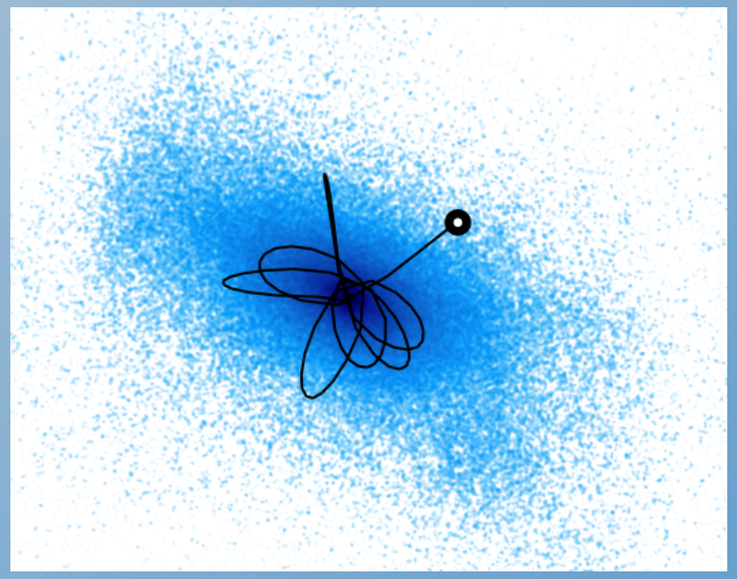


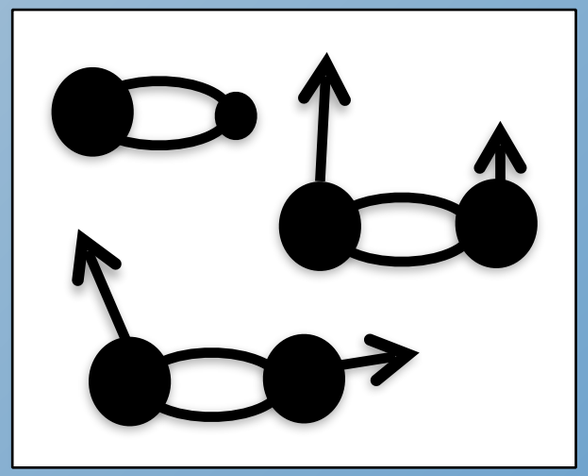
The Observability of
Recoiling Black Holes
as Offset Quasars

Laura Blecha
Einstein and JSI Fellow
University of Maryland
with Paul Torrey, Mark Vogelsberger, Shy Genel, Volker Springel, Debora Sijacki, Greg Snyder, Simeon Bird, Dylan Nelson, Dandan Xu, & Lars Hernquist

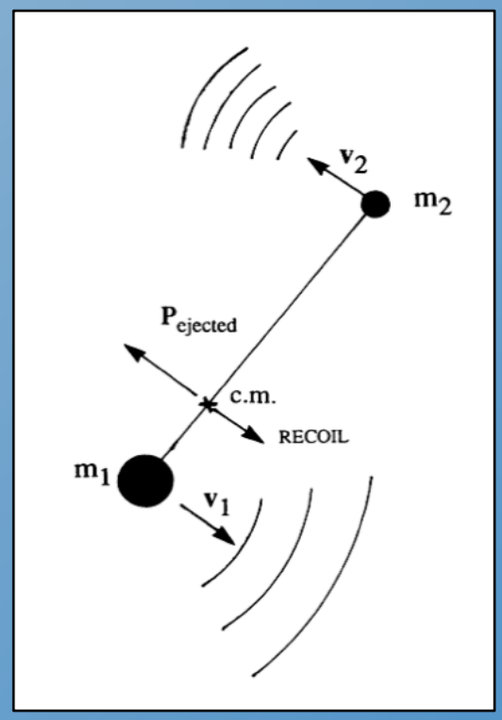
Black Holes in Dense Stellar Clusters
Aspen, CO, Jan, 2015

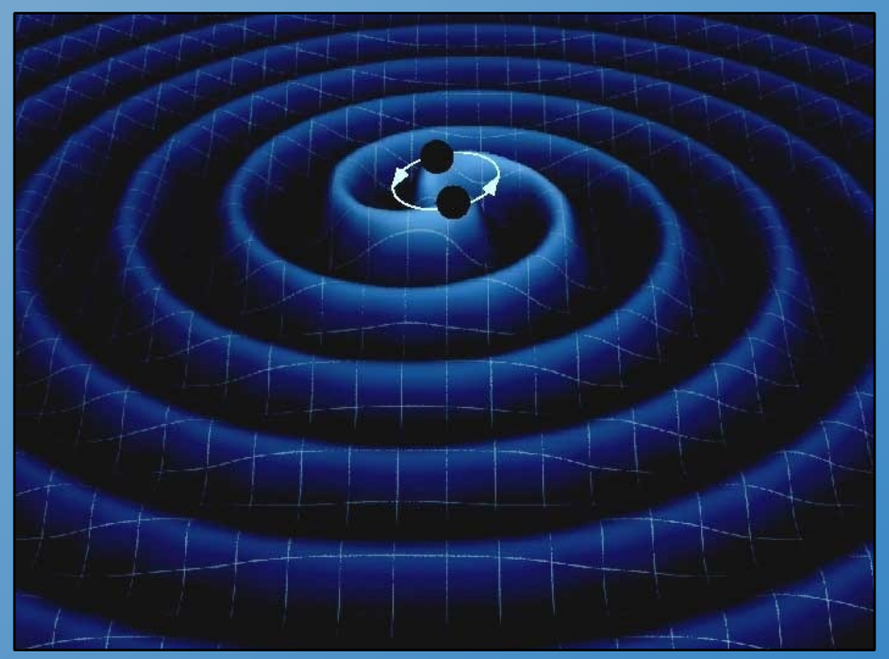
Gravitational-Wave (GW) Recoil

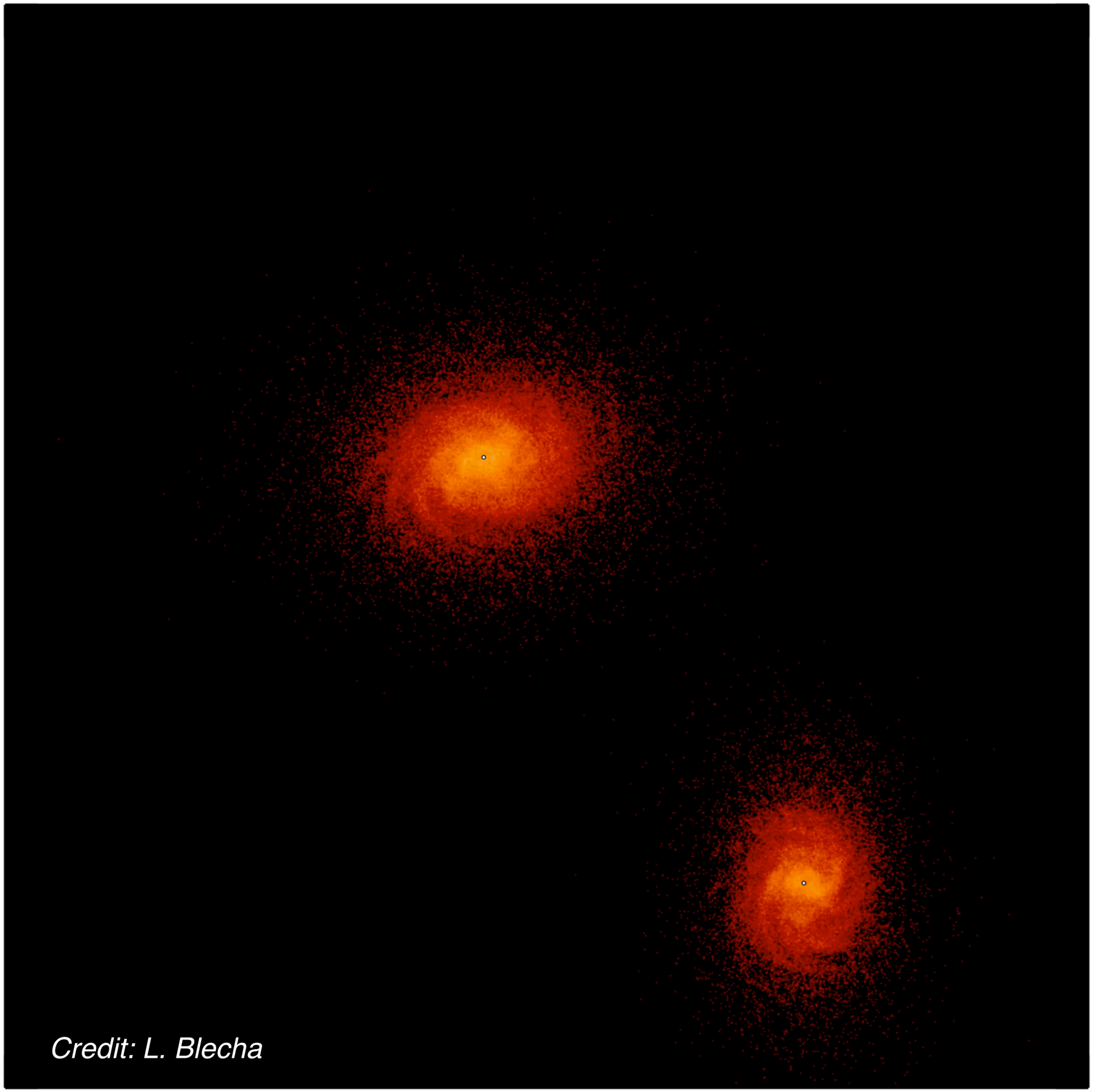
- GW beaming imparts a “kick” to the merged BH
- Max kick is ***~ 5000 km/s!***
  (Campanelli et al. 2007, Lousto et al 2012)
- For randomly-oriented, high spins, ***34% of kicks are > 500 km/s*** *(Lousto et al. 2013)*
- Kicks are lower if ***spin alignment*** occurs prior to merger (more on this later…)
  (Bogdanovic et al 2007, Dotti et al. 2009, 2012, Kesden et al. 2010, Miller & Krolik 2013)



