The Known Unknowns: predicting the landscape of LISA black hole sources

Kelly Holley-Bockelmann
Vanderbilt University and Fisk University
k.holley@vanderbilt.edu

Why can't we predict a (robust) SMBH merger event rate?

Step 0: measure a black hole mass

Step 1: relate BH mass to host galaxy

Step 2: find evidence of binary black holes

Step 3: measure galaxy merger rate to constrain SMBH merger ra

Step 4: Sow SMBH seeds

Step 5: Model SMBH growth

Step 6: Model SMBH merger dynamics to get merger timescales

Step 7: Find the strain, SNR for each merger

Step 0: measure a black hole mass

Step 1: relate BH mass to host galaxy

Step 2: find evidence of binary black holes

Step 3: measure galaxy merger rate to constrain SMBH merger ra

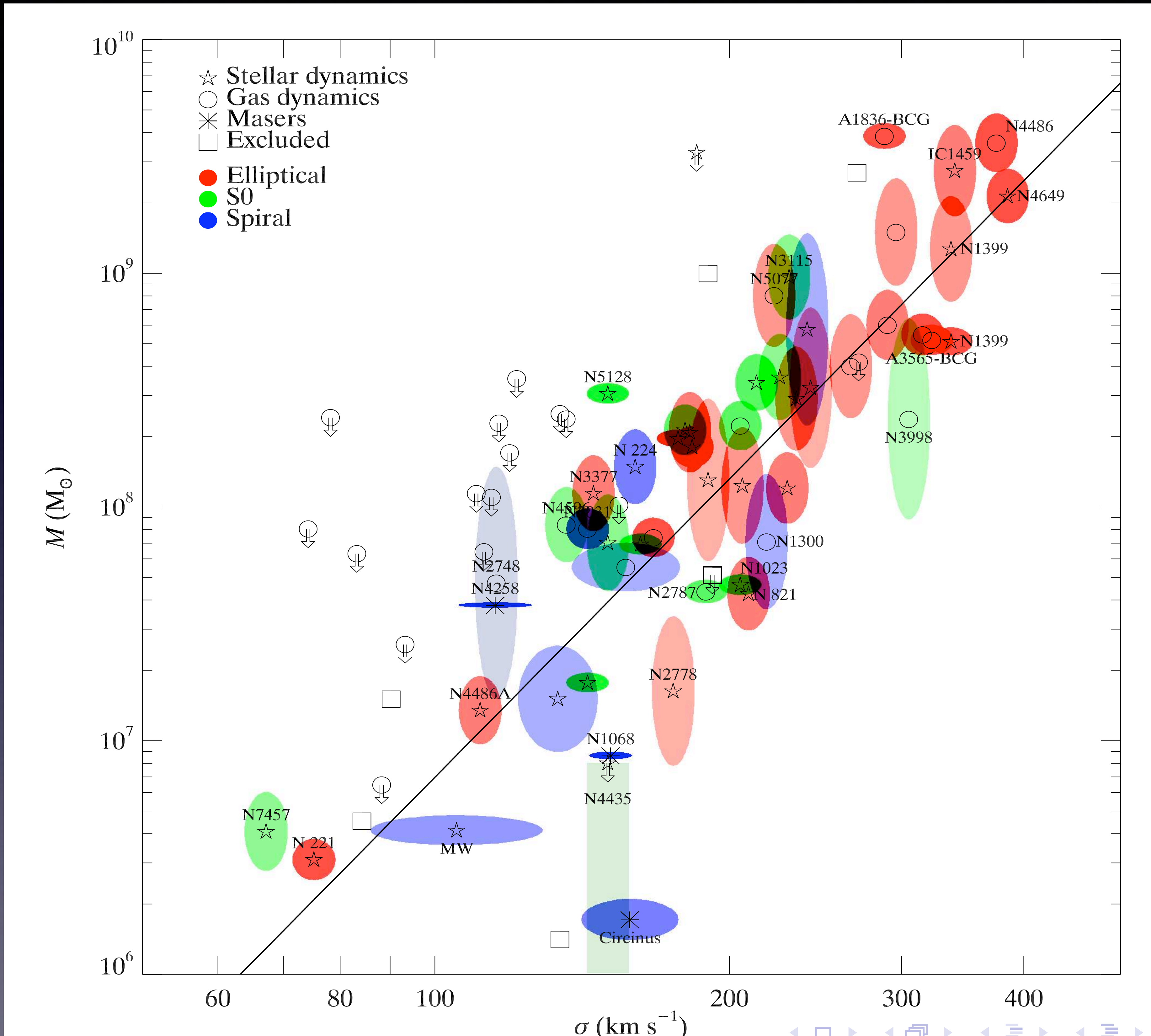
Step 4: Sow SMBH seeds

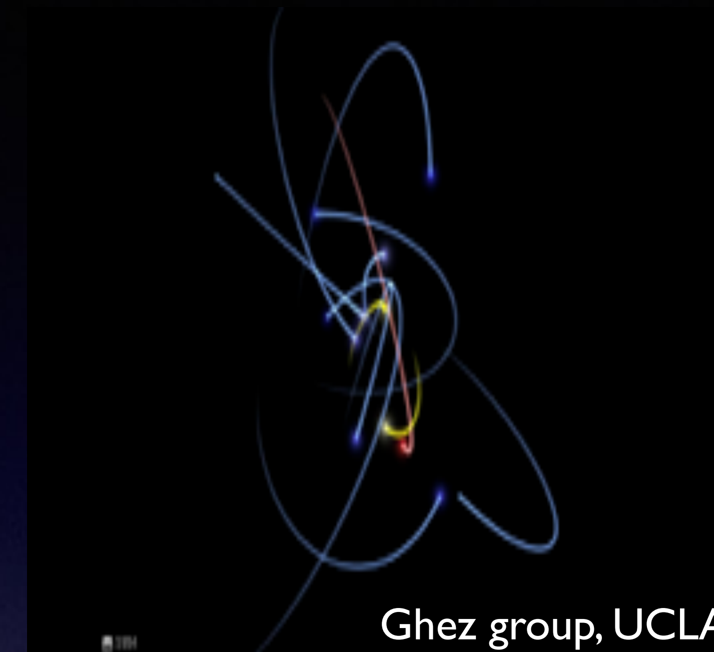
Step 5: Model SMBH growth

Step 6: Model SMBH merger dynamics to get merger timescales

Step 7: Find the strain, SNR for each merger

A Supermassive Black Hole for 'Every' Galaxy





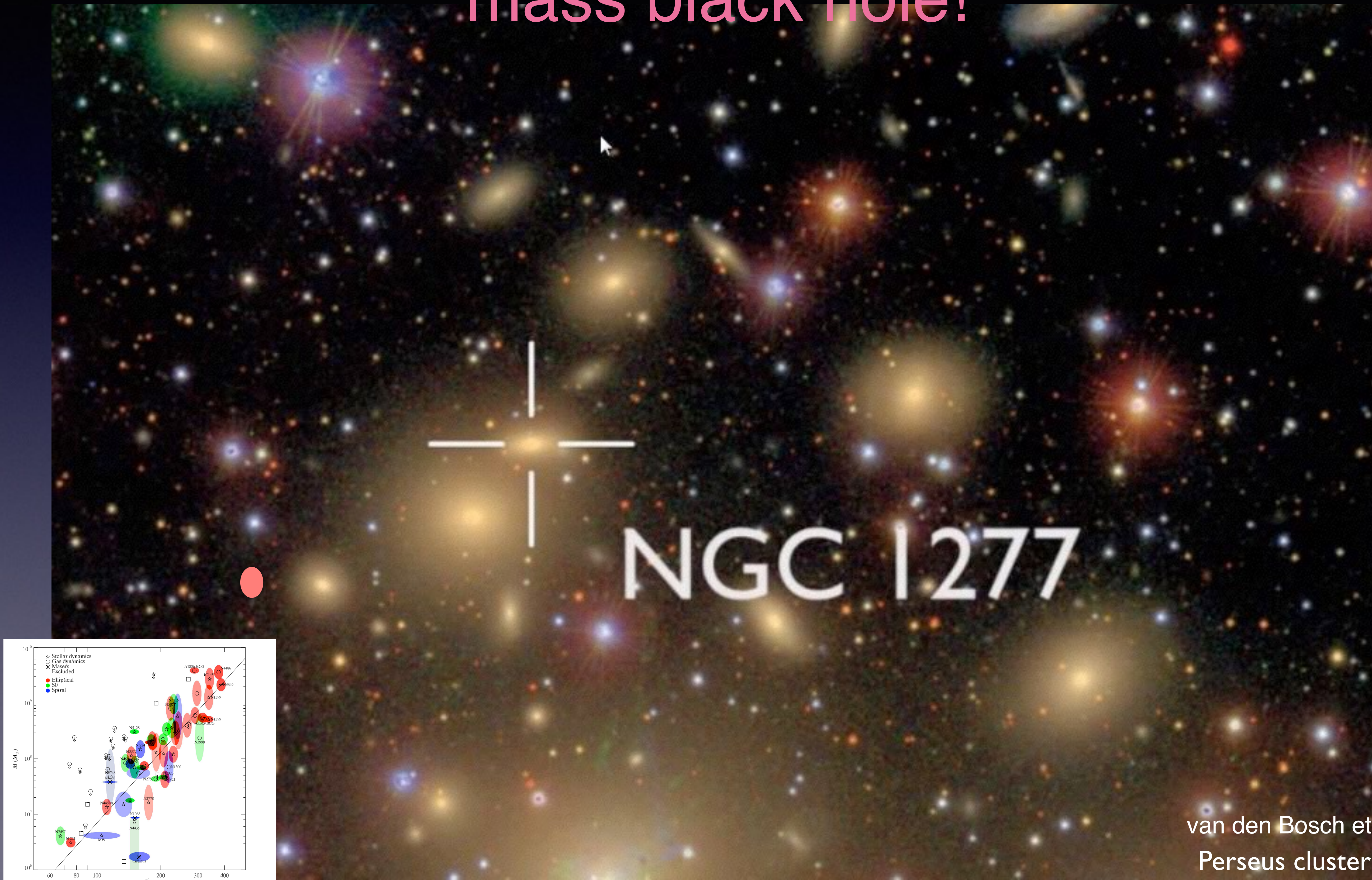
R_{sch}=2 G M/c^2=O(10^{-6})

R_{infl}=G M/σ_0^2=O(10^0) p

R_e=O(10^3) pc

Gultekin et al 2009 -- see also Gebhardt et al 2000; Ferrarese & Merritt 2000: McConnell+Ma 2013...

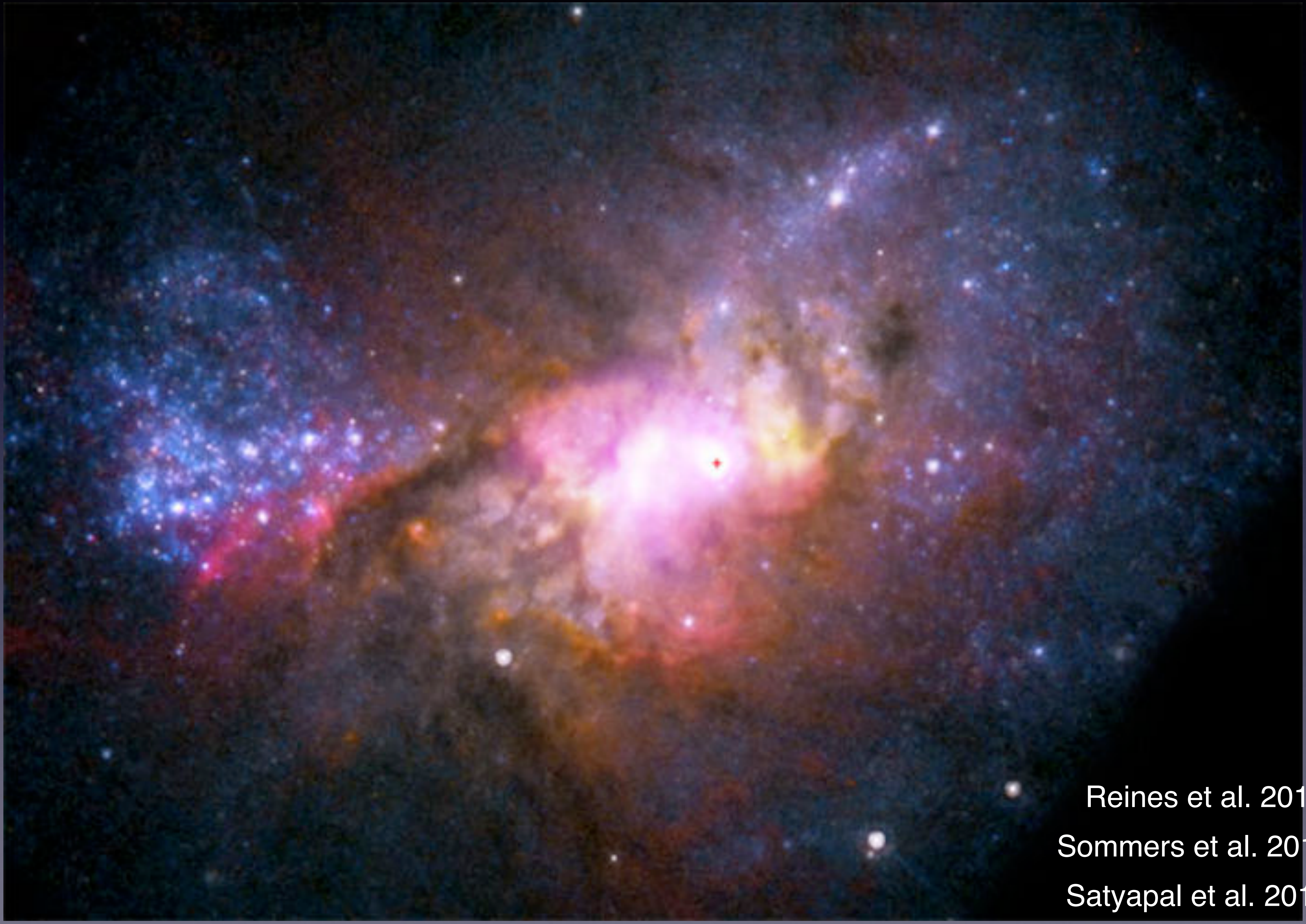
Rule-breaker: Unassuming galaxy with 17 billion solar mass black hole!



Rule-breaker: Unassuming galaxy with 17 billion solar mass black hole!

Heinze 2-10 is dwarf with a million solar mass black hole

and there are SMBHs in bulgeless galaxies,



…and in low surface brightness galaxies, like Malin 1

\

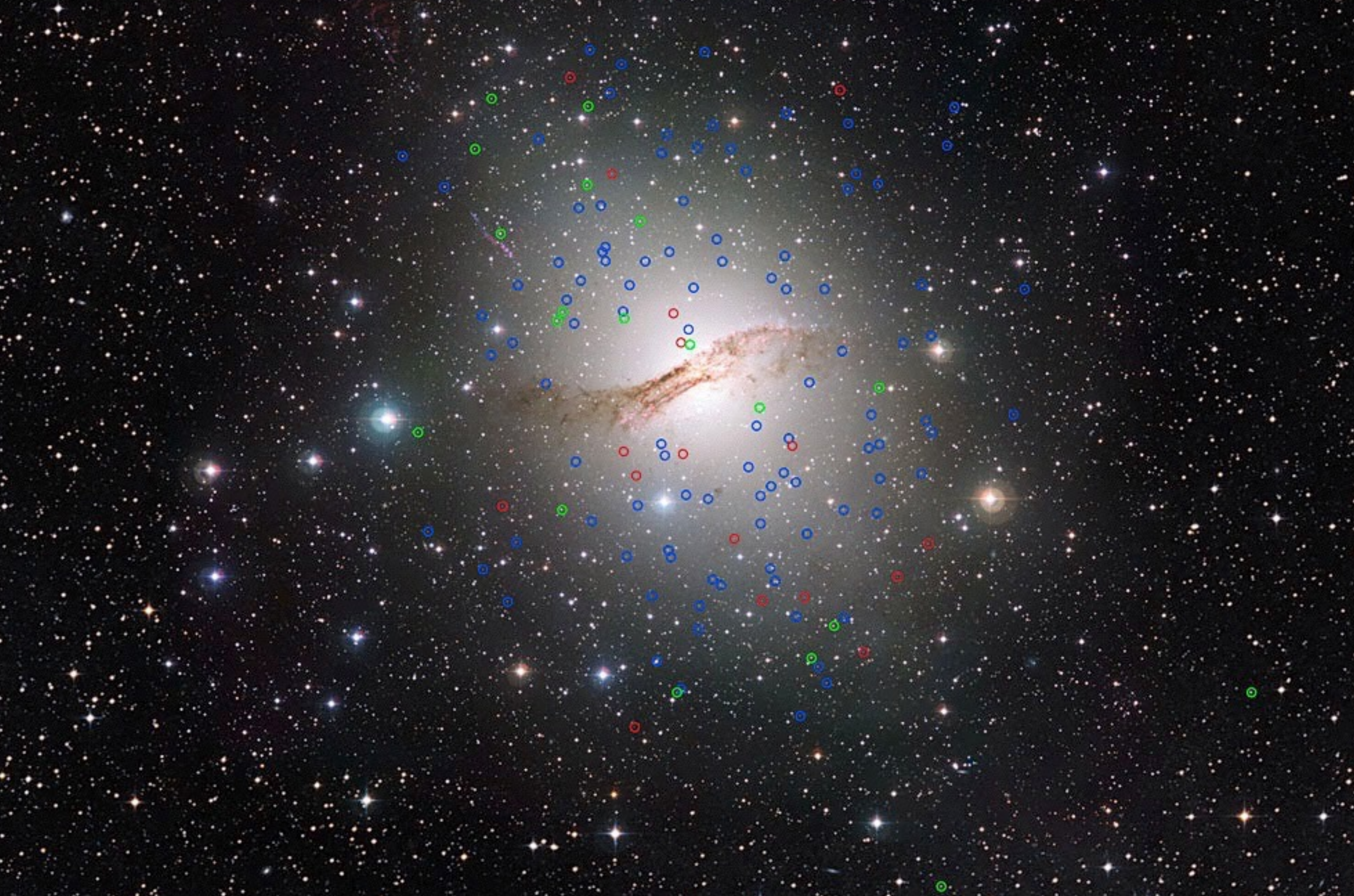
Warning: viral masses — assume line width maps to velocity for Keplerian motion

Subramanian et al. 2015

Evidence of an intermediate mass black hole --- in the outskirts of a galaxy

Newly discovered dark star clusters may contain IMBHs

Taylor et al. 2015; Bovill et al 2016



Step 0: measure a black hole mass

Step 1: relate BH mass to host galaxy

Step 2: find evidence of binary black holes

See Dotti et al. 2012!

