Large-scale clustering of Active Galactic Nuclei *What can we learn?*

Mirko Krumpe (ESO, UCSD)
mkrumpe@eso.org

Collaborators: Takamitsu Miyaji (UNAM-E, UCSD), Alison L. Coil (UCSD), Hector Aceves (UNAM-E), Bernd Husemann (AIP)

Galaxies cluster!

Outline

- introduction to AGN clustering measurements
- AGN clustering measurements through cross-correlation functions
- Halo Occupation Distribution modeling of AGNs
- current picture of AGN clustering

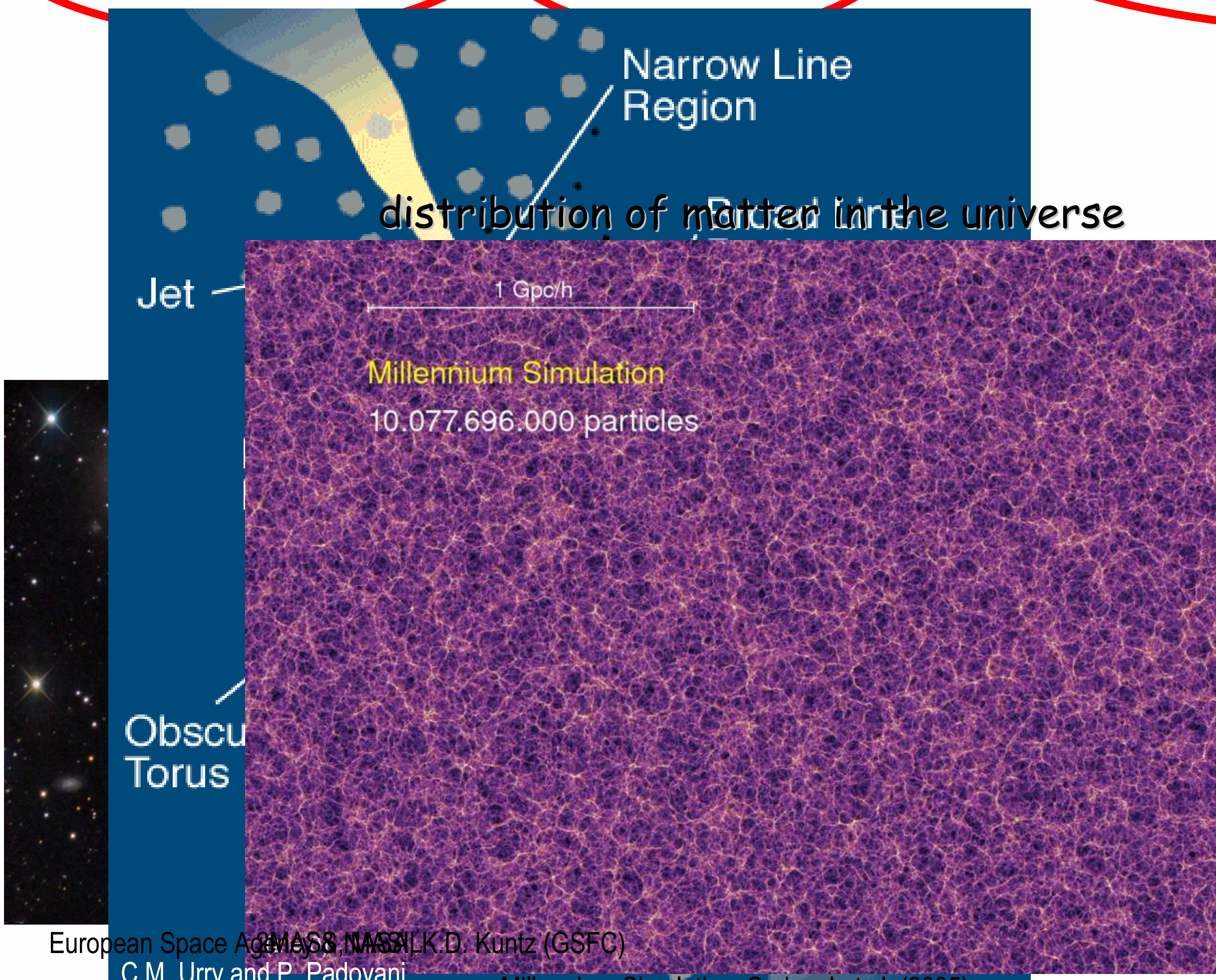
2dFGRS

What are we talking about?

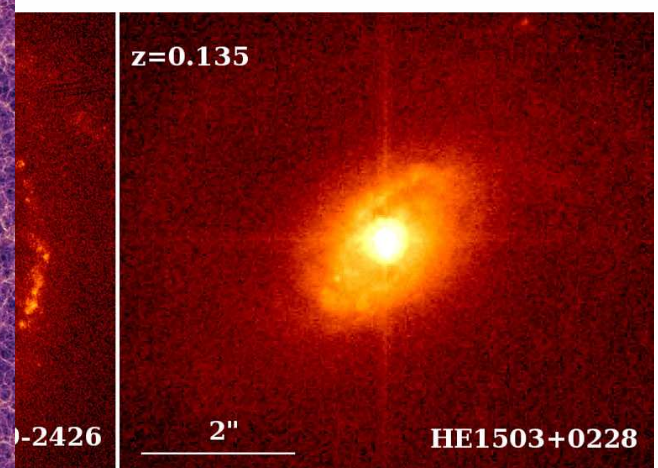
Large-scale clustering of Active Galactic Nuclei

accreting supermassive black holes in the centers of galaxies

distribution of matter in the universe



European Space Agency & NASA
2MASS, NASA, K.D. Kuntz (GSFC)
C.M. Urry and P. Padovani
Millennium Simulation, Springel et al. (2005)

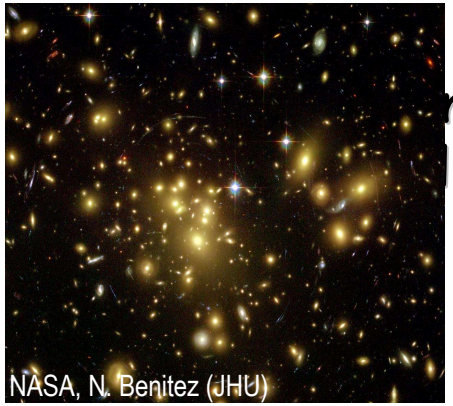


HST/ESO

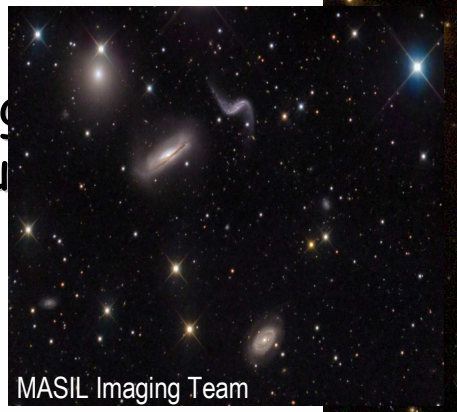
What are we talking about?

Large-scale clustering of Active Galactic Nuclei

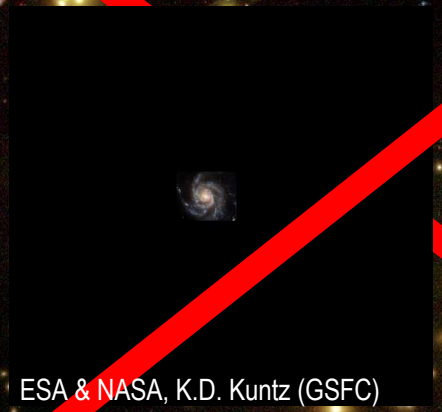
characterize general matter distribution in the universe



