The many lives of AGN II: the formation and evolution of radio jets and their impact on galaxy evolution

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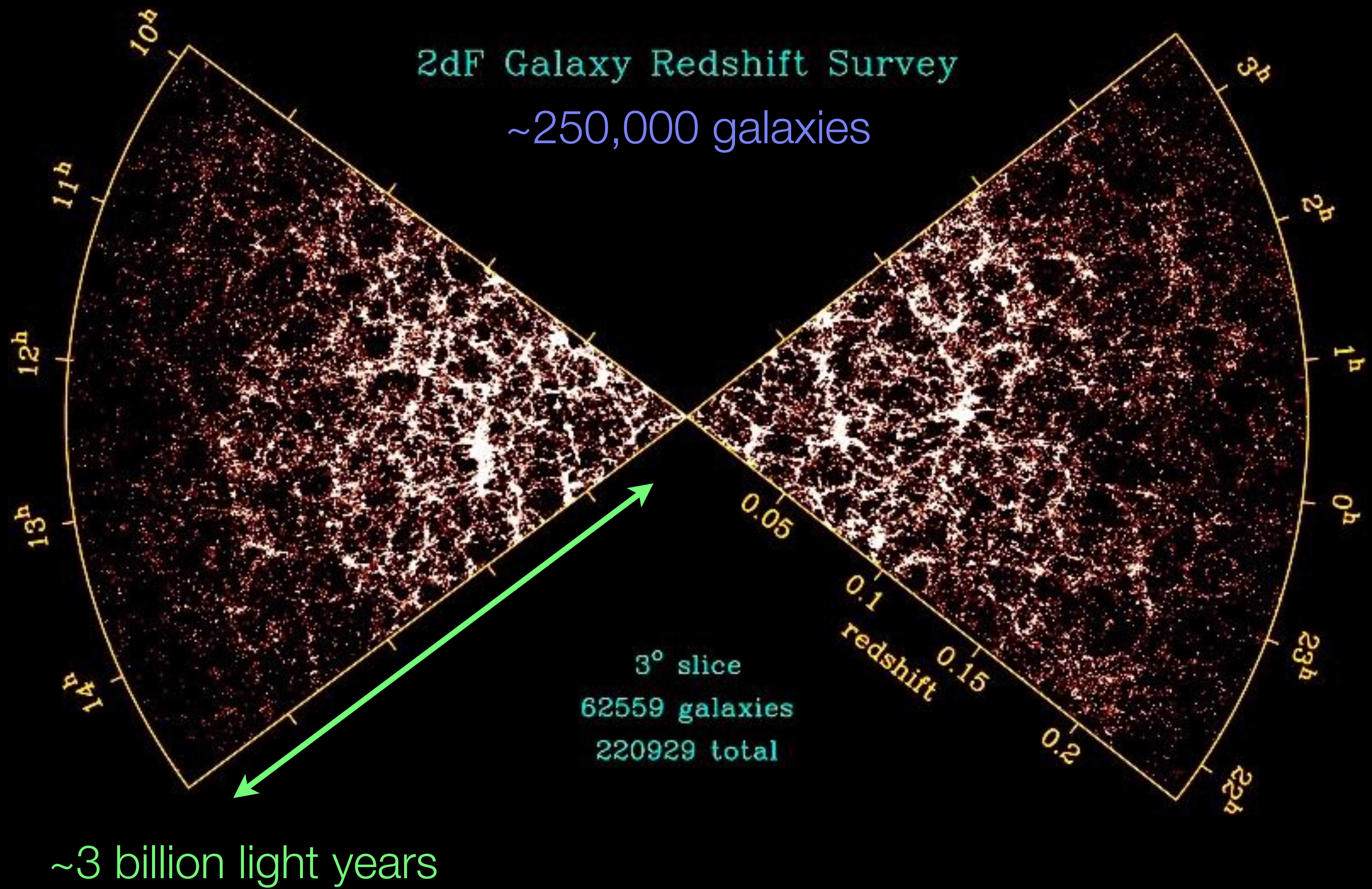
Max Bernyk (seek.com.au)

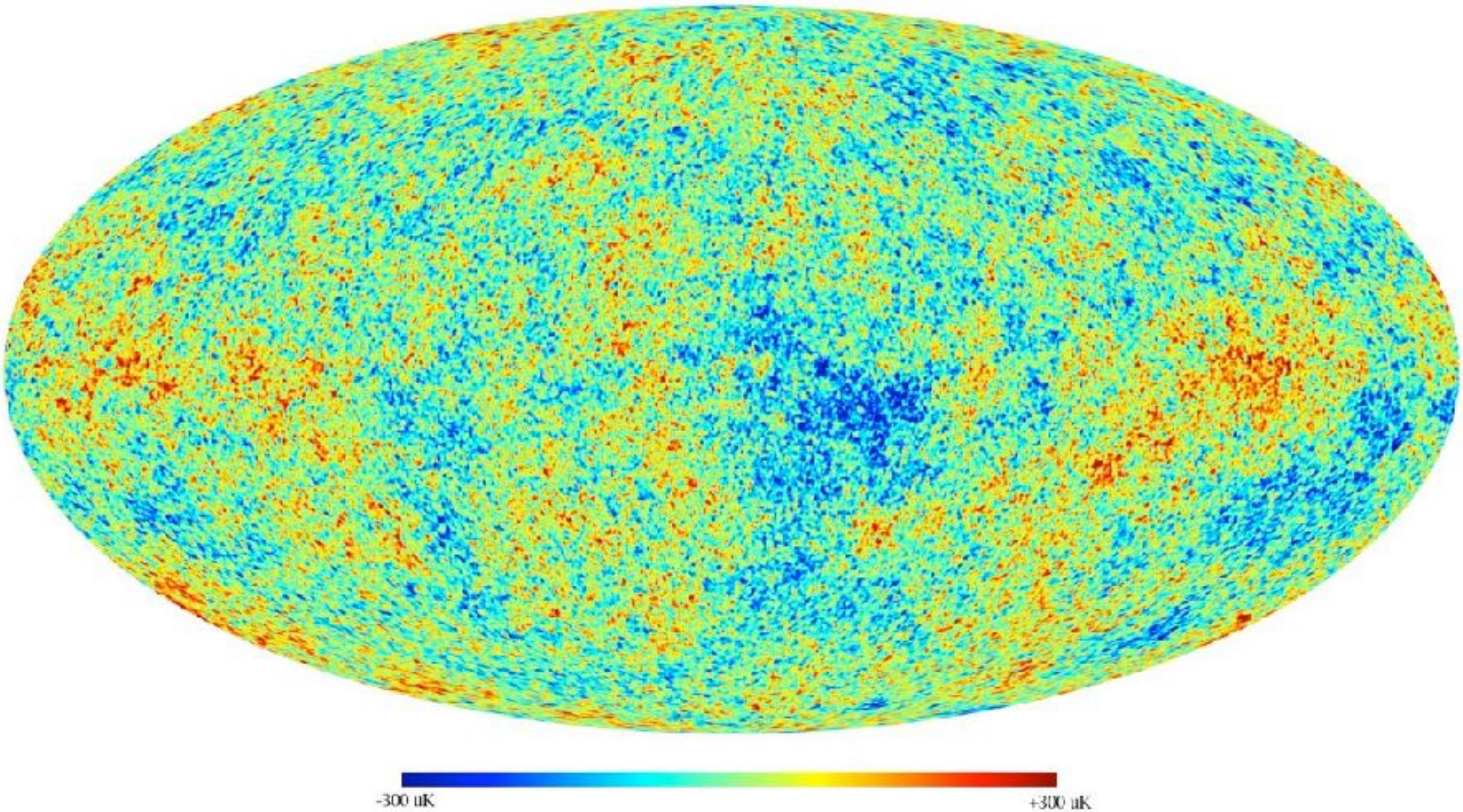
an overview of modelling galaxies across cosmic time

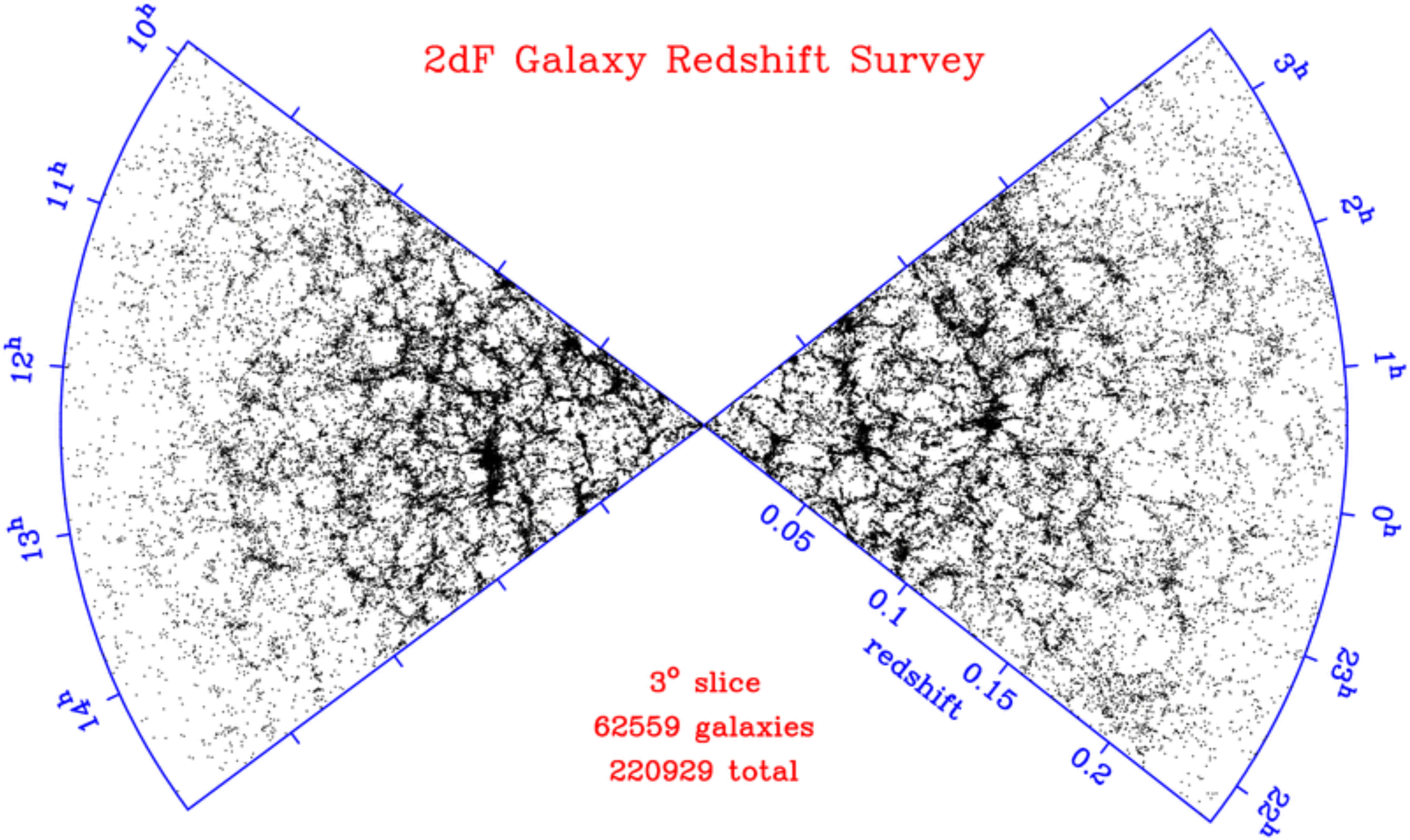
AGN and the radio population

running your own galaxy formation models

accessing pre-made galaxy models for science


2dF Galaxy Redshift Survey
~250,000 galaxies
10h
11h
12h
13h
14h
3h
2h
1h
0h
23h
22h
0.05
0.1
0.15
0.2
redshift
3° slice
62559 galaxies
220929 total
~3 billion light years


-300 uK
+300 uK



2dF Galaxy Redshift Survey
10h
11h
12h
13h
14h
3h
2h
1h
0h
23h
22h
0.05
0.1
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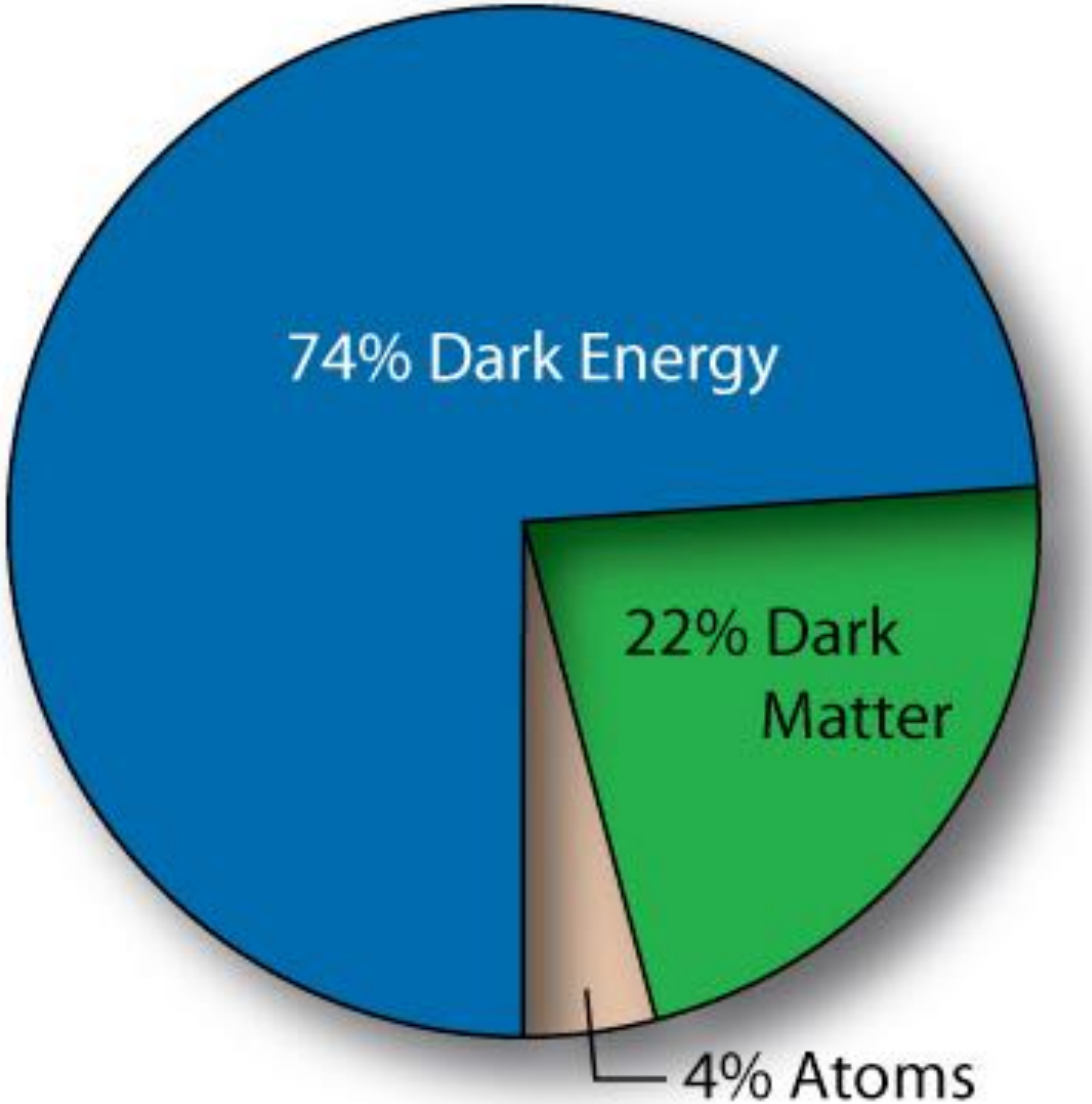
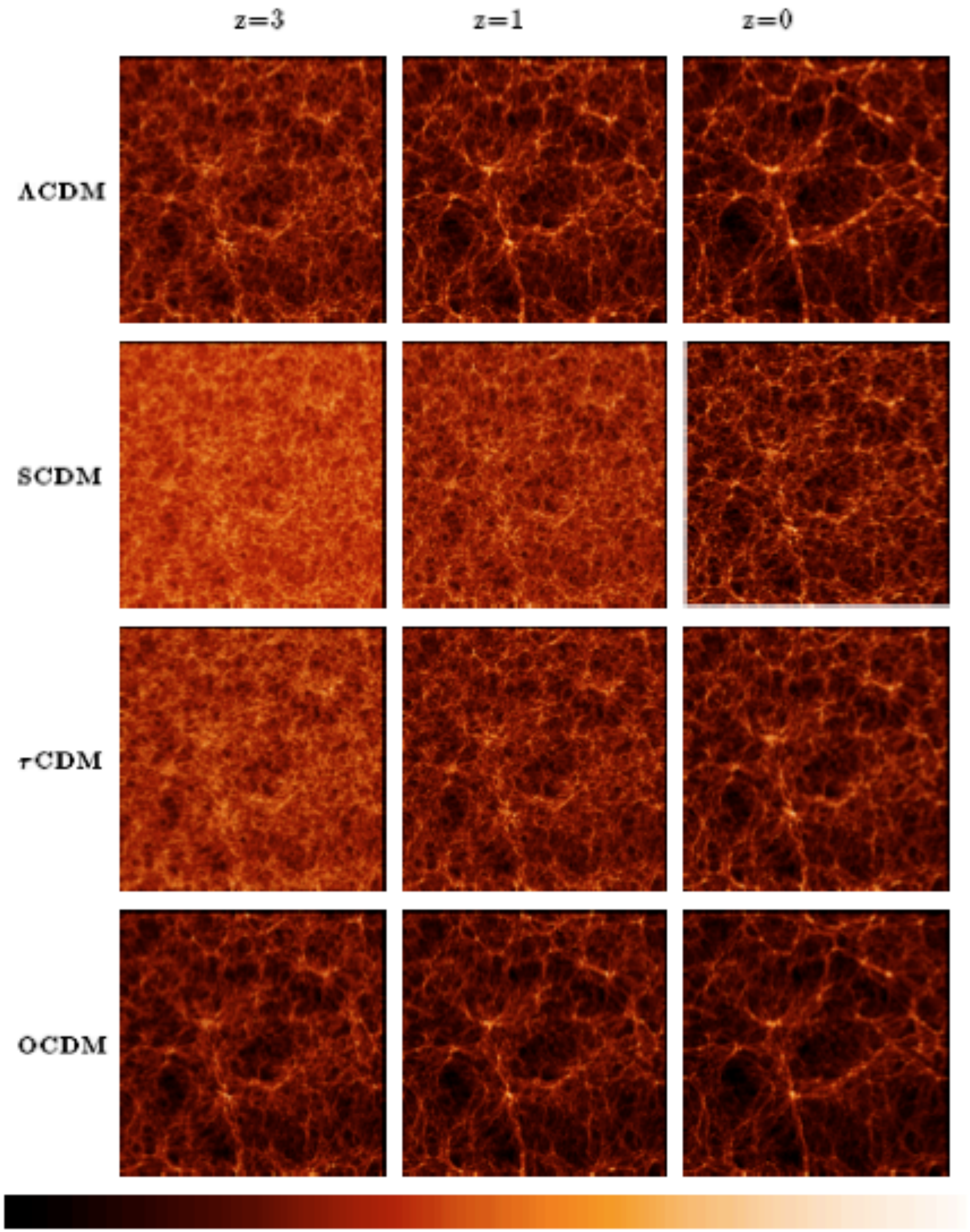
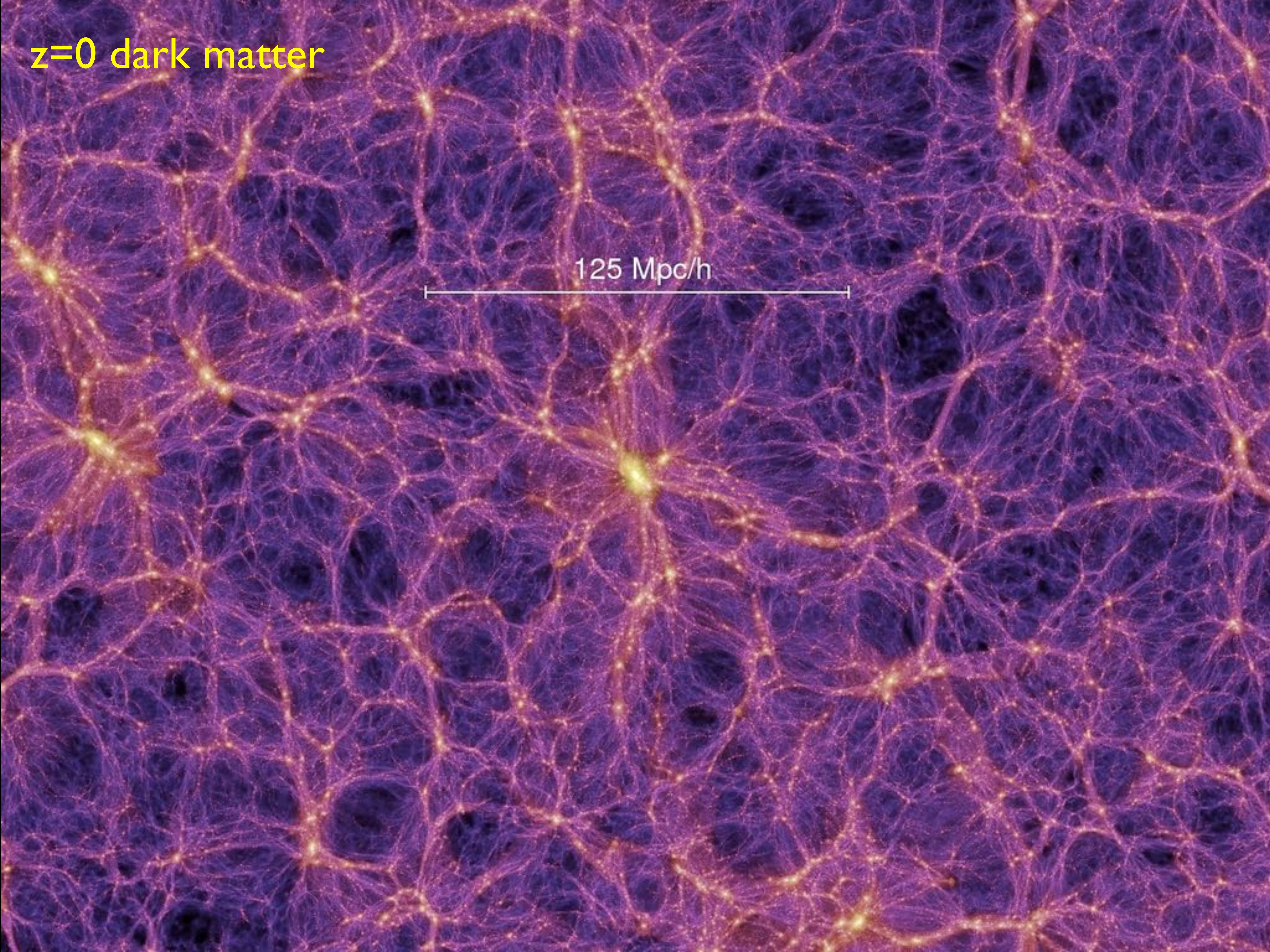
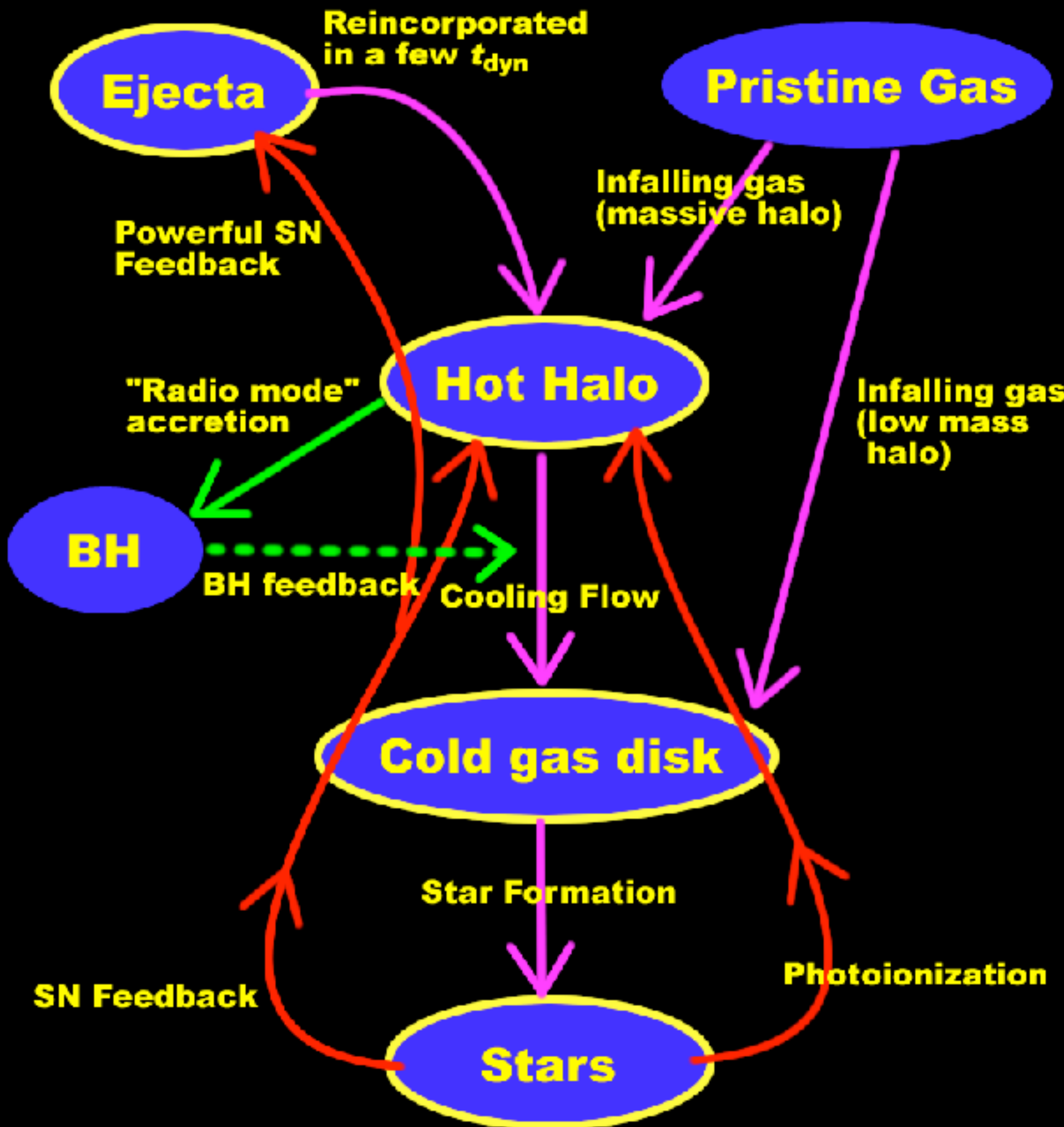
3° slice
62559 galaxies
220929 total


