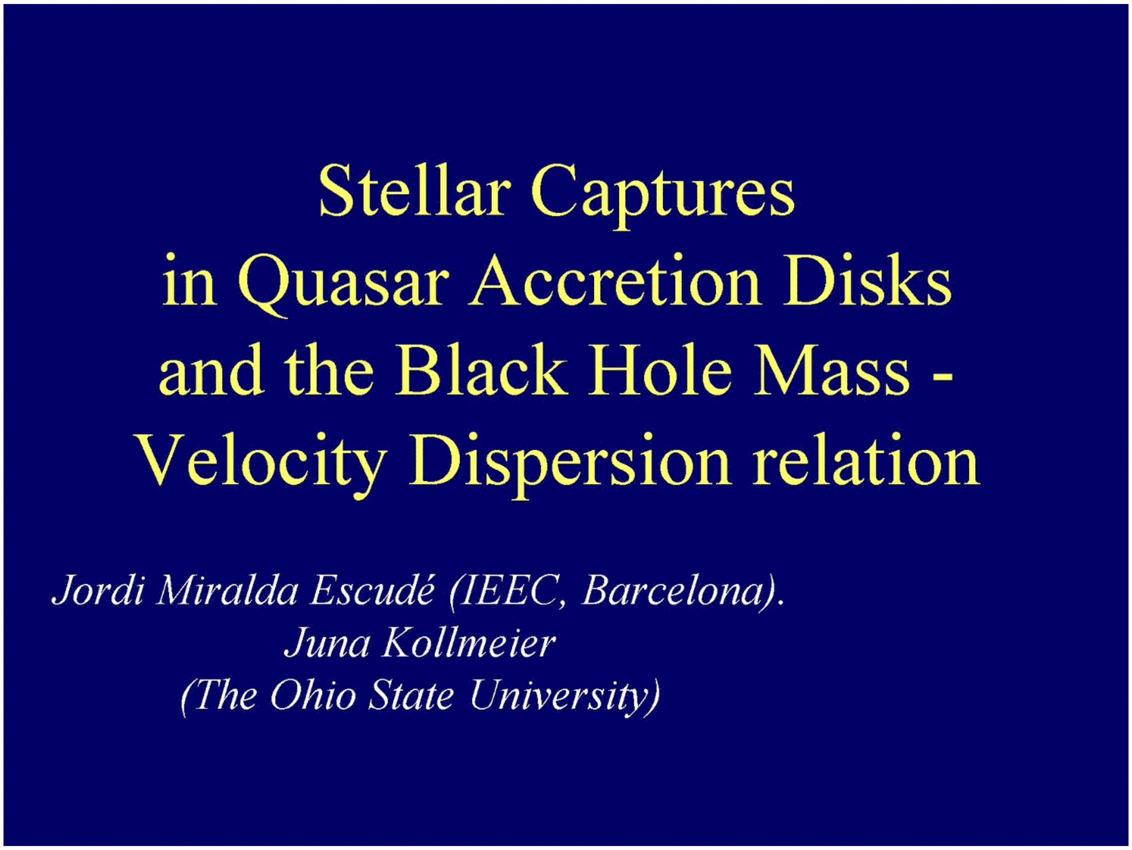

Stellar Captures in Quasar Accretion Disks and the Black Hole Mass - Velocity Dispersion relation