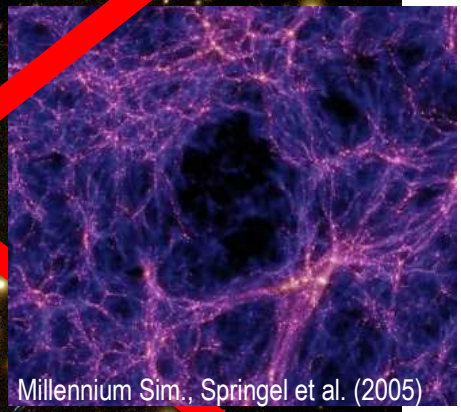
galaxy cluster



group of galaxies



field galaxy

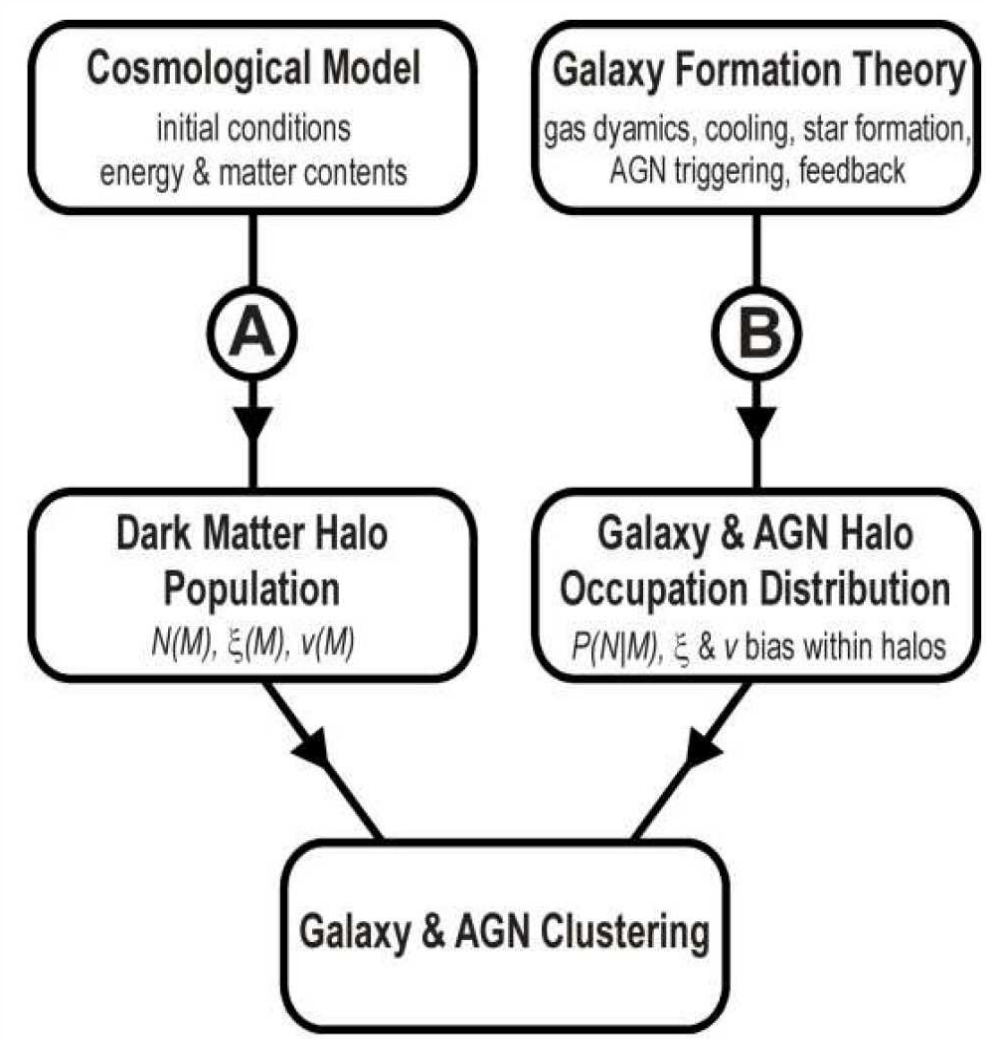


void (underdensity)

highest density environment

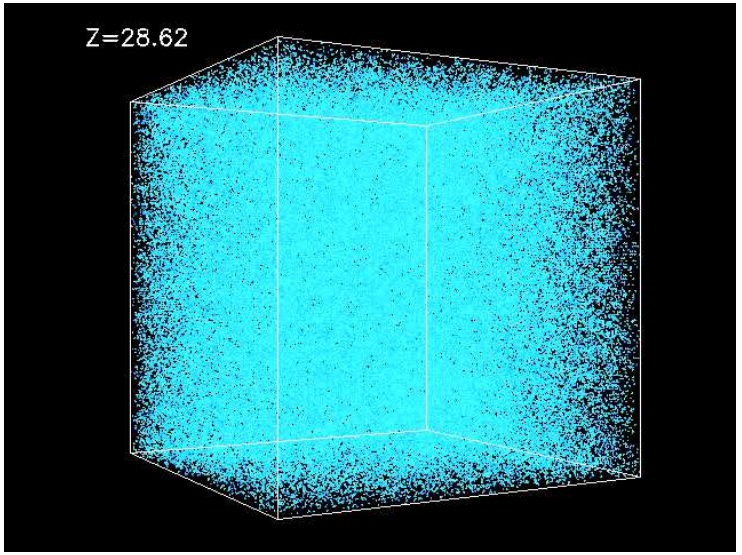
lowest density environment

What drives clustering?



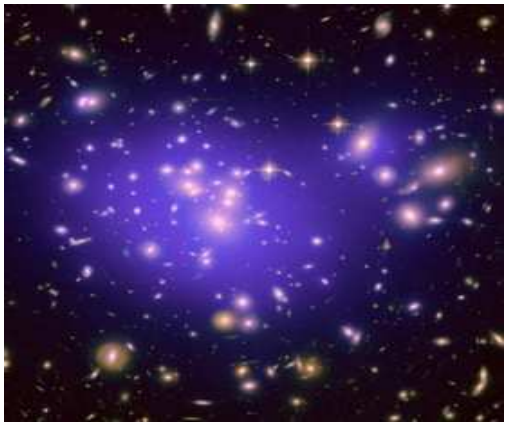
Based on Zheng & Weinberg 2007, Weinberg 2002

1) Cosmology



National Center for Supercomputer Applications(Kravtsov & Klypin)

2) Galaxy distribution within DMHs



NASA, ESA, Jullo, Natarajan, Kneib

AGN clustering measurements: Why?

Can test different AGN evolution models by measuring the observed clustering of AGN, ideally as a function of luminosity, redshift, BH mass, accretion rate

---

AGN clustering measurements can constrain:

- host dark matter halo mass
- host galaxy type
- environment

(clues on AGN/galaxy co-evolution)

- fueling mechanism
- AGN lifetime
- central vs. satellite fraction
- cosmology

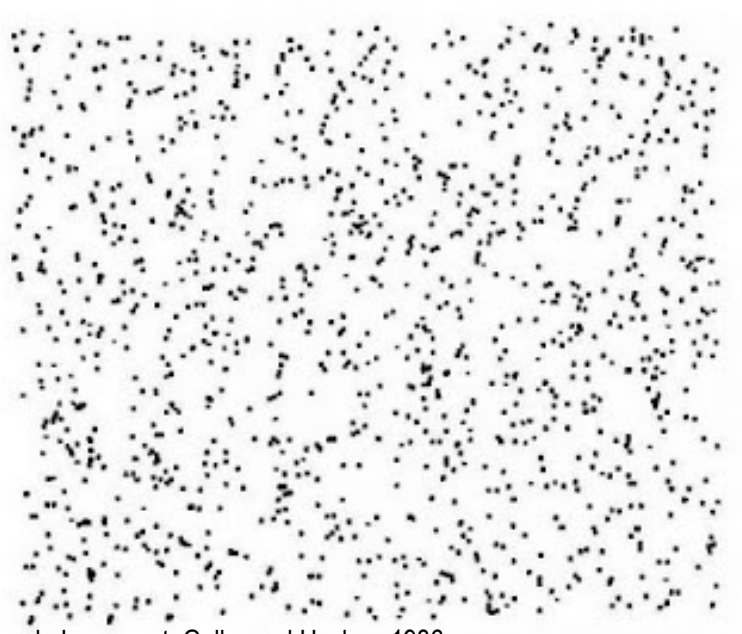
How do we measure large-scale clustering?

AGN clustering measurements: How?