Step 3: measure galaxy merger rate to constrain SMBH merger

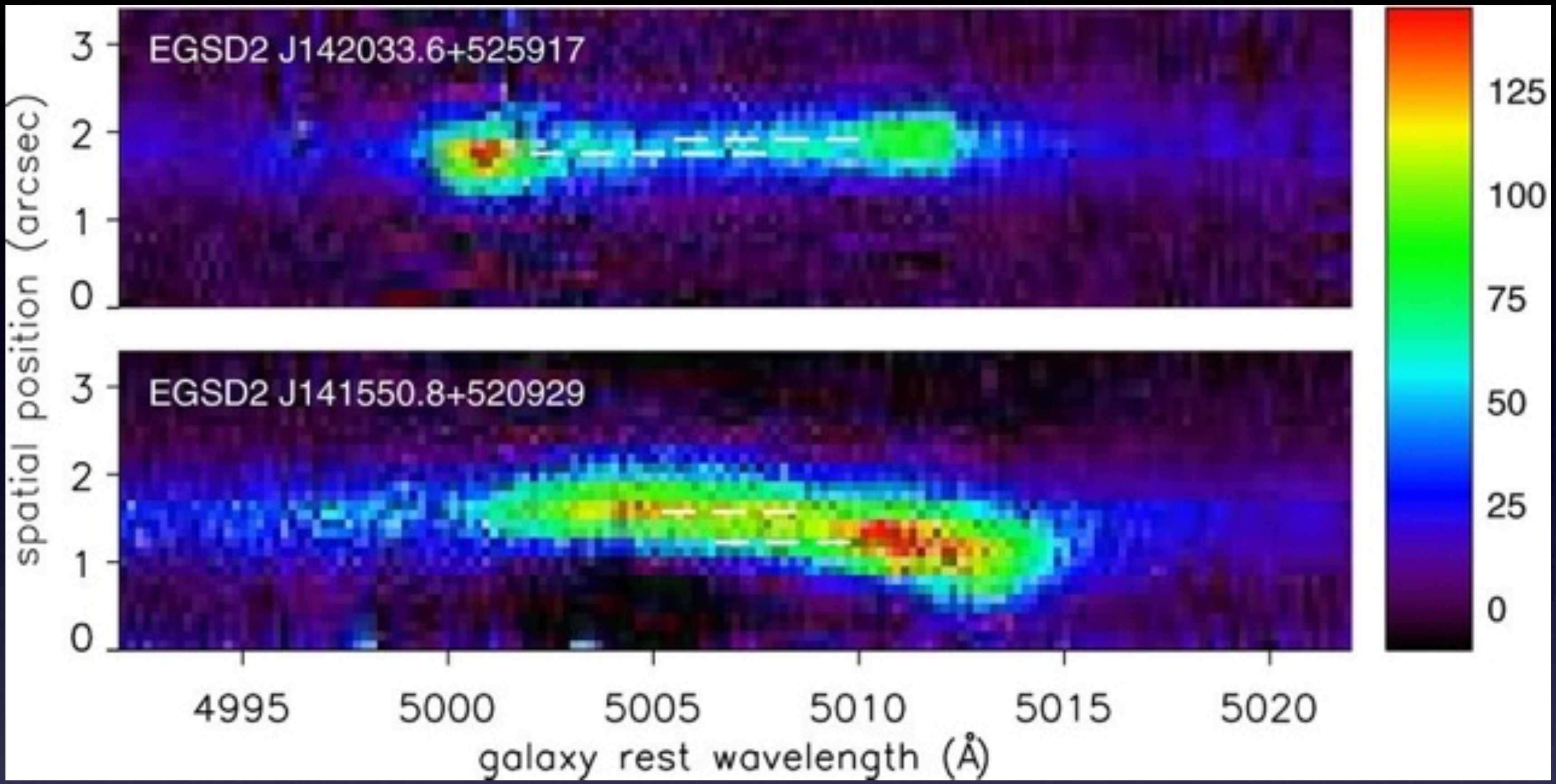
Step 4: Sow SMBH seeds (see Rossi and Latif talks!)

Step 5: Model SMBH growth

Step 6: Model SMBH merger dynamics to get merger timescales

Step 7: Find the strain, SNR for each merger

While there are certainly dual AGN,

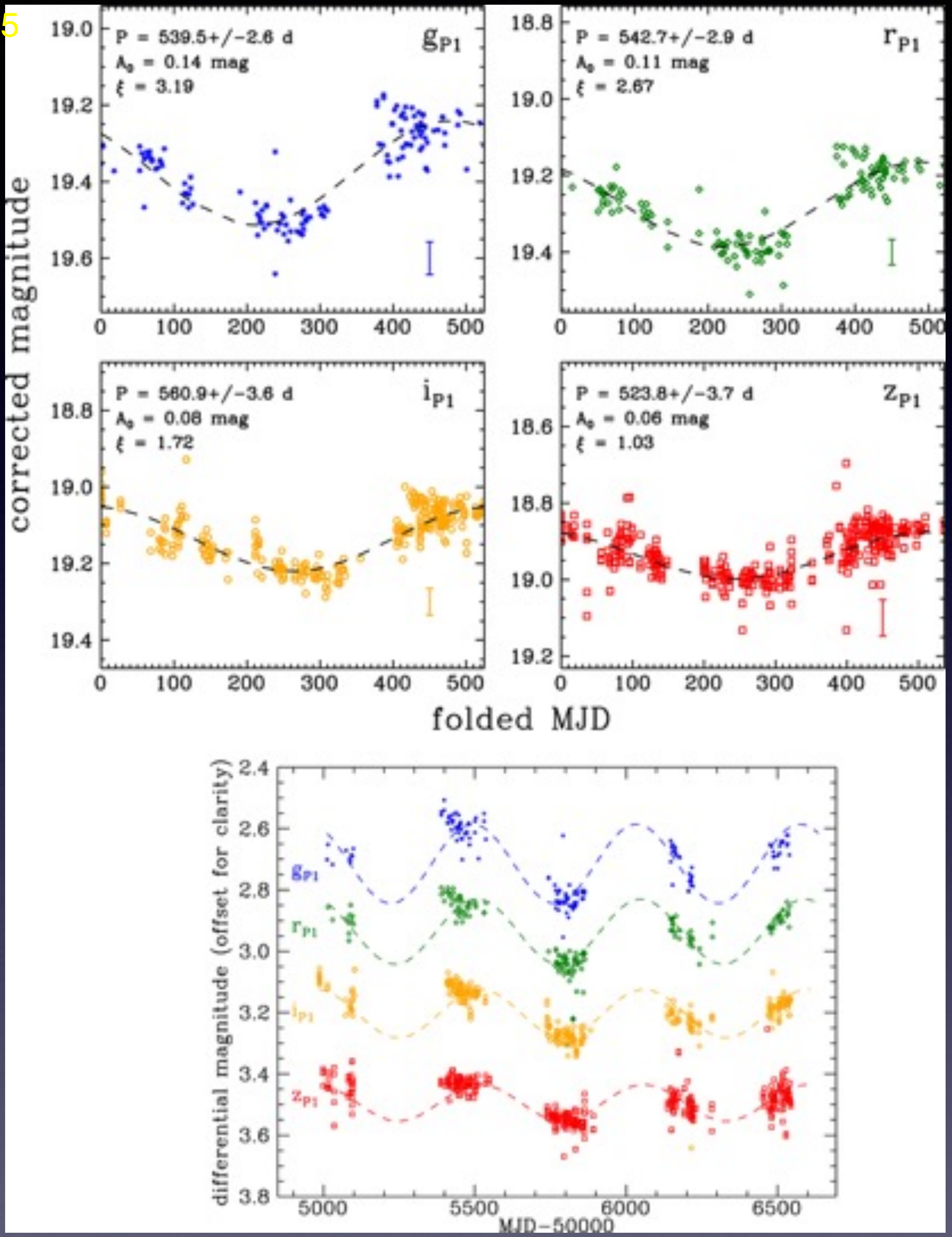


Comerford et al. 2009 — 1kpc separation [OIII]5007

Liu et al. 2013 — image from galaxy

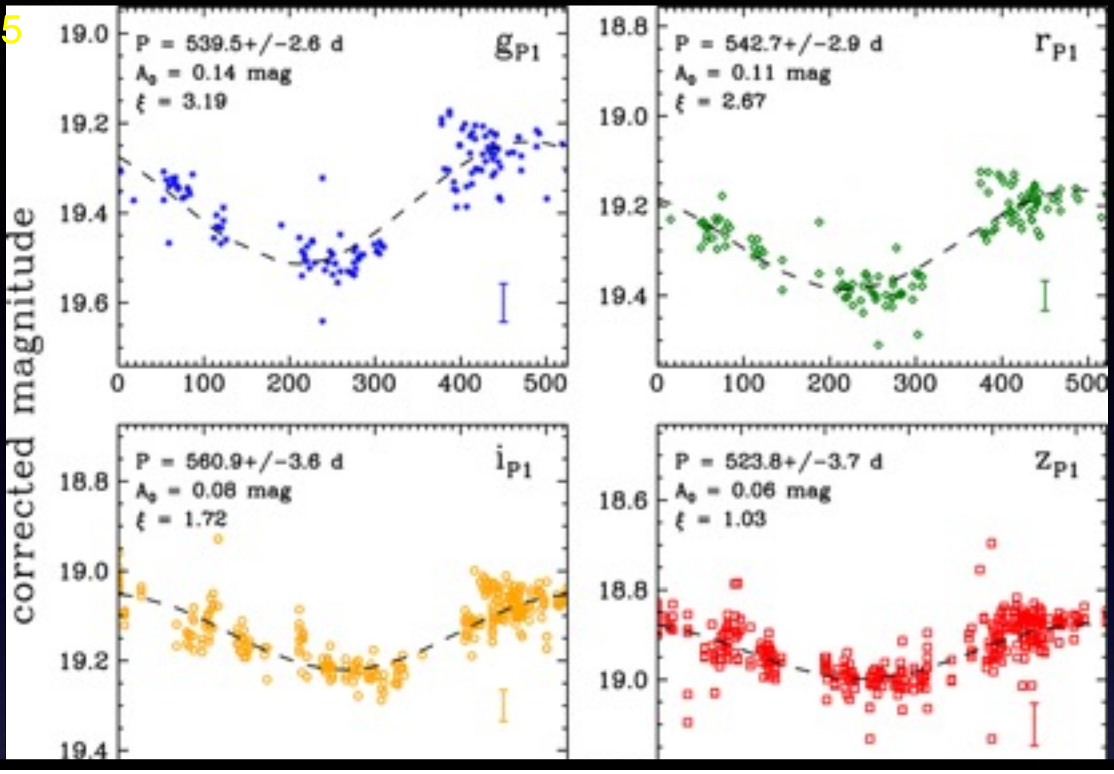
Pan-Starrs PSO J334.2028+01.4075 — Periodicity caused by 542+/- 15 day orbit of a 10^10 solar mass binary at 0.05<q<0.25 @ z=2.06 — separation of ~10 R_s!!

Liu et al. 2015

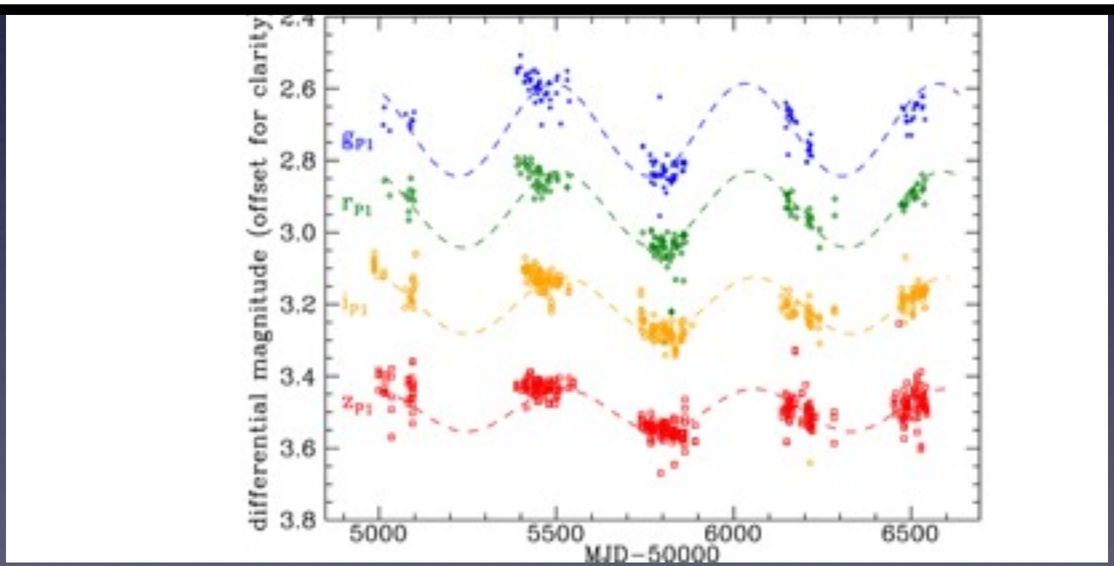


Pan-Starrs PSO J334.2028+01.4075 — Periodicity caused by 542+/- 15 day orbit of a 10^10 solar mass binary at 0.05<q<0.25 @ z=2.06 — separation of ~10 R_s!!

Liu et al. 2015



Not seen in the Catalina Real-time Transit Survey Graham et al. 2015



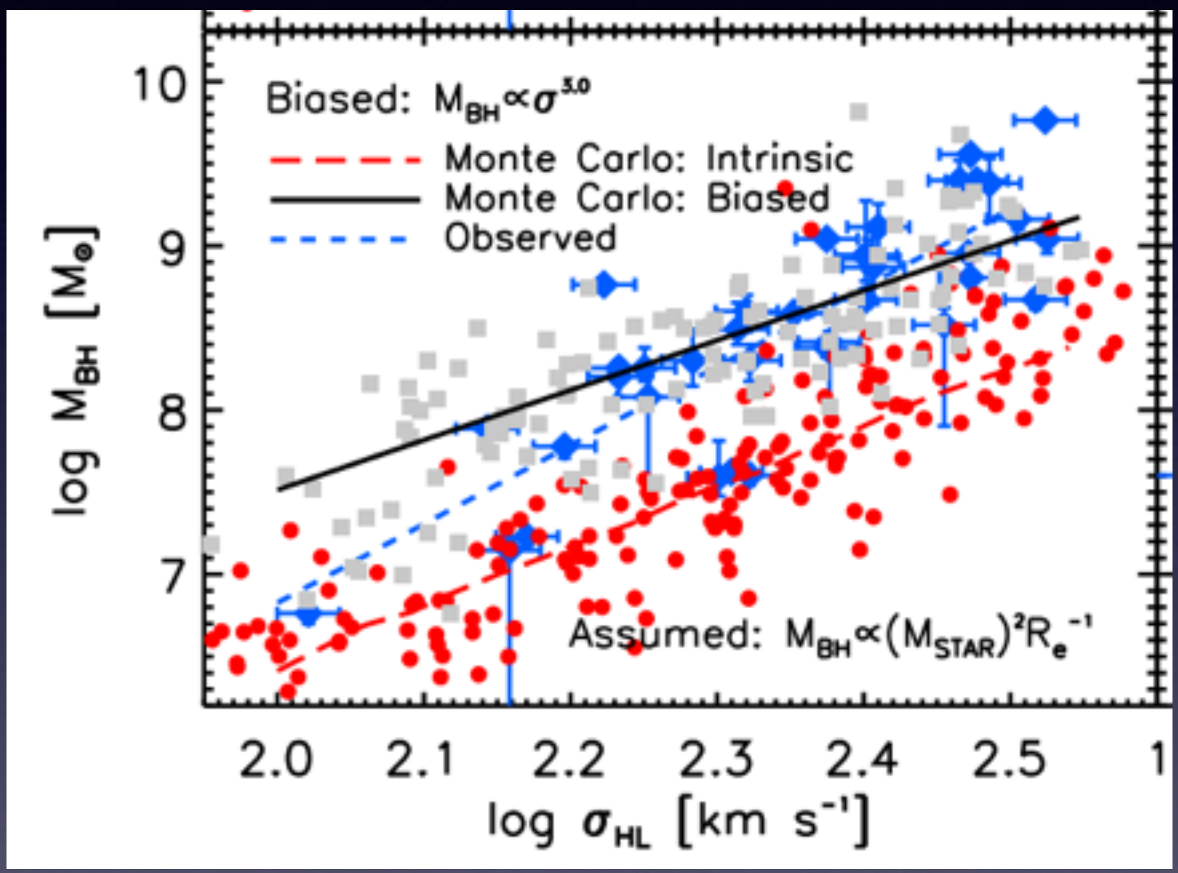
VLBI search OF ~3100 AGN, only 1 found to be consistent with a BBH