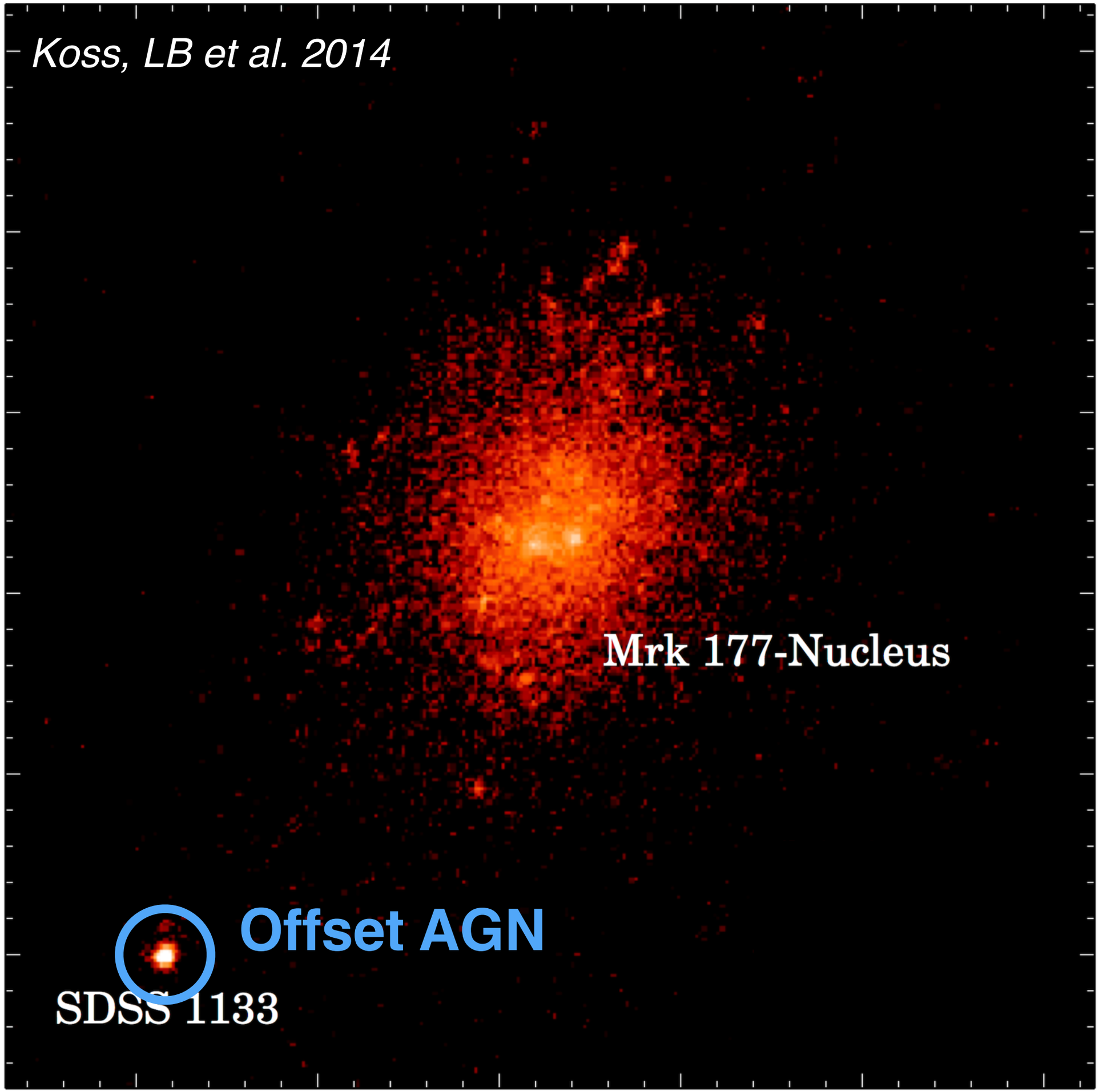
Wiseman 1992







Credit: L. Blecha


Koss, LB et al. 2014
Mrk 177-Nucleus
Offset AGN
SDSS 1133

Recoiling AGN candidates

Kinematic offsets

see Komossa et al. 2008; Shields et al. 2009; Robinson et al. 2010

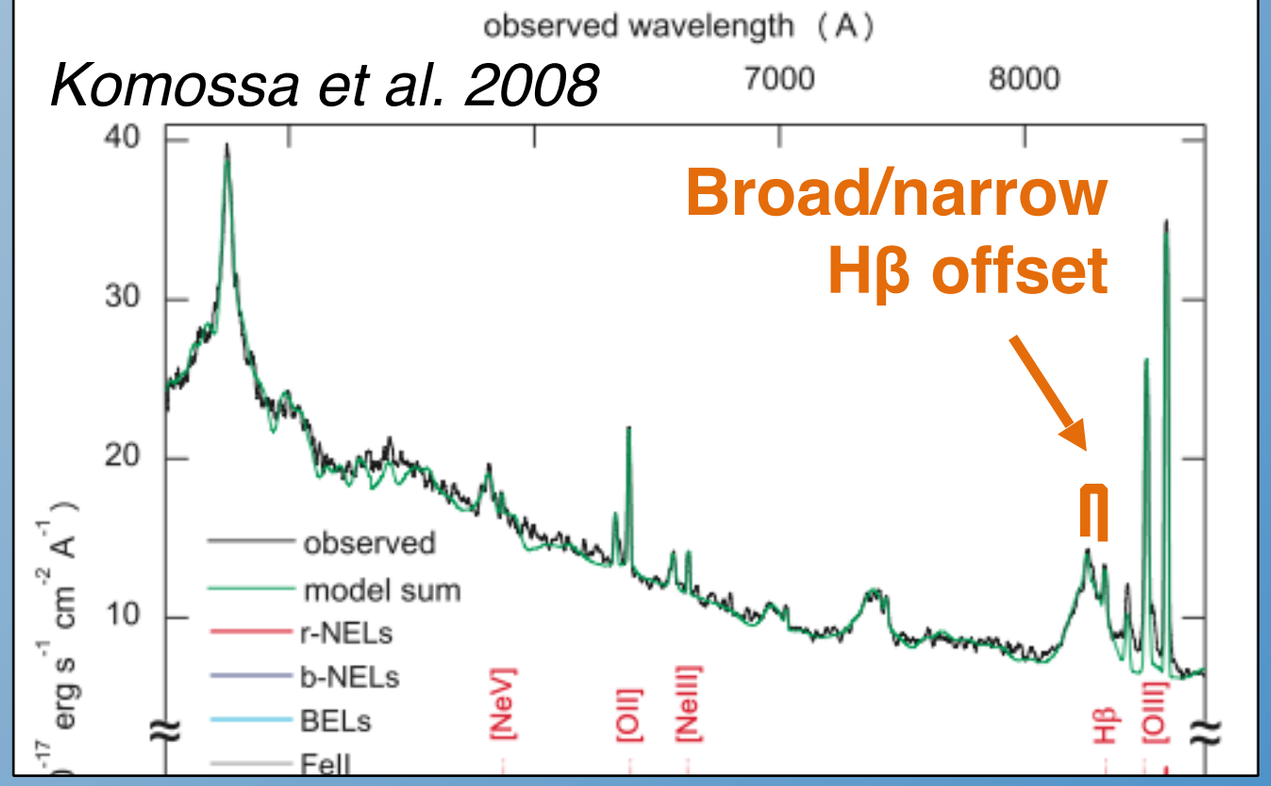
Spatial offsets

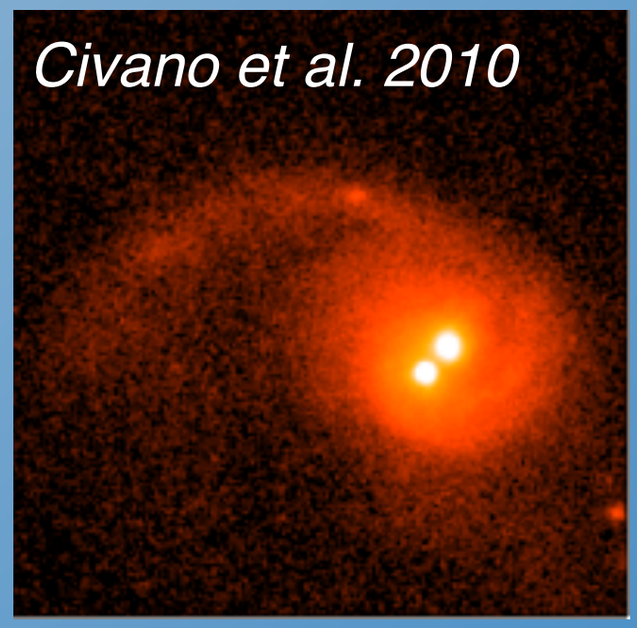
see Batcheldor et al. 2010; Jonker et al. 2010; ***Koss, LB et al. 2014***