The 2-point correlation function $\xi(r)$ measures the spatial clustering of a class of objects **in excess of a Poisson distribution** (Peebles 1980)

$$dP = n\,(1 + \xi(r))\,dV$$

- $\xi(r) = 0$, if objects are distributed randomly in the universe
- $\xi(r) > 0$, if objects are more strongly clustered than a random distribution



de Lapparent, Geller and Huchra, 1986

In practice: via counting pairs of objects with a given separation

$$\xi(r) = (DD(r) / DR(r)) - 1$$

AGN clustering measurements: How?

two major challenges

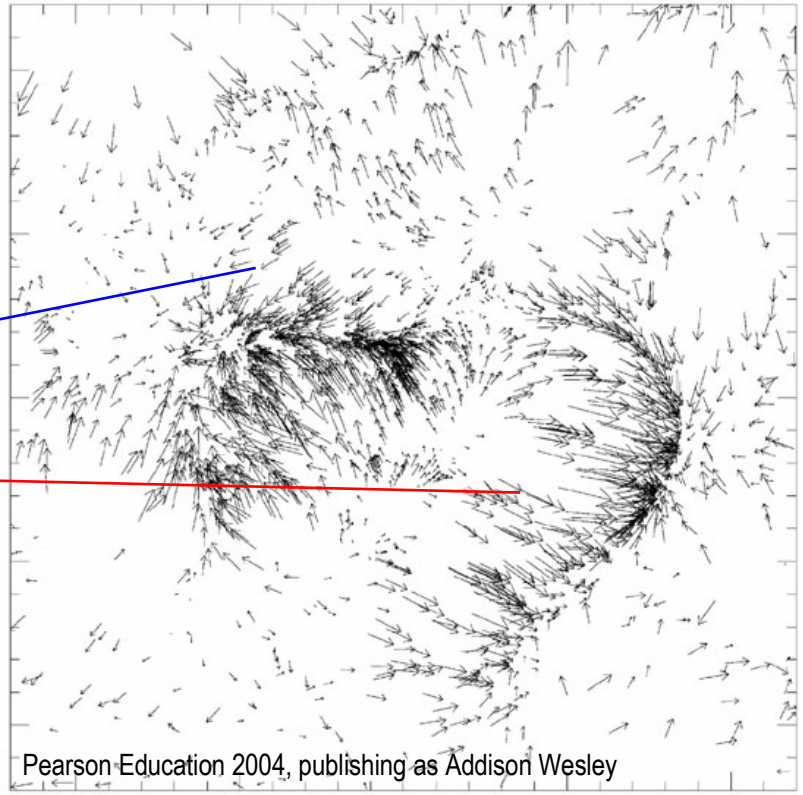
- $\xi(r) = (DD(r)/DR(r)) - 1$ ⇨ **generate catalogue** with randomly distributed sources having the same observational bias

- **no direct measurement of distance** ⇨ redshift is used to derive distances

$$z_{OBS} = z_{TRUE} + v_{PEC}$$

$z_{OBS} < z_{TRUE}$ ⇨ object seems to be closer

$z_{OBS} > z_{TRUE}$ ⇨ object seems to be further away



Pearson Education 2004, publishing as Addison Wesley

AGN clustering measurements: How?

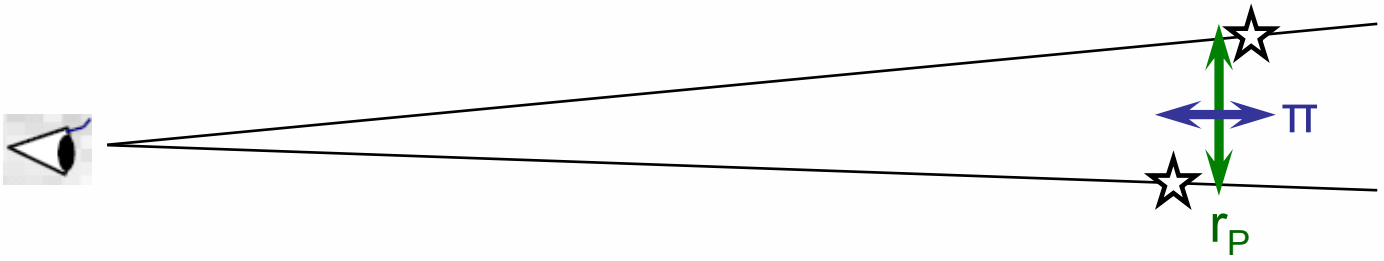
two major challenges

- $\xi(r) = (DD(r)/DR(r)) - 1$ ⇨ **generate catalogue** with randomly distributed sources having the same observational bias

- **no direct measurement of distance** ⇨ redshift is used to derive distances

instead of measuring $\xi(r)$

Calculate $\xi(r_P,\pi)$; r_P- projected distance , π - line-of-sight separation



Galaxy clustering measurements

- to robustly measure clustering, you need:
  - spectroscopic redshifts
  - large volumes
  - well-defined and replicable selection function (spatial + z)

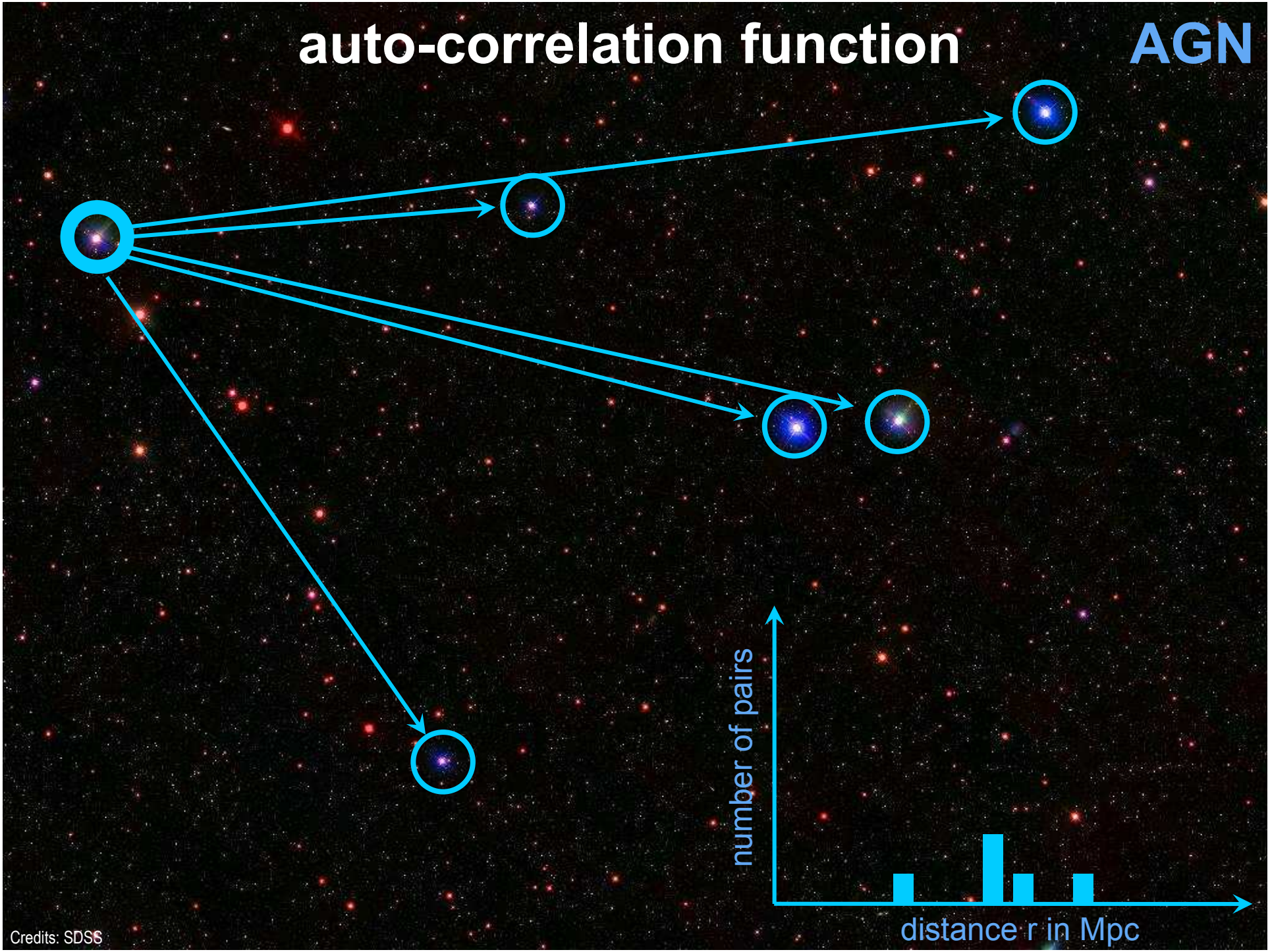
large area surveys (2dF, SDSS, DEEP2, AGES) provide many thousands of galaxies

