Understanding AGN evolution with large X-ray surveys:

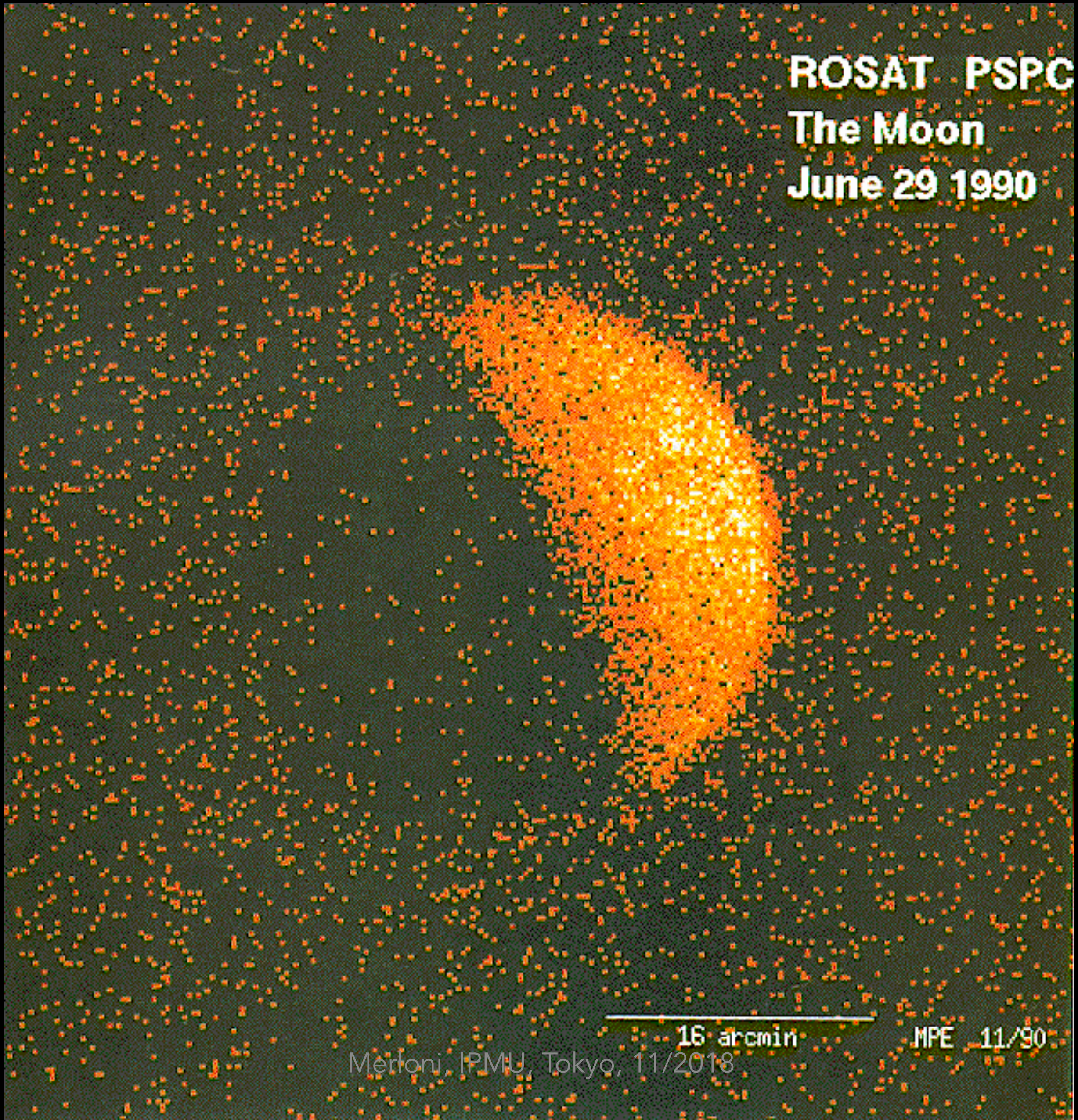
current constraints and prospects for eROSITA

Andrea Merloni (MPE)

Outline

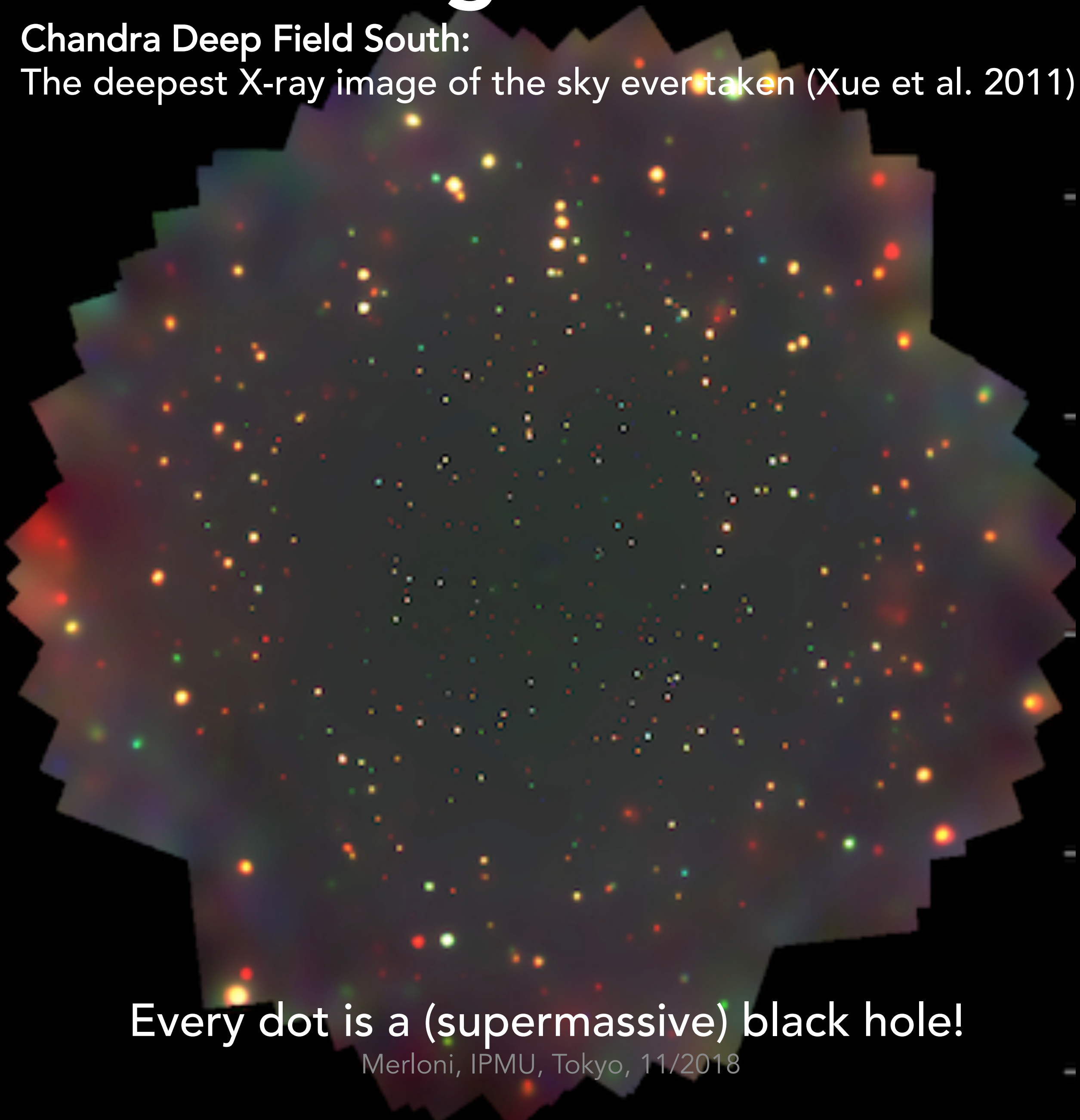
- Active Galactic Nuclei and the history of accretion
- AGN vs. galaxies: feedback and accretion modes
- The future: eROSITA and its all-sky survey

Accreting black holes



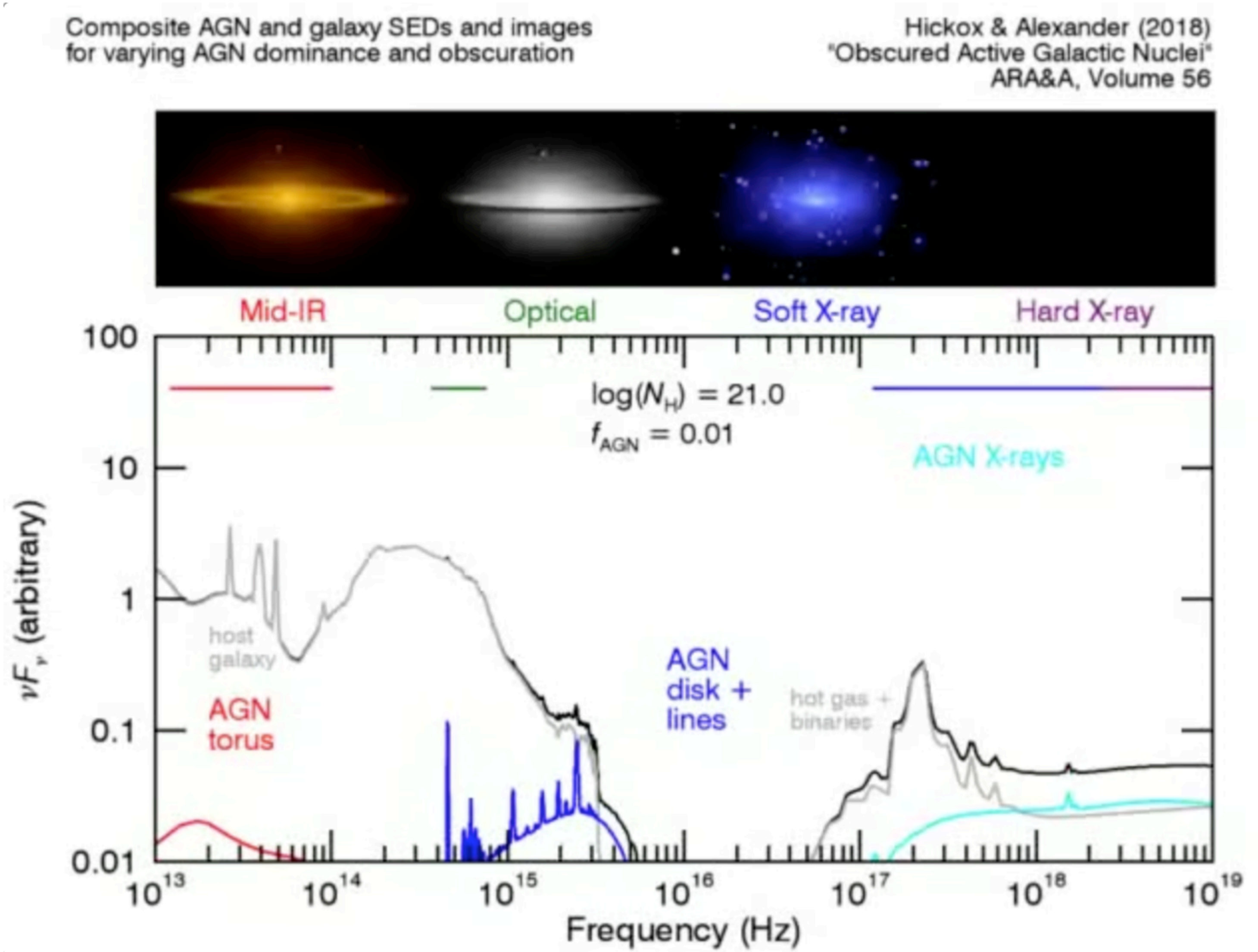
Accreting black holes

Chandra Deep Field South:
The deepest X-ray image of the sky ever taken (Xue et al. 2011)



Every dot is a (supermassive) black hole!

BH census, matter of contamination



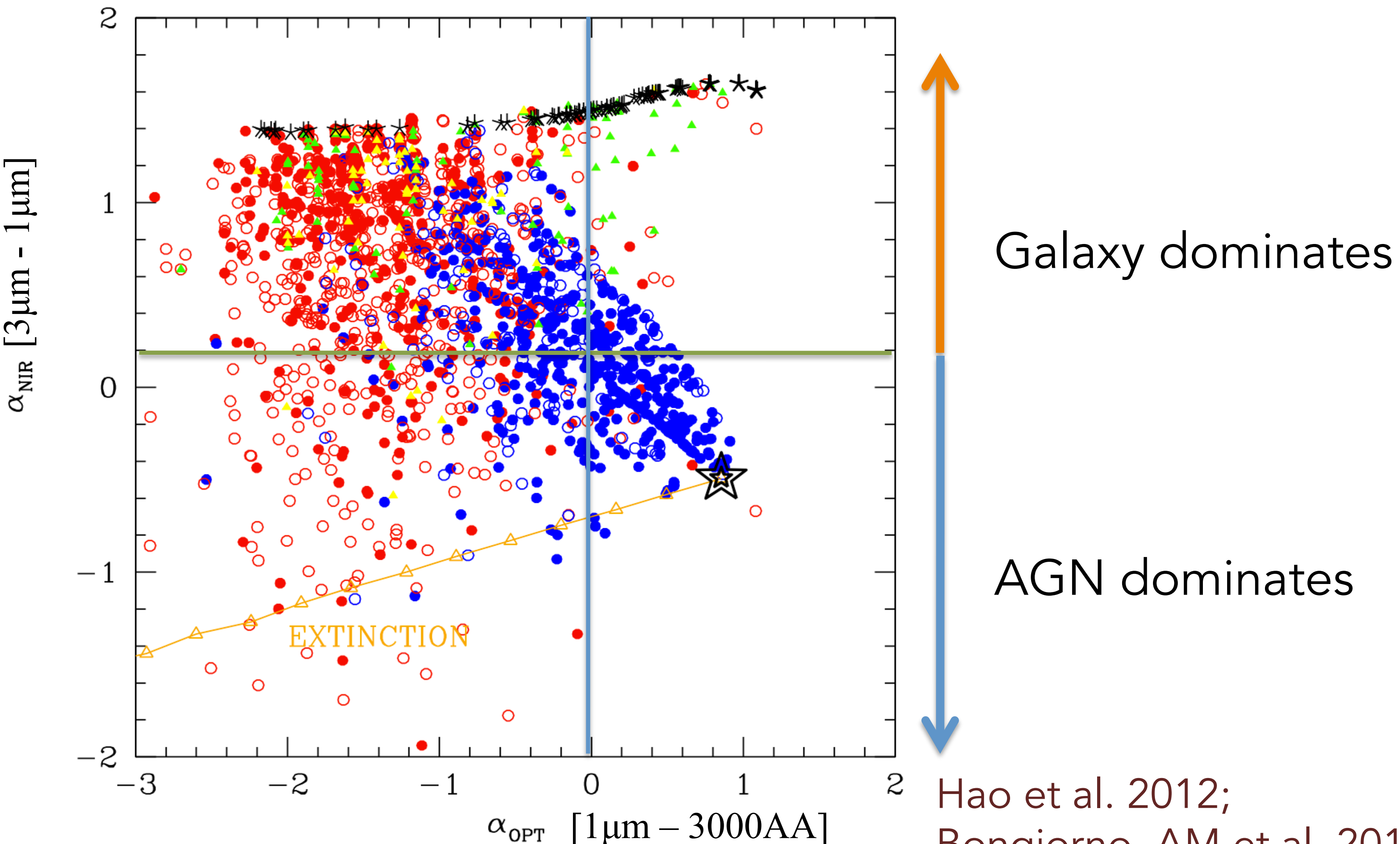
Hickox & Alexander (2018)

AGN selection basics: contrasts

	Critical Eddington rate [M*= $3*10^{10}$ M_{sun}]		"visible fraction
	z=0	z=1	
X-ray	≈ $2*10^{-5}$	≈ $2*10^{-4}$	~ 80%
Radio (η_j=ε)	≈ $3*10^{-5}$	≈ $2*10^{-4}$	ALL? 10%?
MIR	≈ 0.015	≈ 0.13	ALL
Opt/UV	≈ 0.025	≈ 0.2	<50%

