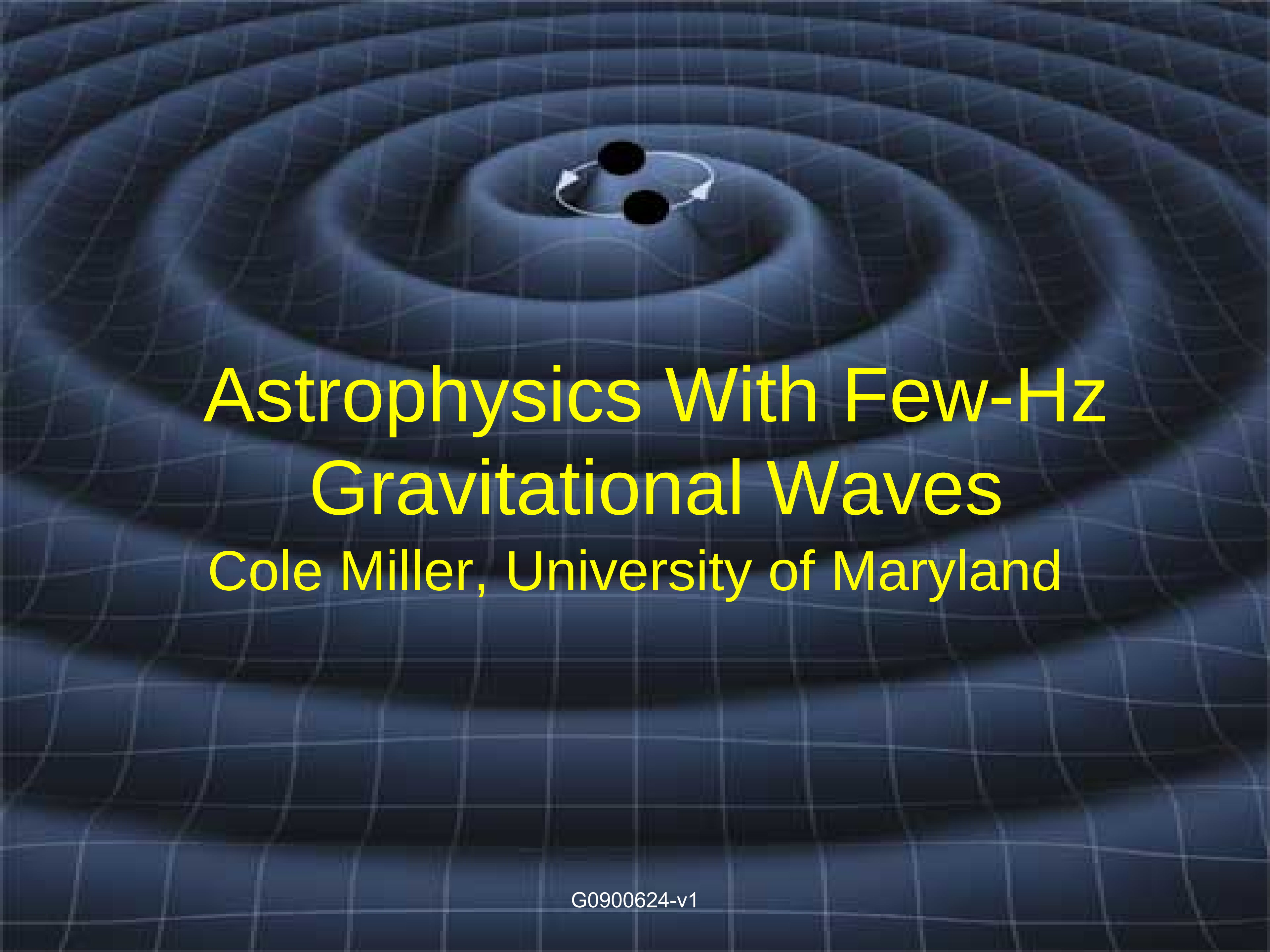

Astrophysics With Few-Hz Gravitational Waves

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G0900624-v1

Outline

- The most massive white dwarfs
- Long lead times for telescopes
- Nonzero eccentricities?
- Intermediate-mass black holes

Will focus on binaries; continuous-wave and burst amplitudes are too low.
Will have theorist's optimism and assume lower limit of 1 Hz.

Amplitude of Gravitational Waves

Binary of reduced mass μ, total mass M.
At luminosity distance d, frequency f_{GW},
dimensionless strain amplitude is

$$h=3\times10^{-23}\,(f_{GW}/1\text{Hz})^{2/3}(M_{ch}/10\ M_{sun})^{5/3}(100\text{Mpc}/d)$$

where $M_{ch}^{5/3}=\mu M^{2/3}$ defines the “chirp mass”.

Frequency of Waves

The frequency at the innermost stable circular orbit (ISCO) for a nonrotating hole is

$f_{GW}(ISCO)=4.4x10^3$ Hz (M_{sun}/M)

For rotating, up to

$f_{GW}(ISCO)\sim 2x10^4$ Hz (M_{sun}/M)

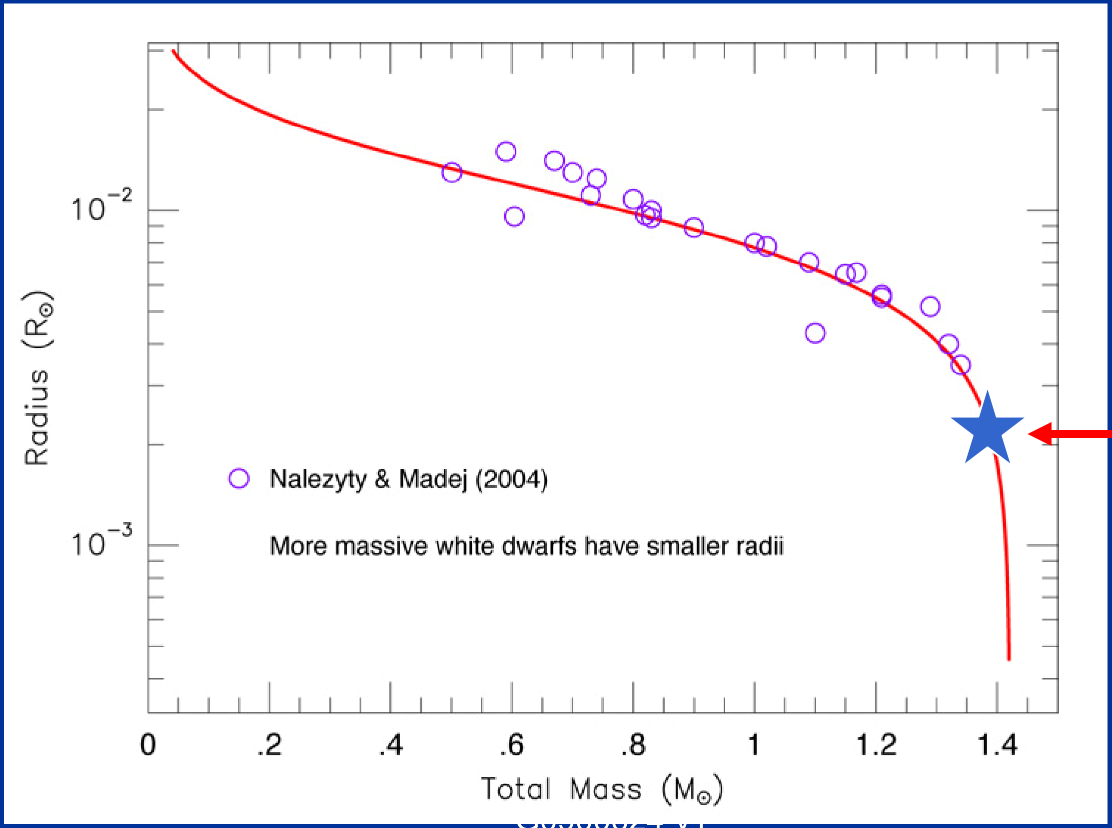
More generally, object of average density ρ has maximum frequency $\sim(G\rho)^{1/2}$

