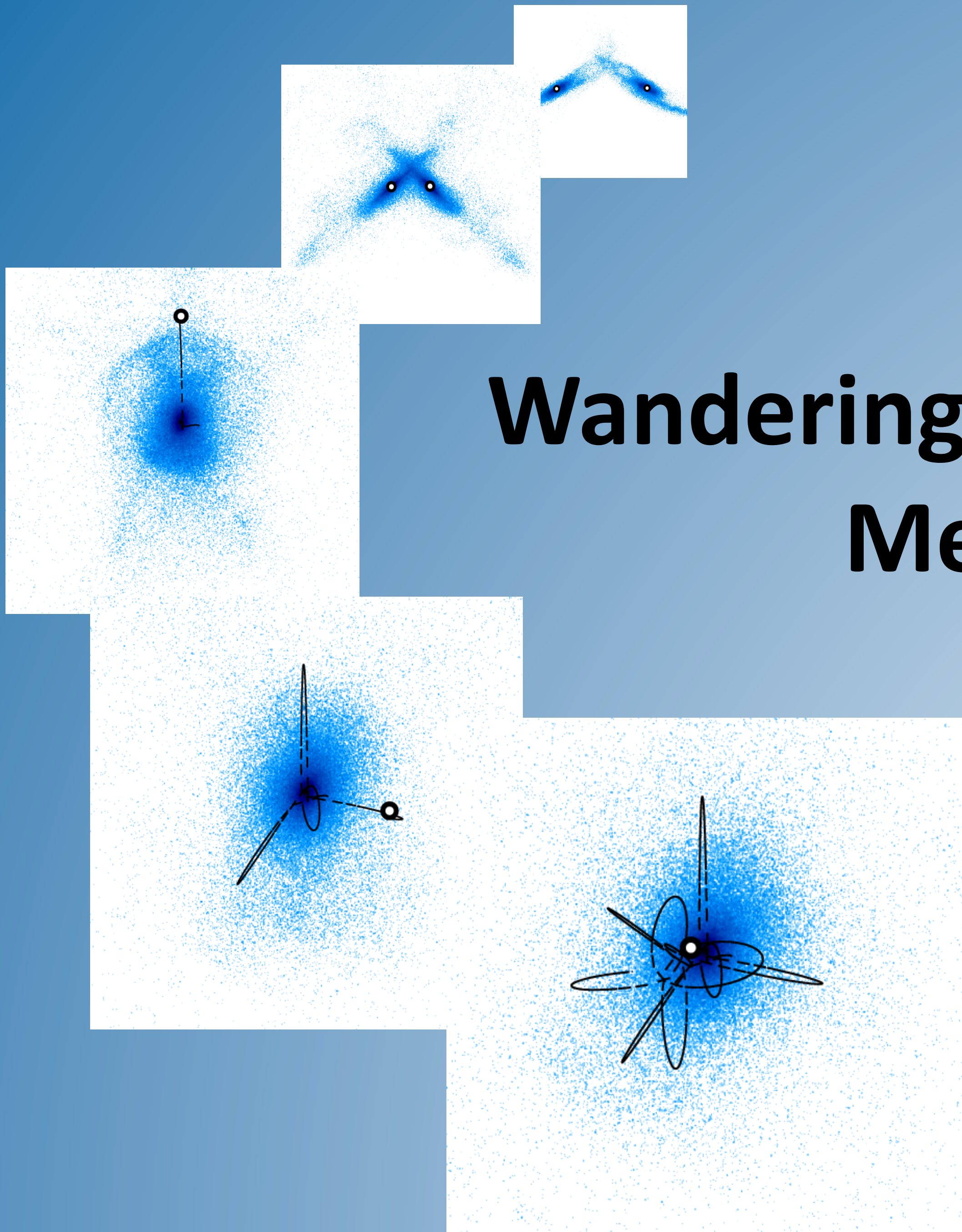

# Wandering Black Holes in Merging Galaxies


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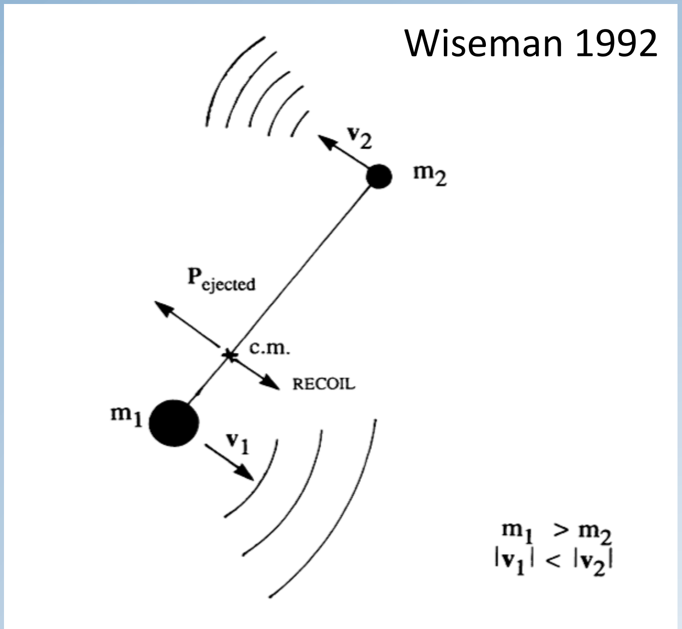
Stars & Singularities Workshop

Weizmann Institute

12/8/09

# Overview of Gravitational-Wave Recoil

- Results from asymmetrical GW emission during BH merger
- Kick speed depends on mass ***ratio*** and spins
- Easier to eject BHs at high redshift (lower $v_{esc}$)
- Major mergers more frequent at high redshift



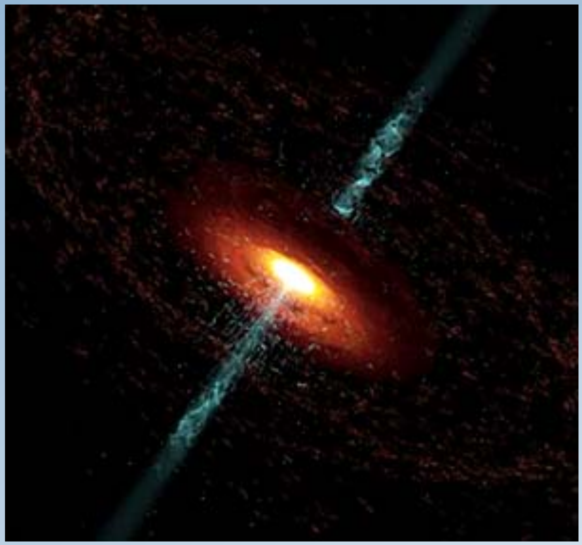
# Overview of Gravitational-Wave Recoil

- Maximum kick speed ~ 4000 km $s^{-1}$
- For high spins & random orientations, fraction of kicks with
  - **$v_k$ > 500 km $s^{-1}$: *12-36%***
  - **$v_k$ > 1000 km $s^{-1}$: *3-13%***

  *(Schnittman & Buonanno 2007, Campanelli et al. 2007, Baker et al. 2008)*
- Kicks could be lower if spins become aligned due to torques from a gas disk *(Bogdanović et al. 2007, Dotti et al 2009)*

# Observable signatures:
## EM counterparts

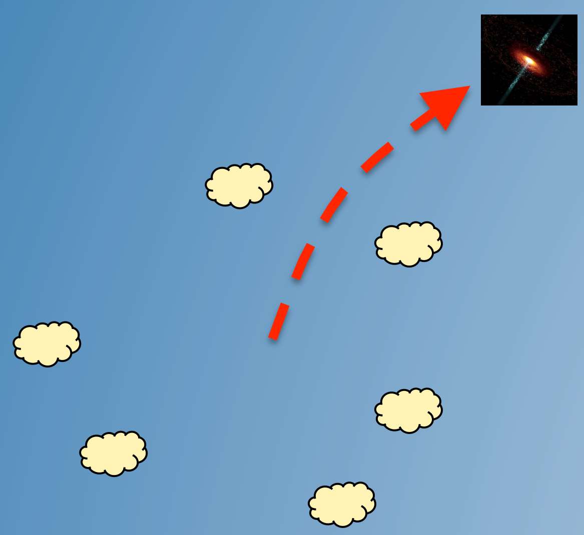
- Recoiling quasars:
  - $r_{ej} \sim G\ M / v_{kick}^2$ *(Loeb 2007)*
  - Spatial offsets
  - Kinematic offsets



