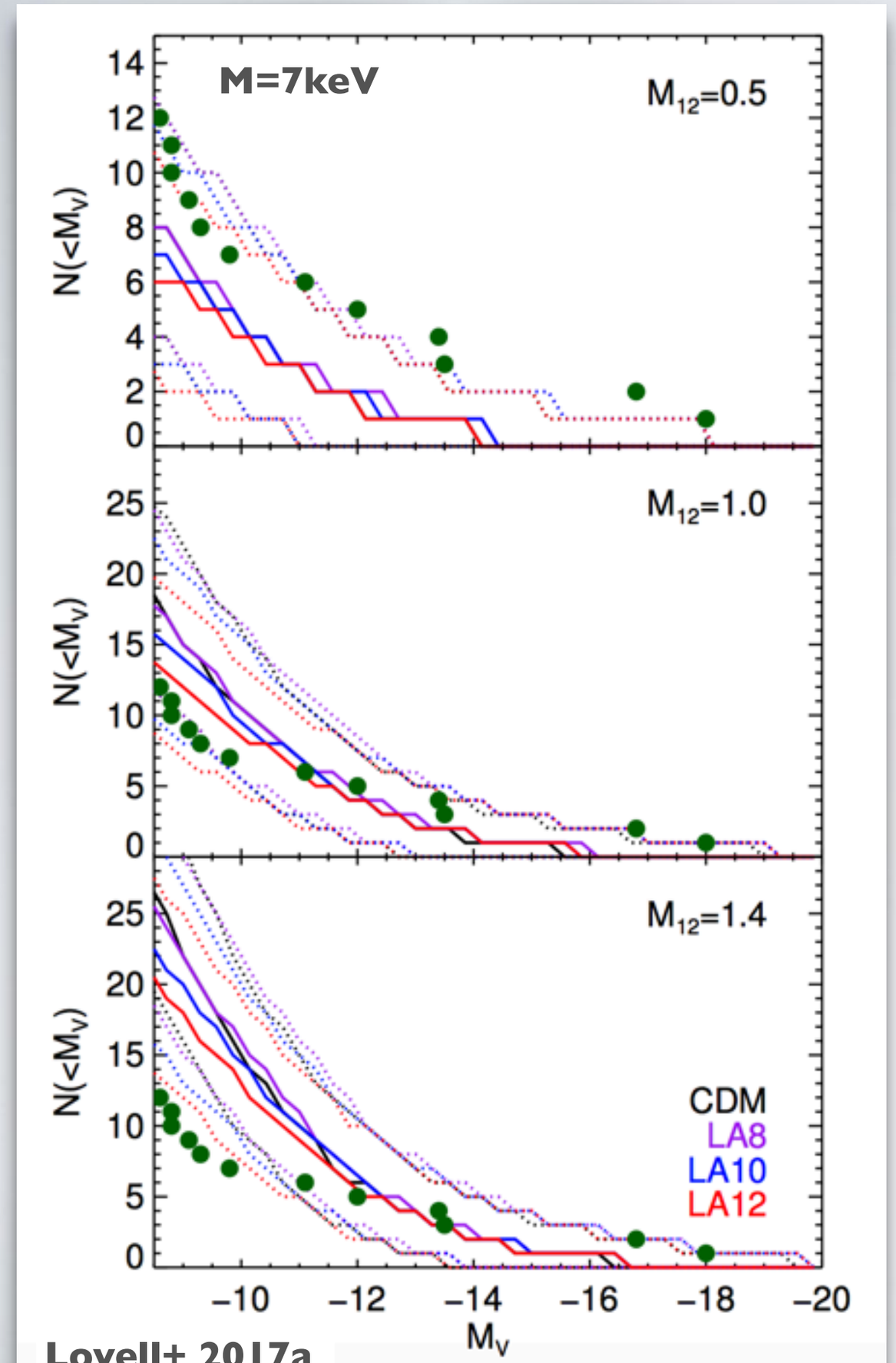
Lovell+ 2017a

Semi-analytics

Predict luminosity functions for ~200 realisations of a M-L6 pair, M=[1-10], L6 =[0-700] (selection)

Iteratively determine which halo masses give ~70 satellites at least 5% of the time.

M. Lovell, MPIA; BAM 05/09/17



Lovell+ 2017a

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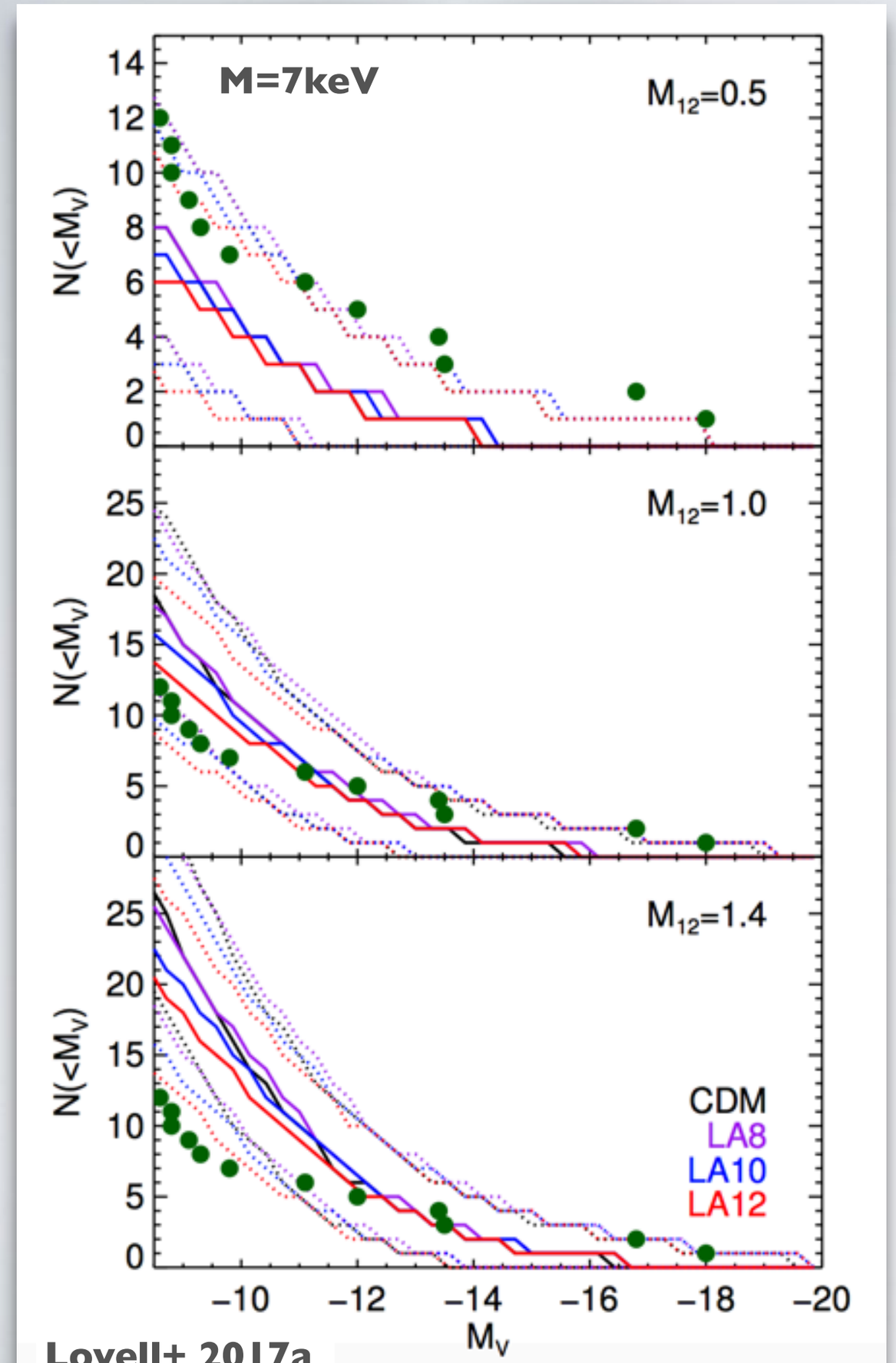