74% Dark Energy
22% Dark Matter
4% Atoms



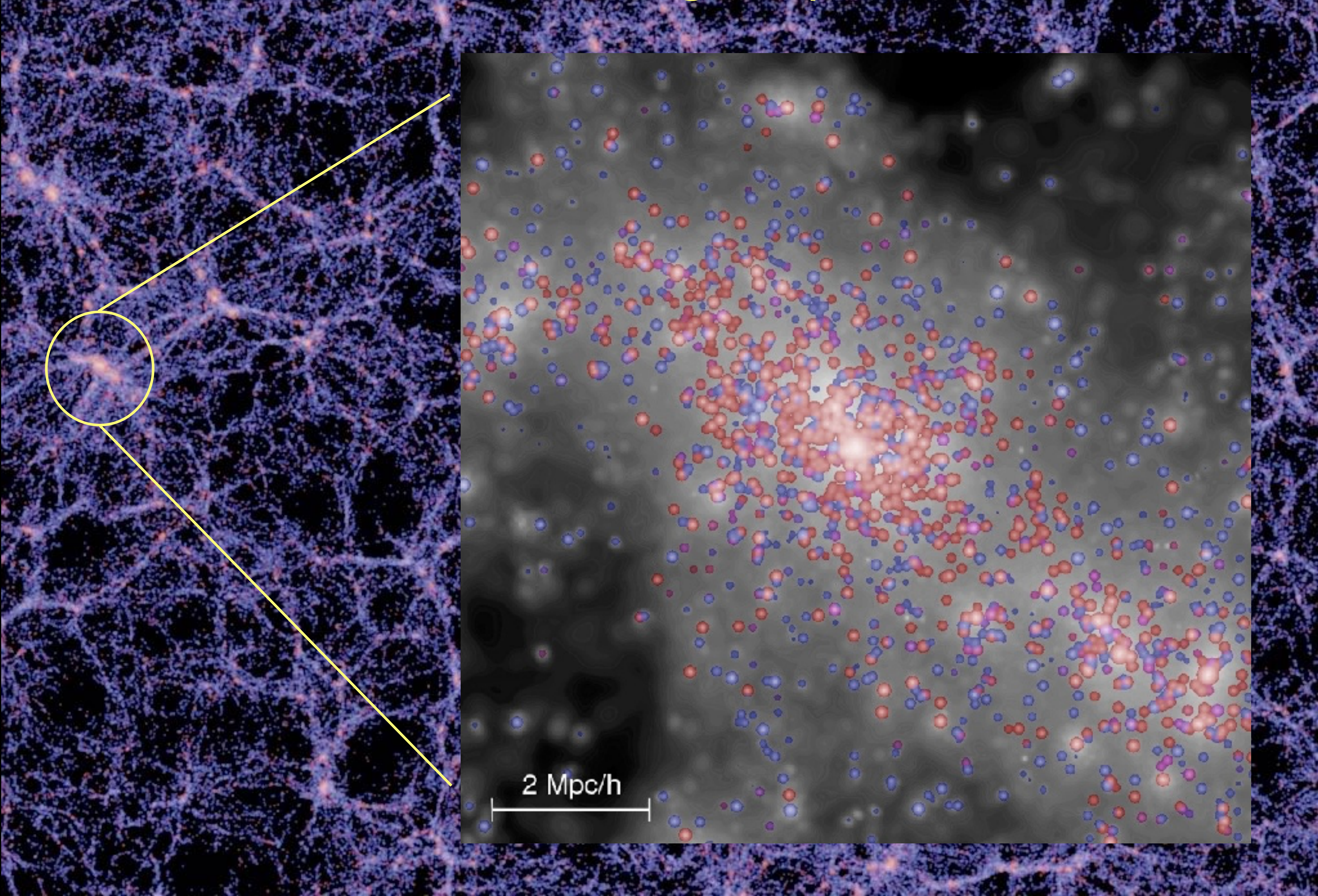
z=3
z=1
z=0
ΛCDM
SCDM
τCDM
OCDM

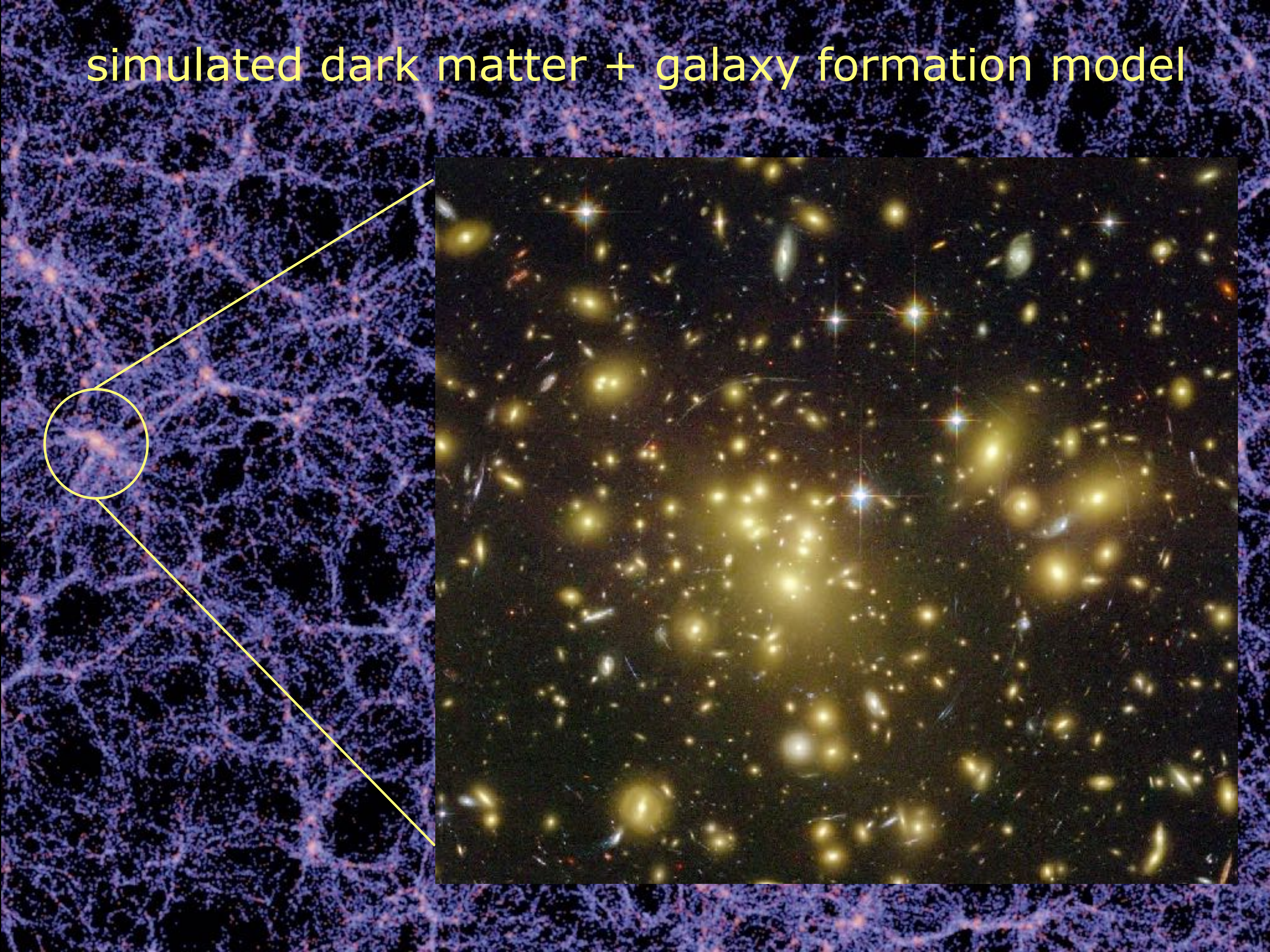

z=0 dark matter
125 Mpc/h



- Schmidt law star formation
- SFR dependent SN winds
- satellite gas stripping
- morphological transformation
- assembly through mergers
- starbursts through mergers
- Magorrian relation BH growth
- jet & bubble AGN feedback

simulated dark matter + galaxy formation model




simulated dark matter + galaxy formation model

Mon. Not. R. Astron. Soc. **365**, 11–28 (2006) doi:10.1111/j.1365-2966.2005.09675.x

The many lives of active galactic nuclei: cooling flows, black holes and the luminosities and colours of galaxies

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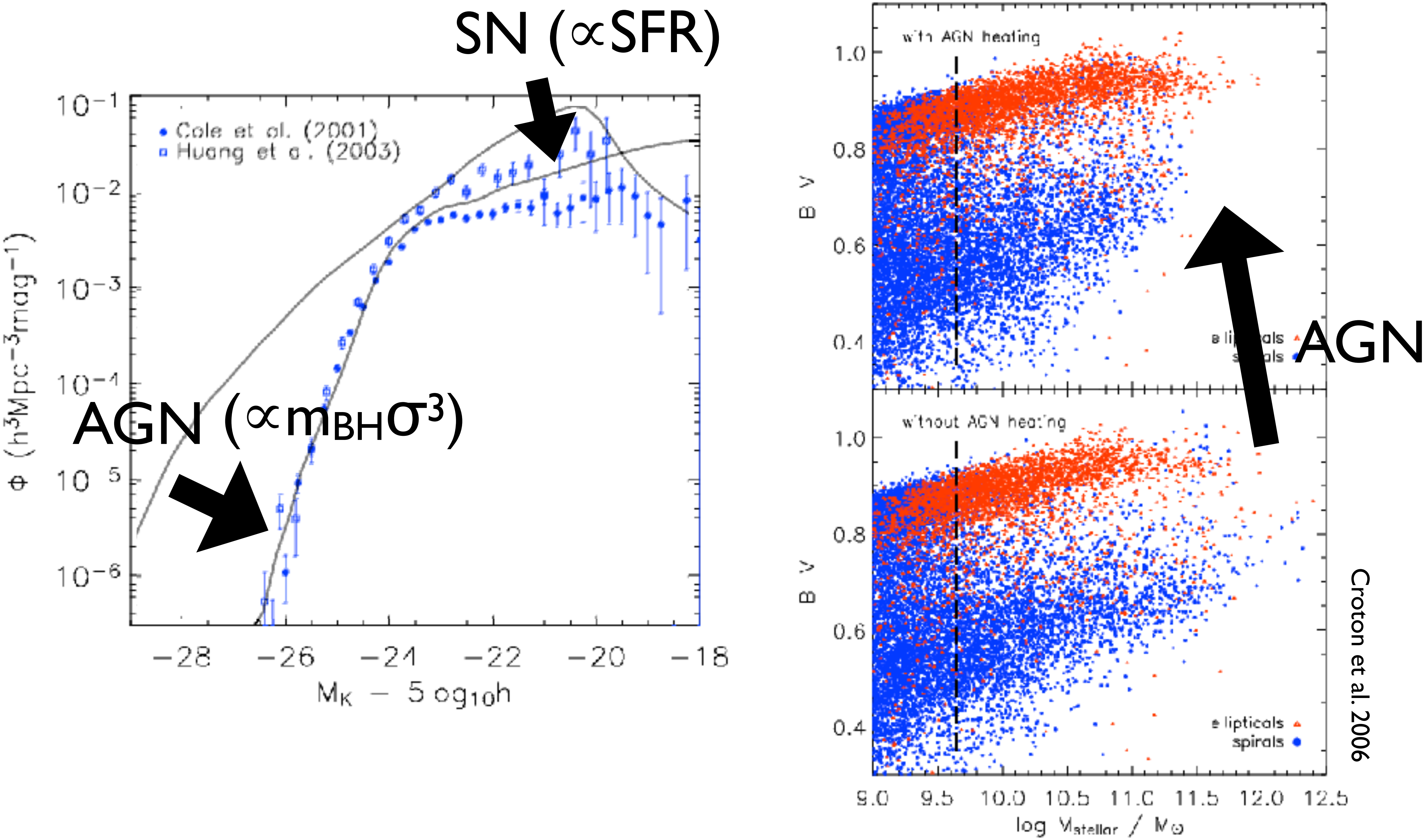
ABSTRACT

We simulate the growth of galaxies and their central supermassive black holes by implementing a suite of semi-analytic models on the output of the Millennium Run, a very large simulation of the concordance Λ cold dark matter cosmogony. Our procedures follow the detailed assembly history of each object and are able to track the evolution of all galaxies more massive than the Small Magellanic Cloud throughout a volume comparable to that of large modern redshift surveys. In this first paper we supplement previous treatments of the growth and activity of central black holes with a new model for 'radio' feedback from those active galactic nuclei that lie at the centre of a quasi-static X-ray-emitting atmosphere in a galaxy group or cluster. We show that for energetically and observationally plausible parameters such a model can simultaneously explain: (i) the low observed mass drop-out rate in cooling flows; (ii) the exponential cut-off at the bright end of the galaxy luminosity function; and (iii) the fact that the most massive galaxies tend to be bulge-dominated systems in clusters and to contain systematically



Croton et al. 2006

SAGE: Semi-Analytic Galaxy Evolution

Croton et al., ApJS, 2016

Goal: release a publicly available semi-analytic codebase that is …

… fast, clean, modular

… easy to install and use

… can run on multiple simulations

https://github.com/darrencroton/sage

Draft version January 25, 2016
Preprint typeset using LaTeX style emulateapj v. 11/10/09

SEMI-ANALYTIC GALAXY EVOLUTION (SAGE): MODEL CALIBRATION AND BASIC RESULTS

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Draft version January 25, 2016

ABSTRACT

This paper describes a new publicly available codebase for modelling galaxy formation in a cosmological context, the "Semi-Analytic Galaxy Evolution" model, or SAGE for short.[a] SAGE is a significant update to that used in Croton et al. (2006) and has been rebuilt to be modular and customisable. The model will run on any N-body simulation whose trees are organised in a supported format and contain a minimum set of basic halo properties. In this work we present the baryonic prescriptions implemented in SAGE to describe the formation and evolution of galaxies, and their calibration for three N-body simulations: Millennium, Bolshoi, and GiggleZ. Updated physics include: gas accretion, ejection due to feedback, and reincorporation via the galactic fountain; a new gas cooling–radio mode active galactic nucleus (AGN) heating cycle; AGN feedback in the quasar mode; a new treatment of gas in satellite galaxies; and galaxy mergers, disruption, and the build-up of intra-cluster stars. Throughout, we show the results of a common default parameterization on each simulation, with a focus on the local galaxy population.

Subject headings: galaxies: active – galaxies: evolution – galaxies: environment – galaxies: halos – methods: numerical

1. INTRODUCTION

Developing a complete theory of galaxy evolution is a formidable task. Without the ability to construct real universes in a laboratory, we are left to test ideas through conducting supercomputer simulations and comparing their results against what we observe. Arguably the most thorough way of doing this currently is through cosmological hydrodynamic simulations (e.g. Carlberg,

body Dark Sky simulations (Skillman et al. 2014) with 10240^3 particles. The addition of hydrodynamics comes at the cost of approximately two orders of magnitude in particle number.

