Hunting for dark matter in the forest
(astrophysical constraints on warm dark matter)

Tom Theuns
ICC, Durham

with the Eagle collaboration: J Schaye (Leiden), R Crain (Liverpool), R Bower , C Frenk, & M Schaller (ICC)
and A Garzilli (Leiden), A Boyarsky (Leiden)

Contents:

- Dark matter: what is it, where is it, do we need it? How much?
- Dark matter: what do we need from it? Cold dark matter!
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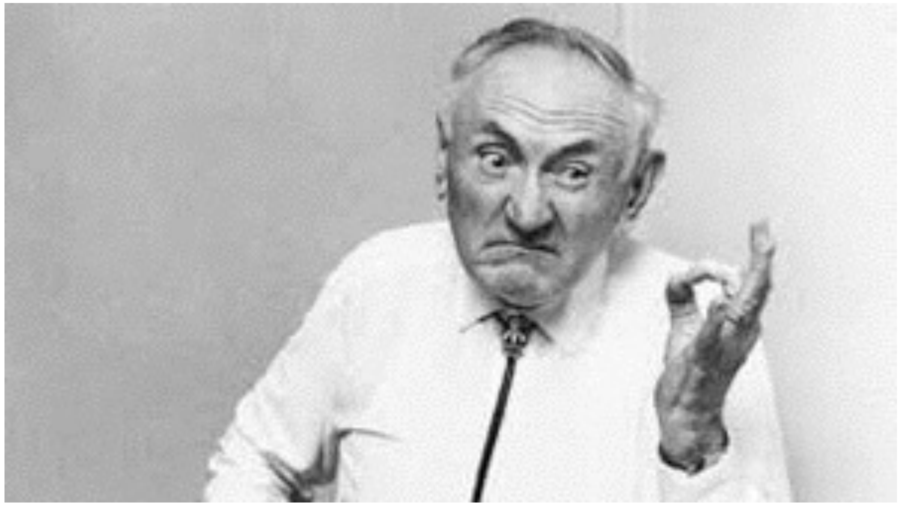
- Dark matter: cut-off in flux power spectra: WDM or thermal
- Future: lensing, and Relhics

Dark matter: Do we need it? What is it? Where is it? How much?

The Dark Matter Rap: Cosmological History for the MTV Generation
by David Weinberg

My name is Fritz Zwicky,
I can be kind of prickly,
This song had better start
by giving me priority.
Whatever anybody says,
I said in 1933.
Observe the Coma cluster,
the redshifts of the galaxies
imply some big velocities.
They're moving so fast,
there must be missing mass!
Dark matter.



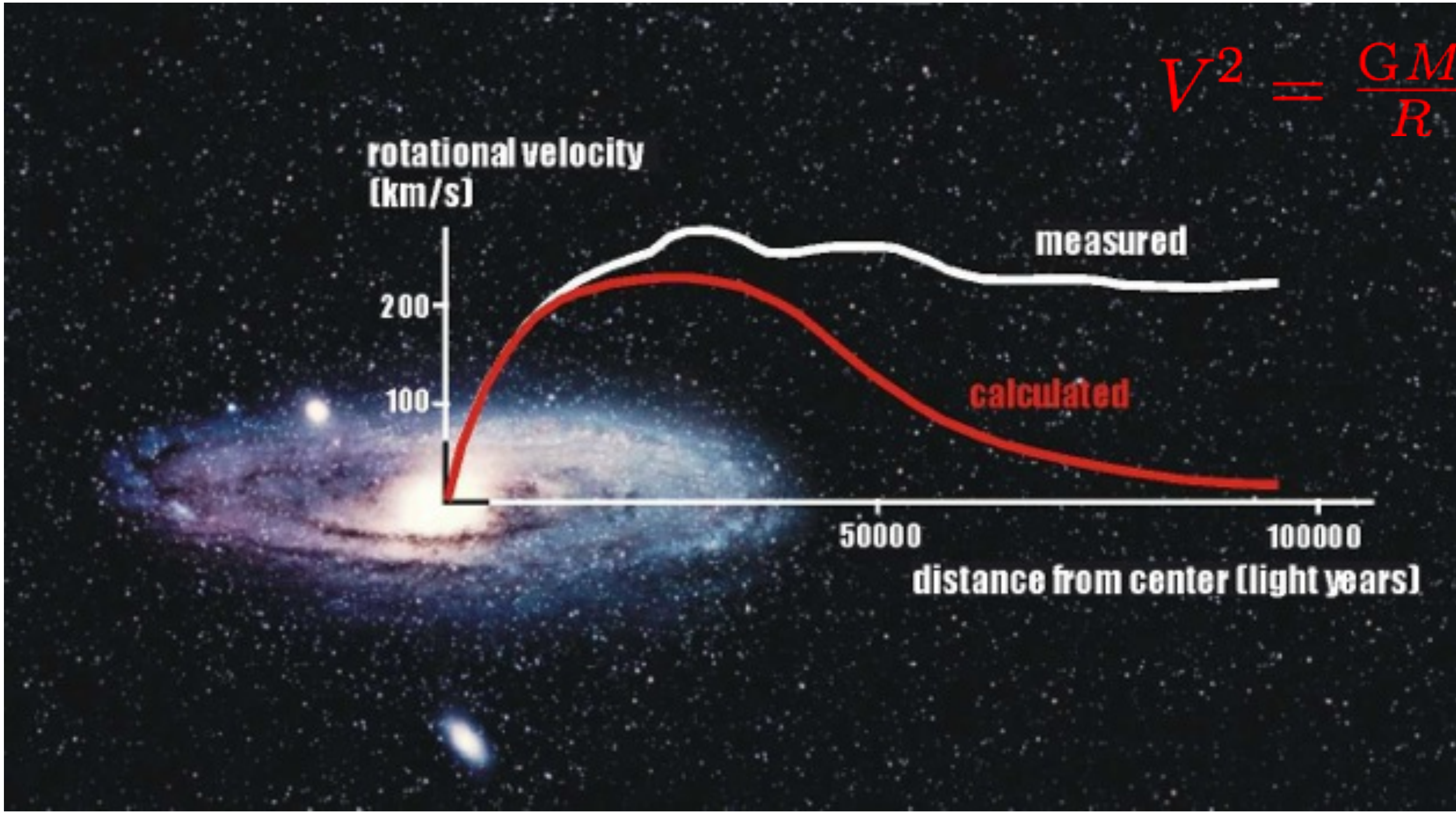
Dark matter: Do we need it? What is it? Where is it? How much?
Do we need it? Do we need it? Do we need it? Do we need it?

Dark matter: Do we need it? What is it? Where is it? How much?

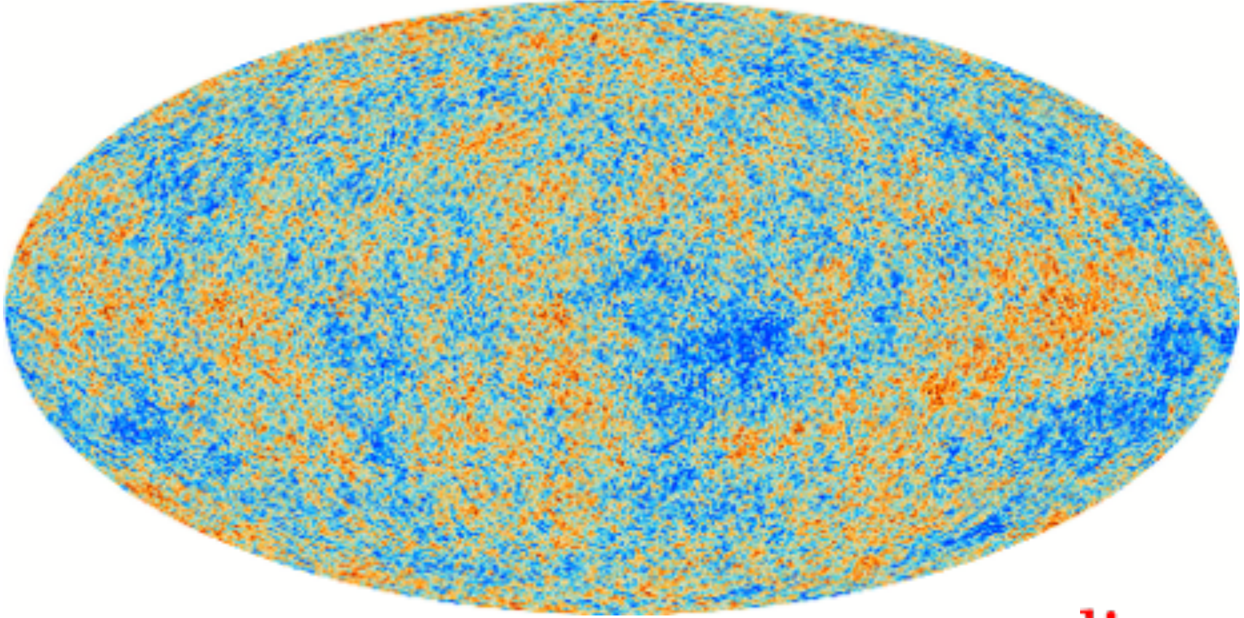
Cosmological History for the Twitter Generation

Galaxies and how they are distributed in the Universe require the existence of mass that does not shine. The nature of this dark matter is presently unknown.

Vera Rubin

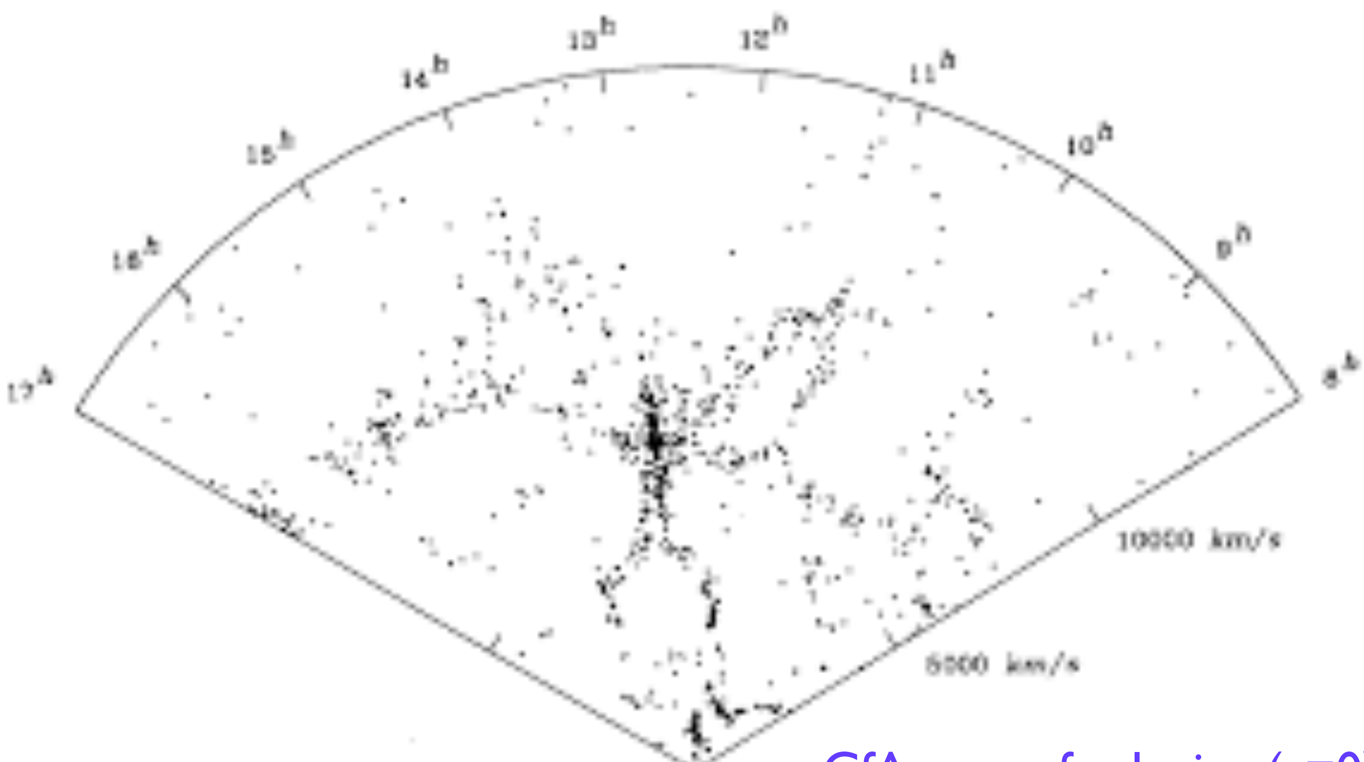


$$V^2 = \frac{GM}{R}$$



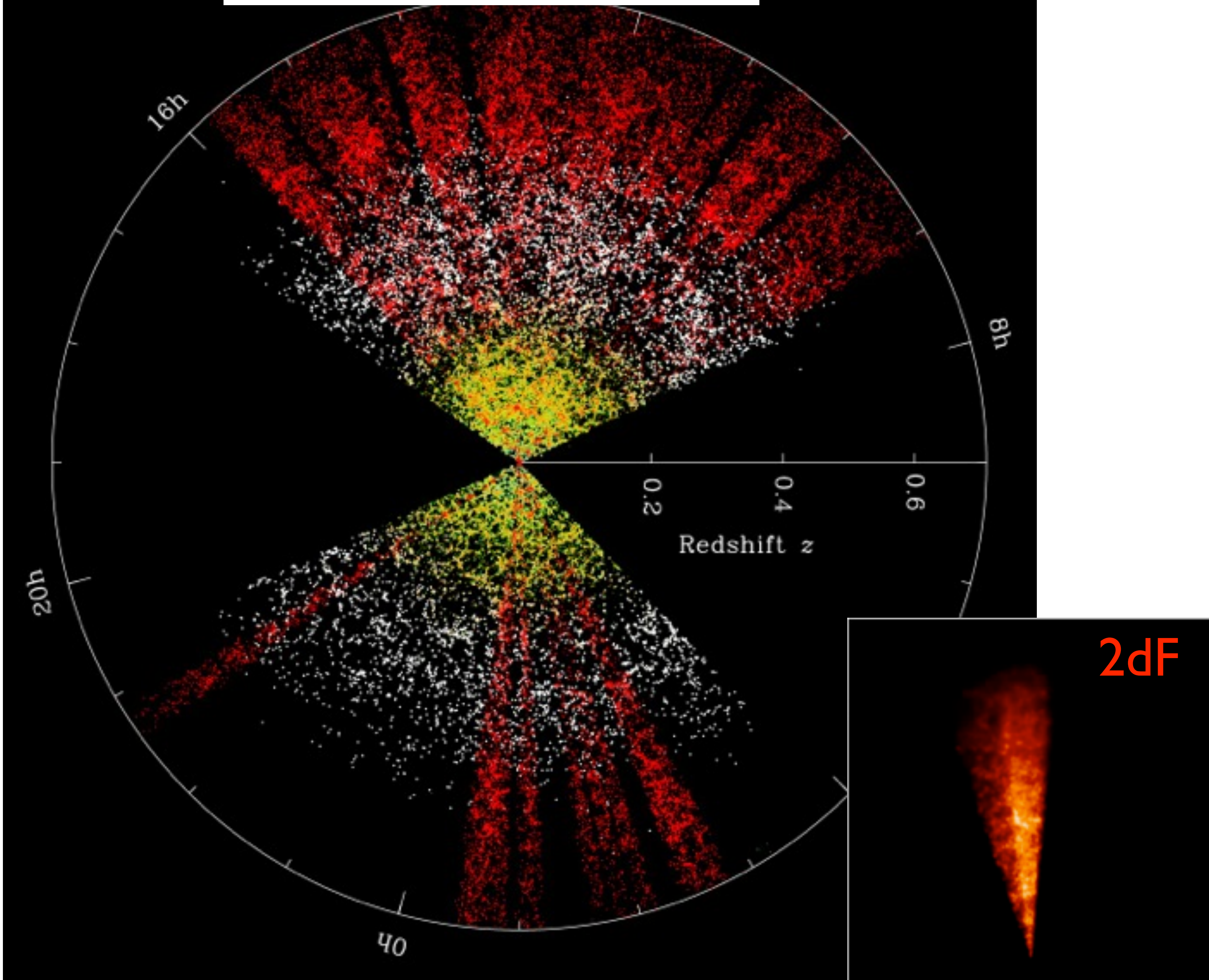
Planck CMB map (z=1000)

linear growth: $\delta \propto \frac{1}{1+z}$



CfA map of galaxies (z=0)

Galaxy clustering: SDSS



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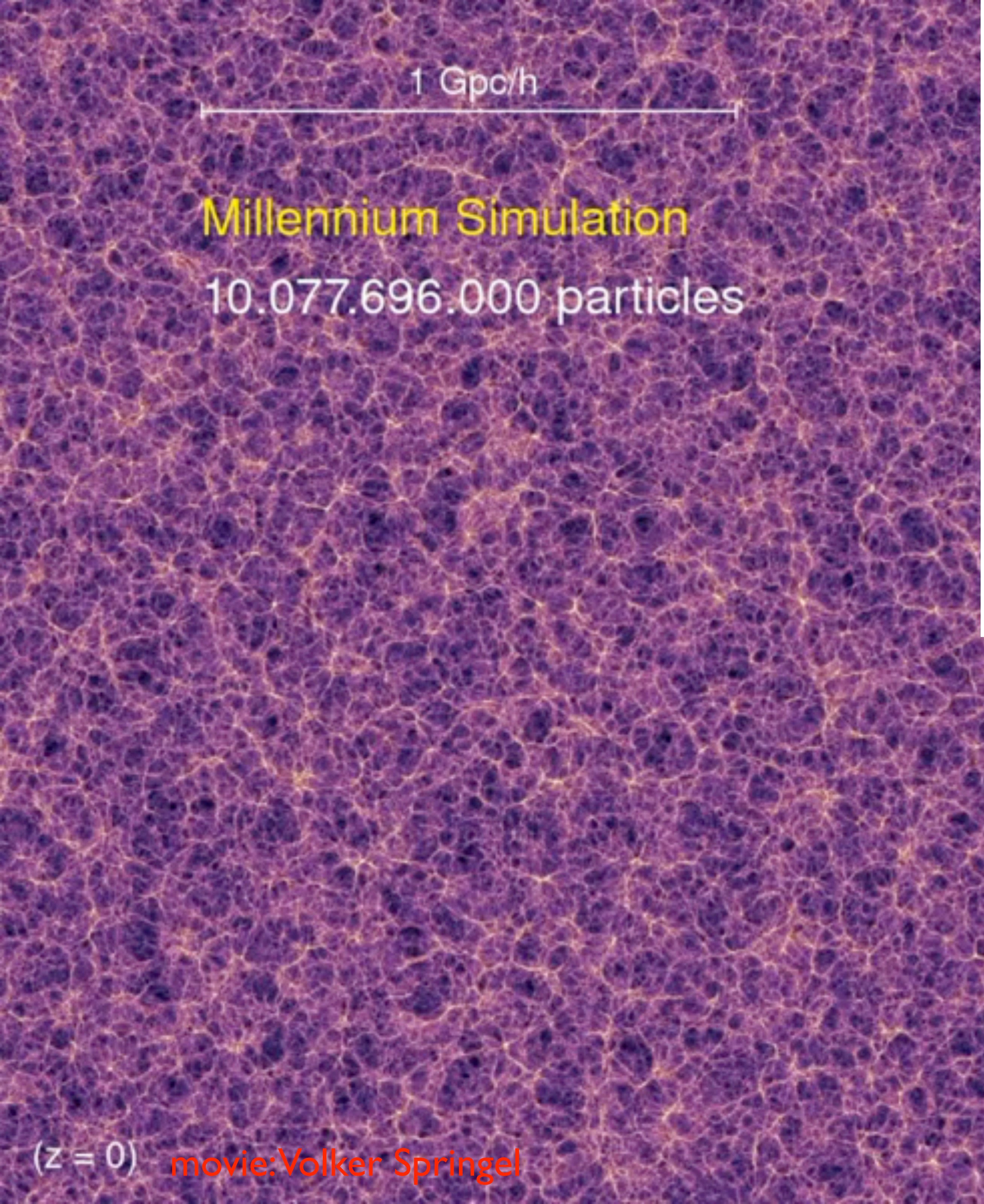
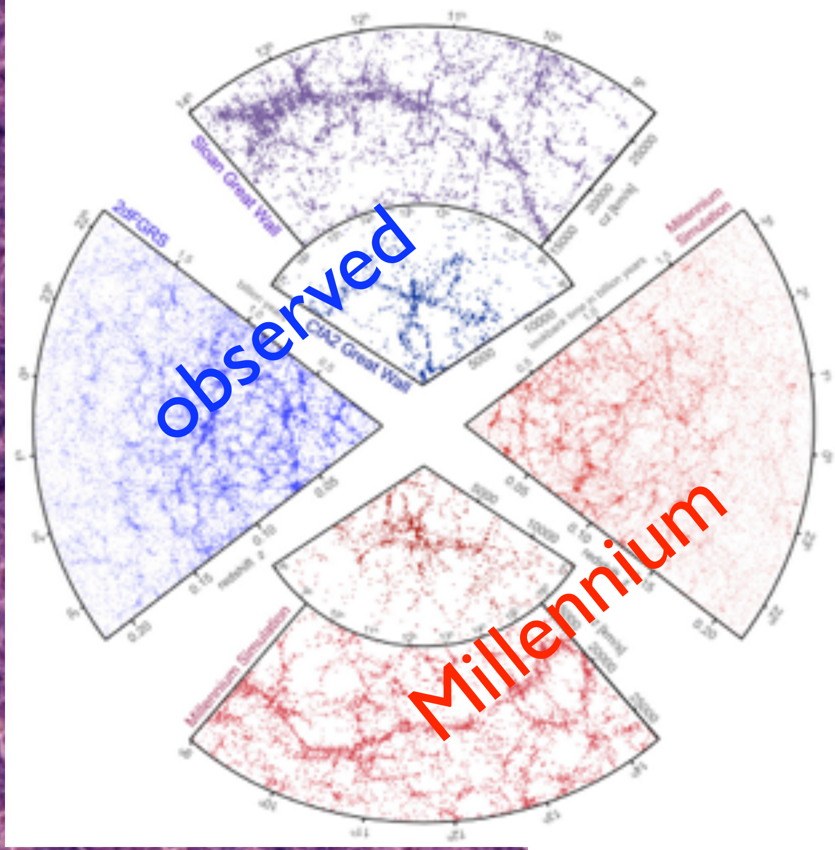