Lovell+ 2017a

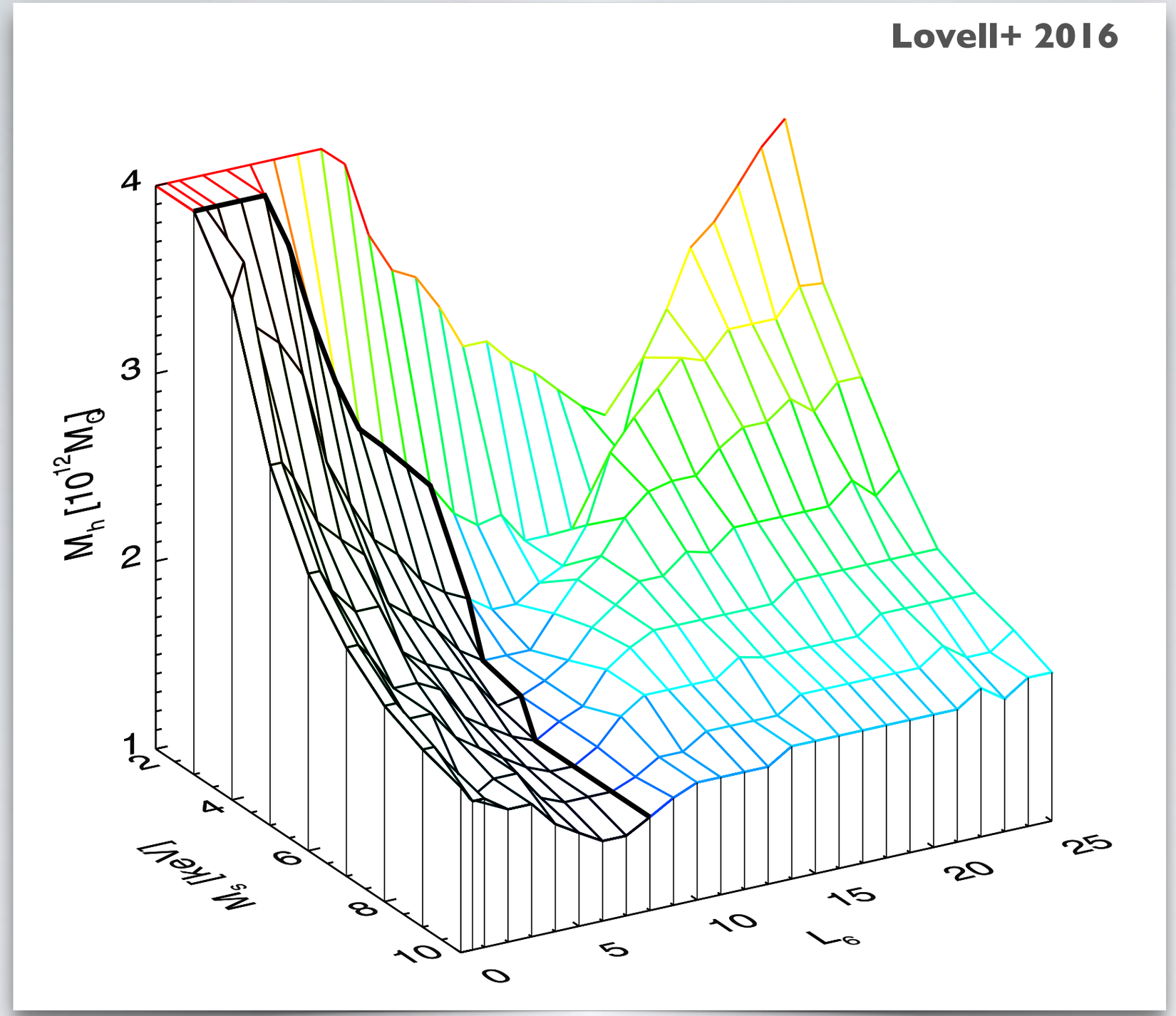
Semi-analytics

Predict luminosity functions for ~200 realisations of a M-L6 pair, M=[1-10], L6 =[0-700] (selection)

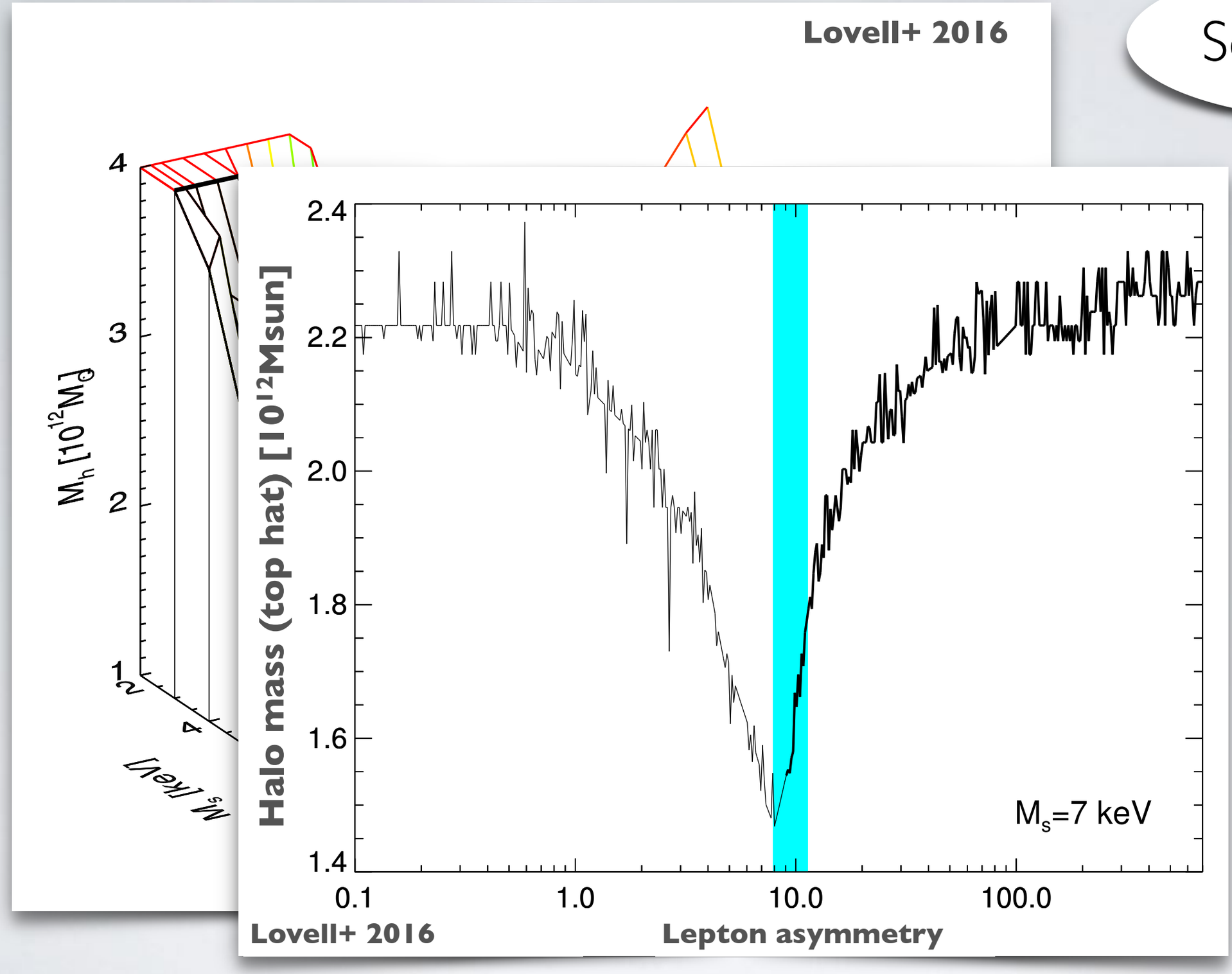
Iteratively determine which halo masses give ~70 satellites at least 5% of the time.

(match classical, SDSS, DES)