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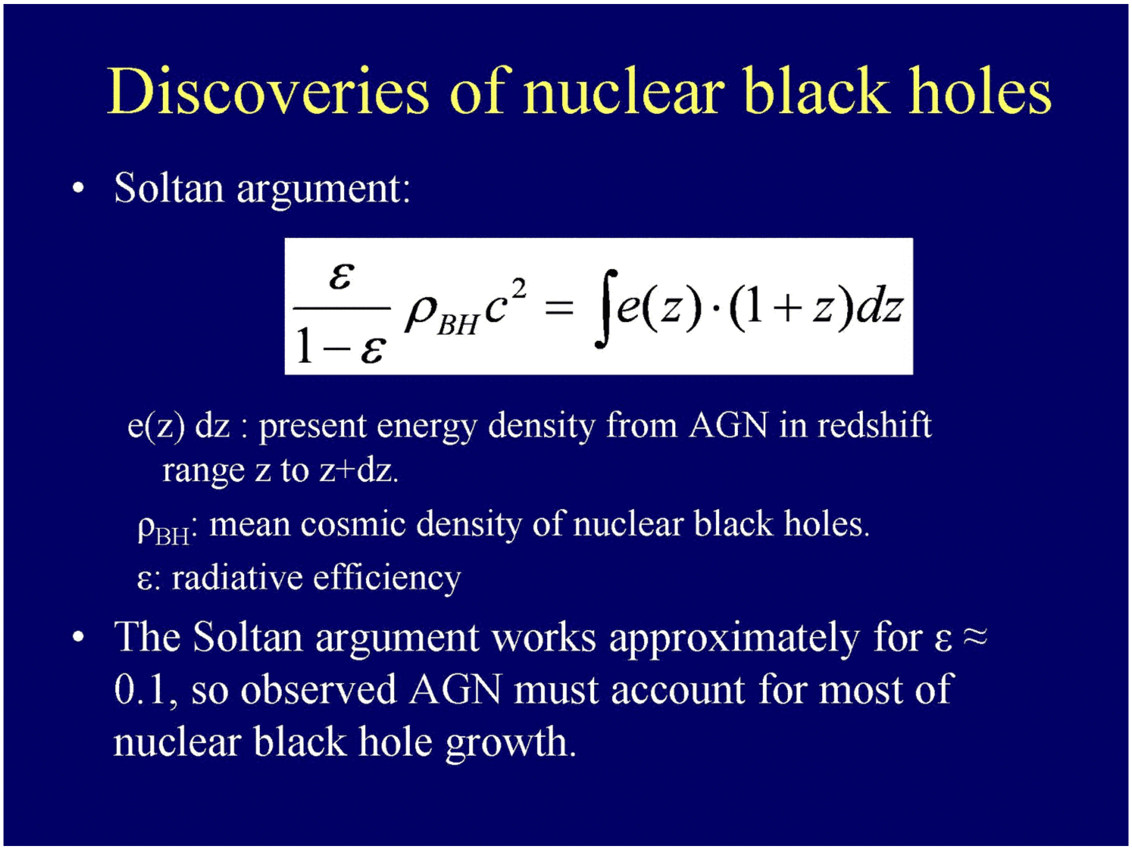


Discoveries of nuclear black holes

- Soltan argument:

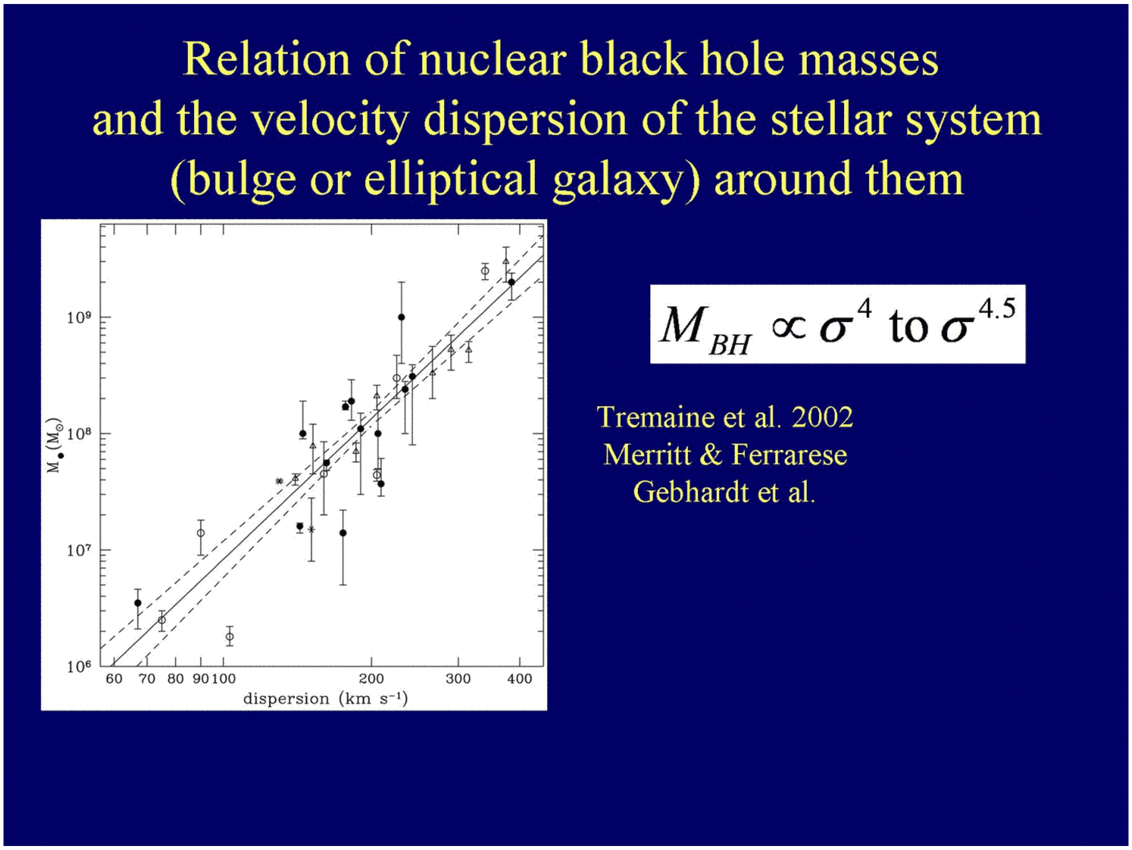
$$\frac{\varepsilon}{1-\varepsilon}\rho_{BH}c^2 = \int e(z)\cdot(1+z)dz$$

