A merger scenario for the formation of supermassive blackholes — from supermassive stars to supermassive black holes

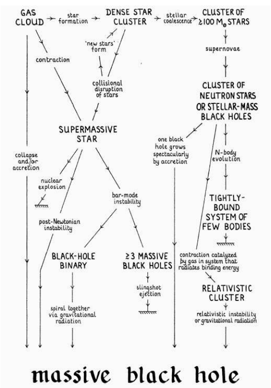
J. Makino
Department of Astronomy,
University of Tokyo

In collaboration with:
Toshikazu Ebisuzaki, Holger Baumgardt, Tatsushi Matsubayashi, Hisaaki Shinkai(RIKEN), Yoko Funato(U. Tokyo), Simon Portegies Zwart(UvA), Piet Hut(IAS), Steve McMillan(Drexel)

Talk Overview

1. Introduction: How to make massive BHs?
2. IMBH candidate in M82
3. The merger scenario
4. Recent works/results
5. Summary

Introduction: How to make MBHs?



Classic View (Rees 1984)

Essentially two possibilities

- Single Supermassive star
- Thermal Evolution of Compact Cluster of Compact stars

Both difficult...

Problem with Supermassive stars

Can we form it?
In an ideal situation:

- top-hat spherical collapse
- no small-scale fluctuation
- No external field

single gas cloud might collapse to a single black hole.

Problem with Compact Clusters

Thermal evolution (gravothermal catastrophe)
→ very small core. (No massive BH).

Unless we have relativistic clusters right from the beginning,

- merging would be rare
- tight binaries will be ejected from cluster

A Fundamental Problem

No theory has observational support, because nobody has ever seen a MBH being built.

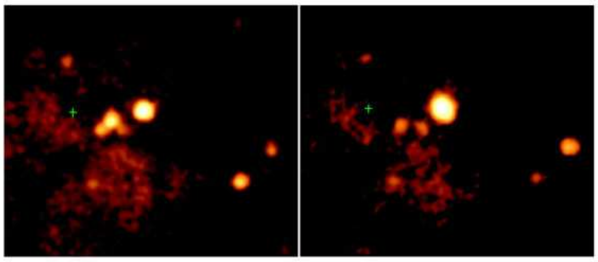
“Gap” in known BHs

- Stellar BHs $\sim 10 M_\odot$
- Massive BHs $> 10^6 M_\odot$

Anything in between?

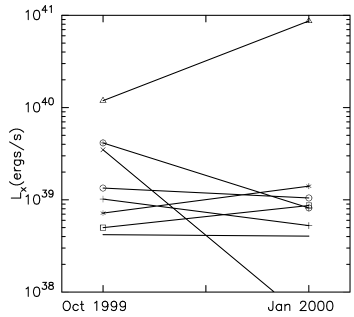
IMBH candidate in M82

Matsumoto *et al.* ApJL 547, L25



Multiple point sources with high variability.

Variability



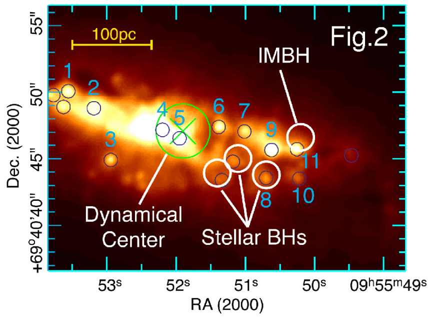
The strongest source shows significant variability.

Implication of M82 IMBH (candidate)

- First candidate BH with mass >> 10, but (most likely) << 10^6
- Eddington mass $\sim 700 M_\odot$ = First IMBH (intermediate-mass BH).
- Off-center: Some 200 pcs away from the dynamical center of M82
- Center of the expanding shell of molecular gas (Matsushita *et al.* ApJ 2000, 545, L107)

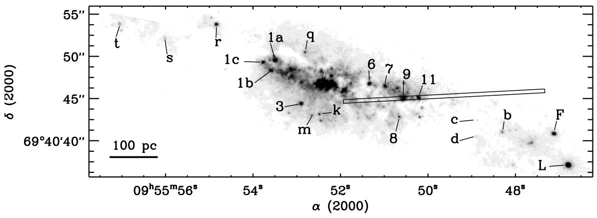
IR Counterpart

SUBARU view of the center of M82 (K' band)



IR Counterpart(2)

HST NICMOS/Keck NIRSPEC
McCrady et al. (astro-ph/0306373)



IMBHs in star clusters?