# Kinematic Signatures of binaries vs. recoils

Recoils

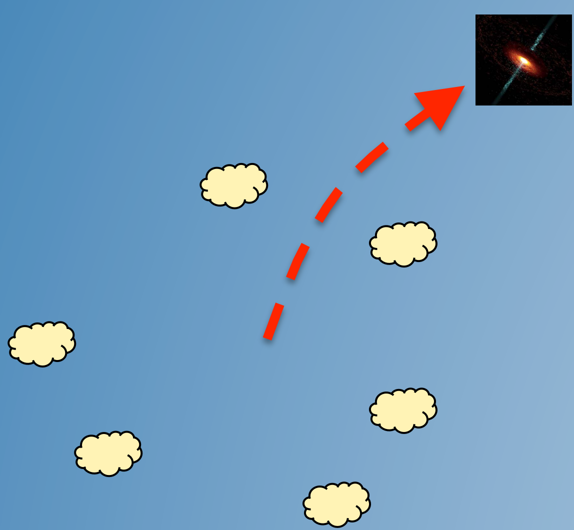
Binaries



**Offset between broad line region (BLR) and narrow line region (NLR)**

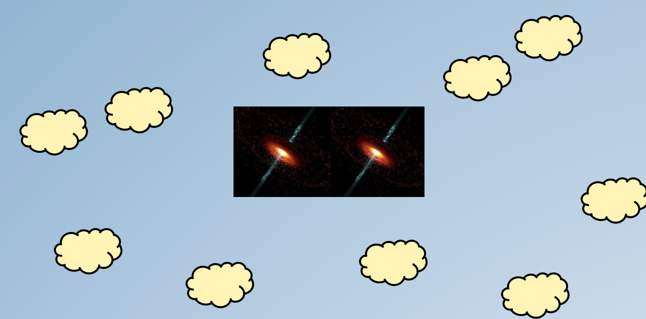
# Kinematic signatures of binaries vs. recoils

## Recoils

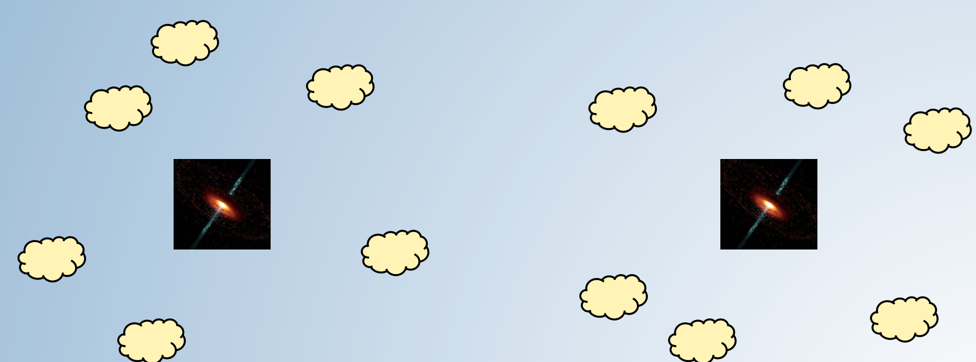


**Offset between broad line region (BLR) and narrow line region (NLR)**

## Binaries

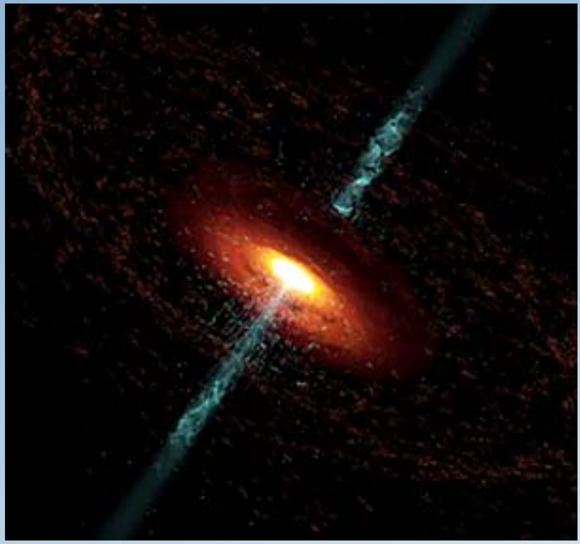


**Double BLR; common NLR**



**Double NLR**

# Signatures of GW recoil:
# EM counterparts

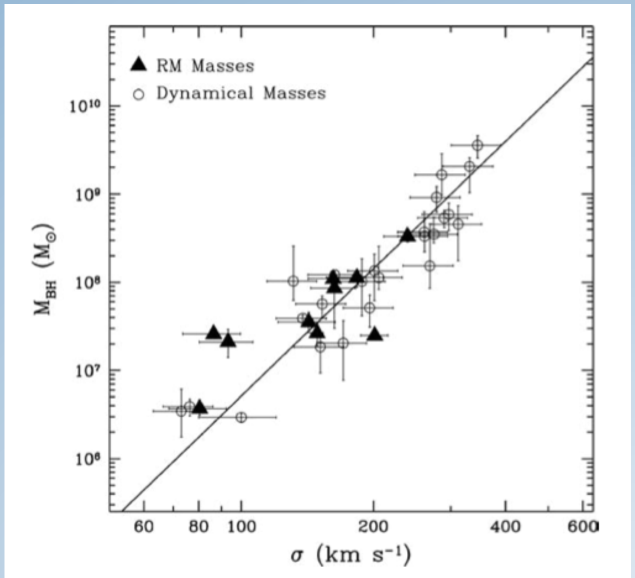


- Recoiling quasars:
  - $r_{ej} \sim G\,M\,/\,v_{kick}^2$ *(Loeb 2007)*
  - Spatial offsets
  - Kinematic offsets
- Recoil ‘fallback’ flares *(Lippai et al. 2008, Shields & Bonning 2008)*
- Recoiling star clusters *(Ryan O’Leary’s talk)*
- Stellar tidal disruption flares *(Nick Stone’s talk)*

# Signatures of GW recoil:
## Host galaxy properties

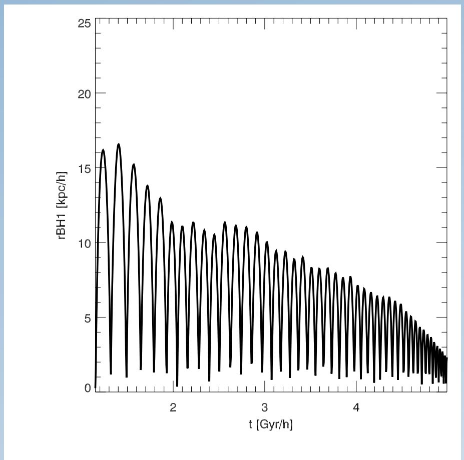
- Scatter, offset, and/or outliers in $M_{BH}$-$\sigma_*$ relation
  - Recoil events could produce under-massive BHs
  - Biggest effect at high *z*; observed *z*=0 relation constrains recoils at low *z*

*(Ferrarese & Ford 2005)*

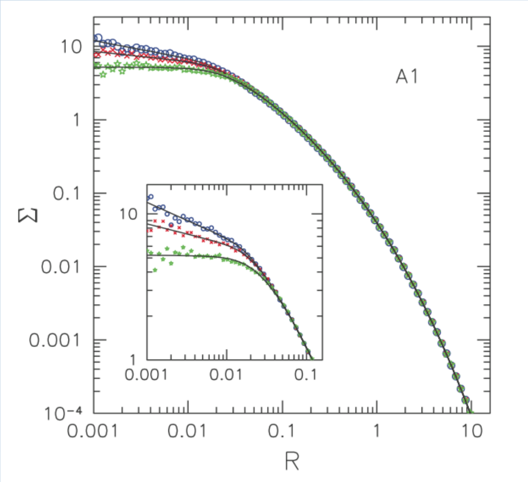


# Signatures of GW recoil:
## Host galaxy properties

- Core-scouring
  - $M_{def}$ ~ few x $M_{BH}$
  - Most efficient in galaxies with very little gas
  - Occurs on small scales – hard to observe or to resolve in SPH simulations




