The Wide Area VISTA Extragalactic Survey (WAVES)

(aka S7 aka Galaxy Evolution Survey)

Joe Liske (co-PI)
Simon Driver (co-PI)

Ivan Baldry, Sabine Bellstedt, Luke Davies, Ken Duncan, Daniel Gruen, Angela Iovino, Marcella Longhetti, Jon Loveday, Jamie McCullough, Aaron Robotham, Luca Tortorelli, and the WAVES team

ICRAR

Universität Hamburg
DER FORSCHUNG | DER LEHRE | DER BILDUNG

CLUSTER OF EXCELLENCE
QUANTUM UNIVERSE

4MOST

WAVES: What and Who?

WAVES
wide area vista extragalactic survey

Original WAVES Consortium Survey


Simon Driver
(UWA, Co-PI)


Joe Liske
(UHH, Co-PI)


Sabine Bellstedt
(UWA, PM)

Community Surveys

StePS


Angela Iovino
(OAB, Co-PI)


Marcella Longhetti
(OAB, Co-PI)

ORCHIDSS


Ken Duncan
(Edinburgh, Co-PI)

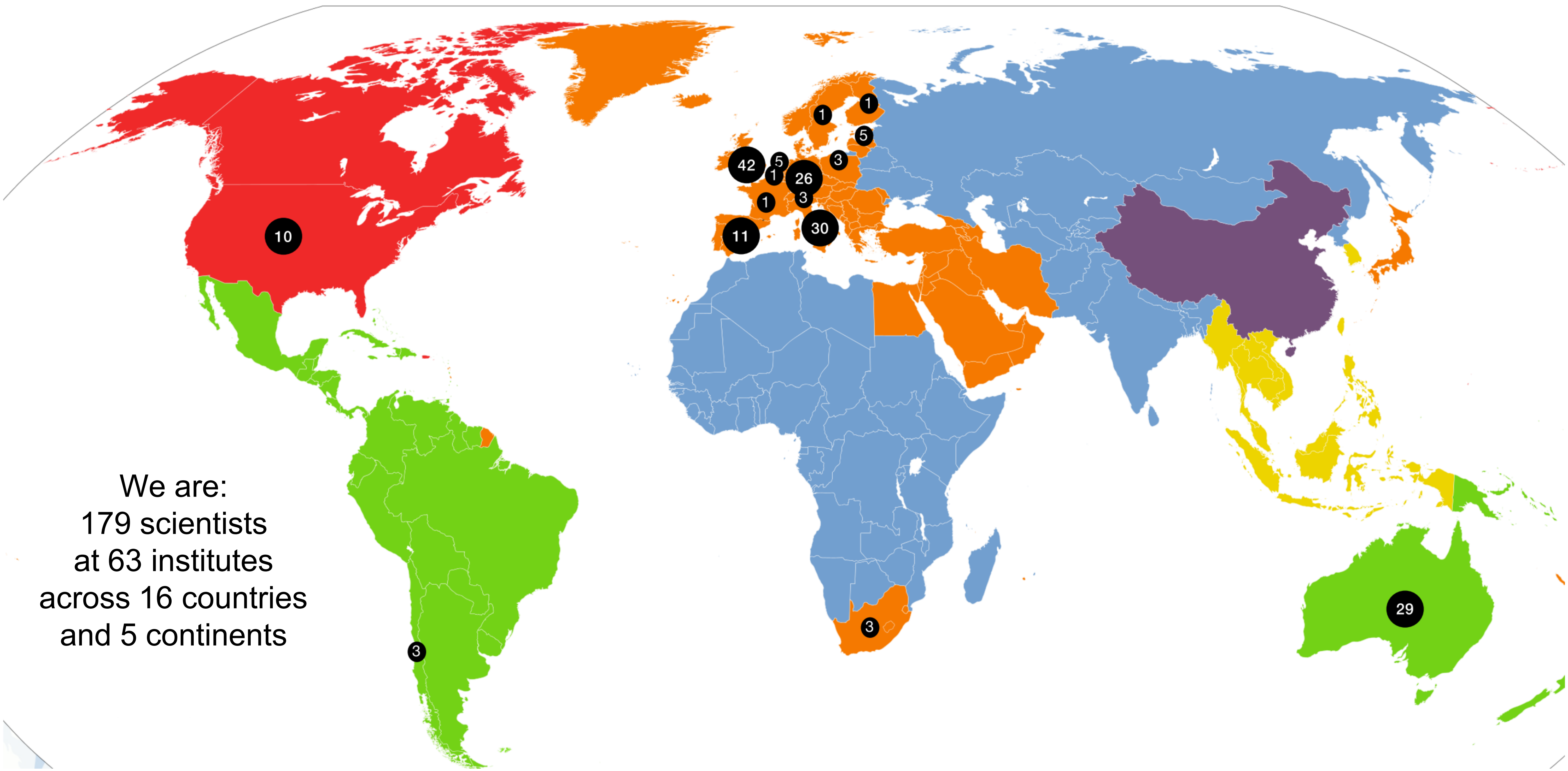
4C3R2


Daniel Gruen
(LMU, Co-PI)


Jamie McCullough
(Princeton, Co-PI)


Luca Tortorelli
(LMU, PS)

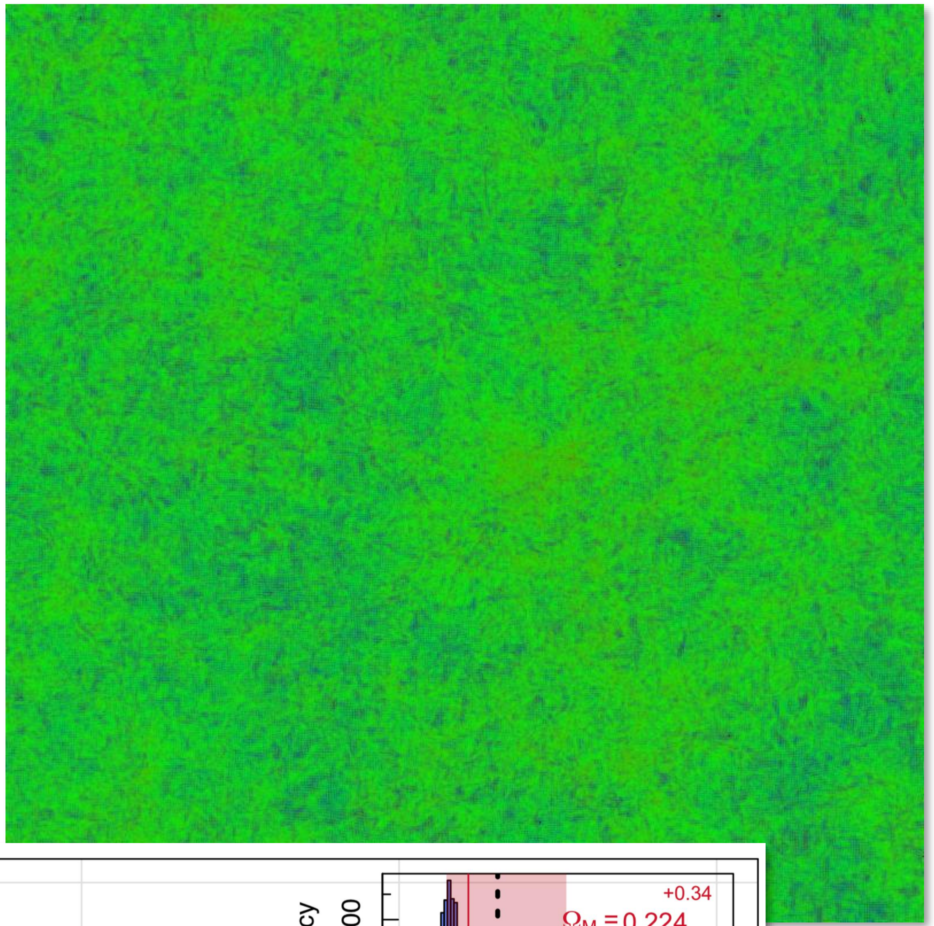
WAVES: Where?

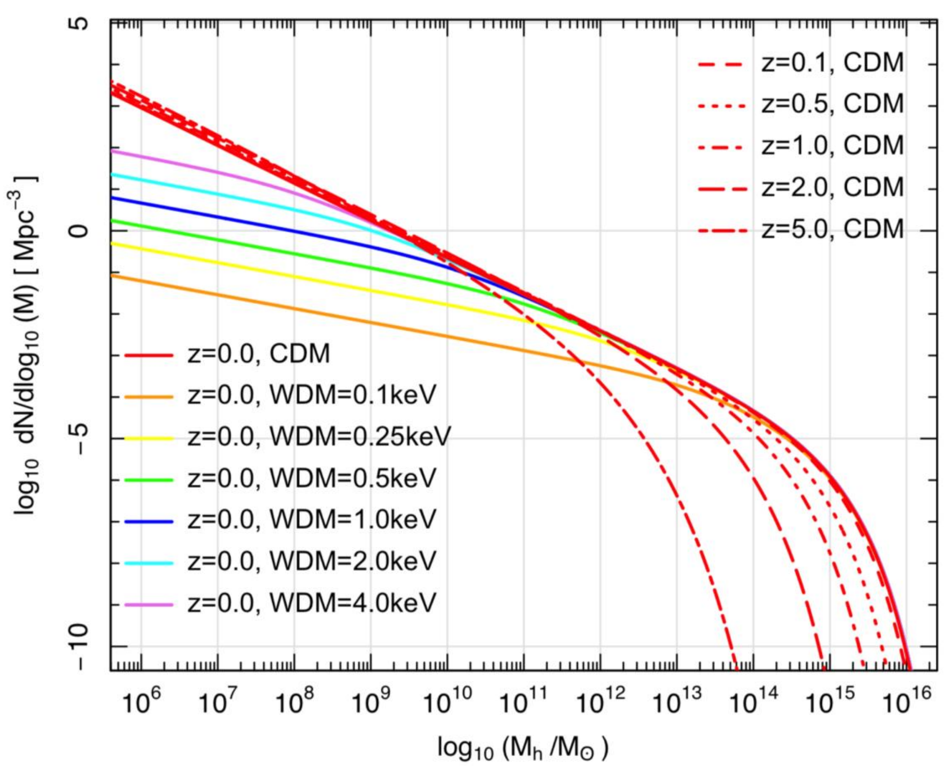


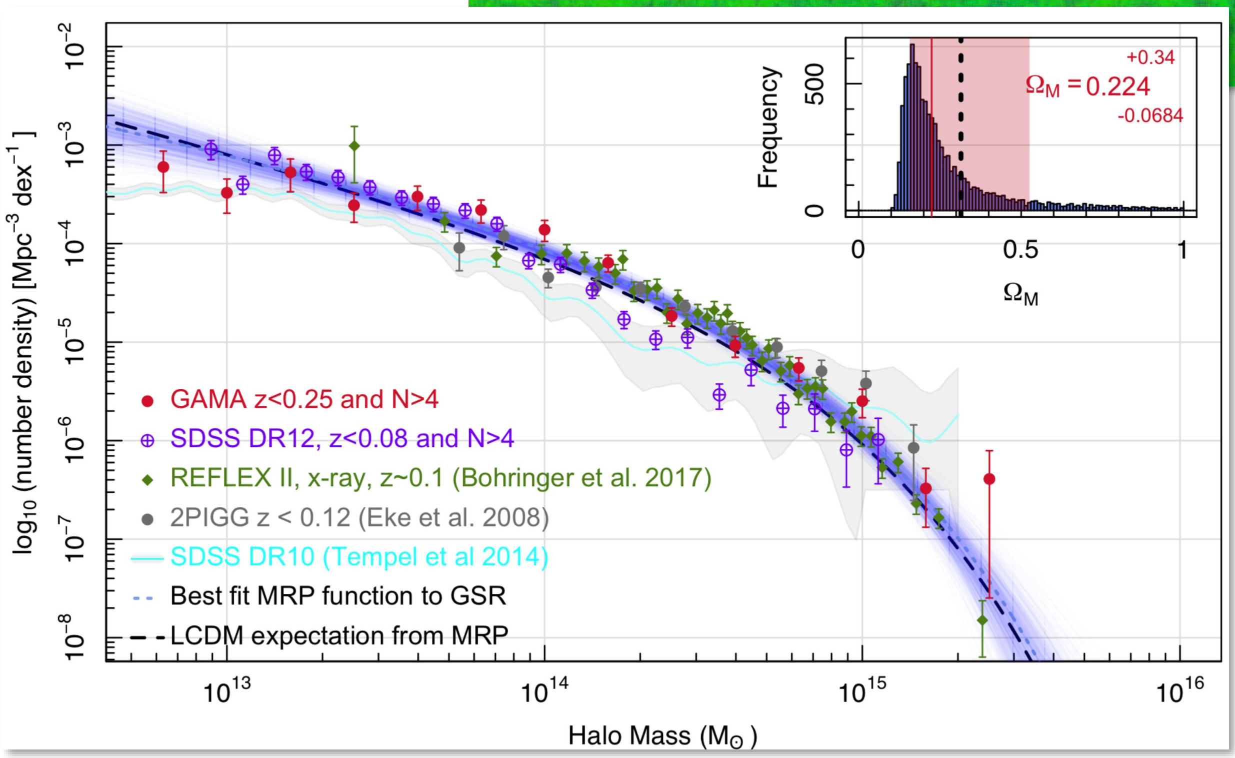
We are:
179 scientists
at 63 institutes
across 16 countries
and 5 continents

WAVES science in a nutshell

- Trace the structure of the Universe
  - Test structure formation: evolution of the high-mass end of the DM halo mass function (HMF)
  - Test the nature of DM: probe the low-mass end of the HMF

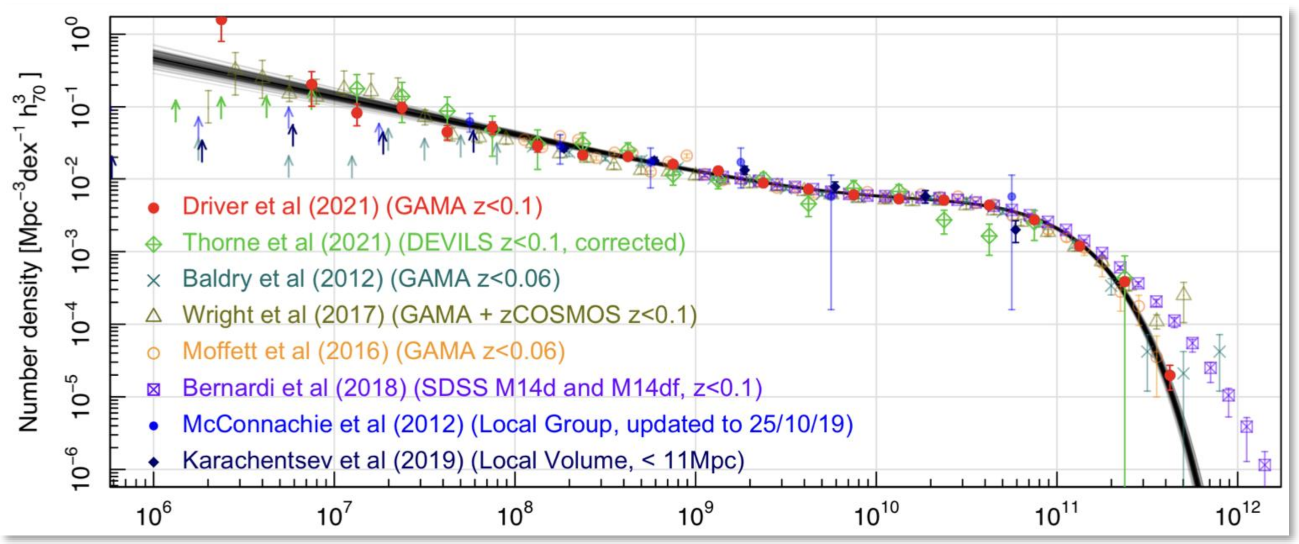


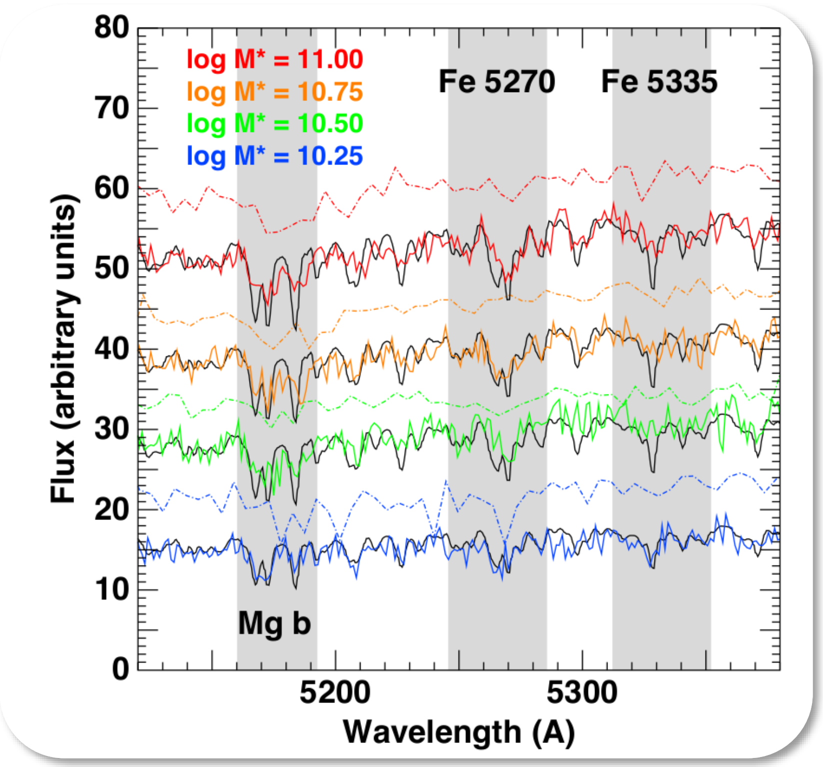




WAVES science in a nutshell

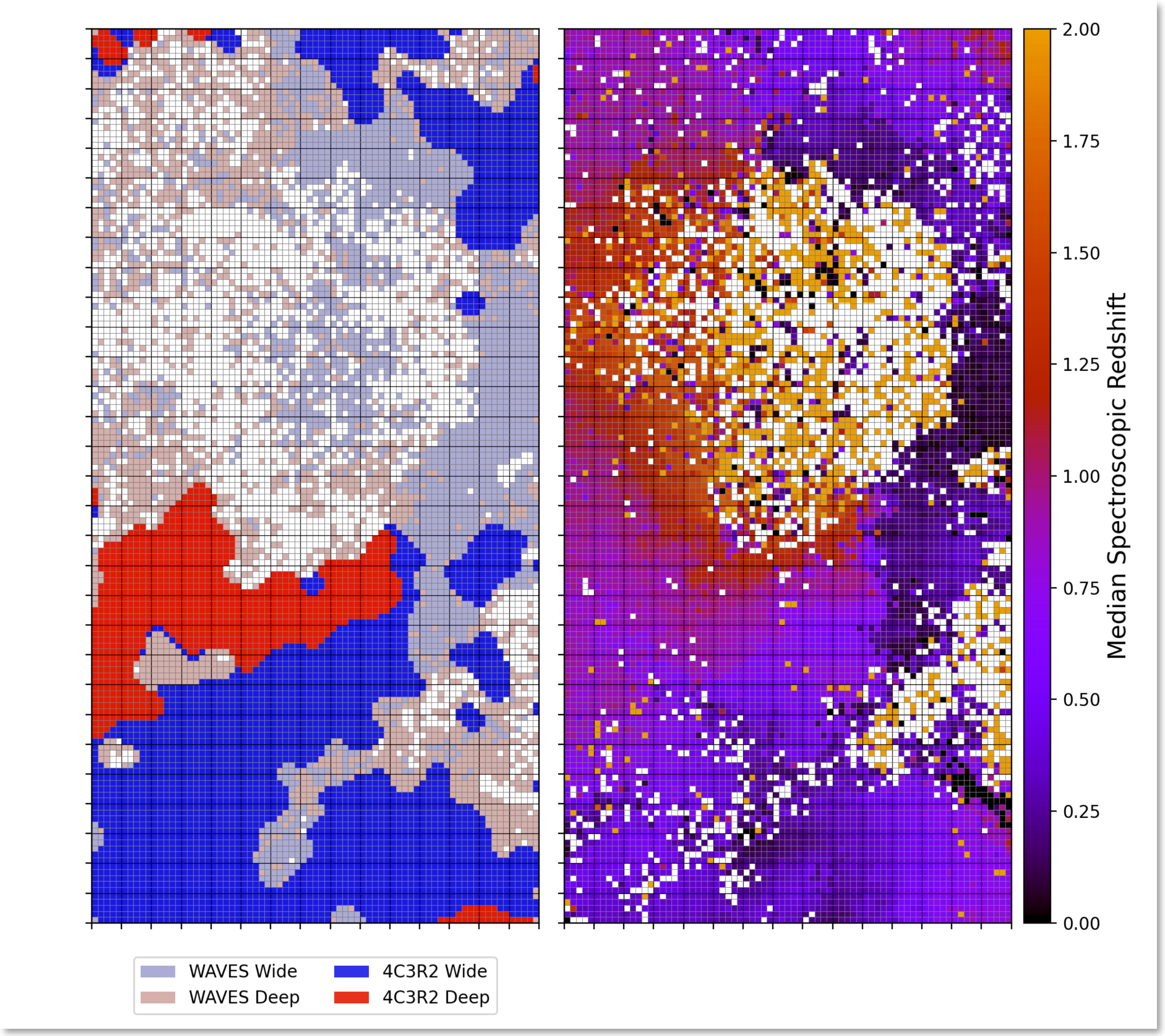
- Extend galaxy evolution studies into unexplored territory over 7 billion years
  - Low stellar and halo mass
  - Emergence of environmental scaling relations
  - High SNR (StePS)
  - HI content (ORCHIDSS)