Semi-analytic models of galaxy evolution take advantage of the relative computational efficiency of N-body simulations by adding the bound baryons to a simulation as a post-processing step. By using information about

Compared to Croton et al. 2006...

NEW! Gas cooling and AGN heating

NEW! Quasar mode feedback

NEW! Ejected gas reincorporation

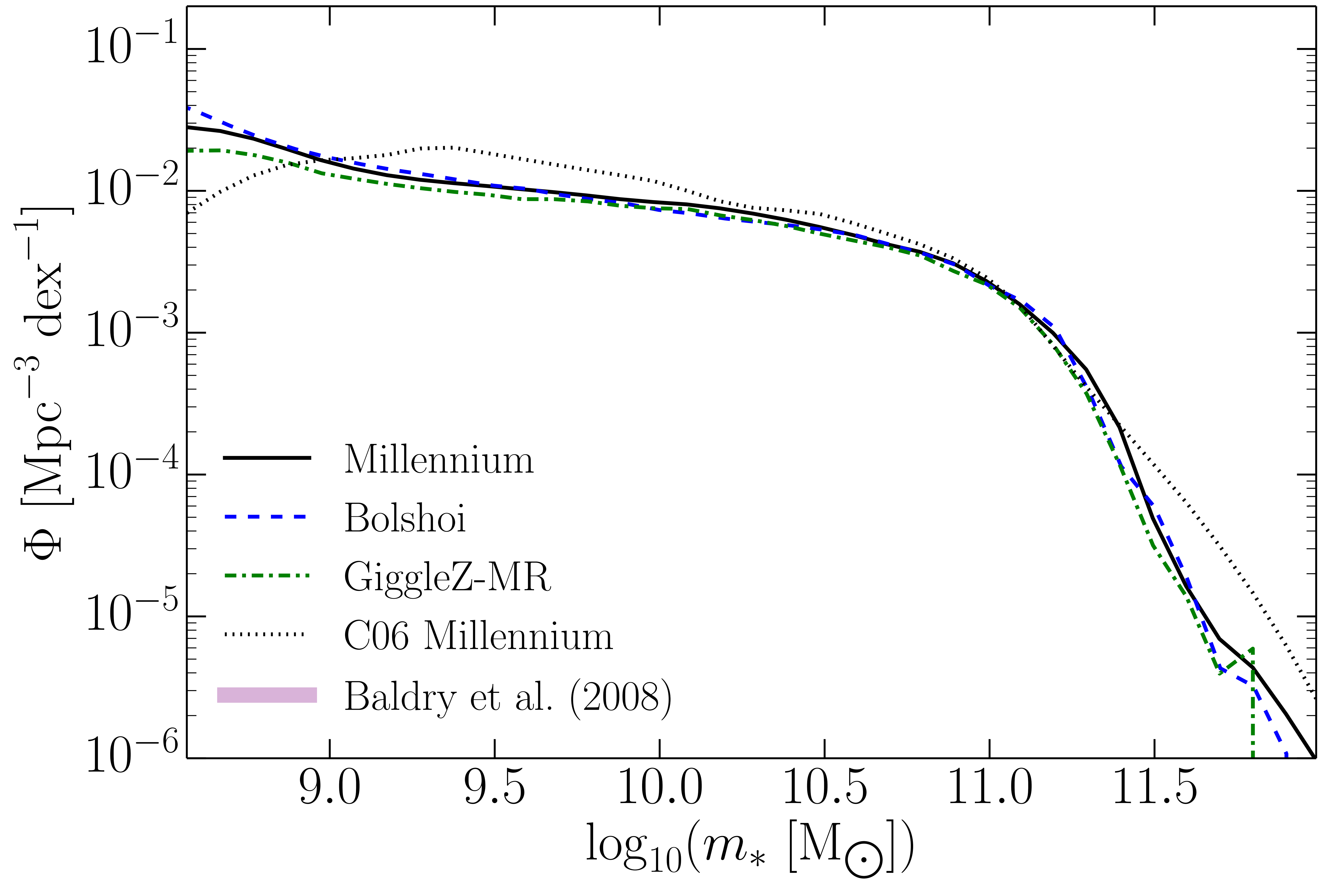
NEW! Satellite galaxies prescription

NEW! Mergers and intra-cluster stars

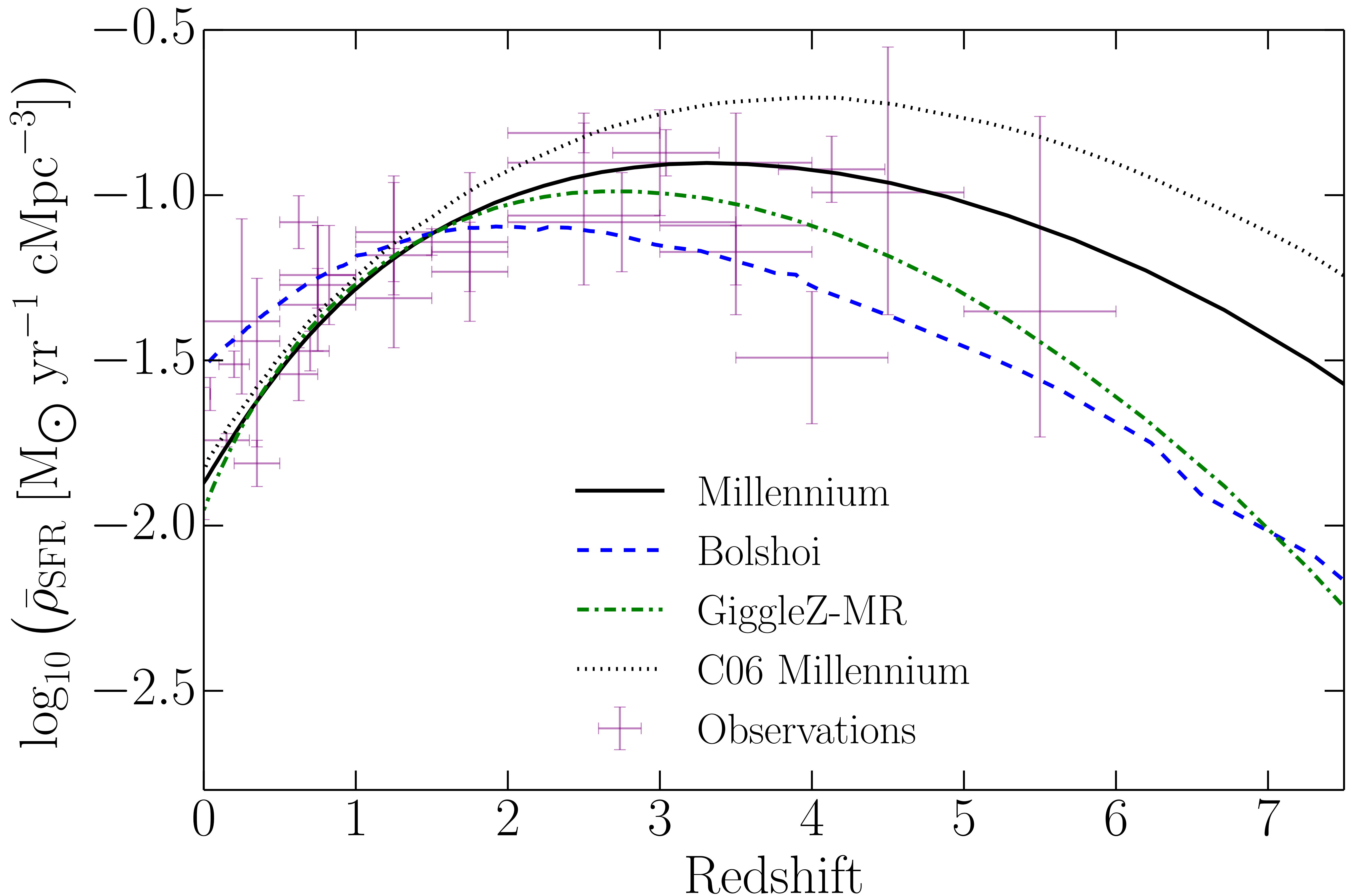
https://github.com/darrencroton/sage

Simulation	$N_{\rm part}$	$M_{\rm part}h$ ($\rm M_{\odot}$)	$l_{\rm box}h$ (cMpc)	Ω_M	σ_8	Code	Subhalo finder	Tree constructor
Millennium	2160^3	8.60×10^8	500	0.250	0.900	GADGET-2	SUBFIND	L-HALOTREE
Bolshoi	2048^3	1.35×10^8	250	0.270	0.820	ART	ROCKSTAR	CONSISTENT-TREES
GiggleZ-MR	520^3	9.50×10^8	125	0.273	0.812	GADGET-2	SUBFIND	Poole et al. (in prep.)

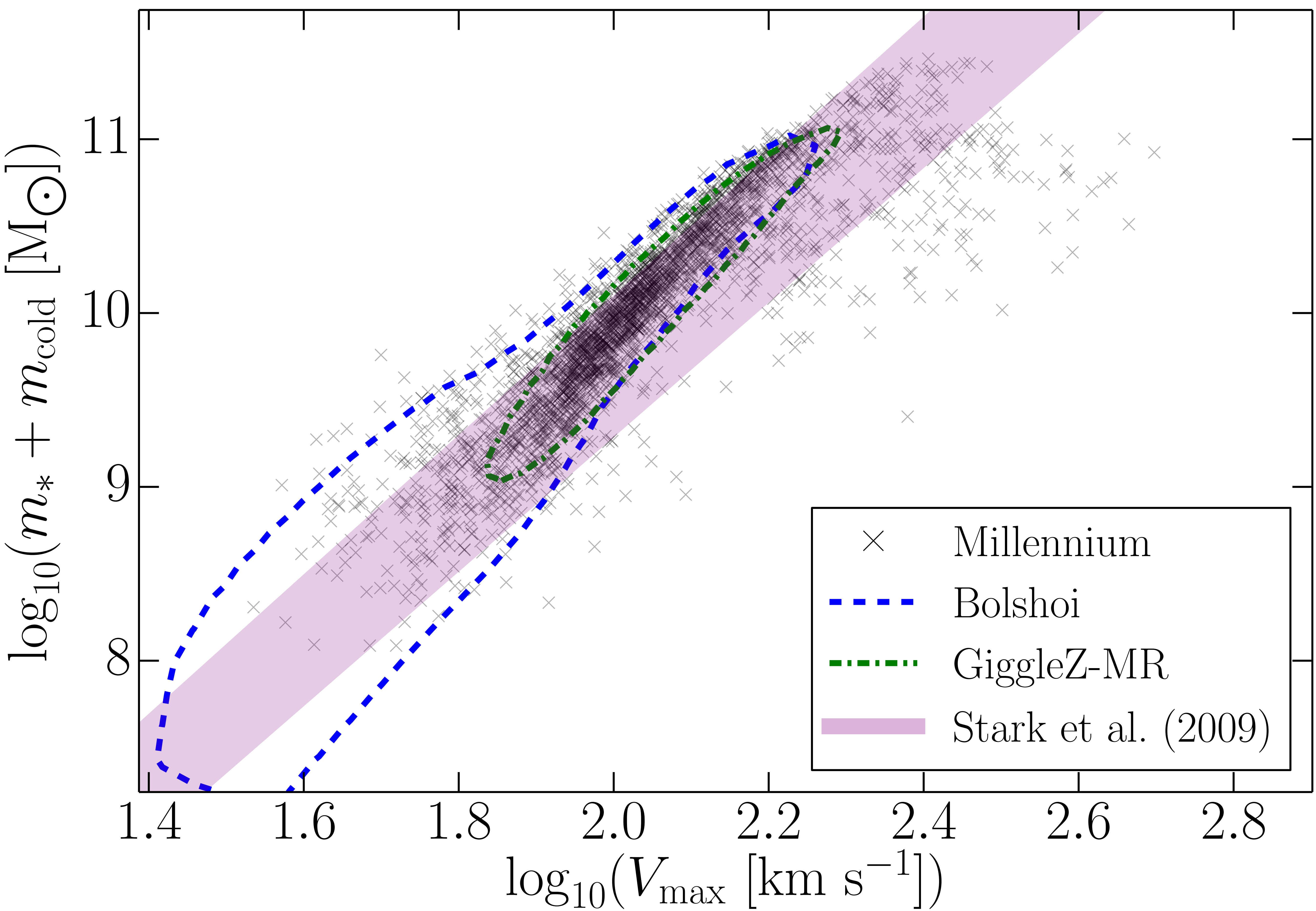
Parameter	Description	Value	C06 value	Fixed	Section(s)
$f_b^{\rm (cosmic)}$	(Cosmic) baryon fraction	0.17, 0.13	0.17	No	4, 5
z_0	Redshift when H II regions overlap	8.0	8.0	Yes	5
z_r	Redshift when the intergalactic medium is fully reionized	7.0	7.0	Yes	5
$\alpha_{\rm SF}$	Star formation efficiency	0.05	0.07	No	7
Y	Yield of metals from new stars	0.025	0.03	No	7
$\mathcal{R}$	Instantaneous recycling fraction	0.43	0.30	Yes	7, 8
$\epsilon_{\rm disc}$	Mass-loading factor due to supernovae	3.0	3.5	No	8
$\epsilon_{\rm halo}$	Efficiency of supernovae to unbind gas from the hot halo	0.3	0.35	No	8
$k_{\rm reinc}$	Sets velocity scale for gas reincorporation	0.15	N/A	Yes	8
$\kappa_{\rm R}$	Radio mode feedback efficiency	0.08	N/A	No	9.1
$\kappa_{\rm Q}$	Quasar mode feedback efficiency	0.005	N/A	No	9.2
$f_{\rm BH}$	Rate of black hole growth during quasar mode	0.015	0.03	No	9.2
$f_{\rm friction}$	Threshold subhalo-to-baryonic mass for satellite disruption or merging	1.0	N/A	Yes	10
$f_{\rm major}$	Threshold mass ratio for merger to be major	0.3	0.3	Yes	10



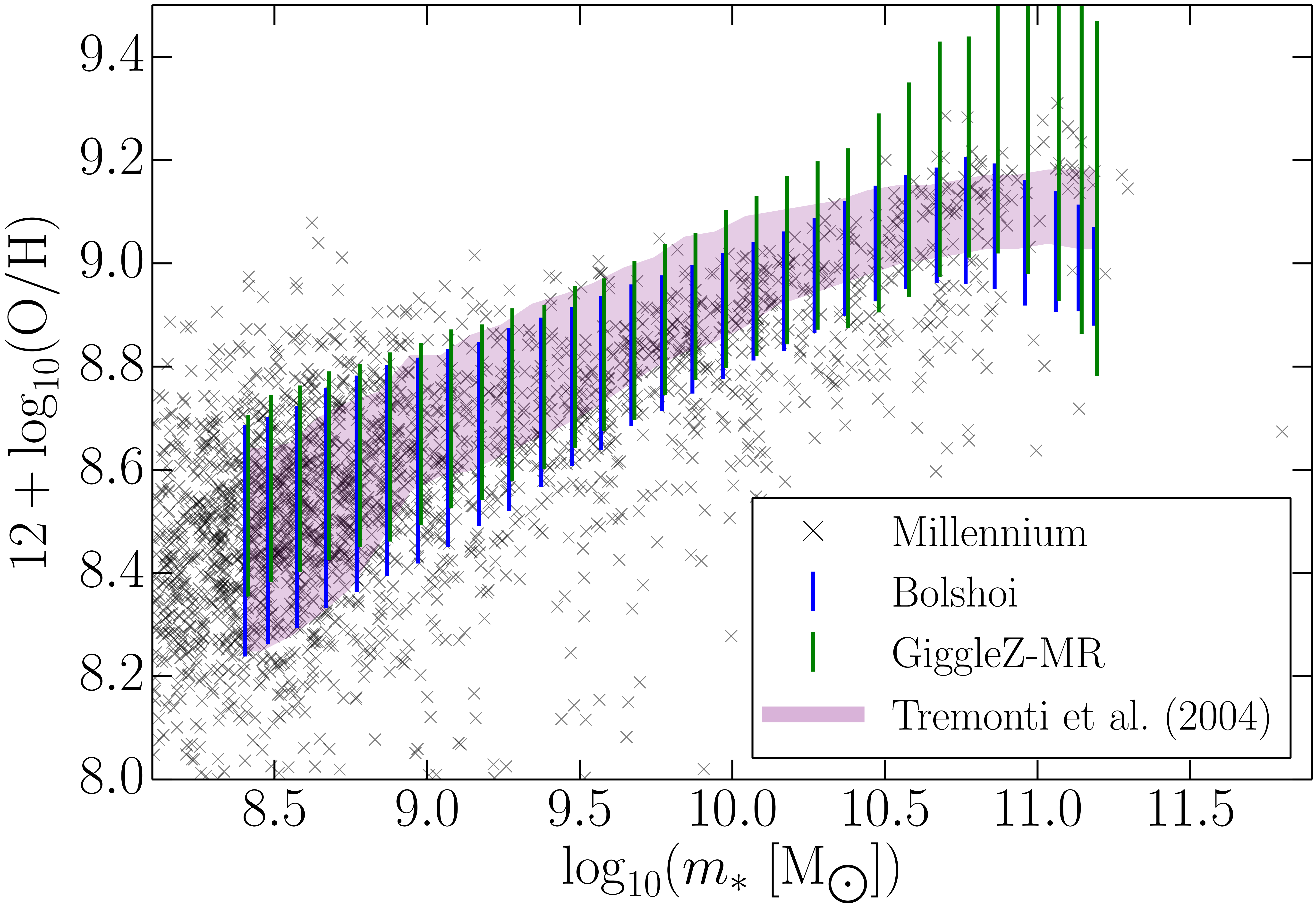
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
Φ [Mpc^{-3} dex^{-1}]
9.0
9.5
10.0
10.5
11.0
11.5
$\log_{10}(m_*\ [\mathrm{M}_\odot])$
Millennium
Bolshoi
GiggleZ-MR
C06 Millennium
Baldry et al. (2008)



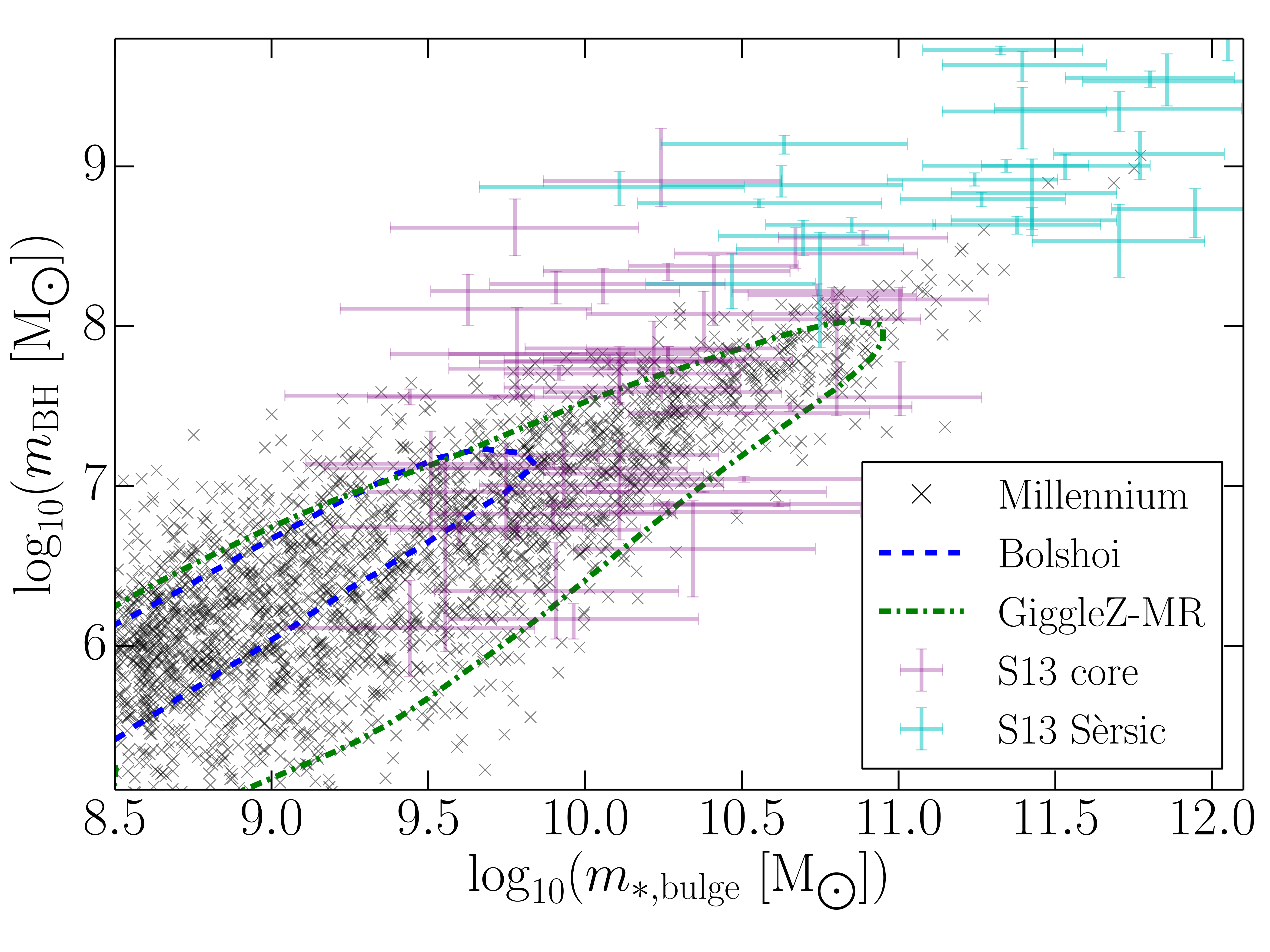
−0.5
−1.0
−1.5
−2.0
−2.5
0
1
2
3
4
5
6
7
Redshift
$\log_{10}\left(\bar{\rho}_{\mathrm{SFR}}\ [\mathrm{M}_\odot\ \mathrm{yr}^{-1}\ \mathrm{cMpc}^{-3}]\right)$
Millennium
Bolshoi
GiggleZ-MR
C06 Millennium
Observations



$\log_{10}(m_* + m_{\rm cold}\ [\mathrm{M}_\odot])$
$\log_{10}(V_{\rm max}\ [\mathrm{km\ s^{-1}}])$
Millennium
Bolshoi
GiggleZ-MR
Stark et al. (2009)
8
9
10
11
1.4
1.6
1.8
2.0
2.2
2.4
2.6
2.8



9.4
9.2
9.0
8.8
8.6
8.4
8.2
8.0
$12 + \log_{10}(\mathrm{O/H})$
8.5
9.0
9.5
10.0
10.5
11.0
11.5
$\log_{10}(m_* \, [\mathrm{M}_\odot])$
Millennium
Bolshoi
GiggleZ-MR
Tremonti et al. (2004)



9
8
7
6
$\log_{10}(m_{\rm BH}\ [{\rm M}_\odot])$
8.5
9.0
9.5
10.0
10.5
11.0
11.5
12.0
$\log_{10}(m_{*,\rm bulge}\ [{\rm M}_\odot])$
Millennium
Bolshoi
GiggleZ-MR
S13 core
S13 Sèrsic

Branches under development…

Seiler et al: Diffuse gas and reionization [progressing]

Tonini et al: Bulge formation and demographics [published]

Stevens et al: Angular momentum in disks [published]

Raouf et al: Radio jets and radio AGN [published]

https://github.com/darrencroton/sage

Towards a better model ...