It is clear *(well, for a theorist...)* that IMBHs coexist with young and compact clusters ($< 10 Myrs$), which experienced LOTS of SNe very recently ($\sim 1 Myrs$).

How IMBHs were formed?

- May have been formed at the same time when the cluster formed.
- May have been formed after the cluster formed

Host cluster kinematics

McCrady et al. 2003 (astro-ph/0306373)
Cluster #11 (MGG-11)

- $\sigma_r = 11.4 \pm 0.8$km/s
- half-light radius 1.2 ± 0.17pc
- kinetic mass $3.5 \pm 0.7 \times 10^5 M_\odot$
- Age $\sim$ 10Myrs.

Low M/L
Short relaxation time ($<$ 10 Myrs)
Mass segregation? Top-heavy IMF?

A possible scenario

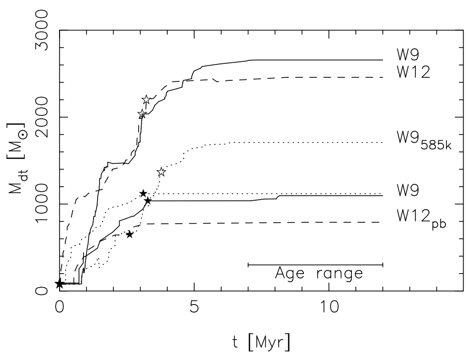
1. A massive star forms through runaway merging of stars in the center of the cluster.
2. IMBH forms through collapse of massive star.
3. IMBH further grows by accreting other stars/BHs.

Simulation

Portegies Zwart et al., in preparation (also see: Poster #6, Baumgardt and Makino)
Initial Condition

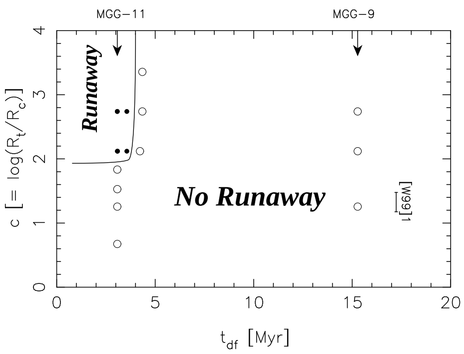
- King model with $W_0 =$ 7-12
- Salpeter IMF (as suggested by McCrady et al)
- Star-by-star simulation for MGG-11 (MGG-9 is scaled)

Result



Runaway merging occurred for MGG-11, if $W_0 \geq 8$.
No runaway for MGG-9 with any W_0.

Result summary



Need to have both short t_r and small (dense) core.

Runaway merging

If the dynamical friction timescale of the most massive stars is short enough (less than their lifetime), runaway merging is inevitable.

The runaway star will end up as a fairly massive BH, like 100–1000 $M_\odot$ or more.

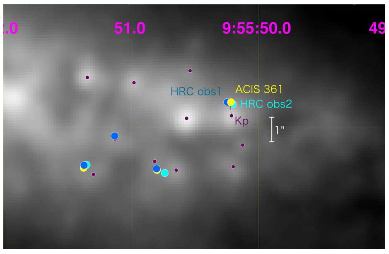
Final outcome depends on main-sequence mass loss and evolution of supermassive stars...

Summary for IMBH theory

- Formation of IMBH through runaway merging and subsequent accretion of stars to the seed BH seems plausible.
- Runaway occurs if relaxation time is short and core is dense.
- This does not rule out other possibilities

At least, runaway merging *can* explain the existence of IMBH in the M82 compact cluster

Is the IMBH in the star cluster?



Tsuru (Tuesday talk)

If you assume 2MASS sources and X-ray sources coinside, X1 is 0".6 off MGG11.

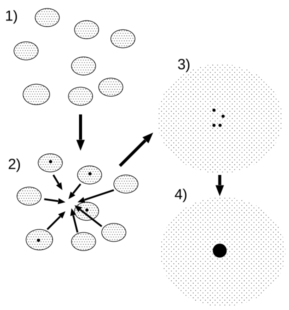
Radiation recoil (merging of IMBH and stellar-mass BH) may be responsible.

Relation between IMBHs and SMBHs?

1. Unrelated?
2. Formed in the same way?
   - Growth timescale would be too large
3. Make SMBH from IMBHs?
   - Might solve timescale problem.