*Gualandris & Merritt 2008*



# Observational constraints

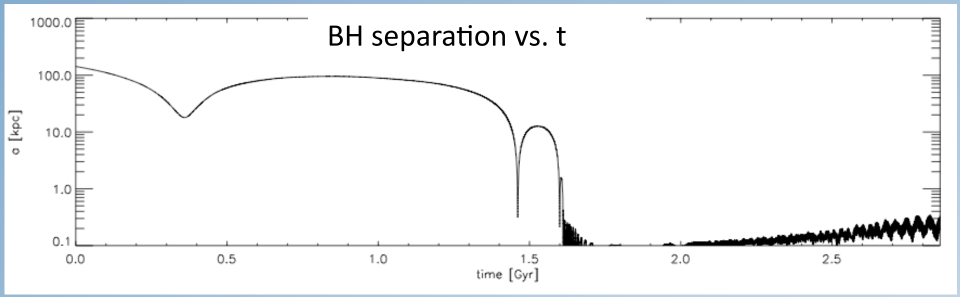
- "Empty" galaxies generally not seen locally
- Small scatter of $M_{BH}$-$\sigma_*$ relation
- Search for kinematic offsets in quasar spectra (SDSS) yielded a ***null result*** *(Bonning et al. 2007)*

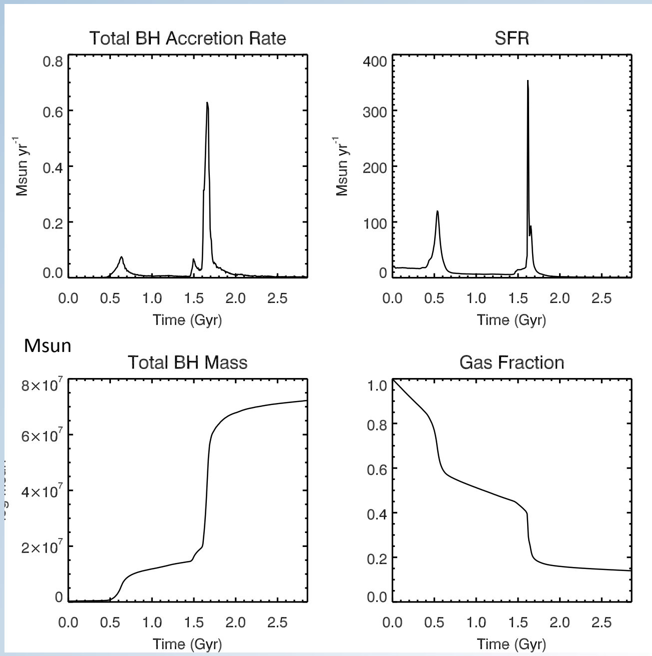
# GW recoil candidates

- SDSS J0927+2943:
  - 2650 km/s offset between BLR & NLR *(Komossa et al. 2008)*
  - May be a binary BH or a superposition of galaxies (*Shields et al. 2008, Heckman et al. 2008, Dotti et al. 2008, & Bogdanović et al. 2008)*
- SDSS J1050+3456:
  - 3500 km/s offset between BLR & NLR *(Shields et al 2009)*
  - May be a feature of rotating gas in a disk
- Note: both candidates have ***extreme*** velocities

# Galaxy merger simulations

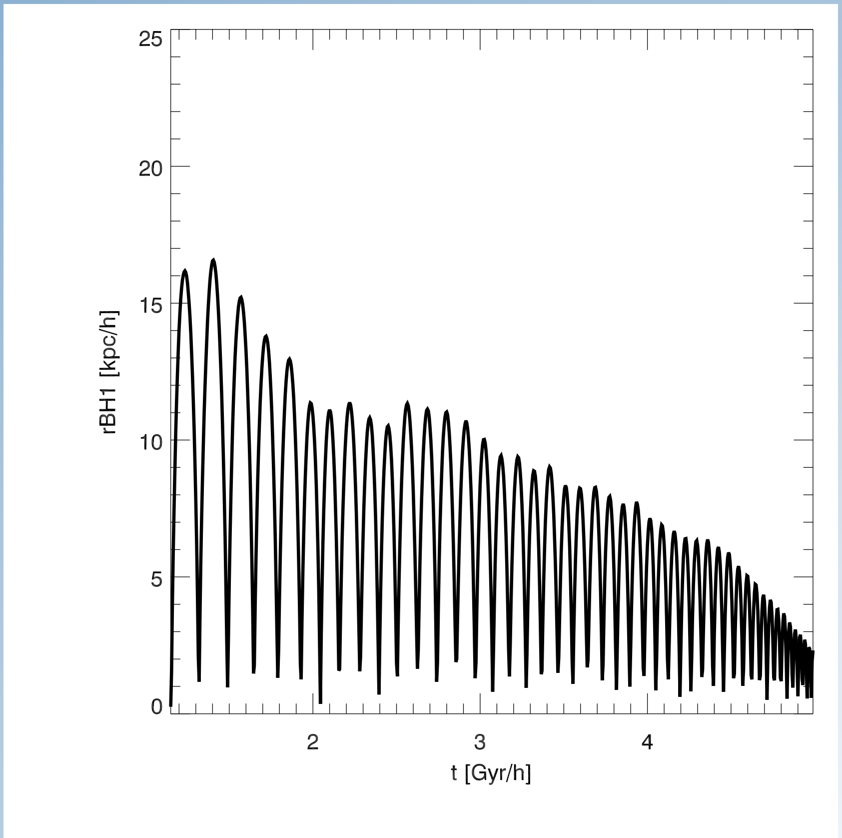
- Major merger of two disk galaxies simulated with GADGET (SPH / N-body code)
- Includes models for BH (Bondi) accretion & feedback, and star formation (Springel et al. 2005)
- Also includes accretion drag on the BH $\propto \dot{M}$



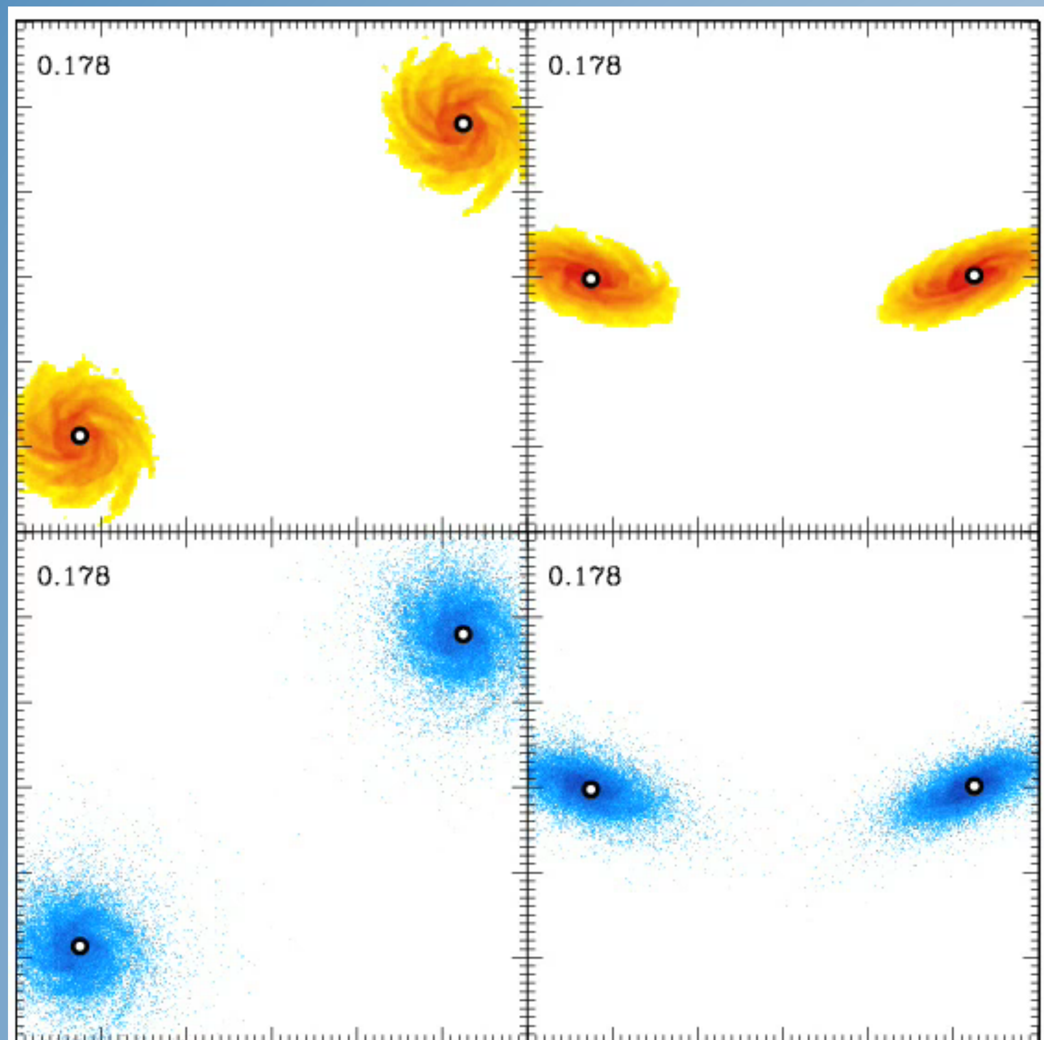
# Galaxy merger simulations with GW recoil