Semi-analytics



Semi-analytics



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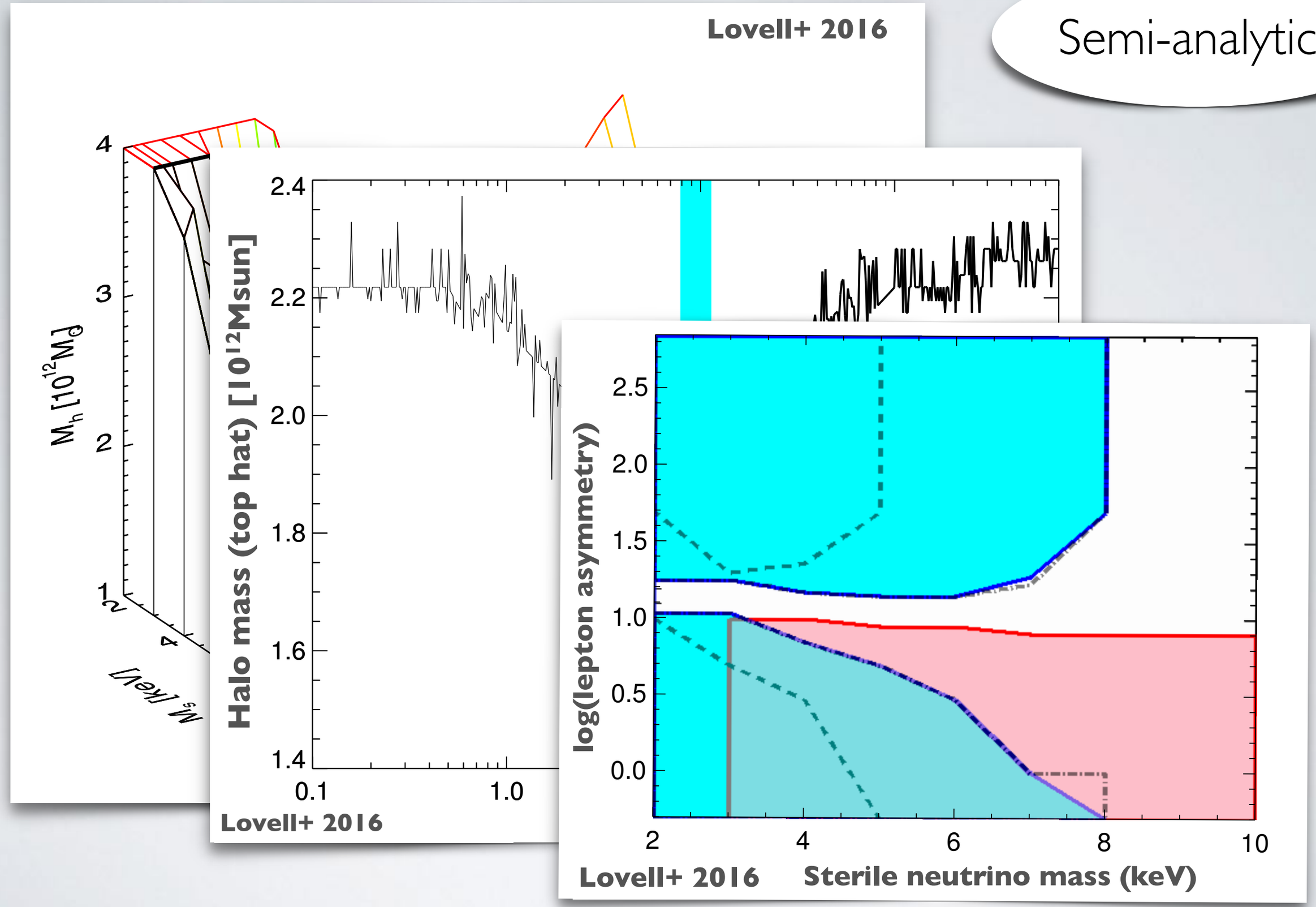
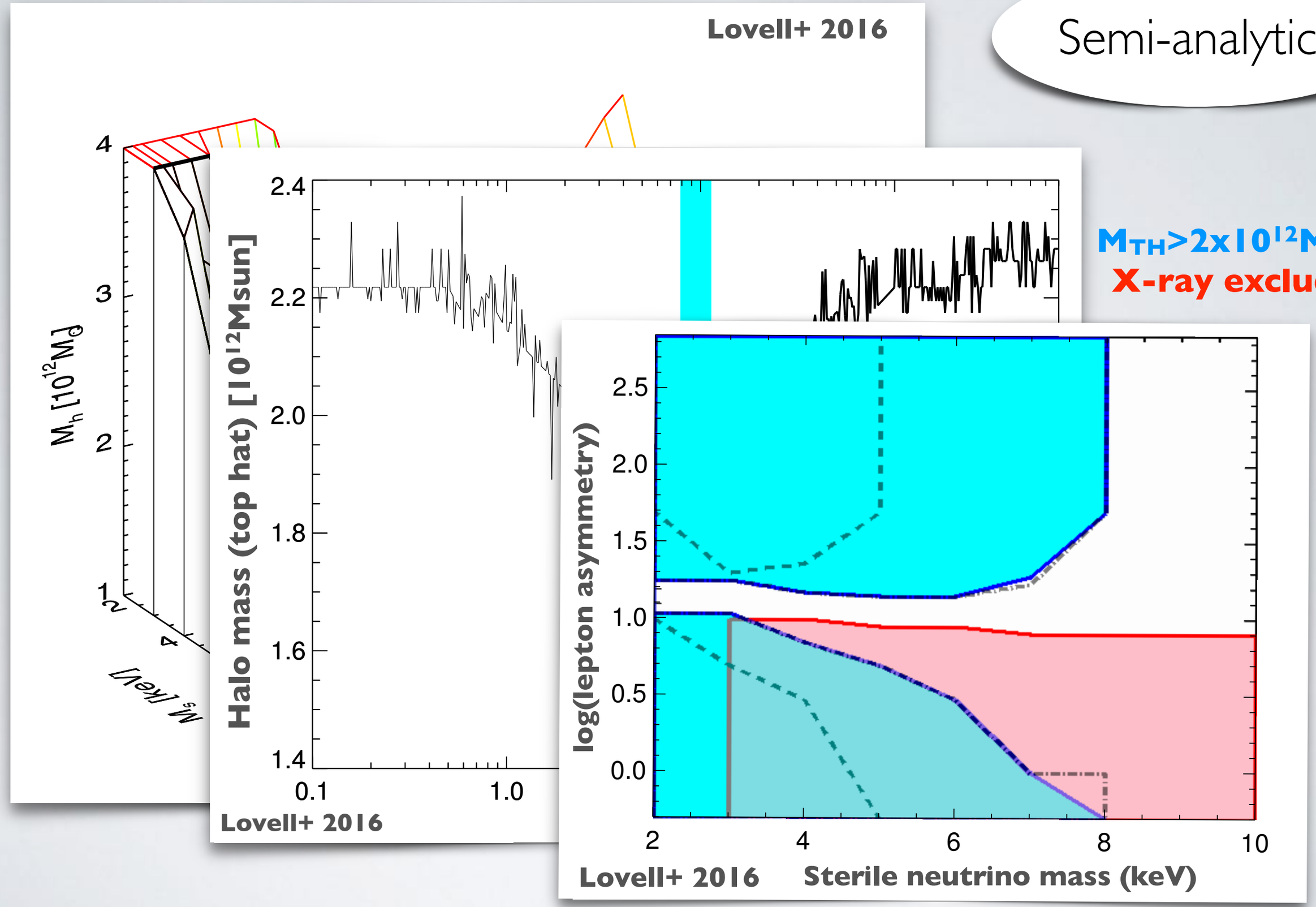
Semi-analytics



