

# **ESO CMO Conference**

## **Summary and Discussion**

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- **Thanks to Nadine, Eric, SOC, LOC and ESO - a very good conference!**
- **Many very fascinating talks!**
- **Apology: a few topics omitted or mentioned only very briefly. They may come up in the discussion!**

# The Galactic Center Black Hole and Nuclear Cluster

- **SMBH:  $4.3 \times 10^6 M_{\odot}$ , coincident with Sgr A\*, based on  $\sim 30$  stellar orbits, particularly S2. Indications for hot spots in relativ. disk (flares, polarization) and wind effects.**
- **IMBH: no evidence. Limit  $M_{\text{int}} < \sim 10^3 M_{\odot}$ . Puzzling 3 stars IRS 13.**
- **Nuclear star cluster – several populations**
  - Central S-stars (B main seq. stars),  $\sim$ spherical, thermal ecc's
  - Clockwise warped disk of young WR stars, counter-rotating component of same age ( $\sim 5 \times 10^6$  yr), ecc's  $\sim 0.3$ , top-heavy IMF
  - Old stellar cluster,  $\sim 10^7 M_{\odot}$   $\sim 10^6 M_{\odot}$  in  $r \sim 1$  pc, density  $r^{-2}$ , core radius  $\sim 0.5$  pc, some rotation, age  $> 1$  Gyr,  $\sim$ extended SFH with normal IMF
- **Different properties (radii, ecc's, types, ages)  $\Rightarrow$  diff. origins.**  
**Currently favoured models:**
  - S-stars: Binary capture (Hills), with massive perturbers & resonant relaxation; low-mass IMBH carrying & randomizing stars still possible
  - Young stellar disks: infalling & colliding gas clouds, in situ SF, rare?
  - Old star cluster: extended SFH

# The Galactic Center Black Hole and Nuclear Cluster

- **SMBH – nuclear cluster connection:** some stars (B-stars) formed *after* SMBH. Favoured origin of S stars *needs* SMBH.
  - Is this a “minor” contributor to the build-up of cluster mass?
  - What are the oldest stars in the cluster? Age indicators of old cluster (AGB?)
- **Young stellar disks with top-heavy IMF may be rare, based on M/L of diffuse cluster light:**
  - How secure is the result?
  - If it is true, why do we see them now?
- **Observed core in the old star cluster density distribution:**
  - No time to form? Again, oldest stars?
  - Destroyed (Past IMBH)?
  - Invisible? What role do collisions play? Evidence? Why IRS 13 dust blobs?
- **Testing the formation scenarios for the young stars:**
  - Does cloud infall scenario for the disks require typical or special initial conditions?
  - Is resonant relaxation the explanation for the warp and the co-/counter-rotating dichotomy? Why are the counter-rotating stars seen in the middle radius range?
  - Binary capture mechanism for S stars: can we constrain outer B star eccentricity distribution?

# Black Holes and Their Scaling Relations

- **Dynamical black hole mass determinations: for ~50 galaxies, give tight  $M_{\text{BH}}$ - $\sigma$  relation. Sinfoni sample ~30 more; issues:**
  - Composite/pseudo-bulge systems suggest  $M_{\text{BH}}$ - $\sigma$  or  $M_{\text{BH}}$ - $M_{\text{class bulge}}$  more fundamental than  $M_{\text{BH}}$ - $M_{\text{total bulge}}$ .
  - Ongoing: extend to low and high mass ends: no curvature yet
  - Is there real scatter (vs. uncertainties in data, modeling)?
  - Modeling uncertainties: sphere of influence often barely resolved; how reliable is  $\Delta\chi^2$  parameter estimation given possible addl. systematics? E.g. nuclear cluster, M/L(r) from population grads & DM, triaxiality, .. Historical estimate ~ factor ~2
- **AGN diagnostics & MW: there are galaxies with BH but without classical bulge. How do we determine their  $\sigma$  for  $M_{\text{BH}}$ - $\sigma$  ?**
- **Accurate BH determinations in megamaser galaxies lie below  $M_{\text{BH}}$ - $\sigma$ , with large scatter. Small classical bulges?  $\sigma$ 's? BHs in LSB galaxies also below the relation. None yet in UCDs. What does scatter tell us?**
- **Scaling relation also with globular cluster systems !?**
- **Coming: More Sinfoni kinematics, disk-dominated galaxies, megamasers; X-ray selected samples; constraints from tidal disruption flares.**