1 Gpc/h
Millennium Simulation
10.077.696.000 particles
(z = 0)
movie: Volker Springel

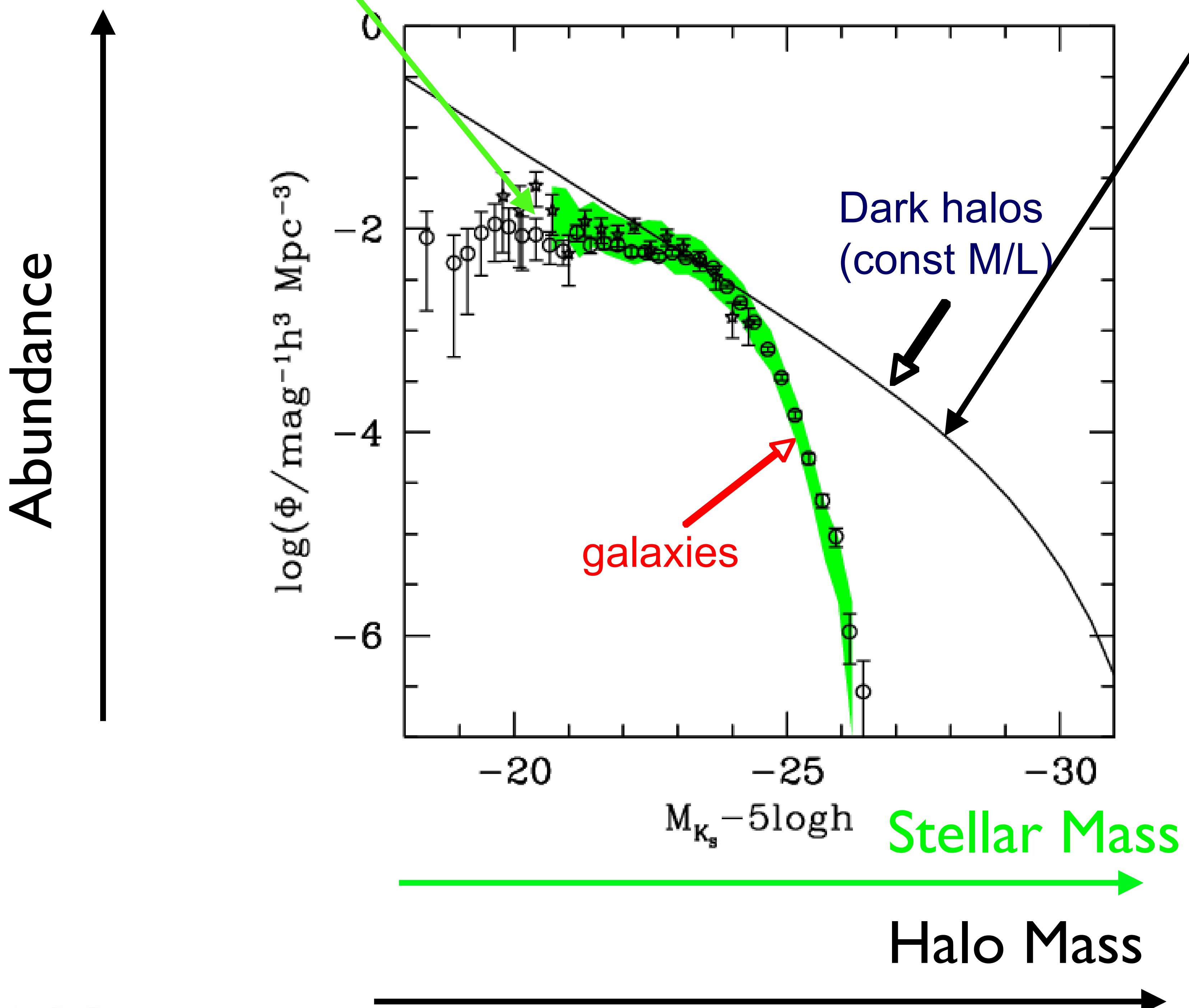

Sloan Great Wall
2dFGRS
CfA2 Great Wall
Millennium Simulation
observed
Millennium

Springel +05


nature
GENOME EDITING
Rewriting the rules for gene therapy
BCL-2 INHIBITORS
Potent new antitumour compounds
HUMAN BEHAVIOUR
Oxytocin — the 'trust hormone'
SURPRISING DINOSAURS
A sauropod, by a short neck
EVOLUTION OF THE UNIVERSE
Supercomputer simulation of the growth of 20 million galaxies

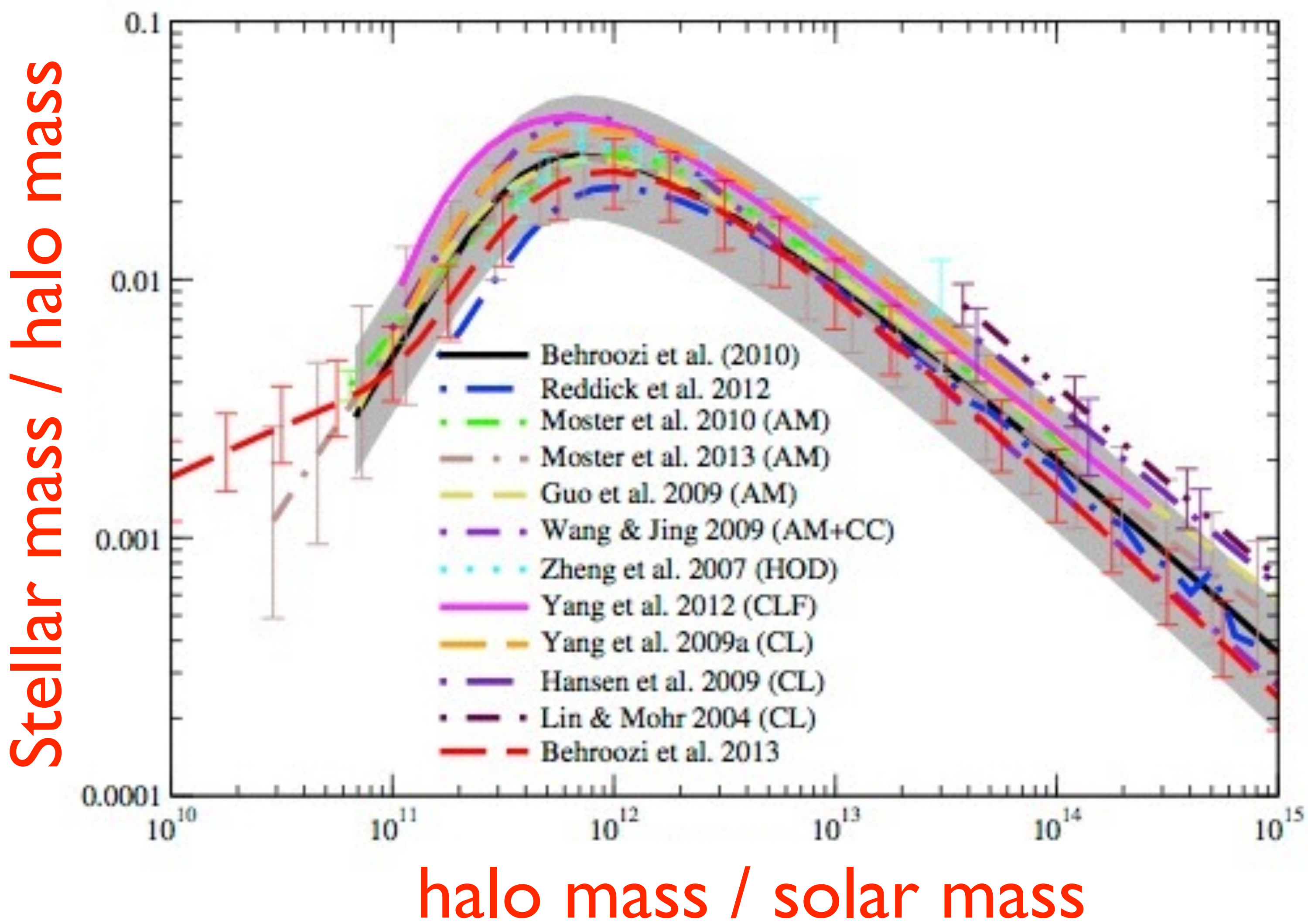

Millennium simulation + galaxy formation model
movie: John Helly (Durham)

Galaxy stellar mass function versus dark matter halo mass function



Bower+06

Galaxy formation efficiency



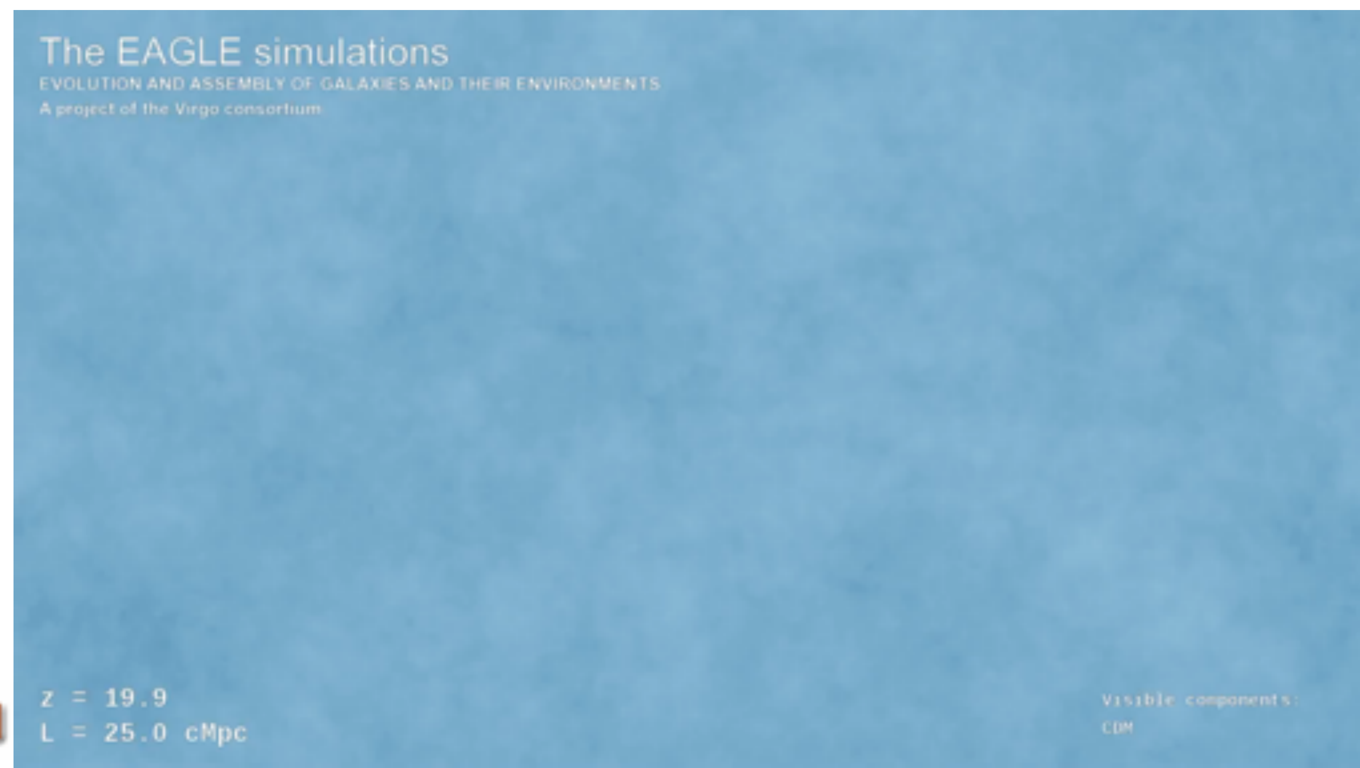
Behroozi +13

The EAGLE project: Simulating the evolution and assembly of galaxies and their environments

Joop Schaye,[1*] Robert A. Crain,[1] Richard G. Bower,[2] Michelle Furlong,[2] Matthieu Schaller,[2] Tom Theuns,[2,3] Claudio Dalla Vecchia,[4,5] Carlos S. Frenk,[2] I. G. McCarthy,[6] John C. Helly,[2] Adrian Jenkins,[2] Y. M. Rosas-Guevara,[2] Simon D. M. White,[7] Maarten Baes,[8] C. M. Booth,[1,9] Peter Camps,[8] Julio F. Navarro,[10] Yan Qu,[2] Alireza Rahmati,[7] Till Sawala,[2] Peter A. Thomas,[11] James Trayford[2]

[1] *Leiden Observatory, Leiden University, P.O. Box 9513, 2300 RA Leiden, the Netherlands*

- 1504^3 Gadget 3 simulation
- $(100\ \mathrm{Mpc})^3$ volume
- baryonic mass $10^6\ M_{sun}$
- Calibrated to z=0 stellar MF
- Local subgrid physics

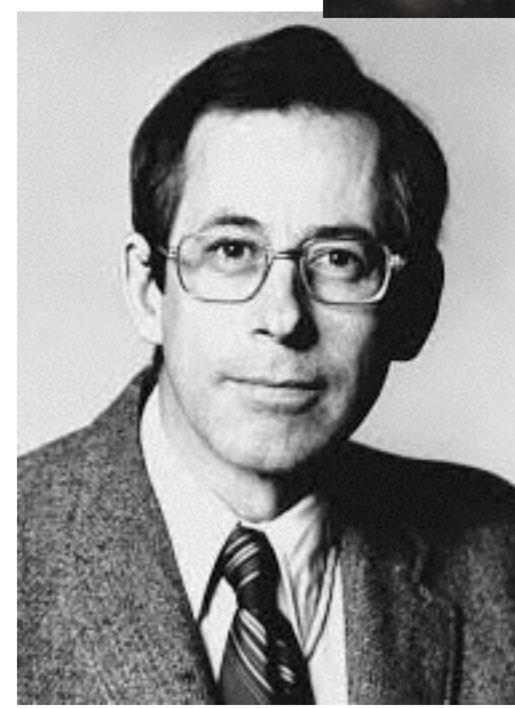


Dark matter: what do we need from it?

non-baryonic, small cross section, does not radiate (much): how about neutrinos?

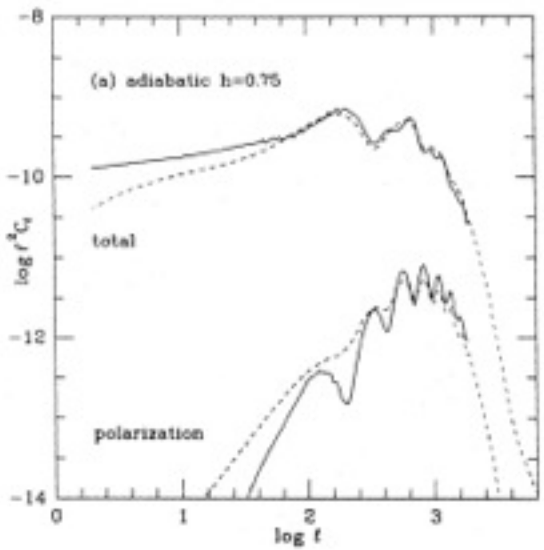
Zel'dovich

actually: that won't make galaxies!