Neutron star: ~2000 Hz

White dwarf: up to ~1 Hz

The Most Massive WD

- ~$10^{8\text{-}9}$ WD binaries in Milky Way
- Even small fraction with M~1.4 M_{sun} gives large number; new category of sources



f_{GW}=1 Hz

http://cococubed.asu.edu/images/coldwd/mass_radius_web.jpg

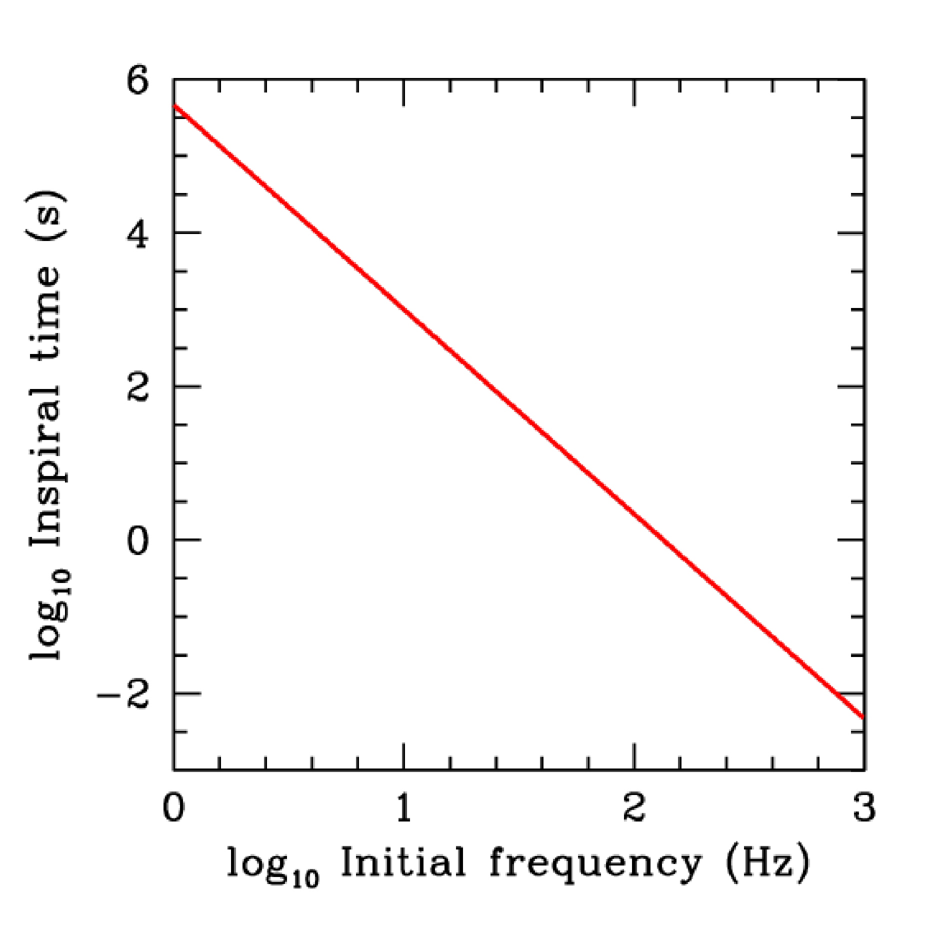
What Can Massive WD Do For You?

- Precise maximum mass depends on composition, other properties
- Massive WD (in binaries with normal stars) thought to be Type Ia SNe progen.
- Mergers would be spectacular but short-lived EM events

  How much lead time do we have?

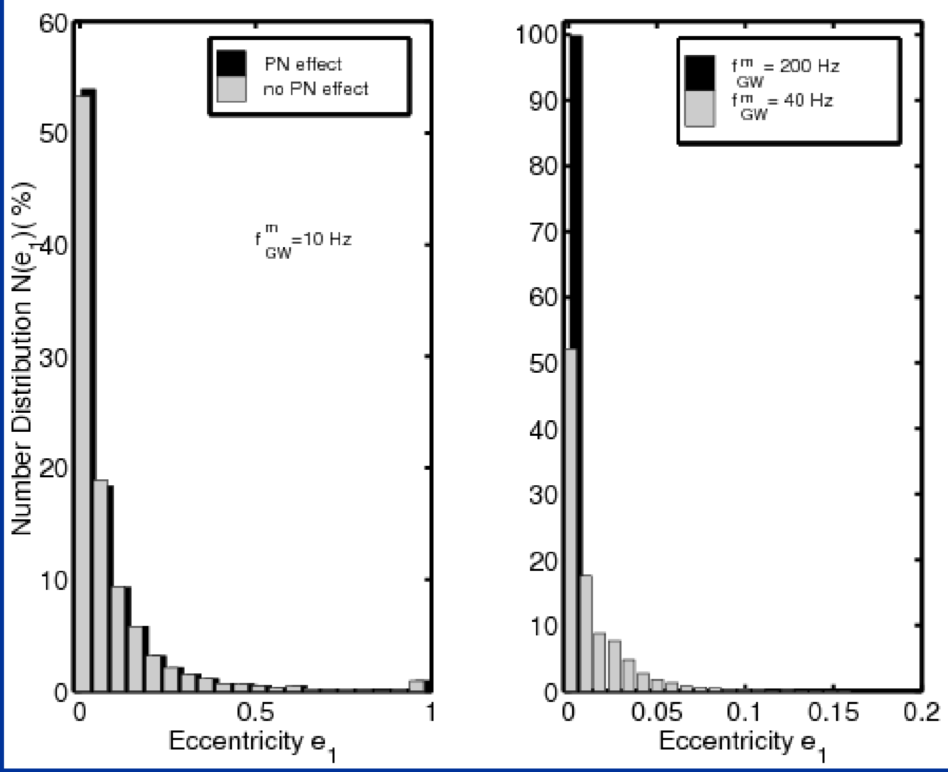
Advance Warning of Merger

- EM counterparts to mergers: lots of info!
  Precise localization
  Nature of transients
- Time to merger scales as $f_{init}^{-8/3}$
- At 1 Hz, could be identified days in advance
- Key: how soon could GW be localized?
  Rotation of Earth?



Nonzero Eccentricities?

- Usually, think of binary GW as circular ~true for >10 Hz or field binaries
- Dynamical interactions can change, e.g., Kozai in dense systems
- e~1/f for e<<1
- Low freq important for inferring dynamic origin



L. Wen 2002

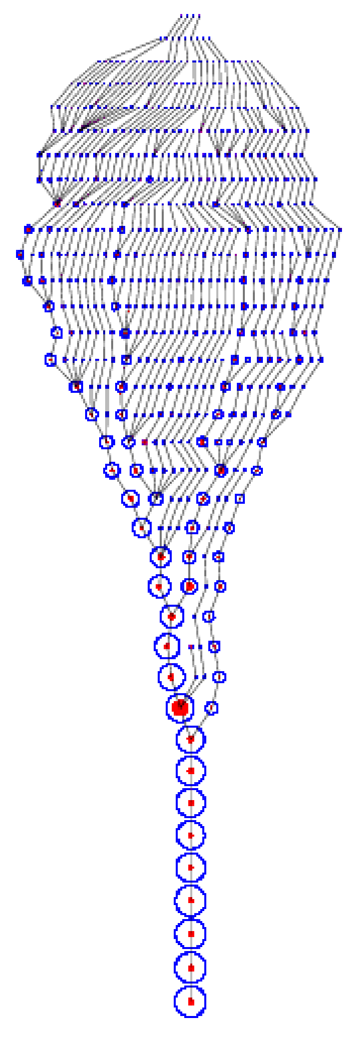
Intermediate-Mass Black Holes

Mass between 10^2 and 10^4 M_{sun}

Too massive to have formed from solitary star in current universe, but smaller than standard supermassive black holes.