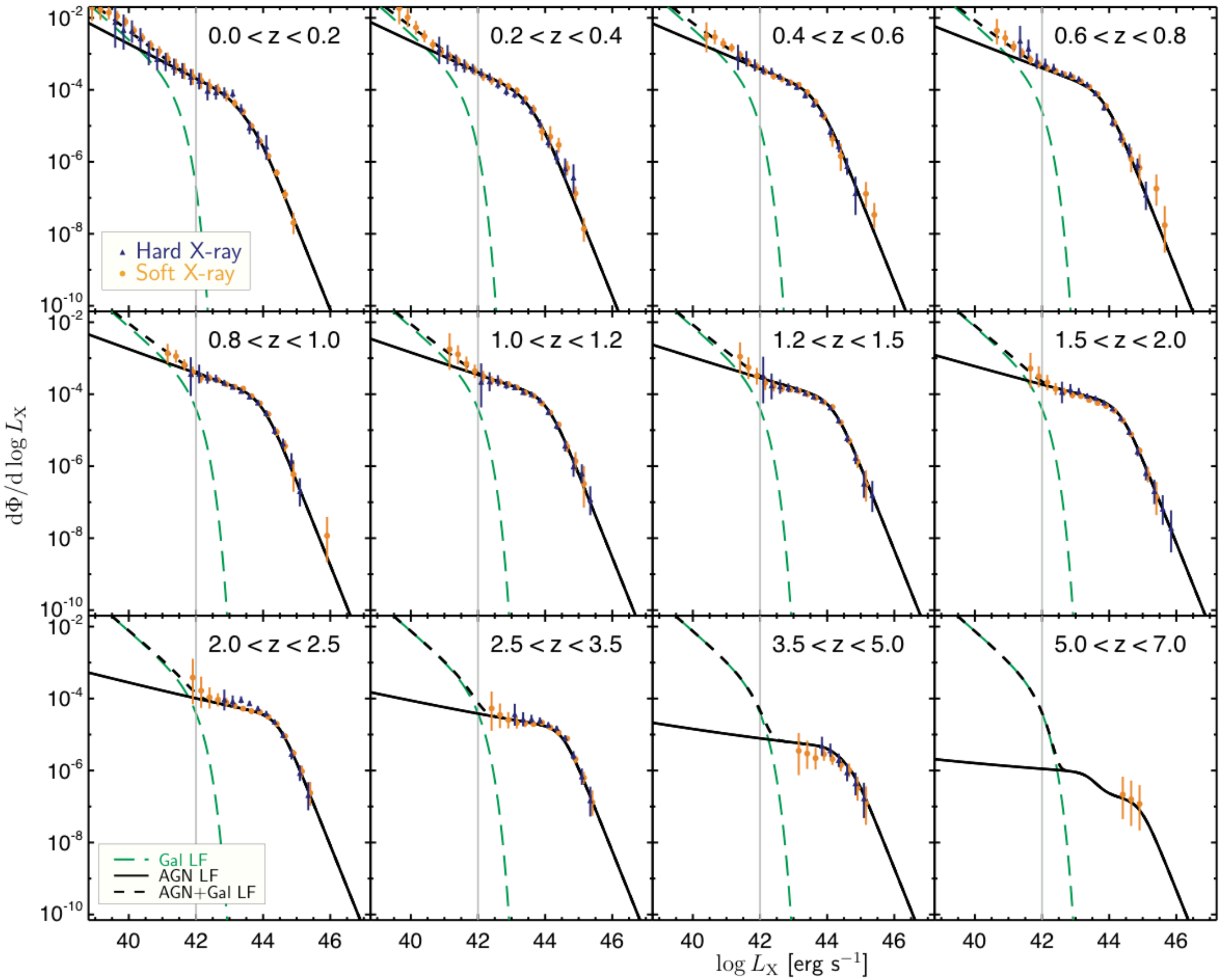
Eddington Rate = Ratio of AGN bolometric to Eddington luminosities
Approx. Scales with ratio of AGN light to galaxy stellar mass

Optical/NIR mixing diagram



Hao et al. 2012;
Bongiorno, AM et al. 2012

X-ray luminosity function

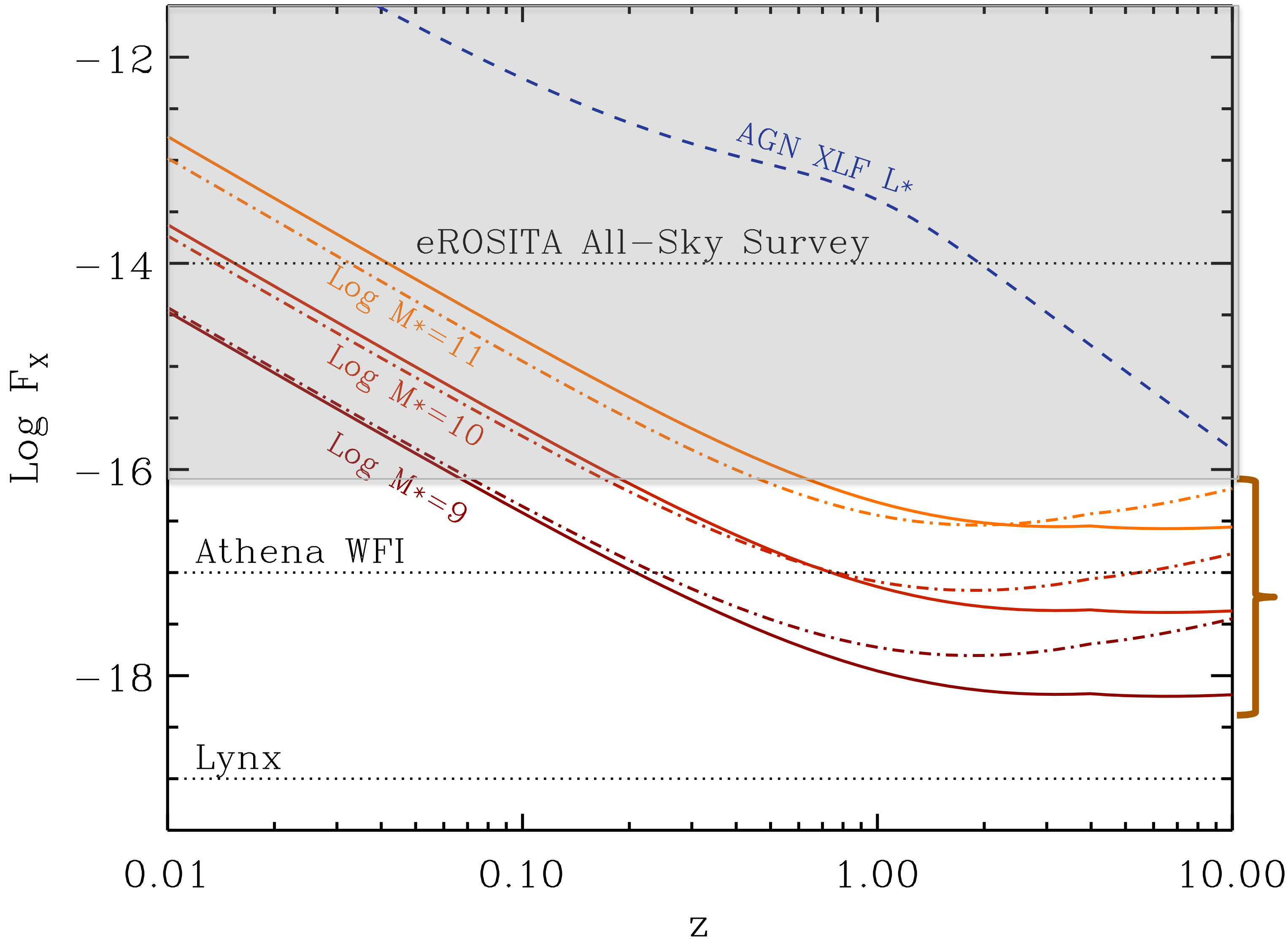


- Explore a wide range in Luminosity AND redshift
- Understand **selection function and absorbing column distribution**
- Combine different surveys

Aird et al. 2015

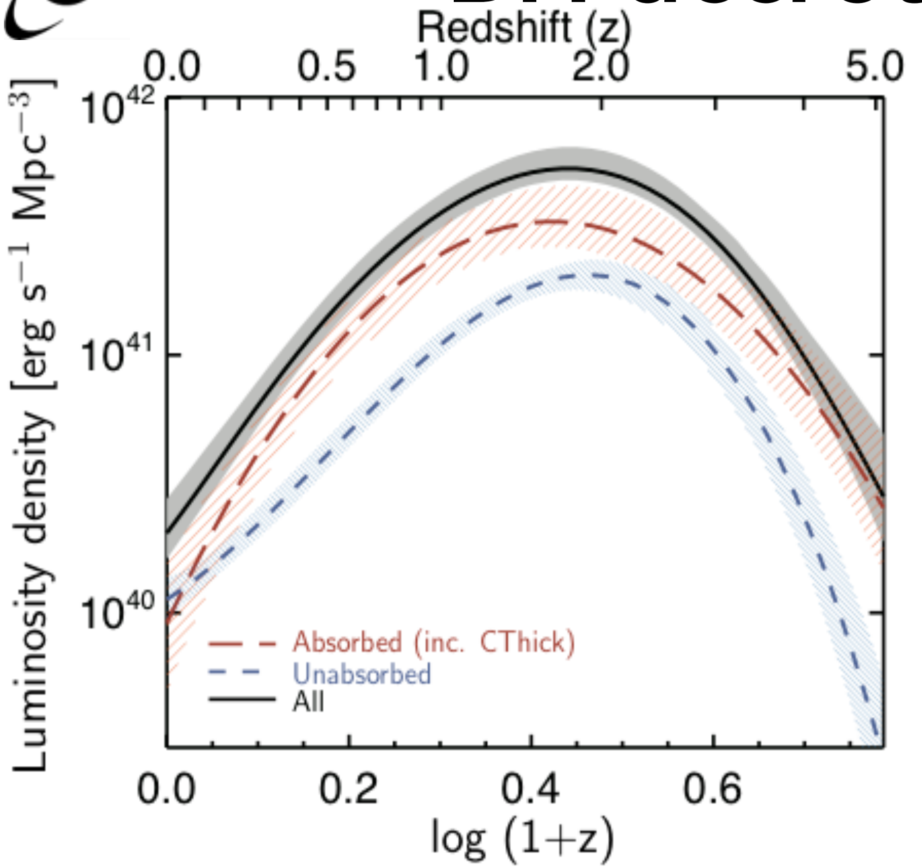
See also Ueda et al. 2014; Buchner et al. 2015; Myiaji et al. 2015

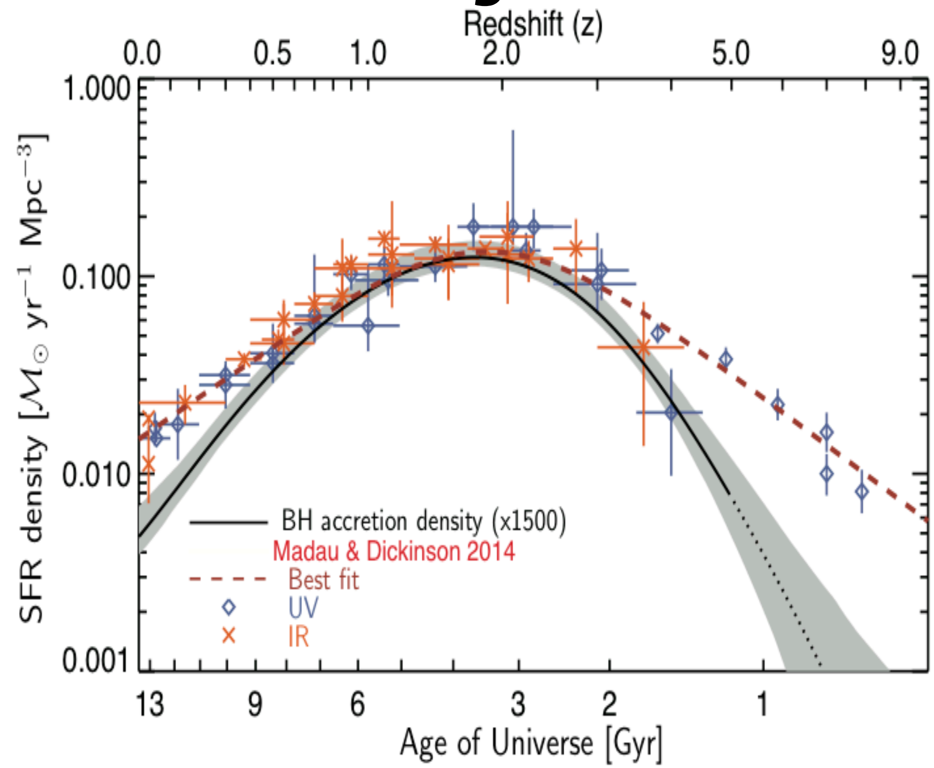
Looking ahead: X-rays for galaxy evolution



Expected flux of Star-forming galaxies on the "main sequence". Aird+ 2016

BH accretion history





Most SMBH growth in radiatively **efficient** flows (Soltan argument) and behind a veil of obscuration

SMBH growth broadly traces evolution of Star Formation Rate in galaxies

Aird et al 2015; Ueda+ 2003; Marconi+ 2004; Merloni & Heinz 2008; Ueda+ 2014; Delvecchio+ 2014; Buchner+ 2015; Myiaji+ 2015, Merloni 2016, etc.

Integral constraint: the Soltan argument

Soltan (1982) first proposed that the mass in black holes today is simply related to the AGN population integrated over luminosity and redshift

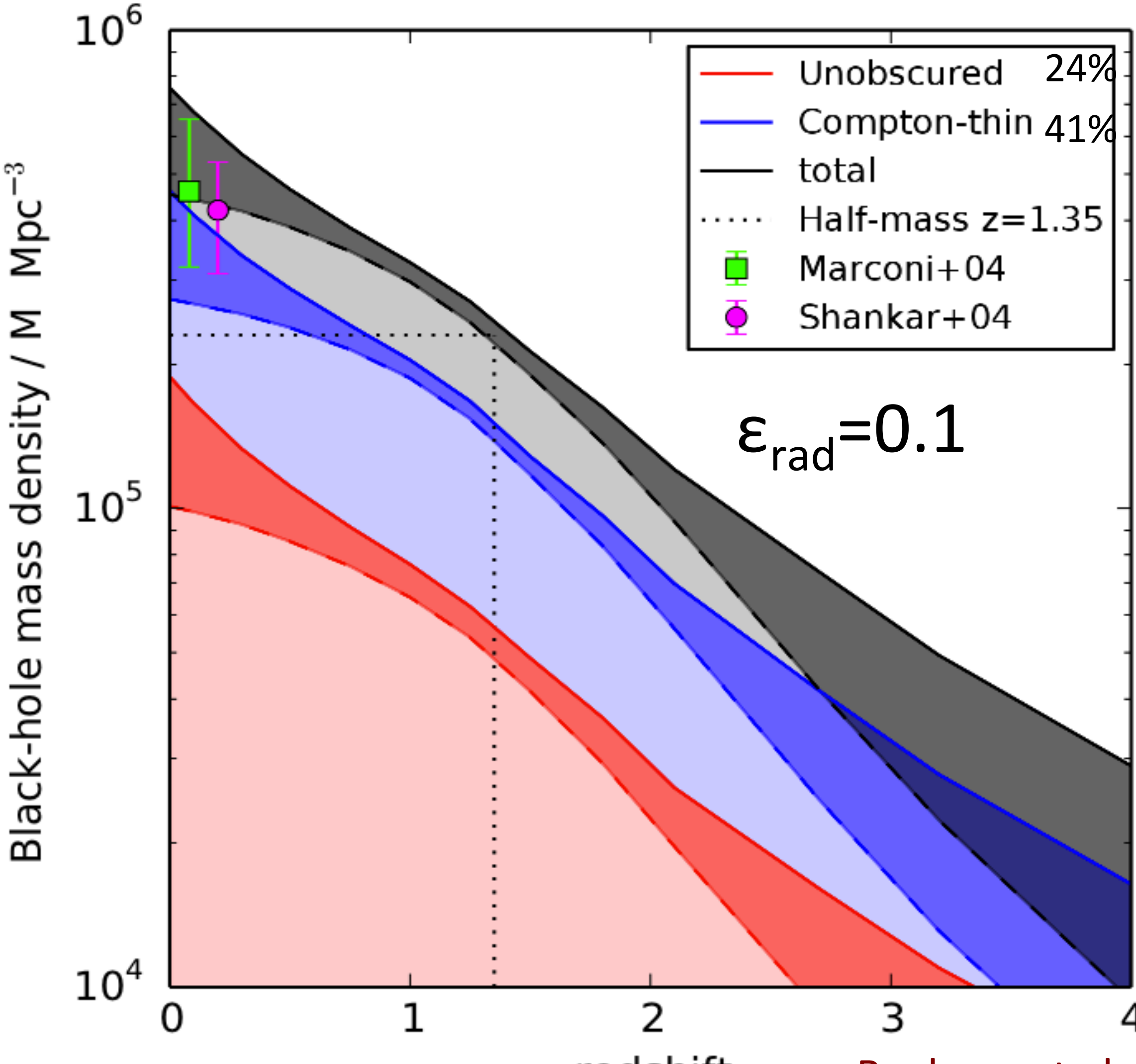
$$L_{\rm bol} = \epsilon_{\rm rad} \dot{M} c^2$$

$$\mathrm{BHAR}(z) \equiv \Psi_{\rm BH} = \int_0^\infty \frac{(1-\epsilon_{\rm rad}) L_{\rm bol}}{\epsilon_{\rm rad} c^2} \phi(L_{\rm bol}, z) dL_{\rm bol}$$

$$\frac{\rho_{\rm BH}(z)}{\rho_{\rm BH,0}} = 1 - \int_0^z \frac{\Psi_{\rm BH}(z')}{\rho_{\rm BH,0}} \frac{dt}{dz'} dz'$$

Fabian and Iwasawa (1999) ε~0.1; Elvis, Risaliti and Zamorani (2002) ε >0.15; Yu and Tremaine (2002) ε>0.1; Marconi et al. (2004) 0.16> ε >0.04; Merloni, Rudnick, Di Matteo (2004) 0.12> ε >0.04; Shankar et al. (2007) ε ~0.07

Most (~3/4) of SMBH growth is "obscured"



Buchner et al. 2015; Merloni 2015

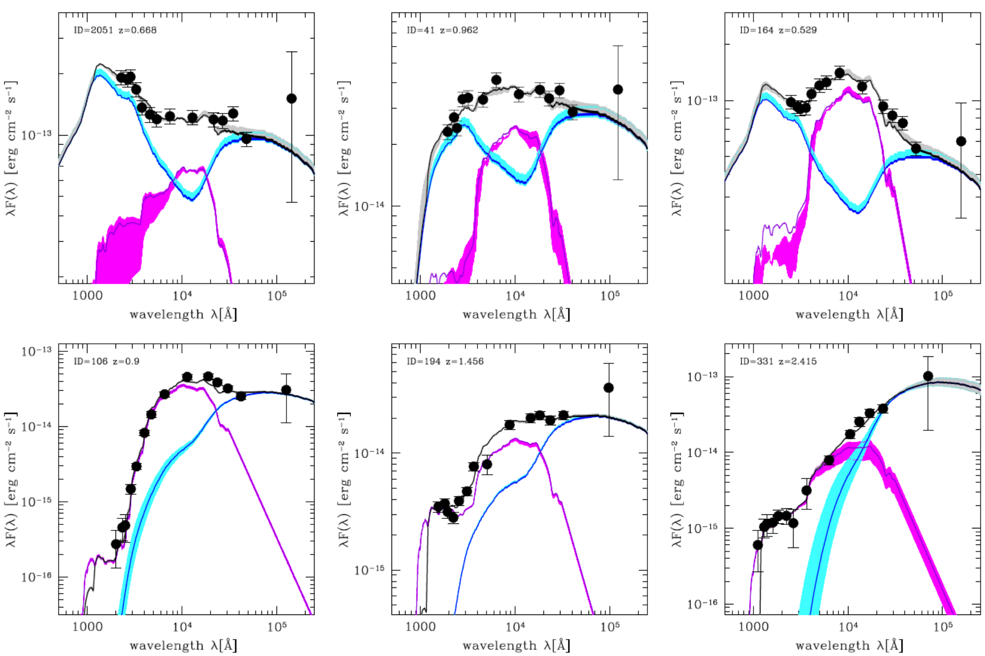
Relationship with host galaxies?