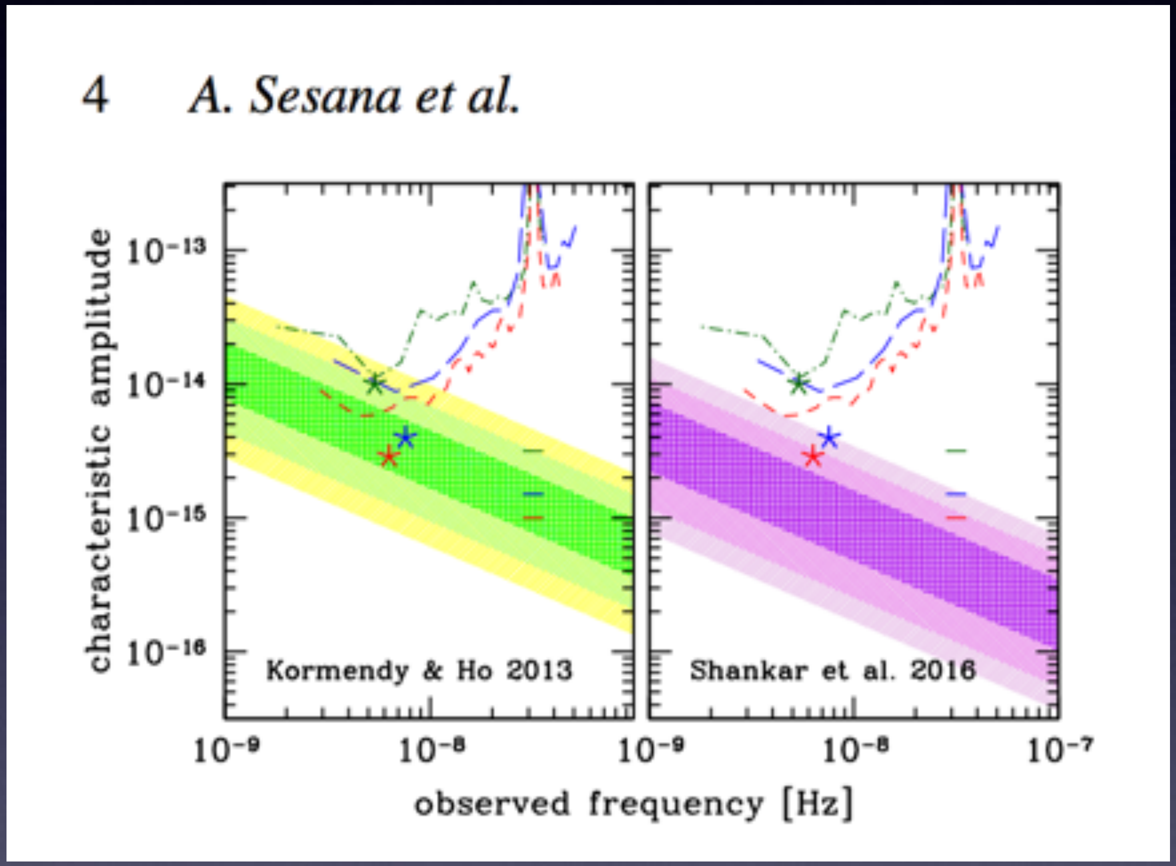
Burke-Spolaor 2011

Stay tuned! Time-domain astronomy will help here…

Sample bias can offset the normalization of SMBH relations

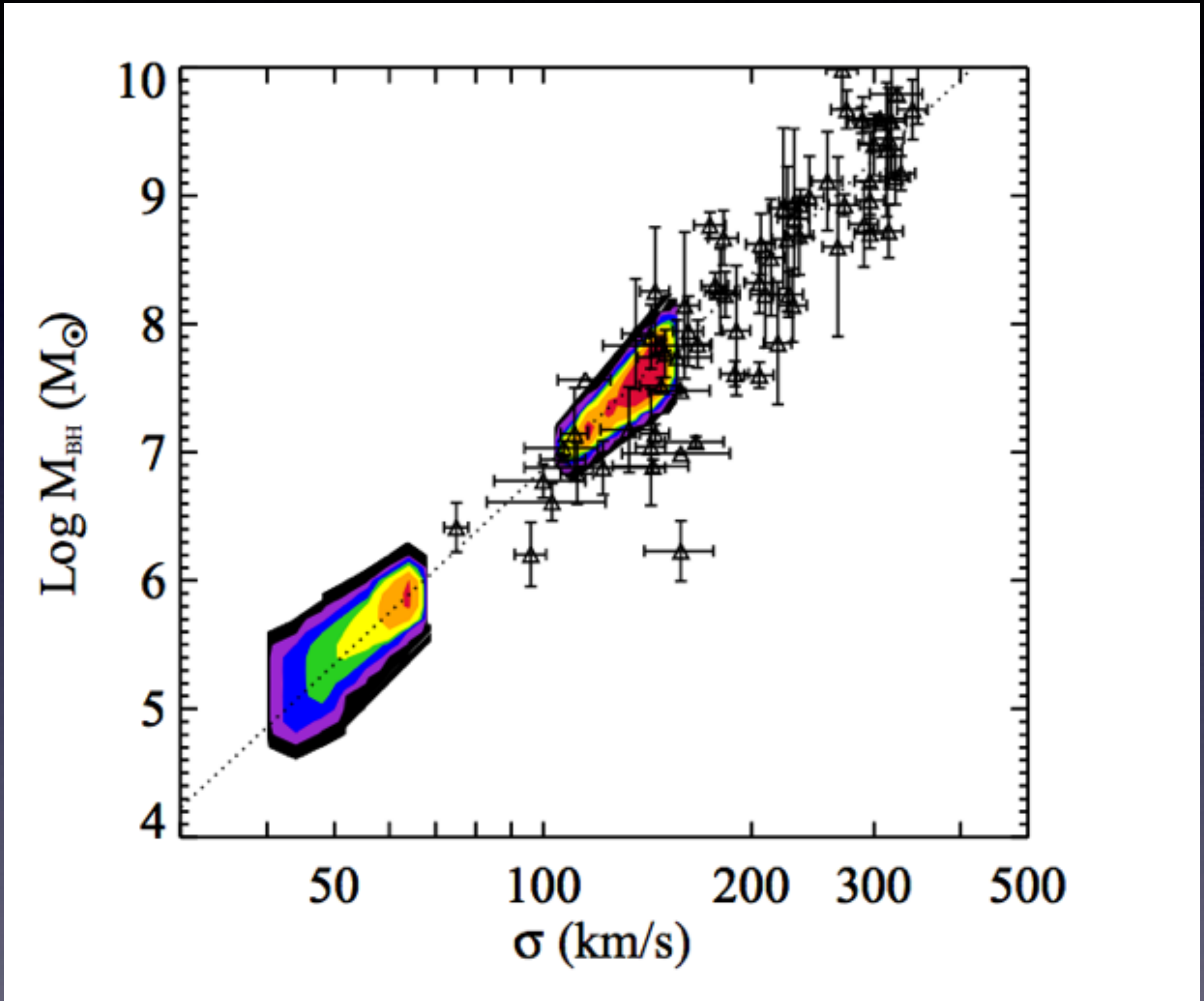
Shankar et al. 2016





Dynamical mass estimates themselves are uncertain by factors of 3-10 by including dark matter and galaxy shape

Orientation changes the measurement of velocity dispersion, too



Bellovary, KHB, et al. 2014

Step 0: measure a black hole mass

Step 1: relate BH mass to host galaxy

Step 2: find evidence of binary black holes

Step 3: measure galaxy merger rate to constrain SMBH merger

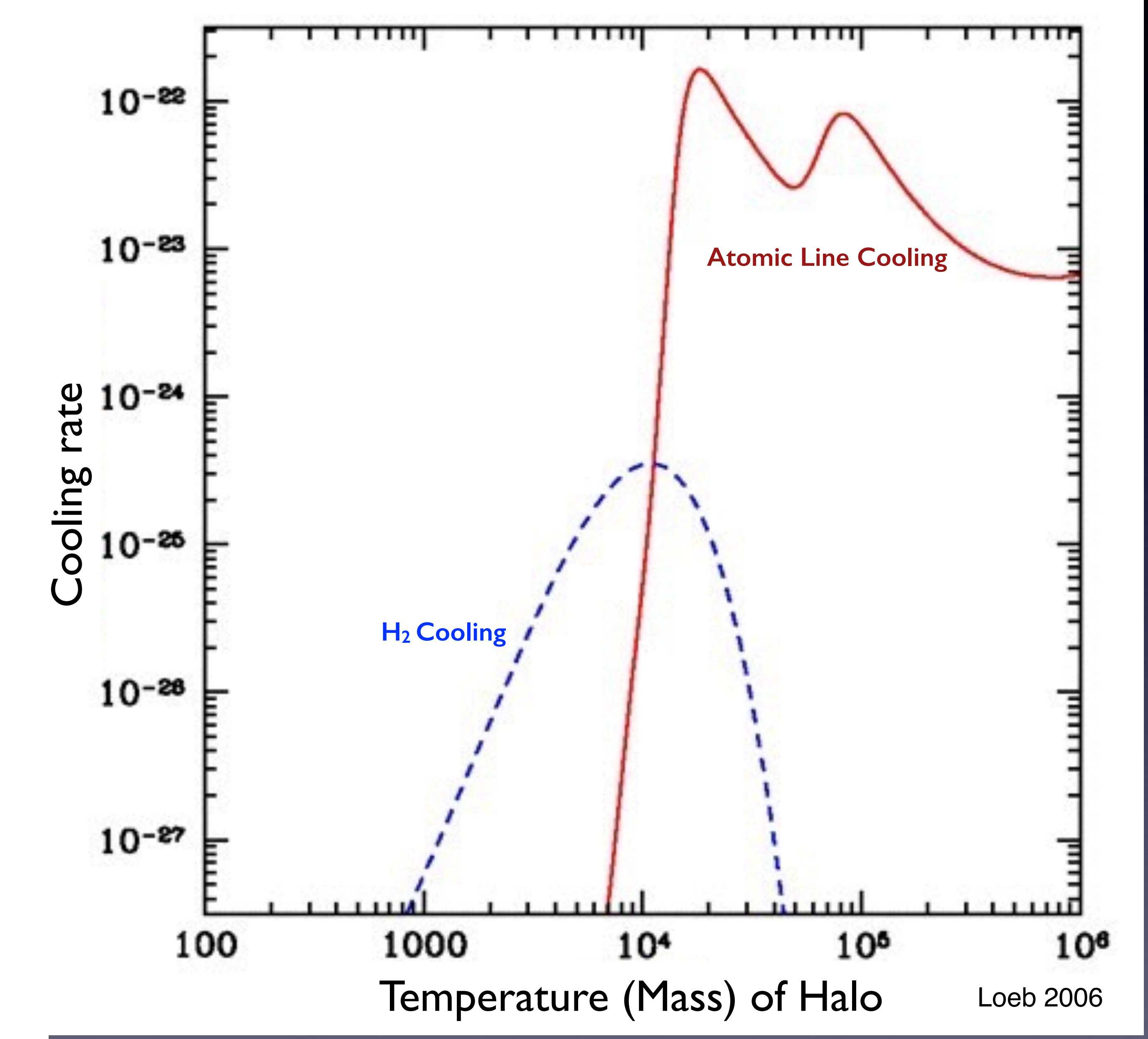
Step 4: Sow SMBH seeds (see Rossi and Latif tal

Step 5: Model SMBH growth

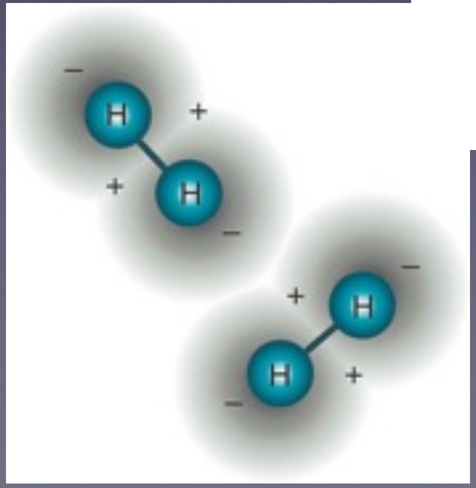
Step 6: Model SMBH merger dynamics to get merger timescale

Step 7: Find the strain, SNR for each merger

To build a massive black hole seed, you must battl fragmentation!

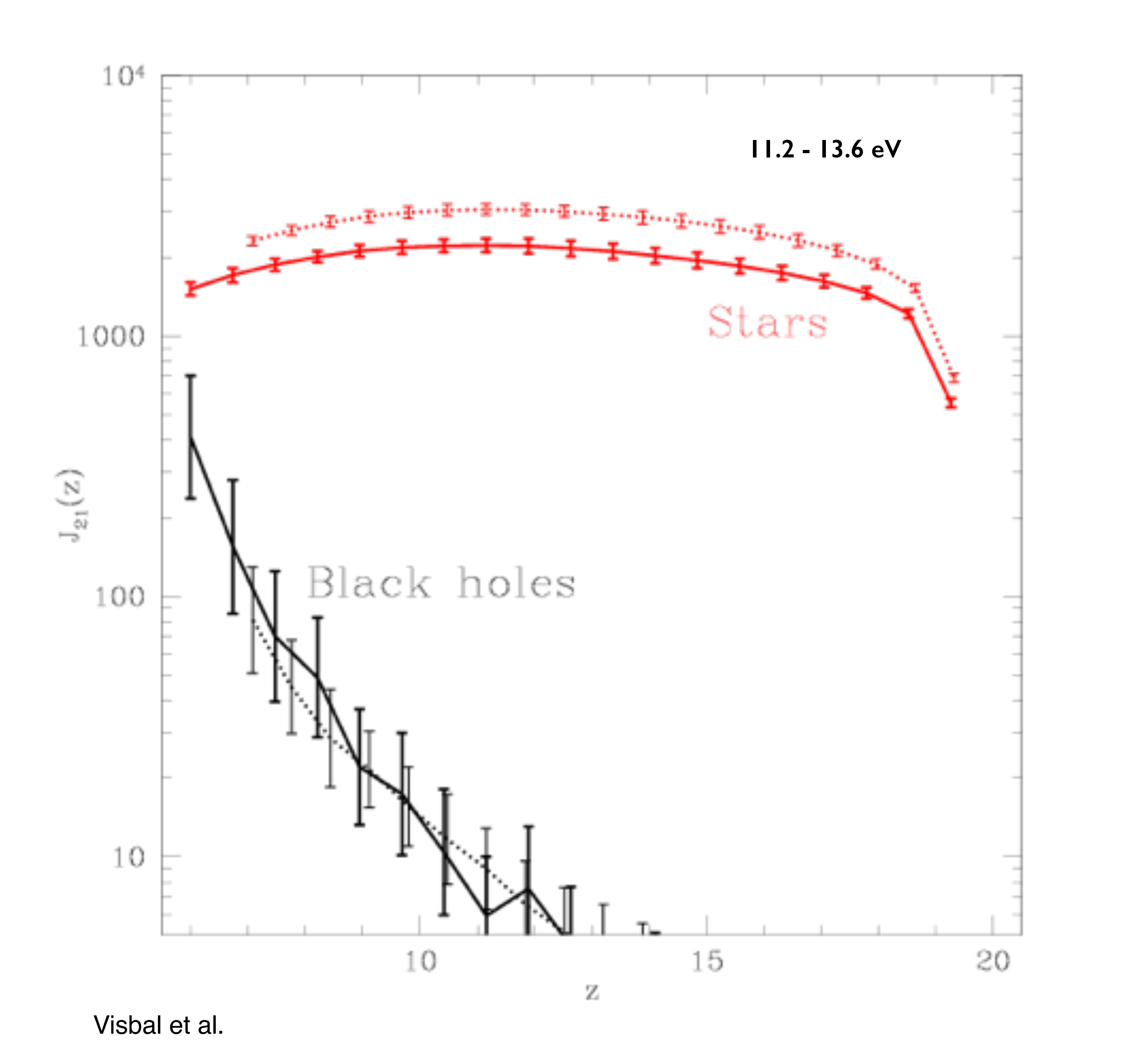


Loeb 2006



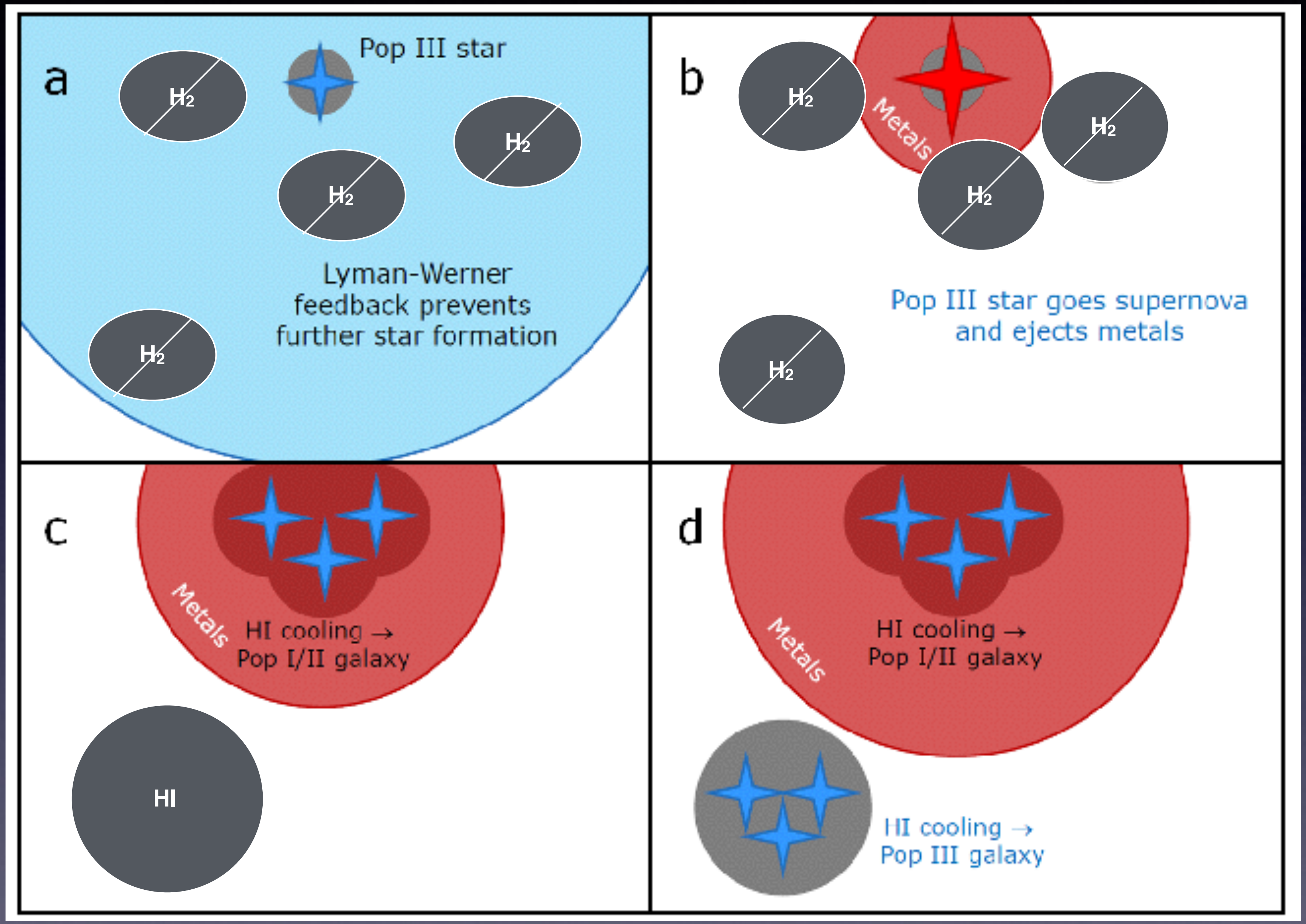
Once halo is polluted with metals, they **really** dominate cooling!

