UNVEILING SUPERMASSIVE BLACK HOLES IN THE NEAR & FAR UNIVERSE

TWENTY YEARS OF CHANDRA SCIENCE SYMPOSIUM
December 3 - 6, 2019

THANKS TO GIACCONI & TANENBAUM

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CURRENT STATUS OF OUR UNDERSTANDING OF SUPERMASSIVE BLACK HOLES (SMBHs)
   From individual sources to the population to the deep fields

THE FORMATION OF SEED BLACK HOLES AT HIGH REDSHIFT
   Light & Massive Initial Seeds of SMBHs

THE FUELING AND GROWTH OF SMBHs
   Accretion of gas & Luminosity Output from SMBHs; Role of Mergers

FEEDBACK FROM ACCRETING SMBHs
   How SMBHs couple to their host galaxies and environments

THE BIG OPEN QUESTIONS
   IMBHs: where are they?
   UMBHs: how common are they?
   Obscured SMBHs: how incomplete is our census?
   BH seeds: when and how do they form?

Twenty Years of Chandra Science Symposium
   December 3-6, 2019
KEY PHYSICS CHALLENGE OF SCALES
INTERPLAY OF STARS, GAS AND DARK MATTER

FOR A MILLION SOLAR MASS BH

- Schwarzchild radius $10^{12}$ cm
  $$R = 2 \frac{GM}{c^2}$$
- Galactic nucleus $10^{20}$ cm
- Stellar extent of galaxy $10^{22}$ cm
- Dark Matter Halo of galaxy $10^{23}$ cm
- Cosmological scales $10^{26}$ cm
GROWTH HISTORY OF ACTIVE SMBHs FROM CHANDRA

SMBHs with $M_{BH} \sim 10^6 - 10^{10} M_\odot$ are found at the centres of most (if not all) galaxies in the local Universe.

Bulk of SMBH mass is built up via accretion (AGN), peaking at $z \sim 1-3$.

- **Rate of SMBH growth via accretion**
- **Late (recent) cosmic time**
- **Early cosmic times**

Gultekin+; Aird+; Treister+; Alexander+; PN+; Gilli+; Hasinger+; Merloni & Heinz
CHANDRA REVEALED ACTIVELY ACCRETING SOURCES & MULTI-WAVELENGTH COUNTER-PARTS

Observed quasars

CXRB

z=0

Urry+; Treister+; Scoville+; Sanders; Faber+; Wu+; Ferguson+; Harrison+; Hasinger+; Comastri+; Gilli+
SMBHs: FROM THE MARGINAL TO STARRING ROLE
Chandra data bridged scales for individual sources

1999 CXC Press Release of Centaurus A (NGC 5128)
UNVEILING ACCRETING POPULATIONS OF SMBHs

CHANDRA DATA extended our knowledge to $z \sim 5$ spanning luminosity range

AGN dominate over X-ray emission from host galaxy

Fainter AGN missed in Optical/IR

Less affected by obscuration than Optical/UV

Banados+ 17; 18; Kulkarni+ 18; PN & Volonteri 14; Trakhtenbrot+17
EFFICIENCY OF X-RAY SURVEYS IN AGN CENSUS

CHANDRA DATA extends to $z \sim 5$
Mapping AGN population & ANCHORS MODELS
CO-EVOLUTION OF GALAXIES & BLACK HOLES OVER COSMIC TIME

Mullaney+; Elbaz+; Barger+; Madau & Haardt; Shankar+; Brusa+; Cimatti+; Treister+;
HOW DO BLACK HOLES GROW?

Accretion
Merger-triggered accretion
BH Mergers
EVIDENCE FOR IMPACT OF BHs ON THEIR ENVIRONMENT

On the smallest scales
ALMA data of NGC 1433 outflows & molecular disk

On the largest scales
CHANDRA data of the Perseus cluster outflows & shells
Abundance & LF of high & low z quasars

CXRB

Lauer+ 05, 06; Bernardi+ 06; PN & Treister 09; McConnell+ 11,12; PN & Volonteri 13; Marziani & Sulentic 12; Mortlock+ 14; Wu+ 2015; Kulier+15; Thomas+ 16; van den Bosch+ 16; Reines+ 14; McConnell+ 13; Jiang, Greene & Ho 11; Gultekin+09; Ferrarese+ 2006; Ferrarese & Merritt 2002; Tremaine+ 2002; Kaspi+ 2005; Cowie+ 14; 17; Barger+ 03; 14; Census from SDSS and 2dF Fan+ 2007; Croom+ 2004; Comastri+ 1995; Ueda+ 2003; Treister & Urry 2005; Merloni+ 2004;
EDDINGTON RATIO DISTRIBUTION & ITS EVOLUTION WITH $z$

KEY INPUT TO AGN DEMOGRAPHIC MODELS

flickering on short time-scales?