Kinematic *and* spatial offsets

see Civano et al. 2010, 12, Blecha et al. 2013

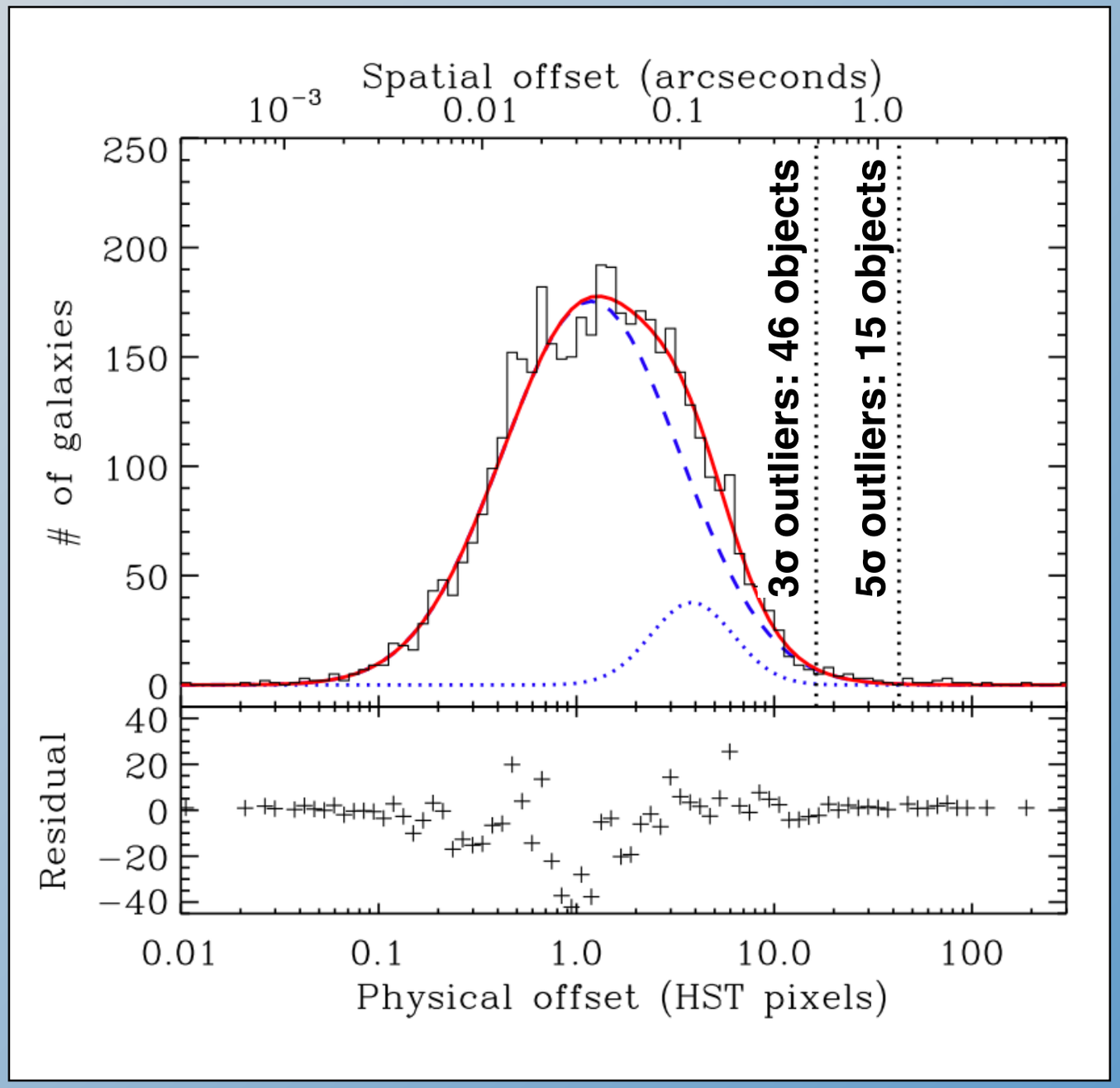
Komossa et al. 2008





Searches for spatially-offset AGN

Civano et al. in prep.



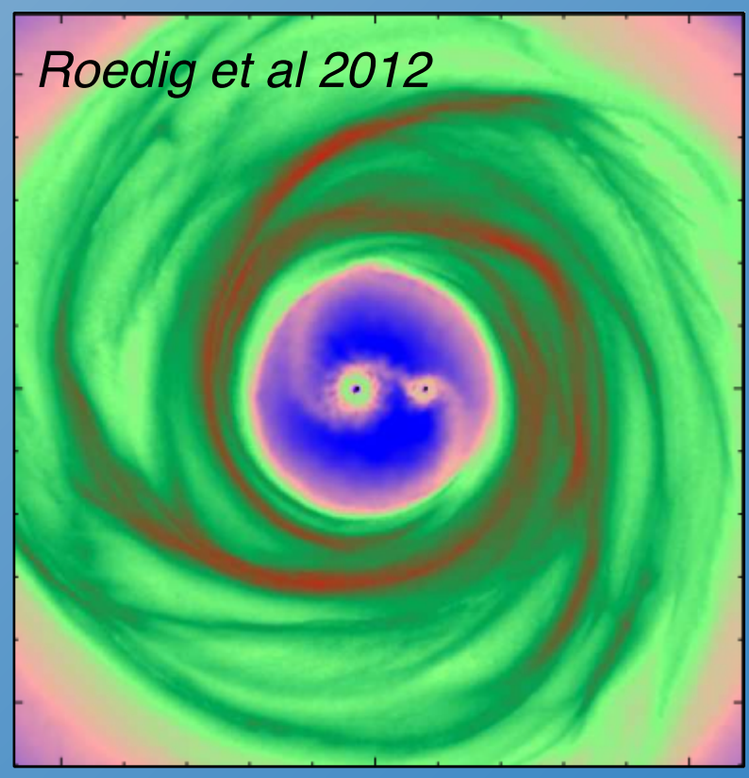
- Survey of galaxies in *HST*-COSMOS (1.7 deg^2)
- Pilot study of ~ 5000 galaxies: ~ **0.3% have significant offsets (>5σ) between AGN & host centroid**

Modeling recoiling AGN in cosmological simulations: Motivation

- Want to design a **targeted, systematic** search for offset AGN
  - How many recoiling AGN do we expect to be observable (as a function of L, Mbh, z, etc.)?
  - What are the most likely **host galaxies** of observable, offset AGN?
- From semi-analytic merger tree models: up to a few tens per deg^2 could be observable *(Volonteri & Madau 2008)*
- Want to know dependence on the **BH spin distribution.** Can we learn something about BH spins from observations of offset AGN?

Hydro effects matter!

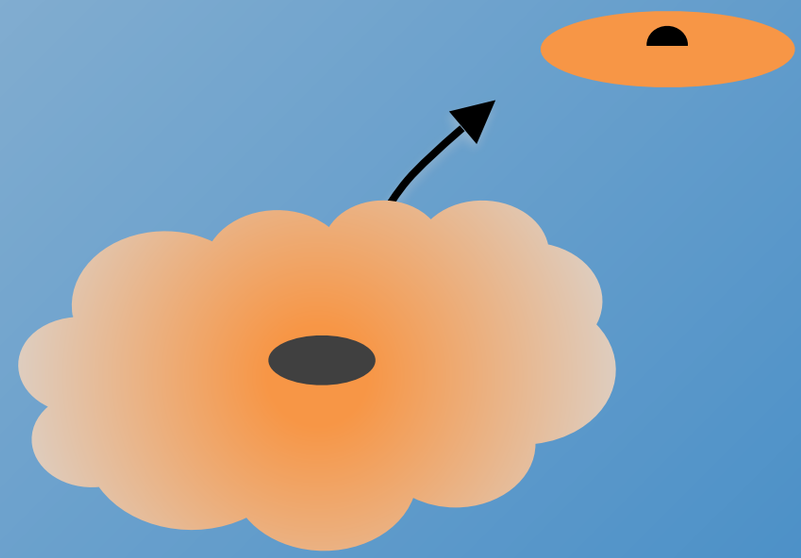
- Recoils trajectories ***suppressed*** in ***gas-rich major mergers*** *(LB et al. 2011, see also Guedes et al. 2011, Sijacki et al. 2011)*
- ***Spin alignment*** prior to merger by a ***circumbinary gas disk*** *(Bogdanovic et al 2007, Dotti et al. 2009, 2012, Miller & Krolik 2013)*
- Maximum kick: ***5000 km/s***
- With perfectly aligned spins: ***< 200 km/s***



Recoiling AGN accretion disks

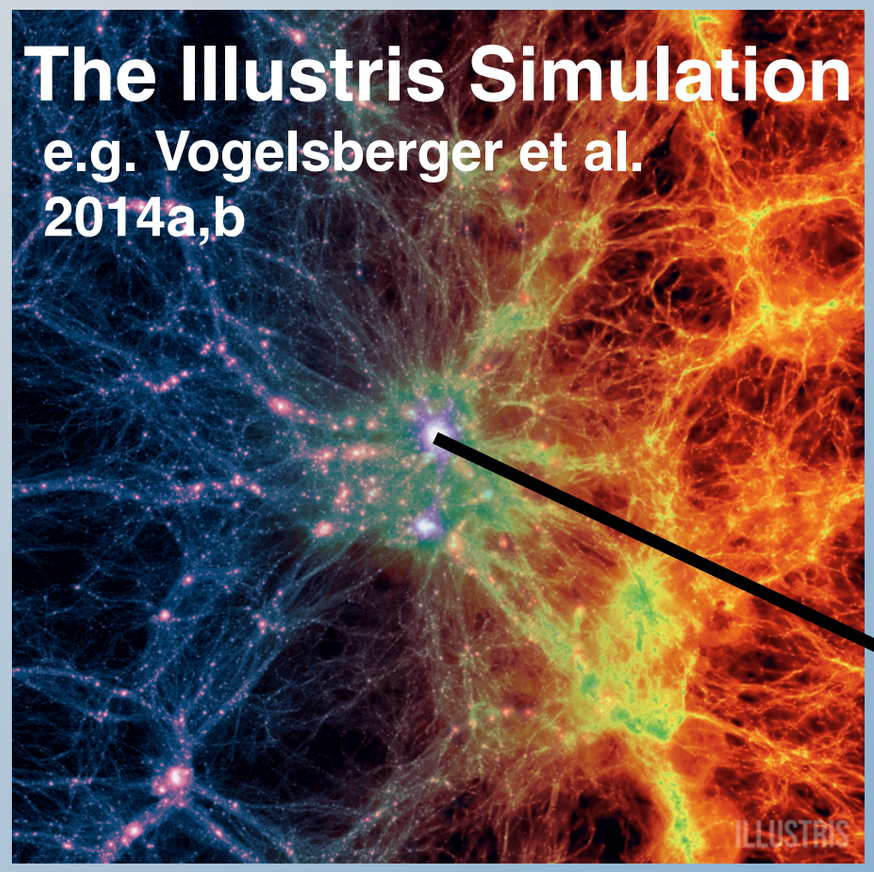
- Accretion rate from an isolated, thin viscous disk decreases as $\dot{M} \propto t^{-19/16}$

