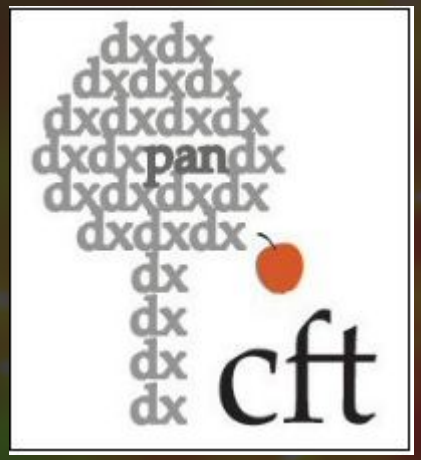
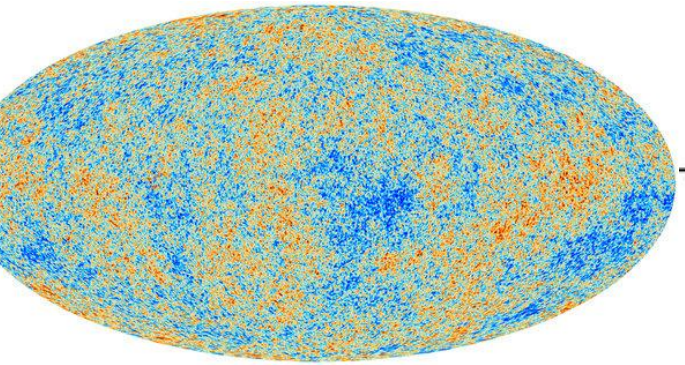
How to falsify CDM model?
(and also test some alternatives)

Wojciech Hellwing
Center for Theoretical Physics PAS, Warsaw



23 October, orbit no #2022, Katowice
Standard Model and Beyond

Planck: CMB temperature anisotropies



Planck coll. 2015

The data confirm the theoretical predictions

The six parameters of minimal ΛCDM model

6 model parameters

CDM+Σm_ν+$N_{\rm eff}$		wCDM+Σm_ν		ΛC
t	68% limits	best fit	68% limits	best fit
	2.274 ± 0.027	2.205	2.204 ± 0.026	2.224
2	0.1227 ± 0.0044	0.1181	0.1176 ± 0.0016	0.1172
5	1.04092 ± 0.00070	1.04139	1.04125 ± 0.00057	1.04190
	0.097 ± 0.015	0.086	0.090 ± 0.013	0.089
5	0.9929 ± 0.0098	0.9595	0.9621 ± 0.0059	0.9654
	3.109 ± 0.031	3.075	3.081 ± 0.025	3.083
	0.46 ± 0.12	0.56	0.55 ± 0.10	0.41
	3.704 ± 0.29	–	–	–
	–	1.39	-1.39 ± 0.12	–
	–	–	–	0.00695
9	0.2690 ± 0.012	0.2693	0.2661 ± 0.0139	0.3027
	70.8 ± 1.5	73.68	74.0 ± 2.1	68.93
1	0.7477 ± 0.0151	0.7902	0.7937 ± 0.0208	0.7434
	4911.951		4908.152	

A 40σ detection of non-baryonic dark matter using only z=1000 data!

Planck collaboration '13

Non-baryonic (particle) dark matter candidates

Type	Example	Mass
hot	neutrino	a few eV
warm	sterile ν majoron	keV-MeV
cold	axion neutralino	$\sim 10^{-25}$eV? ~100GeV?

Incompatible with LSS and CMB!

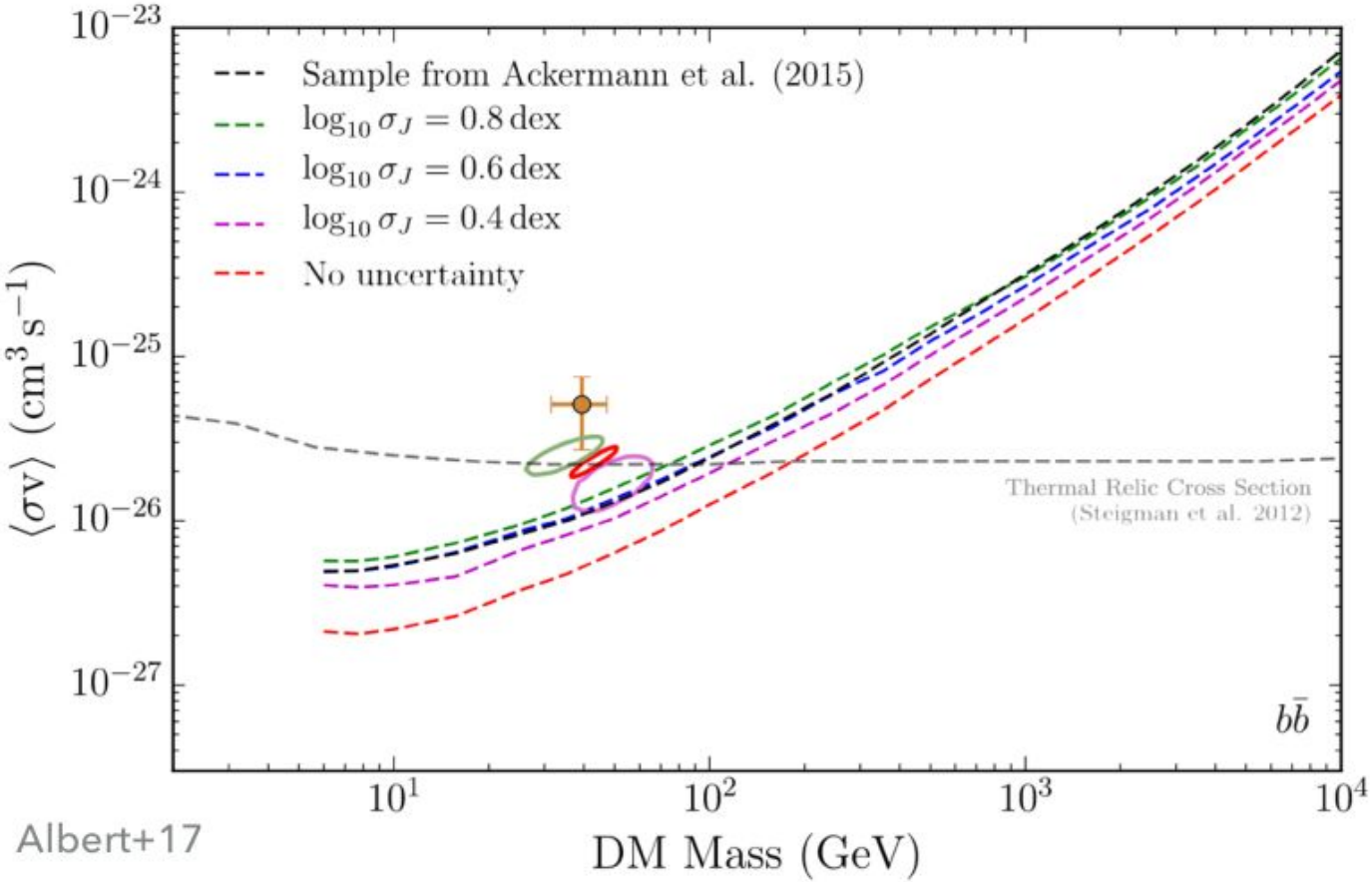
Non-baryonic (particle) dark matter candidates

Both CDM & WDM are compatible with CMB & LSS

Claims that both types of DM have been discovered:

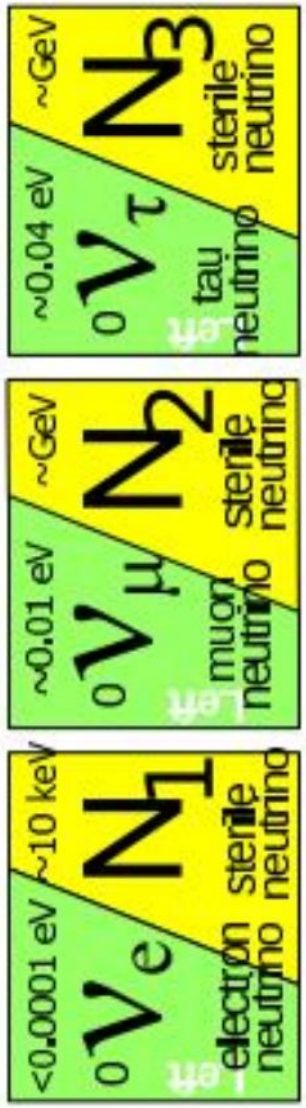
- CDM: γ-ray excess from Galactic Centre

- WDM (sterile ν): 3.5 keV X-ray line in galaxies and clusters



No detection of WIMPs

The WDM: sterile neutrino model fact sheet



Asaka+05/Laine+08/BRS+09

Competitive new dark matter models,(sterile neutrinos, self interacting models)

- **Warm** dark matter model
- Part of vMSM extension to standard model, facilitates neutrino oscillations, baryogenesis
- Two parameters, **mass** (M_s) & **lepton asymmetry** (L_6) ==> **matter power spectrum** & lifetime τ
- **7keV** sterile neutrino decay into X-ray + neutrino; an explanation for the 3.5keV line in clusters, M31, GC
- M_s=7keV: **L_6=[8-11]** (3.5keV line compatible)
- M_s=7keV: L_6=[120] (warmest model available for 7keV)