# Nuclear Star Clusters and Relation to BHs

- NSCs frequent (50-75%) in spirals, S0s, dEs, *not* Es. Large nucleation fractions in Virgo & Fornax. Compact,  $<1''$ . Masses  $10^6 - 10^7 M_{\odot}$ , half-light radii 3 - 5 pc, tail to large  $r_h$ . Complex SFHs, several bursts. Nuclei younger than hosts but  $>2$  Gyr old. Some rotating/flattened, one counter-rotating case. Arches. M54.
- **Origin: first form at galaxy centre or migrate there?**
  - Episodic accretion,  $\sim 10^5 M_{\odot}$  per event, in NSCs in late-type galaxies
  - Migration of globular clusters: infall time-scales  $\sim$ right, model may explain core / no cusp; but multi-episode stellar pops?
  - Star cluster mergers would result in triaxial nuclei - testable
- **Coexistence with BHs:**
  - few good cases, where  $M_{\text{BH}} \sim 0.1 M_{\text{NSC}}$ .
  - Also in nearby Seyferts BH and starburst clusters coexist.
  - Generally NSCs seen in late-type galaxies, BHs in ETGs.
- **Scaling relations: NSC luminosity  $\propto$  total galaxy luminosity, NSCs also seen in pure disk galaxies.**

# Are IMBHs formed in Nuclear / Globular Clusters?

- **Theoretically, they could be:**
  - Run-away collisions in young clusters after core collapse. Original model for MGG11 in M82 reached  $2000M_{\odot}$  star; more recent: stellar evolution/ winds limit growth  $\Rightarrow$  only few  $100M_{\odot}$  reached. [altern.: Pop III stars]
- **Observational signatures for IMBHs in star clusters:**
  - From X-rays: transients in M82+, accreting  $\sim 300 L_{\text{Edd}}$ , with QPOs. X- and radio emission in G1 (M31).
  - From density structure of GCs: core radius and shallow density slope not unique signatures; binary heating resp. pre core collapse
  - From velocity dispersion cusps and dynamical modeling in GCs: hard
  - IMBH suppresses mass segregation, scattering massive stars in binary
- **Observational evidence in GCs controversial – work on-going**
  - $\omega$  Cen controversial: dynamical analysis depends on cluster center & precise  $\sigma$ -profile; mass-dependent  $\sigma$ -profile analysis suggests none.
  - Several candidate clusters with suggestive dynamical evidence: M10, M54, NGC 6388. Data complicated, would like independent confirmation.
- **Few NSCs with embedded BHs – but special place in galaxy where BH could have formed first**

# Star Formation, Inflow/Feeding, Feedback

- **Mechanisms for angular momentum loss and inflow**
  - From large to small scales: mergers, bars, unstable disks (gravitational), three-armed spirals (pressure waves, seen in action in Seyfert nuclei), turbulent viscosity, magnetic stress. All inferred from observations and simulations; circumstances in which each dominates?
- **Star formation and feeding**
  - Lag between starburst and AGN (switch from fast SN to slower winds)
  - Thick, dynamically hot molecular gas disk in Seyfert nuclei meets torus requirements
  - Mass loss from surrounding stars can grow nuclear disk and cause accretion
- **Feedback**
  - Halts inflow, accretion, star formation, can thus regulate BH growth to galaxy formation. Can even cause new inflow, accretion.
  - Momentum-conserving outflows can explain  $M_{\text{BH}}-\sigma$ -relation
  - Radiative hydro models + SF etc: SF & stellar feedback favoured in small systems, BH growth & AGN feedback favoured in high-mass systems

# BH Formation

- **Seed BHs: Pop III, direct collapse of IMBH, in dense star clusters**
- **Explorative power of numerical simulations**
  - Study consequences of physical processes in non-linear collapse, such as suppressing fragmentation by magnetic fields in runaway collapse
  - Study evolution of complex systems under varying assumptions, such as growth and predicted distributions of seed black holes for observational follow-up
  - Constrain merger/accretion growth using statistical data on BH mass and luminosity functions
- **Some issues**
  - Runaway collisions in star clusters at low  $Z$ ?
  - Hypermassive star clusters? Relation to BH formation?
  - Presence/absence of BH signatures in dwarf galaxy stellar orbits?
  - Subgrid models for BH growth in simulations?
- **New observational constraints**
  - Supercompact UV-luminous galaxies in Galex/SDSS surveys – do they contain AGN and what can we learn about BH growth?



## Conference Questions

- **What is the evolutionary/causal connection between nuclear clusters and black holes?**
- **Are intermediate mass black holes formed in nuclear clusters/ globular clusters?**
- **Where do we stand observationally for black holes, nuclear clusters and intermediate mass black holes?**
- **What can the Galactic Centre tell us about the nuclear cluster-black hole connection?**
- **How do the central massive objects relate to the host galaxies?**
- **What do theoretical models tell us about star formation in the extreme gravitational potential near the black hole and under the extreme stellar densities in galactic centers?**
- **What do theoretical models tell us about dynamics, evolution and migration of nuclear star clusters in galaxy centres?**
- **Do we understand the feeding of the central pc? How are nuclear clusters replenished with fresh gas?**