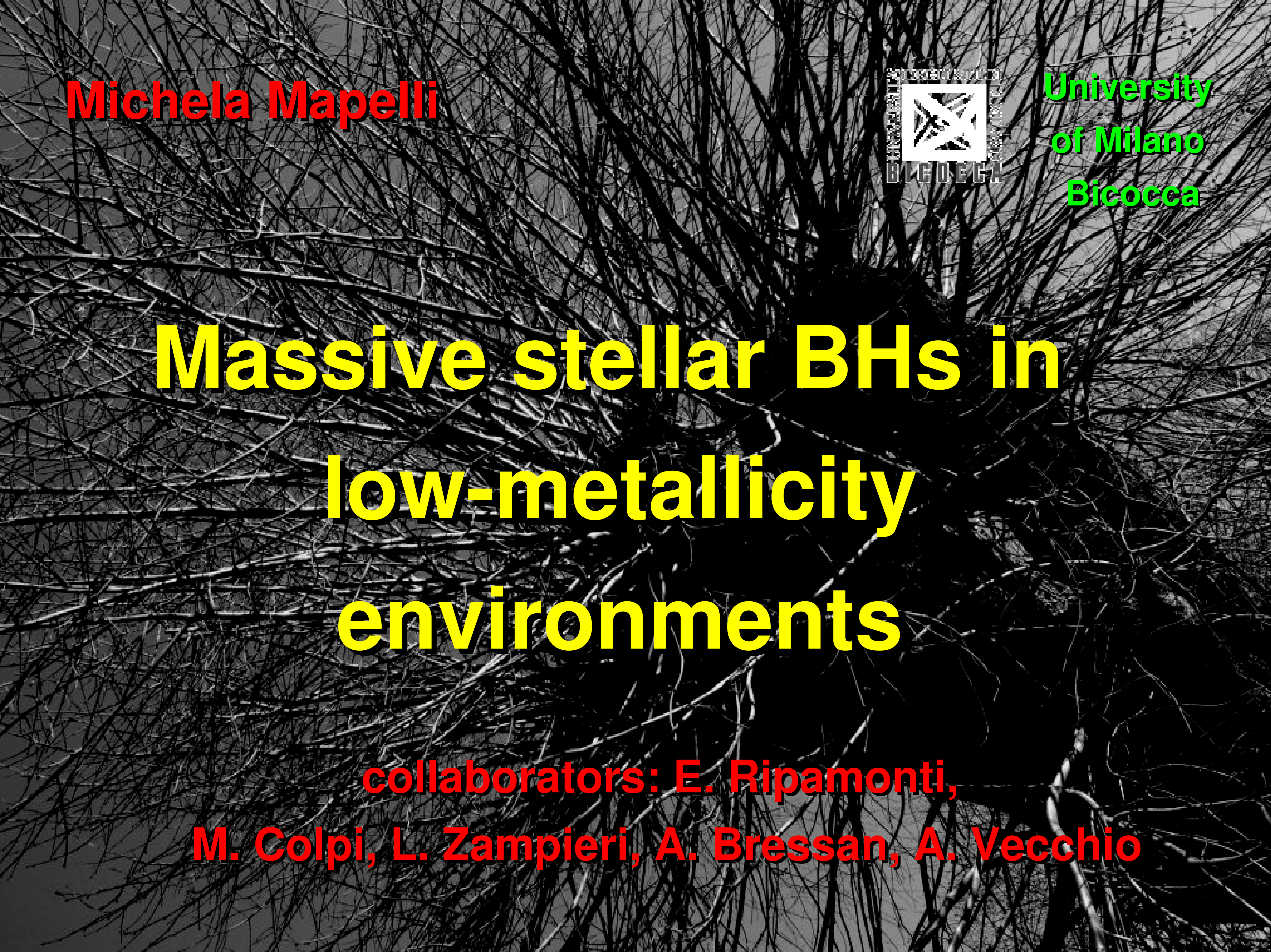


Michela Mapelli

University
of Milano
Bicocca

Massive stellar BHs in low-metallicity environments

collaborators: E. Ripamonti,
M. Colpi, L. Zampieri, A. Bressan, A. Vecchio

OUTLINE

1 – state of the art: mass range for stellar BHs

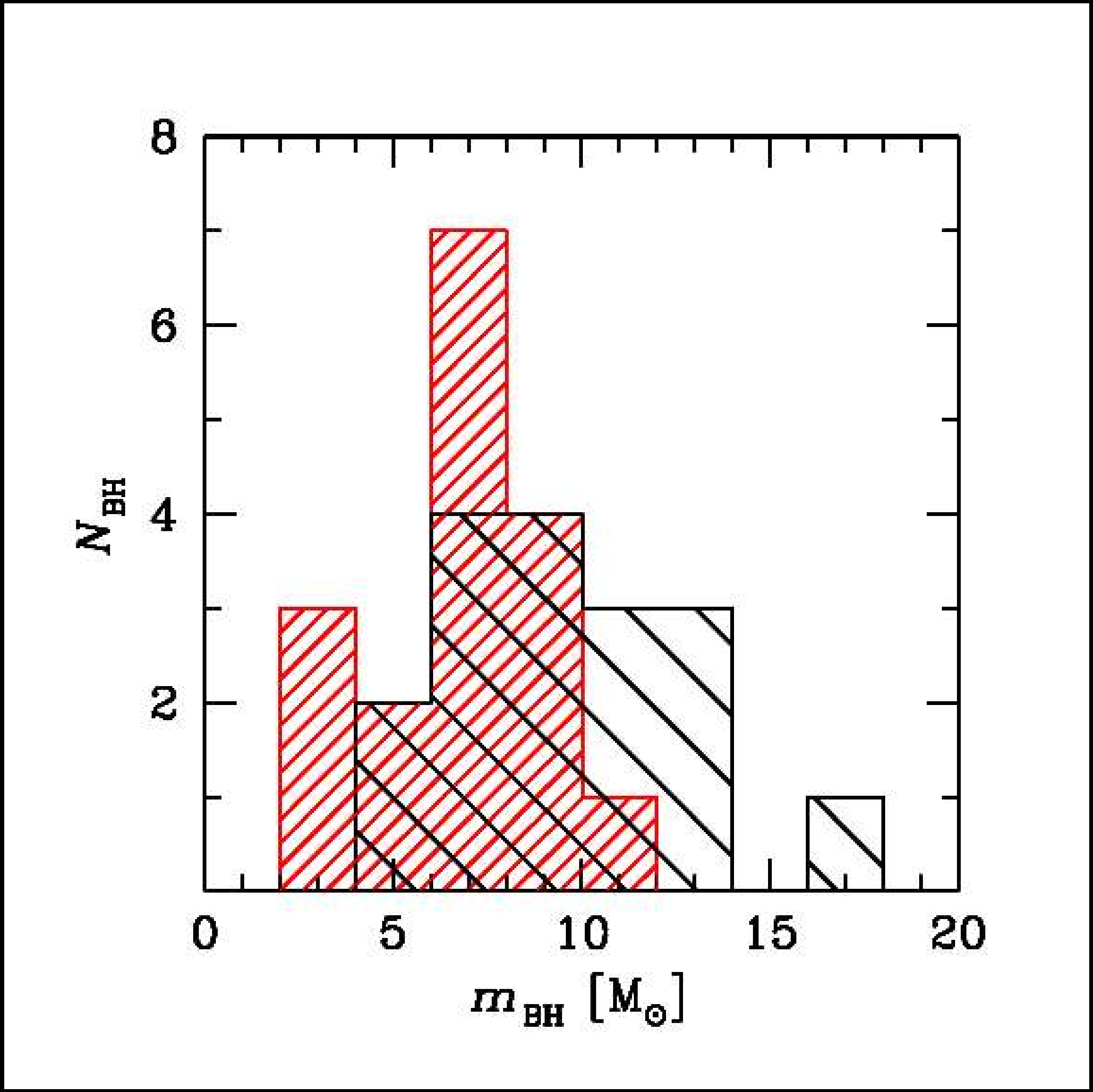
2 - model: predictions for ULXs

3 – comparison data-model for ULXs

4 – ejections of BHs

1 – STATE OF the ART:
mass range of stellar BHs

OBSERVATIONS:



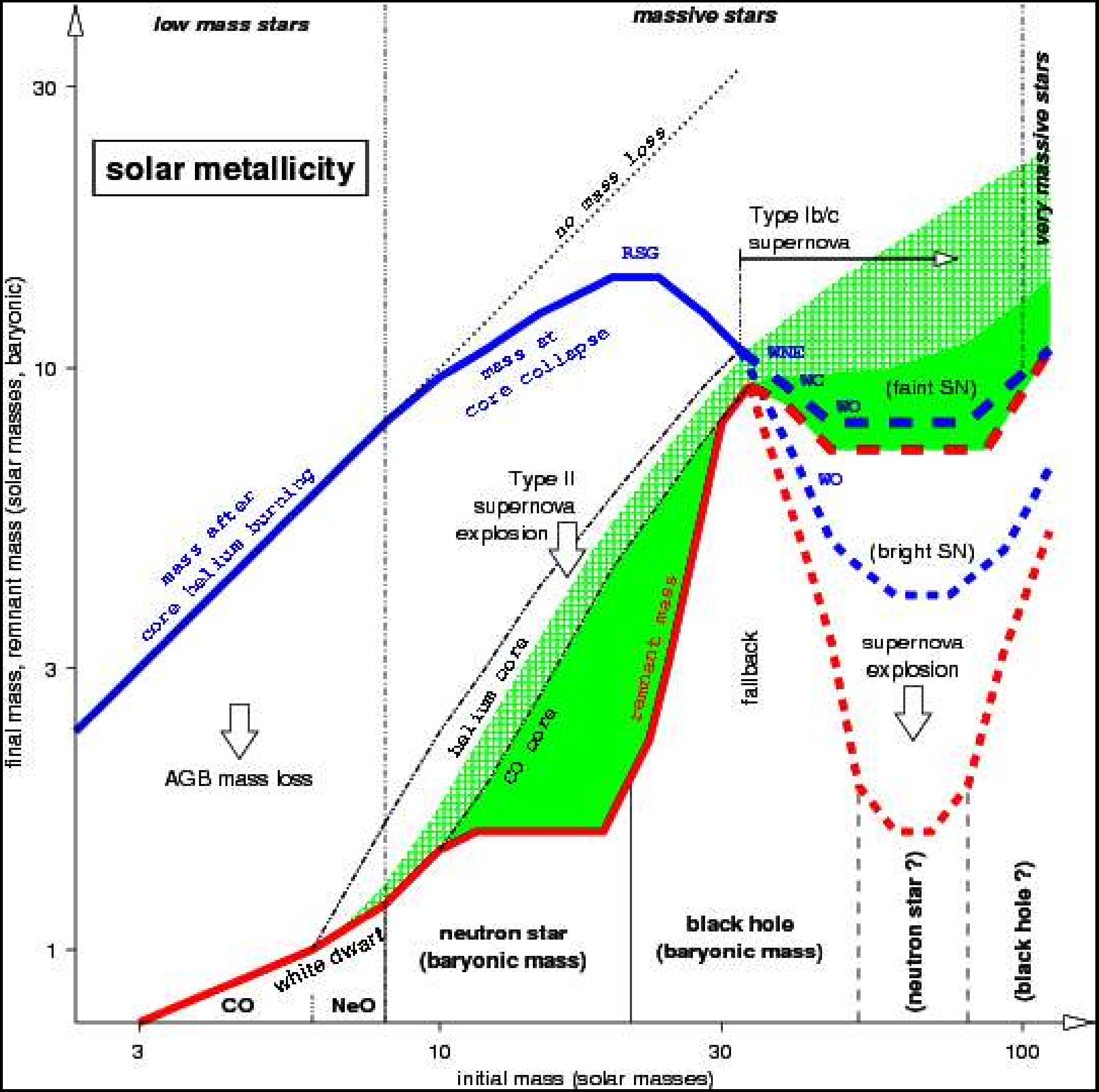
Distribution of stellar BH masses in X-ray binaries in the MW:

3Msun<mBH
mBH<20 Msun

Orosz (2003)

THEORY:

FINAL MASS, REMNANT MASS



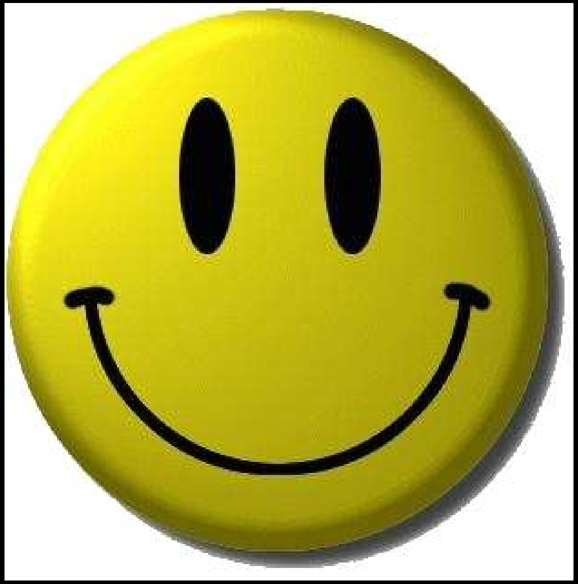
INITIAL MASS

Predicted mass of BHs after SN:
3 Msun<mBH
mBH<10Msun

Heger et al. (2002, 2003)

STATE of the ART:

Agreement between theory and observations of mBH (Milky Way)



STATE of the ART:

Agreement between theory and observations of mBH (Milky Way)

BUT: MISSING ELEMENT!!!

THE METALLICITY

Role of metallicity:

- **STELLAR WINDS depend on metallicity**

$$\dot{M}(Z) \propto \left(\frac{Z}{Z_\odot}\right)^\alpha$$

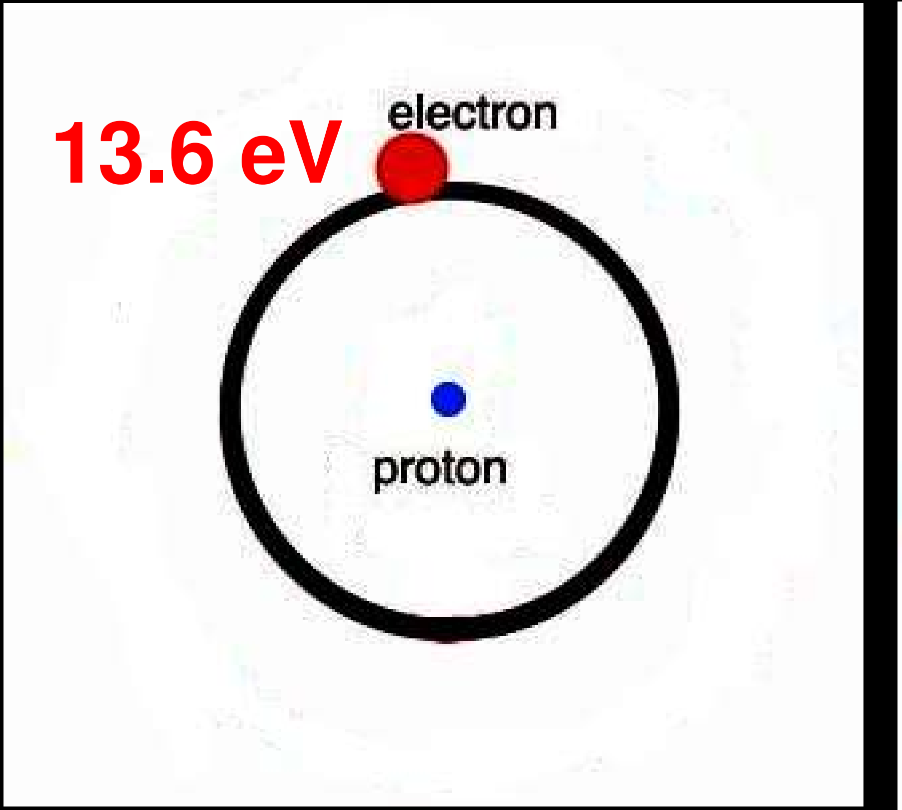
$$\alpha = 0.5 - 0.9$$

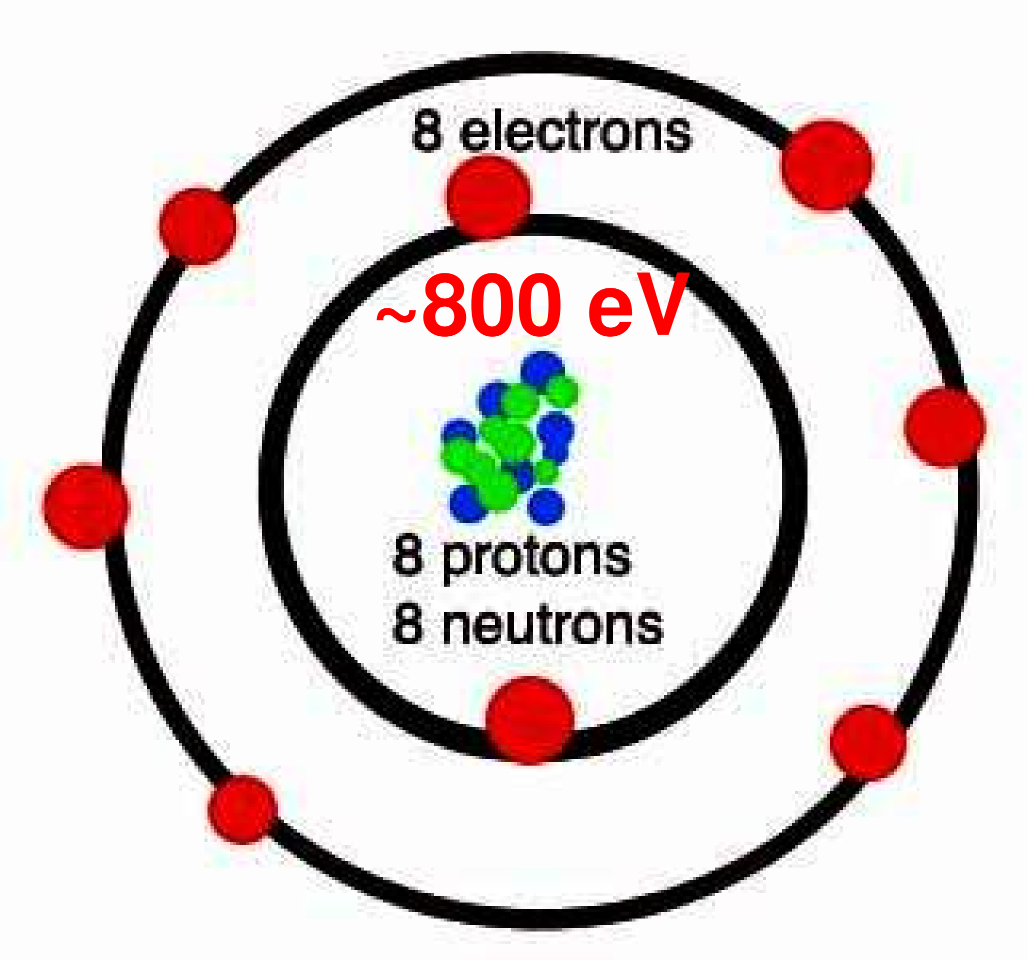
Bertelli et al. (2009)

at lower Z, stars lose less mass due to stellar winds!

Role of metallicity:

- STELLAR WINDS depend on metallicity

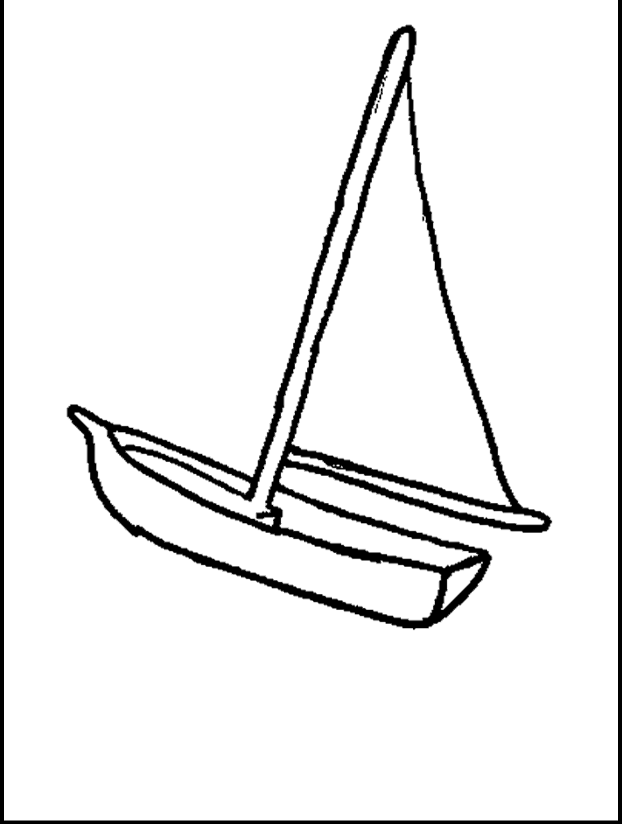




at lower Z, stars lose less mass due to stellar winds!

Role of metallicity:

- **STELLAR WINDS depend on metallicity**



at lower Z, stars lose less mass due to stellar winds!

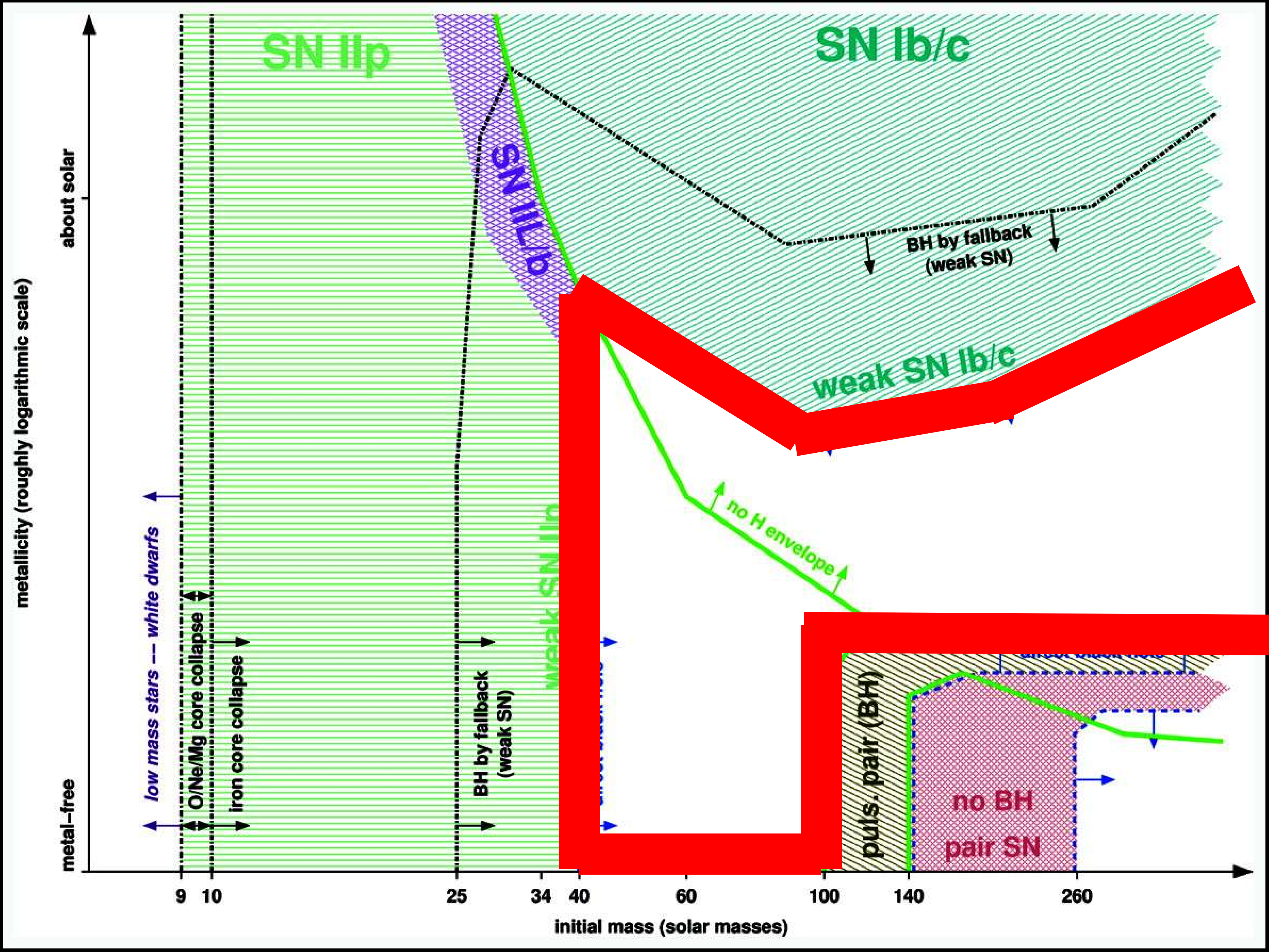
Role of metallicity:

1. Stars with Mfin > 40 Msun directly collapse to BHs
(FAILED SUPERNOVAE, Fryer 1999)

2. STARS DO HAVE Mfin > 40 Msun,
if metallicity is LOW

→ LOW-METALLICITY STARS
DIRECTLY COLLAPSE INTO BHs

Role of metallicity:

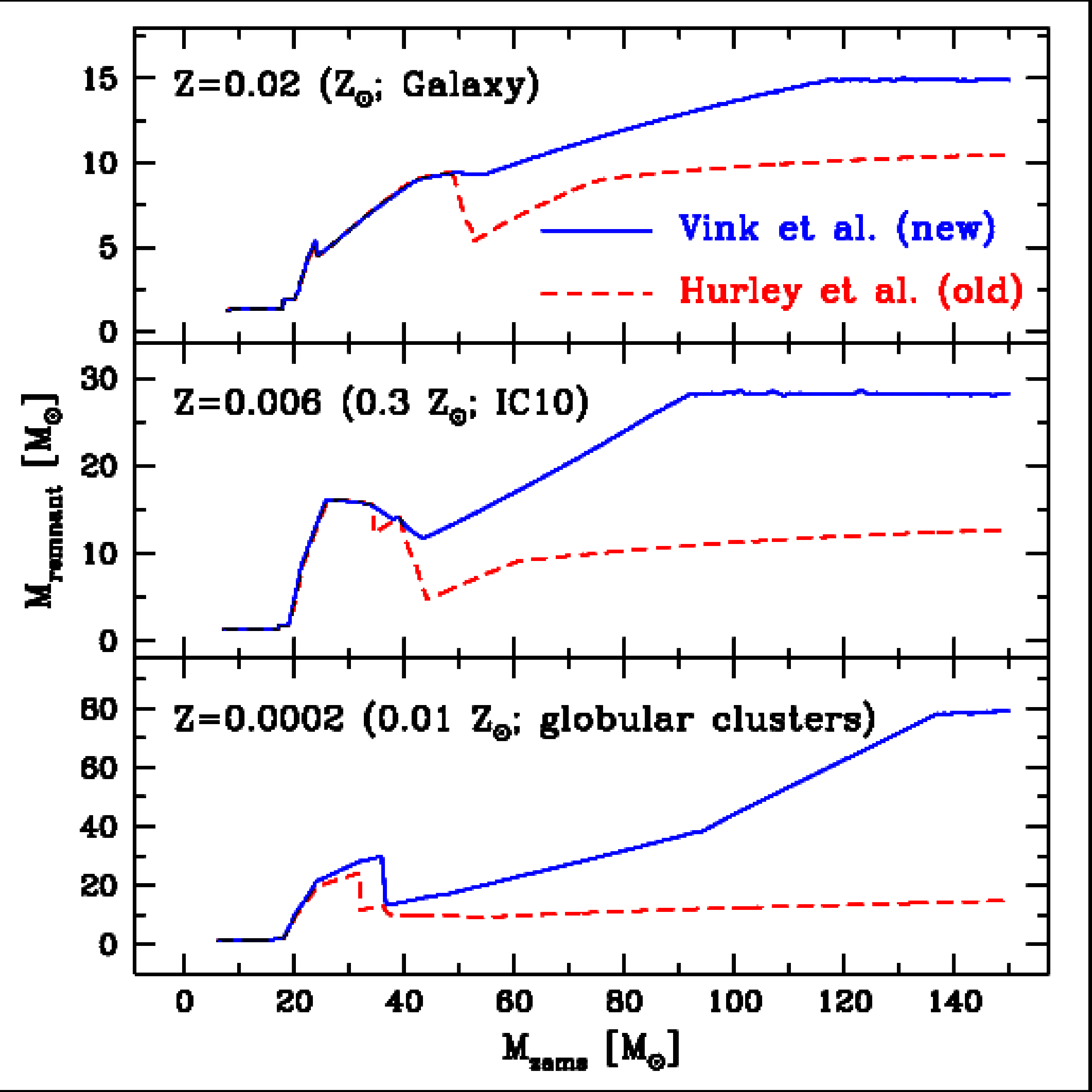


Metallicity

Initial mass (Msun)

Heger et al. (2002, 2003)

Role of metallicity:



30-80 Msun BHs can be formed if Z< 0.4 Zsun

Belczynski et al. (2010)

And so what?

A factor of 3-8 larger mass of stellar BHs

IMPLIES FUNDAMENTAL DIFFERENCES

2-MODEL: predictions for ULXs

ULXs: X-ray sources with L_X>10^39 erg s^-1

if ISOTROPIC,

Eddington luminosity of >7 Msun BH

TOO HIGH!!!

POSSIBLE ORIGIN of ULXs:

1. beamed emission;
2. super-Eddington luminosity;
3. IMBHs;
4. massive BHs in low-metallicity environments!!!