Sterile neutrino: potential channels for detection

THE WAY FORWARD

Detect sterile neutrino and detect m_ν

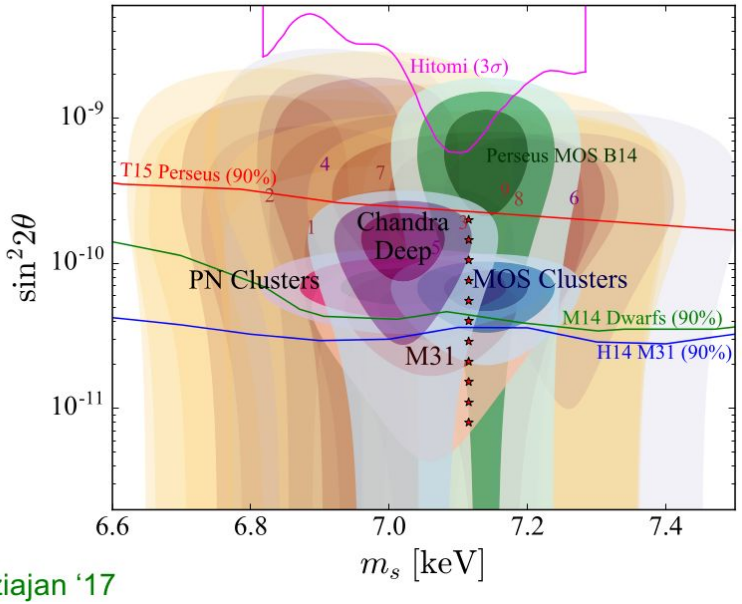
1. **Direct detection**
   If sterile neutrino mix with active neutrinos:
   Tritium β-decay - KATRIN

2. **Indirect detection**
   Decay of keV particles produces an X-ray line!

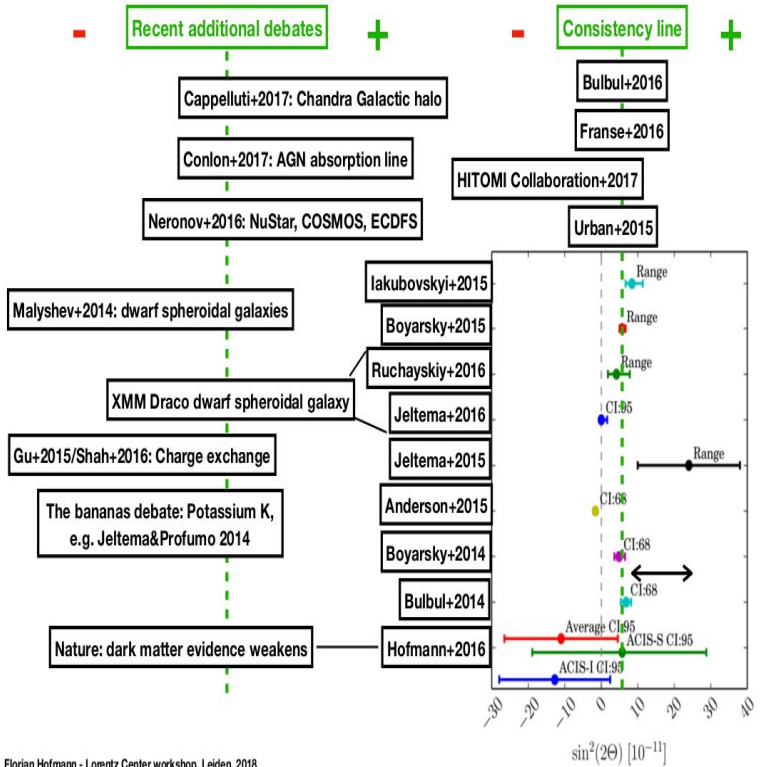
Future X-ray missions:

XRISM (XARM) - 2023 (replacement of Hitomi with soft X-ray spectrometer 0.3-12 keV)

Athena - ~~2028~~ 2031 (0.5-12 keV High-res or large-area)



Abaziajan '17



Sterile neutrino: potential channels for detection

THE WAY FORWARD

Detect sterile neutrino and detect m_ν

1. **Direct detection**
   If sterile neutrino mix with active neutrinos:
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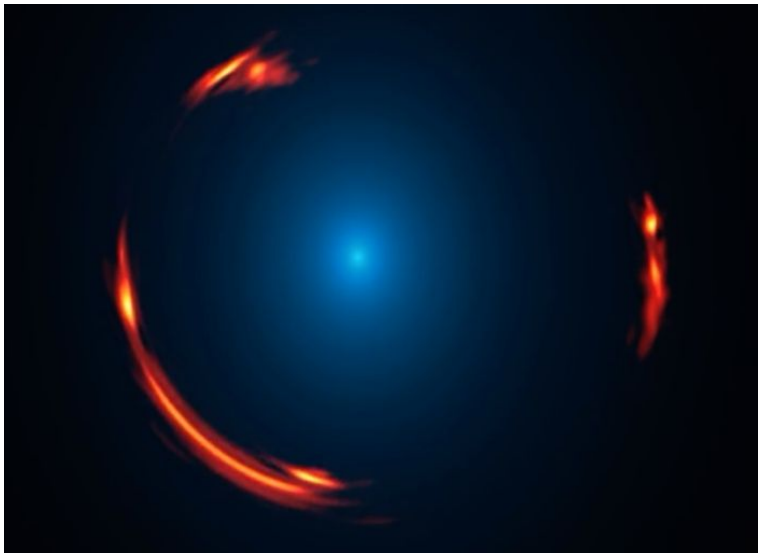
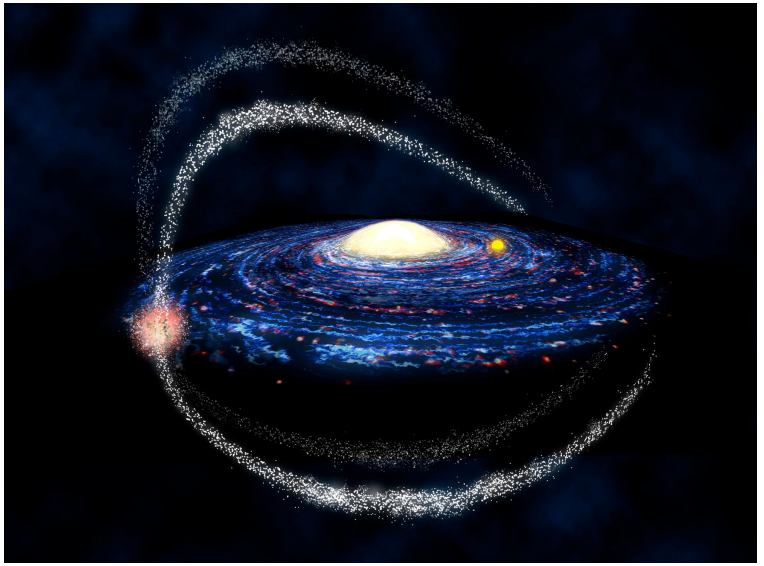
2. **Indirect detection**
   Decay of keV particles produces an X-ray line!

3. **Indirect subtle detection**
   Find strong WDM effect in galaxy formation and evolution





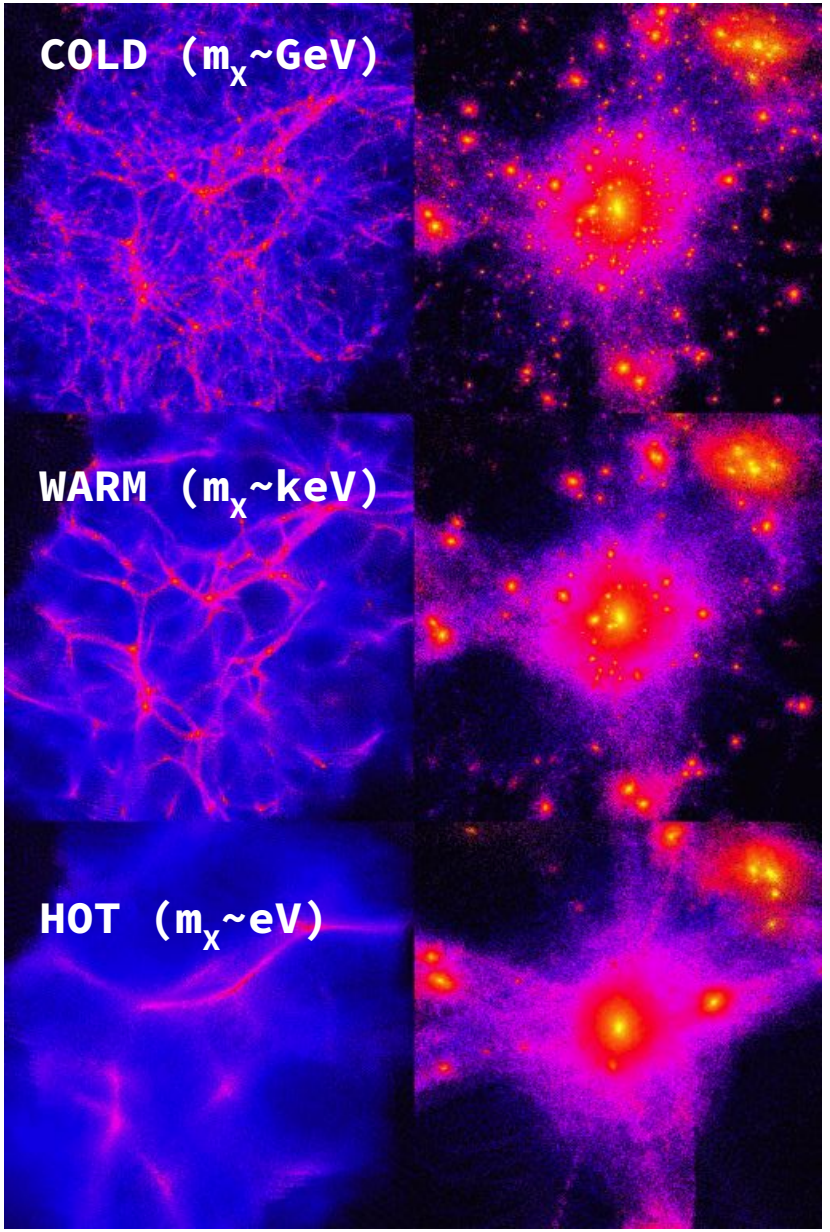
Dark Matter: Cold, Hot or Else?