- Statistically robust assessment of AGN demographics:
  - Which galaxies host (which) AGN?
  - AGN triggering: under which conditions do SMBH grow
    - Relationship between AGN and Star Formatio, morphology, mergers, LSS (clustering)
- Does AGN activity affect galaxies' properties (at the population level)
  - Location of AGN in color-magnitude plots, etc.
  - Smoking guns of AGN feedback?

Coil, Juneau, Trakhtenbrot, Hickox, Netzer, Duras, Goulding

XMM-COSMOS AGN

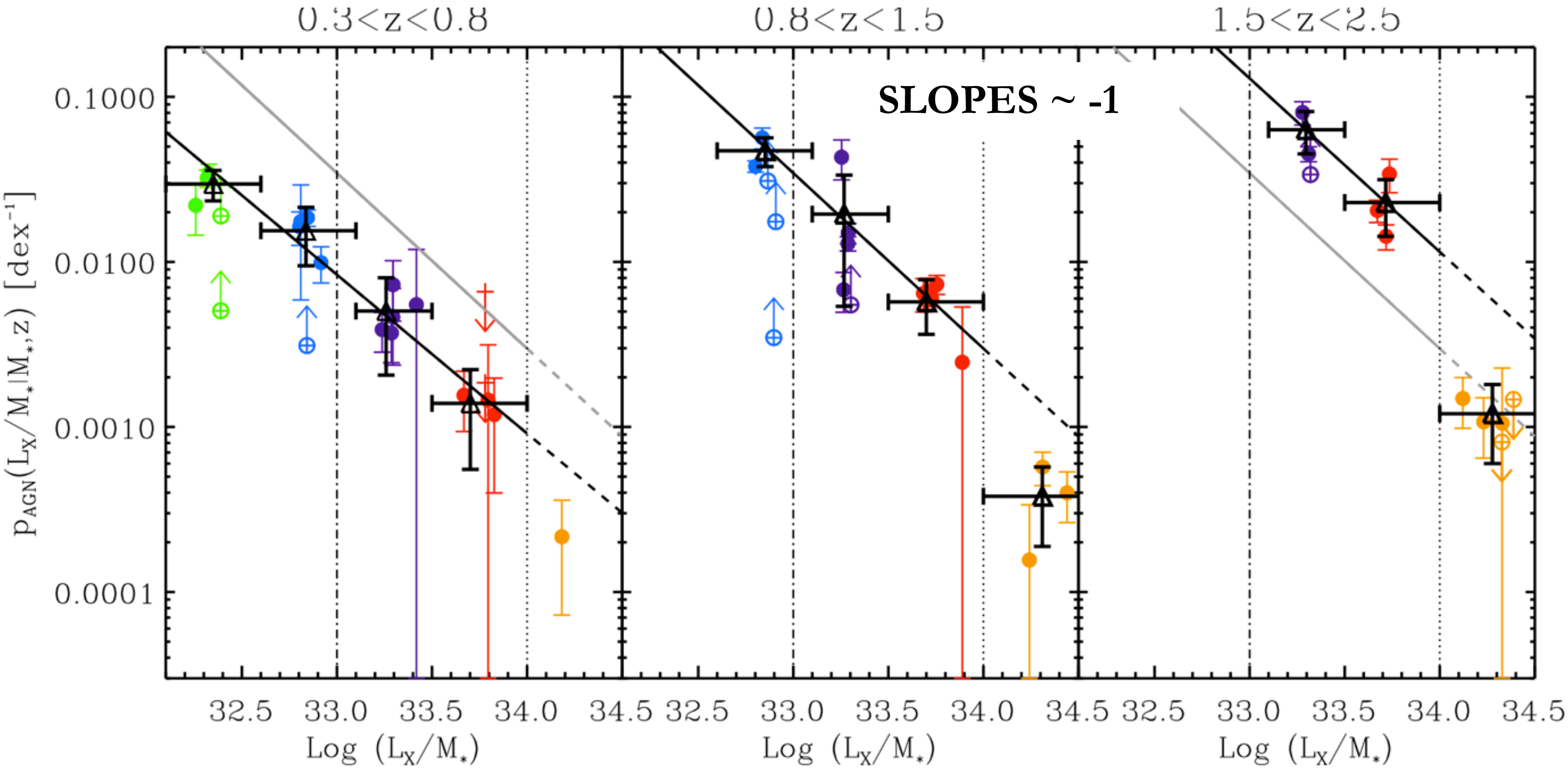
- 1555 X-ray selected AGN (XMM; f_{lim}~ **5×10^{-16}**[0.5-2]; **3×10^{-15}**[2-10])
- **100% redshift complete** (54% specz; 46% photoz)
- 602 Unobscured (71% specz); 953 Obscured (42% specz)
- **Parent sample** ~200k IRAC galaxies (photoz, M_*; Ilbert et al. 2010)



- Uniquely rich multi-wavelength photometry used to **decompose AGN and host galaxy light** in SED fitting

Bongiorno et al. 2012;
Brusa+ 2010; Salvato+ 2009; Lusso+ 2011, 2012; Merloni+ 2014

Specific accretion rate distributions

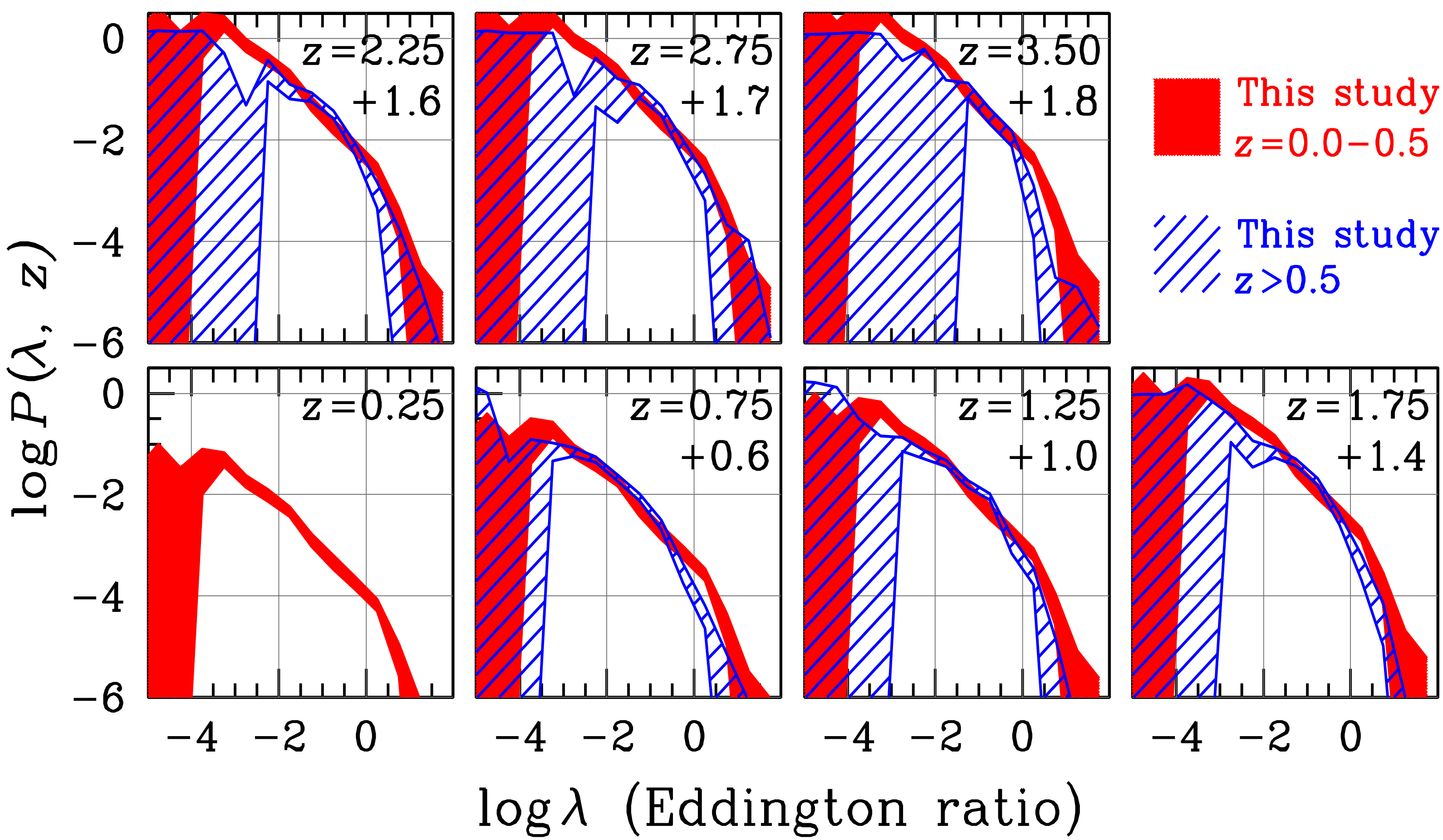


"Specific Accretion rate" (Aird et al. 2012)

Bongiorno et al. 2012

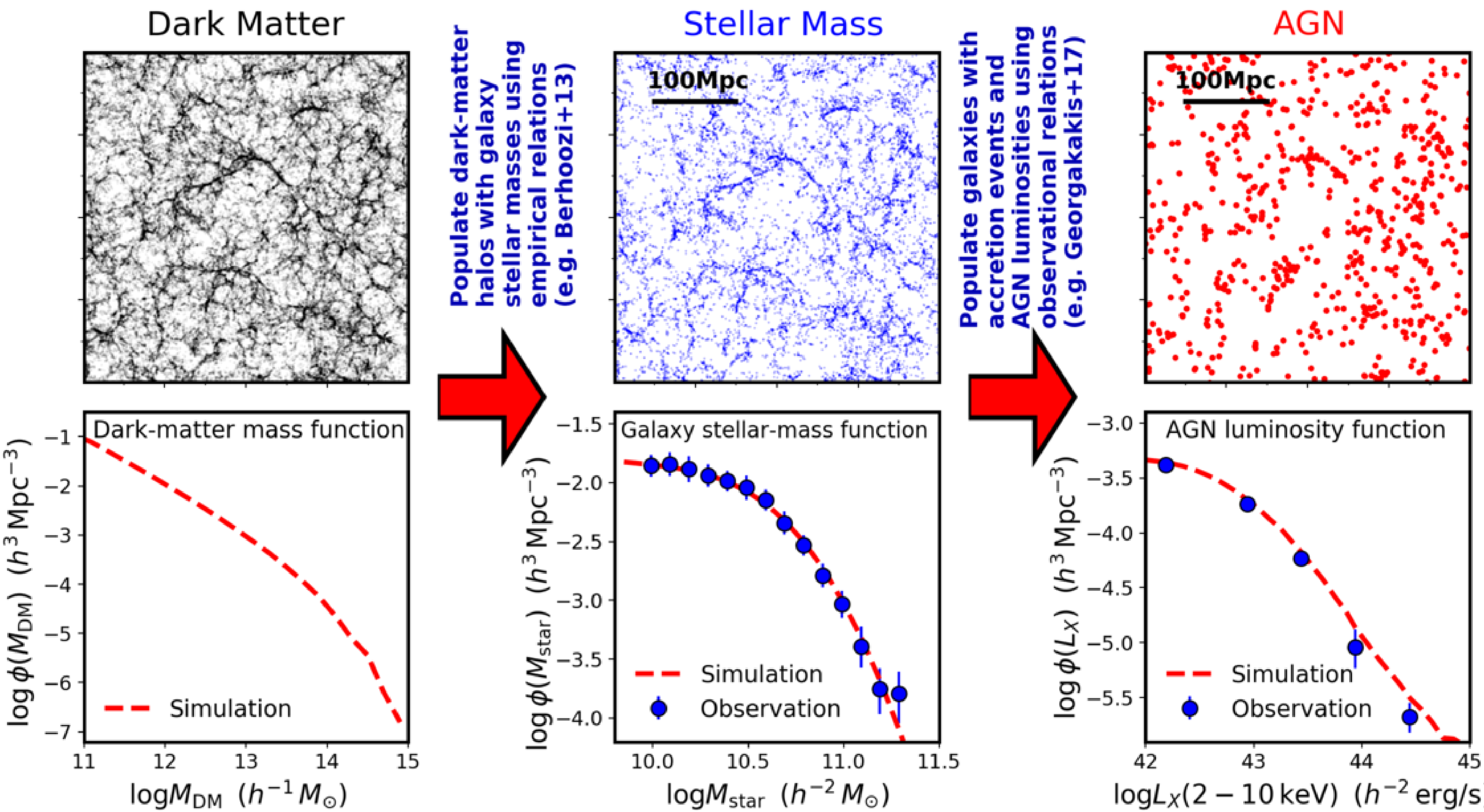
AGN fraction at fixed L_X/M_* ~independent on galaxy mass! Normalization increases as **$\sim(1+z)^4$** [cfr. sSFR density]. Break consistent with **~Eddington limit?**

Eddington rate functions



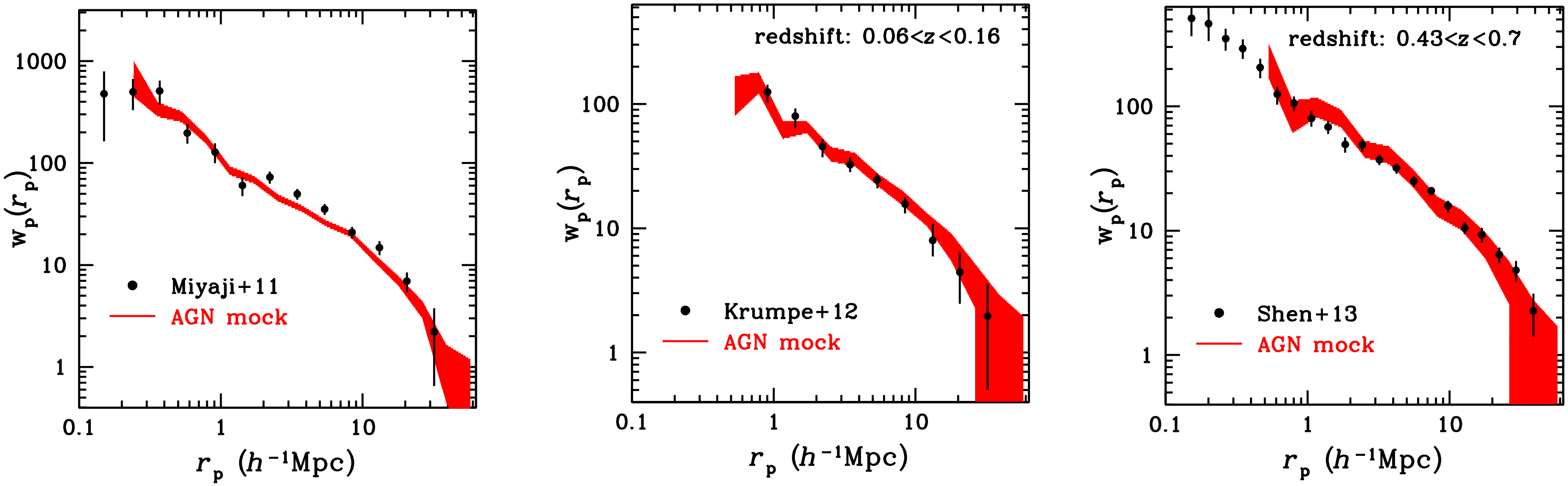
Georgakakis et al. 2017; Aird et al. 2017, see also Bongiorno et al. 2016