Semi-analytics

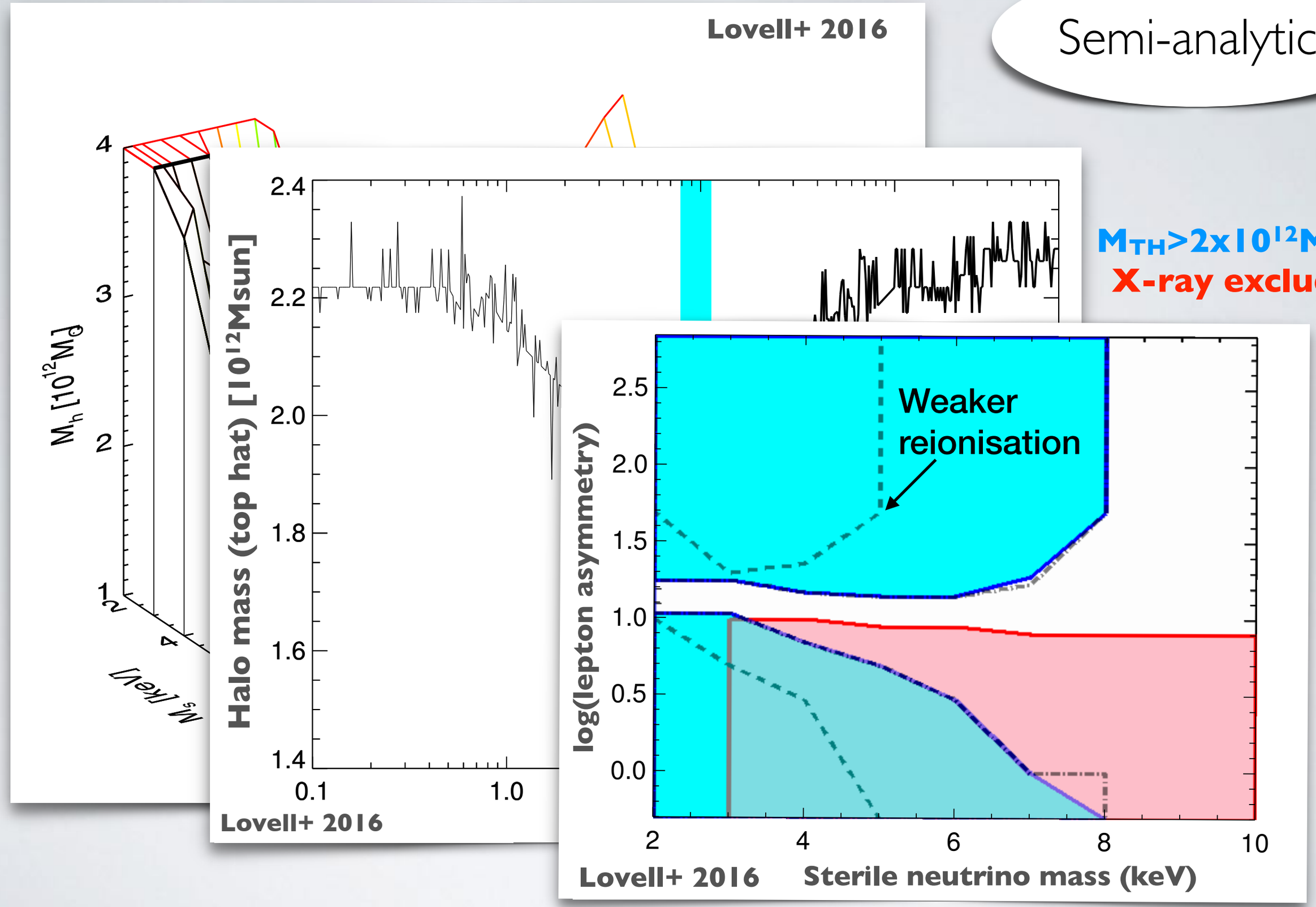


$M_{TH}>2x10^{12}$Msun

X-ray excluded

M. Lovell, MPIA; BAM 05/09/17

Semi-analytics



$M_{TH}>2x10^{12}$Msun

X-ray excluded

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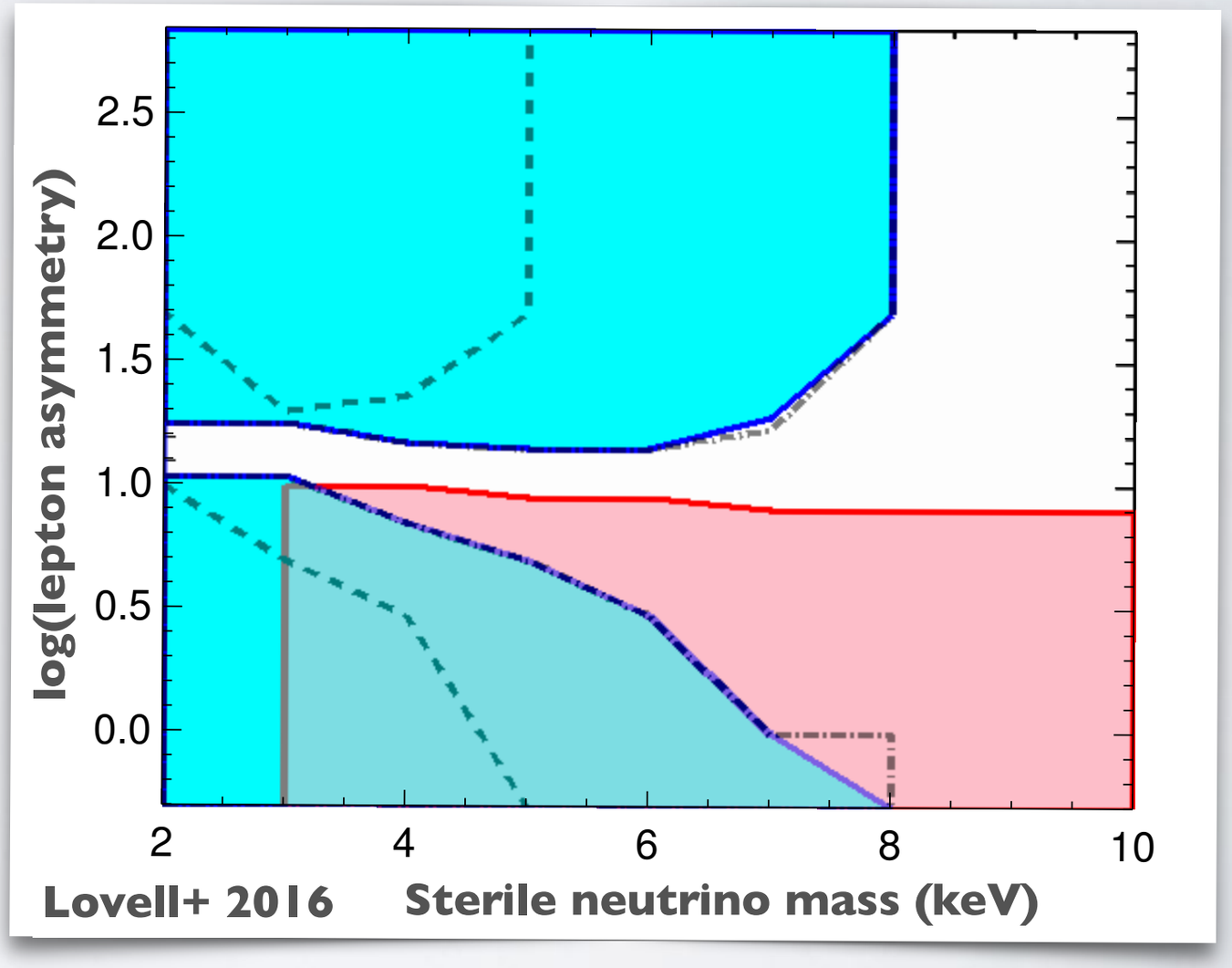
SUMMARY (4)

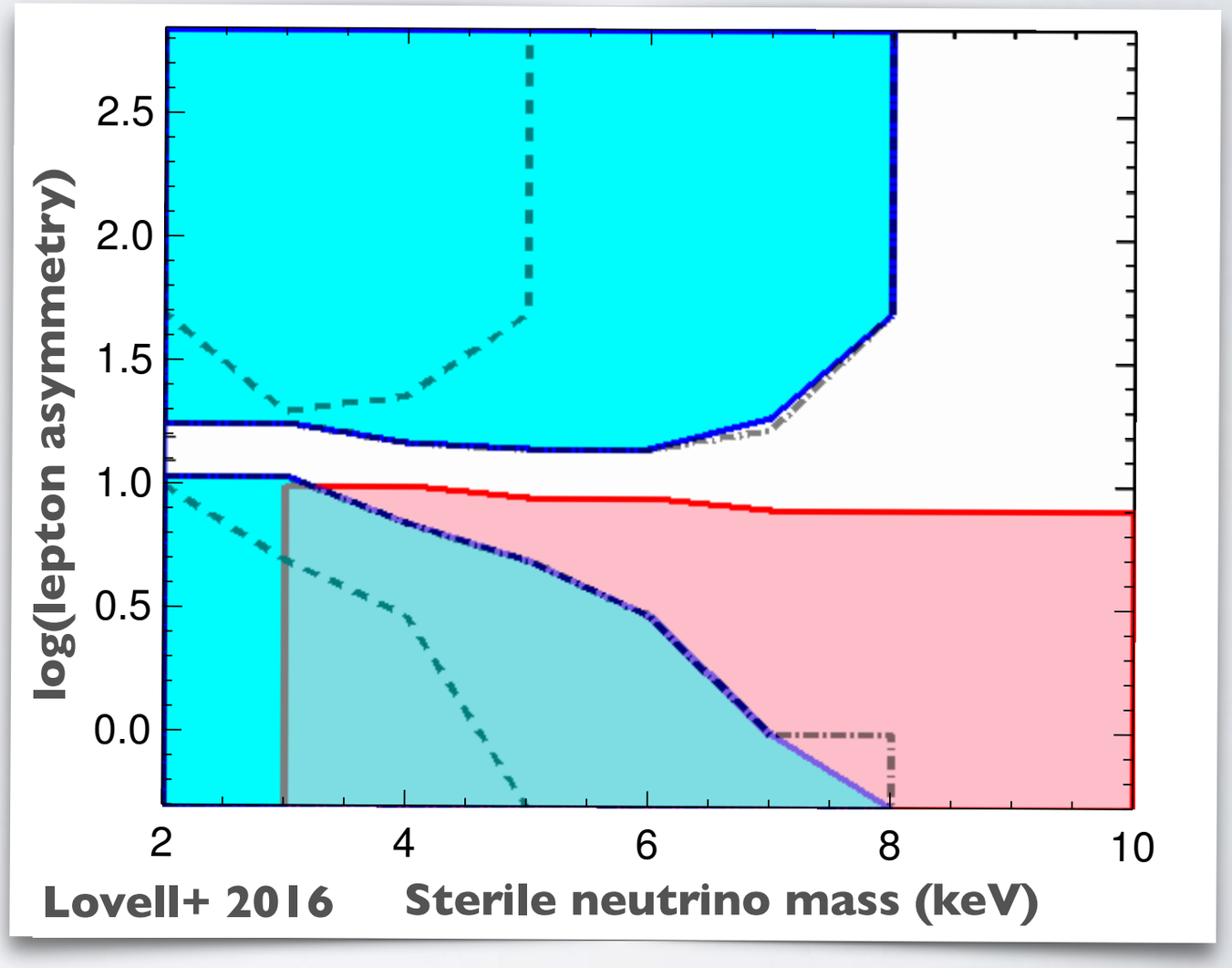
Mh>2x10^{12}Msun
X-ray excluded



SUMMARY (4)

- Predict satellite abundance as a function of host halo mass

Mh>2x10^{12}Msun
X-ray excluded



SUMMARY (4)