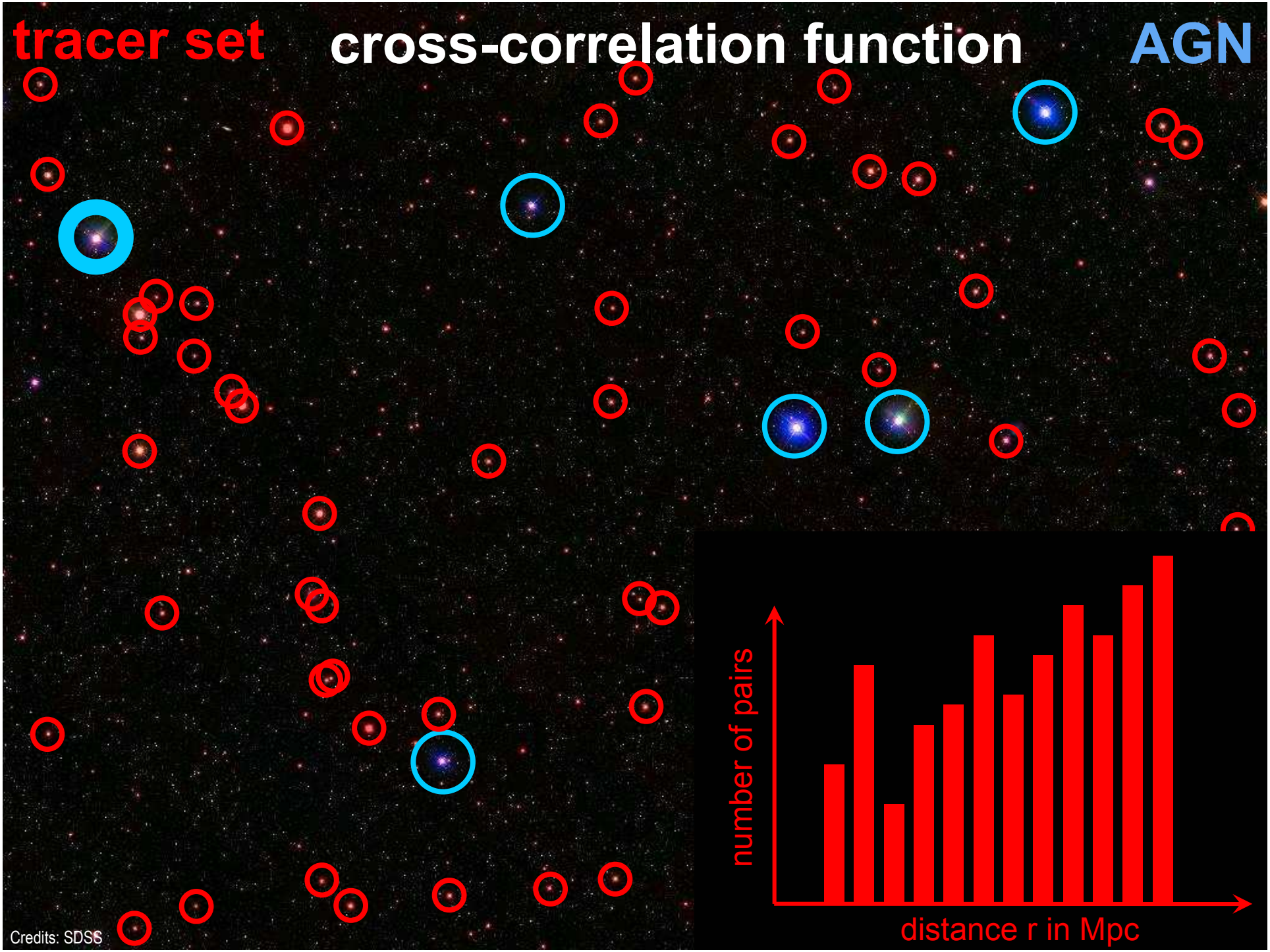
⇨ **Galaxy clustering depends on luminosity, color, morphology**:

- brighter / redder / elliptical galaxies are more clustered than fainter / bluer / spiral galaxies

Only a small fraction of galaxies contain an AGN
⇨ small number statistics limits clustering studies

AGN clustering measurements through cross-correlation functions

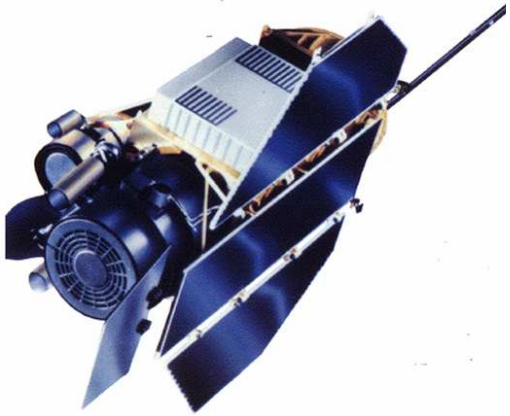

auto-correlation function
AGN
number of pairs
distance r in Mpc
Credits: SDSS

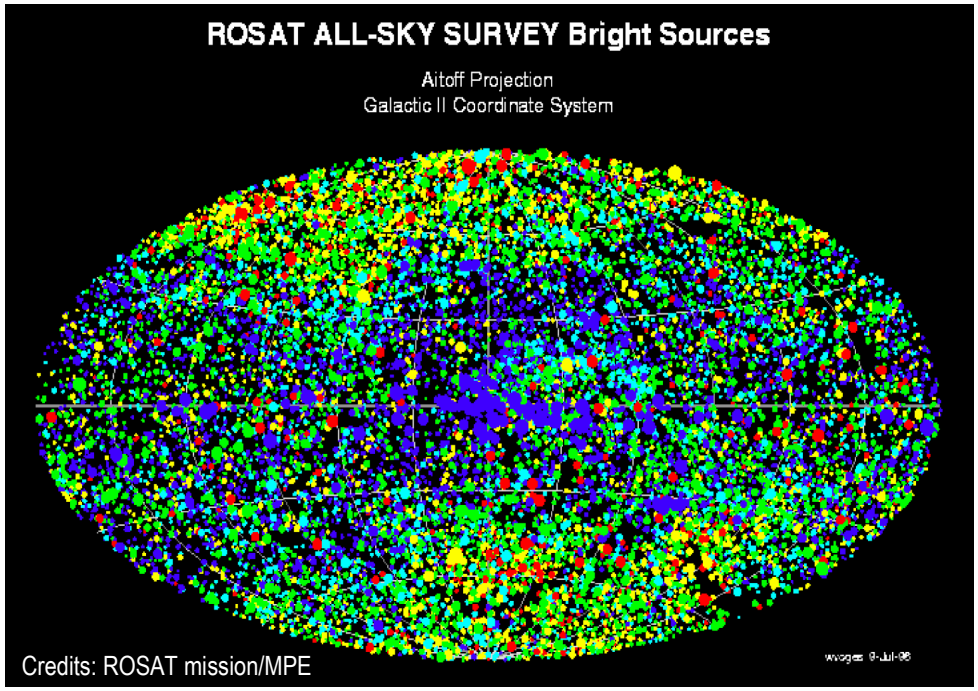

tracer set
cross-correlation function
AGN
number of pairs
distance r in Mpc
Credits: SDSS

RASS AGN sample

1. **AGN sample:** ROSAT All-Sky Survey (RASS)

(Voges et al. 1999, Anderson et al. 2003, 2007)





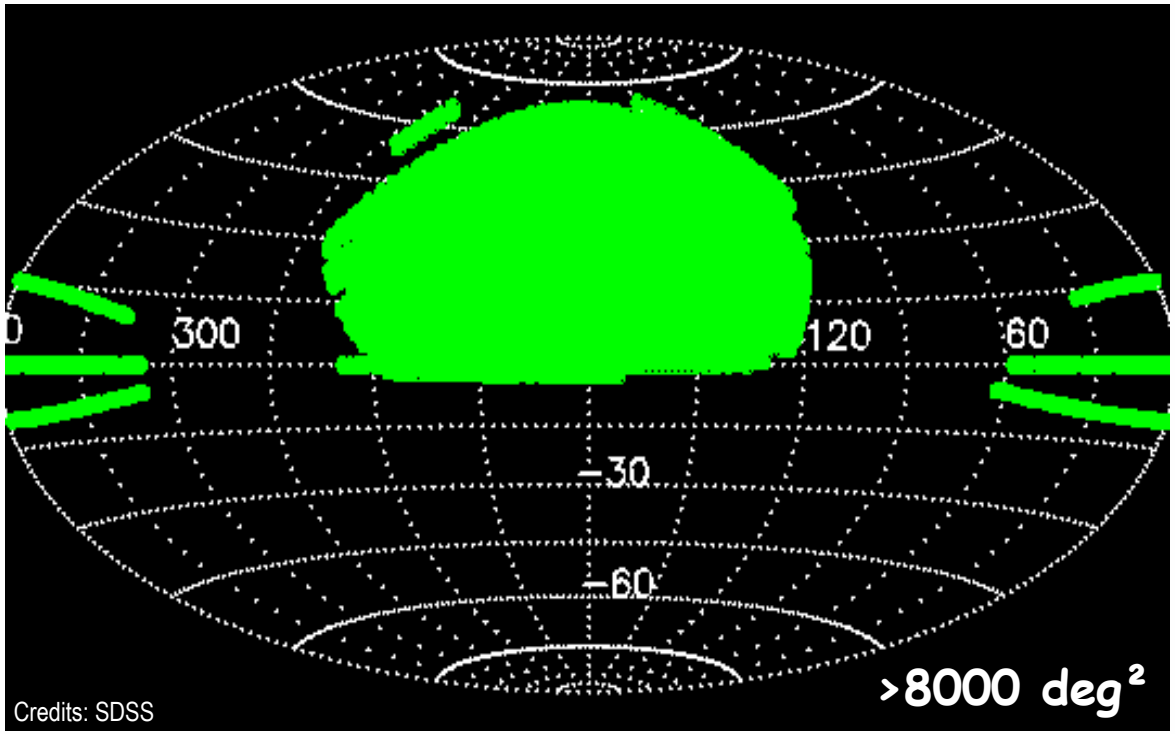
color = soft-band hardness ratio
(soft to hard: red, yellow, green, blue)

