The observational evidence of **intermediate-mass black holes**

Ref paper: Greene et al. 2020 (Greene, J.~E., Strader, J., \& Ho, L.~C.\ 2020, \araa, 58, 257)

Outline

一： **Introduction & Formation paths for IMBHs**

二： **Stellar and gas dynamical Searches for IMBHs**

三： **Reverberation mapping & single-epoch & scaling relations**

四： **Fundamental plane depend on L_xray & L_radio**

五： **X-ray spectra or QPO (quasi-periodic oscillation)**

六： **IMBHs searches with transient phenomena & microlensing**

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一： Introduction & Formation paths

1.1 **Definition**

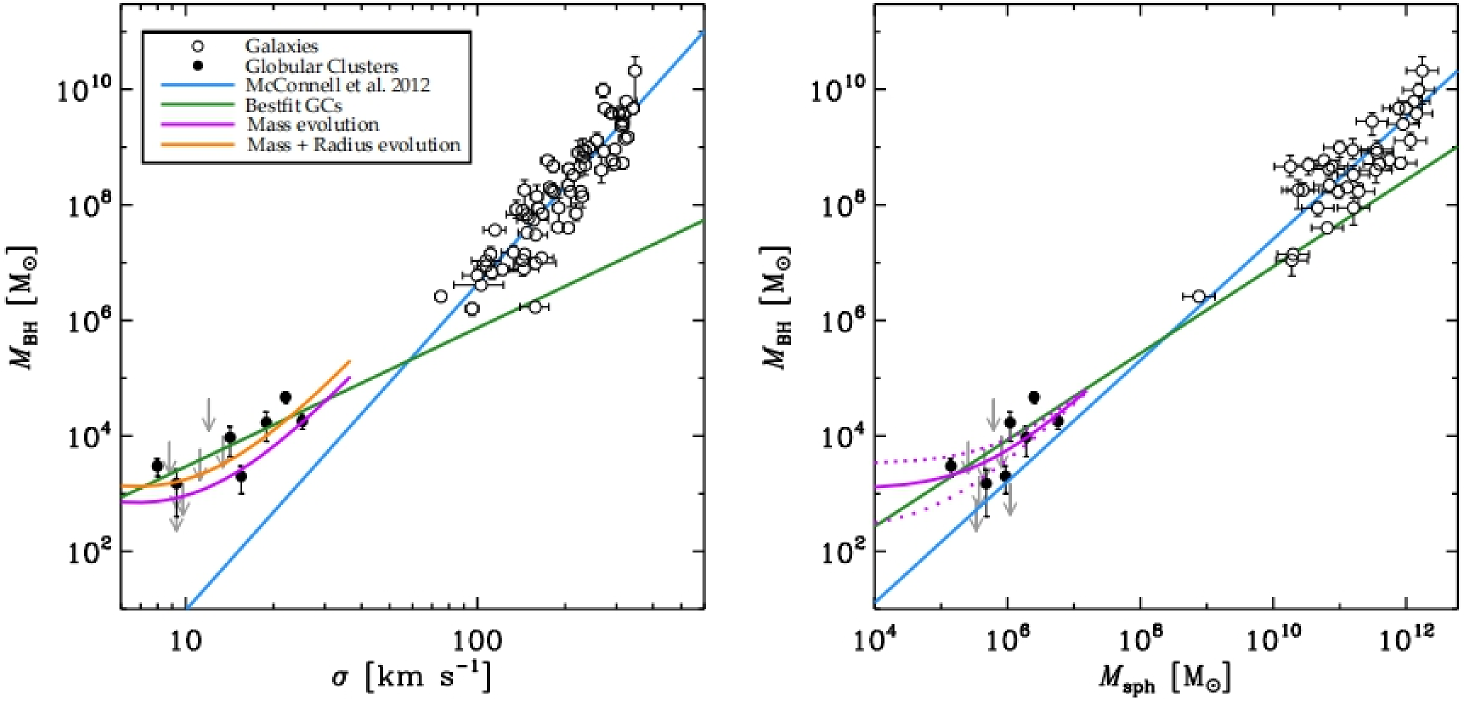
. **Intermediate mass black holes** (IMBHs) are an elusive class of **black holes** that are expected to lie in the $10^2 – 10^5\ M_\odot$ range, between the firmly established **stellar mass black holes** and $>10^6\ M_\odot$ **super-massive black holes**.