Can we estimate the number of these BHs?
from SFR + lifetime of companion + IMF:

$$N_{\mathrm{BH}} = A \int_{\boxed{m_{\mathrm{prog}}(Z)}}^{m_{\mathrm{max}}} m^{-\alpha} \mathrm{d}m$$

$$A = \frac{\boxed{\mathrm{SFR}} \quad t_{\mathrm{co}}}{\int_{m_{\mathrm{min}}}^{m_{\mathrm{max}}} m^{1-\alpha} \, \mathrm{d}m}$$

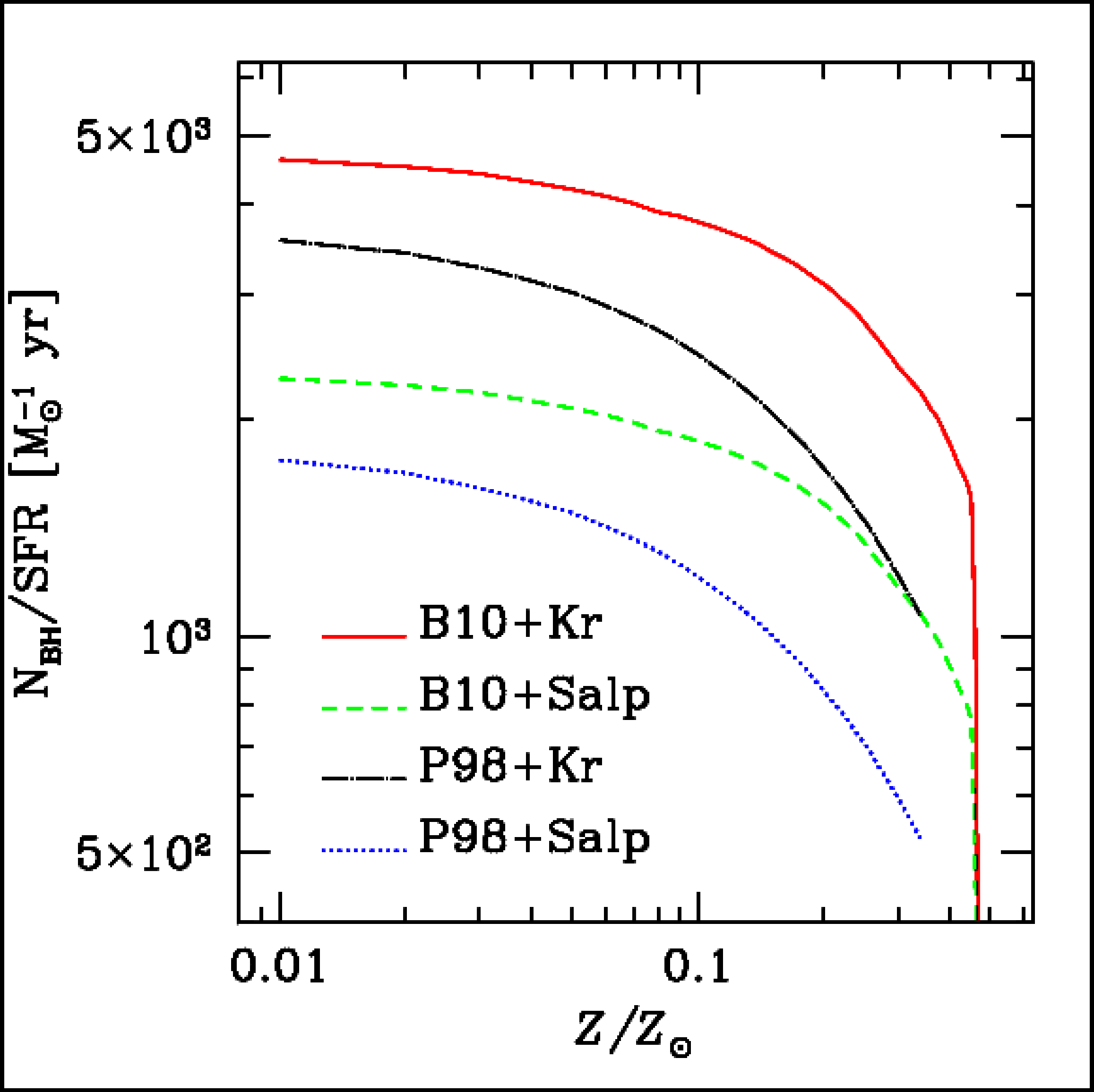
~10^5 massive BHs in Cartwheel for

→ **SFR=20 Msun yr^-1, t_{co}=10^7 yr,**

Salpeter or Kroupa IMF

MM, Colpi & Zampieri 2009

N_{BH}/SFR-Z



MM et al. 2010a

3 – comparison
data - model

The SAMPLE

66 GALAXIES with

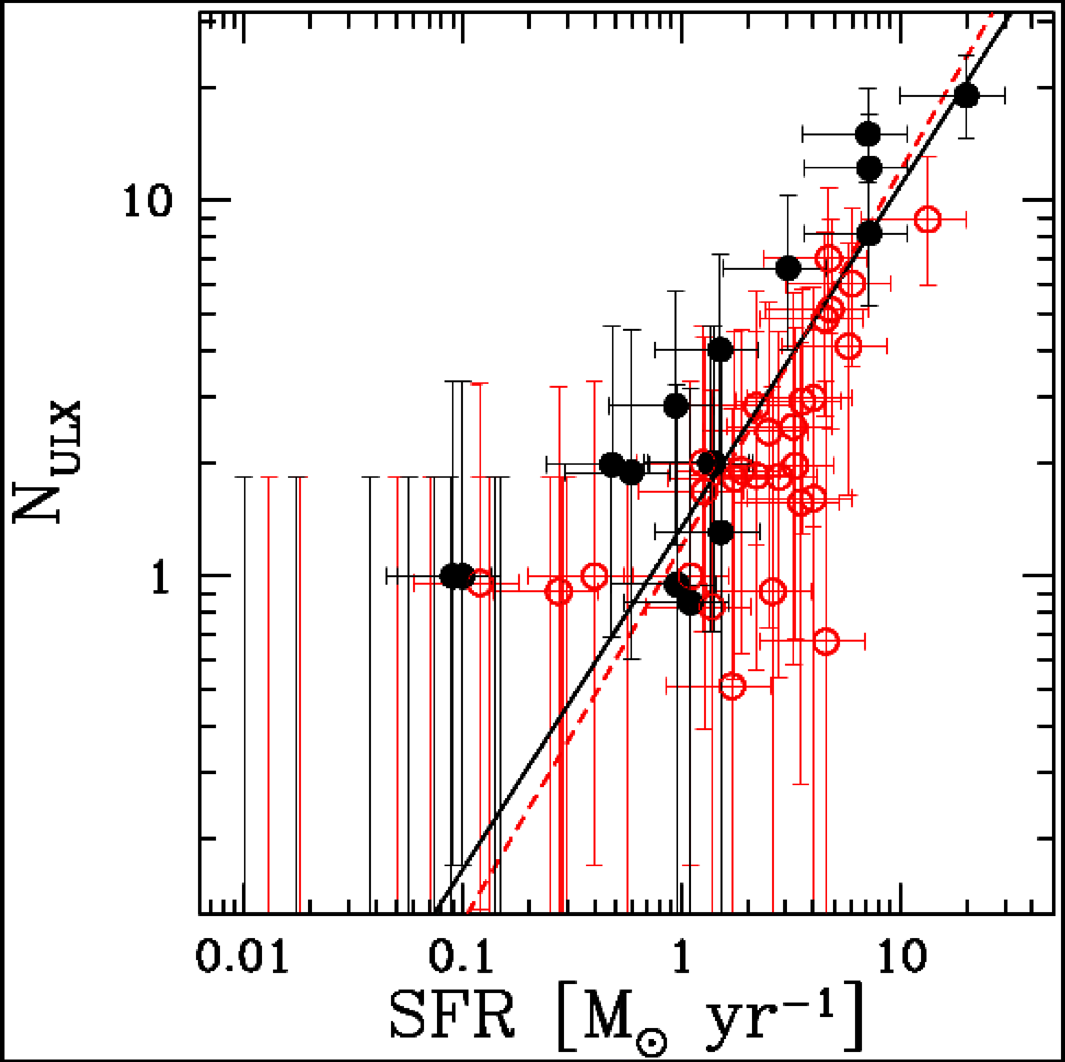
1) X-ray coverage (Rosat catalogue ->Liu & Bregman 2005, Chandra, XMM)

2) SFR measurement (Halpha, FIR, UV, radio,..)

3) homogeneous metallicity measurement and calibration (Pilyugin 2001 calibration)

4) spiral&irregular no ellipticals

NULX-SFR



$$\delta = 0.91^{+0.25}_{-0.15}$$

$$\zeta = 0.13^{+0.10}_{-0.14}$$

consistent with e.g. Grimm, Gilfanov, Sunyaev 2003; Ranalli, Comastri & Setti 2003

$$N_{\rm ULX} = 10^{\zeta}\left(\frac{\rm SFR}{{\rm M}_\odot\ {\rm yr}^{-1}}\right)^{\delta}$$

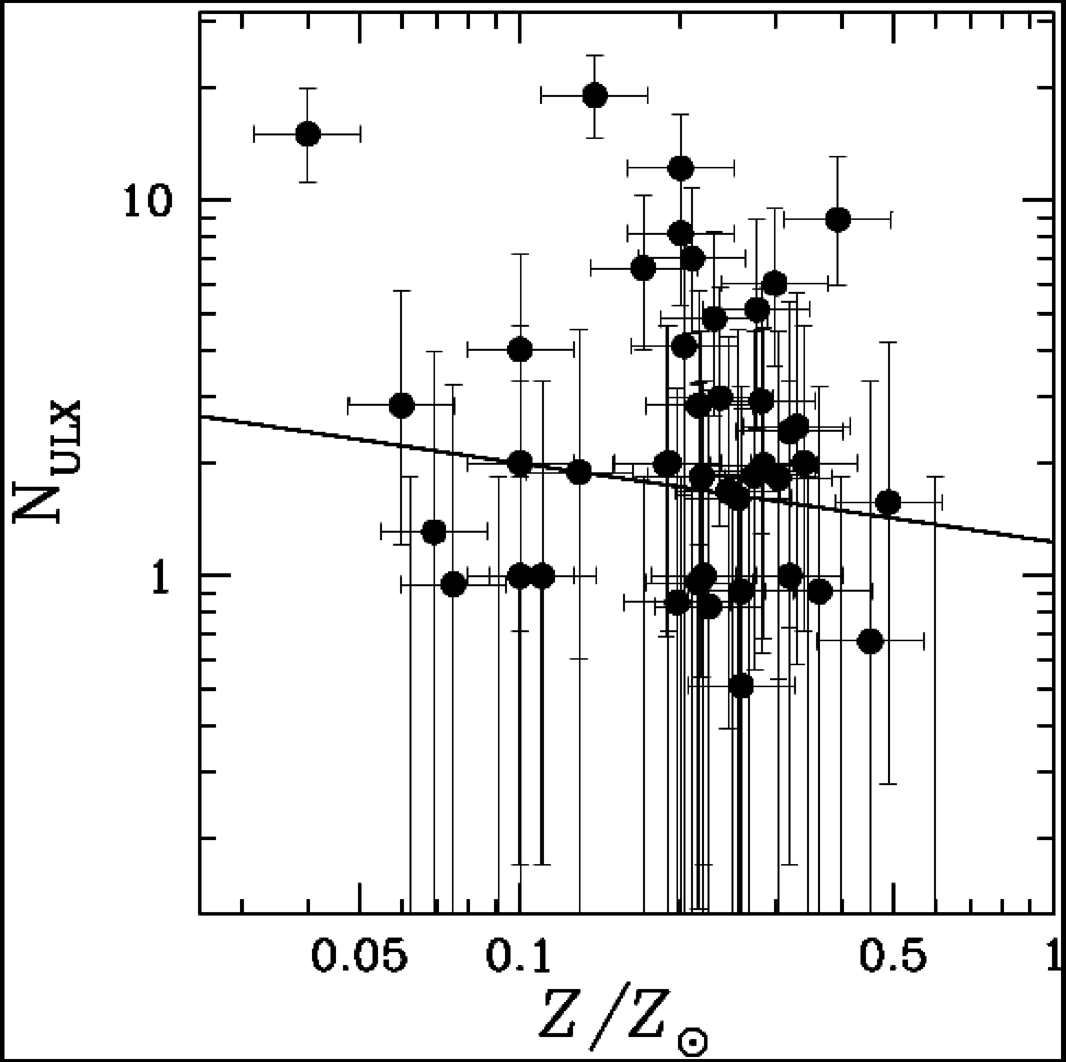
MM et al. 2010a

N_{BH}-SFR

In the DATA: N_{ULX} scales with SFR (slope = 0.91 +/- 0.2)

In the model: We DO assume that N_{BH} scales with SFR (slope = 1)

N_{ULX}-Z



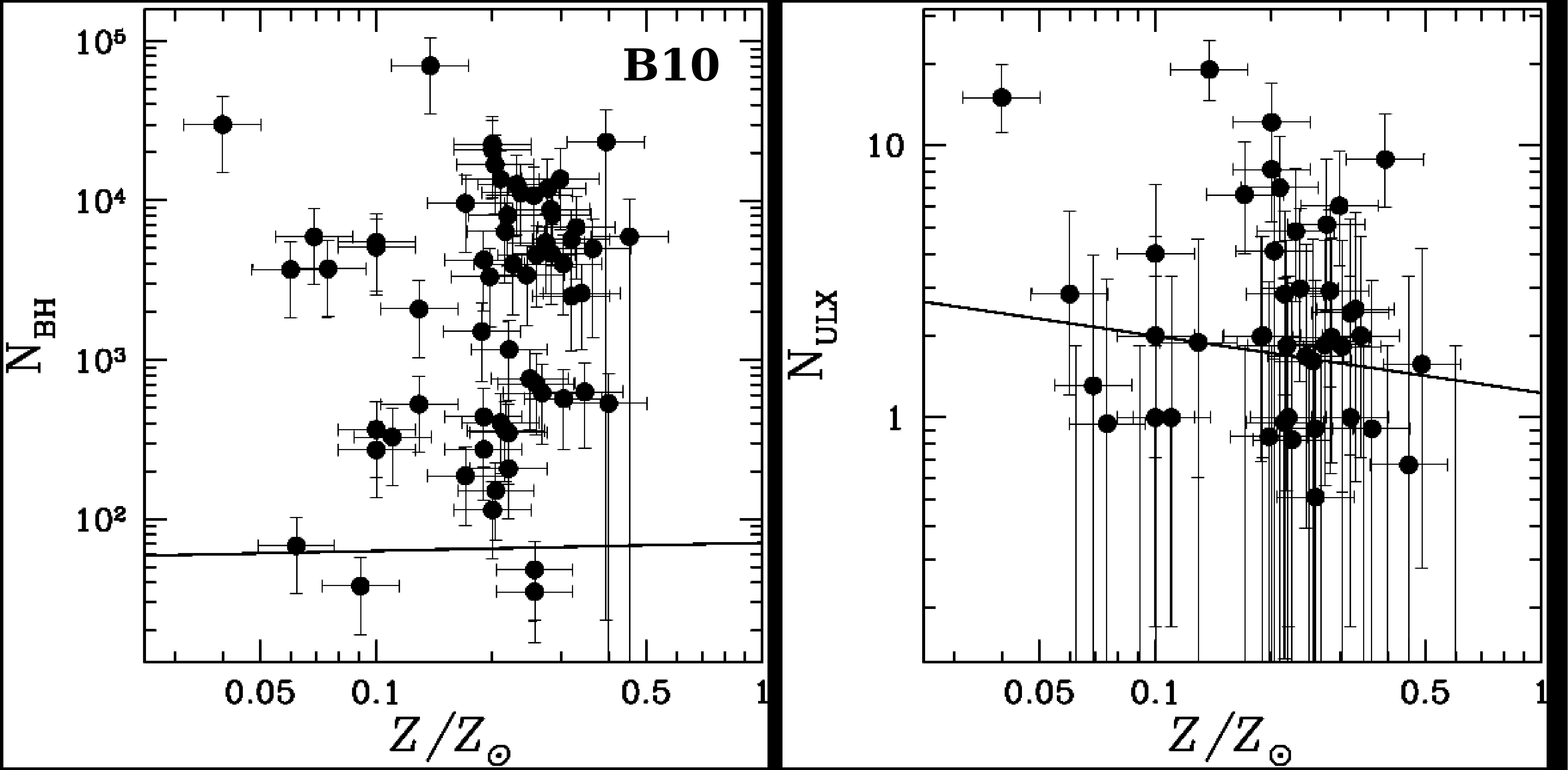
$$\eta = -0.21 \pm 0.27$$
$$\theta = 0.09 \pm 0.20$$

NOT statistically significant!!

$$N_{ULX} = 10^{\theta} \left(Z/Z_\odot\right)^{\eta}$$

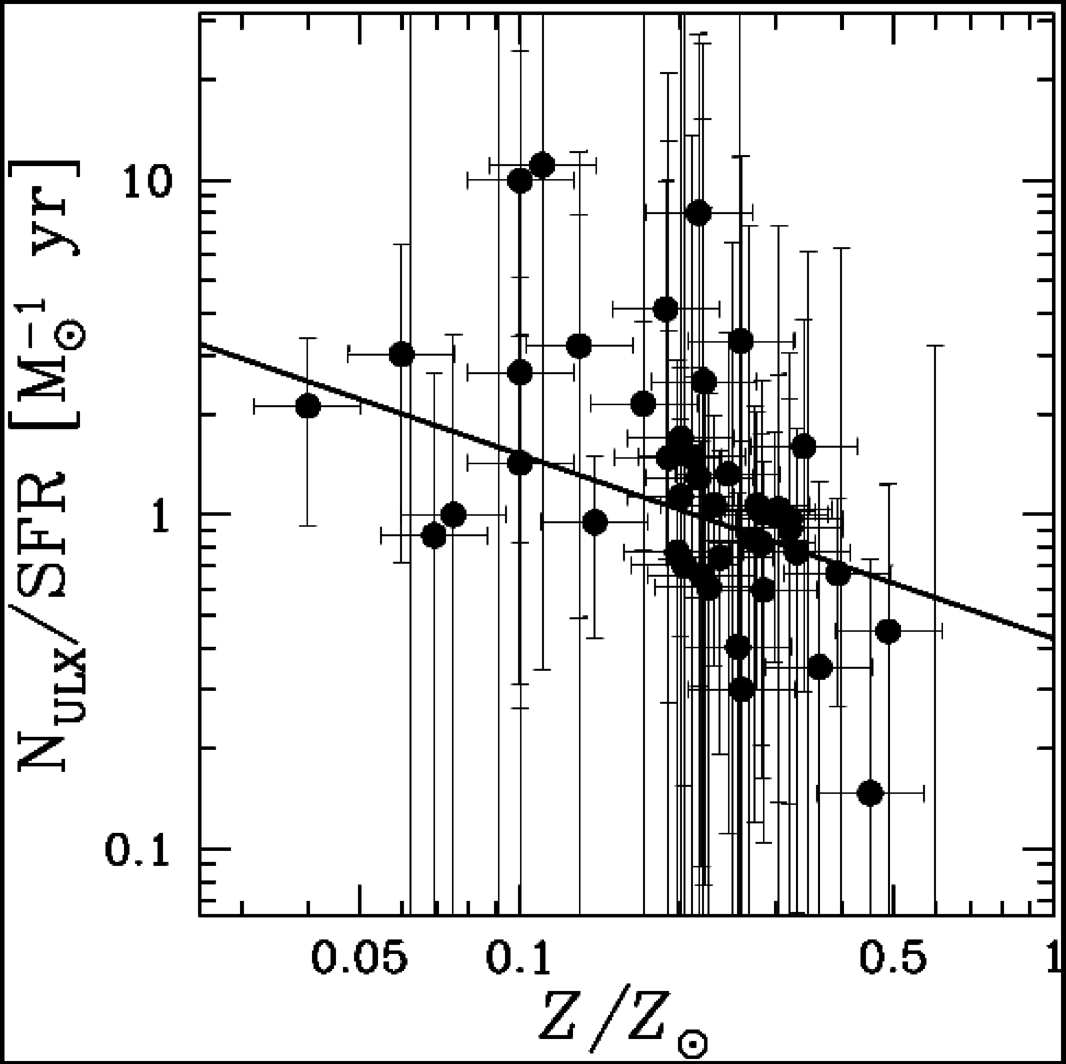
MM et al. 2010a

N_{BH}-Z



Not statistically significant in model & data

NULX/SFR-Z



$$\iota_1 = -0.55 \pm 0.23$$

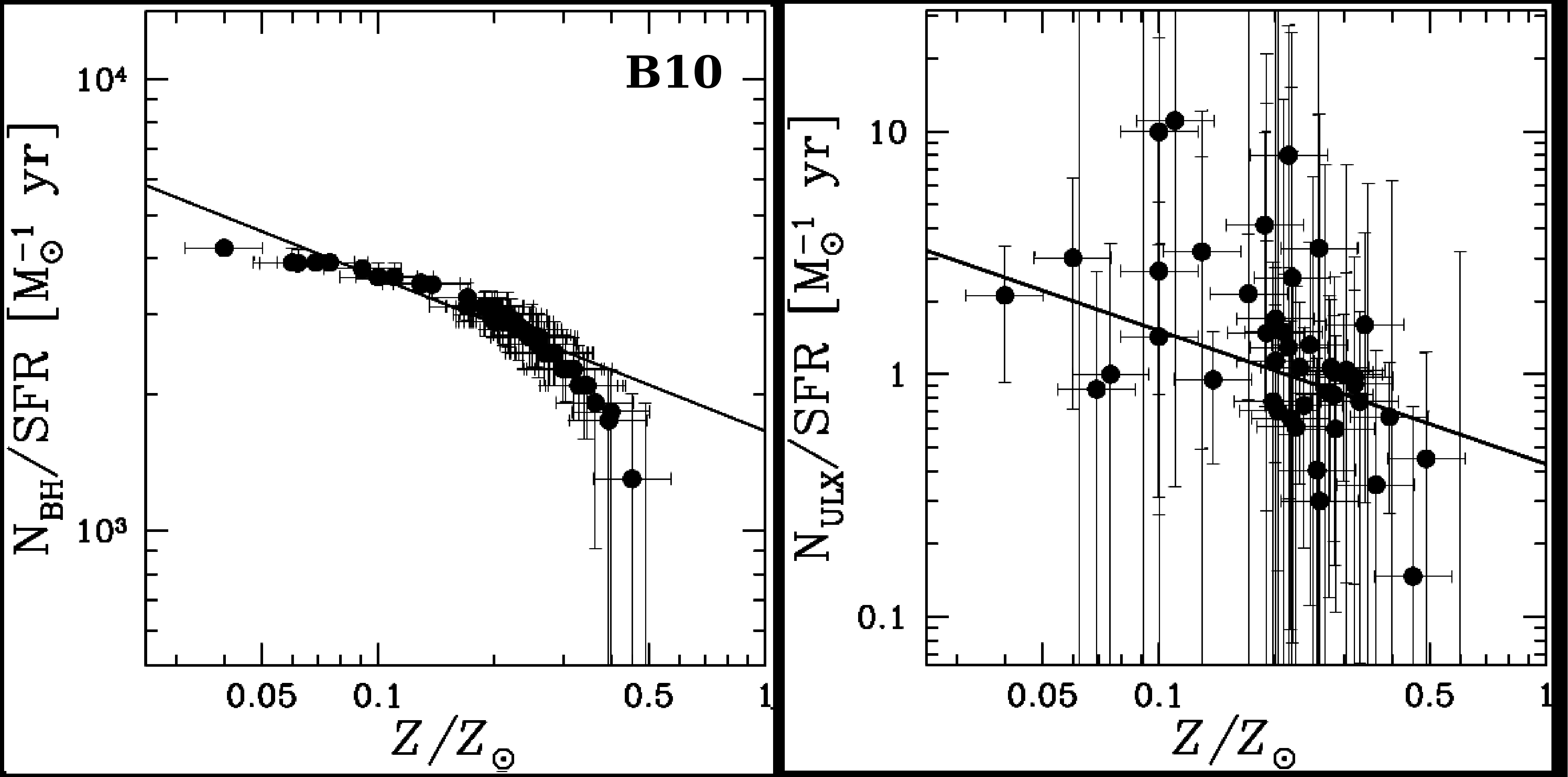
$$\kappa_1 = -0.37 \pm 0.18$$

With F-test significant at 96% confidence level

$$\left(N_{ULX} \frac{M_\odot\ yr^{-1}}{SFR} \right) = 10^{\kappa_1} \left(Z/Z_\odot \right)^{\iota_1}$$

MM et al. 2010a

N_{BH}/SFR-Z



Slope of the model= -0.6 — -0.34

Slope of the data = -0.55 +/- 0.2

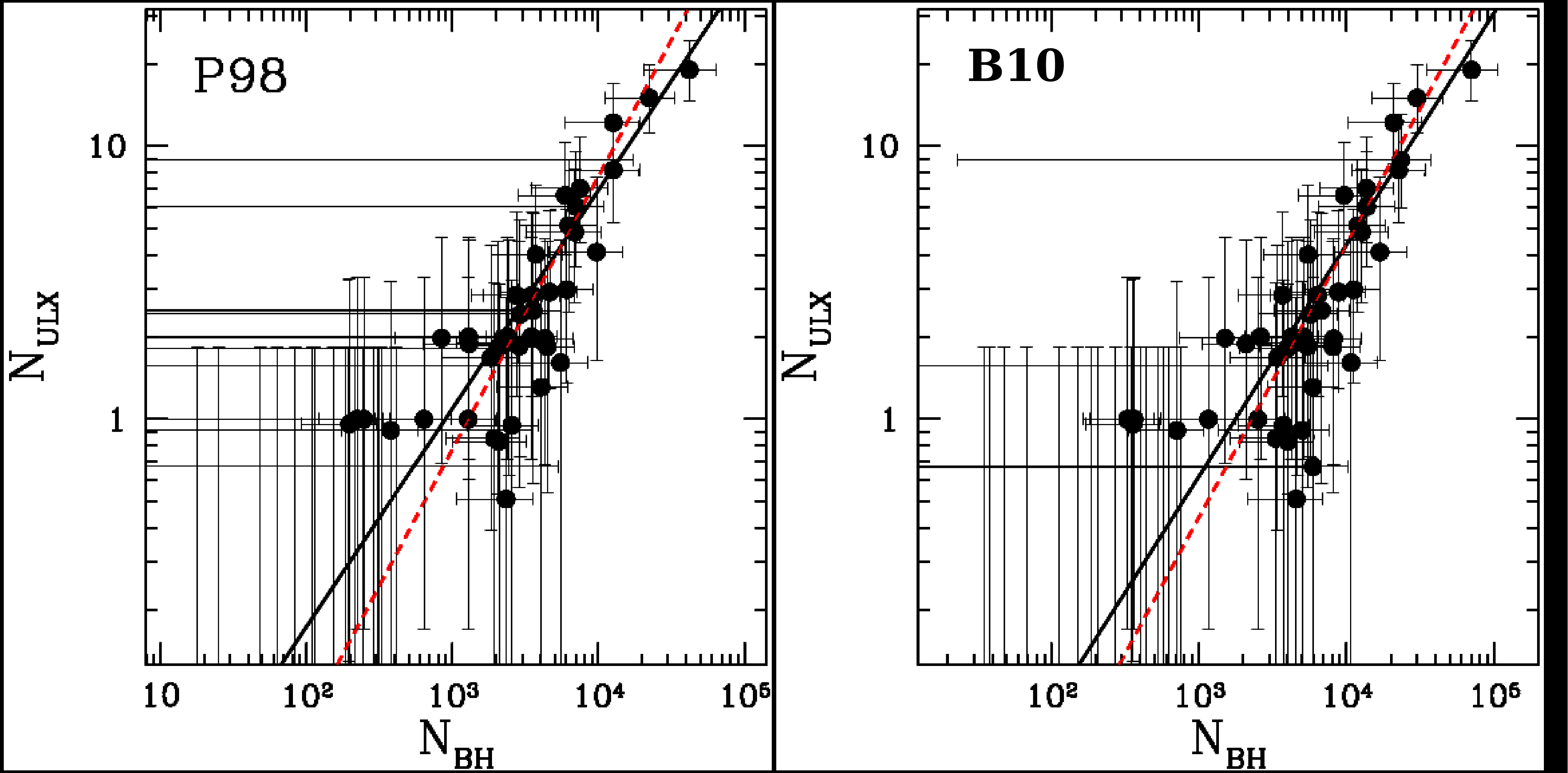
NULX/SFR-Z

Possible role of metallicity (less important than SFR) in forming ULXs

consistent with previous studies:
Pakull & Mirioni (2002), Cropper et al. (2004), Zampieri et al. (2004), Swartz et al. (2008); Mapelli, Colpi & Zampieri (2009); Zampieri & Roberts (2009), etc.

NBH-NULX

$$N_{ULX} = 10^{\gamma}\, N_{BH}^{\beta}$$



$$\beta = 0.80^{+0.16}_{-0.12} \qquad \beta = 0.85^{+0.19}_{-0.13}$$

$$\gamma = -2.36^{+0.45}_{-0.62} \qquad \gamma = -2.76^{+0.53}_{-0.76}$$

We must increase the SAMPLE:

EXTREMELY METAL DEFICIENT GALAXIES (XMDs)

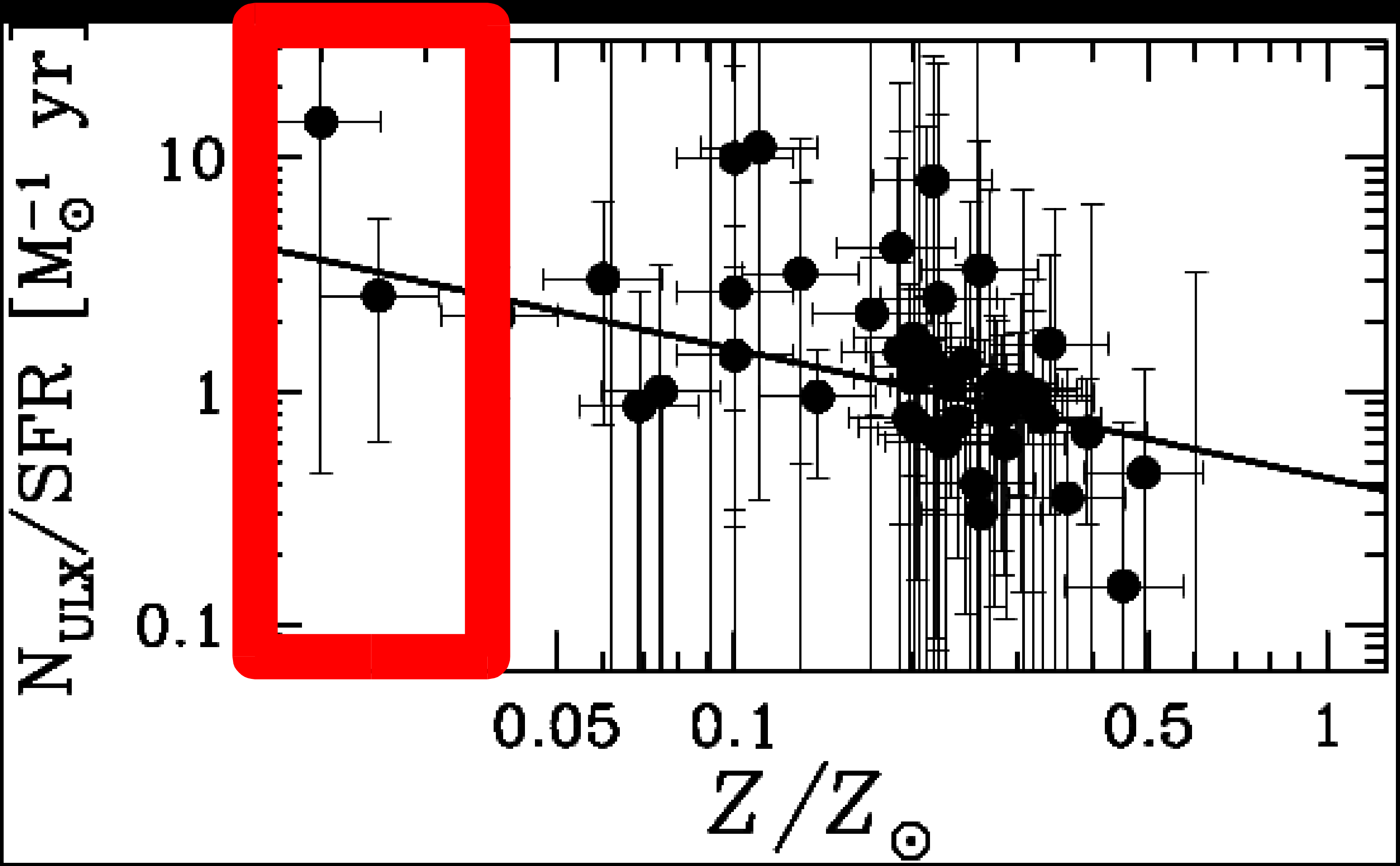
- Z <~1/20 Zsun
- low mass
- high SPECIFIC SFR
- ULXs

(e.g. Thuan et al. 2004)

Galaxy I Zwicky 18

Hubble Space Telescope • ACS/WFC

PRELIMINAR RESULT: 2 XMDs



MM et al. 2010b

THEORETICAL ISSUEs:

1) How can HMXBs form including BHs born through direct collapse?

