星団中での中間質量ブラックホールの形成
—- M82, M15 そして G1

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Talk Overview

1. 前置き
2. M82
    - 観測
    - 解釈
3. M15
    - 観測 — 見えないものを見る
    - モデリング — 見えないものを計算する
    - 解釈 — 両方を合わせる
4. G1
5. Summary

初めに — 2種類のブラックホール(BH)

「知られている」ブラックホールのギャップ

- 恒星質量 ブラックホール $\sim 10M_\odot$ (太陽質量)
  - 大質量星の重力崩壊 (II型超新星) でできる
  - X 線での観測が主な根拠
- 巨大ブラックホール $> 10^6 M_\odot$
  - 円盤銀河 — 楕円銀河の中心に存在
  - クェーサー、活動銀河核の「セントラルエンジン」
  - 観測的根拠は多様

その中間は ???

中間質量ブラックホール

Intermediate-mass blackhole を発見した!!!
という報告

- **700 $M_\odot$ in M82?**

  Matsumoto *et al.* **ApJL 547, L25, Chandra**

- **4000 $M_\odot$ in M15?**

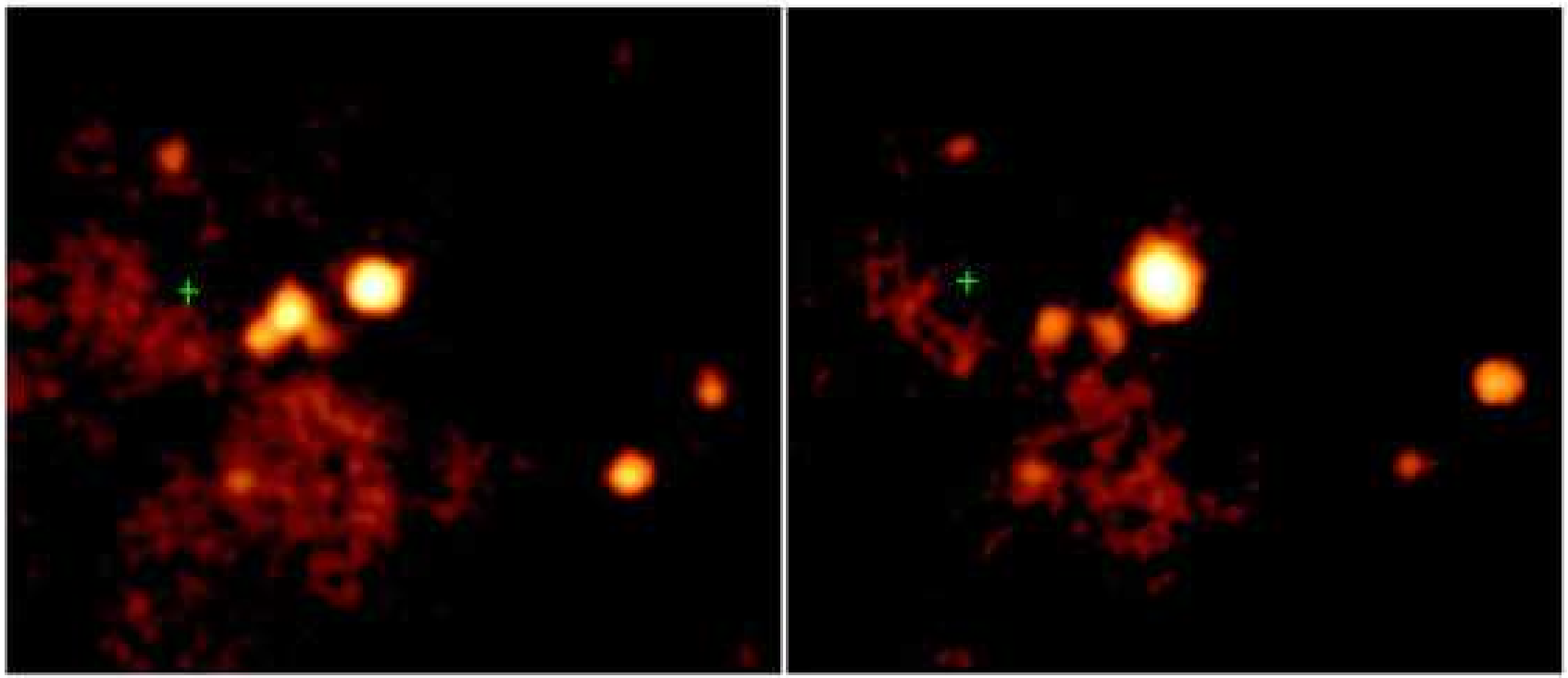
  Gerssen *et al.* **AJ 124, 3270, HST**

- **$2 \times 10^4 M_\odot$ in G1?**

  Gebhardt *et al.* **ApJ 578, L41, HST**

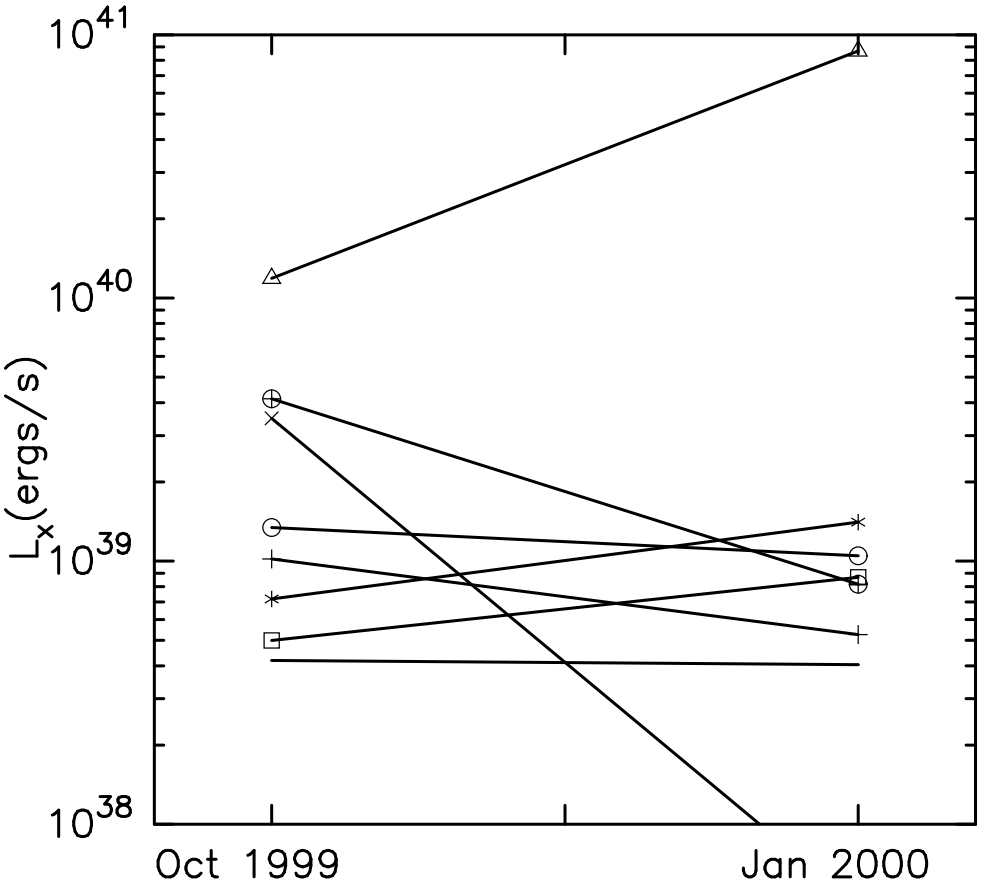
IMBH (candidate) in M82

Matsumoto *et al.* ApJL 547, L25



Multiple point sources with high variability.

Variability



The strongest source shows significant variability.

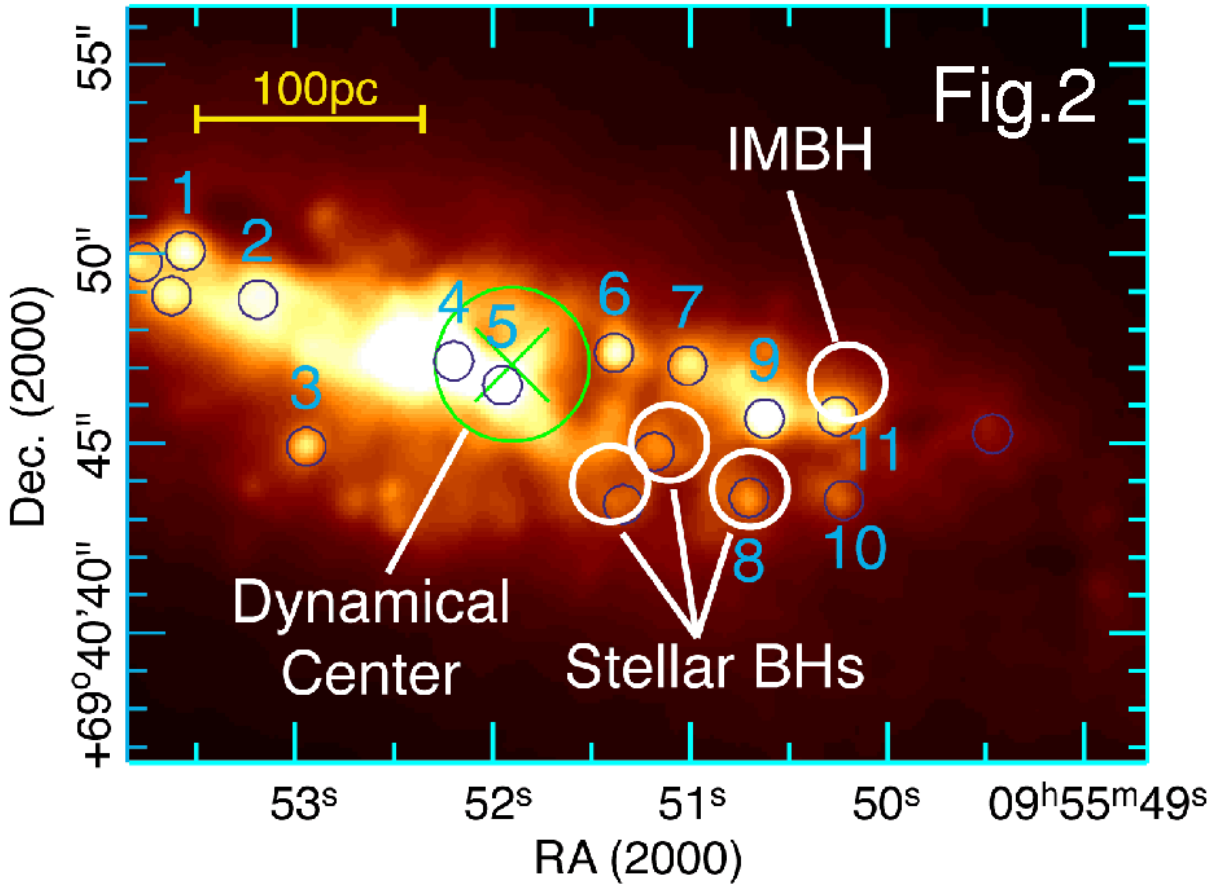
Implication of M82 IMBH (candidate)

- **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 IRCS view of the center of M82 (K' band)

still unpublished...



IMBHs in star clusters?

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

How were IMBHs formed?

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

Single supermassive star

- **Nobody has seen it. The largest known star is $180 M_\odot$ or so.**
- **Dynamical instability?**

Merger of compact object

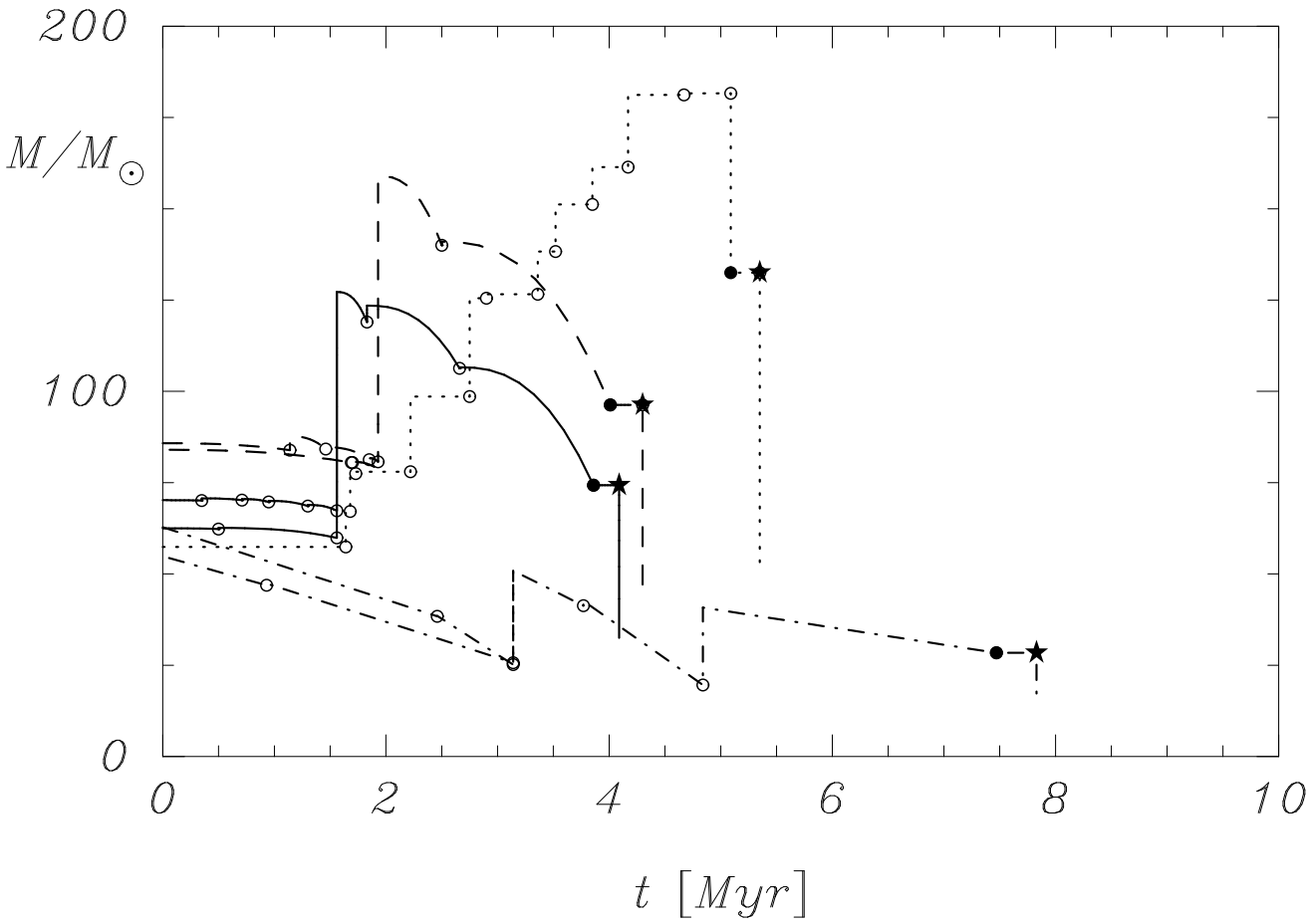
- Thermal evolution timescale too long.
- Binaries would be ejected by three-body slingshot.
- Remnants are less massive than MS stars. Will be ejected out of the core through thermal relaxation.

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.

Simulation of young cluster

N-body simulation by Portegies Zwart et al. 1999 A&A 348,117



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 100–200 $M_\odot$ or more.

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

BH growth after formation

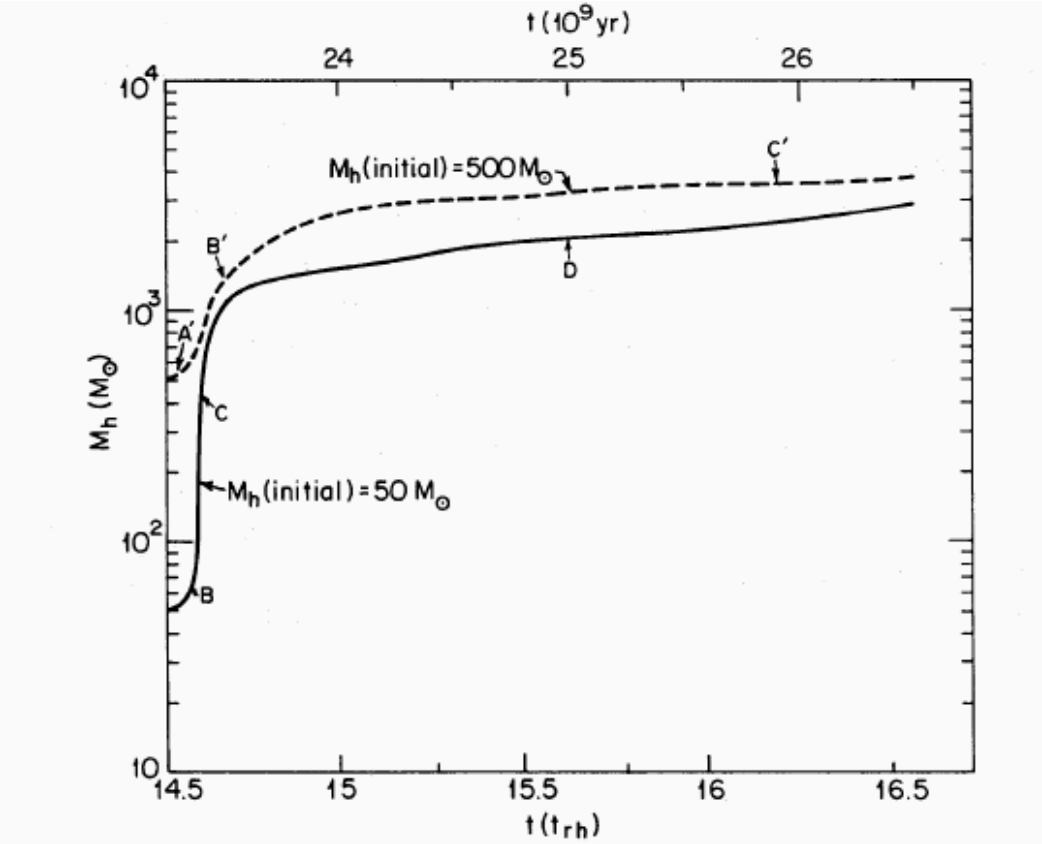


FIG. 8.—Growth of the central black hole is shown for the two cases with $e_a = 1$. M_h(initial) is the initial mass of the black hole inserted at $t = 14.5t_{rh}$. Letters identify times highlighted in the next four figures. By $t = 16t_{rh}$, both models have achieved black holes with mass $M_h \sim 3000\ M_\odot$, but subsequent growth is much slower.