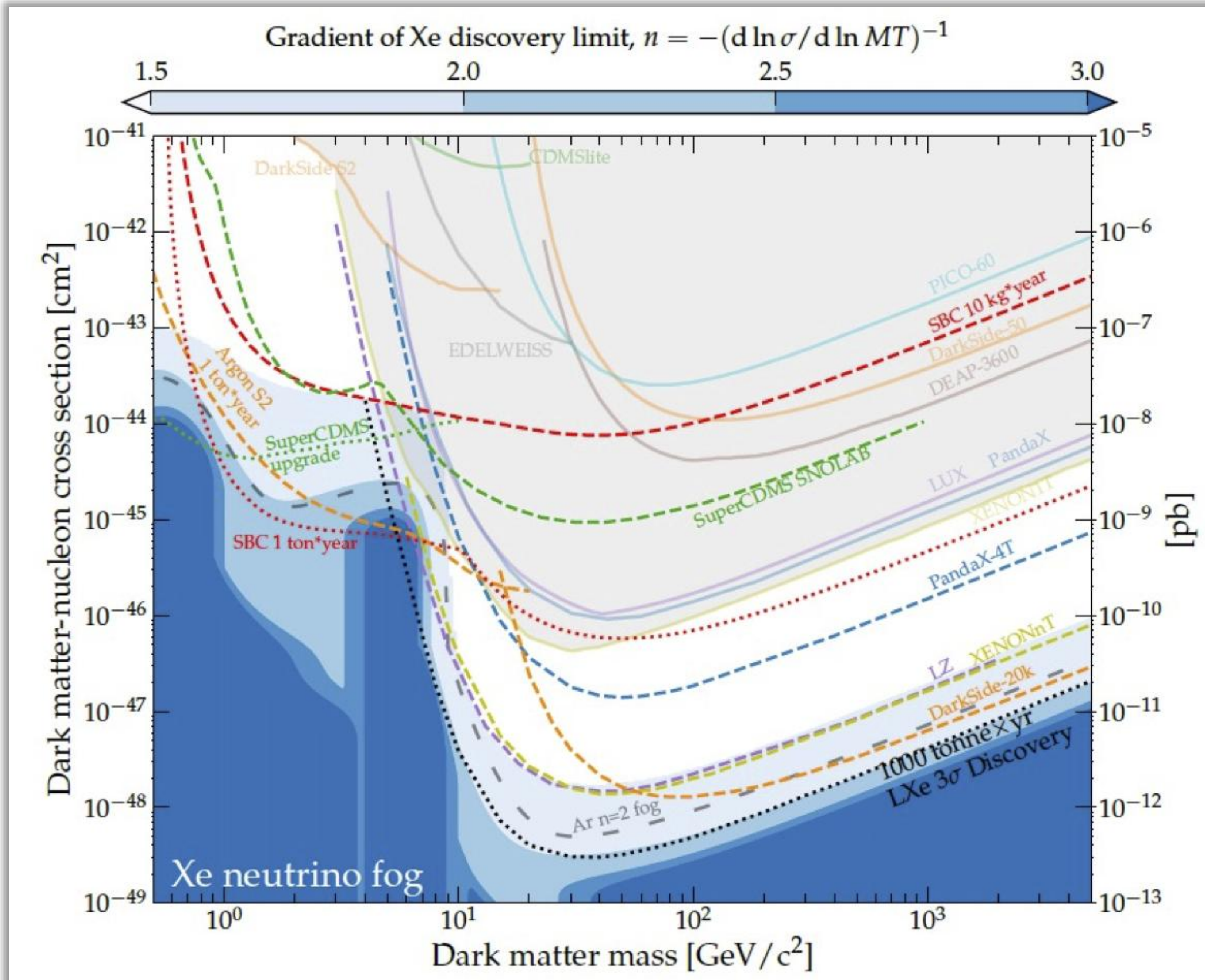
WAVES science in a nutshell

- Extend galaxy evolution studies into unexplored territory over 7 billion years
  - Low stellar and halo mass
  - Emergence of environmental scaling relations
  - High SNR (StePS)
  - HI content (ORCHIDSS)
- Enable future weak lensing experiments
  - Calibrate the colour-redshift relation for Euclid and VRO (4C3R2)



What is Dark Matter?

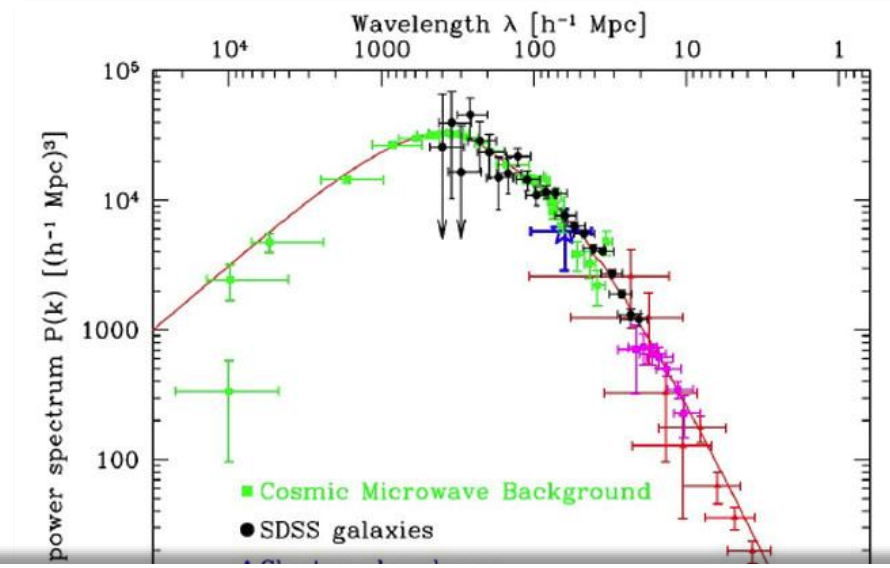
- Astrophysics: it's cold and doesn't interact with baryons or itself (much)
- Physics: simplest model is an as yet unknown weakly interacting massive particle
- So far: no sign of it:



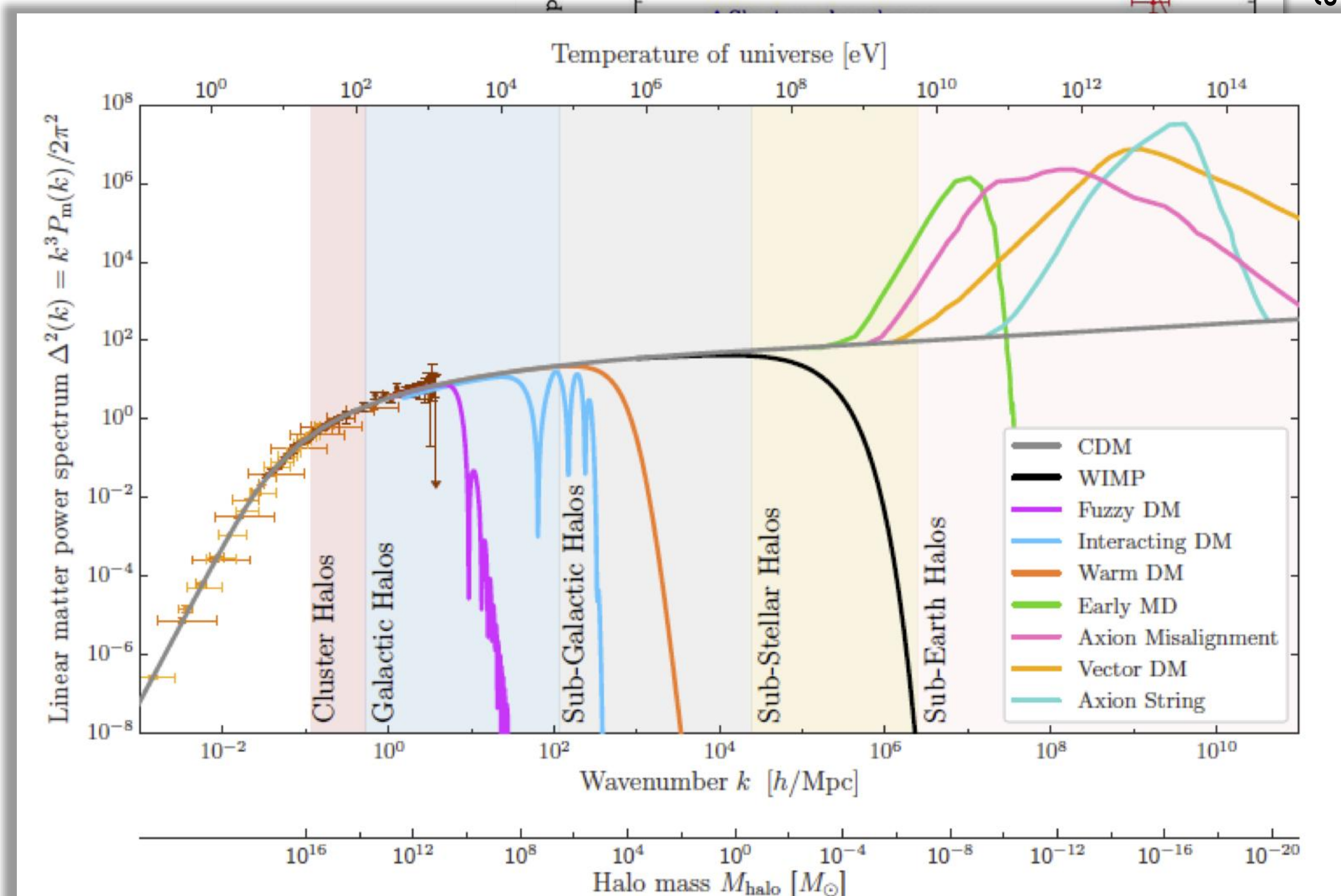
Snowmass (2021)

Alternatives to CDM

- Simple alternatives to CDM could potentially fix its small-scale problems
  - Warm Dark Matter (WDM)
  - Self-interacting Dark Matter (SIDM)
- Lower mass → more "free-streaming damping" in the early Universe → less structure on small scales
- ➢ Interest in the small-scale end of the matter power spectrum



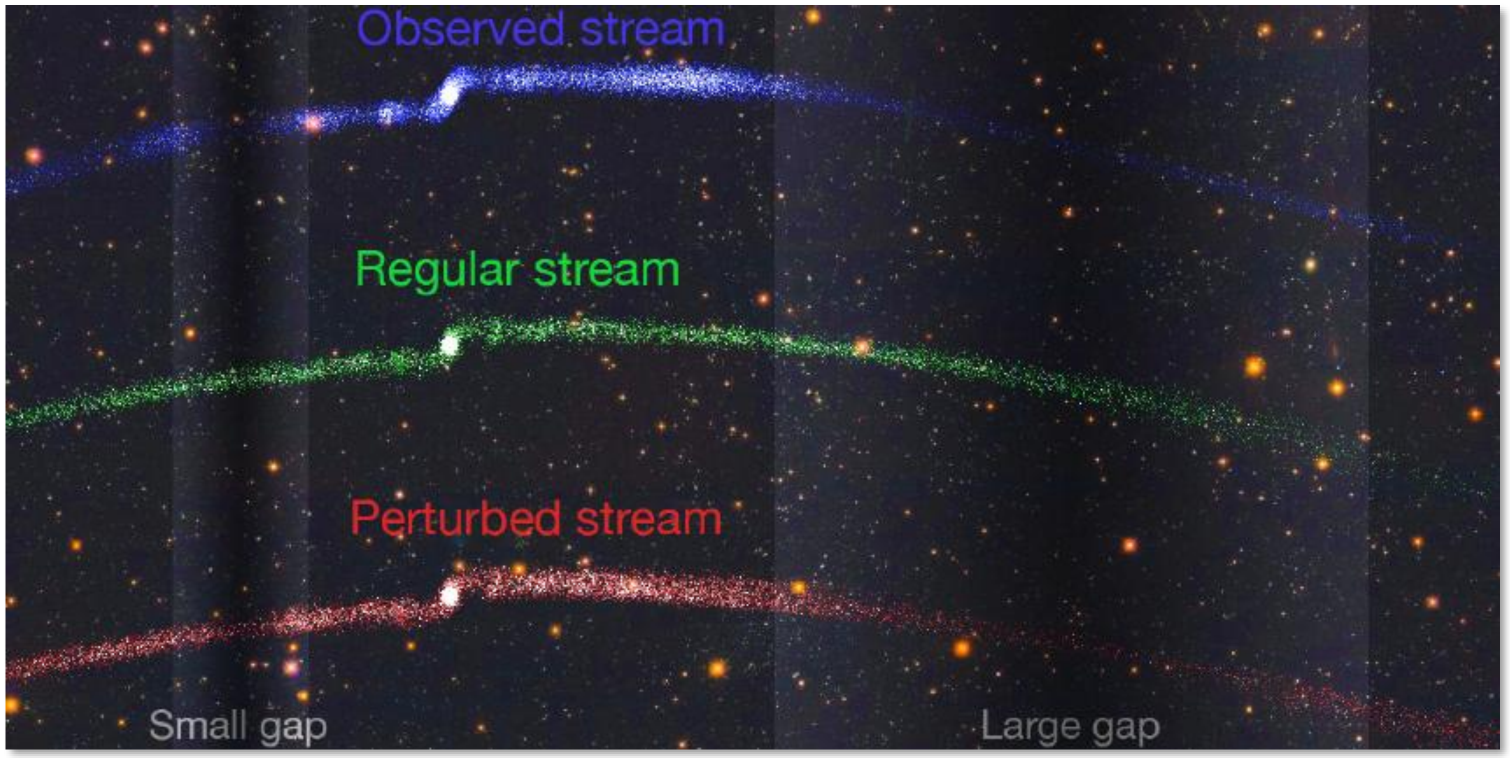
al. (2004)



Snowmass (2021)

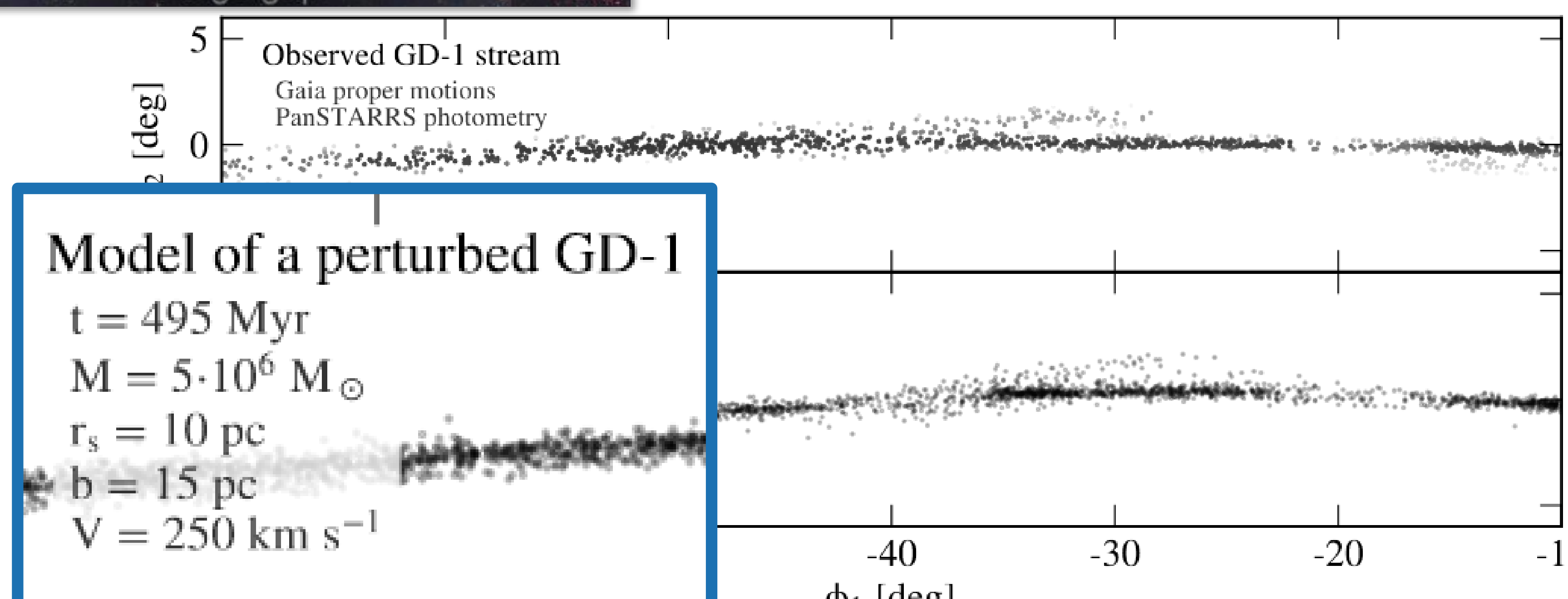
Substructure in DM halo of the MW

Substructure in stellar streams (with Gaia):



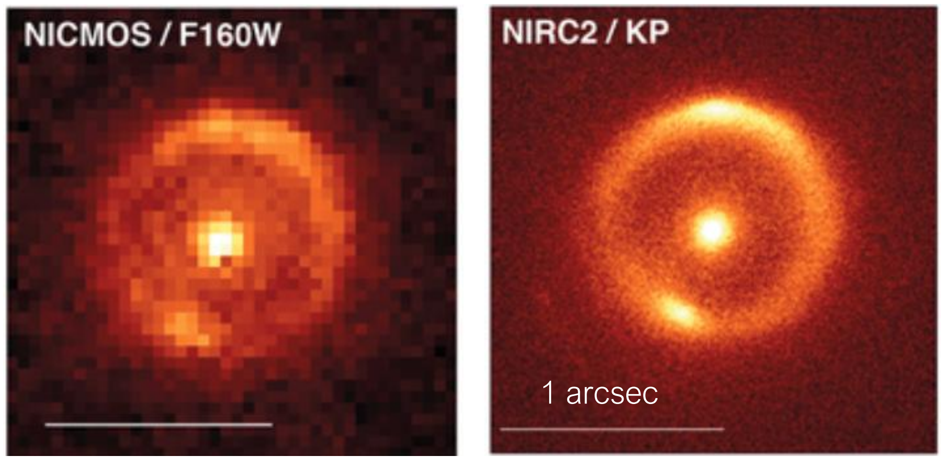
Erkal et al. (2017)

Bonaca et al. (2019)

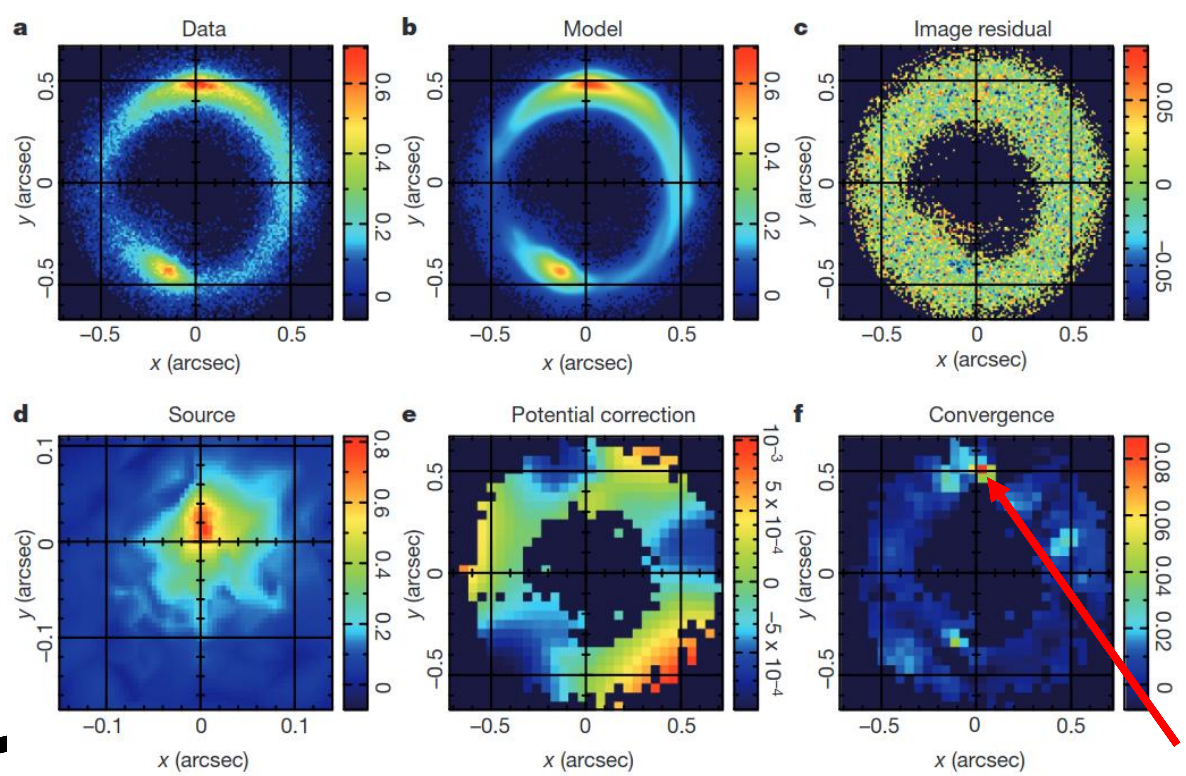


Warm Dark Matter

Best current constraints on the thermal relic WDM particle mass:

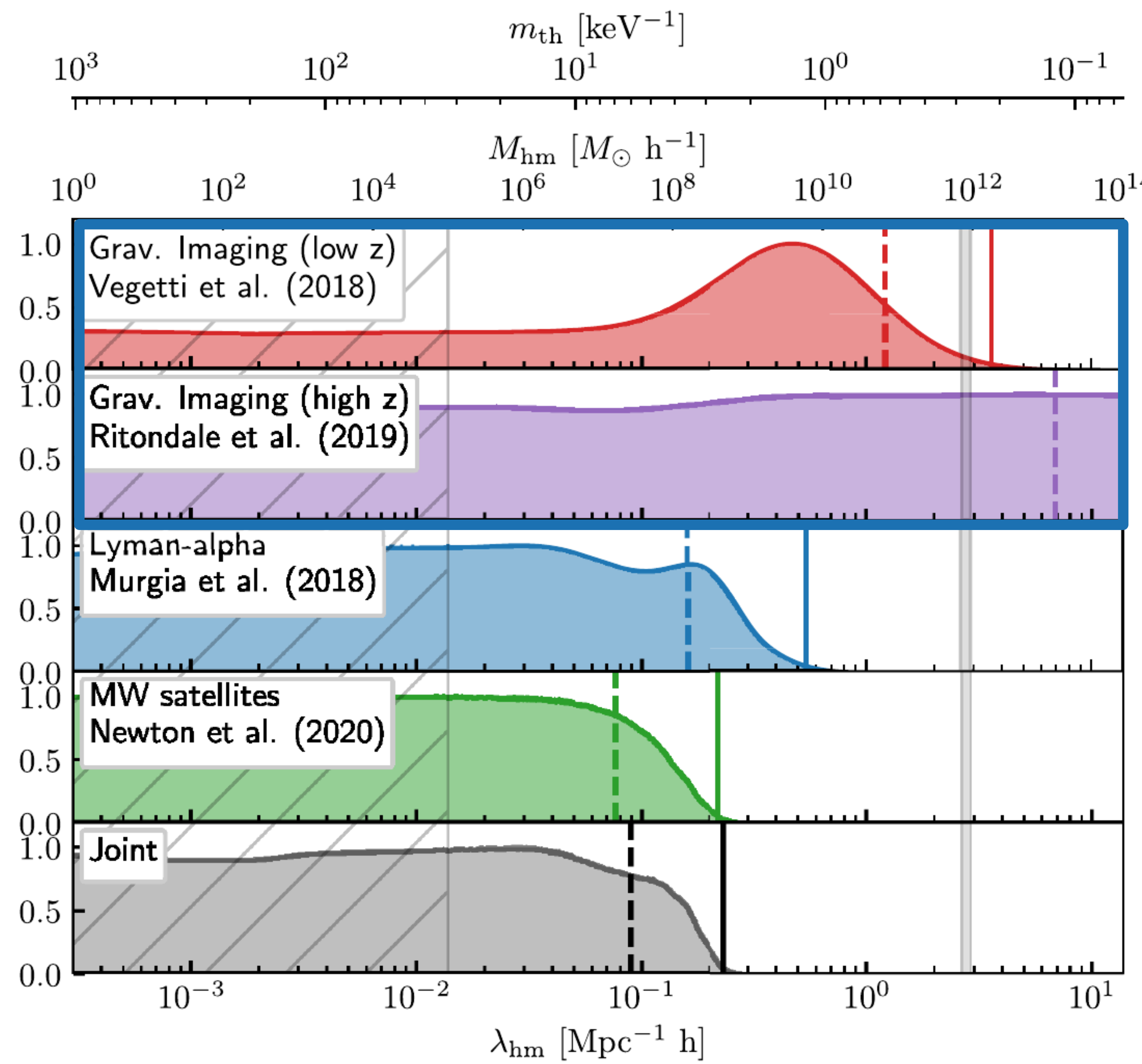


Spingola et al. (2019)



Vegetti et al. (2012)

DM sub-halo with
$M \approx 2 \times 10^8\ M_\odot$

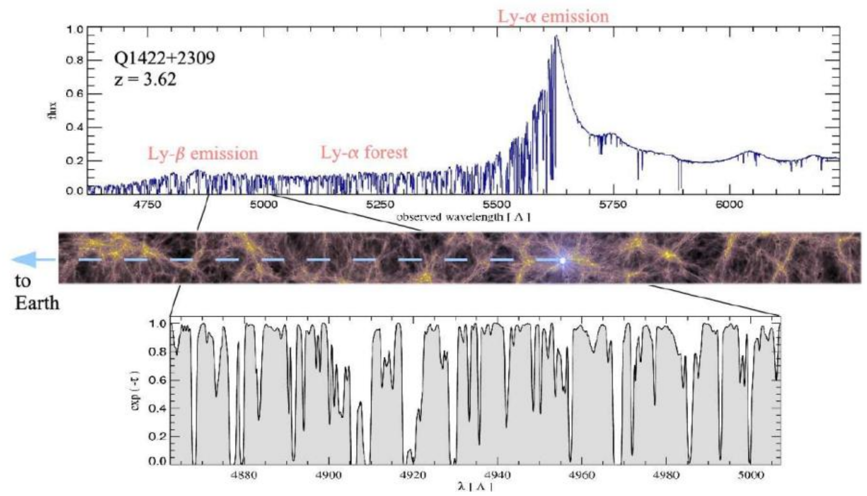


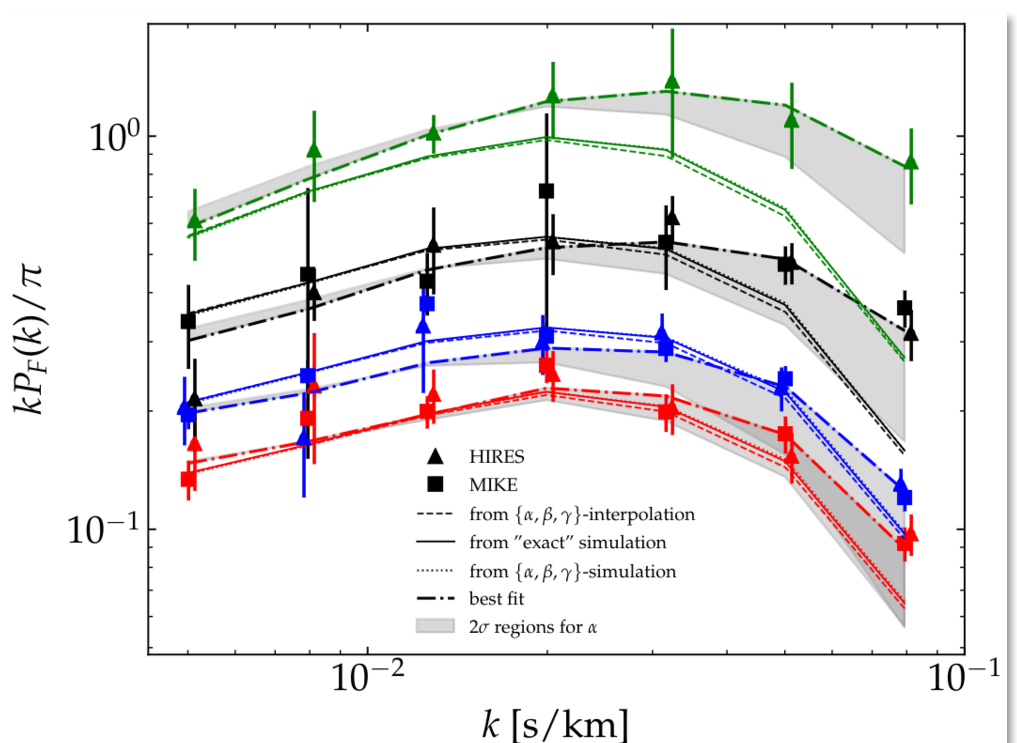
Enzi et al. (2021)
see also Nadler et al. (2021)

Warm Dark Matter

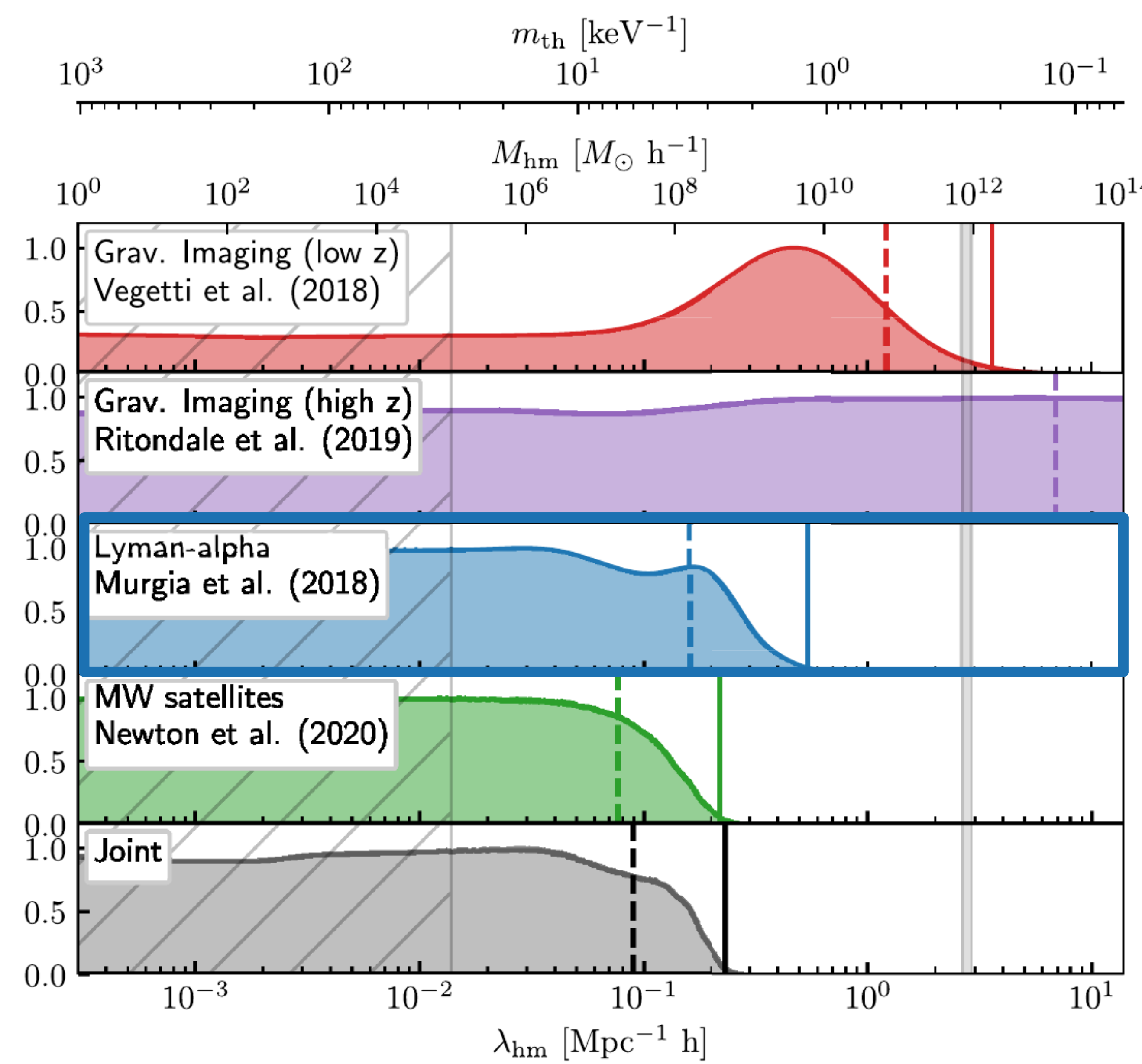
Best current constraints on the thermal relic WDM particle mass:

Springel et al. (2006)





Murgia et al. (2018)

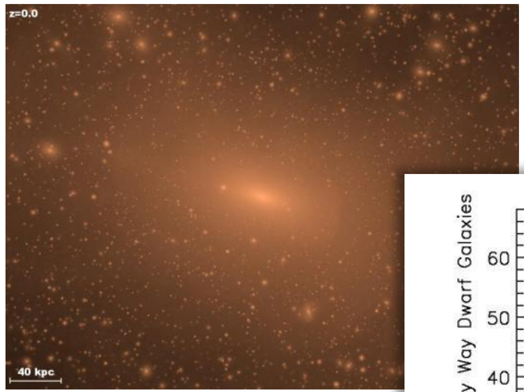


Enzi et al. (2021)
see also Nadler et al. (2021)

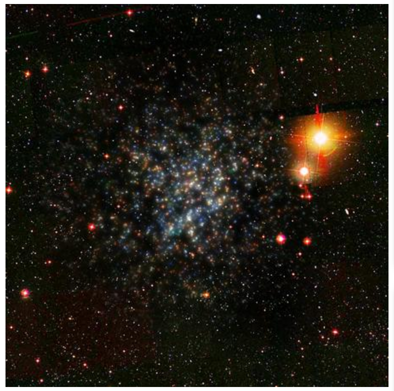
Warm Dark Matter

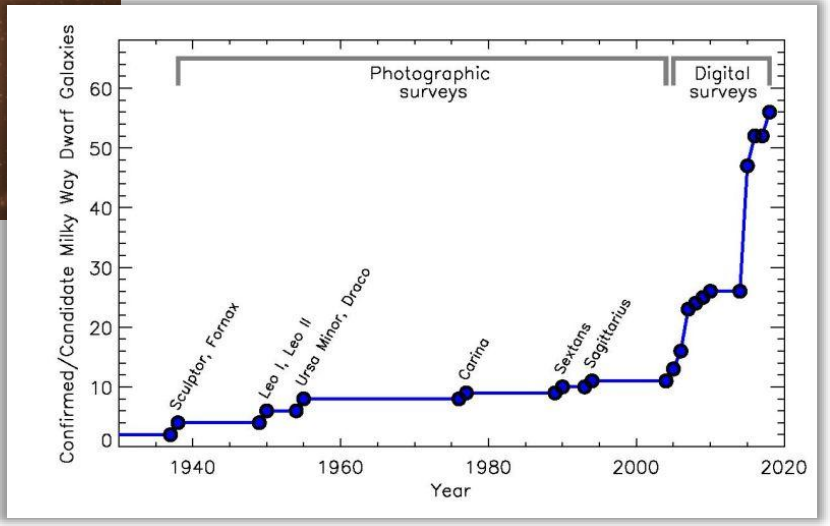
Best current constraints on the thermal relic WDM particle mass:

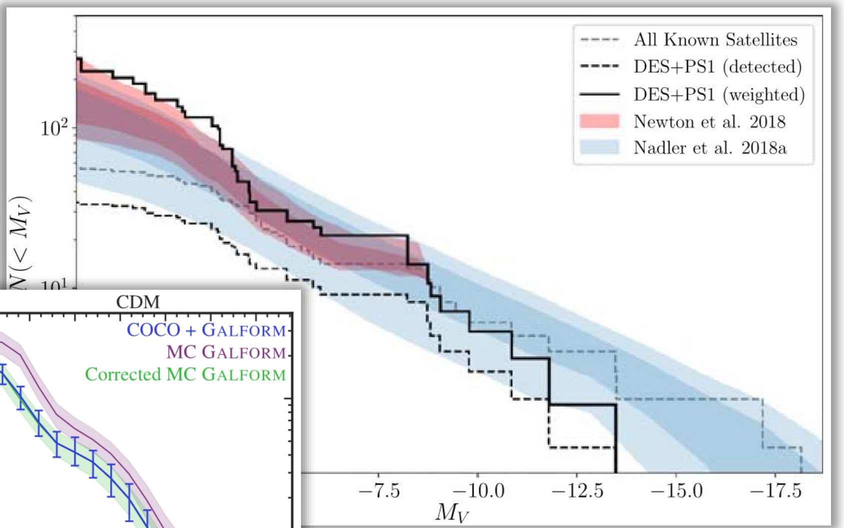
J. Diemand



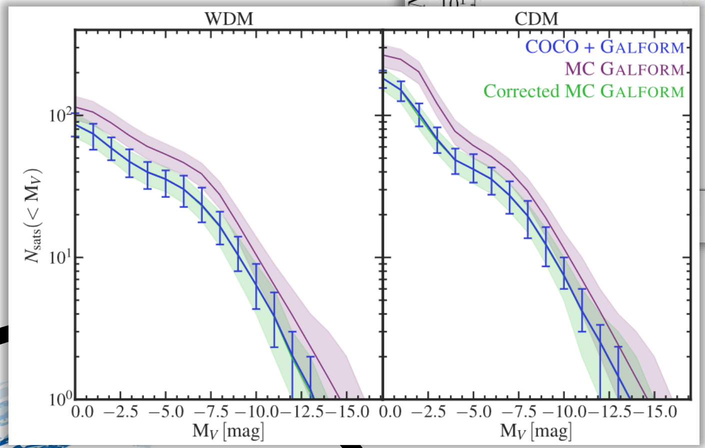
SDSS / V. Belokurov



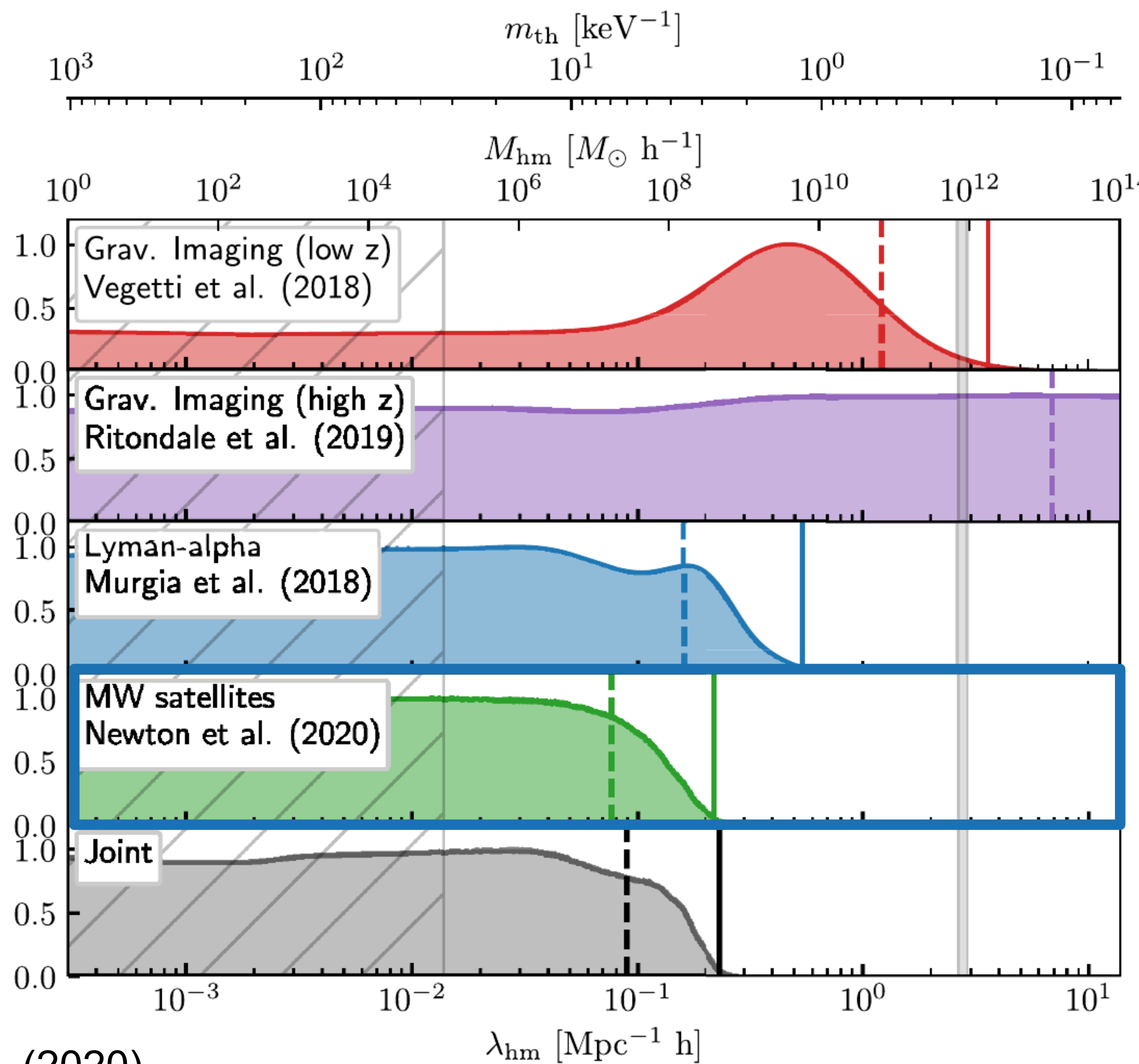




Drlica-Wagner et al. (2020)



Newton et al. (2020)

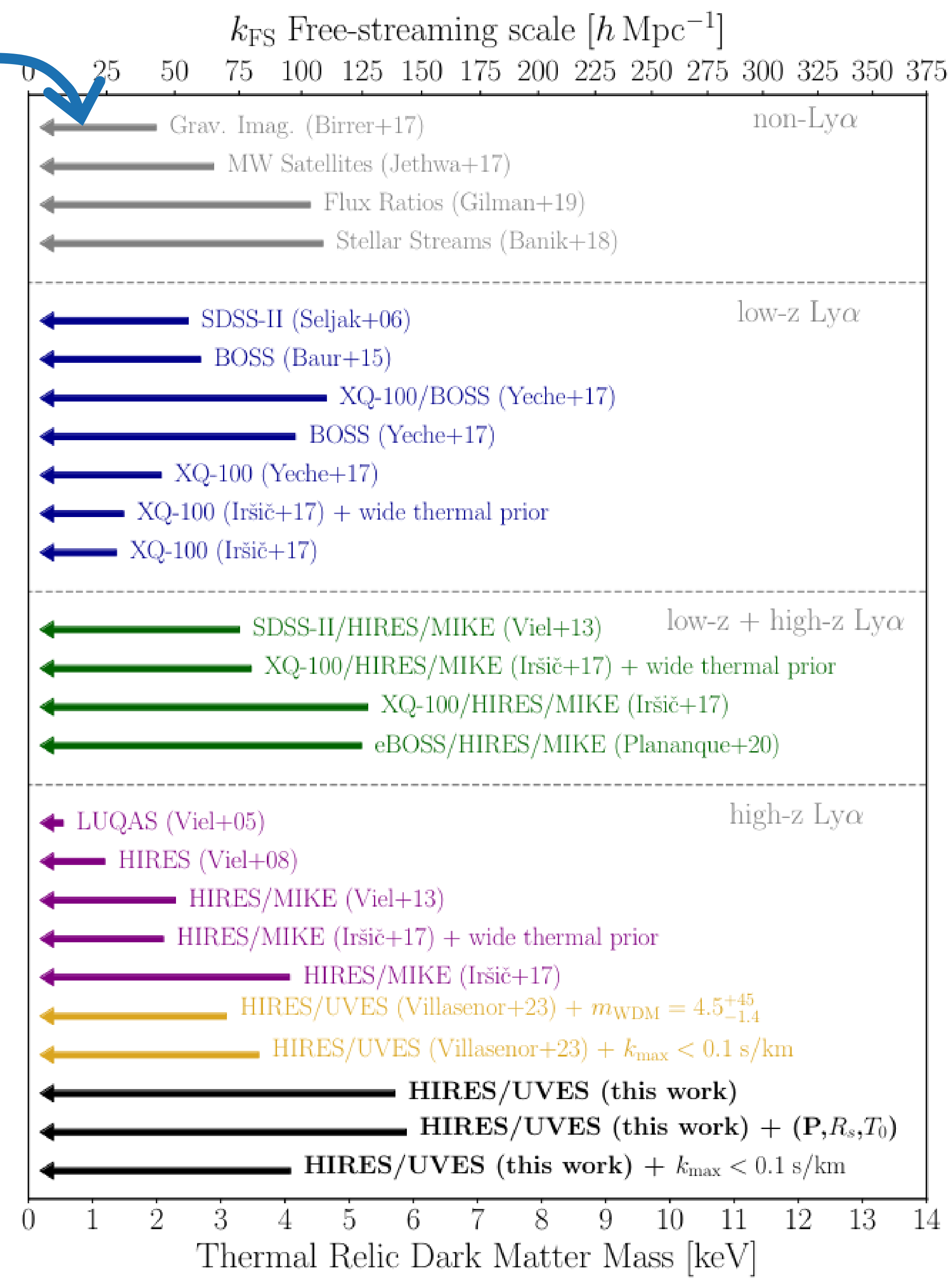


Enzi et al. (2021)
see also Nadler et al. (2021)