- Recoil kick given to BH at time of BH merger
- Kick velocity calculated relative to *total* $v_{esc}$ (incl. baryons and DM)



# Example of recoiling BH trajectory

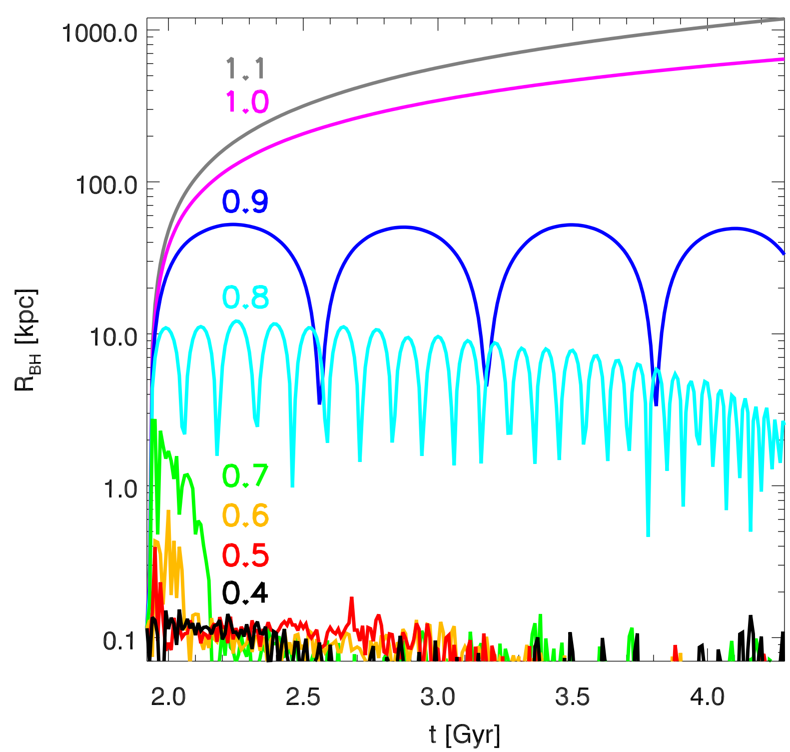
$v_{kick} = 0.9\ v_{esc}$



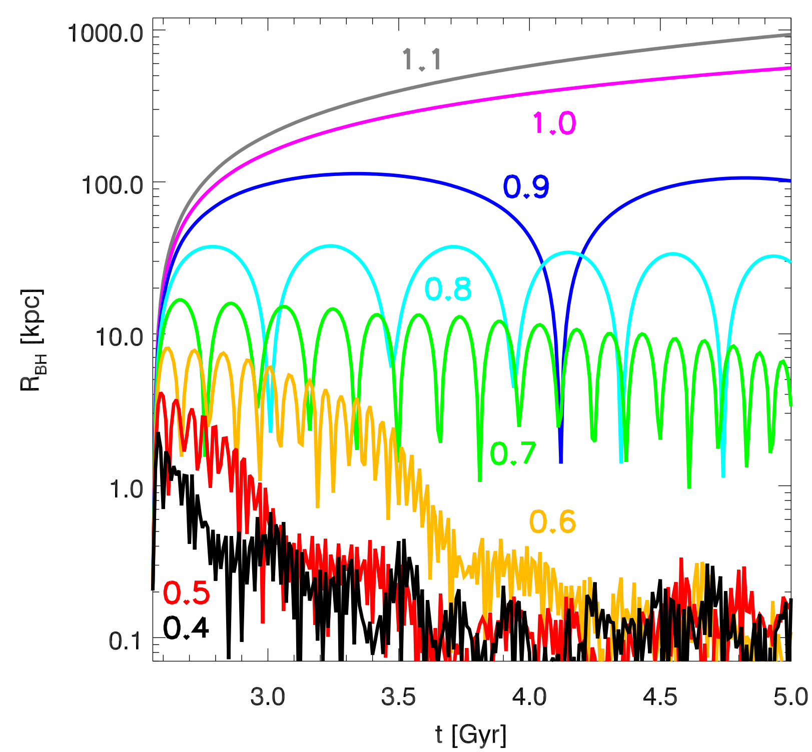
# BH trajectories

## varying $v_{kick}/v_{esc}$

40% initial gas fraction
$v_{esc}(t_{mrg})$ = 950 km/s