e(z) dz : present energy density from AGN in redshift range z to z+dz.

ρ_{BH}: mean cosmic density of nuclear black holes.

ε: radiative efficiency

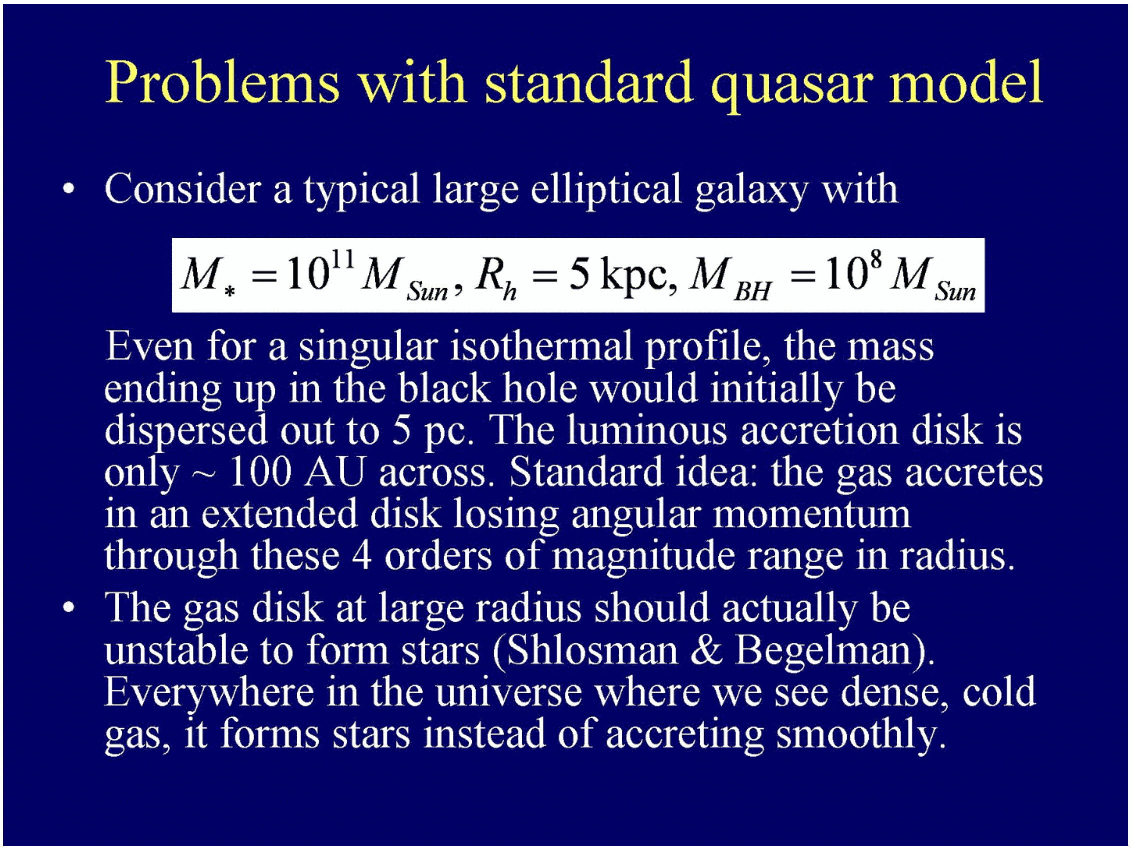
- The Soltan argument works approximately for $\varepsilon \approx 0.1$, so observed AGN must account for most of nuclear black hole growth.