2) Alternative scenarios predicting N_{ULX}-Z relation (e.g. Mass transfer more efficient in low metallicity, Linden et al. 2010)

4 – ejections

Massive BHs affect DYNAMICS in STELLAR CLUSTERs (globular & young):

- collisional systems:
  half-mass relax. time <~ Gyr
- core dominated by 3-, 4-, N- body encounters;
- 30-80 Msun BHs are the most massive objects in star clusters

$$\nu_{3\mathrm{b}} \propto \frac{\boxed{M}\, a}{\sigma}$$

→ Massive BHs likely dominate dynamics in star clusters

Massive BHs affect DYNAMICS in STELLAR CLUSTERs (globular & young):

is it important??????

ULXs found displaced (0.1-1 kpc) from SF regions (Zezas et al. 2002; Swartz et al. 2009; Berghea 2009 PhD thesis)

is it due to ejections?

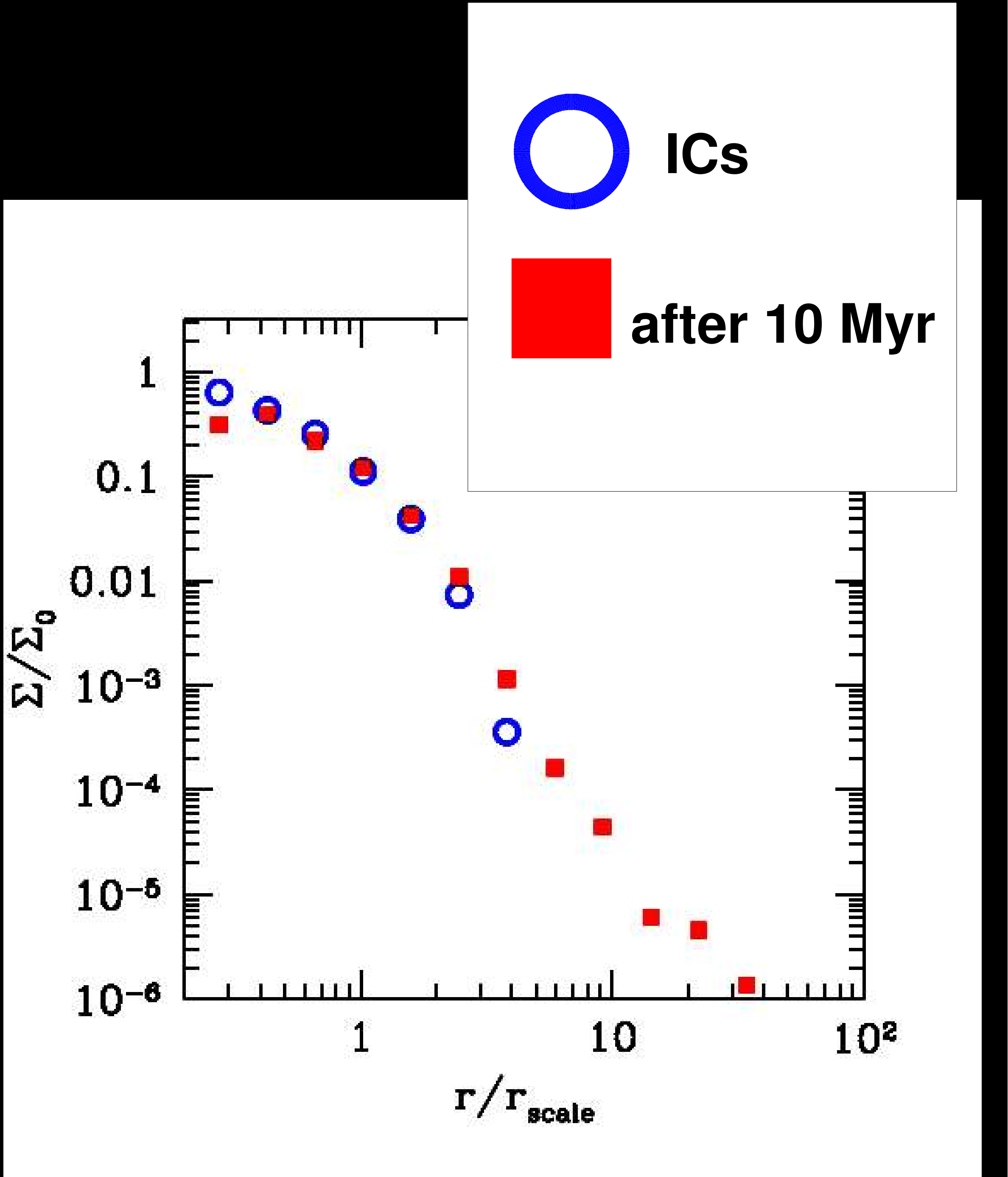
Simulations of young star clusters + massive BH binary with Starlab

Simulations of young star clusters + massive BH binary with Starlab:

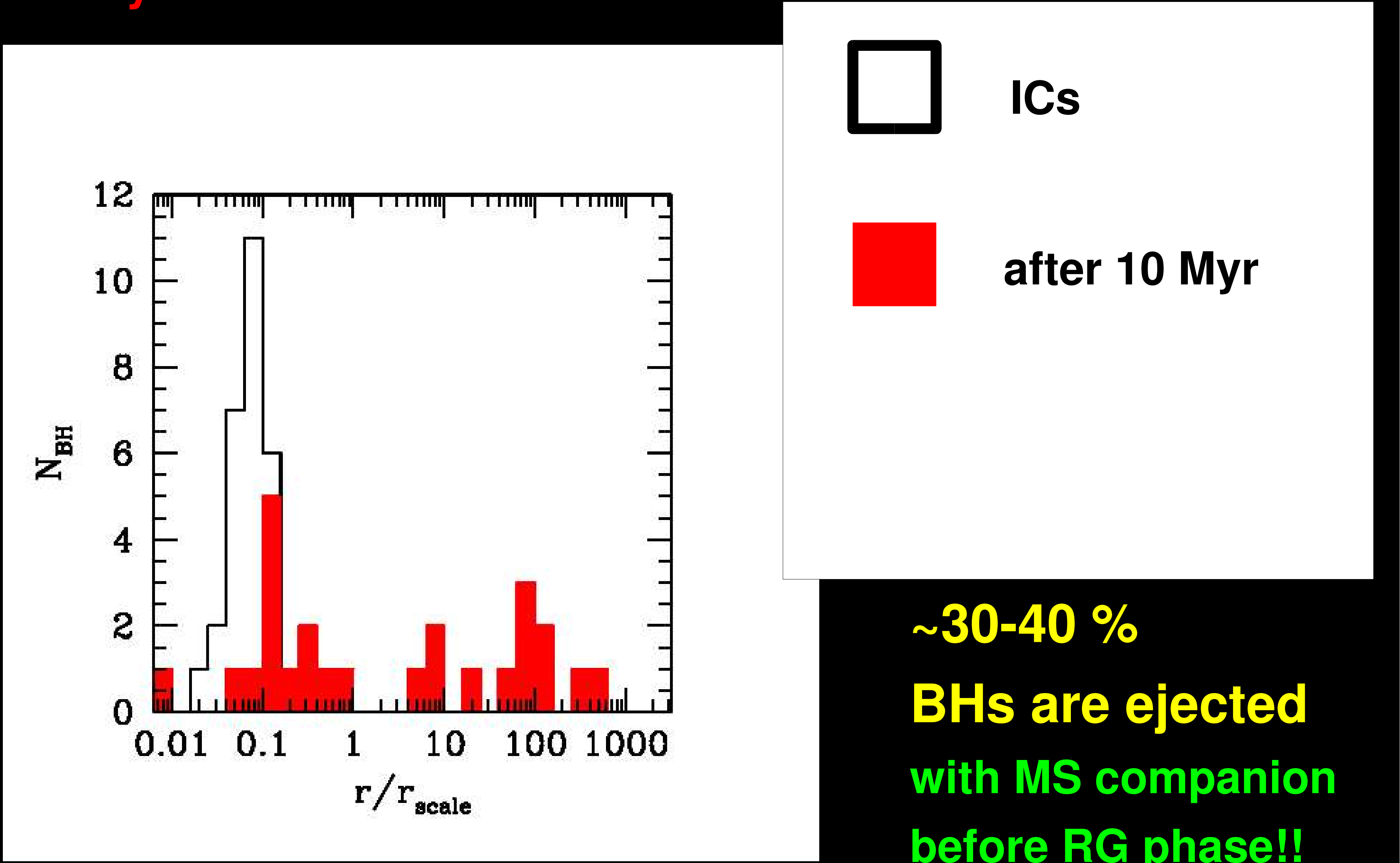
- multiple realization of a star cluster (5000 stars, ~3000 Msun, Salpeter IMF, King profile W=5)

- massive BH (~50 Msun) binary

- direct integration of 3-body encounters



Simulations of young star clusters + massive BH binary with Starlab:



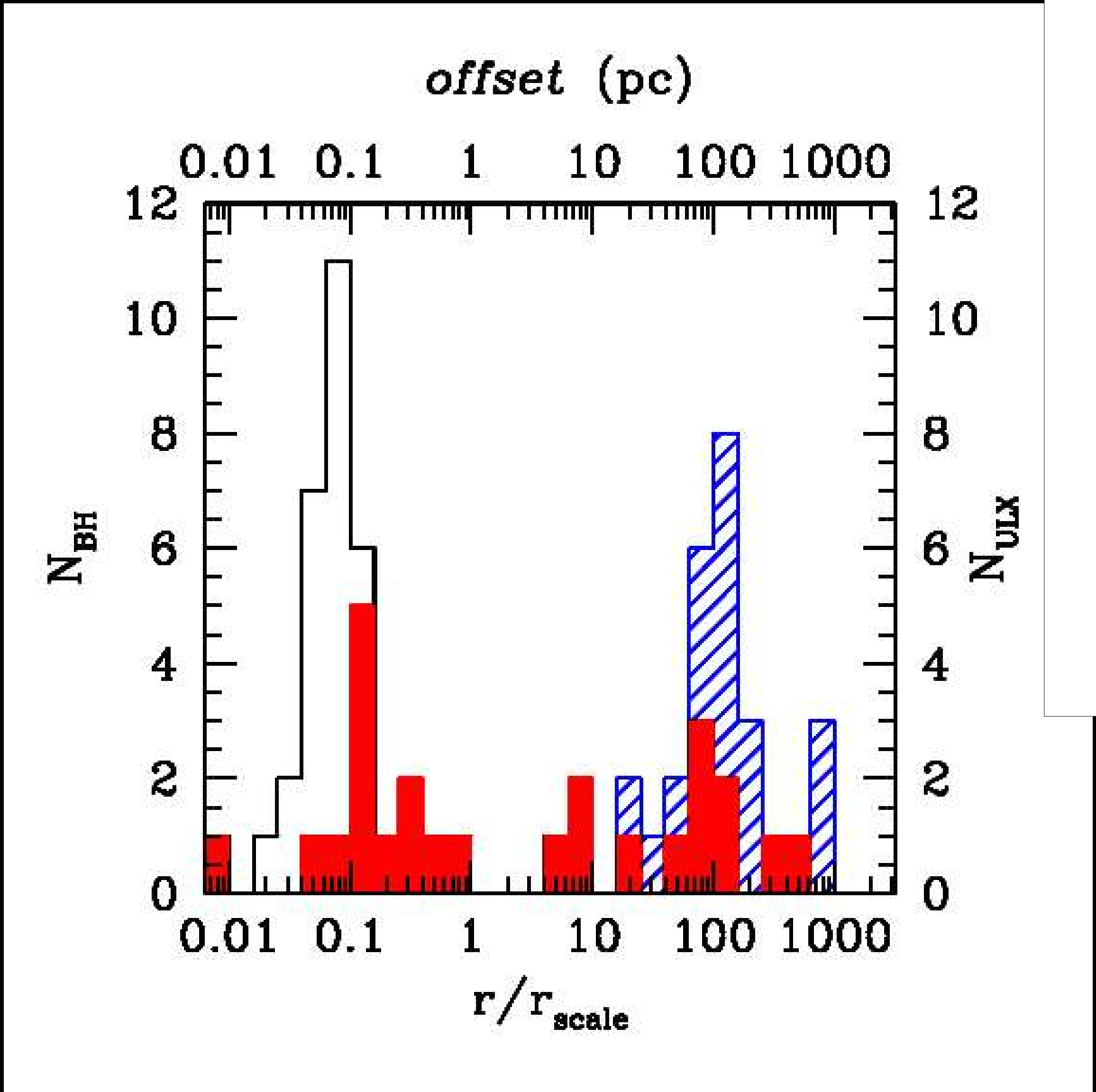
~30-40 %

BHs are ejected

with MS companion

before RG phase!!

Simulations of young star clusters + massive BH binary with Starlab:



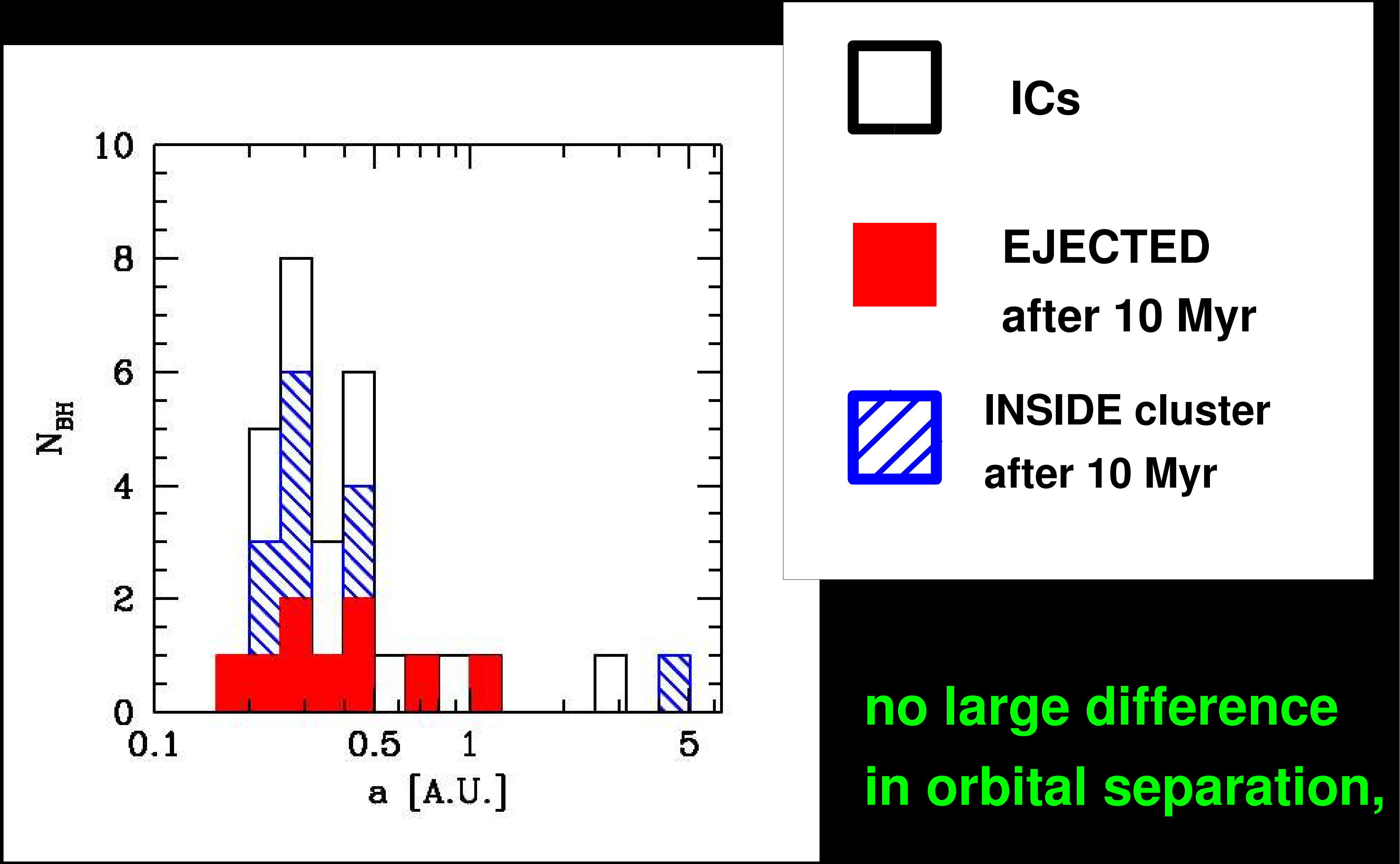
□ ICs

🟥 after 10 Myr

▨ data of ULXs
from Berghea PhD

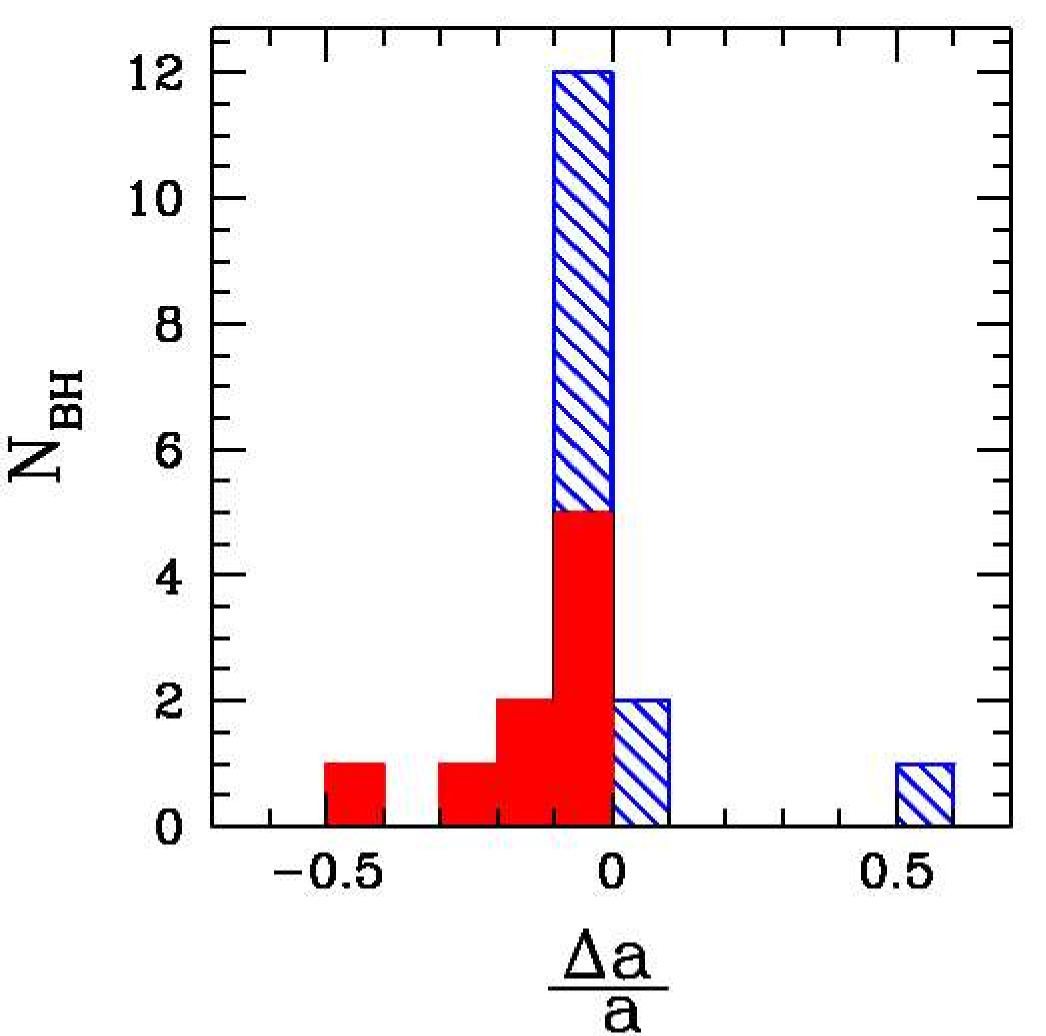
~30-40 %
BHs are ejected
with MS companion
before RG phase!!

More data from Starlab simulations: semi-major axis



no large difference
in orbital separation,

More data from Starlab simulations: semi-major axis

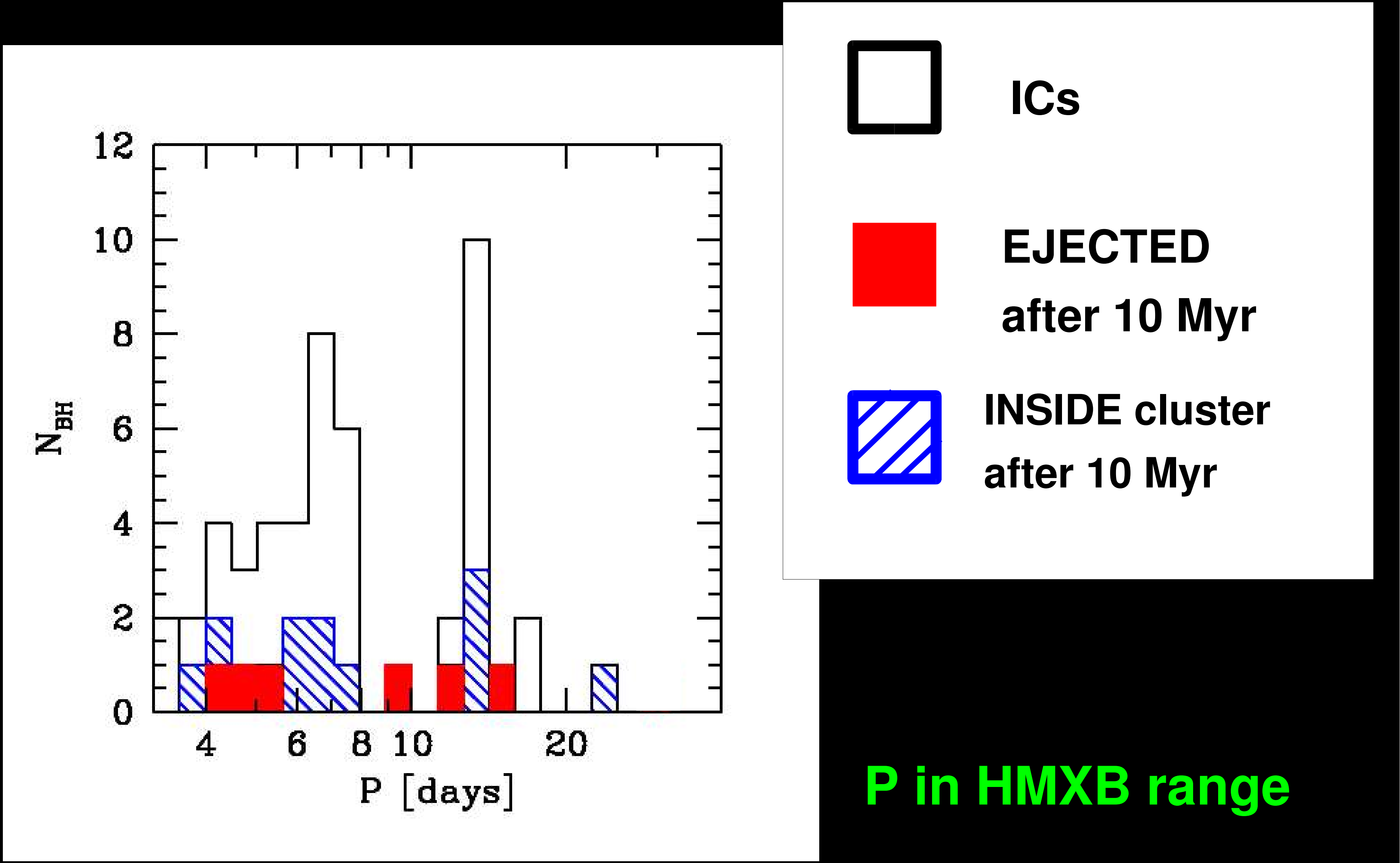


🟥 **EJECTED after 10 Myr**

▨ **INSIDE cluster after 10 Myr**

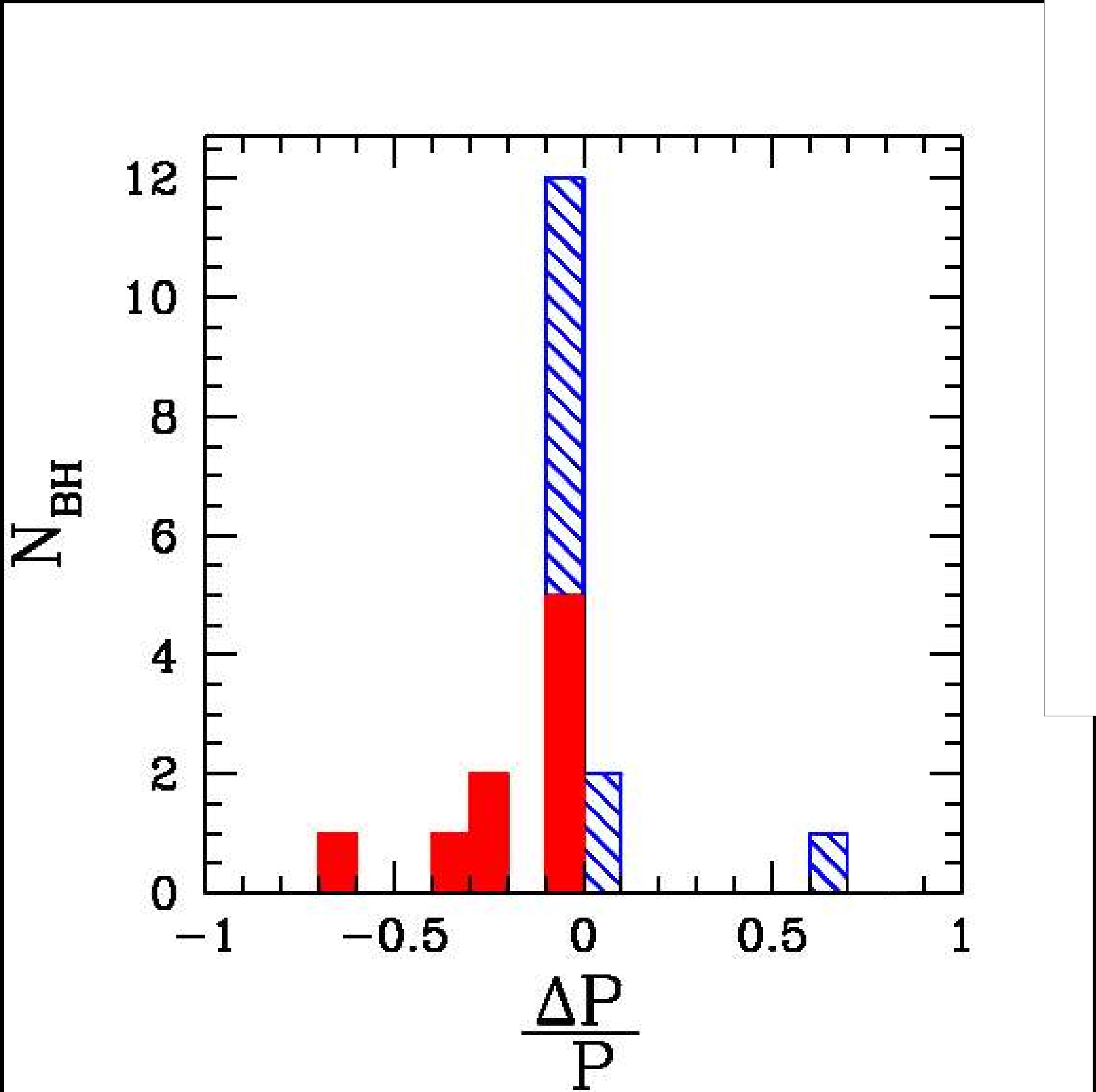
but all ejected binaries shrink (kick sufficient for HMXBs?)