Context and Connections

- In z~5-30 universe, seeds for SMBH
- In local universe, probes of star cluster dynamics
- Potentially unique sources of gravitational waves (ground and space)

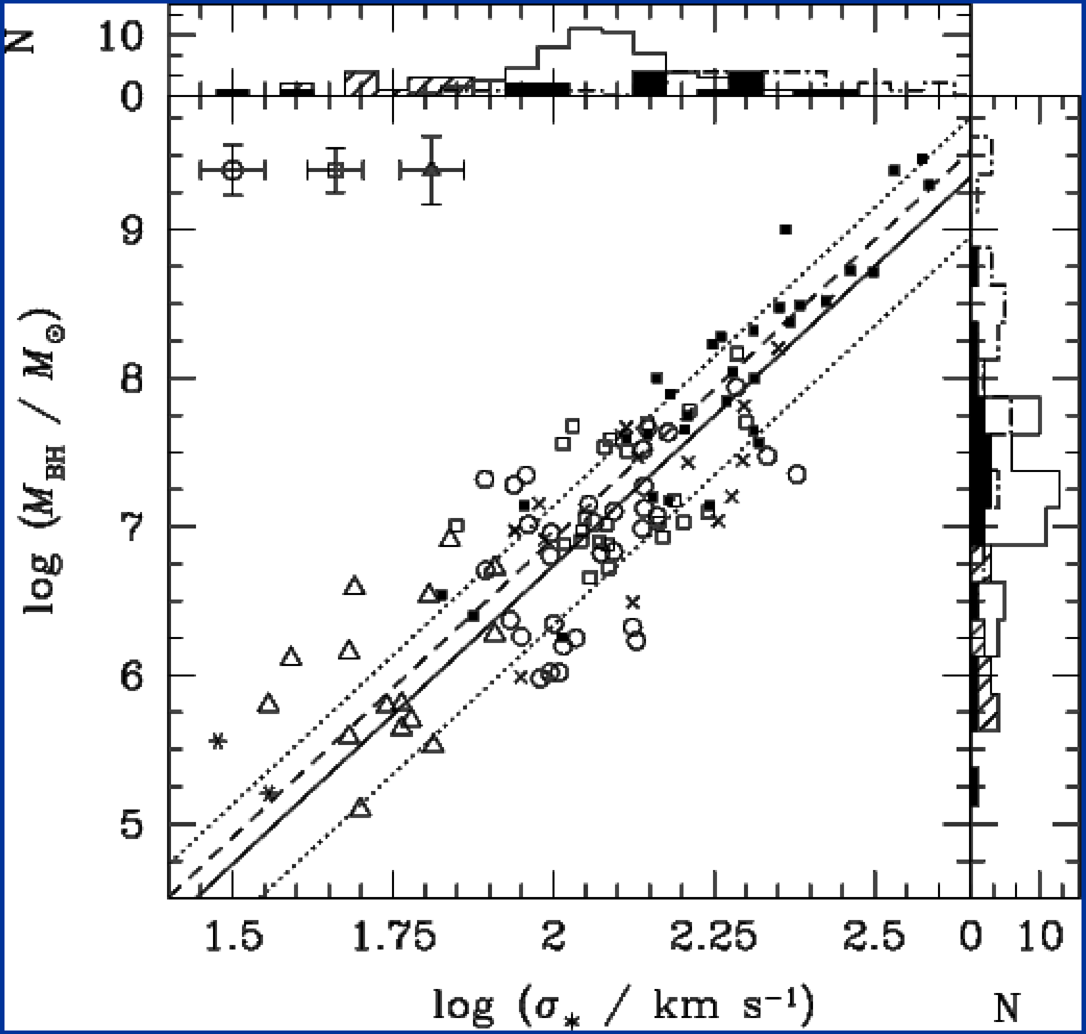


Wechsler et al. 2002

Why Are We Not Sure?

- Stellar-mass (5-20 M_{sun}) and supermassive (10^6-10^{10} M_{sun}) BH are established with certainty
- Why not IMBH (10^2-10^4 M_{sun})?
- Lack of dynamical evidence
  Too rare for easy binary observations
  Too light for easy radius of influence obs
- Attempts being made, but settle for indirect observations in the meantime

Low-Mass SMBH?



Central massive black holes

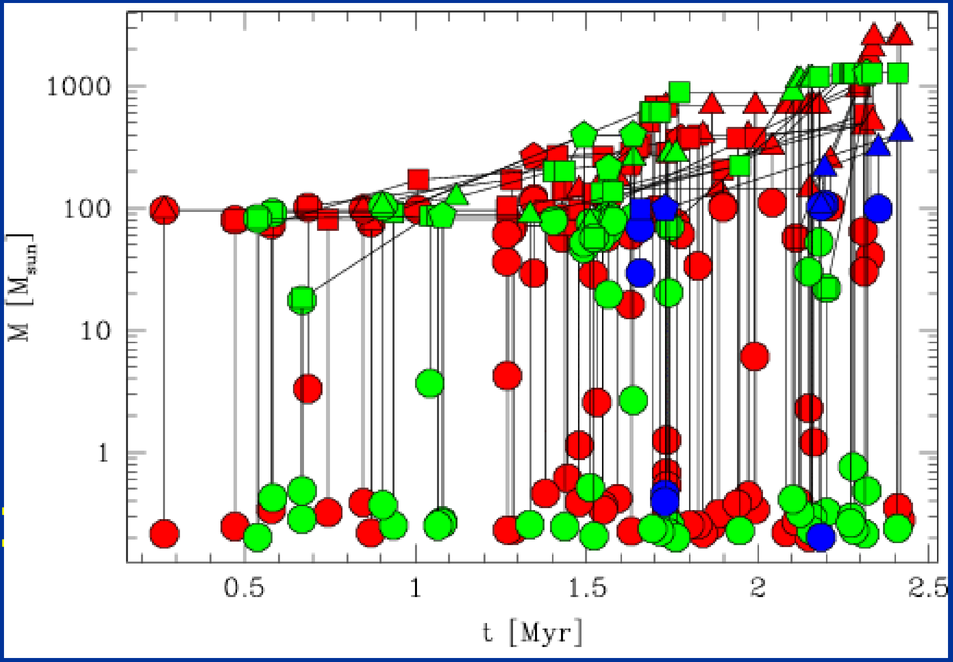
Masses below ~10^6 M_{sun} are inferred indirectly, but extrapolation suggests M~10^4 M_{sun} for numerous small galaxies

Greene and Ho 2006

Formation of IMBHs

- Problem: ~10^3 M_{sun} too much for normal star!
- Population III stars
  Low Z; weak winds
- **Collisions or mergers**
  Needs dense clusters
  Young: collisions Old: three-body

>1 IMBH in single cluster?