Marchant and Shapiro 1980 ApJ 239, 685

Model cluster: globular cluster
$N = 10^5$
1-D MC code

Underestimates the growth rate?
Eddington limit?

Summary for IMBH theory

- Formation of IMBH through runaway merging and subsequent accretion of stars to the seed BH seems plausible.
  - Merging rate is high
  - accretion rate is also high
- This does not rule out other possibilities

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

Do IMBHs relate to (S)MBH?

To make a MBH from IMBH(s)

- **bring IMBHs to galactic center**
- **let many IMBHs merge with one another**
- **or, let one IMBH to grow by accreting gas or stars**

Bringing IMBHs to galactic center

This is an easy part.

- **Parent clusters would sink to the center in a fairly short timescale through dynamical friction.**
- **Evaporation timescale of the parent cluster is long if it is massive enough.**

Can IMBHs merge?

This is the hard part. We need to make BH binary compact enough for gravitational wave to become effective.
Three possibilities

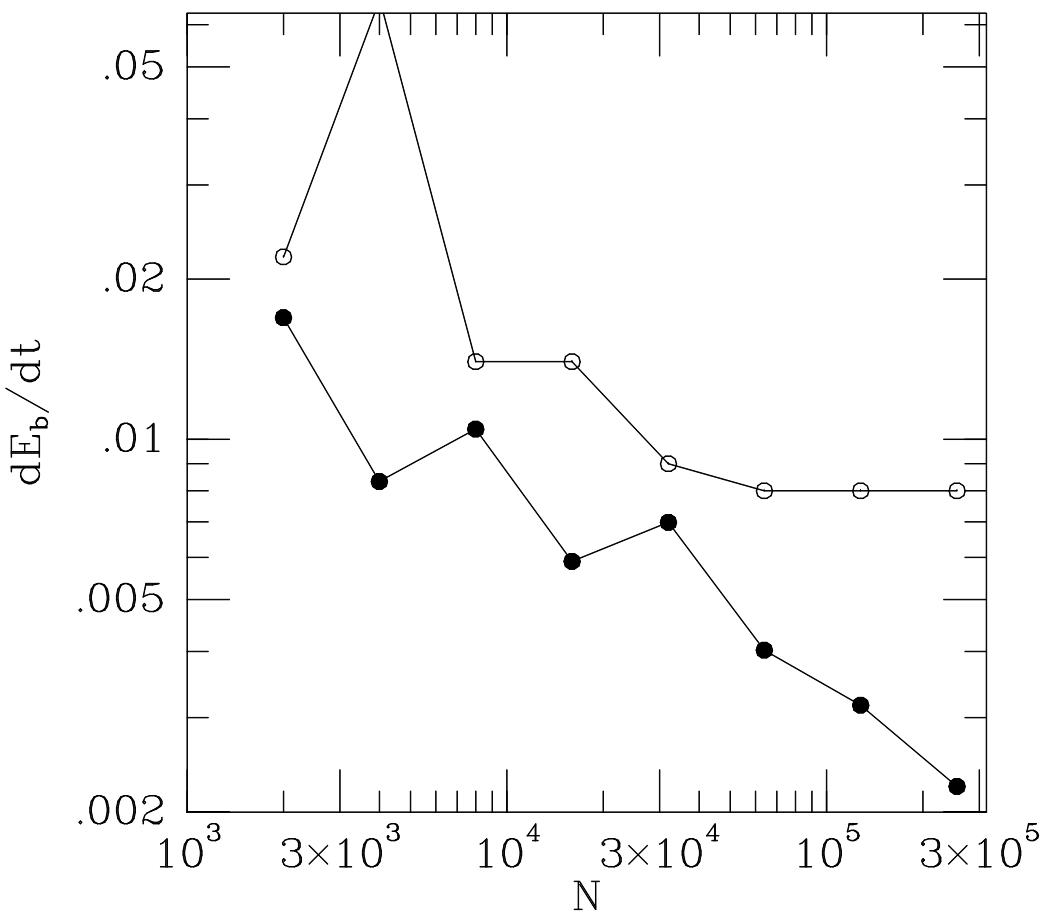
- **binary BH hardens through interaction with other stars/gas in the center**
- **BHs would merge during triple interaction**
- **BH ejected through triple interaction**

N-body simulation

(Makino 1997)
Theoretically, the BH hardening timescale should be proportional to the relaxation timescale (loss-cone refilling).

We tried merger simulation with wide range in N.
(2k — 256k)
Largest N not not too far from the number of stars in GC.

Growth rate

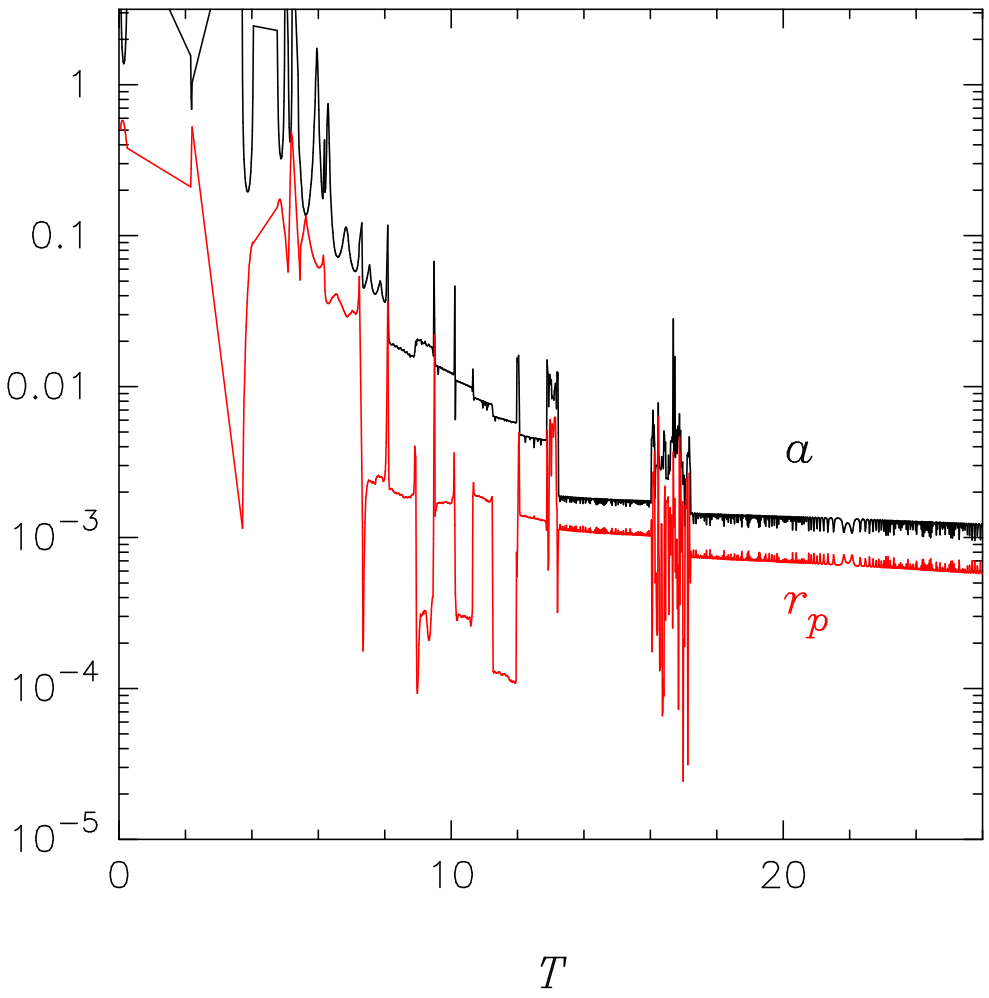


Open: early
Filled: late

Timescale:

Early phase:
converges?
Late phase:
$\propto N^{1/3}$?

Triple BH



Evolution of binary semi-major axis a and periastron distance r_p.

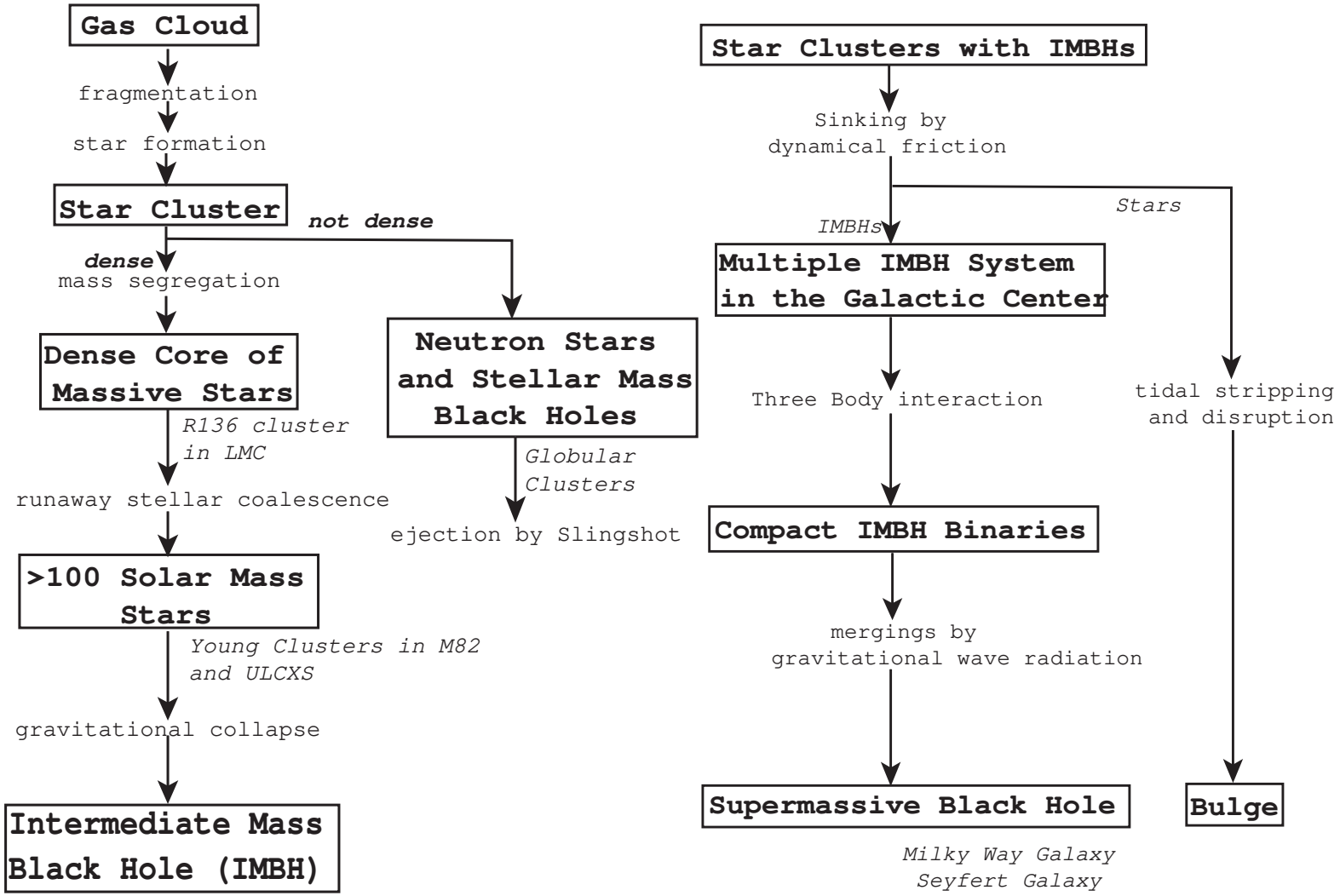
Periastron distance can go very small — gravitational wave would quickly let the bound pair merge.

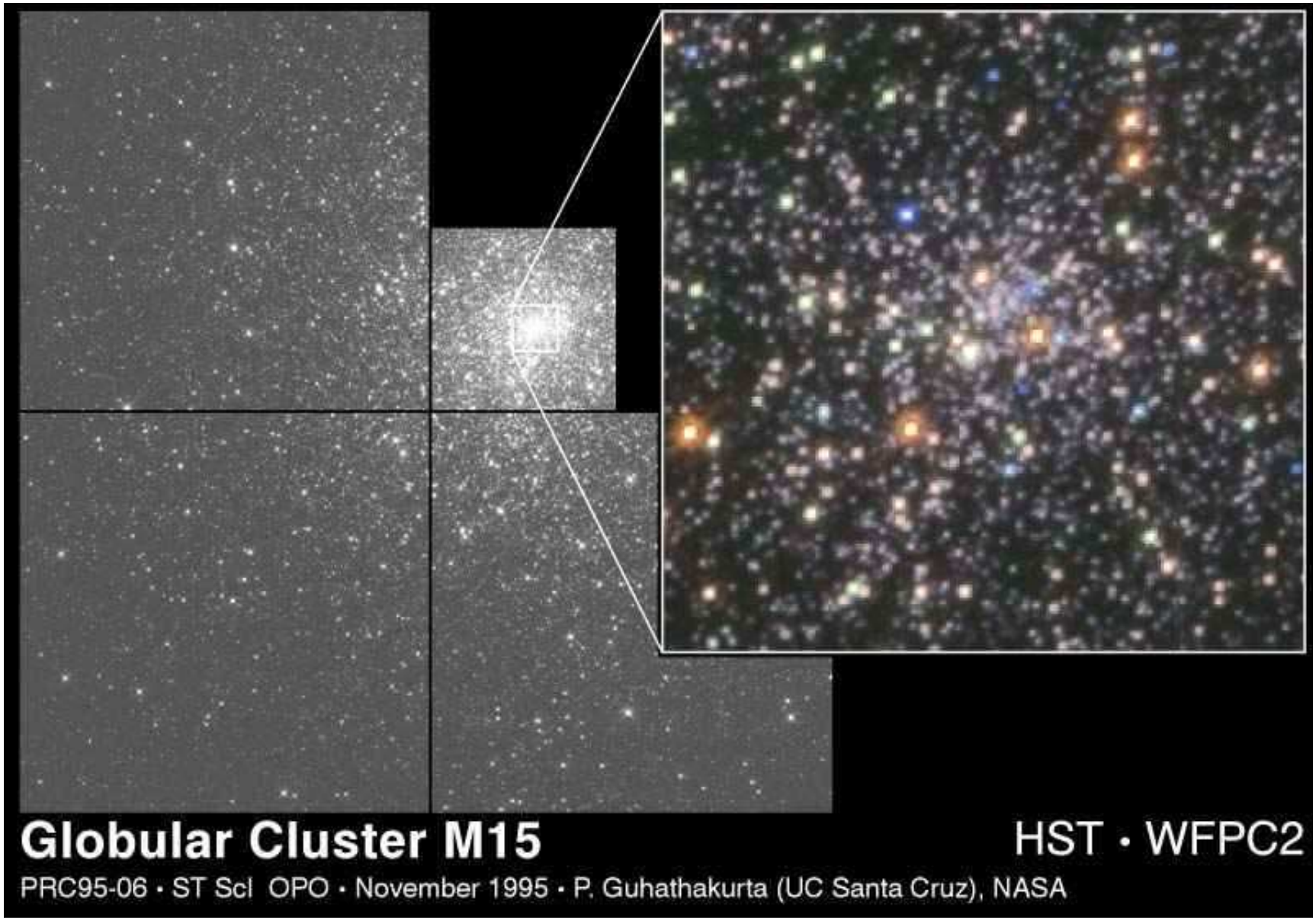
Summary for IMBH growth through merging

- Merging either through binary hardening or triple interaction seems plausible.
- More numerical work clearly necessary...
- LISA would detect HUGE number of events

Combining everyting together

Ebisuzaki et al. 2001 ApJ 562, 19L




Globular Cluster M15
HST • WFPC2
PRC95-06 • ST ScI OPO • November 1995 • P. Guhathakurta (UC Santa Cruz), NASA

M15 — Claims

STScI Press release (Sept 18, 2002)

Van Der Marel led a team that uncovered a black hole in the center of the globular star cluster M15, 32,000 light-years away in the constellation Pegasus. His collaborator Joris Gerssen, also of the Space Telescope Science Institute, pinned down the black hole's mass at 4,000 times that of our Sun.