- Predict satellite abundance as a function of host halo mass

- Narrow allowed region for parameters in fiducial baryon model

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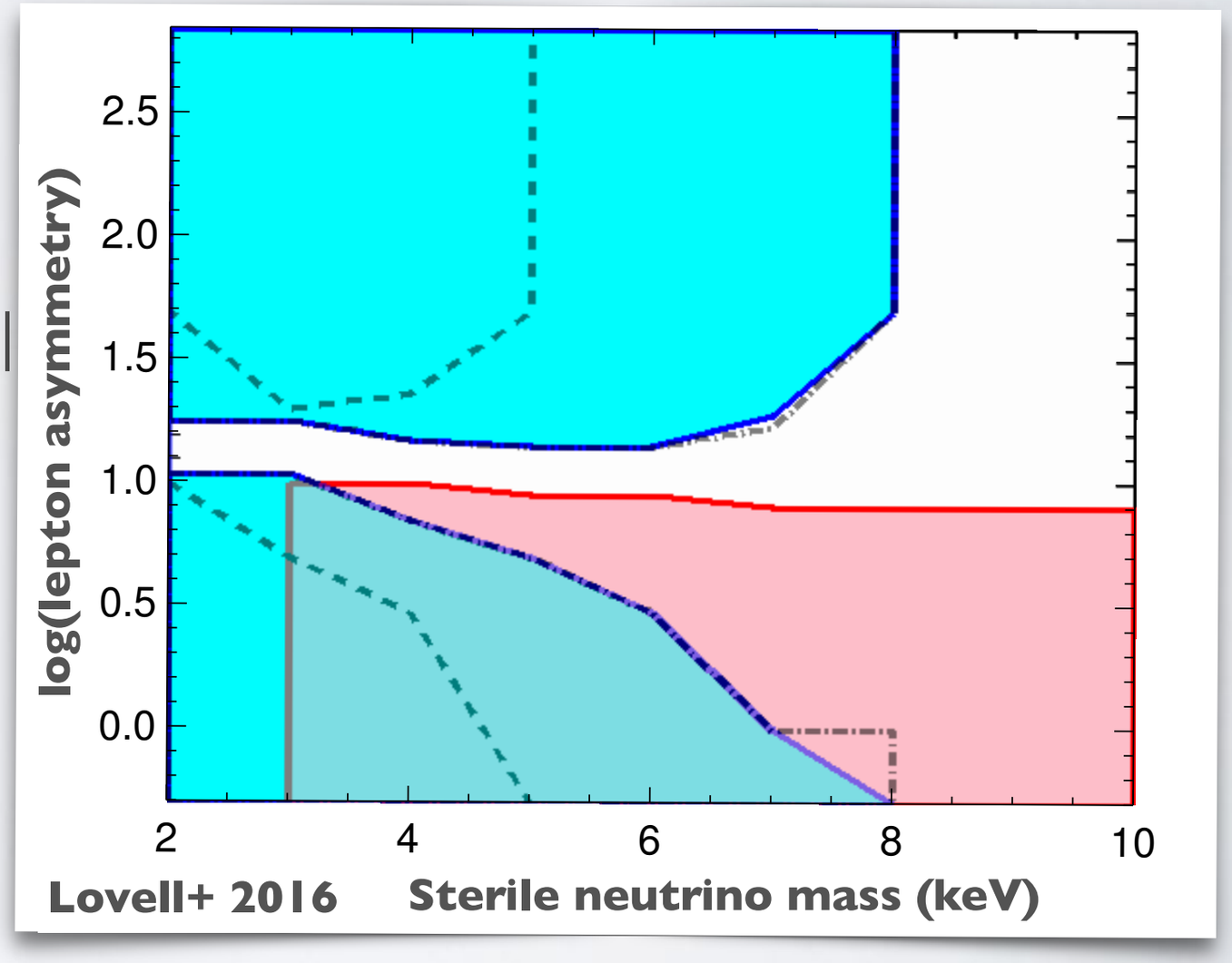

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SUMMARY (4)

- Predict satellite abundance as a function of host halo mass

- Narrow allowed region for parameters in fiducial baryon model

- Highly sensitive to reionisation feedback

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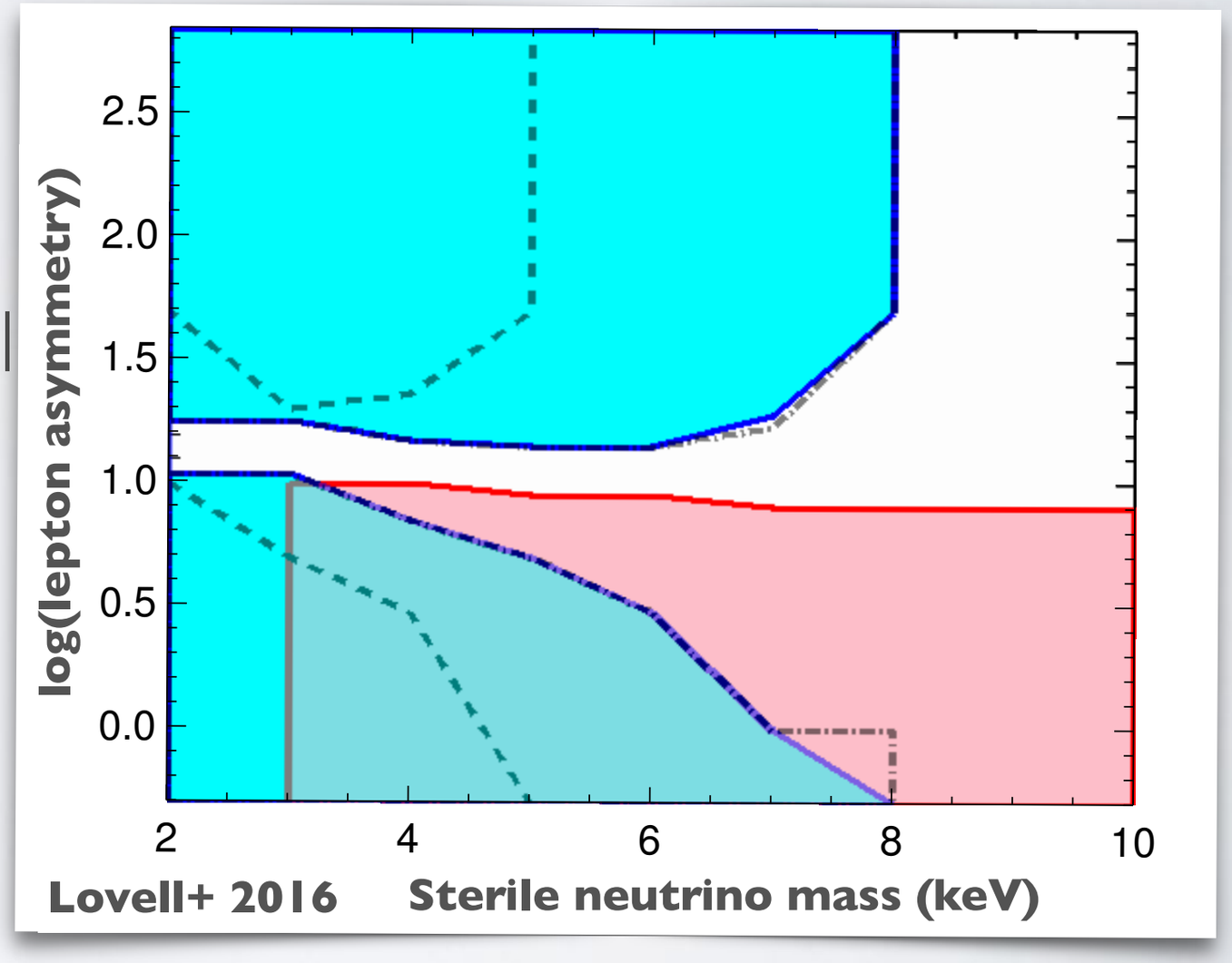
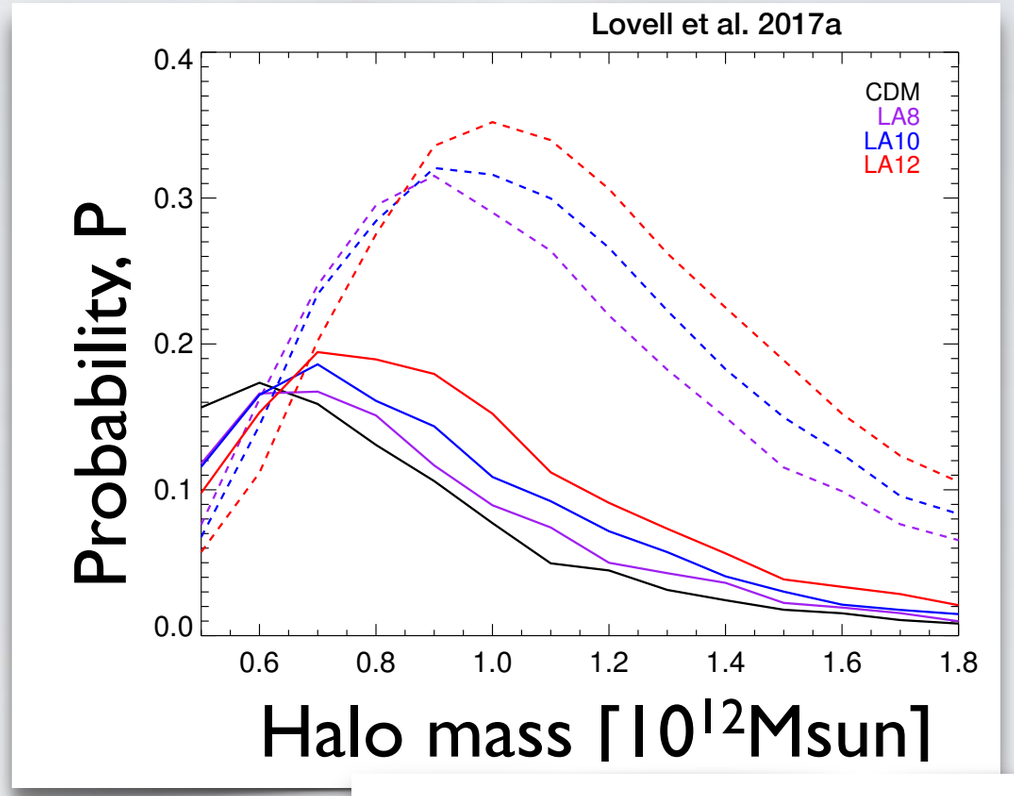
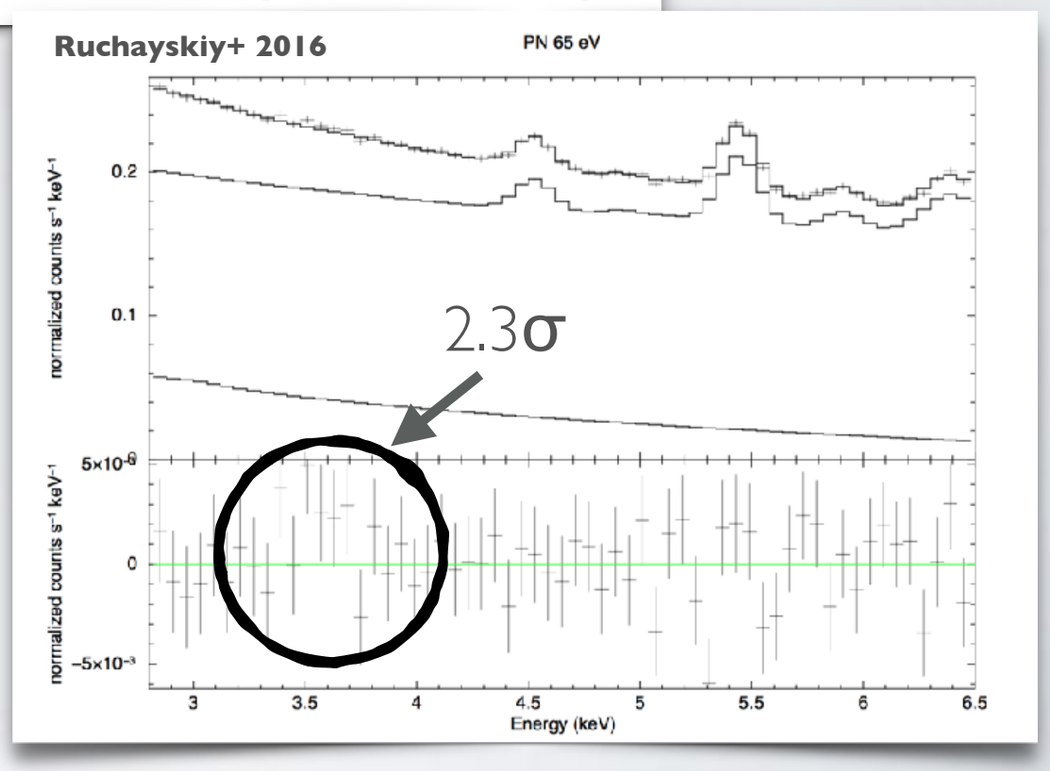