Warm Dark Matter

Best current constraints on the thermal relic WDM particle mass:

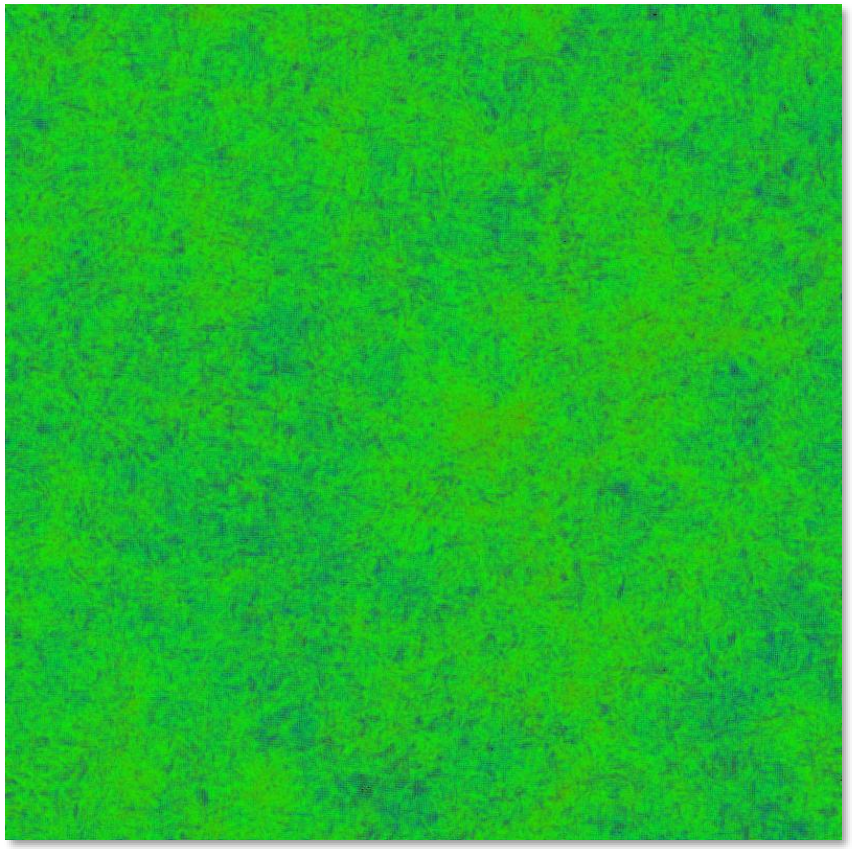
Excluded mass ranges



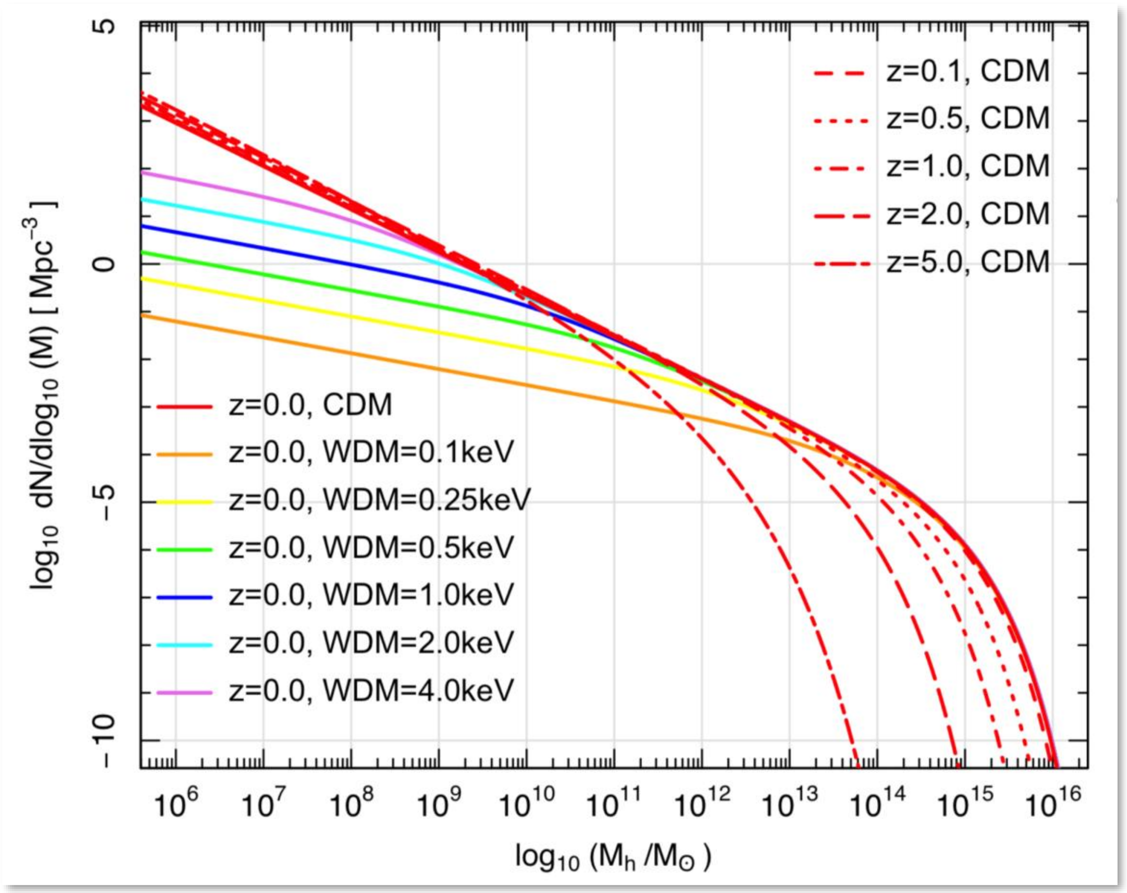
Iršič et al. (2023)

Halo Mass Function

- Alternative is to consider the statistics of collapsed objects, i.e. the abundance of low-mass DM halos
    - ➢ Halo mass function (HMF)
    - ➢ The DM HMF is a robust prediction of structure formation simulations



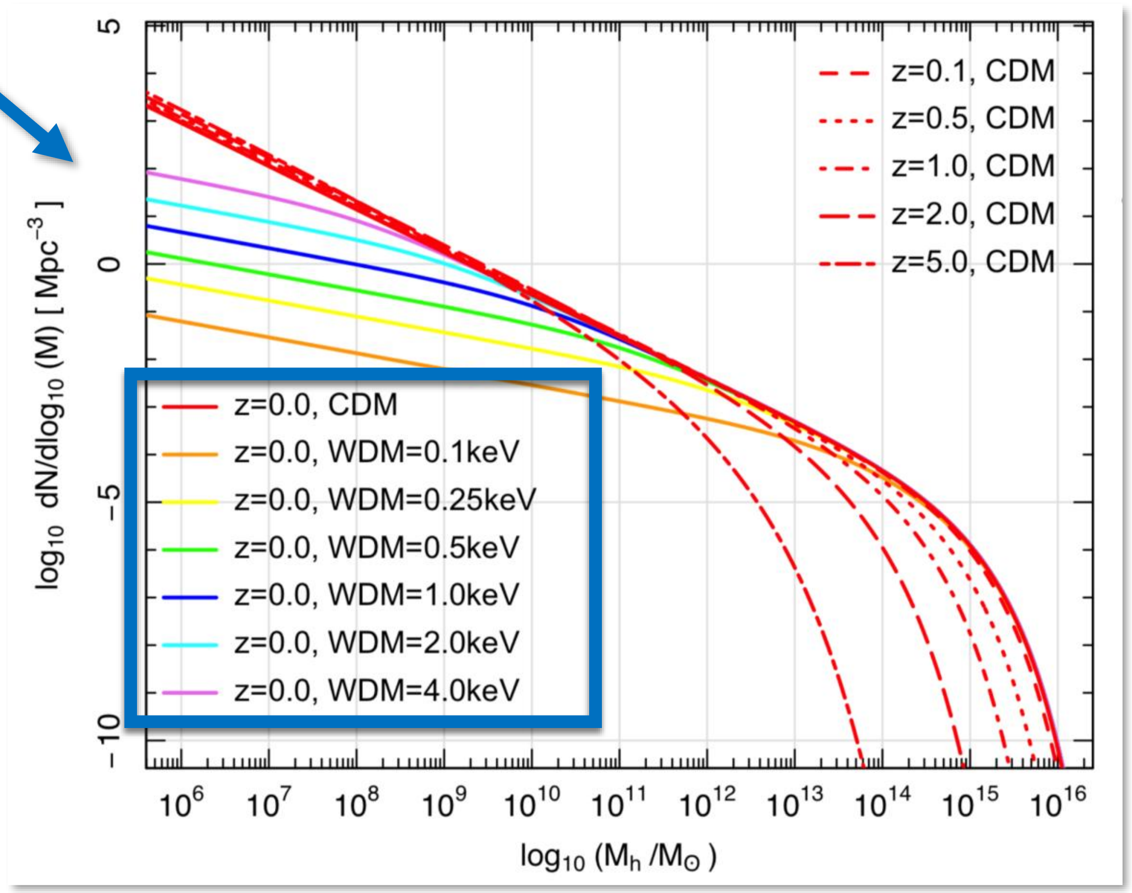
SURFS, Chris Power

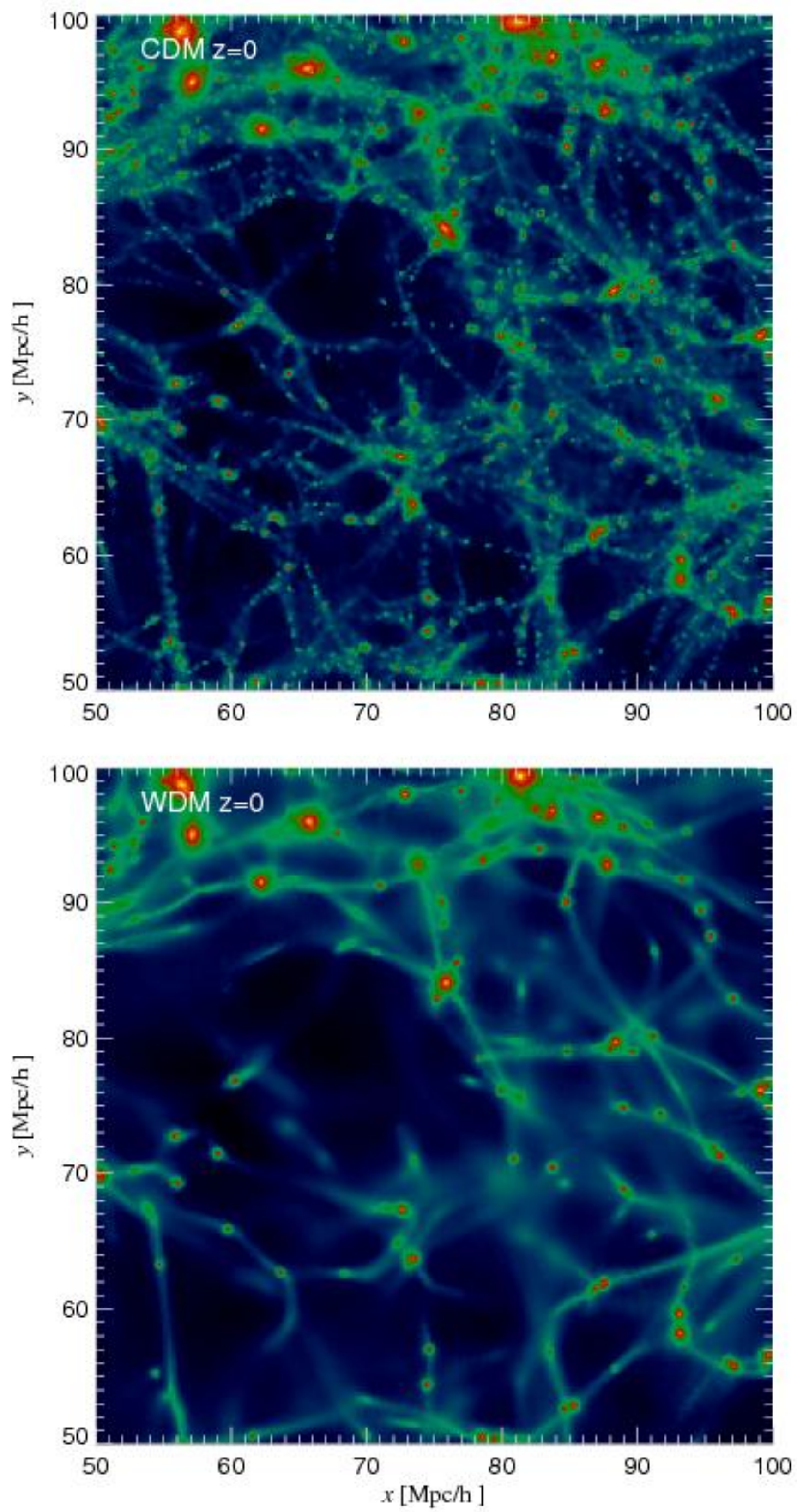


Murray et al. (2013,2021)

Halo Mass Function

- Alternative is to consider the statistics of collapsed objects, i.e. the abundance of low-mass DM halos
- ➢ Halo mass function (HMF)
- ➢ The DM HMF is a robust prediction of structure formation simulations
- ➢ Its low-mass end is sensitive to the properties of DM:

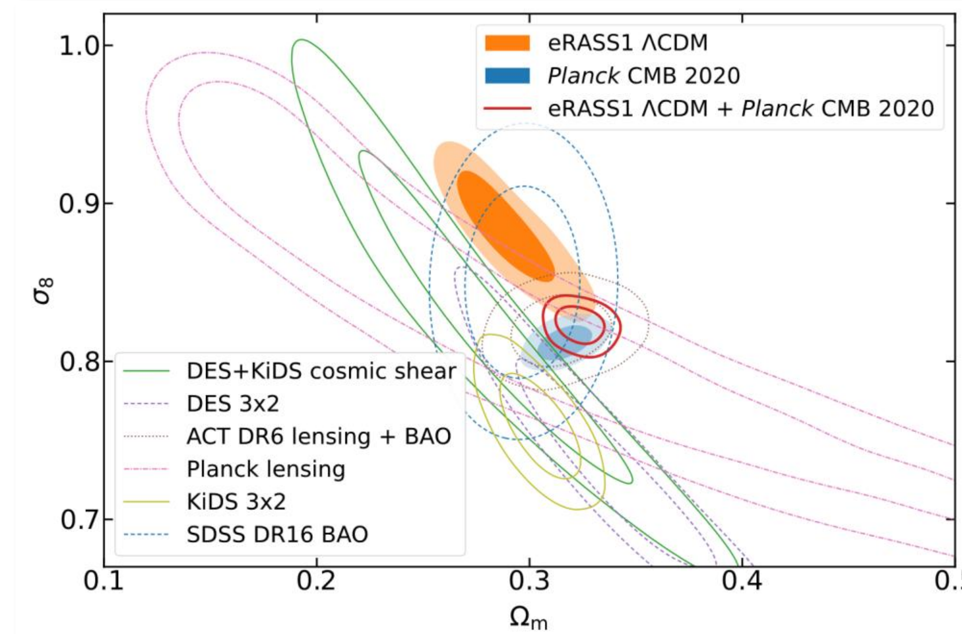




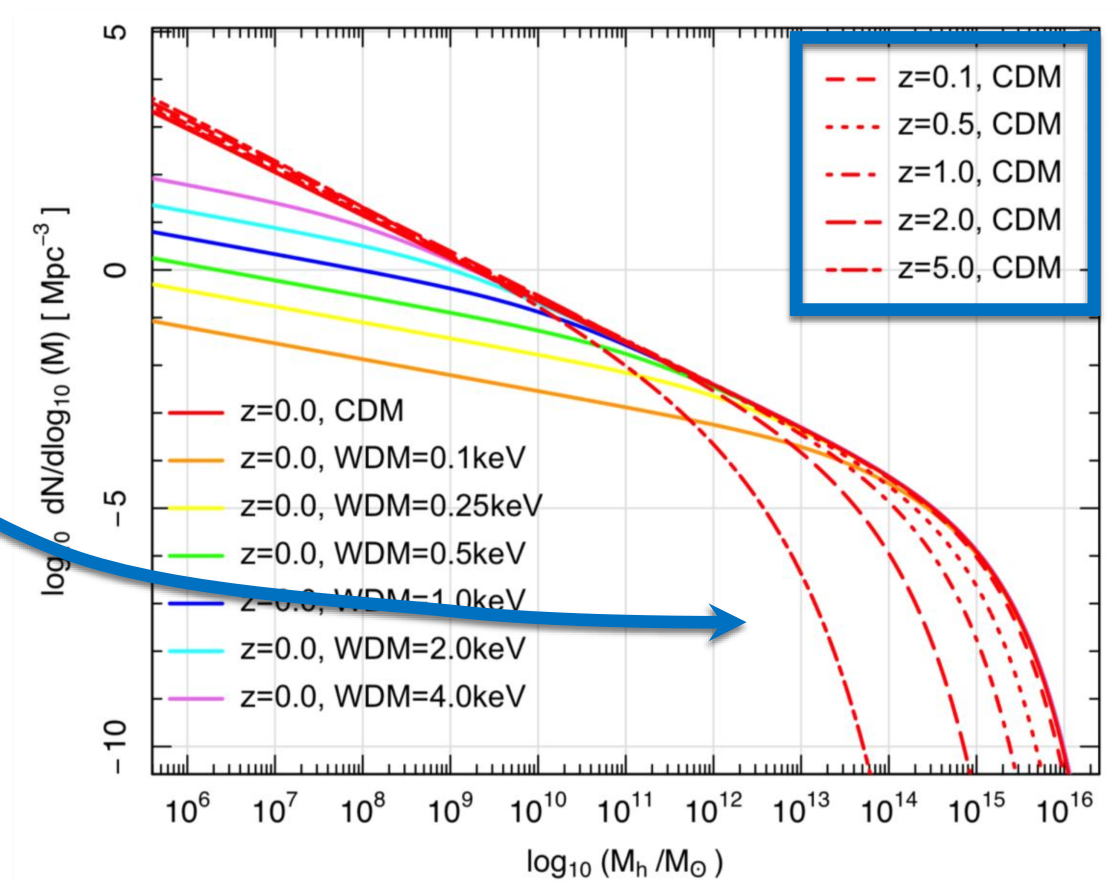
SURFS, Chris Power

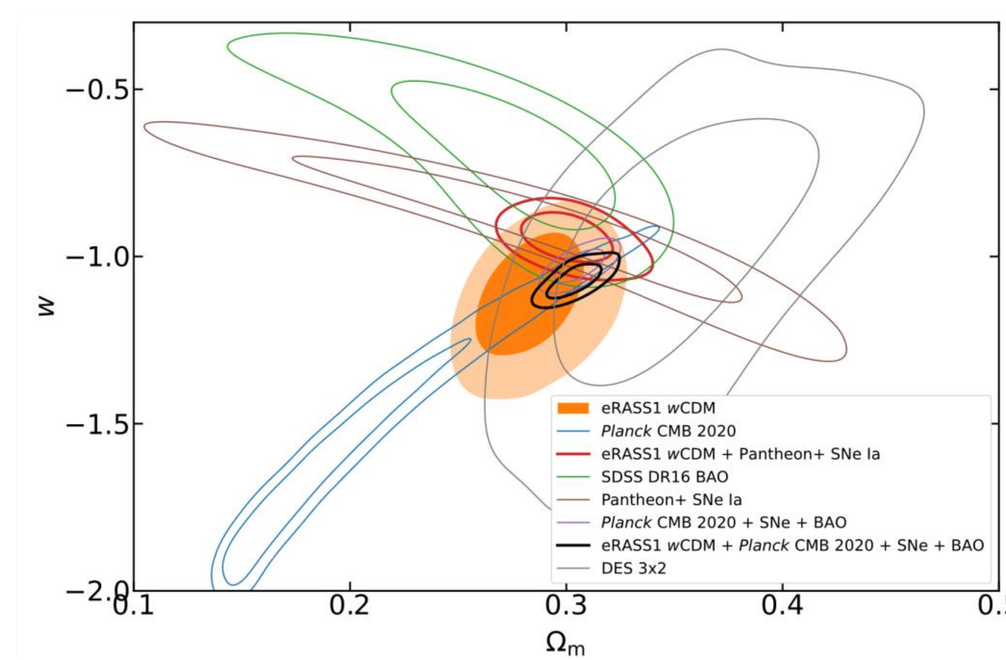
Halo Mass Function

- The high-mass end of the HMF also carries valuable information: at z = 0, the abundance of clusters helps to break degeneracies and constrains the matter density and the normalisation of the matter power spectrum
- The *evolution* of the high-mass end of the HMF probes a generic feature of structure formation: hierarchical growth – and constrains DE



Ghirardini et al. (2024)