Previously, X-ray observations ..... have identified ultra-bright X-ray sources that could also be interpreted as intermediate-mass black holes in star-forming galaxies. However, alternative interpretations for these X-ray sources continue to exist. By contrast, Hubble's measurements are based on the velocities of stars .....which yield a direct measurement of the black hole masses.

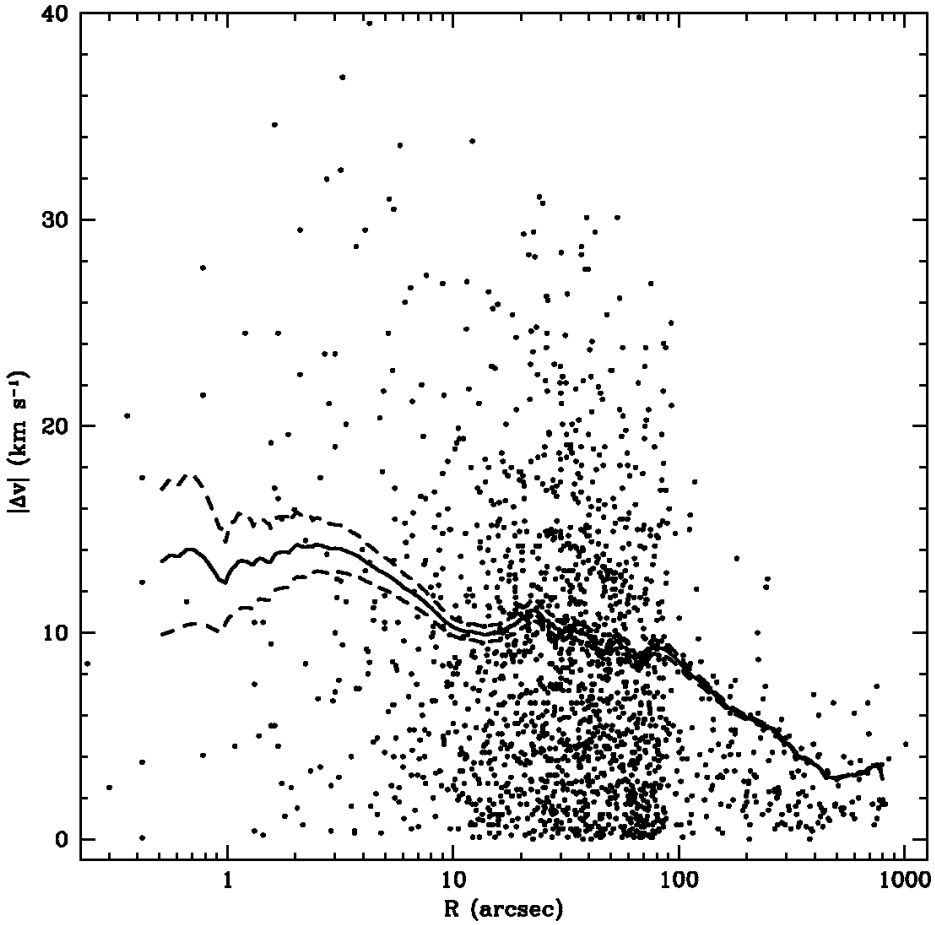
M15 — 適当な訳

宇宙望遠鏡科学研究所プレスリリース (2002/9/18)
STScI Press release (Sept 18, 2002)

宇宙望遠鏡科学研究所のファン・デア・マレル博士が率いるチームは、ペガサス座の方向、3万2千光年の彼方にある球状星団 $M15$ にブラックホールを発見しました。彼の協力者で、やはり宇宙望遠鏡科学研究所のゲルセンは、ブラックホールの質量が太陽の4000倍だということを突き止めました。

これまで、 X線での観測で .... 星形成銀河に非常に明るい X線源が見つかっていました。これは中間質量ブラックホールとも解釈できるものでしたが、他の解釈もできるものでした。これに対し、ハッブル (宇宙望遠鏡) による測定は、個々の星の速度に基づくもので、直接ブラックホールの質量を与えるものです。

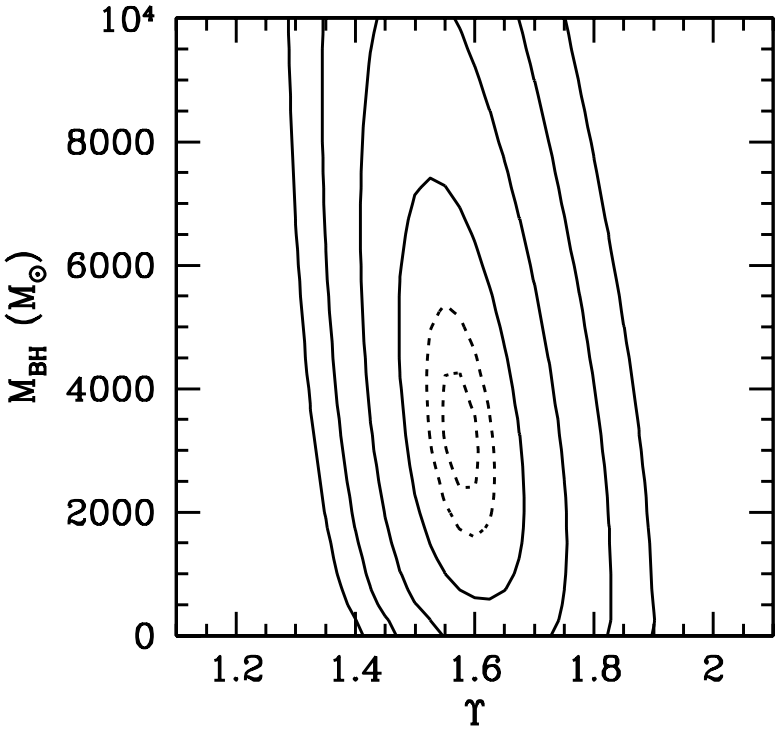
M15 — 観測

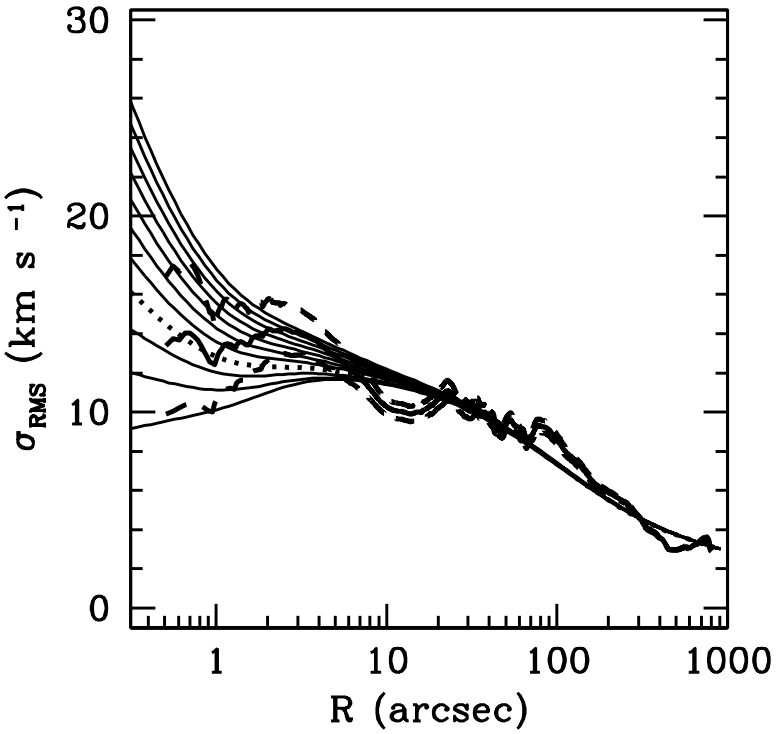


RMS velocity profile by Gerssen *et al.* (astro-ph/02090315).

HST STIS, CFHT and other data combined.

何故ブラックホールがあると主張するか?
— モデル





3000 $M_\odot$ black hole!

モデルの作り方 — Jeans equation

球状星団の星の分布関数は力学平衡、つまり無衝突ボルツマン方程式

$$\frac{\partial f}{\partial t} + \mathbf{v} \cdot \nabla f - \nabla \Phi \cdot \frac{\partial f}{\partial \mathbf{v}} = 0, \tag{1}$$

の定常解になっている。で、これに対して星団が球対称で、平均の流れがない (どこで積分しても平均速度は 0) と仮定すると

$$\frac{d(\nu \overline{v_r^2})}{dr} + \frac{\nu}{r}\left[2\overline{v_r^2} - \left(\overline{v_\theta^2} + \overline{v_\phi^2}\right)\right] = -\nu \frac{d\Phi}{dr} \tag{2}$$

但し、$\nu = \int f d^3\mathbf{v}$ (空間密度)

Jeans equation (等方)

速度分布が等方的とすれば、結局

$$\frac{1}{\nu}\frac{d(\nu\overline{v_r^2})}{dr} = -\frac{d\Phi}{dr} \tag{3}$$

すなわち

$$M(r) = -\frac{r\overline{v_r^2}}{G}\left(\frac{d\ln\nu}{d\ln r} + \frac{d\ln\overline{v_r^2}}{d\ln r}\right) \tag{4}$$

これは、ポテンシャルを作るものの質量密度と、そのなかで
動いているものの密度、速度の間の関係を与える。

観測の解釈

いいかえると、**Jeans** 方程式を使うと

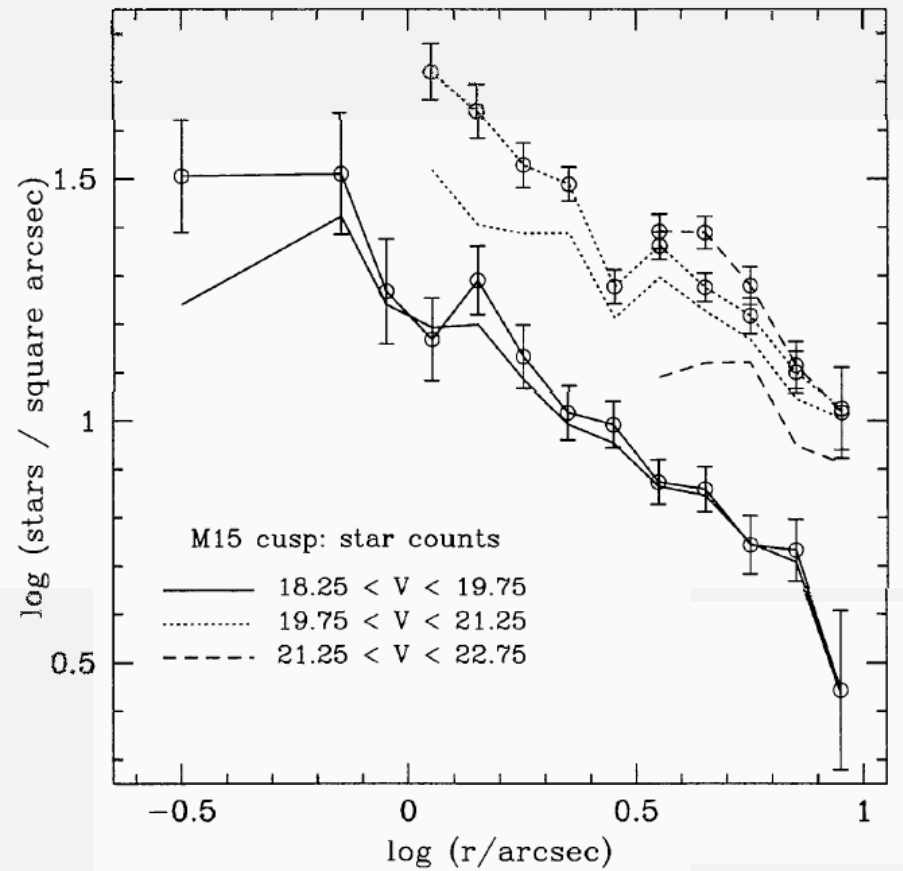
- (見えないものも含めた) 質量分布
- (見えるものの) 密度分布
- (見えるものの) 速度分布

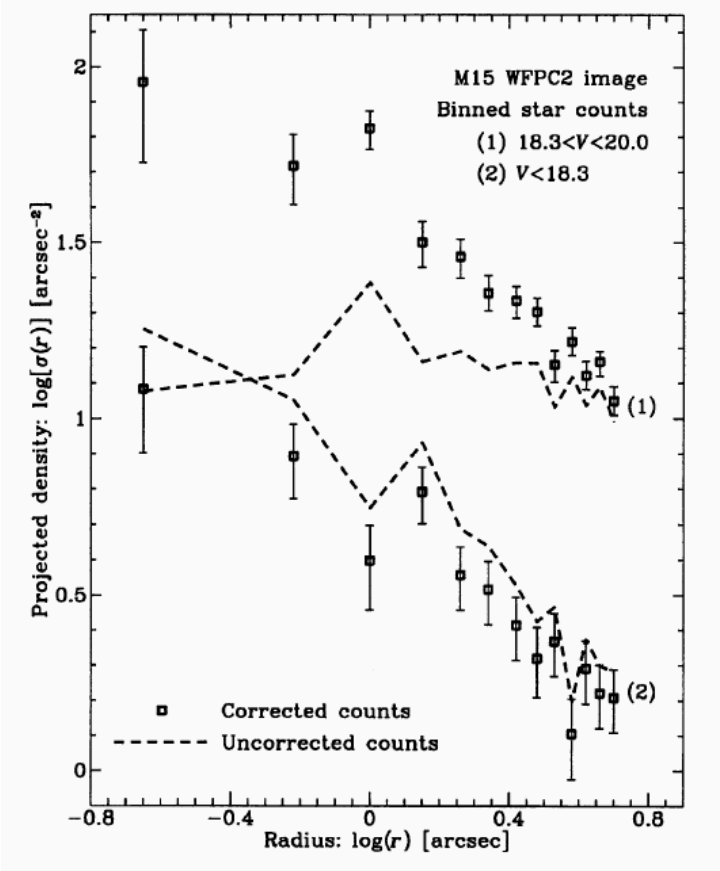
のうち **2** つがわかればもうひとつがわかる。

Gerssen et al. のやったこと

1. “ Mass follows Light” を仮定して、(見えるものの) 密度分布に何か定数γ を掛けると (見えないものの) 質量分布が求められると信じる。
2. 質量分布から速度分布を求めてみる。
3. これは、定数をふってみても速度分布の観測結果とあわない
4. 中心にいろいろな質量のブラックホールを仮定して、速度分布を計算しなおす
5. χ^2 残差が最小になったところで、「ブラックホール発見!」

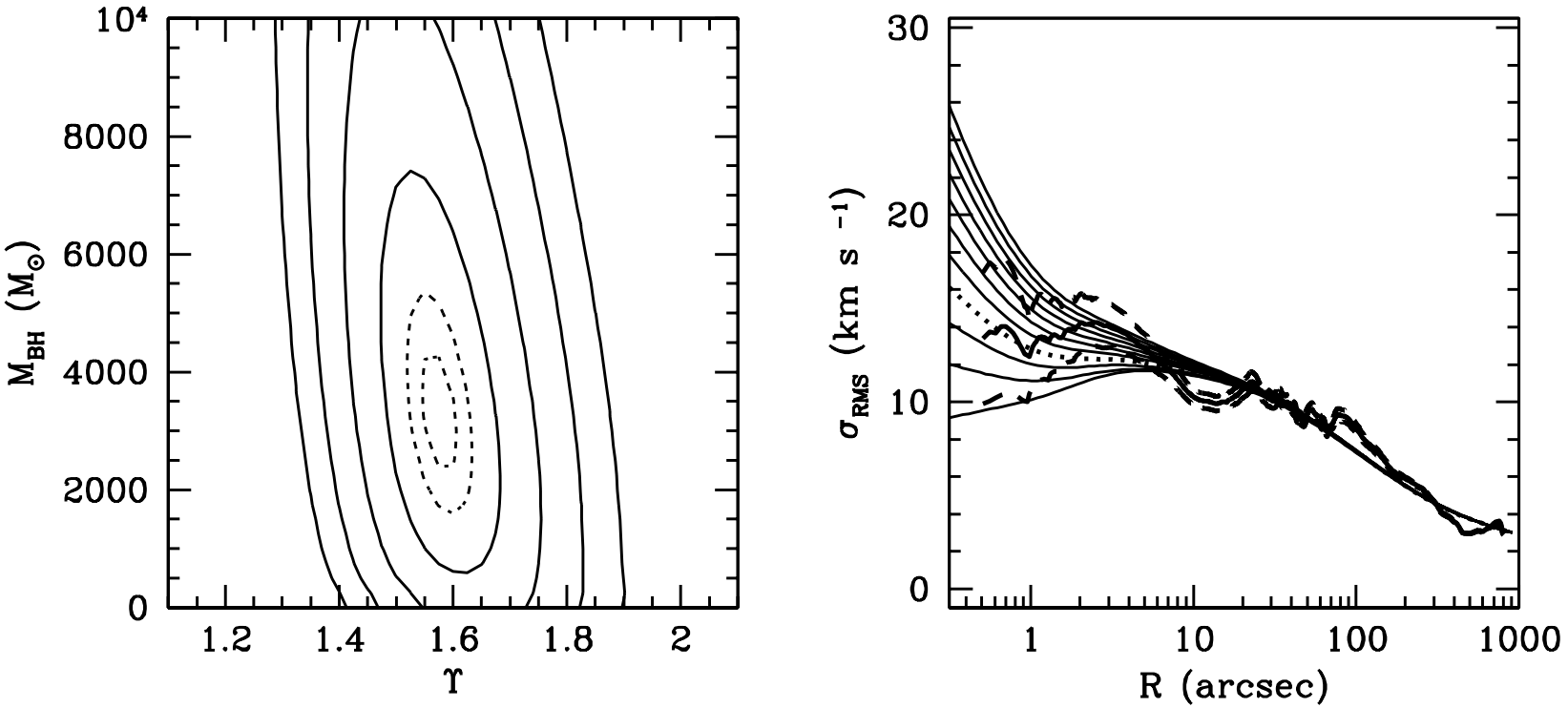
表面輝度





Left: Sosin & King 1997, Right: Guhathakurta *et al.* 1996.