SUMMARY

- 2.3σ 'detection' in Draco X-rays
- WDM satellites densities do better than CDM given the baryon physics, prefer a more massive halo.
- Younger stellar populations in WDM satellites
- Narrow allowed region for parameters in fiducial baryon model, highly sensitive to reionisation feedback





2) TOO BIG TO FAIL AND SEMI-ANALYTICS

TBTF & SEMI-ANALYTICS

- N-body simulations predict population of massive haloes not observed among the Milky Way satellites hosts — Too Big to Fail (TBTF)

- Solutions include:

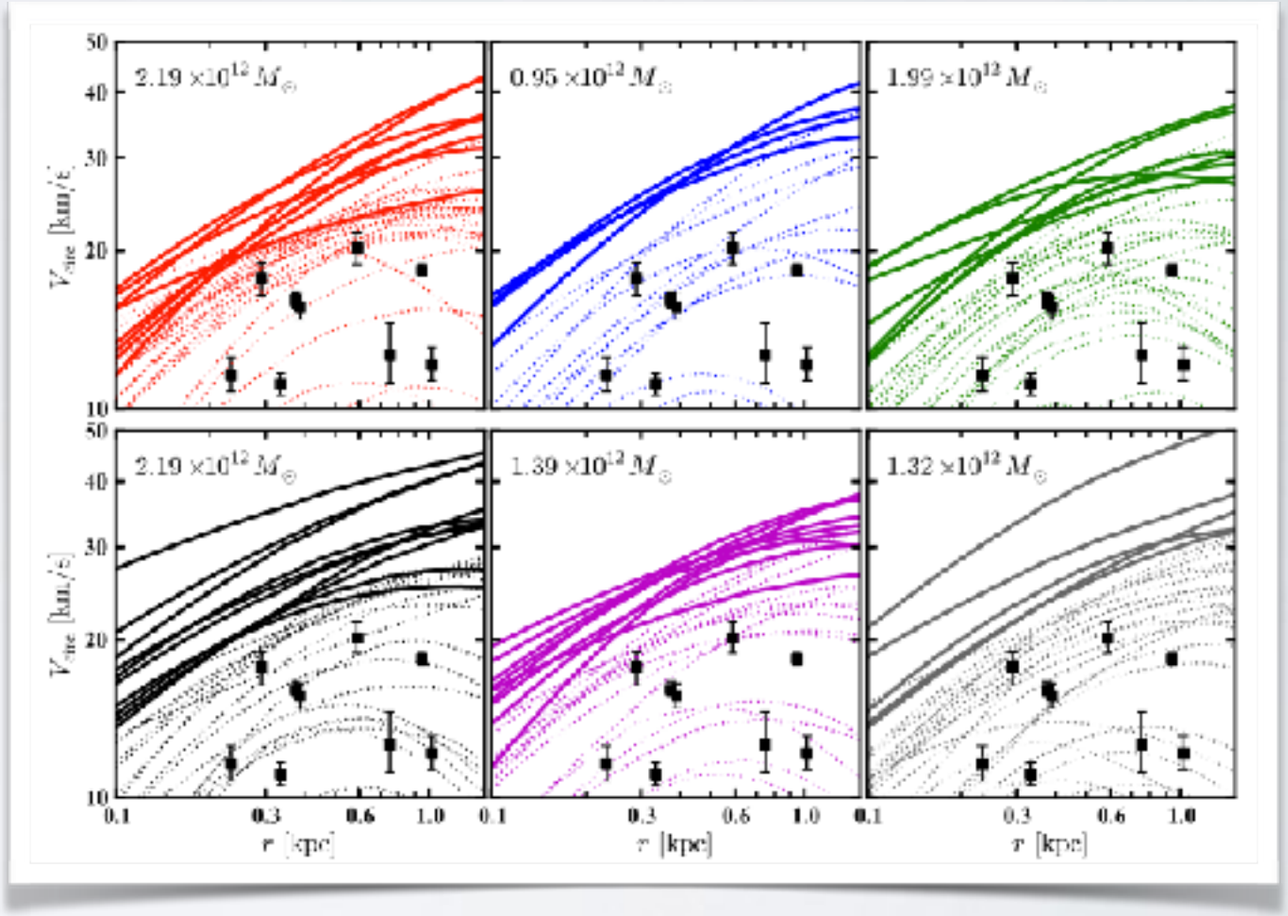
  - Lower MW halo mass

  - Better statistics

  - ρ(<1kpc) / Vmax suppressed by feedback

  - Incomplete samples ('luminosity bias')

