The Millennium-II Simulation:

Overview and database-enabled science

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with thanks to: Gerard Lemson, Volker Springel, Simon White, Adrian Jenkins

Southern California CGE Center for Galaxy Evolution

Millennium Workshop
Garching
17 December 2012

Extending the Millennium Simulation's reach to lower masses (see Raul's talk for extending it to higher masses / rarer objects)

Simulation	**Millennium** Springel et al. 2005	**Millennium-II** MBK et al. 2009
N_p	**2160^3**	**2160^3**
Box Size	**685 Mpc**	**137 Mpc**
Mass Resolution	**1.2×10^9 M_{sun}**	**9.4×10^6 M_{sun}**
Force Resolution	**6.85 kpc**	**1.37 kpc**

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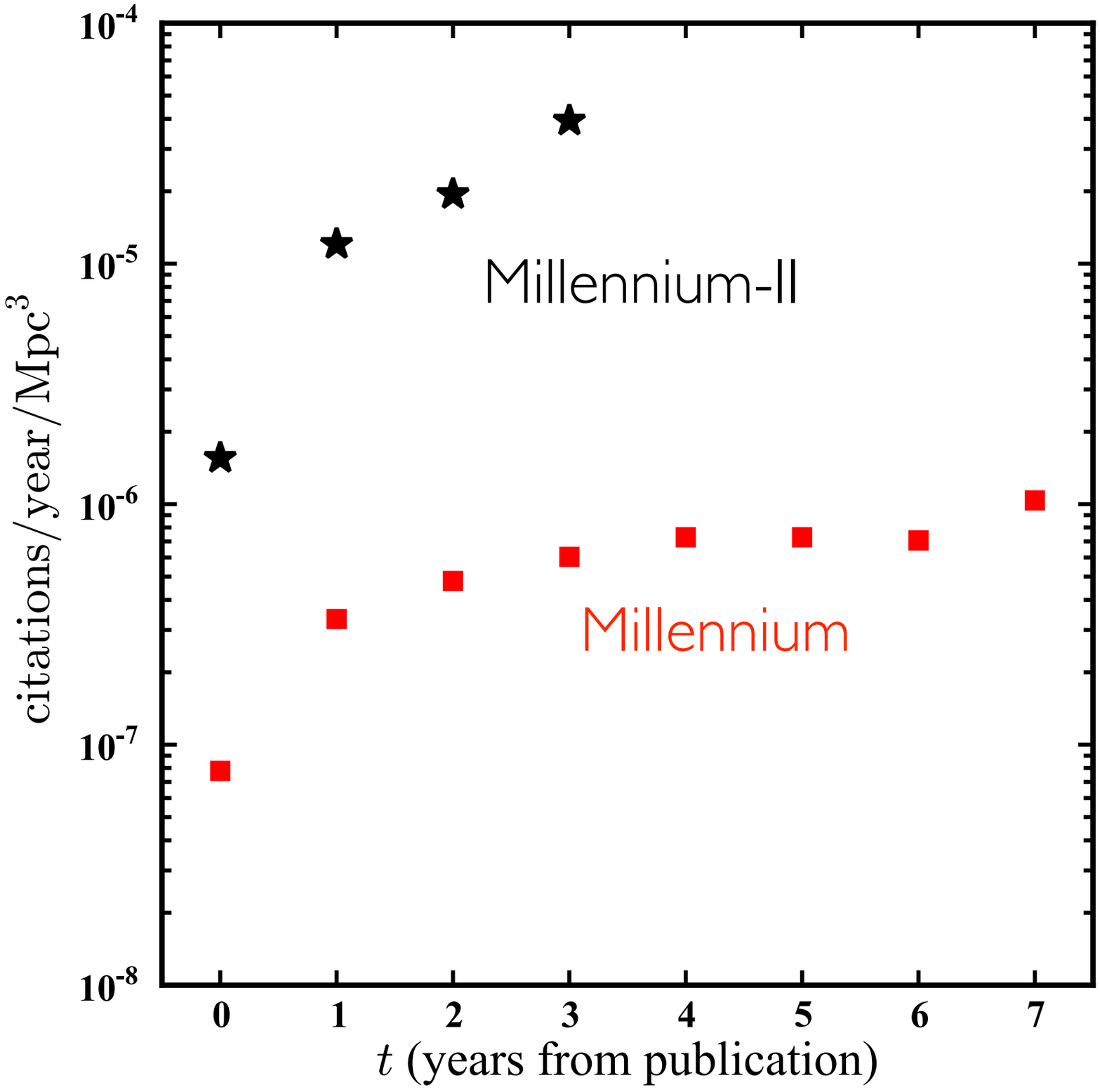
Force Resolution	**6.85 kpc**	**1.37 kpc**
# of citations	**~~~1300~~ ~1500**	**~~~125~~ ~190**
# of citations/Gpc^3	**~~~4050~~ ~4700**	**~~~48000~~ ~74000**

(as of August 2011, today)