The "free-streaming" effect, perturbations that enter horizon are affected by the DM velocities. If at that time DM is relativistic, perturbations of that size gets "smeared-out".

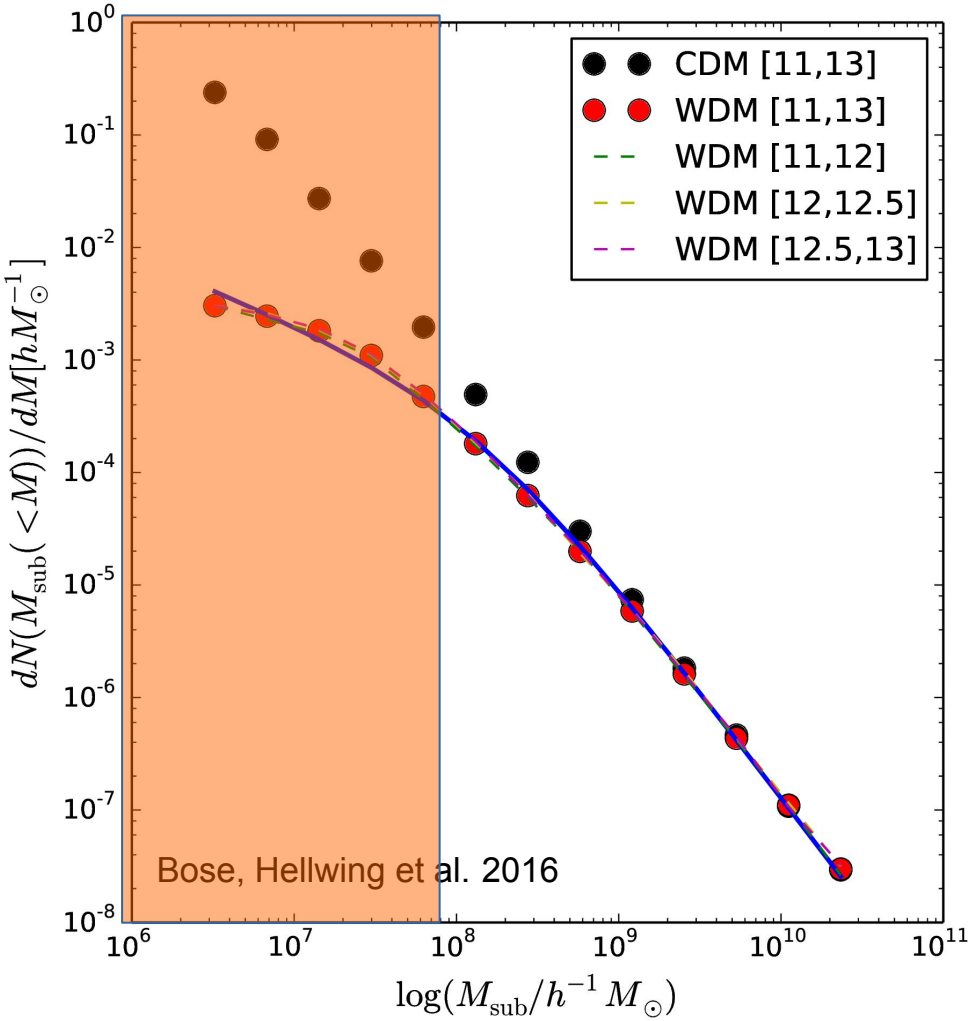
For galaxy size perturbations λ_{Galaxy}~1Mpc, T_U~1keV (10^7 K) today we have:

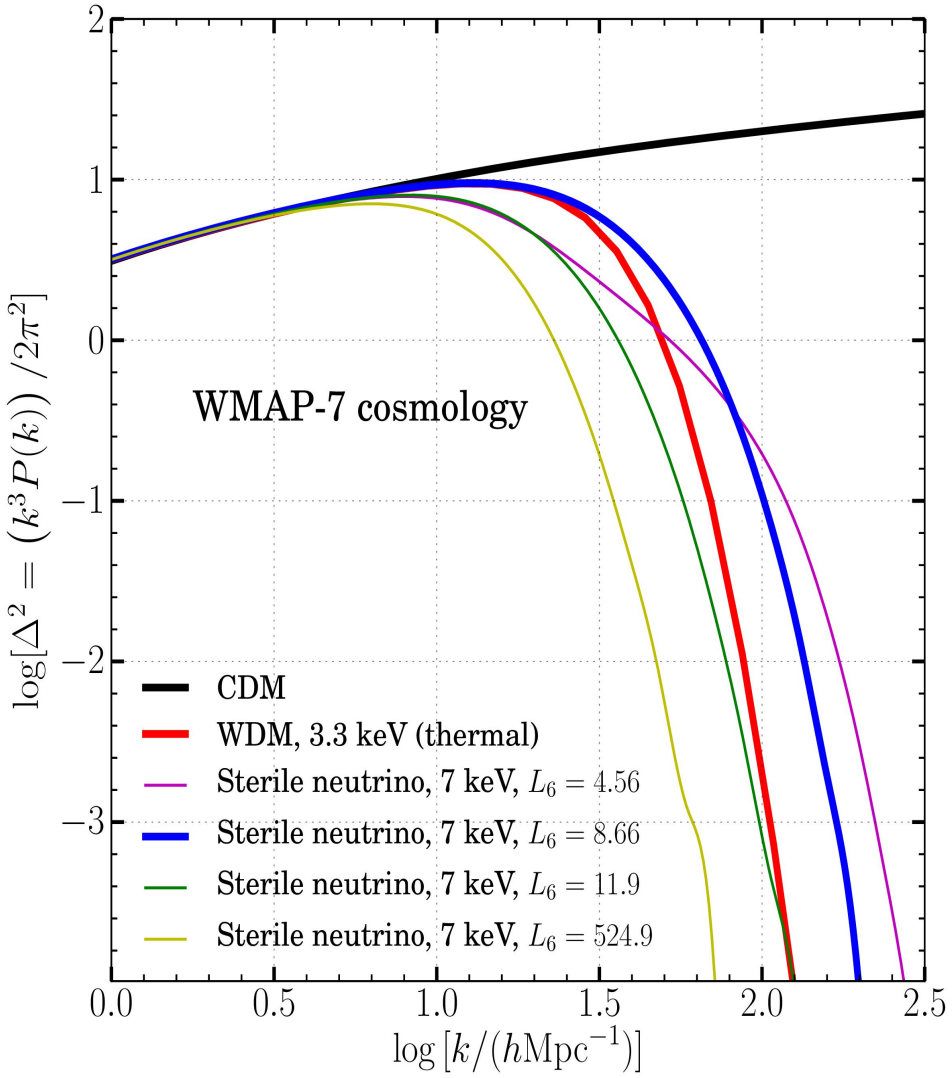
- Hot Dark Matter is relativistic at T_U~1keV
- Warm Dark Matter is semi-relativistic at T_U~1keV
- Cold Dark Matter is non-relativistic at T_U~1keV

thus, M_{dump}=~$10^{15}M_\odot$:~$10^{9}M_\odot$:~$10^{-6}M_\odot$:



Warm & Cold Copernicus Complexio





Satellite (subhalo) mass function

APOSTLE
full hydro
simulations

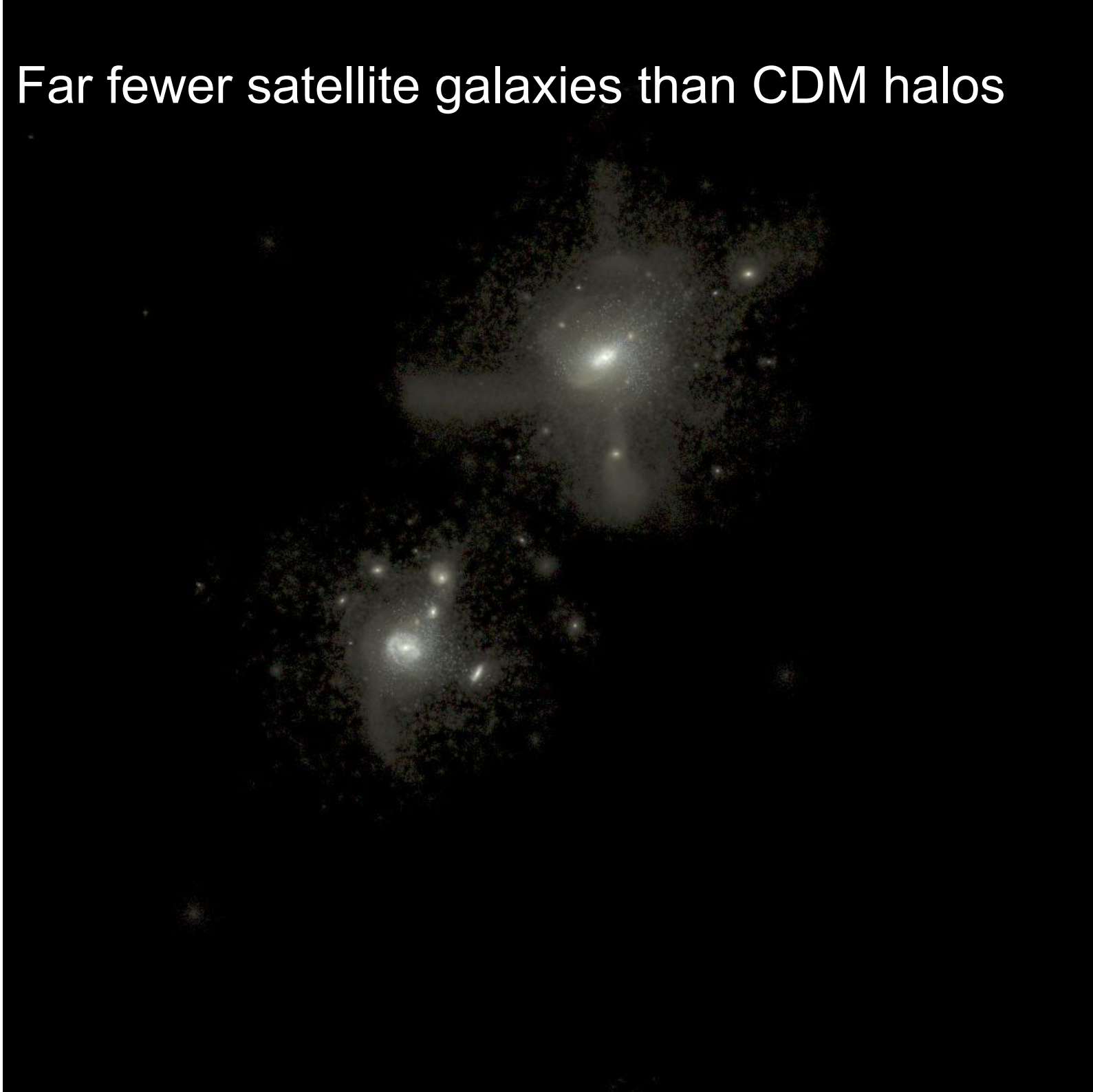
Sawala et al ‘15

Local Group

VIRGO

Far fewer satellite galaxies than CDM halos

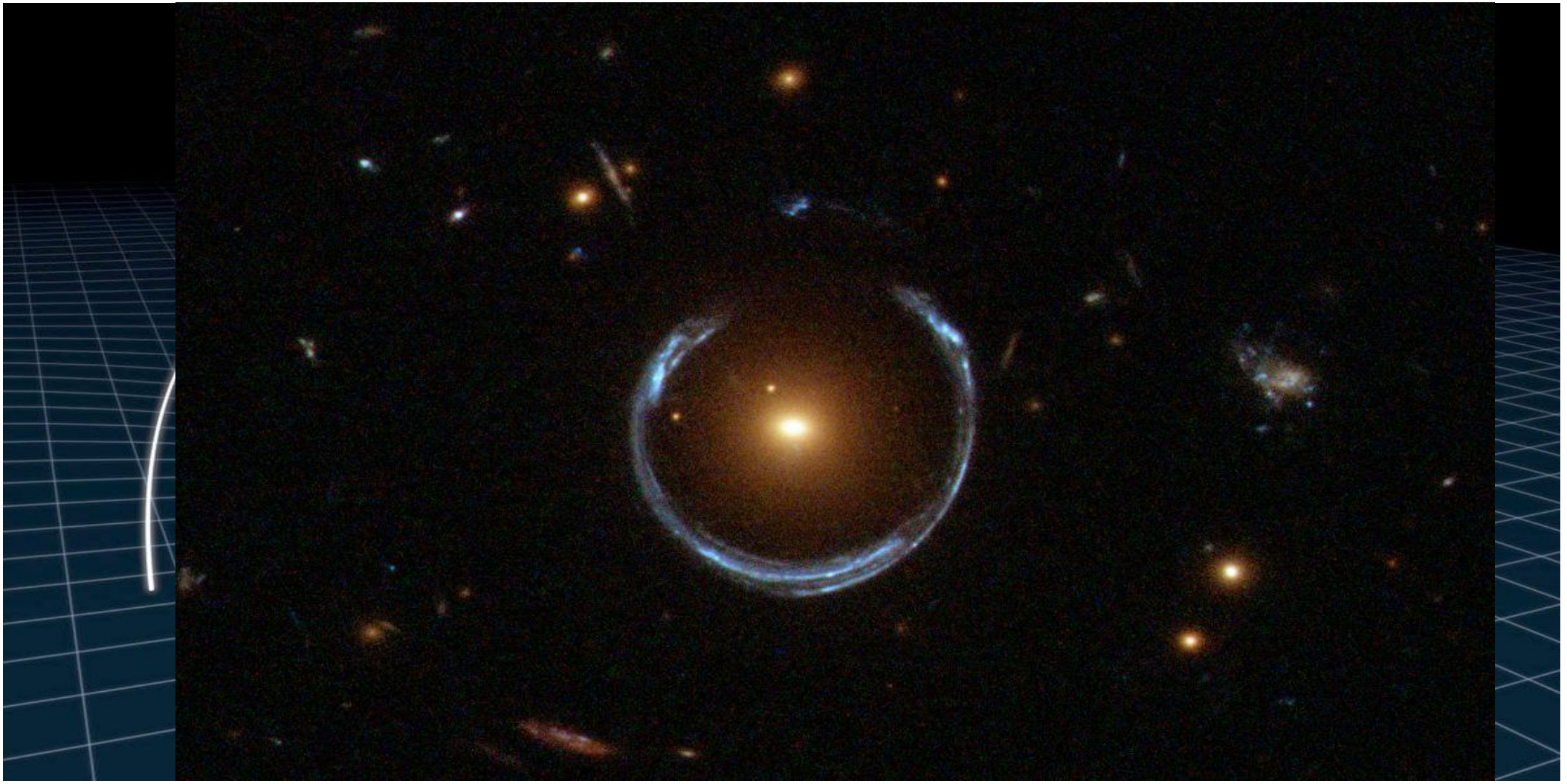
APOSTLE
full hydro
simulations



Sawala et al ‘15

Local Group

Warm & Cold Copernicus Complexio



Strong lensing observations can detect dark haloes!

Warm & Cold Copernicus Complexio

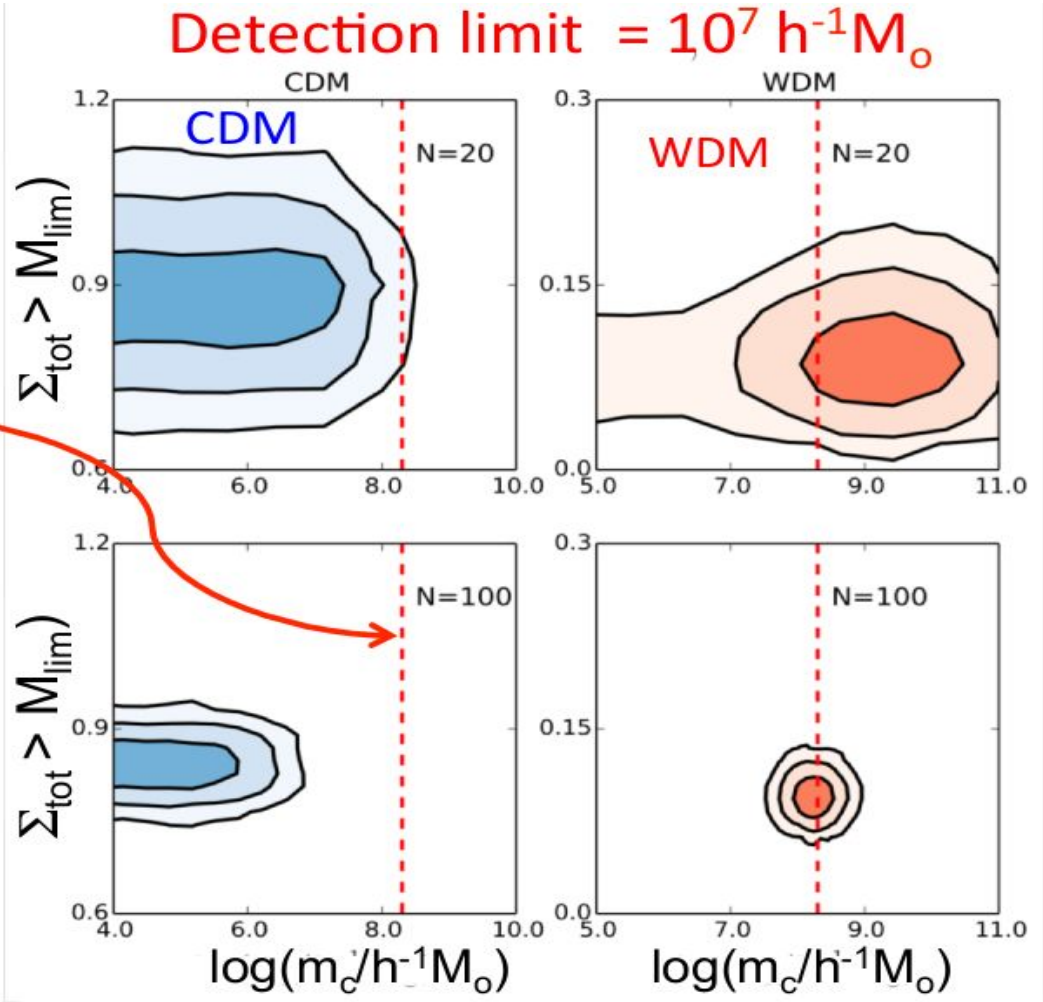
Σ_{tot}= projected halo number density within Einstein ring