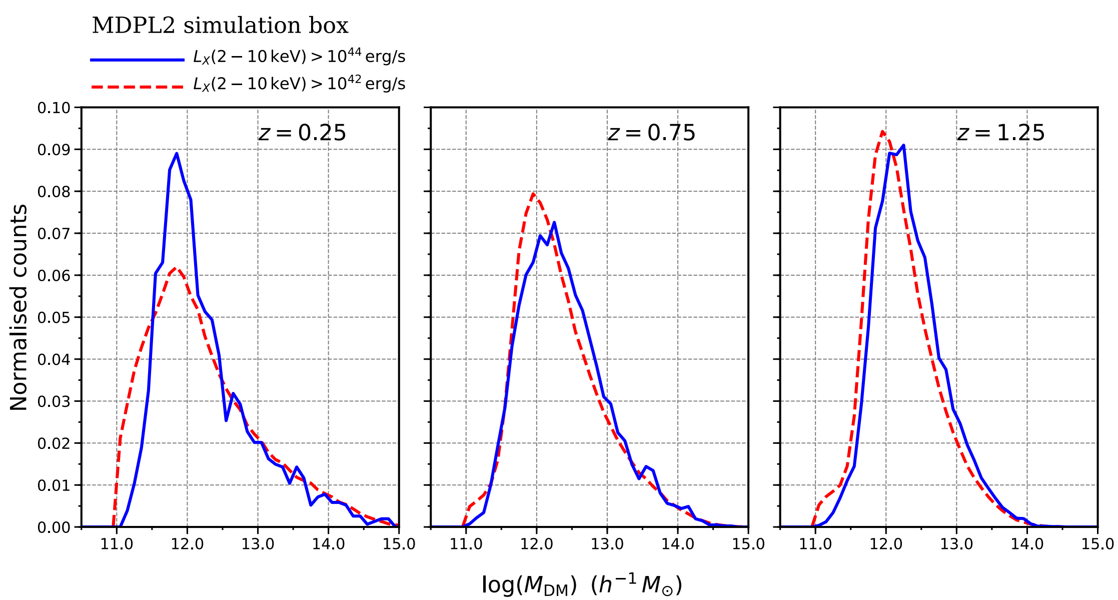
AGN mocks in LSS



Georgakakis et al. 2018, submitted

AGN mocks and LSS



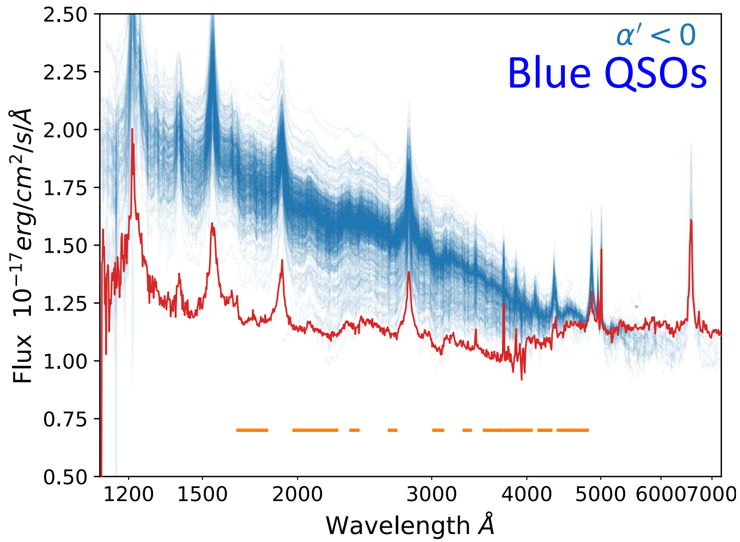


Georgakakis et al. 2018, submitted

High-power AGN and their relevance for feedback

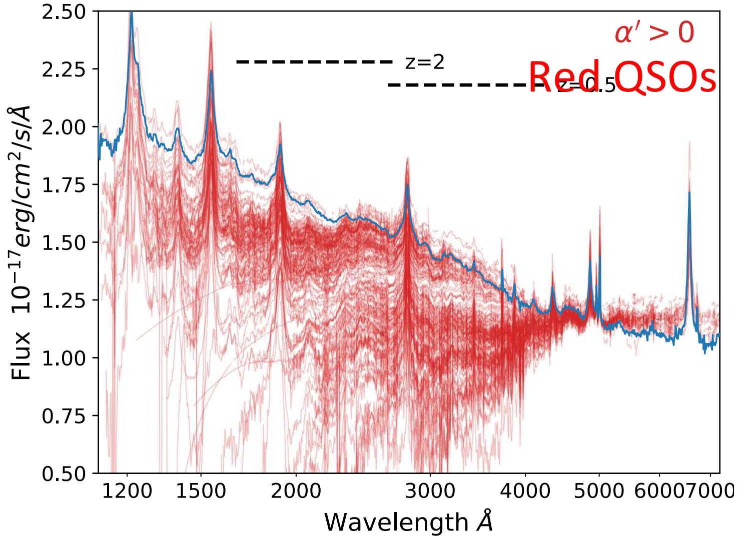
- Feedback from powerful QSOs ('radiative' mode) is needed to:
  - Maintain the observed close connection between the growth of SMBH and the growth of galaxies
  - Ensure a tight relation between black hole mass and galaxy mass/ velocity dispersion
  - Help establishing the color-bimodality of galaxies
- Massive outflows are expected/observed from luminous QSOs, and their effect on the Narrow Line Regions can be studied in detail
- Sample selection is critical to move from sporadic events to an assessment of the population
- Present here a study of X-ray selected AGN in XMM-XXL, with uniform optical (SDSS/BOSS) spectroscopic follow- up (~3000 SDSS/BOSS spectra of X-ray selected AGN in ~20 deg^2); [Menzel+'16,'19, Liu+'17]

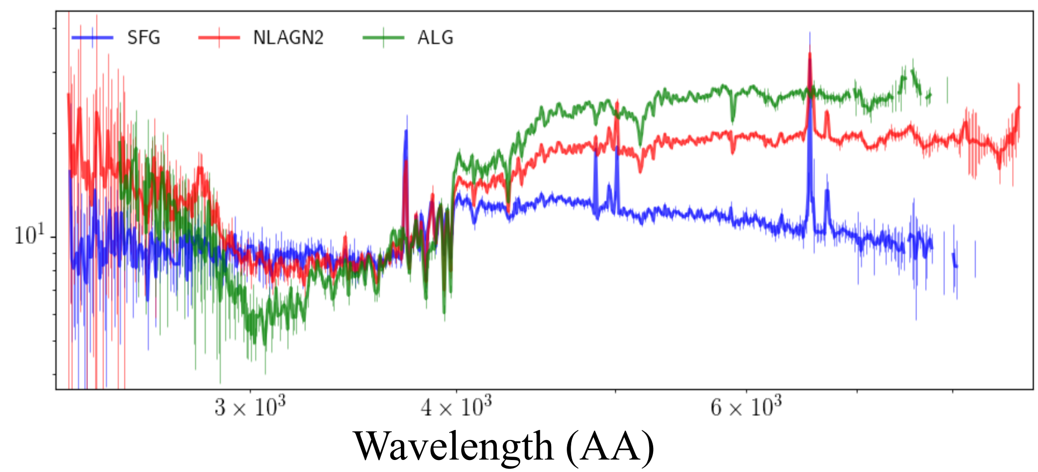
X-ray AGN: optical spectra



~1500 BLAGN (0<z<4)
~150 X-ray obscured BLAGN (0<z<3)
[Also split in Red and Blue QSOs]

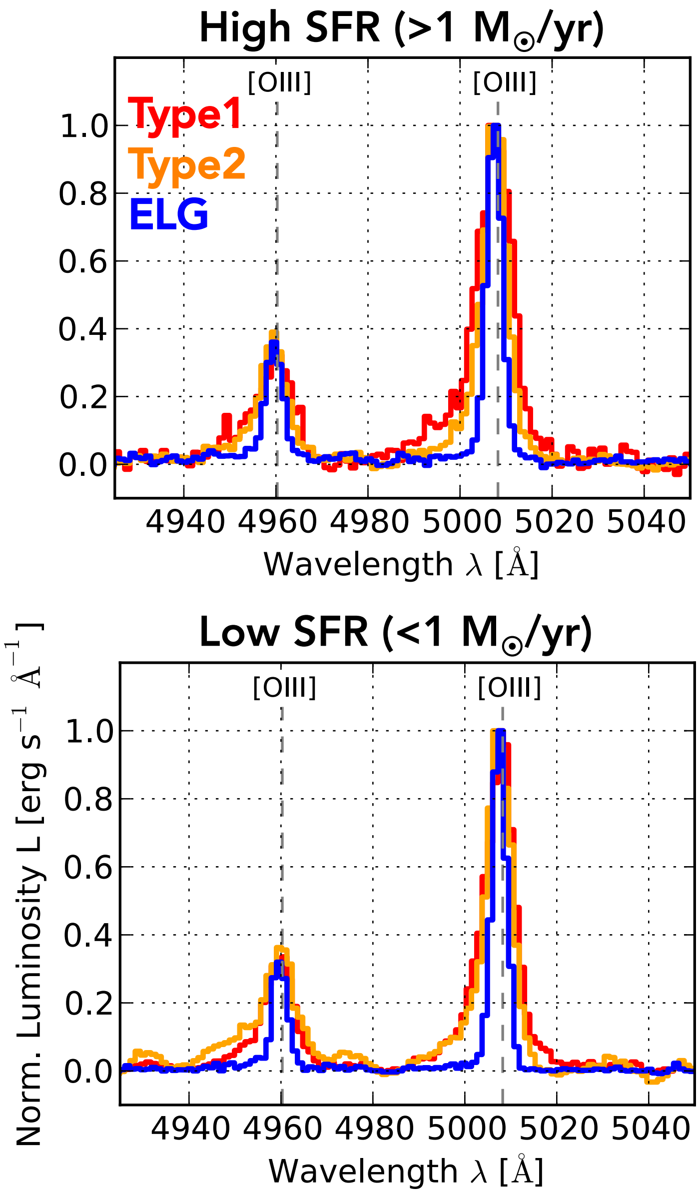
~550 NLAGN2 (0<z<1)
~80 'elusive' AGN in SFG (0<z<0.8)
~90 'elusive' AGN in ALG (0<z<0.8)





Menzel et al.m2016; Liu et al. 2018

NLR Kinematics: AGN impact



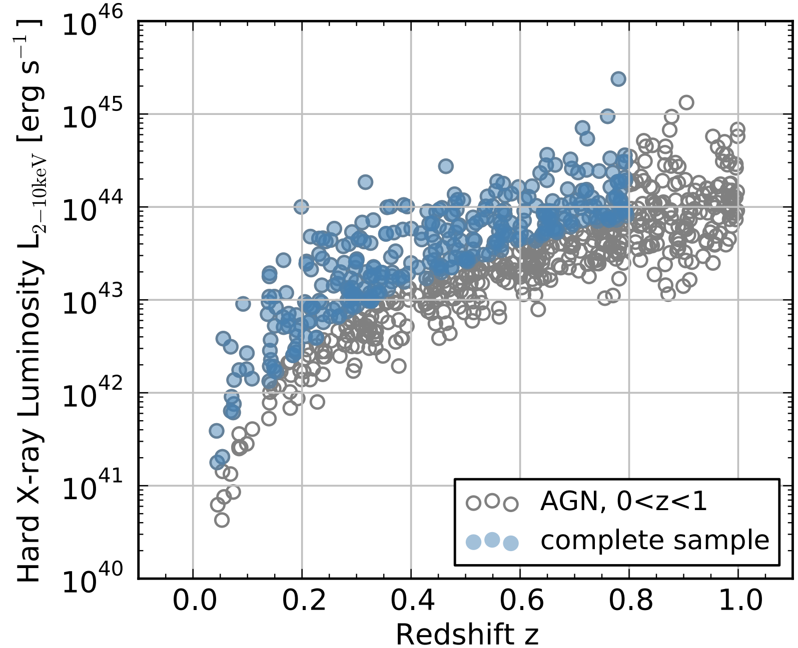
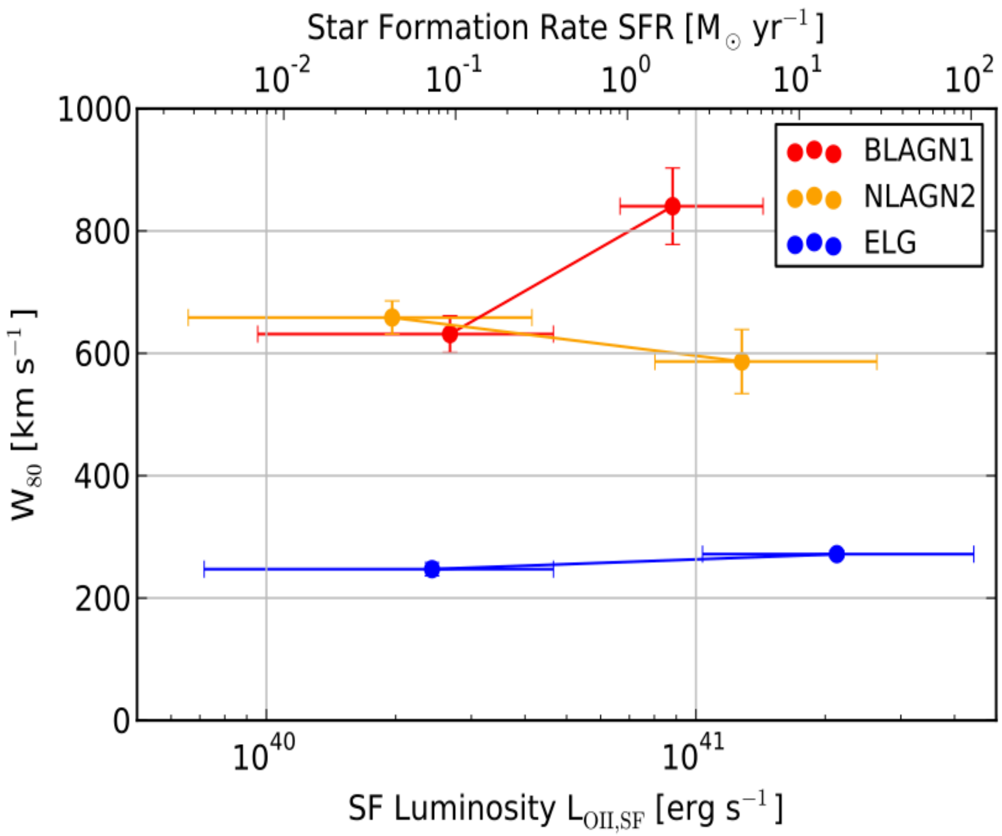


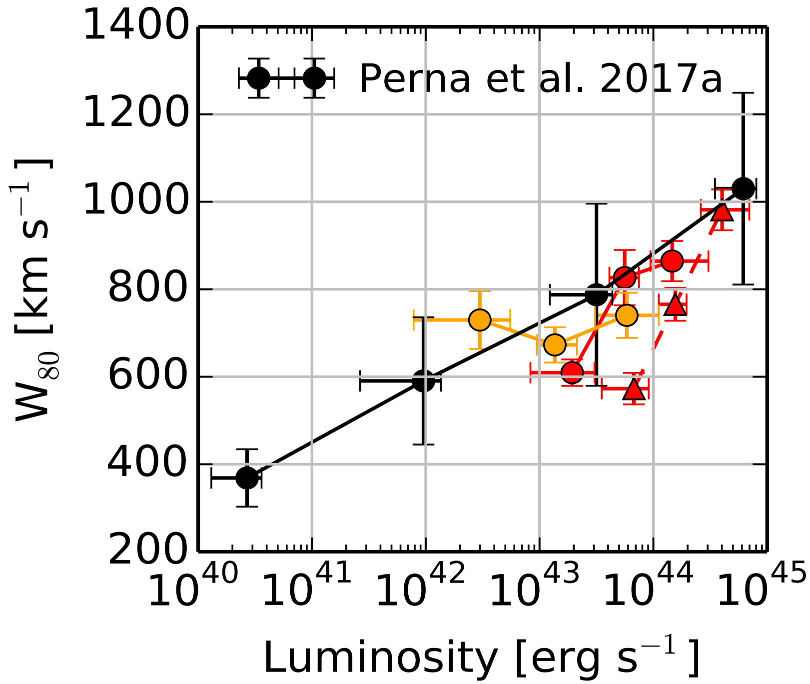
Table 4.2.: Fraction of ionized [OIII] outflows/inflows in BLAGN1 and NLAGN2.