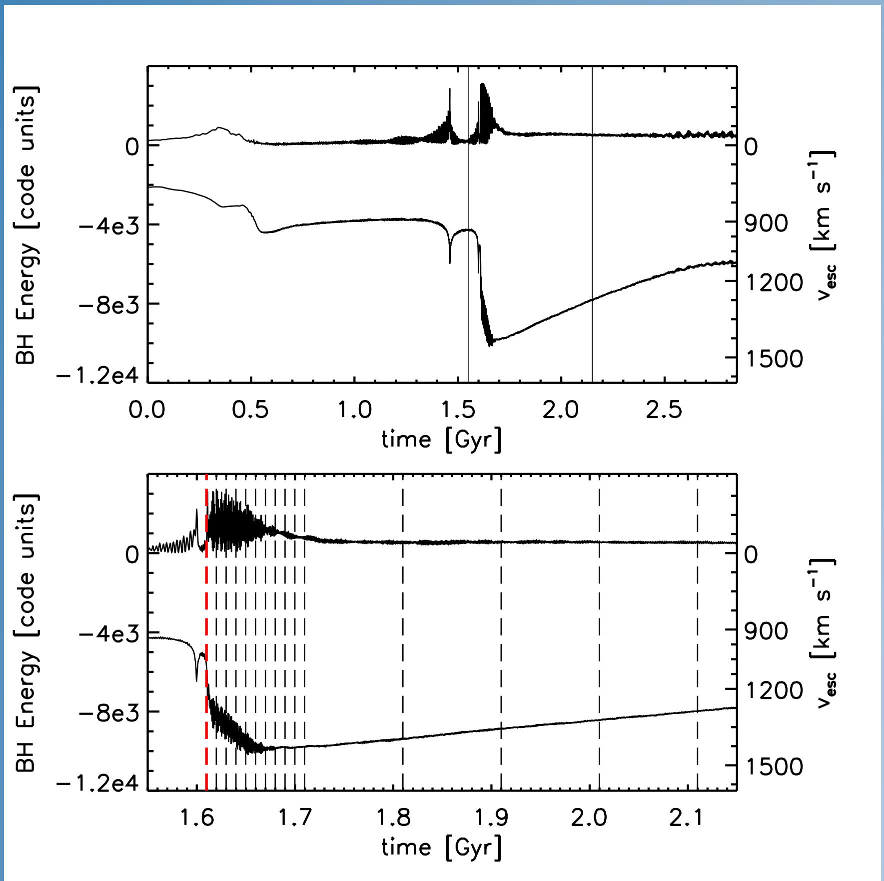



No gas
$v_{esc}(t_{mrg})$ = 700 km/s

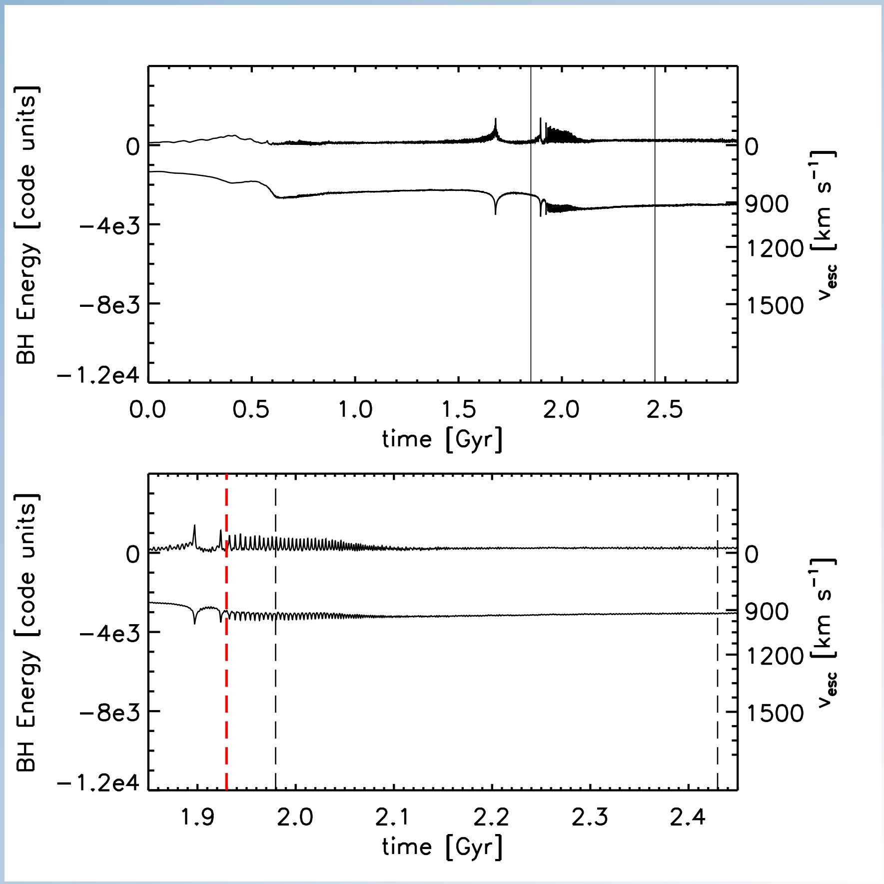


# Evolution of BH escape velocity

Equal mass merger,
40% initial gas fraction



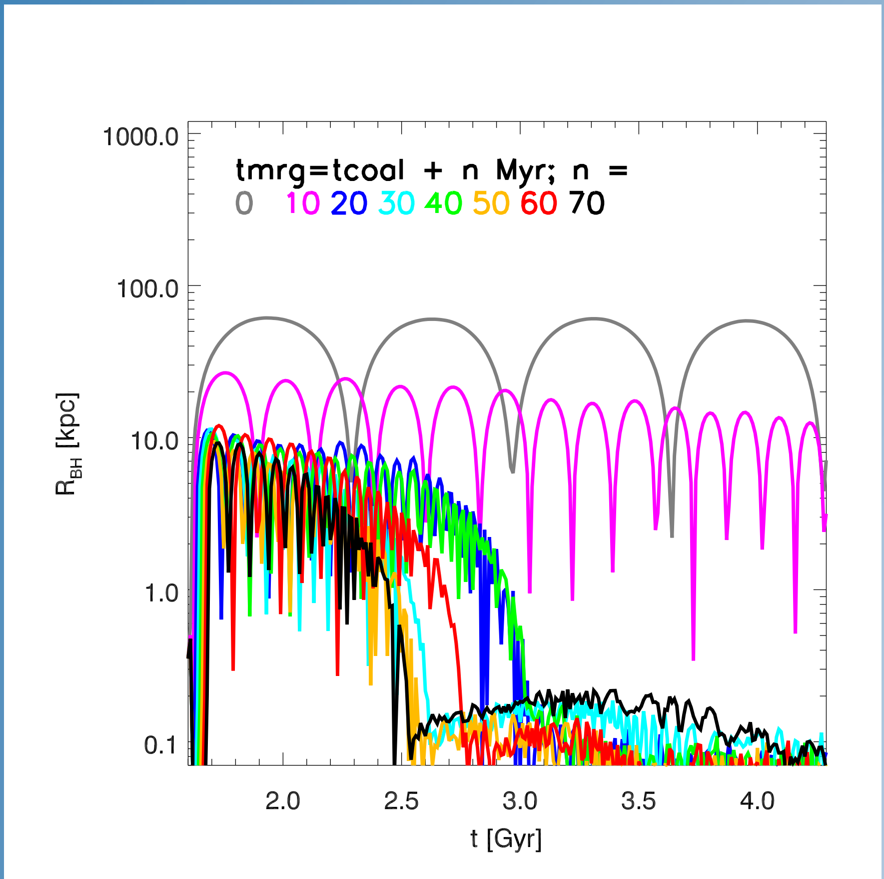

Mass ratio q = 0.5,
40% initial gas fraction

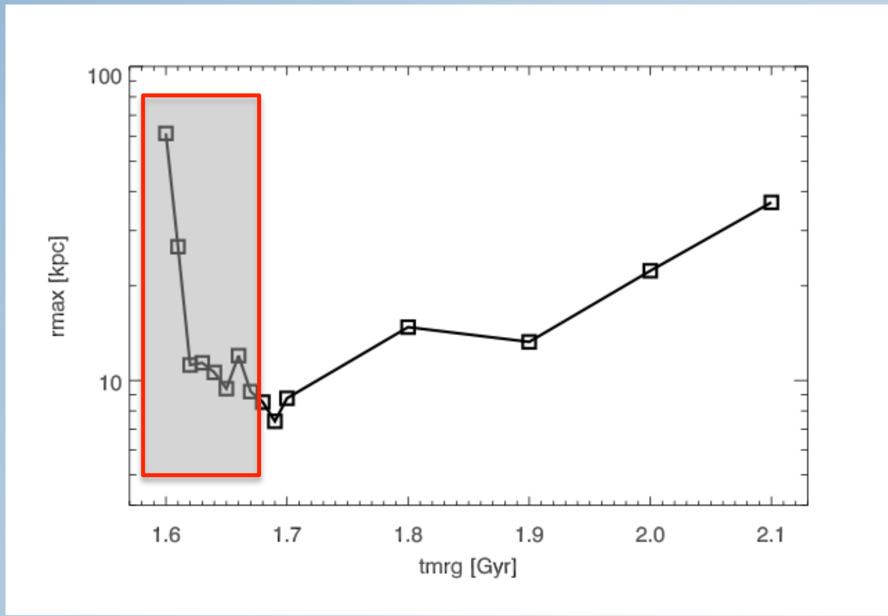


# BH trajectories

delayed merger time