Relation of nuclear black hole masses and the velocity dispersion of the stellar system (bulge or elliptical galaxy) around them

$$M_{BH} \propto \sigma^4 \text{ to } \sigma^{4.5}$$

Tremaine et al. 2002
Merritt & Ferrarese
Gebhardt et al.



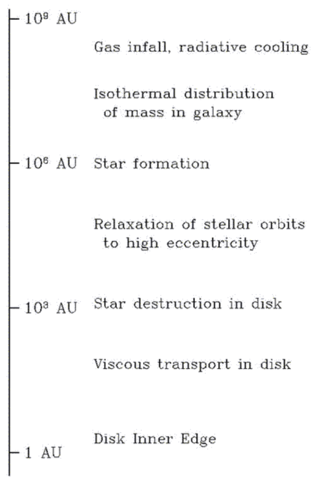
Problems with standard quasar model

- Consider a typical large elliptical galaxy with

$$M_* = 10^{11} M_{Sun}, R_h = 5\,\text{kpc}, M_{BH} = 10^8 M_{Sun}$$

Even for a singular isothermal profile, the mass ending up in the black hole would initially be dispersed out to 5 pc. The luminous accretion disk is only ~ 100 AU across. Standard idea: the gas accretes in an extended disk losing angular momentum through these 4 orders of magnitude range in radius.

- The gas disk at large radius should actually be unstable to form stars (Shlosman & Begelman). Everywhere in the universe where we see dense, cold gas, it forms stars instead of accreting smoothly.



Key questions:

- How is the large BH mass transported to the small nuclear disk?
- Why is the BH mass related to the spheroidal stellar system, and not the galactic disk? What establishes the M-σ relation?

A new quasar model: feeding the disk with stars

- Black holes grow by accreting gas from a thin disk, and matter is delivered to the disk by stars plunging through it.
- Quasars are active during nuclear starburst episodes, when a high density of young stars is present in the nucleus with rapid rates of orbital relaxation. Stars crash on the disk when their orbits become highly eccentric.

Assumptions of the model

- Stars are slowed by ordinary drag as they cross the disk, and captured into the disk after many crossings (Ostriker 1983, Syer etal 1991, …).
- Surface density profile of thin α-disk, Shakura-Sunyaev model
- Capture occurs from very eccentric orbits. Relaxation keeps phase space density constant (full loss-cone).
- There is a steady state of mass delivered into the disk by stars, and mass accreted from the disk to the black hole. The M-σ relation is established by the required density of stars for this mass supply rate.

How are stars captured by the disk?

- Stars slow down as they cross the disk:

$$\Delta v \approx (\Sigma_{disk} / \Sigma_*) v$$

  - Typically, $\Sigma_{\mathrm{disk}} << \Sigma_*$, $v \sim 10^4$ km/s
- The star is captured when the energy lost by crossing the disk near pericenter p is equal to the orbital energy:

$$\Delta E = v \Delta v \approx \frac{\Sigma_d(p)}{\Sigma_*} \frac{GM}{p} \approx \frac{GM}{a}$$

$$\frac{\Sigma_d(p)}{\Sigma_*} \approx \frac{p}{a}$$

Radius out to which most stars can be captured

- We assume the loss-cylinder is kept full.
- A star at semimajor axis a has probability 2p/a of reaching pericenter p at every orbit if the loss-cylinder is kept full, so for a quasar lifetime t_S and orbital period P(a), most stars are captured within the semimajor axis a obeying

$$\frac{\Sigma_d(p)}{\Sigma_*} \approx \frac{p}{a} \approx \frac{P(a)}{t_S}$$

- a will be identified with the zone of influence of the black hole after all the stars within a have been captured by the disk and accreted by the black hole.
- t_S will be identified with the Salpeter time.