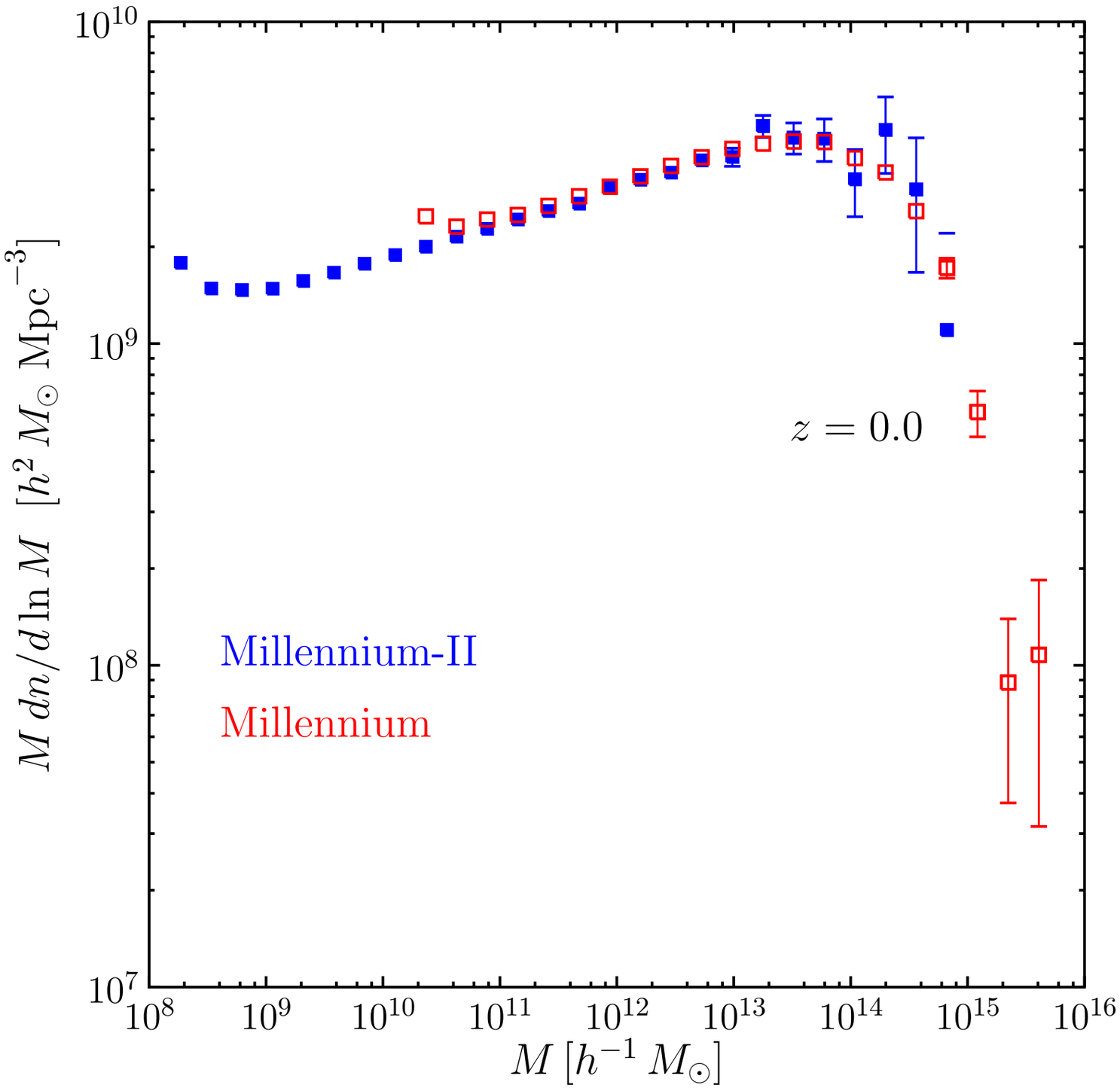
Cosmic citation rate density



Primary Science Goals for Millennium-II

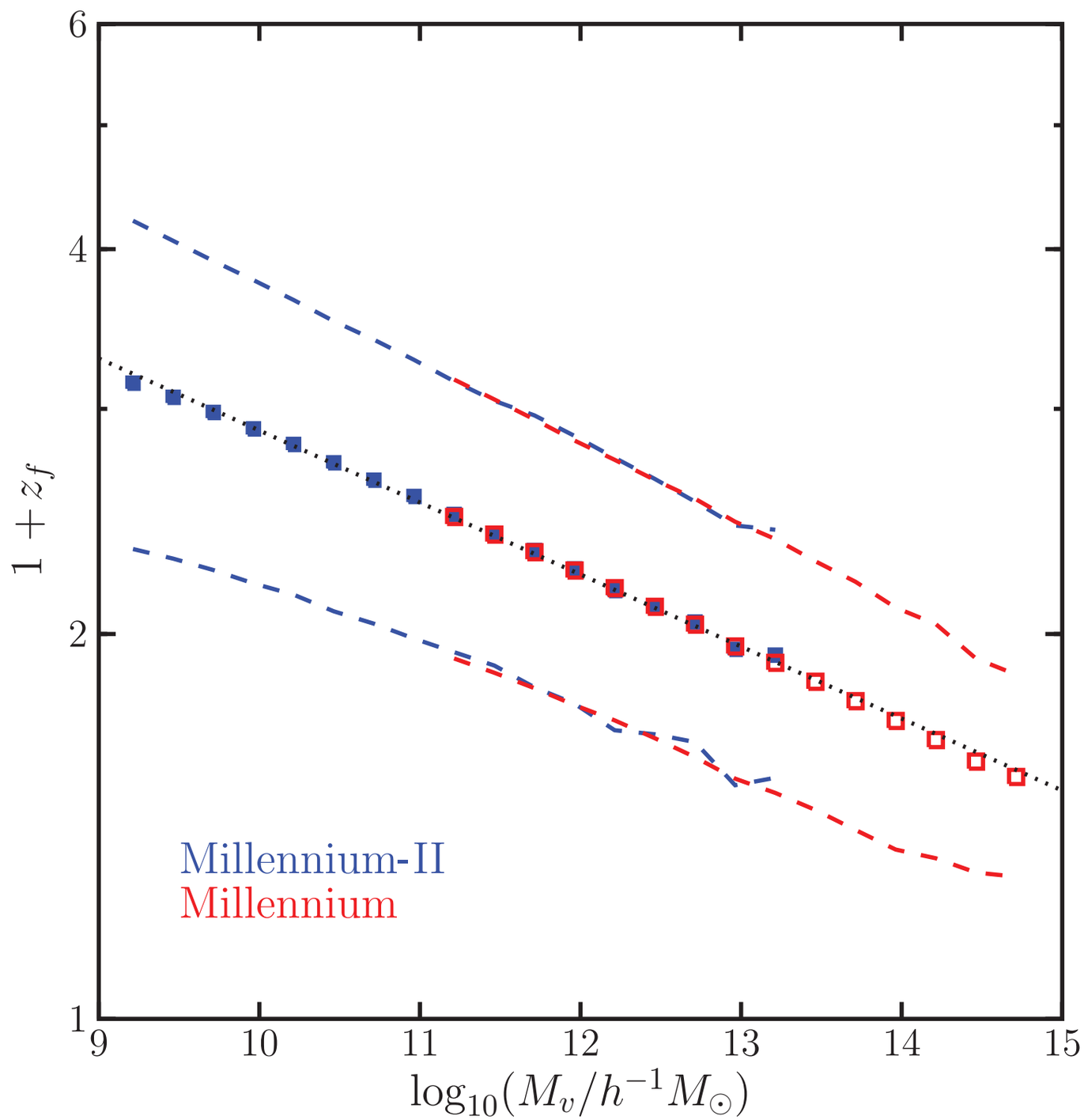
- Statistical understanding of the assembly, properties, and substructure of galaxy-mass dark matter halos
  - Needed for resolving the Milky Way and its bright satellites directly: $N_p = 10^5$
  - Good statistics: need >1000 halos
  - Together, these set minimum requirement for MS-II (>100 Mpc, $M_p < 10^7\ M_{sun}$)
  - *Bonus*: use same initial conditions as run from which Aquarius halos were selected ⇒ Aquarius halos are present in MS-II as well
- Complement and extend Millennium Simulation in this regime
  - where does numerical resolution become an issue?
  - what changes are needed in galaxy formation models (c.f. Qi, Bruno)?
  - make predictions about satellite / galaxy pairs down to SMC scale