ブラックホールありモデルの速度分布



3000 $M_\odot$ black hole!

何故ブラックホール?

実際に観測された速度分散は、中心5秒角の範囲で (わずかではあるが) 中心にいくに従って増加

中心5秒角内の表面輝度はスロープ -0.8 のべき (カスプ)

↓

質量と光が比例してれば、速度分散も弱いべきではあるが中心に向かって下がるはず

なので、ブラックホールがある

明らかな問題:
質量と光は比例するのか?
速度分散は等方的なのか?

質量と光の関係

常識的な理解: 球状星団では質量と光の関係は「単純ではない」

球状星団の年齢: 熱力学的な緩和時間よりずっと長い
重い星は、エネルギーを失って中心に集まることができる

この時、十分に進化が進むと中心部はほとんど重い星だけになり、そこの分布はべき乗 $\rho \sim r^{-2.23}$ になる。

球状星団のもっとも重い星: 中性子星 $(1.4\ \mathrm{M}_{\odot})$、重い白色矮星 (見えない)
観測している星: 赤色巨星 $(0.8\ \mathrm{M}_{\odot})$

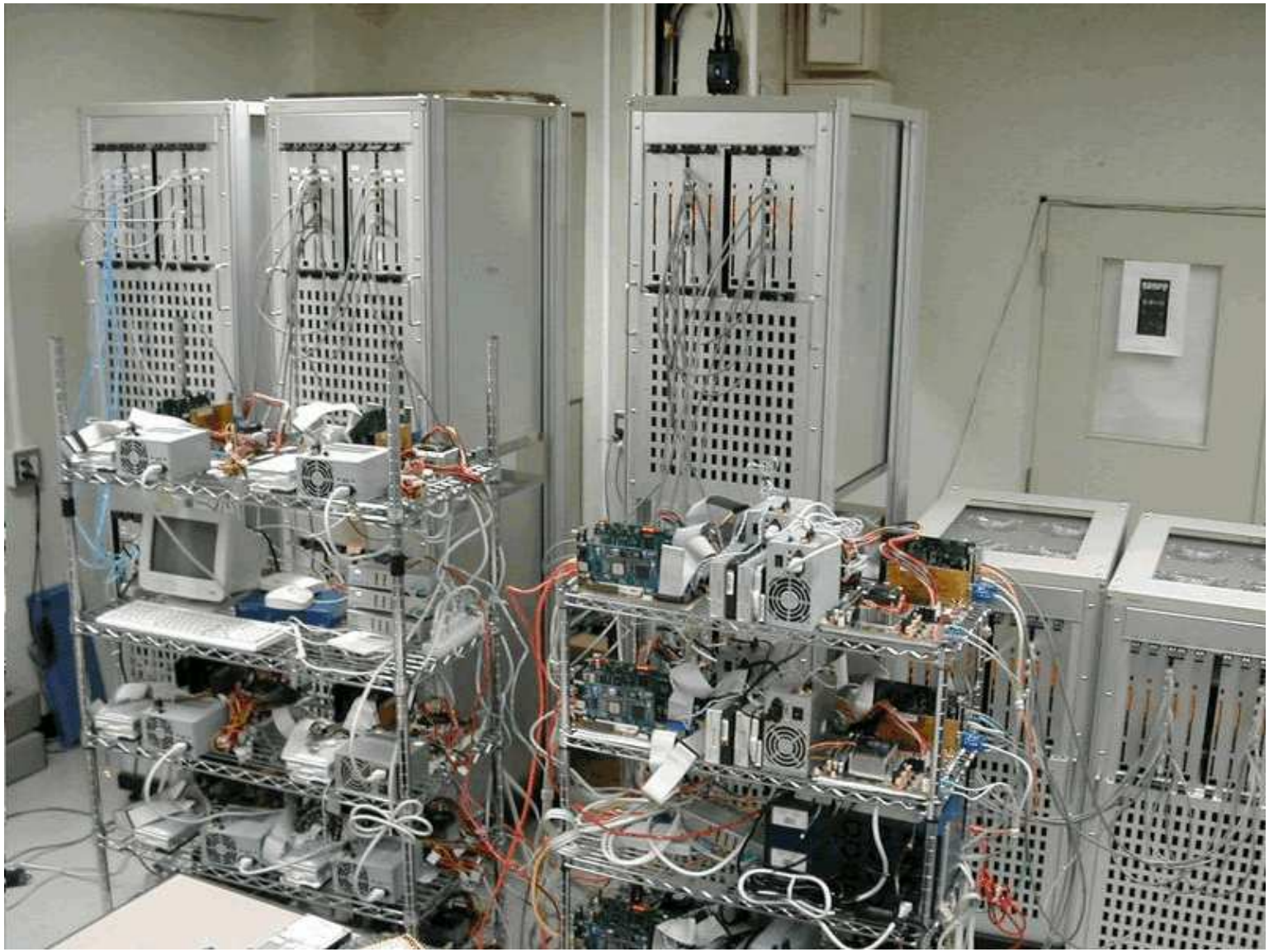
数値シミュレーションでもうちょっと細かくみてみる。

N-body simulation

Baumgardt and Makino (MNRAS accepted)

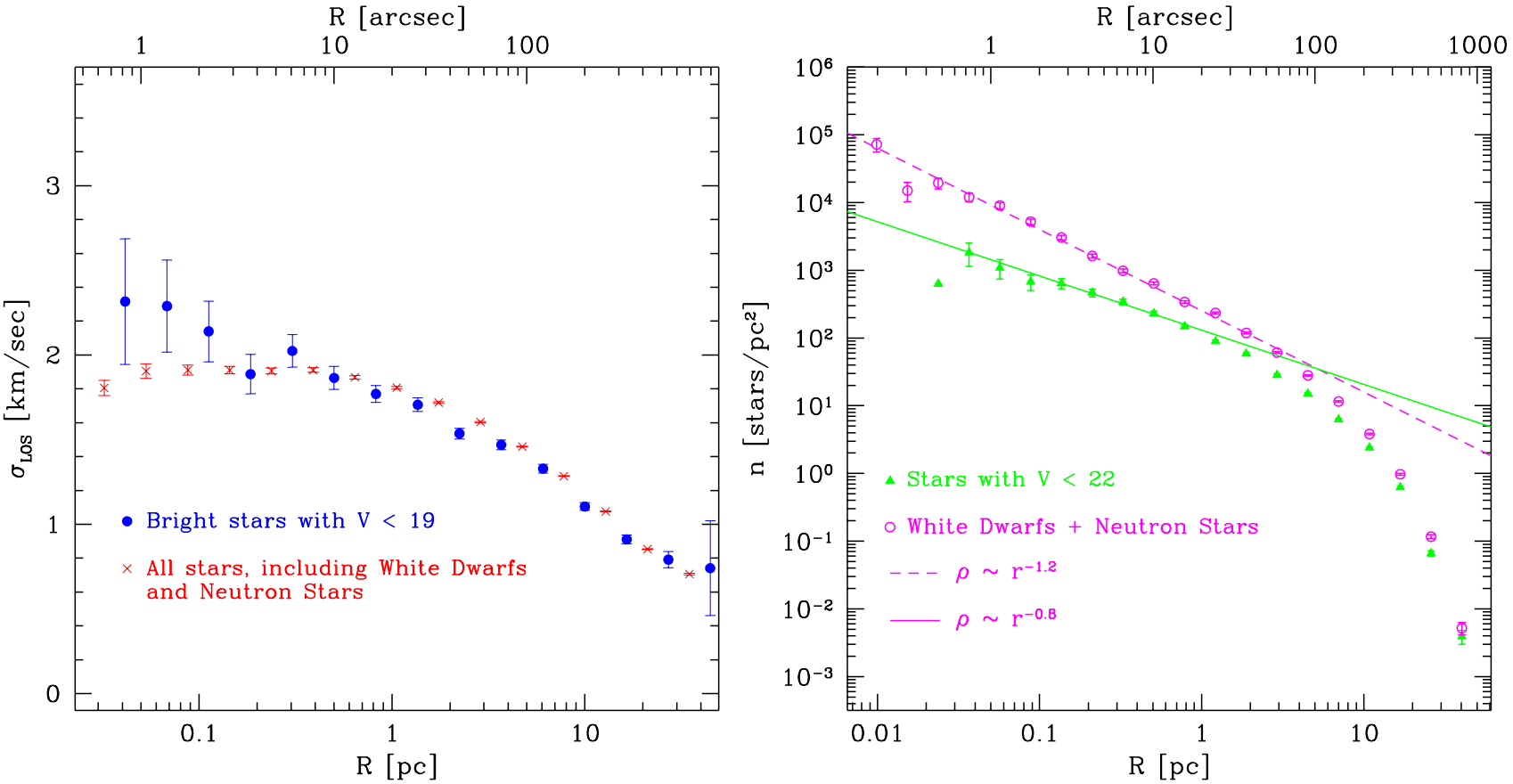
- **N=128k (mass at core collapse = $2 \times 10^4 M_\odot$ (∼1/40 of M15)**
- **Kroupa (2001) IMF (15 $M_\odot$ cutoff)**
- **Hurley *et al.* (2000) Stellar evolution**
- **NBODY4 on GRAPE-6**
- **$W_o = 7$ King model at 8.5kpc from GC**
- **reached core collapse at 12.6 Gyrs**
- **40 days on a 4-Tflops GRAPE-6.**

GRAPE-6



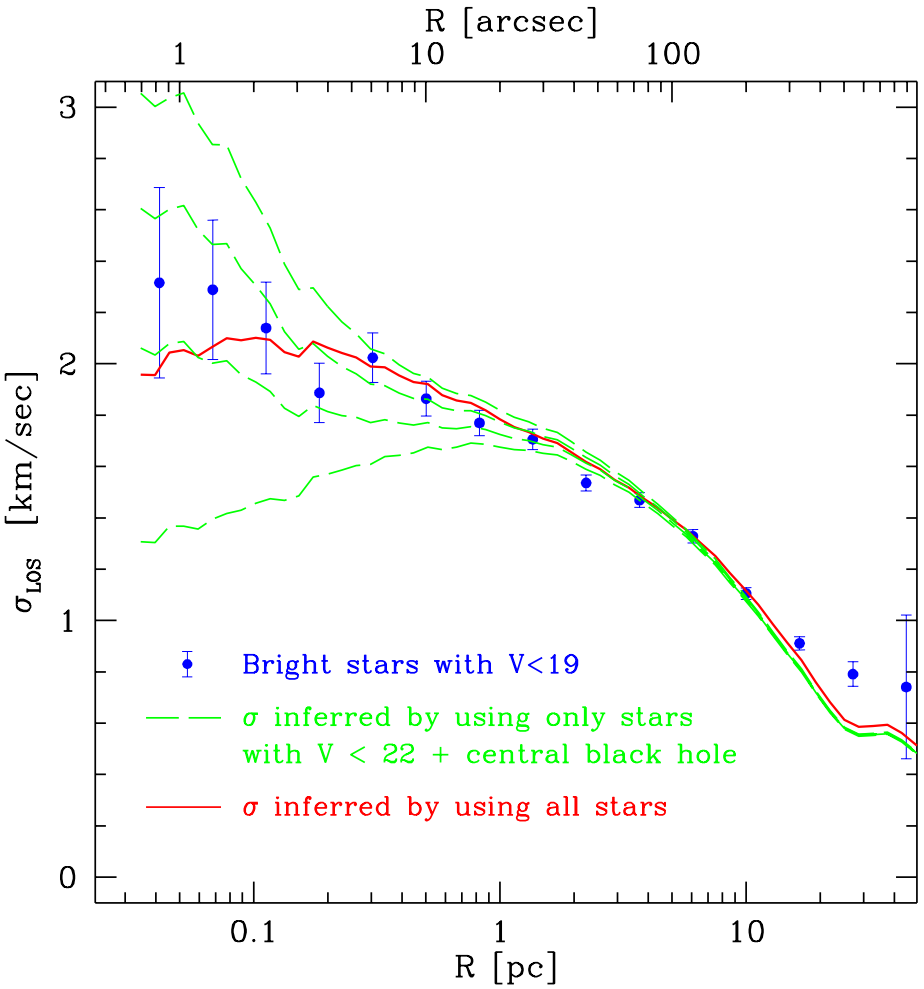
Results

astro-ph/0210133, ApJ accepted.



Left: velocity dispersion; Right: Surface density.

And we "found" BH...



Inversion of surface number density of bright stars gives too small central velocity dispersion without central BH.

Black hole mass $= 80 M_{\odot}$.

If scaled to M15,

$\sim 3 \times 10^3 M_{\odot}$ **(Gerssen** *et al.*: $\sim 3 \times 10^3 M_{\odot}$**)**

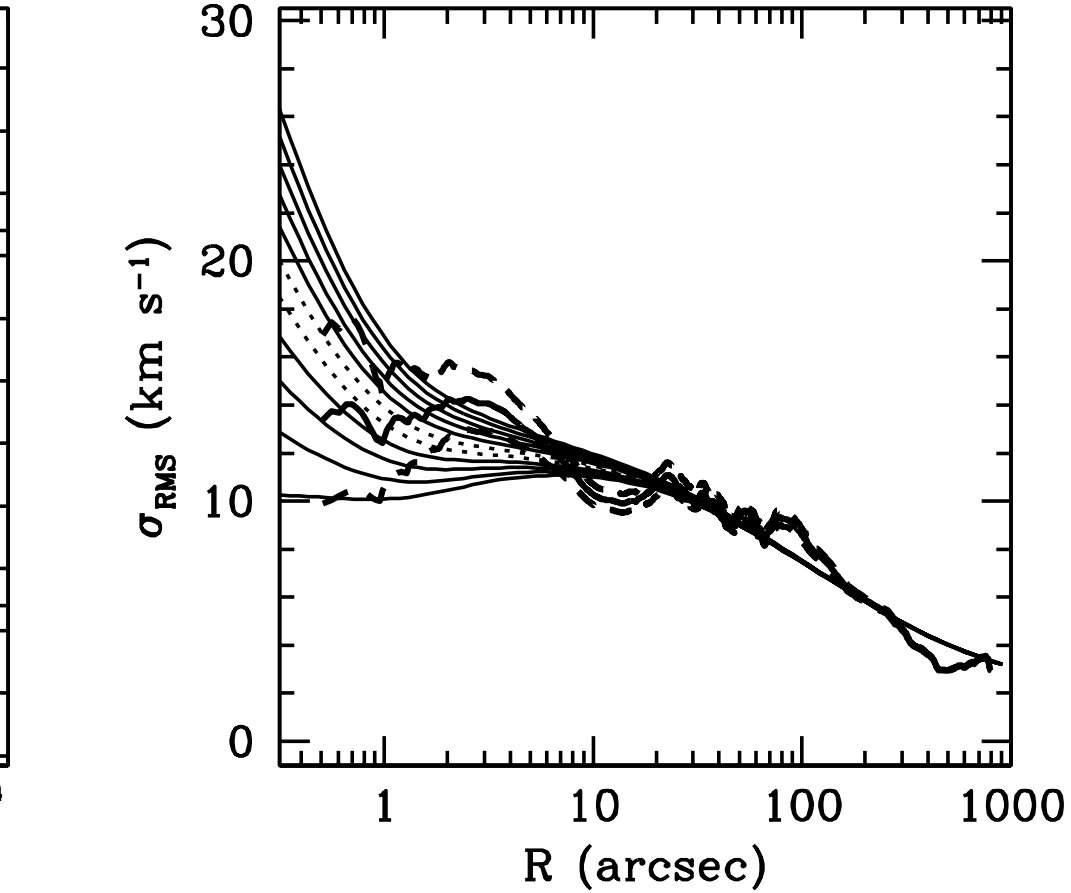
Why we "found" BH?