Merger Scenario

Ebisuzaki et al. 2001 ApJ 562, 19L



1. Many compact star clusters are formed during a starburst
2. IMBHs are formed in some clusters; Clusters sink to the center of the parent galaxy through dynamial friction
3. Clusters are tidally disrupted, leaving IMBHs at the center
4. IMBHs merge through gravitational wave radiation to form SMBH

Theoretical questions

- Do IMBHs really form? — Yes!
- Why they are not in globular clusters? (Are they not?) — Baumgardt et al., Portegies Zwart et al.
- Can parent clusters bring IMBHs to the galactic center before they are disrupted? — Poster # 48, Matsubayashi et al.
- Can IMBHs merge and grow, without being ejected out? — Baumgardt et al.
- Can we observe mergings? — Poster # 76, Matsubayashi et al.

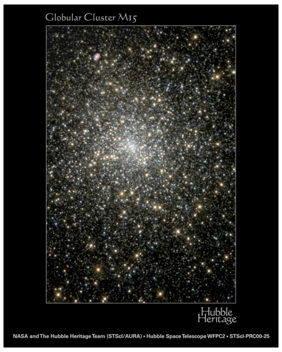
Why IMBHs are not in globular clusters?

Standard Answer:

1. GCs have long relaxation time $\sim 10^9$ yrs.
2. GC cores were not initially small.

Well, are they not there? How about M15 and G1?

M15



Archtypical "Core Collapse" cluster.

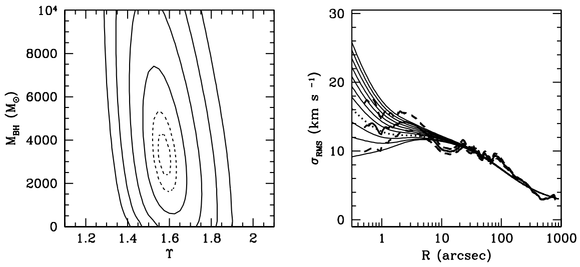
No core (individual stars are visible)

Central cusp slope ~ -0.8,

consistent with both central BH and gravothermal collapse.

Model with central IMBH

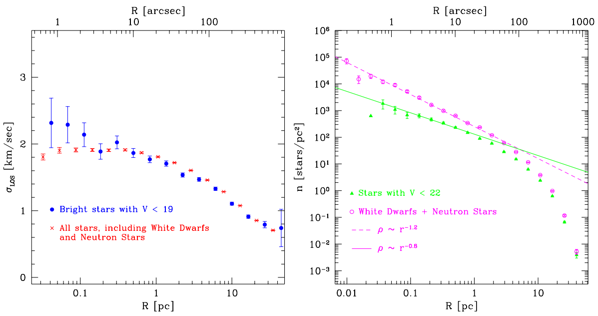
Gerssen et al. 2002



3000 $M_\odot$ black hole !?

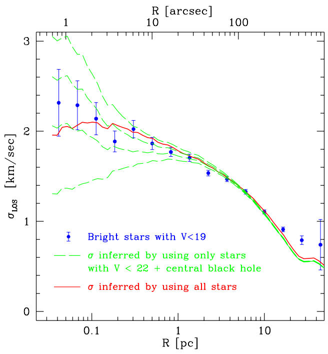
Evolutionary model without BH

N-body calculation by Baumgardt et al.(ApJ 2003, 582, L21)



Left: velocity dispersion; Right: Surface density.

We "found" BH in our model



Analysis of our simulated cluster using the same method as was used for M15 gives central BH, though no BH is there.

Central concentration of NSs and massive WDs behave as central dark mass.

IMBHs in GCs?

Certainly not in M15. M15 is much better explained by the standard evolutionary model at core collapse.

G1 seems even more unlikely (Baumgardt et al. ApJL, 2003, 589, L25)

IMBHs in GC? (continued)

Did we looked at the right place?
How a GC with a central IMBH look like?

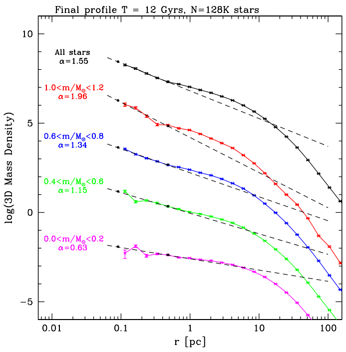
Theory (Bahcall and Wolf 1976)
rate): $\rho \propto r^{-7/4}$.
Luminocity cusp should be -0.75.

Caveats:

- -0.75 is asymptotic profile.
- all stars were assumed to have the same mass.