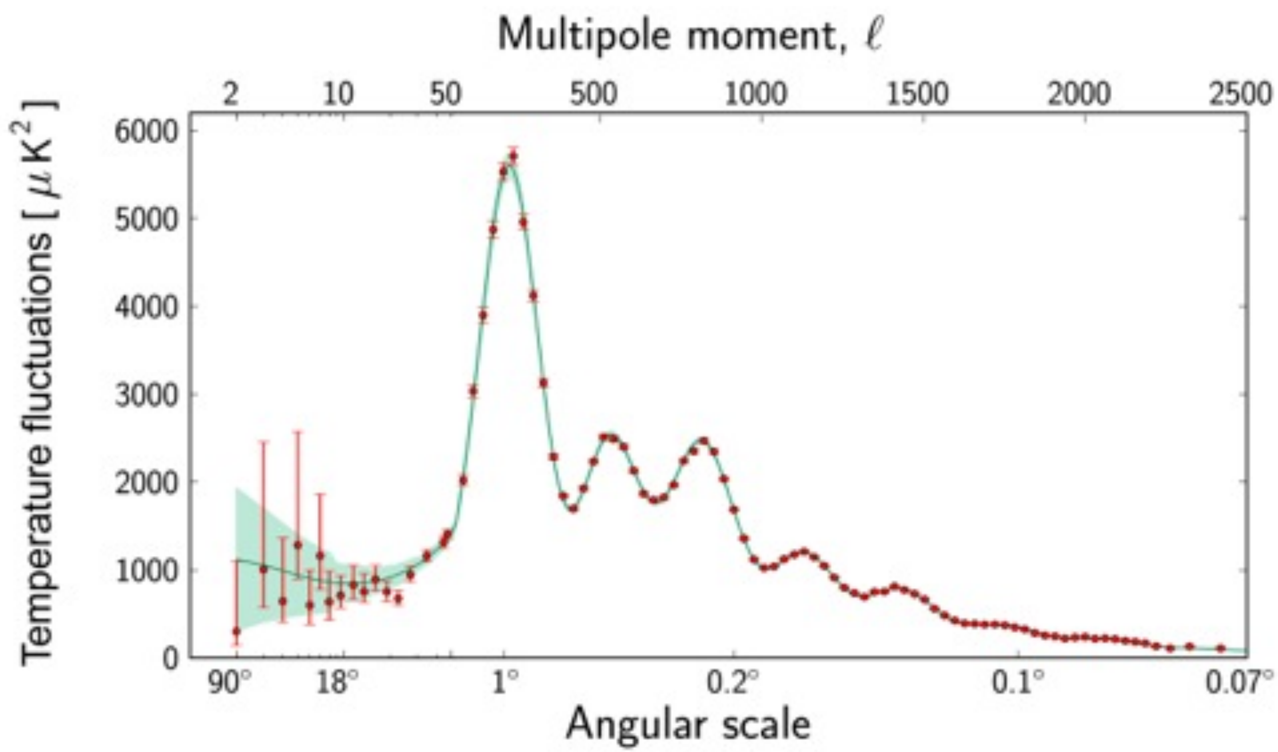


Peebles

The cold dark matter power spectrum



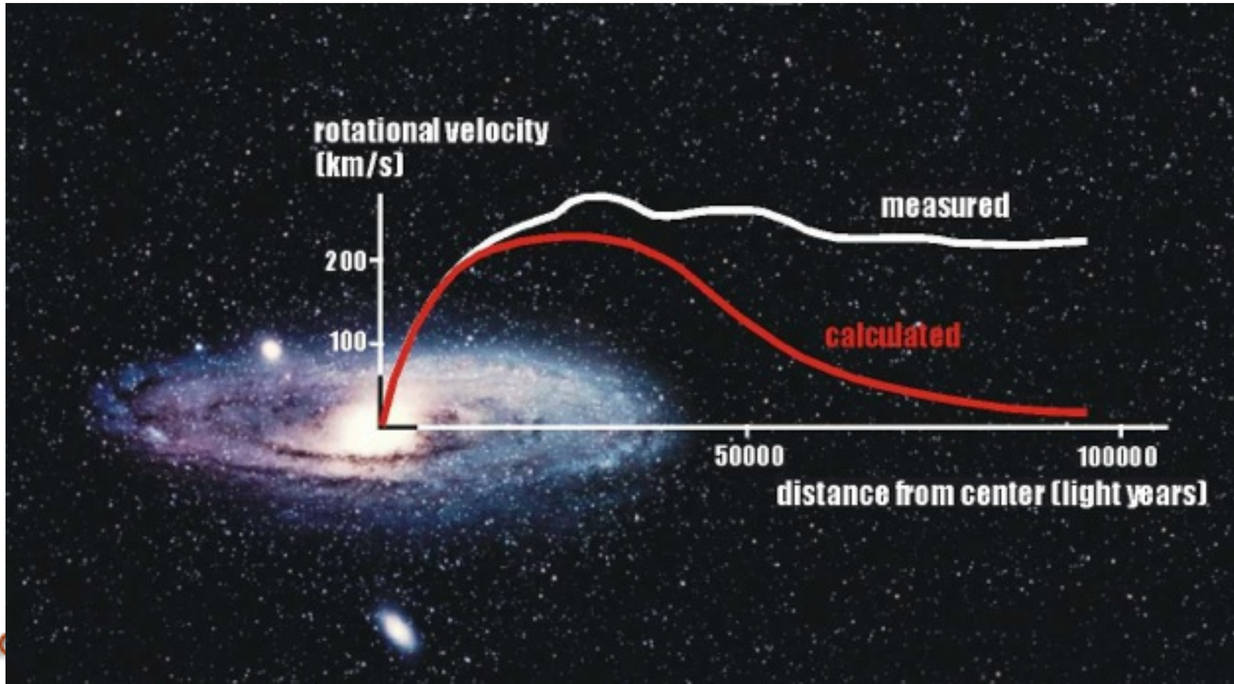
… as computed by Bond & Efstathiou '87



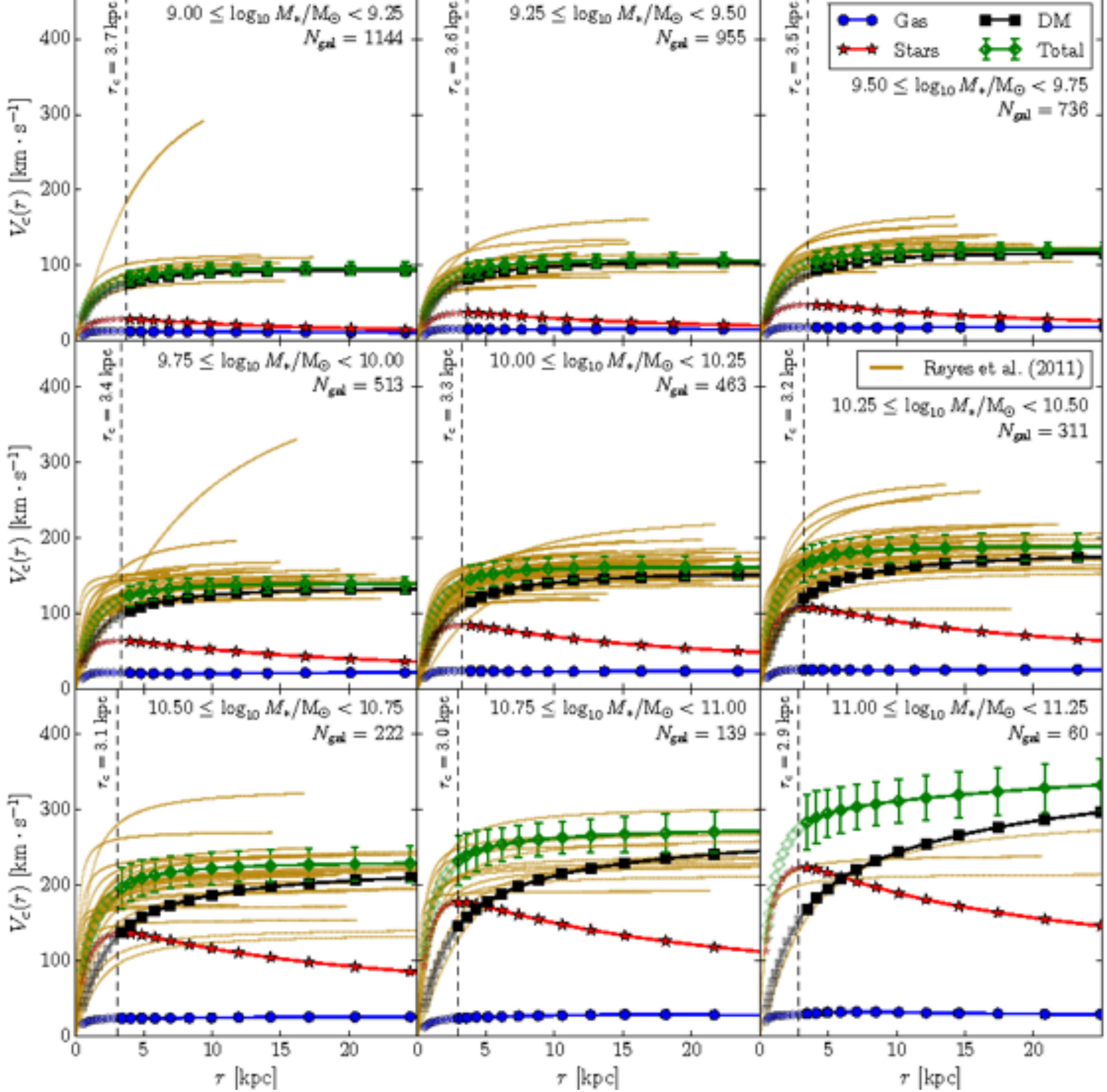
…and as measured by Planck

NFW in profile

NFW profile: $$\rho(r) = \frac{\rho_s}{(r/r_s)(1 + r/r_s)^2},$$



Eagle



Schaller +15

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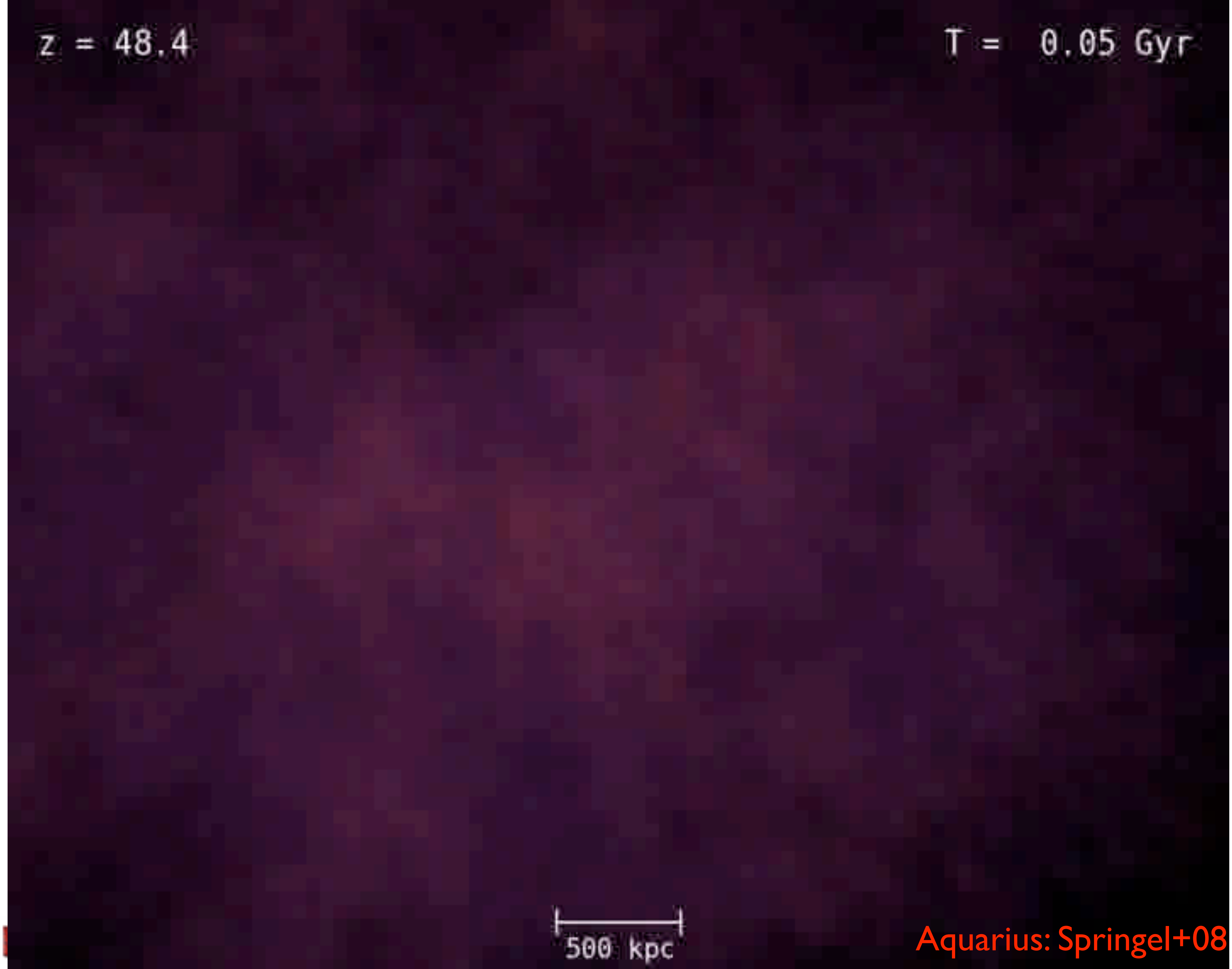

Aquarius: Springel+08

HALO FORMATION IN WARM DARK MATTER MODELS

PAUL BODE AND JEREMIAH P. OSTRIKER
Princeton University Observatory, Princeton, NJ 08544-1001
AND
NEIL TUROK

Three (four?) issues with CDM:

Discrepancies have emerged between the predictions of standard cold dark matter (CDM) theory and observations of clustering on subgalactic scales. Warm dark matter (WDM) is a simple modification of CDM in which the dark matter particles have initial velocities due either to their having decoupled as thermal relics or to their having been formed via nonequilibrium decay. We investigate the nonlinear gravitational clustering of WDM with a high-resolution N-body code and identify a number of distinctive observational signatures. Relative to CDM, halo concentrations and core densities are lowered, core radii are increased, and large halos emerge with far fewer low-mass satellites. The number of small halos is suppressed, and those present are formed by "top-down" fragmentation of caustics, as part of a "cosmic web" connecting massive halos. Few small halos form outside this web. If we identify small halos with dwarf galaxies, then their number, spatial distribution, and formation epoch appear in better agreement with the observations for WDM than they are for CDM.

HALO FORMATION IN WARM DARK MATTER MODELS

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Princeton University Observatory, Princeton, NJ 08544-1001
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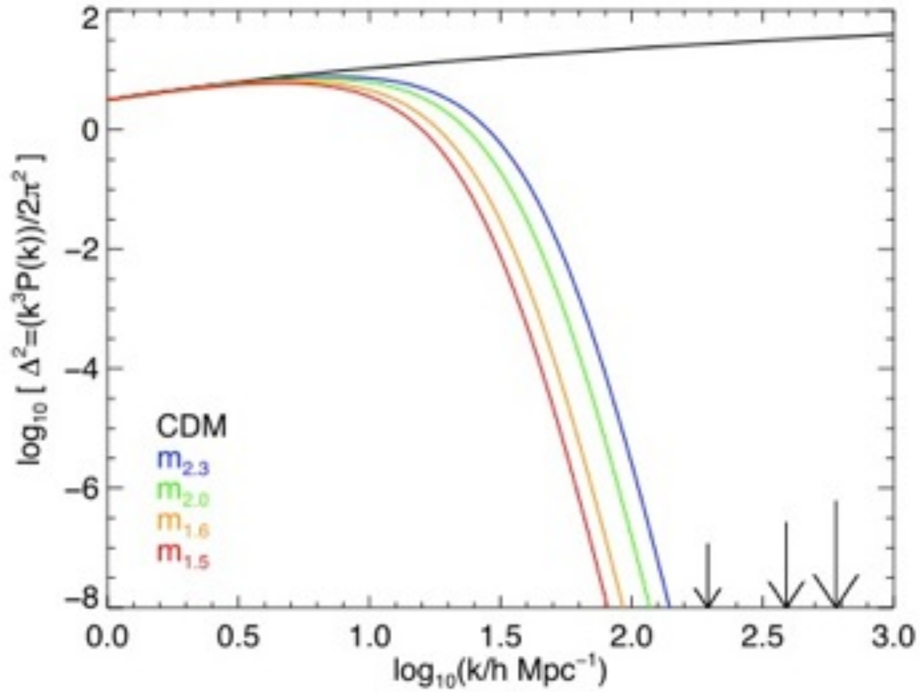
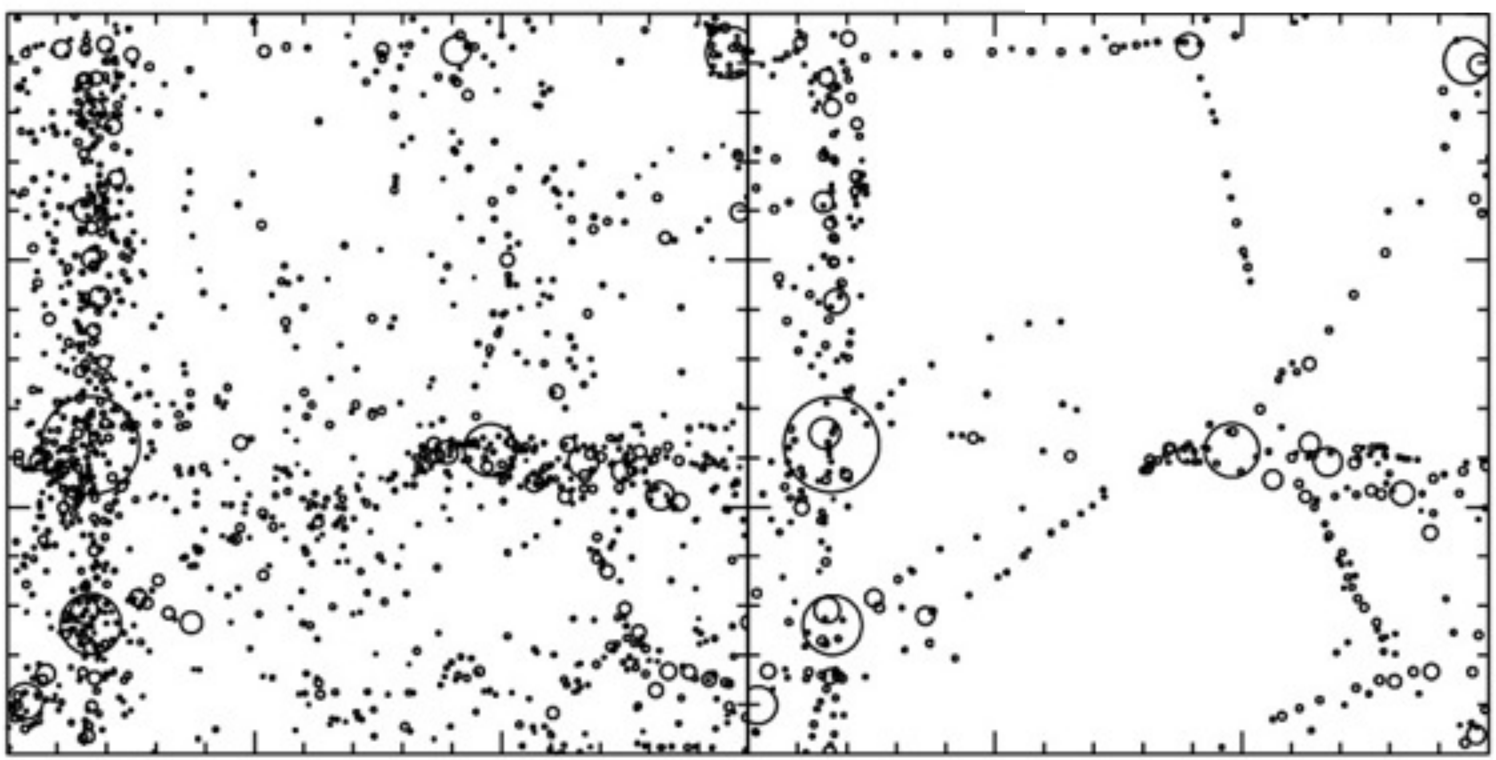


All these can be solved be warm dark matter

CDM WDM



LCDM m = 1.5 keV

Tom Theuns

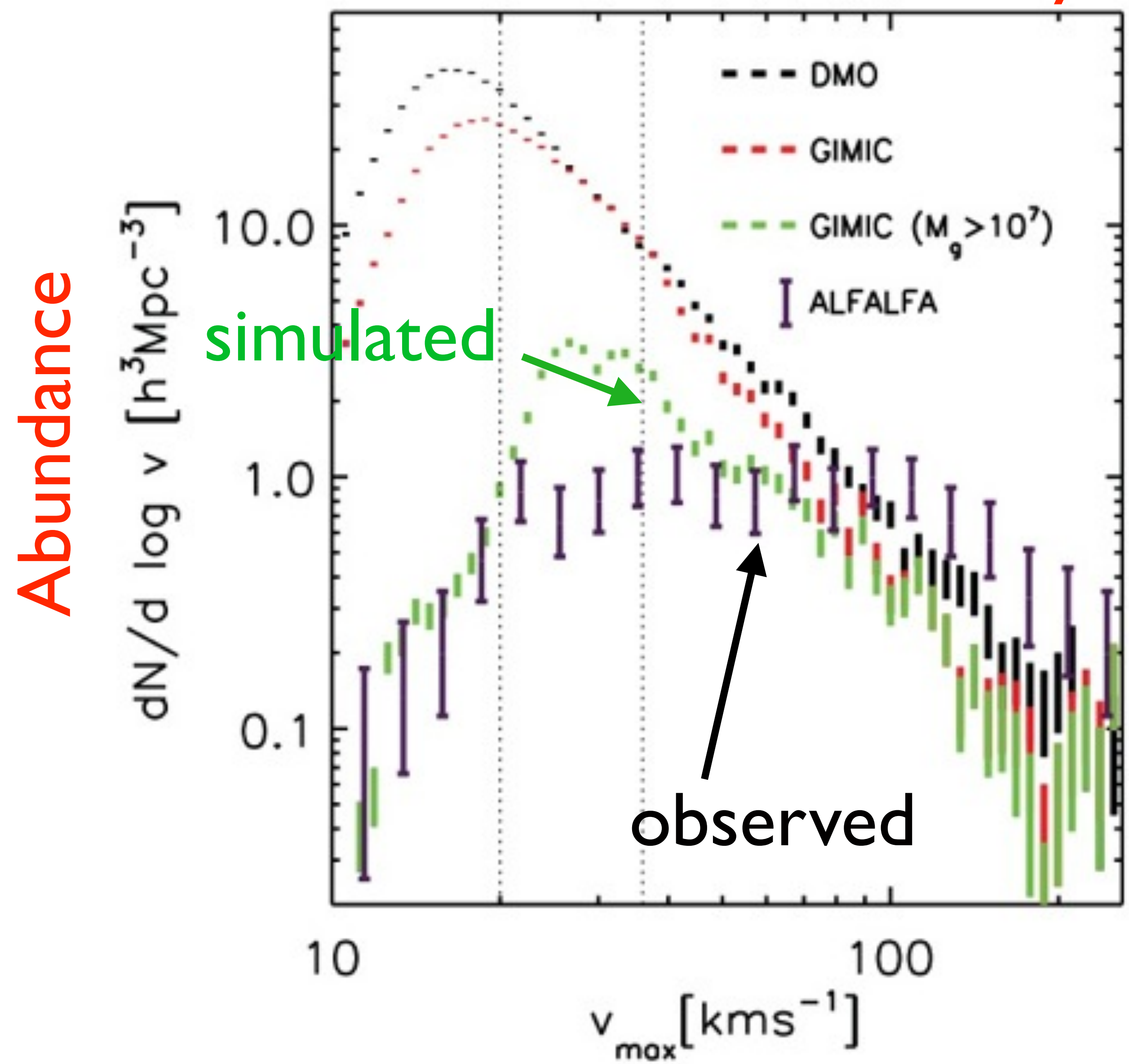
I "Observed voids are more empty than in cold dark matter"

(Peebles)

Eagle

Which dark matter halos are "observable"?

halos observable in neutral hydrogen

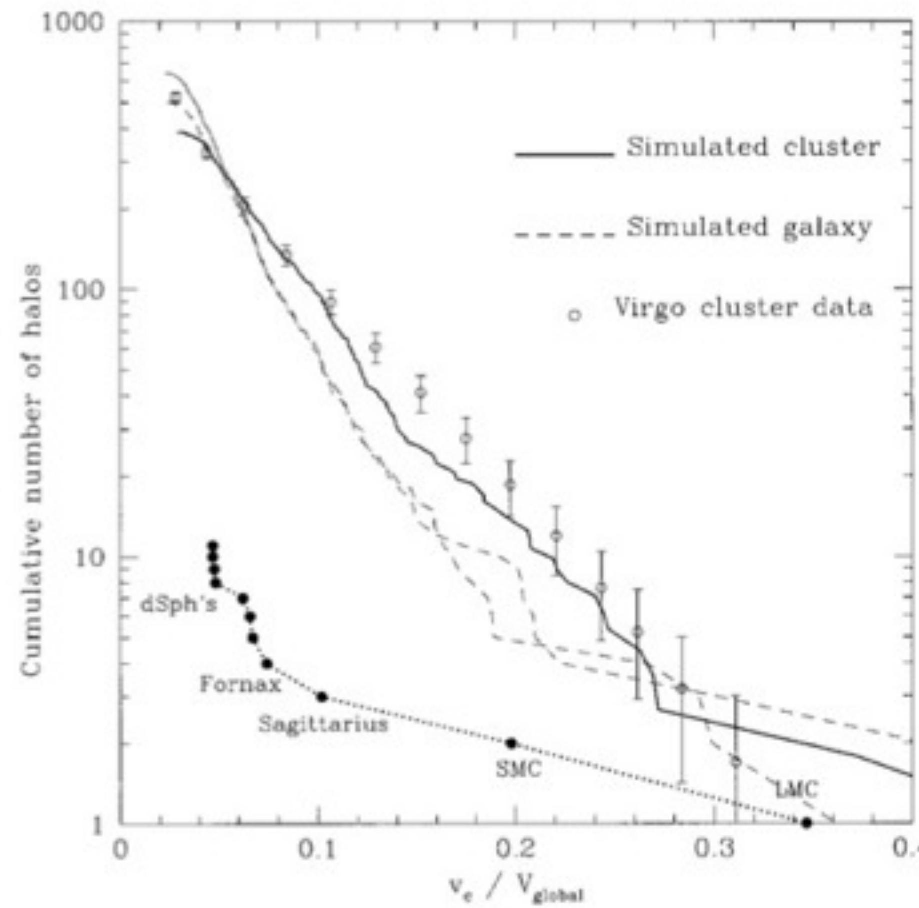


Sawala +13

2: “Cold dark matter predicts too many satellites”

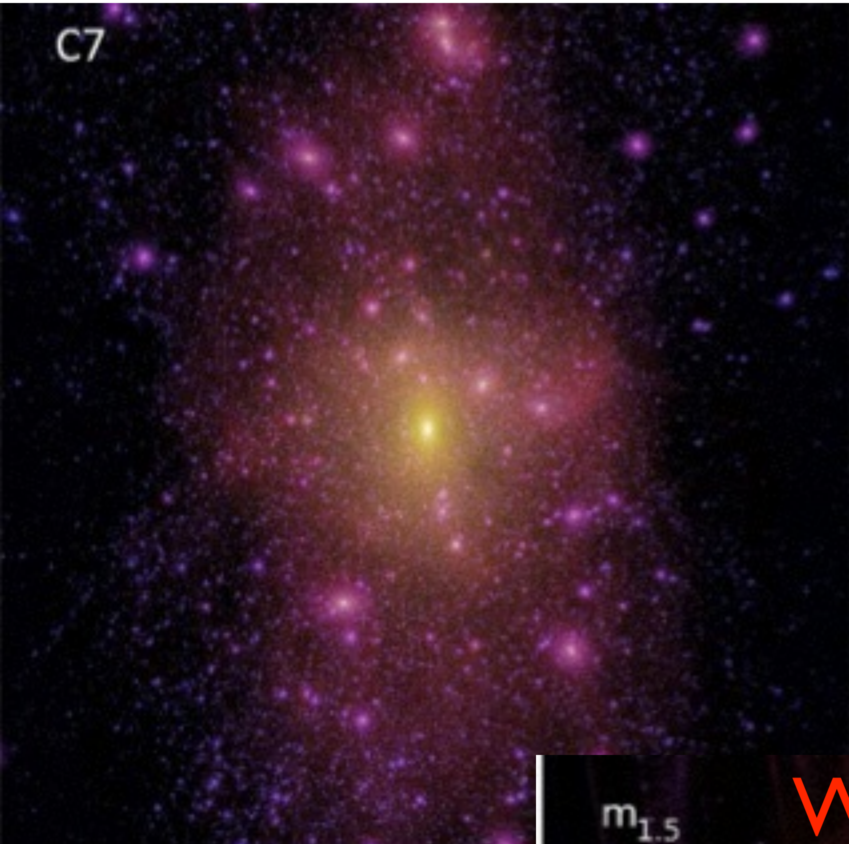
DARK MATTER SUBSTRUCTURE WITHIN GALACTIC HALOS

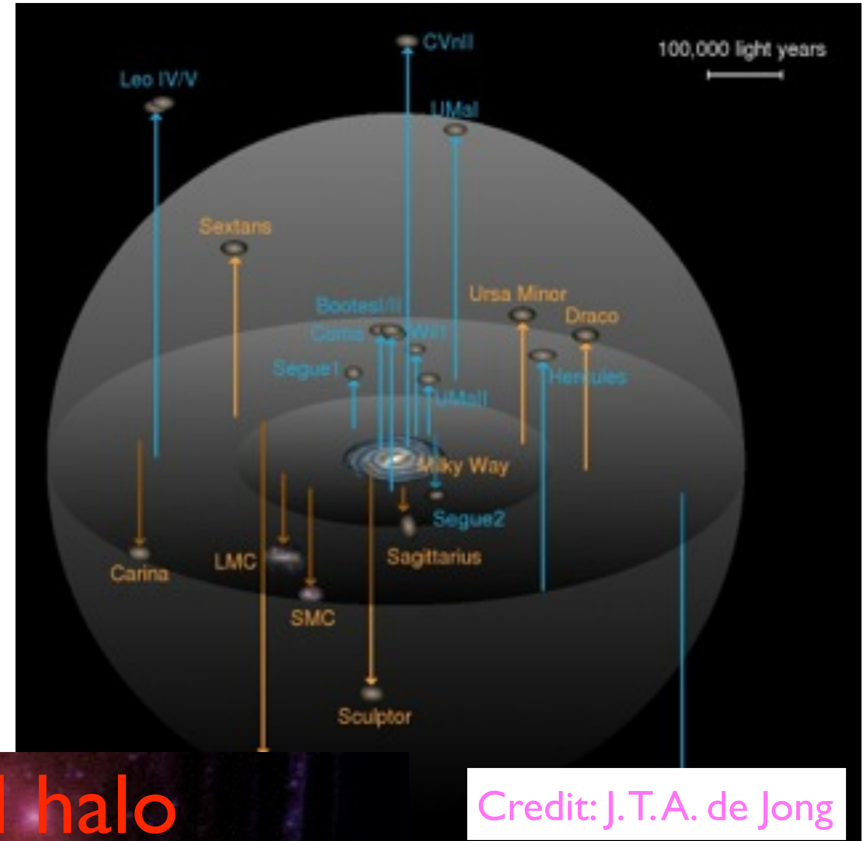
Ben Moore, Sebastiano Ghigna, and Fabio Governato
Department of Physics, Science Laboratories, South Road, University of Durham, Durham, England, DH1 3LE, UK;
ben.moore@durham.ac.uk, ssg@durham.ac.uk, fabio@antares.merate.mi.astro.it
George Lake, Thomas Quinn, and Joachim Stadel
Department of Astronomy, Box 351580, University of Washington, Seattle, WA 98195-1580;
lake@hermes.astro.washington.edu, trq@hermes.astro.washington.edu, stadel@hermes.astro.washington.edu