. **Stellar mass black holes : M_{bh}** ~Several $M_\odot$ $–10^2\ M_\odot$

. **Supper mass black holes (SMBH) : M_{bh} >** $10^6\ M_\odot$

一： Introduction & Formation paths

1.1 **Motivation**



Are intermediate-mass black holes deviating from the scaling relations?

M• ~ σ and M• ~ Mstellar relation for supermassive black holes and IMBHs.
Kruijssen & L¨utzgendorf 2013

一： Introduction & Formation paths

1.1 **Motivation**

1

- To understand the formation of **supermassive black holes** and their co-evolution with their host galaxies.

2

- **Extending scaling relations** to this regime may **provide unique insight** into the evolution of black holes, along with the feedback for dwarf galaxies.

3

- IMBHs will also be **a major source of gravitational radiation.**

一： Introduction & Formation paths

1.1 **Motivation**

As observations of **young quasars** push to earlier and earlier times (e.g., Fan et al. 2006, Mortlock et al. 2011, Bañados et al. 2018), the community has recognized the significant challenge of **creating such massive black holes** so quickly (e.g., Haiman 2013); this has led researchers to search for a **theoretical mechanism** that makes **massive black hole seeds**, which further motivates searches for **IMBHs**.

一： Introduction & Formation paths

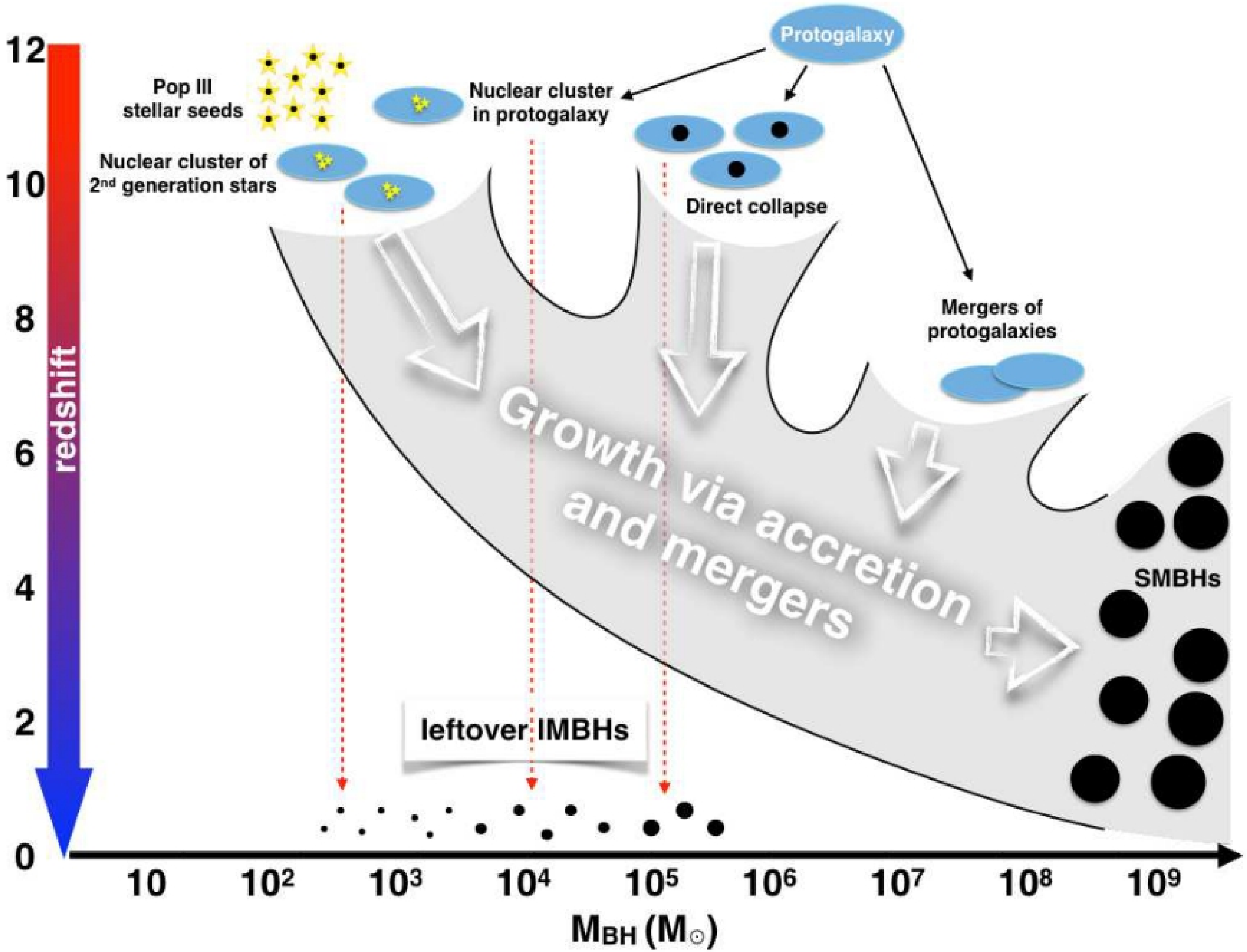
1.2 Formation paths:

1. - **Direct-Collapse Channels**: is that of **collapsing gas clouds forming a massive seed black hole** without passing through all the phases of stellar evolution.

2. - **Seeding model: IMBHs are evolved from Population III stars.** The first generation of stars (Pop III) formed from truly metal-free primordial gas (molecular hydrogen) in the high-redshift Universe.

3. - **Gravitational Runaway:** A final class of models generates ∼10^3–10^4 M⊙ black holes in a gravitational runaway event **within a dense stellar cluster**.

一： Introduction & Formation paths



From **Mezcua at al. (2017)**: Formation scenarios for IMBHs. Seed BHs in the early Universe could form from **Population III stars**, from mergers in dense stellar clusters formed out either from the **second generation of stars** or from inflows in protogalaxies, or fromdirect **collapse of dense gas in protogalaxies**, and **grow via accretion and merging to 10^9 M☉ by z～7.** SMBHs could also directly form by **mergers of protogalaxies** at z～6. Those seed BHs that did not grow into SMBHs can be found in the local Universe as **leftover IMBHs**.

一： Introduction & Formation paths

1.3 Formation paths:

Model	Redshift	Tooth fairies	F_{occ} 10^8	F_{occ} 10^9	# Mpc^{-3} nuclei	M_{BH} today	# Mpc^{-3} wander
Direct collapse	$z > 10$	UV background pristine gas	0.2–0.4	0.4–0.8	0.1–0.15	10^4–10^6	0.1–0.3
Population III	$z > 15$	Super-Eddington accretion	0.2–1.0	0.5–1.0	0.1–0.4	10^4–10^6	0.1–0.3
Fast runaway	All	BH retention high stellar density	0.1–0.7	0.1–1.0	0.02–0.25	10^3–10^5	>0.3
Slow runaway	All	BH retention high σ_*	0.1–0.7	0.1–1.0	0.02–0.25	10^3	>0.3

Table show the range of occupation fractions and implied number densities for each seed formation channel. **The direct-collapse** numbers are based on **Bellovary et al. (2019)**, and the **Population III numbers** are based on **Ricarte &Natarajan (2018)**. Roughly **～0.1% mass fractions are predicted from gravitational runaway** scenarios.