- still the most sensitive all-sky X-ray survey, with ~110,000 sources
- sensitive in soft X-rays (0.1-2.4 keV)
- sampled unabsorbed (6224 type I) AGNs, not very sensitive to absorbed AGNs (515 type II)
- spectroscopic redshifts from SDSS
- $L_X \sim 10^{43}$-10^{45} erg s^{-1}

SDSS AGN sample

2. AGN sample: SDSS AGNs

(Schneider et al. 2010, Richards et al. 2002)



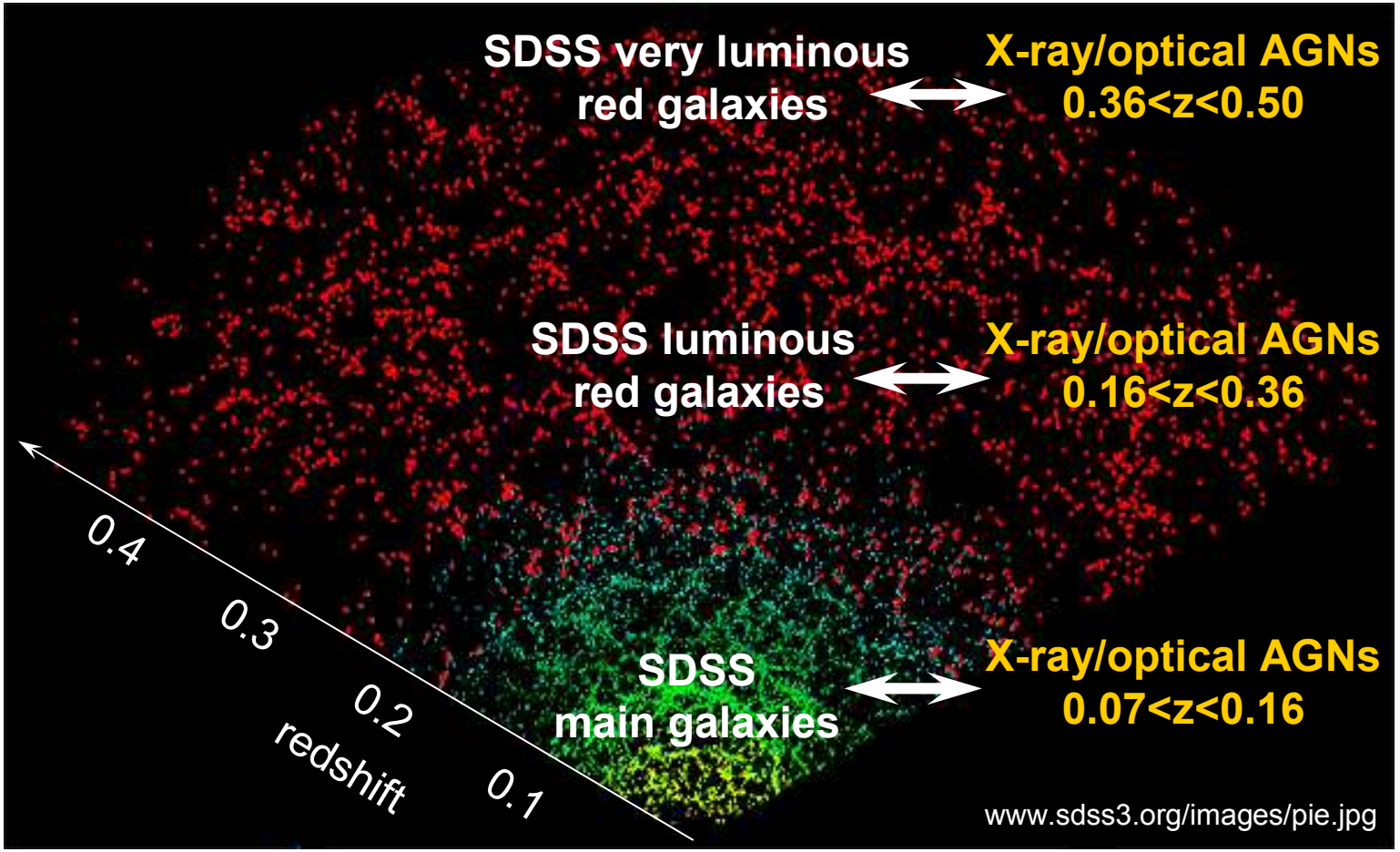
area map of SDSS spectroscopic footprint

- ~18 candidates per deg^2
- 105,783 broad-line AGNs
- fainter i~15 mag
- $M_i \leq -22$ mag

Finding the right tracer set

requirements for tracer set:

high number density (>> AGN) & well-defined and replicable selection



AGN clustering measurements through CCF

From the AGN-galaxy cross-correlation measurement:

⇨ divide by the measured auto-correlation of tracer galaxies

⇨ infer the AGN auto-correlation function (Krumpe et al. 2010)

$$\xi_{ACF(AGN)} = \xi^{2}_{CCF(AGN\text{-}Gal.)} / \xi_{ACF(Gal.)}$$

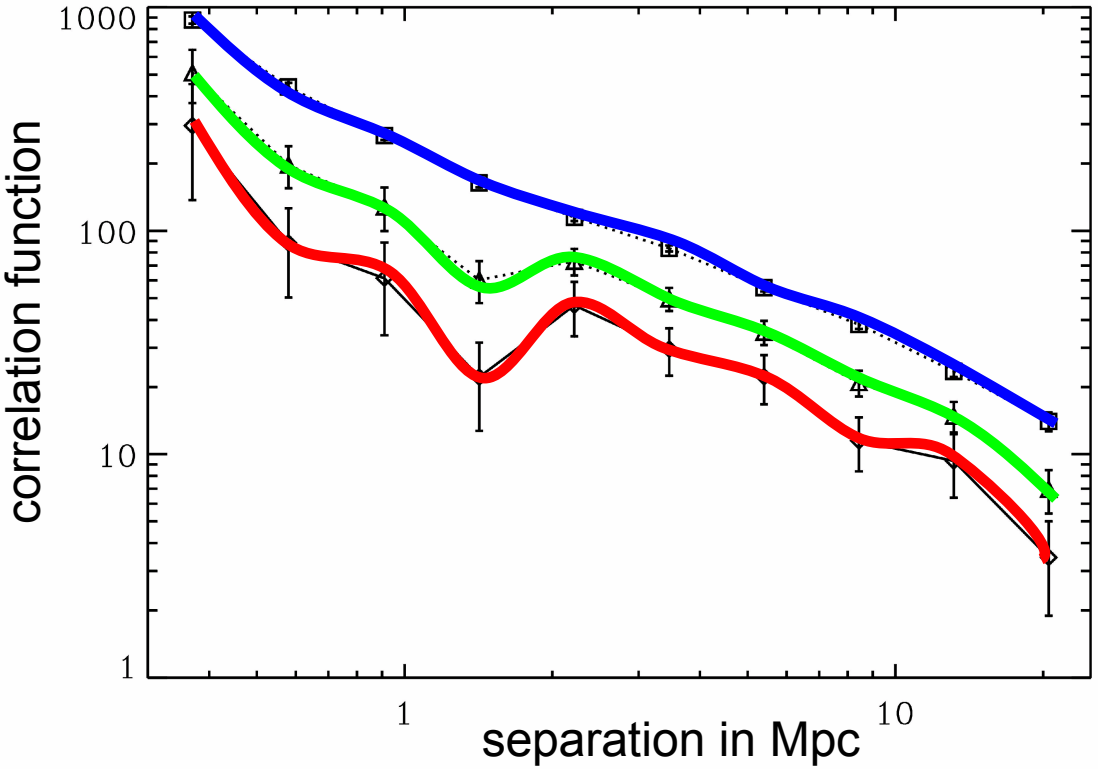
(Coil et al. 2009)