Lyman-Werner radiation from the first stars and black holes can dissociate H_2



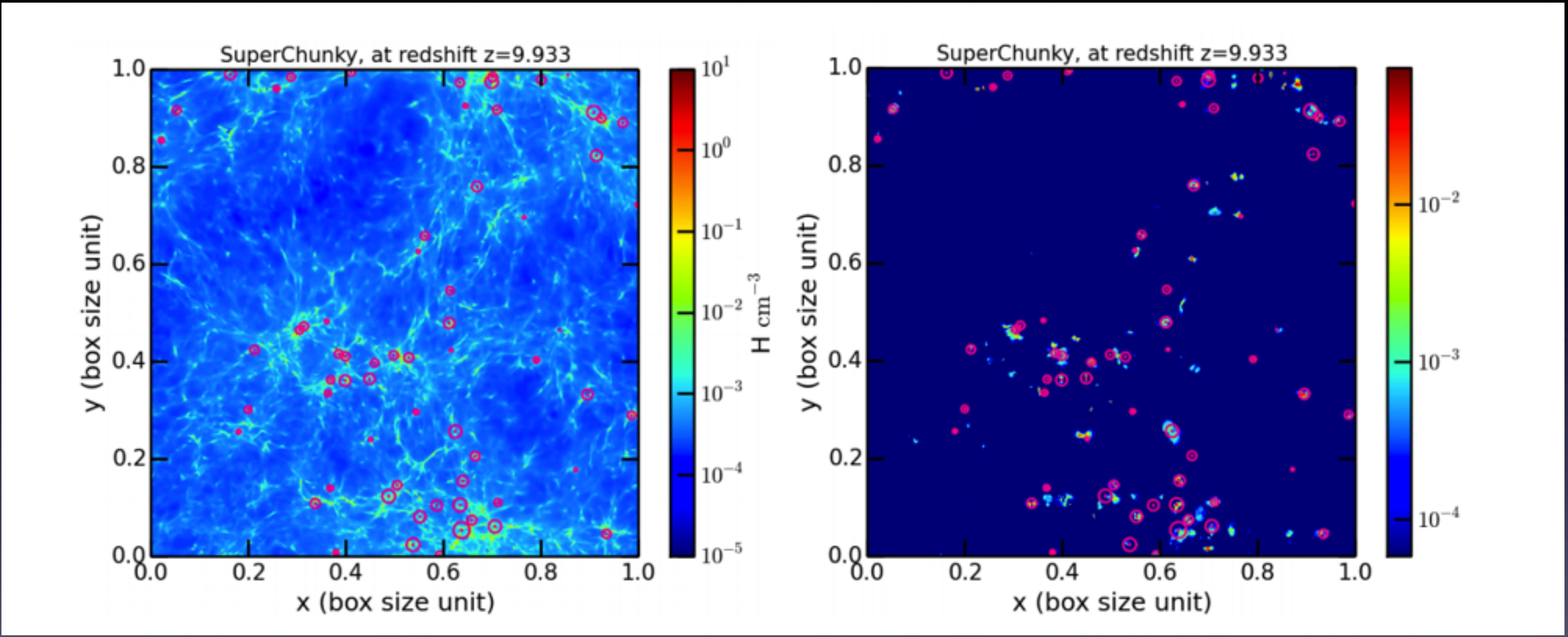
Low mass halos bathed in Lyman-Werner Flux can fo Direct Collapse BHs

10^5—10^6 solar mas



adapted from Zackrisson et al. 2012

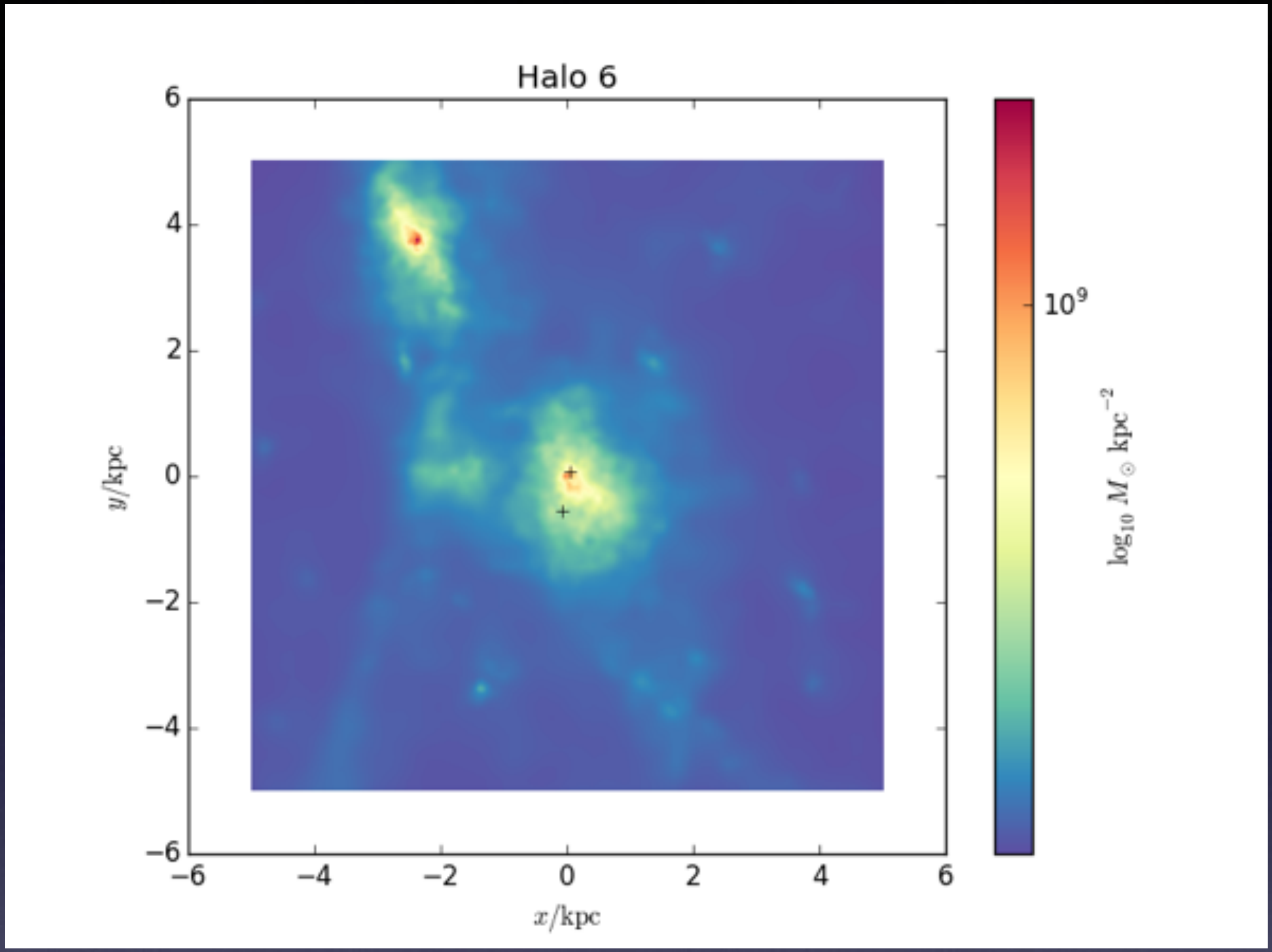
Rare SMBH birthplaces in a uniform UV backgr



Habouzit et al 2016

See also Agarwal et al. 2013; Akutalp et al. 2014

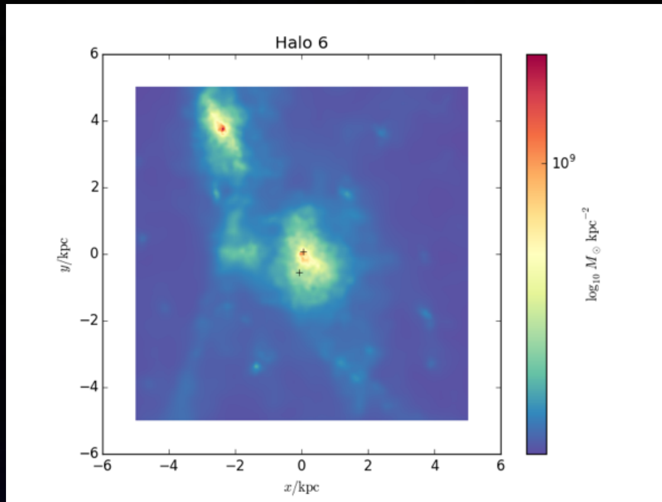
In progress:

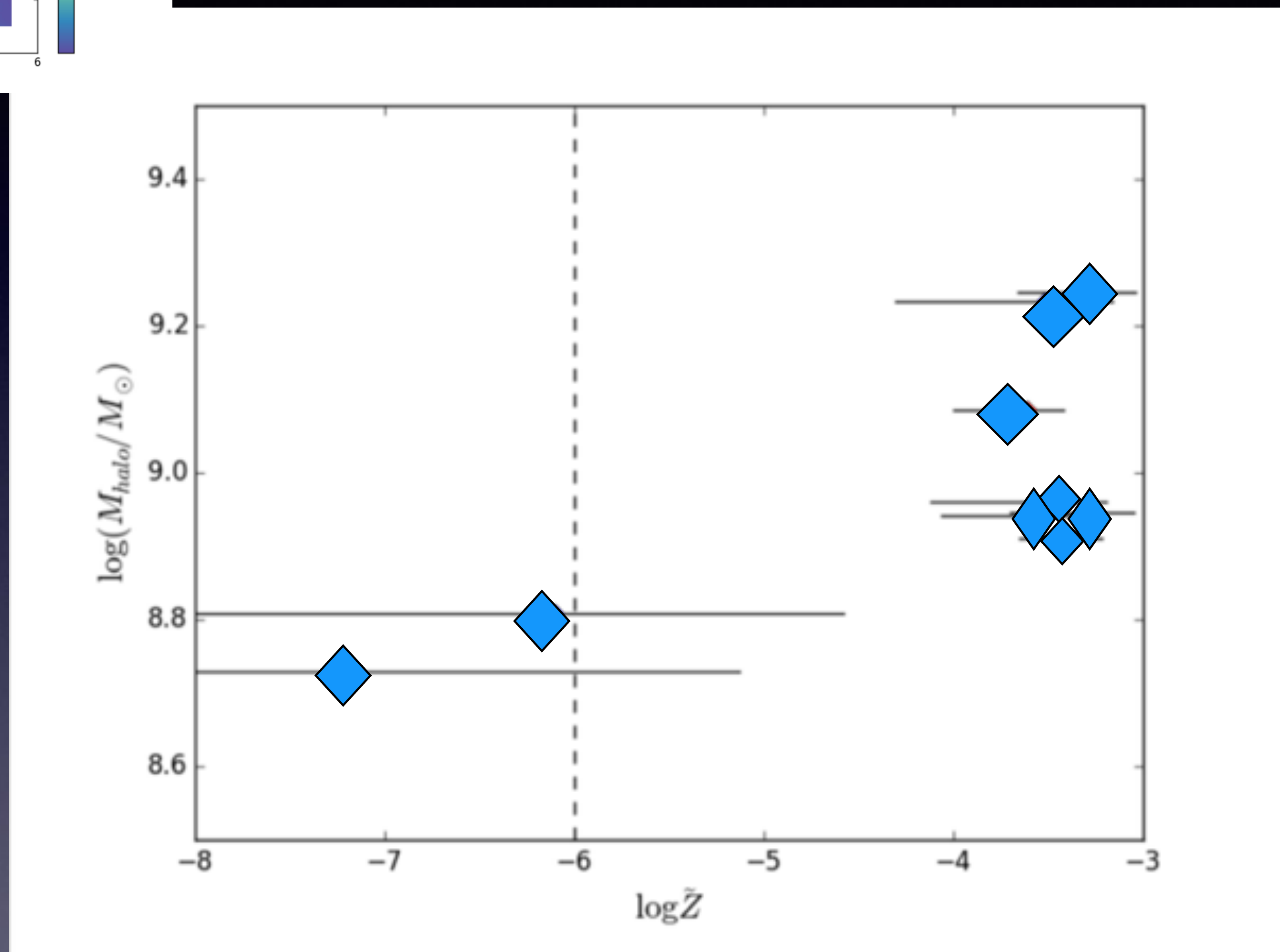


Cosmological Hydrodynamical Simulations of Direct Collapse Black Hole Formation

Dunn, KHB, Bellovary,Christensen

Surprises so far — several Direct Collapse Black Holes can form in a single halo





…and seeds can form in 'high' metallicity halos, too!