***constant*** $v_{kick}/v_{esc}$ = 0.9



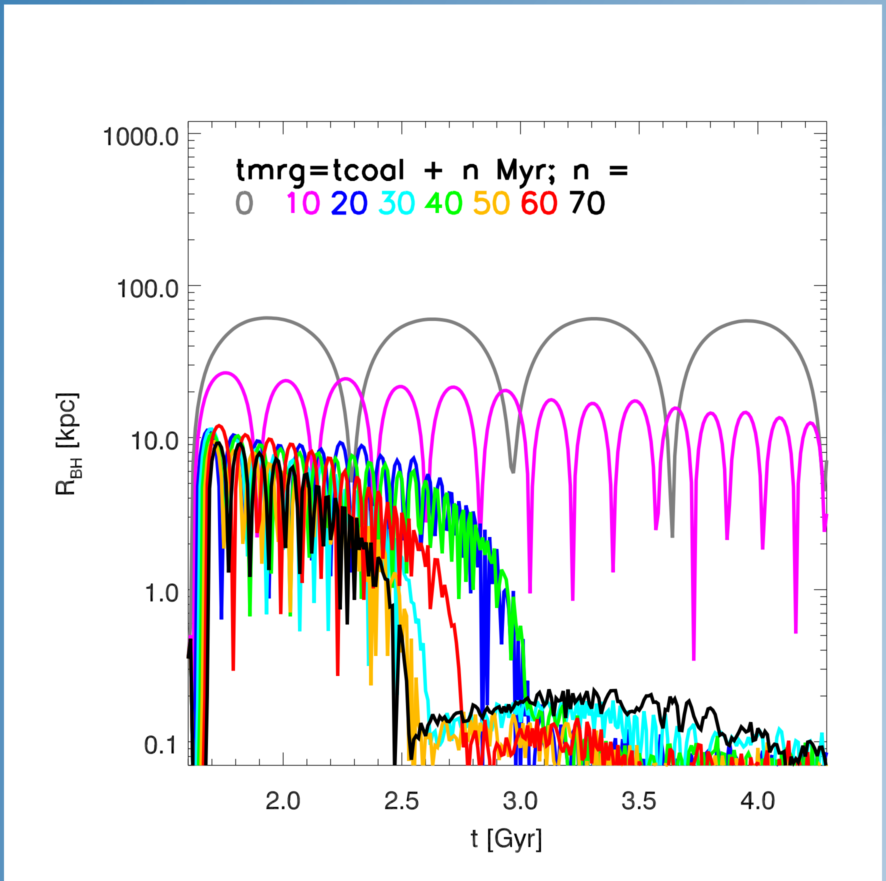



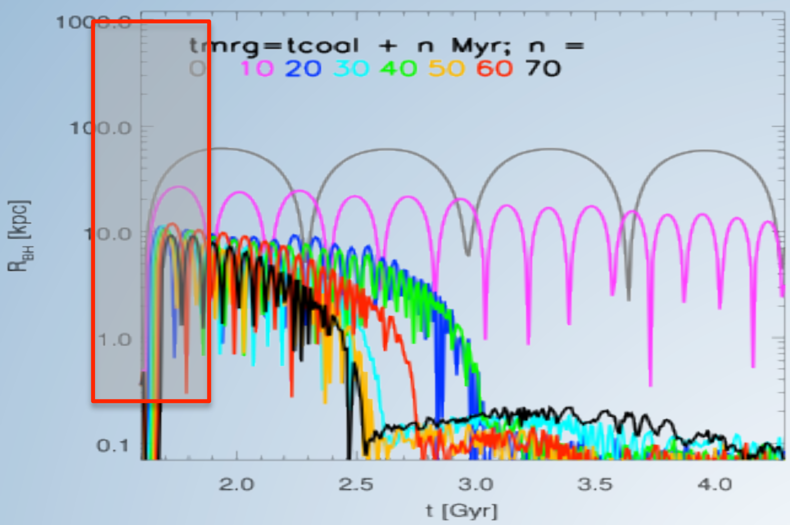
# BH trajectories

delayed merger time

***constant*** $v_{kick}/v_{esc} = 0.9$

***gas drag is important!***



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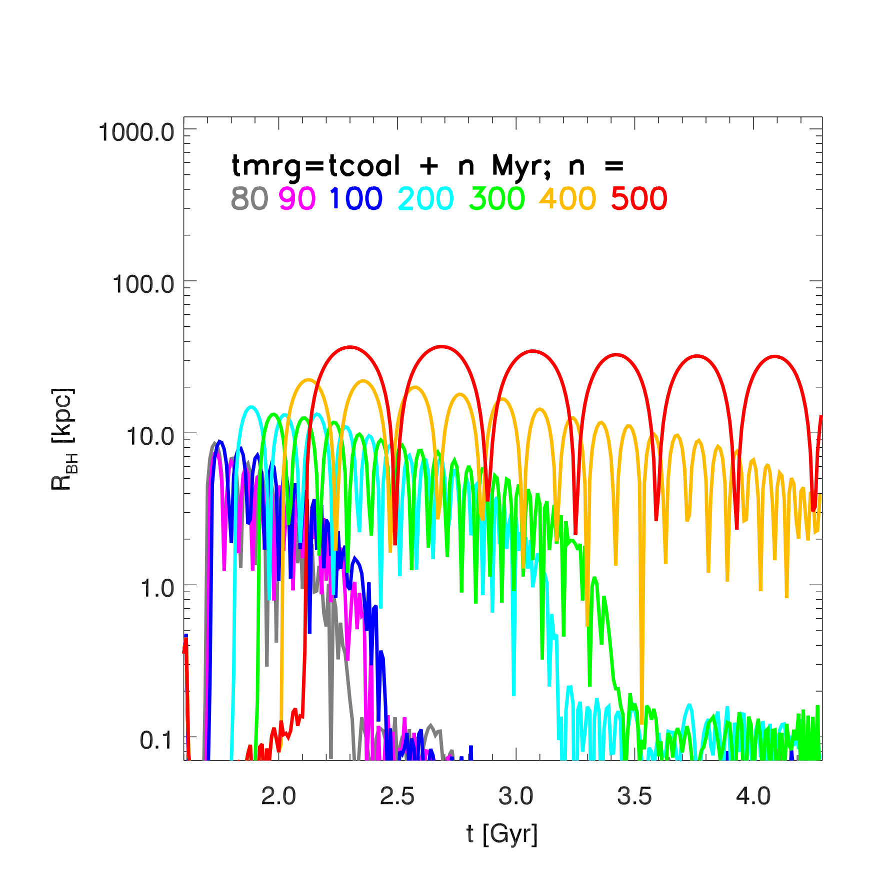
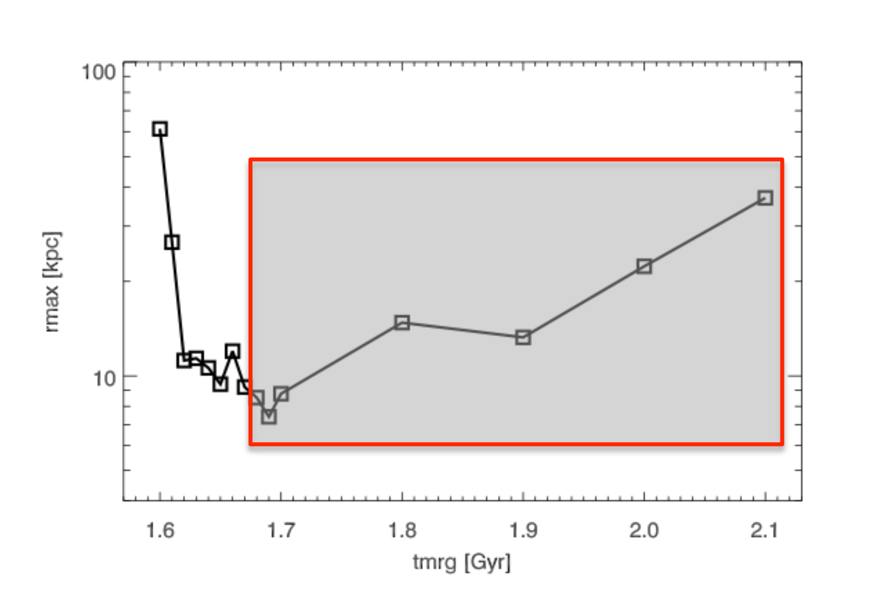
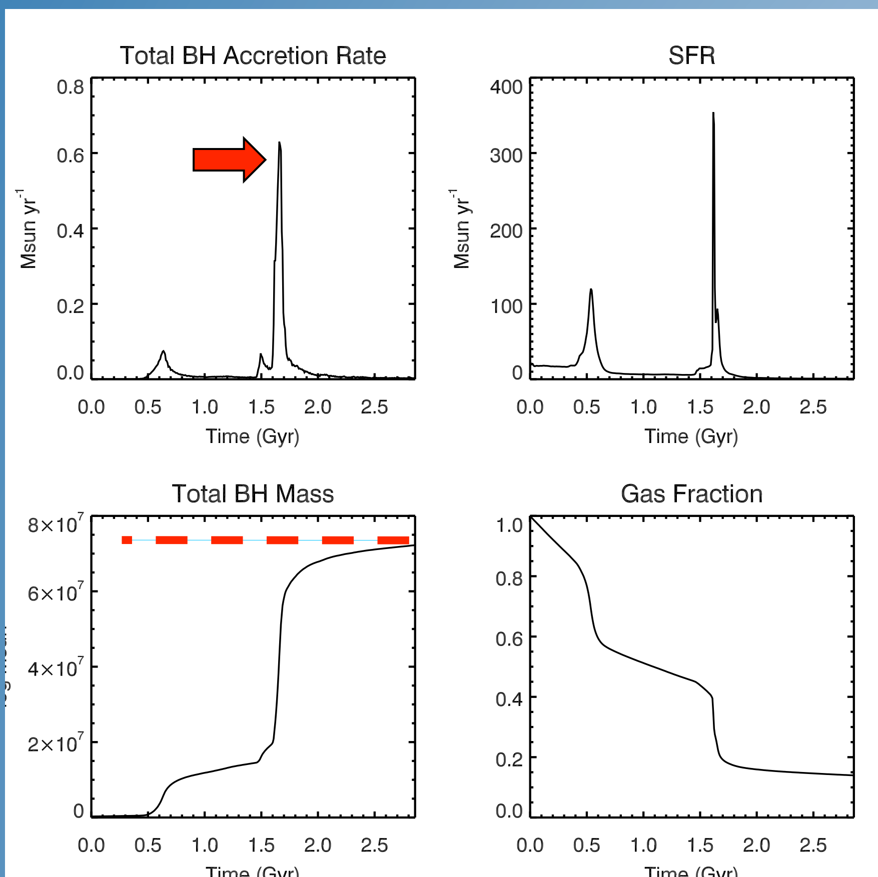