⇨ **bias parameter**

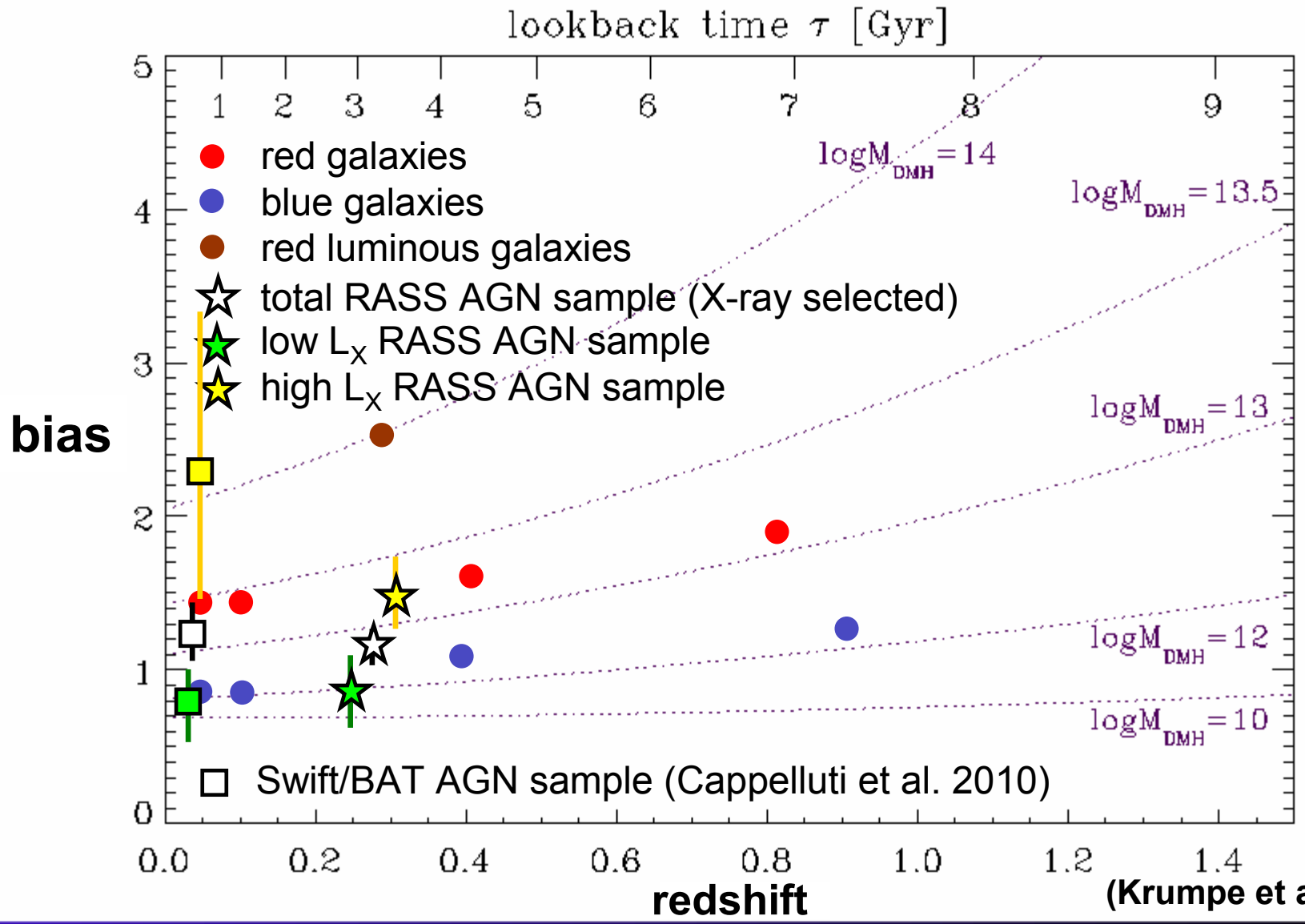
(how strongly a particular class of objects is clustered relative to DM density distribution)

⇨ **average mass of the host dark matter halos**

(compare to dark matter simulations)

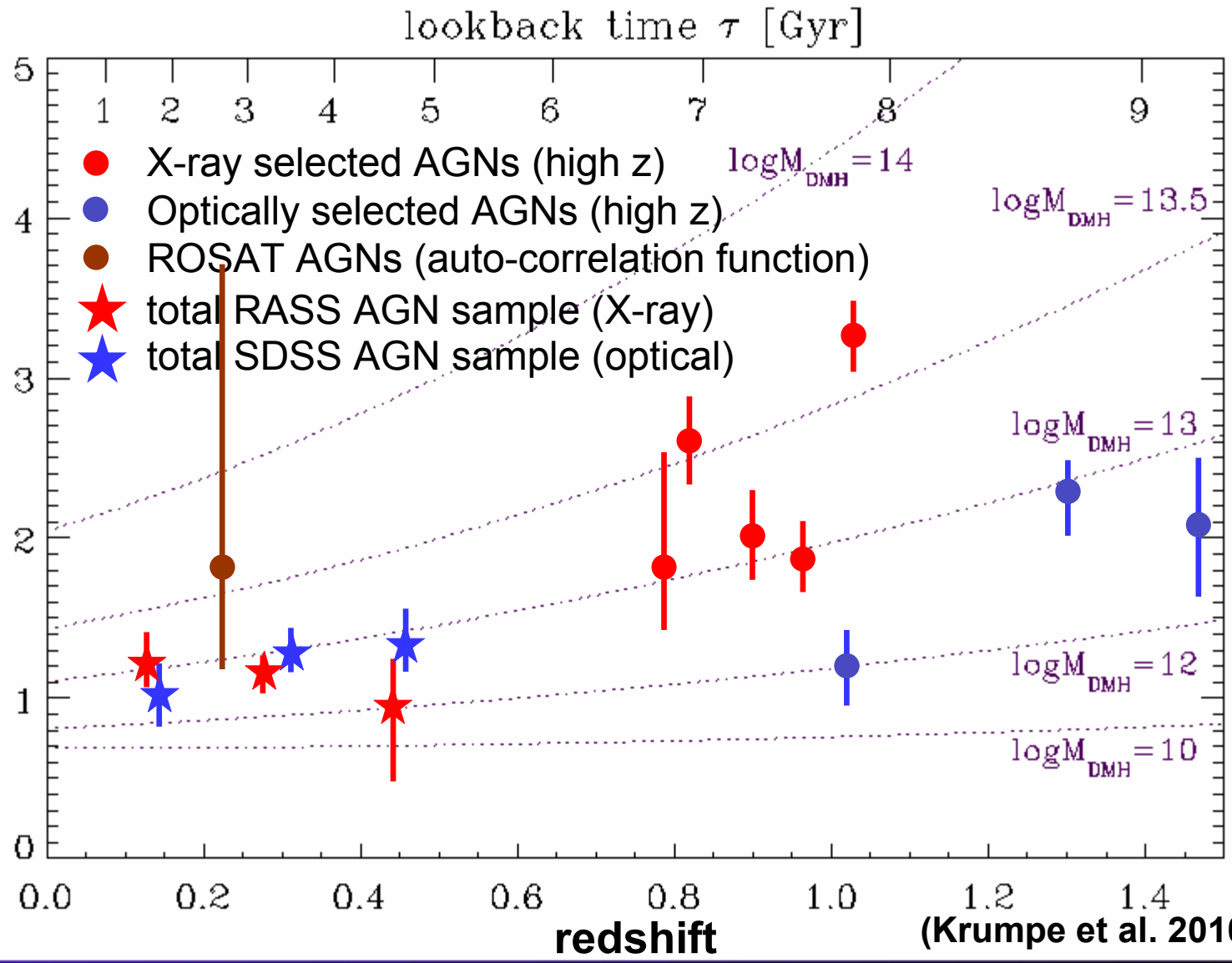


BL-AGN/galaxy bias parameter vs. redshift



(Krumpe et al. 2010)