Step 0: measure a black hole mass

Step 1: relate BH mass to host galaxy

Step 2: Sow SMBH seeds

Step 3: Model SMBH growth

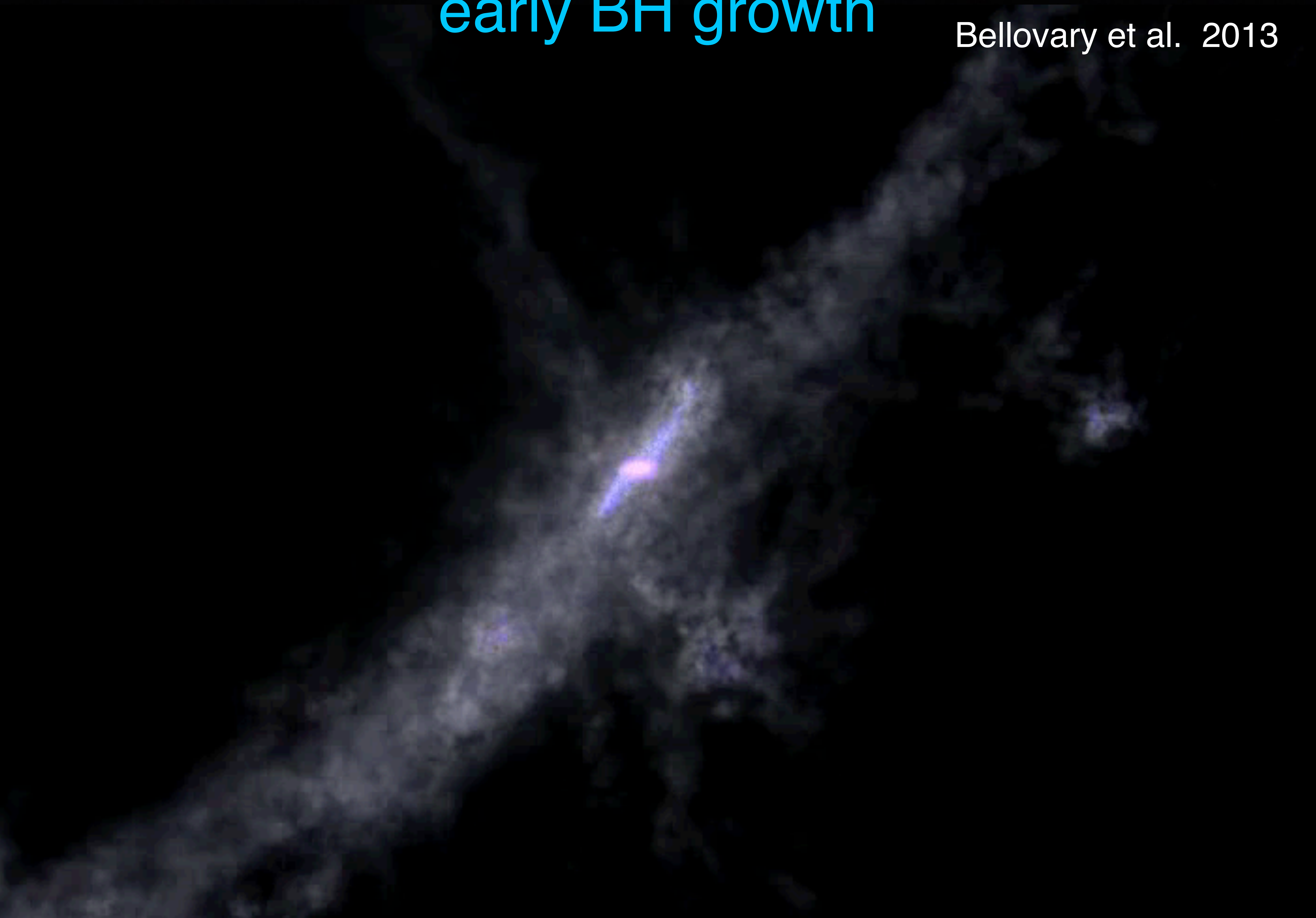
Step 4: Model SMBH merger dynamics to get merger times

Step 5: Use number of galaxy mergers to find the rate of SMB

Step 6: Find the strain, SNR for each merger

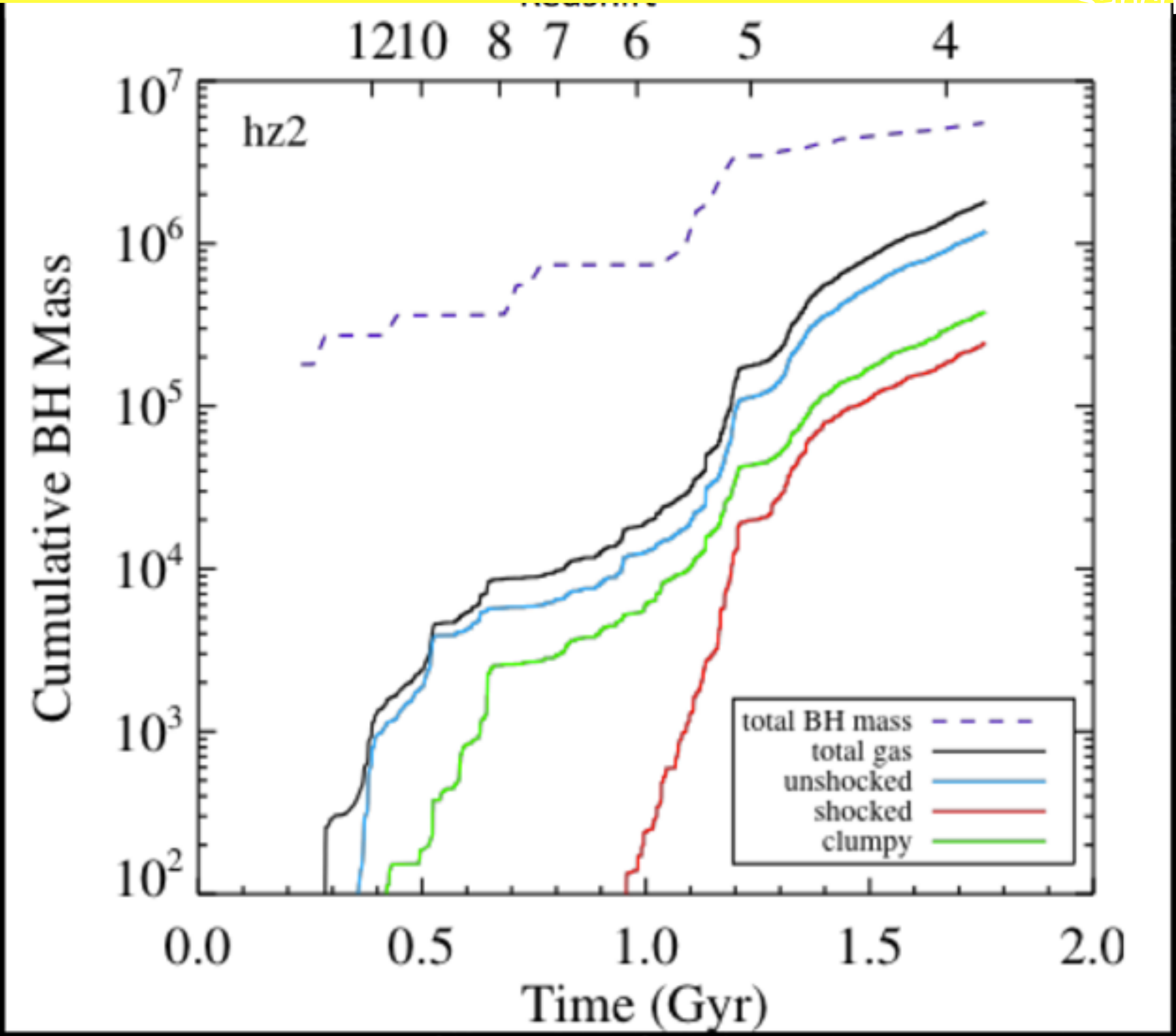
Cosmological Hydrodynamical simulation of early BH growth

Bellovary et al. 2013



Most of the early SMBH growth is not from gas...
...and the gas that does fuel the SMBH is not from galaxy mergers

Sanchez, Bellovary and KHB 2



We simulated the growth of MW-like SMBHs using cosmological N-body simulations

KHB et al. 2010

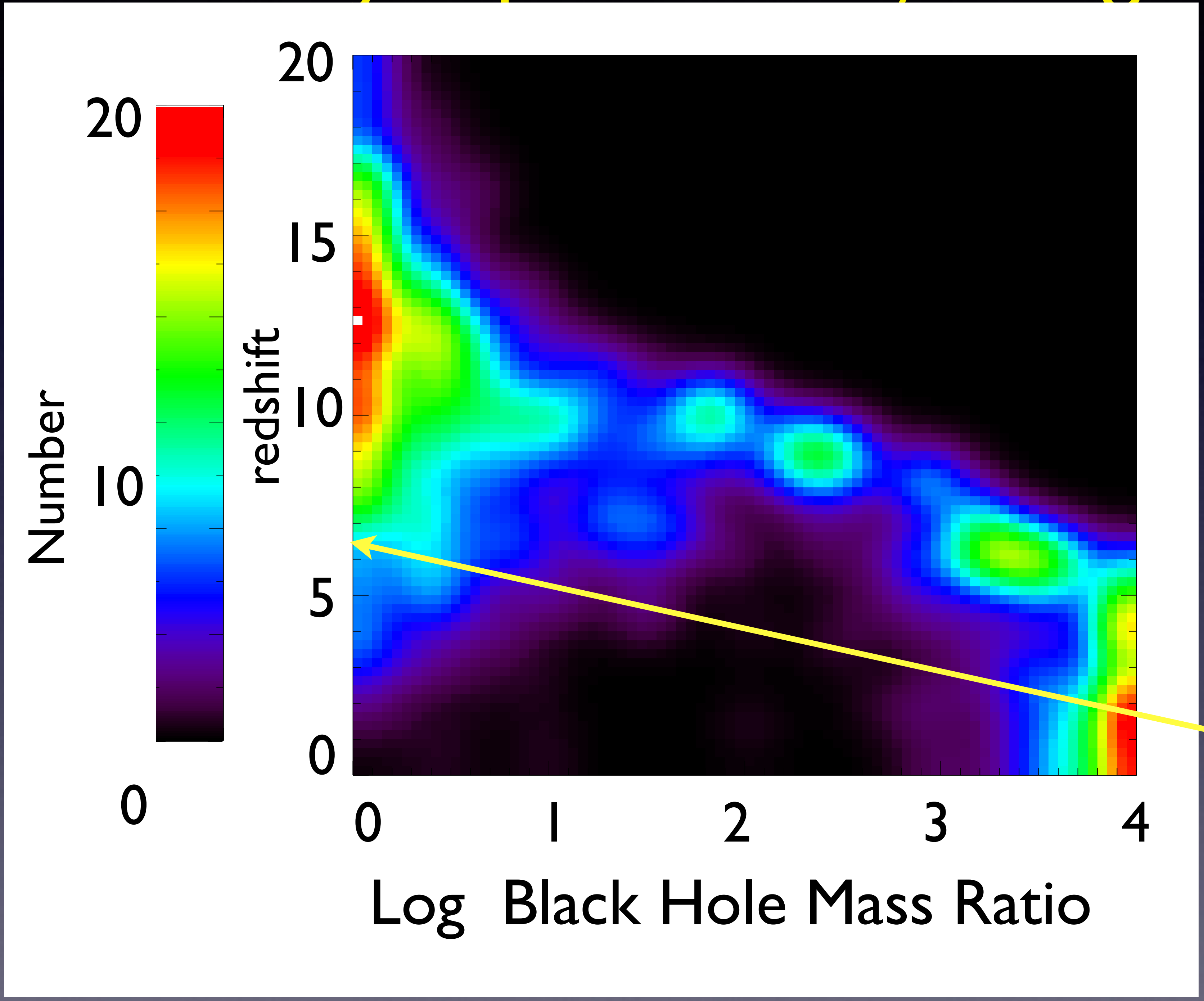
Massive central

Slowly sinking

Ejected

Light SMBHs (like our own) don't assemble from equal mass (or even nearly equal mass) mergers

KHB et al. 2010

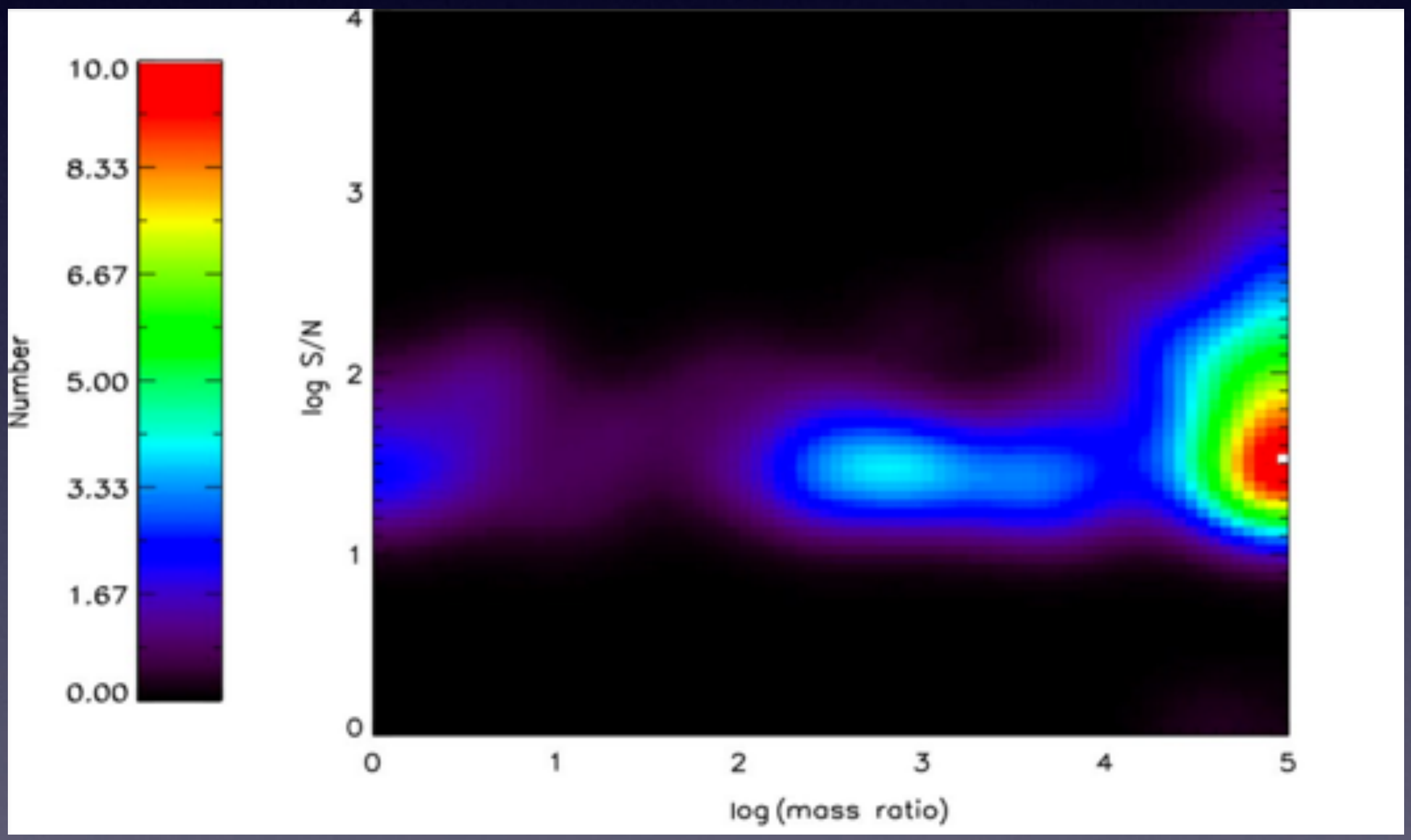


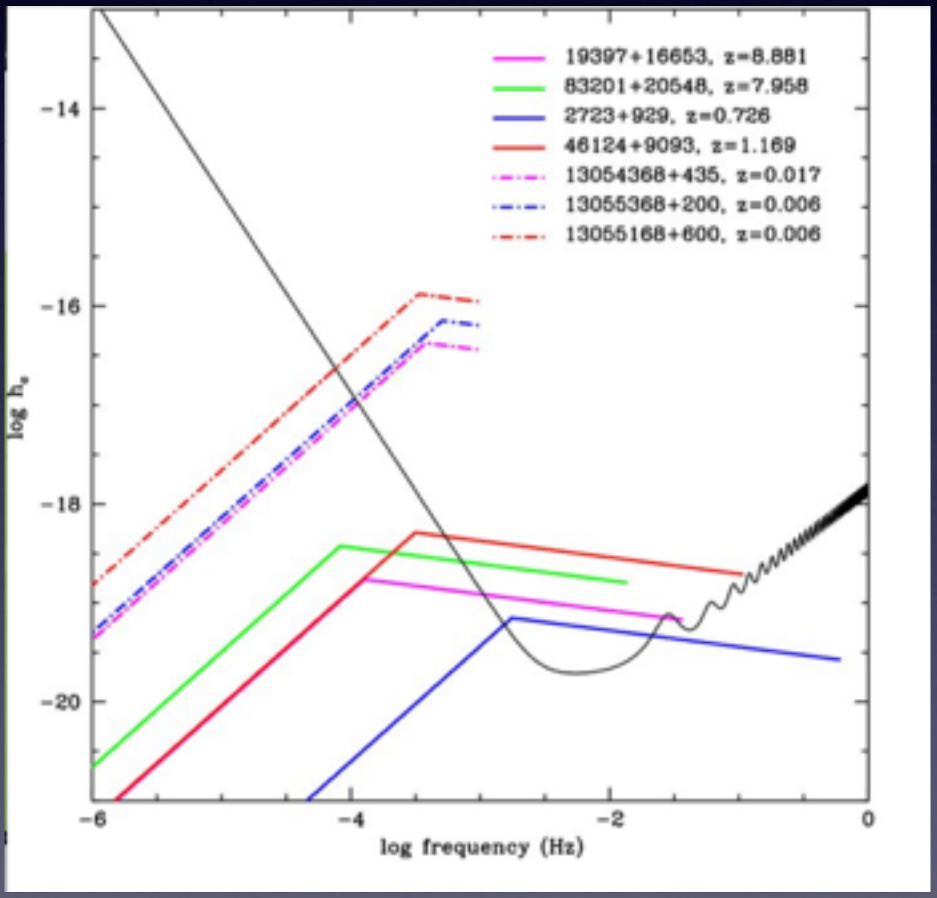
after the dark ages, there are few major mergers