— want AGN properties, not just galaxy properties

— self consistent cooling/heating cycle

— move from phenomenology to physically motivated

Mon. Not. R. Astron. Soc. **000**, 1–14 (2012) Printed 22 June 2017 (MN LaTeX style file v2.2)

The many lives of active galactic nuclei-II: The formation and evolution of radio jets and their impact on galaxy evolution

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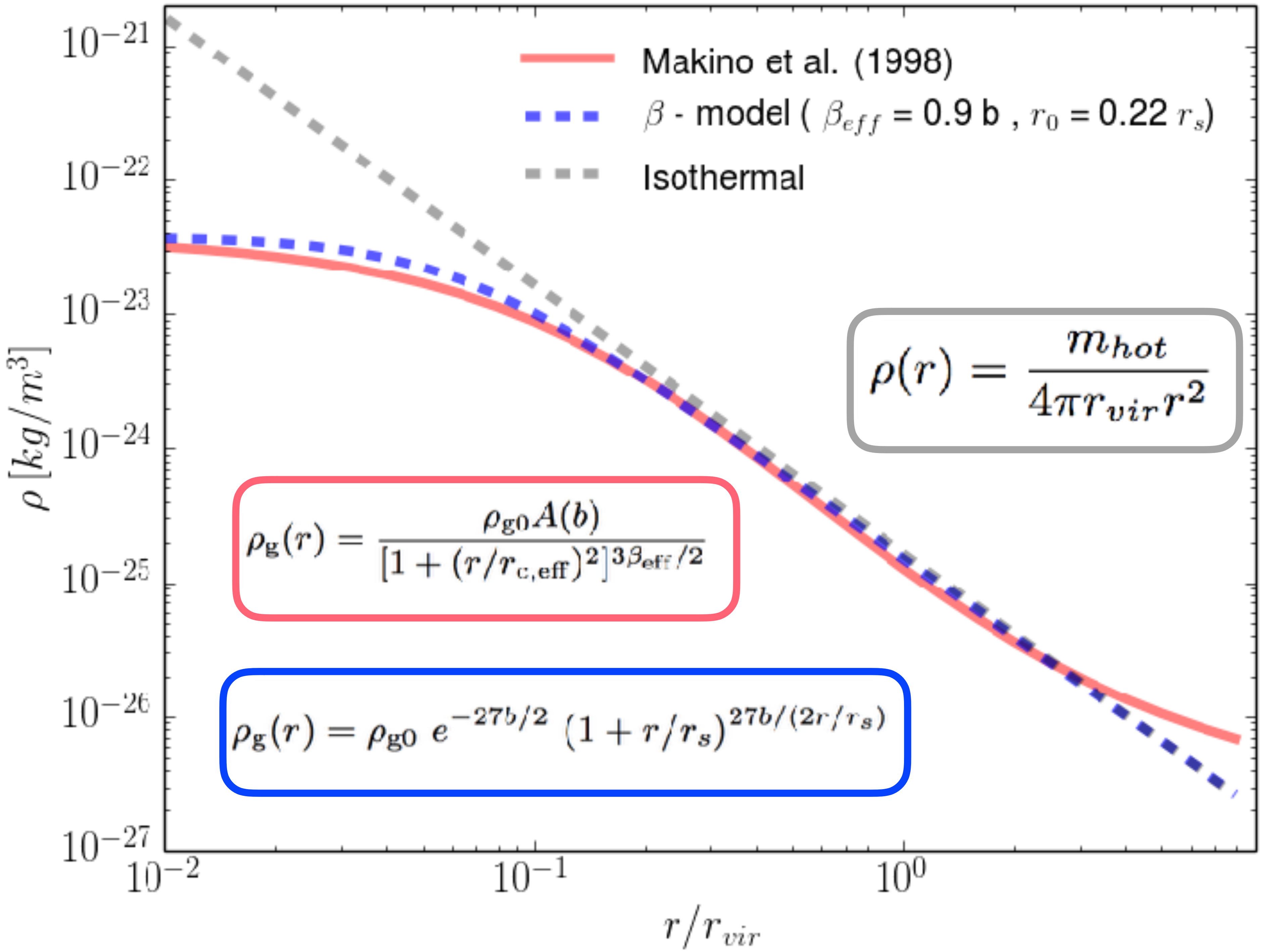
[3] *School of Physical Sciences, Private Bag 37, University of Tasmania, Hobart, TAS 7001, Australia*

ABSTRACT

We describe new efforts to model radio active galactic nuclei (AGN) in a cosmological context using the SAGE semi-analytic galaxy model. Our new method tracks the physical properties of radio jets in massive galaxies, including the evolution of radio lobes and their impact on the surrounding gas. This model also self consistently follows the gas cooling-heating cycle that significantly shapes star formation and the life and death of many galaxy types. Adding jet physics to SAGE adds new physical properties to the model output, which in turn allows us to make more detailed predictions for the radio AGN population. After calibrating the model to a set of core observations we analyse predictions for jet power, radio cocoon size, radio luminosity, and stellar mass. We find that the model is able to match the stellar mass–radio luminosity relation at $z \sim 0$, and the radio luminosity function out to $z \sim 1$. This updated model will make possible the construction of customised AGN-focused mock survey catalogues to be used for large-scale observing programs.

Key words: galaxies: active – galaxies: evolution – galaxies: environment – galaxies: halos – methods: numerical .

DENSITY PROFILE



Raouf, Shabala, DC et al. 2017; Shabala et al. 2009

SHOCK EXPANSION

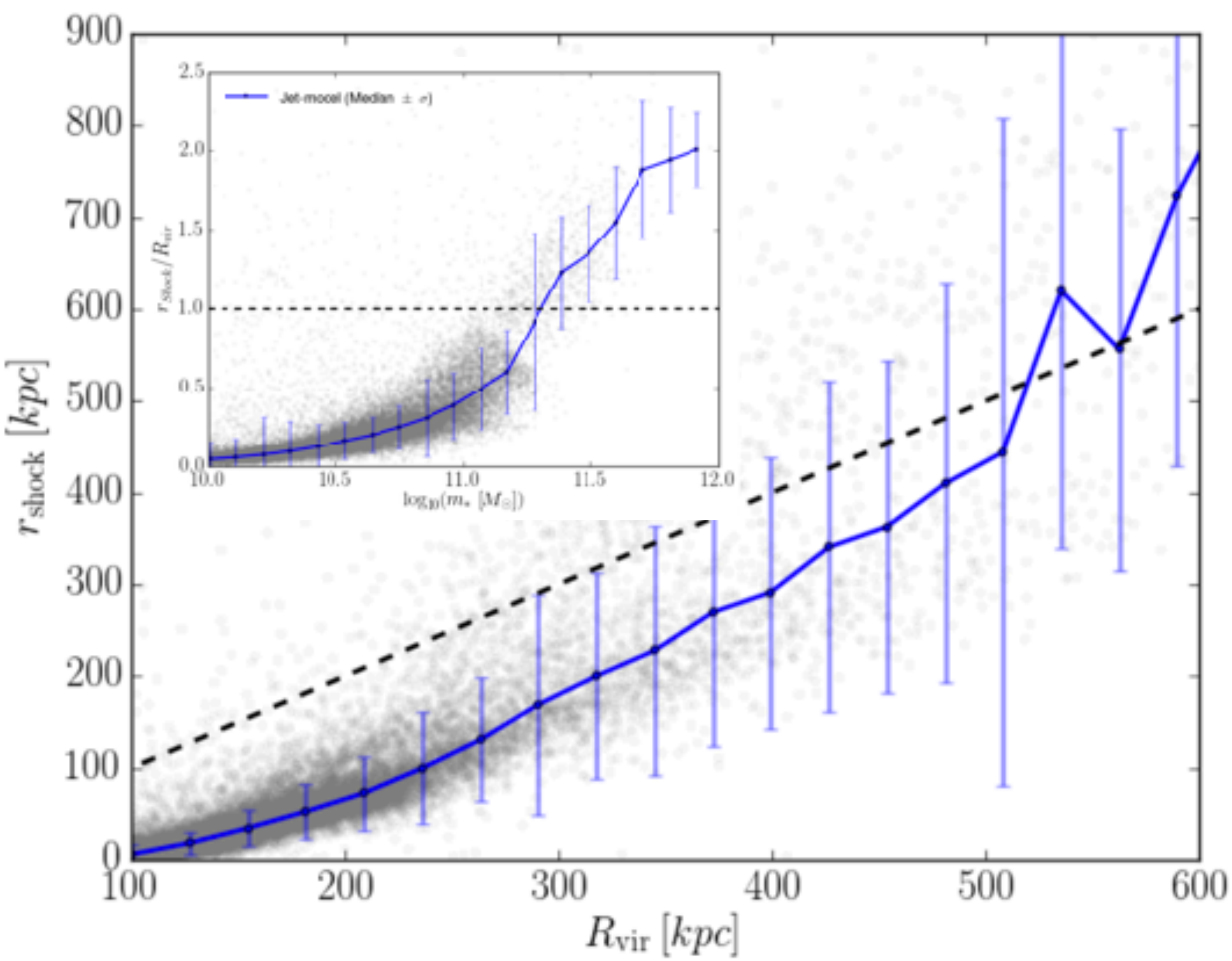
$$R_{cocoon}(t) = a_D r_0 \left(\frac{t}{\tau}\right)^{3/(5-\beta)}$$

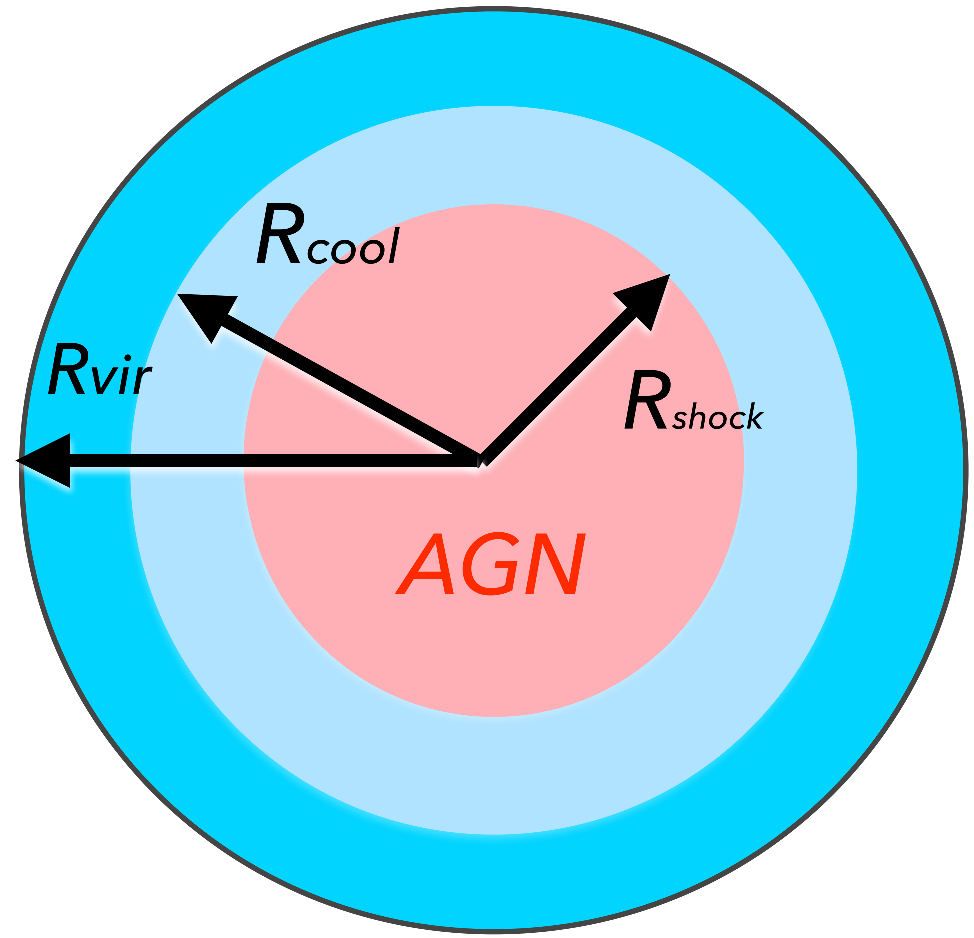
Kaiser & Alexander (1997) →

$$R_{shock} = \frac{1}{\lambda} R_{cocoon}$$

time scale: $\tau = \left(\frac{r_0^5 \rho_0}{Q_{\rm jet}}\right)^{1/3}$

$$Q_{jet,hot} = \eta \dot{M}_{BH} c^2$$





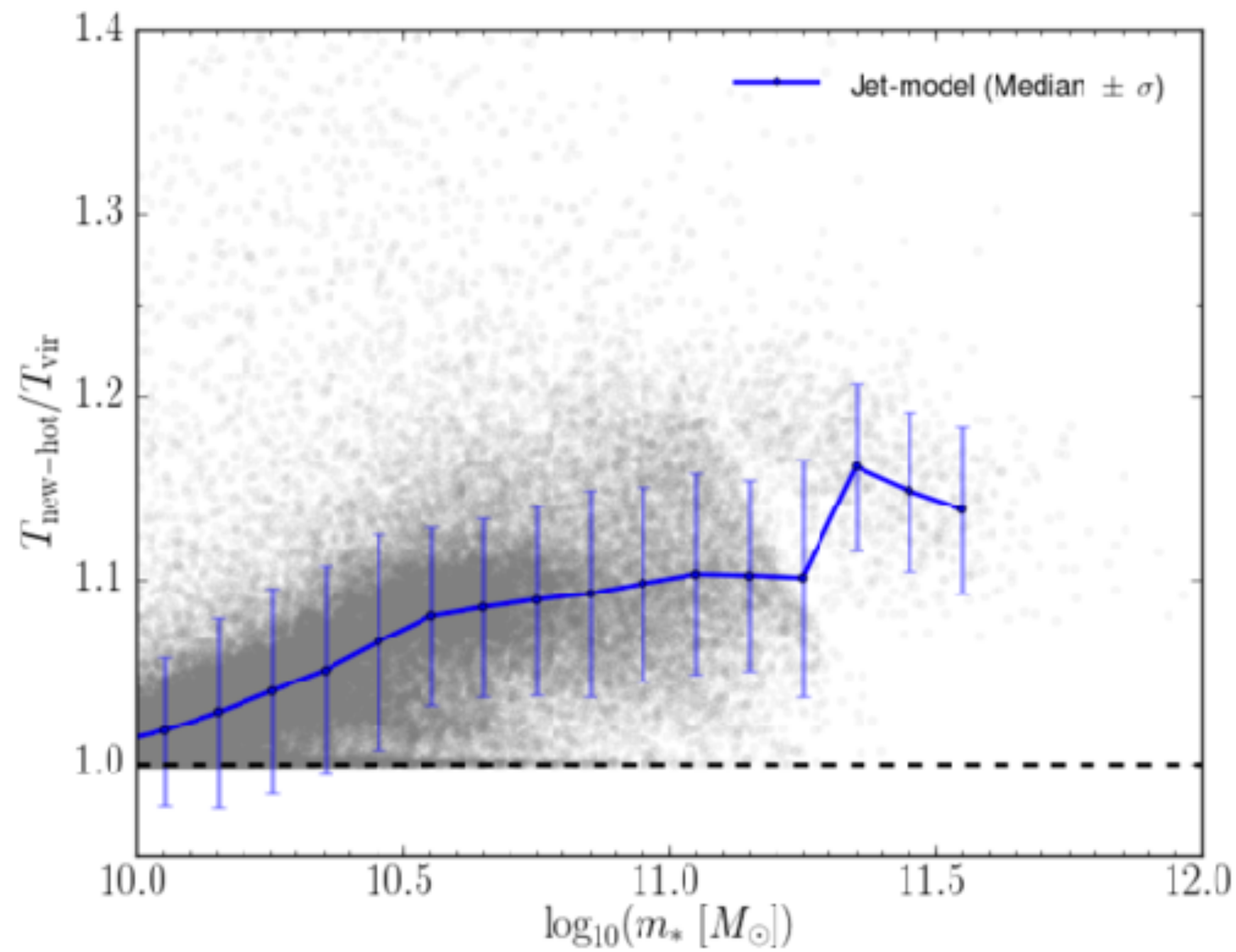
Raouf, Shabala, DC et al. 2017; Shabala et al. 2009

SHOCK TEMPERATURE

$$T_{shock} = \frac{15}{16}\frac{3-\beta}{11-\beta}(\frac{\mu m_H}{k_B})\dot{R}^2_{shocked}$$

$$M_{shock}(R_{shock}) = 16\pi\rho_{g0}r_0^3[\ln(1+\frac{R_{shock}}{r_0}) - \frac{R_{shock}}{R_{shock}+r_0}]$$

$$T_{new-hot} = \frac{M_{shock}T_{shock} + m_{hot}T_{hot}}{M_{shock} + m_{hot}}.$$