More data from Starlab simulations: orbital period



P in HMXB range

More data from Starlab simulations: orbital period



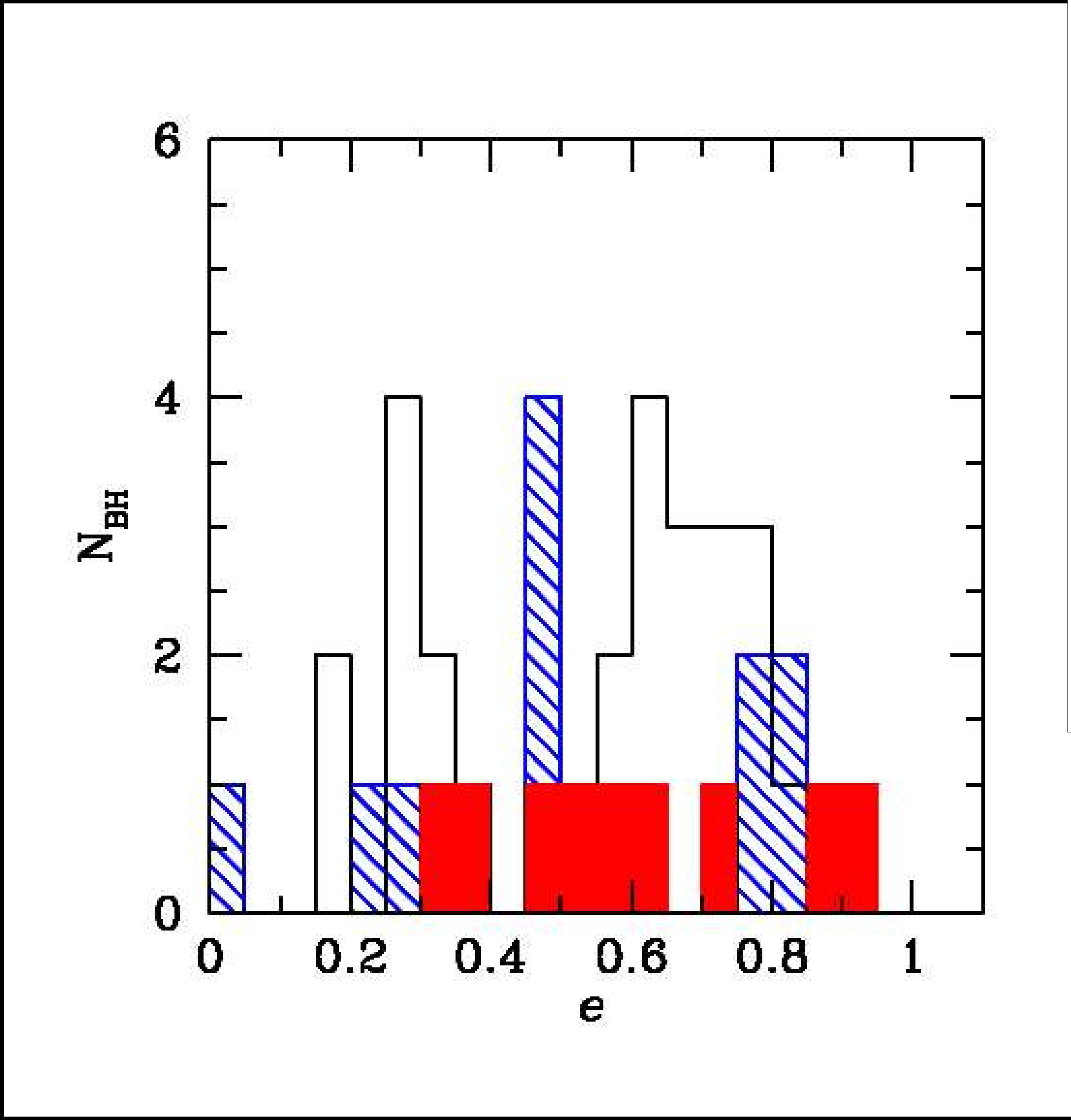
☐ ICs

🟥 EJECTED
after 10 Myr

▨ INSIDE cluster
after 10 Myr

P reduces in ejected binaries

More data from Starlab simulations: eccentricity



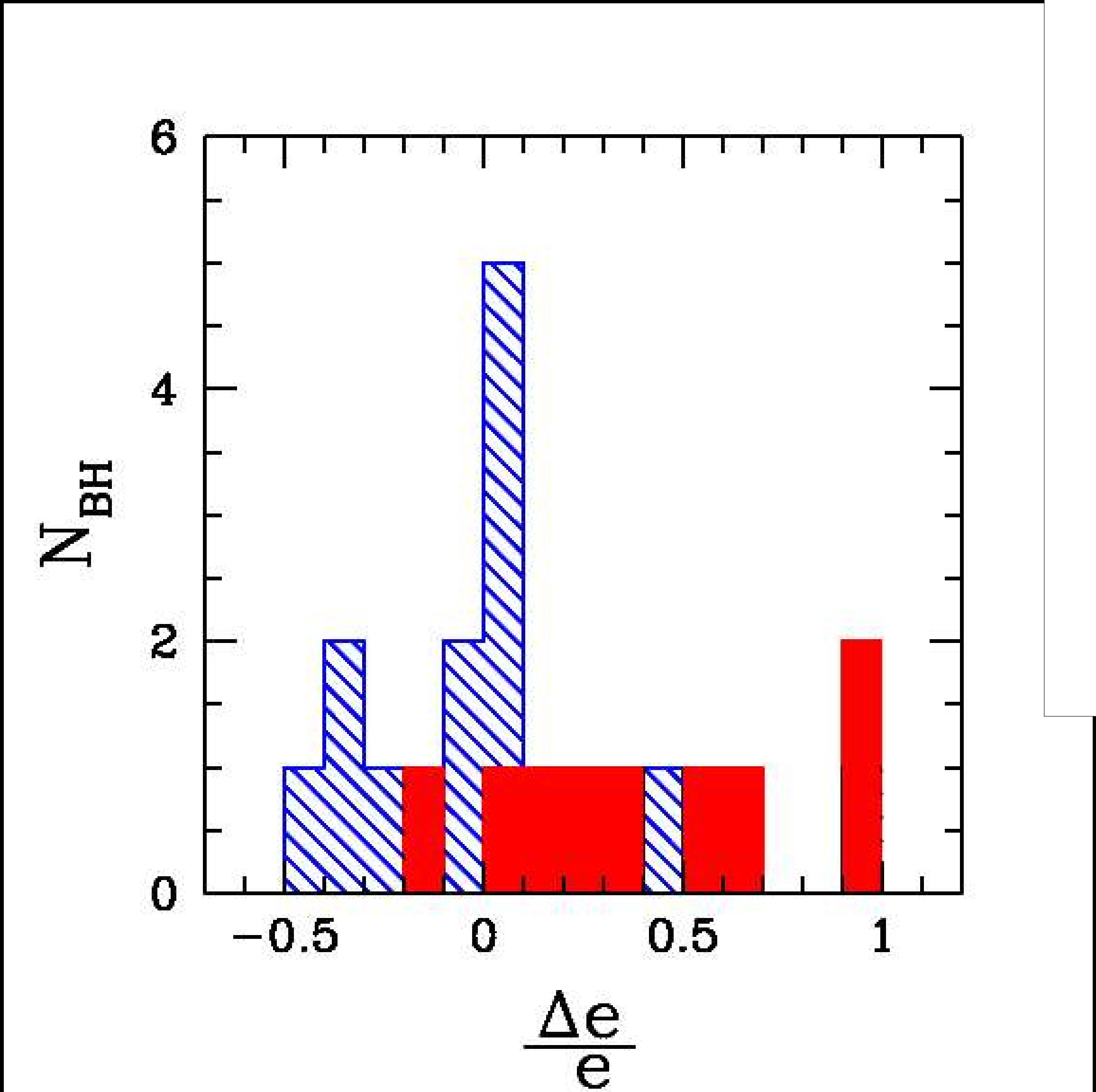
☐ **ICs**

🟥 **EJECTED after 10 Myr**

▨ **INSIDE cluster after 10 Myr**

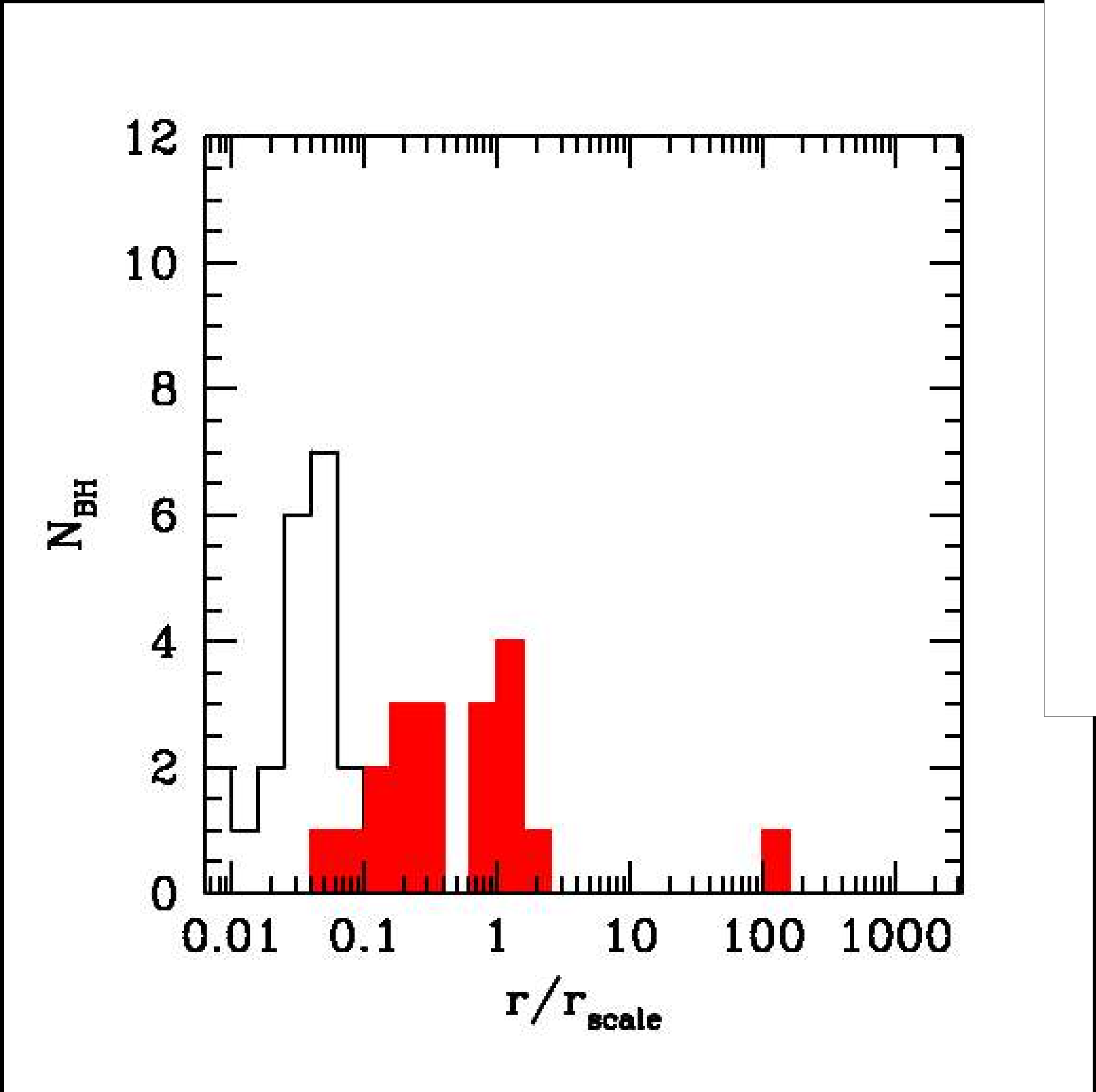
increase of ecc. in escapers

More data from Starlab simulations: eccentricity



increase of ecc. in escapers, but circularization time short (~1000 yr)

More data from Starlab simulations: IMBHs (300 Msun)



☐ **ICs**

🟥 **after 10 Myr**

only 1 escaper

CONCLUSIONS:

1) METALLICITY strongly AFFECTS BH mass

2) ULXs might be explained as massive BH binaries

3) Massive BH binaries important in star clusters

FUTURE:

1) More data for understanding ULXs (XMDs)

2) Comparison with data ULX displacement- BH ejections

3) theoretical models of mass transfer (HMXBs?)

3) contribution of massive BHs to GWs

4) failed SNAe reduce stellar yields:
chemical evolution of galaxies must be revised

THANKS

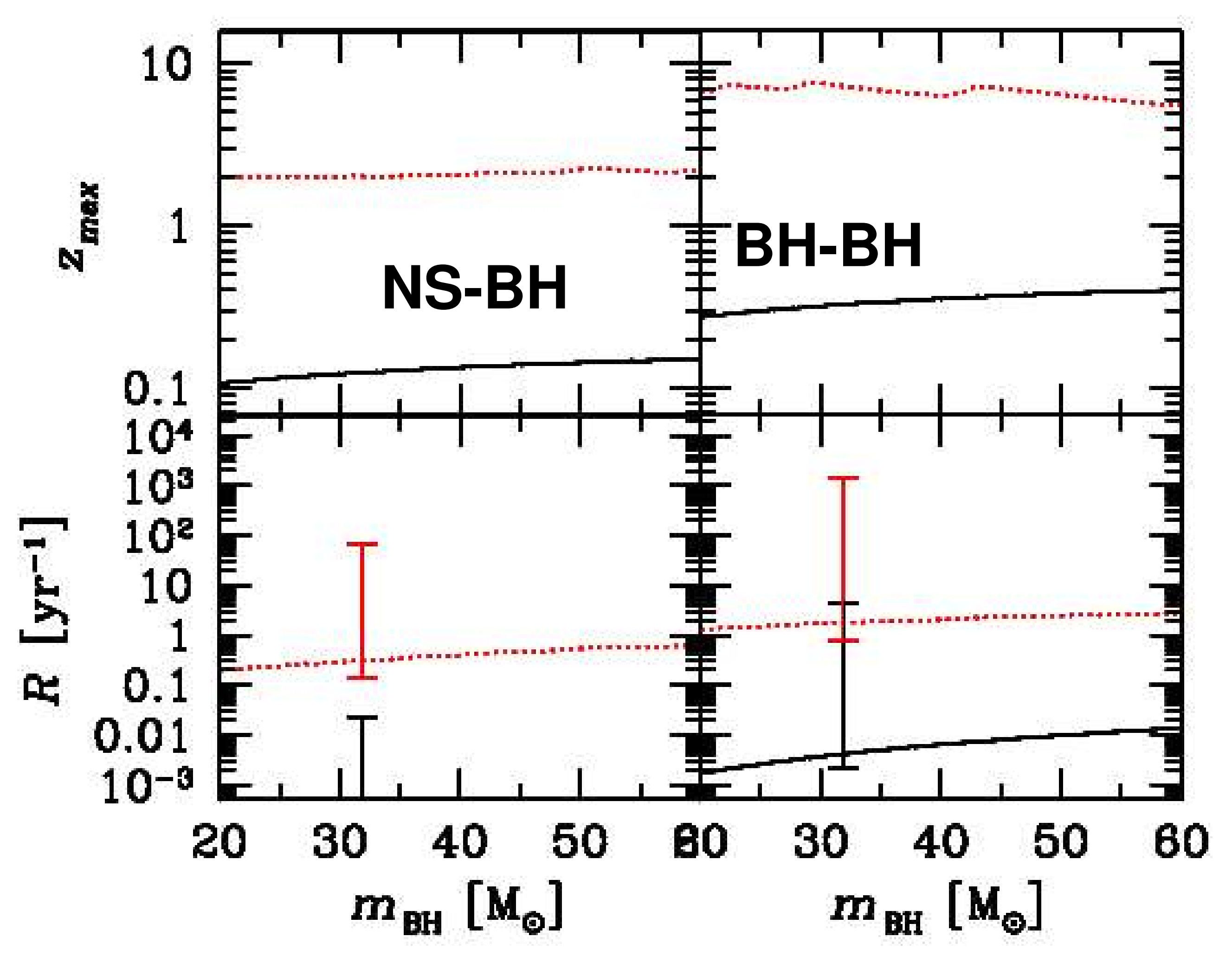
5 – gravitational waves

GWs from massive BHs, INGREDIENTS:

- density of BHs correlates with cosmic SFR (from Hopkins & Beacom 2006 data) BUT ONLY AT LOW METALLICITY!
- merger rate from 3-body rate
- instrumental range from Ajith et al. (2008, 2009)
- accurate integration over comoving volume

Different BH mass changes predictions for GW detection?

Predictions for MASSIVE BHs:



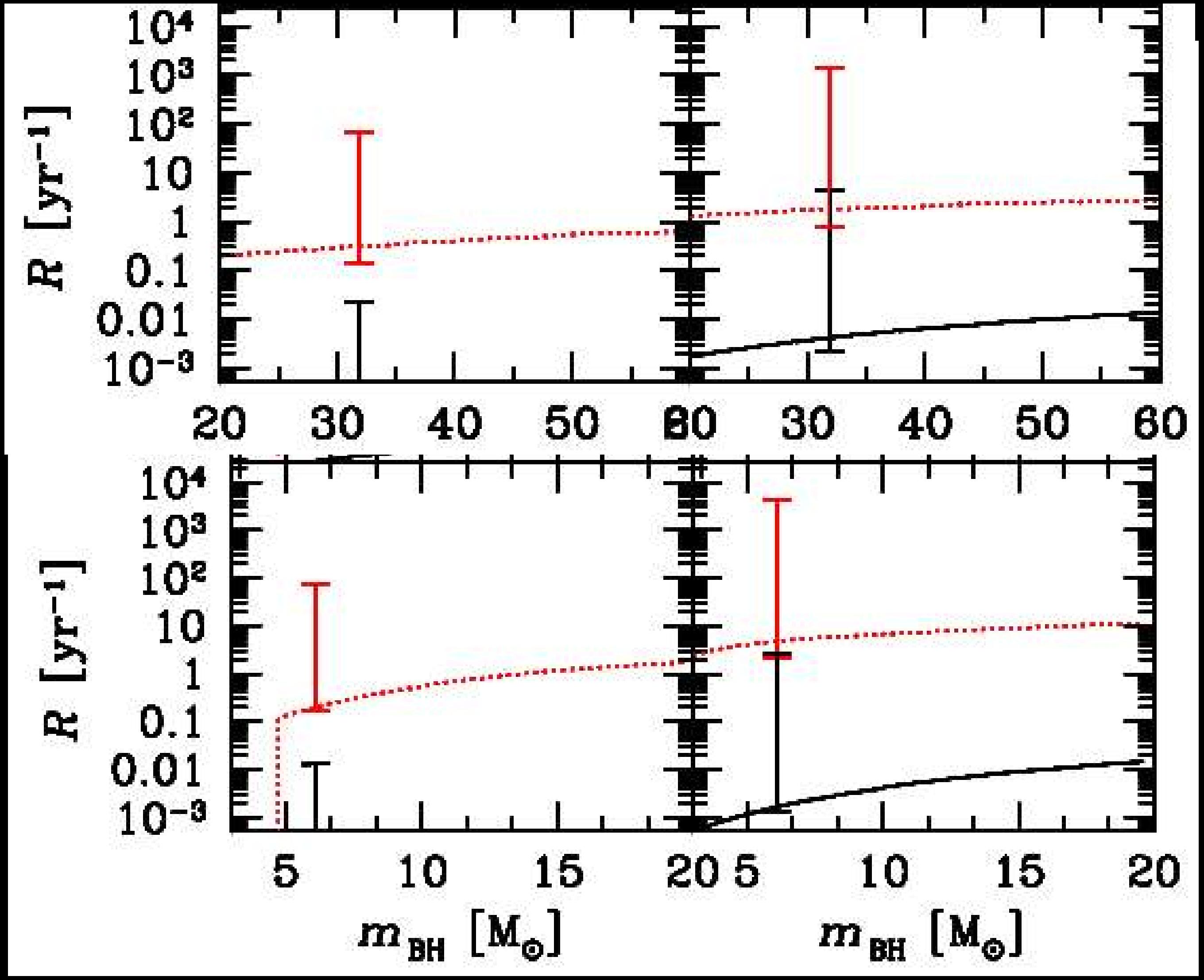
RED:
Einstein
Telescope

BLACK:
Advanced
LIGO

Bruno et al., in preparation

Different BH mass changes predictions for GW detection?

Comparison stellar BHs (bottom) / massive BHs (top)

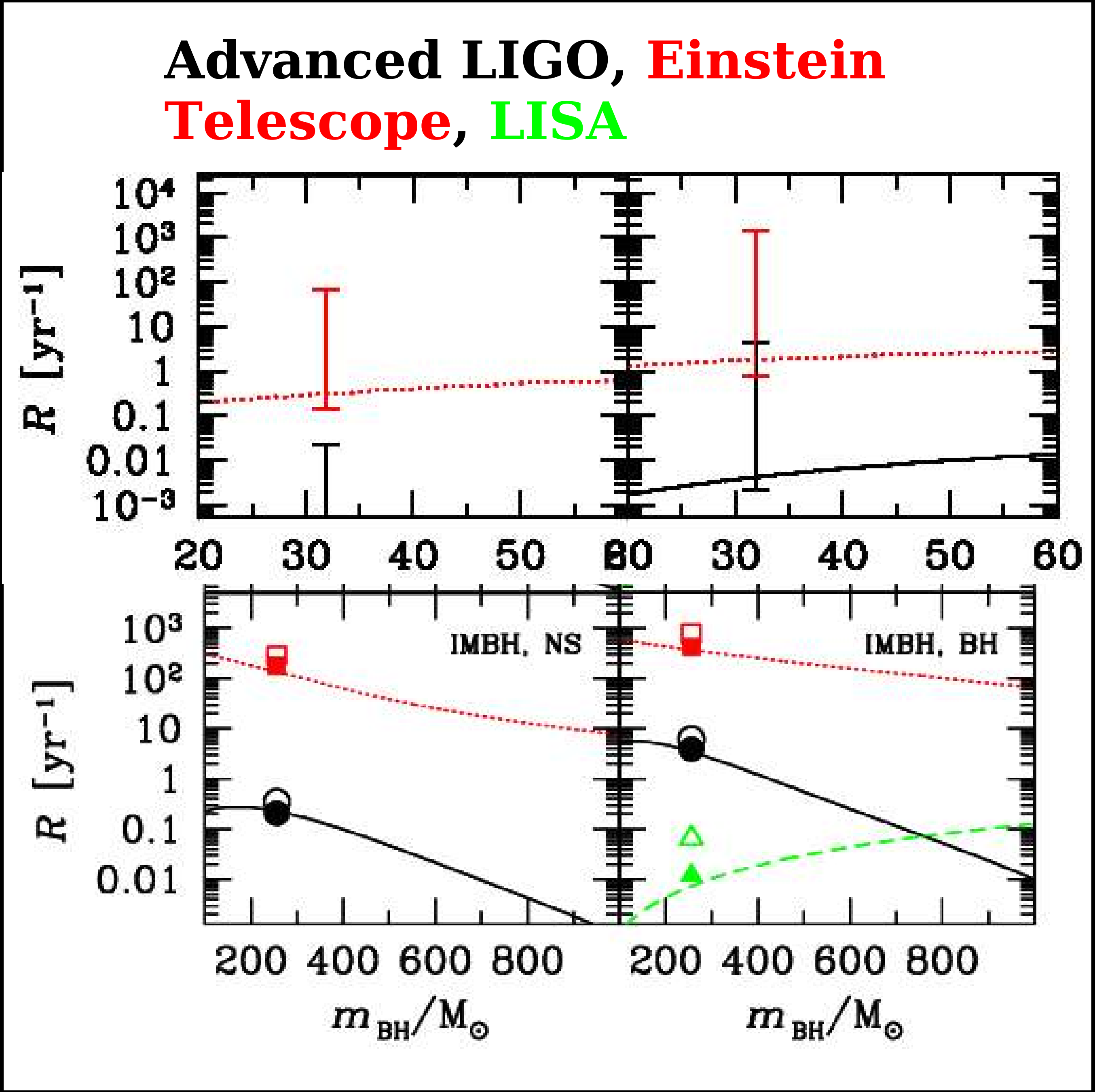


RED: Einstein Telescope

BLACK: Advanced LIGO

Bruno et al., in preparation

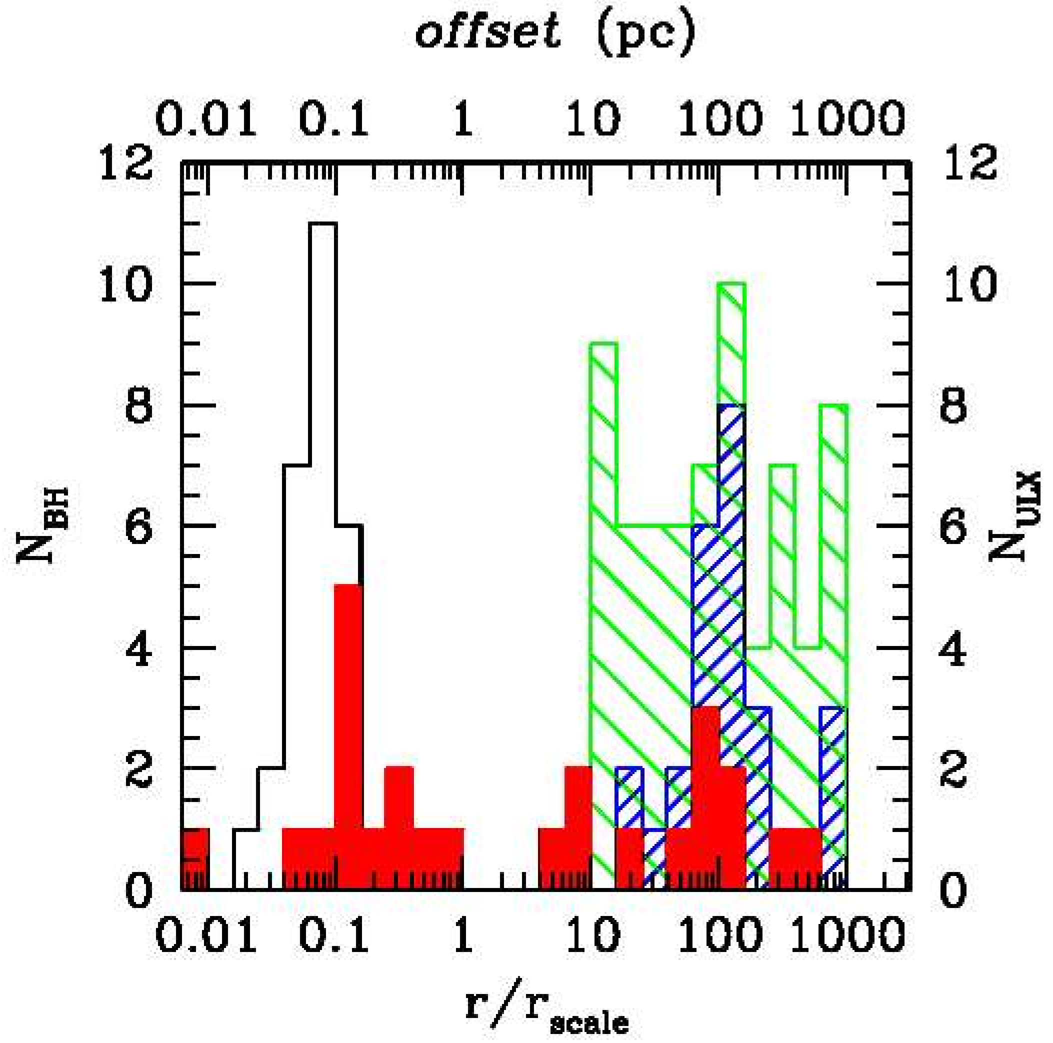
Comparison IMBHs (bottom) / massive BHs (top)



MM et al. 2010

THANKS

Simulations of young star clusters + massive BH binary with Starlab:



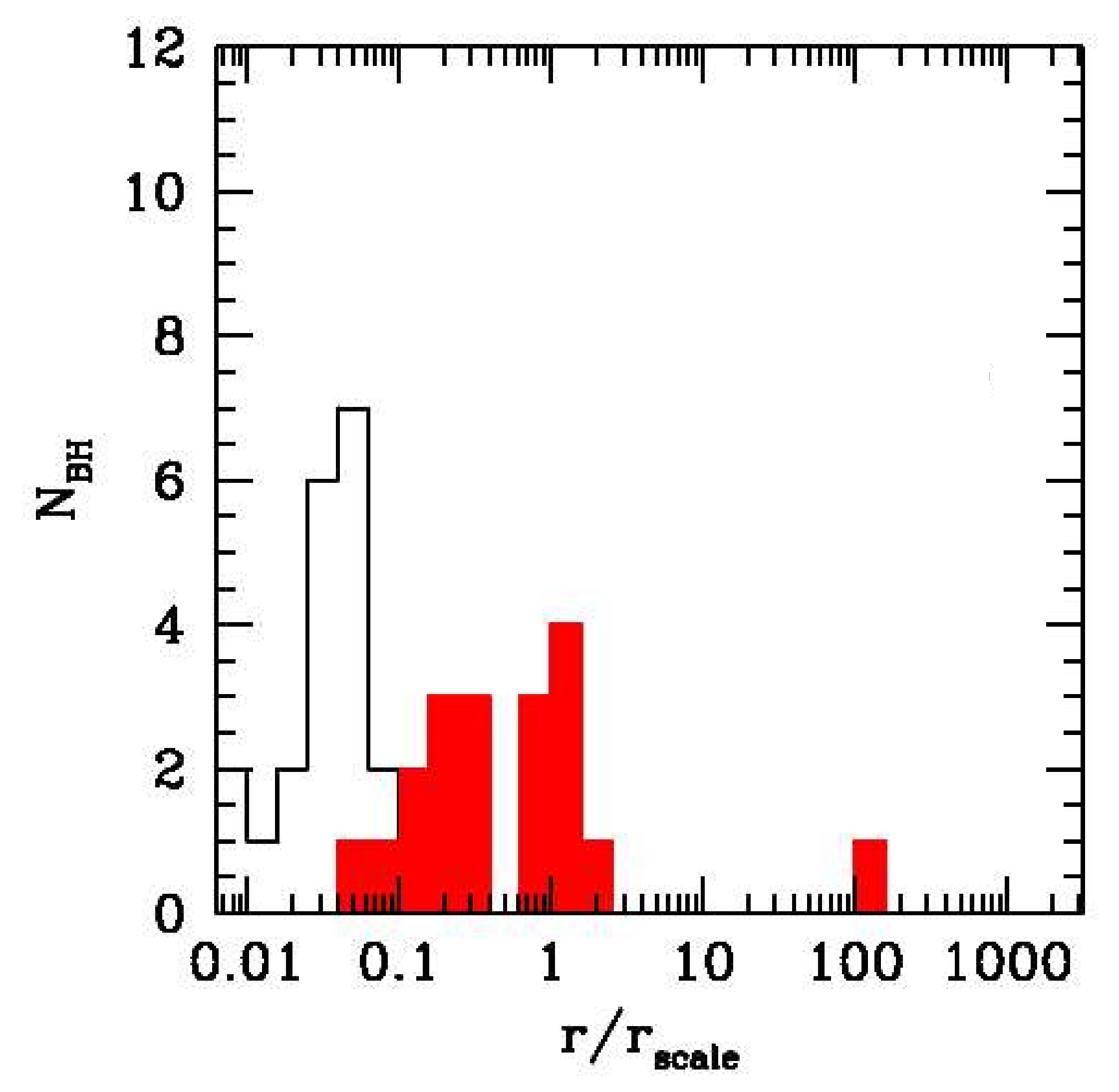
□ ICs

🟥 after 10 Myr

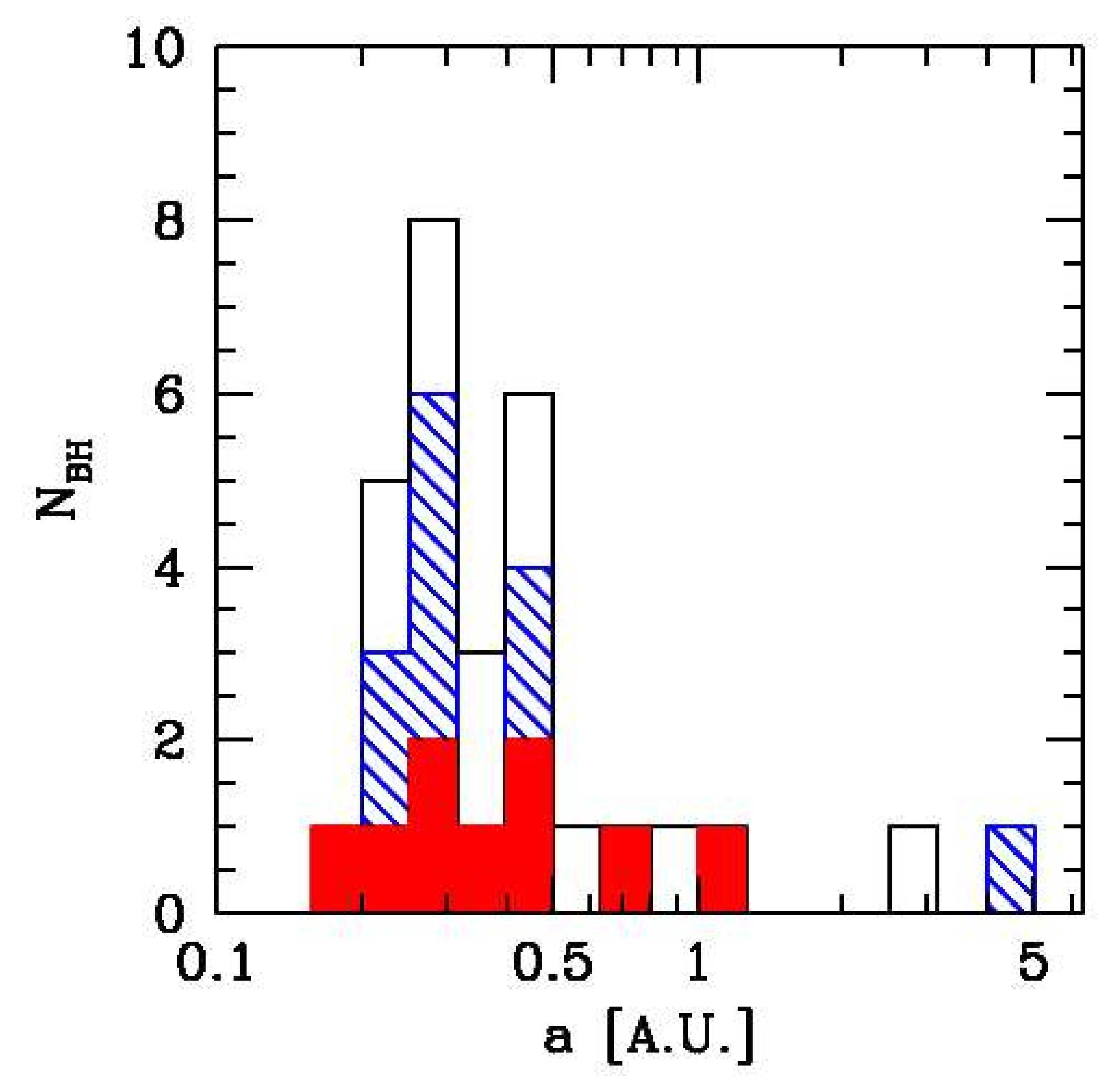
▨ data of ULXs from Berghea PhD

▨ data of X-ray sources from Kaaret et al. (2004)