AGN bias parameter vs. redshift



(Krumpe et al. 2010, 2012)

Halo Occupation Distribution modeling of ROSAT broad-line AGNs

HOD modeling of ROSAT BL-AGNs: Why?

instead of typical dark matter halo mass:

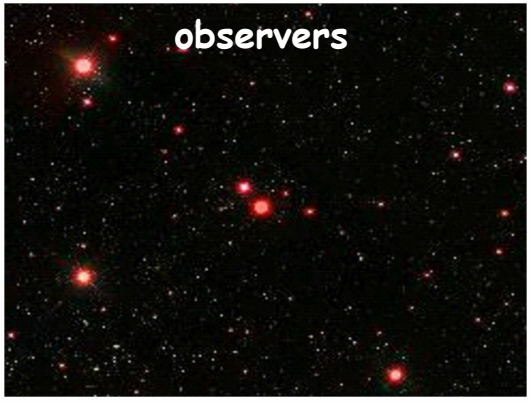
⇨ **full distribution of AGNs as a function of DMH mass**

⇨ currently popular way to model galaxy correlation functions

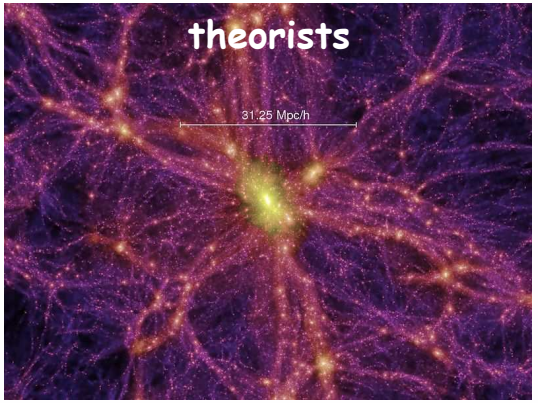
• observers see the universe as galaxies, AGNs, clusters etc..

• theorists see the universe as a bunch of DMH

⇨ HOD gives recipe how to populate DMHs with observable objects



SDSS



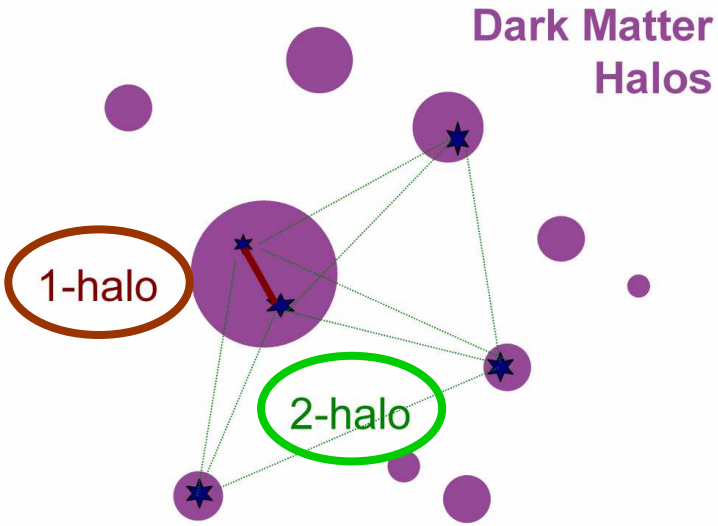
Millennium simulation, Murray

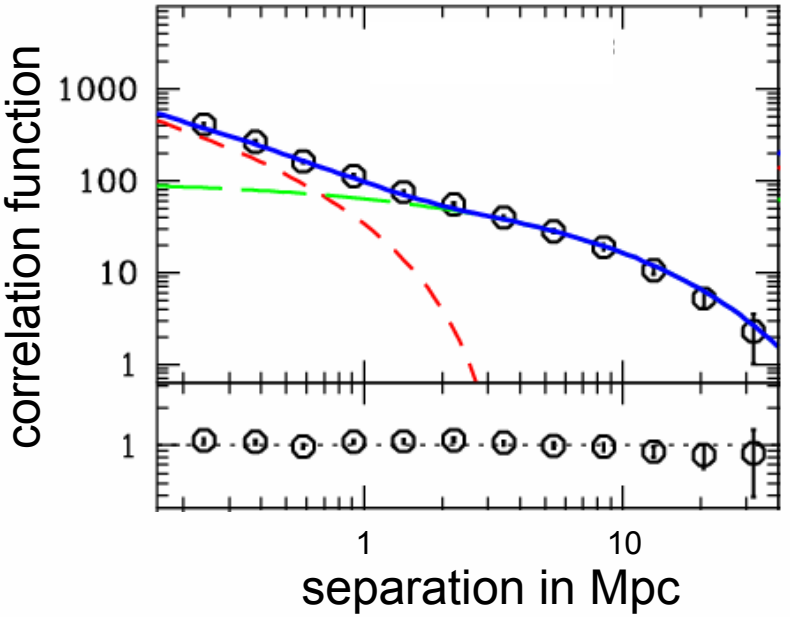
• determine number of central and satellite AGNs

HOD modeling of ROSAT BL-AGNs: How?

⇨ model the correlation function as the sum of the contributions from pairs:

- within the same DMH
- from different DMHs





$$\xi_{CCF} = \xi_{CCF,1h} + \xi_{CCF,2h}$$

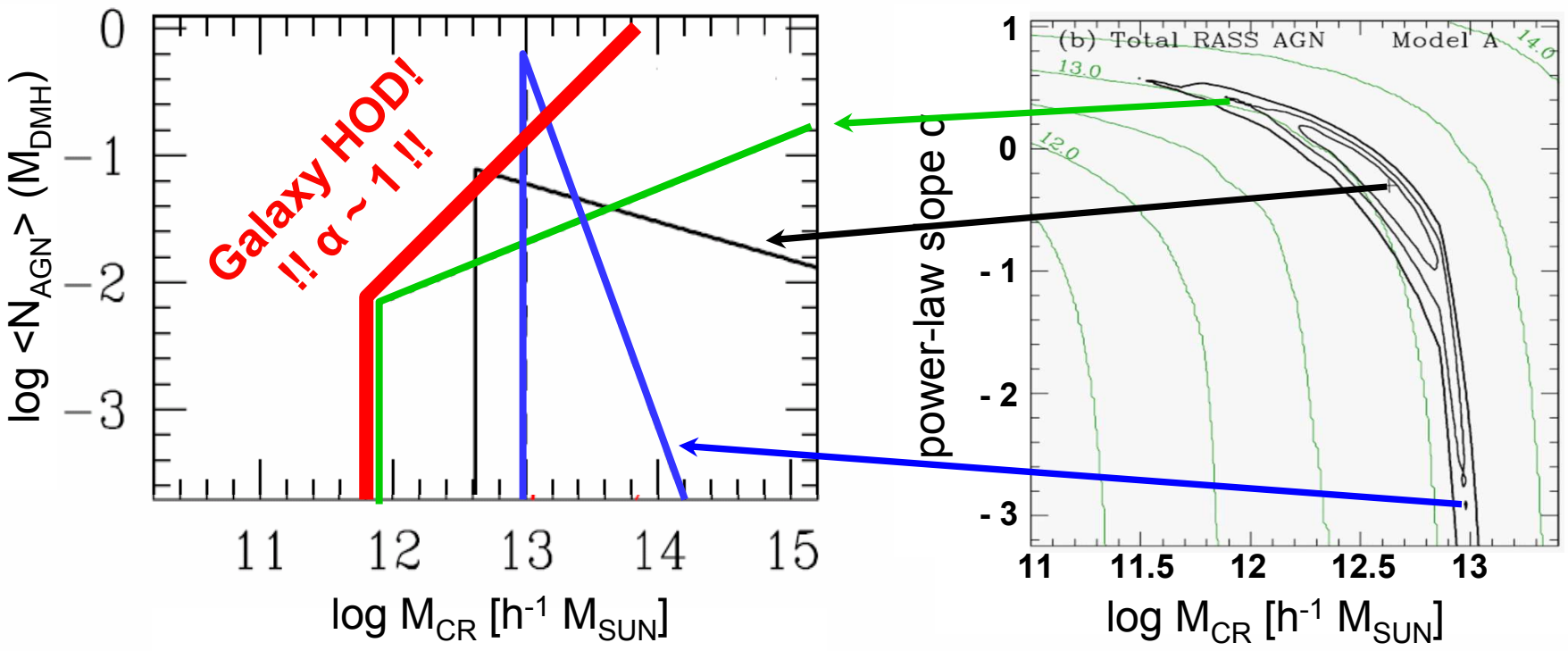
(Miyaji, Krumpe, et al. 2011)