We "found" BH because we assumed constant M/L.

If we use the true M/L, of course we do not need BH.

But didn't Gerssen *et al.* try realistic M/L as well?

"Realistic" M/L

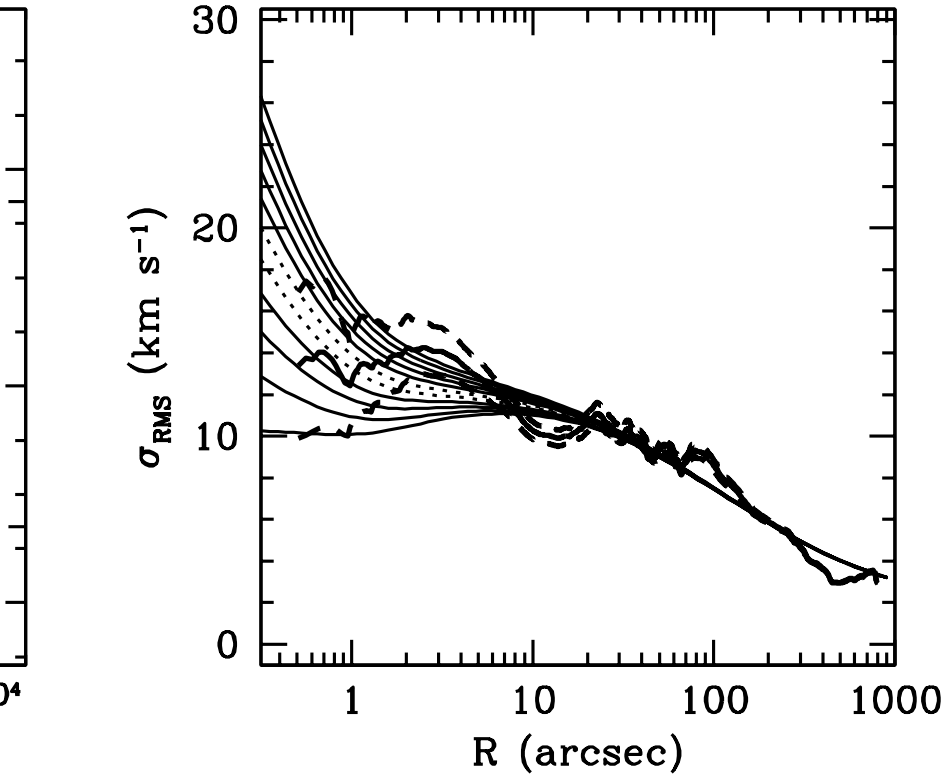


M/L profile from multi-mass Fokker-Planck calculation by Dull *et al.* (1997)

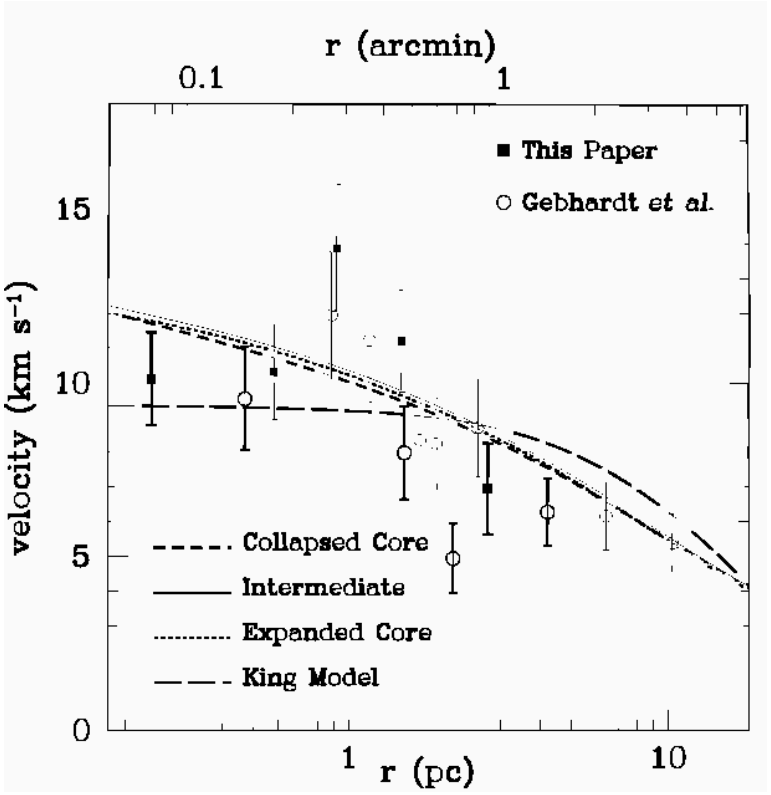
Very small change in the velocity profile. Large BH still necessary.

So why the difference?

Gerssen



Dull



Using same M/L, they got very different velocity profiles.

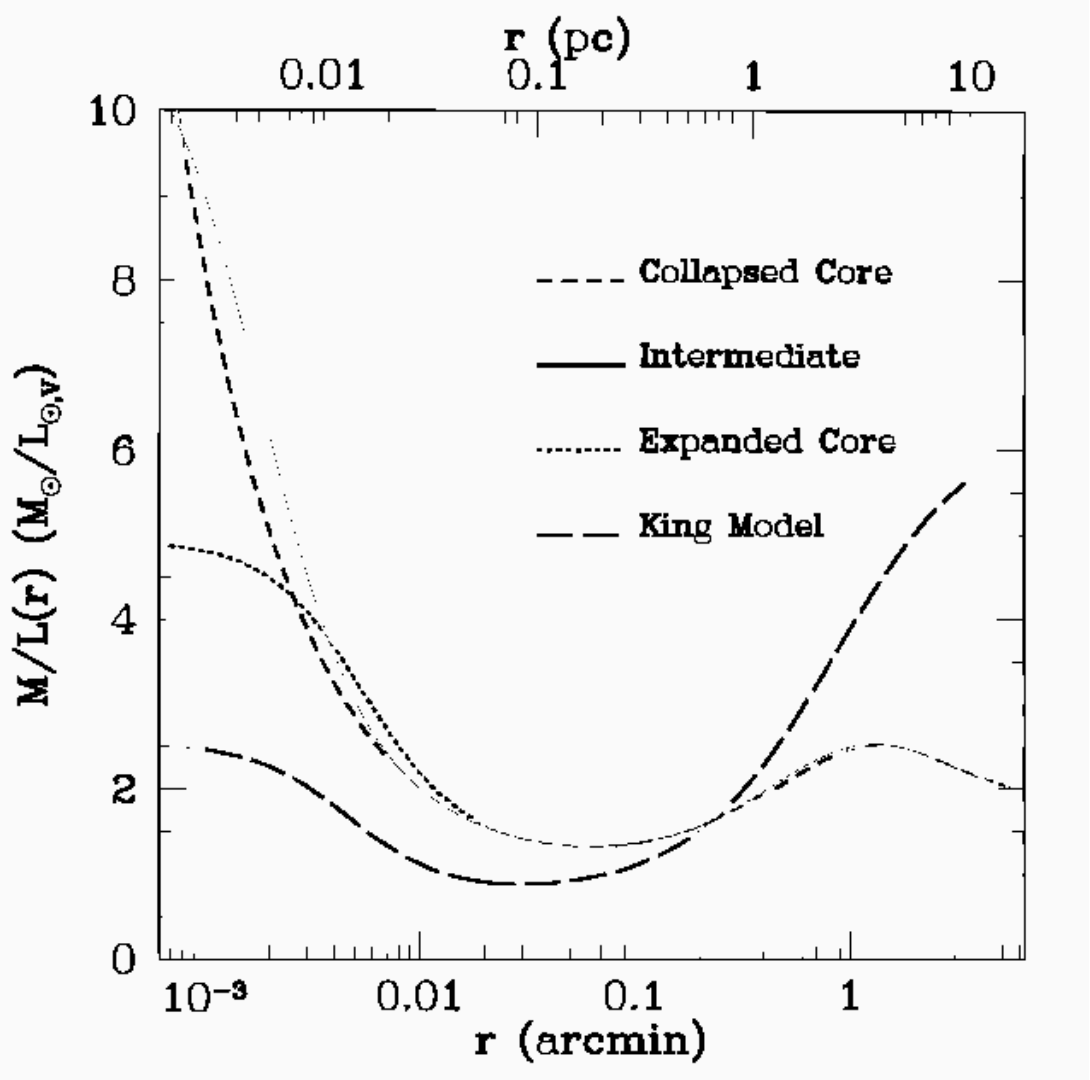
Addendum :

Gerssen et al. astro-ph/0210158 (Oct 8, 2002).

...

After the completion of our paper, the authors of the D97 paper discovered an unfortunate error in their Figures 9 and 12. The labeling along the abscissa of these figures is incorrect due to a coding error in supermongo plotting routines (H. Cohn and B. Murphy, private communication, 2002). The units along the top axis should have read 'arcmin' instead of 'pc', and the labeling in arcmin along the bottom axis is incorrect. The net result is that the radial scale of these figures in the D97 paper is too compressed by a factor 2.82.

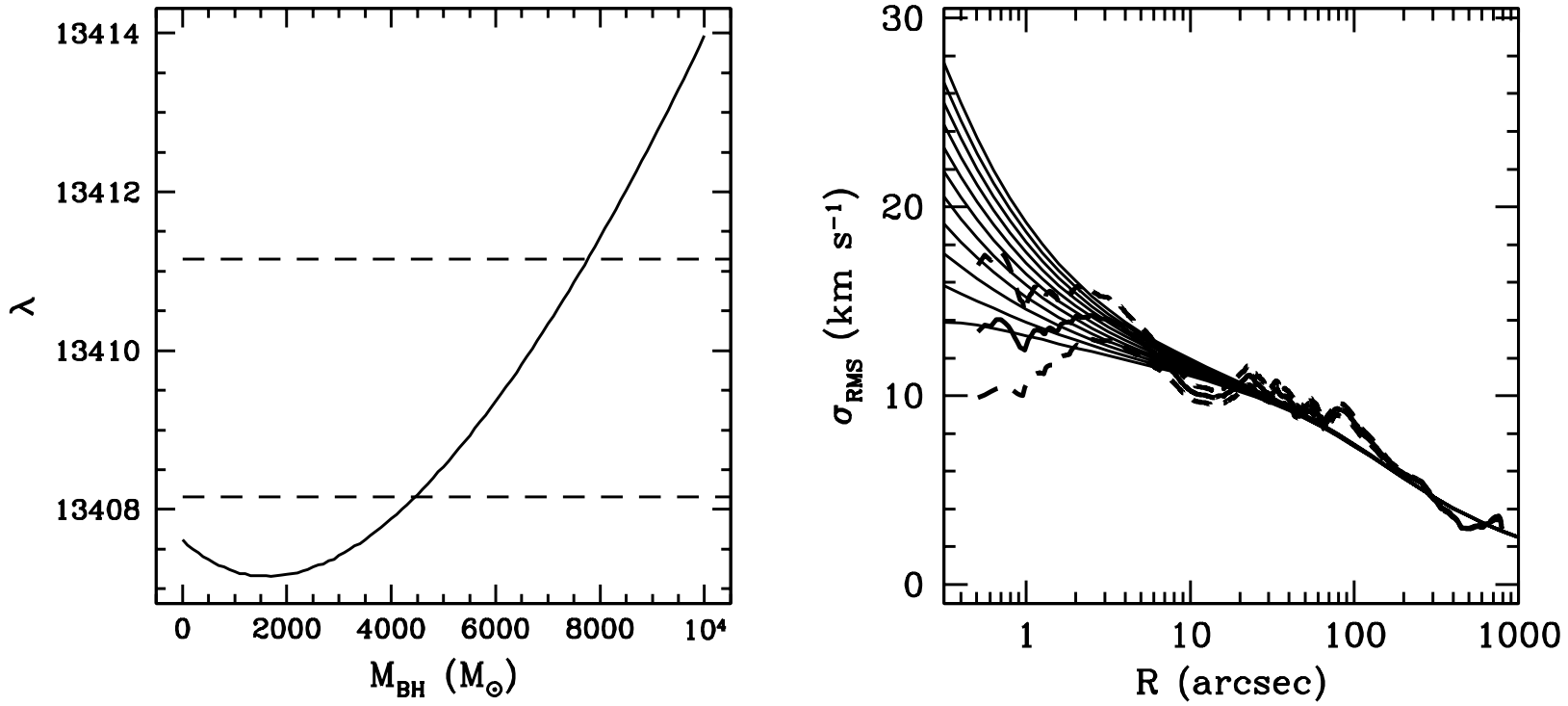
Dull M/L



should have read ‘arcmin’ instead of ‘pc’

New plot

New plot (astro-ph/0210158):

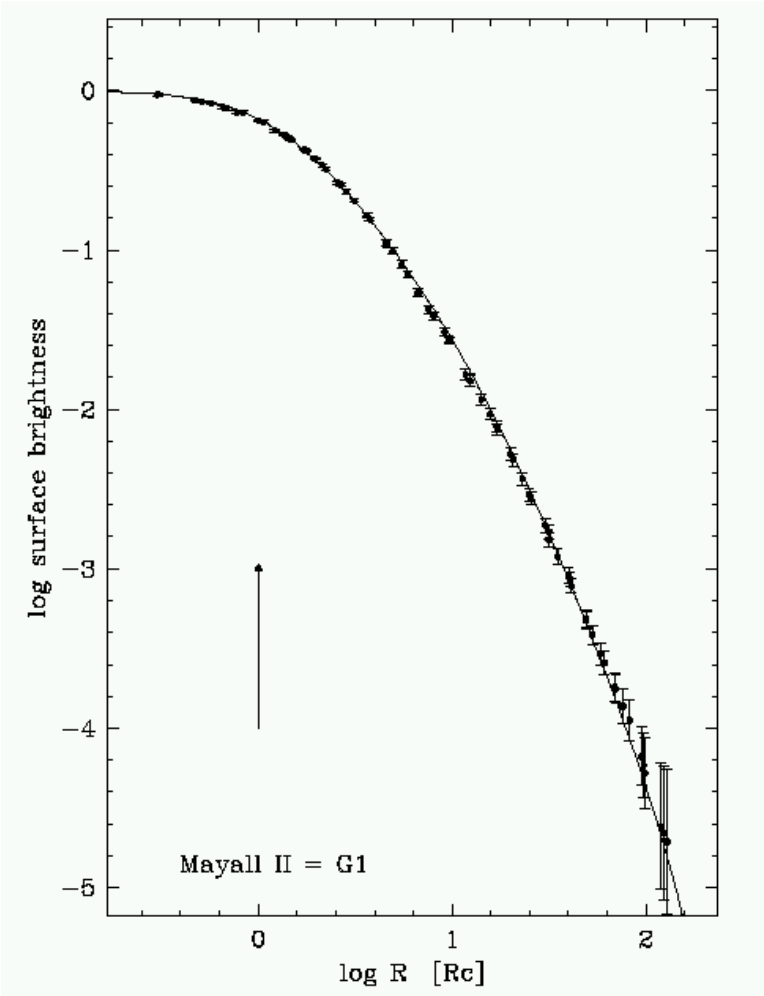


Black hole disappeared, or *"0.6 − σ detection"*.