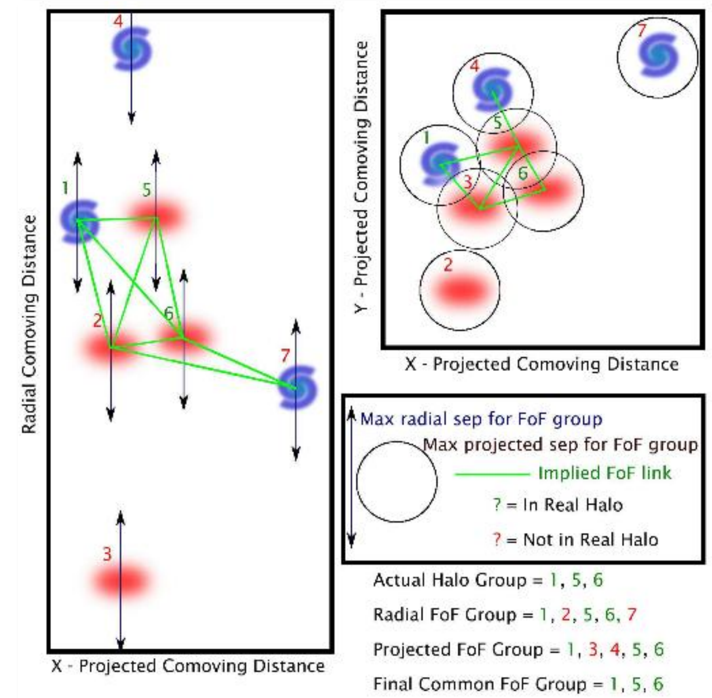


Halo Mass Function

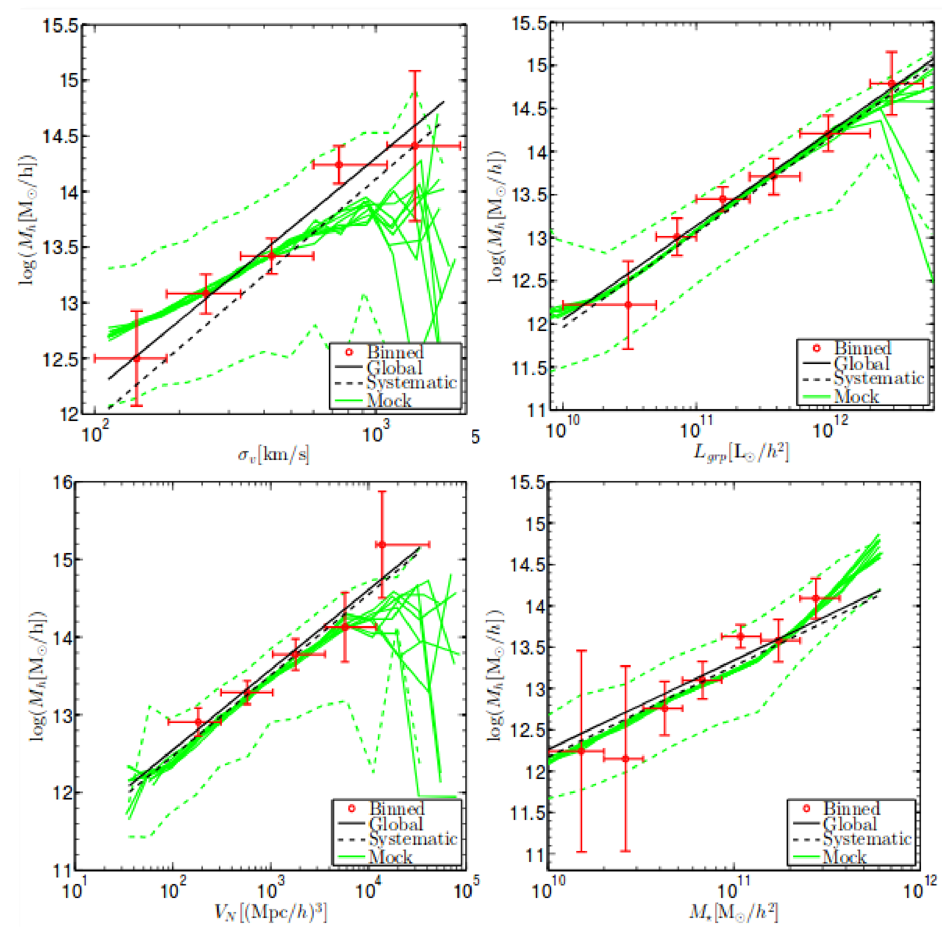
The HMF can be measured in several ways.
In WAVES:

- Obtain redshifts for a large sample of galaxies, unbiased, with high completeness
- Identify groups of galaxies (e.g. using a friends-of-friends algorithm)
- Estimate the total (i.e. DM) mass of each group from a suitable combination of group properties (involving galaxy dynamics) calibrated against simulations and/or weak lensing
- Apply volume corrections, correct for Eddington bias → HMF

➢ WAVES will directly “resolve” the majority of Dark Matter in representative volume of the Universe

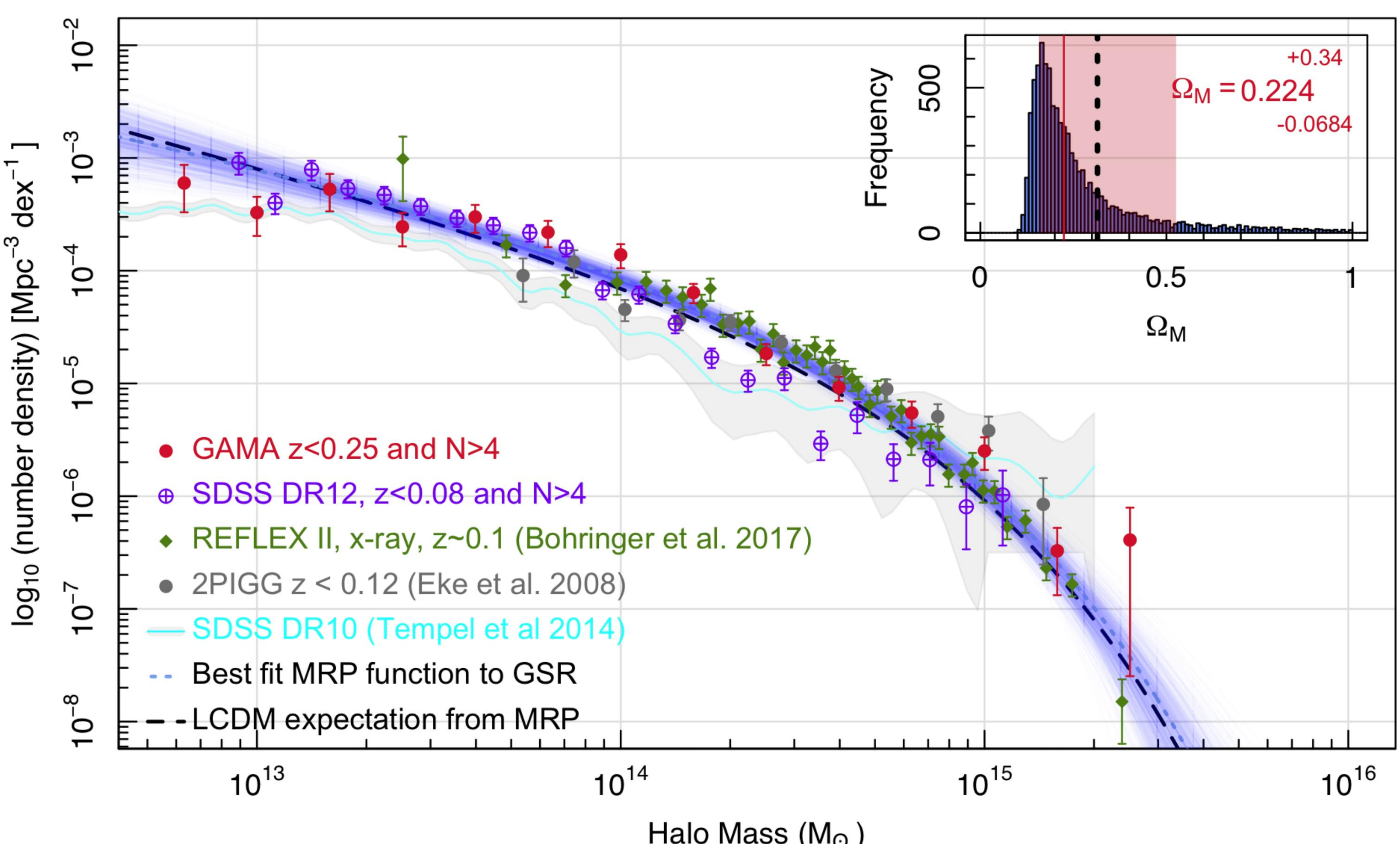


Robotham et al. (2011)



Han et al. (2015)

HMF from GAMA+SDSS12+REFLEX II

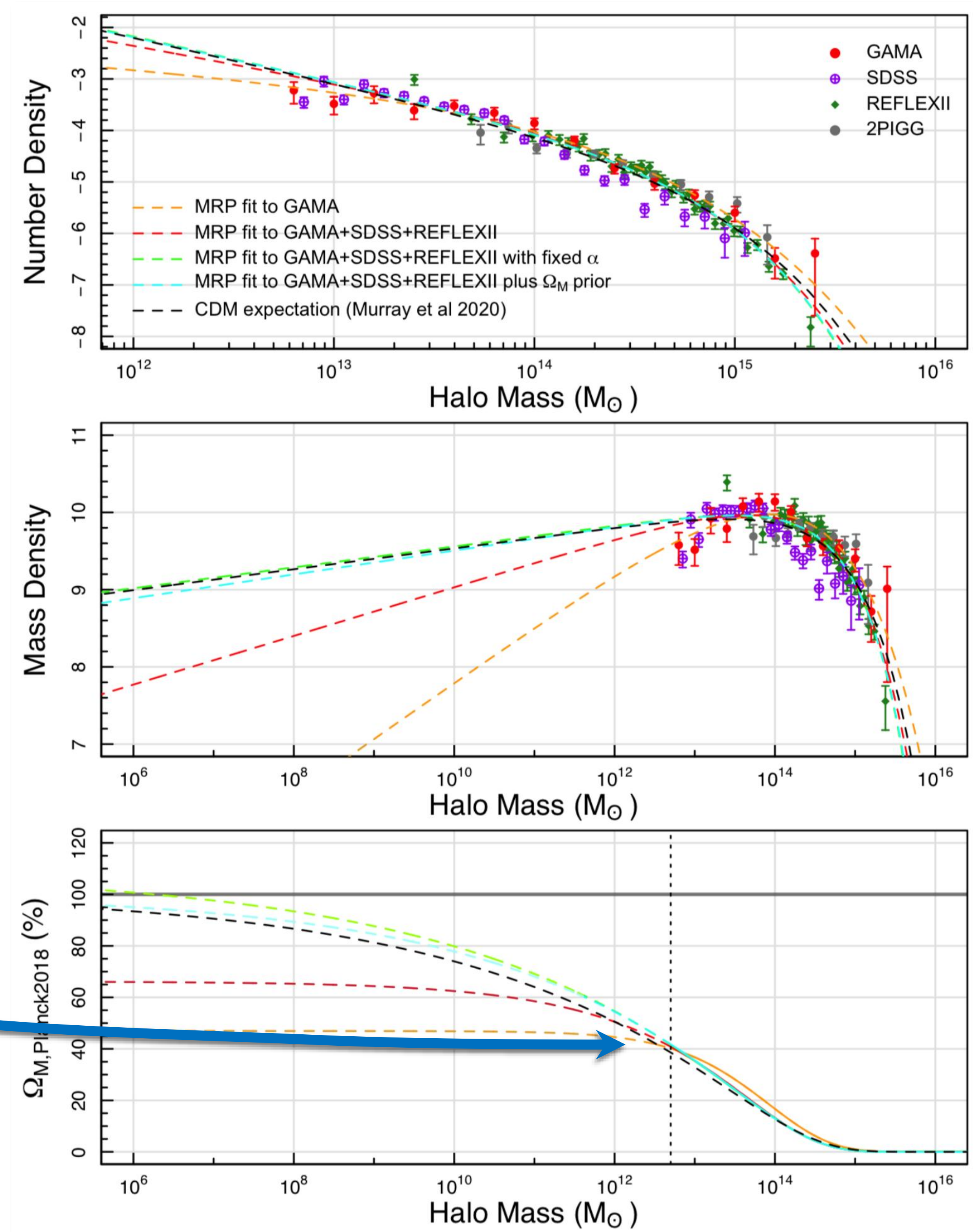


Driver et al. (2022)

HMF from GAMA+SDSS12+REFLEX II

- How much of the DM have we already "resolved"?

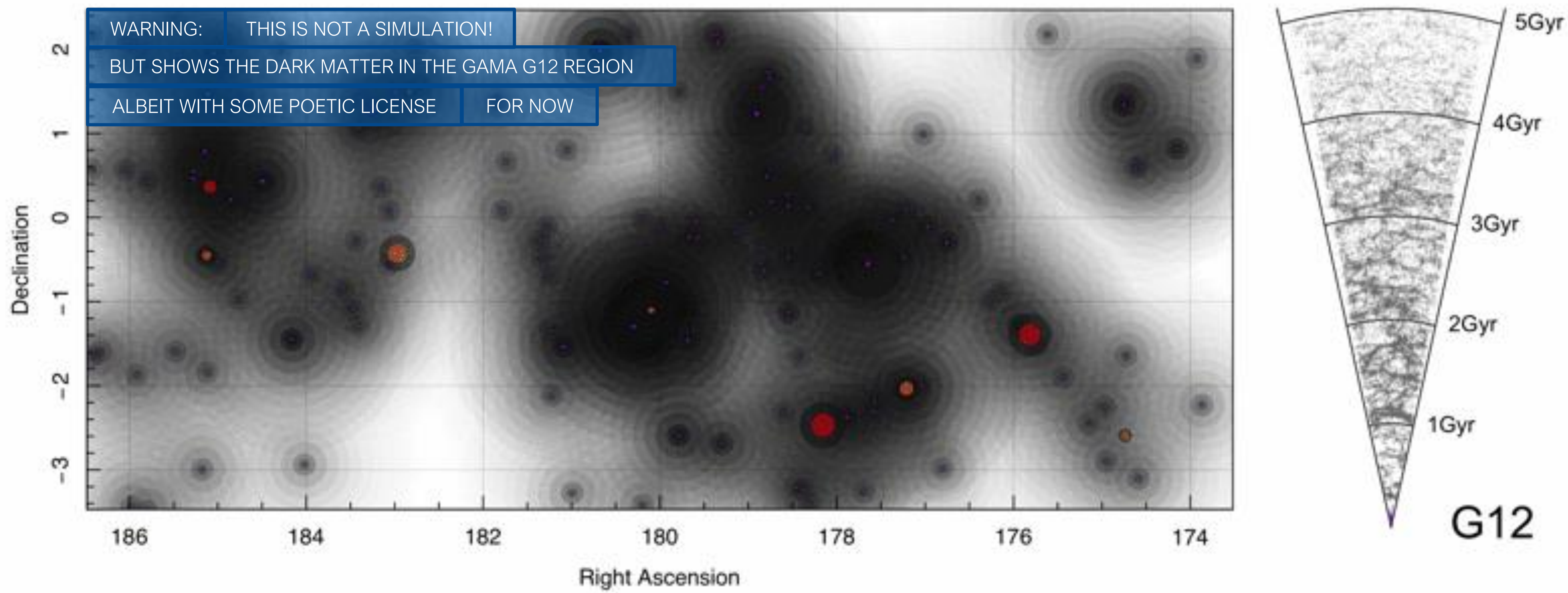
41 ± 5%



Driver et al. (2022)

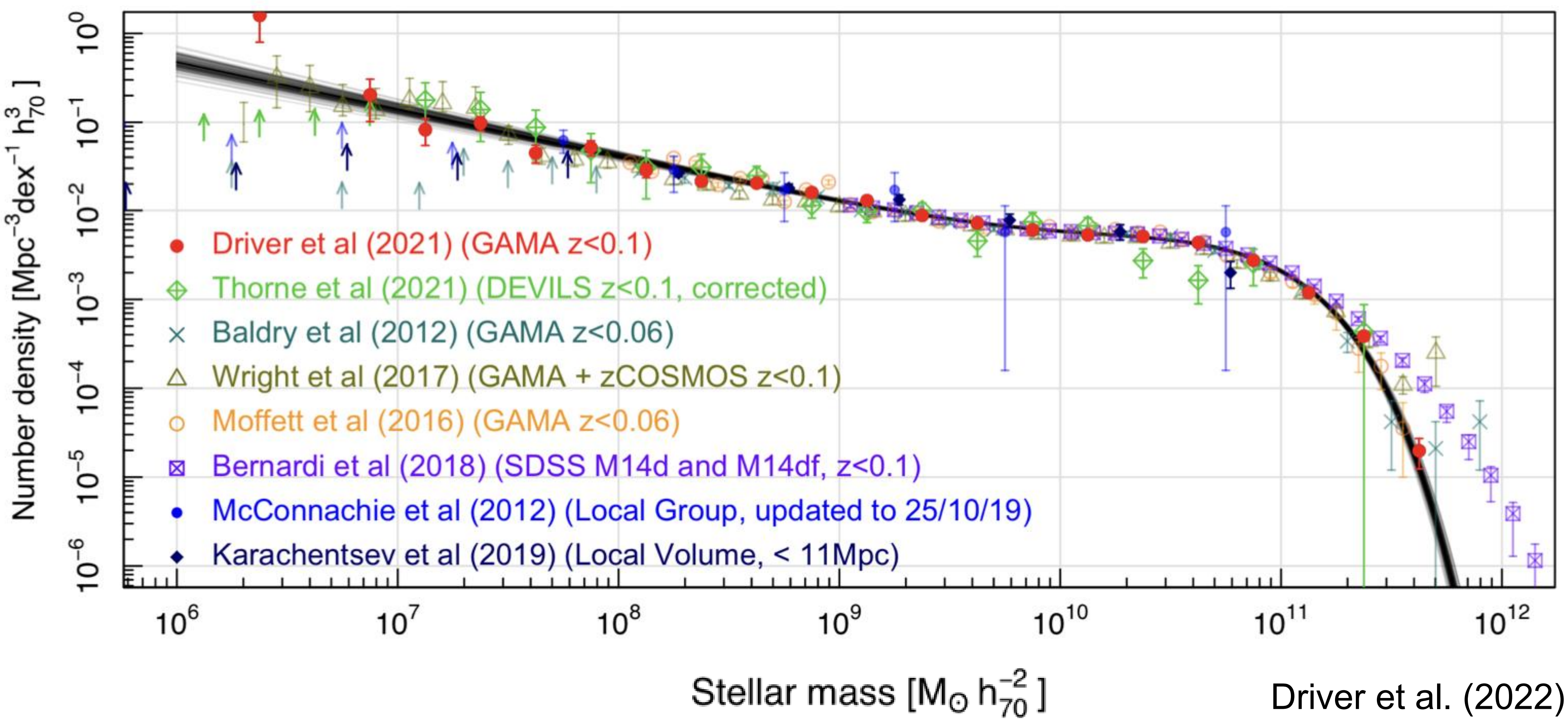
HMF lessons learned

- Measuring the HMF is tricky, glossed over all the details here
- At face-value, our GAMA+ HMF shows good agreement with ΛCDM to $10^{12.8}$ $M_\odot$
- Need to push to lower masses and higher redshifts → WAVES



Galaxies at low stellar and halo masses

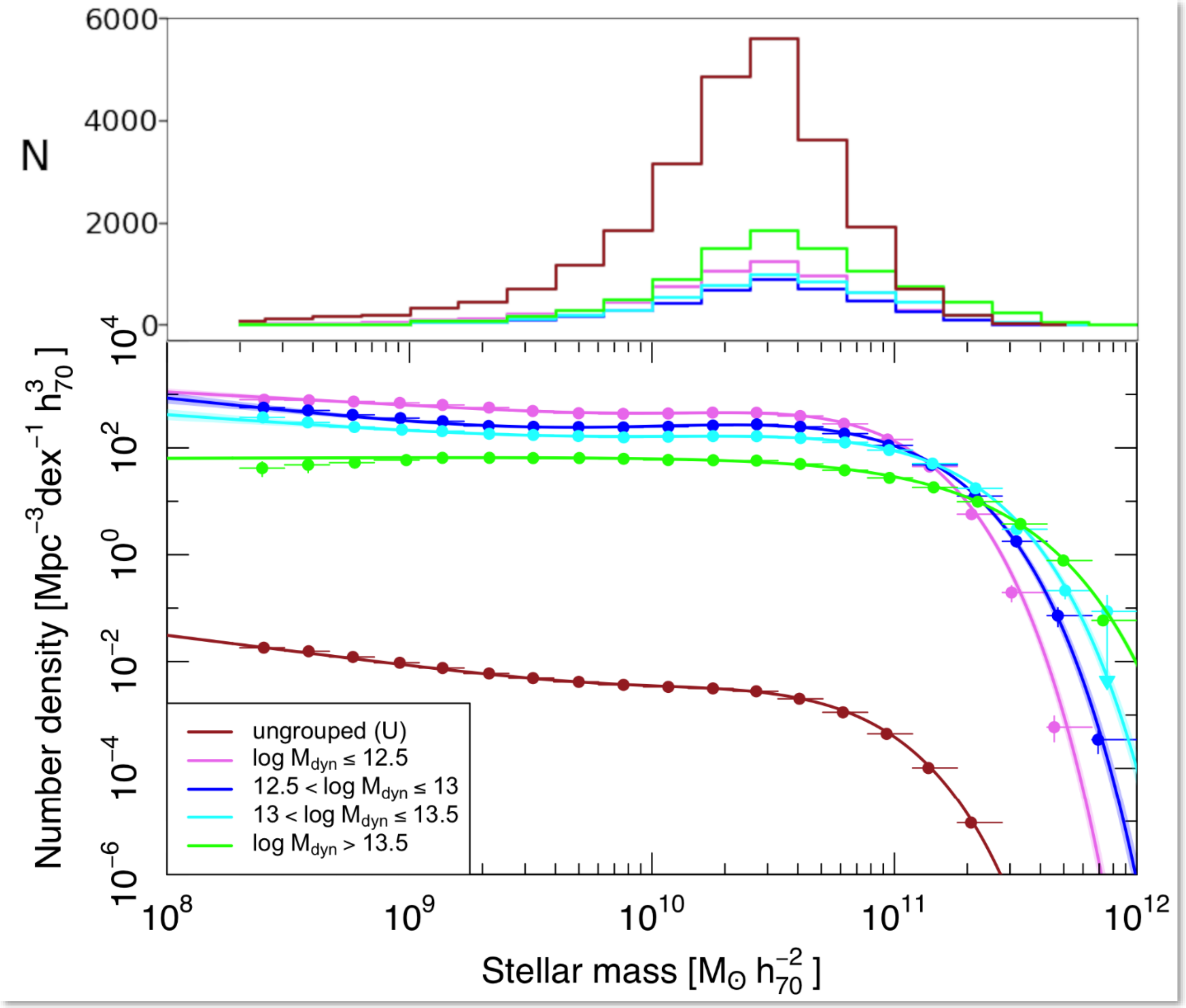
- Stellar mass and environment are key parameters controlling galaxy evolution
- But even in this fundamental parameter space the observational picture is still incomplete:



Driver et al. (2022)

Galaxies at low stellar and halo masses

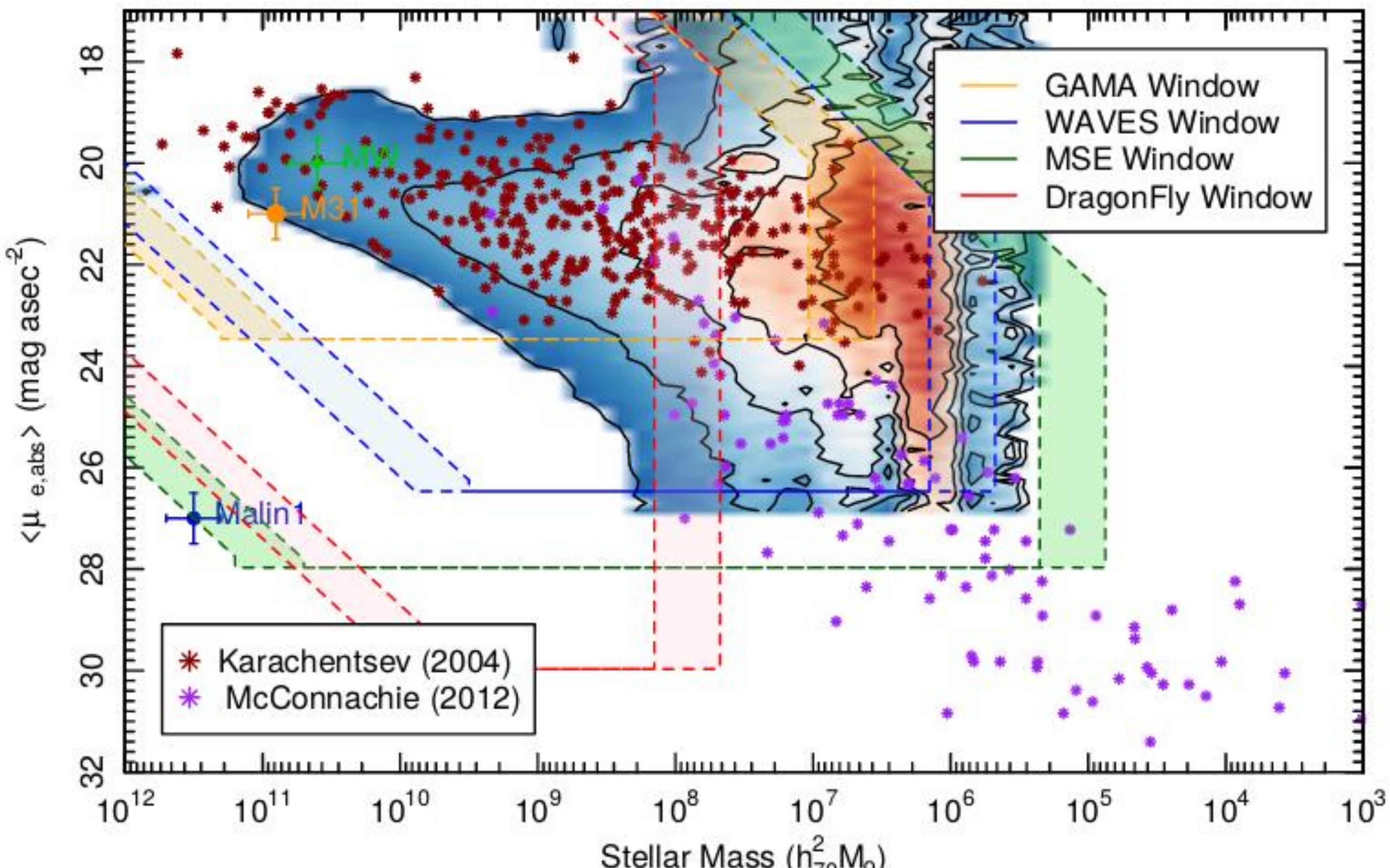
- Stellar mass and environment are key parameters controlling galaxy evolution
- But even in this fundamental parameter space the observational picture is still incomplete:



Sbaffoni, JL, et al. (2025)

Galaxies at low stellar and halo masses

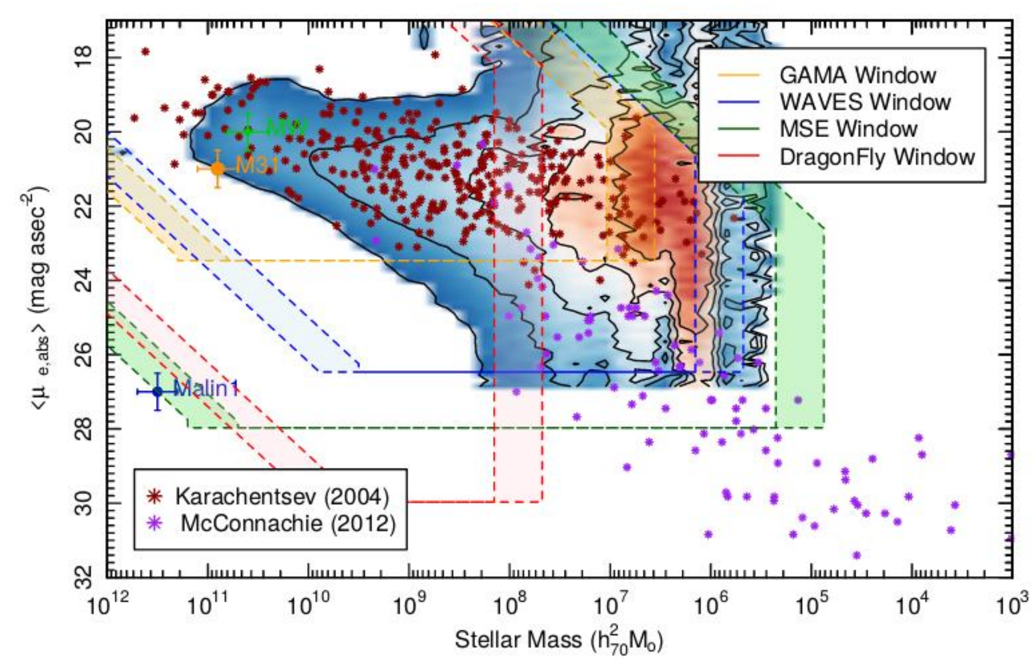
- Stellar mass and environment are key parameters controlling galaxy evolution
- But even in this fundamental parameter space the observational picture is still incomplete:



Wright et al. (2017)

Galaxies at low stellar and halo masses

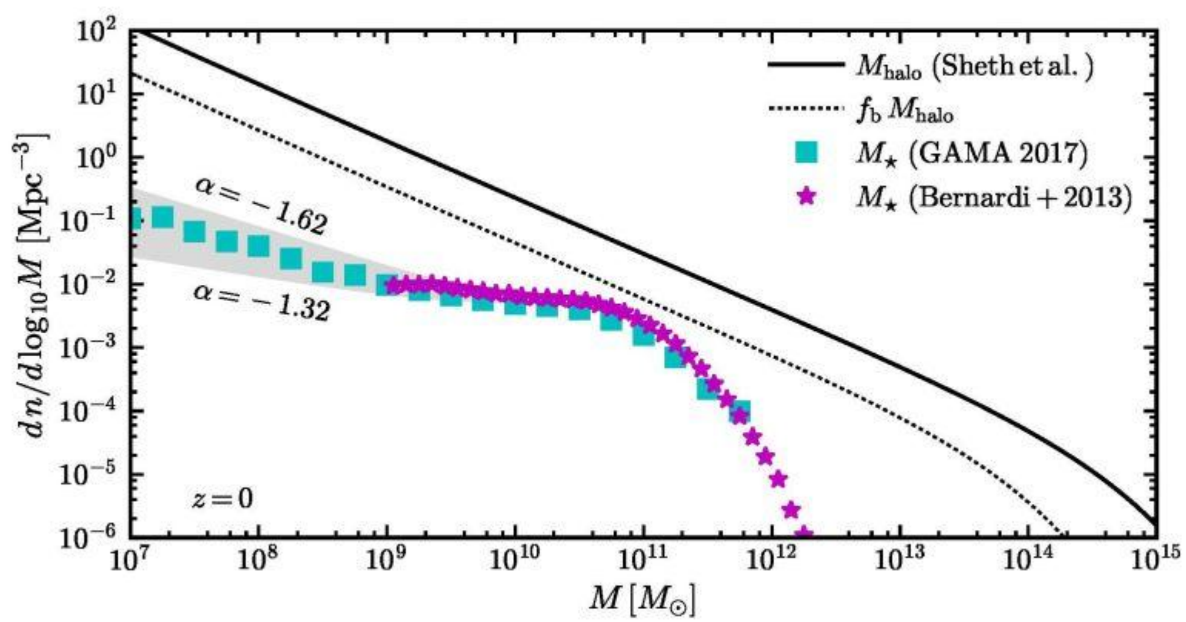
- Stellar mass and environment are key parameters controlling galaxy evolution
- But even in this fundamental parameter space the observational picture is still incomplete
- Dwarf galaxies are the building blocks of larger galaxies (see Gaia results!)
- Our ignorance of dwarf galaxies beyond the Local Group represents a severe limitation on galaxy formation models

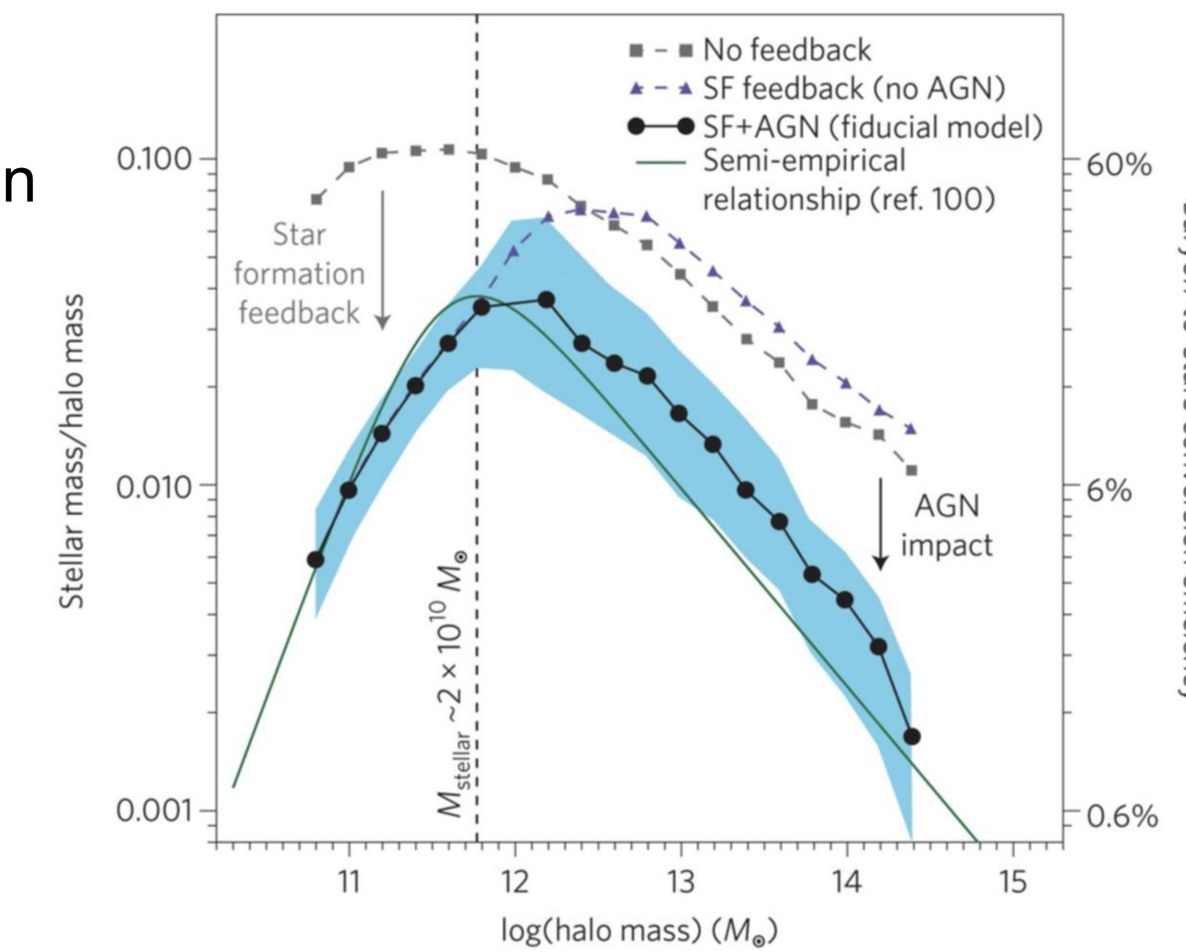


Wright et al. (2017)

Galaxies at low stellar and halo masses

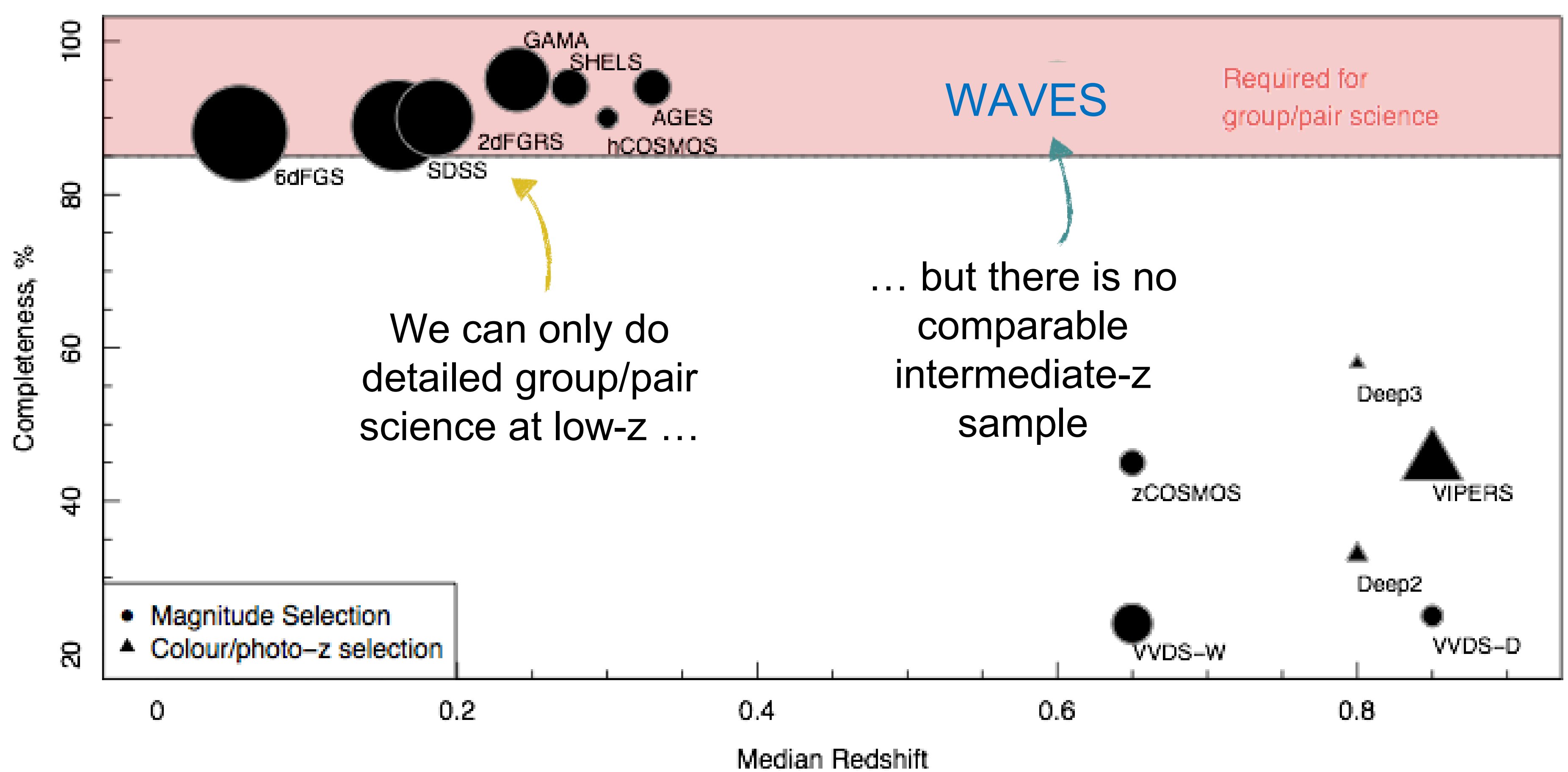
- The stellar to halo mass ratio varies as a function of halo mass
- Presumably because of different feedback mechanisms acting at high and low masses
- ➢ Peak of star-formation efficiency at $M_{halo} \approx 10^{12}\ M_{\odot} \approx$ M(MW halo)
- But no large samples of halos in this mass range available
- ➢ Cannot systematically study one of the most fundamental features of the galaxy population





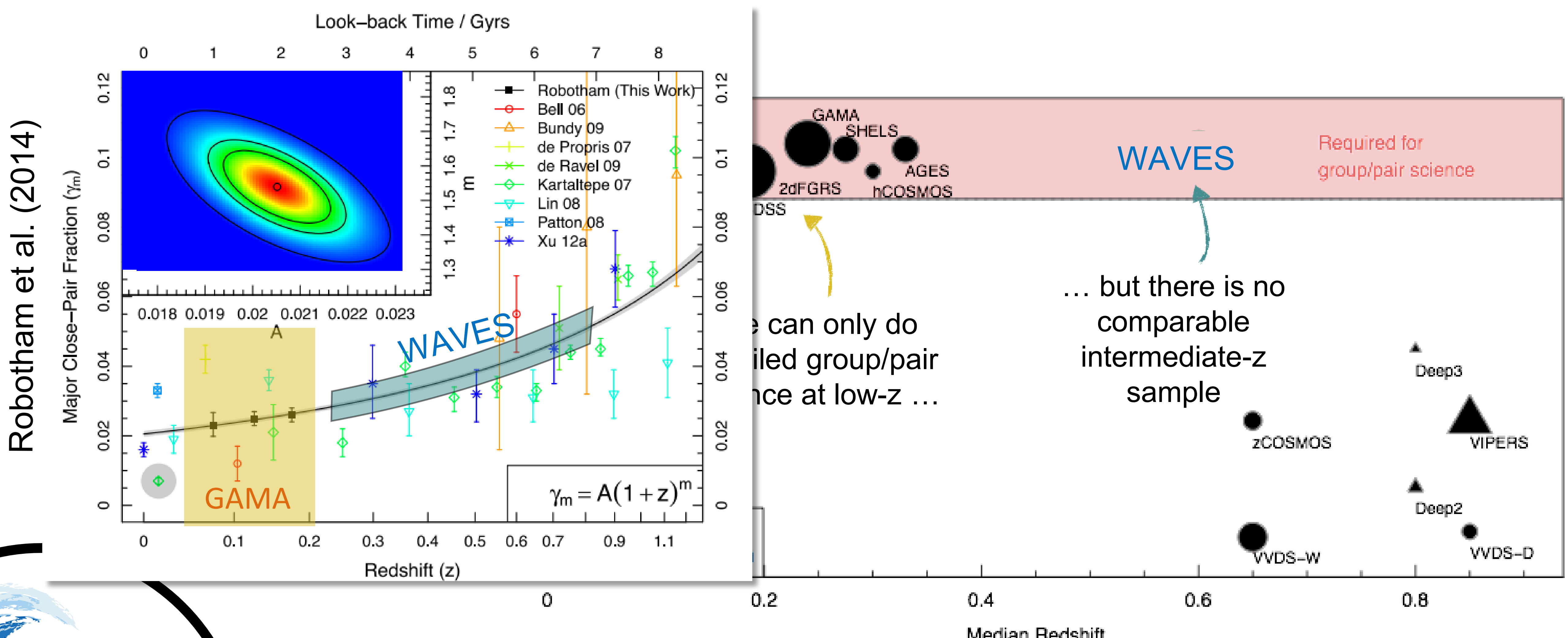
Evolution of environmental relations

- Many galaxy properties are known to correlate with environment
- These relations are known to evolve (and even reverse)
- But studying the co-evolution of, e.g., the SFR-density and morphology-density relations, or the evolution of the merger rate requires highly complete samples at higher redshifts as well