z=0 FOF mass function



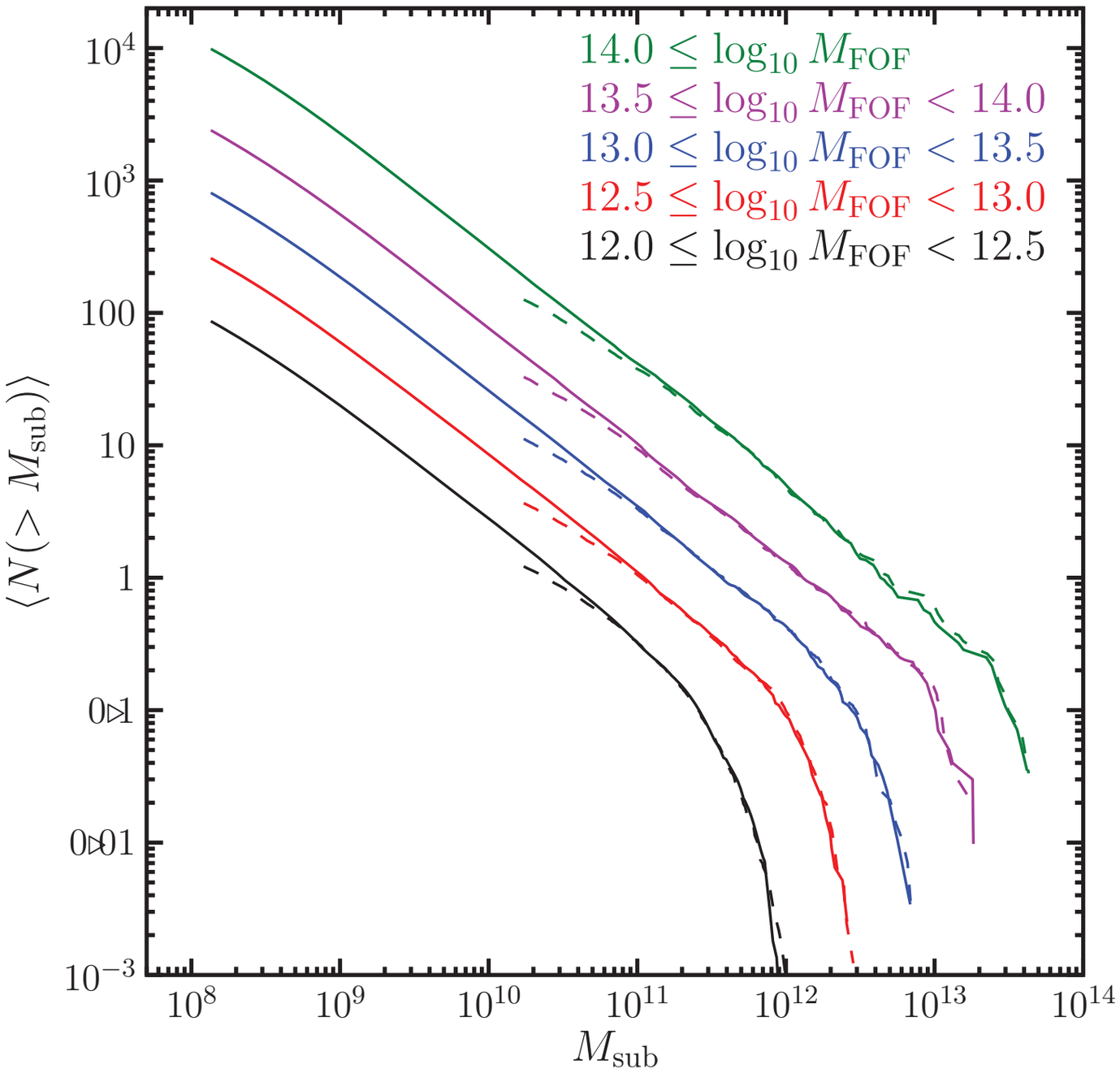
MBK, Springel, White, Jenkins, Lemson 2009

Half-mass formation times



MBK, Springel, White, Jenkins, Lemson 2009

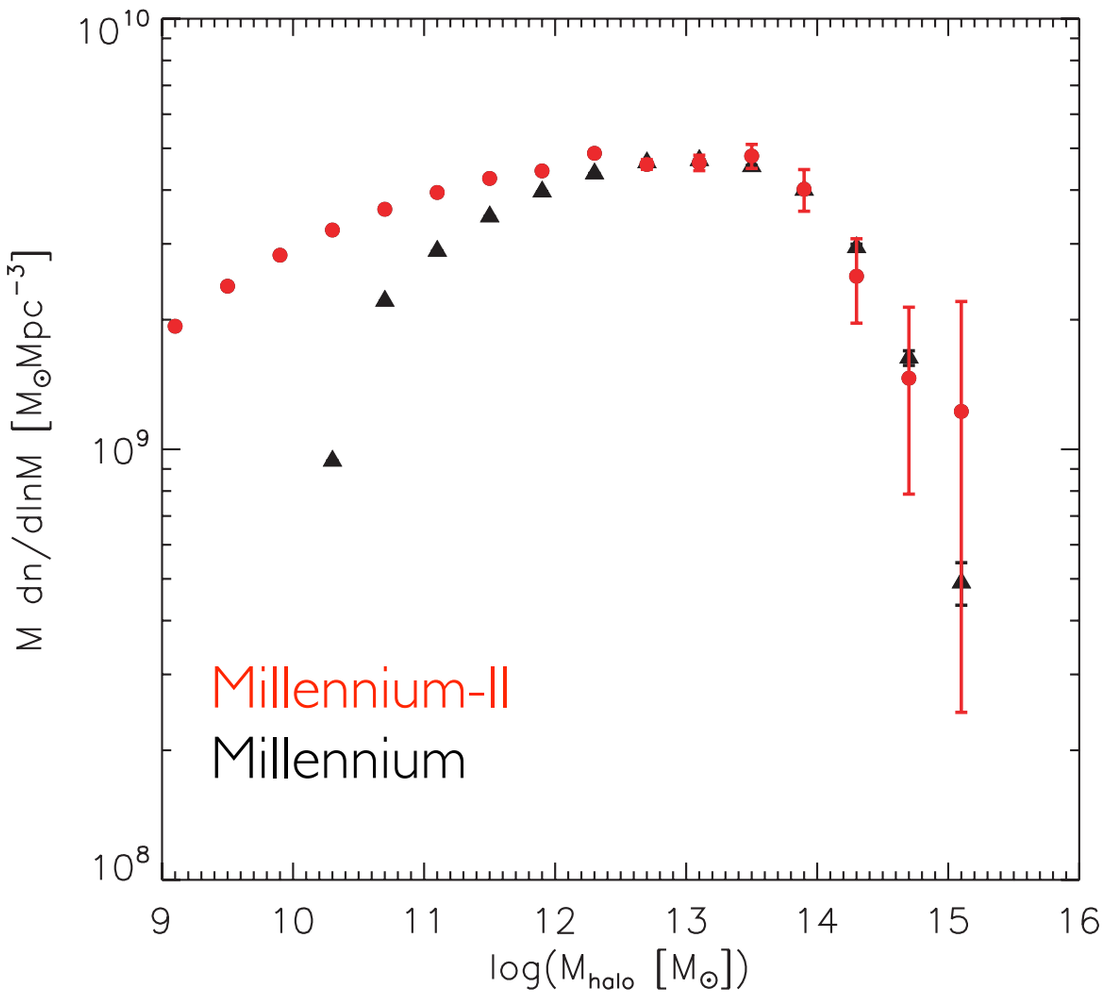
Subhalo abundance



Solid: MS-II
Dashed: mini-MS-II
(resolution of Millennium)