Gurkan et al. 2006

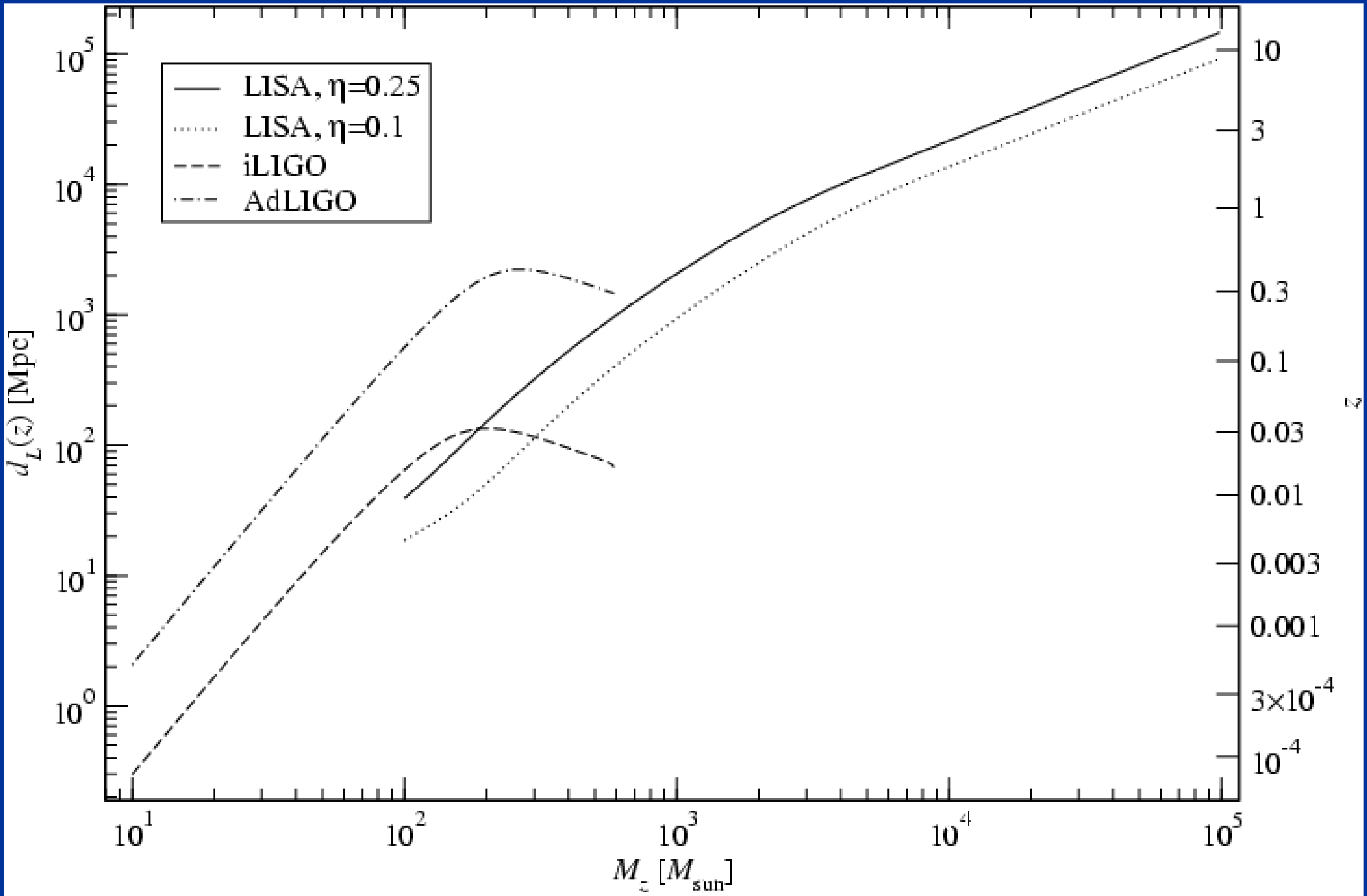
Portegies Zwart & McMillan

Observing GW from IMBH

- Stellar-mass BH with IMBH?
  Promising at >1 Hz (Mandel et al. 2008)
- IMBH with IMBH
  Plausible with low freq; occur if binary fraction >10% (Fregeau et al. 2006)

IMBH-IMBH Visibility

- ~1000 M_{sun} binary visible to z~1.
- Reasonable rates: few tens per year at >1 Hz
- Unique probe of dense cluster star formation



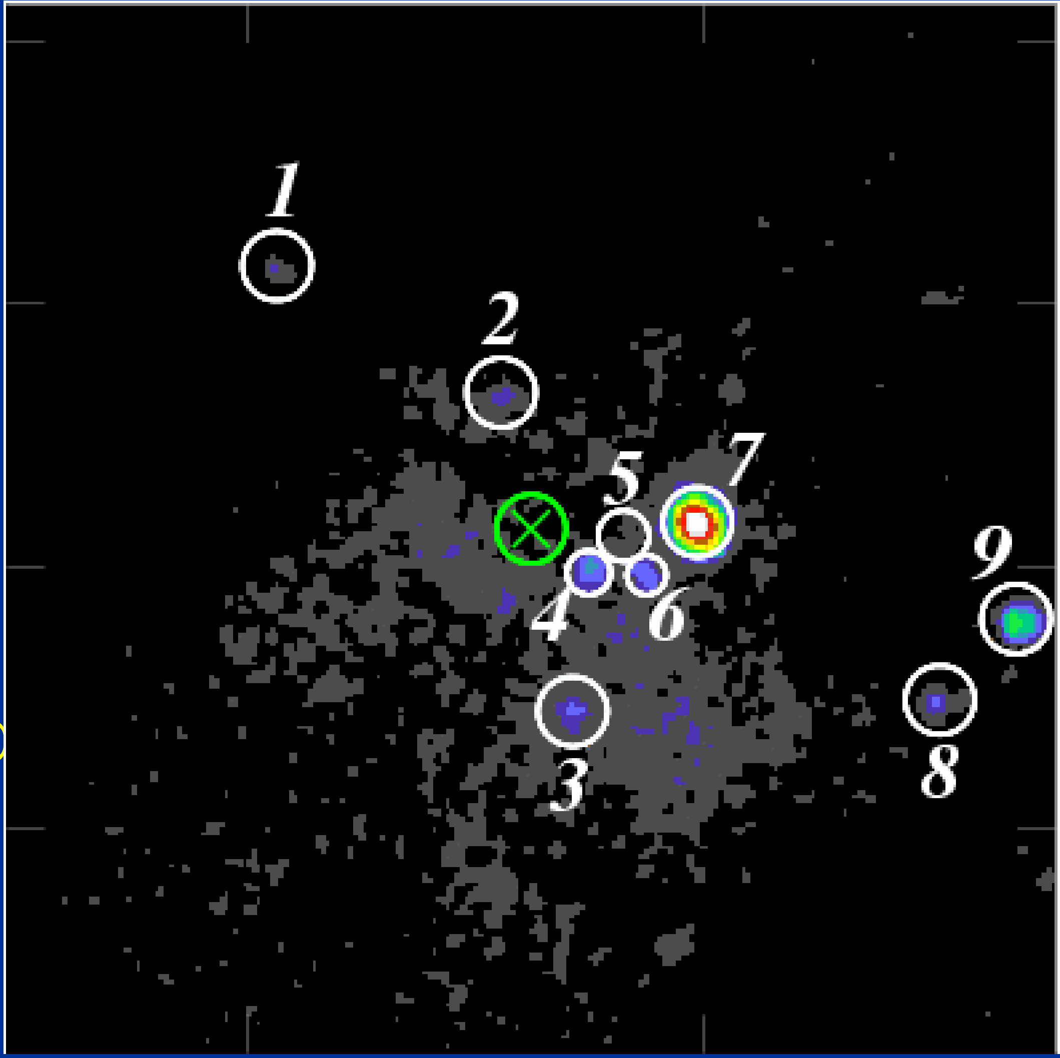
Fregeau et al. 2006

Conclusions

- The ~few Hz range contains qualitatively new sources: heavy WD and IMBH
- Long lead time will allow pointing of large telescopes if the direction can be established to within a few degrees
- Very worth pursuing!

Ultraluminous X-ray Sources

- Ultraluminous X-rays: Variable L_{iso}>10^{39-40} erg/s Some near dense clusters
- Not in galactic centers Thus, not SMBH; would sink to center
- No dynamical mass measurements yet

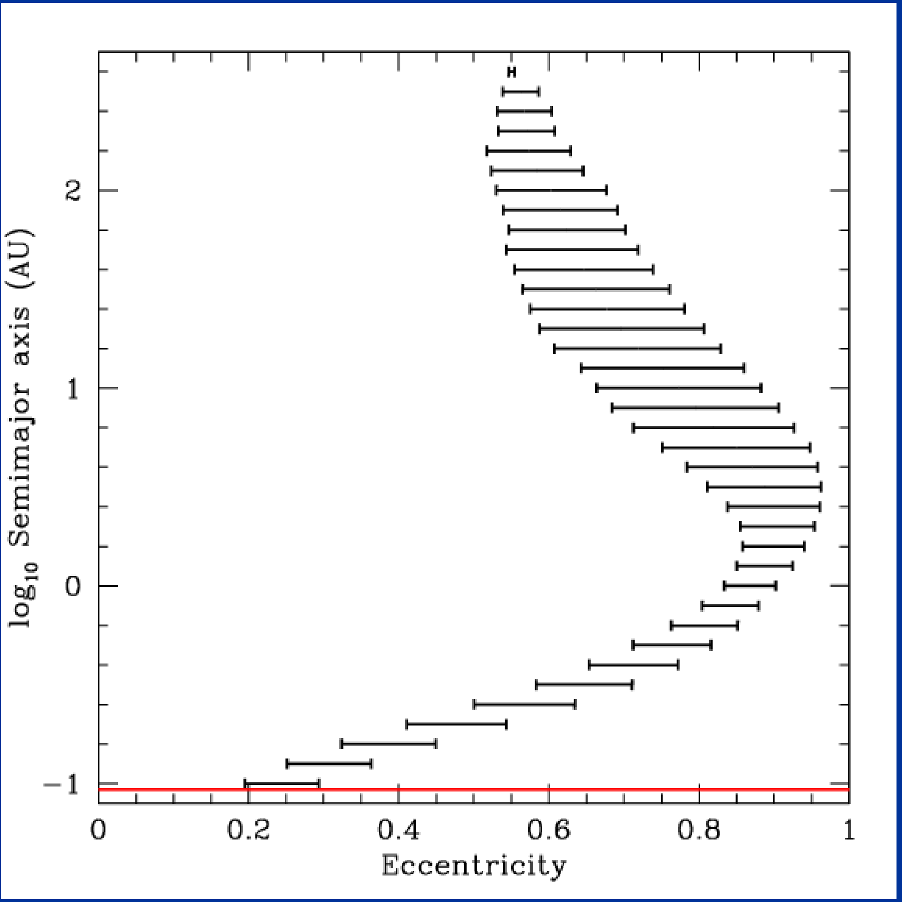


Matsumoto et al. 2000

Properties of Bin IMBH Mergers

- Amaro-Seoane, Miller, and Freitag 2009
- Major results:
  Cluster stays intact
  <10^8 yr merger
  Circular at 1 Hz
- Good probes of clustered star formation