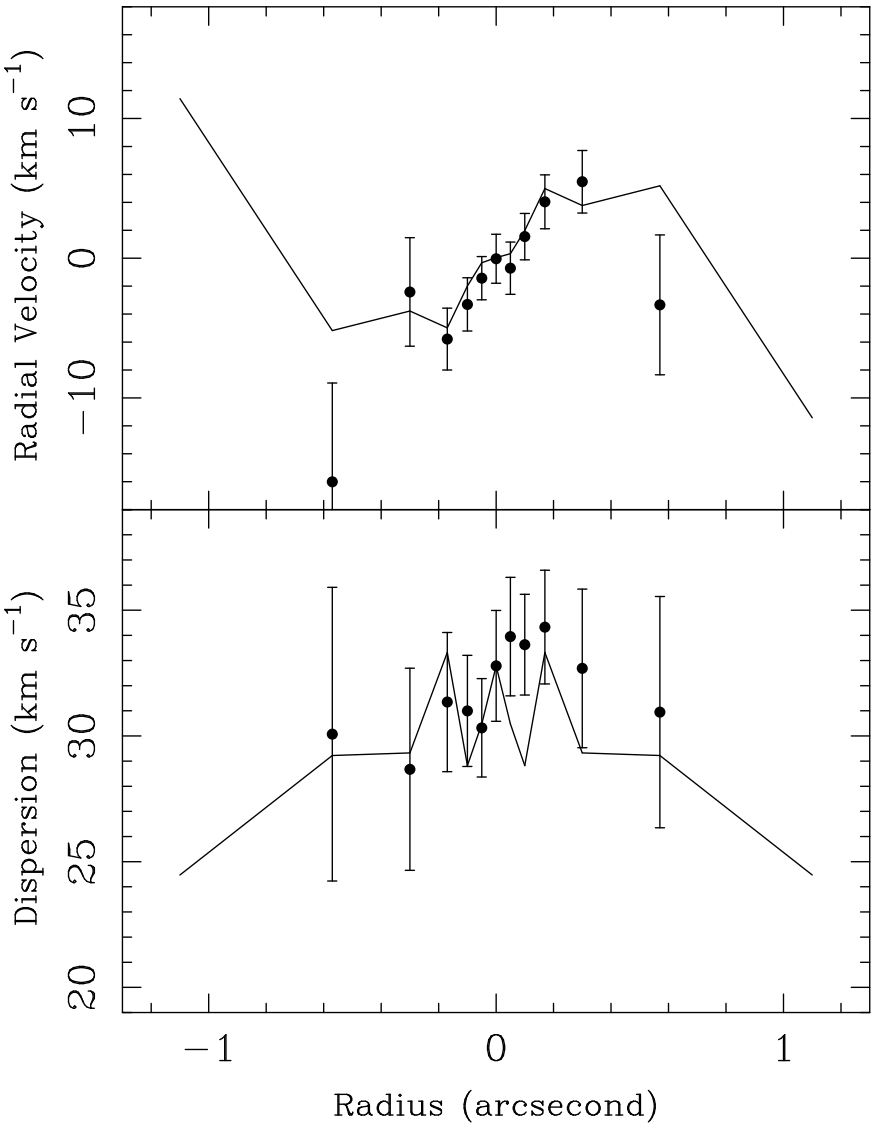
ここまでのまとめ

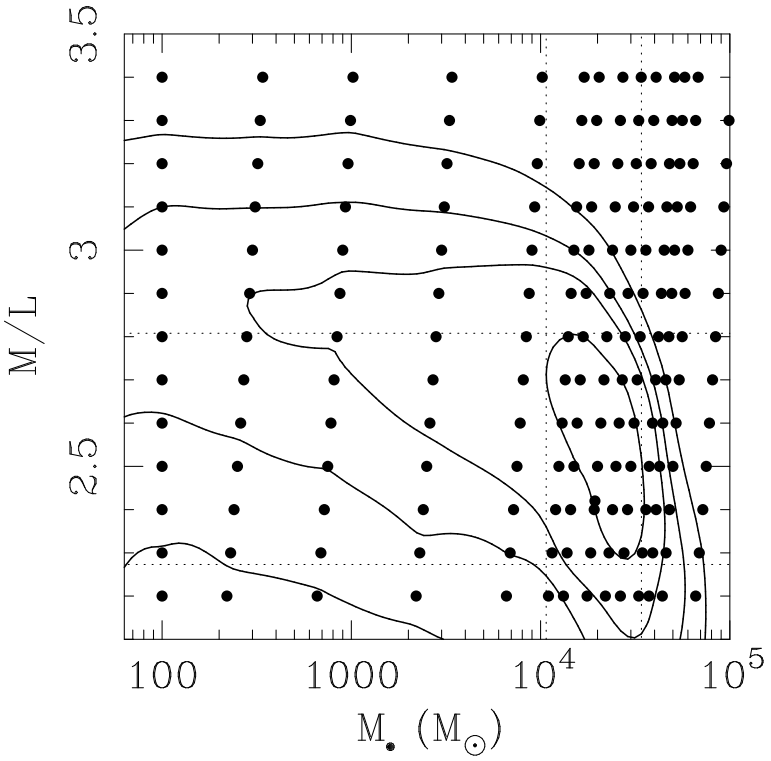
- 球状星団 $\mathbf{M15}$ の中心にブラックホールが見つかったという報告は基本的には計算間違いによるものであった。
- まあ、その傍証として、標準的な初期条件から普通に N 体シミュレーションした結果で、ブラックホールなしで観測された密度分布と速度分布の定性的な特徴は再現できる。(あるとあわないとは断言できない)
- これはむしろ、我々の球状星団に対する標準的な理解は「かなり本当らしい」ということを観測結果が示唆していると解釈してもいいのではないだろうか？

G1 — Photometry



G1 — Spectroscopy





G1 の特徴

Meylan et al (2001)

- (近傍で) 最大の球状星団 ($1.5 \times 10^7 M_\odot$)
- resolved core を持つ
- Multimass King model で合う
- 緩和時間が非常に長い ($> 40 Gyrs$)

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つまり、、、、

- 緩和時間が長いのに緩和しているように見える
- コアがあるのにブラックホールがある？

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なんかおかしいんではないか?

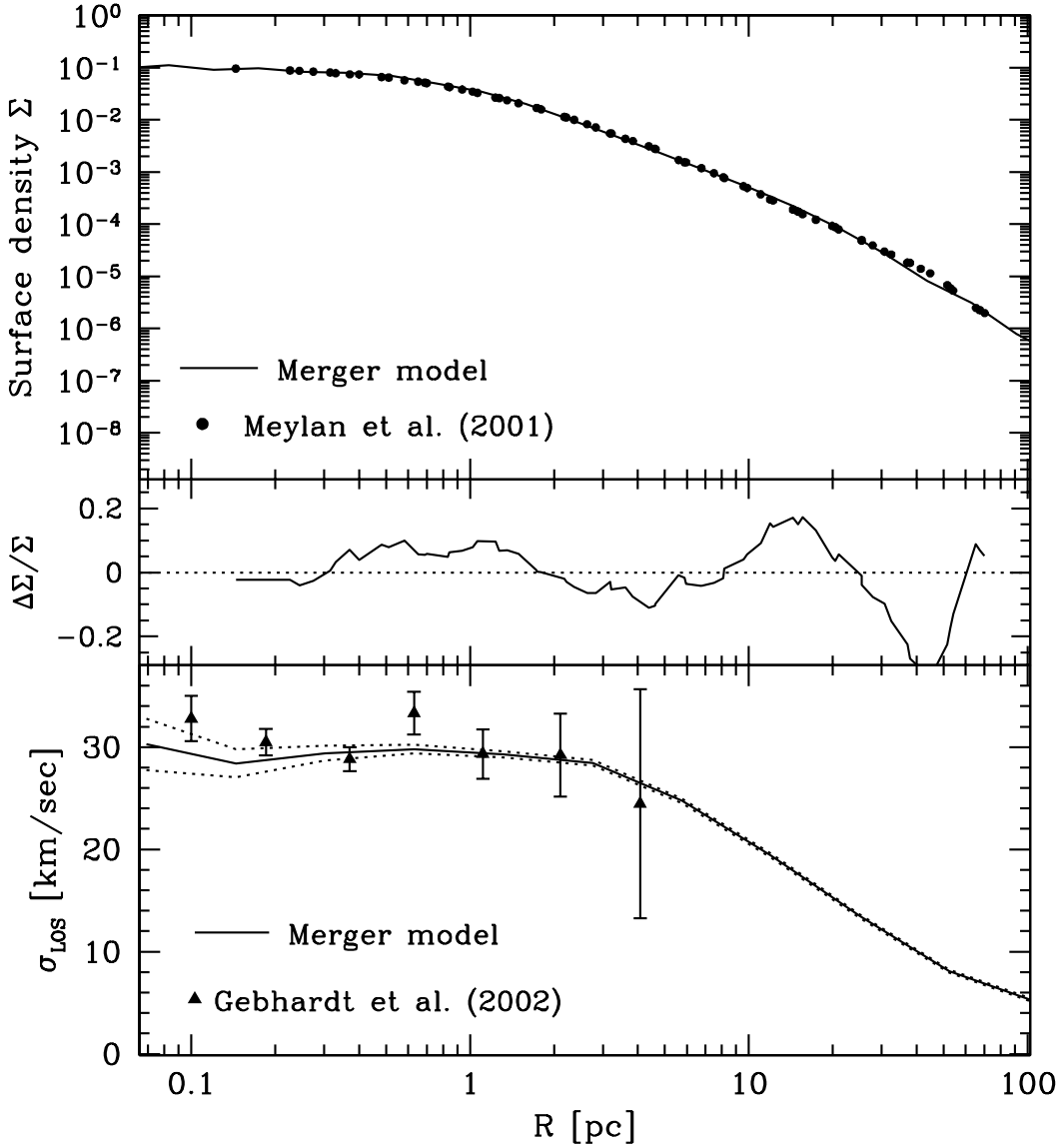
G1 の evolutionary model

Baumgardt et al. (astro-ph/0301469)

- **Binary globular cluster** からの進化
- コア半径、有効半径が観測に合う初期条件を捜す (結果的に **King**, $\psi_0 = 6.5$)
- 速度プロファイル等を観測と比べてみる

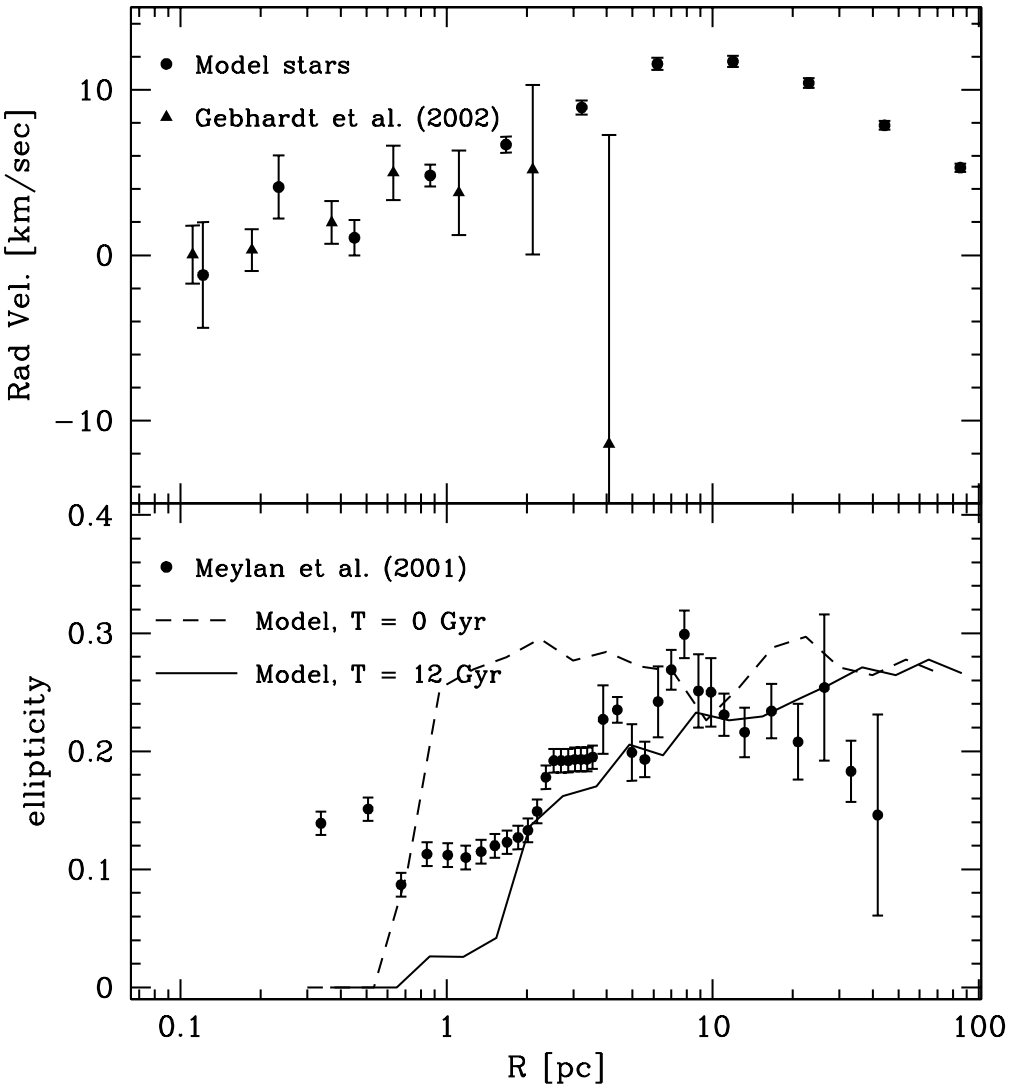
(**runaway merging** とかは起きない初期条件なので、ブラックホールはない)

結果(1)



- 密度プロファイルは非常に良く合う
- 速度分散もエラーバーの範囲

結果(2)



- 回転速度も妙に良く合う
- Ellipticity まで合う

つまり、、、

極めて標準的な

- まだ core collapse にいたっていない大きなコアを持つ。
- 合体時の violent relaxation 由来の r^{-4} 的ハローを持つ
- ブラックホールはない

モデルで、実際上「すべて」の観測データに合う。

質量: $M_C = (8 \pm 1) \times 10^6\ M_\odot$.
(ハローが緩和していないので M/L が小さい)

G1 にブラックホールがあると思ったのは一体何故？

K. Gebhardt (private communication)

- 速度分散プロファイルは確かに BH なしと矛盾しない
- 高次のモーメントがある

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

多分高次のモーメントは幻覚

G1 のまとめ

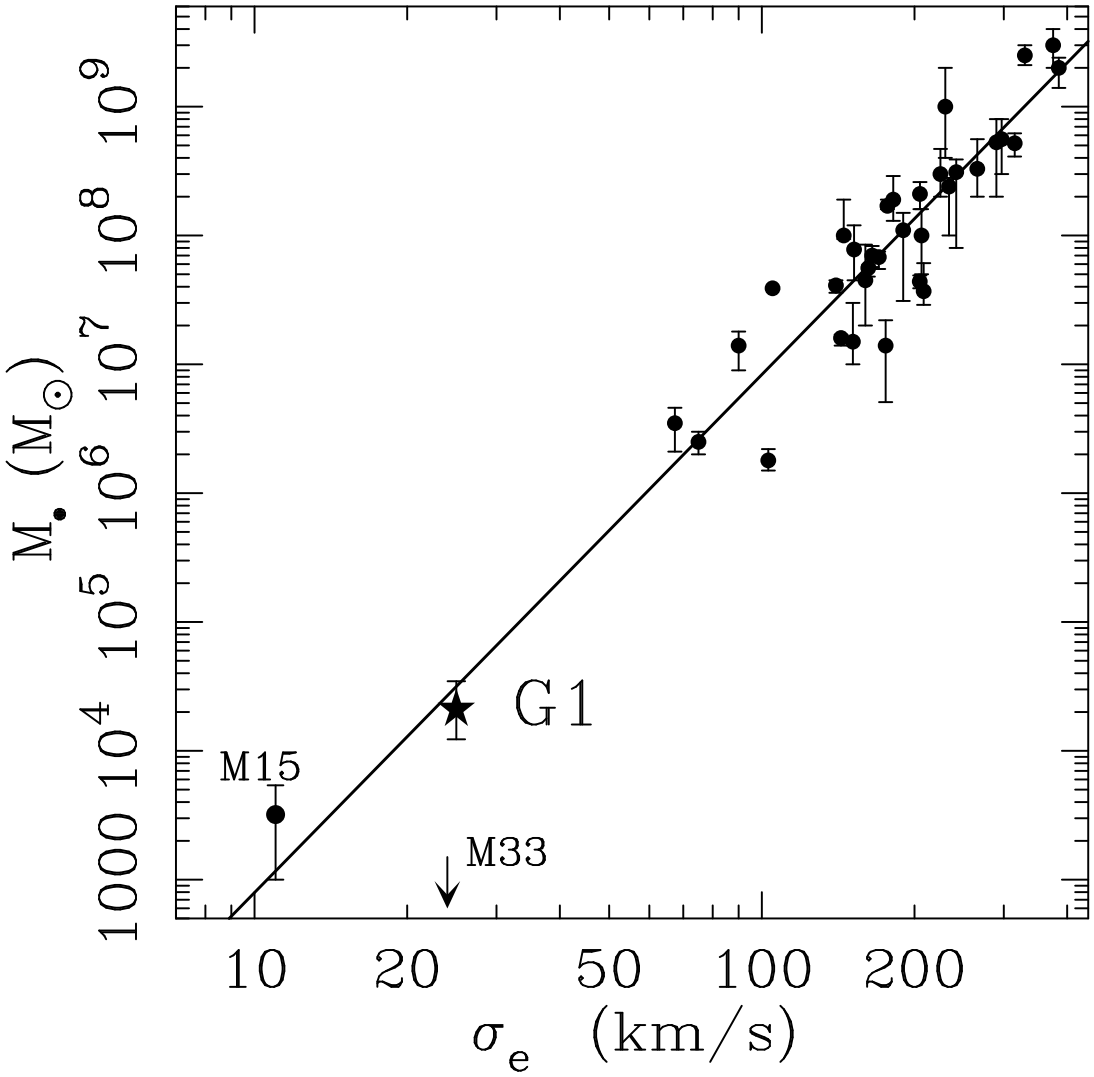
- G1 の構造は比較的素直な初期条件からの進化モデルで再現できる。
- 回転と密度分布を同時に説明する方法の一つは、連球状星団を初期条件とすること。
- 緩和時間が長いので、 M15 で起こったような stellar remnant の中心集中は起きない。
- Gebhardt et al. がブラックホールが必要と結論したのは、多分速度分散の高次のモーメントの解析に問題があるため。