Elvis+; Siemiginowska+; Narayan & Yi; Fabbiano+; McDowell +
EVOLUTION OF THE SPACE DENSITY OF AGN

$z = 0 - 5$

- Luminosity-dependent evolution
- Strong decline in space densities at $z > 3$ for all luminosities

Data points: Miyaji et al. (2015)
Lines + shading: Aird et al. (2015)

Vito et al. (2014)
see also Georgakakis et al. (2015), Weigel et al. (2015)
SYSTEMS APPROACH TO THE PROBLEM

LSS framework

Initial Seeding

Accretion Physics

Merging Dynamics

Seed formation
Analytic model
Early seed Growth
Simulations

Cosmological Simulations
LCDM model

High resolution GRMHD simulations

GR simulations
TRACKING GROWTH HISTORY OF BLACK HOLES OVER COSMIC TIME

Correlation Between Black Hole Mass and Bulge Mass

- Ten billion solar masses
- One billion solar masses
- One million solar masses
- No black hole

Mass of central bulge

Merging galaxies

Obscured quasar

Unobsced quasar
INSIGHTS FROM CHANDRA DATA THAT INFORM MODELING

KEY CHANDRA INPUTS FOR MODELING ACCRETION PHYSICS

- Inferred Eddington Ratio Distributions
- Insights into geometry of inner regions of AGN
- Census of obscured vs. unobscured populations
- Constraints from CXRB

KEY CHANDRA INPUTS FOR MODELING FEEDBACK

- Relation between AGN activity & star formation in hosts
- Insights into population from Chandra Deep Fields
SEEDING MODELS

massive and light initial seeds (only high-z seeding)

ACCRETION MODELS

• AGNMS: \( \text{BHAR} = 1e^{-3} \times \text{SFR} \) (Mullaney+ 12)

• PowerLaw: Eddington ratio distribution derived from XLFs

MERGER DYNAMICS

SMBHs instantly merge with a 10% probability after the dynamical friction timescale after a major merger, wander otherwise

PREDICTED PROPERTIES FOR THE BH POPULATION

Ricarte & PN 18b; PN, Ricarte+ 19 NASA LISA Science Team Decadal White Paper
HOW DO THE FIRST SEED BLACK HOLES FORM?

**LIGHT SEEDS**
- PopIII
  - \( \sim 10^{1-2} \text{ M}_{\odot} \)

**MASSIVE SEEDS**
- Nuclear star cluster
  - \( \sim 10^3 \text{ M}_{\odot} \)
- Supermassive Star/DCBHs
  - \( \sim 10^{4-6} \text{ M}_{\odot} \)
- Quasi star

**EARLY AMPLIFIED GROWTH**
STANDARD ACCRETION & SLIM DISK ACCRETION

$0.01 \dot{M}_{Edd} < \dot{M} < \dot{M}_{Edd}$

$L = L(\dot{M})$

$\dot{M} > \dot{M}_{Edd}$

\[ L \propto \dot{M} \]

FEEDBACK LIMITED

\[ L \propto \ln(\dot{M}) \]

GAS SUPPLY LIMITED

Begelman+; Choi+; Park+; Pacucci & Ferrara; Pacucci+; PN+
EARLY BH SEED MASS BUILD-UP AT HIGH REDSHIFT

**THIN DISK ACCRETION**
FEEDBACK LIMITED MODE
Inefficient growth, outflows, High radiative efficiency
~ 15% or so of gas accreted
Eddington limited accretion rate

**SLIM DISK ACCRETION**
GAS SUPPLY LIMITED MODE
Efficient growth, outflows unimportant, low radiative efficiency, radiation advected in
~ 80% or so of gas accreted
Super-Eddington accretion rates

Growth is jump-started for larger initial black hole seed masses
\[ M_{\text{gas}} > M_{\text{crit}} \]

Alexander & PN 14; Park, Ricotti, PN+15; Pacucci+15; Pacucci, PN+ 18
AGN LUMINOSITY FUNCTIONS FROM X-RAY DATA & MODELS

DATA FROM WIDE+DEEP CHANDRA SURVEYS
CDFS-4Ms, AEGIS 800ks, C-COSMOS
STRONG EVOLUTION SEEN
Luminosity+density evolution for all AGN
Evolving mix of obscured & unobscured