  - Dark matter physics



Boylan-Kolchin et al. 2012

TBTF & SEMI-ANALYTICS

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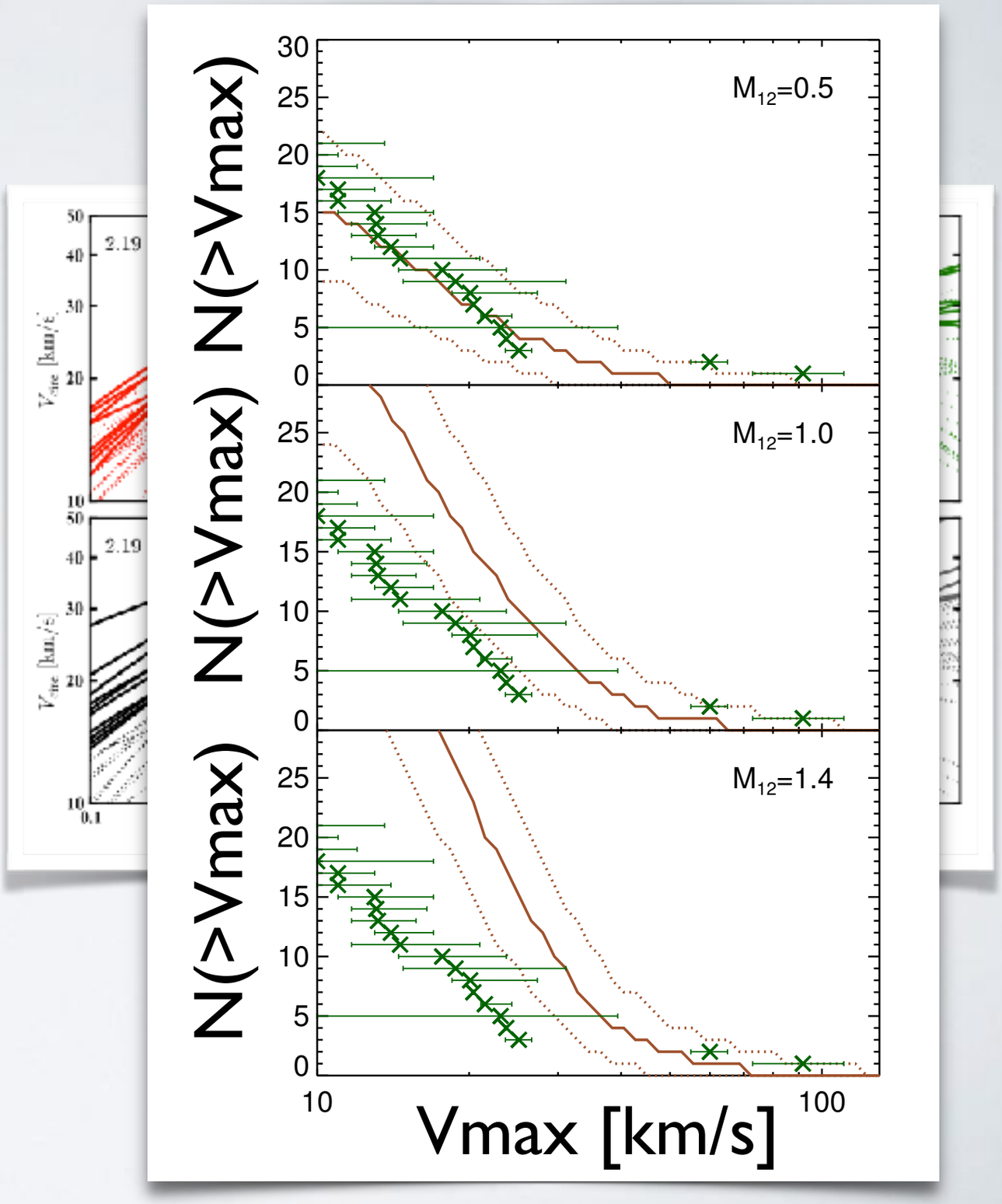


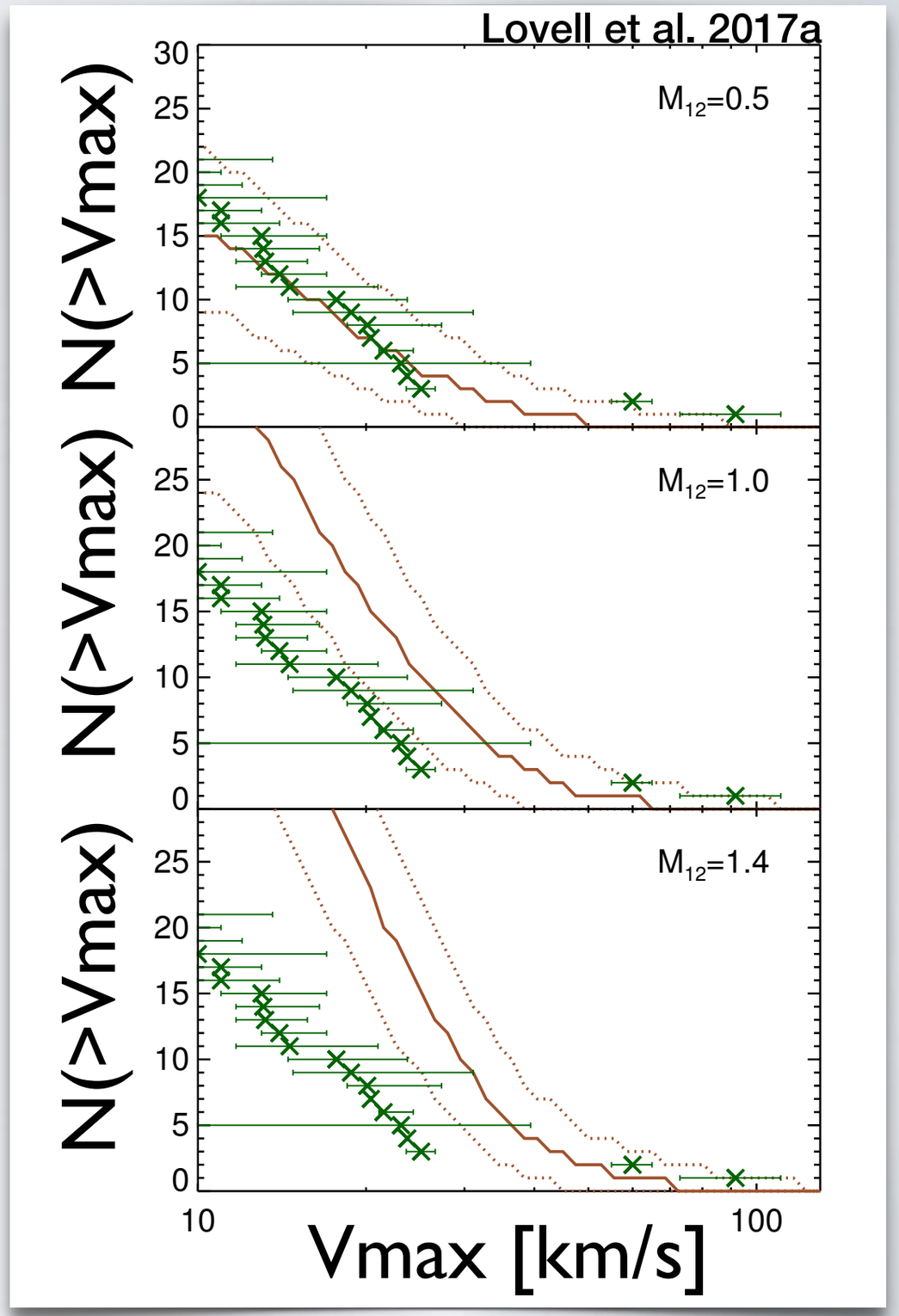
TBTF & SEMI-ANALYTICS

- Generate ~1000 x10 MW halo mass satellite populations using EPS methodology

- Predict z=0 Vmax functions with semi-analytic stripping model of Jiang & vd Bosch 2017

- Predict satellite luminosities with semi-analytic galaxy formation of Lacey et al. 2016 (Galform)

- Predict central density / Vmax suppression from hydrodynamical simulations of Sawala et al. 2016