Massive central

Assembling a MW SMBH results in dozens of resolvable sources, mostly IMRIs

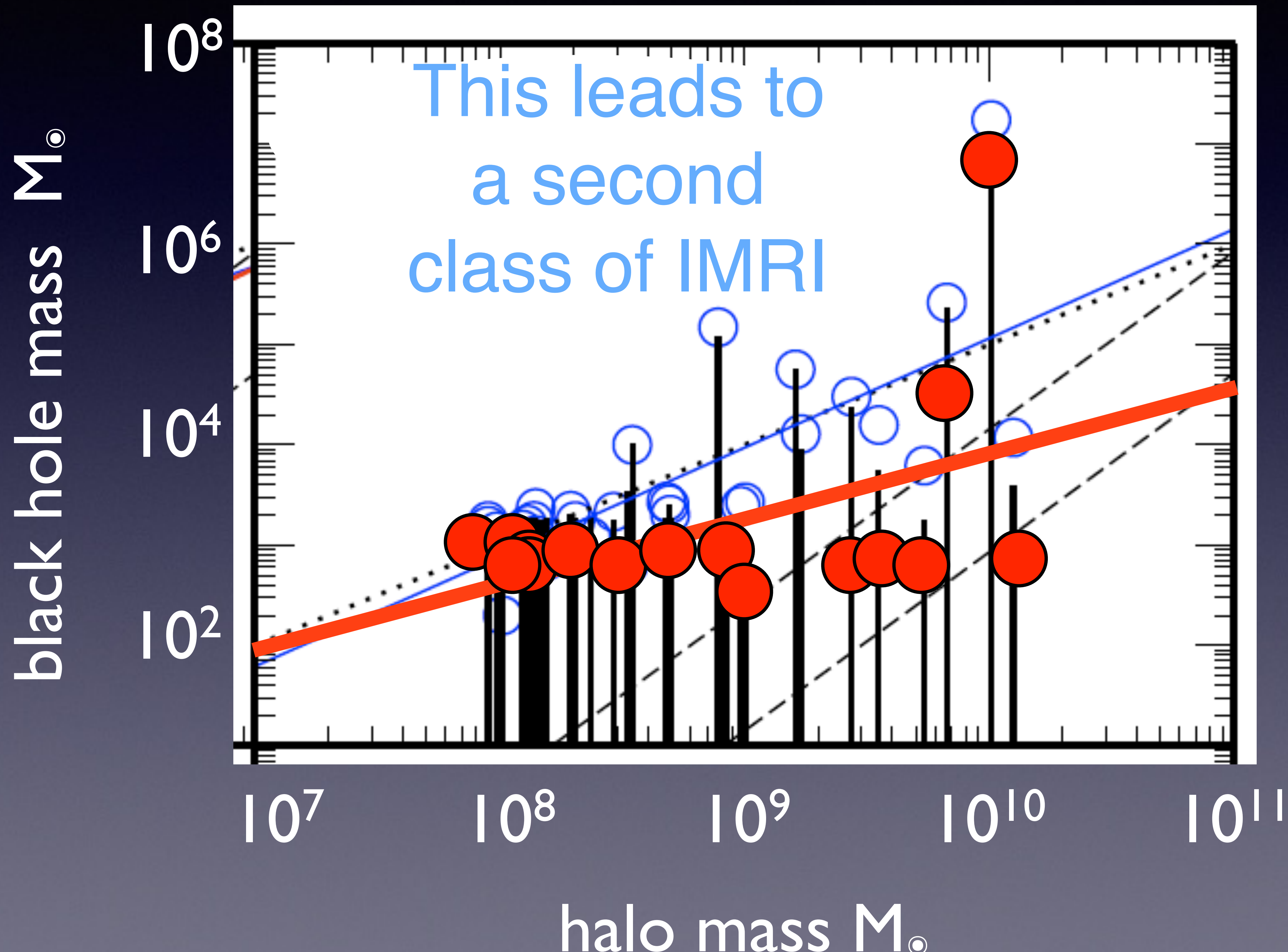
scaling to the universe, ~ 500 sources with SNR>30 fo



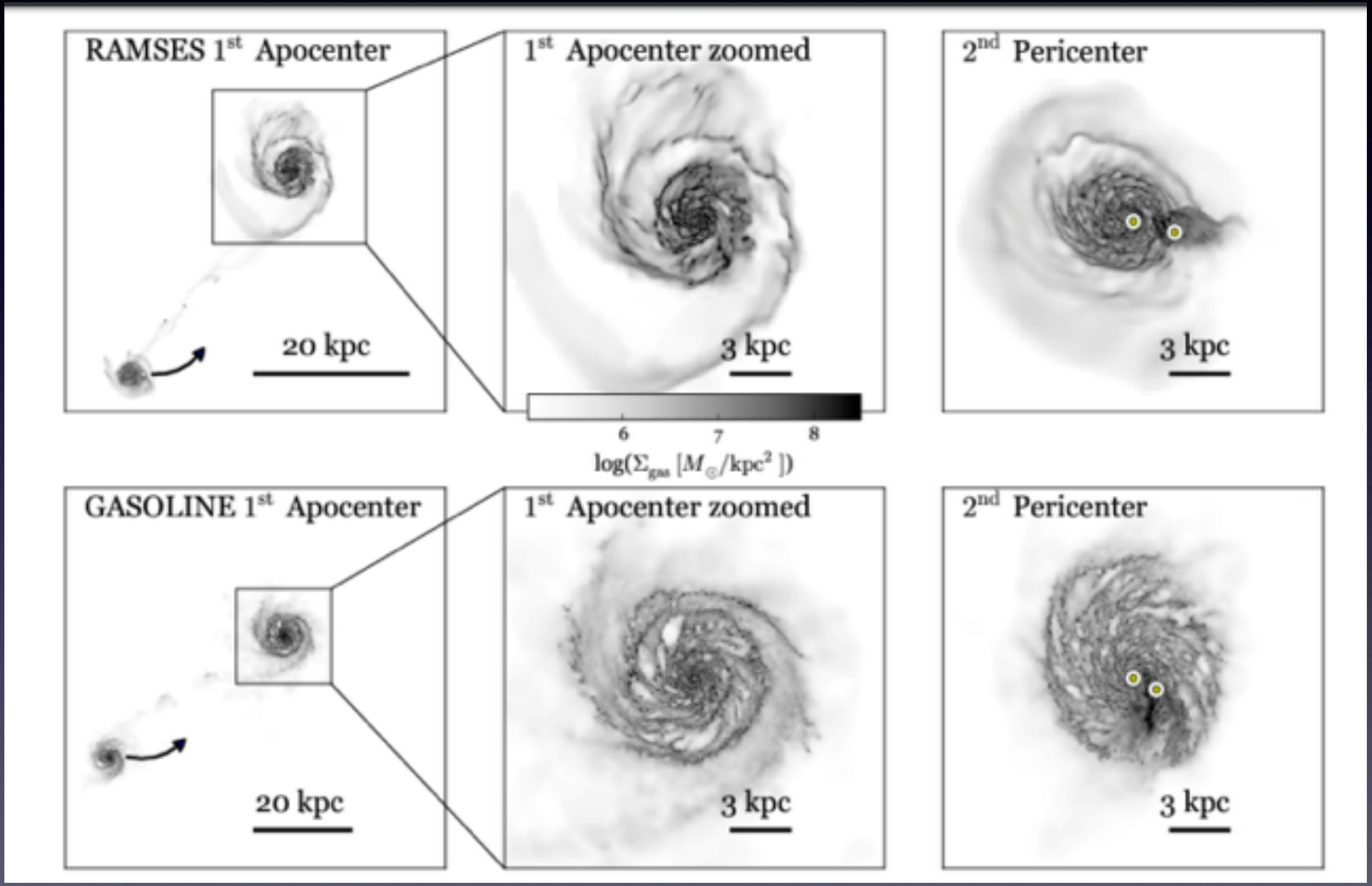


Dwarf galaxies may also have central black holes

see also Micic, KHB 2007, Volonteri + Priya 2009, Pe
2010



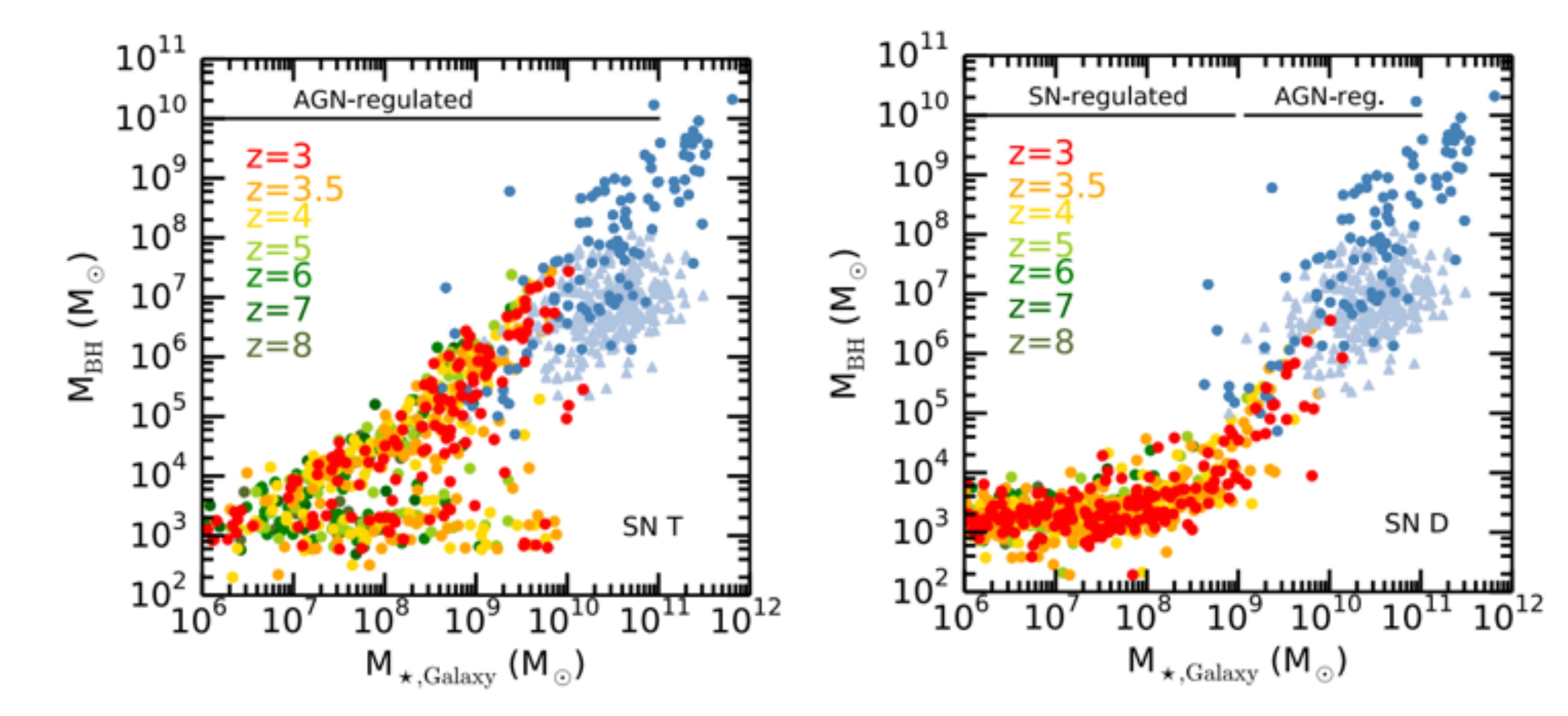
Warning: BH growth depends on the hydrodynamic code



BHs grow less, take longer to merge

Gabor et al. 2015

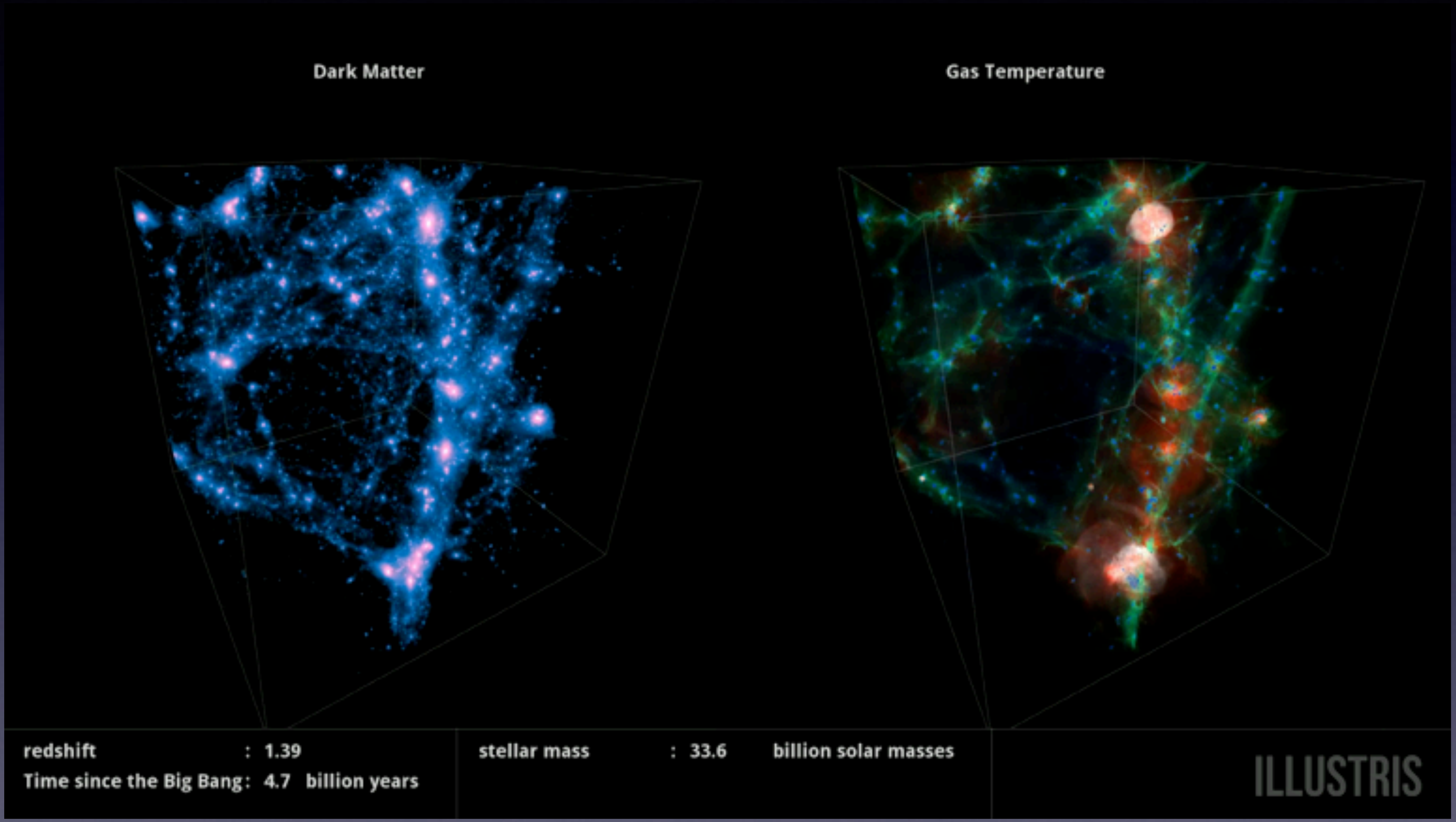
Warning: BH growth depends on a feedback recipe



(!) box
Habouzit et al
2016
see also Dubois
2015

Warning: Over-zealous AGN feedback stifles BH growth (and star formation, too)