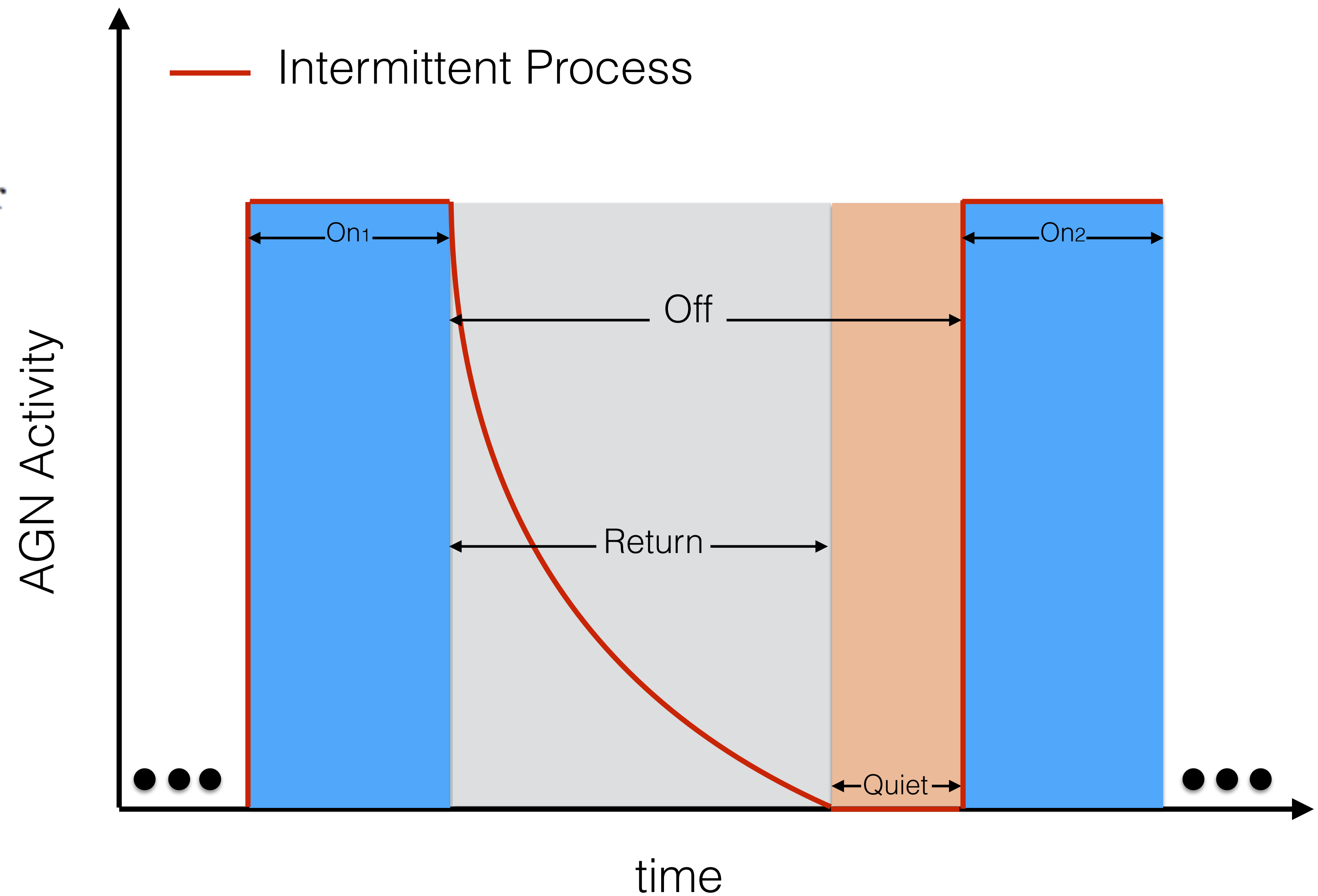
Raouf, Shabala, DC et al. 2017; Shabala et al. 2009

GAS UPLIFTING

$$t_{\rm on} = 120 \left[\frac{m_*}{10^{11}\mathrm{M}_\odot}\right]^{0.7} \ \mathrm{Myr}$$

$$t_{\rm return} = 2\frac{r_{\rm shock}}{c_s}$$

$$t_{off}(M_*, t_{on}) = t_{on}(\frac{1}{\delta} - 1)$$



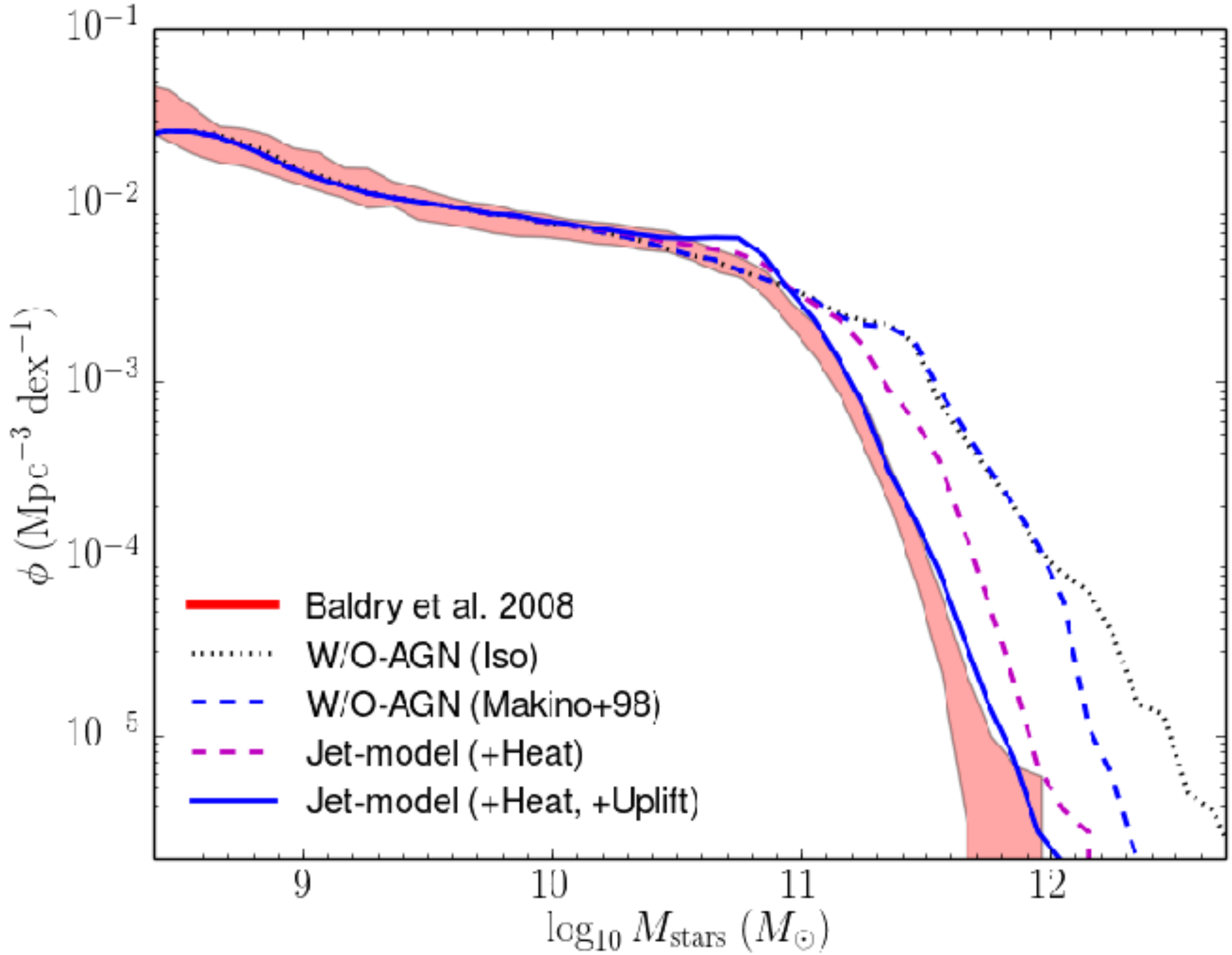
$$f_{\rm cool} = \frac{t_{\rm quiet}}{t_{\rm on} + t_{\rm off}} + \left[\frac{t_{\rm on} + t_{\rm return}}{t_{\rm on} + t_{\rm off}}\right]\left(\frac{m(r_{\rm cool}) - m(r_{\rm shock})}{m(r_{\rm cool})}\right)$$

$$\dot{m}'_{\rm cool} = f_{\rm cool}\,\dot{m}_{\rm cool}$$

Raouf, Shabala, DC et al. 2017; Shabala et al. 2009

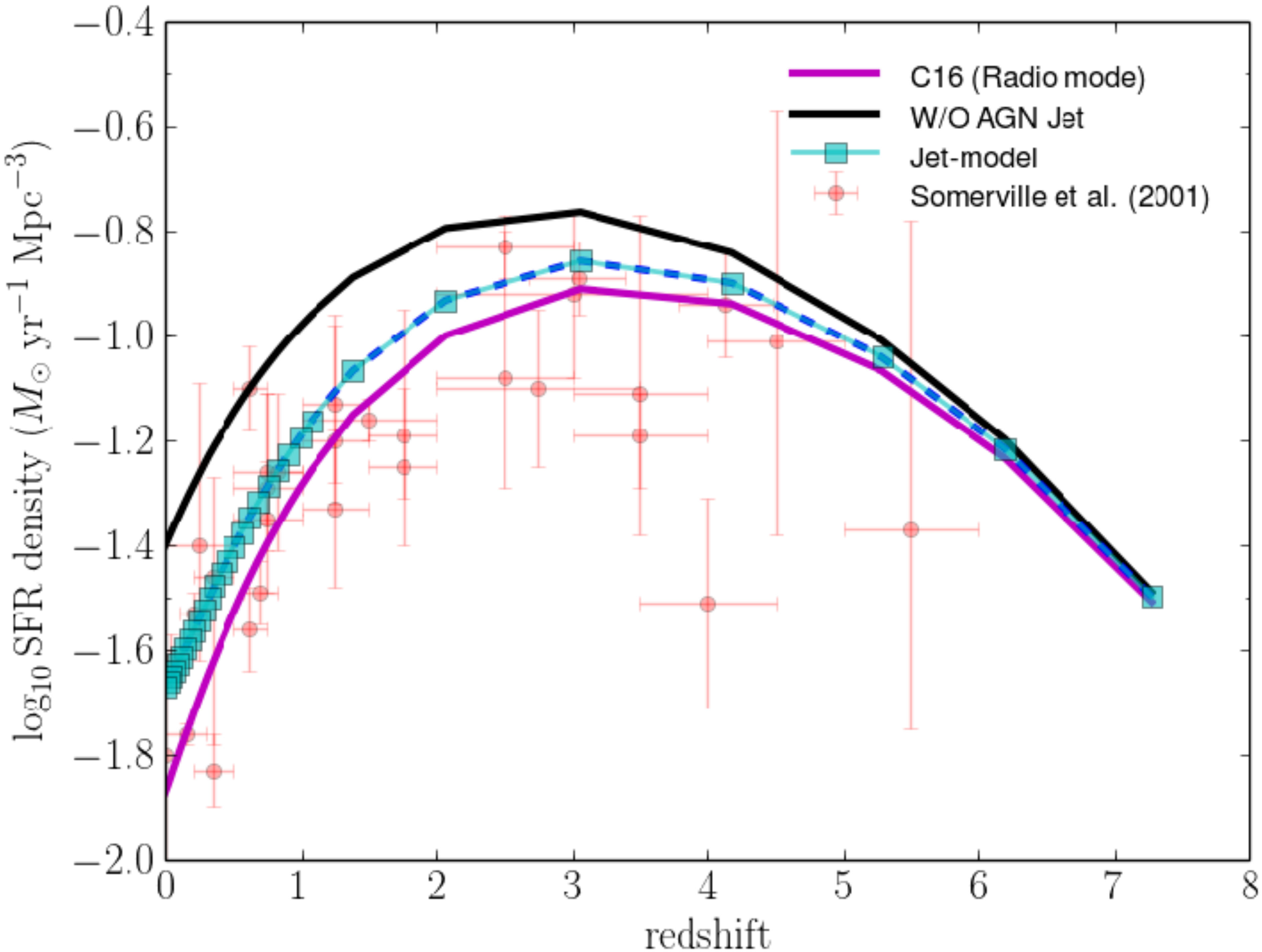
jet power,
shock radius,
radio luminosity.