The predicted M-σ relation

- For a thin α-disk model, with viscosity proportional to gas pressure:

$$\Sigma_d(p) \propto M^{4/5} / p^{3/5} \left(\dot{m}^{3/5} / \alpha^{4/5} \right)$$

Goodman 2003

$$\frac{M^{4/5}}{p^{3/5}} \propto \frac{M^{4/5}}{(aP)^{3/5}} \propto P \, ; \; M^{4/5} \propto a^{3/5} P^{8/5} \propto \frac{a^3}{M^{4/5}}$$

$$a \propto M^{8/15}$$

- If $\sigma^2 \sim M/a$, then: $M \propto \sigma^{30/7}$

Result of the calculation (ApJ 2005)

$$M = 6.3\cdot 10^7\, M_\Theta \left(\frac{M_*}{M_\Theta}\right)^{5/7} \left(\frac{\sigma}{200\,\mathrm{km/s}}\right)^{30/7} \left(\frac{v_{e\Theta}}{v_{e*}}\right)^{20/7} \left(0.1\dot{m}\right)^{-5/7} \alpha_{-2}^{\;4/7}$$

- It agrees with observation fairly well, but note the uncertainties:
  - Parameters: $\alpha, \quad \dot{m} = L/(\varepsilon\, L_{\mathrm{Edd}})$
  - Assumption of full loss-cone.
  - Relation between σ of the nuclear starburst when the quasar was active and the observed value today in the remnant galaxy.

The fate of captured stars

- The stars will gradually circularize their orbits, merge into the disk, and dissolve into the gaseous disk component. If stars did not dissolve, their density would be so great that they would collide with each other, disintegrating or coalescing. Coalescence would lead to very massive, big stars that would be even more easily destroyed.

Angular momentum problem

- The captured stars are selected from a very narrow loss-cylinder, so phase space density is likely uniform. Counter-rotating stars are more easily captured, so negative angular momentum is being added to the disk.
- Two possible solutions:
  - A quasar wind blows out most of the disk matter, at less than the escape velocity so that it mixes with matter at larger radius, from an extended disk supplied with matter from stellar mass loss, with high specific angular momentum.

Two possible solutions

(relying on rotation of stellar system) :

- A quasar wind blows out most of the inner disk matter, at less than the escape velocity so that it mixes with outer disk matter supplied from stellar mass loss, with high specific angular momentum.
- Most angular momentum is exchanged in the final phase of orbital grinding, when the loss-cone is not very narrow and its phase space density may be non-uniform with more prograde than retrograde orbits.

How is the M-σ relation established?

- When a nuclear starburst takes place, a seed black hole and accretion disk are assumed to be present.
- As long as the black hole mass is below the M-σ relation, the time to capture the black hole mass to the disk is shorter than a Salpeter time, so black hole growth continues.
- After reaching the M-σ relation, the mass accretion rate gradually falls compared to the Eddington rate. An increasingly long time is required to double the black hole mass. If at some critical accretion rate, the accretion switches from a thin disk to a hot flow, capture of stars ceases and the quasar turns off, fixing the final M-σ relation.

What a close-up picture of a quasar might look like…

- Typical pericenter of capture is hundreds of AU (for ~ 10^8 M_{Sun} black hole). Thousands of stars are found at any time within this region, plunging through the opaque accretion disk radiating at ~ 10^5K, probably with star tails of matter lifted from the disk during the passages (could these star tails be related to the BLR? Zuker et al. 1994).

Tests of the model

- If we could resolve the central parsec…
- No evolution of M-σ.
- Effects of the stars on metal abundances?
- High density of stars in the nucleus: after the quasar phase, it can decrease due to black hole mergers, or a top-heavy IMF.
- Dependence of M-σ normalization on L/L_{Edd}
- Disk mass ~ stellar mass at $M_{BH} \sim 10^5\ M_{Sun}$
- X-ray flares, broad-emission lines.

Summary

- A new quasar model is proposed in which matter is delivered to the accretion disk by plunging stars that are perturbed by relaxation processes to highly eccentric orbits.
- The model accounts for how enough matter is brought to a galaxy nucleus to fuel a quasar and grow the black hole, and can explain the origin of the black hole – bulge M-σ relation.