Volgelsburger et al. 2014



Step 0: measure a black hole mass

Step 1: relate BH mass to host galaxy

Step 2: Sow SMBH seeds

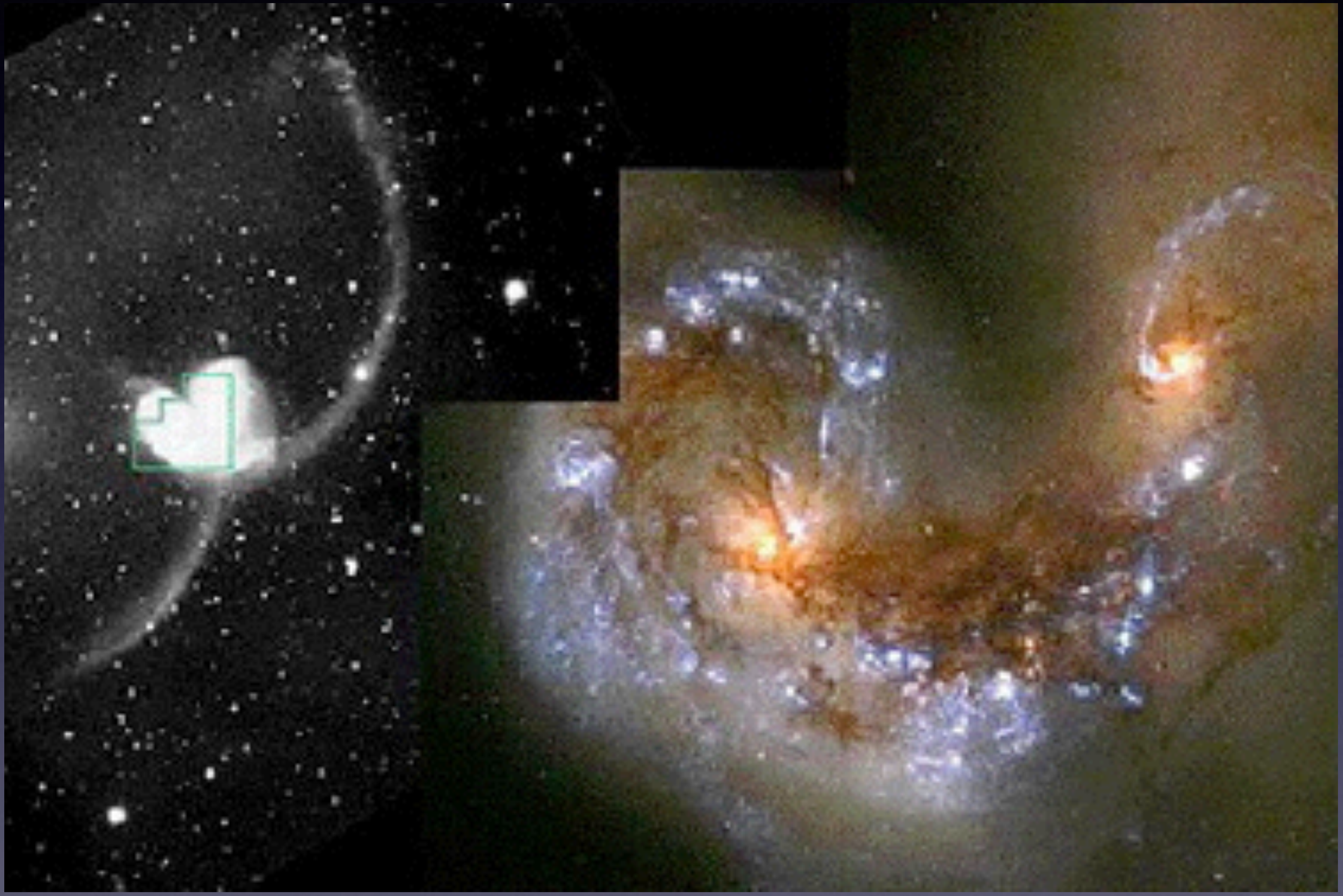
Step 3: Model SMBH growth

Step 4: Model SMBH merger dynamics to merger timescales

Step 5: Use number of galaxy mergers to find the rate of SMB

Step 6: Find the strain, SNR for each merger

Galaxy mergers sink black holes though dynamical friction

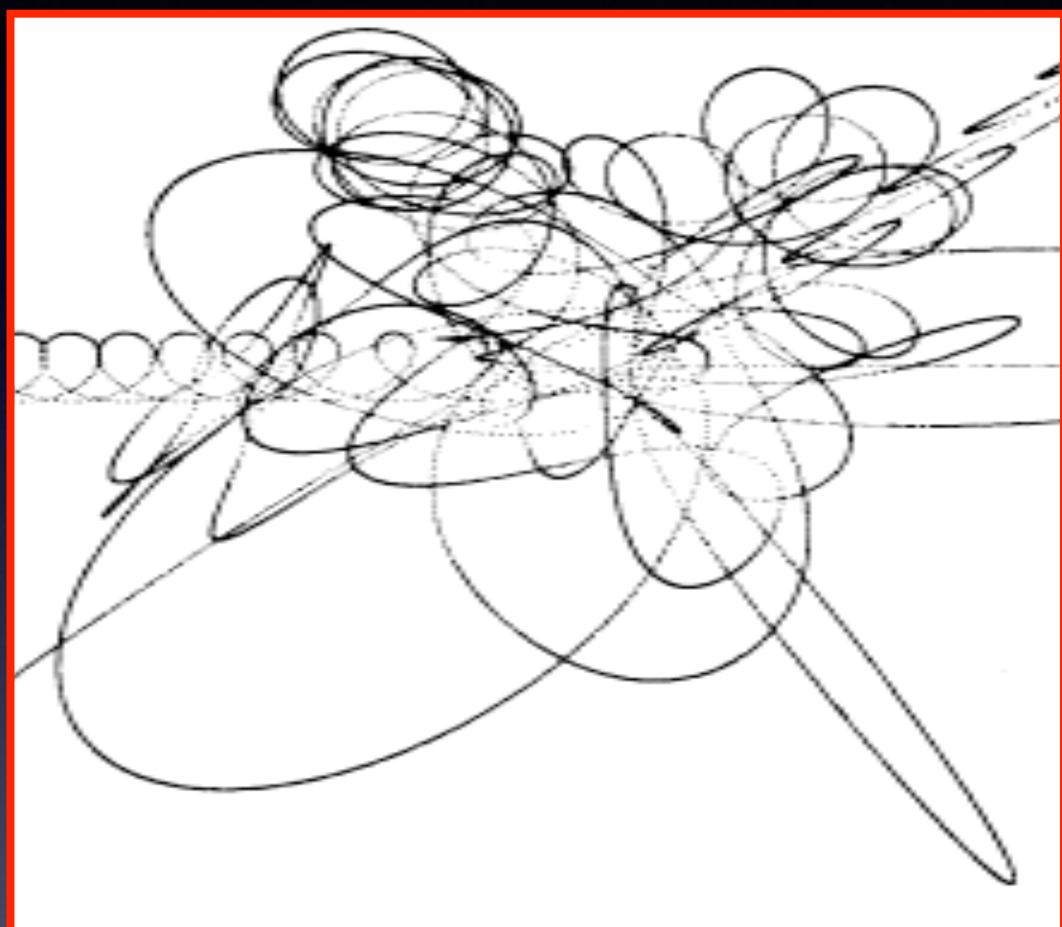


Separation:
$O(10^5)$ pc

Timescale:
$O(10^8)$ yr

Next: black holes sink closer via 3-body scattering.

Quinlan 1997; Sesana et al 2006,2007



$$a_h := \frac{G\mu_r}{4\sigma^2} \sim \frac{1}{4}\frac{q}{(1+q)^2} r_h,$$

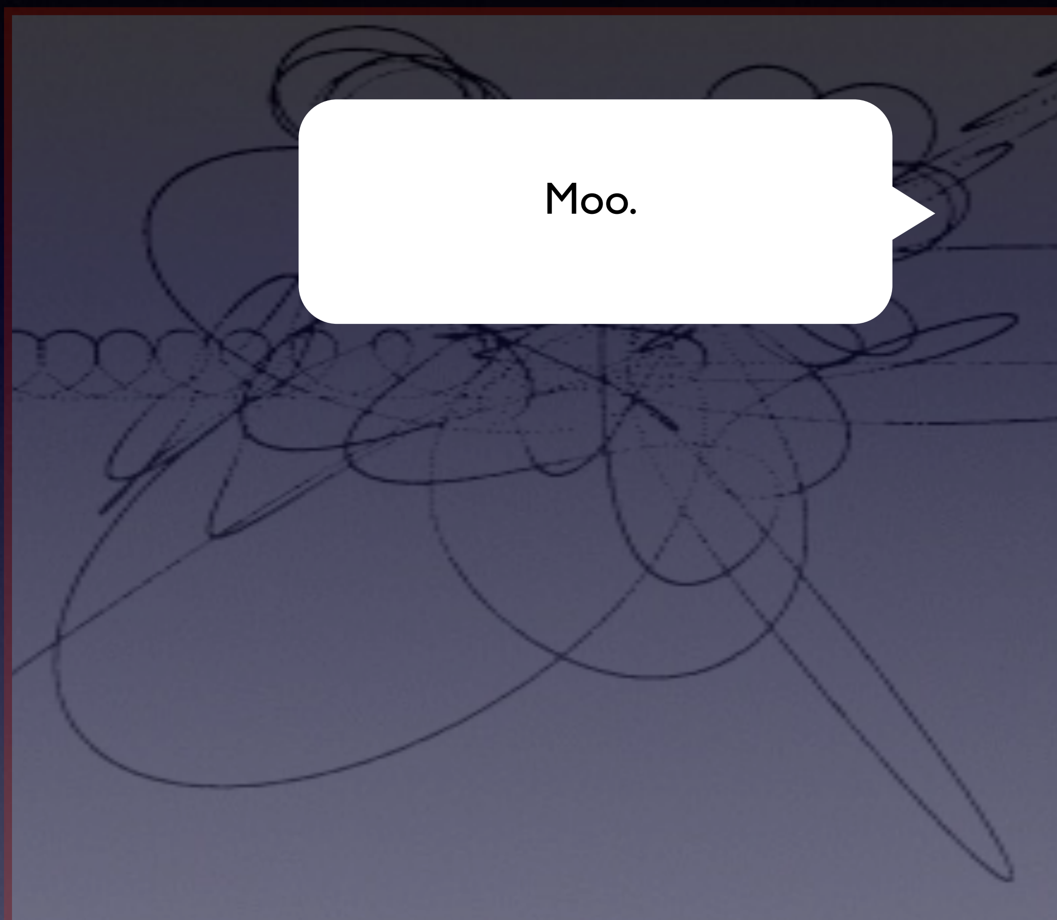
O(10) pc

> $O(10^{10})$ yr!**

**in a static spherical galaxy with permanent ejections and no resonances

The final parsec problem -- refilling a spherical loss cone takes > t_{Hub}

Quinlan 1997; Sesana et al 2006, 2007,

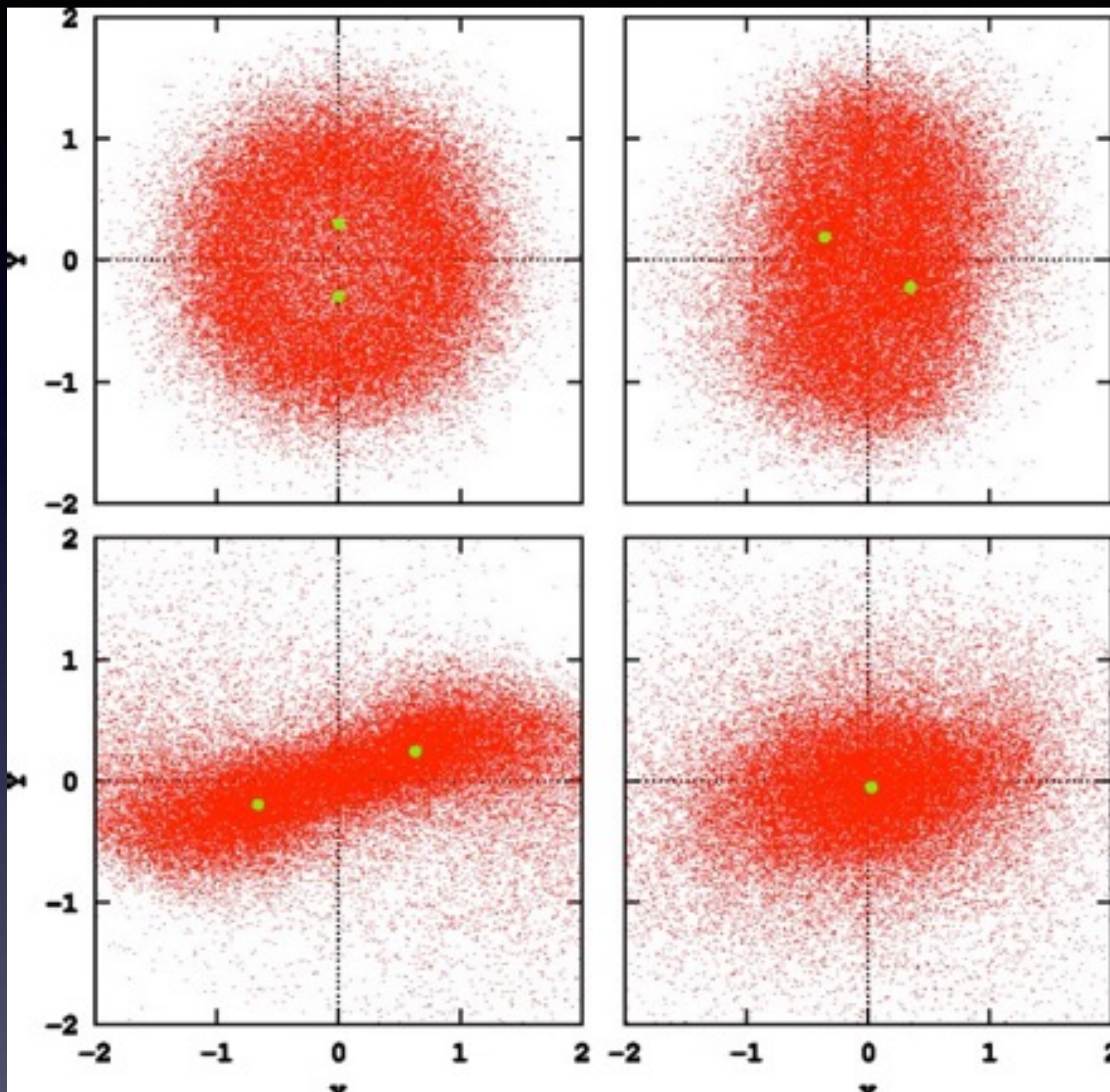


$$a_h := \frac{G\mu_r}{4\sigma^2} \sim \frac{1}{4}\frac{q}{(1+q)^2} r_h,$$

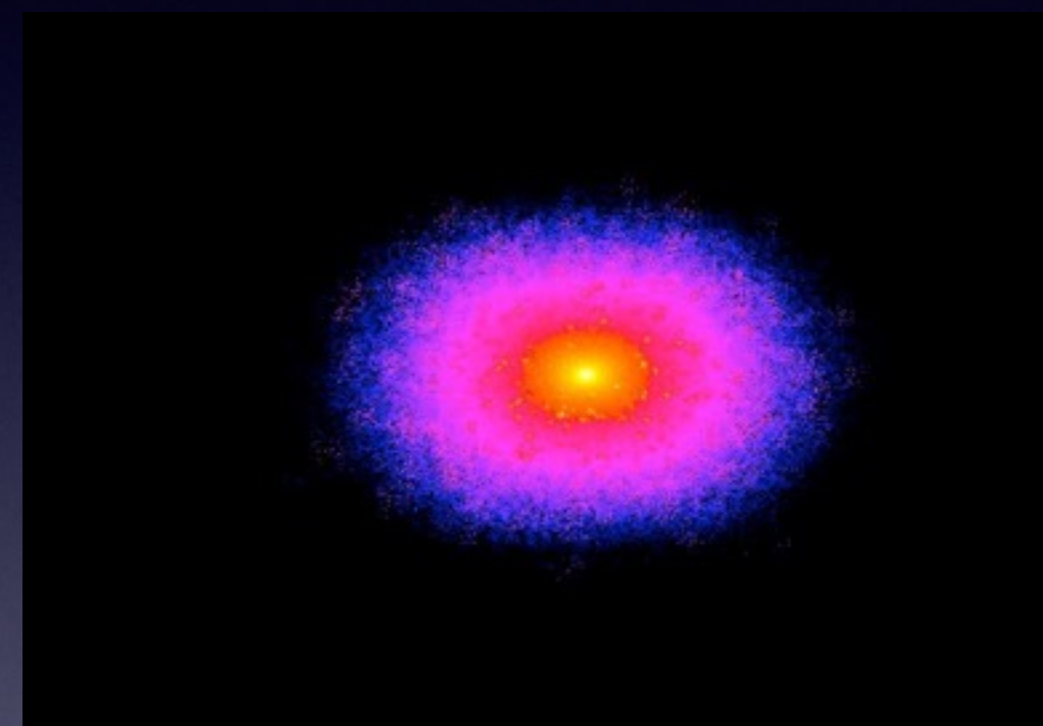
O(10) pc

**in a static spherical galaxy with permanent ejections and no resonances

Final Parsec Problem? Not a problem for a non-spherical galaxy!