楕円銀河は大丈夫？

Magorrian et al. (1998) のデータの相当数: G1 と同程度の有意性

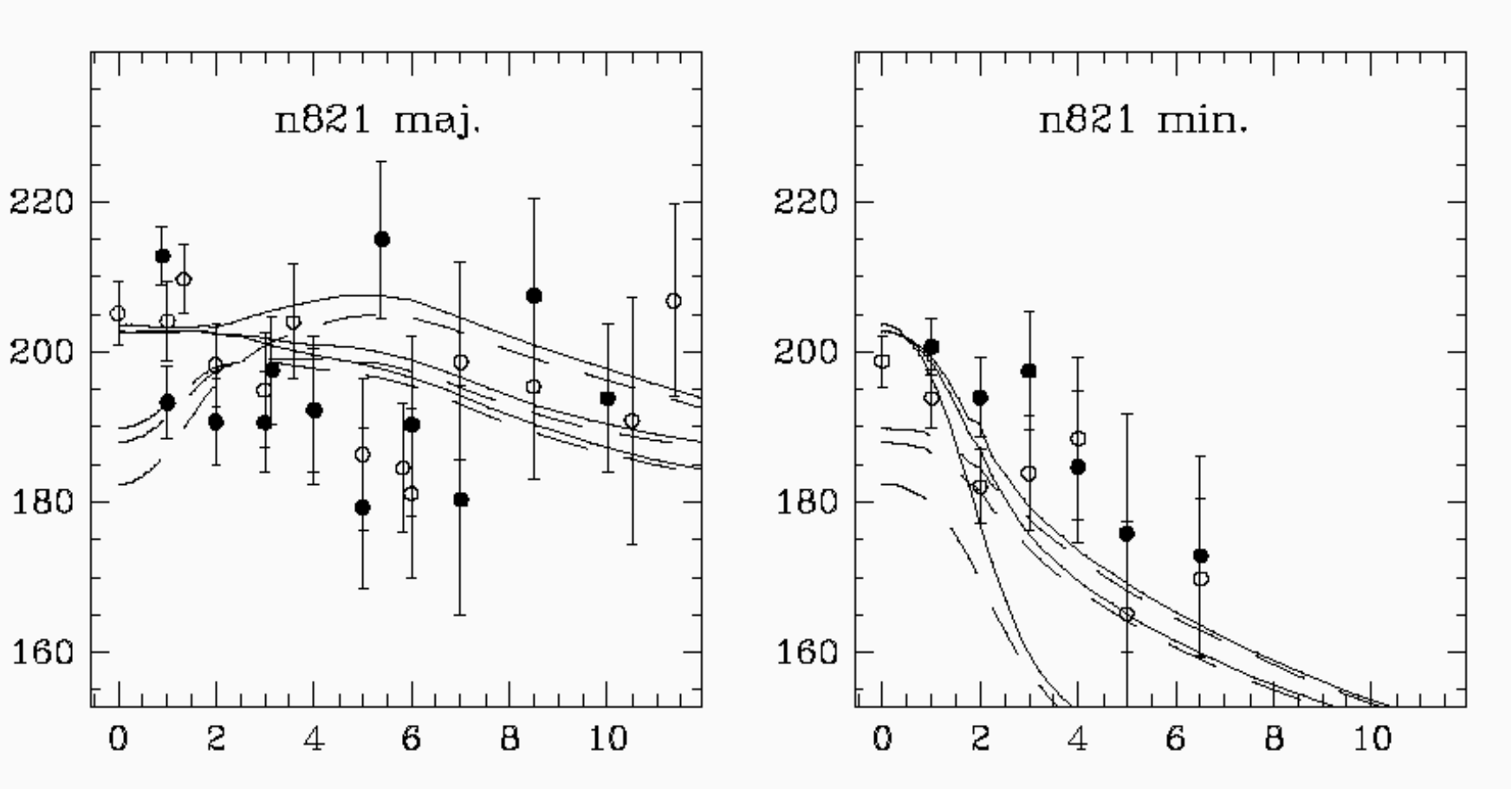
解析方法も同じ

???



典型的「BHあり楕円銀河」

NGC821 (From Magorrian et al 1998)



まとめ (1)

- 高密度で若い星団の中では、 dynamical friction で大質量星が星団コアに沈んで、そこで暴走的合体を起こすことで超大質量星から中間質量ブラックホールを形成できる (かもしれない)。
- このシナリオは、 M82 の中心近くに見つかった中間質量ブラックホールが、星団と重なった場所にあるという観測結果を自然に説明できる。

まとめ (2)

- 球状星団 M15 の中心にブラックホールが見つかったという報告は基本的には計算間違いによるものであった。
- その傍証として、標準的な初期条件から普通に N 体シミュレーションした結果で、ブラックホールなしで観測された密度分布と速度分布の定性的な特徴は再現できる。(BH があるとあわないとは断言できない)
- G1 も間違いの可能性高い。但し、こちらはモデルのどこに問題があったかはまだ完全にはわかってない。
- G1 が怪しいとすると楕円銀河の相当数も怪しい。

Summary

- **The likely formation mechanism for this IMBH is runaway merging of massive stars in the cluster core.**
- **Recent M15 observation is in perfect agreement with our resent N-body simulation, where no central BH presents.**
- **In fact, Observation is also consistent with FP result, again without BH.**
- **Though not impossible, it's unlikely that M15 harbors IMBH.**
- **A young star cluster in M82 hosts an IMBH candidate, which is most likely a missing link between stellar-mass BHs and MBHs.**

NS retention ratio

Both we and Dull *et al.* assumed 100% retention.

"realistic" ratio may be $< 10\%$.

Currently a run with 0% retention is underway.

The effect would not be too large

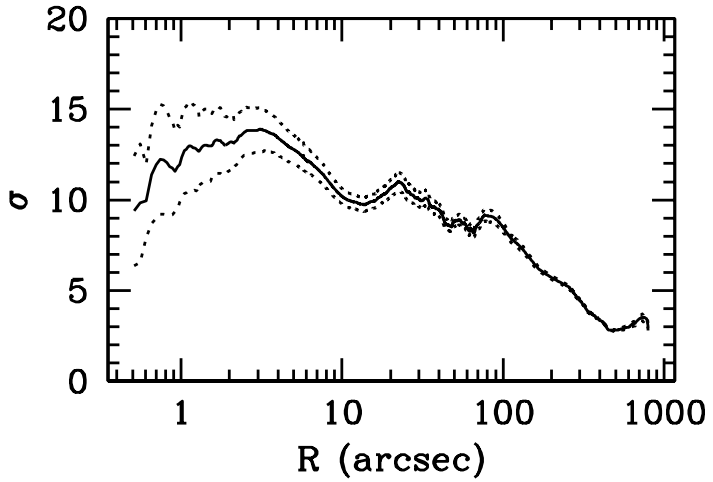
- **2× mass in massive WDs than in NS**
- **our model actually has too much dark mass in the center. Removal of NS would make the fit to M15 better.**

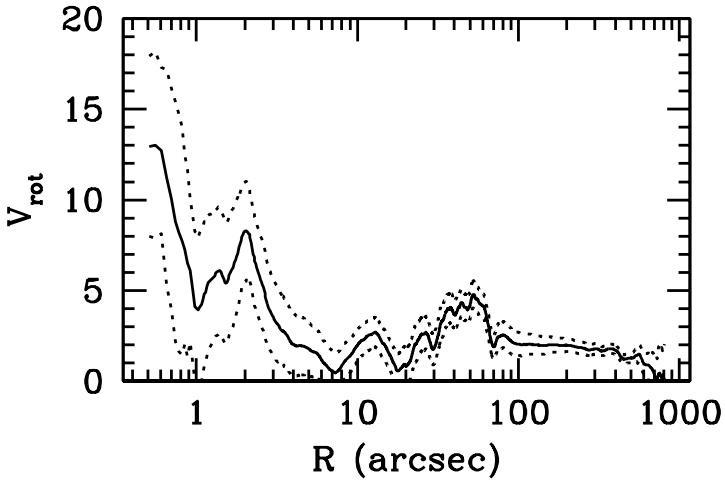
How about G1?

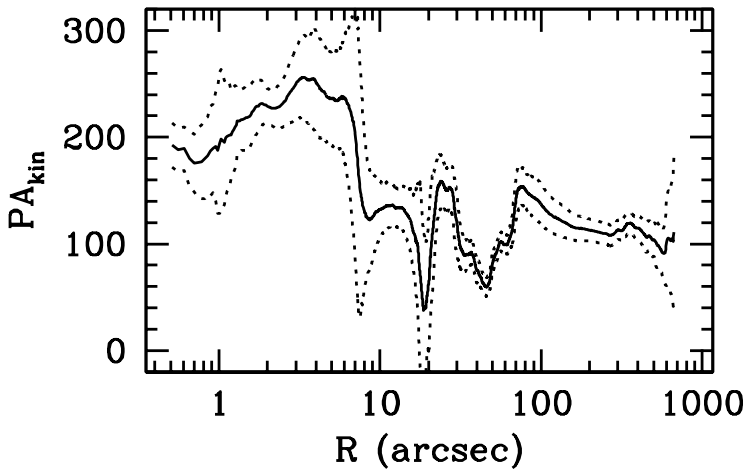
- Central thermal relaxation time $\sim 10^7$ yrs.
- Gebhardt et al. used constant M/L fitting.

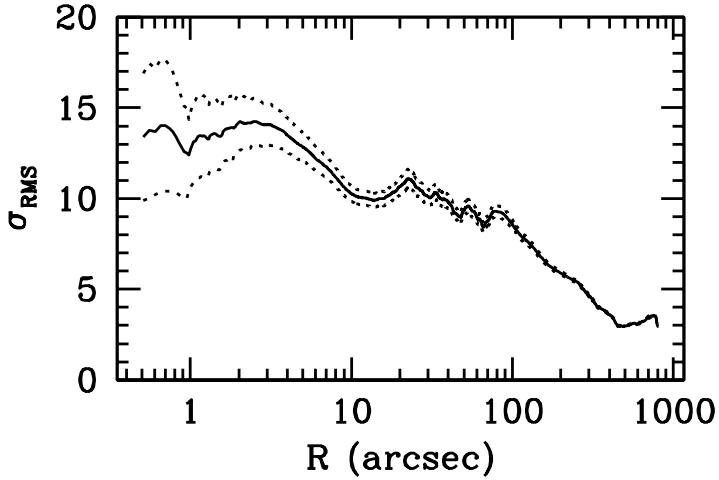
Too early to draw any conclusion, but...

Rotation?

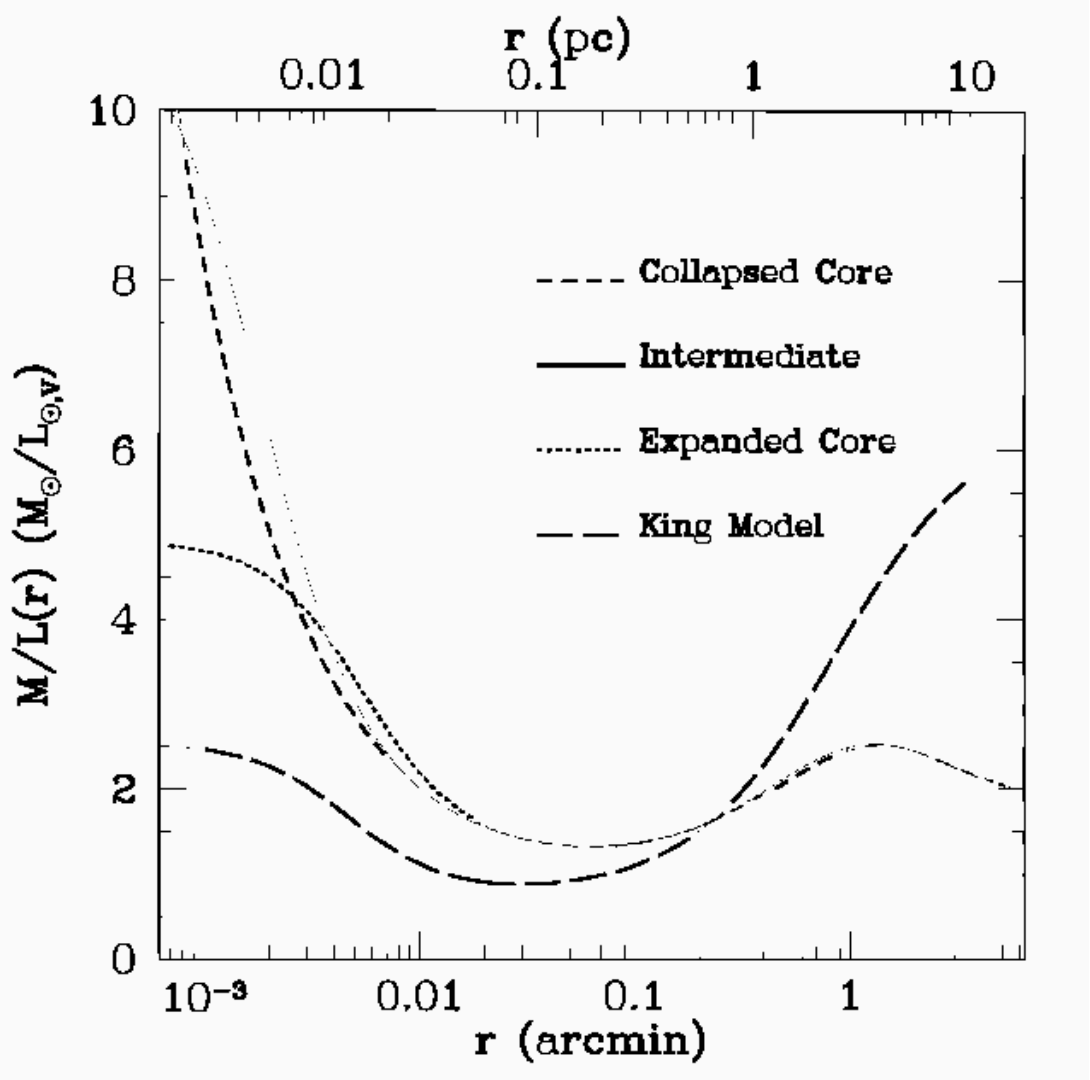




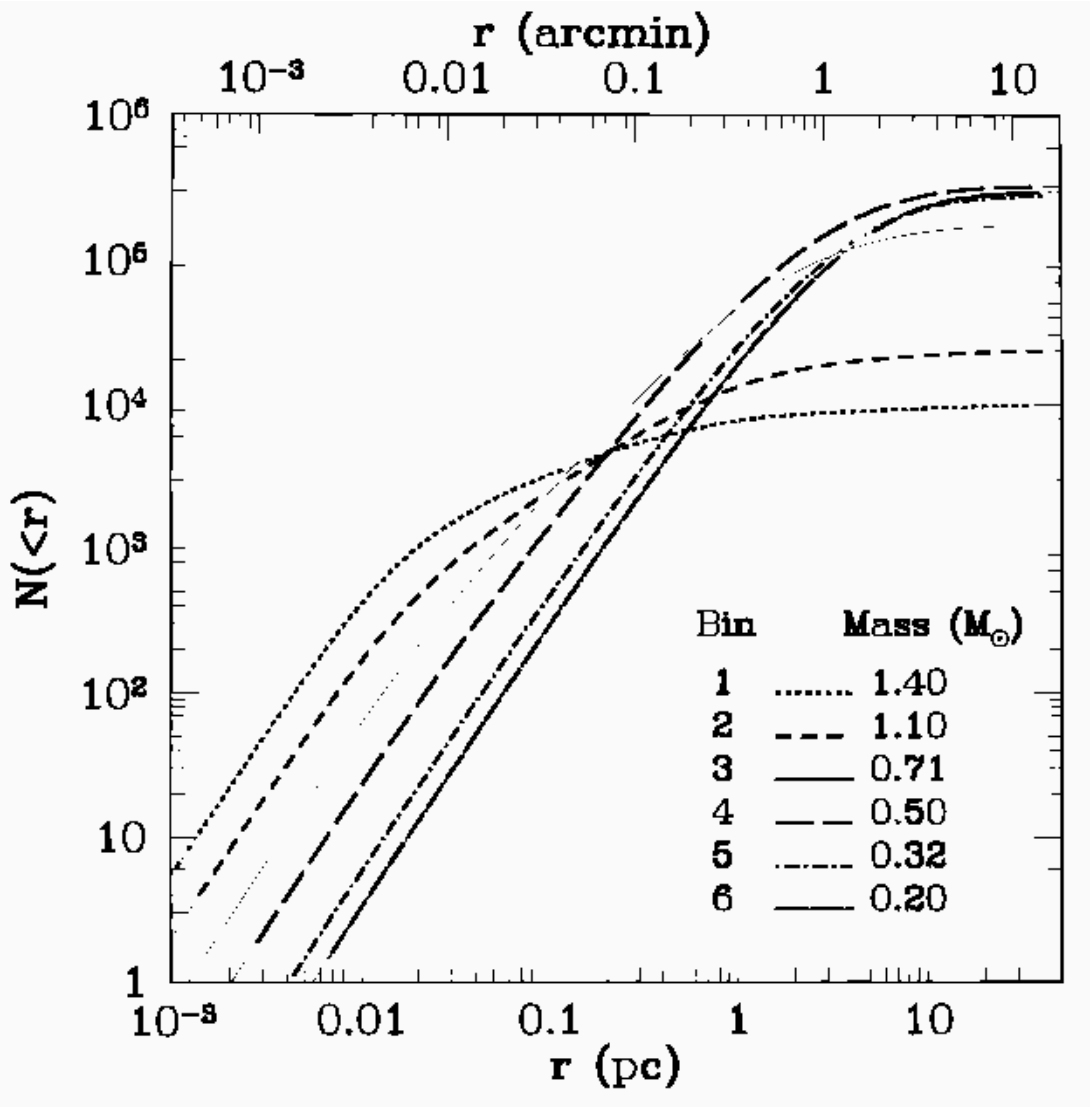




Dull M/L


r (pc)
0.01
0.1
1
10
M/L(r) (M⊙/L⊙,V)
Collapsed Core
Intermediate
Expanded Core
King Model
10⁻³
0.01
0.1
1
r (arcmin)

Dull Cumulative mass



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)
$\longrightarrow$ 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**

Continuous accretion?