	ELG [per cent]	0<z<1 BLAGN1 [per cent]	0<z<1 NLAGN2 [per cent]	complete sample BLAGN1 [per cent]	complete sample NLAGN2 [per cent]
$SN_{\rm med} > 1$	1.0 ± 0.3	24 ± 3	16 ± 2	41 ± 6	28 ± 5
$SN_{\rm med} > 3$	1.8 ± 0.1	30 ± 3	19 ± 3	43 ± 6	31 ± 5
$SN_{\rm med} > 10$	-	55 ± 9	29 ± 6	60 ± 11	40 ± 10

Menzel et al. 2018, submitt.; PhD thesis

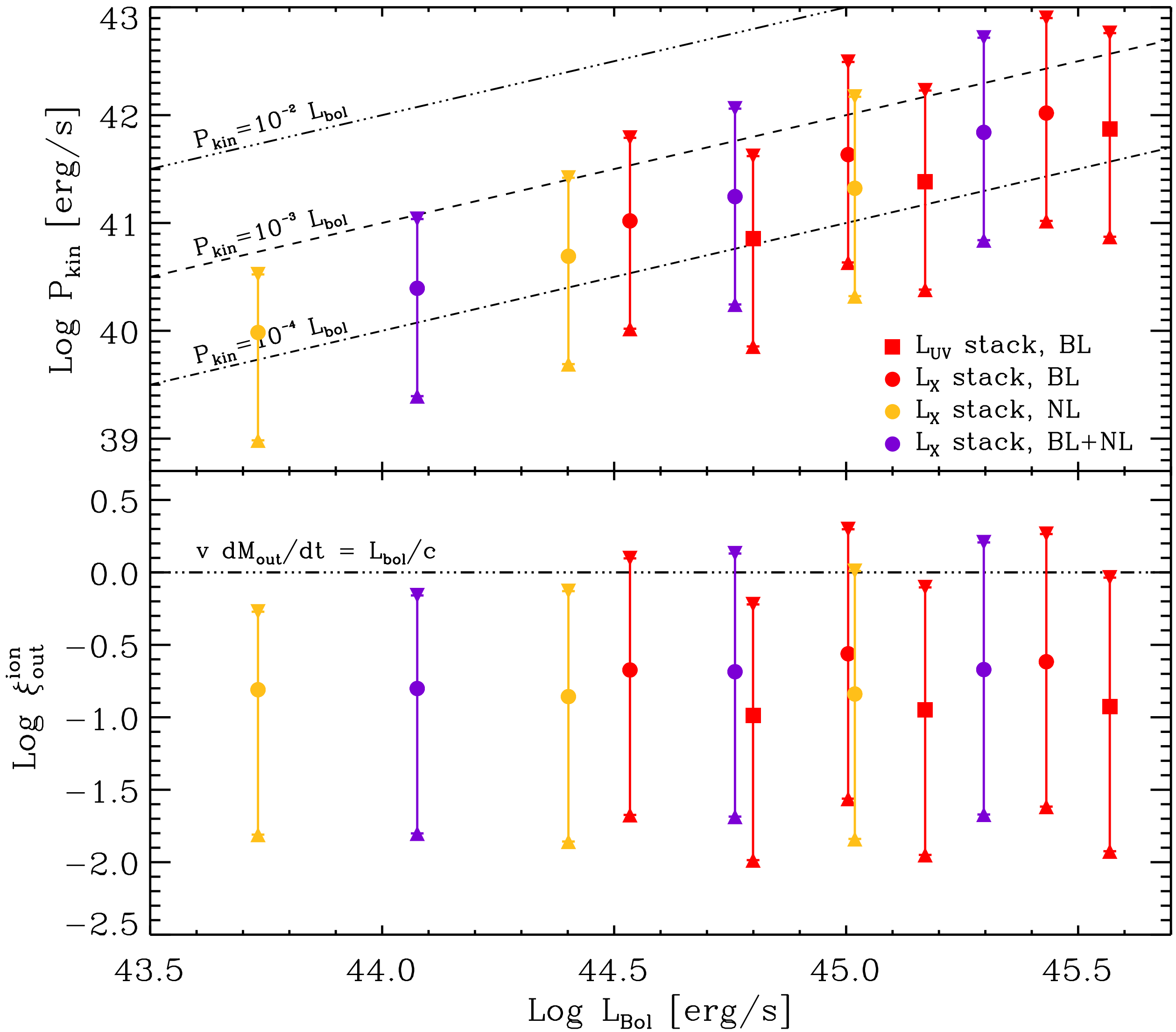
Ionized outflow are AGN driven





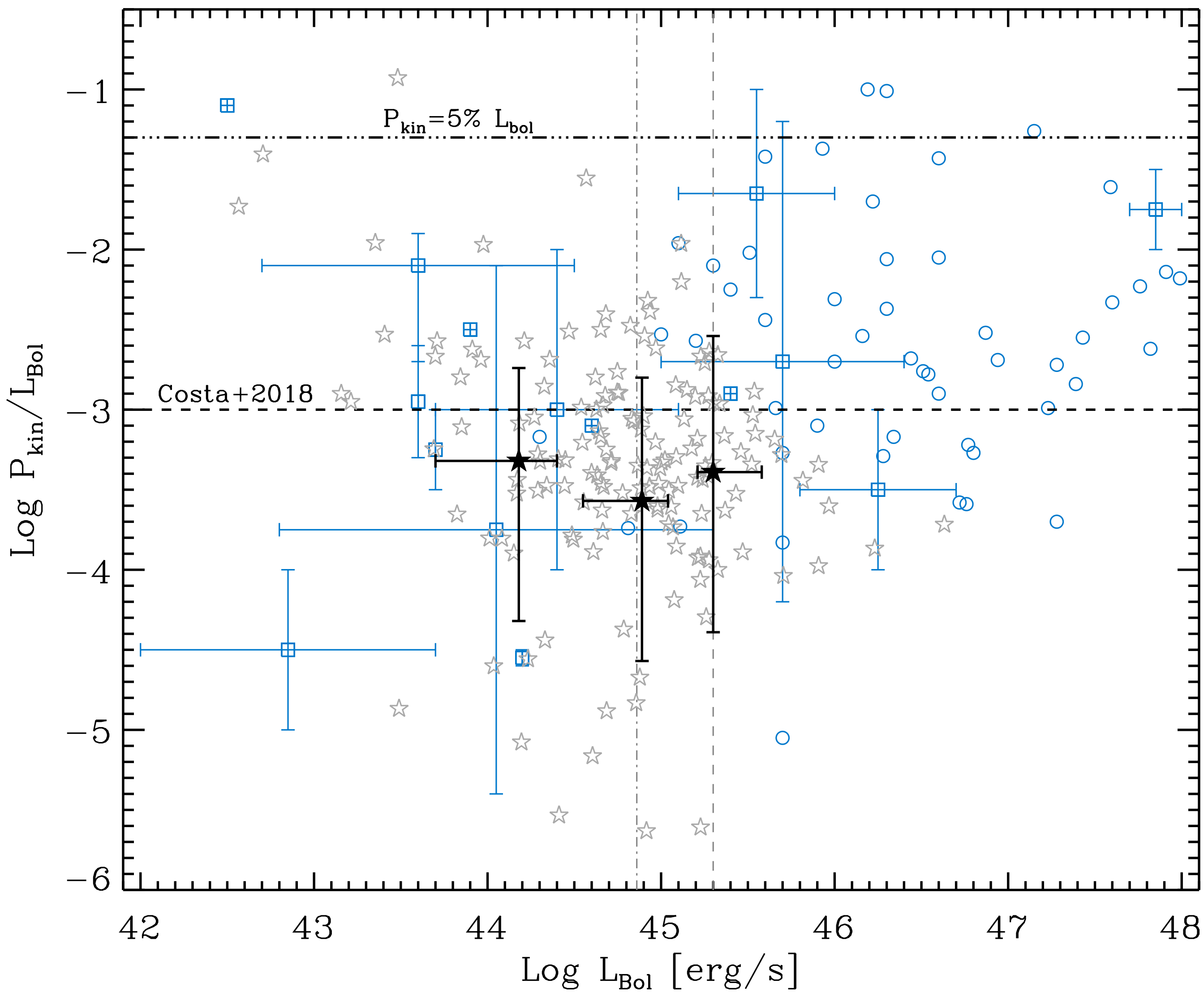
Menzel et al. 2018, submitt.; PhD thesis

Ionized outflows energetics



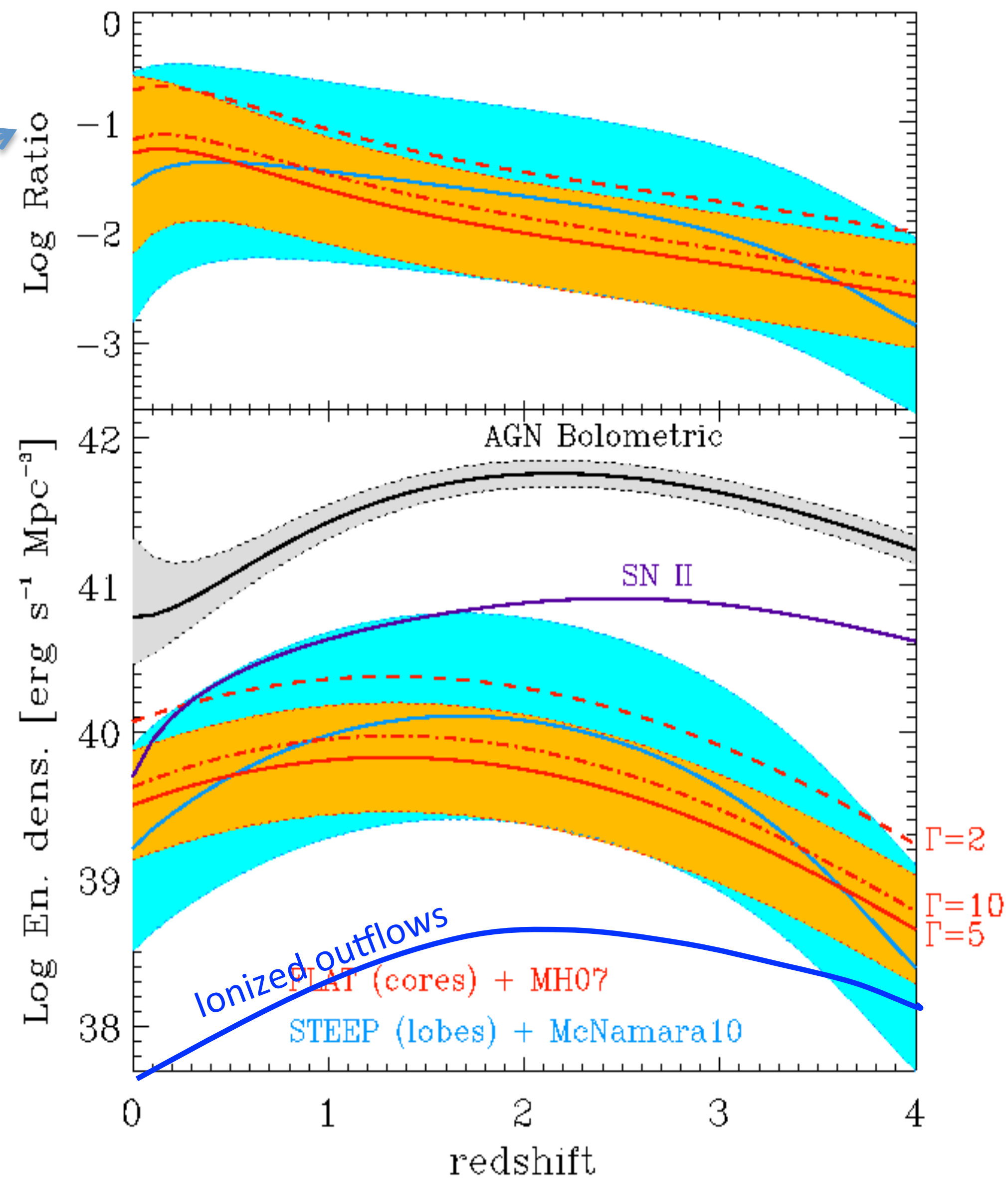
Menzel et al. 2018, submitt.; PhD thesis

High Power AGN: "QSO mode"



SMBH growth: weighting modes

Kinetic to radiative energy density ratio



$\text{Log } L_{kin} = 45.2 \times 0.8 \text{ Log}(P_{core} / 10^{25})$
(Merloni & Heinz 2007)

$\text{Log } L_{kin} = 44.6 \times 0.7 \text{ Log }(P_{1.4} / 10^{25})$
(Cavagnolo 2010, "cavity power")

Heinz, Merloni and Schwaab (2007); Körding, Jester and Fender (2007); Merloni & Heinz (2008); Cattaneo and Best (2009)

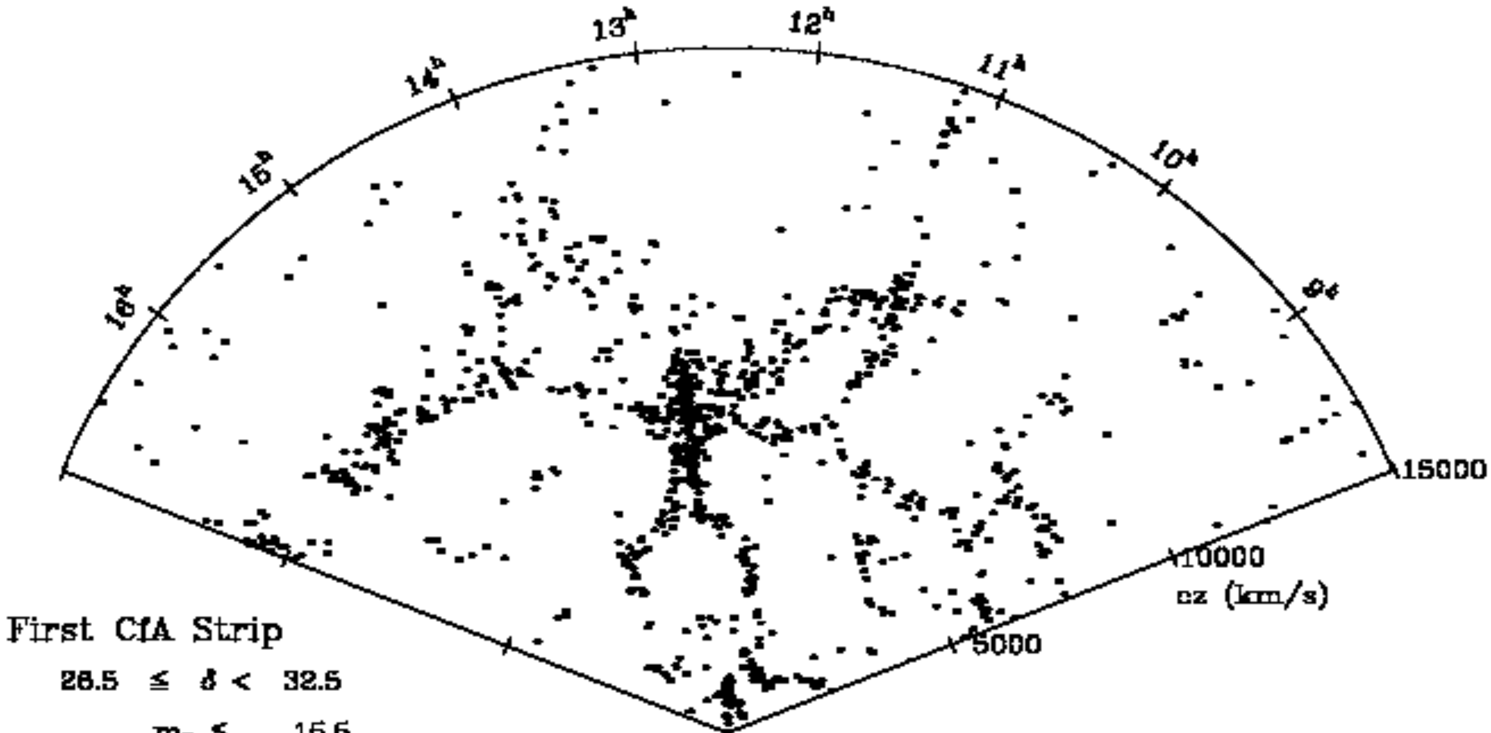
Summary of Part I: History of Accretion

- X-ray surveys provide the least biased view of AGN (against obscuration/extinction and galaxy dilution)
- We have probed most of the accretion history in the Universe (at least in mass-averaged terms). Most of SMBH mass accumulated in radiatively efficient phases of accretion
- Accretion rate distributions are key diagnostics of AGN evolution and connection to triggering
- Little evidence of ‘typical’ AGN being different that overall galaxy population
- A stochastic phenomenon; some particular condition may enhance this probability: mergers, central vs. satellite, etc., but evidence is tantalizing

Summary of Part I: The need for larger samples

- Existing X-ray surveys are limited by the sample size (~a few 10^3), mainly because of the limited field of view of sensitive, focusing, X-ray telescopes.
- Larger samples are mandatory to accurately study DISTRIBUTIONS of AGN vs. L, z, λ, N_H, SFR, M* (stochasticity of AGN phenomenon)
- The next step forward will be to bring the study of AGN evolution to the level of statistical significance that galaxy evolution studies enjoyed since the advent of SDSS (-> 10^6)