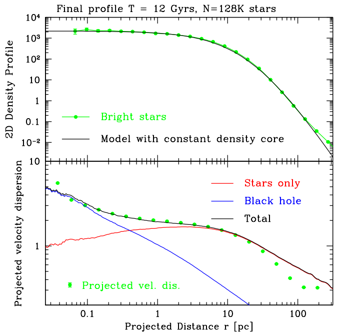
Simulation from initial model with a central BH ($W_0 = 10$ King model)
Baumgardt et al, in preparation

3D density profile



- Slope shallower for less massive stars
- Most massive: ~ -2 (not $-7/4$!)

Projection



- "Flat core"
- Subtle increase in the central velocity dispersion within the core.

IMBHs may hide in normal-looking "King" clusters.

Can parent cluster bring IMBHs to the galactic center?

Matsubayashi et al. (poster # 48)

— Seems Okay.

Clusters are tidally stripped as they sink to the center.

But they are not completely disrupted if their initial central density is high.

Can IMBHs merge and grow?

Early phase (merging of two IMBHs) — easy to occur

- hardening timescale short
- loss-cone depletion unimportant
- GW timescale short

Late phase (accretion of IMBHs to SMBH) — more difficult?

- loss-cone depletion maybe important
- GW timescale long

IMBHs may accumulate at the center and form a cluster... What happens then?

Simulation

- 1 $10^6 M_\odot$ SMBH
- 100 $10^4 M_\odot$ IMBH
- 10^5 $10^3 M_\odot$ "stars"
- No GW
- BHs merge when IMBH comes to the Schwarzschild radius of the SMBH

Result

- 23 IMBHs accreted to SMBH in 0.6 Myrs.
- $3 \times 10^5 M_\odot / Myrs$

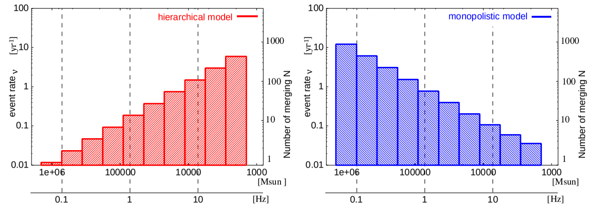
Late stage evolution, driven by 2-body relaxation between IMBHs, is very fast.
SMBH can be built up using IMBHs.

What can we observe?

- IMBHs
  - More “M82 X-1s”
  - GC, “super star cluster” kinematics
  - IMBH-stellar BH merging: LIGO2
- star cluster evolution near galactic center — kinematics of central star cluster
- SMBH growth from IMBHs — GW observation

SMBH growth mode

Matsubayashi et al. (poster # 76)



Red: Hierarachical growth
Blue: IMBH accretion to SMBH — much more low-freq events.
LISA should be able to see what’s going on.

Summary

- M82 hosts an IMBH candidate, which is most likely a missing link between stellar-mass BHs and MBHs.
- We propose a two-step growth scenario from stellar-mass to IMBH and IMBH to MBH.
- IMBHs are formed through runaway merging of massive stars in compact star clusters.
- Parent clusters sink to the center of galaxy, bringing IMBHs to the center.
- IMBHs merge through dynamical friction & GW
- LISA should tell...

Continuous accretion?

In principle, a $10 M_\odot$ BH can grow to 10^8 in 10^9 yrs or so, assuming $10\times$ Eddington rate ($\eta \sim 0.1$)

Not impossible, but hard to explain QSOs at $z \geq 5$.

But ... supercritical accretion???

Summary for G1 model calculation

A pretty standard model cluster with

- large core before collapse
- r^{-4}-like halo formed by merging
- no BH

reproduces *all* available observational data.

Mass: $M_C = (8 \pm 1) \times 10^6\ M_\odot$.
roughly half of the multi-mass King fitting

Why was BH needed for G1?

K. Gebhardt (private communication)

see also: http://www.space.com/scienceastronomy/blackhole_trick_030120.html

- velocity dispersion is consistent with No BH.
- Higher order moments suggest BH.

Radius(”)	H3	dH3	H4	dH4
0.00	-0.009	0.020	-0.046	0.018
0.05	-0.035	0.019	-0.051	0.013
0.10	0.026	0.013	-0.052	0.007
0.17	-0.025	0.024	-0.039	0.019
0.30	-0.017	0.025	-0.046	0.019
0.57	0.003	0.034	-0.055	0.017
1.10	0.022	0.056	-0.034	0.063

H4 does not decrease outward — error in data reduction?