二： Stellar and gas dynamical Searches for IMBHs

2.1 Dynamics from Integrated Light Measurements

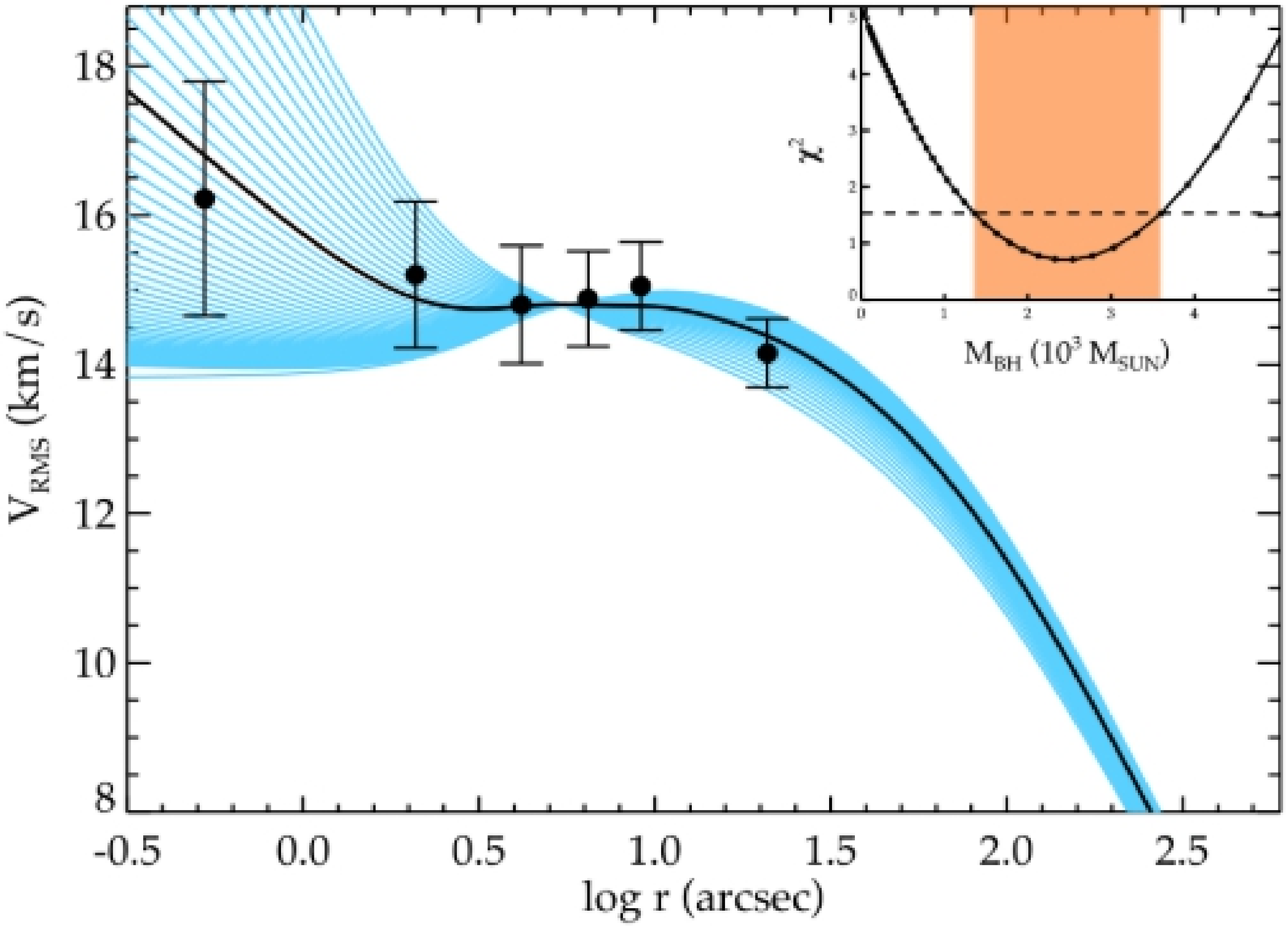
•The **kinematics** can be measured from either **stars or gas in small radius for the vicinity** of the black hole.

•The stellar-mass profile is modeled from the light, which is then converted to a mass profile by solving for the **stellar mass-to-light ratio (M/L)** (e.g., Gebhardt & Thomas 2009).

For **stellar-dynamical modeling**, state-of-the-art codes use **Schwarzschild modeling** (Schwarzschild 1979) to jointlymodel the mass density of the central black hole, stars, and darkmatter by orbit superposition (e.g., Rix et al. 1997, Gebhardt et al. 2003).