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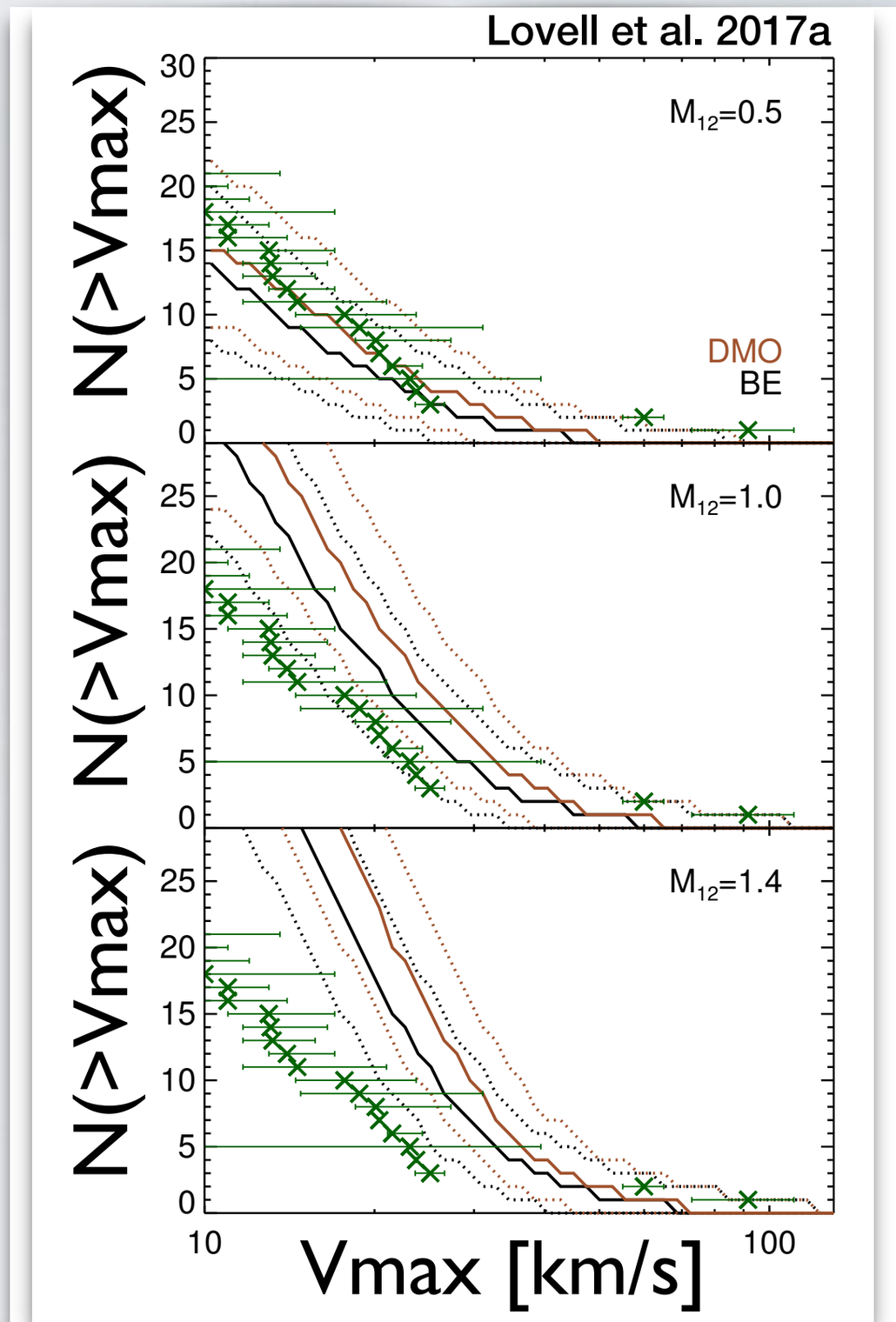
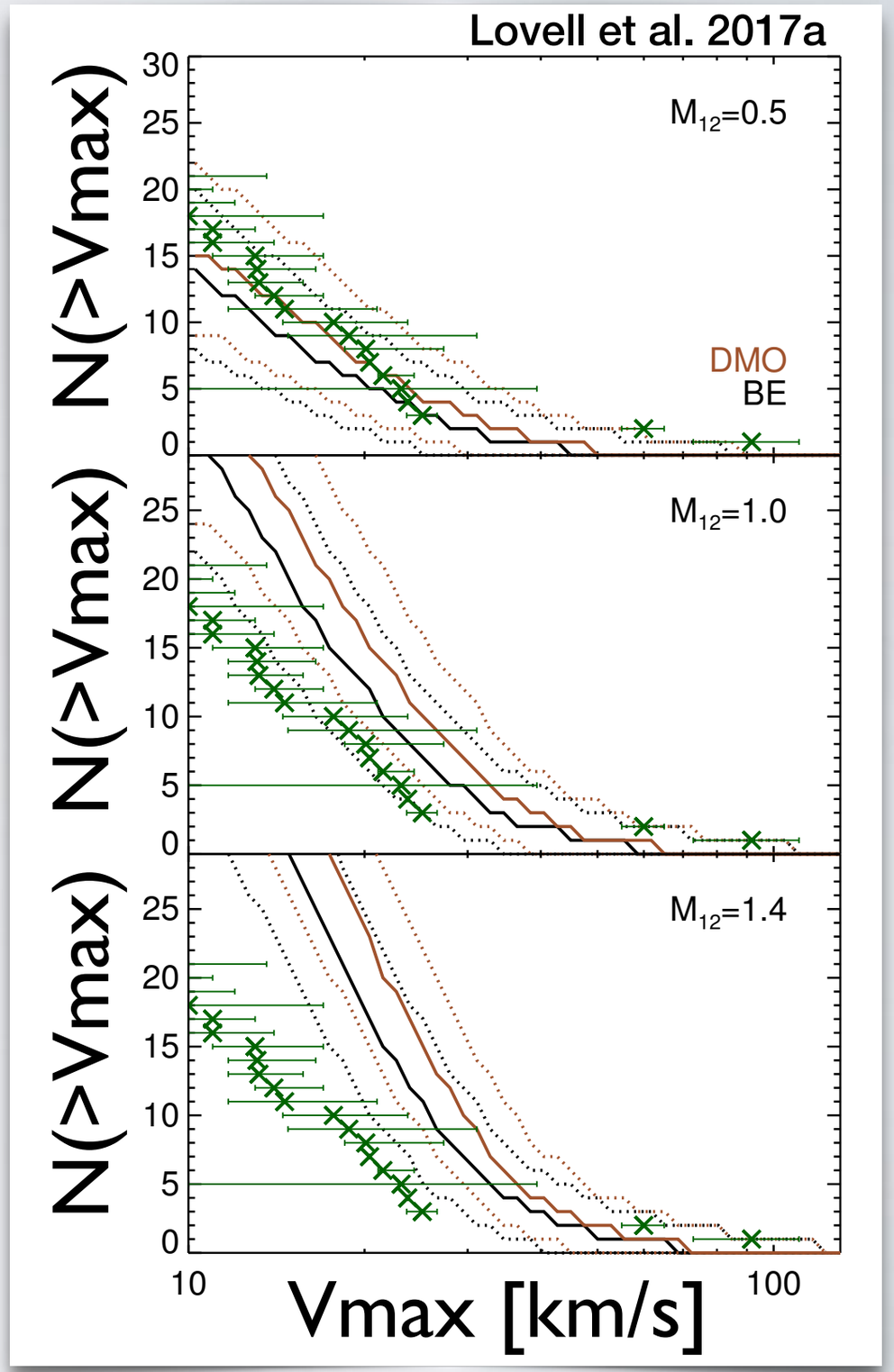


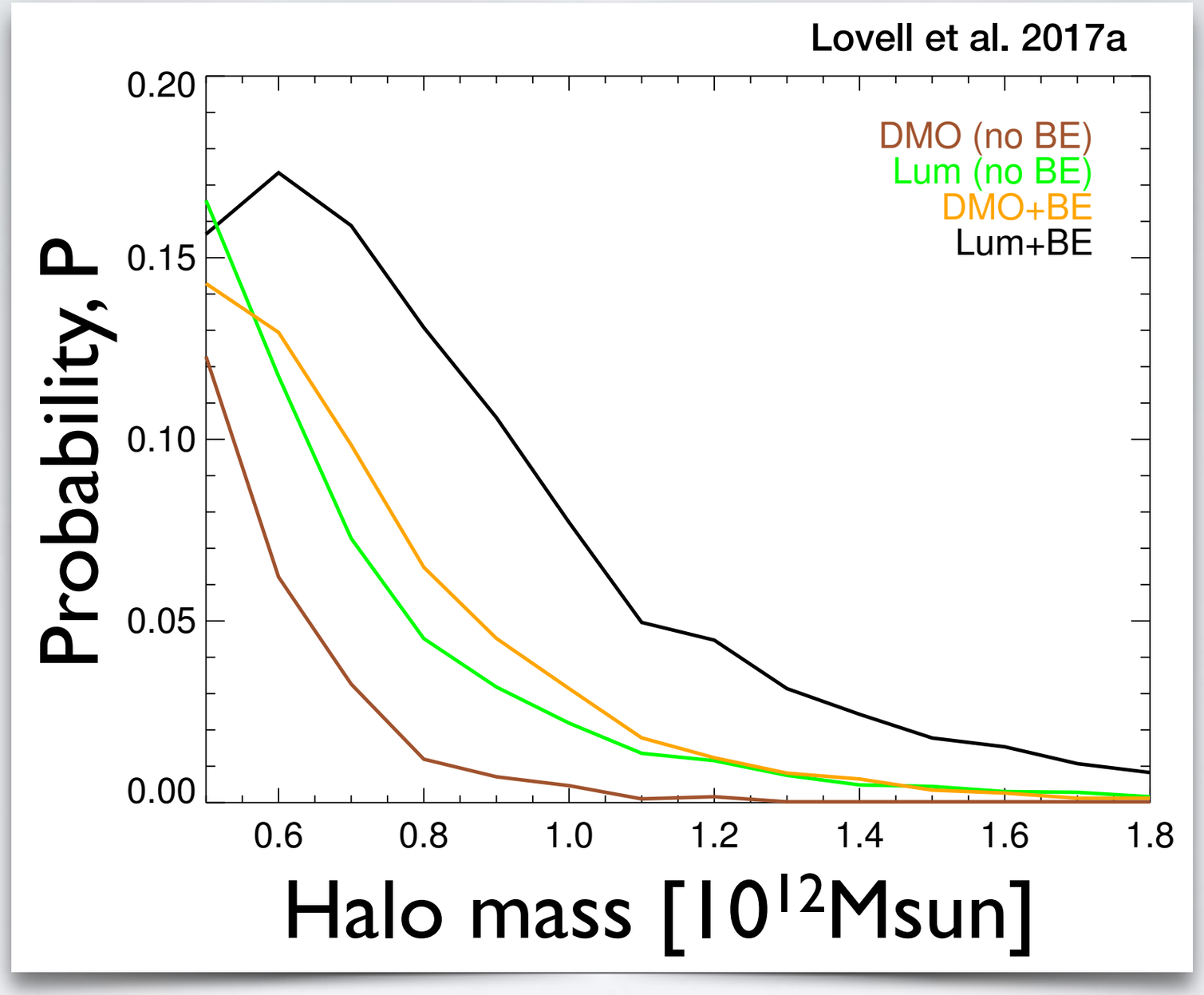
TBTF & SEMI-ANALYTICS

- Calculate probability of drawing the MW satellite Vmax function from theoretically obtained functions using method of Jiang & van den Bosch 2015

- Compare ranked lists of nine highest Vmax satellites, then nine most luminous satellites



TBTF & SEMI-ANALYTICS



BUT WHAT ABOUT WDM?

TBTF & SEMI-ANALYTICS + WDM

- WDM of interest because:
  - Sterile neutrino well-motivated on particle physics grounds
    - Claimed decay detection at 3.5keV
    - Reduces abundance of satellites
    - Reduces density while maintaining Vmax — satellites live in more massive haloes (WDM modified Vmax)
- Repeat analysis for three 3.5keV-fitting sterile neutrinos