10^3 M_{sun} - 10^3 M_{sun} coalescence



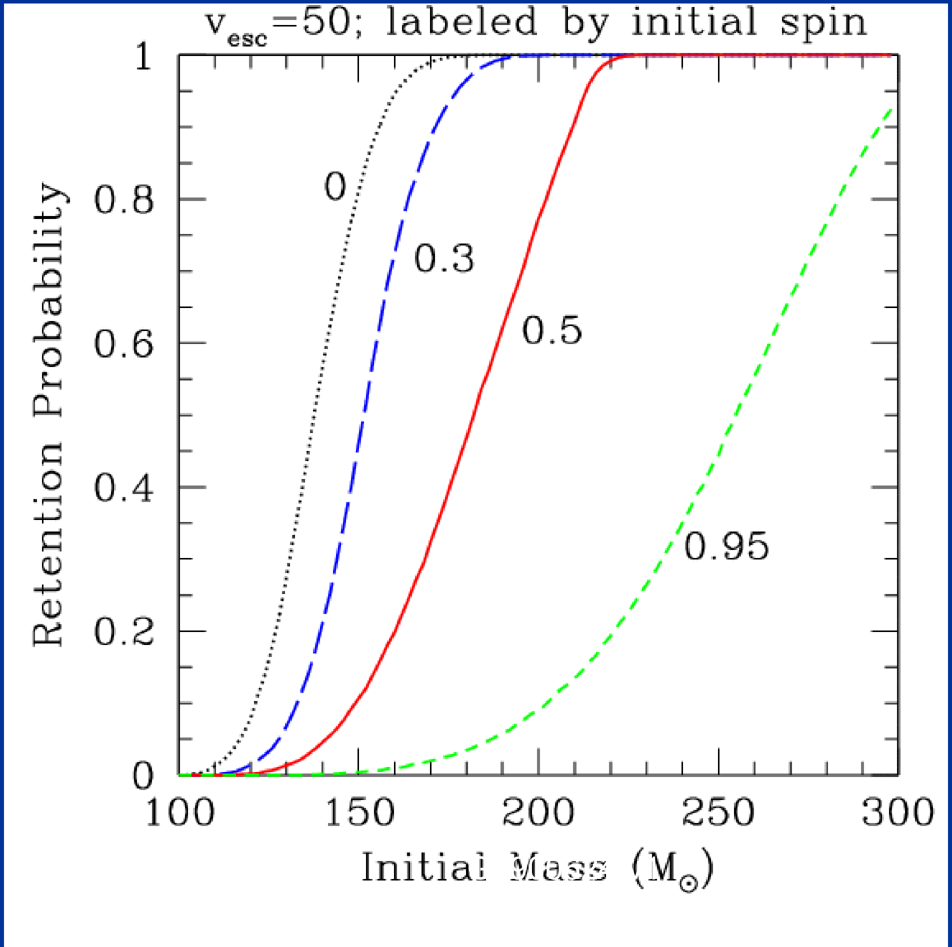
Amaro-Seoane et al. 2009

Competing Ideas

- Beaming (geometrical or relativistic)
  King et al.; are spectra, variability okay?
- True super-Eddington accretion
  Begelman; interesting idea with many consequences to be worked out.
  But no direct evidence that this happens
- All ideas face challenges to explain this unique class of accreting black holes!

Retaining IMBH in Globulars

- Escape speed only ~50 km/s or less
- >300 M_{sun} retained, but IMBH spin crucial

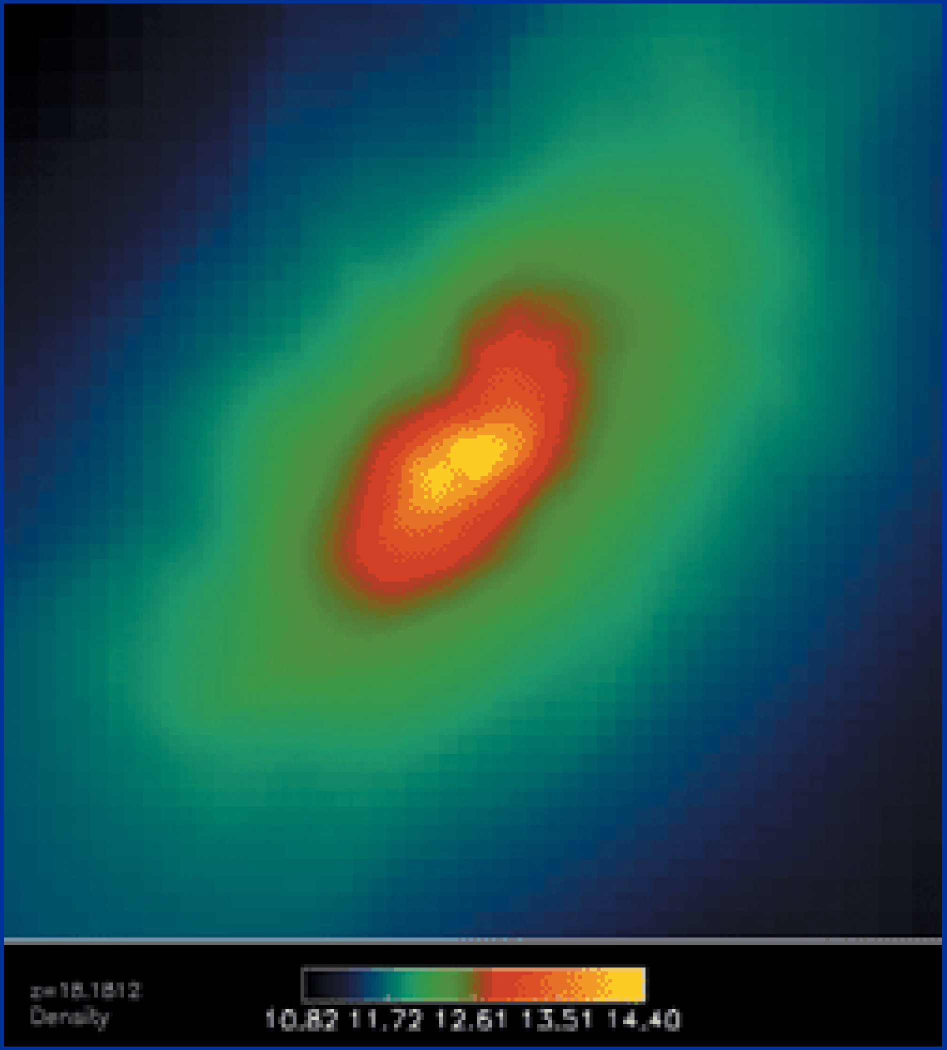


Open Question: IMBH Spin

- Important for dynamics and gravitational wave detection
- Initial collapse: a/M=0.93 (~MHD limit, e.g., Gammie)?
- Random mergers with giants, MS stars? Would decrease spins
- Need coupled stellar evolution, bin/single cluster dynamical evolution

Formation of IMBHs

- Problem: ~10^3 M_{sun} too much from normal star!
- **Population III stars**
  Low Z; weak winds
- Collisions or mergers
  Needs dense clusters
  Young: collisions   Old: three-body