STELLAR MASS FUNCTION



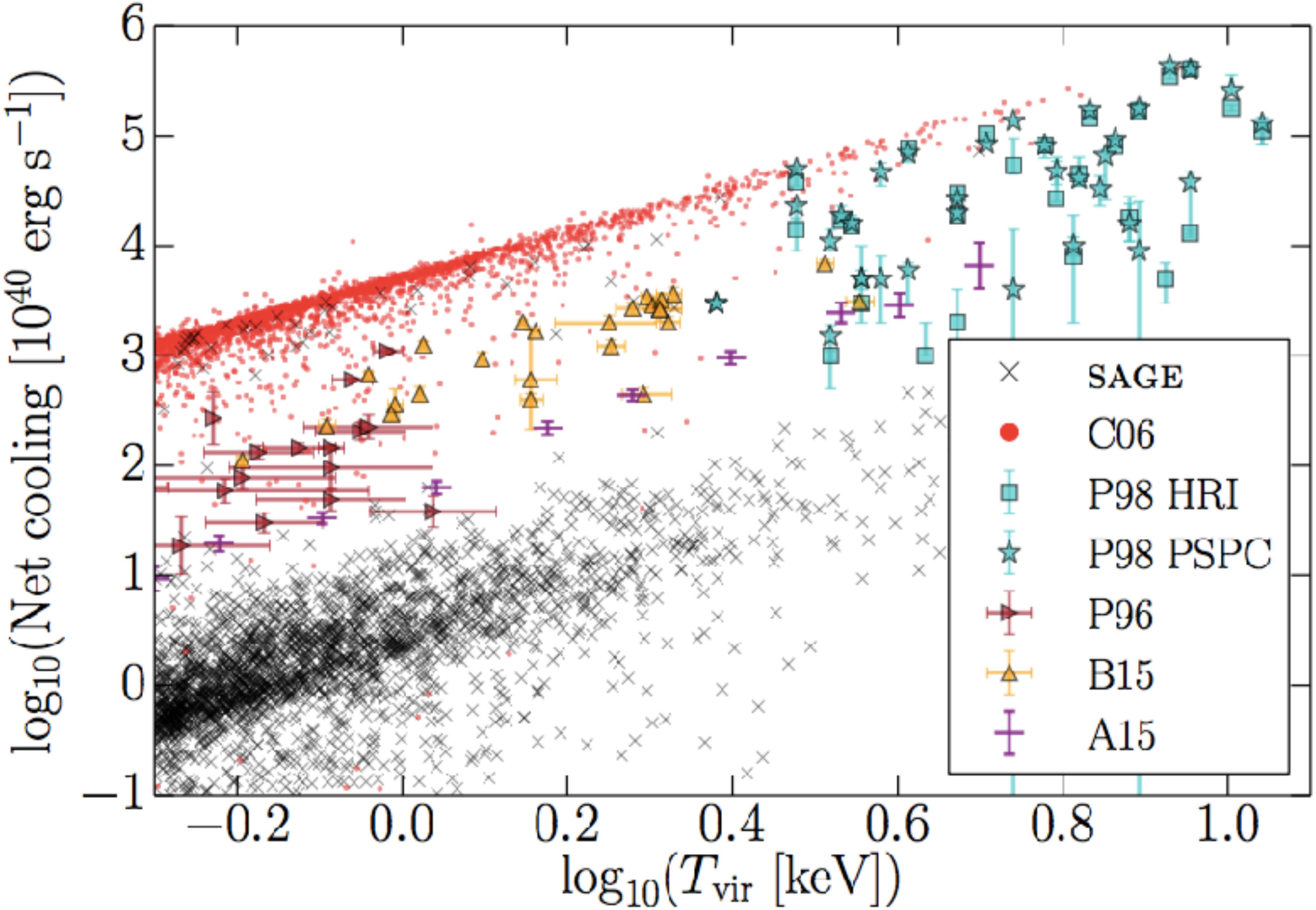
Raouf, Shabala, DC et al. 2017

SFR DENSITY

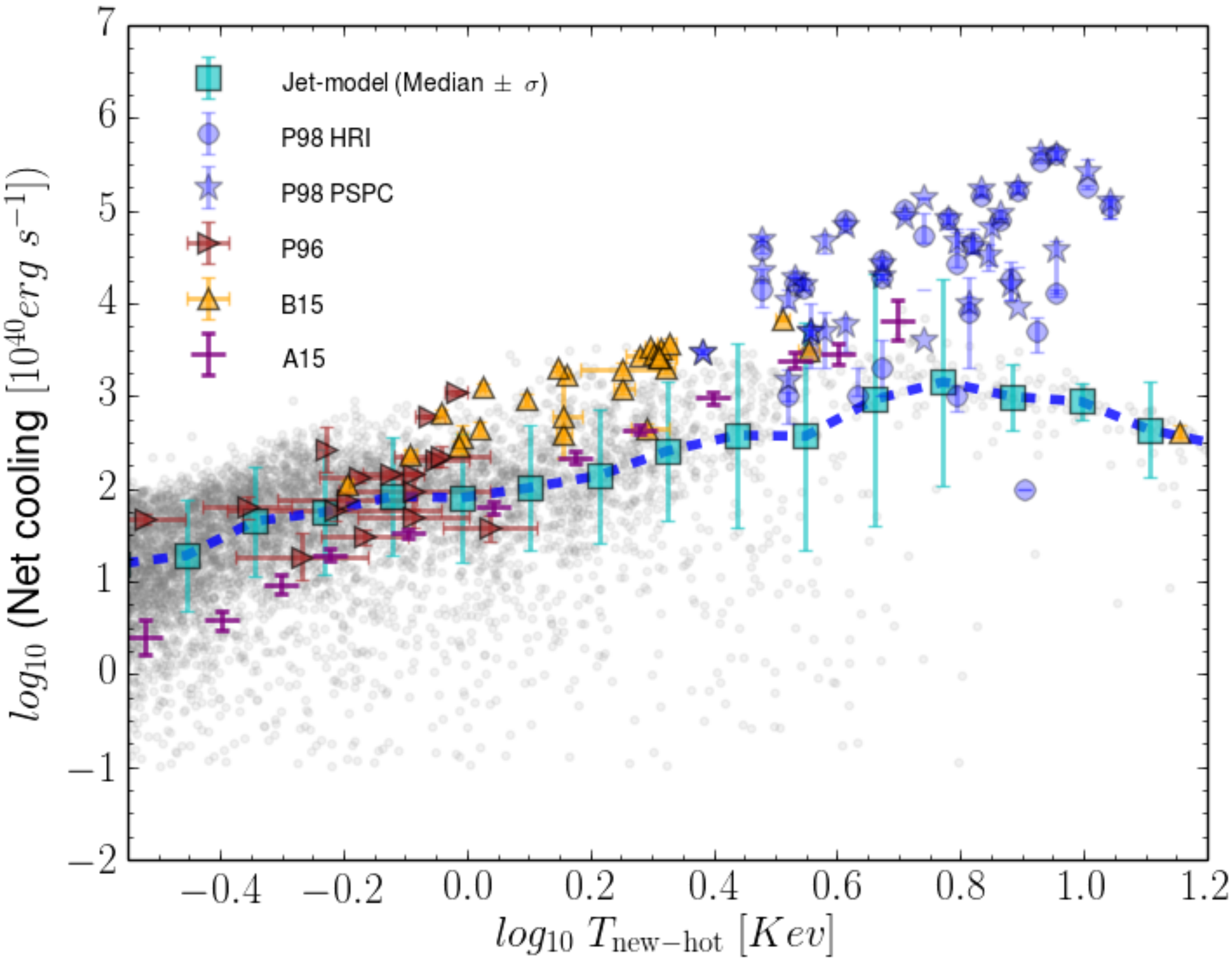


Raouf, Shabala, DC et al. 2017

COOLING LUMINOSITY



COOLING LUMINOSITY

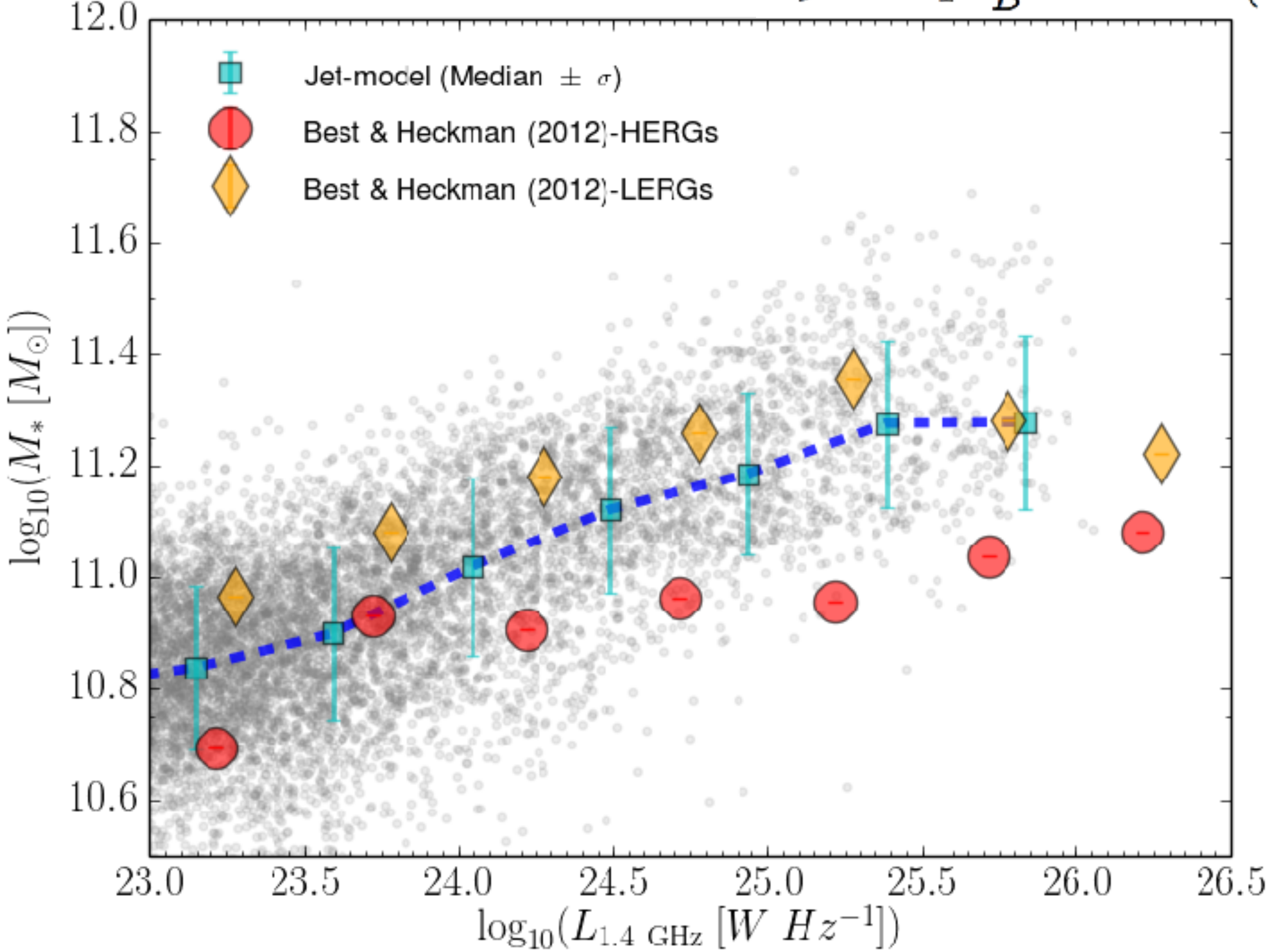


Raouf, Shabala, DC et al. 2017

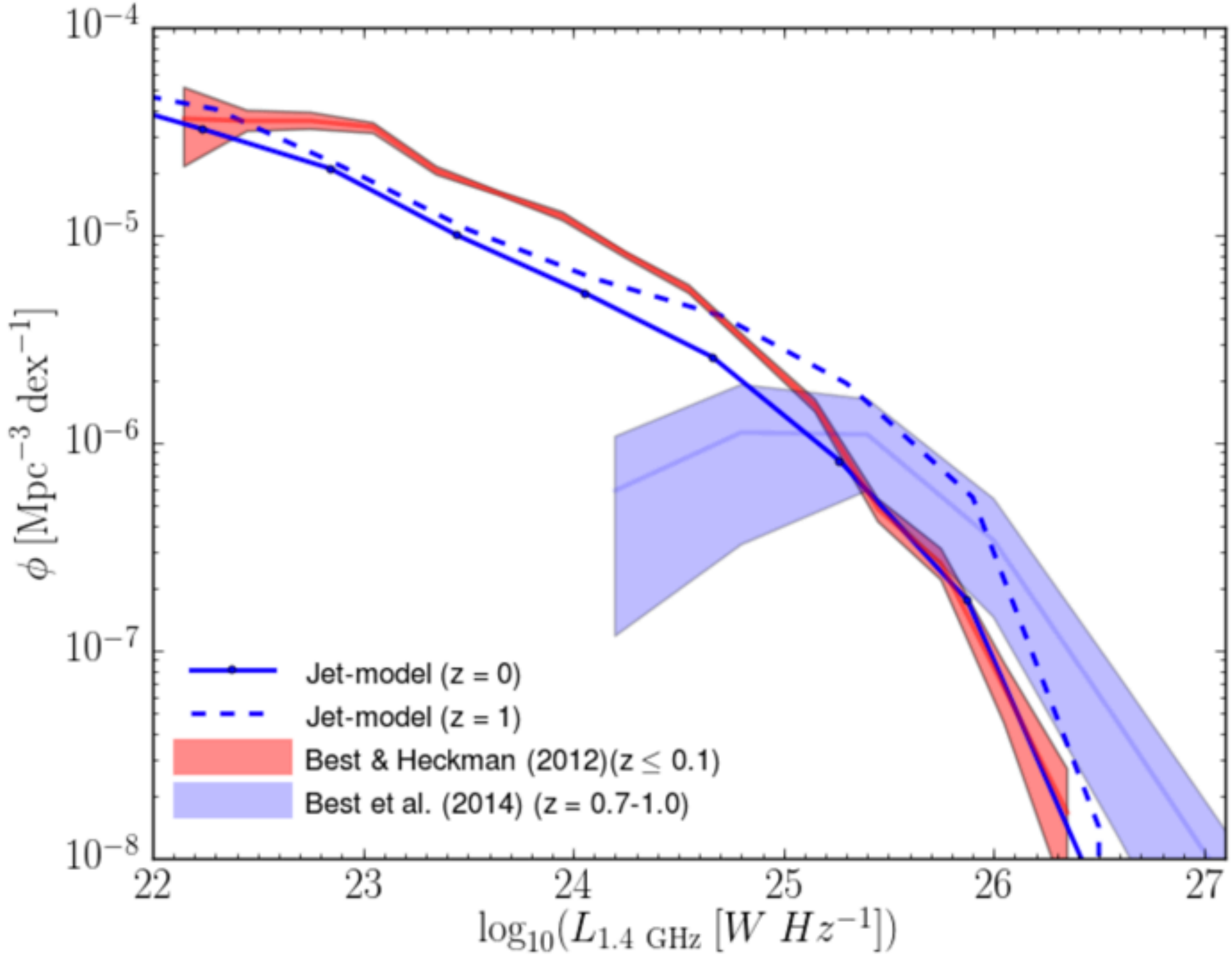
RADIO LUMINOSITY

Shabala et al. 2013

$$L_\nu = A_1 u_B^{\frac{5+p}{4}} V \nu^{\frac{1-p}{2}} (1+z)^{\frac{(3-p)}{2}}$$

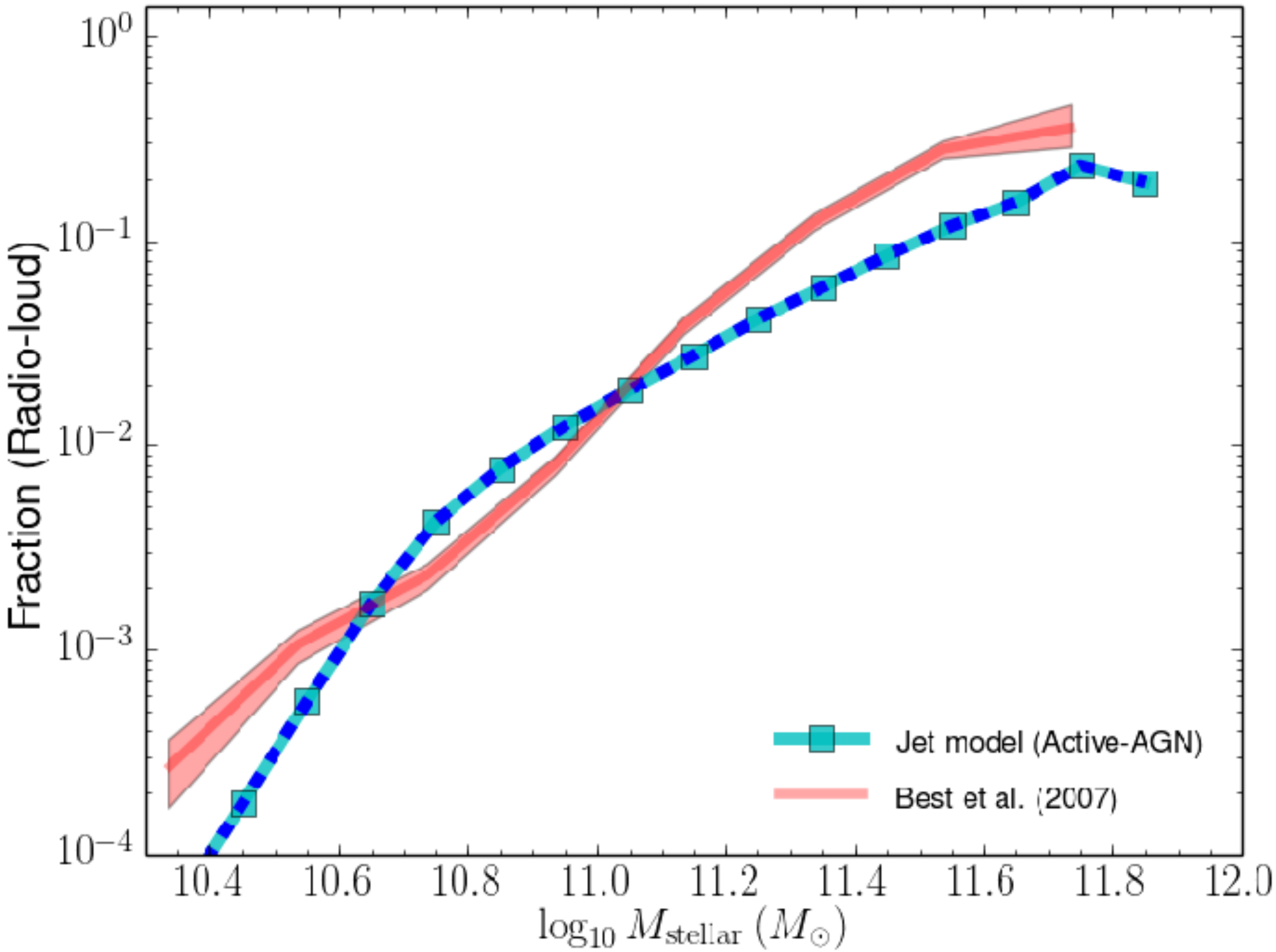


RADIO LUMINOSITY



Raouf, Shabala, DC et al. 2017

RADIO-LOUD AGN FRACTION



Raouf, Shabala, DC et al. 2017

Our new model can reproduce all the previous global galaxy statistics plus additional radio-AGN specific properties.

The data and code are publicly available to use.

$\beta(p,q) = \frac{\Gamma(p)\Gamma(q)}{\Gamma(p+q)}$
$\Gamma(y) = \int_0^\infty e^{-x} x^{y-1} dx$
$\sigma_x = \sqrt{\frac{\sum_{i=1}^{n}(x_i - \langle x \rangle)^2}{n}}$
$P(x) = \frac{\lambda^x e^{-\lambda}}{x!}$

Decadal Plan eScience White Paper:

Astronomy data is most efficiently exploited when it is exposed to the largest number of astronomers, which can be effectively achieved through online federated data hubs.

From pure arguments of economy, this both maximises the investment of taxpayer’s money and the opportunity for scientific discovery, and hence should be a community and institutional priority.

Virgo - Millennium Database

Documentation

CREDITS/Acknowledgments

Registration

News

FAQ

Public Databases

- DGalaxies
- DHalotrees
- Guo2010a
- MField
- MillenniumII
- millimil
- miniMilII
- MMSnapshots
- MPAGalaxies
- MPAHaloTrees
- MPAMocks

Private (MyDB) Databases

- darren_db (rw) (context)

Welcome Darren Croton.
Streaming queries return unlimited number of rows in CSV format and are cancelled after 420 seconds.
Browser queries return maximum of 1000 rows in HTML format and are cancelled after 30 seconds.

Query (stream)

Query (browser)

Help

Maximum number of rows to return to the query form: 10

Demo queries: click a button and the query will show in the query window.
Holding the mouse over the button will give a short explanation of the goal of the query. These queries are also available on this page.

Mainly Halos: H 1 H 2 H 3 H 4 H 5 HF 1 HF 2 HF 3

Mainly Galaxies: G 1 G 2 G 3 G 4 G 5 G 6 HG 1 HG 2 GF 2

Metadata queries: The SQL statements under these buttons provide examples for querying and managing the state of a private database.
Holding the mouse over the button will give a short explanation of the goal of the statement.

ShowTables | Show Views | Show Columns | Show Indexes | MyDB Size | MyDB Table Size

Create View | Drop Table | Create Index

https://www.nectar.org.au/all-sky-virtual-observatory

nectar

connecting • sharing • collaborating

The All Sky Virtual Observatory

Search

What is the All-Sky Virtual Observatory

New telescopes and facilities coming online in the next three to five years will produce data in volumes never previously experienced in Australian astronomy. To gain maximum scientific benefit from this data flood, the federation of datasets from all types of astronomical facilities in Australia will be needed. This will involve creating the hardware, tools and services to bring together data from radio telescopes, optical telescopes and supercomputers, covering all parts of the southern sky, under a Virtual Observatory.

After extensive consultation with the entire astronomy community, two Australian astronomical facilities were chosen to form the first pillar of the All-Sky Virtual Observatory:

The primary observational dataset will come from the SkyMapper facility, an optical telescope located at Siding Spring Observatory, NSW, built by the Australian National University. SkyMapper is producing the most detailed and sensitive digitized map of the southern sky at optical wavelengths. This nationally significant dataset will be a fundamental reference for astronomers in Australia, and internationally, for many decades.

The Theoretical Astrophysical Observatory (TAO), being developed at Swinburne University of Technology, will house the growing ensemble of Australian theory data sets and galaxy formation models, with value-add tools that will allow astronomers to observe each virtual universe as if it was real. This will be achieved by mapping the simulated data onto an observer's viewpoint and the application of custom telescope simulators, beginning with SkyMapper. TAO provides a direct and vital link between the theoretical and observational aspects of data collection and analysis.

Who is Astronomy Australia?

Astronomy Australia Ltd (AAL) is a not-for-profit company whose members are all the Australian universities and research organisations with a significant astronomical research capability.

Our vision is that astronomers in Australia will have access to the best astronomical research infrastructure. AAL will achieve its

VLs in project negotiation

The All Sky Virtual Observatory

Climate and Weather Science Laboratory

Humanities Networked Infrastructure (HuNI) unlocking and uniting Australia's cultural data

The Genomics Virtual Laboratory

The Characterisation Virtual Laboratory: research environments for exploring inner space