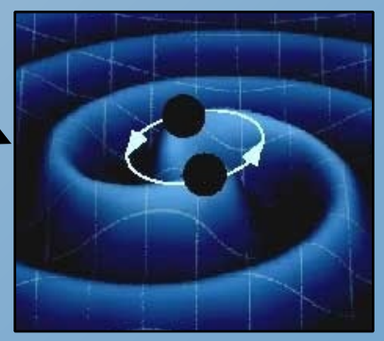
- For recoiling AGN: shorter 'bright' AGN phase, but ***longer total AGN lifetime*** (vs. constant $\dot{M}$ model; LB et al. 2011)



Modeling offset AGN

in cosmological simulations *(Blecha et al. in prep)*





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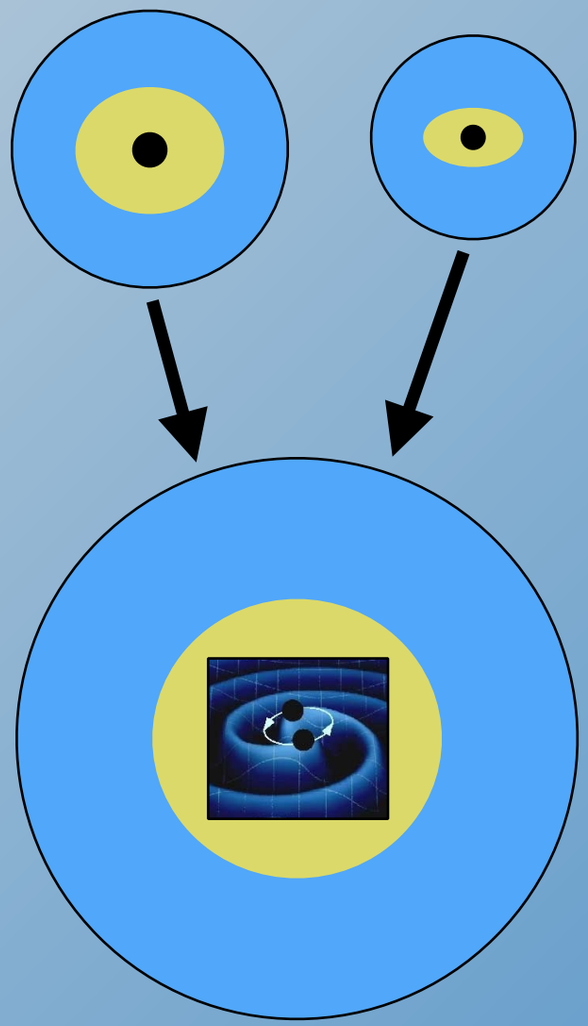
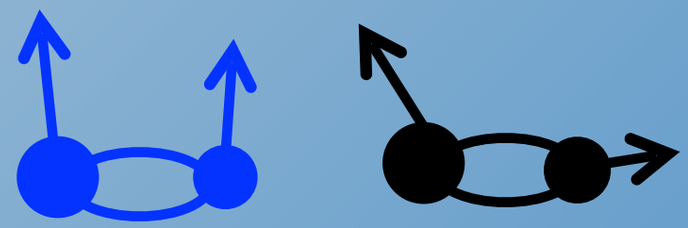
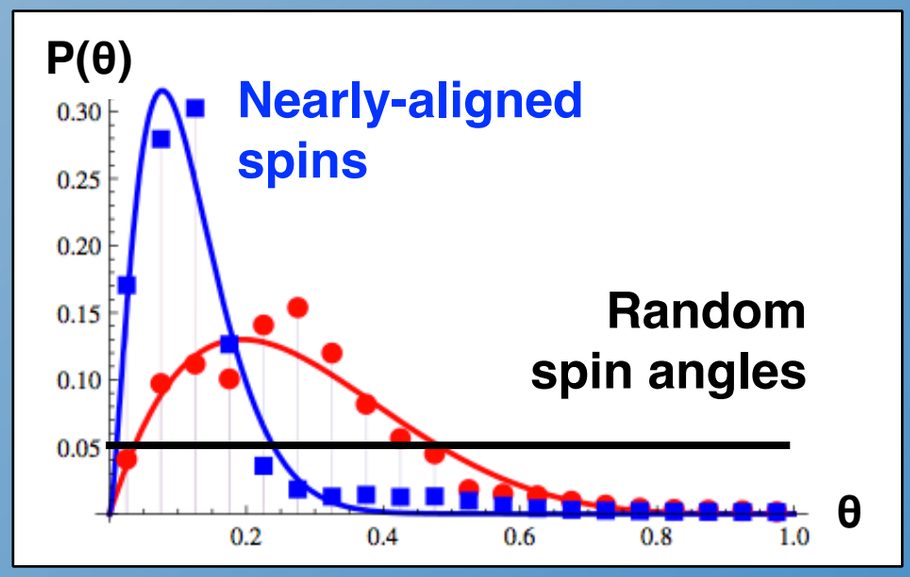
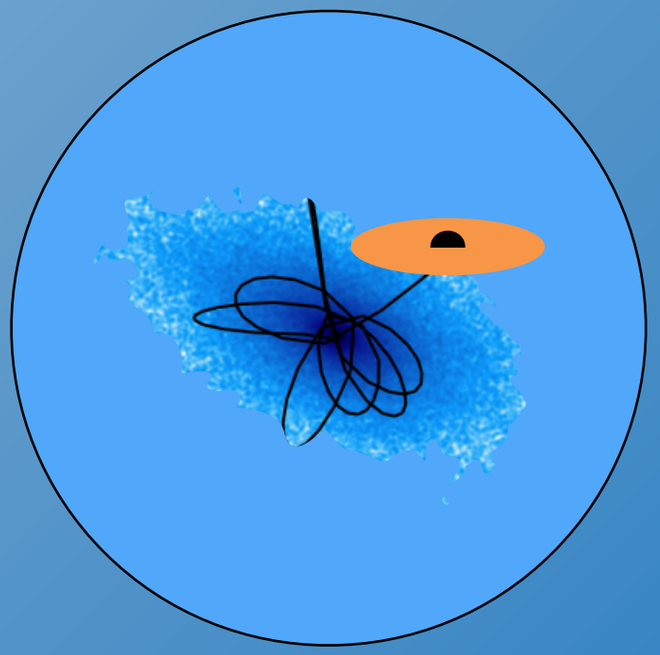


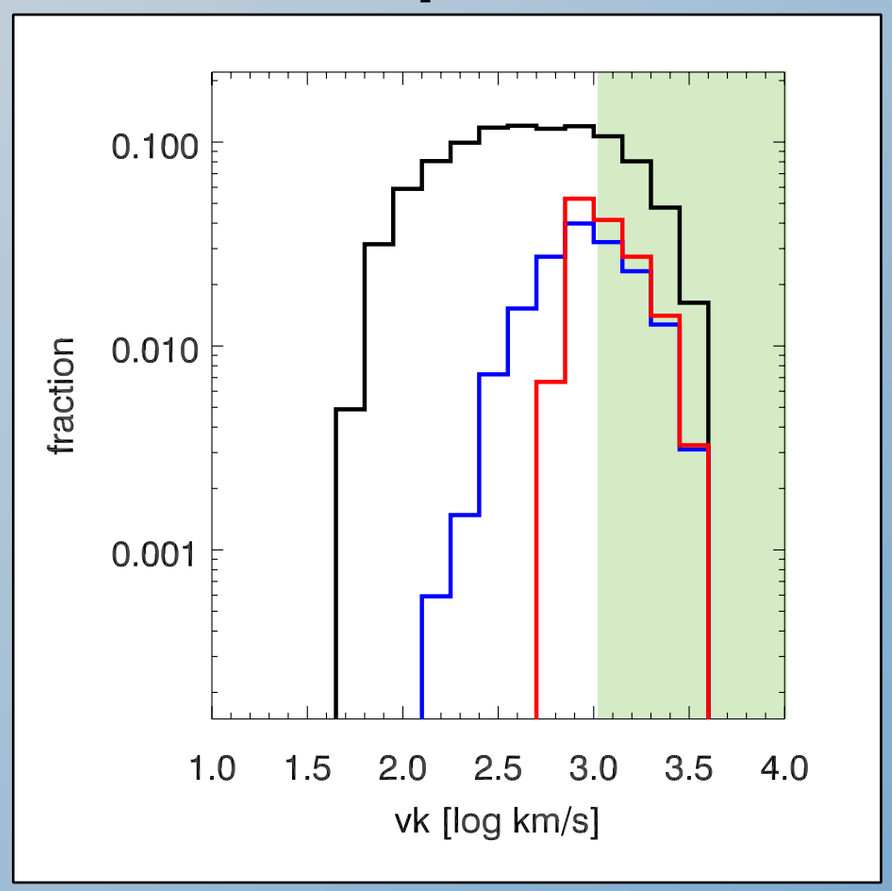






Recoil kick distributions
(from BH mergers in Illustris)