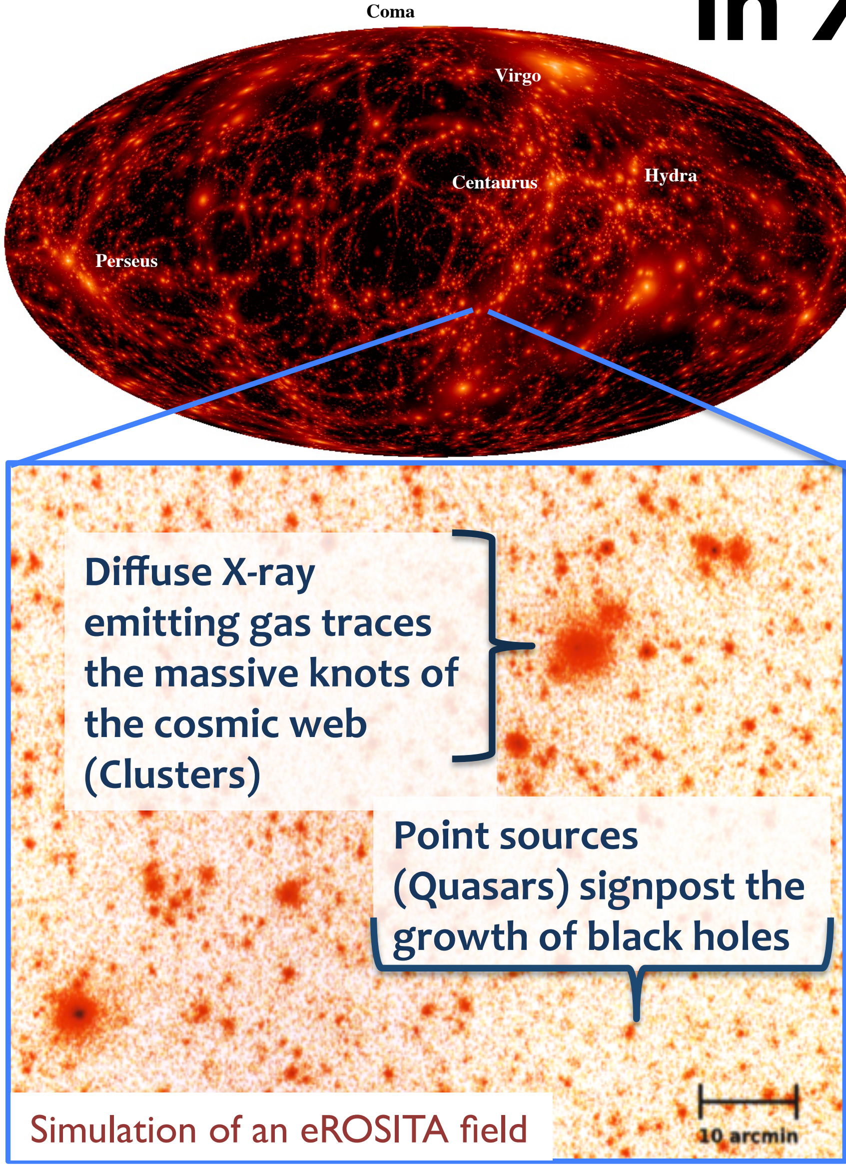
Mapping the Universe



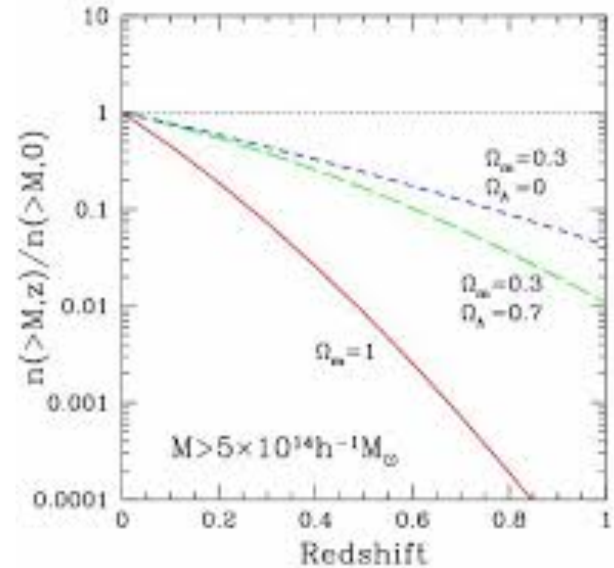
"Constrained"
Hydro simulations
e.g. J. Sorce+2016

Courtesy of K. Dolag (LMU)

Mapping the Universe In X-rays



Images coutesy of K. Dolag (LMU), M. Mühlegger (MPE), O. Hahn (ETH)



Rosati, Norman, Borgani 2002

- A signature of clusters is the detection of hot (~10^7 K) ICM
- Clusters are *exponentially sensitive* tracers of **growth of structures**
- Cosmological constraints with (well calibrated) ROSAT samples ~100 obj.

eROSITA: the Project

PI: Peter Predehl; PS: A. Merloni (MPE)

Core Institutes (DLR funding):
MPE, Garching/D
Universität Erlangen-Nürnberg/D
IAAT (Universät Tübingen)/D
SB (Universität Hamburg)/D
Astrophysikalisches Institut Potsdam/D

Associated Institutes:
MPA, Garching/D
IKI, Moscow/Ru
USM (Universität München)/D
AIA (Universität Bonn)/D

Industry:

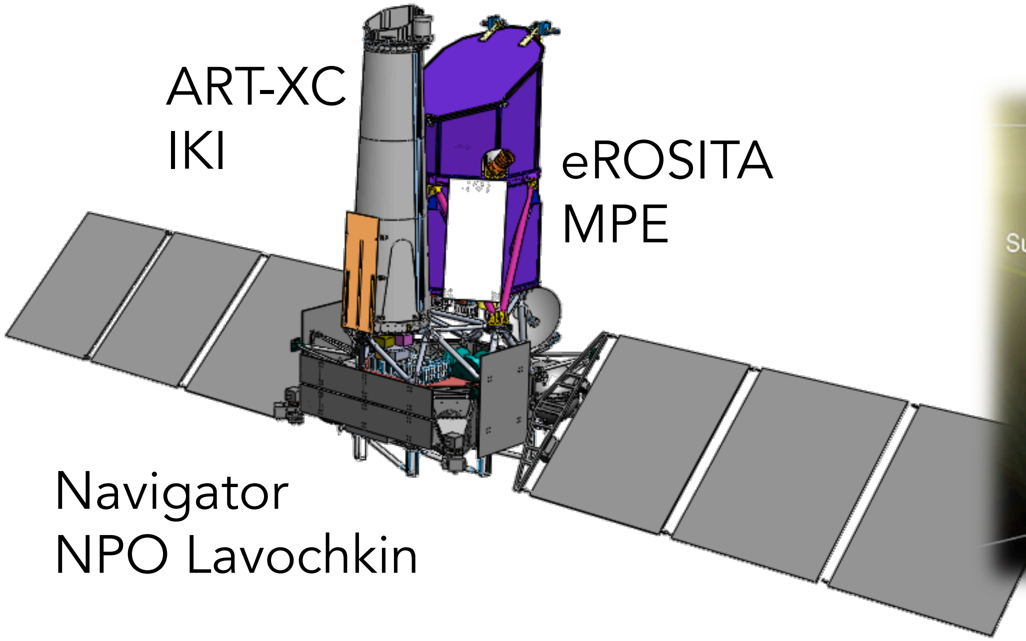
Media Lario/I	Mirrors, Mandrels
Kayser-Threde/D	Mirror Structures
Carl Zeiss/D	ABRIXAS-Mandrels
Invent/D	Telescope Structure
pnSensor/D	CCDs
IberEspacio/E	Heatpipes
RUAG/A	Mechanisms
HPS/D,P	MLI

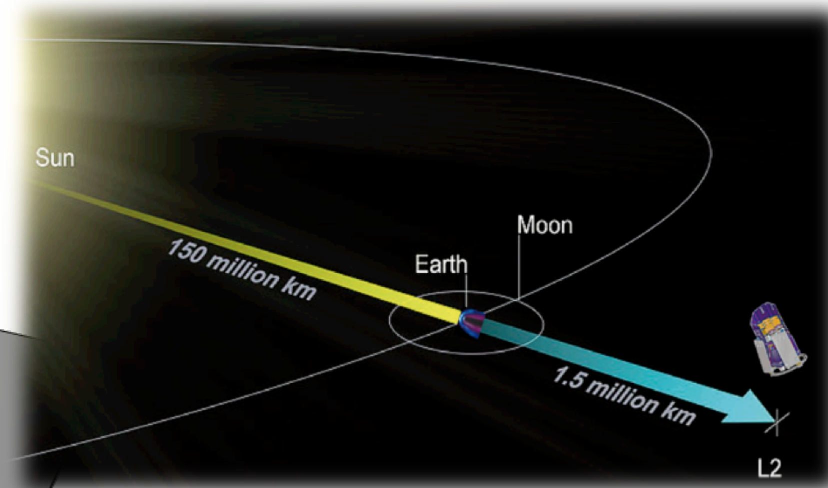
\+ many small companies

COSTS: ~90 M€ (eROSITA)
~250-300 M€ (SRG)

MPE: Scientific Lead Institute, Project Managment
Instrument Design, Manufacturing, Integration & Test
Data Handling & Processing, Archive etc.

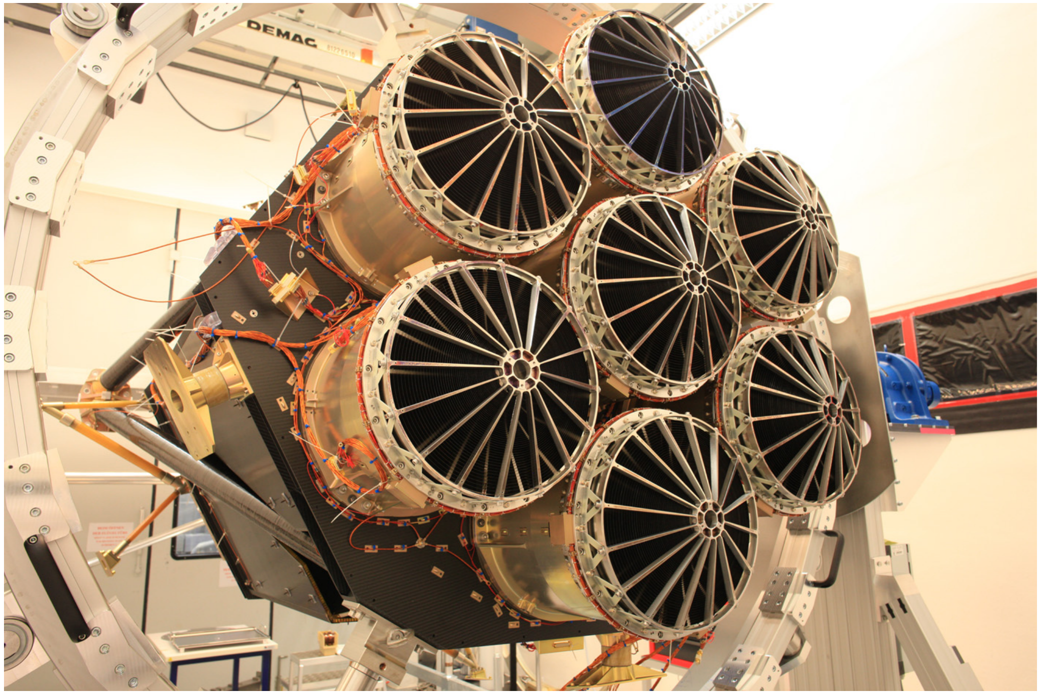
SRG: Mission Profile

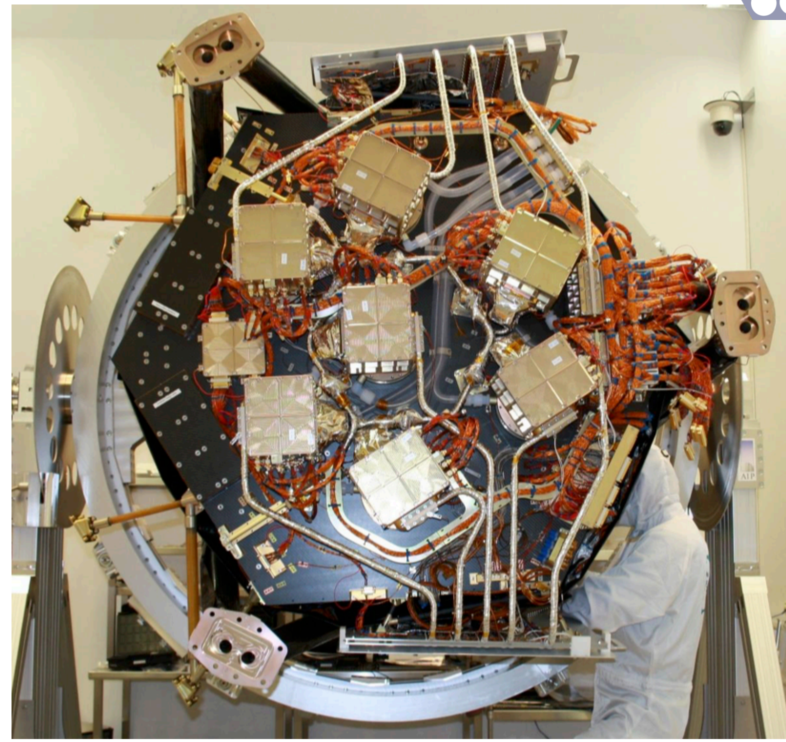




- **Launch**: From Baykonour, Proton–Block-DM
- **3 Months**: flight to L2, PV and calibration phase
- **4 years**: 8 all sky surveys (eRASS:1-8; scanning mode: 6 rotations/day)
    - Re-visit LMC & SMC every ~month (to $L_{0.5\text{-}2\,\mathrm{keV}} \sim 10^{34}$ erg/s)
- **2.5 years**: pointed observations, including ~20% GTO. 1 AO per year
- **Ground Segment**: 2 x 70m antennas (Bear Lakes and Ussirisk), daily contact (up to ~4 hours); telemetry transfer directly to MPE via Moscow NPOL/IKI Control Center

7 Mirrors + pnCCDs



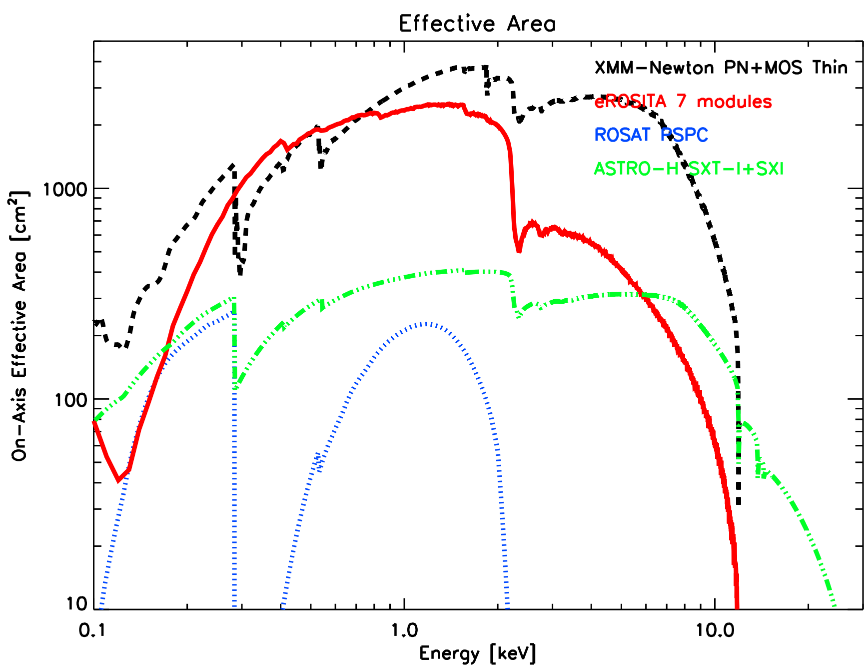


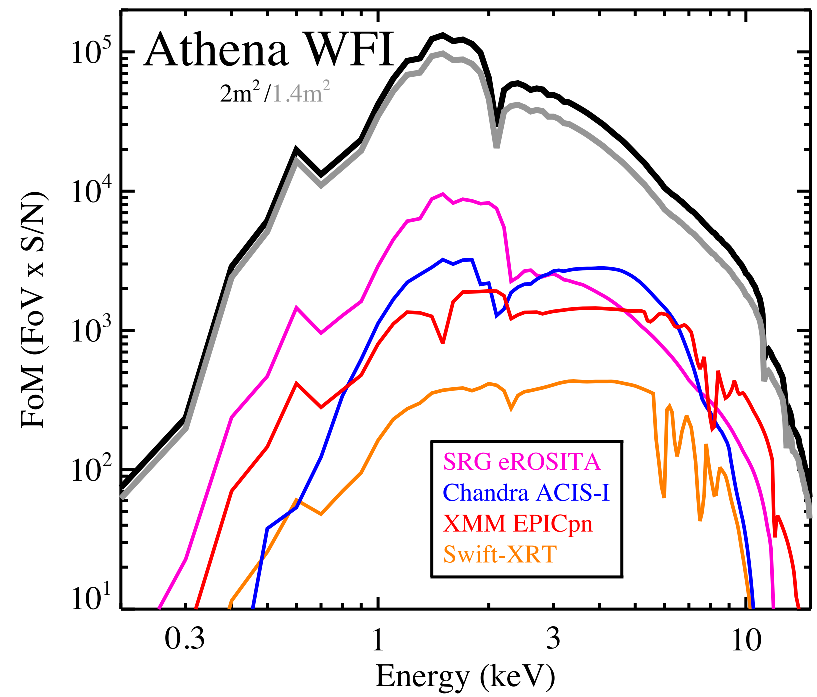
- Focal length: 1.6 m, Field of view: 1 degree (diameter)
- Half-Energy width **(HEW) ~18" (on-axis); 27" (FoV avg.)**
- Source location accuracy ~3-10"
- X-ray baffle (10µm precision alignment): 92% stray light reduction

• **Spectral resolution** at all measured energies within specs (**R~20 @1.5keV**)
• Extremely **good uniformity**, no chip gaps

Effective Area and Grasp

Effective Area: ~1700 cm² (FoV avg. @1keV)