In principle, a $10M_\odot$ 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???

Possibilities

Back to Rees' view

- **IMBH has formed directly (or through a massive star) from gas cloud**
- **IMBH has formed through merging of stellar BHs/NSs**

Both unlikely...

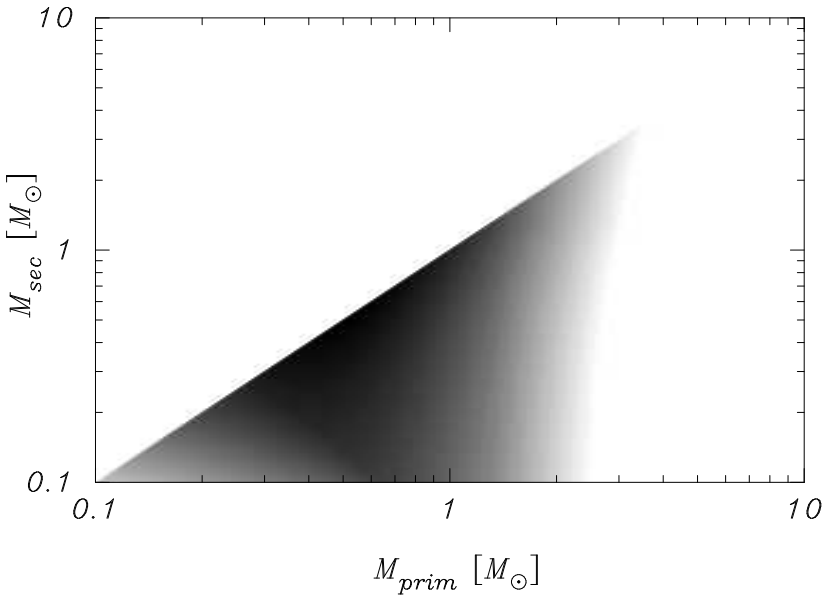
What's new?

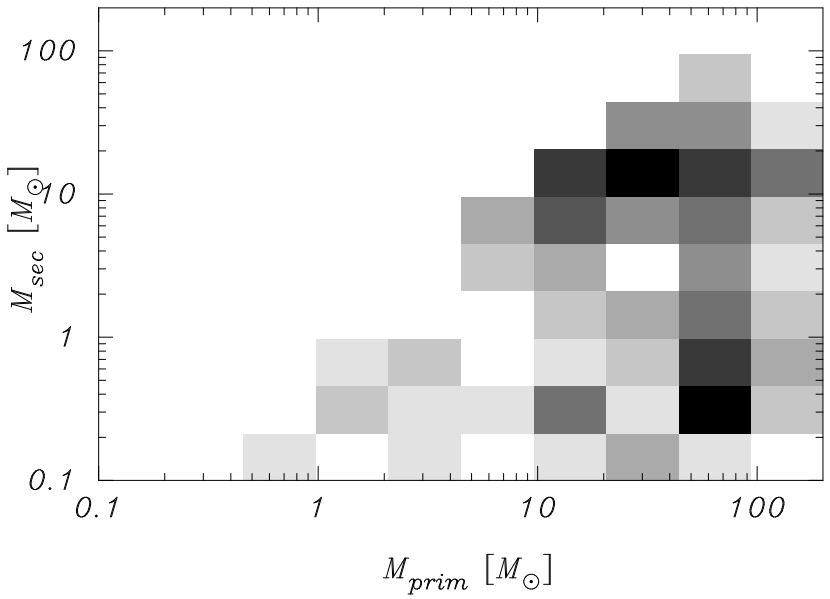
- Take into account the merging of young, massive stars.
  Merging of massive stars is many orders more frequent than that of compact stars.
- Merging is easy in star clusters with low velocity dispersion.
- Some numerical support...

New results from simulation

- Mergings occur much more often than simple back-of-the-envelope estimate tells.
- Mergings occur primarily between most massive stars in the cluster.
- Mergings occur in the very center of the cluster.

How often is often?





Theory **Simulation result**

Theoretical estimate: less than 1 collision

Numerical result: around 30 collisions

Why such a huge difference?

- Massive stars sink to the center through dynamical friction
- Massive stars form binaries by triple encounters
- Binary-single star interaction cross section is much larger than direct collision cross section
- Large fraction of resonant binary-single star interaction result in merging of two stars (Hut and Inagaki 1985)

Unknowns

Observation:

- **Kinematical data of the star cluster. Size, radial profile, velocity dispersion etc etc.**

Theory

- **Evolution of supermassive ($> 100 M_{\odot}$) star.**
- **Structure and evolution of BH-MS star merger remnant.**

Is M82 a typical galaxy?

— Certainly not... nearby starburst, past interaction with M81

Are there any other IMBHs in any other galaxy?

NGC3628

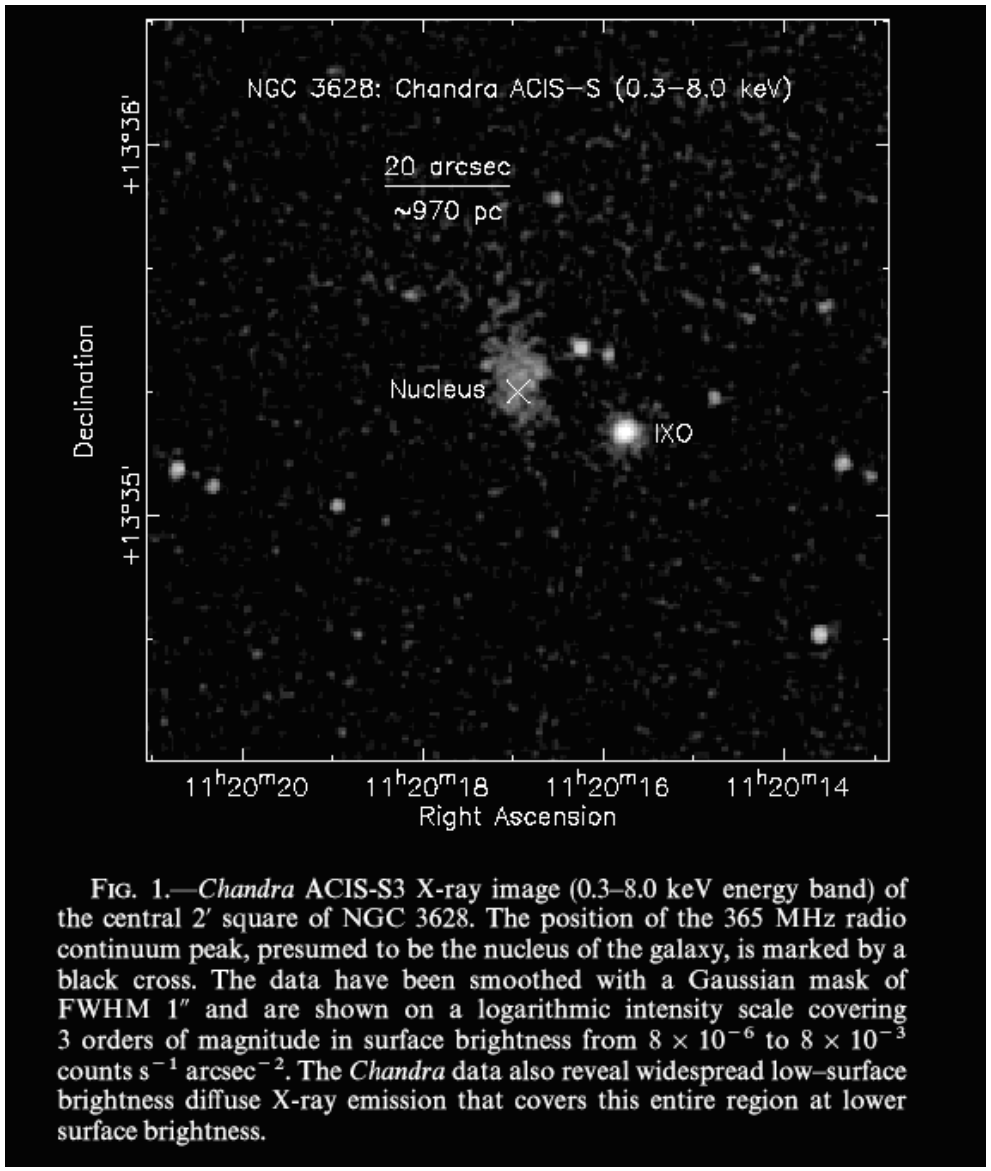


FIG. 1.—*Chandra* ACIS-S3 X-ray image (0.3–8.0 keV energy band) of the central 2′ square of NGC 3628. The position of the 365 MHz radio continuum peak, presumed to be the nucleus of the galaxy, is marked by a black cross. The data have been smoothed with a Gaussian mask of FWHM 1″ and are shown on a logarithmic intensity scale covering 3 orders of magnitude in surface brightness from 8×10^{-6} to 8×10^{-3} counts s^{-1} $arcsec^{-2}$. The *Chandra* data also reveal widespread low–surface brightness diffuse X-ray emission that covers this entire region at lower surface brightness.

Strickland et al. 2001, ApJ 560, 707

Nearby starburst (10Mpc)
$L_x \sim 5 \times 10^{40} ergs/s$

First found 1991 (ROSAT)
Disappeared in 1994
Reappeared in 2000 (Chandra)

Other IMBH candidates

- At leat more than one found.
- Both in Starburst — consistent with our picture
- No optical/IR counterpart known (no deep image yet...)

Far from conclusive, but looks promising.

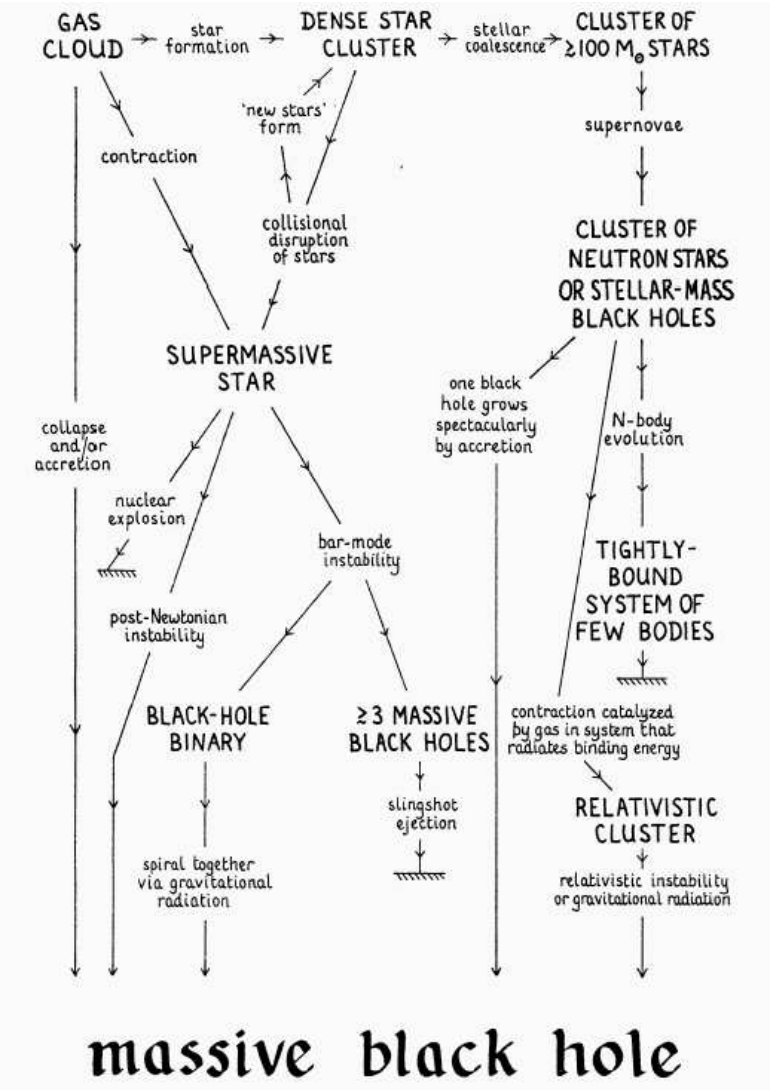
How far we have come?

Our scenario: covers stellar-mass BH, IMBH and MBH in starburst galaxies.

Spiral galaxies: may have experienced starburst

QSOs and E: Major merger? growth from MBH to SMBH

Introduction: How to make MBHs?



"Classic" View (Rees 1984)

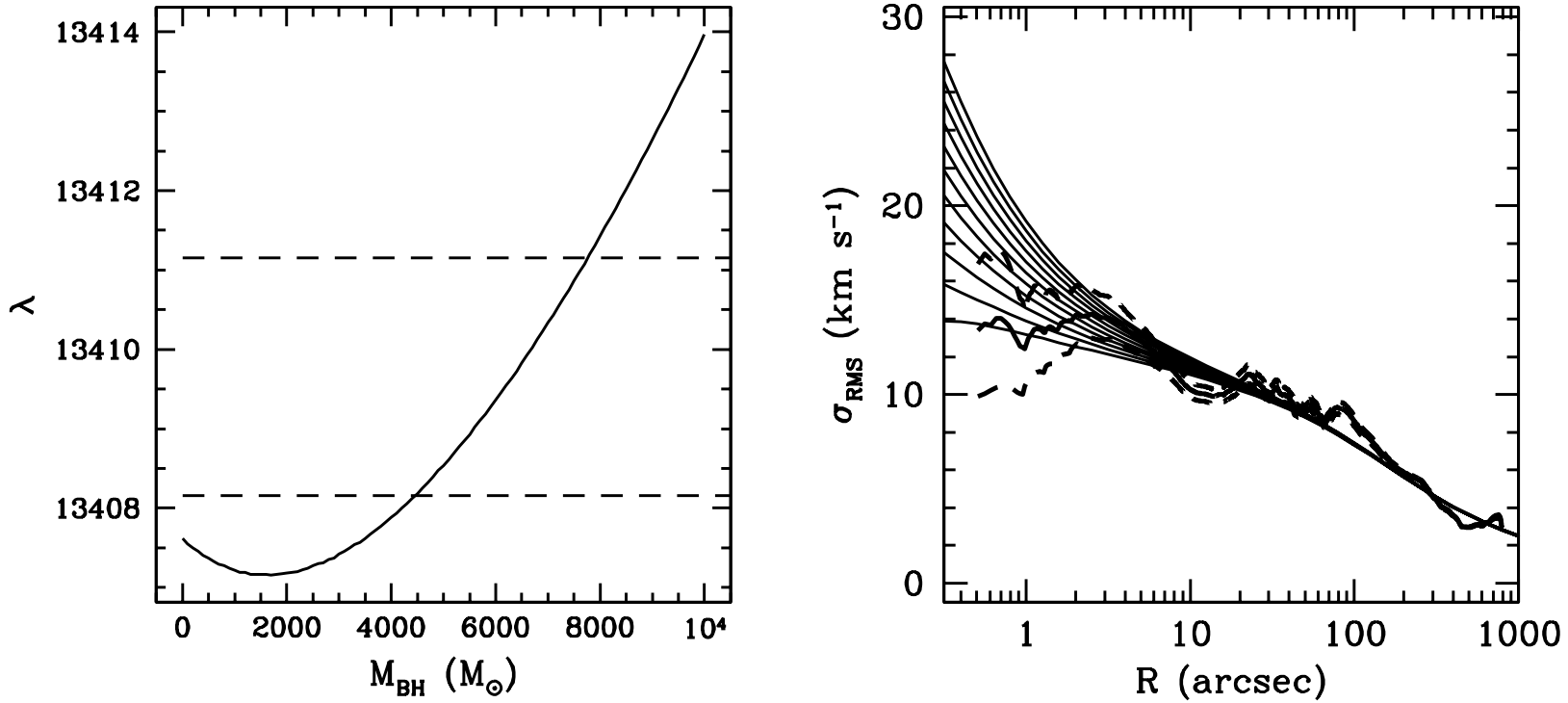
Essentially two possibilities

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

Both difficult...

So why the difference? (cont'd)

Dull et al. M/L plot turned out to be wrong. New plot:



So why the difference? (cont'd)

Velocity dispersions are different.

On the other hand...

Same M/L is used.
Same luminocity profile is used. (Both from HST observations)

Dull *et al.* results are internally consistent.

We cannot judge whether Gerssen *et al.* results are internally consistent or not. Neither luminosity nor M/L are in their paper.