Berczik et al. 2006

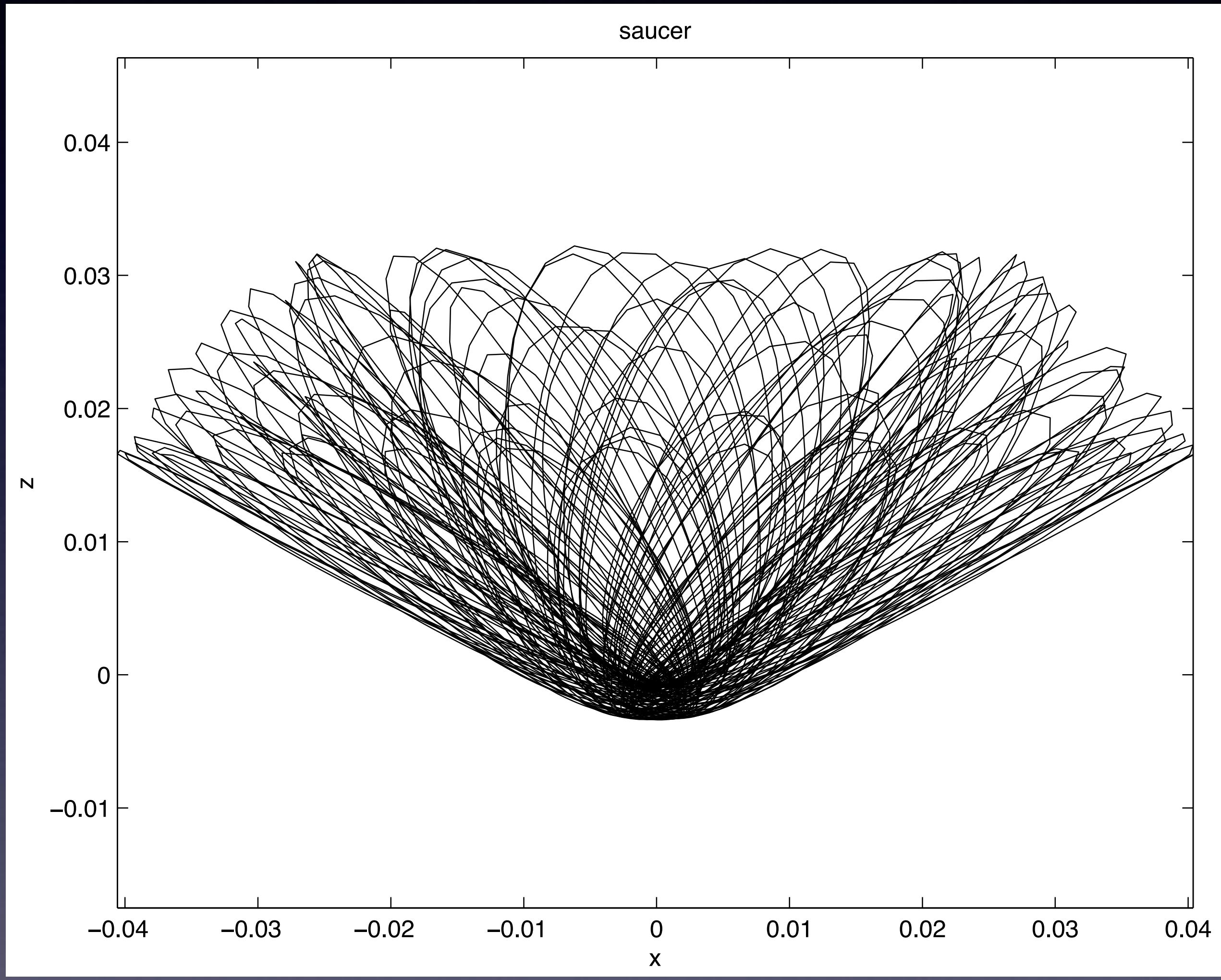


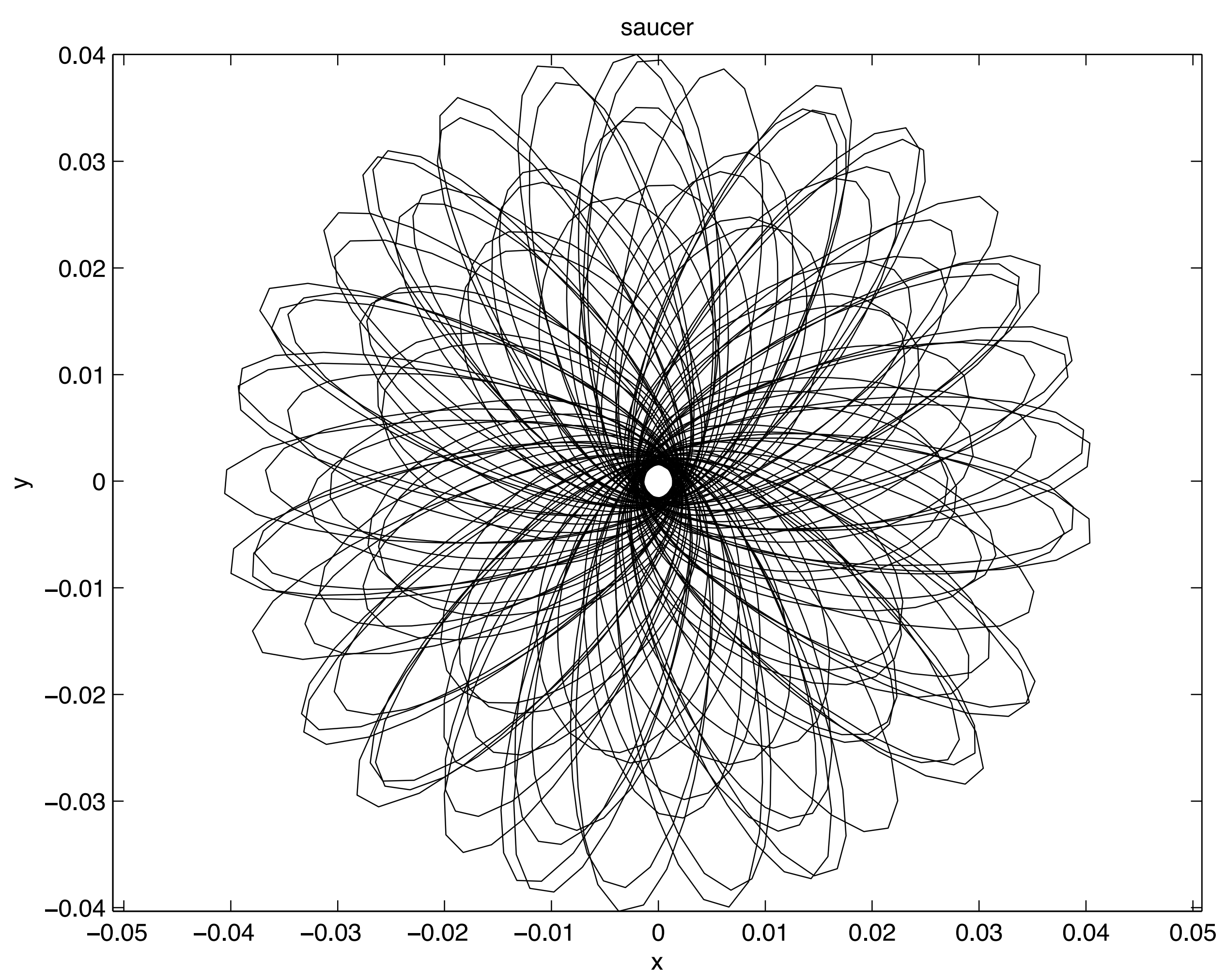
KHB+Sigurdsson 2006
Khan+KHB 2013

Expect 10^8 M☉ Binary BHs to take less than 3 Gyr to coalesce in an equilibrium axisymmetric galaxy

Supported by NSF CAREER award and NSF MRI for GPU cluster

Axisymmetric galaxies have low angular momentum orbits that overfill the loss cone



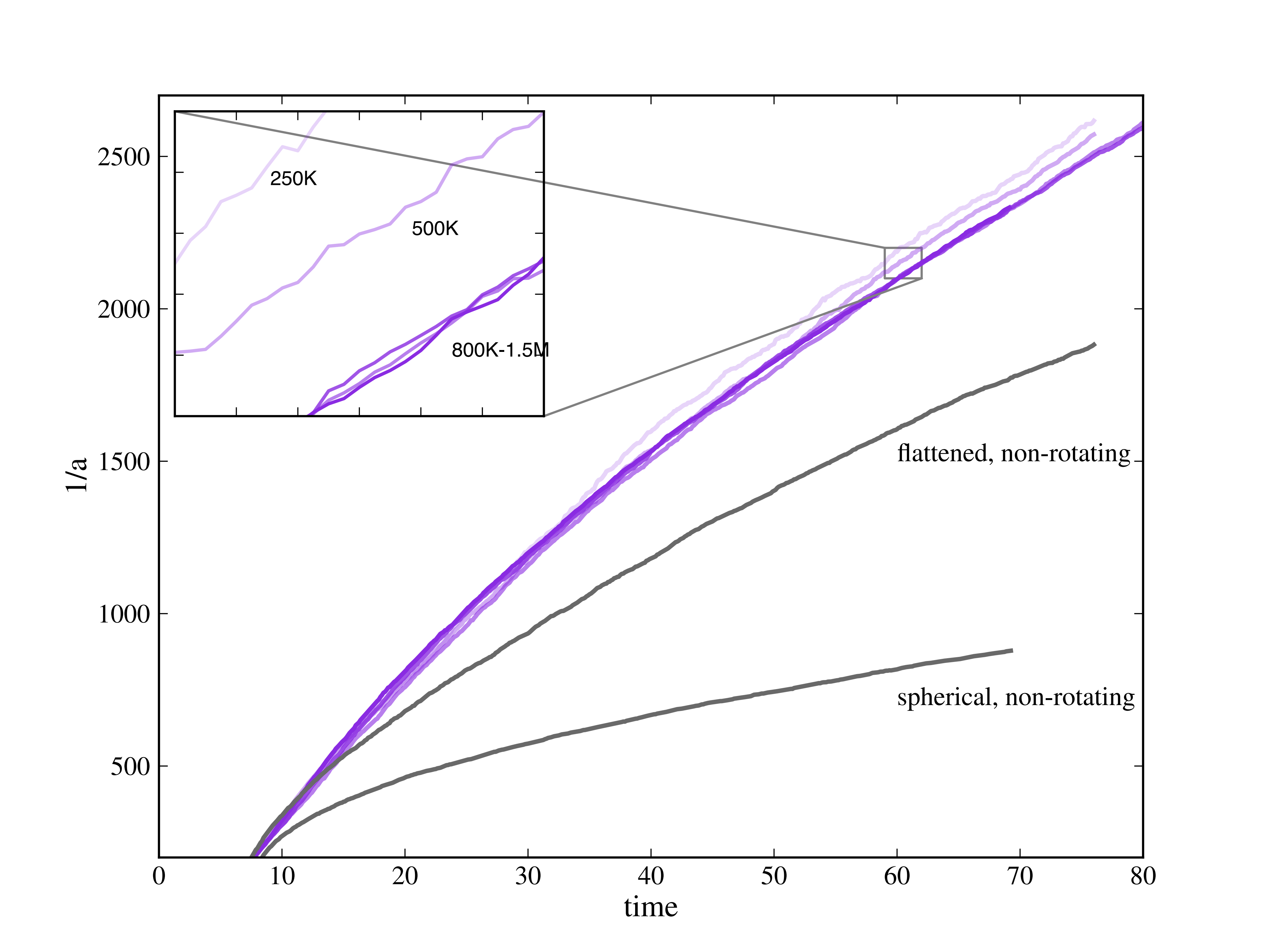


Li, KHB+Khan 2015

~60% of the stars within the inner 100 pc are saucers

Now, let's add rotation — and the black hole orbit shri

KHB+Khan 2014



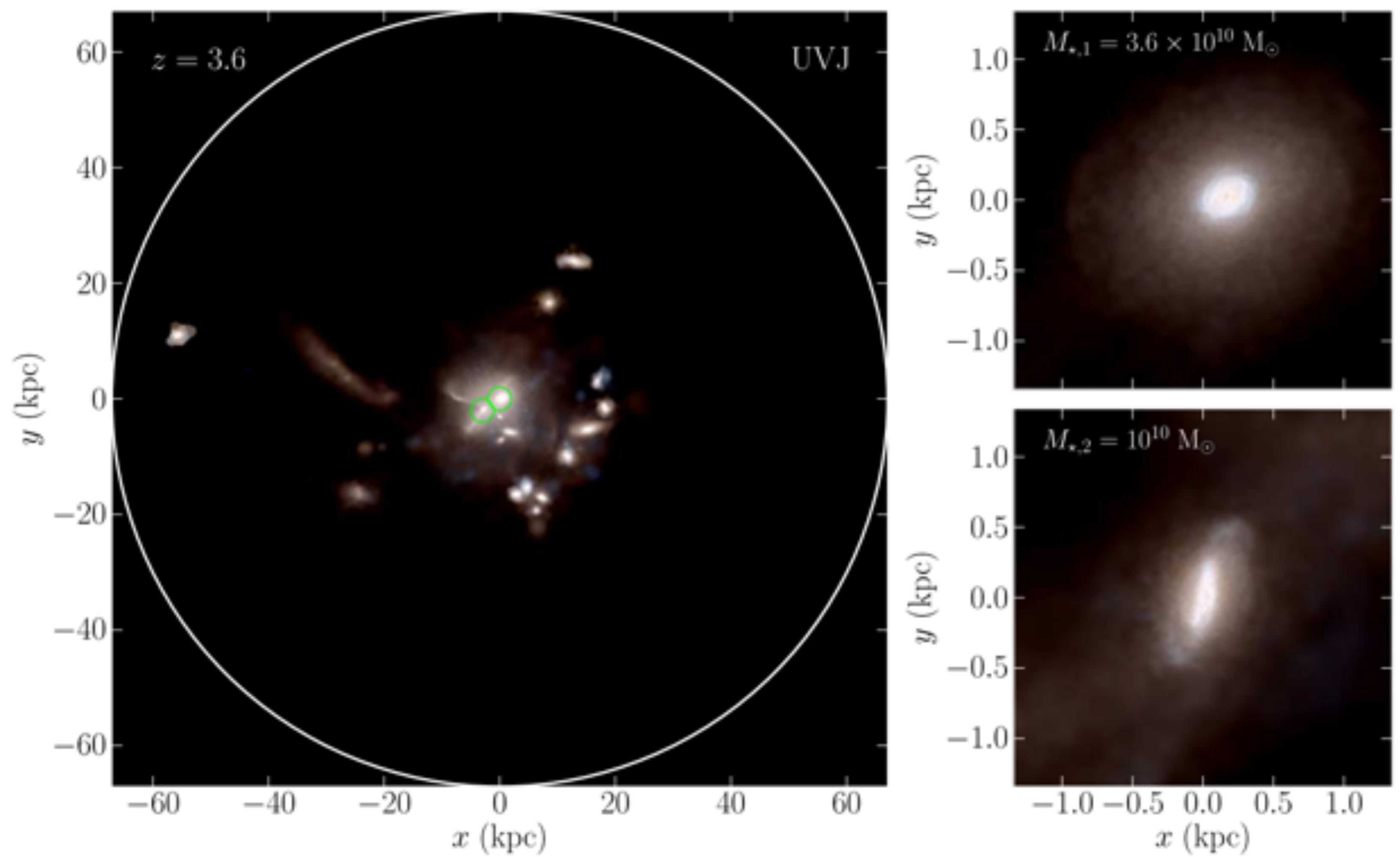
Direct N-body code with GPU acceleration and 2.5 PN terms included.

Black holes *can* merge quickly…or not.

galaxy type	black hole merger timescale	eccentricity in the gw regime
spherical	> 15 Gyr	N/A
axisymmetric (c/a=0.75)	3 Gyr (t$_{Hub}$@z~0.4)	0.1
axisymmetric, rotating $v/\sigma = 0.6$	1 Gyr	0.1
axisymmetric, counterrotating	100 Myr	~1
triaxial	O(10) Myr	large
Gas-Rich	10 Myr — 1Gyr	~0.0

Latest advance: BBH merger in a cosmological volu — 10 Myr!

merger caused not by gas — by new star formation



Khan et al. 2016

~few Gyr SMBH merger times interestingly long -- subparsec dual BHs abound? Triple black holes less rare?

Need to add realistic merger times to semi-analytic models and simulations to help predictions for PTA, BH growth, circumbinary disk observational signals, and so **much**

We need to calculate merger timescales for a realistic suite of galaxy models/interactions.

Why can’t we predict an accurate SMBH mer rate?

We need to get robust SMBH masses

We need to know the real SMBH-galaxy correlation

We don’t know how black holes are born

We don’t understand SMBH accretion and feedback (including secular mass growth from, e.g., stellar plunges)

We need to include accurate SMBH

For more information: P.S. Please cite generously!

KHB, Khan, Li 2015

Li, KHB, Khan, 2015

Khan, KHB, et al 2013

Bellovary et al. 2013

Sinha + HB 2012

HB, Wise + Sinha 2012

Palladino, HB, Morrison, Durrell, Ciardullo, Feldmeier, Wade, Kirkpatrick, Lowrance, 2012

Lang, HB, Bogdanovic, Sesana, Amaro-Seoane, Sinha, 2013

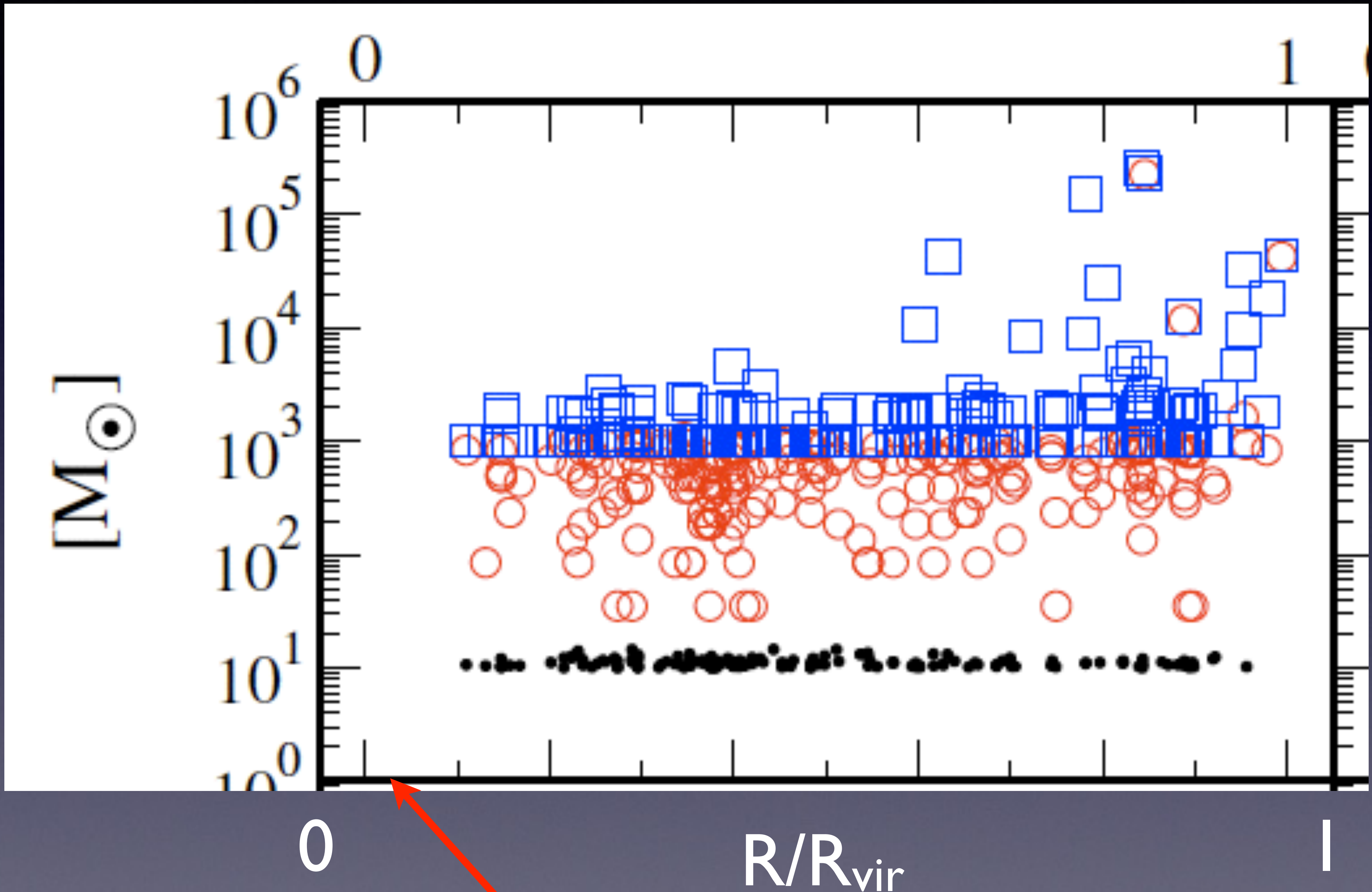
Micic, HB + Sigurdsson 2011

HB, Micic, Sigurdsson + Rubbo 2010

Micic, HB + Sigurdsson 2008

Rogue Black Holes sit in the outer halo

see also Micic, KHB 2007, Bellovary et al. 2011



Slowly sinking

⊙