Random spins, *a=0.9*

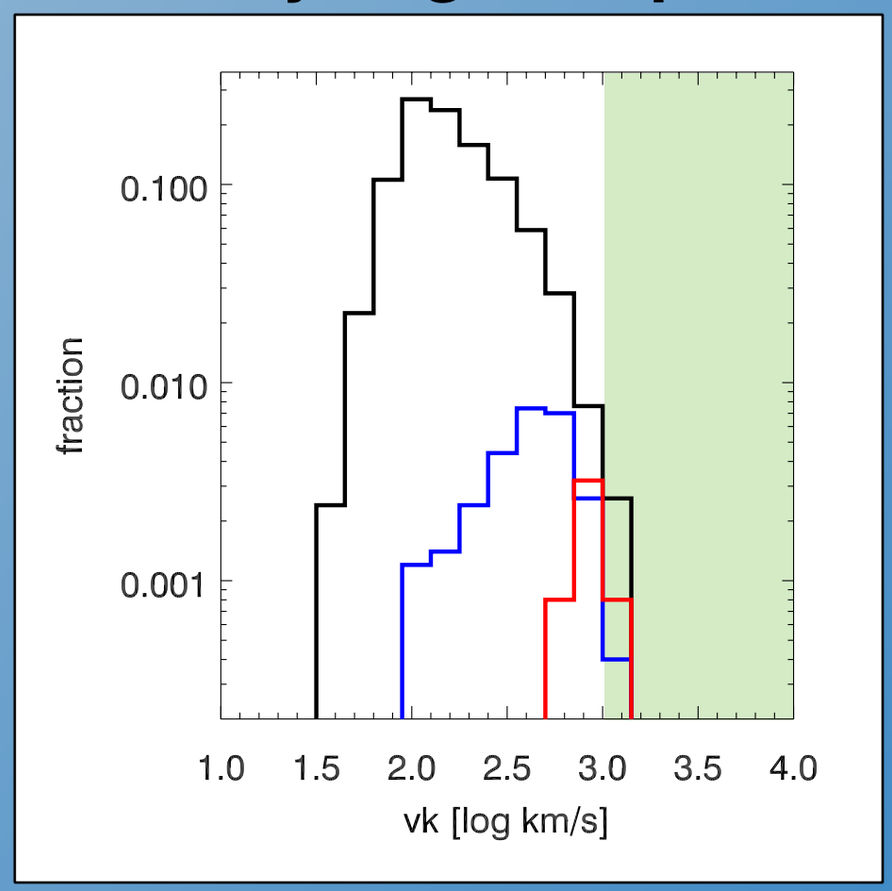


All $v_k/v_{esc} > 0.1$

Spatially-offset AGN

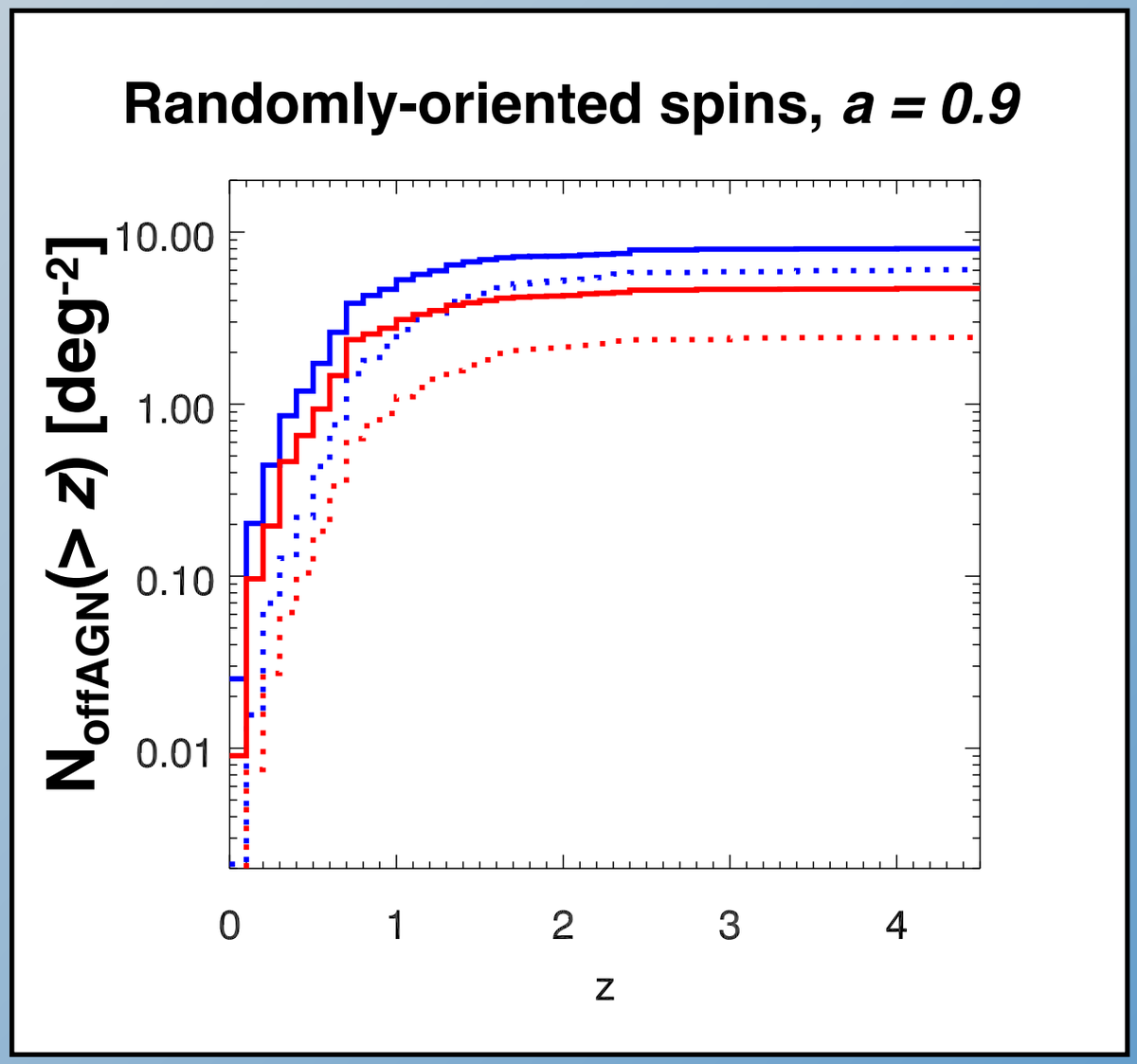
Velocity-offset AGN

Nearly-aligned spins



Blecha et al., in prep

Recoiling AGN source counts



Spatially-offset AGN (assumes *HST* res.)

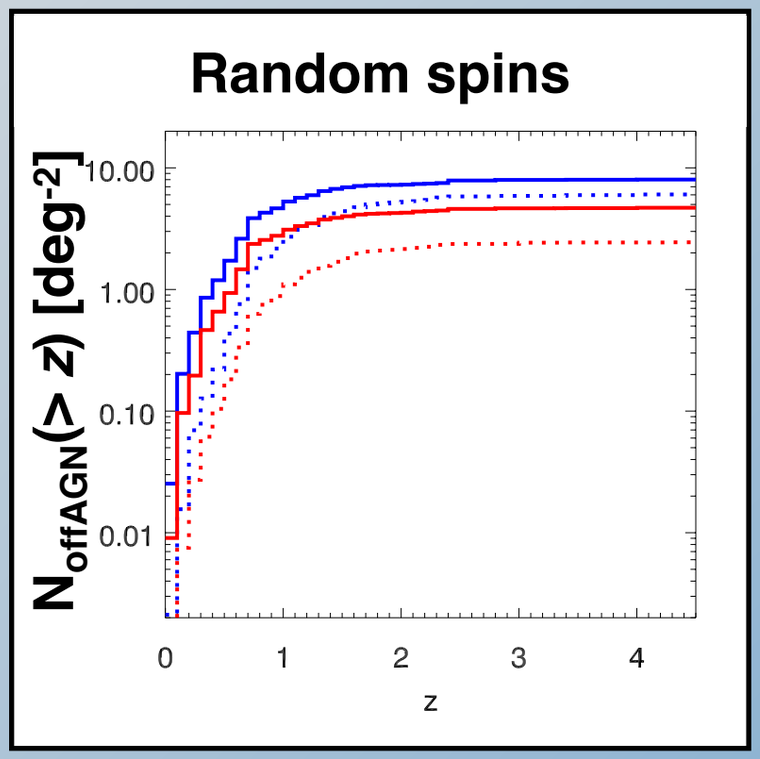
Velocity-offset AGN (>600 km/s)