HOD modeling of ROSAT BL-AGNs

(Miyaji, Krumpe, et al. 2011)

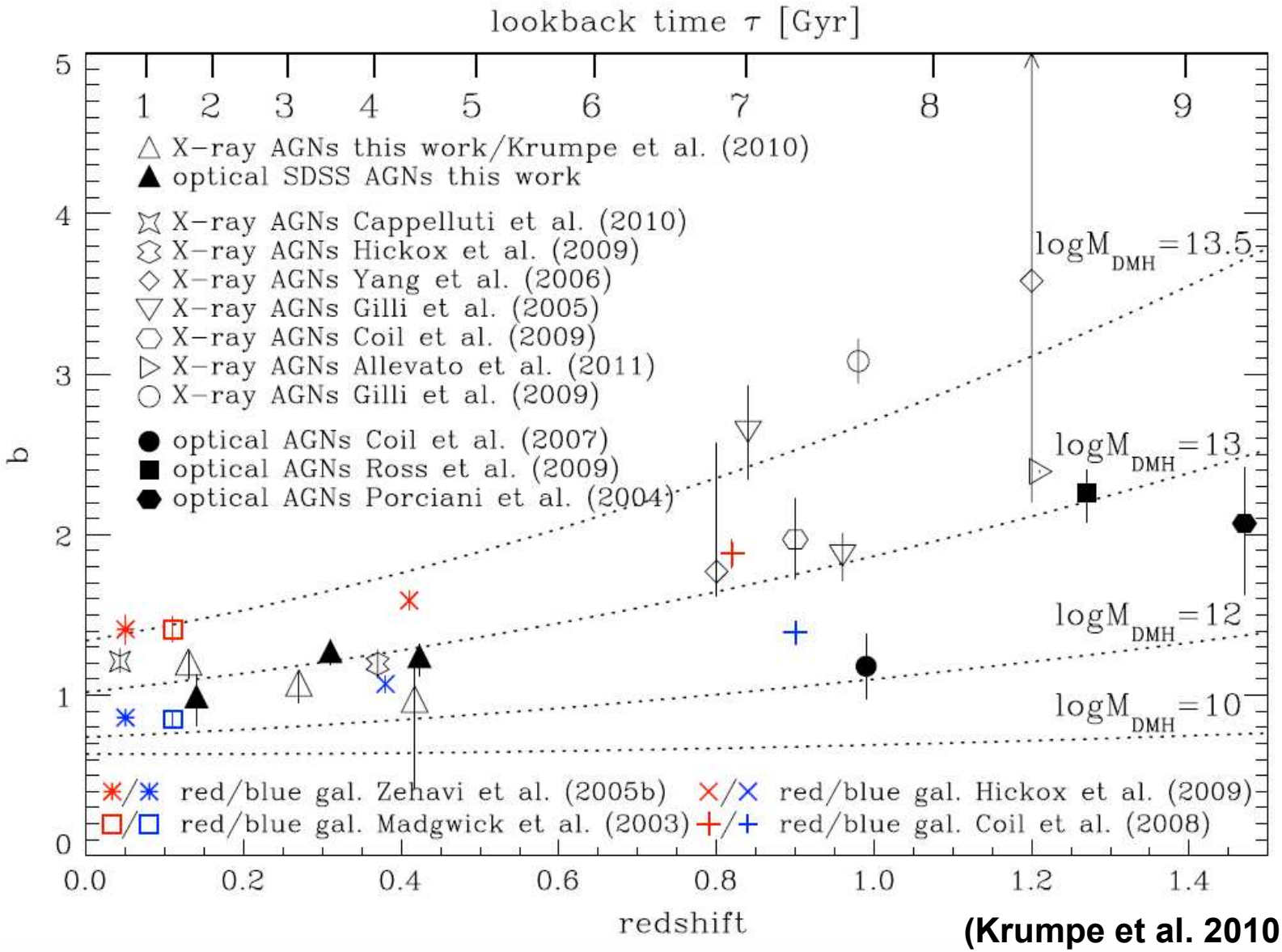
simple truncated power-law form, 2 parameters:

- critical DMH mass (M_{CR}) above which it can host an AGN
- power-law slope α (increase of N_{AGN} with DMH mass)



models preferred where the AGN/galaxy fraction among satellites decreases with DMH mass beyond $M_{DMH} > 10^{12}\ h^{-1}\ M_{SUN}$

Current picture of AGN clustering



(Krumpe et al. 2010, 2012)

Current picture of AGN clustering

low redshift (z<0.5)

- broad-line and narrow-line cluster like ≥L* galaxies or a small galaxy group of ~L*; AGN/galaxy fraction decreases with M_{DHM}
- no statistically convincing difference in the clustering of X-ray and optically selected broad-line AGNs
- weak luminosity dependence of the clustering for broad-line AGNs (high L_X AGNs ⇨ cluster higher ⇨ similar to red galaxies)

---

high redshift

- X-ray selected AGNs appear to cluster more strongly than optically selected AGNs ⇨ real?
  ⇨ why: different populations, different luminosities?
- mergers do not account for the majority of moderate L_X AGNs

Conclusions

• large-scale clustering measures the distribution of matter in the universe
(commonly measured with the 2 point correlation function)

• AGN clustering measurements extend to higher redshifts than galaxies and test an important phase in galaxy evolution

• Cross-correlation measurements are a very powerful tool to determine AGN clustering at low redshifts (if tracer set)

⇨ very high precision, very low systematics

⇨ complete picture of AGN clustering at low & high redshifts is emerging

Conclusions

• together with HOD modeling

⇨ new insights into AGN physics, AGN/galaxy co-evolution, and cosmology

⇨ constrain: host dark matter halo mass distribution, host galaxy type, fueling mechanism, AGN lifetime, central vs. satellite fraction

(Krumpe et al. 2010; Miyaji, Krumpe, et al. 2011; Krumpe et al. 2012)

---

recent review on clustering of X-ray selected AGNs

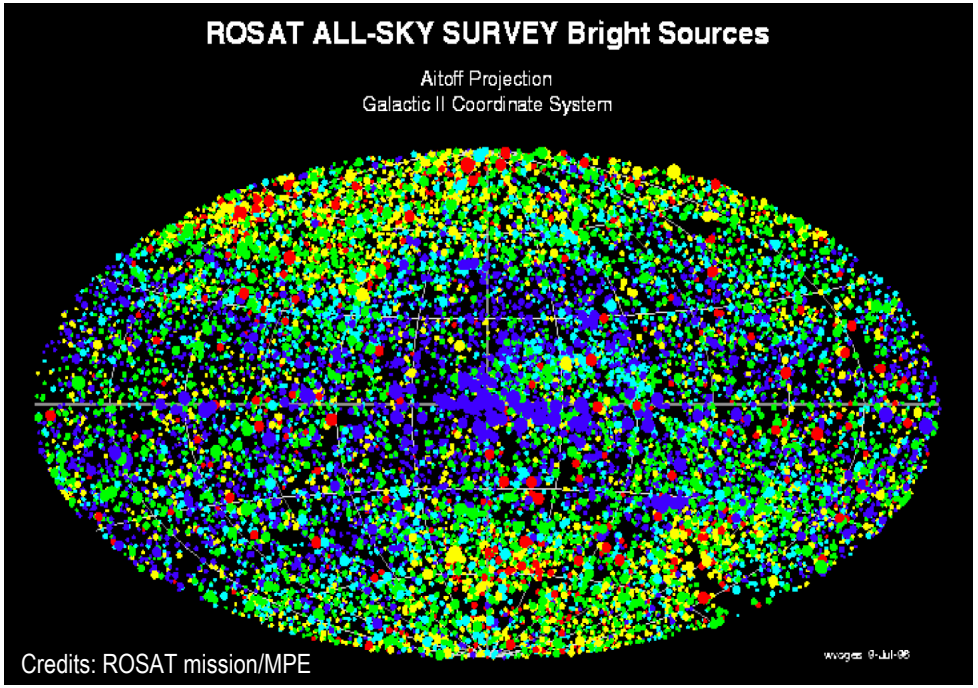
⇨ Cappelluti et al. 2012, arXiv:1201.3920

"AGN Clustering in the X-ray Band"

Future

eROSITA

- X-ray regime is one of the most efficient wavelength ranges to select AGNs



launch date:
end 2013

eROSITA is expected to detect ~ 3 million AGNs and will boost the research field of AGN clustering measurements