CDM halo

Milky Way's satellites



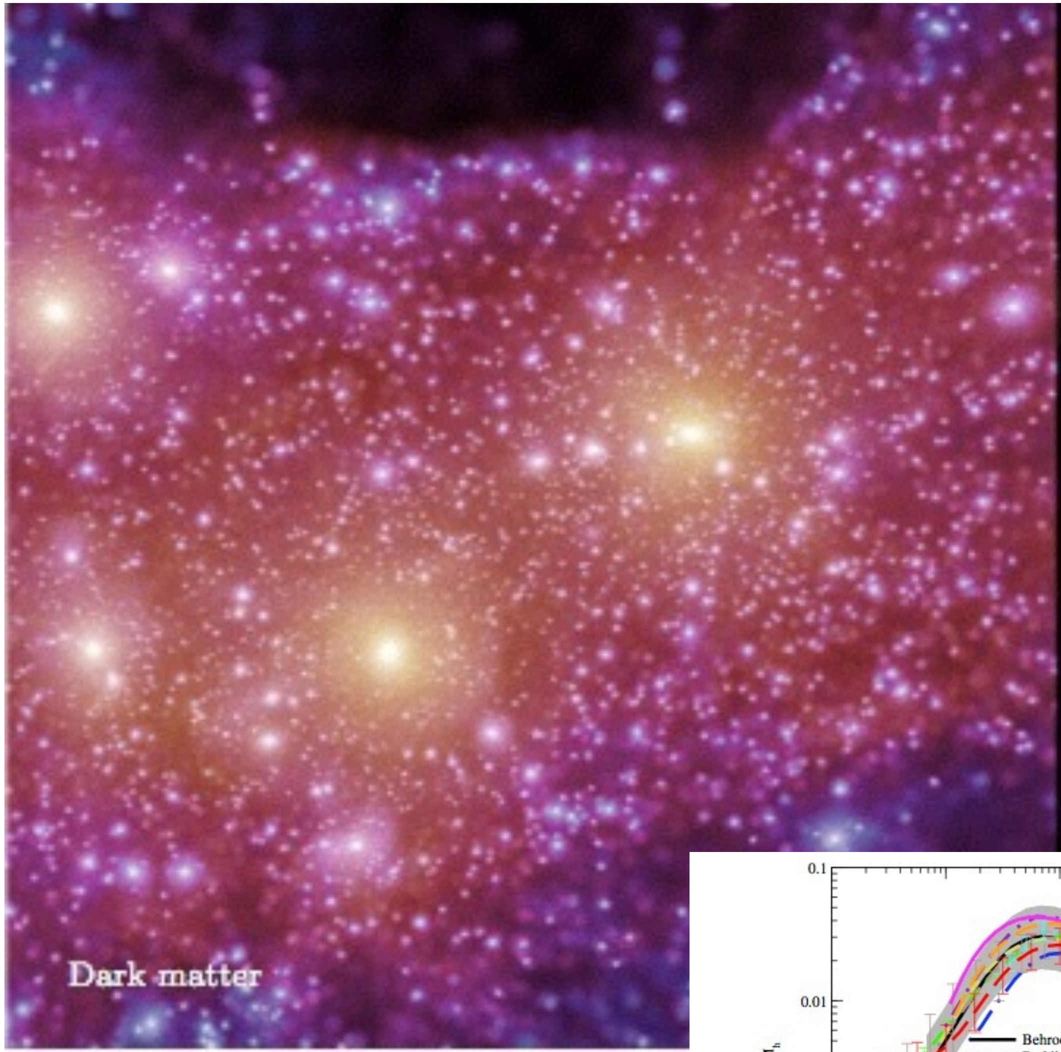


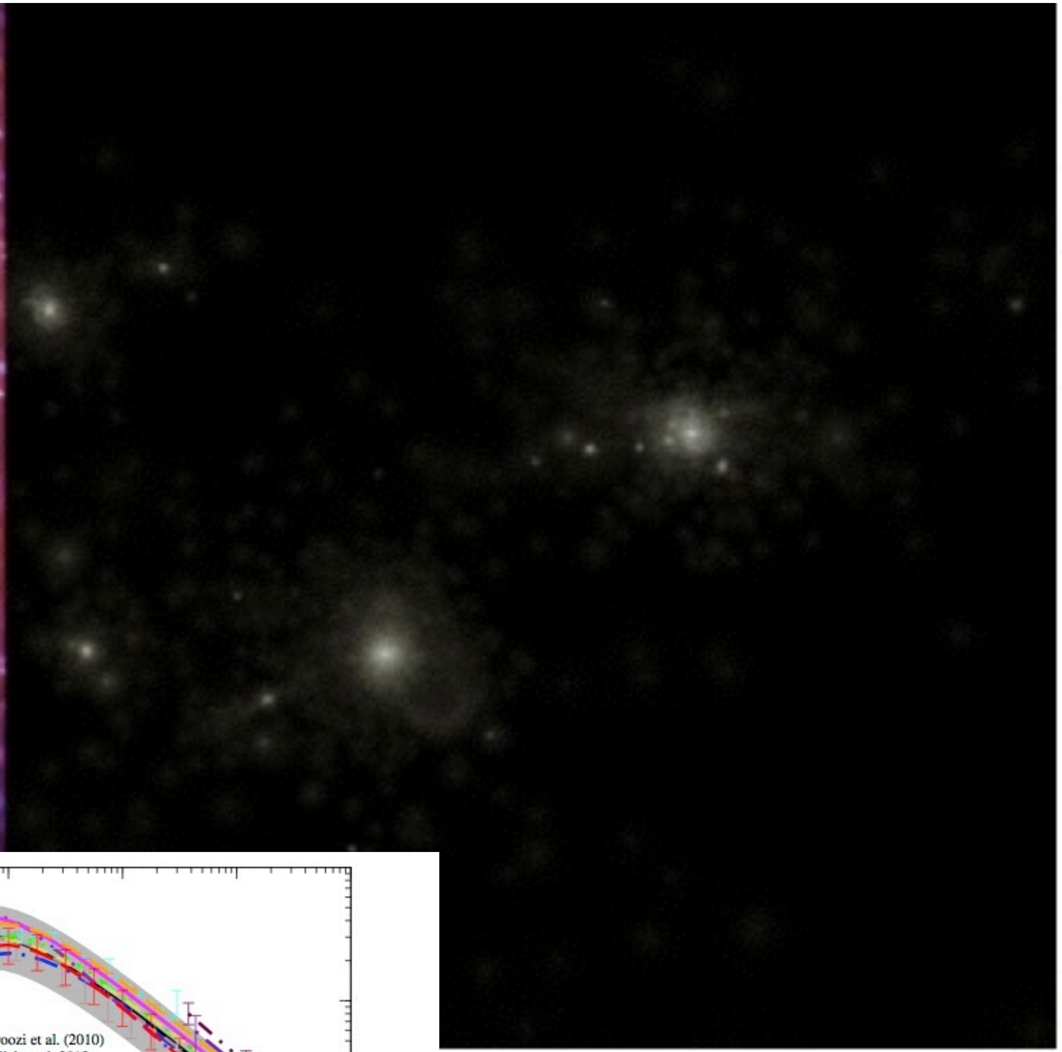
Credit: J.T.A. de Jong

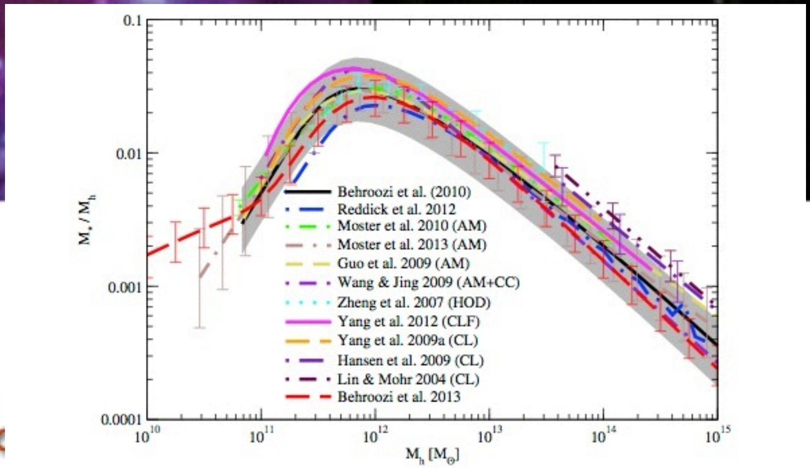
WDM halo

Eagle

Dark matter view (halos) Observable view (galaxies)





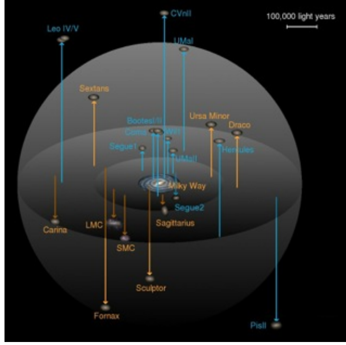


ICC Institute for Computati

Sawala+14

Eagle

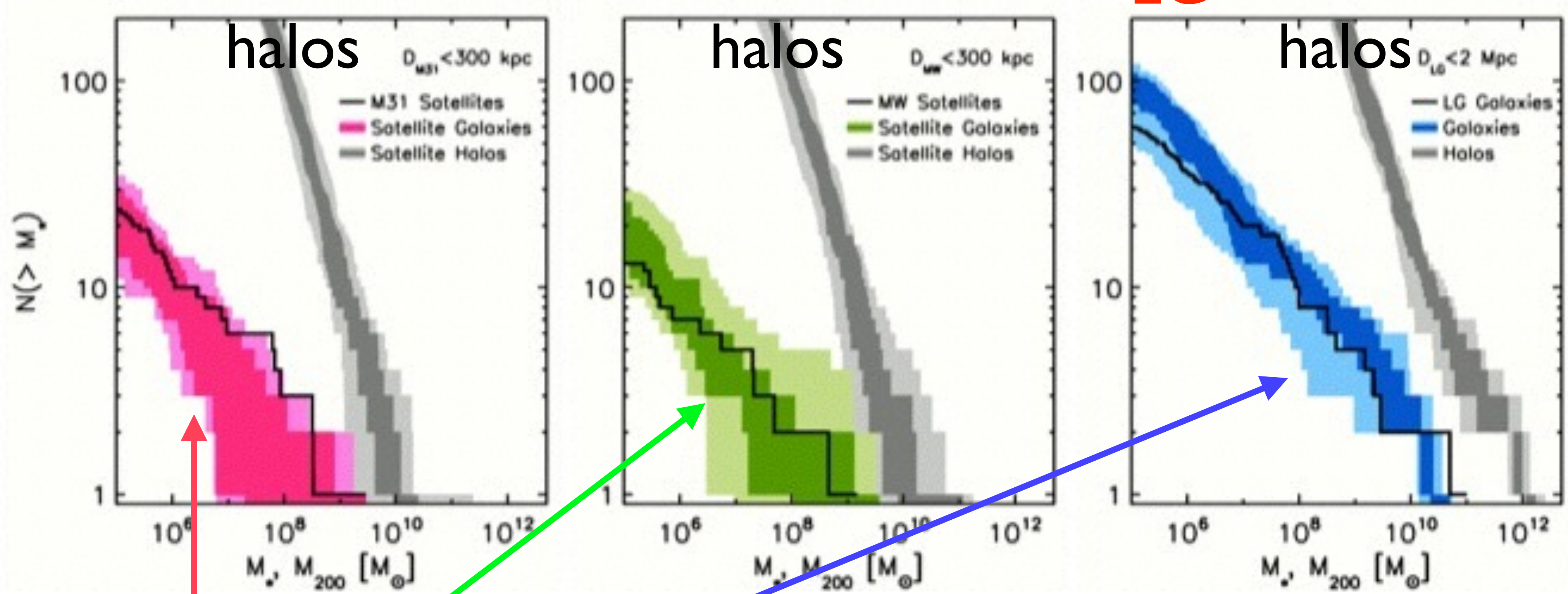
Galaxies vs halos



M31

MW

LG



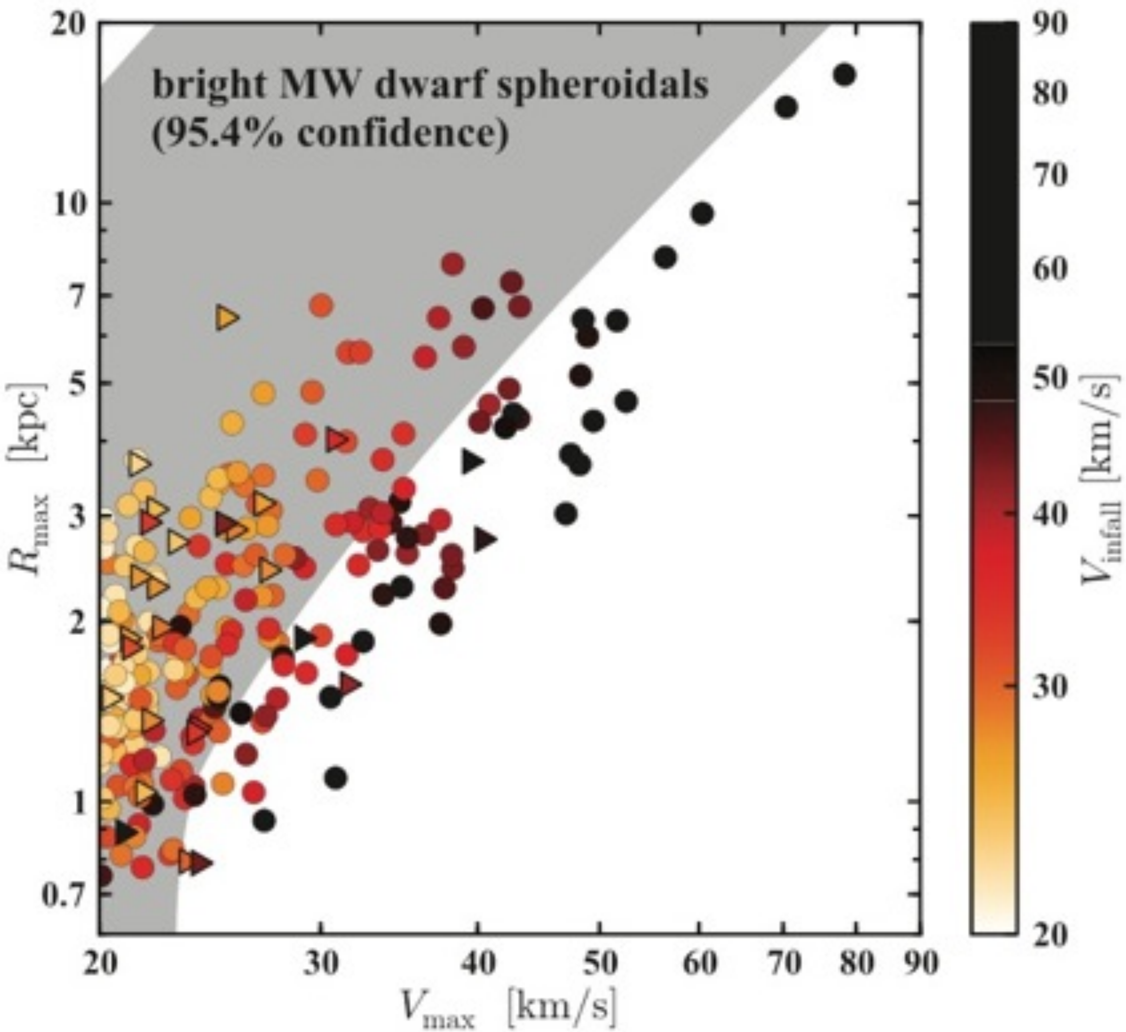
Galaxies

Sawala+14

3 “Massive substructures are too big not to host satellite”

Too big to fail? The puzzling darkness of massive Milky Way subhaloes

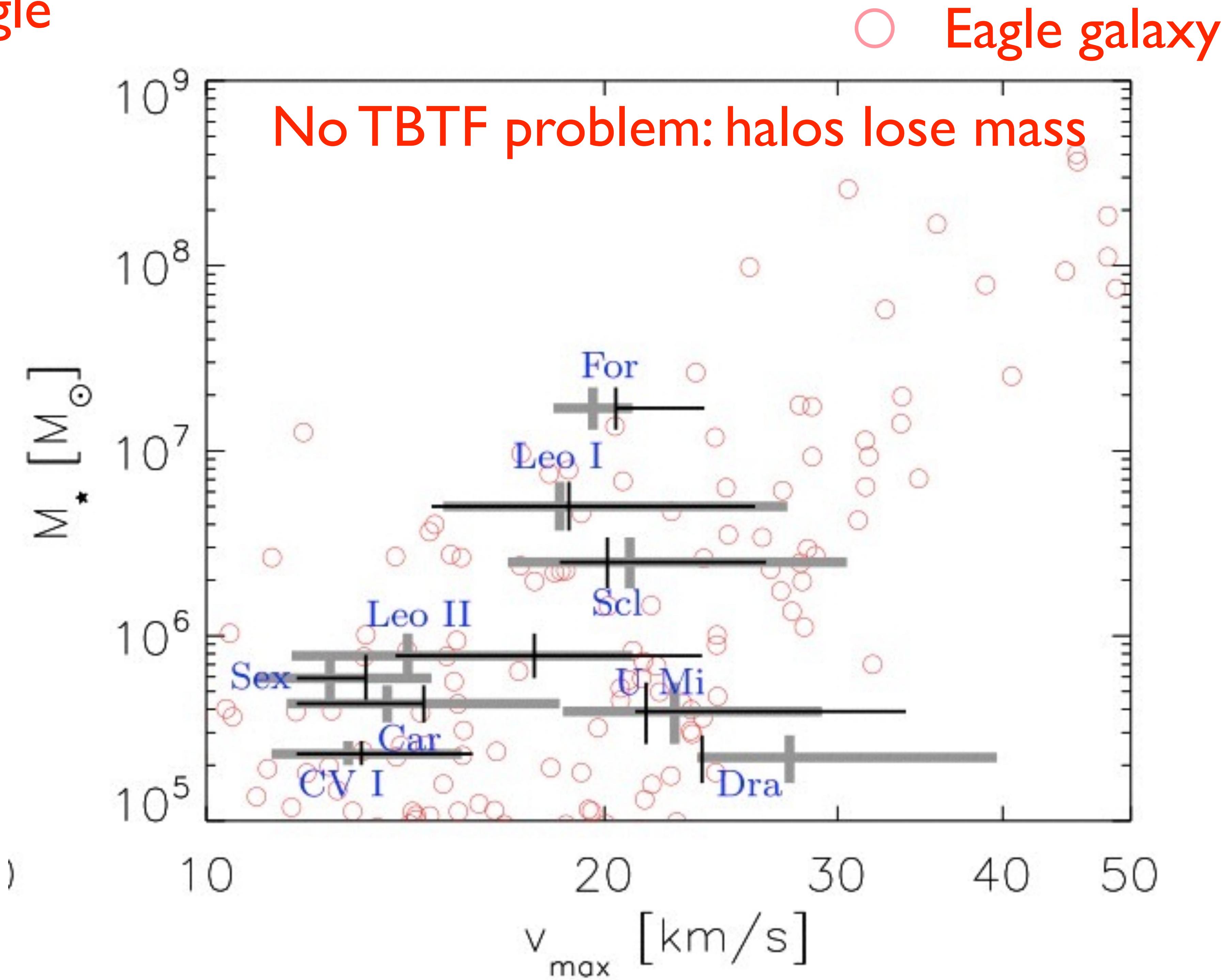
Michael Boylan-Kolchin,★† James S. Bullock and Manoj Kaplinghat



Measure halo mass of observed satellites

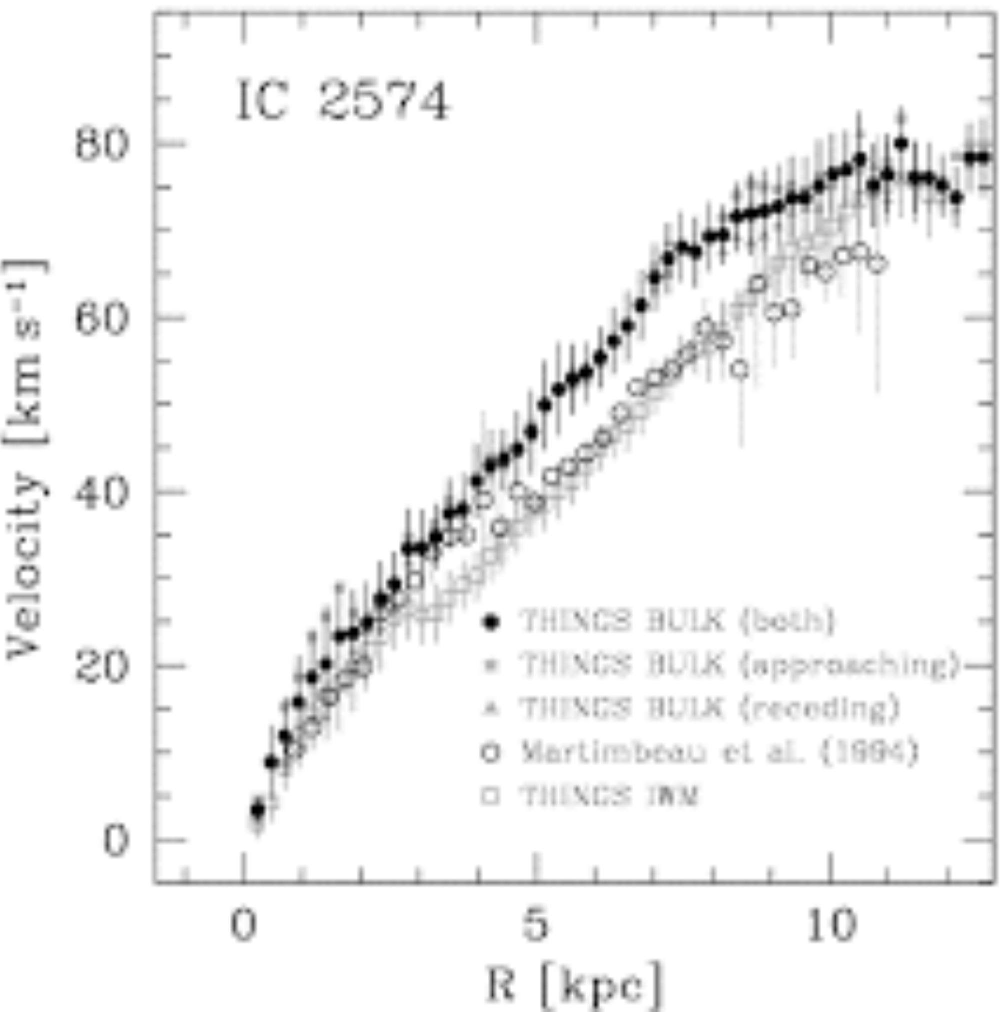
$$V^2 = \frac{GM}{R}$$

Eagle



Sawala+16

4: "Cold dark matter halos are cusped, observed haloes have cores."