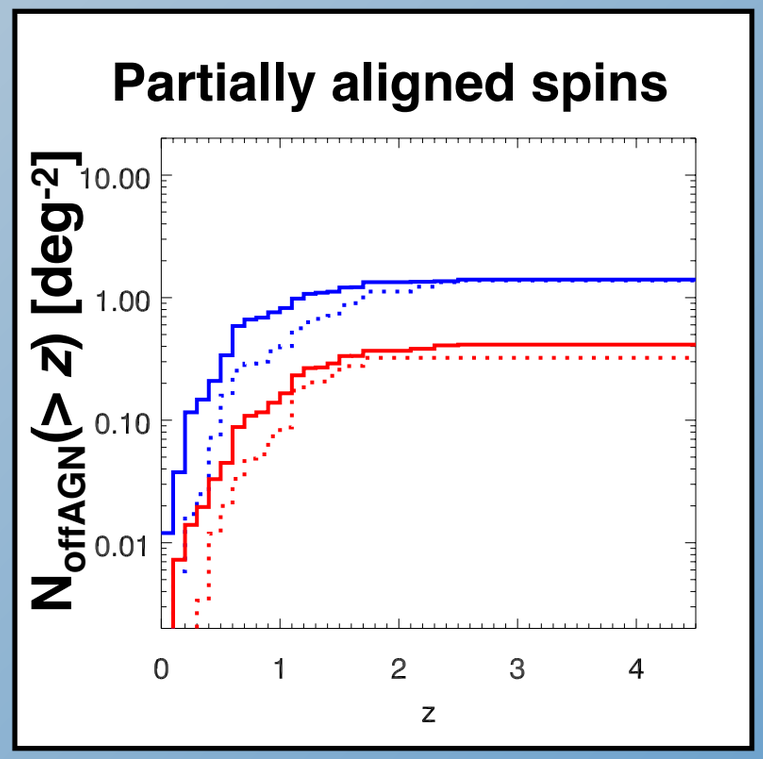
Time-varying Mdot

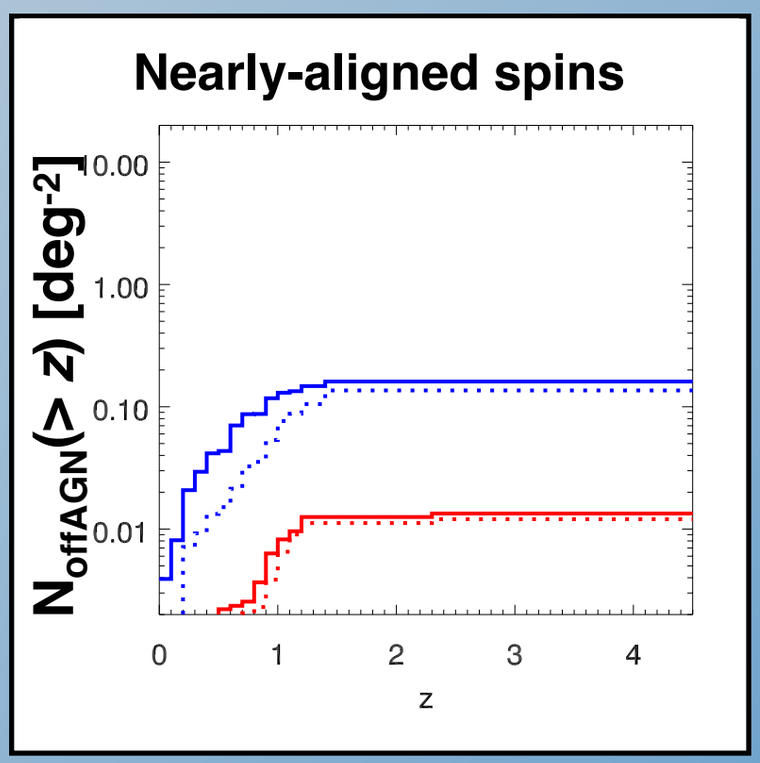
Const Mdot

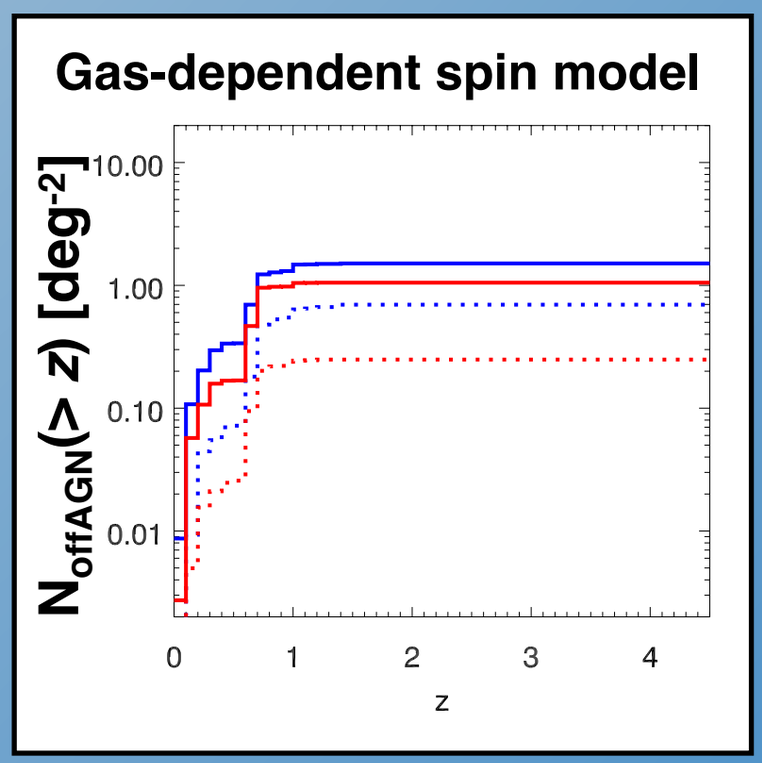
Blecha et al., in prep

Recoiling AGN source counts









Spatially-offset AGN (assumes *HST* res.)

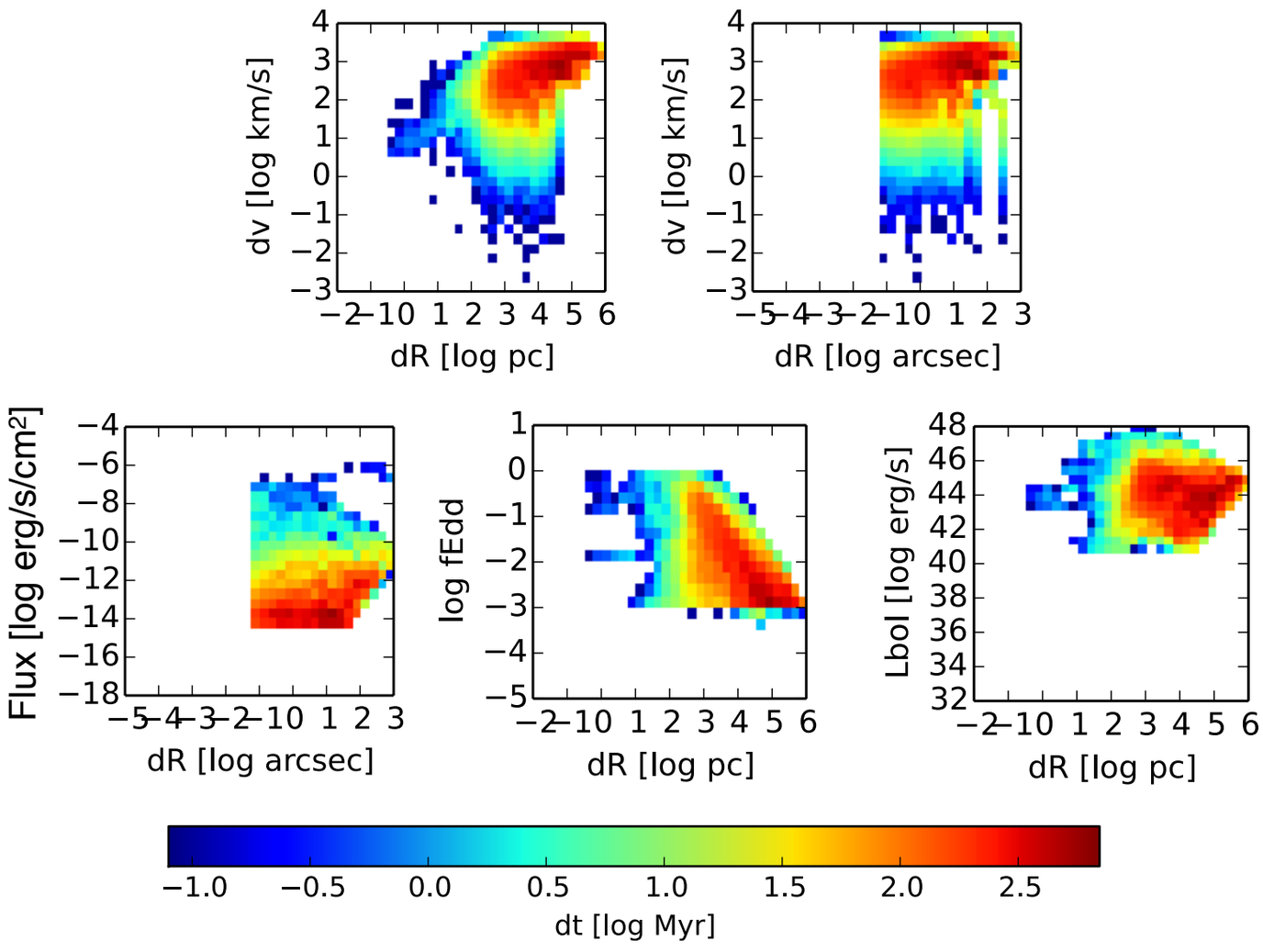
Velocity-offset AGN (>600 km/s)