Model Predicted Bolometric LFs as a function of BH seed mass

Ricarte+; PN+; Pezzuli+; Shankar+; Volonteri+; Aird+; Hickox+; Powell+; Steffen+;
Ueda+; Miyaji+; Buchner+; Cappelluti+; Civano+; Treister+; Koss+; Gilli+; Lusso & Risaliti+
PREDICTIONS & MATCH WITH AGN CLUSTERING DATA
PREDICTED HIGH REDSHIFT LUMINOSITY FUNCTIONS

A LynX deep field down to a flux limit of $10^{-19}$ erg s$^{-1}$ cm$^{-2}$
Predicted AGN abundance expected in future deep fields
GROWING DCBH SEED + STELLAR COMPONENT

SLIM DISK AND STANDARD DISK

SLIM DISK: X-RAY OBSCURED, IR BRIGHT SOURCES

STANDARD DISK: X-RAY BRIGHT, IR BRIGHT SOURCES

Volonteri+; PN+; Pacucci+; Pezzuli+; Stark+; Tanaka+; Ricotti+
LOCAL OCCUPATION FRACTION OF BHs
dependence on seeding & accretion model

Greene+, Reines+, Baldassare+, Gallo+, Desroches & Ho+, Ricarte & PN, Tremmel+; Sharma+
EXPLORING CORRELATIONS IN THE ROMULUS SUITE

BH growth traces star-formation independent of larger-scale environment

SMBHs & their host galaxies co-evolve
Hosts with stellar masses $10^8 \text{--} 10^{12} \text{Msun}$ and star-forming co-evolve independent of mass, environment, redshift or stellar mass!

Ricarte, Tremmel, PN+
M-SIGMA AND THE FOUR MODEL VARIANTS

No Steady Mode

Burst + steady BHAR = SFR/1000

Burst + Steady drawn from ERDF

PowerLaw, but old sigma mapping
OPEN QUESTIONS: BH IMFs & IMBHs?

LETTER

A luminous X-ray outburst from an intermediate-mass black hole in an off-centre star cluster

Time (Gyr)

Mass (M☉)

Redshift of BH Formation

Growth via accretion and mergers
LONG-LIVED THERMAL & KINEMATIC S-Z FROM QUASAR OUTFLOWS
redshift distribution of from dormant high-z sources

\[ \frac{\Delta T}{T} \approx 3 \times 10^{-4} \left( \frac{\tau}{10^{-2}} \right) \left( \frac{v_{\text{sweep}}}{3000 \text{ km s}^{-1}} \right) \left( \frac{L_{\text{QSO}}}{10^{48} \text{ erg s}^{-1}} \right)^{\frac{1}{3}} \left( \frac{1+z}{1+3} \right)^2. \]

\[ \frac{\Delta T}{T} = \left( \frac{2kT_e}{m_e c^2} \right) \tau = 3.45 \times 10^{-6} \left( \frac{T_e}{10^6 \text{ K}} \right). \]

High-z BHs from massive initial seeds will have larger S-Z decrements and will be detectable more easily

Natarajan & Sigurdsson 98; 99; Chatterjee+; Lacy+19; PN 19
CONCLUSIONS FOR NOW & FUTURE PROSPECTS

KEY OBSERVABLES FOR MODELS

- high-redshift luminosity functions for accreting black holes
- local occupation fraction of black holes
- X-ray/IR/Optical afterglows & pre-cursors from merging SMBHBs
- Low & High mass end of the local SMBH mass function
- Sunyaev-Zeldovich decrements from high-redshift quasar outflows
- Low mass high z SMBHs GWs from SMBHB mergers - LISA events

Future observations with CHANDRA, JWST, WFIRST, LISA & ATHENA, LynX will help discriminate between seeding models & help disentangle seeding from accretion physics & dynamics
Astro2020 Decadal White Papers: for example - Bellovary+; Haiman+; Pacucci+; Natarajan+; Wang+; Kashlinsky+....others

Early Galaxies: Bouwens+; Bradac+; Oesch+; Atek+; Coe+; Zitrin+; McLoed+; Livermore+; Infante+; Laporte+; Bradley+; Salmon+; Behroozi+; Harikane+; Ishigaki+; Bowler+; Trenti+; Finkelstein+; Springel+; Robertson+; Madau+; Naidu+; Smit+; Stark+; Schmidt+…others

Early Black Holes: Natarajan+; Ricarte+; Pacucci+; Agarwal+; Volonteri+; Capelo+; Angels-Alcazar+; Hopkins+; Haiman+; Inayoshi+; Ferrara+; Schneider+; Pezzuli+; Bromm+; Wise+; Abel+; Khochfar+; Stacy+; Omukai+; Greene+; Reines+; Pretorius+; Campanelli+; Holley-Bockelman+; Bellovary+; Mayer+; Sesana+……..others