MBK, Springel, White, Jenkins, Lemson 2009

Resolution and semi-analytics

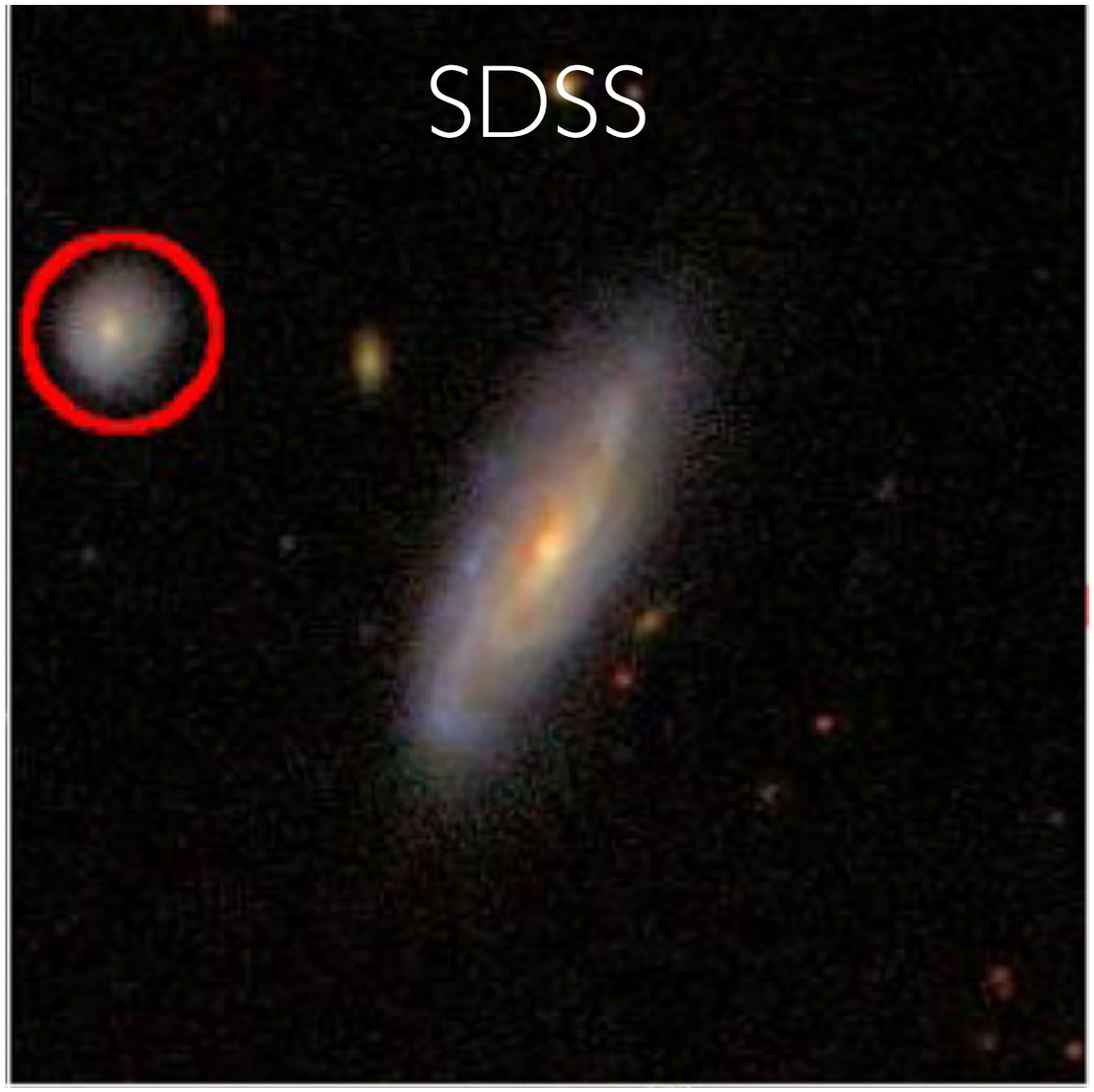


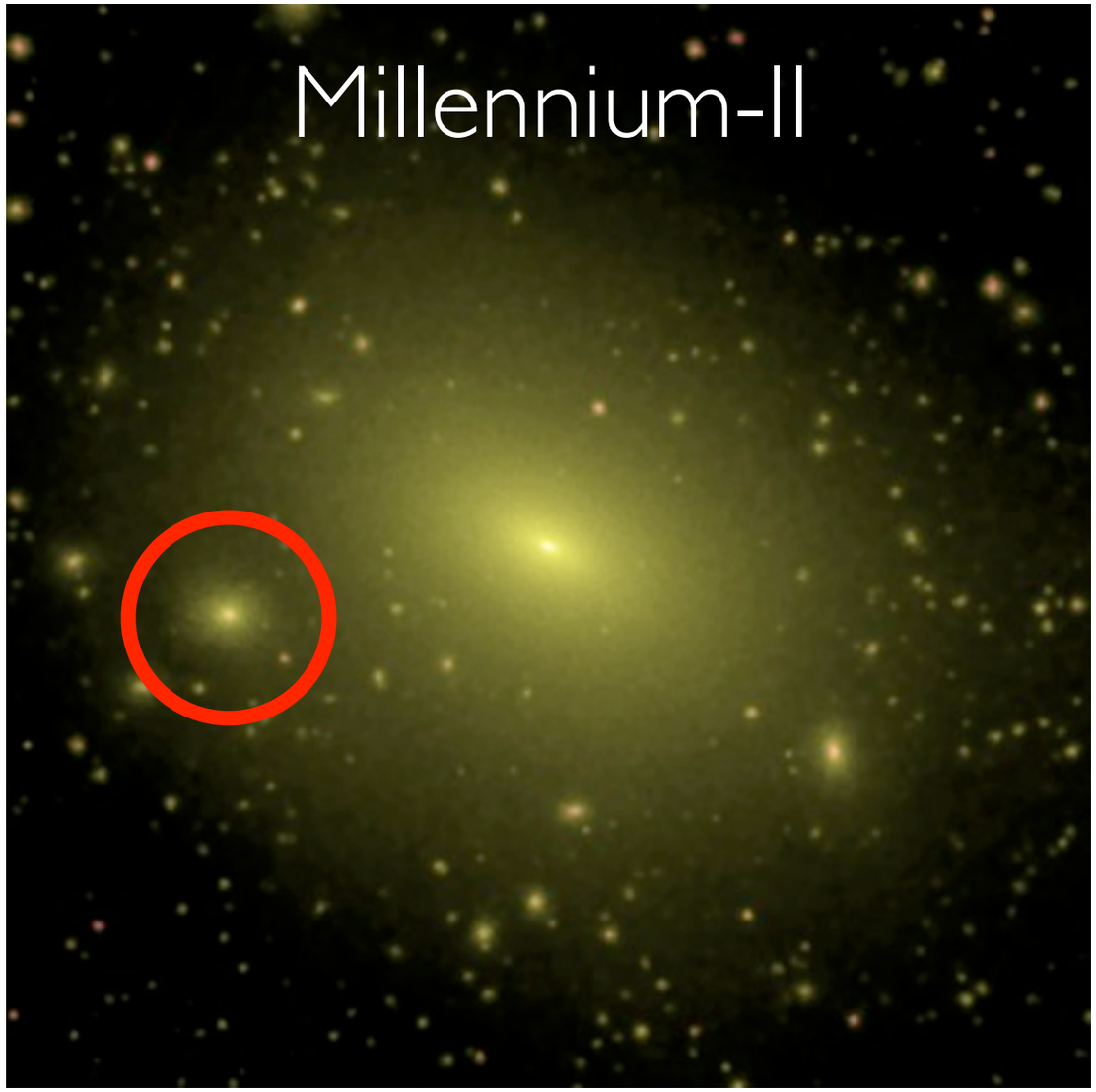
Guo, White, Li, MBK 2010

- Mass function based on infall mass indicates mass functions are complete only for **~2000** particles and greater (!!!!!)
- Numerical suppression of halo mass function leads to better, but artificial, agreement between galaxy luminosity function and halo mass function at faint end
- With Millennium + Millennium-II: can resolve all halos having $\log_{10}(M/Msun) > 10$, i.e., full galaxy population observable outside of the Local Group

Satellite kinematics in the nearby Universe

SDSS: spectroscopically complete to M_r =-18.3 (~LMC) within z=0.034; this volume matches Millennium-II very well.