—— **Time-varying Mdot**

..... **Const Mdot**

Blecha et al., in prep

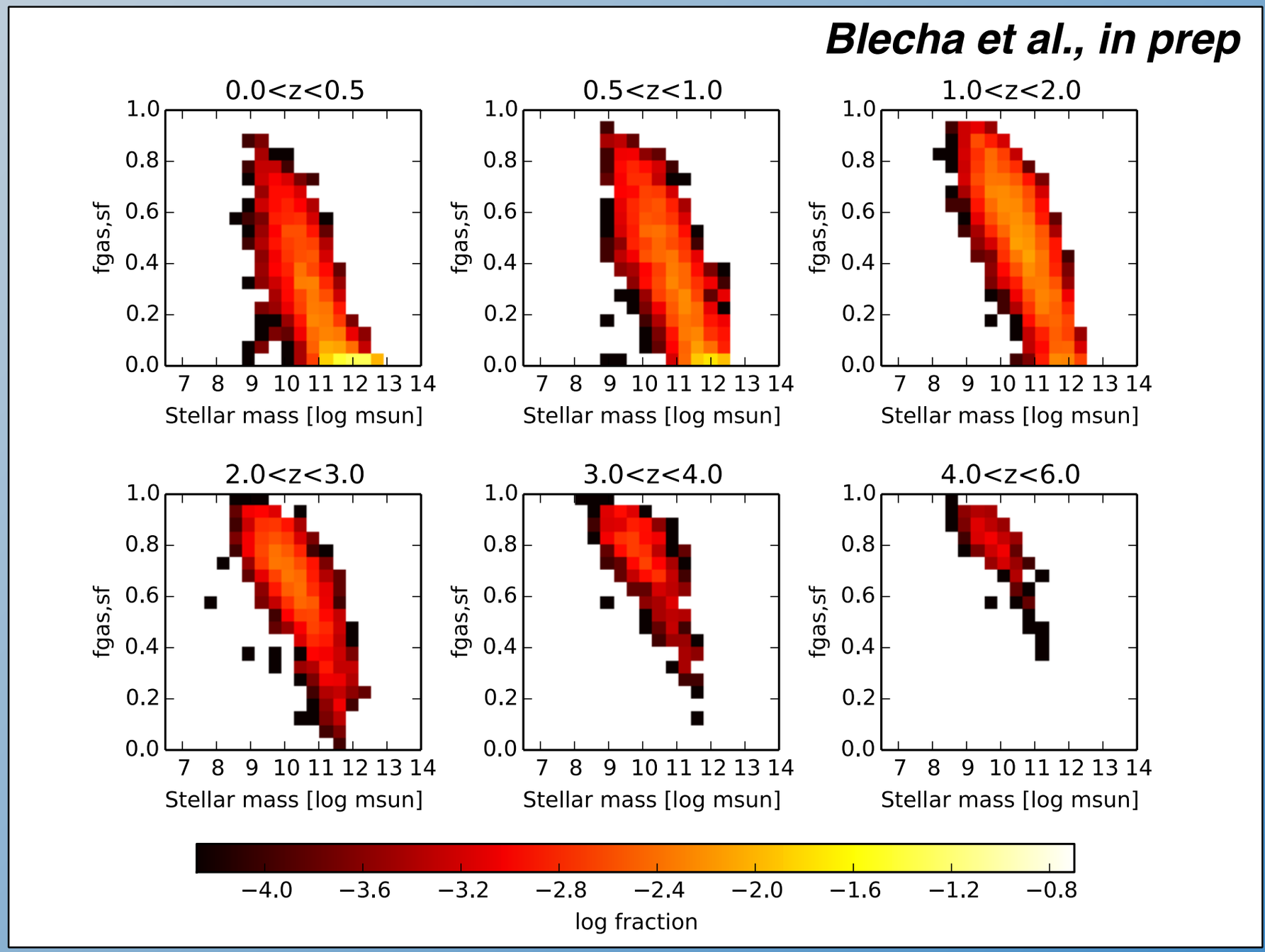
Observable spatially-offset AGN



- Distribution of dR is dominated by largest separations (> kpc) and by events with $v_k/v_{esc} \sim 1$
- Observable offset AGN also dominated by low Eddington ratios
- Survey sensitivity will be a more limiting factor than spatial resolution

Host galaxy properties

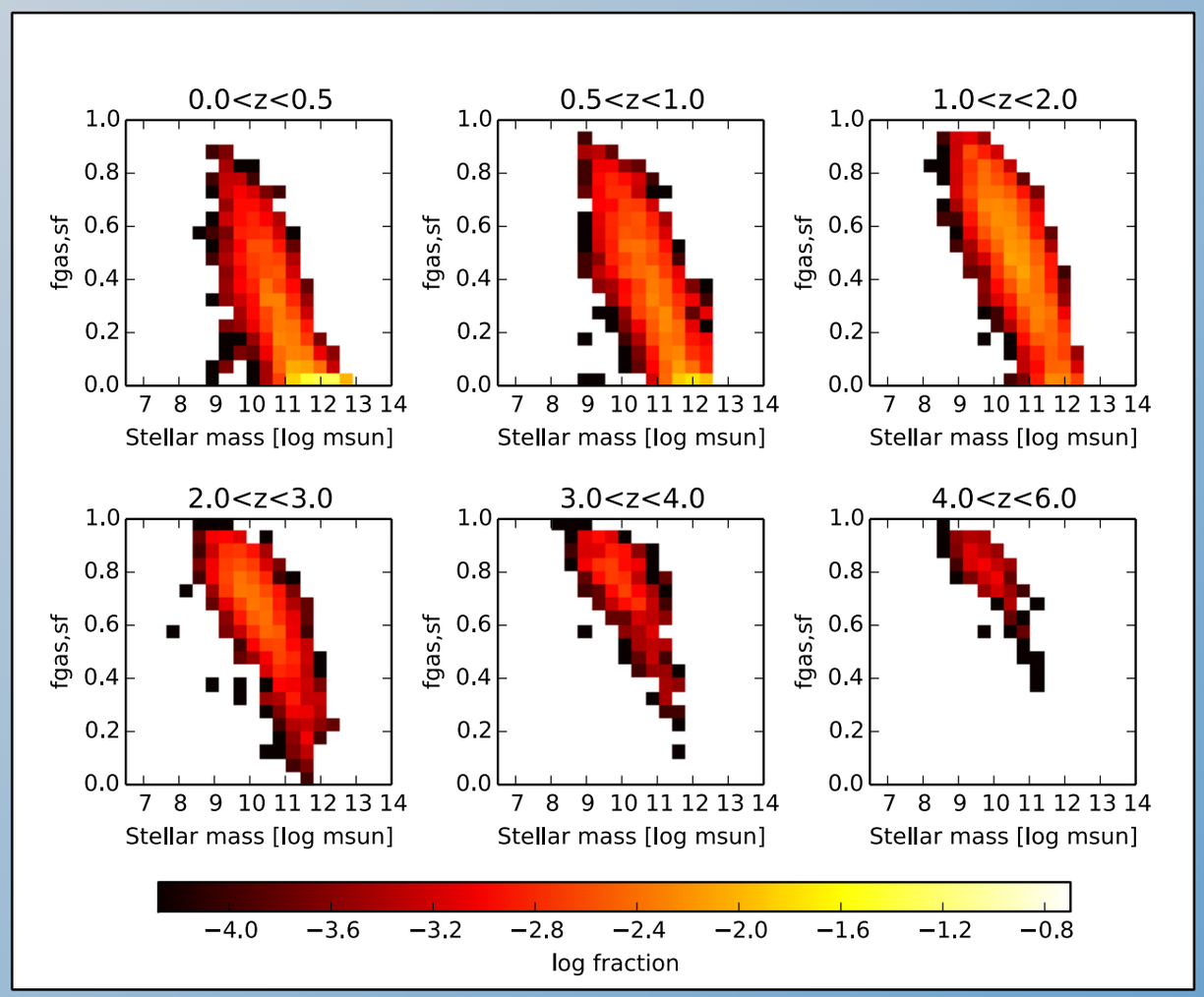
Cold gas fraction vs. stellar mass — all BH merger hosts



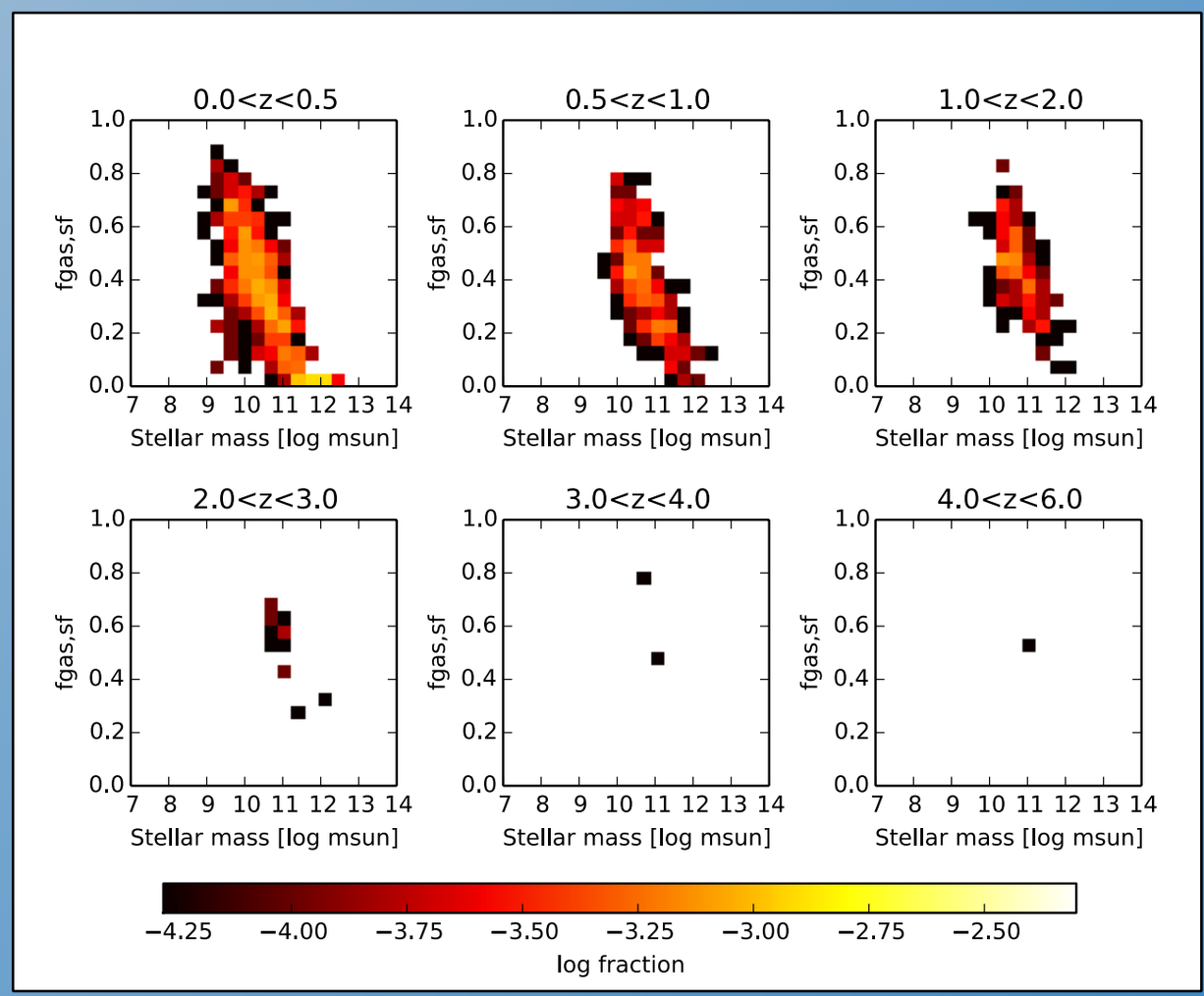
Host galaxy properties

Cold gas fraction vs. stellar mass

All BH merger hosts



Offset AGN hosts (random spin model)