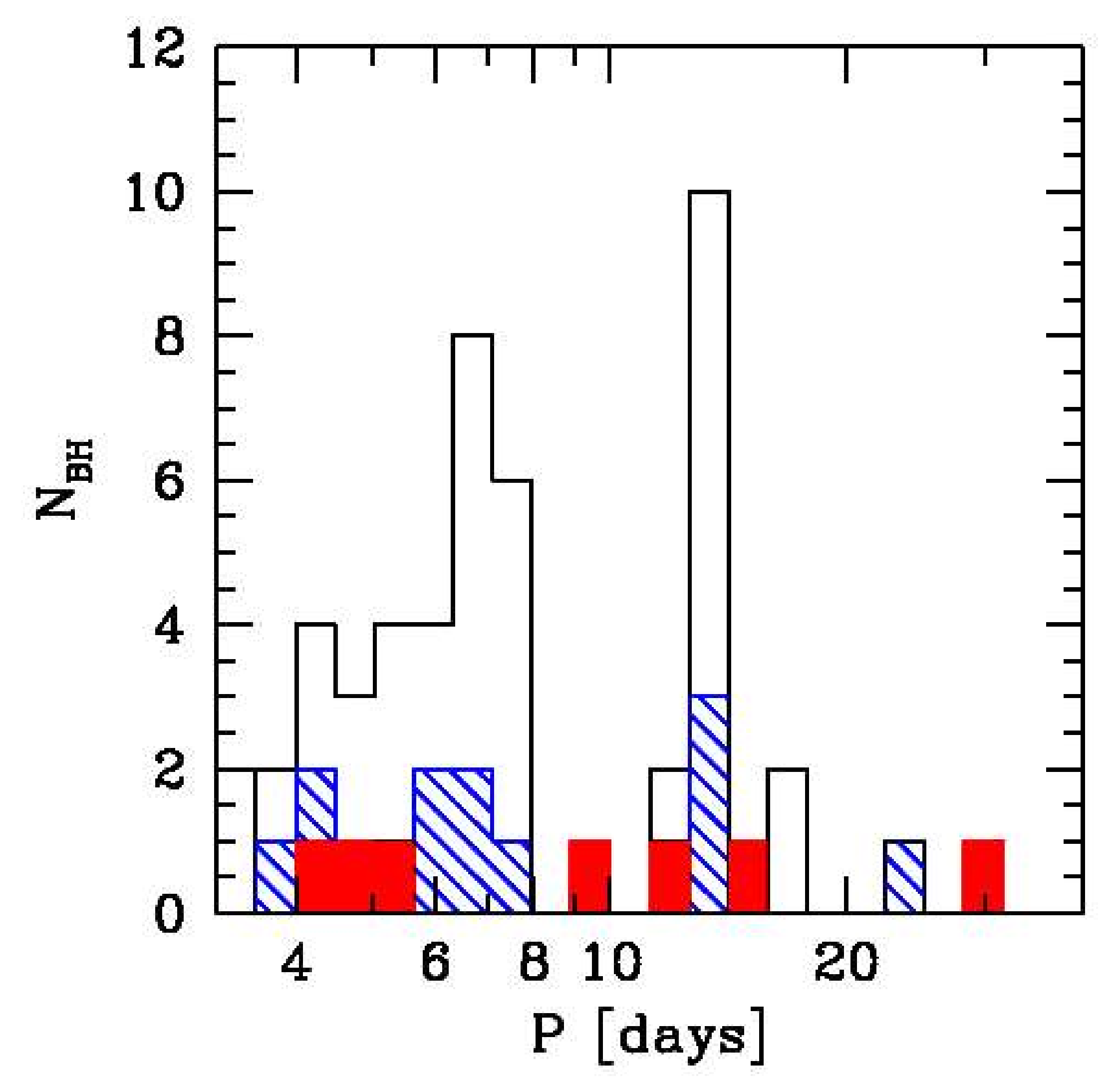
More data from Starlab simulations: IMBHs (300 Msun)



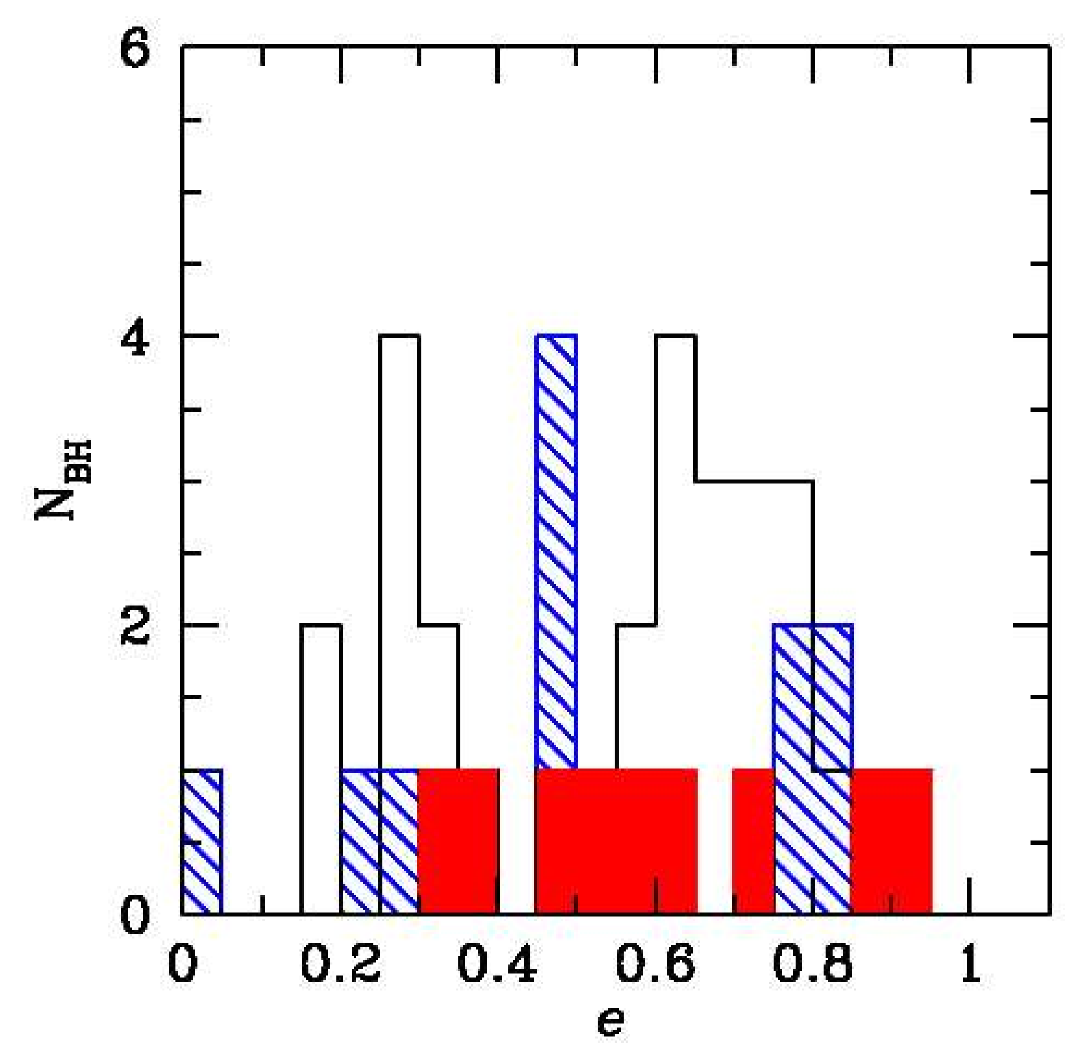
More data from Starlab simulations: semi-major axis



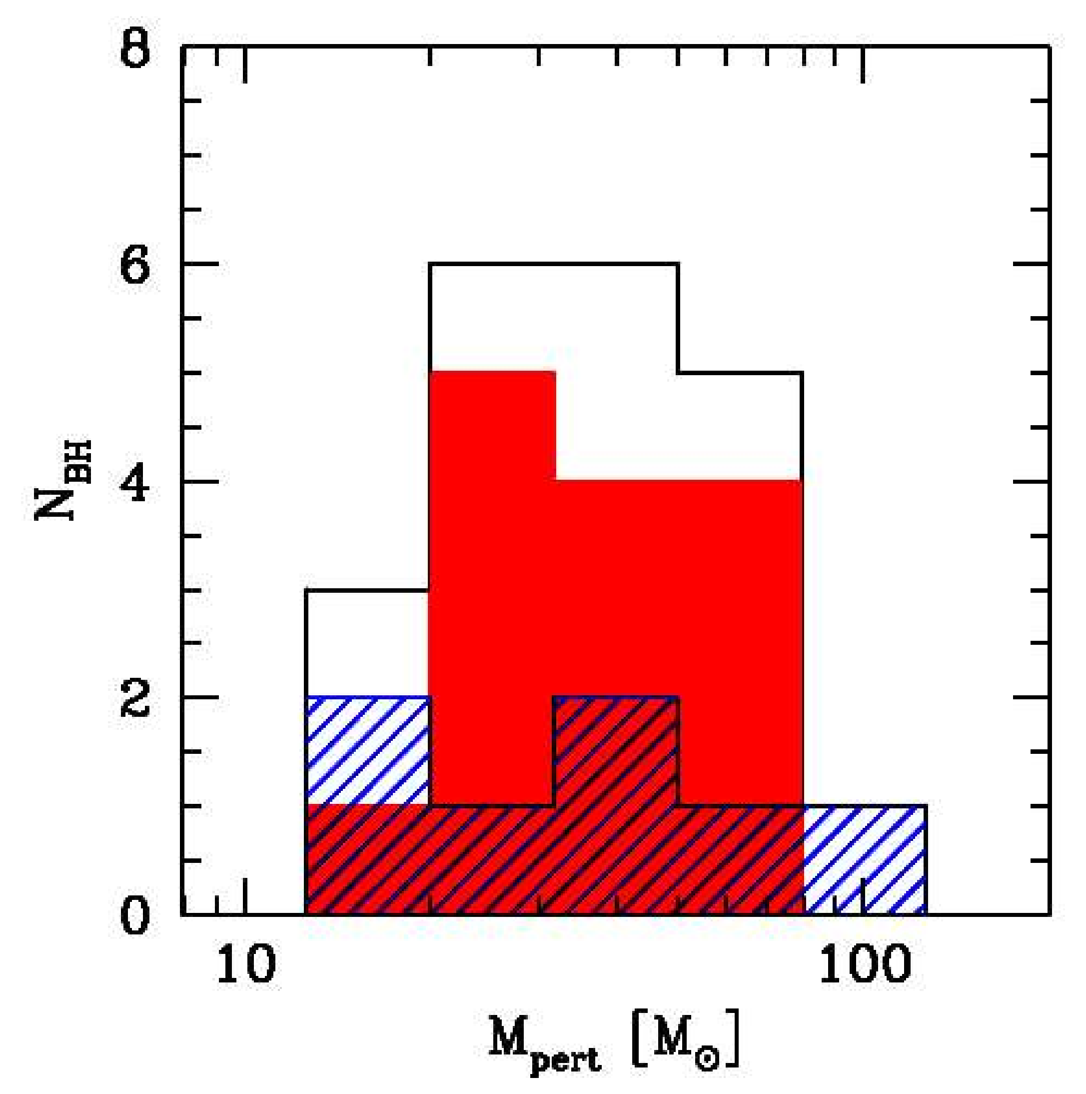
More data from Starlab simulations: orbital period



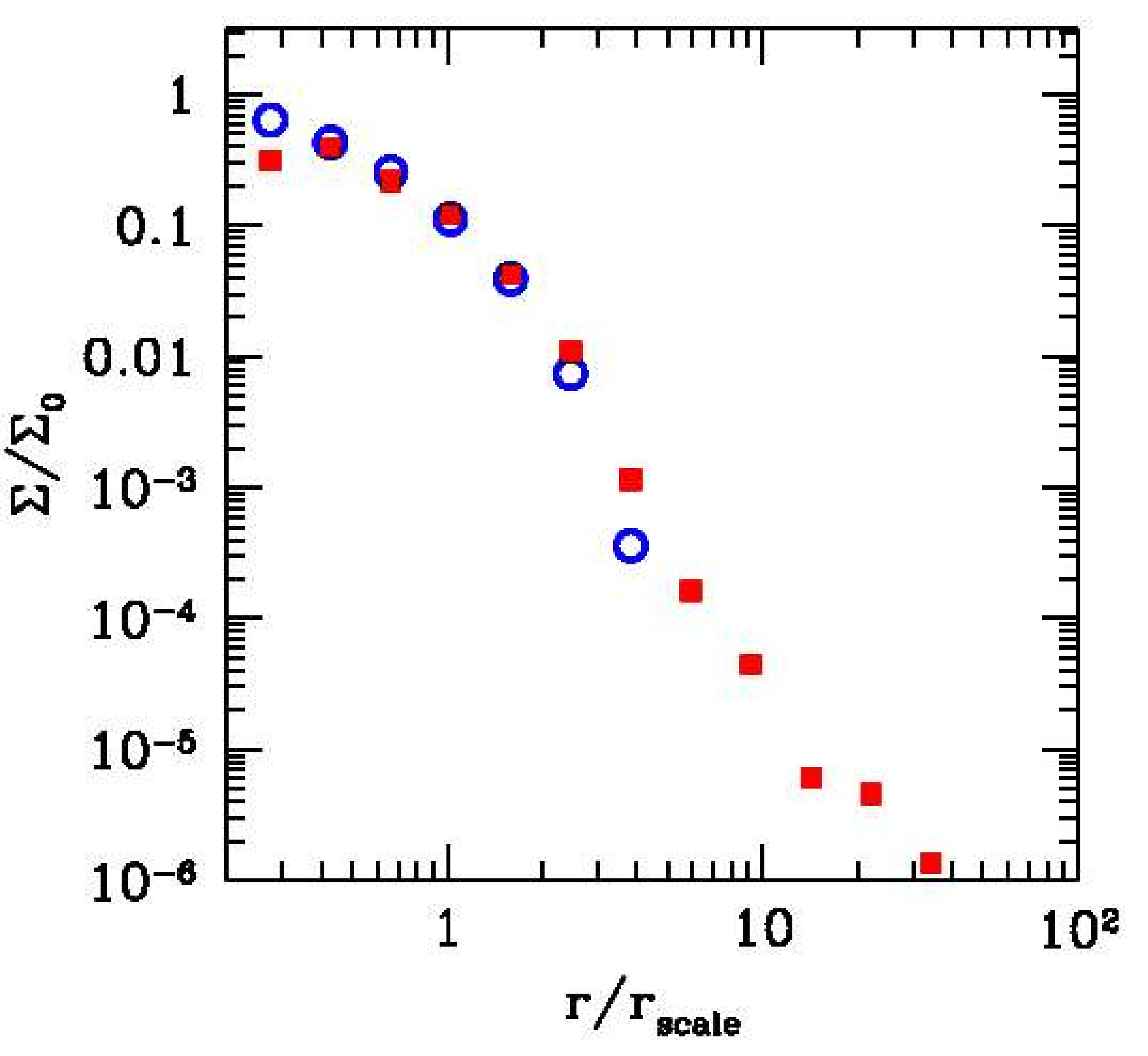
More data from Starlab simulations: eccentricity



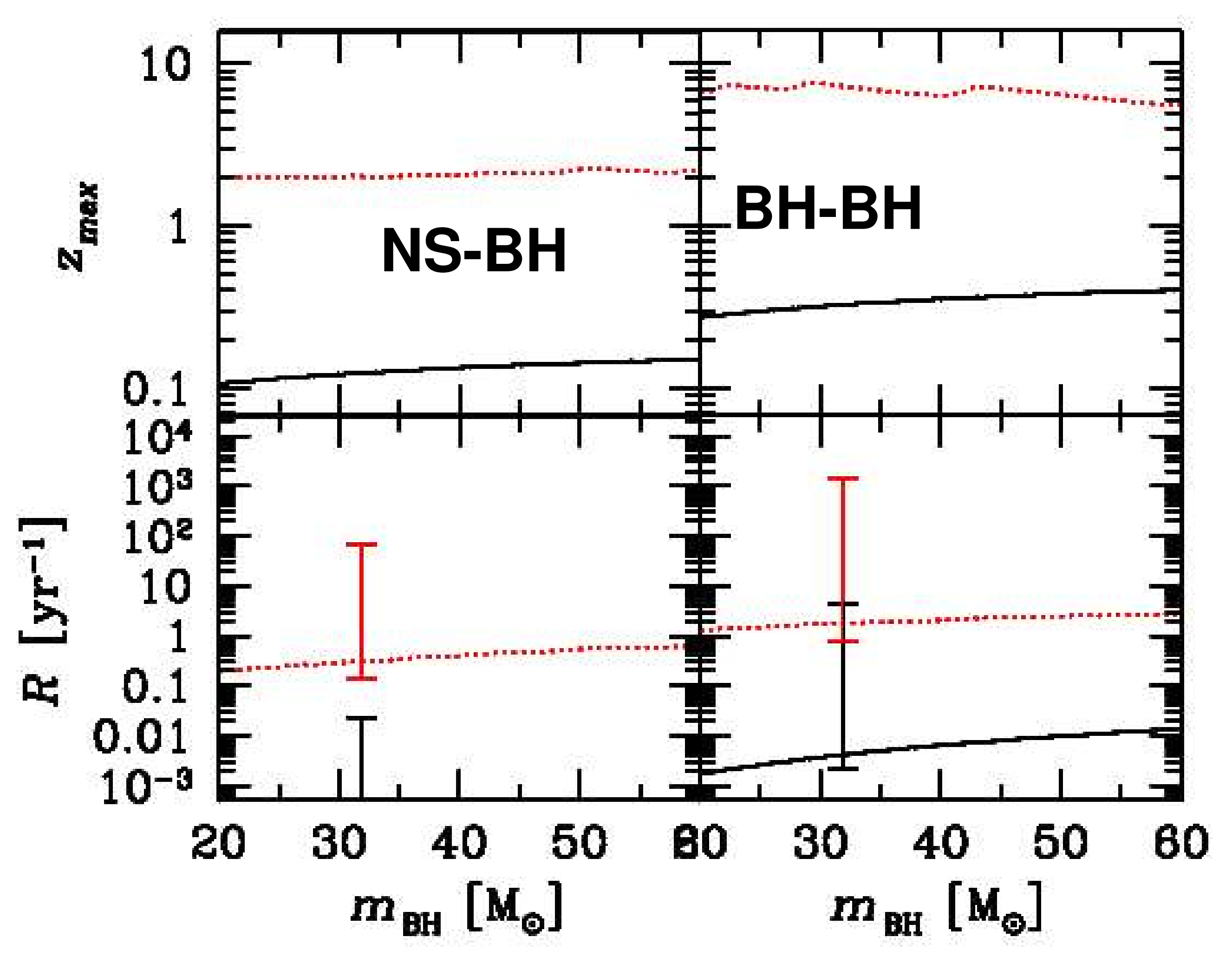
More data from Starlab simulations: perturber mass



More data from Starlab simulations: cluster profile



Different BH mass changes prediction for GW detection:



RED:

Einstein

Telescope

BLACK:

Advanced

LIGO

Bruno et al., in preparation

GWs from massive BHs, INGREDIENTS:

$$R = \int_{m_1}^{m_2} \mathrm{d}m_{\rm BH} \int_0^{z_{\rm max}(m_{\rm BH},m_{\rm co})} \mathrm{d}\tilde{z} \frac{\mathrm{d}^3 N_{\rm merg}}{\mathrm{d}m_{\rm BH}\,\mathrm{d}t_{\rm e}\,\mathrm{d}V_{\rm c}} \frac{\mathrm{d}t_{\rm e}}{\mathrm{d}t_{\rm o}} \frac{\mathrm{d}V_{\rm c}}{\mathrm{d}\tilde{z}}$$

$$\frac{\mathrm{d}^3 N_{\rm merg}}{\mathrm{d}m_{\rm BH}\,\mathrm{d}t_{\rm e}\,\mathrm{d}V_{\rm c}} = f_{\rm merg} \frac{\mathrm{d}^2 n_{\rm BH}}{\mathrm{d}m_{\rm BH}\,\mathrm{d}t_e}$$

$$\frac{\mathrm{d}^2 n_{\rm BH}}{\mathrm{d}m_{\rm BH}\,\mathrm{d}t_e} = \frac{\dot{\rho}_*}{\int_{m_{\rm min}}^{m_{\rm max}} m^{1-\alpha}\mathrm{d}m} 2^{1-\alpha}\, m_{\rm BH}^{-\alpha}$$

$$f_{\rm merg} = f_{\rm BH+co}\, f_{\rm coalescence}$$

$$f_{\rm coalescence} = \frac{t_{\rm life}\, f_{\rm evap}}{\tau_{\rm GW}}$$

1 – IMBHs
in
YMCs

INGREDIENTS:

- density of YMCs correlates with cosmic SFR (from Hopkins & Beacom 2006 data)

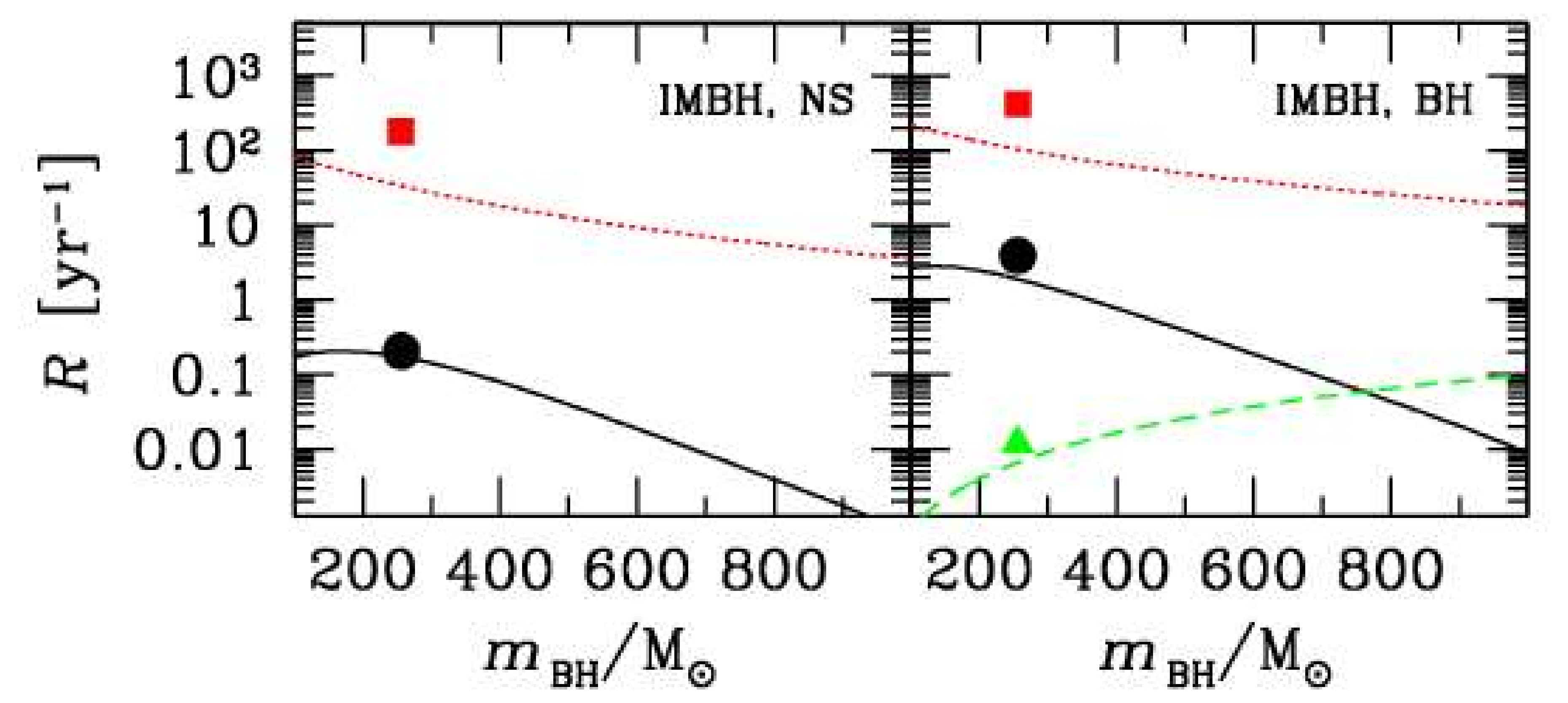
- merger rate from 3-body rate:

$$\nu_{3b} \sim 2\,\pi\,G\,m_{\rm BH}\,n_{\rm c}\,a\,\sigma_{\rm c}^{-1}$$

- instrumental range from Ajith et al. (2008, 2009)

- accurate integration over comoving volume

Approximation:



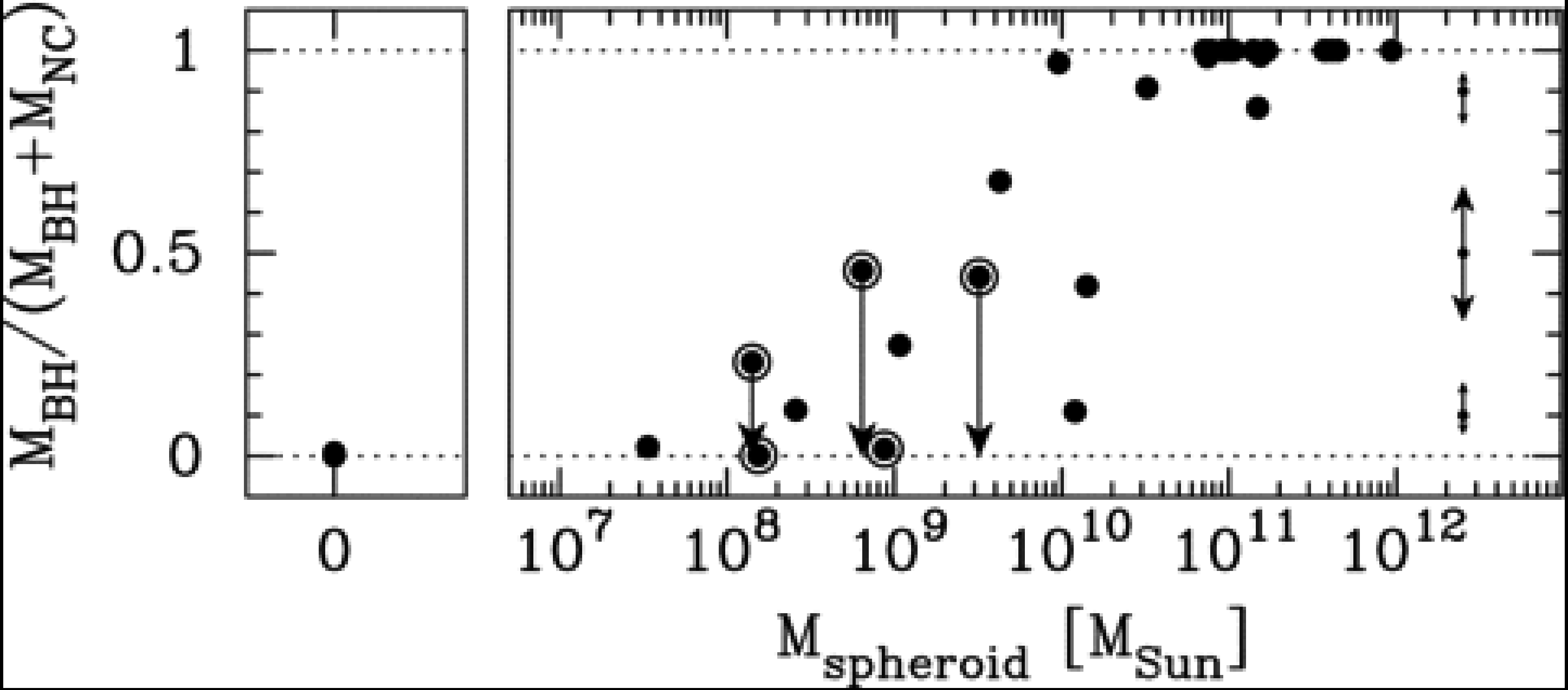
$$R \approx f_{\rm tot}\,\frac{n_{\rm YC}(z=0, m_{\rm BH})}{\rm T_{mrg}(m_{BH})}\,V_{\rm c}(z_{\rm max})$$

2- SMBH in nuclear star clusters (NCs)

INGREDIENTS:

- spheroids with mass 10^8-10^10 Msun

host both SMBH and NC (Graham & Spitler 2009)



$$\nu(m_{\mathrm{BH}}) = \left(\frac{22}{2\,\pi}\right)\ \left(\frac{m_*}{m_{\mathrm{BH}}}\right) f_{\mathrm{co}}\,\nu_{3\mathrm{b}}$$

INGREDIENTS:

- spheroids with mass 10^8-10^10 Msun
host both SMBH and NC (Graham & Spitler 2009)

- merger rate from 3-body rate:

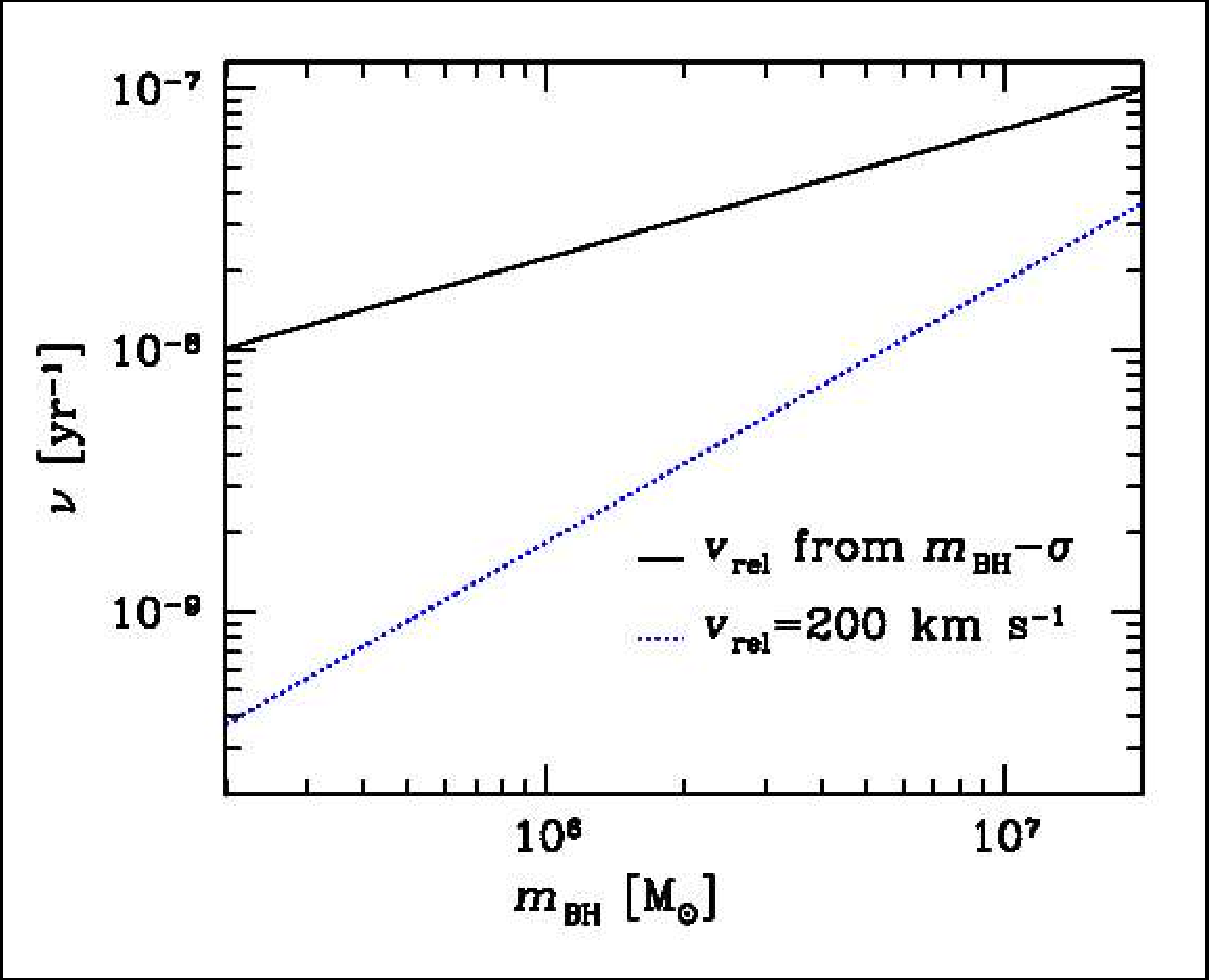
$$\nu(m_{\rm BH}) = \left(\frac{22}{2\,\pi}\right) \left(\frac{m_*}{m_{\rm BH}}\right) f_{\rm co}\, \nu_{\rm 3b}$$

- instrumental range from Ajith et al. (2008, 2009)

- accurate integration over comoving volume

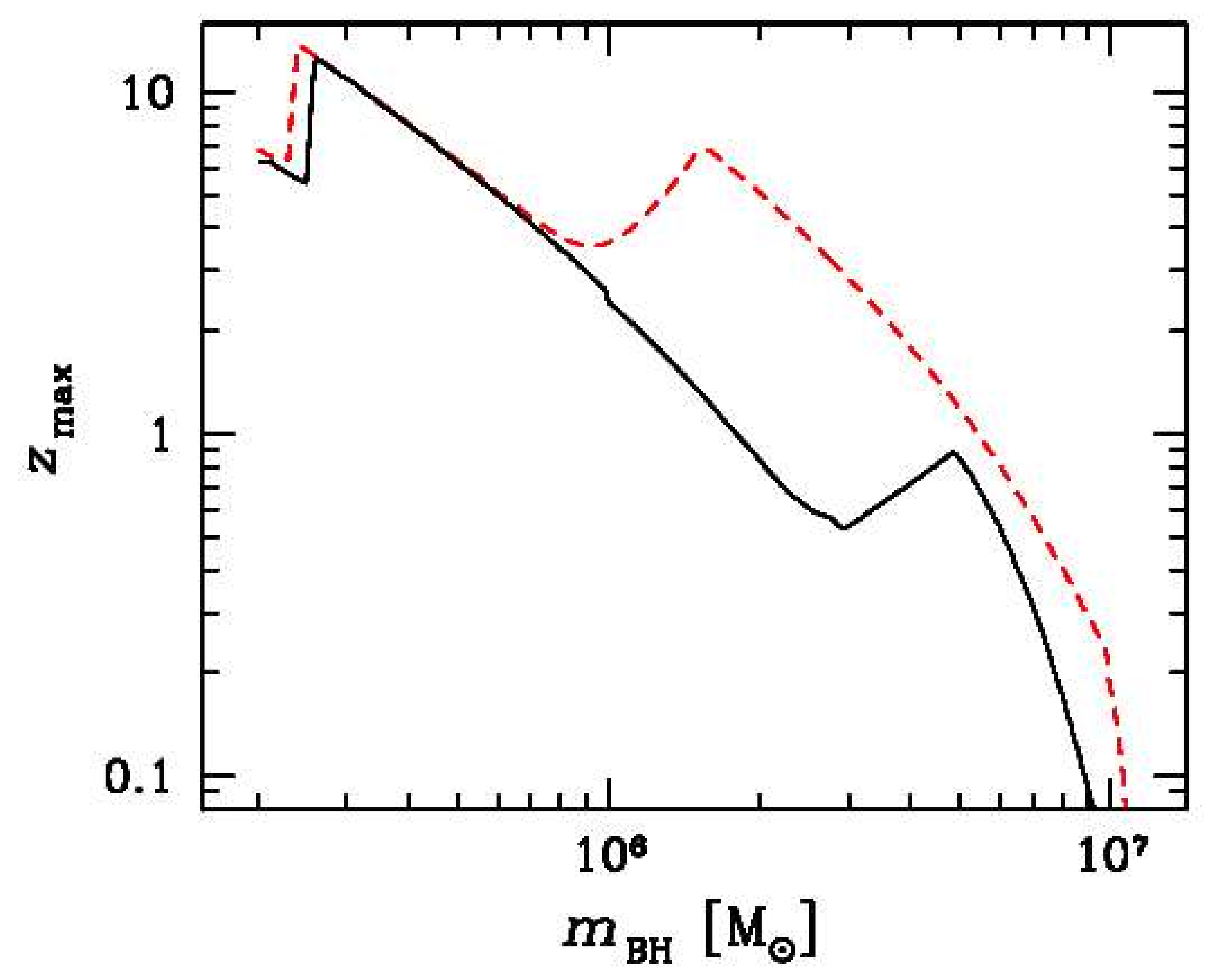
- halo number density from Press & Schechter formalism

MERGER RATE:

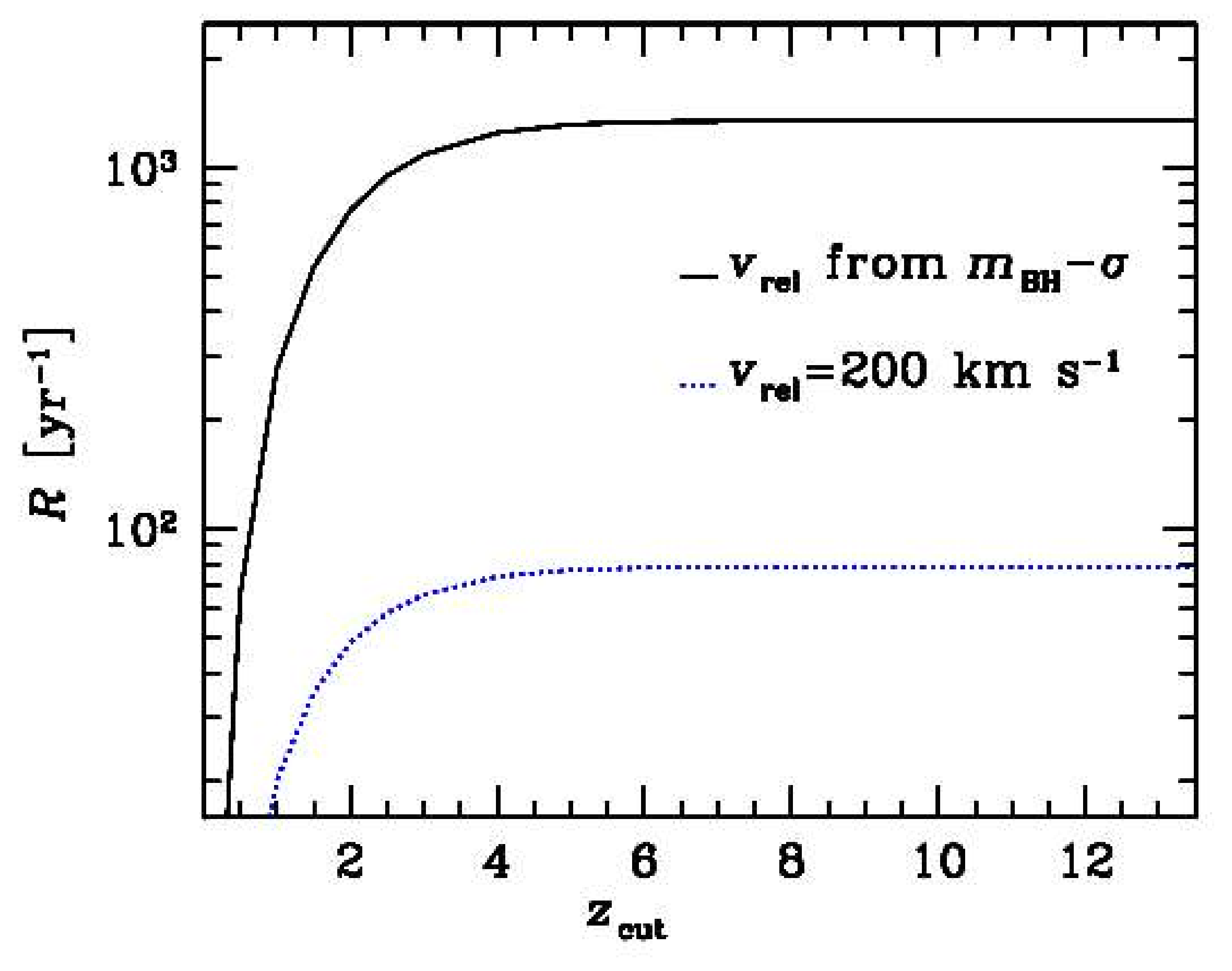


10^{-7}
10^{-8}
10^{-9}
ν [yr^{-1}]
10^{6}
10^{7}
$m_{\rm BH}$ [$M_\odot$]
$v_{\rm rel}$ from $m_{\rm BH}-\sigma$
$v_{\rm rel}$=200 km s^{-1}

MAXIMUM REDSHIFT FROM MERGER RATE:



DETECTION RATE as function zcut:



6 – stellar yields

Failed supernovae reduce stellar yields in ISM:

WORK IN PROGRESS!!

Main problem with ULXs:

isotropic Luminosity above Eddington limit for ~7 Msun compact objects

Is there any way to produce stellar BHs with mass > 10 Msun?

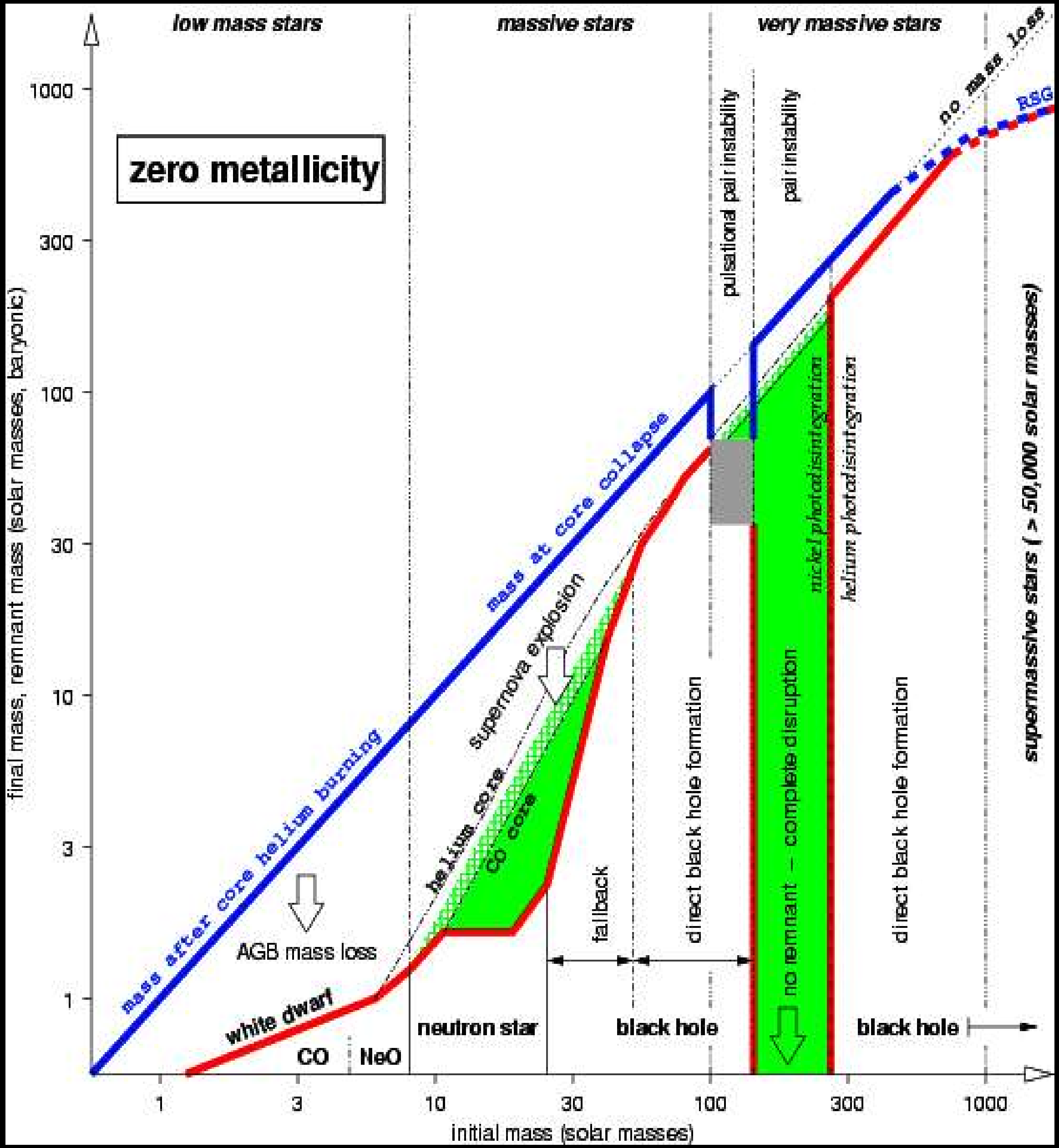
LOW METALLICITY

What prevents stellar remnants from having large masses?

Mass losses due to winds and SN explosion

Is there any way to reduce mass losses and avoid SN explosion?

low metallicity



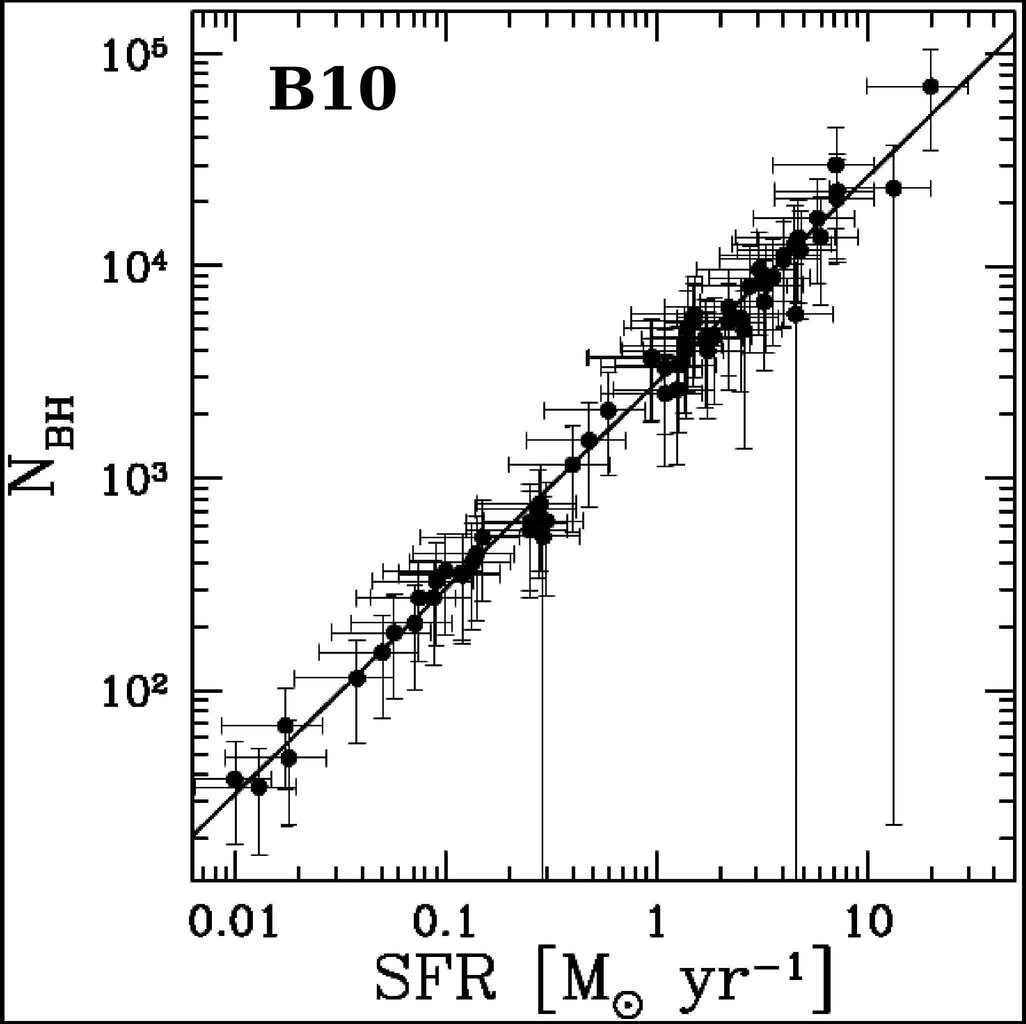
(Heger et al. 2002)

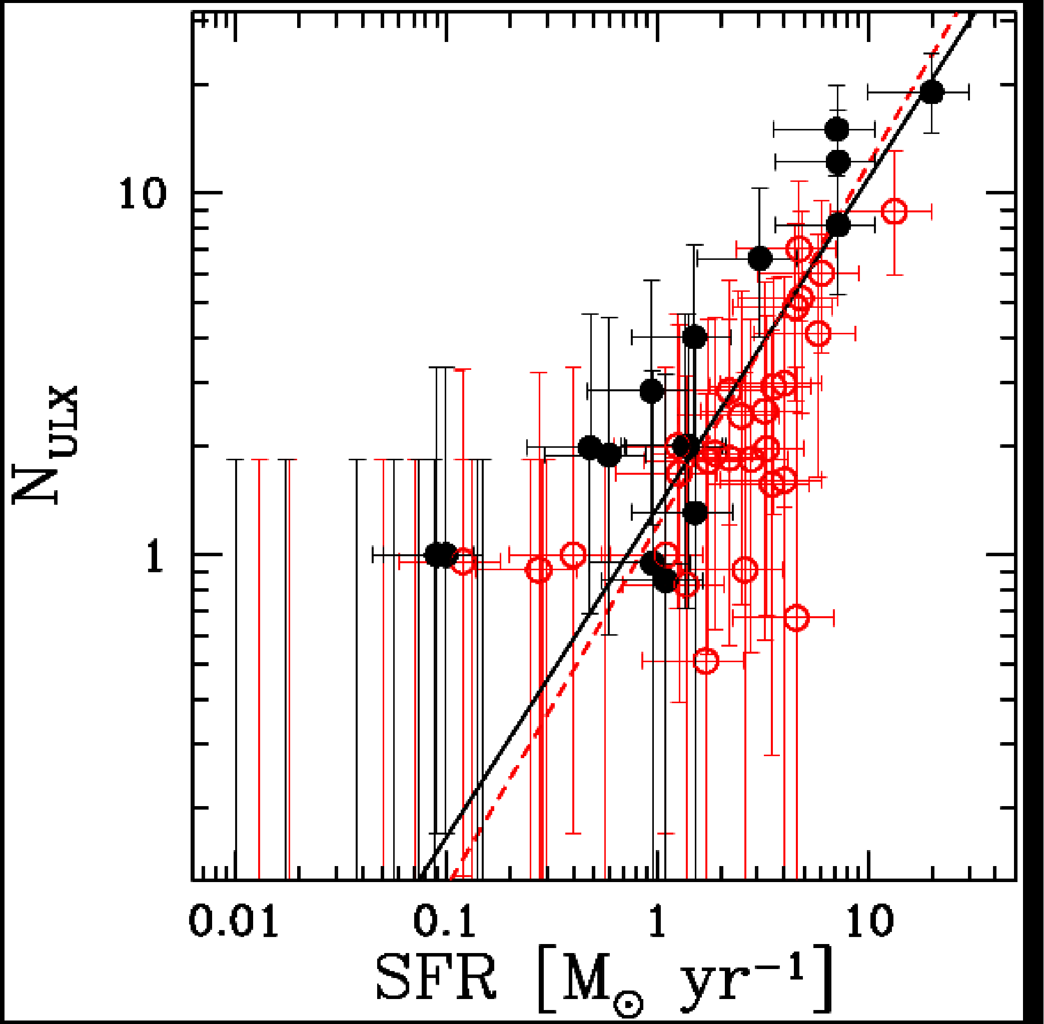
REFERENCES:

1) MM, Colpi M., Zampieri L., 2009, MNRAS

2) MM, Ripamonti E., Zampieri L., Colpi M., Bressan A., 2010, MNRAS

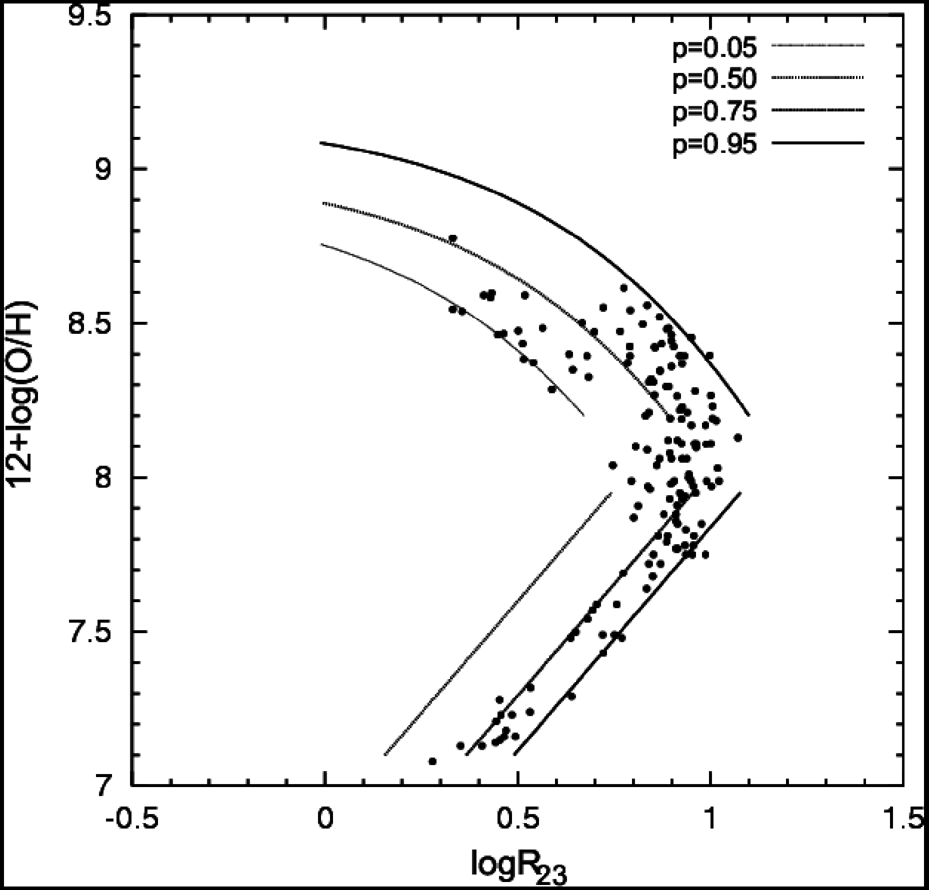
N_{BH}-SFR





Slope of the model= 1
Slope of the data = 0.91 +/- 0.2

Pilyugin metallicity calibration



Pilyugin (2003)

$$R_{23} = \frac{[OII](3727,3729) + [OIII](4959,5007)}{H_\beta}$$

$$P = \frac{[OIII](4959,5007)}{[OII](3727) + [OIII](4959,5007)}$$

Low-metallicity calibration

If we measure OIII 4363, we do not need Pilyugin: galaxy is low metallicity and calibration is unambiguous

A0035 'the cartwheel' 477

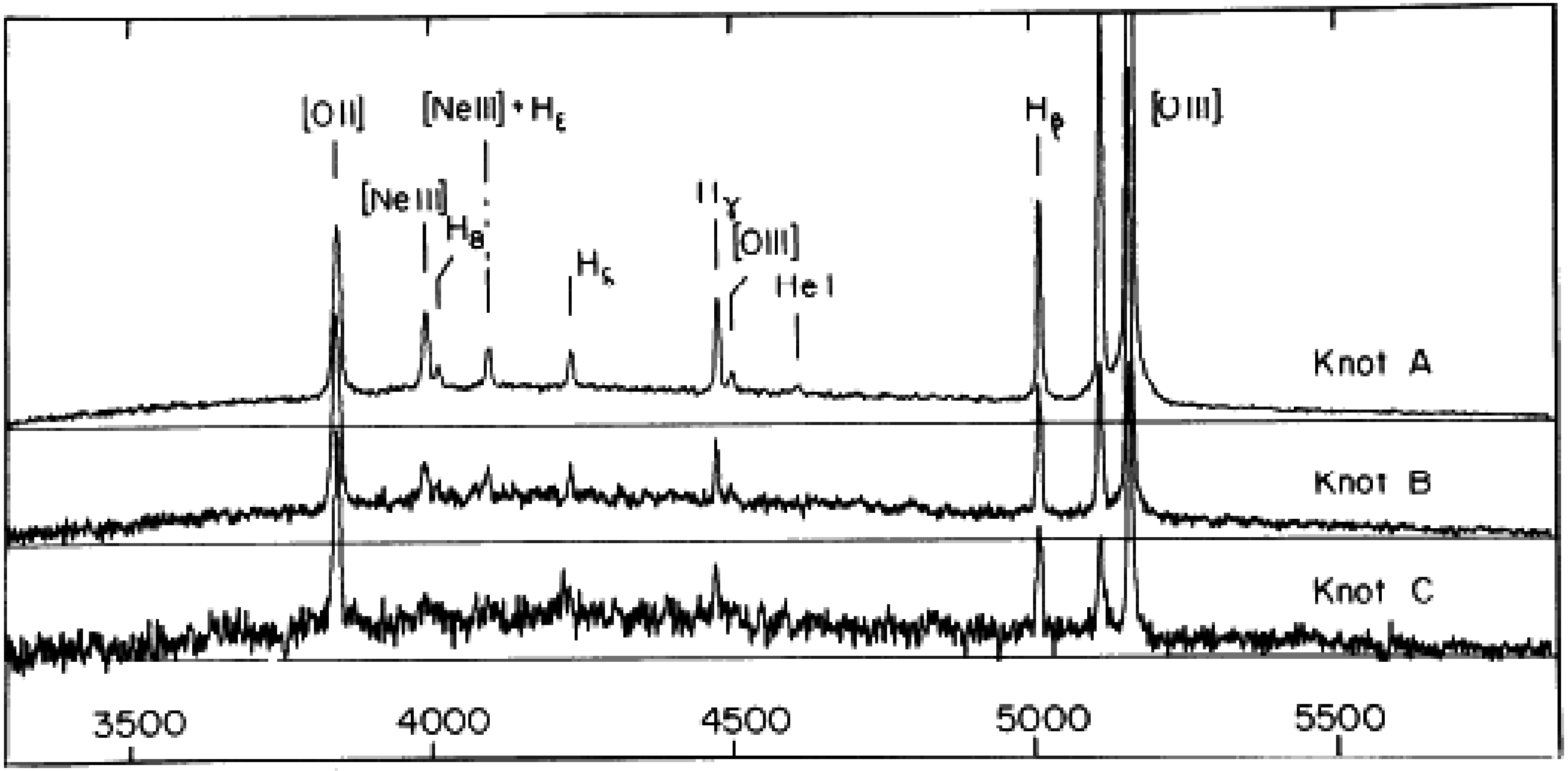
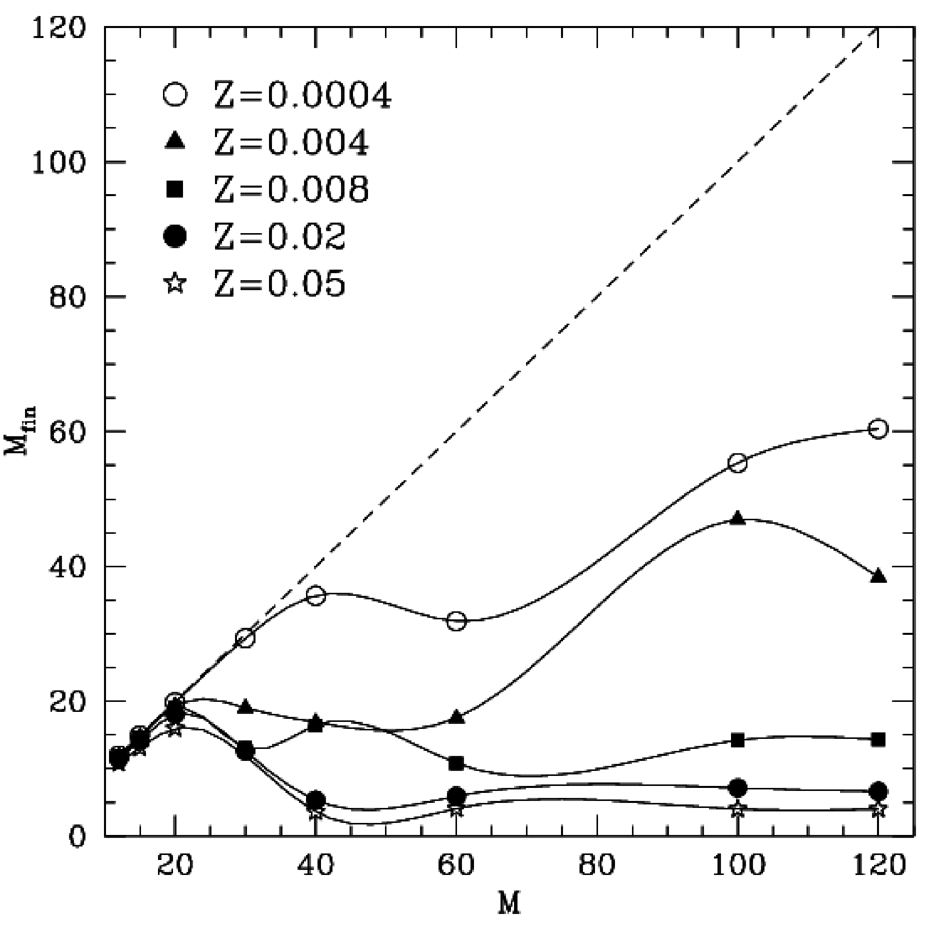


Figure 2. Scans of three of the H II regions in the ring.