http://www.npaci.edu/enVision/v17.4/images/star2.gif

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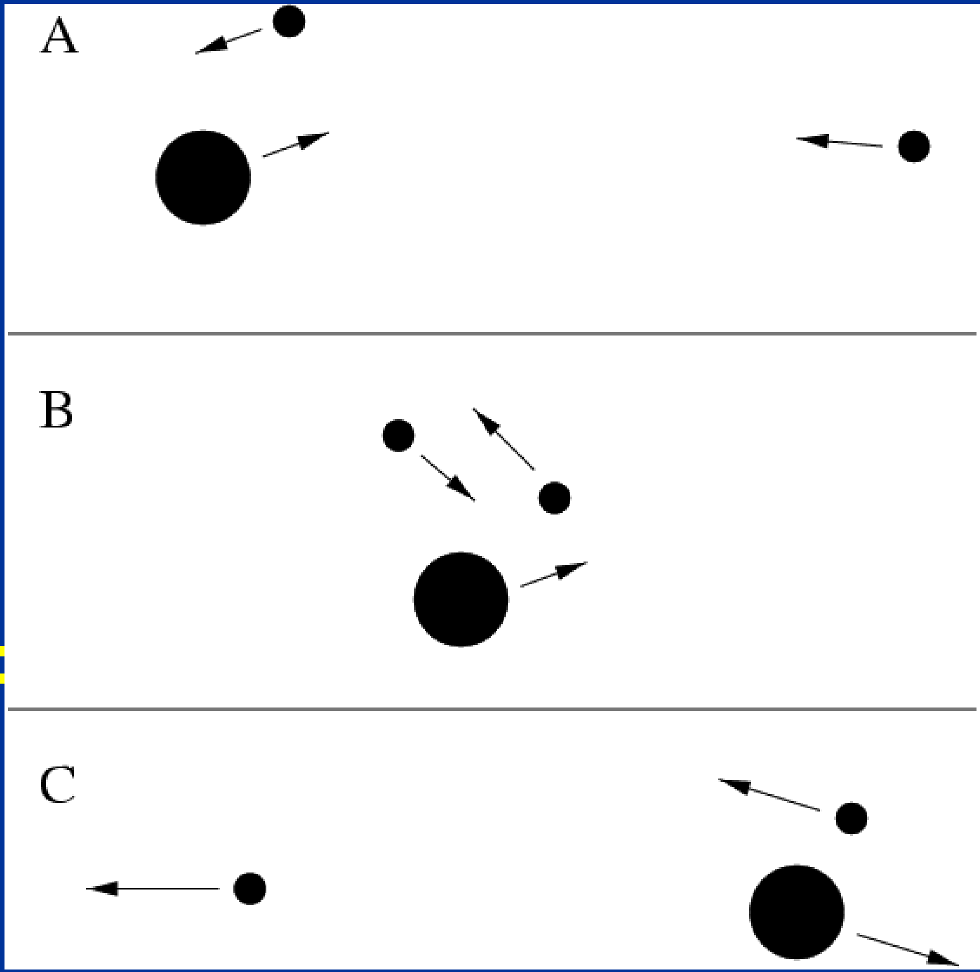


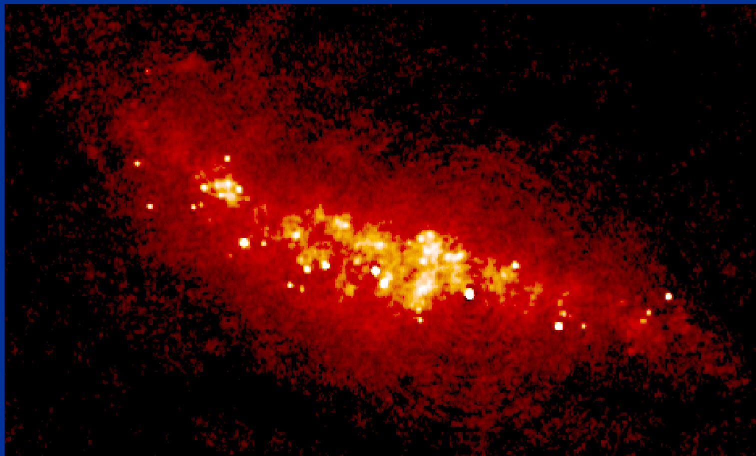
Open Question: Collision Product

- Runaway collisions are promising
- But, how does collision product evolve?
  Not a star!
  Collisions faster than cooling time
  Lumpy; N-body core dynamics?
- When some core collapses, is there a direct collapse or a supernova?
- What is the spin parameter of the IMBH?

Open Question: Super Star Cluster Numbers

- For runaway, need $>10^5$ M_{sun}, short relaxation time
  How much star formation is in this mode?
  Does it depend on total SFR?
  Does it depend on metallicity?
- Could imagine being more important at z~1, or z~20, than now.

M82

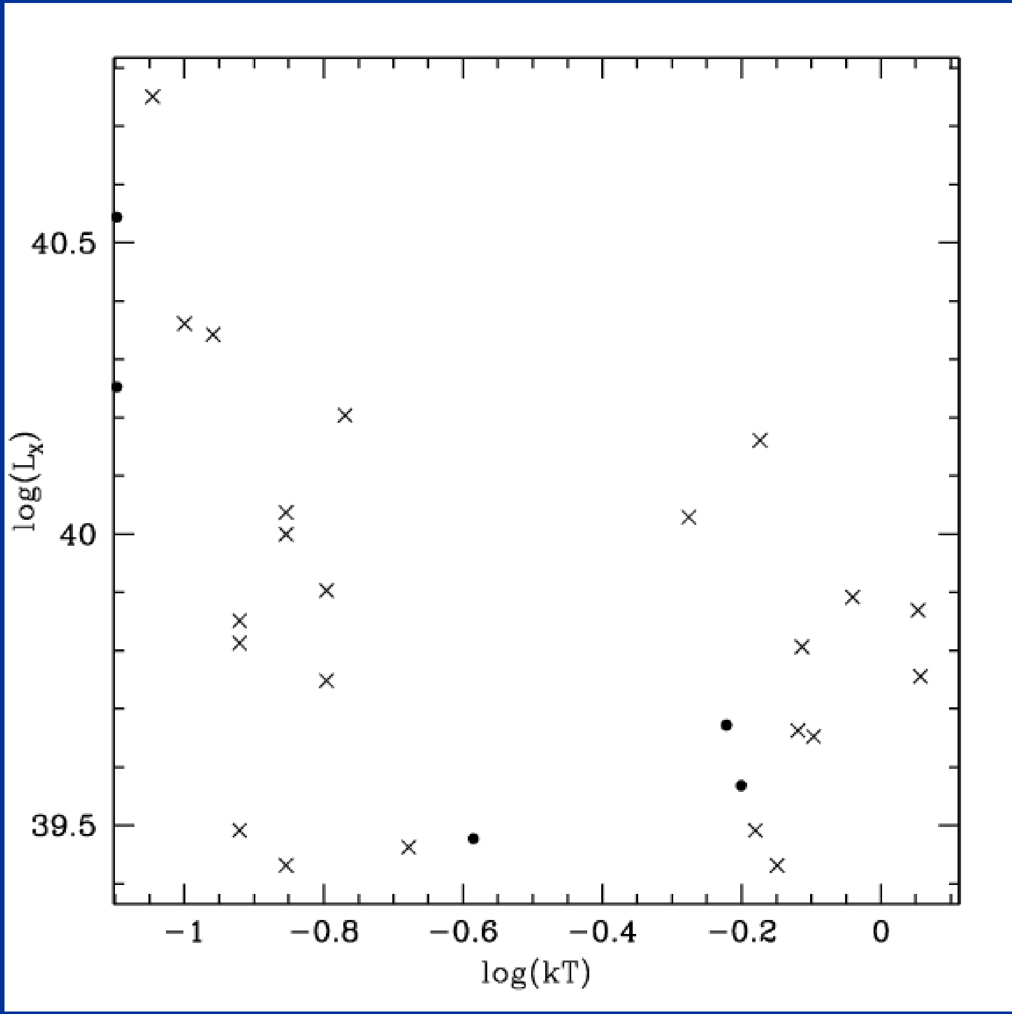


Summary of Formation

- Modulo open questions, runaway collapse seems reasonable
  Then, can have collisionless growth to ~500 M_{sun} (Gultekin et al. 2006)
- Early universe Pop III might have happened
- Seems difficult to avoid IMBH on way to SMBH in most cases
- But what about observations?