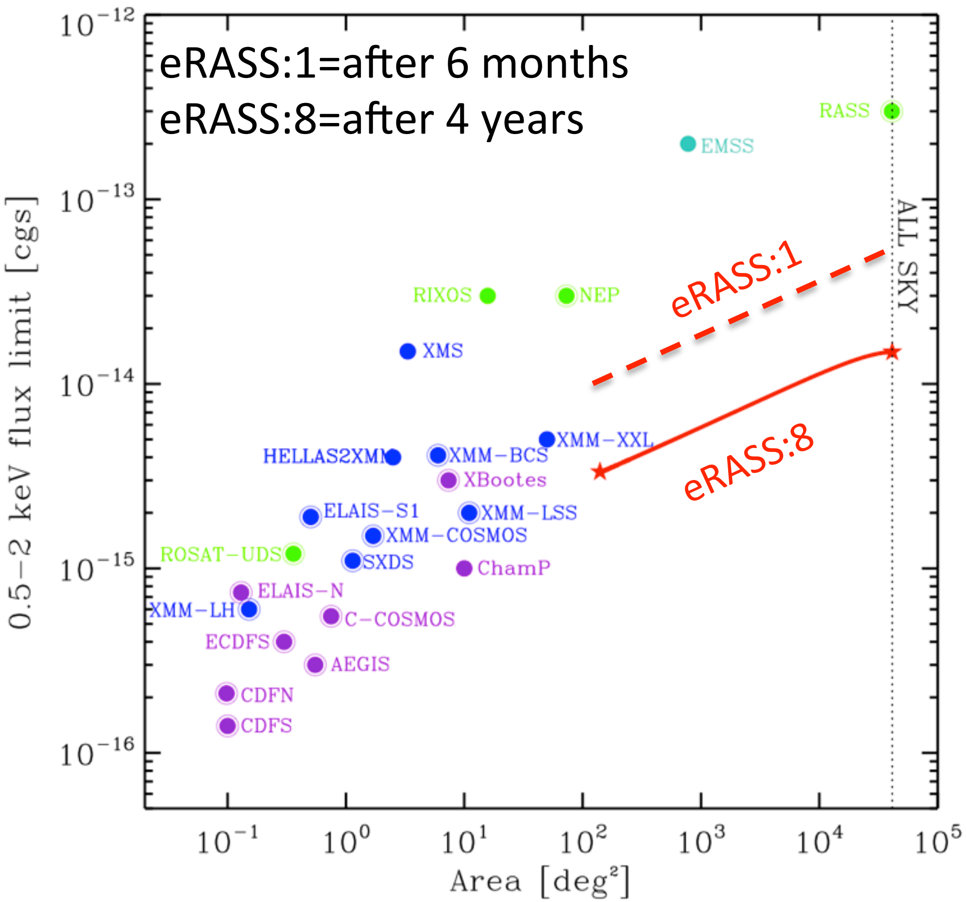




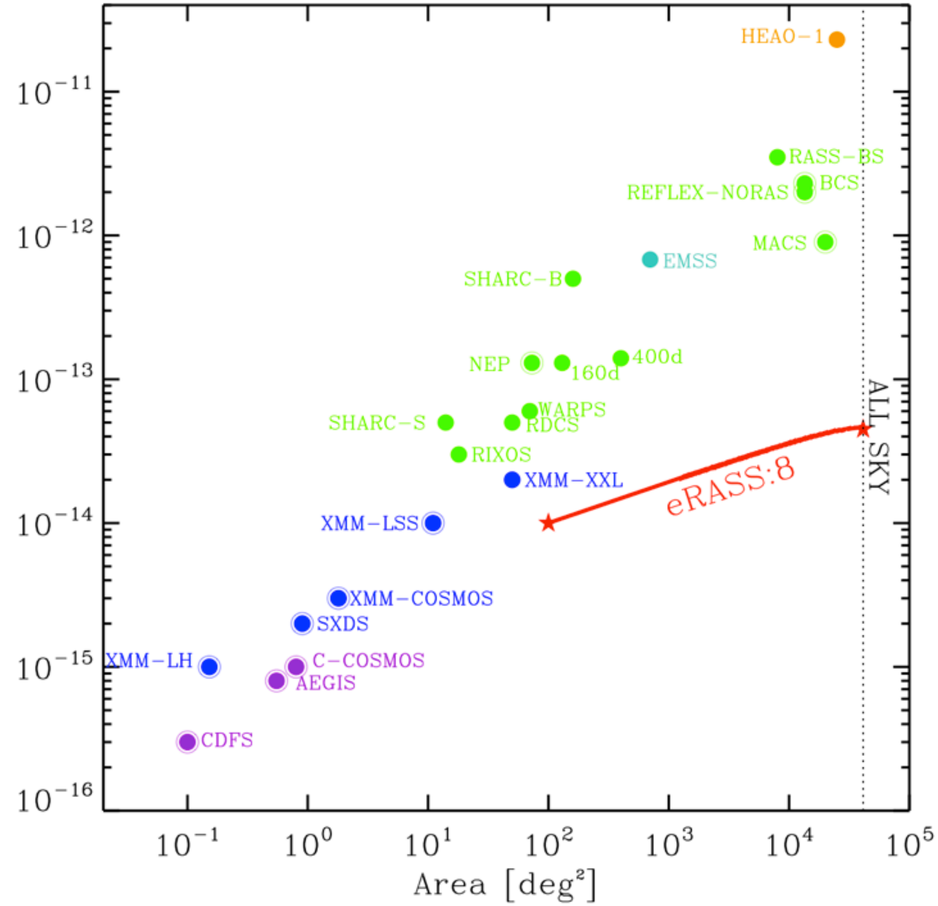
- Effective area at 1keV comparable with XMM-Newton
- Factor ~7-8 larger surveying speed (and 4 years dedicated to all sky survey)
- Survey FoM≈A_{eff}*FoV/(θ*Bkgn) (courtesy of Wik & Horsheimer)

eROSITA surveys in context

Point sources sensitivity



Extended sources sensitivity

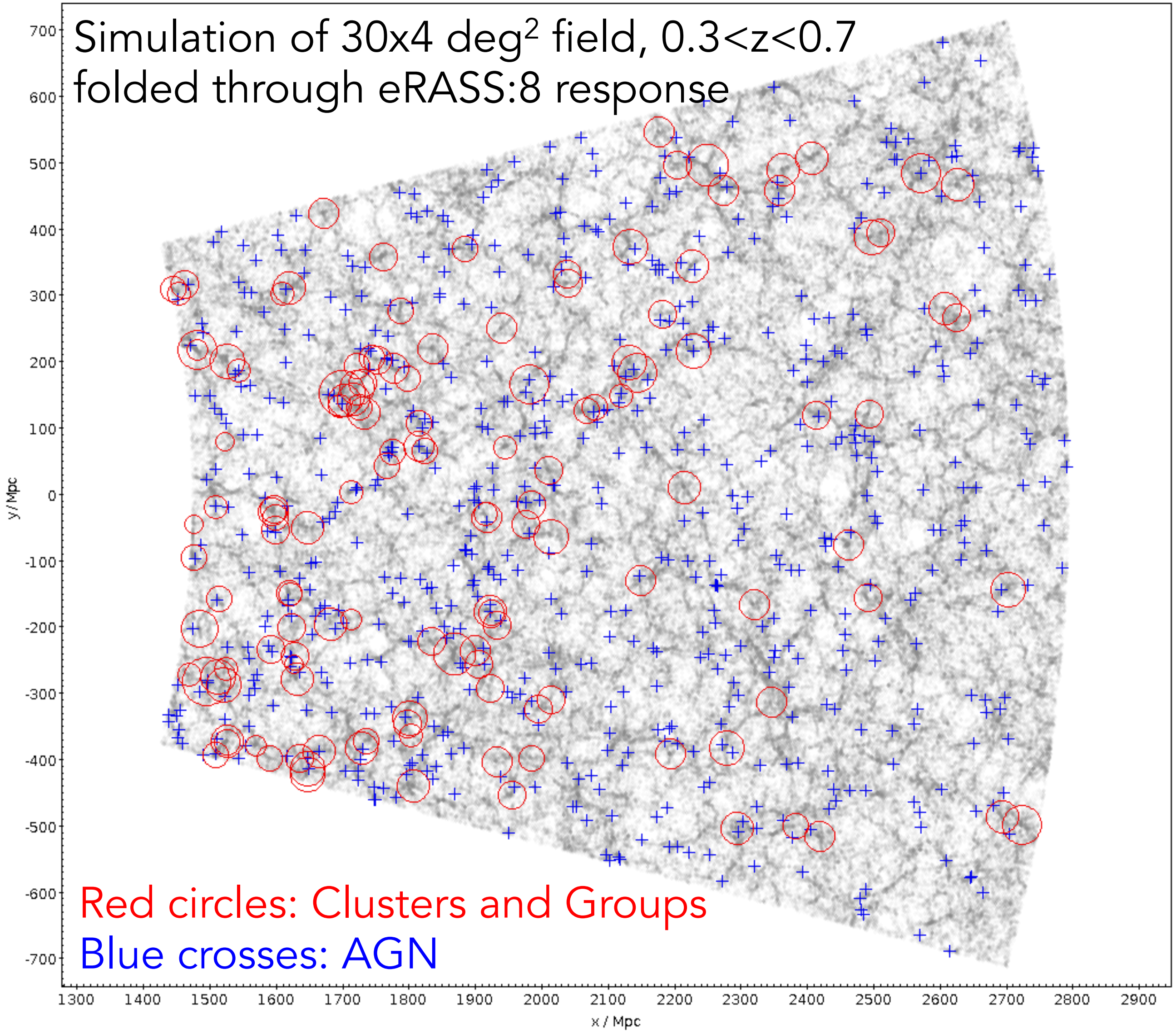


All sky: 10^{-14} (0.5-2 keV)
$2{\times}10^{-13}$ (2-10 keV) [erg/cm^2/s]

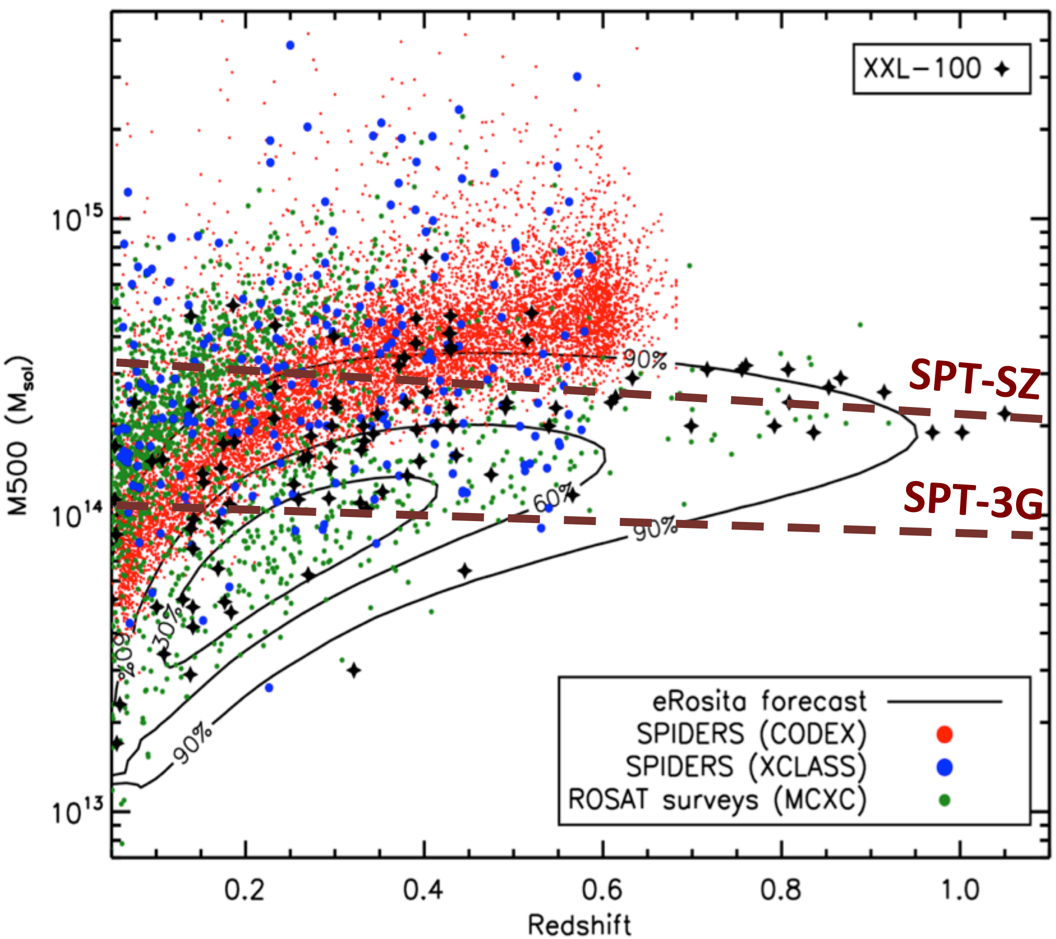
All sky: 3.4×10^{-14} (0.5-2 keV)

Merloni et al. 2012

X-ray Large Scale Structure

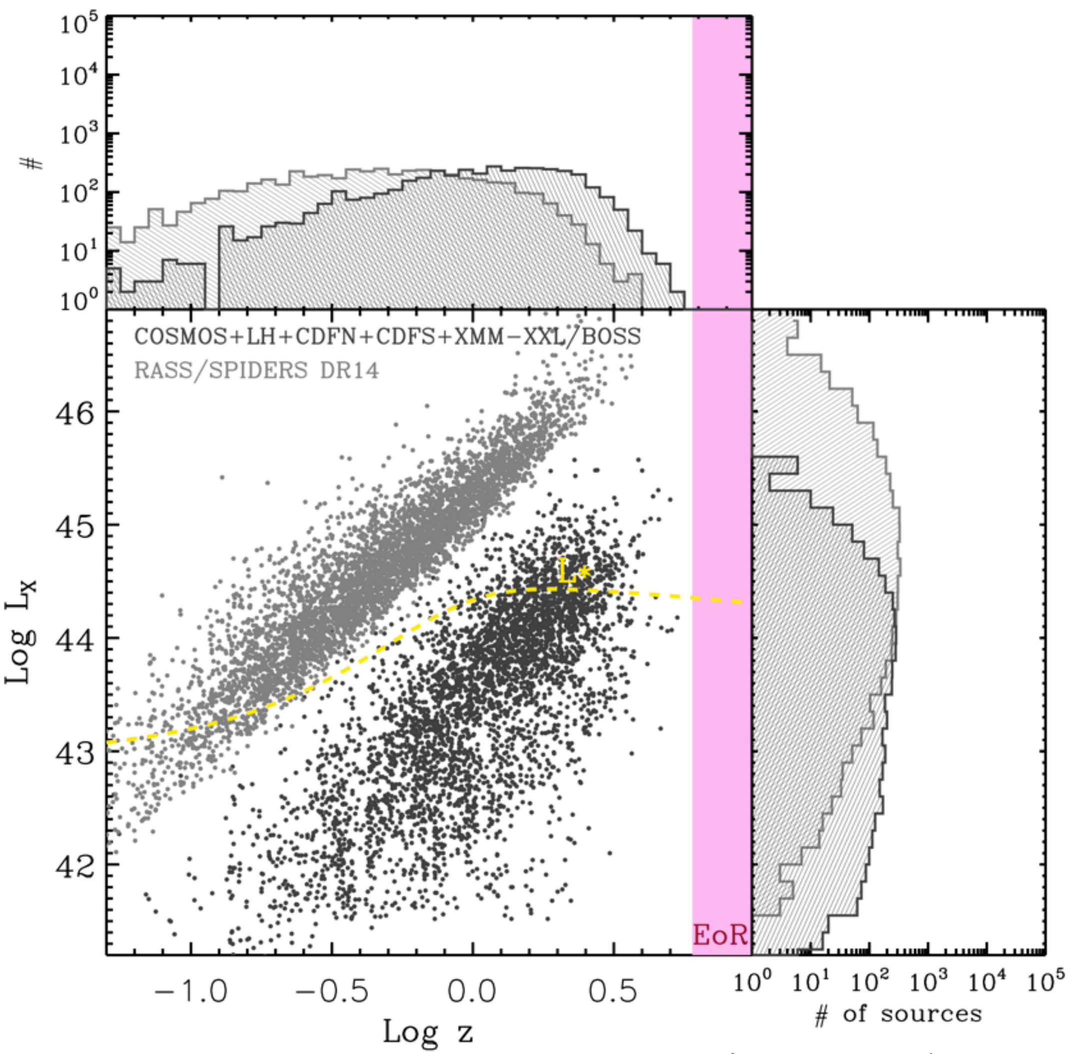


ALL Massive Clusters



- eROSITA will detect ~110k clusters with more than 50 net counts; 2k with more than 1000 counts
- ~20k clusters with good redshift determination, up to z~0.45
- ~2k clusters with precise Temperature (to <10%)
- eROSITA PSF is good enough to resolve ~$0.3R_{500}$ regions at z=1 for $10^{14}M_{\odot}$ clusters
- For cosmology, M_{gas} and core-excised L_X are excellent mass proxies with very low scatter (~10%)

3 Million AGN: physics and cosmology



- The most luminous AGN, tracers of large scale structure: the "quasar" mode of AGN feedback
- (Obscured and Un-obscured) accretion history
- High-z AGN
- Huge effective volume, BAO with biased tracers
- SED vs. L, L/L_{EDD}
- Soft spectral response
- Uninterrupted view!