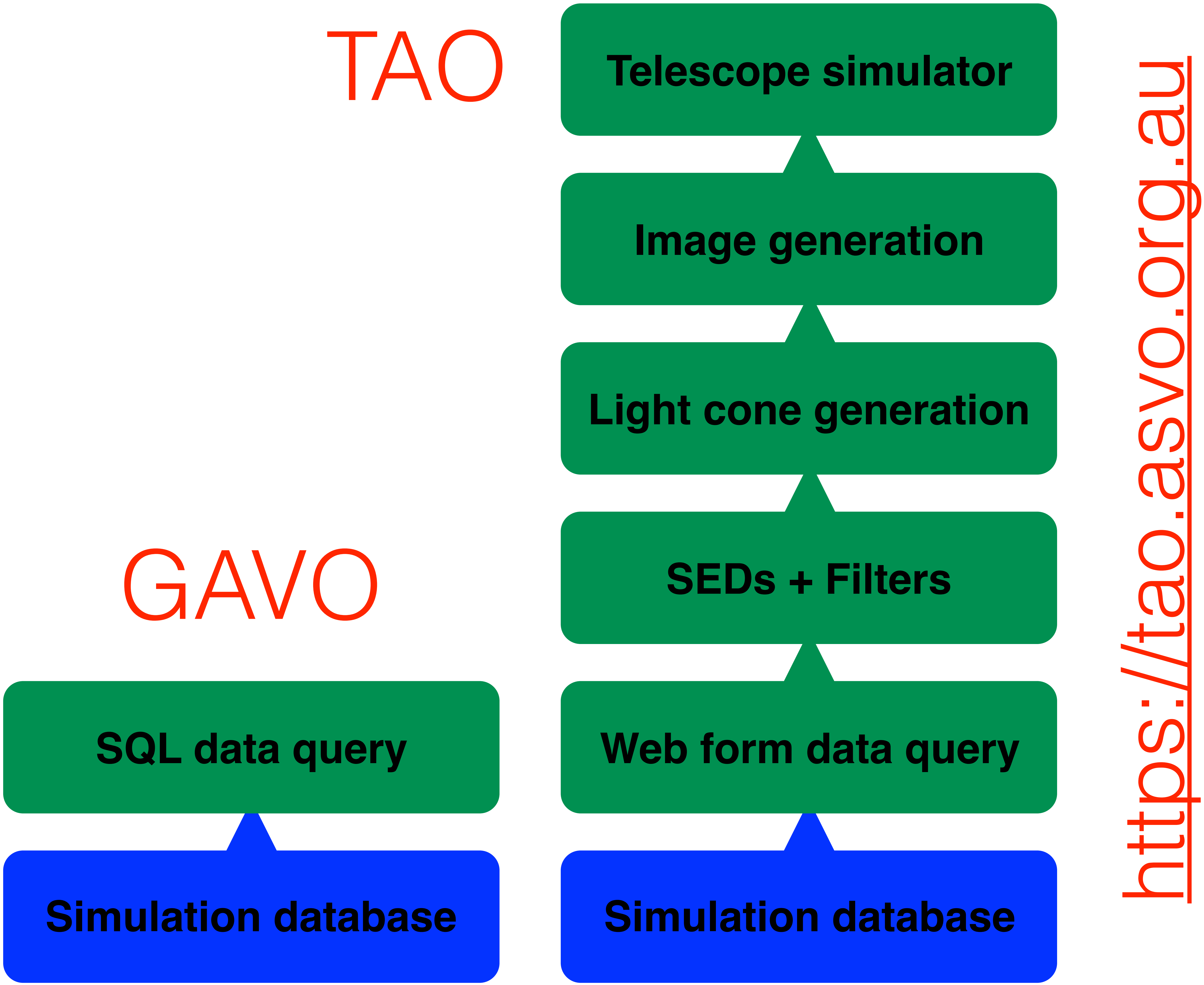
Early Activities

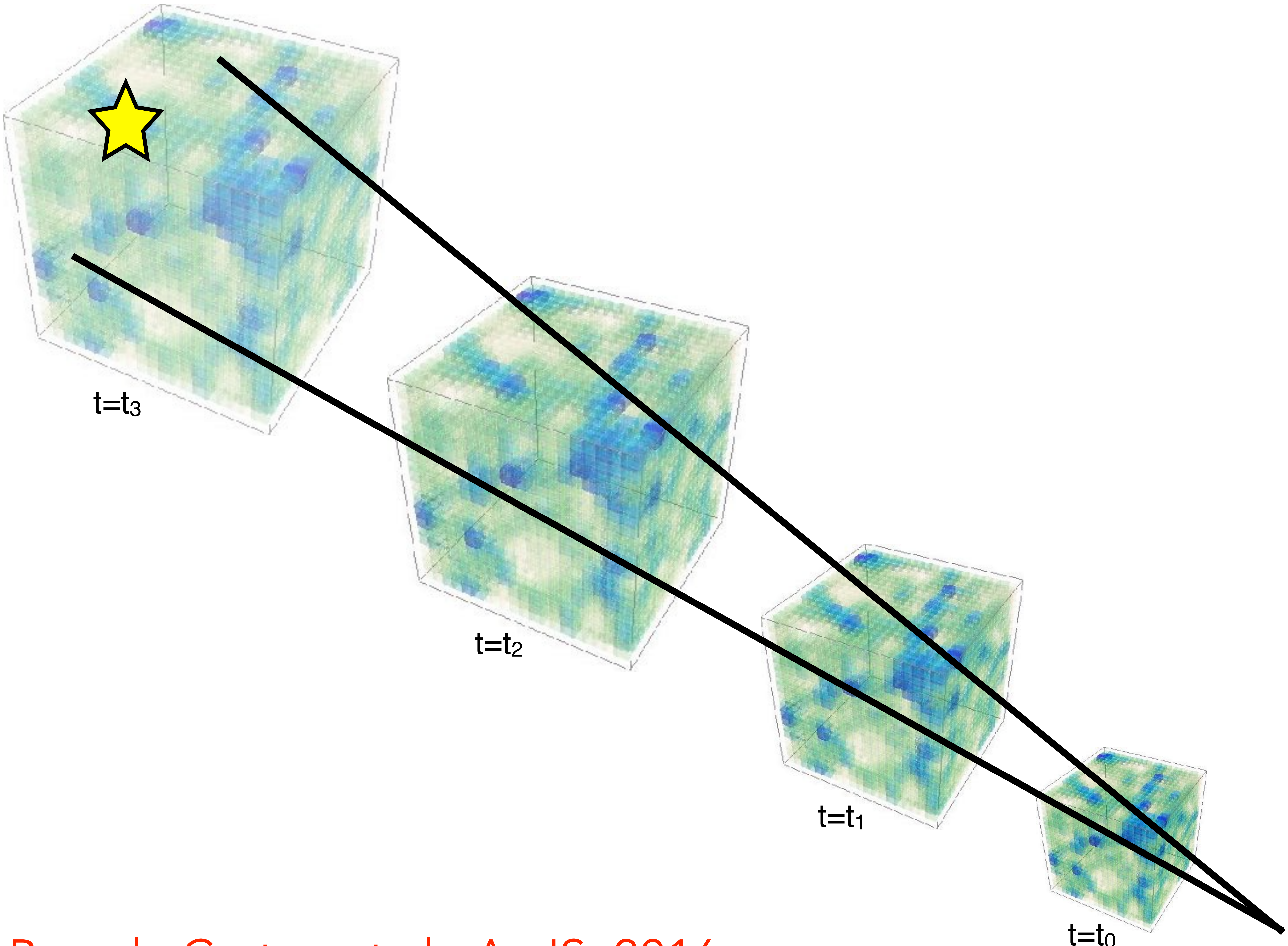
CSIRO - Virtual Geophysics Laboratory

University of Queensland - Virtual Genomics Laboratory

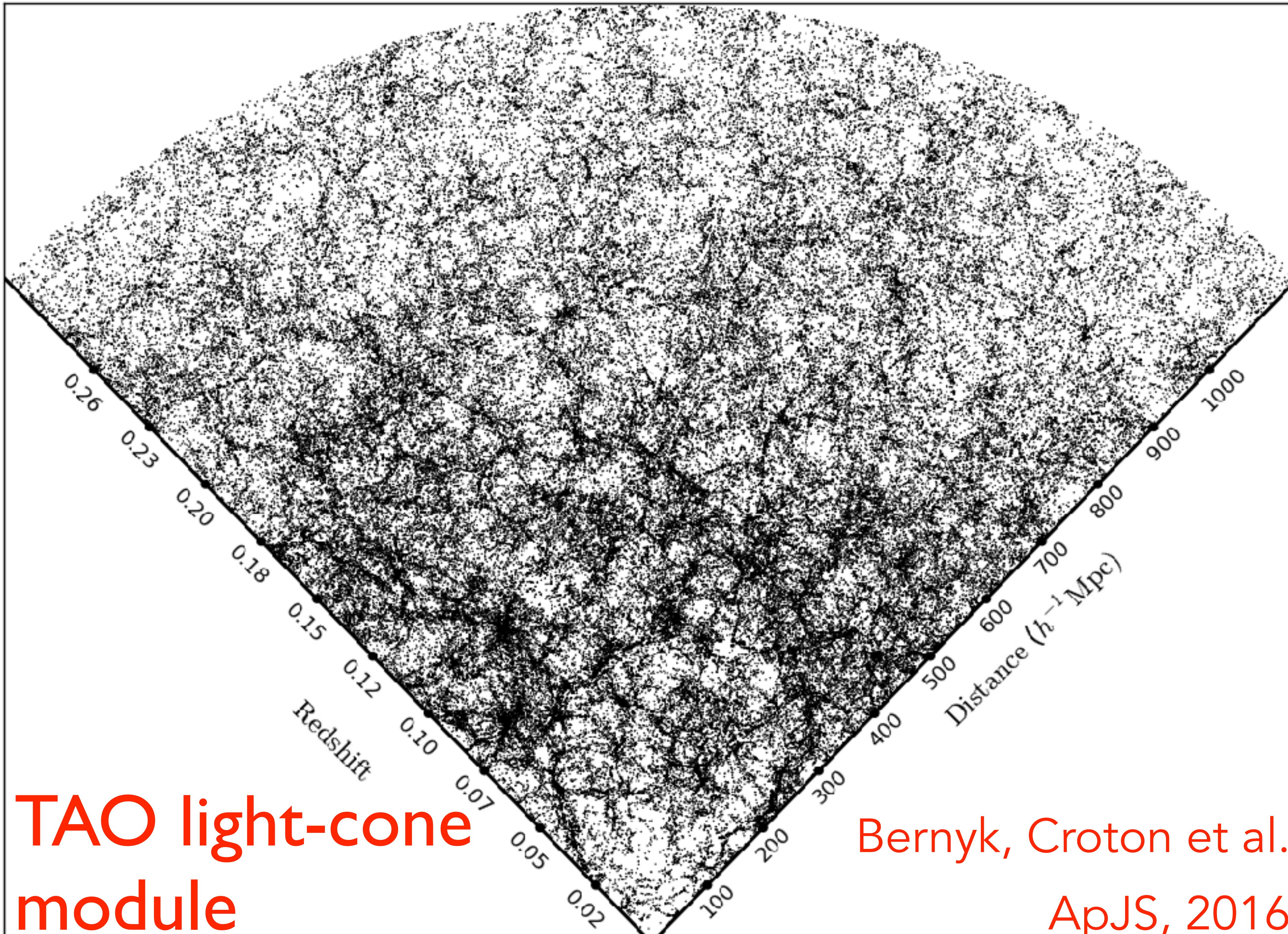
University of Tasmania - Marine Virtual Laboratory

Latest News ...


TAO
Telescope simulator
Image generation
Light cone generation
SEDs + Filters
Web form data query
Simulation database
GAVO
SQL data query
Simulation database
https://tao.asvo.org.au



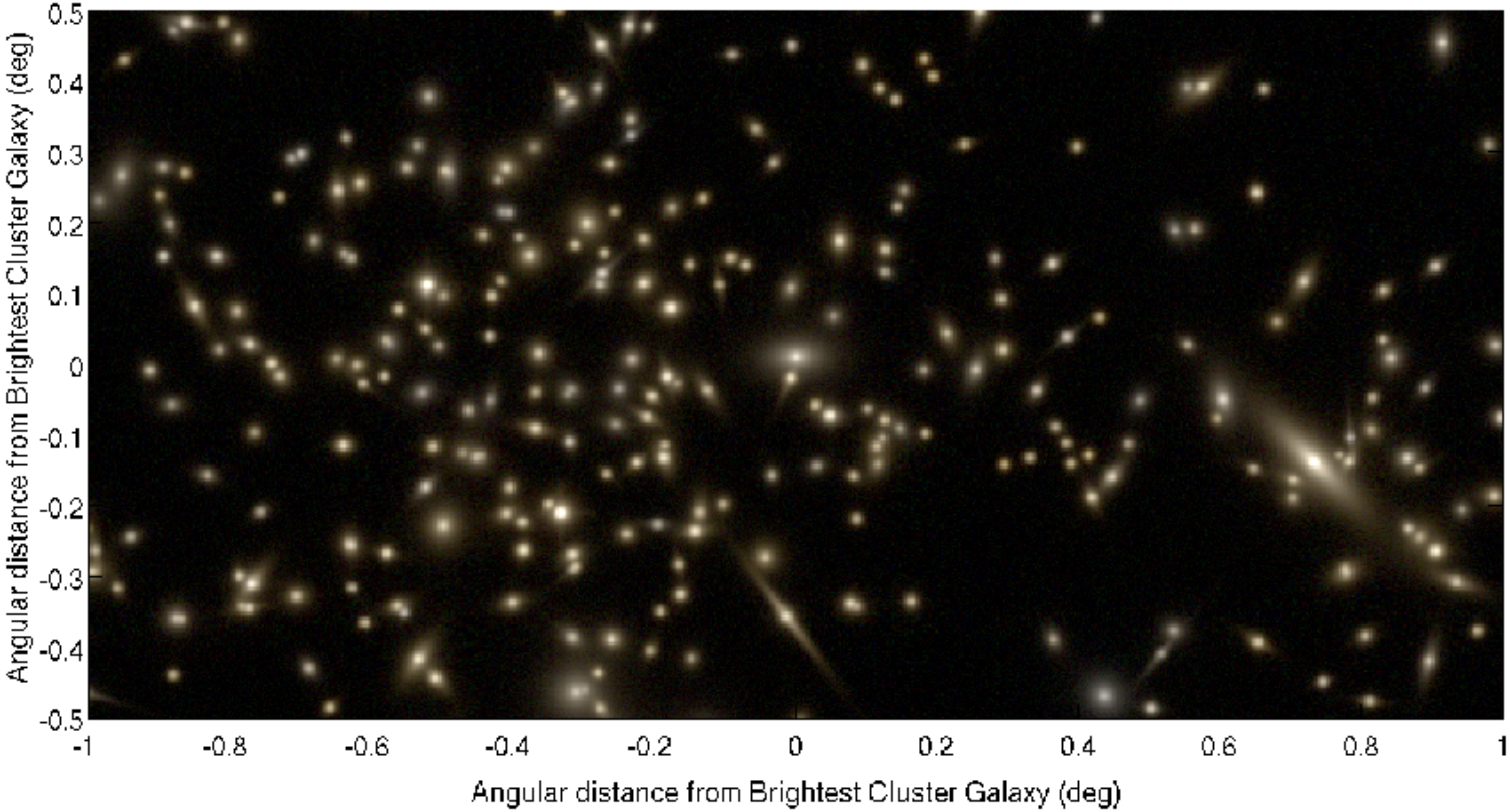
Bernyk, Croton et al., ApJS, 2016



TAO light-cone module

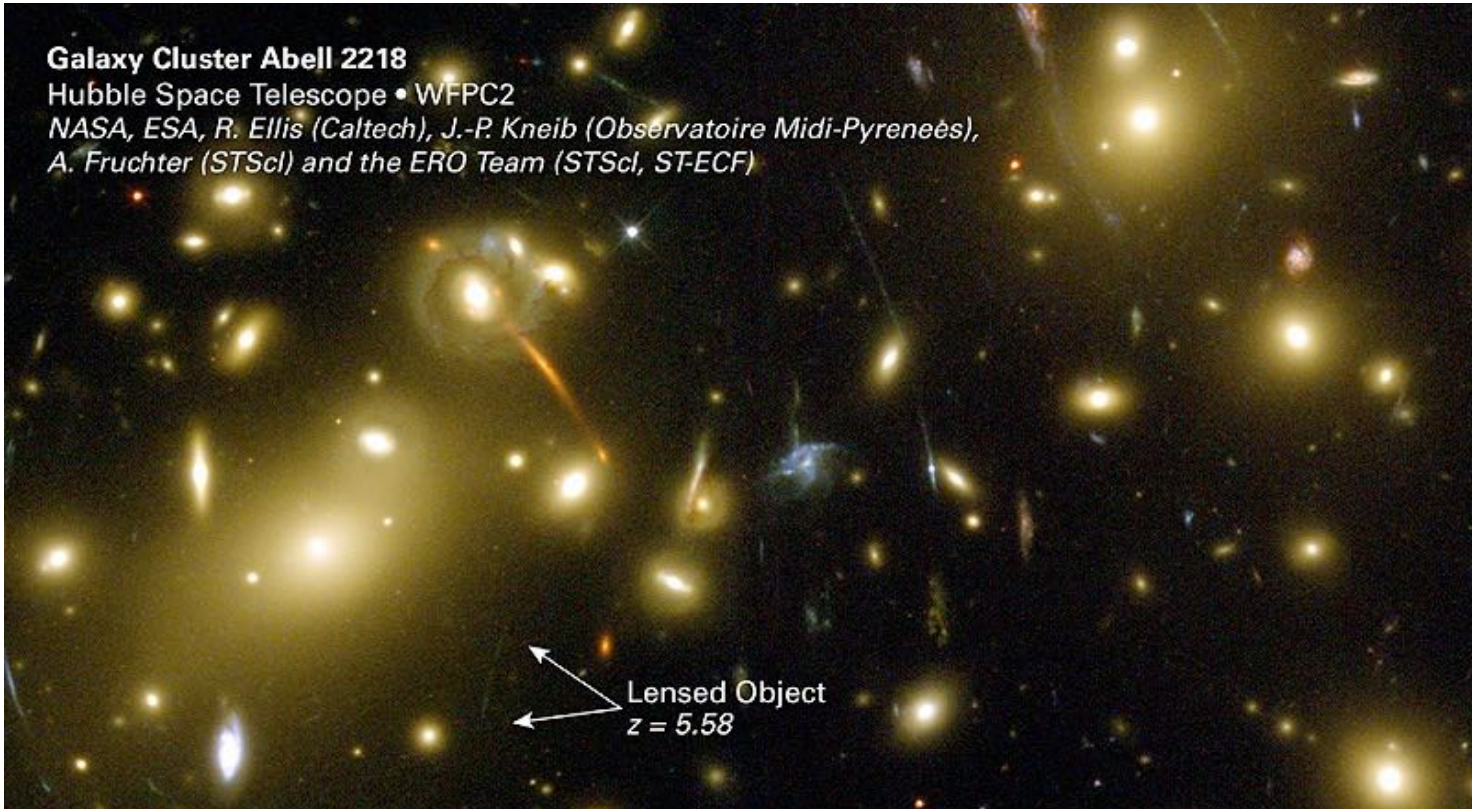
Bernyk, Croton et al.
ApJS, 2016

The TAO image module



Bernyk, Croton et al., ApJS, 2016

The TAO image module



Bernyk, Croton et al., ApJS, 2016

https://tao.asvo.org.au

Usage Case:

The “Wide Area VISTA Extra-galactic Survey” (WAVES)

- 4MOST Consortium Design Reference Survey.
- Will use the VISTA/4MOST facility to spectroscopically survey ~ 2 million galaxies.
- TAO used for predictions and to argue the science case.

- Ensemble of Milky-Way sized systems to test CDM
- The low surface brightness and dwarf domains
- The evolution of galaxy structure (with Euclid)
- The evolving HI universe (with ASKAP/SKA)

WAVES Survey

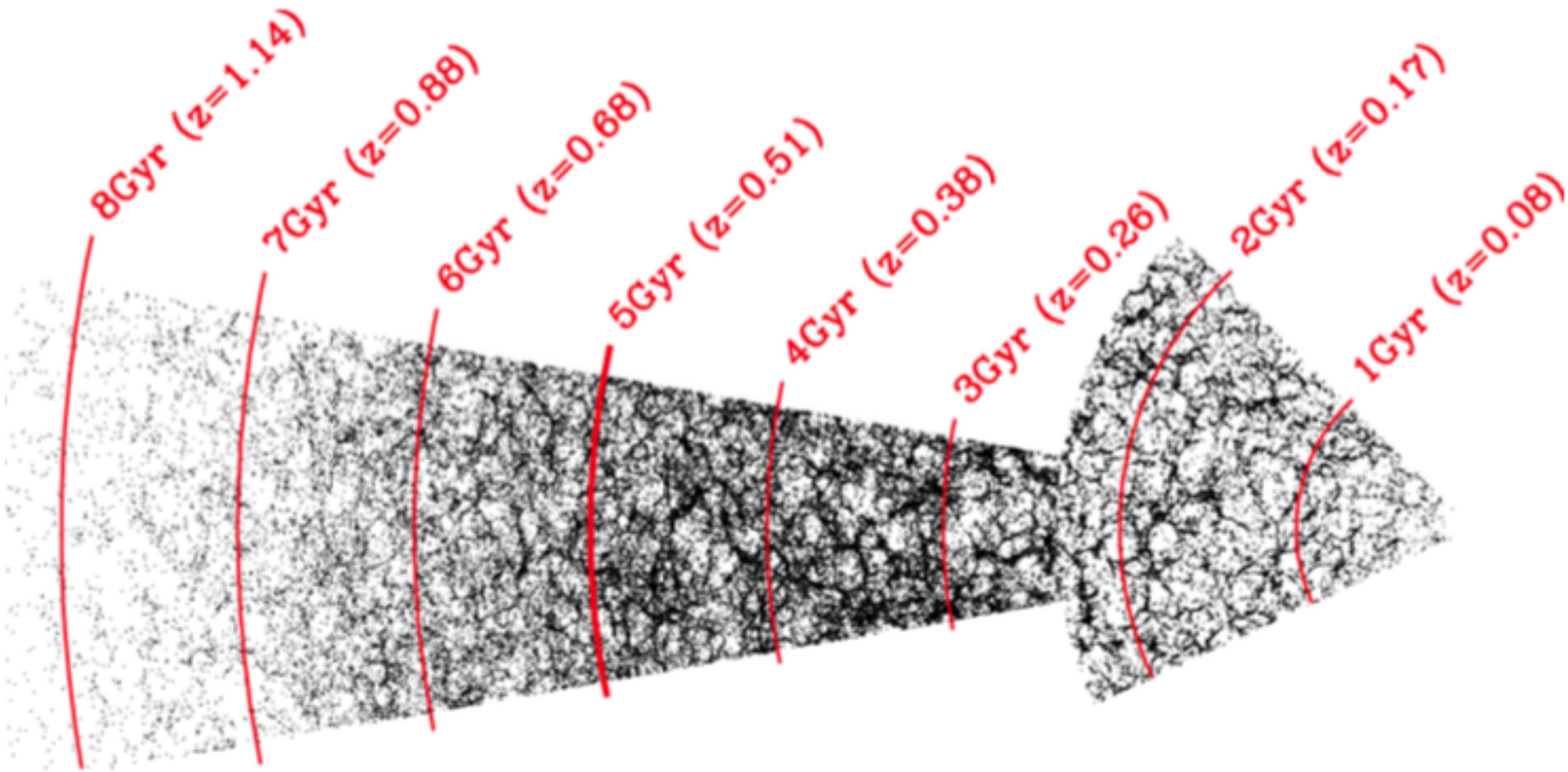


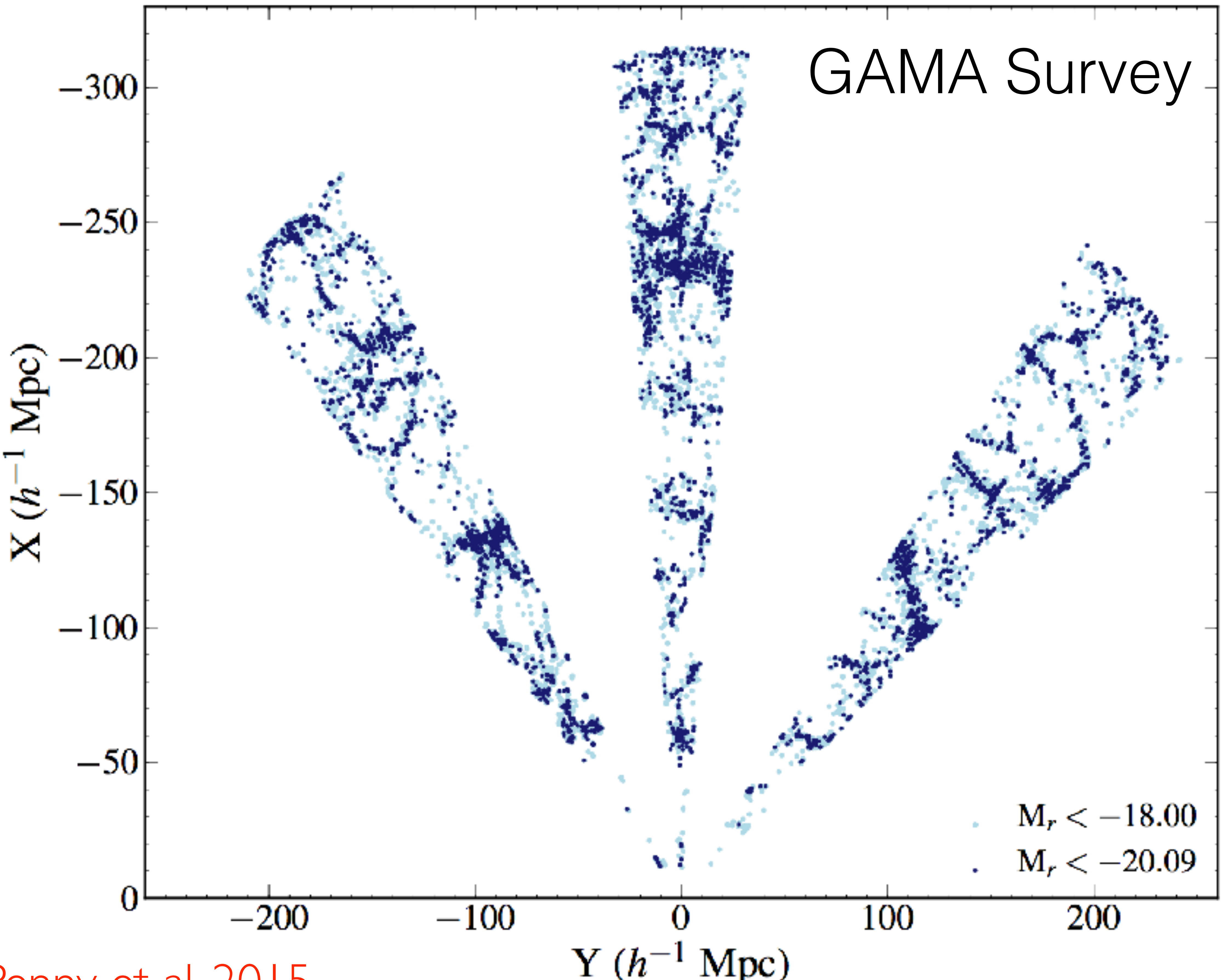
Fig. 1 A representation of the RA geometry of the WAVES survey (derived from the Theoretical Astrophysical Observatory), highlighting the complexity of structures that will be sampled.