m_c= halo cutoff mass

m_c= 1.3 ×10^8 $h^{-1}M_o$ for coldest 7 keV sterile neutrino

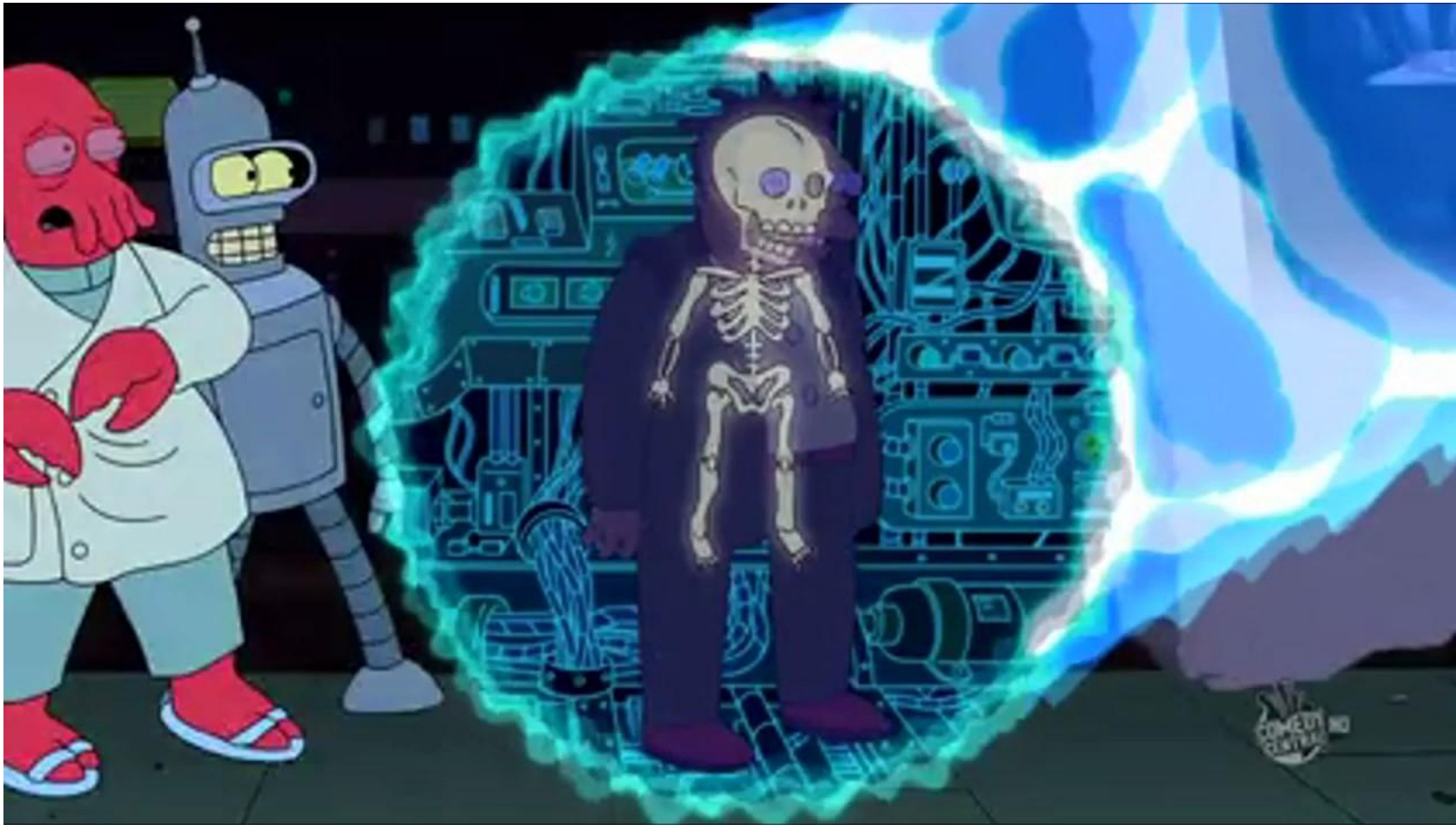
100 Einstein ring systems and detection limit: $m_{low} = 10^7\ h^{-1}M_o$

- If DM is CDM → rule out 7 keV sterile ν at many σ
- If DM is 7 keV sterile ν → rule out CDM at 3σ!



Strong lensing observations can detect dark haloes! Li, Frenk, Cole, Gao, Bose, **WH** 2016