$$V^2 = \frac{GM}{R}$$

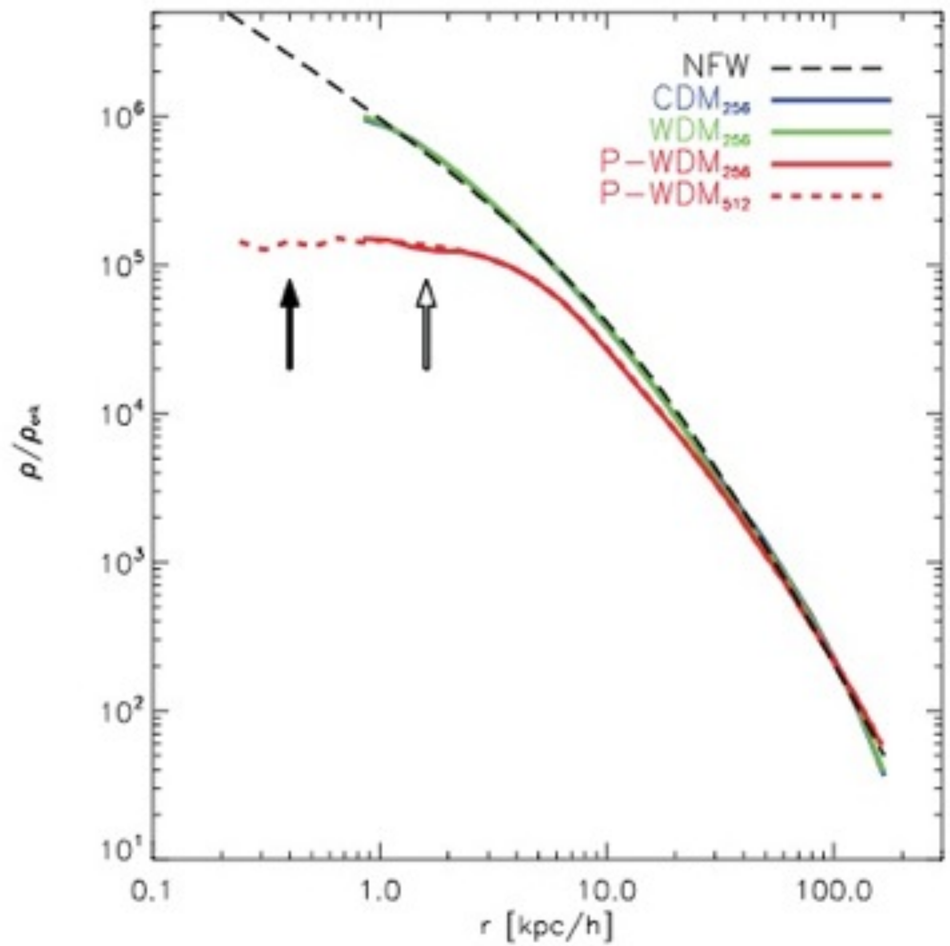
$$V_c \propto R \rightarrow \rho(R) = \mathrm{const}$$

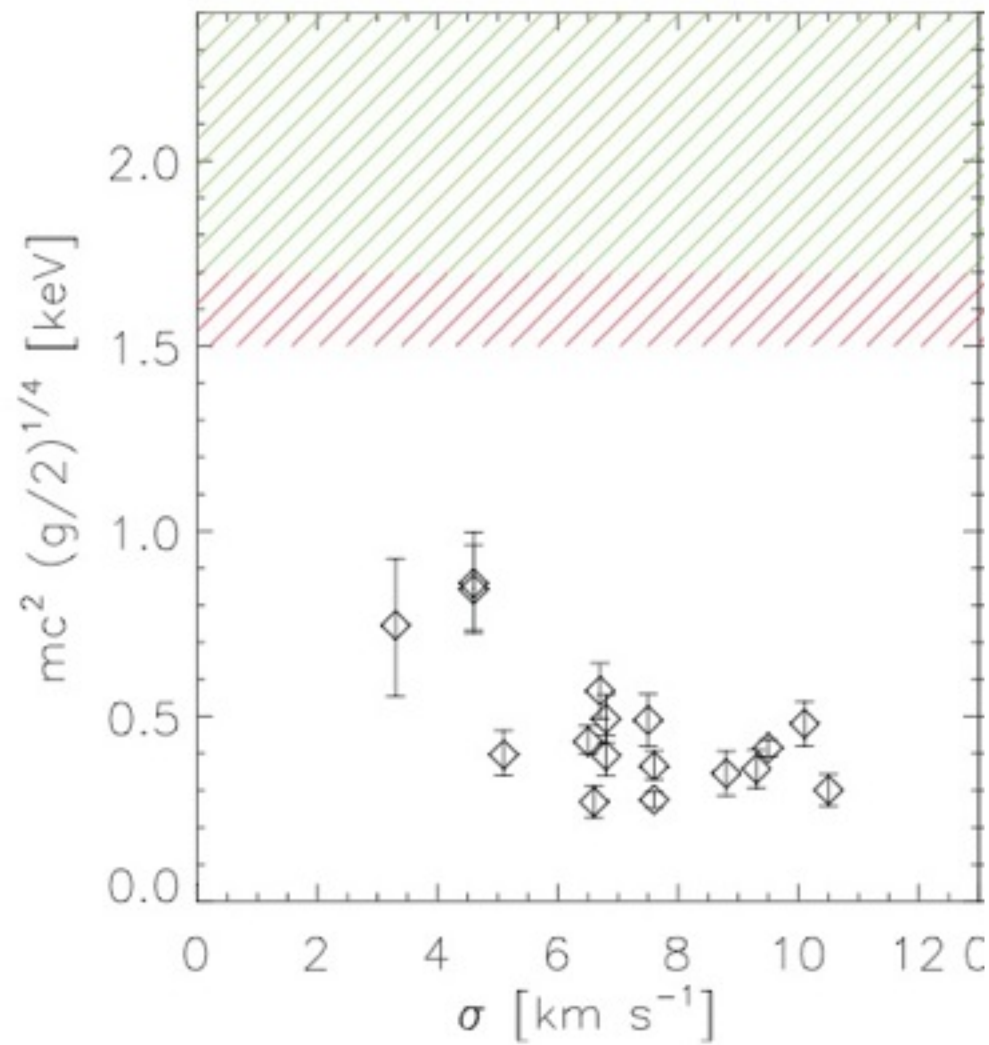
Oh +, 08

Does WDM generate cores?

The phase-space density of fermionic dark matter haloes

Shi Shao,[1★] Liang Gao,[1,2] Tom Theuns[2,3] and Carlos S. Frenk[2]



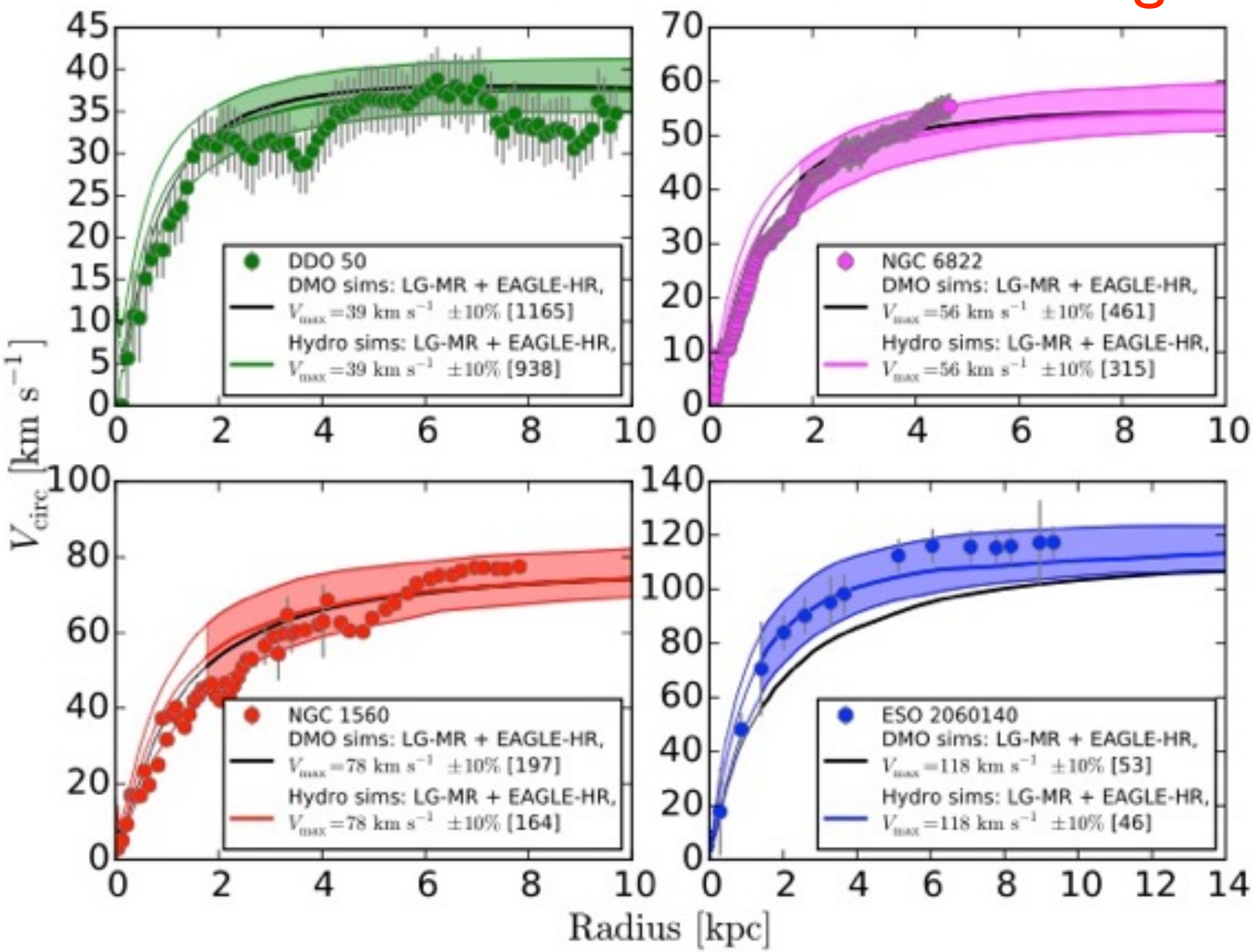


Yes! But they are too small

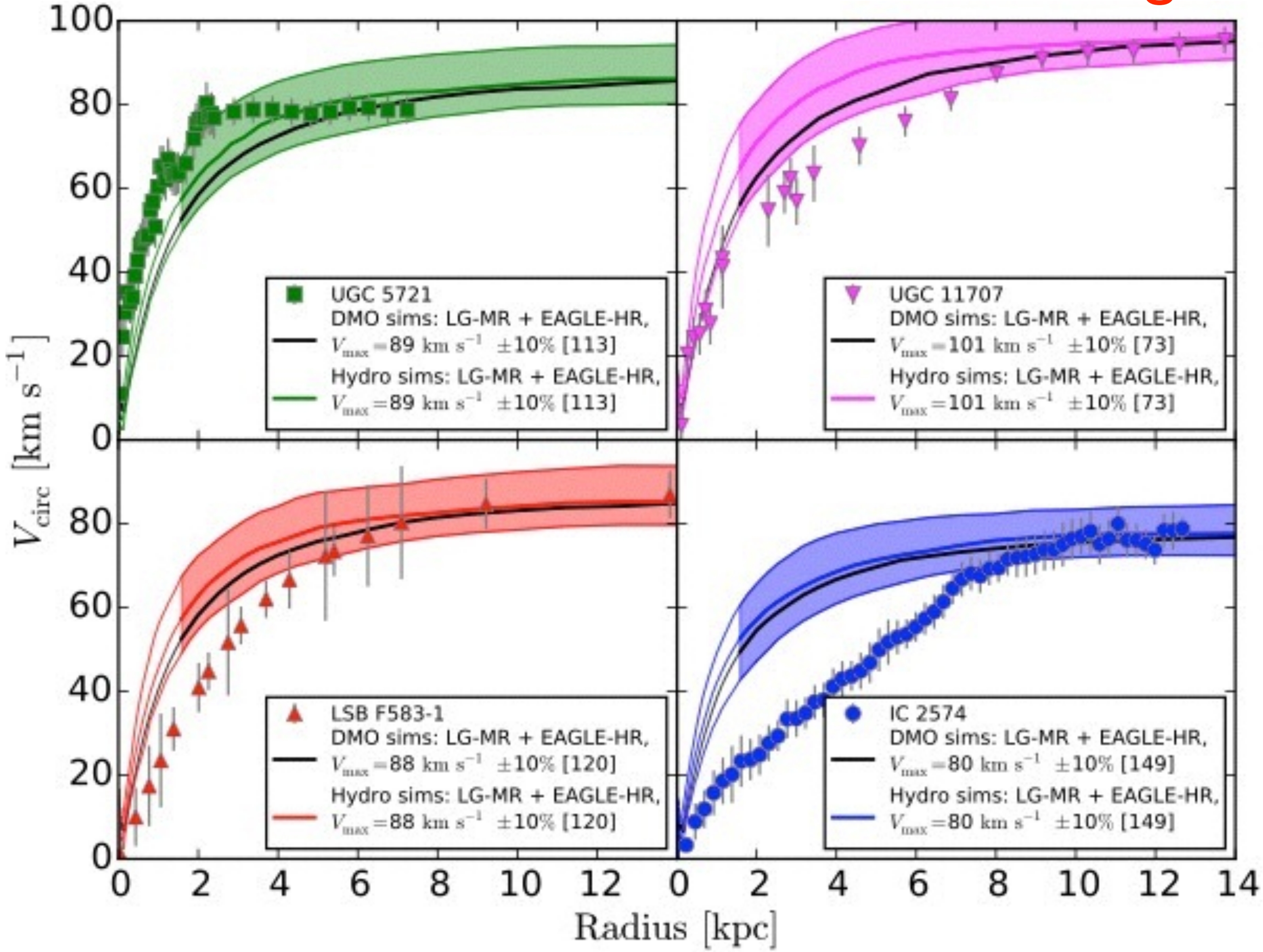
The unexpected diversity of dwarf galaxy rotation curves

Kyle A. Oman[1,*], Julio F. Navarro[1,2], Azadeh Fattahi[1], Carlos S. Frenk[3], Till Sawala[3], Simon D. M. White[4], Richard Bower[3], Robert A. Crain[5], Michelle Furlong[3], Matthieu Schaller[3], Joop Schaye[6], Tom Theuns[3]

Eagle



Eagle

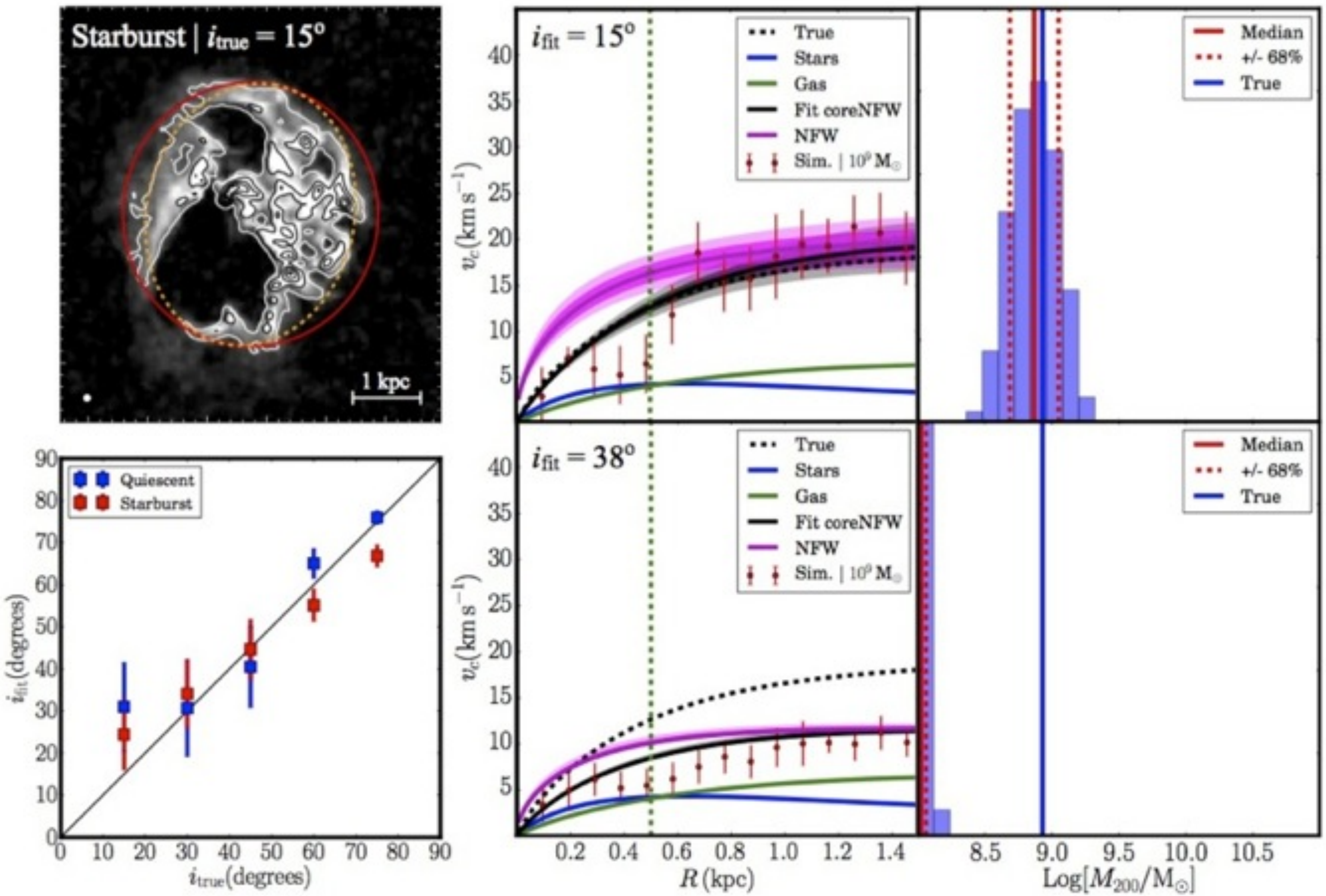


UGC 5721
DMO sims: LG-MR + EAGLE-HR,
V_{max} =89 km s^{-1} ±10% [113]
Hydro sims: LG-MR + EAGLE-HR,
V_{max} =89 km s^{-1} ±10% [113]
UGC 11707
DMO sims: LG-MR + EAGLE-HR,
V_{max} =101 km s^{-1} ±10% [73]
Hydro sims: LG-MR + EAGLE-HR,
V_{max} =101 km s^{-1} ±10% [73]
LSB F583-1
DMO sims: LG-MR + EAGLE-HR,
V_{max} =88 km s^{-1} ±10% [120]
Hydro sims: LG-MR + EAGLE-HR,
V_{max} =88 km s^{-1} ±10% [120]
IC 2574
DMO sims: LG-MR + EAGLE-HR,
V_{max} =80 km s^{-1} ±10% [149]
Hydro sims: LG-MR + EAGLE-HR,
V_{max} =80 km s^{-1} ±10% [149]
V_{circ} [km s^{-1}]
Radius [kpc]

Understanding the shape and diversity of dwarf galaxy rotation curves in ΛCDM

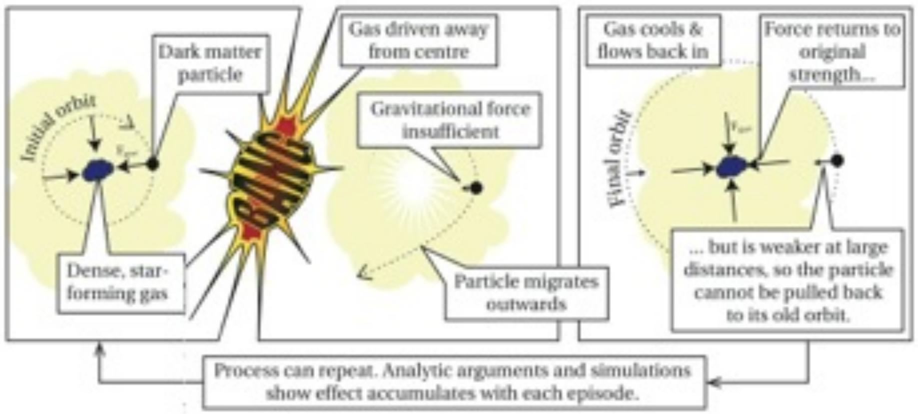
J. I. Read[1*], G. Iorio[2,3], O. Agertz[1], F. Fraternali[2,4]

1

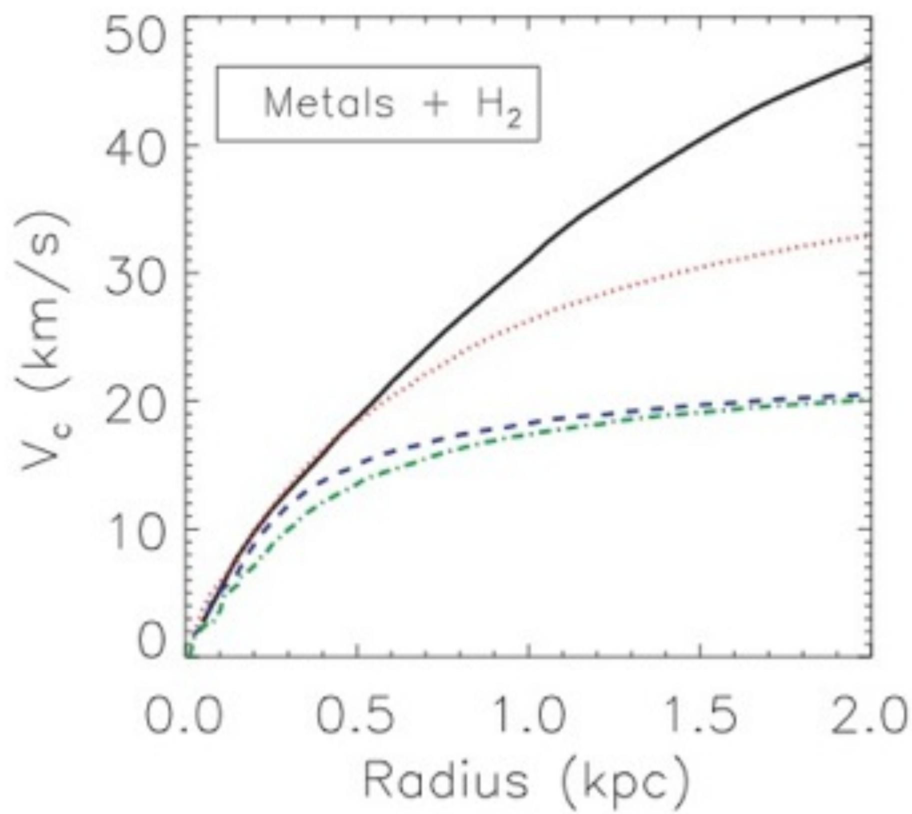


Theuns

Feedback can generate cores



Pontzen & Governato 13



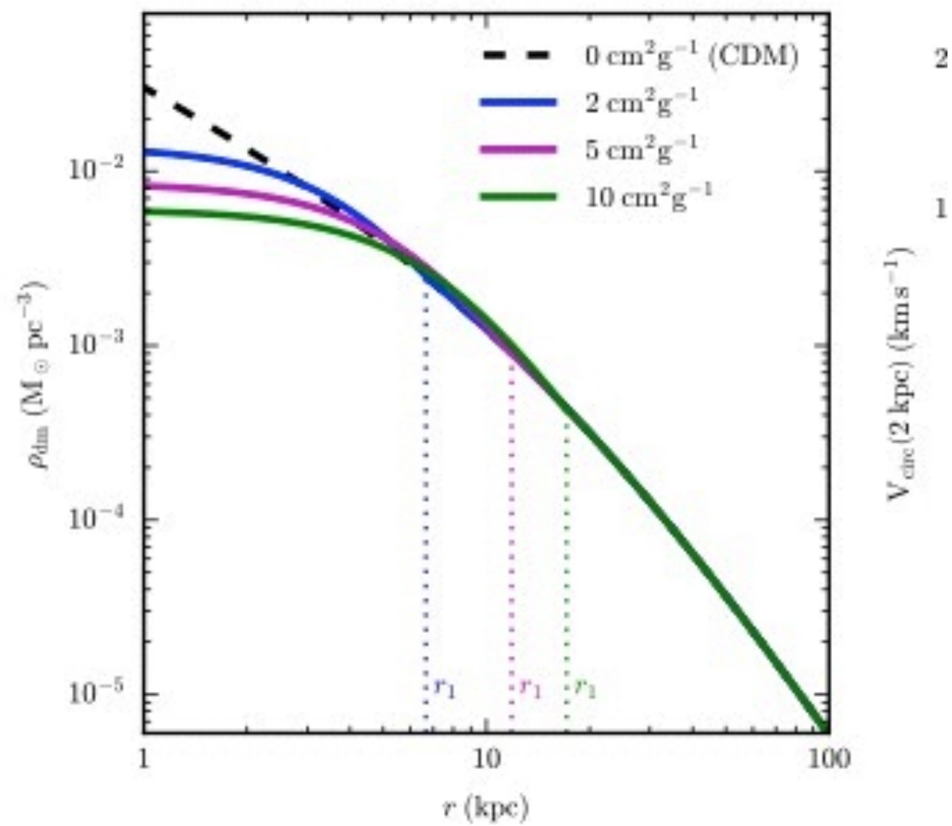
Governato+12

Self-interacting dark matter scattering rates through cosmic time

Andrew Robertson*, Richard Massey, Vincent Eke, Richard Bower
Institute for Computational Cosmology, Durham University, South Road, Durham DH1 3LE, UK