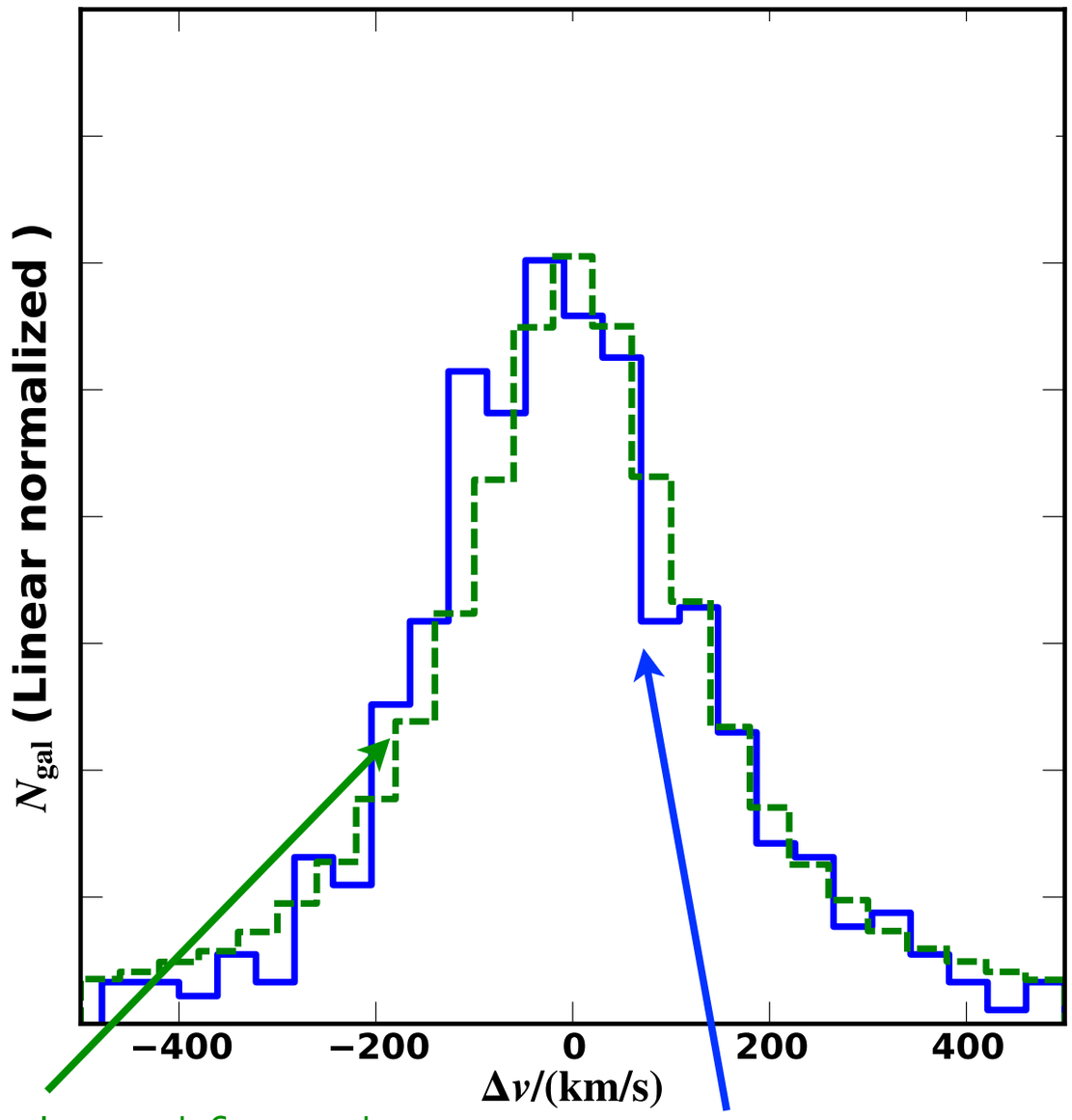


Use MS-II to maximize purity / completeness of satellite-host pairs

Tollerud, MBK, Barton, Bullock, & Trinh (2011)

Satellite kinematics in the nearby Universe

Pair-wise velocity dispersion and radial distribution of satellites match MS-II + abundance matching



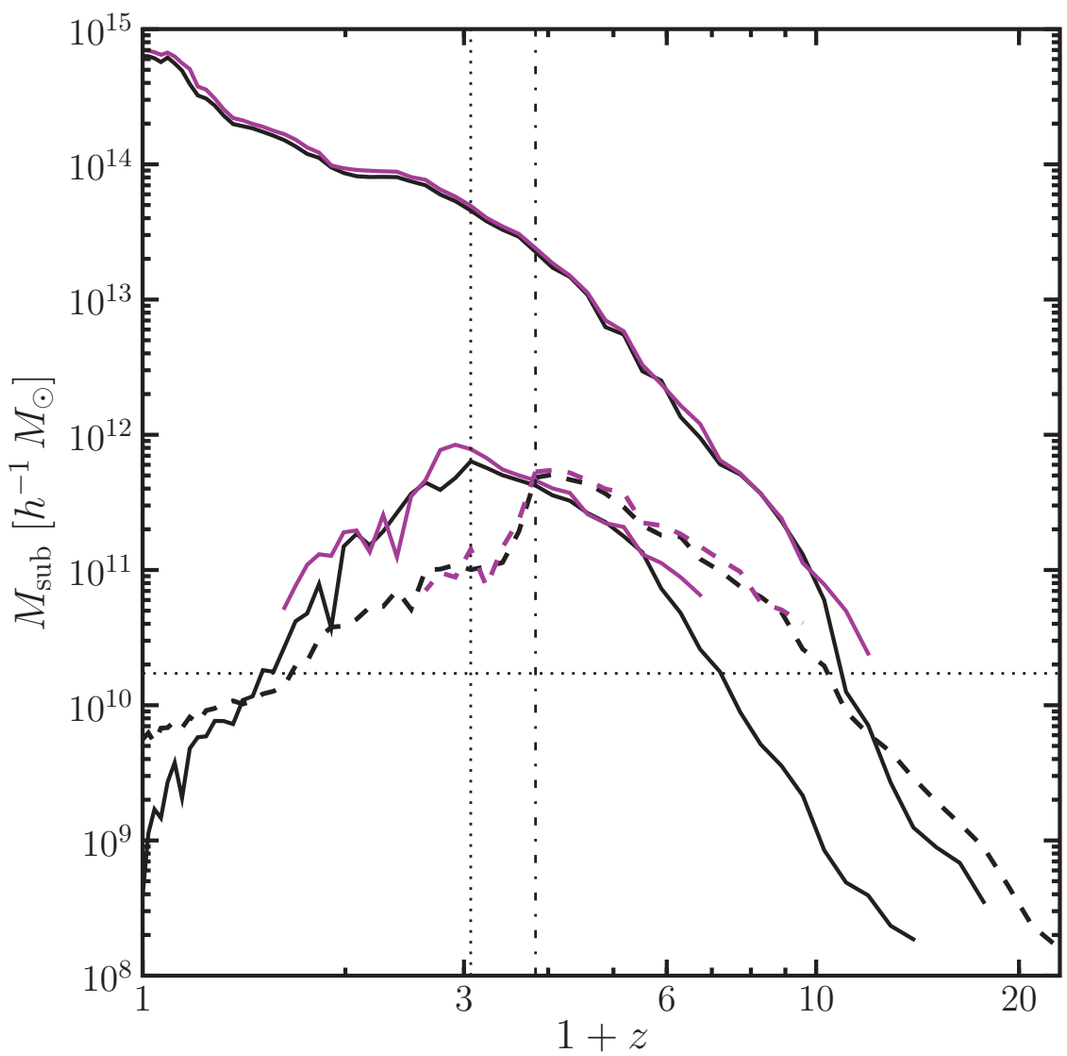
halos selected from the Millennium-II Simulation