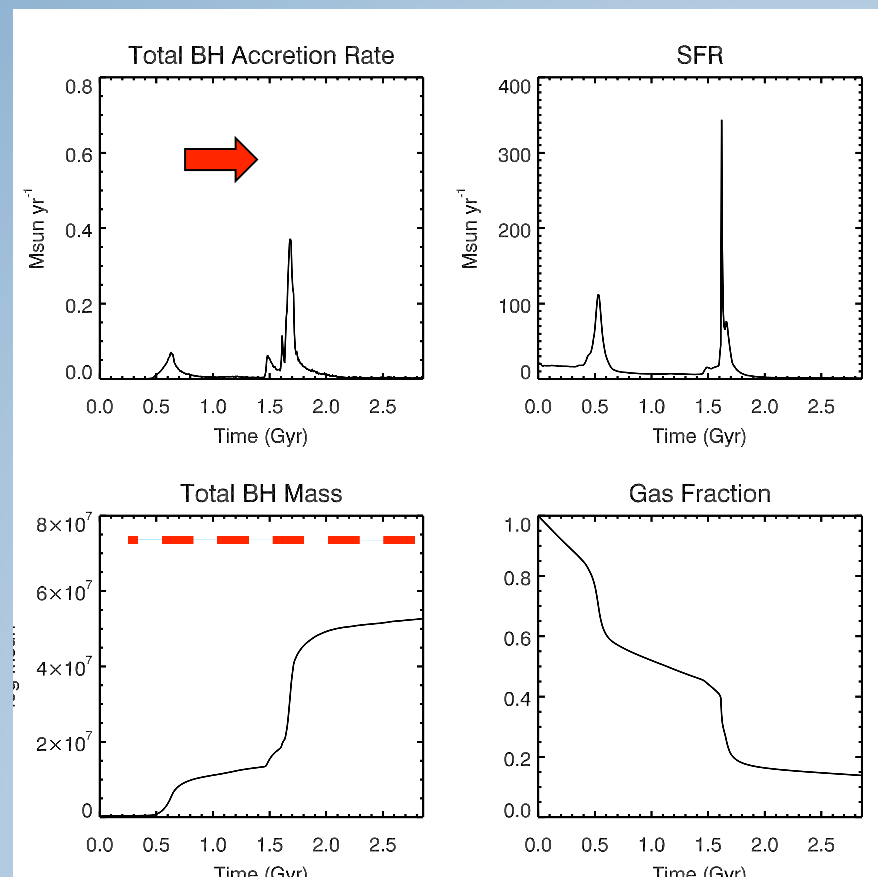



# BH accretion and star formation

## No Kick



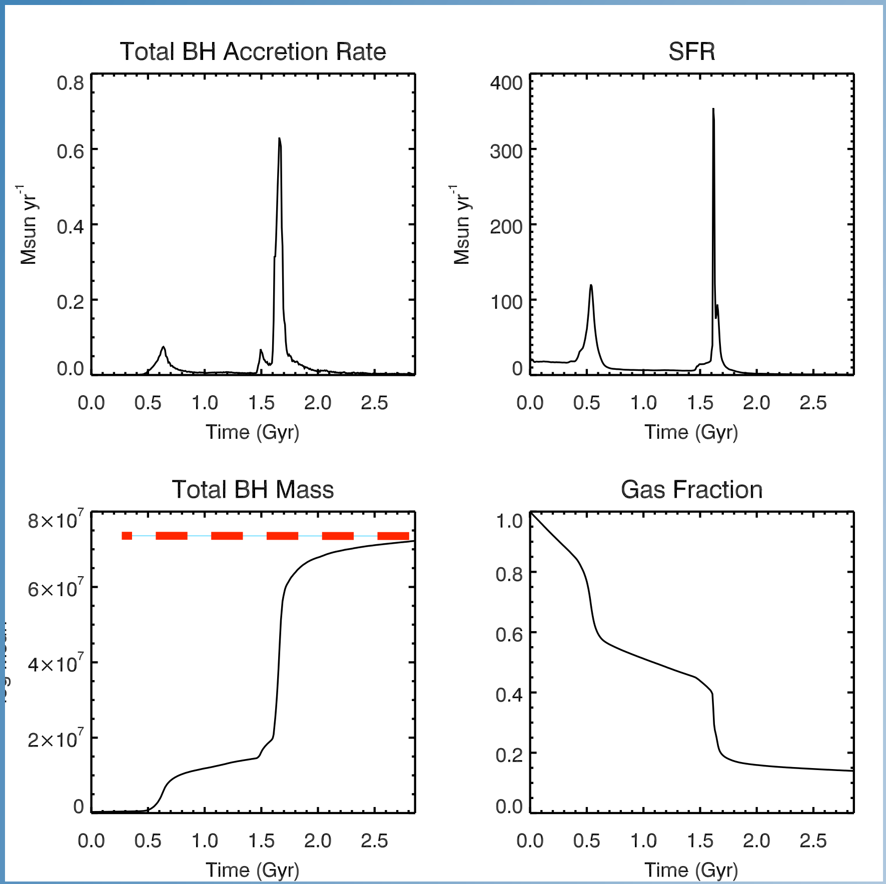

## $v_{kick}/v_{esc} = 0.4$

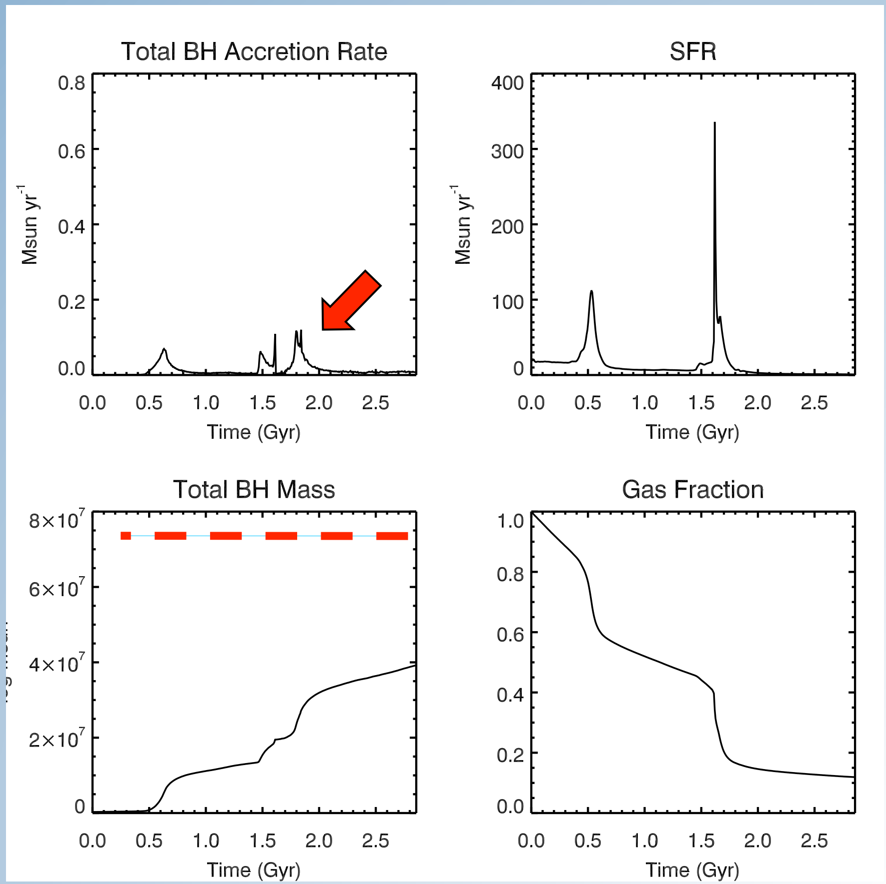


# BH accretion and star formation

No Kick

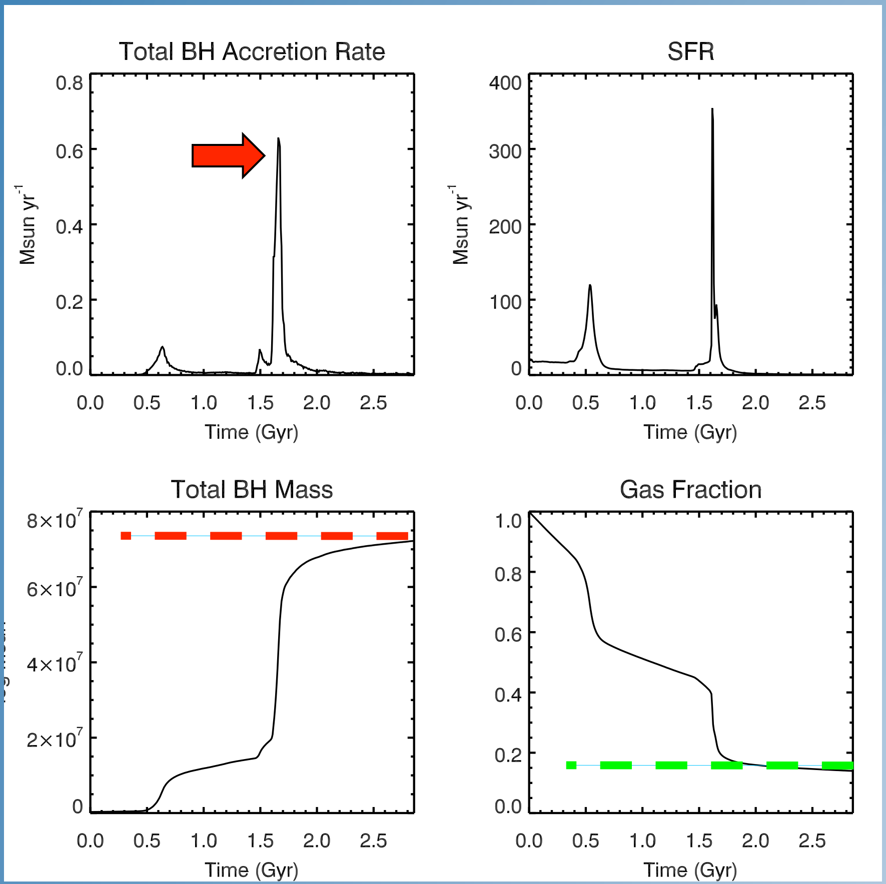
$v_{kick}/v_{esc} = 0.6$



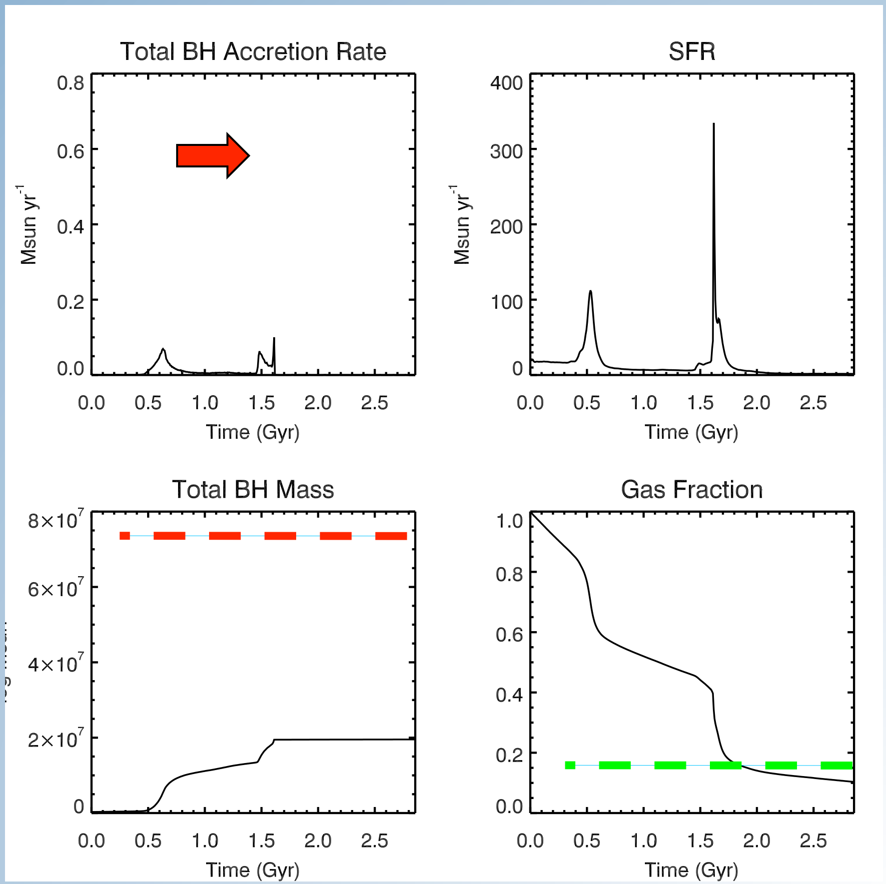



# BH accretion and star formation

No Kick




$v_{kick}/v_{esc} = 0.8$



# BH accretion and star formation

- **$v_{kick}/v_{esc} = 0.4$**
  - Mild suppression of BH accretion
  - slightly smaller final BH
- **$v_{kick}/v_{esc} = 0.6$**
  - Accretion truncated at time of kick
  - Later episode of accretion when BH settles
  - BH undermassive by factor of ~ 2
- **$v_{kick}/v_{esc} \gtrsim 0.8$**
  - Accretion truncated at kick, does not restart
  - Slightly more star formation due to absence of BH feedback
  - BH undermassive by factor of ~ 4

# Summary

- ***BHs kicked with $v \lesssim v_{esc}$ can reach large radii ($R > R_{gal}$) and may wander for up to a few Gyr***

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  - Largest kicks correspond to shortest quasar duty cycles
  - Recoils were likely larger and more frequent at high *z*
  - Recoil motion may be suppressed in nearly-equal-mass, gas-rich mergers (more typical at high *z*)

# Summary

- ***BHs kicked with $v \lesssim v_{esc}$ can reach large radii ($R > R_{gal}$) and may wander for up to a few Gyr***
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  - Recoils were likely larger and more frequent at high *z*
  - Recoil motion may be suppressed in nearly-equal-mass, gas-rich mergers (more typical at high *z*)
- ***Indirect effects of recoil***
  - Undermassive BHs may produce scatter, offset, and/or outliers in $M_{BH}$-$\sigma_*$ relation
  - Amount of star formation in the central cusp may increase when BH (& feedback) are removed from the galactic center