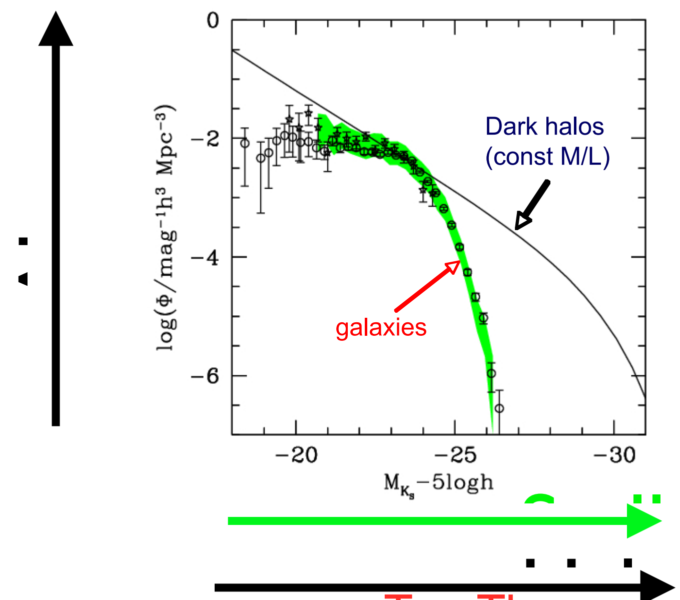
Spreading out and staying sharp - Creating diverse rotation curves via baryonic and self-interaction effects

Peter Creasey[1]*, Omid Sameie[1], Laura V. Sales[1], Hai-Bo Yu[1]†, Mark Vogelsberger[2]‡ and Jesús Zavala[3]



1. Voids
2. Number of satellites
3. Too big to fail (massive substructures)
4. cores vs cusps

No (?) issues with CDM when including galaxy formation physics



Tom Theuns

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Probing dark matter with quasars

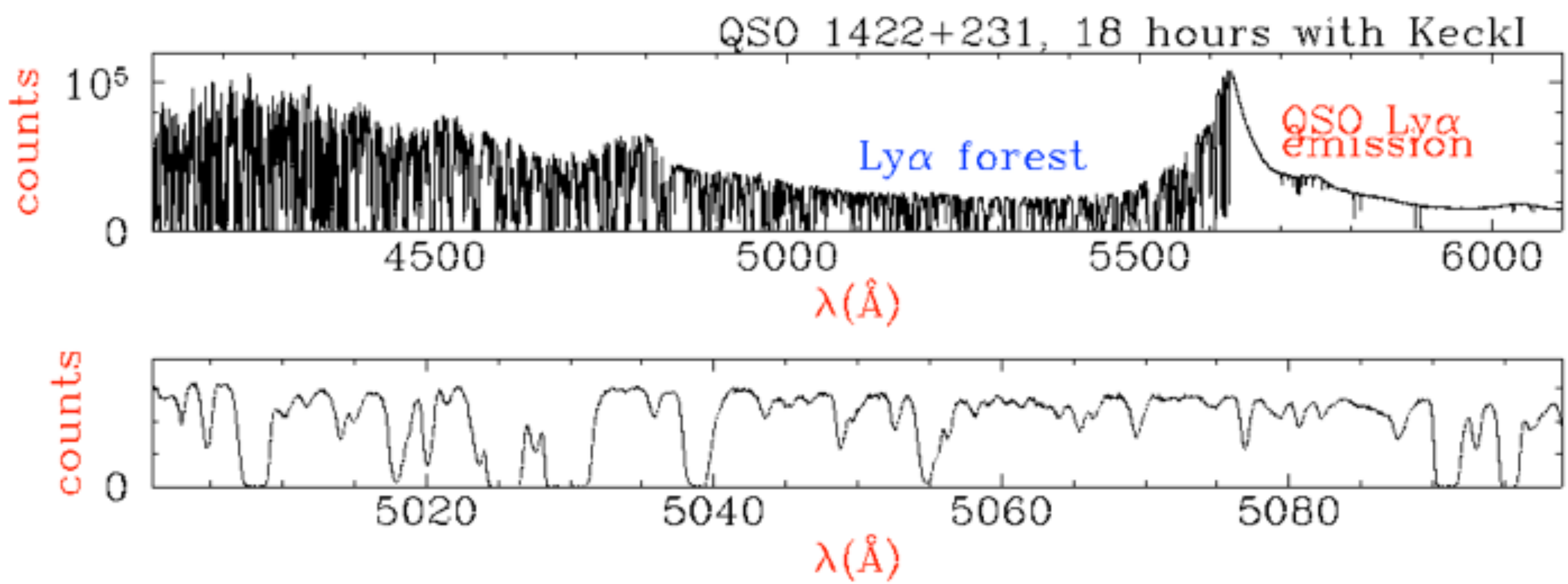
3C 273 : A STAR-LIKE OBJECT WITH LARGE RED-SHIFT

By DR. M. SCHMIDT

Mount Wilson and Palomar Observatories, Carnegie Institution of Washington, California Institute of Technology, Pasadena

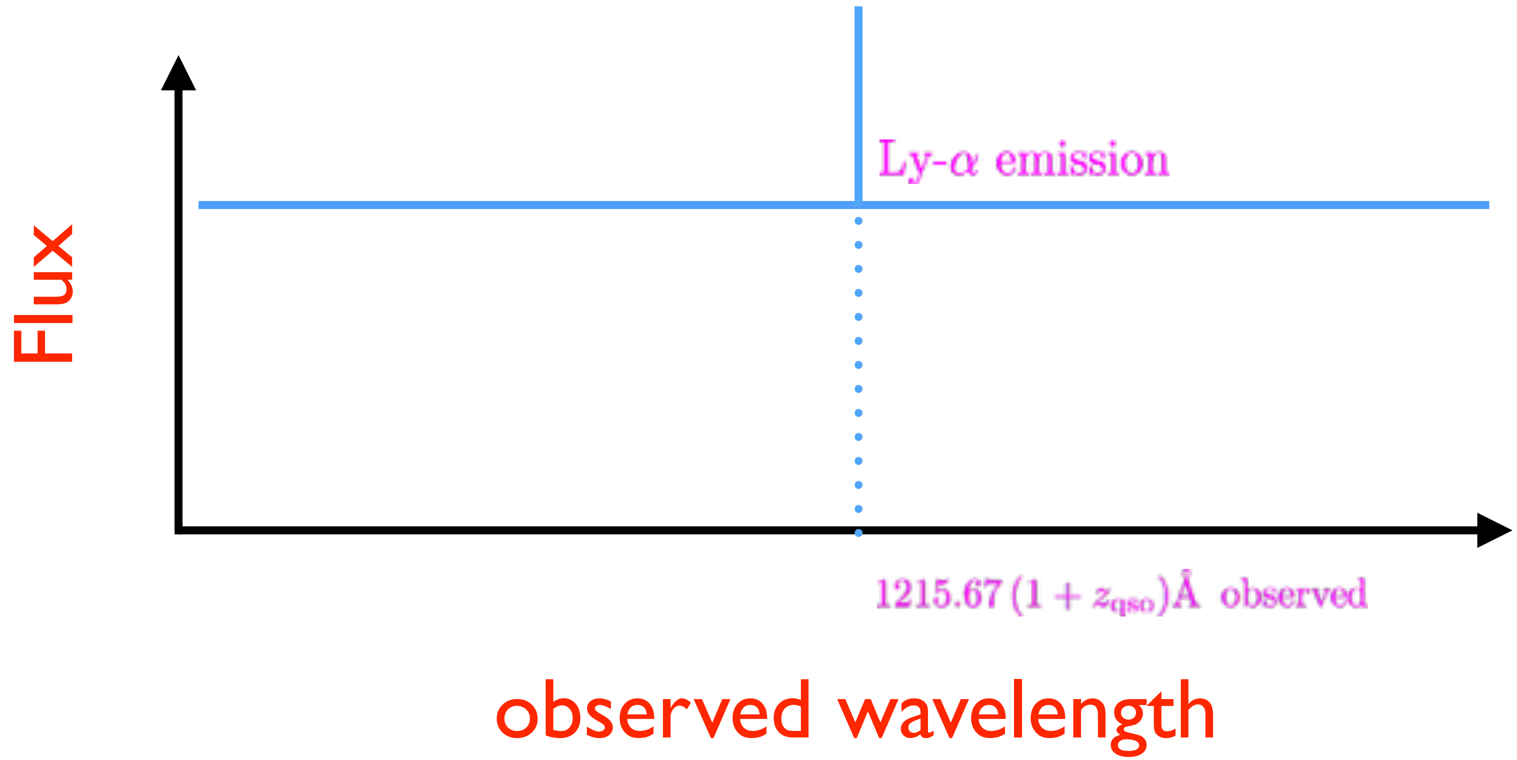
Nature, '63

z=7.1 ULAS J1120+064
Mortlock +, Nature 11

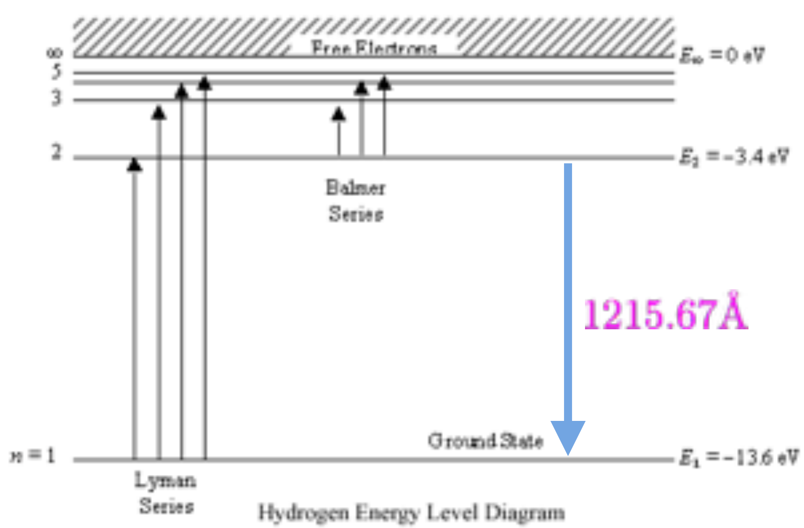


Intervening absorption in quasar spectra

A (very simple) intrinsic quasar spectrum



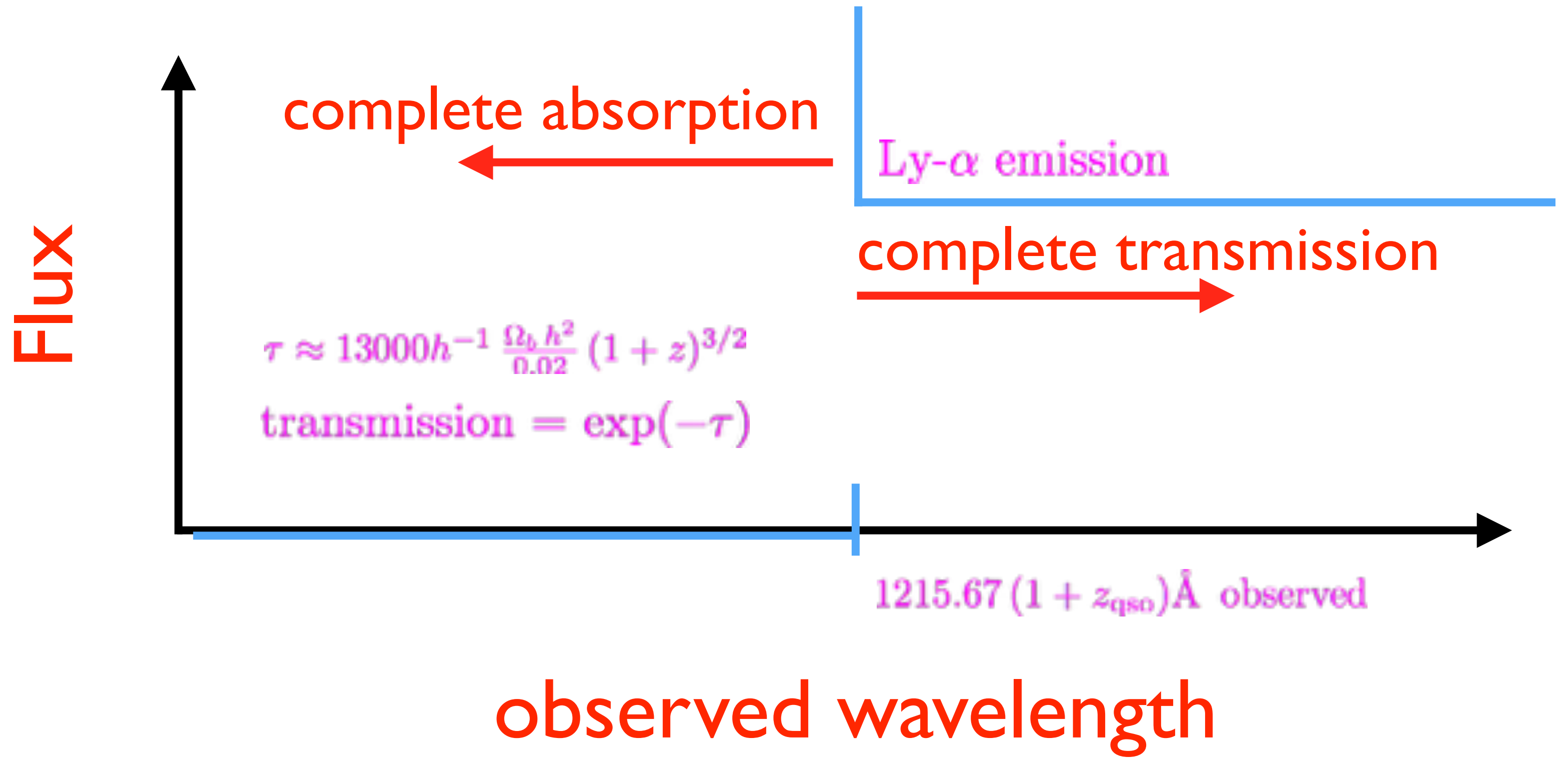
Hydrogen atom

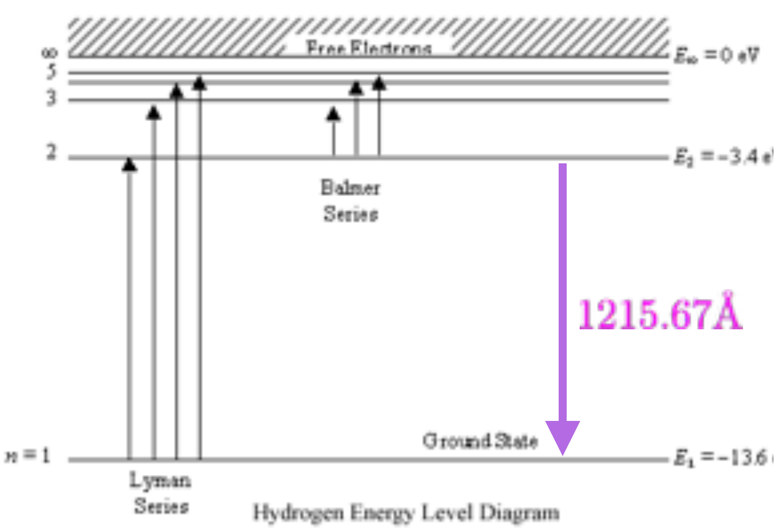


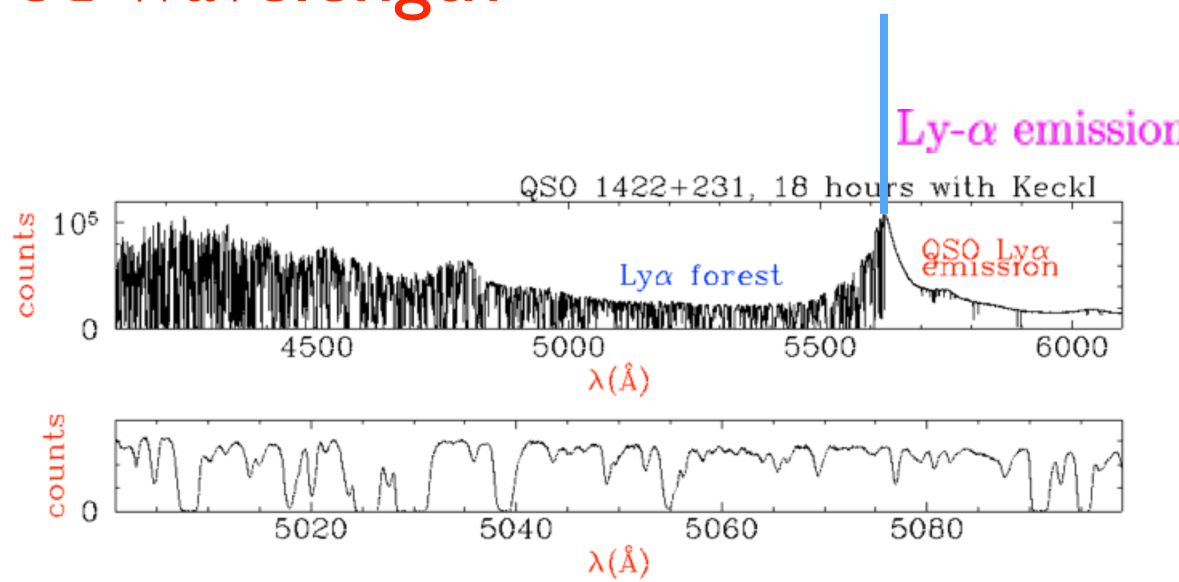
mology

Tom Theuns

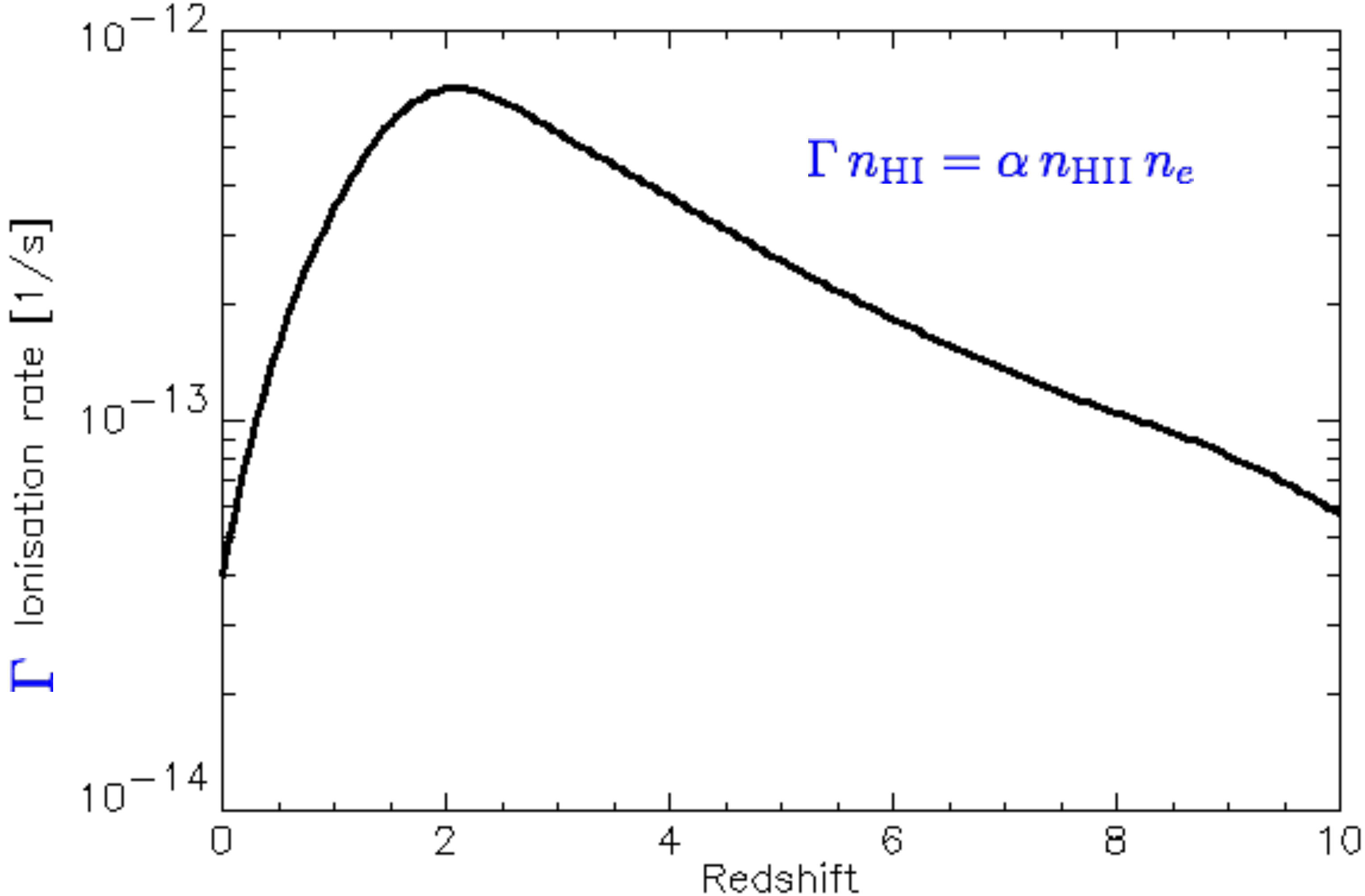
Expected observed spectrum due to intervening absorption