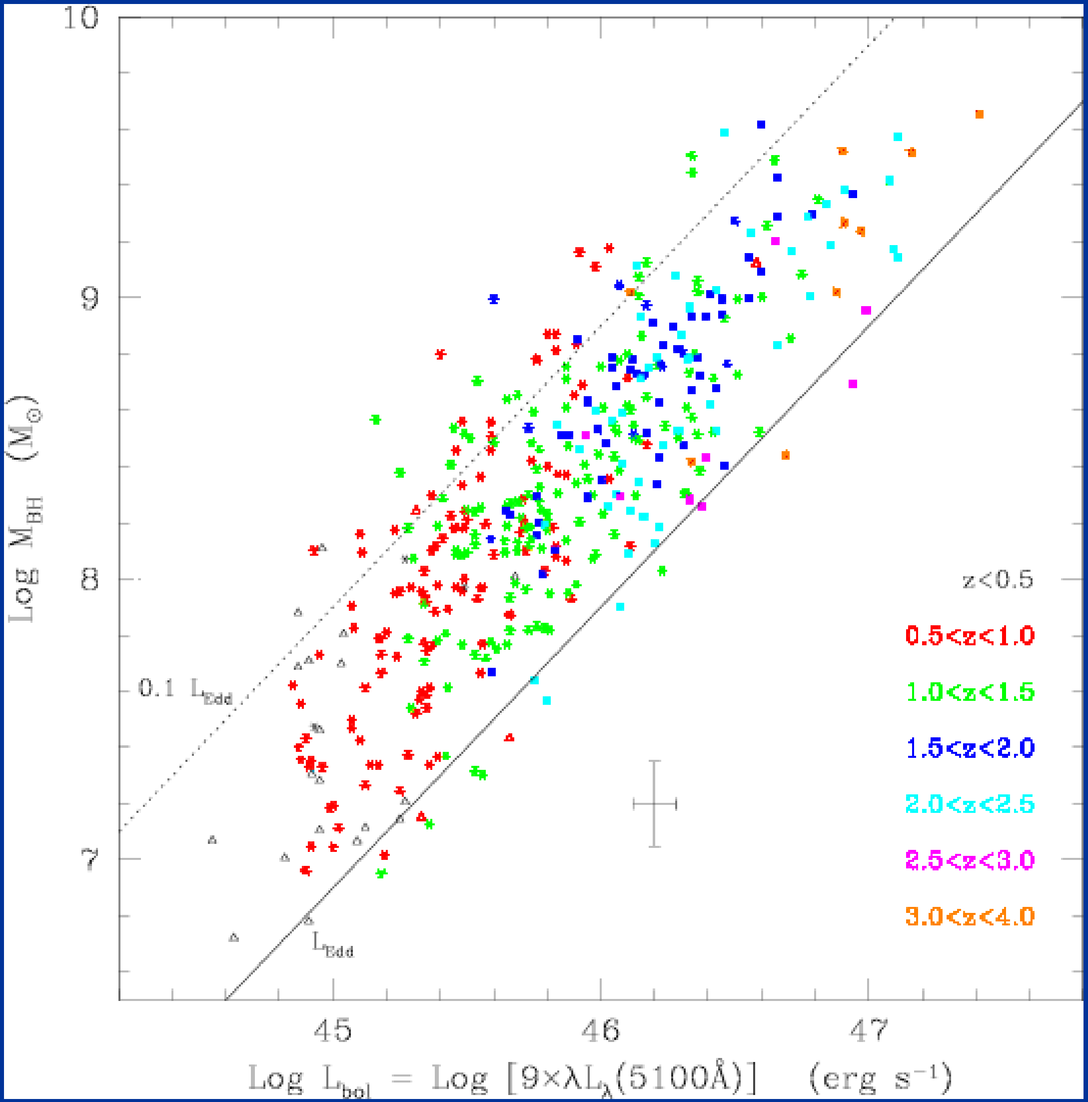
Spectral Properties

- XMM spectra often require two-comp fits
  MCD and power law
- Many need cool disk
  $T \sim M^{-1/4}$; high mass?
  Some don't; two classes?
- Low temp, high L means large emitting area
- Low L_{opt}/L_X
  Not relativistically beamed
- Evidence for new type of object.



Winter et al. 2005

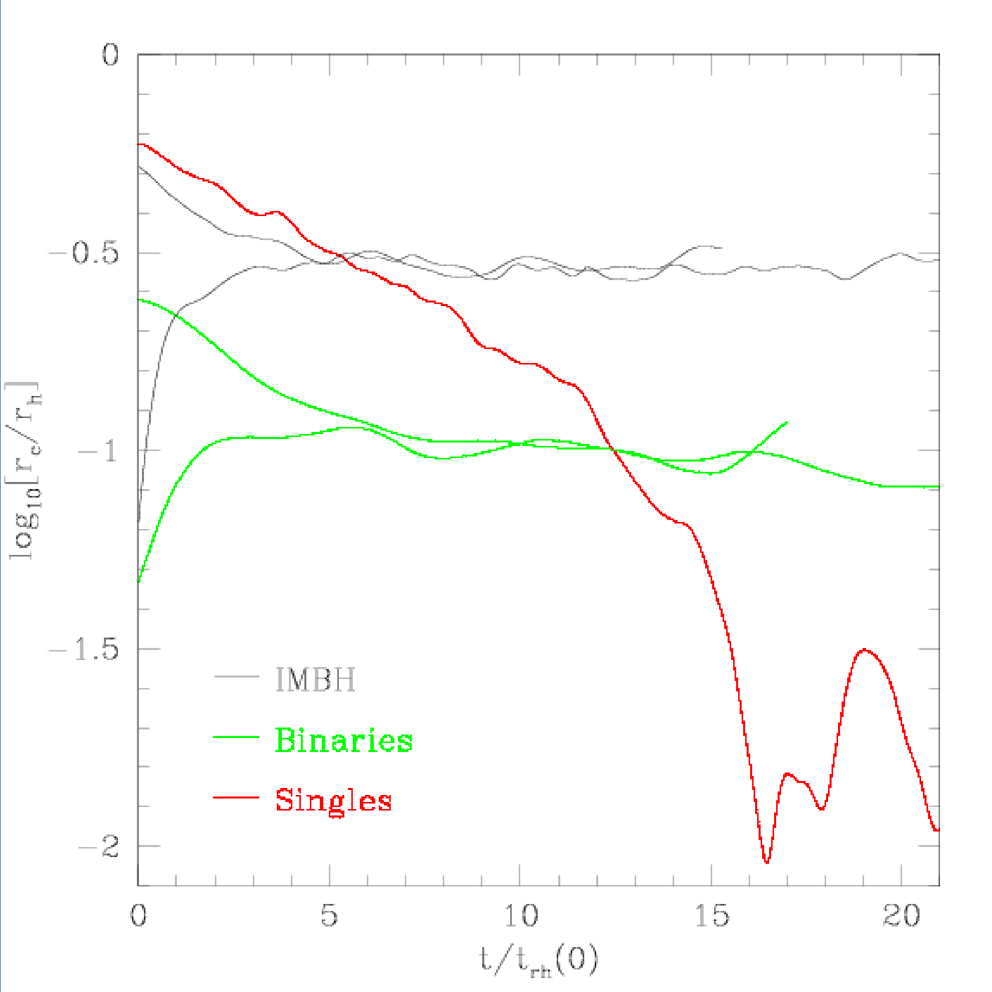
Super-Eddington Emission?



Kollmeier et al. 2006; AGN Eddington ratios

Indirect Dynamical Evidence?

- In globular, outer parts expand. Must provide energy.
- Singles are inefficient; need high density.
- Binaries more efficient
- IMBH still more; can lead to high r_c/r_{half}
- Complications must be explored (tidal shocks)



Trenti 2006

Open Question: Mass Function?

- Period, radial velocity of companion would give lower mass limit One example would establish IMBH
- Issue: unique identification
  Nearest ULX are few Mpc away!
  Even O, B stars are ~24th mag
- Maybe He II 4686A emission lines?
  Some candidates being pursued

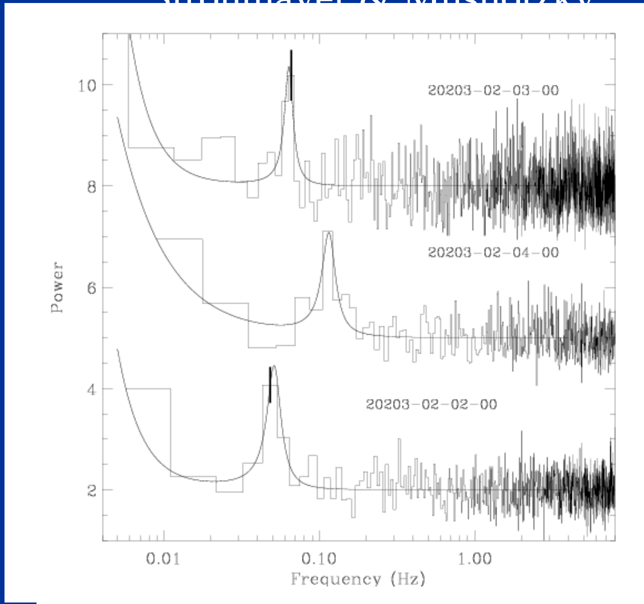
Summary of Observations

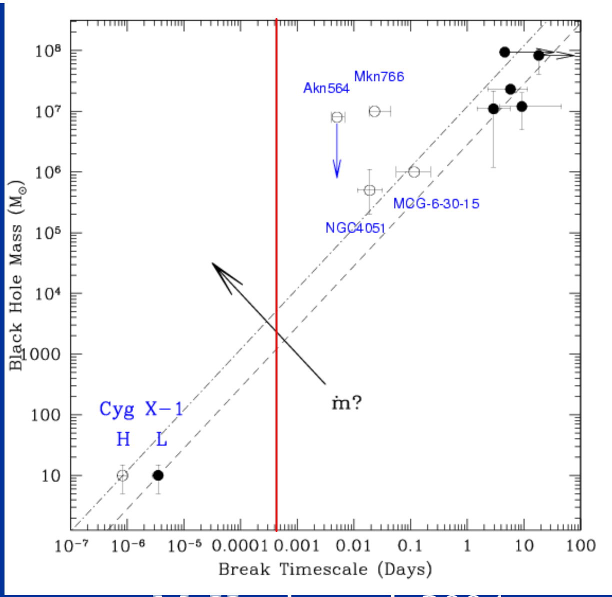
- Strong circumstantial evidence
  Also timing (QPOs, breaks)
  Surrounding nebulae; no strong beaming
- Still missing compelling dynamics
  Globular properties are interesting
  Work underway for more detailed obs.
  comparisons (M. Trenti, MCM, et al.)