Fosbury & Hawarden 1977

Portinari, Chiosi, Bressan 1998 (P98)



$$\dot{M} \propto Z^{0.5}$$

Kudritzki 1989

Belczynski et al. 2010

STANDARD

_ stellar evolution recipes by

Hurley, Pols & Tout (2000)

_ population synthesis code

StarTrack (Belczynski & Kalogera)

NEW

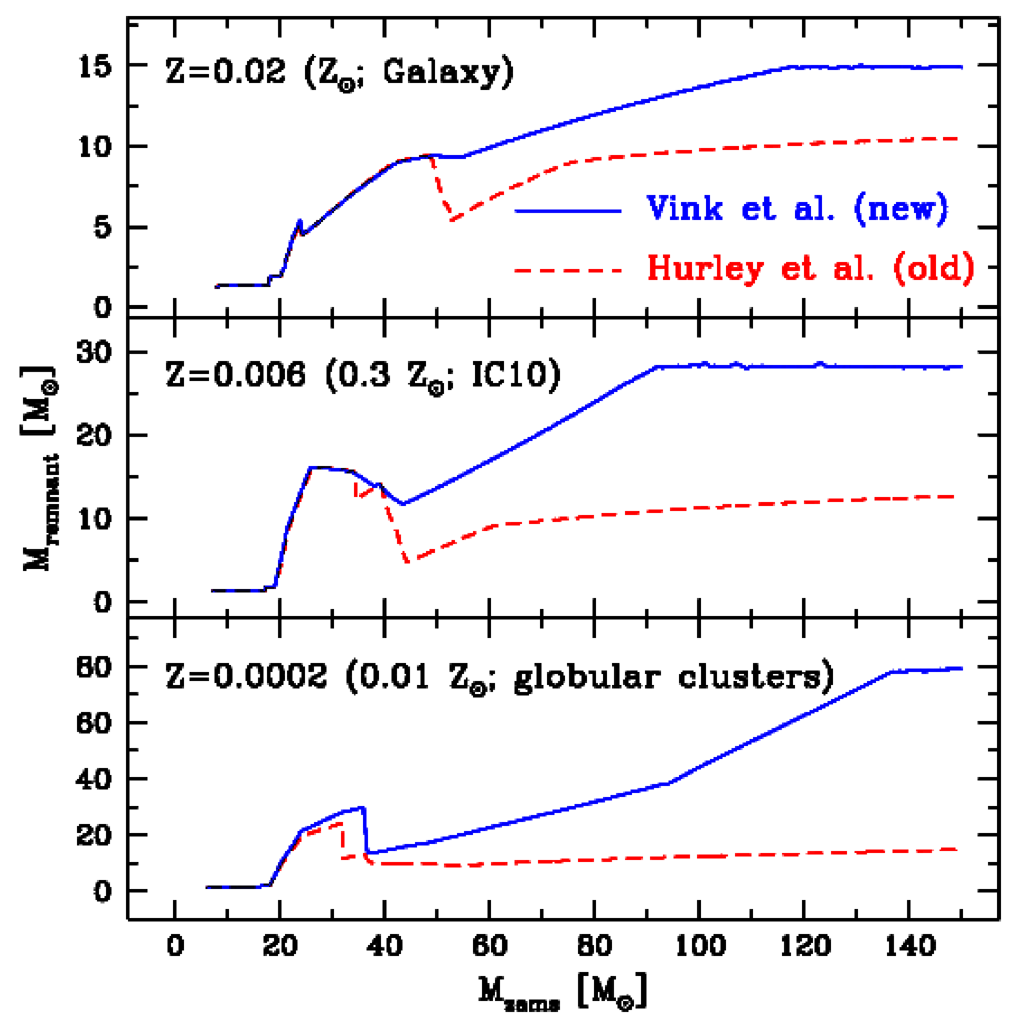
_ updated WINDS (Vink et al. 2001)

_ updated remnant mass

allowing direct collapse of massive

metal-poor stars (Fryer 1999;

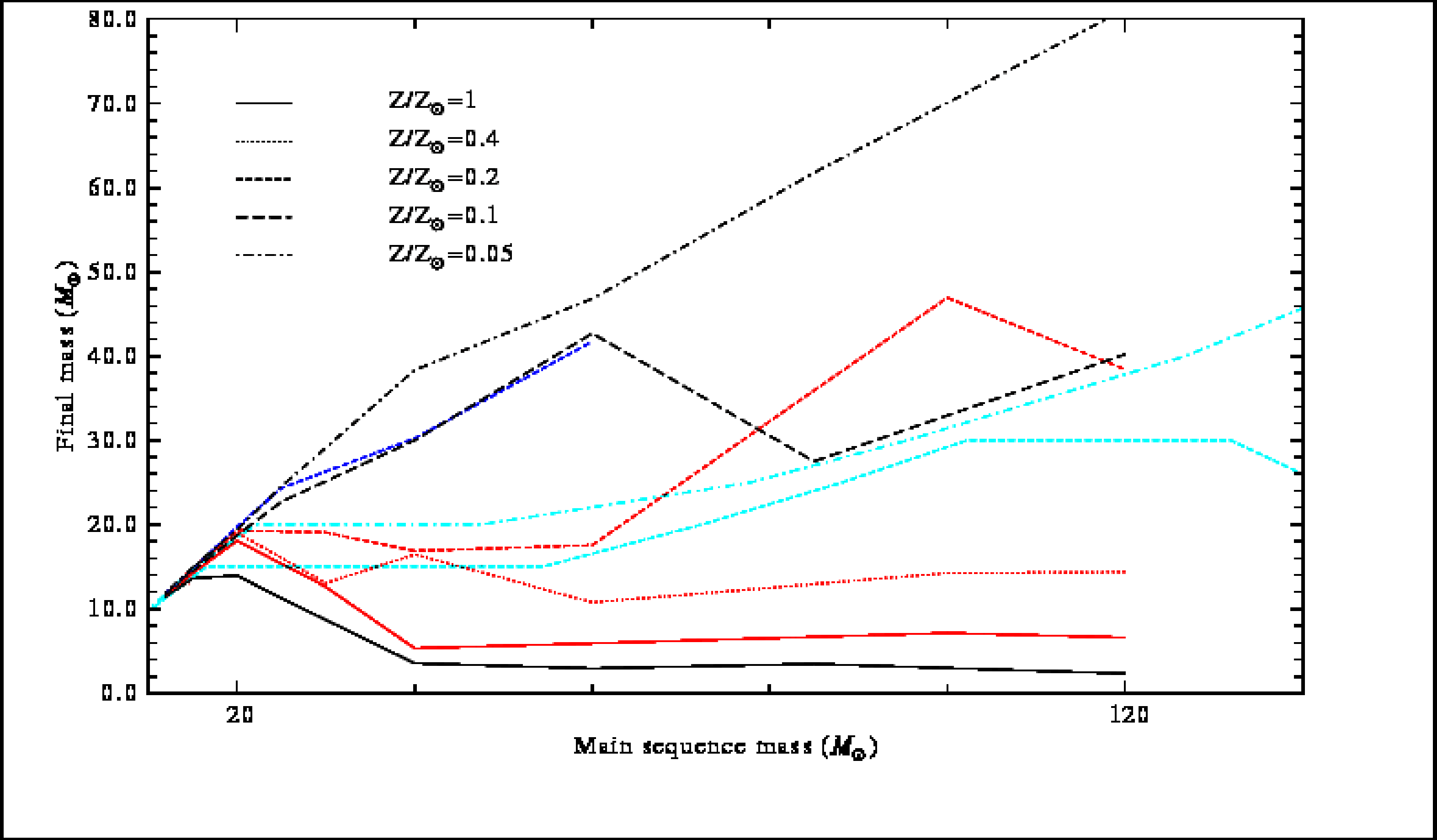
Fryer & Kalogera 2001)



Zampieri & Roberts 2009

_ Sub-solar Z stars with **M>30-40 Msun** may **retain massive envelopes** at the time of SN.

_The **SN shock wave** loses energy trying to unbind the envelope until it **stalls** and the star collapses into BH



EXTREMELY METAL DEFICIENT galaxies

DEFINITION: blue compact dwarf galaxies with *Z*~0.02 *Z*sun

Chandra data for SBS0335-052, SBS 0335-052W, I Zw 18 indicate >=1 ULX in each of them (Thuan et al. 2004)

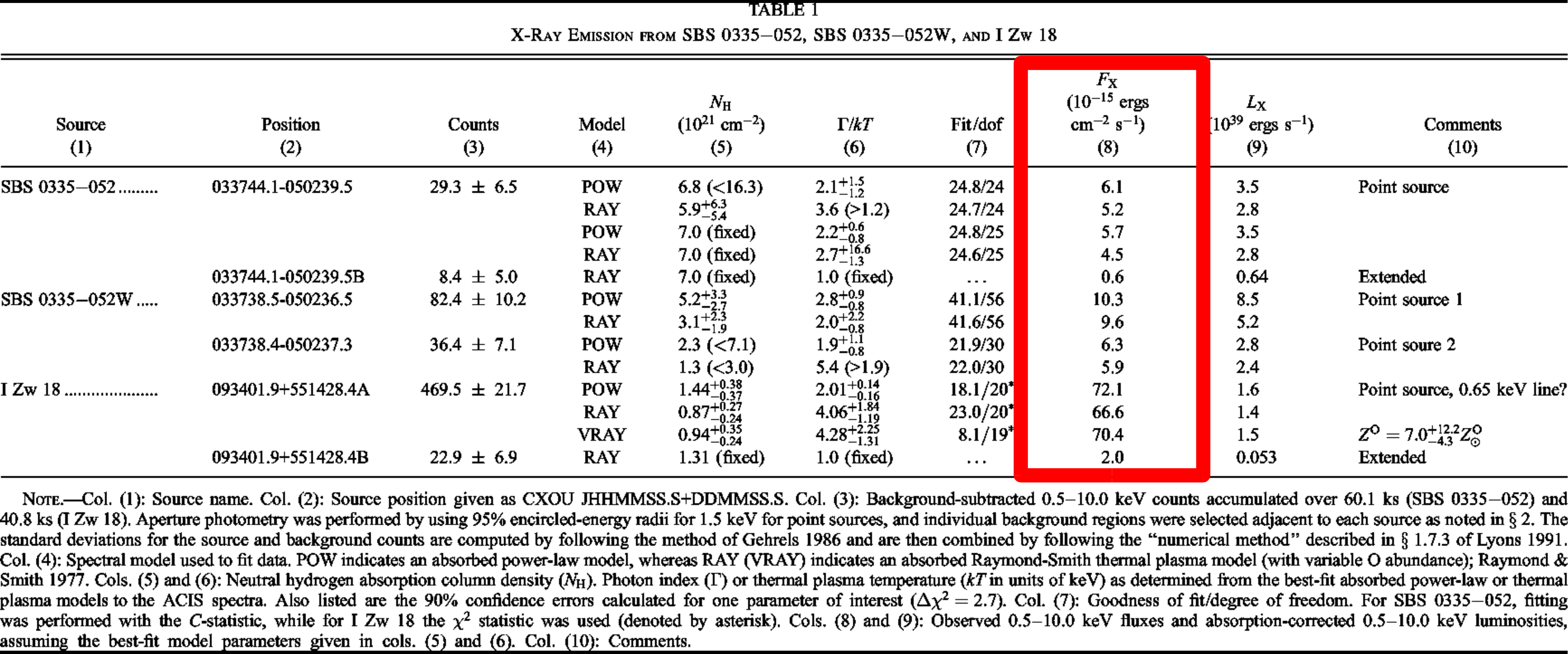


TABLE 1

X-Ray Emission from SBS 0335−052, SBS 0335−052W, and I Zw 18

Source (1)	Position (2)	Counts (3)	Model (4)	N_H (10^{21} cm^{-2}) (5)	Γ/kT (6)	Fit/dof (7)	F_X (10^{-15} ergs cm^{-2} s^{-1}) (8)	L_X (10^{39} ergs s^{-1}) (9)	Comments (10)
SBS 0335−052	033744.1-050239.5	29.3 ± 6.5	POW	6.8 (<16.3)	$2.1^{+1.5}_{-1.2}$	24.8/24	6.1	3.5	Point source
			RAY	$5.9^{+6.3}_{-5.4}$	3.6 (>1.2)	24.7/24	5.2	2.8	
			POW	7.0 (fixed)	$2.2^{+0.6}_{-0.8}$	24.8/25	5.7	3.5	
			RAY	7.0 (fixed)	$2.7^{+16.6}_{-1.3}$	24.6/25	4.5	2.8	
	033744.1-050239.5B	8.4 ± 5.0	RAY	7.0 (fixed)	1.0 (fixed)	...	0.6	0.64	Extended
SBS 0335−052W	033738.5-050236.5	82.4 ± 10.2	POW	$5.2^{+3.3}_{-2.7}$	$2.8^{+0.9}_{-0.8}$	41.1/56	10.3	8.5	Point source 1
			RAY	$3.1^{+2.3}_{-1.9}$	$2.0^{+2.2}_{-0.8}$	41.6/56	9.6	5.2	
	033738.4-050237.3	36.4 ± 7.1	POW	2.3 (<7.1)	$1.9^{+1.1}_{-0.8}$	21.9/30	6.3	2.8	Point soure 2
			RAY	1.3 (<3.0)	5.4 (>1.9)	22.0/30	5.9	2.4	
I Zw 18	093401.9+551428.4A	469.5 ± 21.7	POW	$1.44^{+0.38}_{-0.37}$	$2.01^{+0.14}_{-0.16}$	18.1/20*	72.1	1.6	Point source, 0.65 keV line?
			RAY	$0.87^{+0.27}_{-0.24}$	$4.06^{+1.84}_{-1.19}$	23.0/20*	66.6	1.4	
			VRAY	$0.94^{+0.35}_{-0.24}$	$4.28^{+2.25}_{-1.31}$	8.1/19*	70.4	1.5	$Z^{O} = 7.0^{+12.2}_{-4.3} Z^{O}_{\odot}$
	093401.9+551428.4B	22.9 ± 6.9	RAY	1.31 (fixed)	1.0 (fixed)	...	2.0	0.053	Extended

Note.—Col. (1): Source name. Col. (2): Source position given as CXOU JHHMMSS.S+DDMMSS.S. Col. (3): Background-subtracted 0.5–10.0 keV counts accumulated over 60.1 ks (SBS 0335−052) and 40.8 ks (I Zw 18). Aperture photometry was performed by using 95% encircled-energy radii for 1.5 keV for point sources, and individual background regions were selected adjacent to each source as noted in § 2. The standard deviations for the source and background counts are computed by following the method of Gehrels 1986 and are then combined by following the "numerical method" described in § 1.7.3 of Lyons 1991. Col. (4): Spectral model used to fit data. POW indicates an absorbed power-law model, whereas RAY (VRAY) indicates an absorbed Raymond-Smith thermal plasma model (with variable O abundance); Raymond & Smith 1977. Cols. (5) and (6): Neutral hydrogen absorption column density (N_H). Photon index (Γ) or thermal plasma temperature (kT in units of keV) as determined from the best-fit absorbed power-law or thermal plasma models to the ACIS spectra. Also listed are the 90% confidence errors calculated for one parameter of interest ($\Delta\chi^2 = 2.7$). Col. (7): Goodness of fit/degree of freedom. For SBS 0335−052, fitting was performed with the *C*-statistic, while for I Zw 18 the χ^2 statistic was used (denoted by asterisk). Cols. (8) and (9): Observed 0.5–10.0 keV fluxes and absorption-corrected 0.5–10.0 keV luminosities, assuming the best-fit model parameters given in cols. (5) and (6). Col. (10): Comments.

L – SFR conversions:

UV SFR from Munoz & Mateos (2007)

$$\mathrm{SFR} = \frac{L(\mathrm{H}\alpha)}{1.26 \times 10^{41}\,\mathrm{erg\,s^{-1}}}\,\mathrm{M_\odot\,yr^{-1}}$$

Kennicutt 1998

$$\mathrm{SFR} = \frac{L(\mathrm{FIR})}{2.2 \times 10^{43}\,\mathrm{erg\,s^{-1}}}\,\mathrm{M_\odot\,yr^{-1}}$$

Kennicutt 1998

RADIO SFR from Bell (2003)

Subtraction of background:

1 - integrate differential log(N)-log(S) by Hasinger et al. (1998) accounting for (i) different band, (ii) different assumptions on spectral slopes (2 and 1.7), (iii) absorption from Galaxy ---->

we get the surface number density of contaminating sources q (number of contaminating sources with flux > Slim= limit flux)

2 - combine q with min(A_{obs}, A_{25})

A_{obs}=observed area, A_{25}= area within R_{25}

Possible contamination from old stellar populations:

Colbert et al. (2004) ~0.2 of ULXs in spirals are due to old stellar populations

Liu, Bregman, Irwin (2006) suggest that all ULXs in ellipticals may be explained with contaminating sources --> no ULXs from old stellar populations?

---> contamination may be neglected as 0th-order approximation

X-ray in the sample:

52/64 galaxies from Liu & Bregman (2005) ROSAT-catalogue (most of them have new Chandra and/or XMM data, which are accounted for)

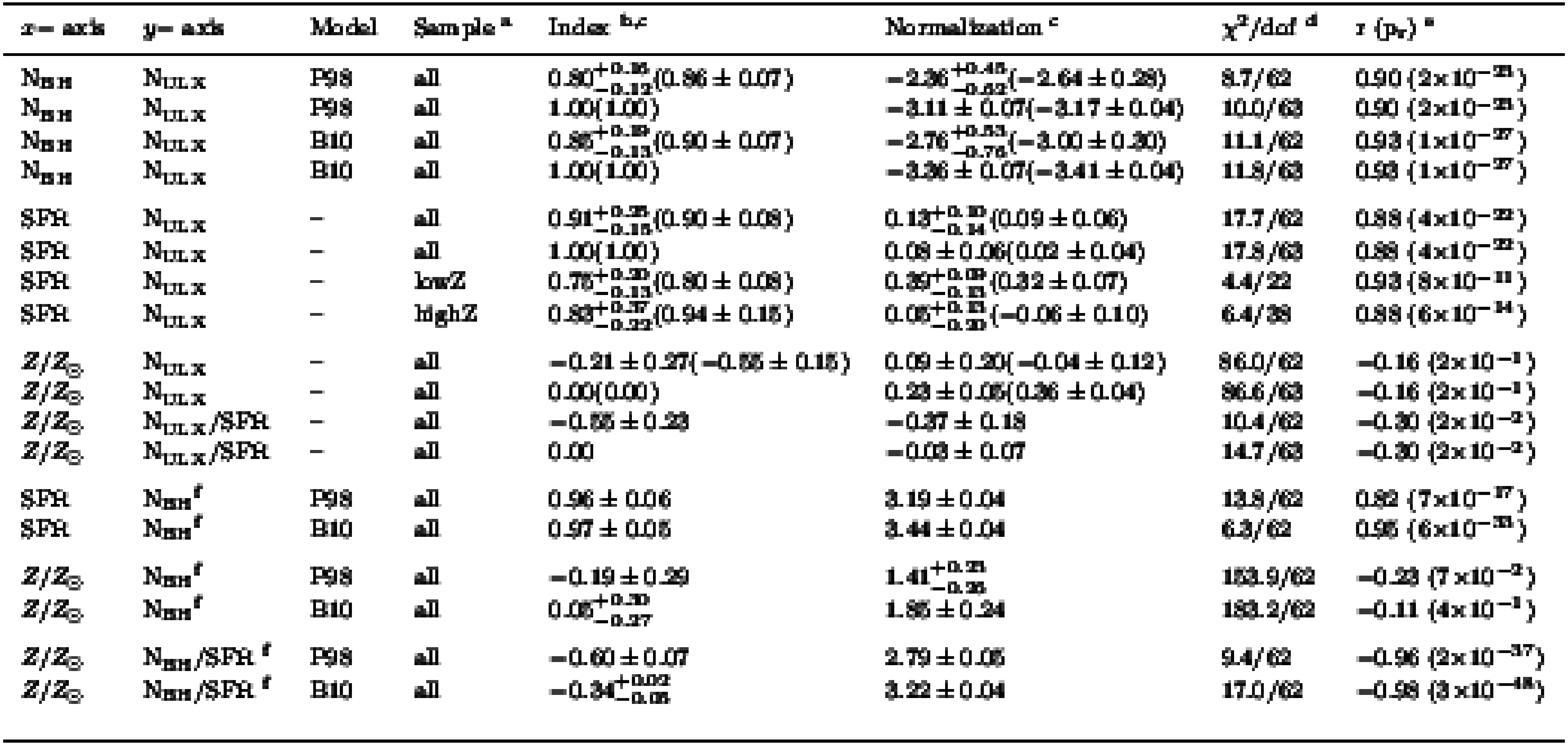
5/64 Local Group galaxies (MW, SMC, LMC, IC10, NGC598)

7/64 non local galaxies (Cartwheel, Antennae, Mice, NGC628, NGC 1058, NGC 5408, Circinus)

The big list:

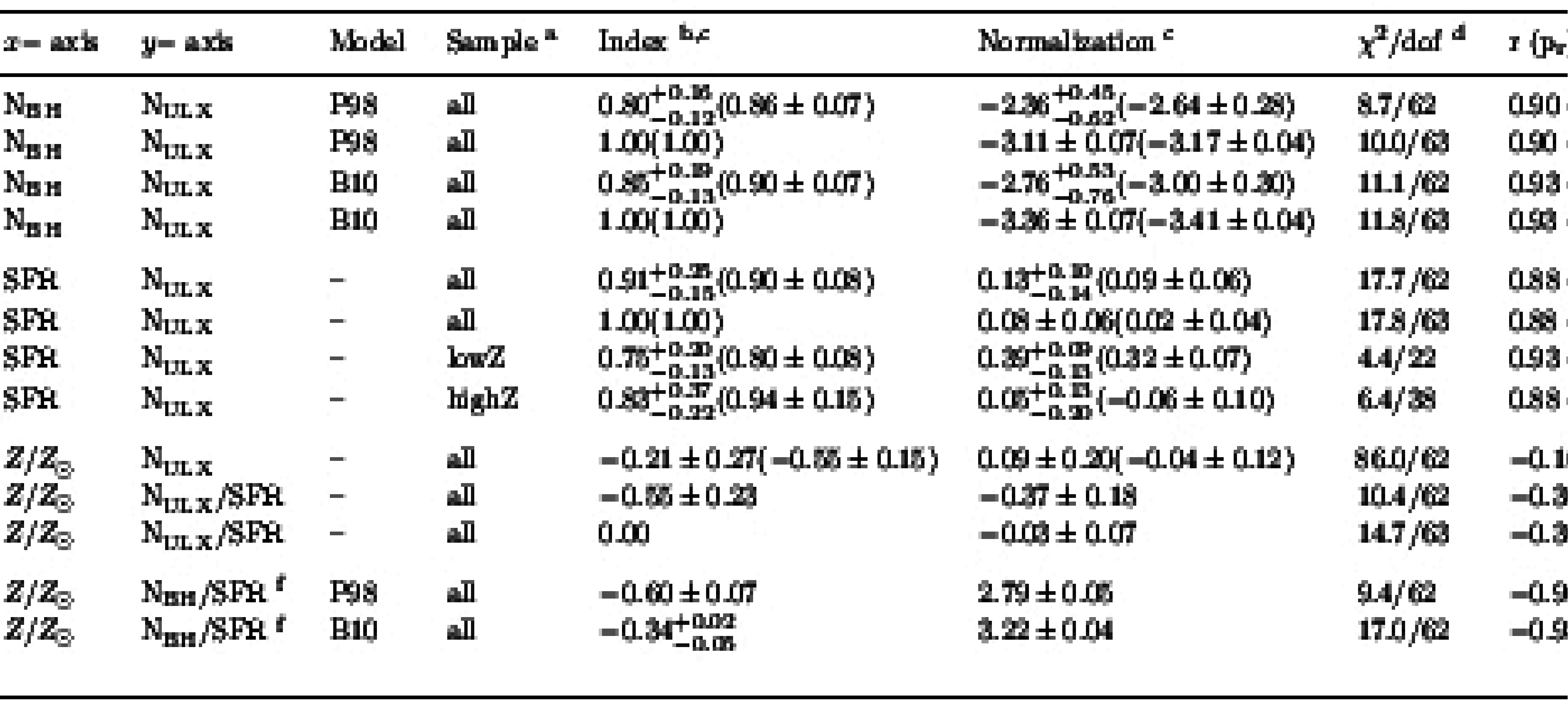
The Cartwheel, NGC253, NGC300, M33, M74, NGC1058, NGC1073, NGC1291, NGC1313, NGC1365, IC342, NGC1566, NGC1705, NGC2366, NGC2403, NGC2442, HoII, NGC2903, M81, NGC3049, IC2574, NGC3310, NGC3395-6, PGC35286, PGC35684, Ngc3738, NGC3972, Antennae, NGC4144, NGC4214, NGC4236, NGC4248, M99, M106, M61, M100, NGC4395, NGC4449, NGC4485-90, NGC4501, NGC4559, NGC4631, NGC4651, NGC4656, The Mice, NGC4736, NGC4861, PGC45561, NGC5033, M63, M51, M83, Mkn 1479, NGC5408, M101, Circinus, NGC6946, IC5201, NGC7714-5, NGC7742, MW, IC10, SMC, LMC

The fits:



$x-$ axis	$y-$ axis	Model	Sample [a]	Index [b,c]	Normalization [c]	χ^2/dof [d]	r {p_r} [e]
N_{BH}	N_{ULX}	P98	all	$0.80^{+0.16}_{-0.12}(0.86 \pm 0.07)$	$-2.36^{+0.45}_{-0.62}(-2.64 \pm 0.28)$	8.7/62	0.90 {2×10^{-23}}
N_{BH}	N_{ULX}	P98	all	1.00(1.00)	$-3.11 \pm 0.07(-3.17 \pm 0.04)$	10.0/63	0.90 {2×10^{-23}}
N_{BH}	N_{ULX}	B10	all	$0.86^{+0.19}_{-0.13}(0.90 \pm 0.07)$	$-2.76^{+0.53}_{-0.76}(-3.00 \pm 0.30)$	11.1/62	0.93 {1×10^{-27}}
N_{BH}	N_{ULX}	B10	all	1.00(1.00)	$-3.36 \pm 0.07(-3.41 \pm 0.04)$	11.8/63	0.93 {1×10^{-27}}
SFR	N_{ULX}	–	all	$0.91^{+0.25}_{-0.15}(0.90 \pm 0.08)$	$0.13^{+0.10}_{-0.14}(0.09 \pm 0.06)$	17.7/62	0.88 {4×10^{-22}}
SFR	N_{ULX}	–	all	1.00(1.00)	$0.08 \pm 0.06(0.02 \pm 0.04)$	17.8/63	0.88 {4×10^{-22}}
SFR	N_{ULX}	–	lowZ	$0.78^{+0.20}_{-0.13}(0.80 \pm 0.08)$	$0.39^{+0.09}_{-0.11}(0.32 \pm 0.07)$	4.4/22	0.93 {8×10^{-11}}
SFR	N_{ULX}	–	highZ	$0.83^{+0.37}_{-0.22}(0.94 \pm 0.15)$	$0.05^{+0.13}_{-0.20}(-0.06 \pm 0.10)$	6.4/38	0.88 {6×10^{-14}}
$Z/Z_{\odot}$	N_{ULX}	–	all	$-0.21 \pm 0.27(-0.55 \pm 0.15)$	$0.09 \pm 0.20(-0.04 \pm 0.12)$	86.0/62	−0.16 {2×10^{-1}}
$Z/Z_{\odot}$	N_{ULX}	–	all	0.00(0.00)	$0.23 \pm 0.05(0.36 \pm 0.04)$	86.6/63	−0.16 {2×10^{-1}}
$Z/Z_{\odot}$	N_{ULX}/SFR	–	all	-0.55 ± 0.23	-0.37 ± 0.18	10.4/62	−0.30 {2×10^{-2}}
$Z/Z_{\odot}$	N_{ULX}/SFR	–	all	0.00	-0.03 ± 0.07	14.7/63	−0.30 {2×10^{-2}}
SFR	N_{BH} [f]	P98	all	0.96 ± 0.06	3.19 ± 0.04	13.8/62	0.82 {7×10^{-17}}
SFR	N_{BH} [f]	B10	all	0.97 ± 0.05	3.44 ± 0.04	6.3/62	0.95 {6×10^{-33}}
$Z/Z_{\odot}$	N_{BH} [f]	P98	all	-0.19 ± 0.29	$1.41^{+0.21}_{-0.25}$	153.9/62	−0.23 {7×10^{-2}}
$Z/Z_{\odot}$	N_{BH} [f]	B10	all	$0.05^{+0.30}_{-0.27}$	1.85 ± 0.24	183.2/62	−0.11 {4×10^{-1}}
$Z/Z_{\odot}$	N_{BH}/SFR [f]	P98	all	-0.60 ± 0.07	2.79 ± 0.05	9.4/62	−0.96 {2×10^{-37}}
$Z/Z_{\odot}$	N_{BH}/SFR [f]	B10	all	$-0.34^{+0.02}_{-0.05}$	3.22 ± 0.04	17.0/62	−0.98 {3×10^{-45}}