Driver et al. 2015

Usage Case:

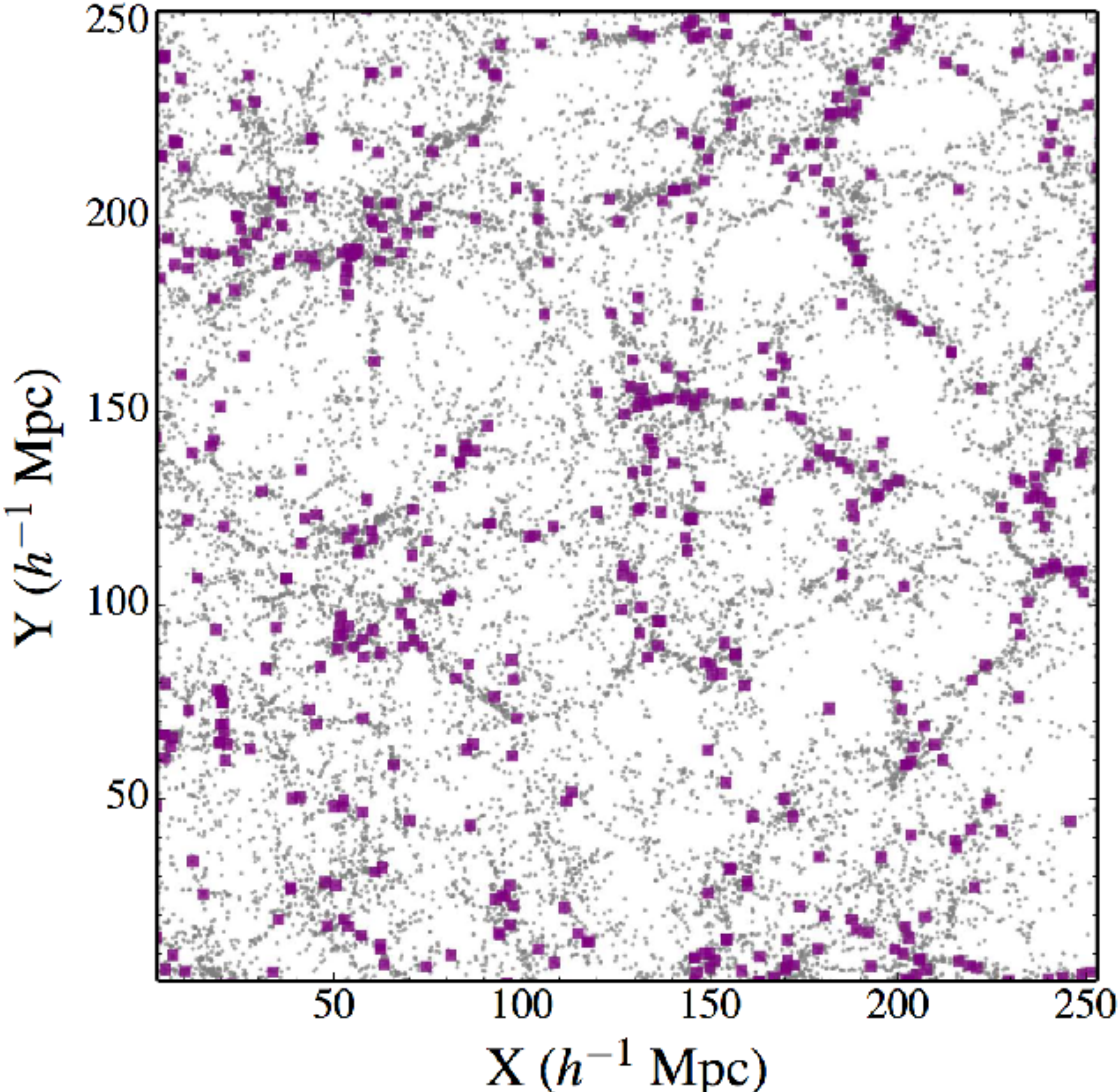
Cosmological-scale holes in the local Universe - (GAMA)

- There are massive regions of the Universe *almost* totally devoid of galaxies.
- Where do the “lost” galaxies that do live there come from?
- TAO allows access to the latest theoretical modelling.



Penny et al. 2015

TAO Galaxies



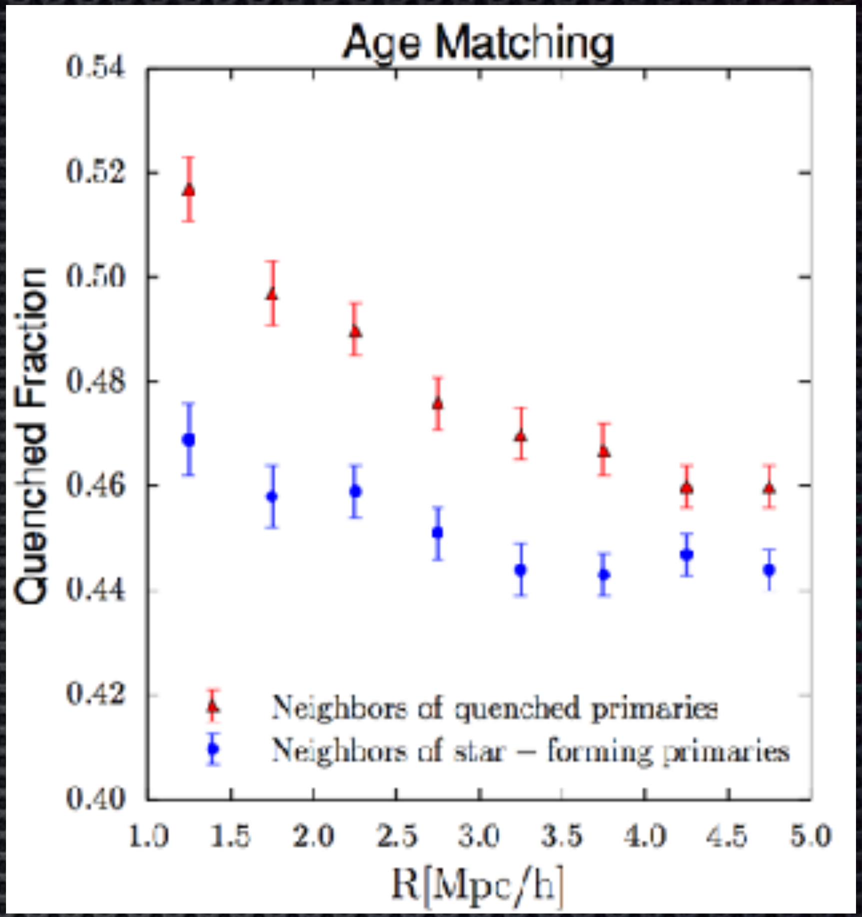
Purple = recent galaxy-galaxy collision

Grey = all TAO galaxies

Penny et al. 2015

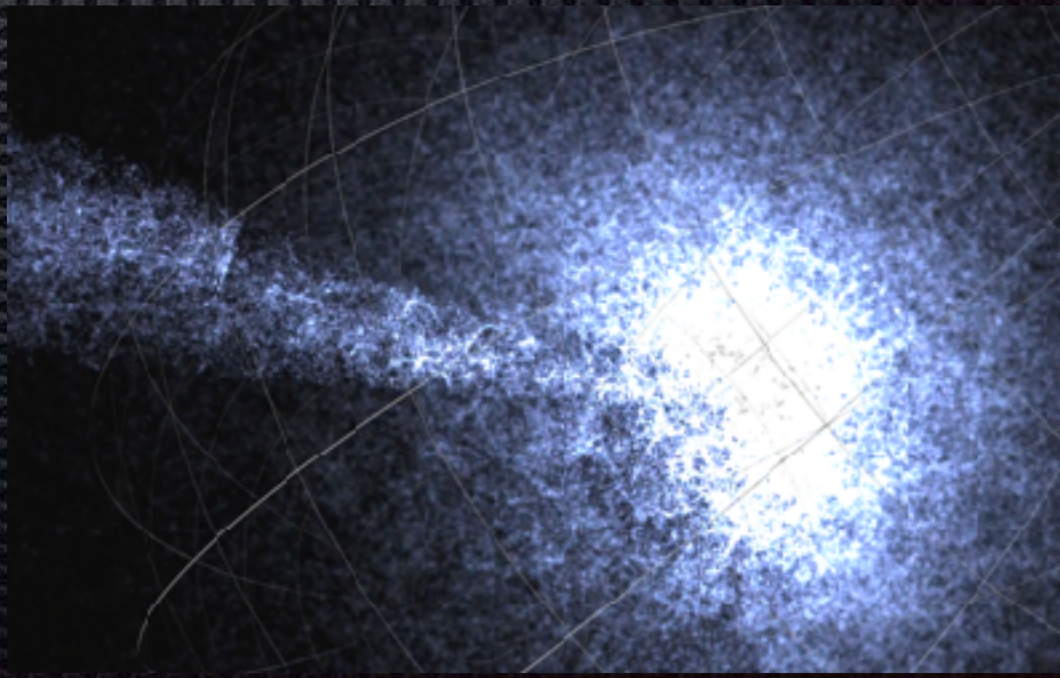
Usage Case: SDSS Cosmic conformity

- Galaxies “conform” over scales much larger than their local physics can impact. Why? (Hearin et al. 2014)



Usage Case: ASKAP Radio Surveys

- How many galaxies will ASKAP see? What kinds of galaxies? (Duffy et al. 2012)



TAO development timeline...

more simulations and models [ongoing]

data import tools [ongoing]

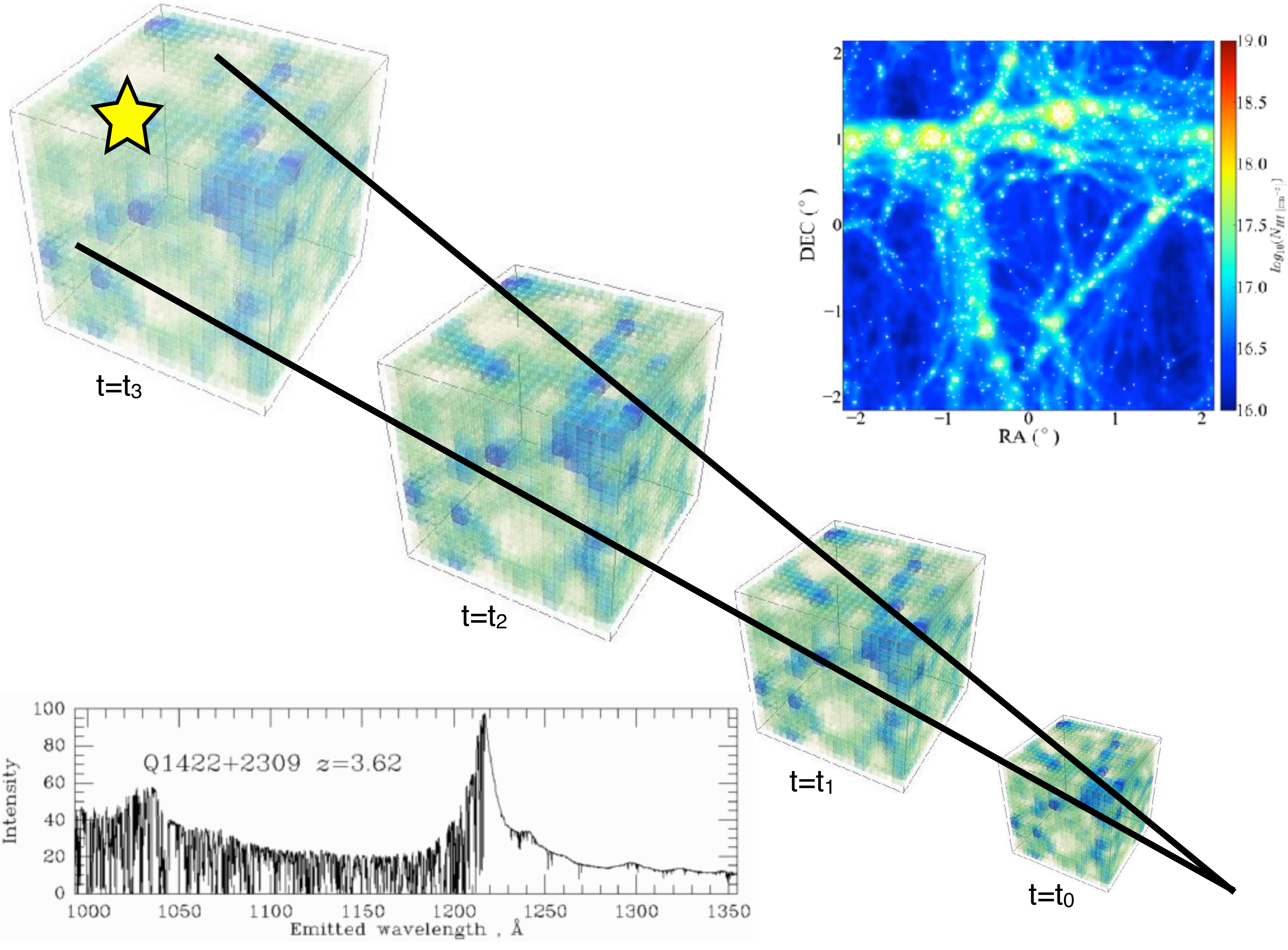
hydrodynamic simulation data [ongoing]

TAOcom: Command line TAO [started]

real-time image generation [started]

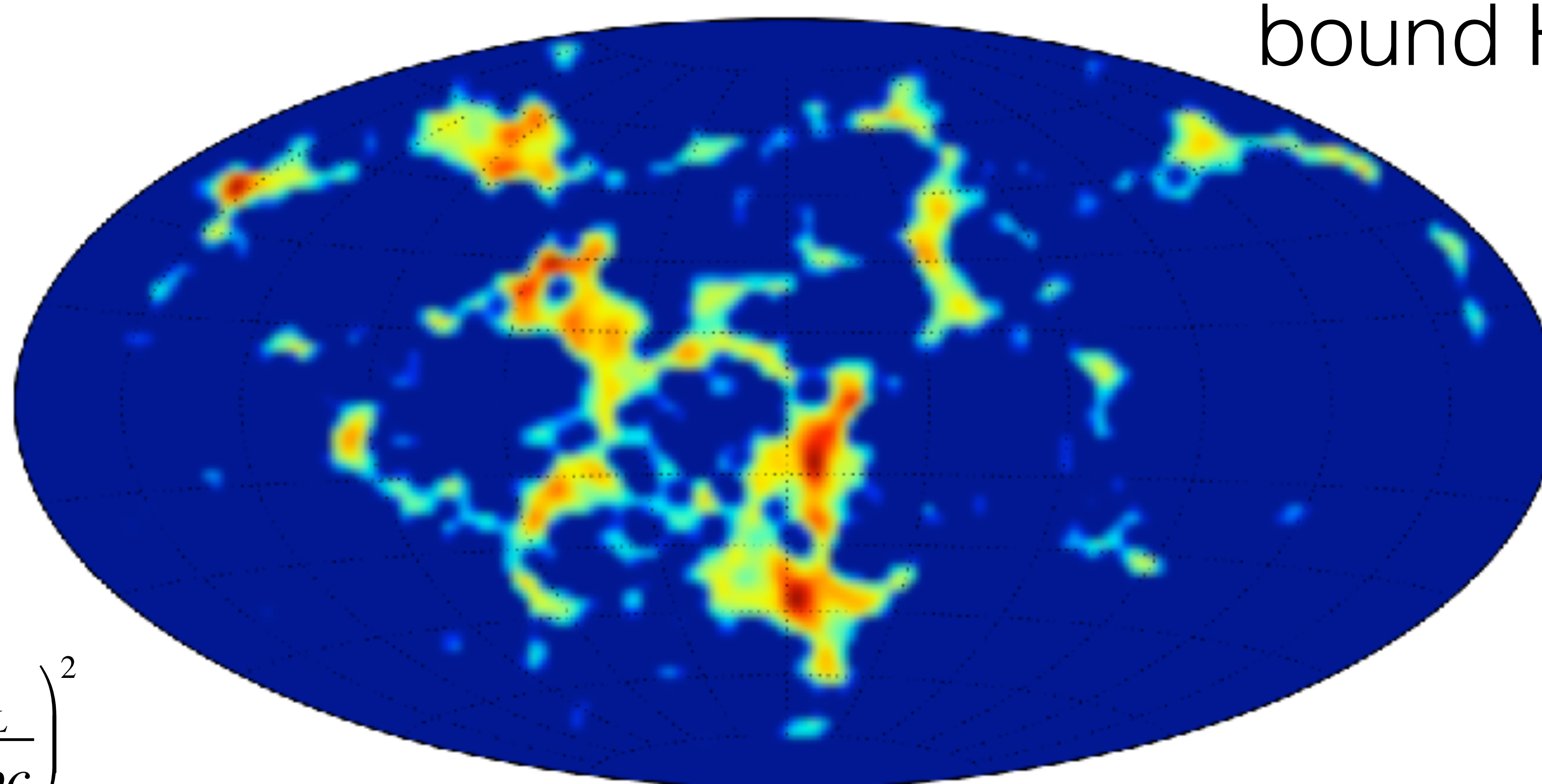
national/international/cloud TAO nodes [funded]

TAO for Teams (TfT) [completed]



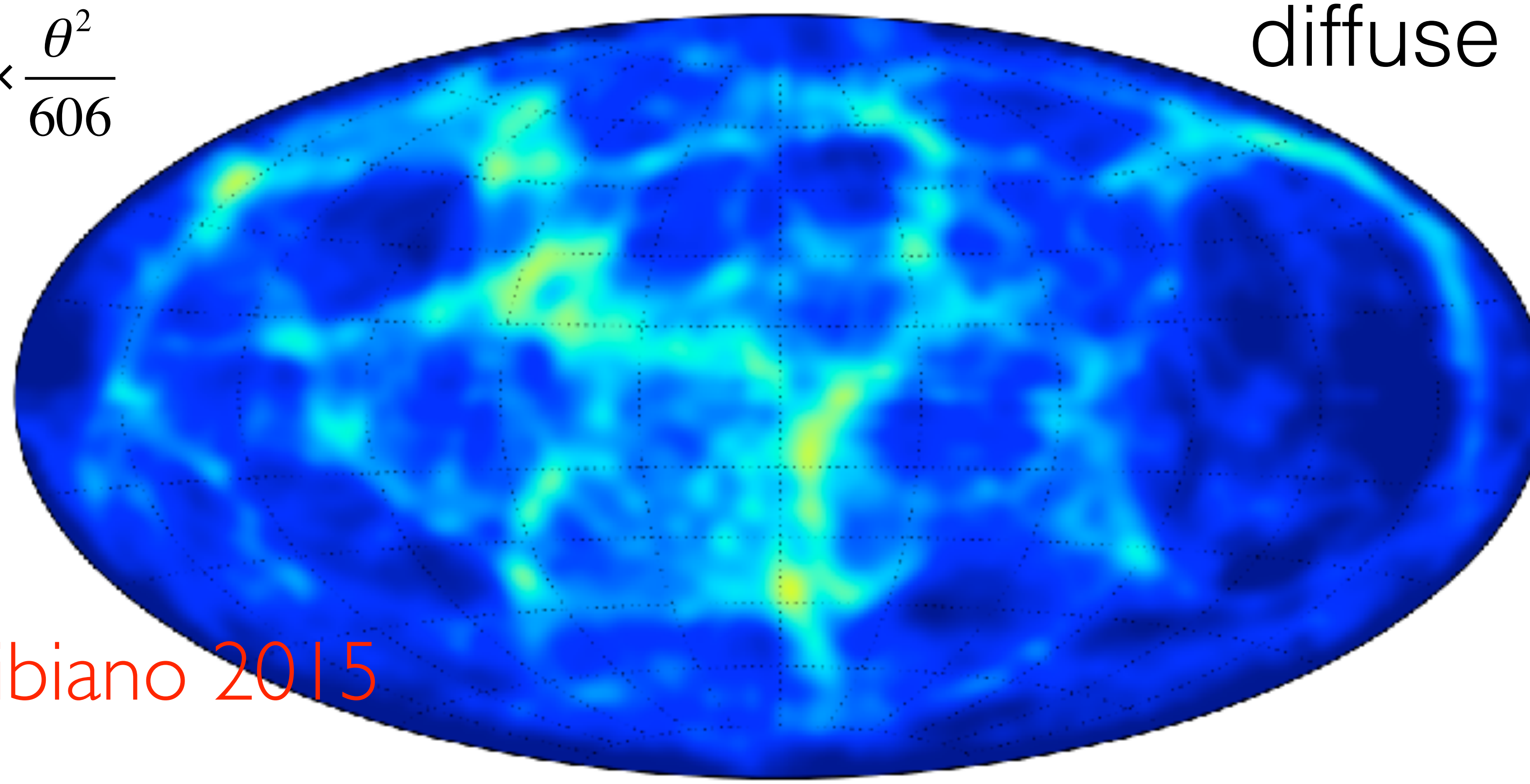
t=t3
t=t2
t=t1
t=t0
DEC (°)
RA (°)
log10(N_HI [cm^-2])
19.0
18.5
18.0
17.5
17.0
16.5
16.0
Q1422+2309 z=3.62
Intensity
Emitted wavelength , Å
100
80
60
40
20
0
1000
1050
1100
1150
1200
1250
1300
1350

All-Sky HI Maps



$$\frac{M_{HI}}{M_{\Theta}} = \frac{236}{1+z} \times \frac{S_{\text{int}}}{mJy\ km\ s^{-1}} \left(\frac{D_L}{Mpc} \right)^2$$

$$\frac{S_{\text{int}}}{mJy\ km\ s^{-1}} = \frac{N_{HI}}{1.823 \times 10^{18}\ cm^{-2}} \times \frac{\theta^2}{606}$$



Shattow, Croton & Bibiano 2015
Seiler et al. (in prep.)

The TAO project is part of the ASVO NeCTAR Virtual Laboratory, supported by

Swinburne University, Astronomy Australia Limited, and the Commonwealth Government

through ANDS/NeCTAR/RDS NCRIS and EIF funding

http://tao.asvo.org.au

http://www.asvo.org.au

https://www.nectar.org.au/all-sky-virtual-observatory

SAGE in Github:
https://github.com/darrencroton/sage

Croton et al. 2016

Models in TAO:
https://tao.asvo.org.au

Bernyk et al. 2016