SDSS DR7: satellites of isolated galaxies

Tollerud, MBK, Barton, Bullock, & Trinh (2011)

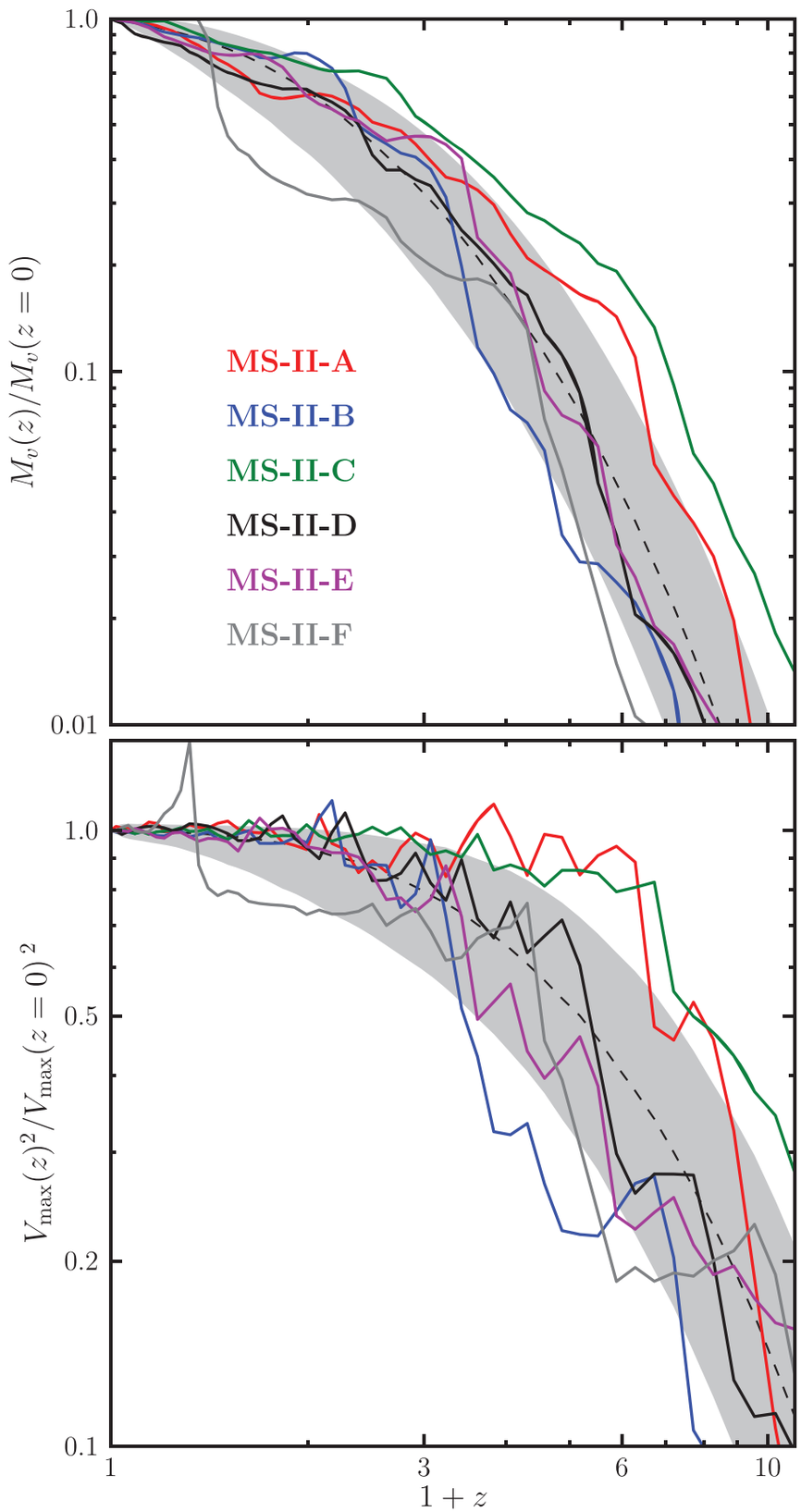
How I learned to love SQL

- Millennium II: very highly clustered
  - largest tree file in MS-II has 90 million halos (compare to 500,000 in Millennium) - 1/6 of all halos in the simulation (!!)
  - accessing the formation history of an individual halo is often very inefficient



Making this plot requires reading and holding 10 GB of data in memory if using data files; requires ~1000 bytes when using the database