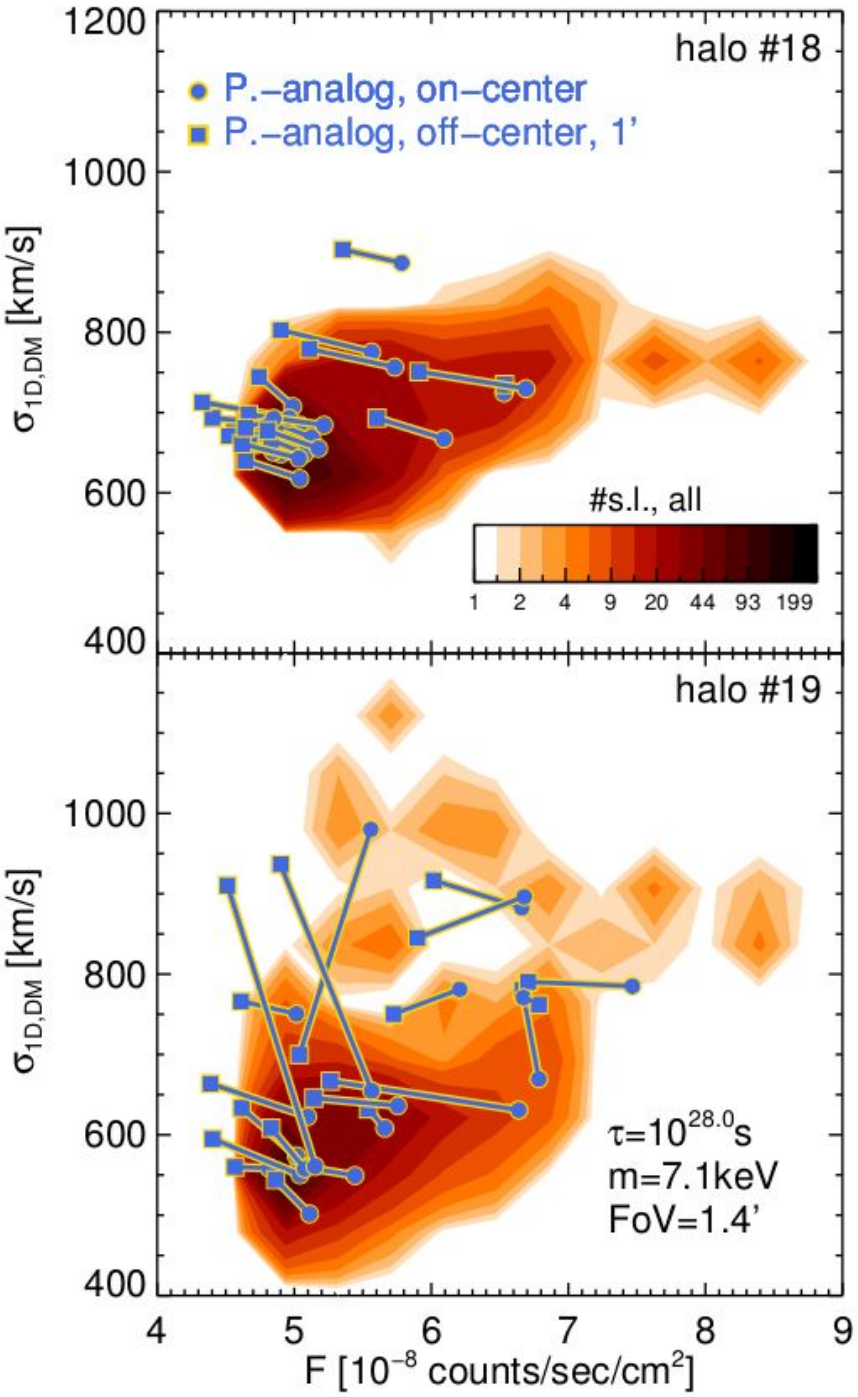
The window for indirect detection

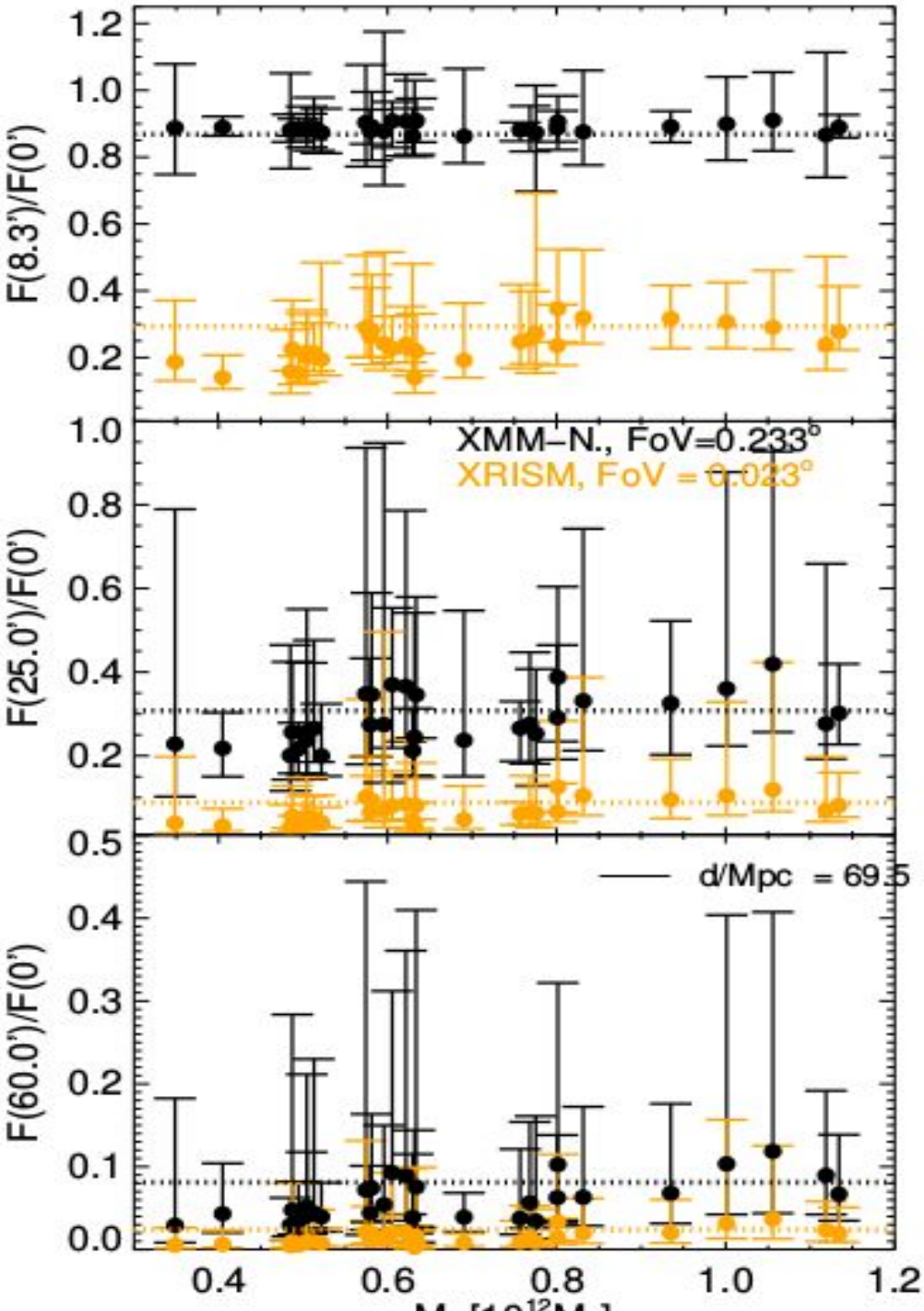


X-rays!