The fits:



x– axis	y– axis	Model	Sample [a]	Index [b,c]	Normalization [c]	χ^2/dof [d]	r (p
N_{BH}	N_{ULX}	P98	all	$0.80^{+0.16}_{-0.12}(0.86 \pm 0.07)$	$-2.36^{+0.45}_{-0.62}(-2.64 \pm 0.28)$	8.7/62	0.90
N_{BH}	N_{ULX}	P98	all	1.00(1.00)	$-3.11 \pm 0.07(-3.17 \pm 0.04)$	10.0/63	0.90
N_{BH}	N_{ULX}	B10	all	$0.86^{+0.19}_{-0.13}(0.90 \pm 0.07)$	$-2.76^{+0.53}_{-0.76}(-3.00 \pm 0.30)$	11.1/62	0.93
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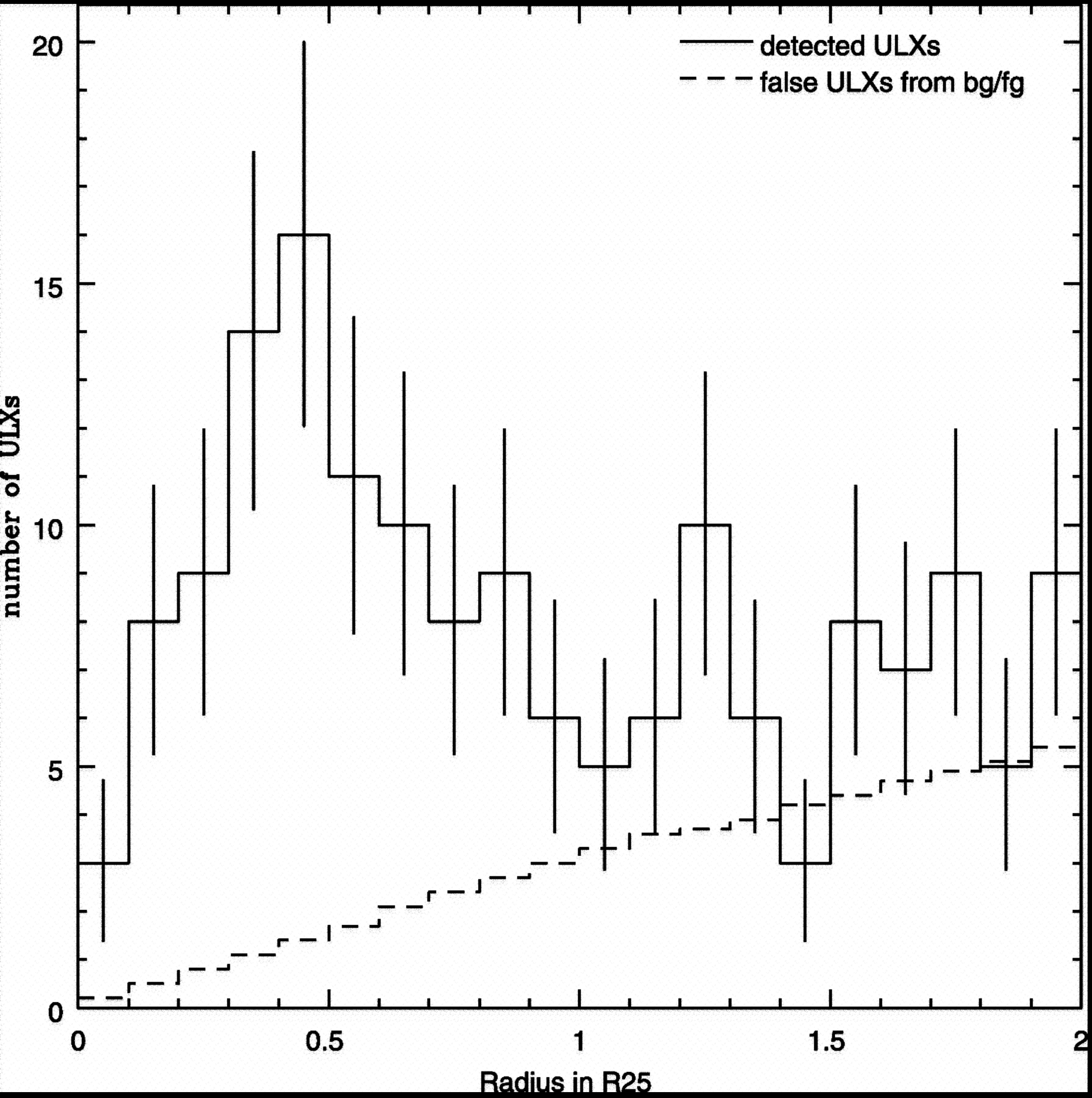
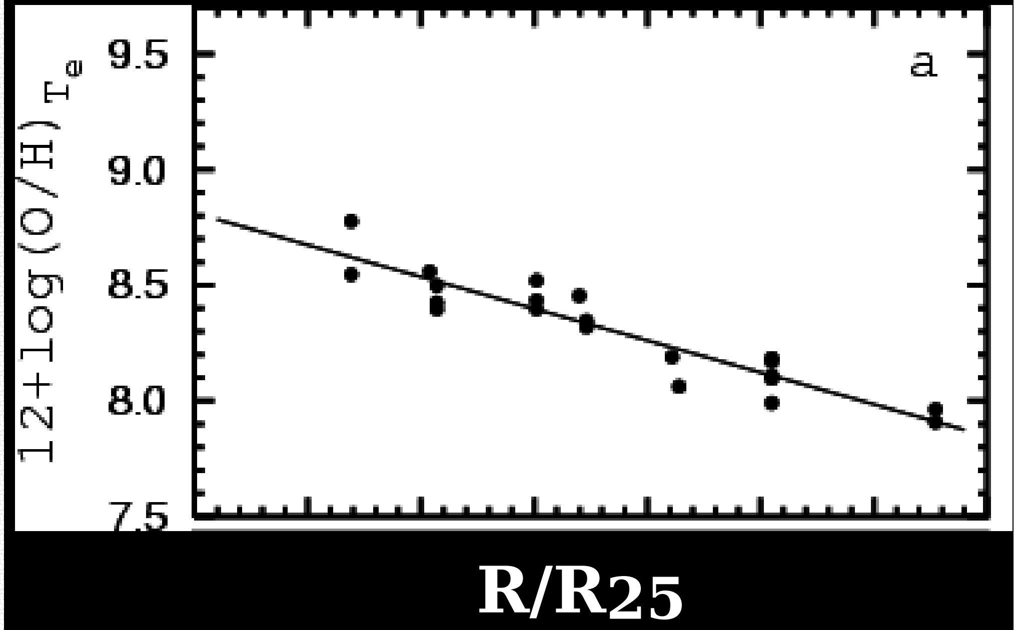
SFR	N_{ULX}	–	lowZ	$0.76^{+0.20}_{-0.13}(0.80 \pm 0.08)$	$0.39^{+0.09}_{-0.13}(0.32 \pm 0.07)$	4.4/22	0.93
SFR	N_{ULX}	–	highZ	$0.83^{+0.37}_{-0.22}(0.94 \pm 0.15)$	$0.05^{+0.13}_{-0.20}(-0.06 \pm 0.10)$	6.4/38	0.88
$Z/Z_{\odot}$	N_{ULX}	–	all	$-0.21 \pm 0.27(-0.55 \pm 0.15)$	$0.09 \pm 0.20(-0.04 \pm 0.12)$	86.0/62	−0.1
$Z/Z_{\odot}$	N_{ULX}/SFR	–	all	-0.55 ± 0.23	-0.37 ± 0.18	10.4/62	−0.3
$Z/Z_{\odot}$	N_{ULX}/SFR	–	all	0.00	-0.03 ± 0.07	14.7/63	−0.3
$Z/Z_{\odot}$	N_{BH}/SFR [f]	P98	all	-0.60 ± 0.07	2.79 ± 0.05	9.4/62	−0.9
$Z/Z_{\odot}$	N_{BH}/SFR [f]	B10	all	$-0.34^{+0.02}_{-0.05}$	3.22 ± 0.04	17.0/62	−0.9

Why Z at 0.7 R_{25}?

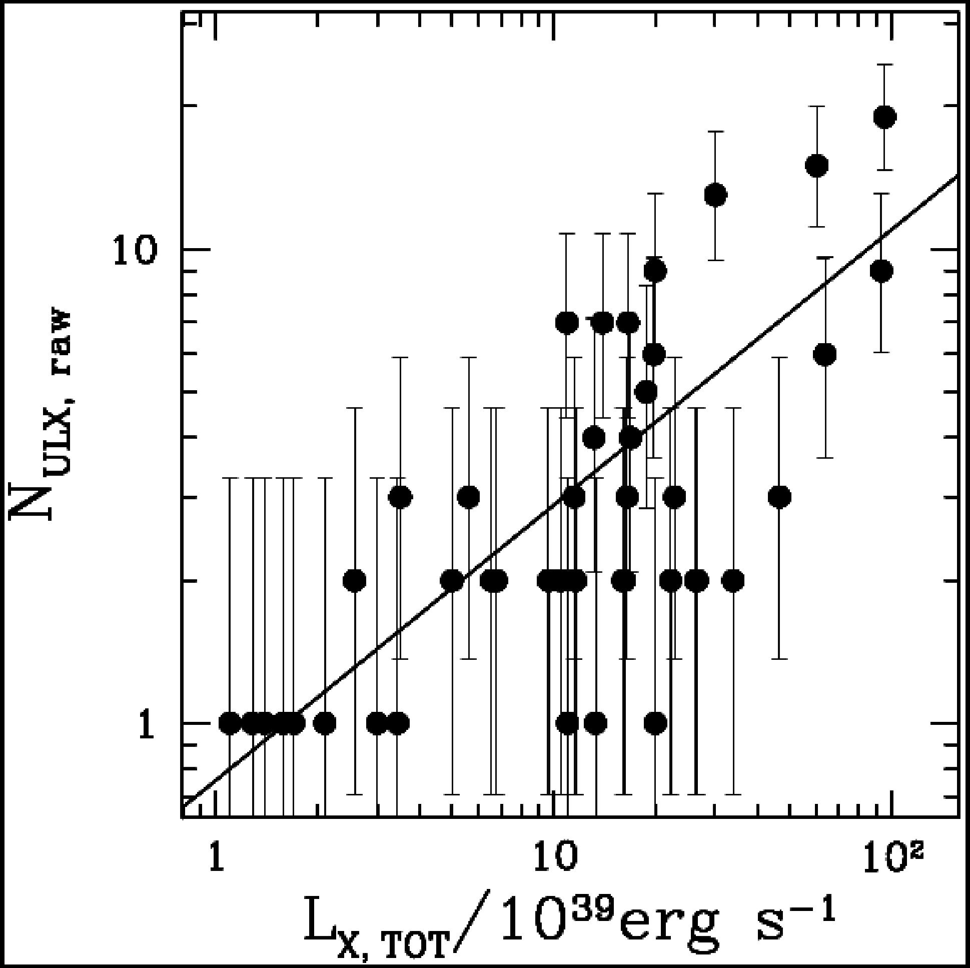
average ULX distance from the centre in spiral galaxies (Liu, Bregman & Irwin 2006):



we use metallicity gradients



L-SFR relation in our sample



BUT we prefer to use N_{ULX} because:

1. straightforward comparison with N_{BH}

2. less dependent on L variability

3. we do not have to integrate the spectrum over a given range

Slides riserva

1) pilyugin

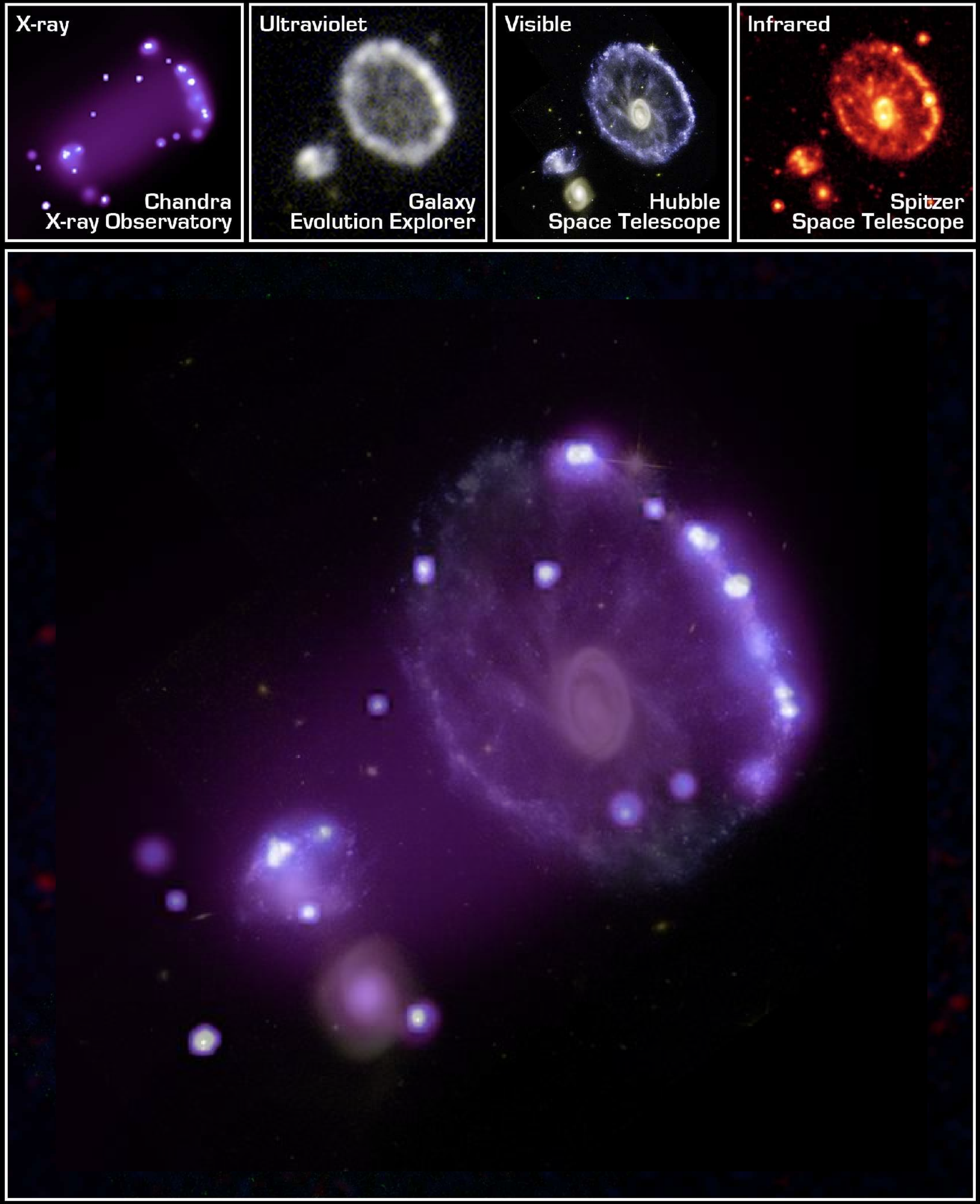
2) lista galassie?

3) SFR conversion?

4) comparison bressan – belczynski

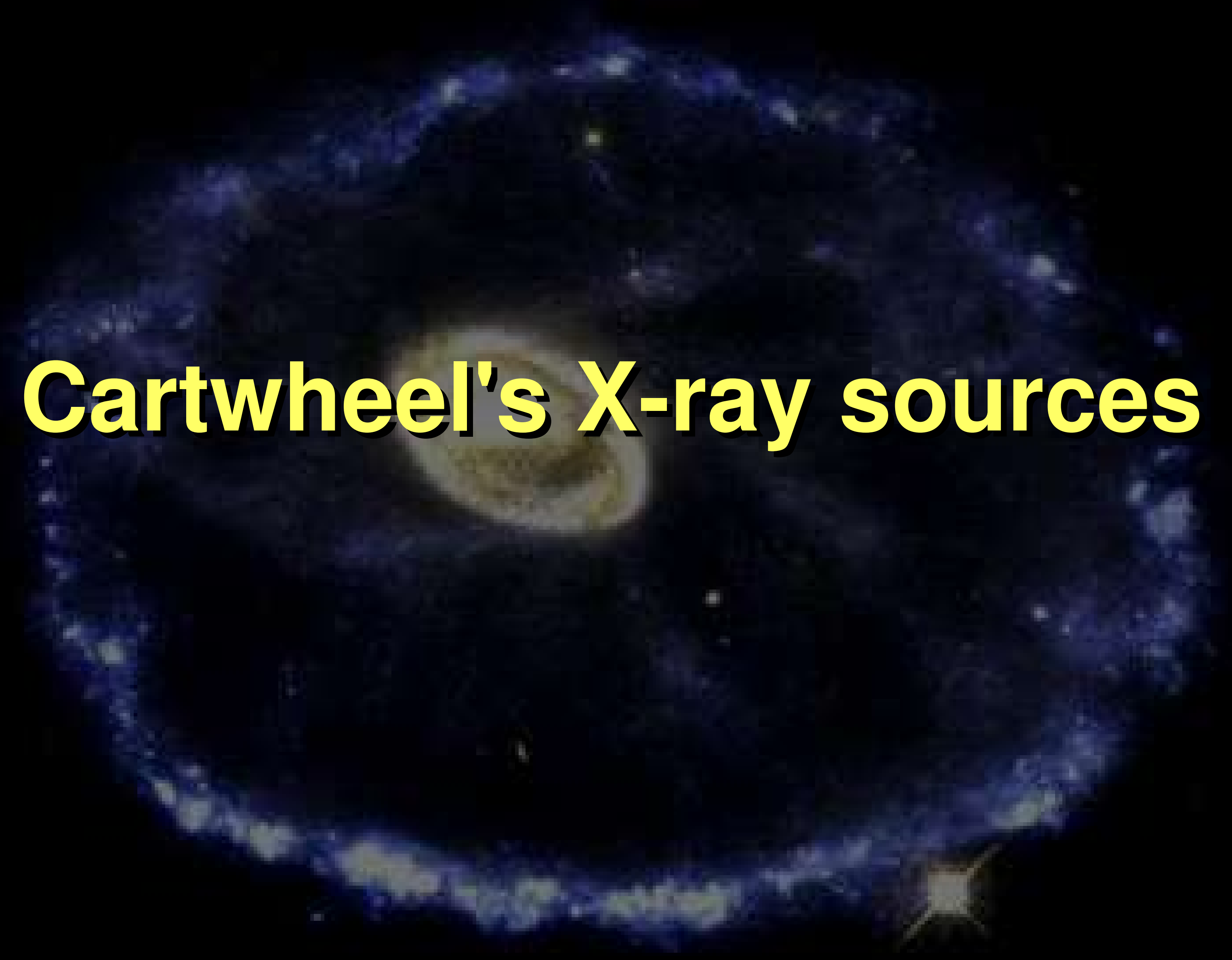
5) metal deficient galaxies

Cartwheel properties:



- multifrequency observations
- gas-rich star forming ring
- stars young in ring-intermed. age in bulge
- SPOKES associated with stars
- X-RAY sources in the RING

Cartwheel's X-ray sources



Are ULXs powered by IMBHs?

IMBHs can be:

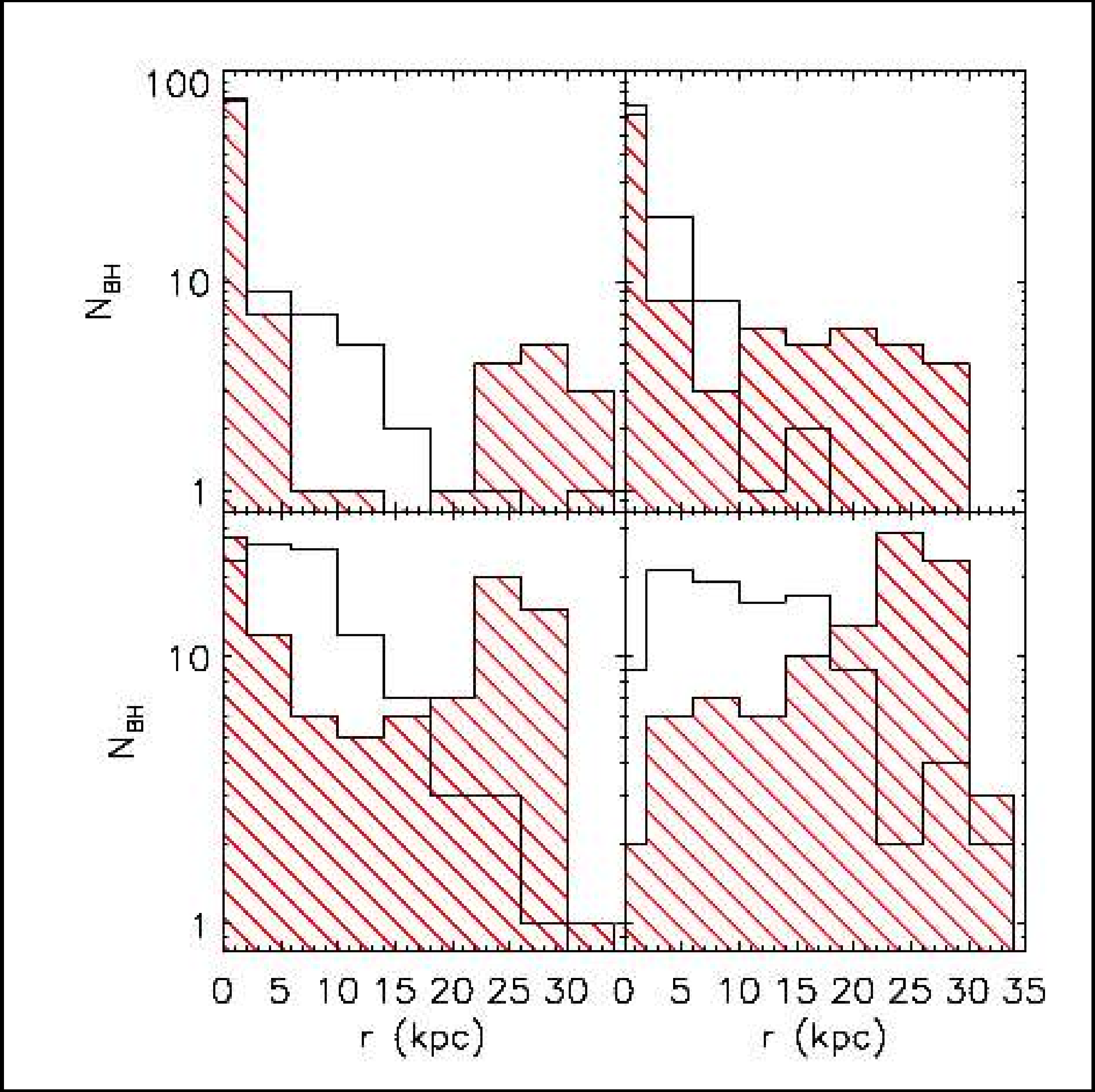
- HALO population, if born at high redshift
  by pop III stars

form only BEFORE the galaxy collision

-DISC population, if formed by runaway
collapse in young clusters

form both before and after the collision

Are ULXs powered by IMBHs?



during the interaction
-HALO IMBHs remain
almost unperturbed

NO ULXs

- 50-80 % of pre-existing disc BHs are ejected in the ring

maybe ULXs

MECHANISMs of ACCRETION

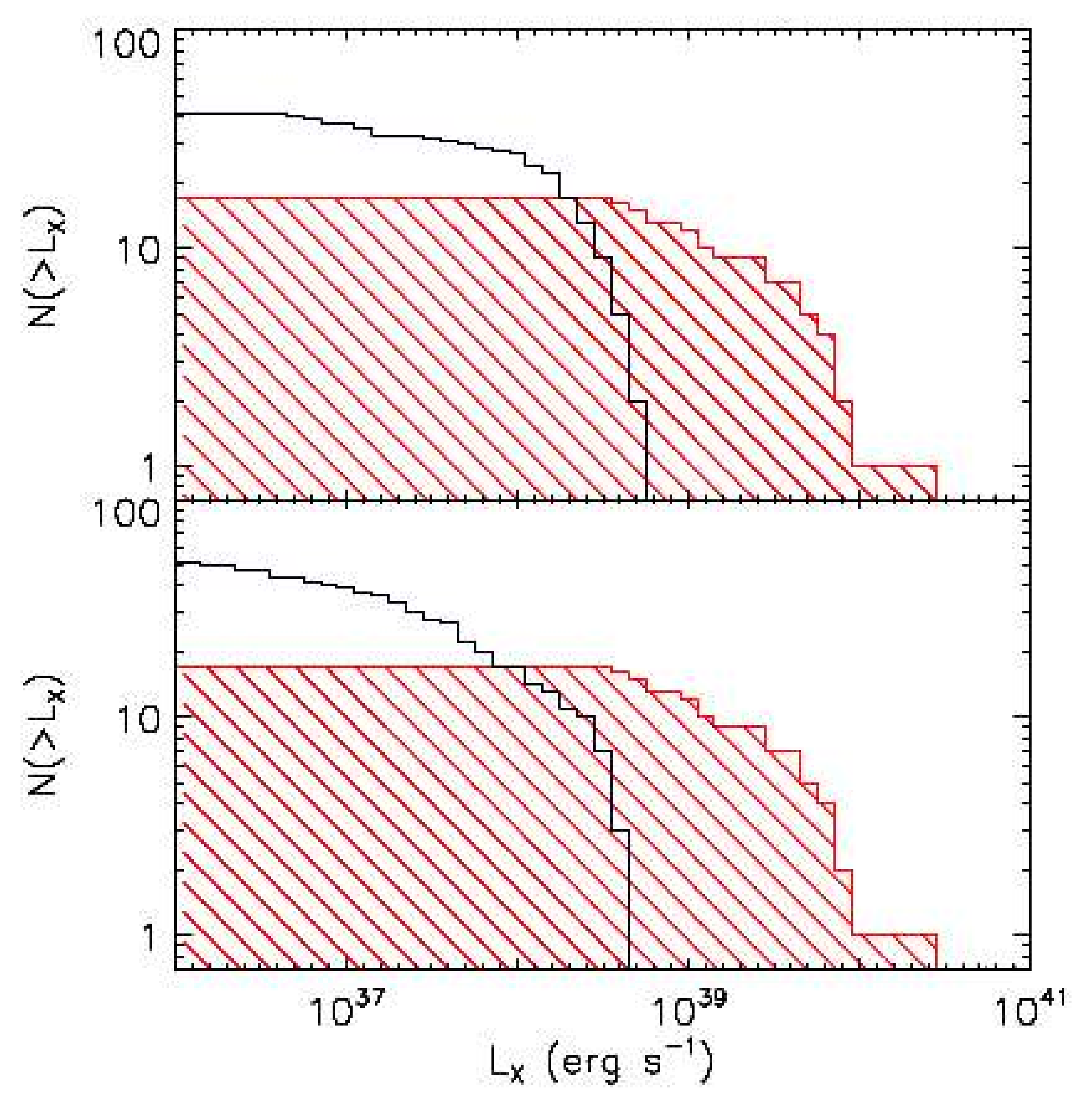
1) IMBHs accrete gas from surrounding dense clouds

BONDI-HOYLE

2) IMBHs in binary systems accrete from companion stars via mass transfer

MECHANISMs of ACCRETION

1) IMBHs accrete gas from surrounding dense clouds



1000 Msun IMBHs

rad. efficiency =0.1

<u>NO ULXs due to gas accreting disc IMBHS</u>

MECHANISMs of ACCRETION

1) IMBHs accrete gas from surrounding dense clouds

BONDI-HOYLE

2) IMBHs in binary systems accrete from companion stars via mass transfer

-spend 3 % of their life in mass transfer (Blecha et al. 2006)

-if companion mass <10 Msun (~40 Myr) TRANSIENT ULXs
(Portegies Zwart et al. 2004)

-if companion mass >= 10 Msun PERSISTENT ULXs
(Patruno et al. 2005)

MECHANISMs of ACCRETION

2) IMBHs in binary systems accrete from companion stars via mass transfer

-spend 3 % of their life in mass transfer (Blecha et al. 2006)

↓

out of 100 IMBHs in the ring
only ~3 do mass transfer at present

$$N_{BH,MT} = 2.4 \left(\frac{f_{MT}}{0.03} \right) \left(\frac{N_{BH,ring}}{79} \right)$$

MECHANISMs of ACCRETION

2) IMBHs in binary systems accrete from companion stars via mass transfer

-spend 3 % of their life in mass transfer (Blecha et al. 2006)

-if companion mass <10 Msun (~40 Myr) TRANSIENT ULXs
(Portegies Zwart et al. 2004)

-if companion mass >= 10 Msun PERSISTENT ULXs
(Patruno et al. 2005)

↓

disc IMBHs accreting from stars formed before the collision give only TRANSIENT ULXs, but we observe also persistent ones

MECHANISMs of ACCRETION

2) IMBHs in binary systems accrete from companion stars via mass transfer

-spend 3 % of their life in mass transfer (Blecha et al. 2006)

-if companion mass <10 Msun (~40 Myr) TRANSIENT ULXs (Portegies Zwart et al. 2004)

-if companion mass >= 10 Msun PERSISTENT ULXs (Patruno et al. 2005)

↓

> 500 disc IMBHs accreting from YOUNG stars are required to produce 15 bright X-ray sources: HUGE

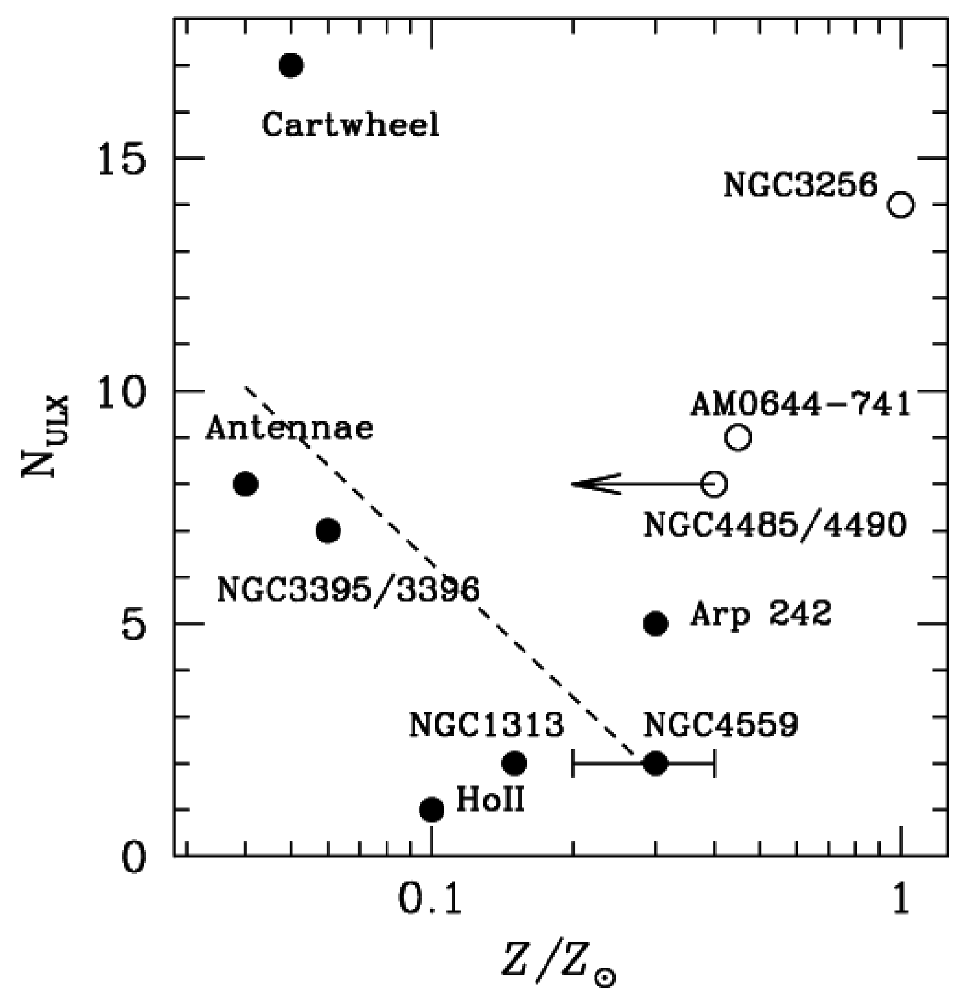
CONCLUSIONs for Cartwheel's ULXs:

1) HALO IMBHs can never produce ULXs

2) DISC IMBHs accreting gas do not produce ULXs

3) DISC IMBHs accreting YOUNG MASSIVE stars can account ONLY for the BRIGHTEST X-RAY SOURCES (<~5)

Comparison with other galaxies



Is the metallicity very low in all the galaxies which host many ULXs?

$$\beta = -9.53$$
$$\gamma = -3.25$$

$$N_{\rm ULX} = \beta \log_{10}(Z/Z_\odot) + \gamma$$

MM, Colpi & Zampieri 2009

Alternative mechanisms to form massive BHs

Can these BHs account for ~17 ULXs?

$$\epsilon_{\rm BH} \equiv \frac{\rm N_{ULX}}{\rm N_{BH}} \sim 10^{-5} - 10^{-4}$$

reasonable efficiency

MM, Colpi & Zampieri 2009

FUTURE:

1) Cosmological simulations should address the problem of peculiar galaxies (dedicated zooms)

2) More comparisons with observations!

- velocity fields of LSBs

- metallicity measurements in galaxies with ULXs

- comparison between simulations and archival data of lopsided galaxies