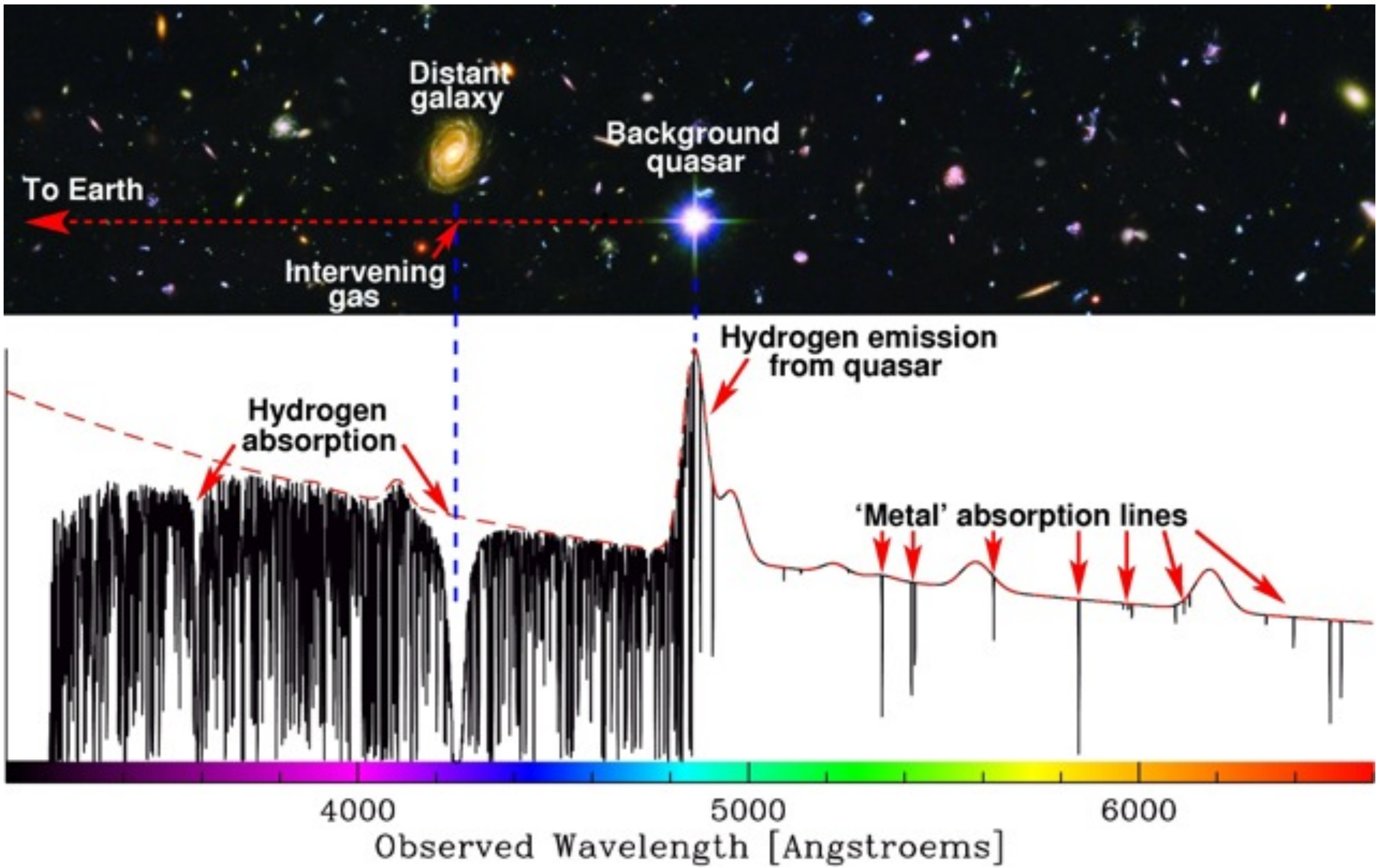


Conclusion: the Universe is highly ionised



Ionization rate from galaxies & quasars
as computed by Haardt & Madau

Intervening absorption

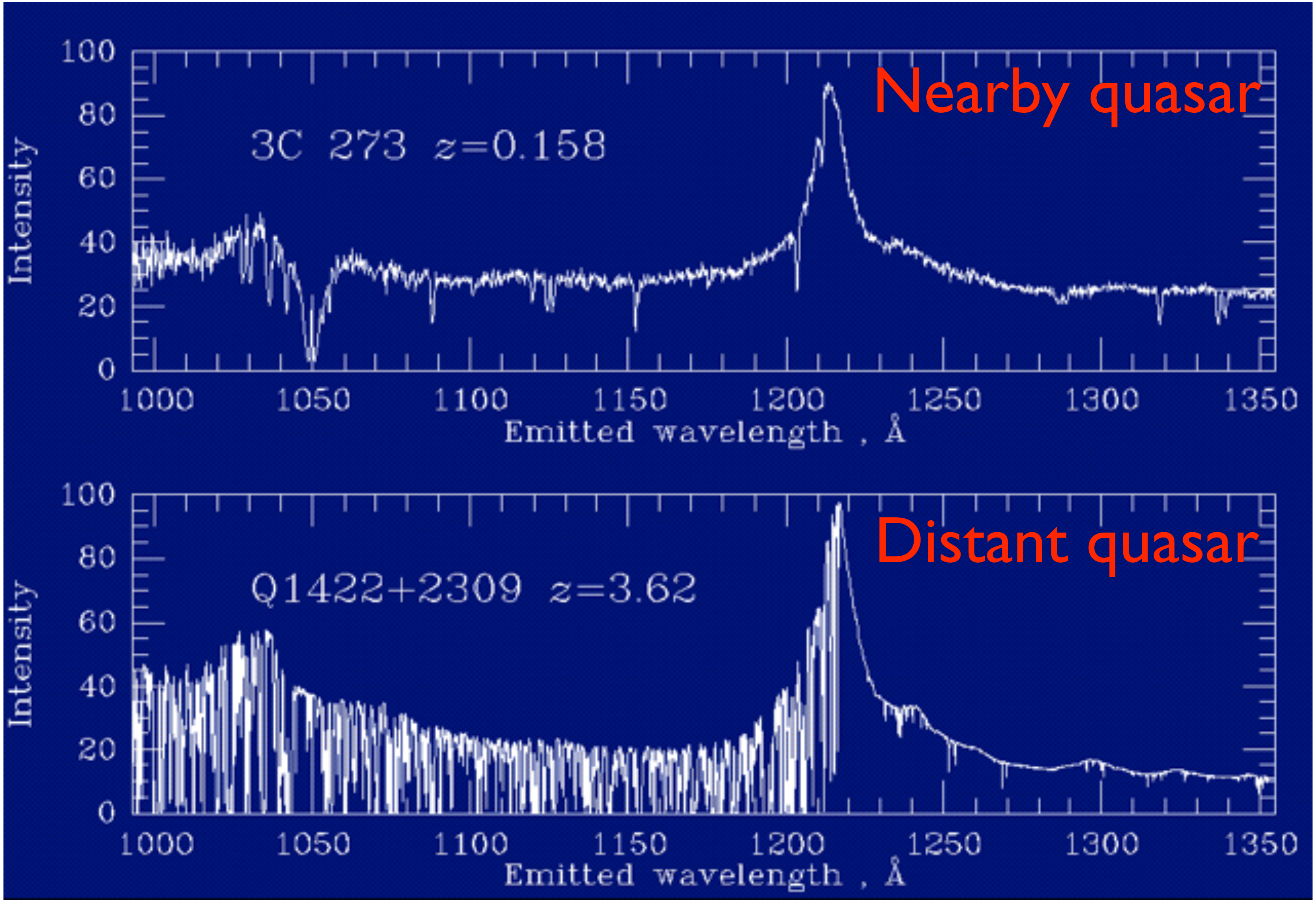


Fan+03

Fan+01, 06

Much more absorption at higher redshifts

a lot of absorption ← → complete transmission



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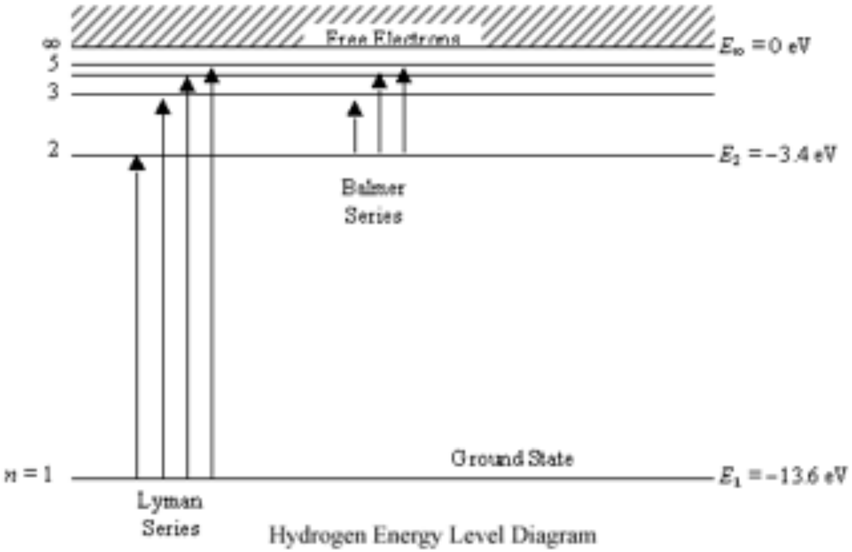
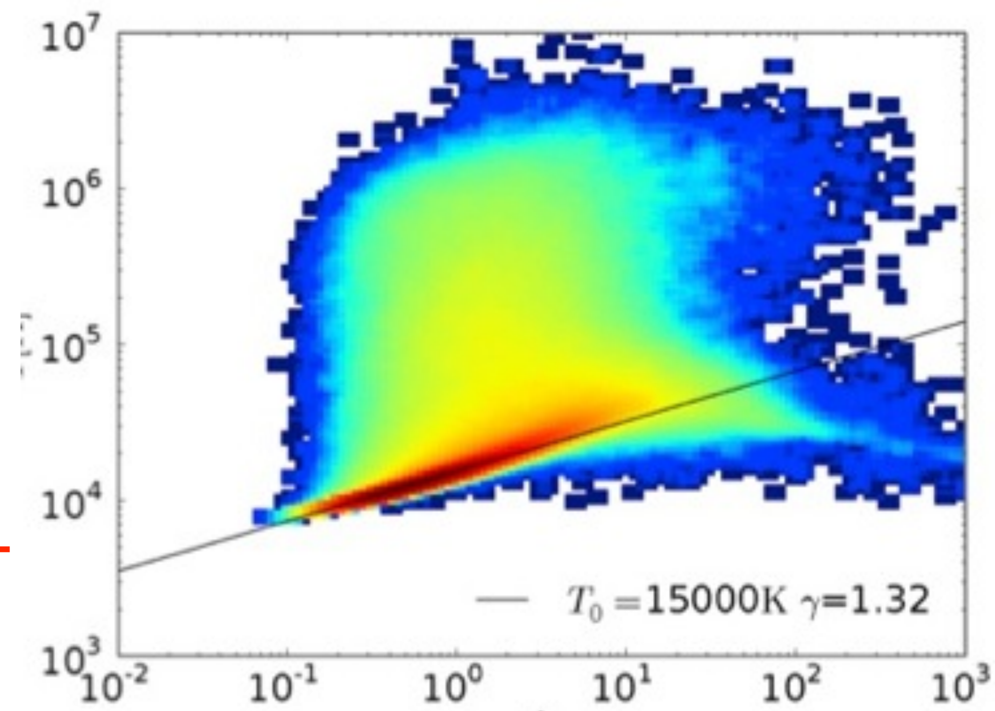
- Future: lensing, and Relhics

Photo-ionisation also heats gas: photo-heating



Resulting temperature-density relation

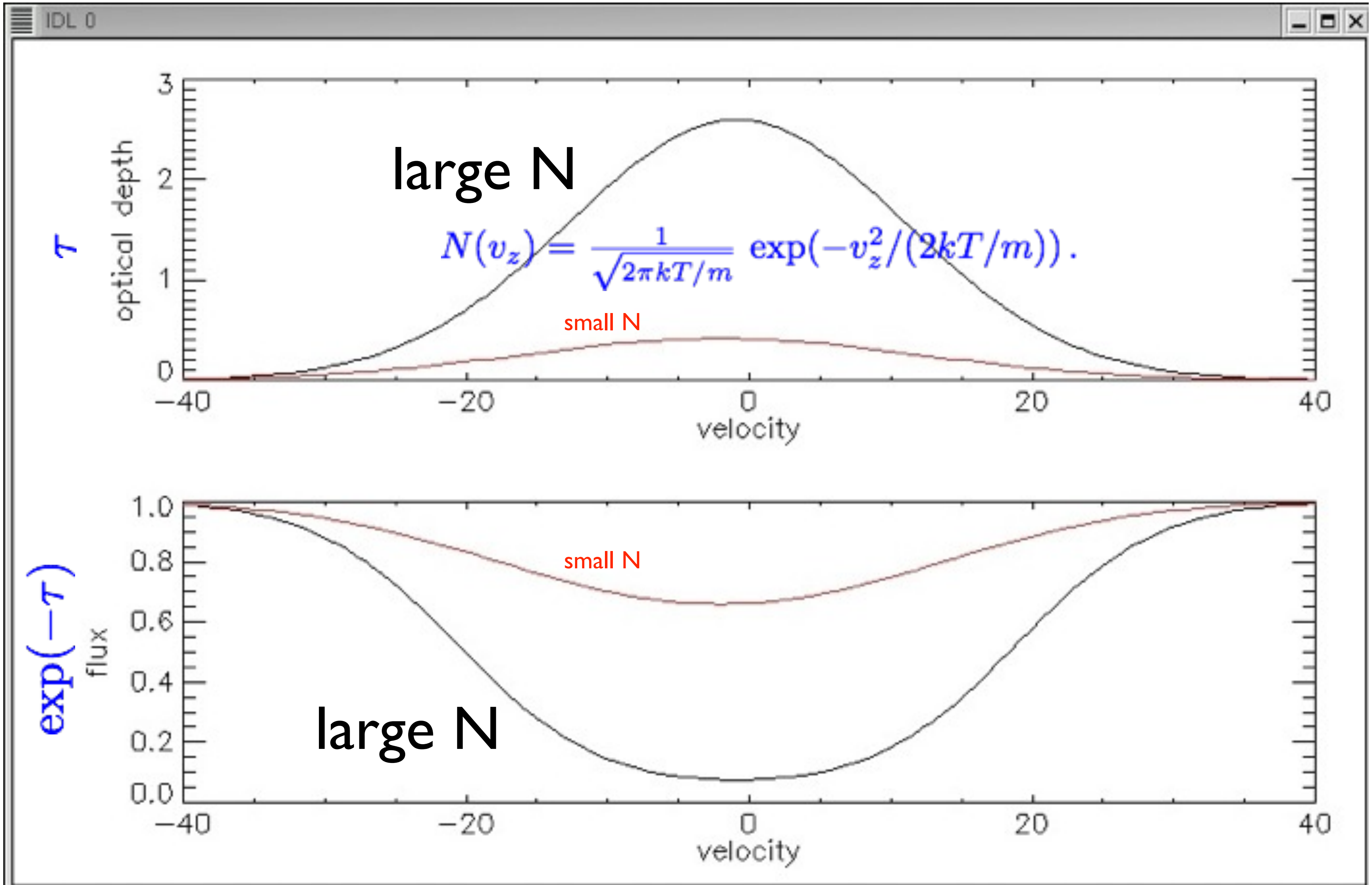
Temperature / K



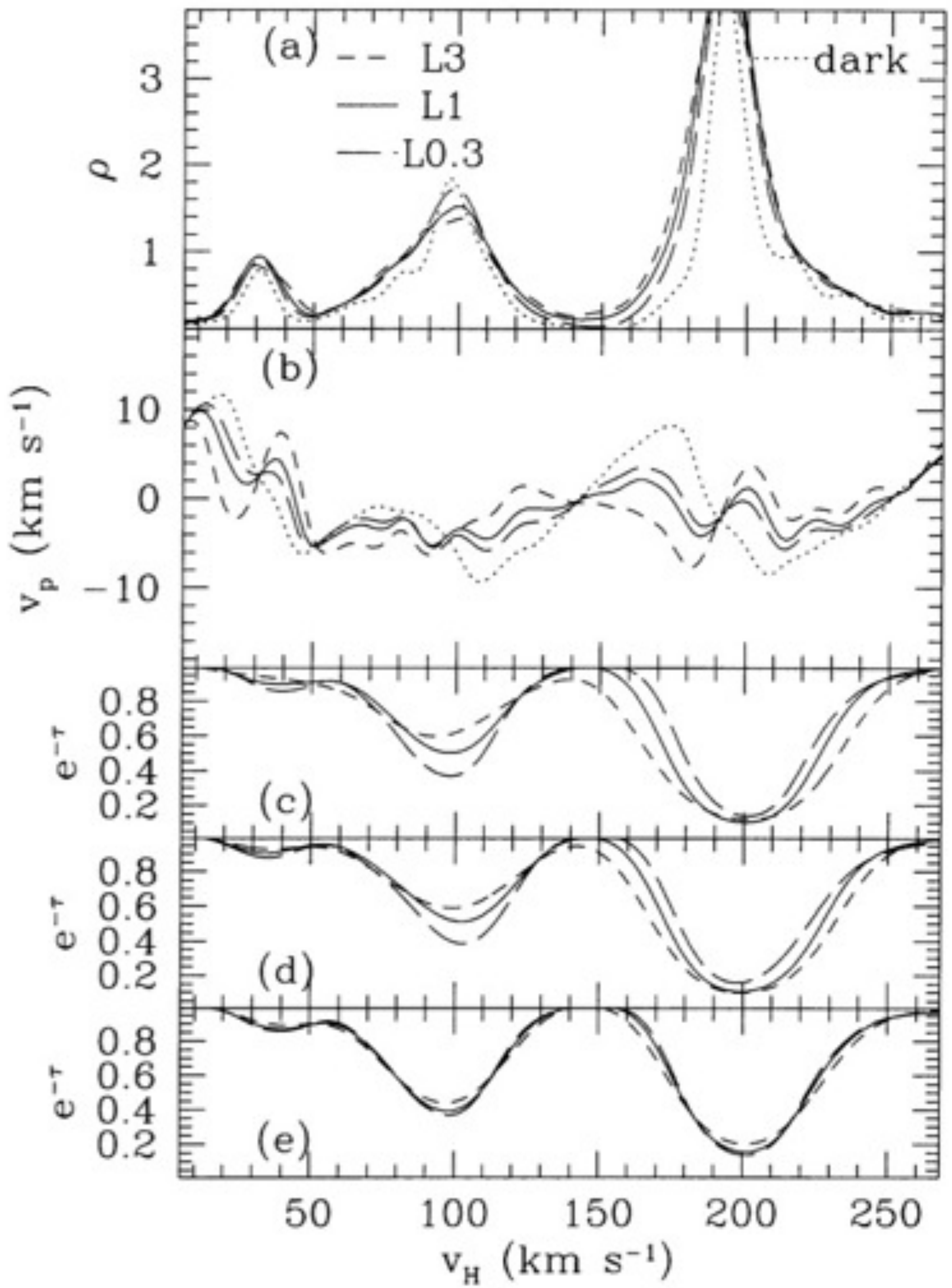
Density / mean density

Garzilli+15

Line broadening: thermal broadening



Line broadening: Jeans filtering

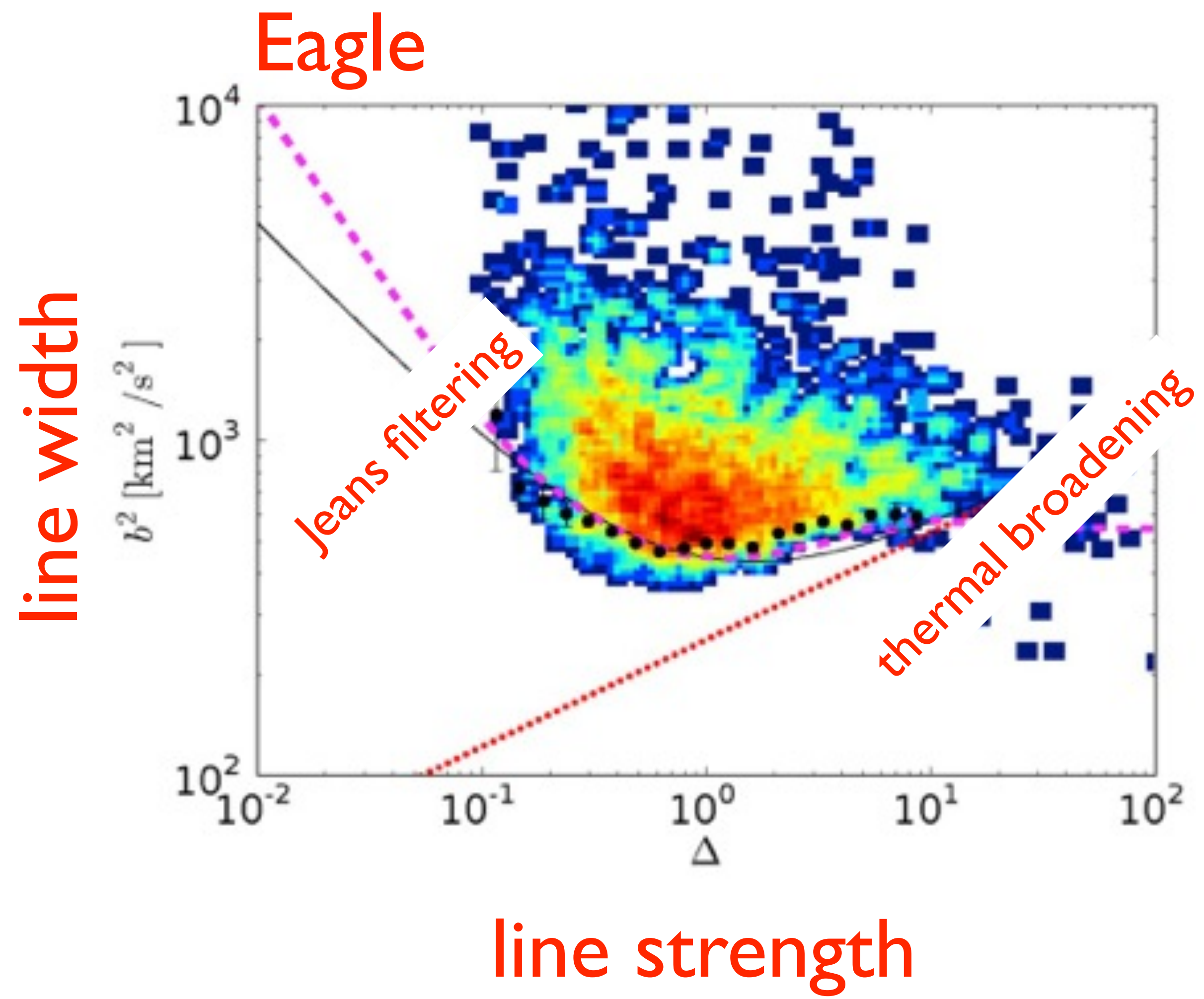


ICC Institute for

Theuns +00

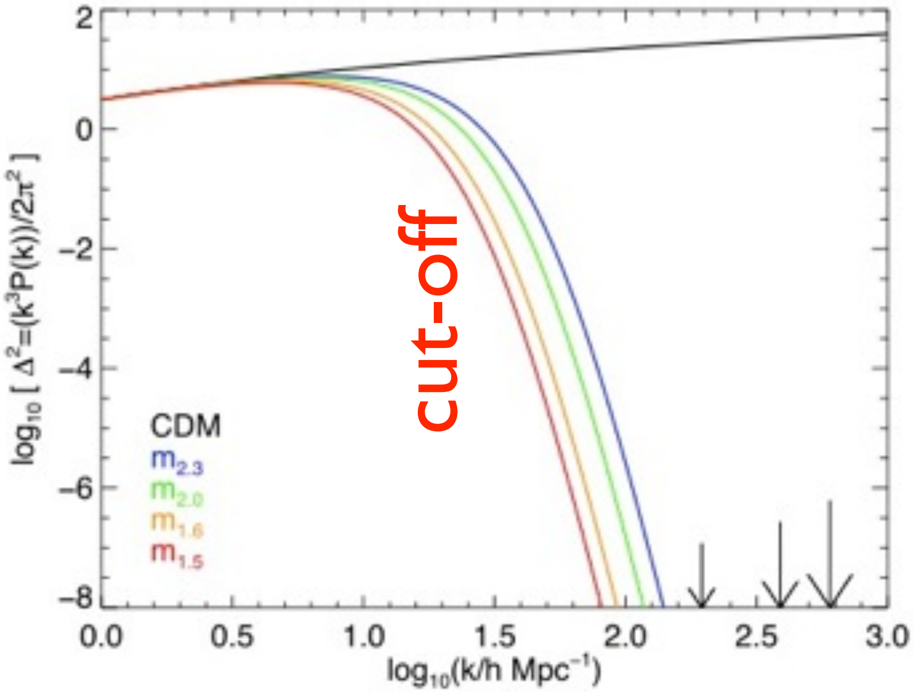
Line broadening = smoothing operation introduces a cut-off in the power spectrum