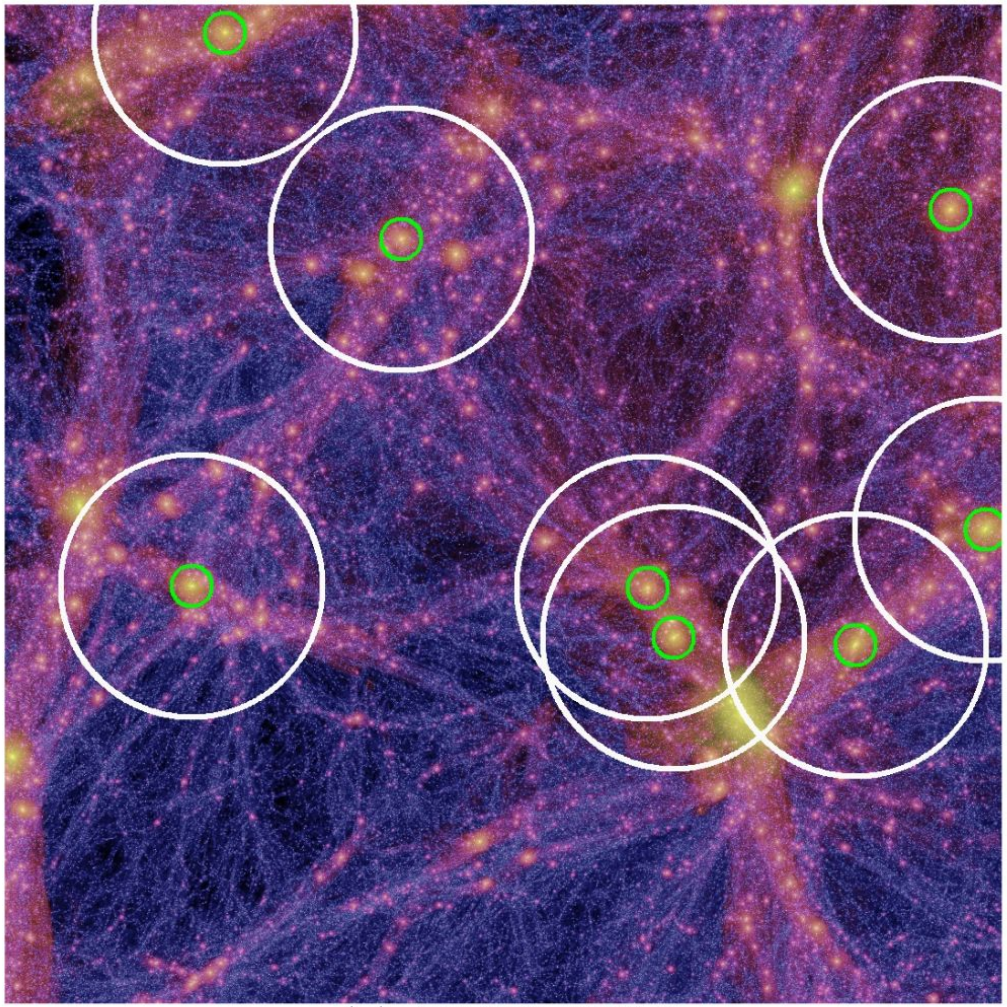
Lovell,...,WH et al., ApJ'19

Perseus cluster offset flux ratio

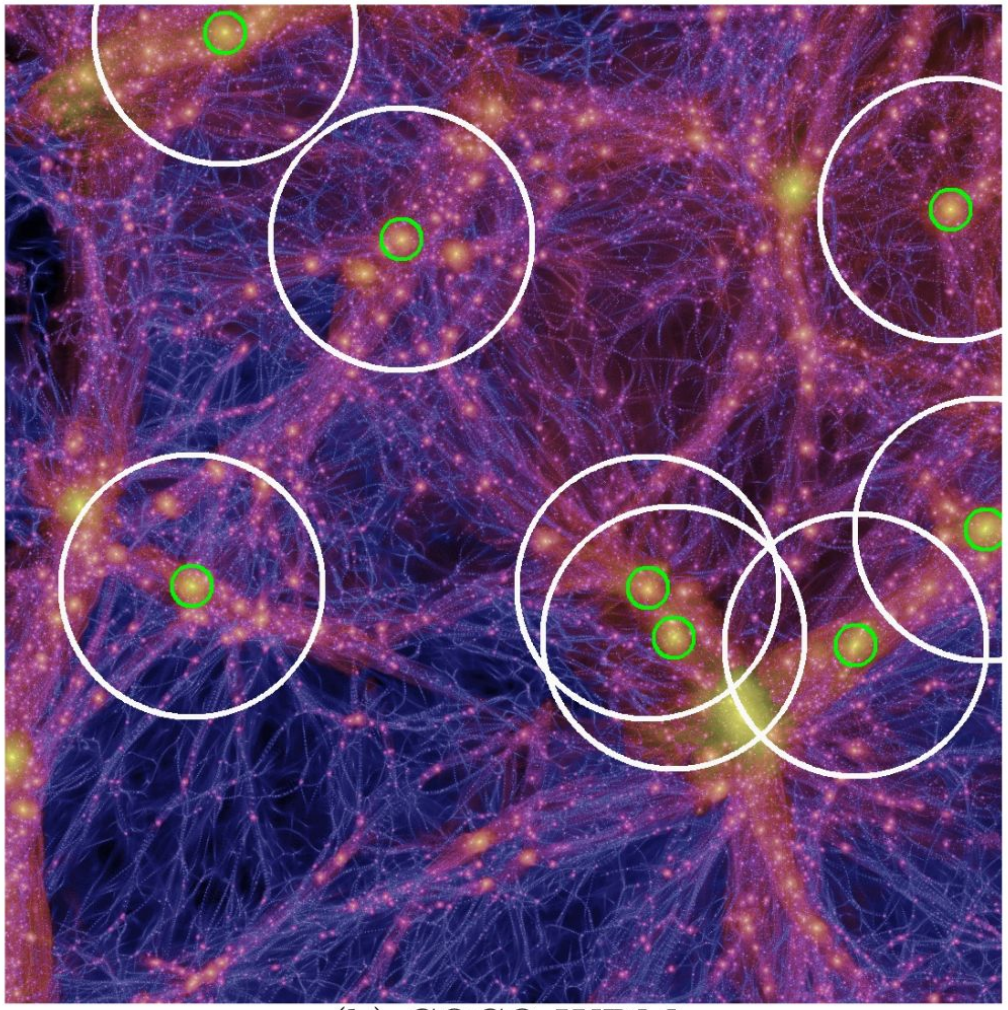




Local Universe: subtle topological effects on dwarfs

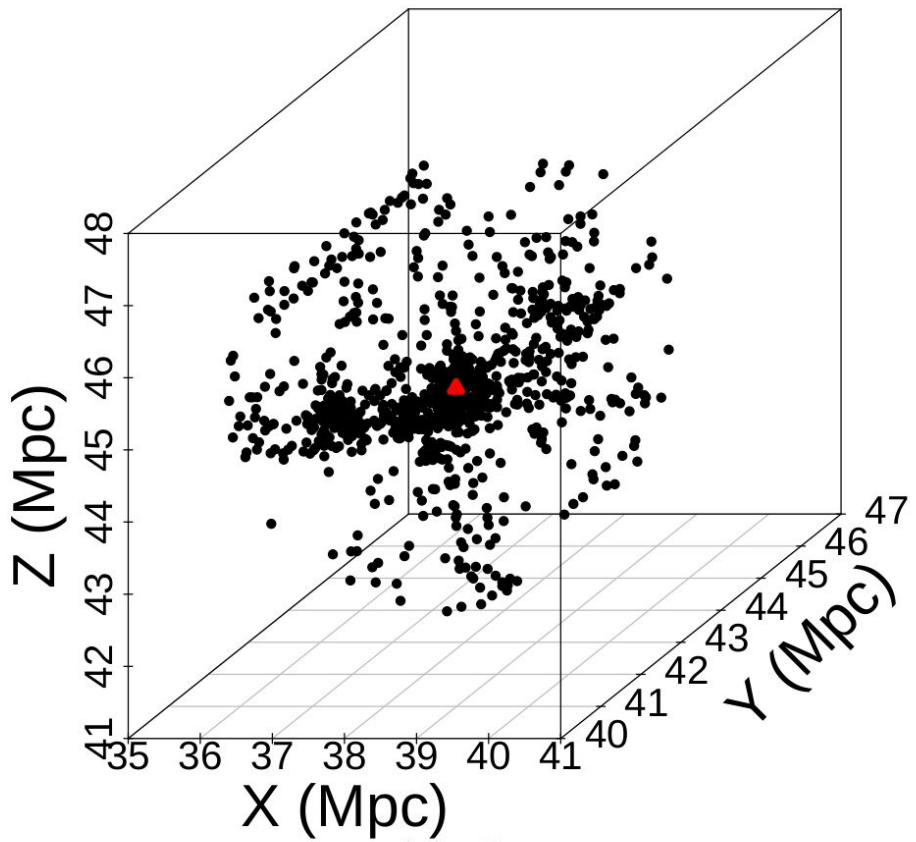


(a) COCO-CDM

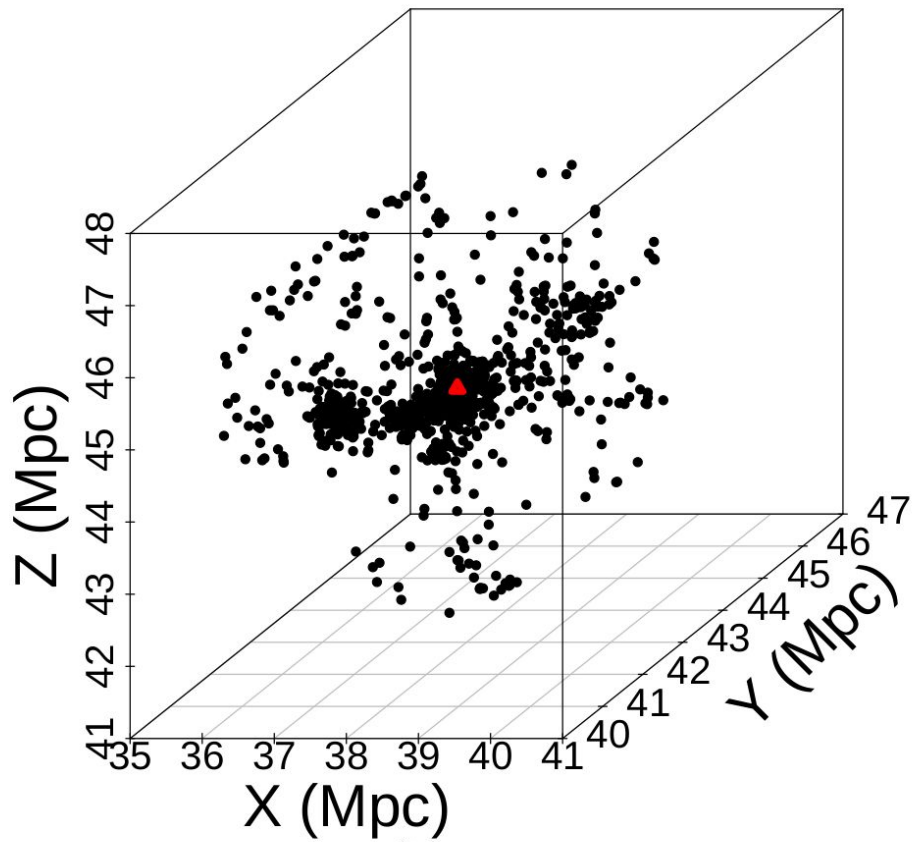


(b) COCO-WDM

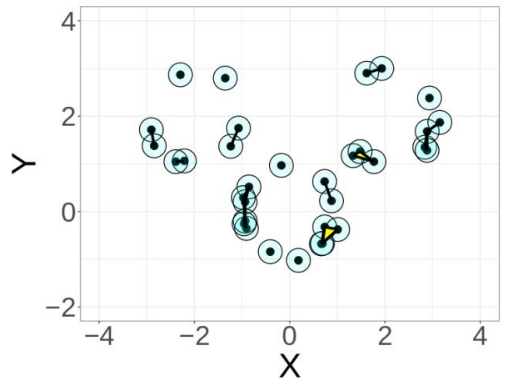
Local Universe: subtle topological effects on dwarfs