MBK, Springel, White, Jenkins, Lemson 2009

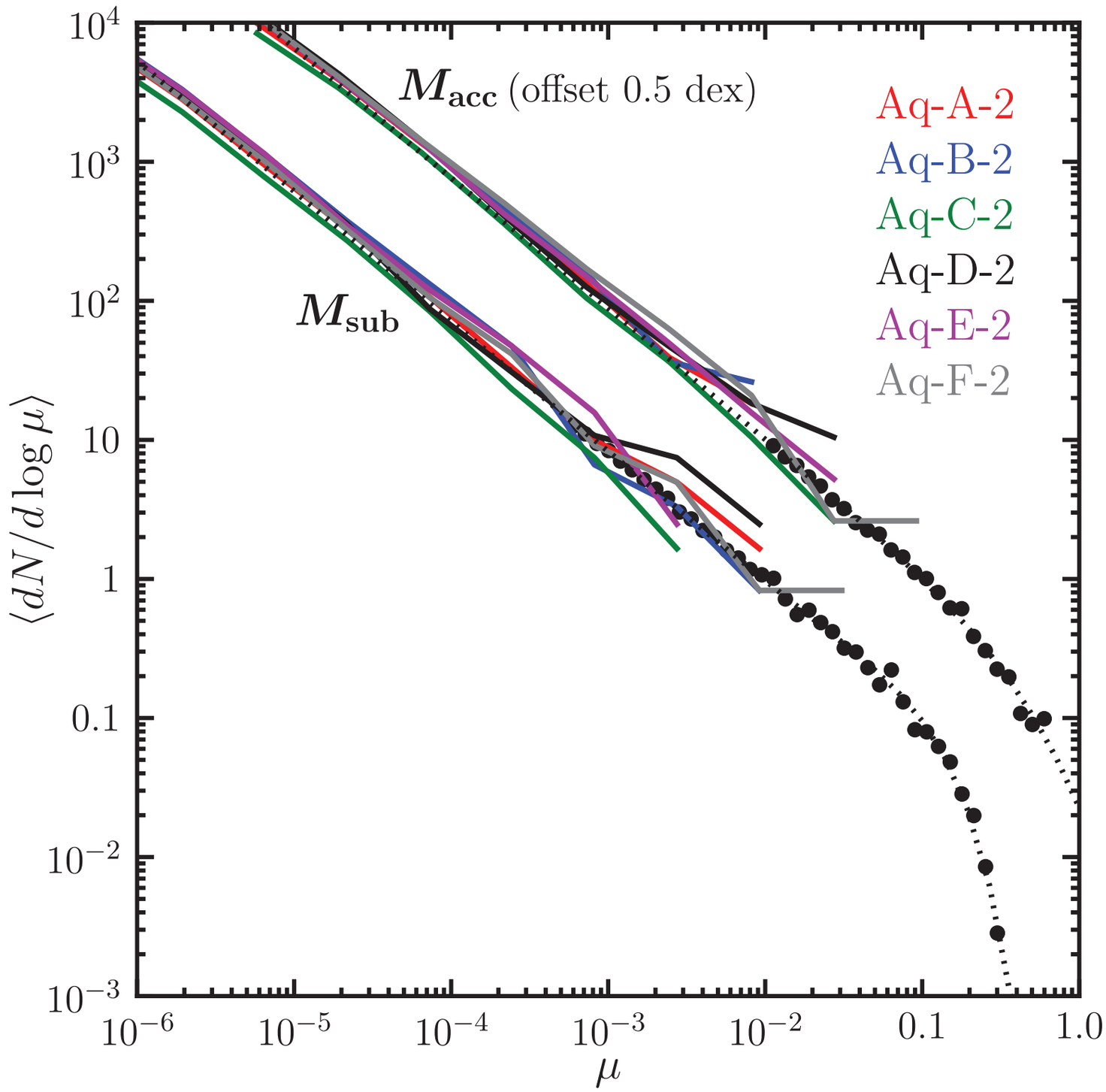


Mass accretion histories for thousands of Milky Way-mass halos

Dashed: median mass accretion history
Shaded: 68% of data

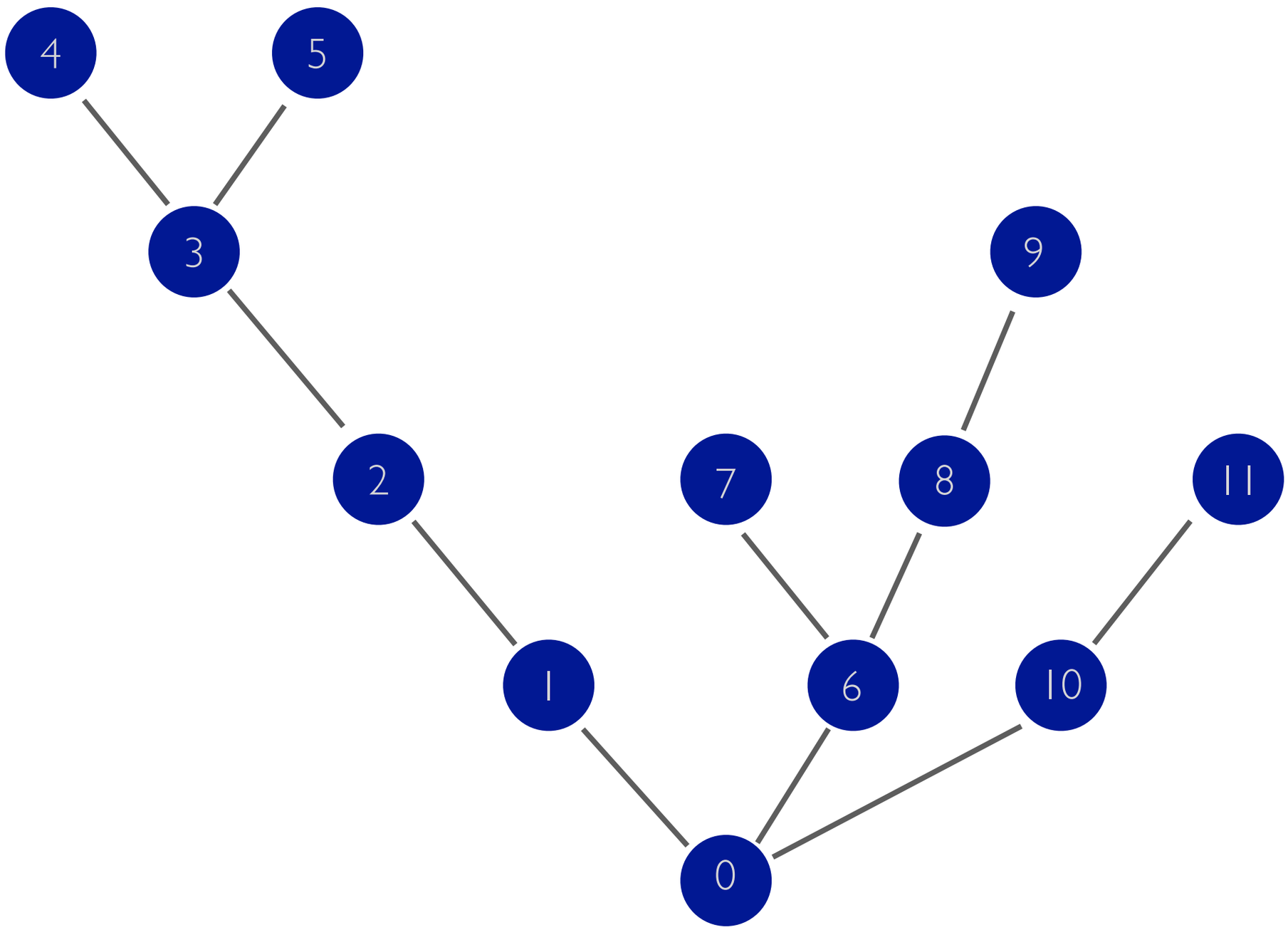
MBK, Springel, White, Jenkins (2010)

Binned subhalo mass functions



MBK, Springel, White, Jenkins (2010)