$$b^2 = b_T^2 + b_\rho^2$$

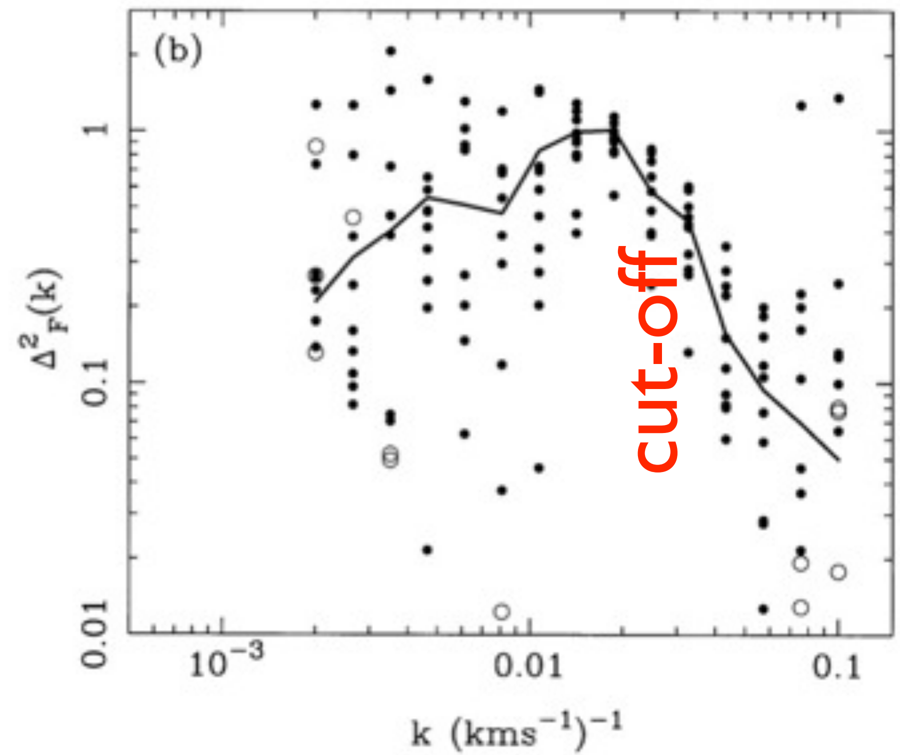


Garzilli + 15

linear transfer function



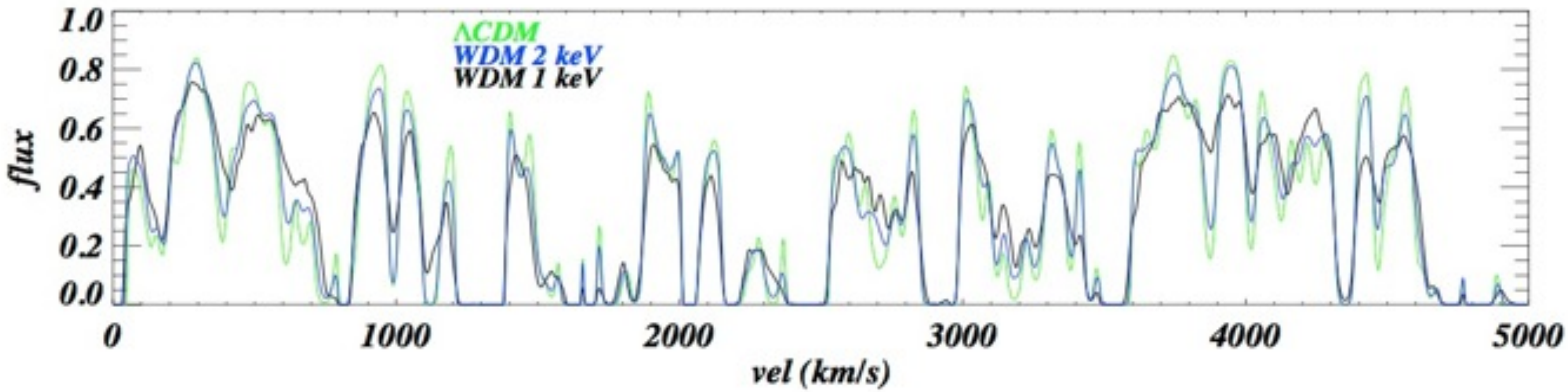
Flux power spectrum



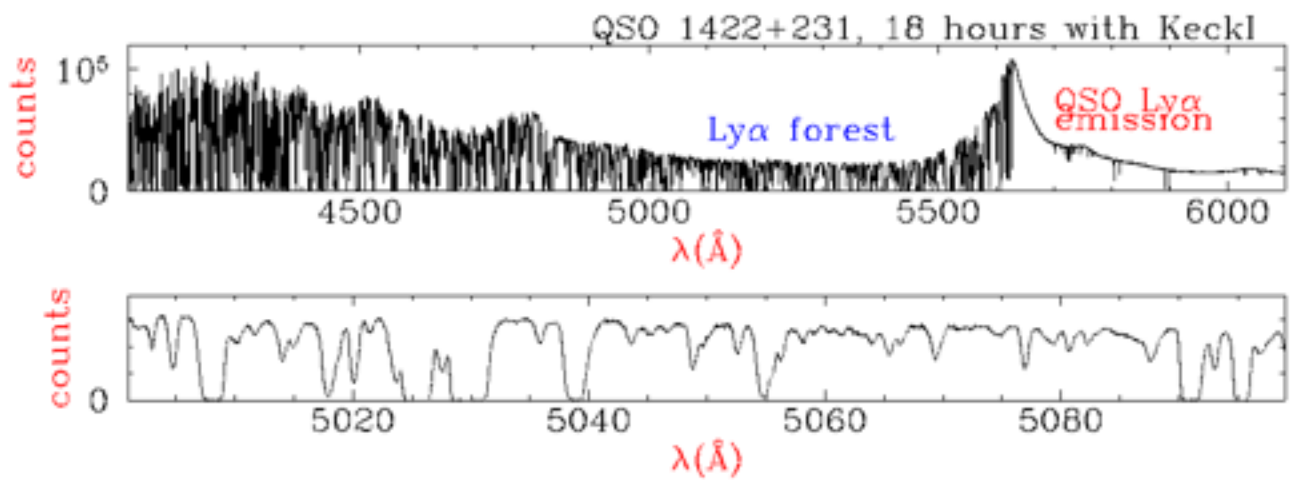
Croft +99

Is the observed cut-off due to WDM?
Or due to the temperature of the gas?

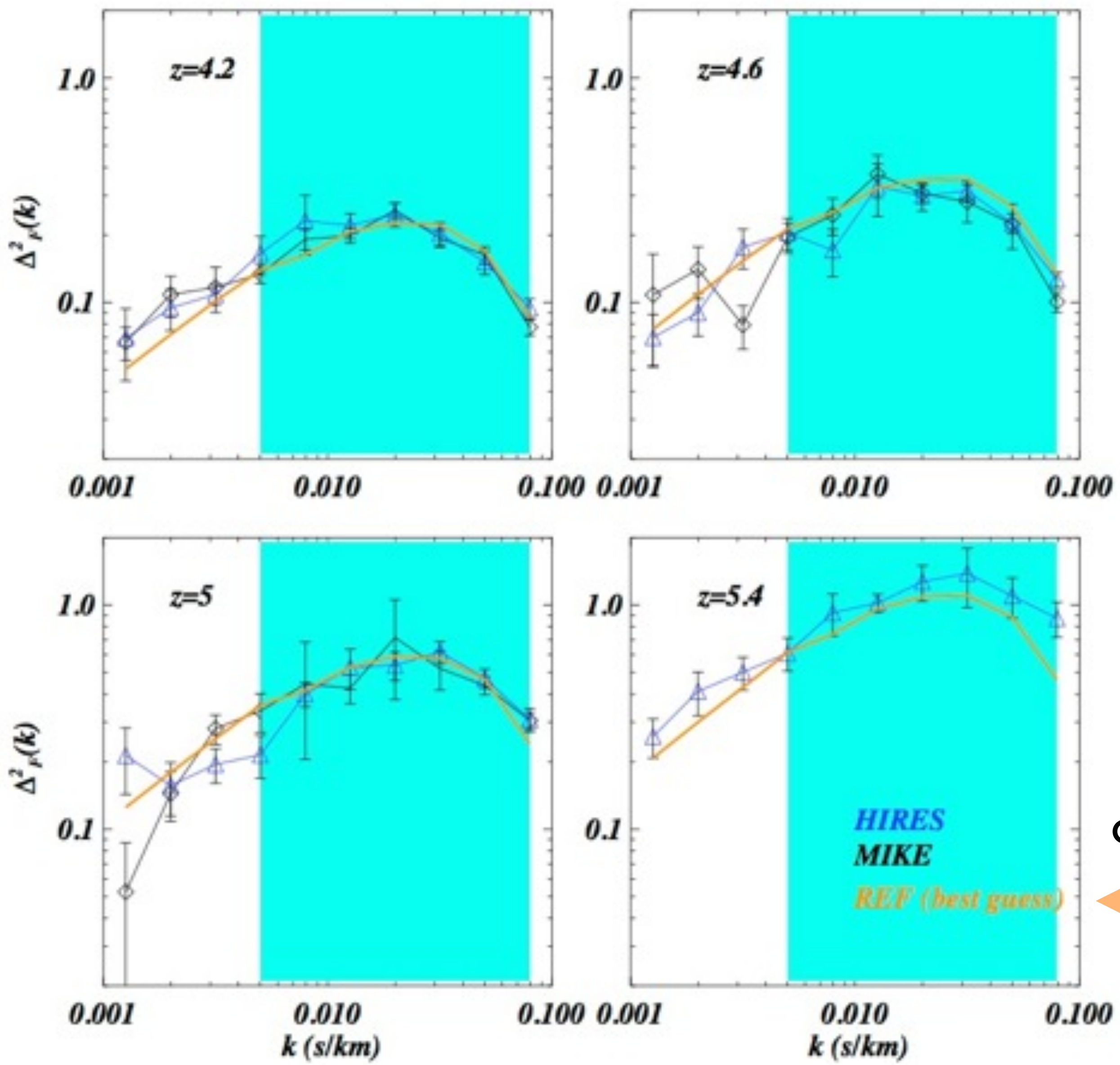
Mock quasar spectrum



Viel+13



Flux power spectra at different redshifts

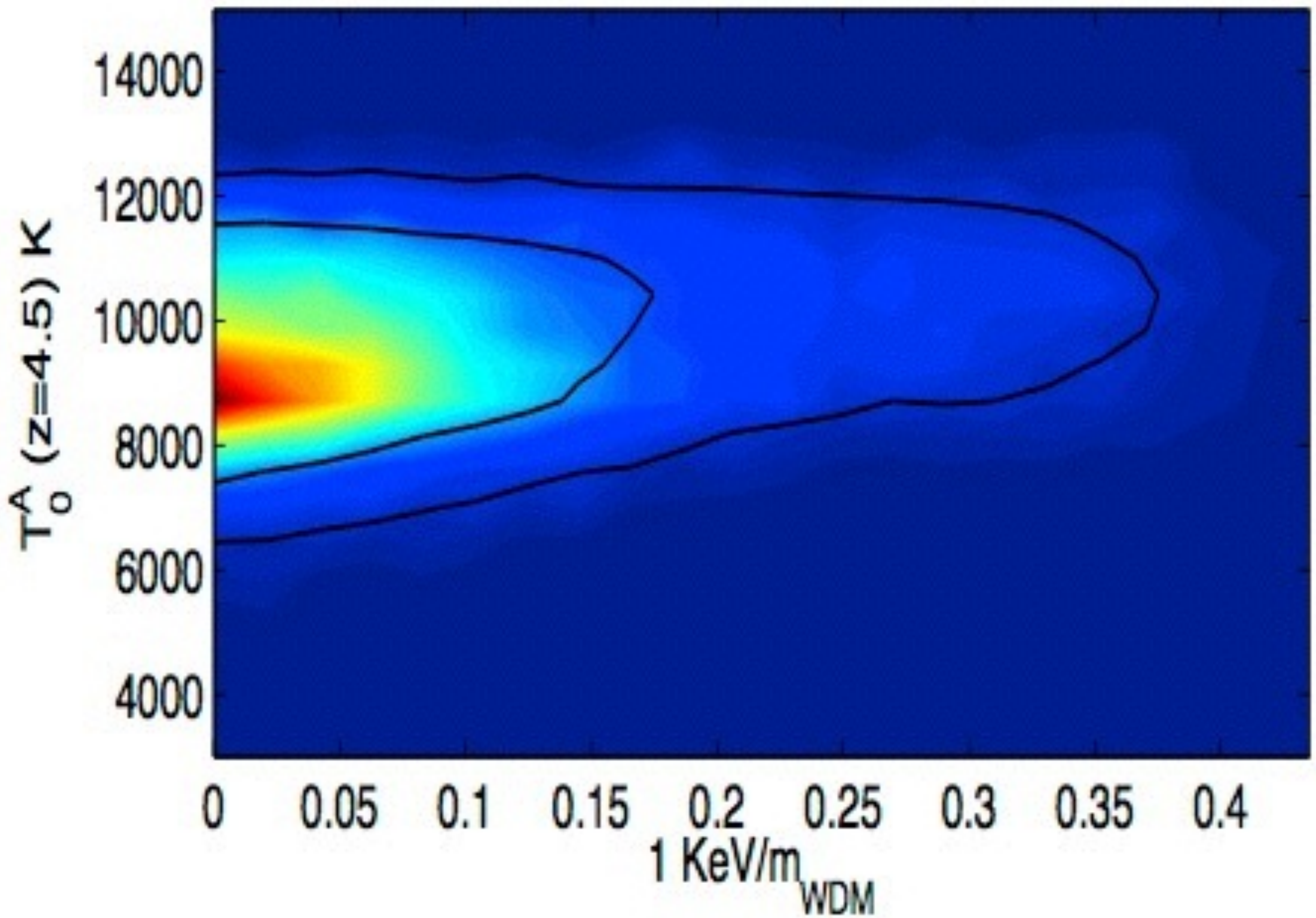


observed

Mock

Viel+13

(Lack of) degeneracy between thermal and WDM cut-off



Viel+13

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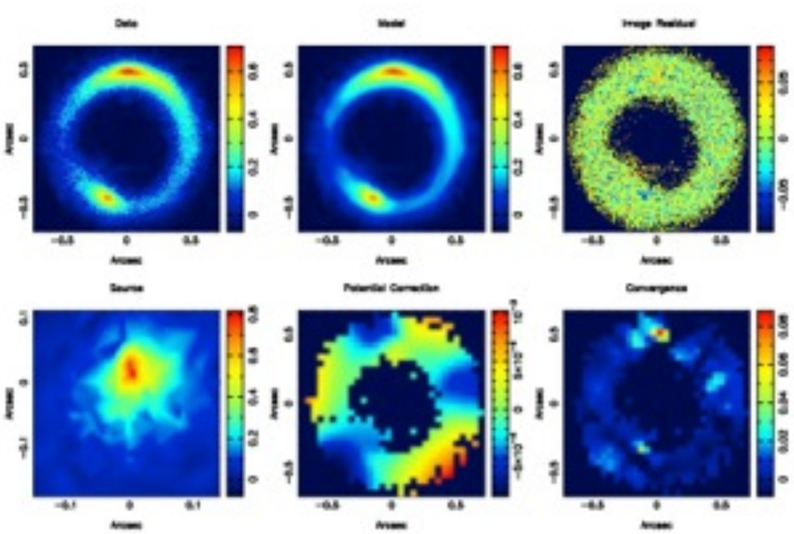
Future:

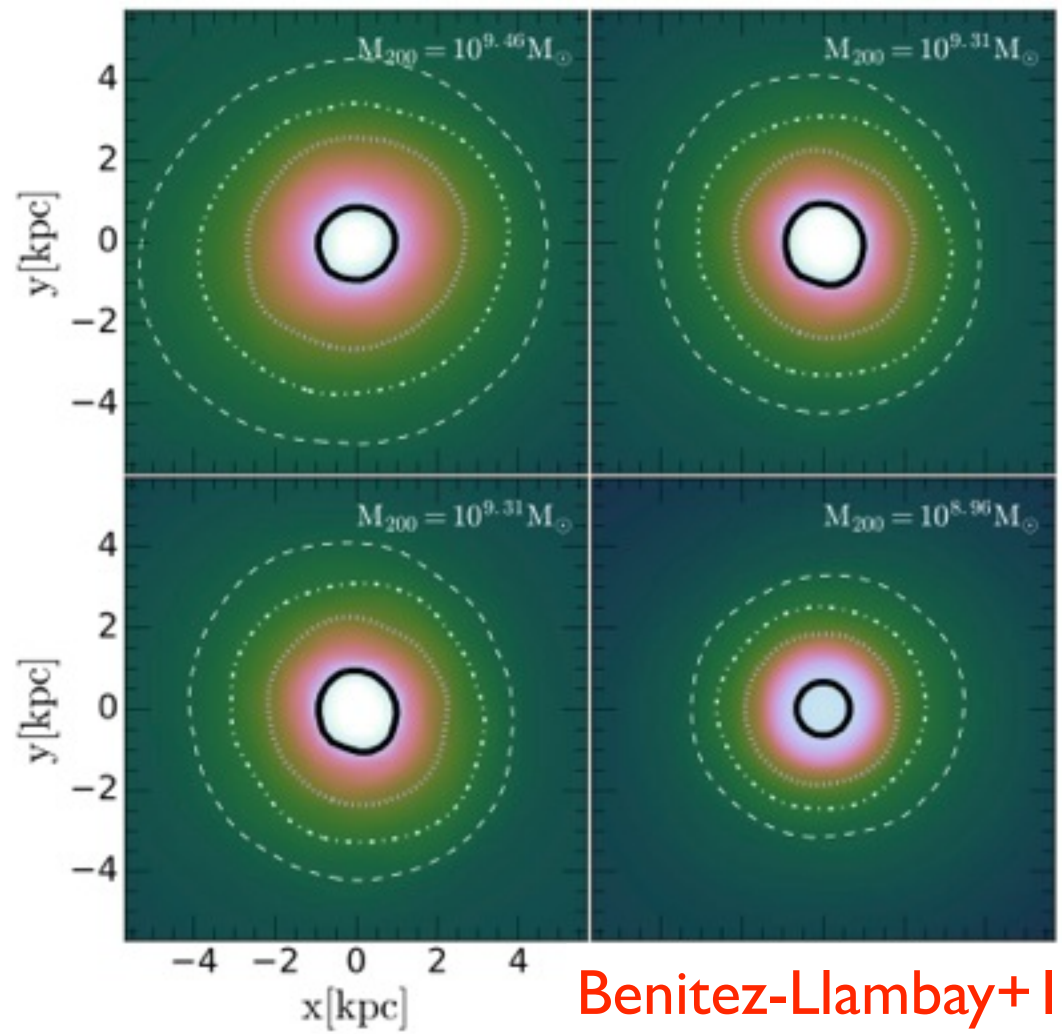
- gravitational lensing - astro-ph 1512.06507
- satellites (again)
- stellar streams
- Relhics

Lensing: Vegetti +12



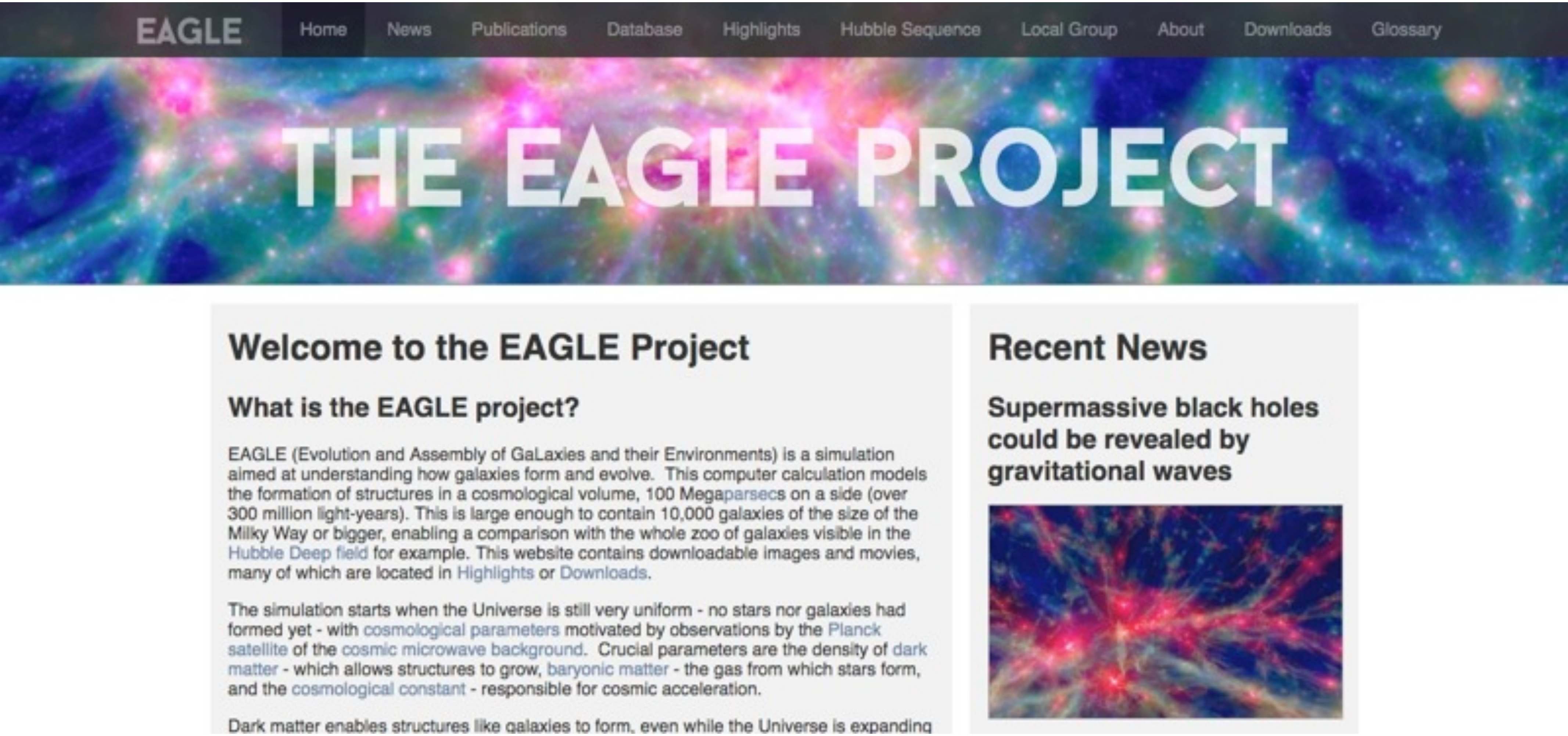
Eagle

Relhics



Benitez-Llambay+17

I want to be involved!



Hunting for dark matter in the forest
(astrophysical constraints on warm dark matter)

Tom Theuns
ICC, Durham

with the Eagle collaboration: J Schaye (Leiden), R Crain (Liverpool), R Bower , C Frenk, & M Schaller (ICC)
and A Garzilli (Leiden), A Boyarsky (Leiden)