Variability

- Expectation: freq~1/M
- No high-frequency power >1 Hz.
- Definite QPO in one source; maybe two more
- M82 X-1, 26 mHz break
- All consistent with ~10^3 M_{sun}, but basic understanding is lacking.
- Why not more QPOs?

Strohmayer & Mushotzky



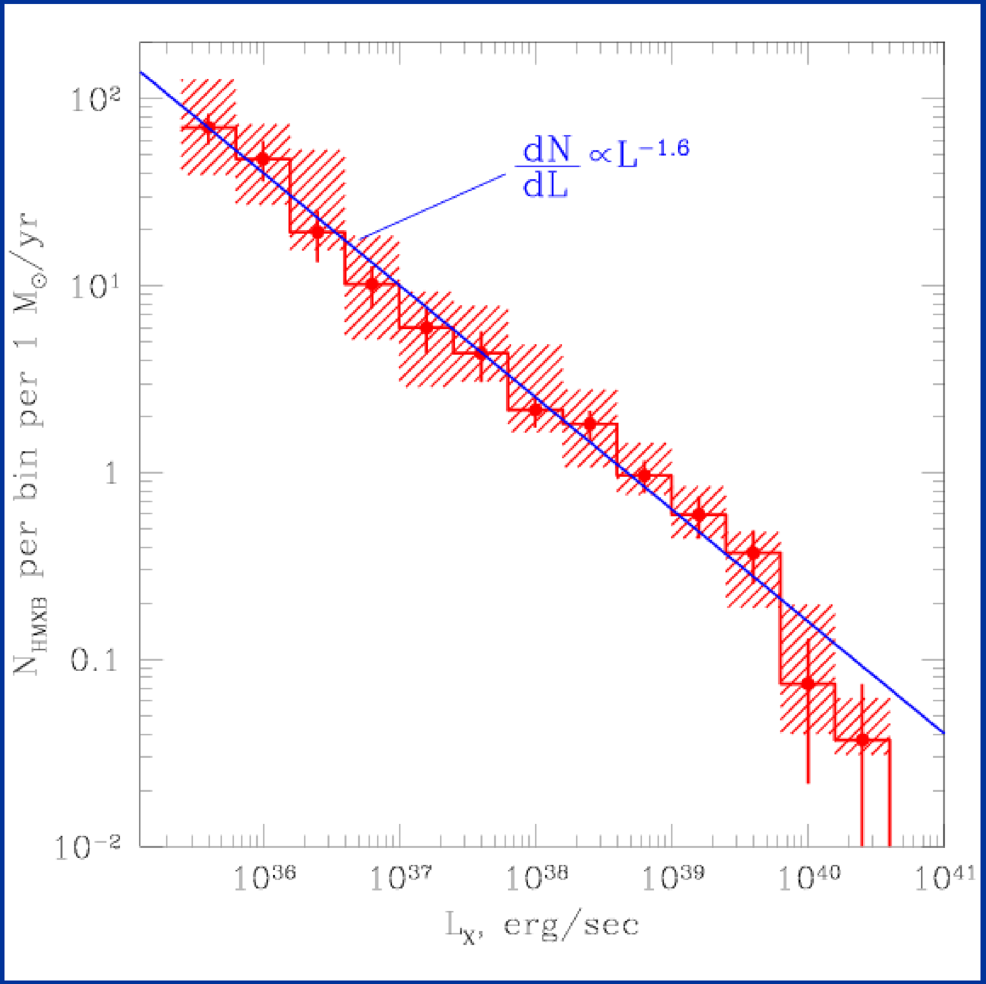


G0900624-v1

McHardy et al. 2004

Lack of Constraint from LF

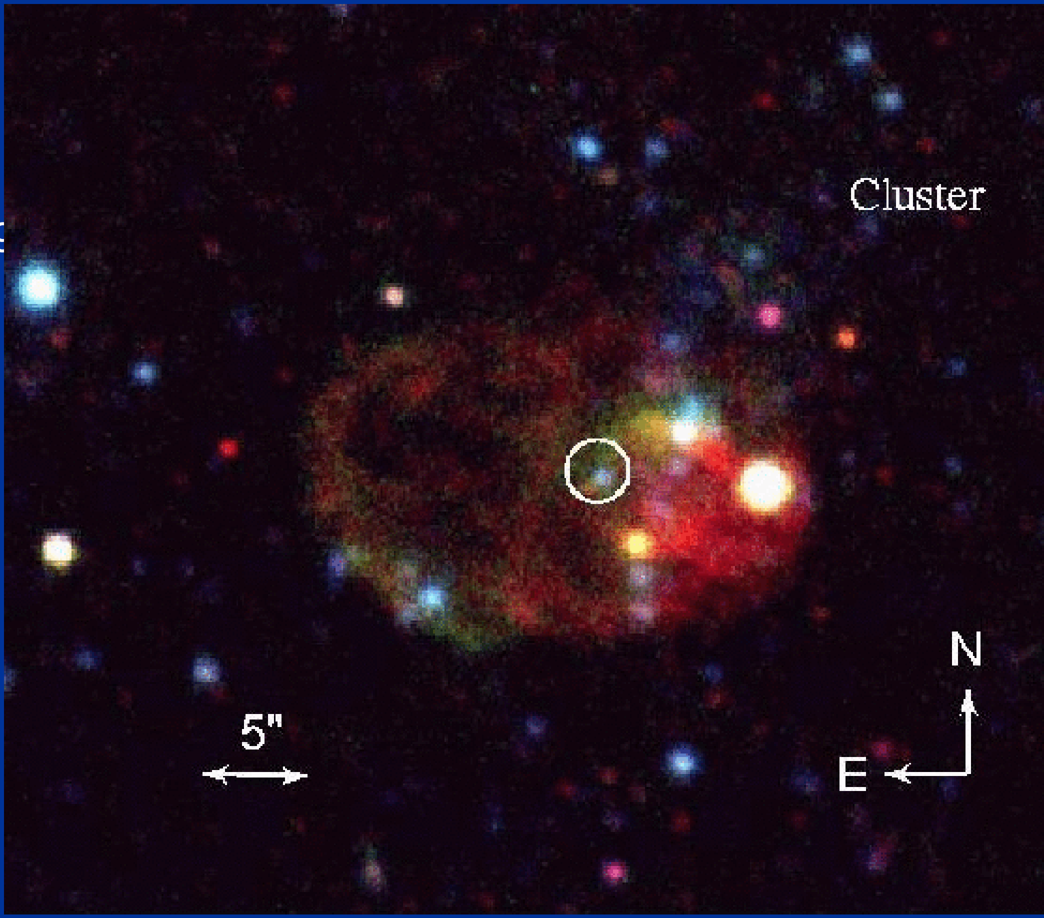
- HMXB LF corrected for star formation rate.
- No break at 10^{39} erg/s, 10 M_{sun} Eddington.
- Evidence against IMBH? Requires one population?
- No! No break at 10^{38}, either (NS Eddington).
- All models involve new things >10^{39} erg/s; little info.



Gilfanov et al. 2003

Nebulae and Counterparts

- Many ULX in huge (50-800 pc) nebulae
- If beamed, expect L<10^{39} erg/s, but...
- Few x 10^{39} erg/s over ~10^{6} years
- O, B stars?
- P_{orb}=62d? Kaaret et al.
- He II 4686 emission 300 km/s, NGC 1313?
- P, v_{rad} give mass.



Pakull et al. 2006; NGC 1313 X-2