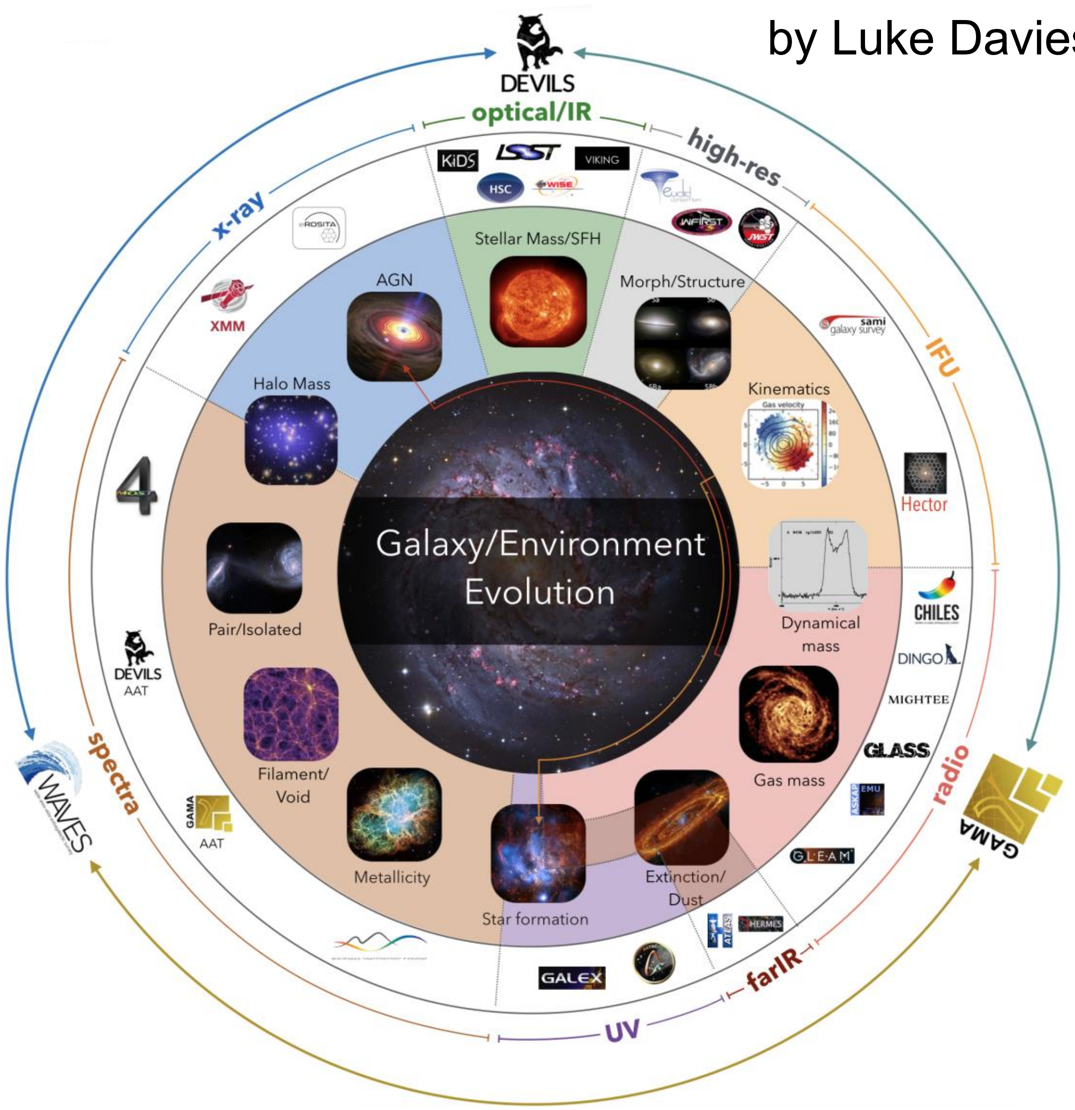


Evolution of environmental relations

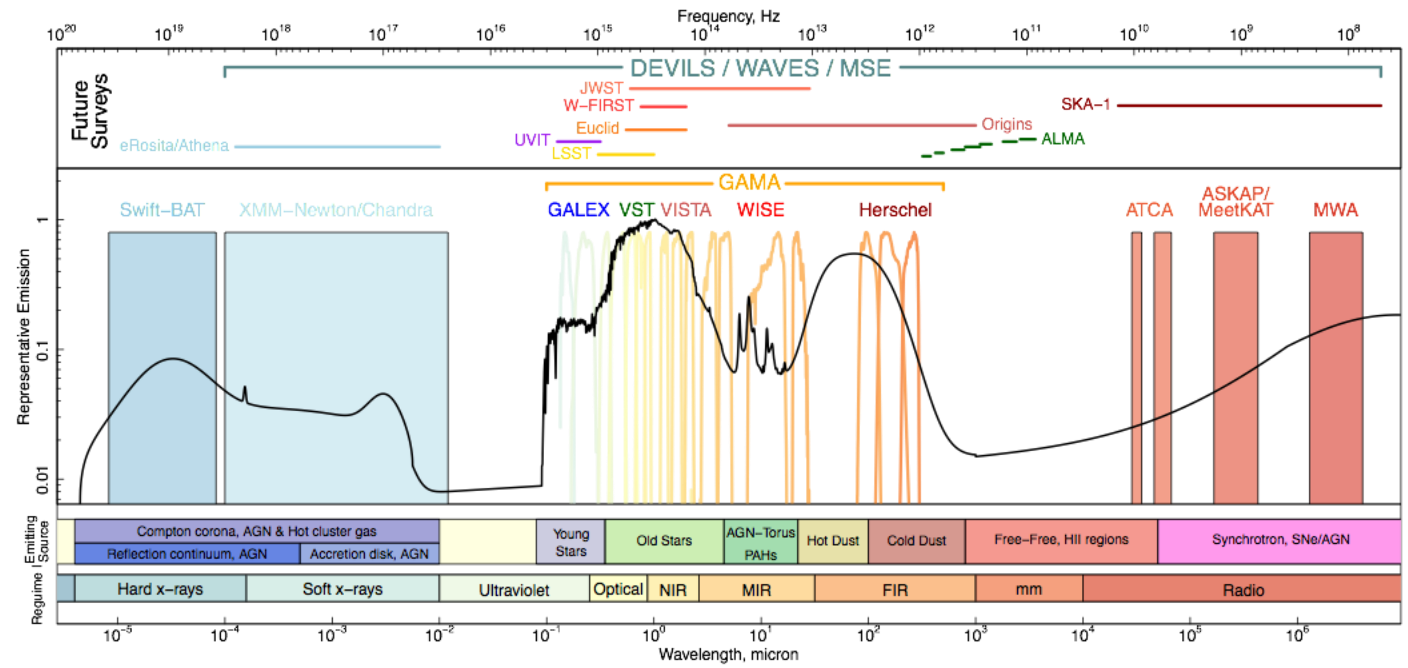
- Many galaxy properties are known to correlate with environment
- These relations are known to evolve (and even reverse)
- But studying the co-evolution of, e.g., the SFR-density and morphology-density relations, or the evolution of the merger rate requires highly complete samples at higher redshifts as well



Taking a step back …



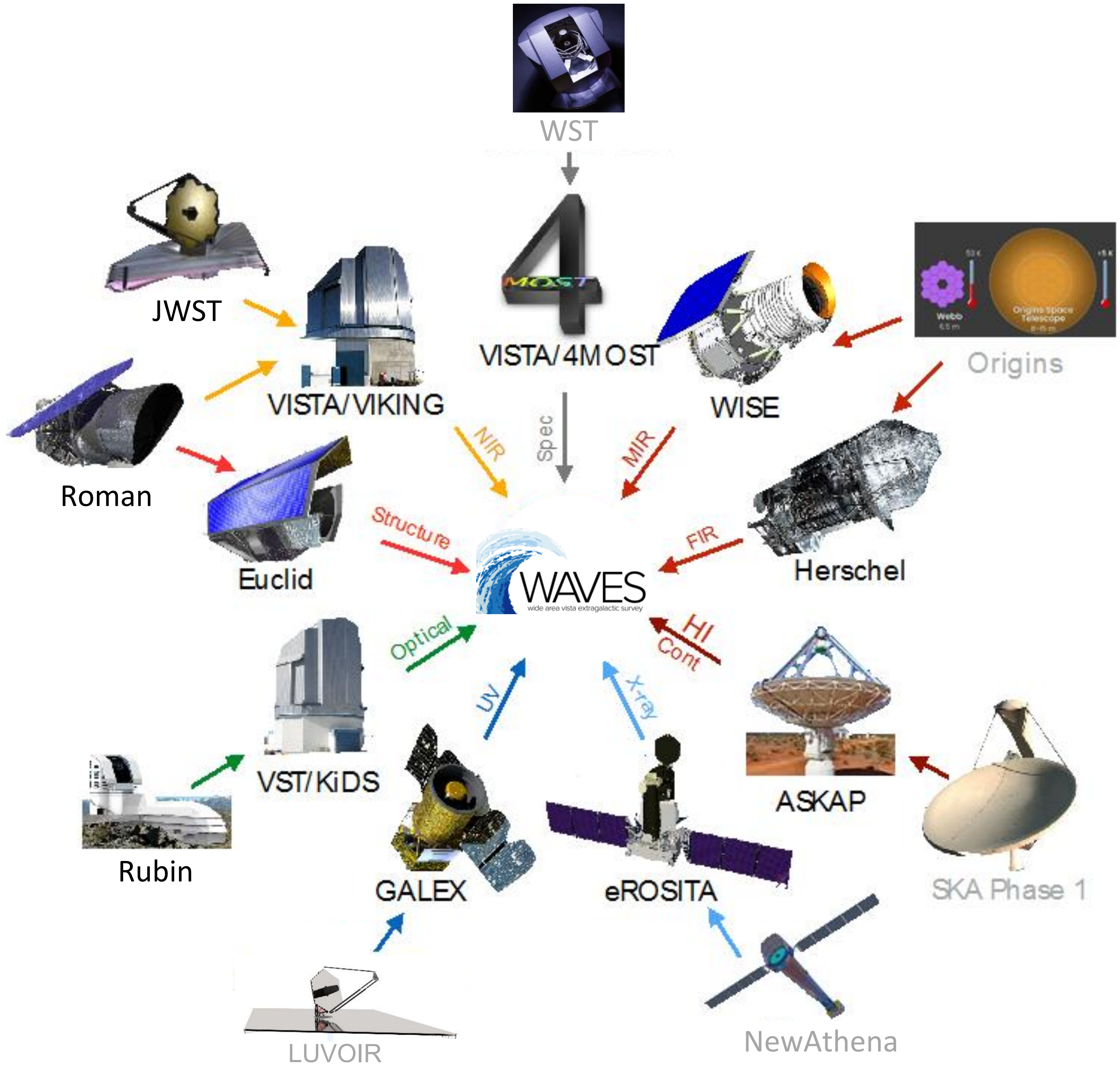
by Luke Davies



Ultimately, we want:

- Large samples for slicing parameter space
- Highly complete spectroscopy (environment)
- Multi-λ photometry from X-ray to radio
- High-res imaging (morphology)
- In an ideal world: 2D spectroscopy

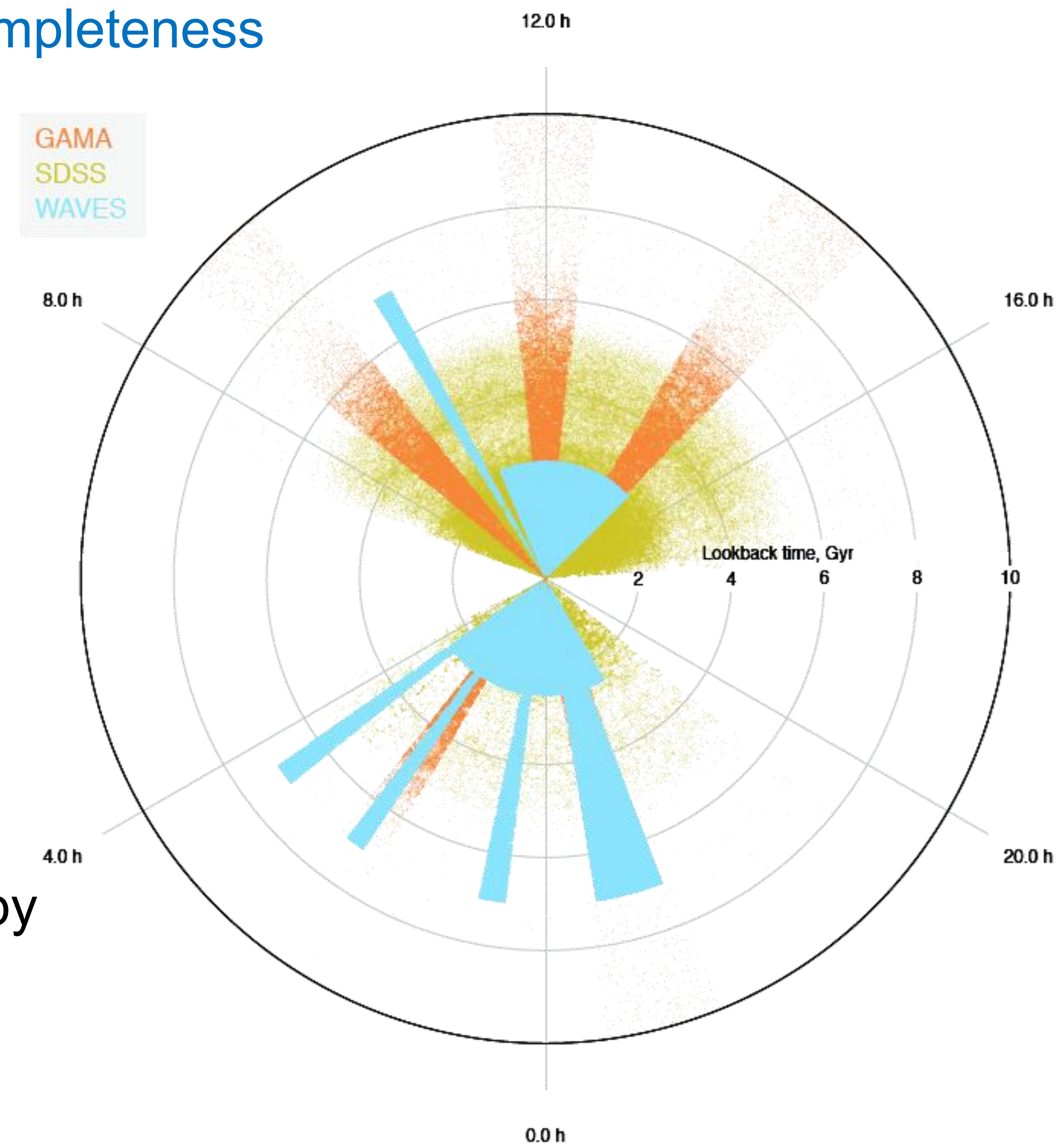
WAVES: a multi-λ endeavour



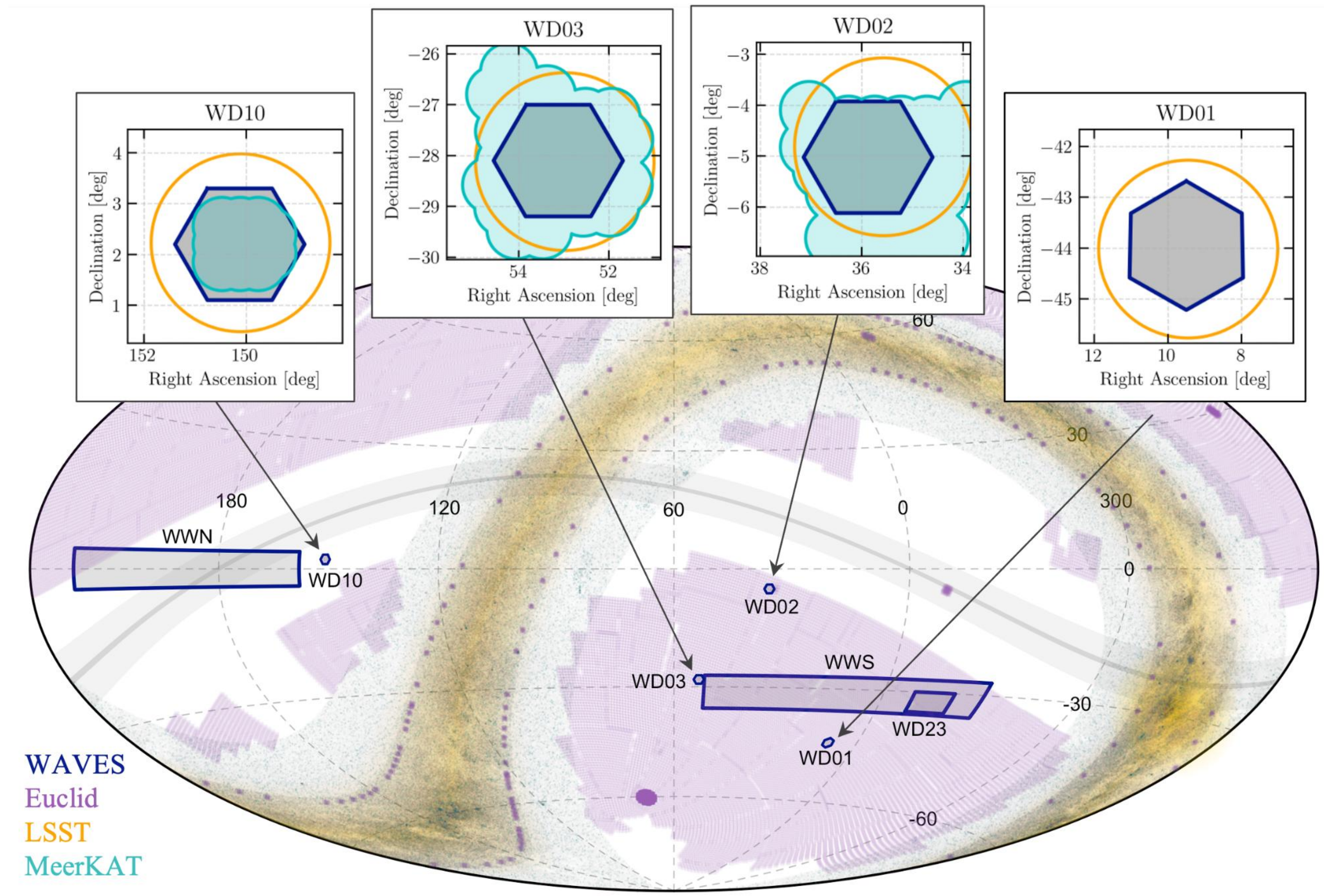
WAVES design

7 sub-surveys:

- WAVESwide: 1.9×10^6 galaxies @ 90% completeness
  - $Z < 21.2$, $z_{phot} < 0.2$ over 1134 deg^2
  - ➢ 50,000 halos down to $\sim 10^{11}\ M_{\odot}$
- WAVESdeep: 6.1×10^5 galaxies @ 90%
  - $Z < 21.25$, $z_{phot} < 0.8$ over 65 deg^2
  - ➢ 20,000 halos down to $\sim 10^{14}\ M_{\odot}$
- StePS: 3700 galaxies
  - $I_{ab} < 20.5$ and $0.3 < z < 0.7$
- ORCHIDSSwide, deep: 1.3×10^5 galaxies
  - Radio continuum and photo-z selection
- 4C3R2wide, deep: 1.1×10^6 galaxies
  - Selecting from colour cells not covered by WAVESwide or WAVESdeep



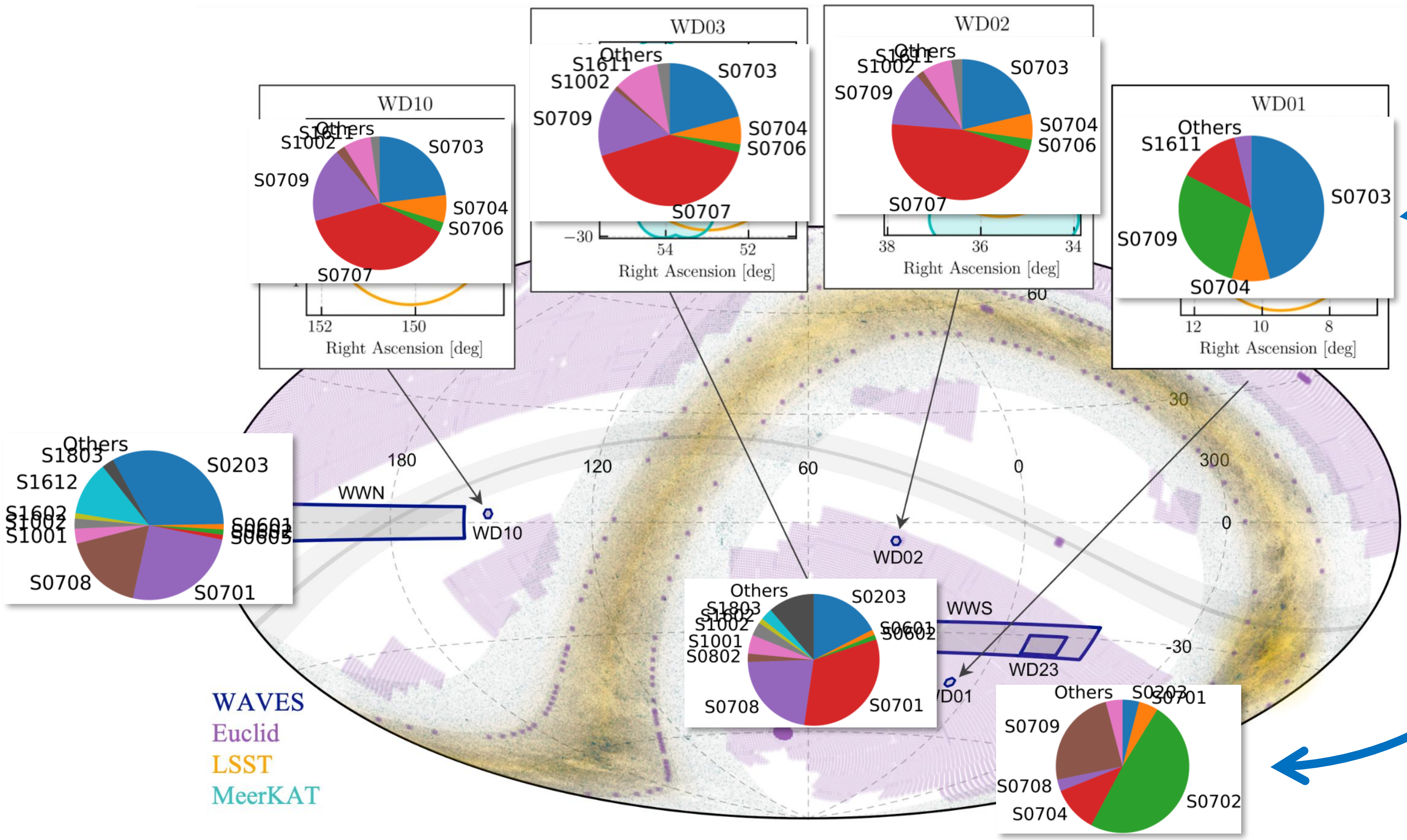
WAVES design



Bellstedt et al. (2026)