Additions to tree pointers from MS to MS-II



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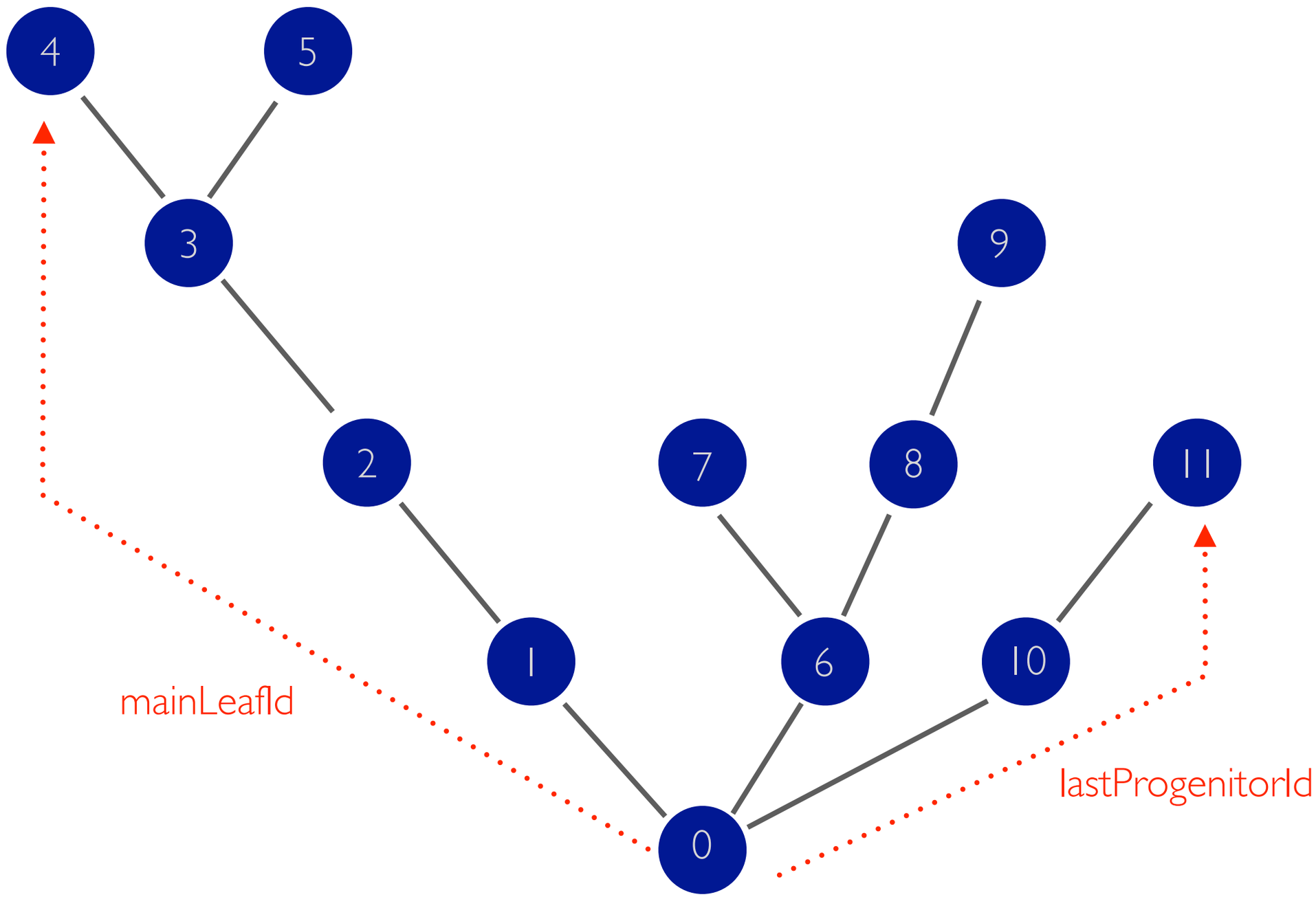

Functions and functionality I learned to love

- insert into
  - personal databases allow very customizable data storage and access
- rank () over (partition by)
  - use this often to find halo properties at a specific time (e.g., when V_{max} or mass is maximized) along a main progenitor branch for ensembles of halos
- row_number() over
  - rank objects at different redshifts, then compare easily across redshifts
- create your own function
  - example: distance between two points, taking into account periodic boundaries

```
CREATE FUNCTION distance
(
@boxsize FLOAT,
@x1 FLOAT, @y1 FLOAT, @z1 FLOAT,
@x2 FLOAT, @y2 FLOAT, @z2 FLOAT
)
RETURNS FLOAT AS
BEGIN
RETURN
POWER(
POWER(ABS(@x1-@x2)-@boxsize*FLOOR(abs(@x1-@x2)/@boxsize*2.0),2.0)+
POWER(ABS(@y1-@y2)-@boxsize*FLOOR(abs(@y1-@y2)/@boxsize*2.0),2.0)+
POWER(ABS(@z1-@z2)-@boxsize*FLOOR(abs(@z1-@z2)/@boxsize*2.0),2.0)
,0.5)
```

Millennium-II
Papers

Home | Data | Documentation | Papers | Links | Private

Reference papers:

- Lemson G. and the Virgo Consortium (2006), arXiv:astro-ph/0608019 (public release of the Millennium Simulation database)
- Springel V., et al. (2005), Nature, 435, 629 (main paper for the Millennium Simulation)
- Springel V., et al. (2008), MNRAS, 391, 1685 (introductory paper for the Aquarius Project)
- Springel V., White S. D. M., Tormen G., Kauffmann G. (2001), MNRAS, 328, 726 (introduction of the SUBFIND algorithm)

Papers using data from the Millennium-II Simulation:

Please contact us if you know of any papers that are missing from this list of papers that directly use data from the Millennium-II Simulation.

1. arXiv:0903.3041 [pdf, other]
   Title: Resolving Cosmic Structure Formation with the Millennium-II Simulation
   Authors: Michael Boylan-Kolchin (1), Volker Springel (1), Simon D. M. White (1), Adrian Jenkins (2), Gerard Lemson (3, 4)
   (1) MPA, (2) Durham, (3) ARI-ZAH, (4) MPE
   Comments: 16 pages, 13 figures; matches version published in MNRAS. Halo catalogs and merger trees, along with movies, images, and additional information, are available at this http URL
   Journal-ref: Mon.Not.Roy.Astron.Soc. 398, 1150 (2009)

2. arXiv:0908.2428 [ps, pdf, other]
   Title: Extragalactic gamma-ray background radiation from dark matter annihilation
   Authors: Jesus Zavala, Volker Springel, Michael Boylan-Kolchin
   Comments: 21 pages, 16 figures, submitted to MNRAS

Sixty papers have directly used MS-II data

58. arXiv:1210.7185 [pdf, ps, other]
    Title: Modeling the Redshift Evolution of the Normal Galaxy X-ray Luminosity Function
    Authors: M. Tremmel T. Fragos, B. D. Lehmer, P. Tzanavaris, K. Belczynski, V. Kalogera, A. R. Basu-Zych, W. M. Farr, A. Hornschemeier, L. Jenkins, A. Ptak, A. Zezas
    Comments: Submitted to ApJ, 16 pages, 3 tables, 7 figures

59. arXiv:1211.3752 [pdf, ps, other]
    Title: Massive black hole seeds born via direct gas collapse in galaxy mergers: their properties, statistics and environment
    Authors: Silvia Bonoli, Lucio Mayer, Simone Callegari (University of Zurich)
    Comments: 14 pages, 10 figures, submitted to MNRAS

60. arXiv:1212.1717 [pdf, ps, other]
    Title: Simulations of the galaxy population constrained by observations from z=3 to the present day: implications for galactic winds and the fate of their ejecta
    Authors: Bruno Henriques (MPA), Simon White (MPA), Peter Thomas (Sussex), Raul Angulo (Stanford), Qi Guo (Beijing), Gerard Lemson (MPA), Volker Springel (HITS)
    Comments: 25 pages, 14 figures, submitted to MNRAS

Thank you to everyone involved!