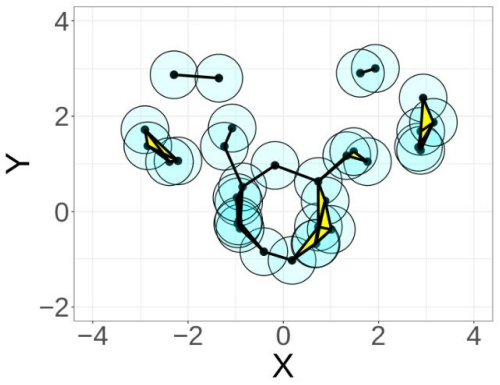
(a) CDM



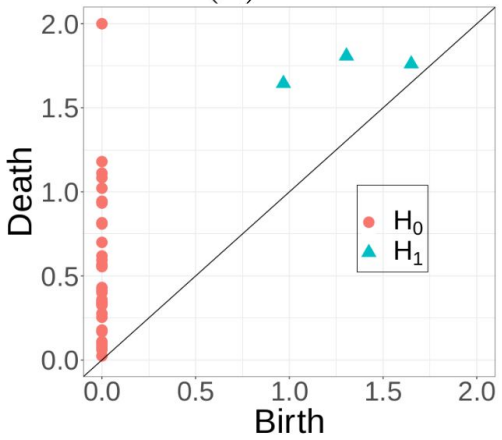
(b) WDM



(a) Data with $t = 0.5$ balls

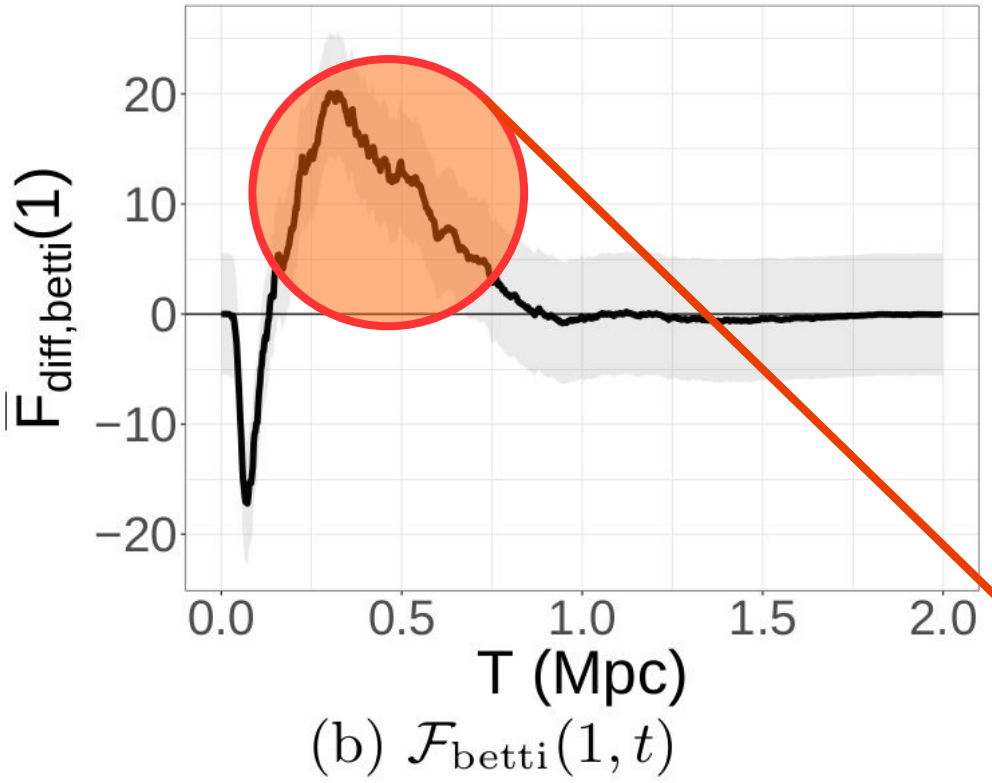


(b) Data with $t = 1$ balls

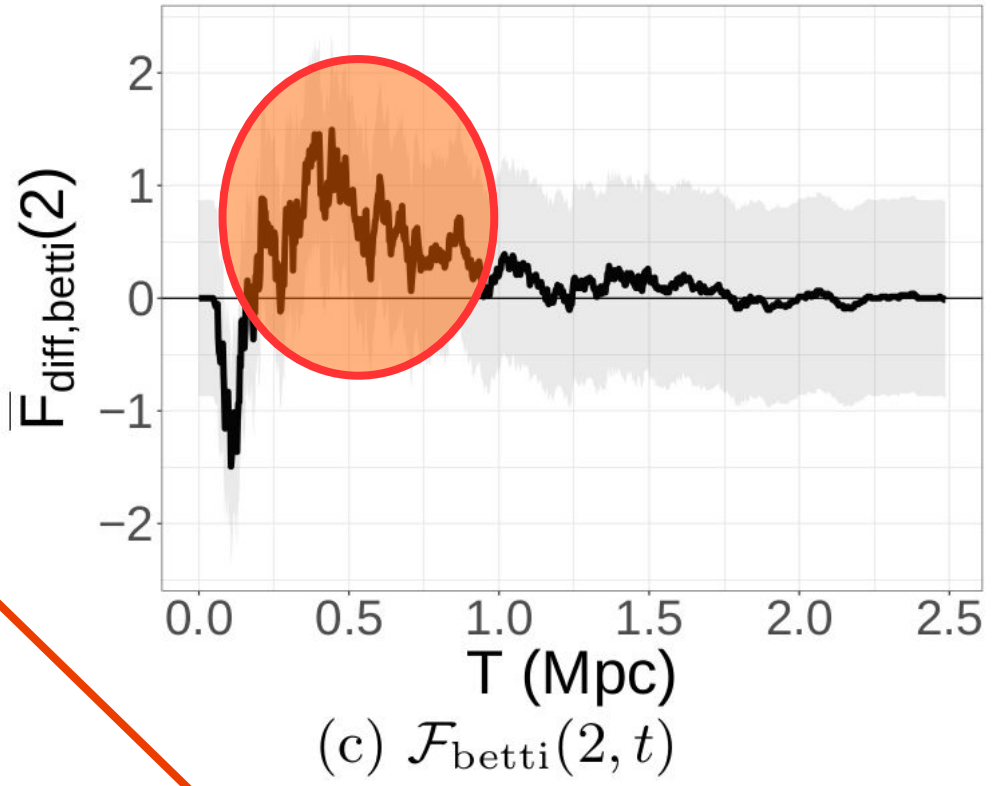


(c) Persistence diagram

Local Universe: subtle topological effects on dwarfs



(b) $\mathcal{F}_{\mathrm{betti}}(1,t)$



(c) $\mathcal{F}_{\mathrm{betti}}(2,t)$

3σ detection

Cisewski-Kehe, Fasy, WH, et al. 2022

TAKE HOME MESSAGES

The indirect (astro/cosmo) window for detection appears to be very promising in **this** decade

- X-ray emission lines from its decay can be observed by future space missions

- 3.5 keV line is Gaussian and Perseus cluster on/off center measurement can provide ~>3σ detection

- Counting luminous satellites/dwarf galaxies is a **non-conclusive** test!

- dark substructure -> Minimum halo mas -> possible falsification of either WDM or CDM at ~>3.5 σ level

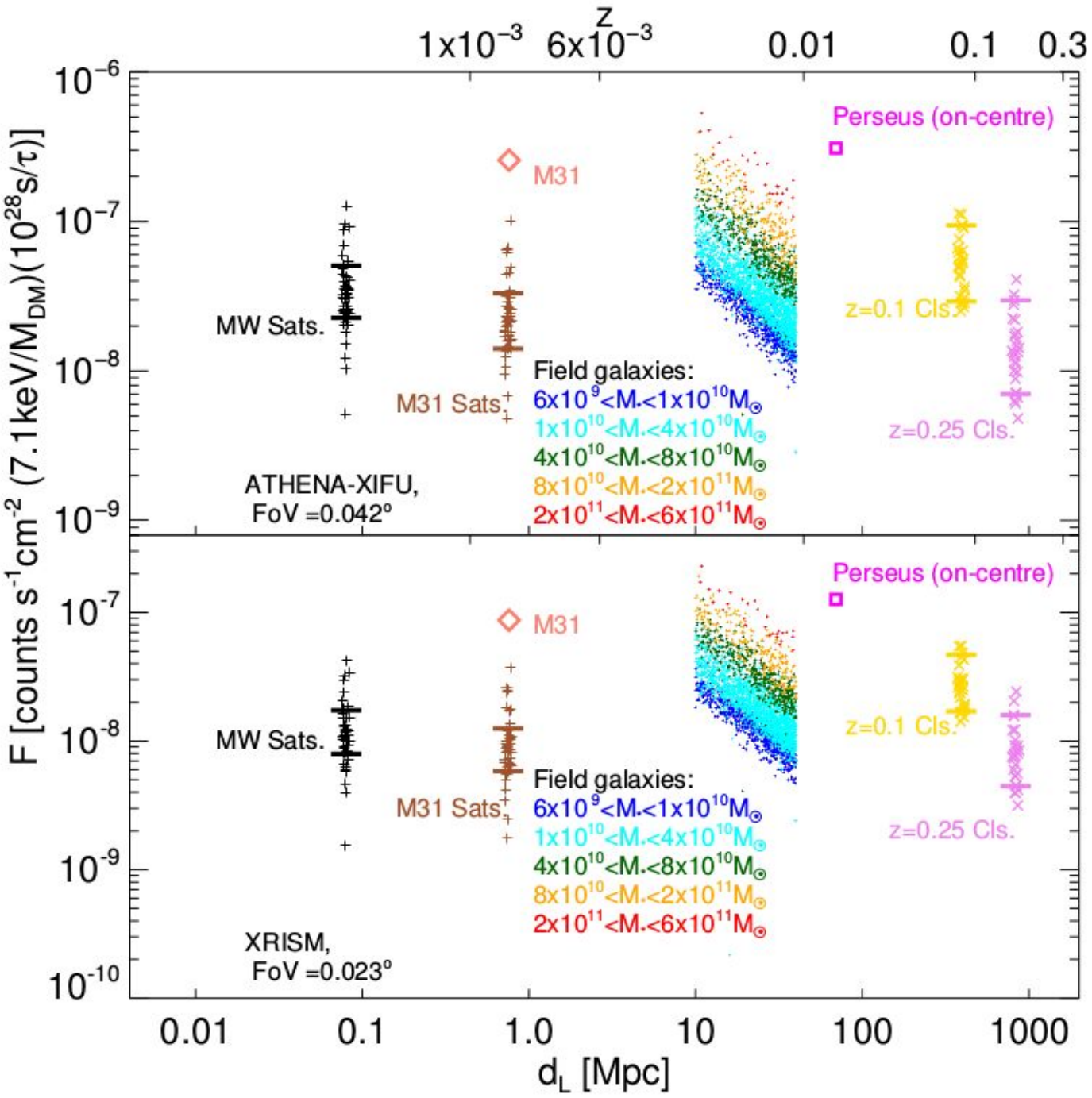
- Topological measures of **complete** Local Universe galaxy sample may yield another ~>3σ detection

CDM and WDM X-ray decay fluxes

Local Universe decay fluxes:

ATHENA-WFI (top)

and XRISM (bottom)



Lovell,...,WH et al., MNRAS'18

CDM and WDM X-ray decay fluxes

If there are N dark matter simulation particles in the FoV, the flux, F, is:

$$F = 1.18 \times 10^{20} \sum_{i=0}^{N} \frac{m_{\mathrm{DM},i}}{M_{\mathrm{DM}} \tau} \frac{1}{4\pi d_i^2} \text{ counts s}^{-1}\text{cm}^{-2} \qquad (1)$$

where d_i is the distance between the i-th particle and the observer in kpc, M_{DM} is the mass of the dark matter candidate particle in keV, τ is the particle lifetime in seconds and $m_{\mathrm{DM},i}$ is the mass of the i-th simulation dark matter particle in $\mathrm{M}_\odot$;

3 instruments specifications:
XMM-Newton: 28' x 28' FoV
XRISM: 3' FoV
ATHENA: *Wield Field Imager* (WFI) 40'x40'
and *X-ray Integral Field Unit* (X-IFU) 5.3'