Regions	Name	RA† (deg)	Dec† (deg)	Area (sq deg)	Rotation* (deg)	photo-z limit	mag limit (Z-band mag)
WAVES-Wide North	WWN	157.25, 225.0	−3.95, +3.95	535	-	0.2	21.1
WAVES-Wide South	WWS	330.0, 51.6	−35.6, −27.0	599	-	0.2	21.1
WAVES-Deep G23	WD23	339.0, 351.0	−35.0, −30.0	~ 50	-	0.8	21.25
WAVES-Deep DDF1 (ELAIS-S1)	WD01	9.50	−43.95	4.17	0	0.8	21.25
WAVES-Deep DDF2 (XMMLSS)	WD02	35.875	−5.025	4.17	30	0.8	21.25
WAVES-Deep DDF3 (ECDFS)	WD03	53.125	−28.1	4.17	30	0.8	21.25
WAVES-Deep DDF4 (COSMOS)	WD10	150.125	+2.20	4.17	30	0.8	21.25

WAVES design

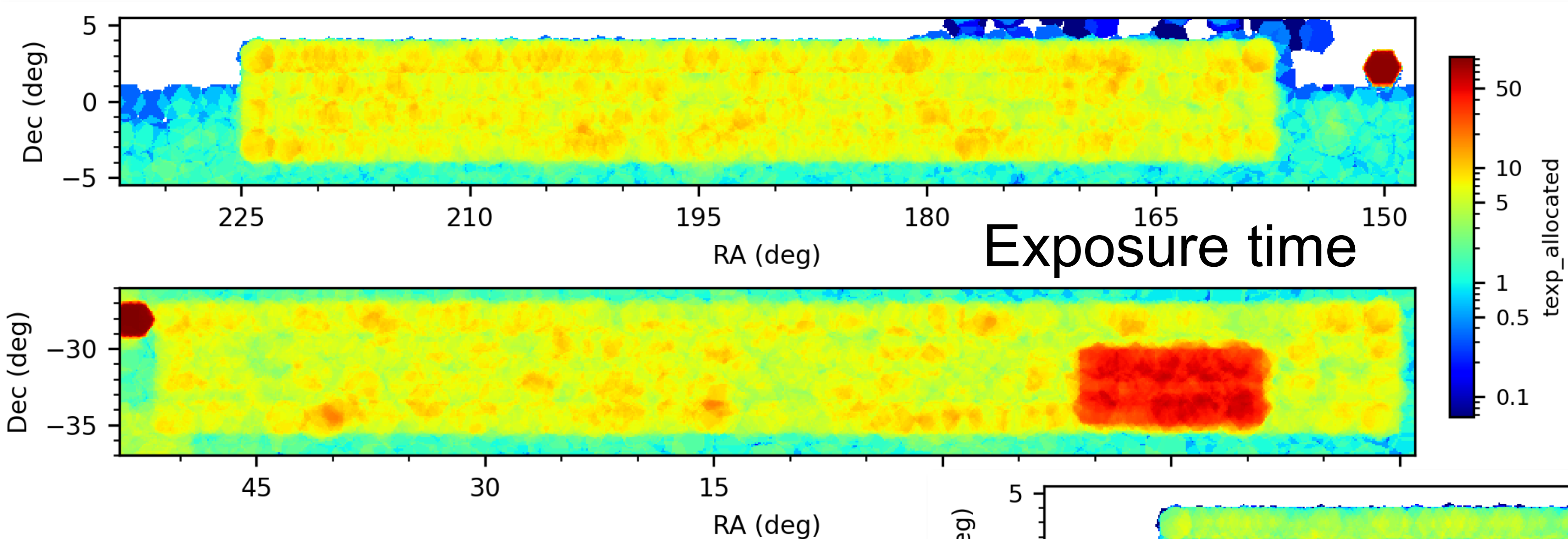


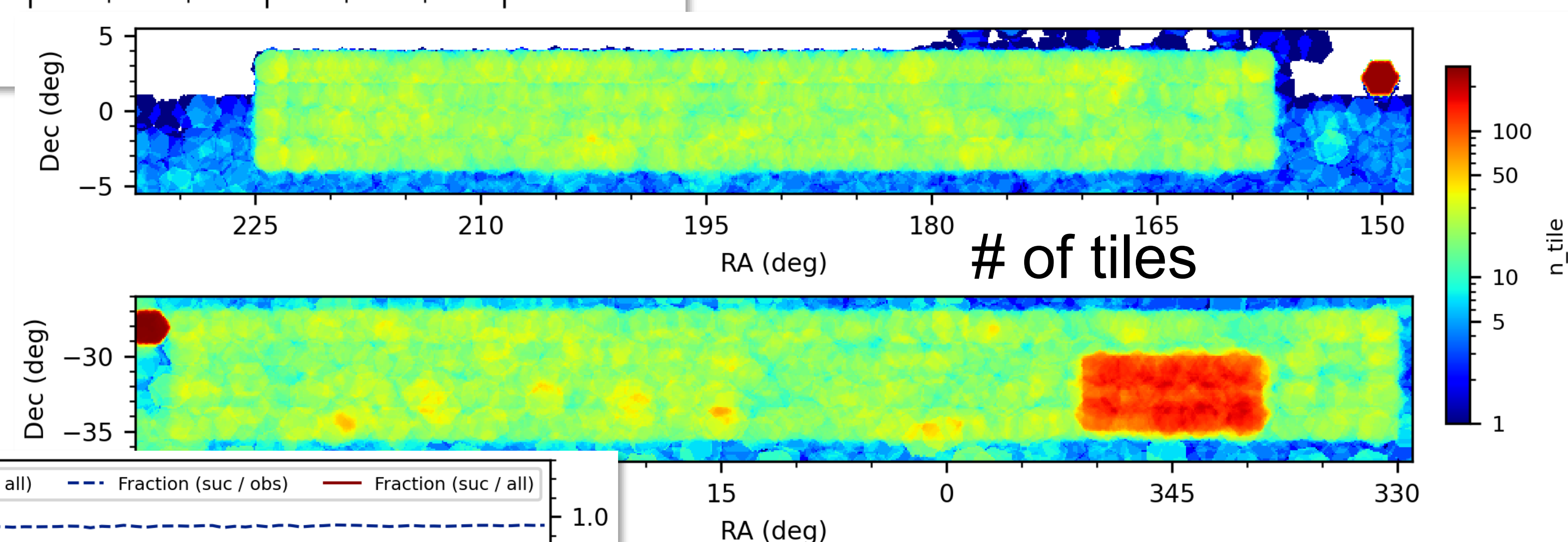
Fraction of requested time by subsurvey

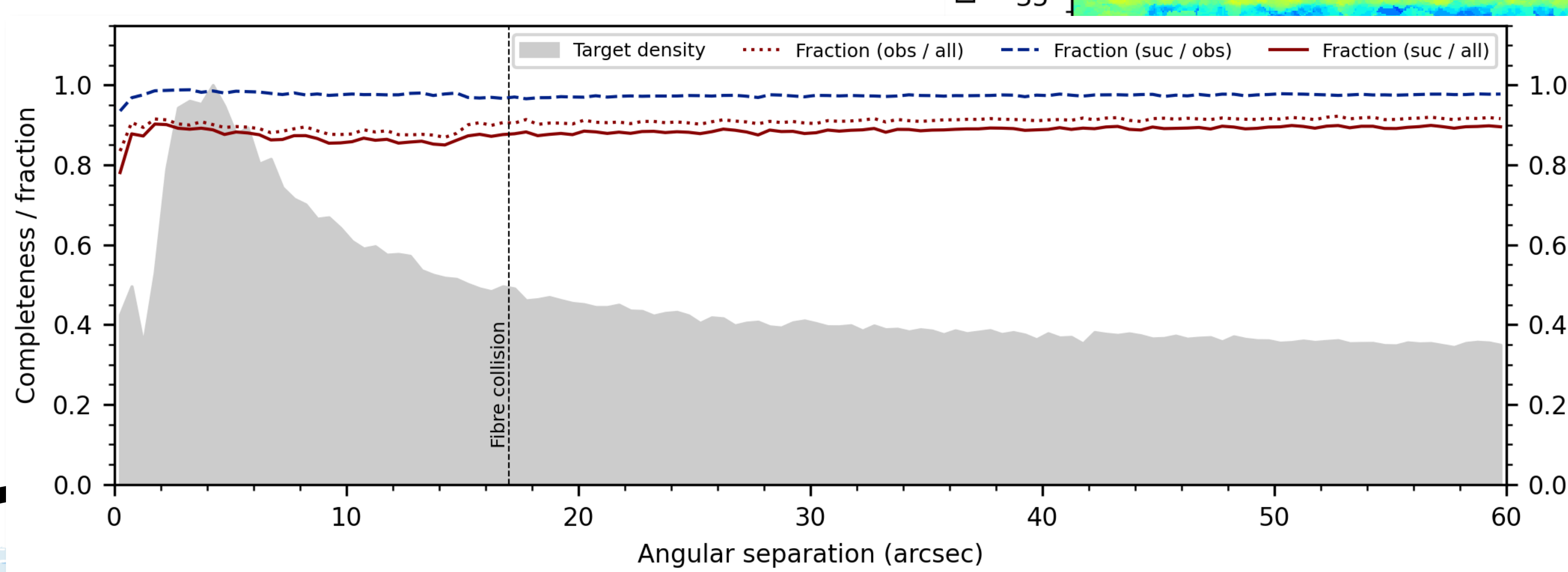
Bellstedt et al. (2026)

Regions	Name	RA[†] (deg)	Dec[†] (deg)	Area (sq deg)	Rotation* (deg)	photo-z limit	mag limit (Z-band mag)
WAVES-Wide North	WWN	157.25, 225.0	−3.95, +3.95	535	-	0.2	21.1
WAVES-Wide South	WWS	330.0, 51.6	−35.6, −27.0	599	-	0.2	21.1
WAVES-Deep G23	WD23	339.0, 351.0	−35.0, −30.0	∼ 50	-	0.8	21.25
WAVES-Deep DDF1 (ELAIS-S1)	WD01	9.50	−43.95	4.17	0	0.8	21.25
WAVES-Deep DDF2 (XMMLSS)	WD02	35.875	−5.025	4.17	30	0.8	21.25
WAVES-Deep DDF3 (ECDFS)	WD03	53.125	−28.1	4.17	30	0.8	21.25
WAVES-Deep DDF4 (COSMOS)	WD10	150.125	+2.20	4.17	30	0.8	21.25

WAVES design

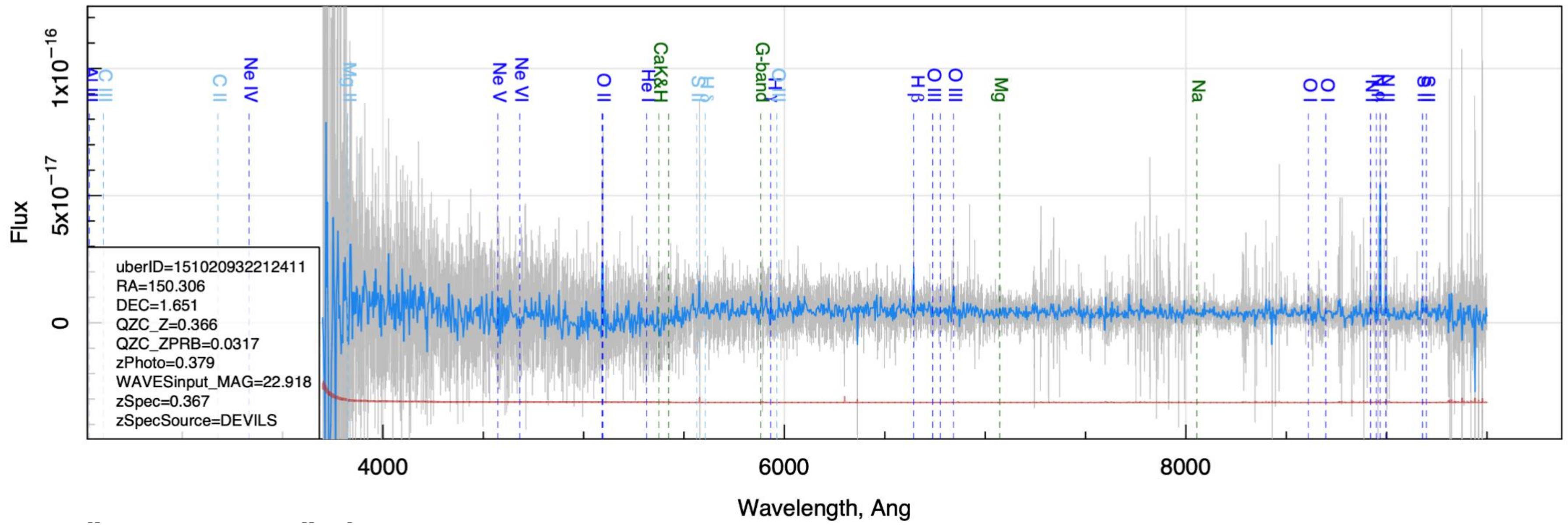


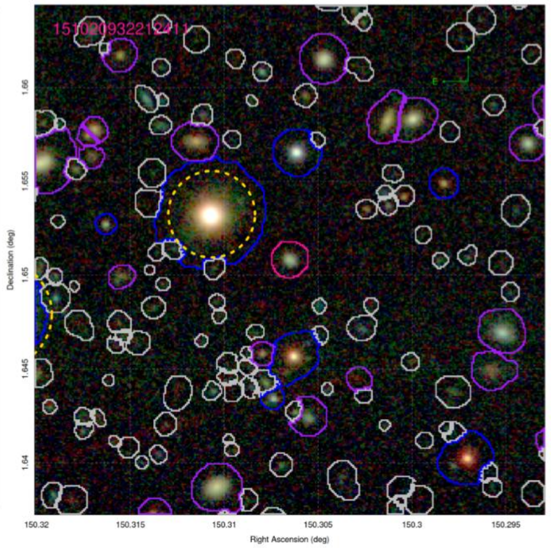




Large number of tiles crucial for high completeness in dense regions!

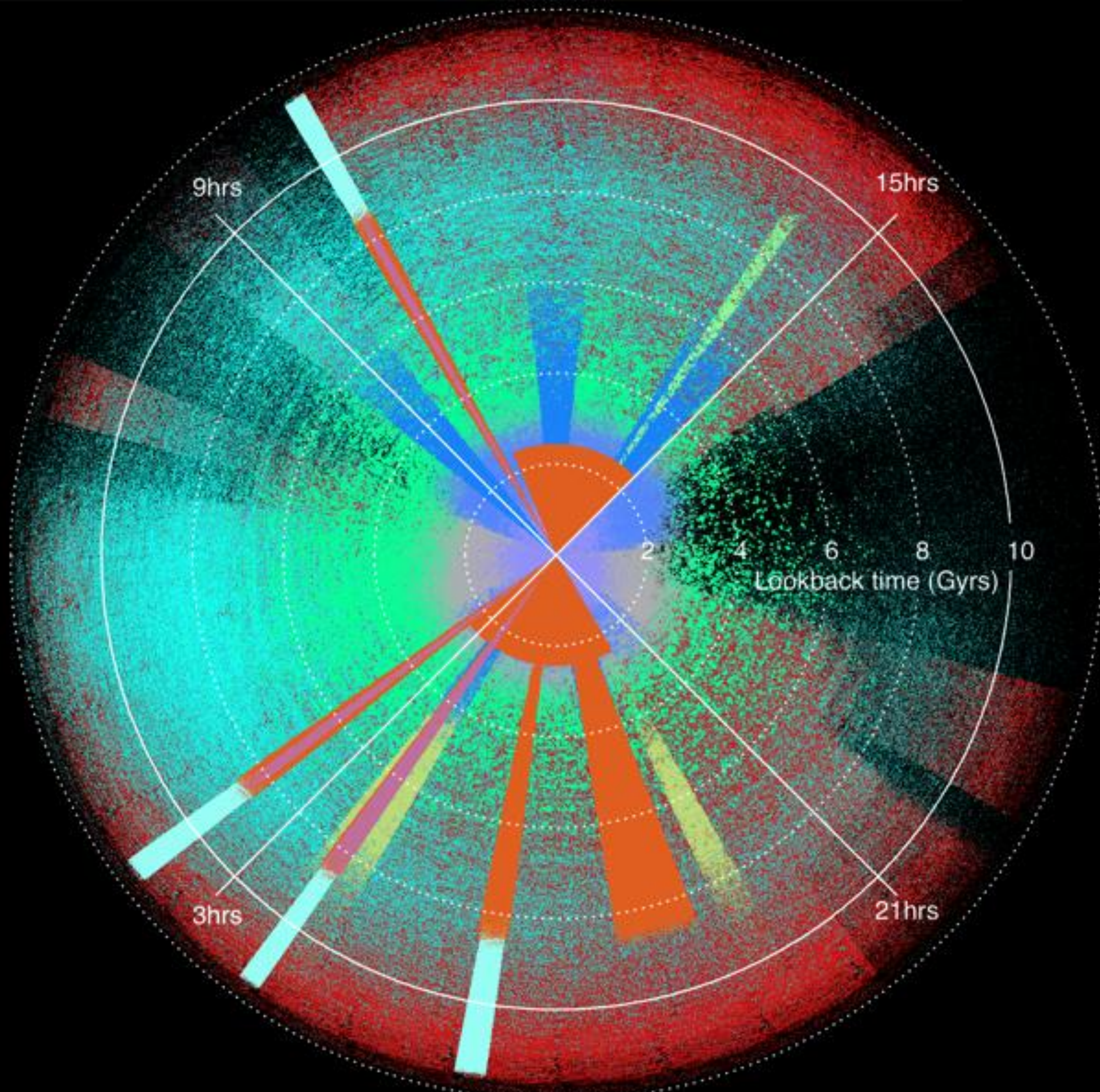
Ongoing SPV analyses

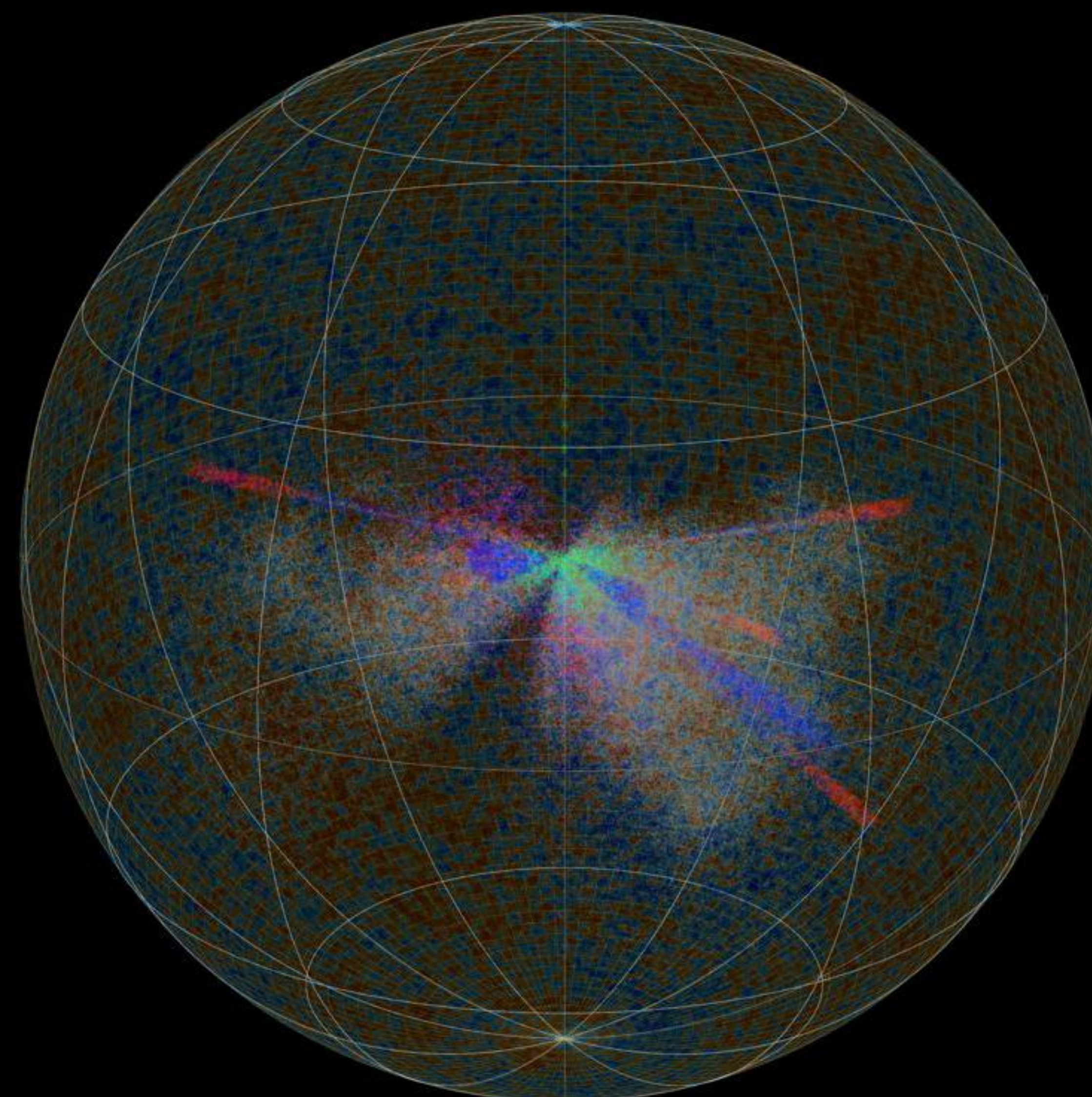




- Test of selection boundaries of target catalogue
  - star/galaxy separation
  - photo-z limits
- Test of predicted exposure times required for a successful redshift measurement as a function of
  - magnitude
  - spectral template, z
- Does stacking of 30 h of data work?
- Redshift success as a function of SOM cell

Cosmology AGN Clusters WAVES MOONS





Showing 1% of each 4MOST ex-gal survey