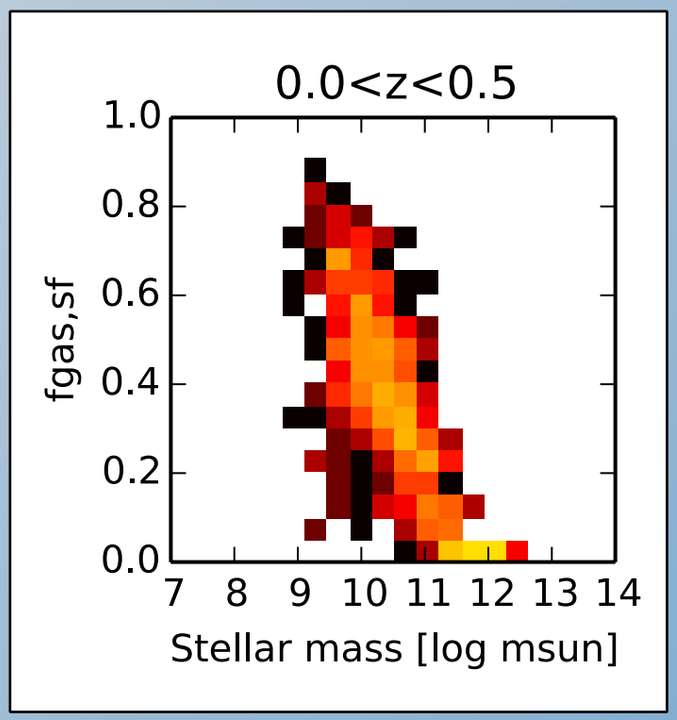


Blecha et al., in prep

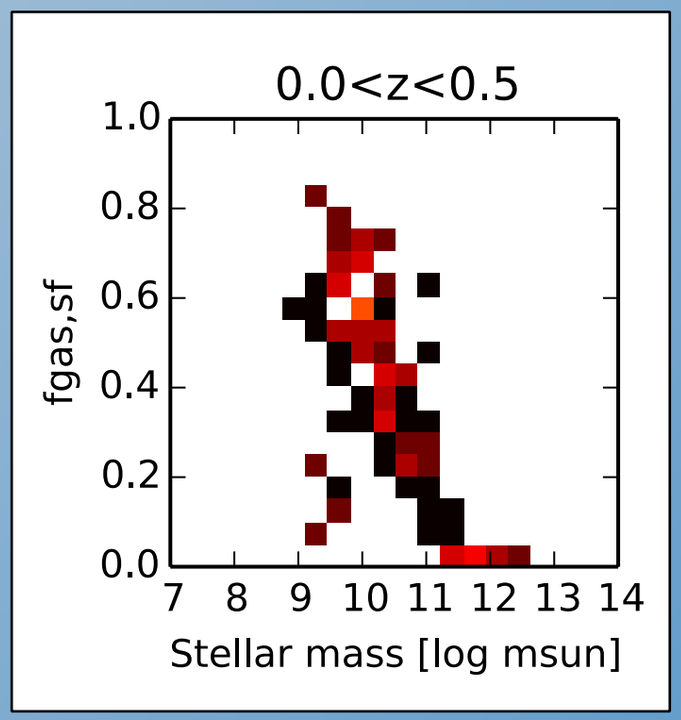
Host galaxy properties

Cold gas fraction vs. stellar mass

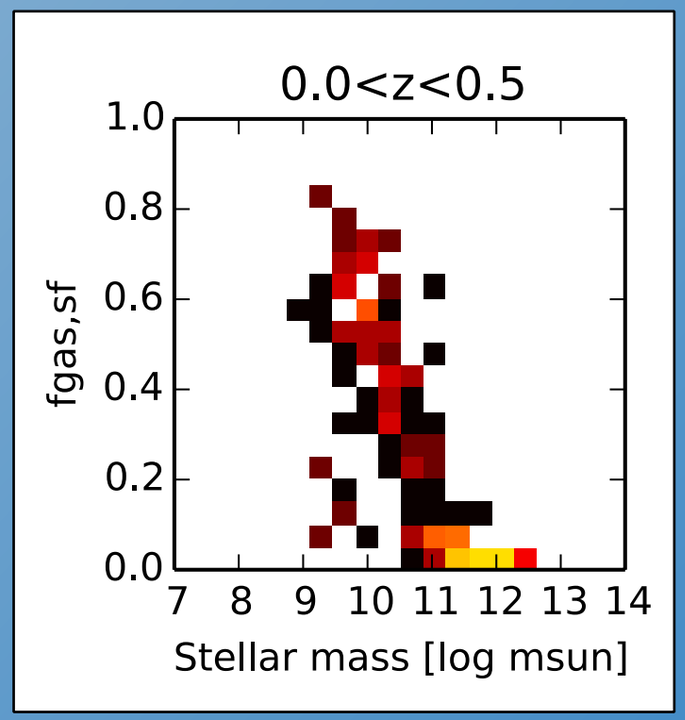
Random spin model



Nearly-aligned spin model



Gas-dependent spin model

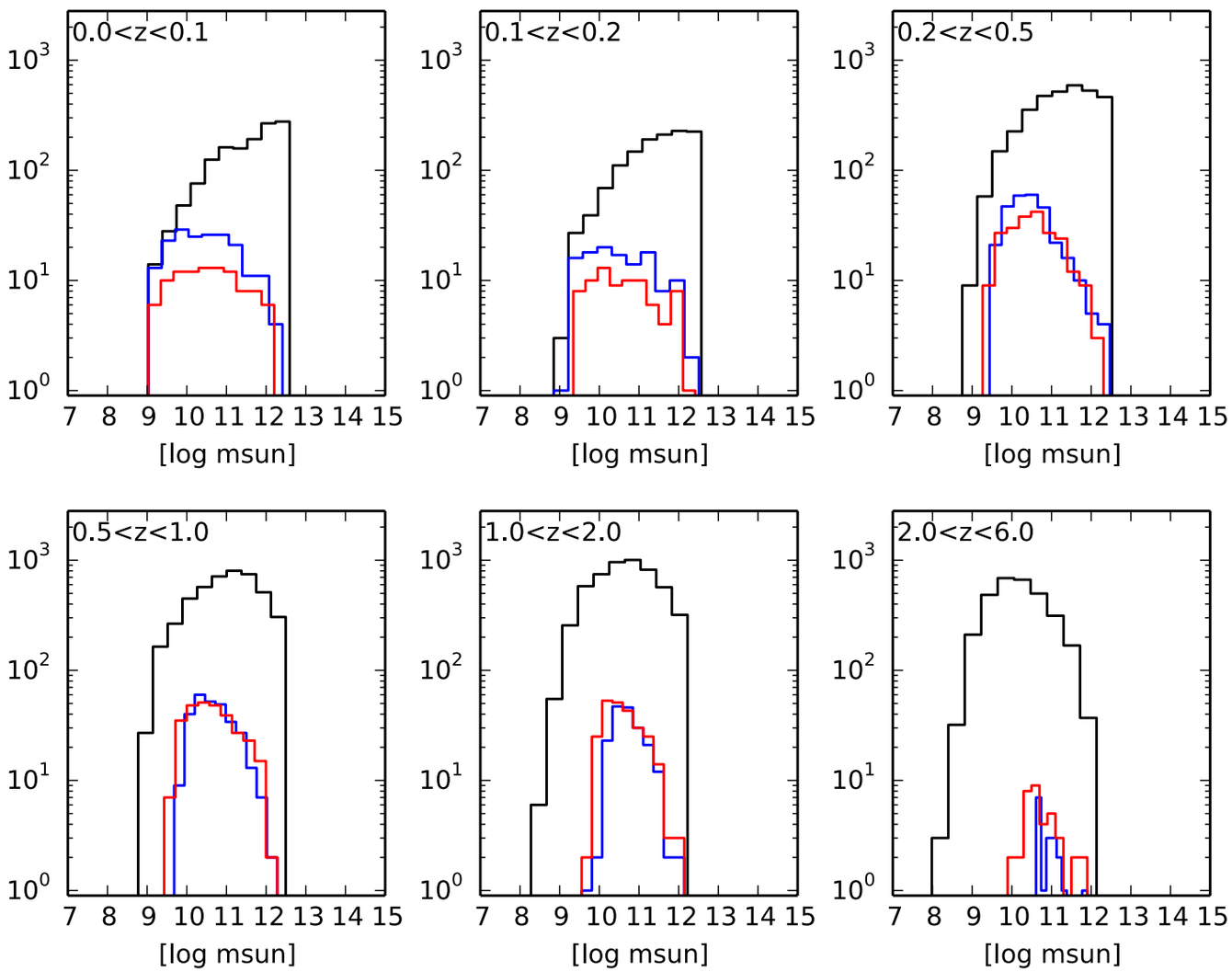


Blecha et al., in prep

Host galaxy properties

Offset AGN host stellar mass
(random spin model)

Black: All BH mergers;
Blue: spatially offset AGN; Red: velocity offset AGN



- At low z, host mass distribution is broad & is bound by the simulation resolution limit.
- For random spins, **almost all BH mergers in low-mass galaxies** at z<0.1 result in spatially offset AGN.
- For highest mass hosts, ~1% of mergers yield observable offsets for random spins. *(With efficient spin alignment, closer to 0%)*.
- For z>0.2, the host mass distribution for offset AGN cuts off at the low mass end **and** the high mass end
- Thus, for z>0.2, there is an apparent **preference for offset AGN hosts** with log M_* ~ 10-10.5.

Summary

- Until actual GW detections, observations of GW recoil events are likely the best prospects for identifying SMBH mergers
- Promising candidate recoiling AGN have been identified, and more systematic searches are underway
- For spatially-offset AGN, large offsets (~1-100 kpc) dominate — thus, flux sensitivity is a more limiting factor than resolution
- Several per deg^2 may be observable in the most optimistic case
- Offset AGN appear to inhabit preferred host galaxies
- At low redshift ($z<0.1$), host mass distribution is broad, and **most** BH mergers in low-mass galaxies ($M_* < 10$) may result in observable spatial offsets
- At higher redshift ($z>0.2$), host mass distribution is peaked around $\log M_* \sim 10 - 10.5$.
- Find tentative indications that recoiling AGN may be able to distinguish between models for BH spin alignment