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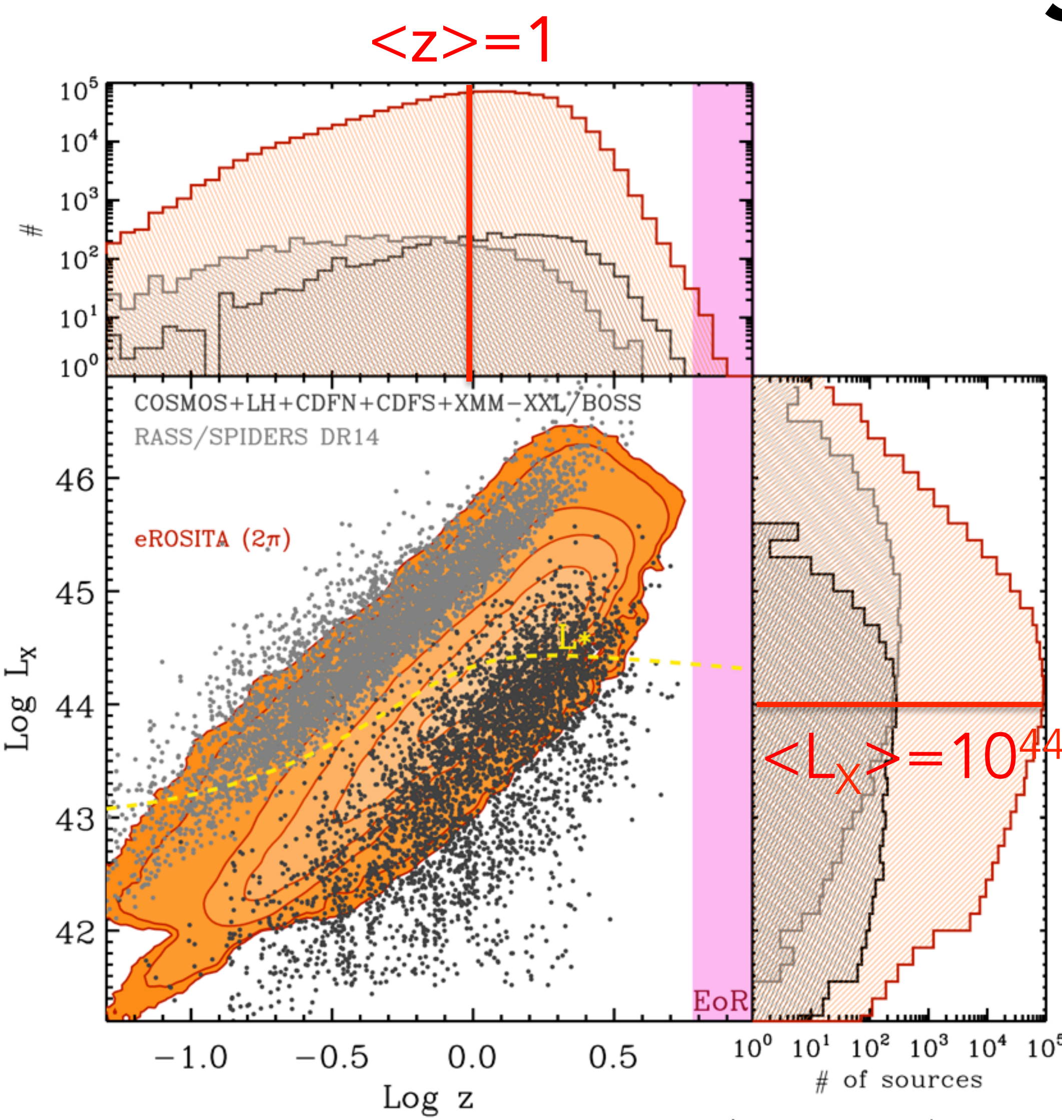

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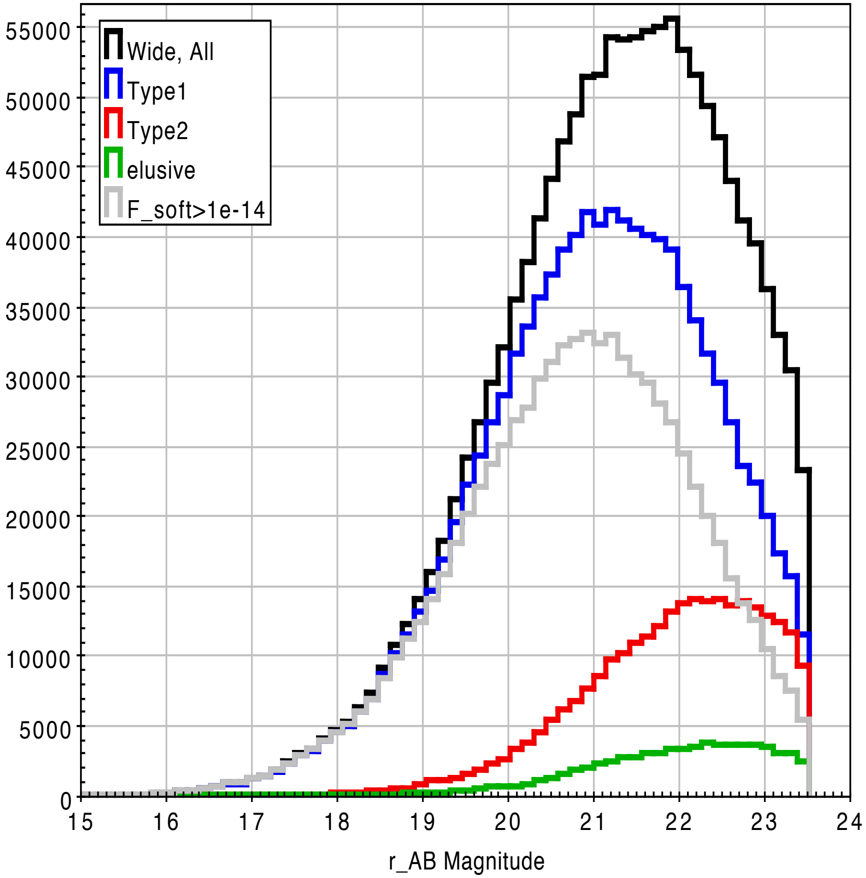
AGN Follow-up requirements



ID fraction	r_{AB} limit [5 σ]	i_{AB} limit [5 σ]	K_{AB} limit [5 σ]
0.9	22.8	22.5	20.4
0.95	23.5	23.2	20.7
0.99	24.5	24.2	21.3

SDSS: r_{AB}<22.2; 13,000 deg^2
PS1: r_{AB}<22; 32,000 deg^2
VST/ATLAS: r_{AB}<22.5; 4,500 deg^2
DES: r_{AB}<24.3; 5,000 deg^2
HSC WIDE: r_{AB}<25.2; 1,500 deg^2
DECaLS: r_{AB}<23.2; 6,000 deg^2
DeROSITAS/BLISS: r_{AB}<23.2; ~3,000 deg^2
LSST: r_{AB}<25.8; 18,000 deg^2

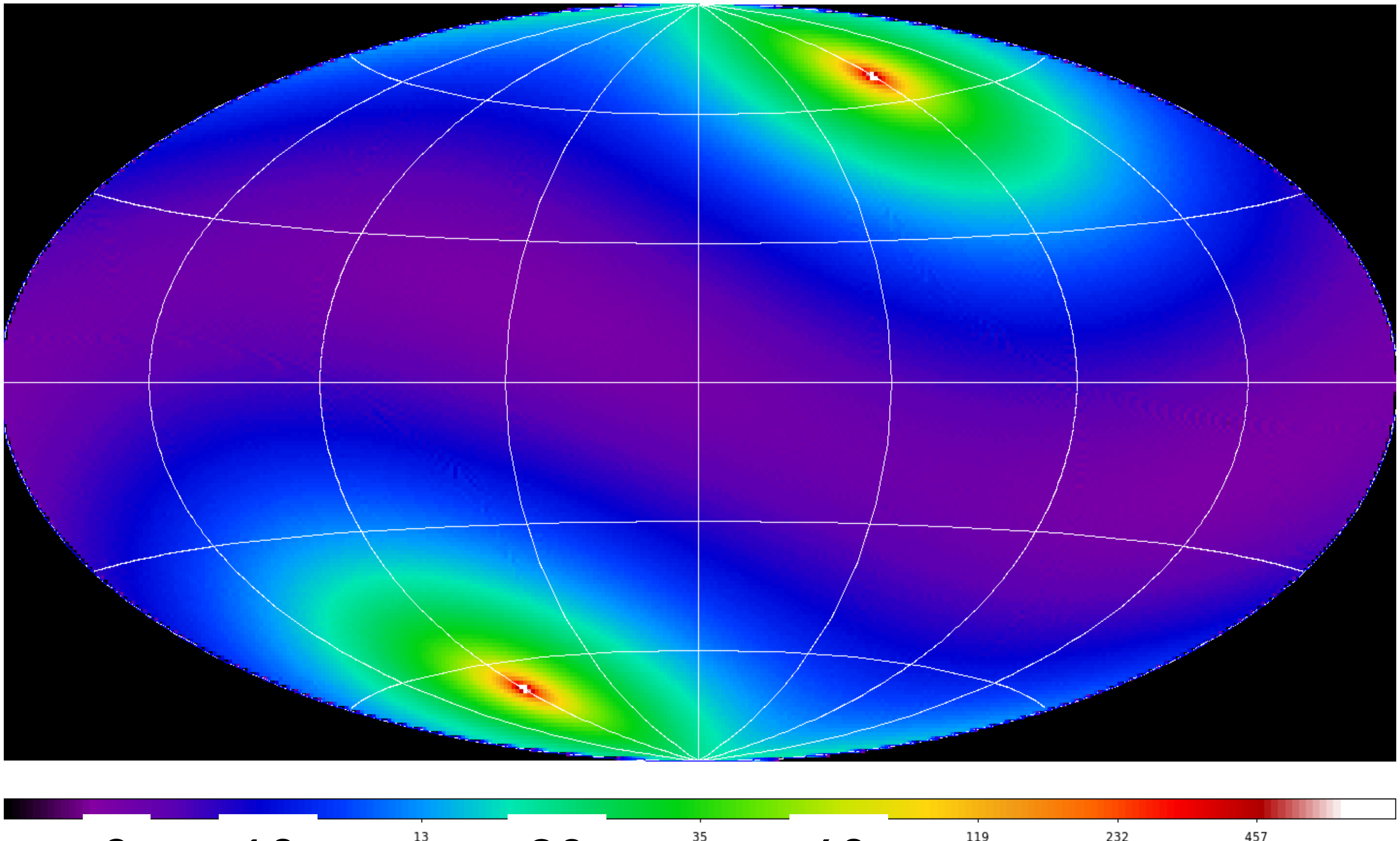
- **Type 1** (un-obscured, Broad line) **~66%**
- **Type 2** (obscured, Narrow line) **~20%**
- **"Elusive"** AGN **~6%**
- **Stars ~8%**

NOTE: **WISE** has detected ~**65%** of all AGN that eROSITA will see

Spectroscopic follow-up

- **TAIPAN (2019-2023)** taipan-survey.org
  - 1.2m UK Schmidt Telescope at Siding Spring Observatory, 2.5π
  - Limited to **i<17**: 0.6-1 AGN/deg^2 mostly RASS sources, 20k redshifts
- **SDSS-V (2020-2024)** www.sdss.org/future/
  - SDSS + LCO full-sky coverage complete follow-up of eRASS:2 over ~10,000 deg^2 (250k AGN spectra to **i~21.5**, 80k galaxies in 10k clusters)
- **VISTA/4MOST (2023-2027)** www.4most.eu
  - Complete, systematic follow-up of both Clusters and AGN from eROSITA:8 reach >90% completeness for eRASS:8 (down to **r~23**)
  - ~700k AGN spectra $0<z<6$
  - ~1M galaxies in ~50k X-ray selected clusters (Clusters clustering, RSD, velocity dispersion, gravitational redshift)

eROSITA Cadence Map



8 10 20 60

→ # of daily eROSITA visits over 4yrs

1 daily visit → $F_{0.5\text{-}2} \sim 4\times10^{-14}$ erg/s/cm^2 →
$L_X > 10^{43}$ at D<1.5 Gpc (z~0.3); $L_X > 10^{44}$ at D<4.5 Gpc (z~0.7)

"Legacy science"

- Provide a detailed view of the compact objects (NS, BH) population of the Milky Way
- Survey of 600k active (young, magnetic) stars
- Map the diffuse X-ray emission and the hot ISM in the Milky Way and in the Solar neighborhood
- Study nearby star-forming galaxies and galaxy groups
- Provide a dynamical view of the X-ray sky and identify transients and variable sources, including 1000's TDEs
- Serendipity…

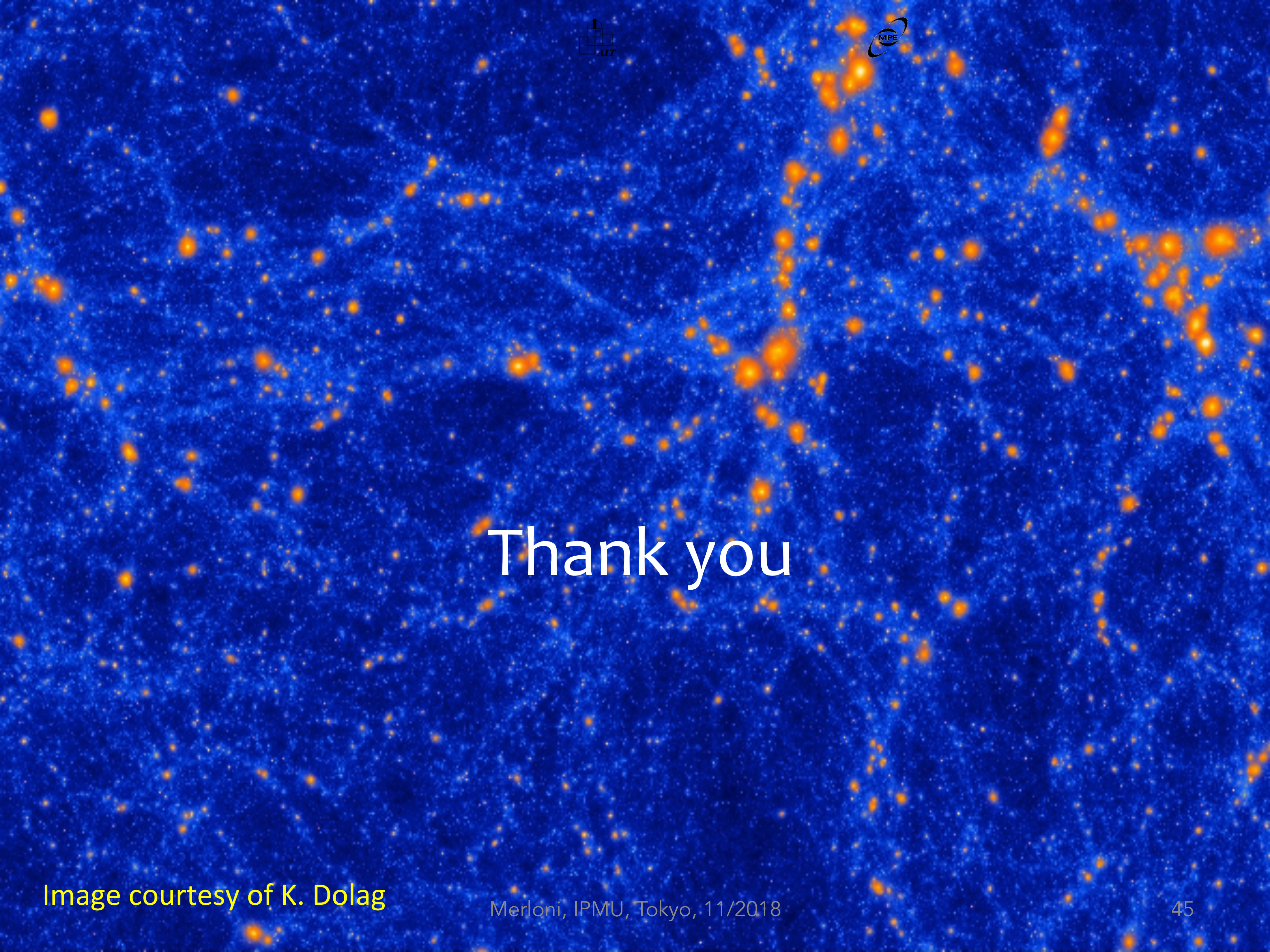
[eROSITA Science Book: Merloni et al. 2012, arXiv:1209.3114]

Working with eROSITA

- **eROSITA is a PI instrument**
  - Scientific exploitation of data shared between the partners: 50% MPE and 50% IKI, West/East (gal. coord.)
  - German data public after 2 yrs, 3 releases (‘20, ‘22, ‘24; TBC)
  - Proprietary access via eROSITA_DE (/RU) consortium
  - Projects/papers regulated by working groups
- **Working Groups**:
  - Science: Clusters/Cosmology, AGN, Normal galaxies, Compact objects, Diffuse emission/SNR, Stars, Solar System, Time Domain Astrophysics
  - Infrastructure: Data analysis and catalogues, Multiwavelength follow-up, Calibration, Background
- **Collaboration policy (German Consortium):**
  - Individual External Collaborations (proposal to WGs)
  - Group External Collaborations (team-to-team MoUs)

Conclusions

- X-ray (and radio) surveys provide the least biased view of the AGN evolution
- Current samples reveal AGN as stochastic phenomena occurring in all kind of galaxies
- Sample size are still small to unambiguously reveal trends with galaxy properties and large scales
- Not clear the overall global impact of AGN feedback at high Edd. Ratio (winds and outflows)
- eROSITA is ready for launch in 2019!
- Future of AGN studies with eROSITA and multiwavelength large surveys (WISE, LOFAR, ASKAP, DESI, 4MOST, HSC) is bright: larger sample will allow new phenomena to be discovered



Thank you

Image courtesy of K. Dolag