二：　Stellar and gas dynamical Searches for IMBHs

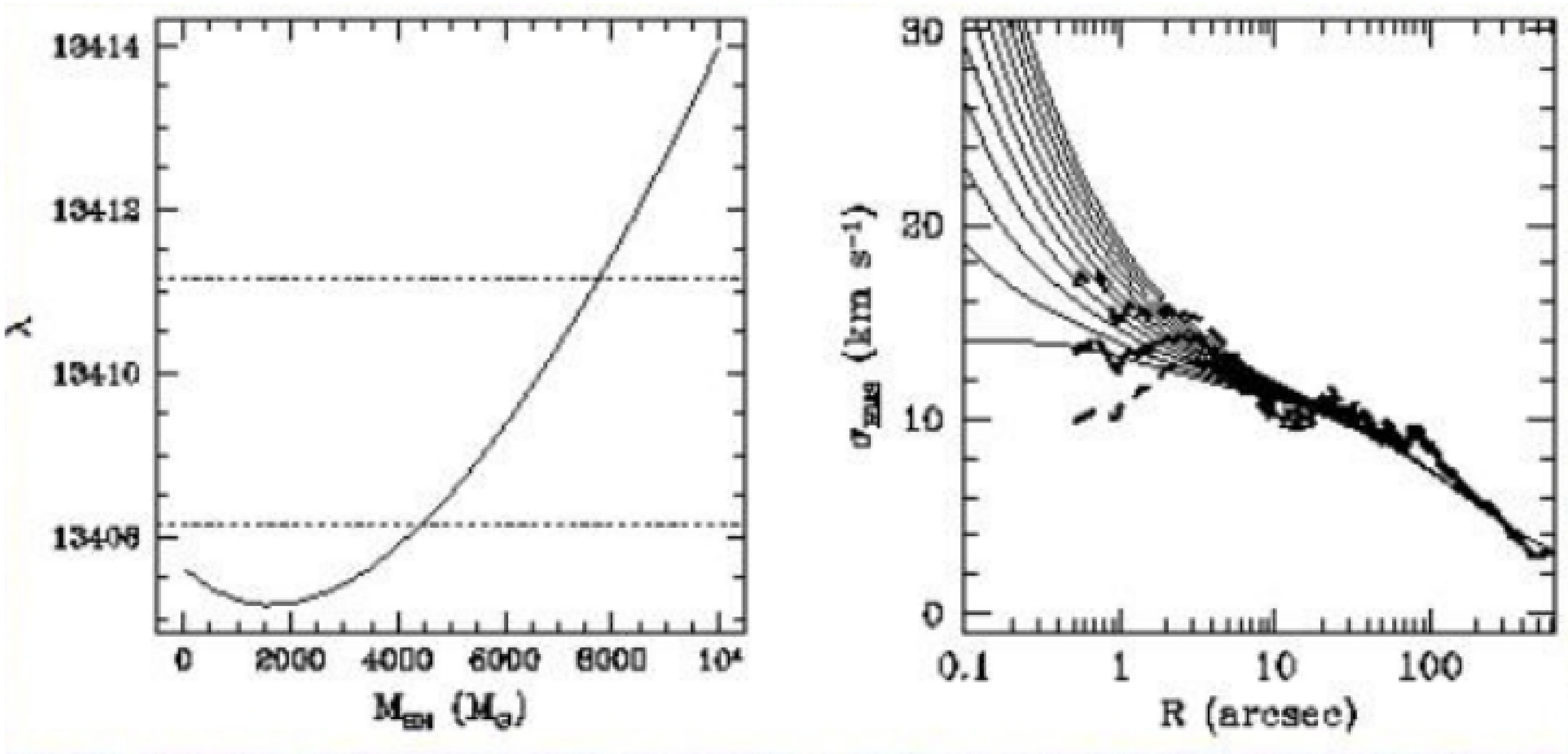
2.2 Jeans model



Velocity-dispersion profile of **NGC 6266 along the radial direction** overplotted by **Jeans models** (Neumayer &Walcher 2012) with different black-hole masses. The χ2 values is shown in the upper right and the best fit model indicated by the black sold line.

二： Stellar and gas dynamical Searches for IMBHs

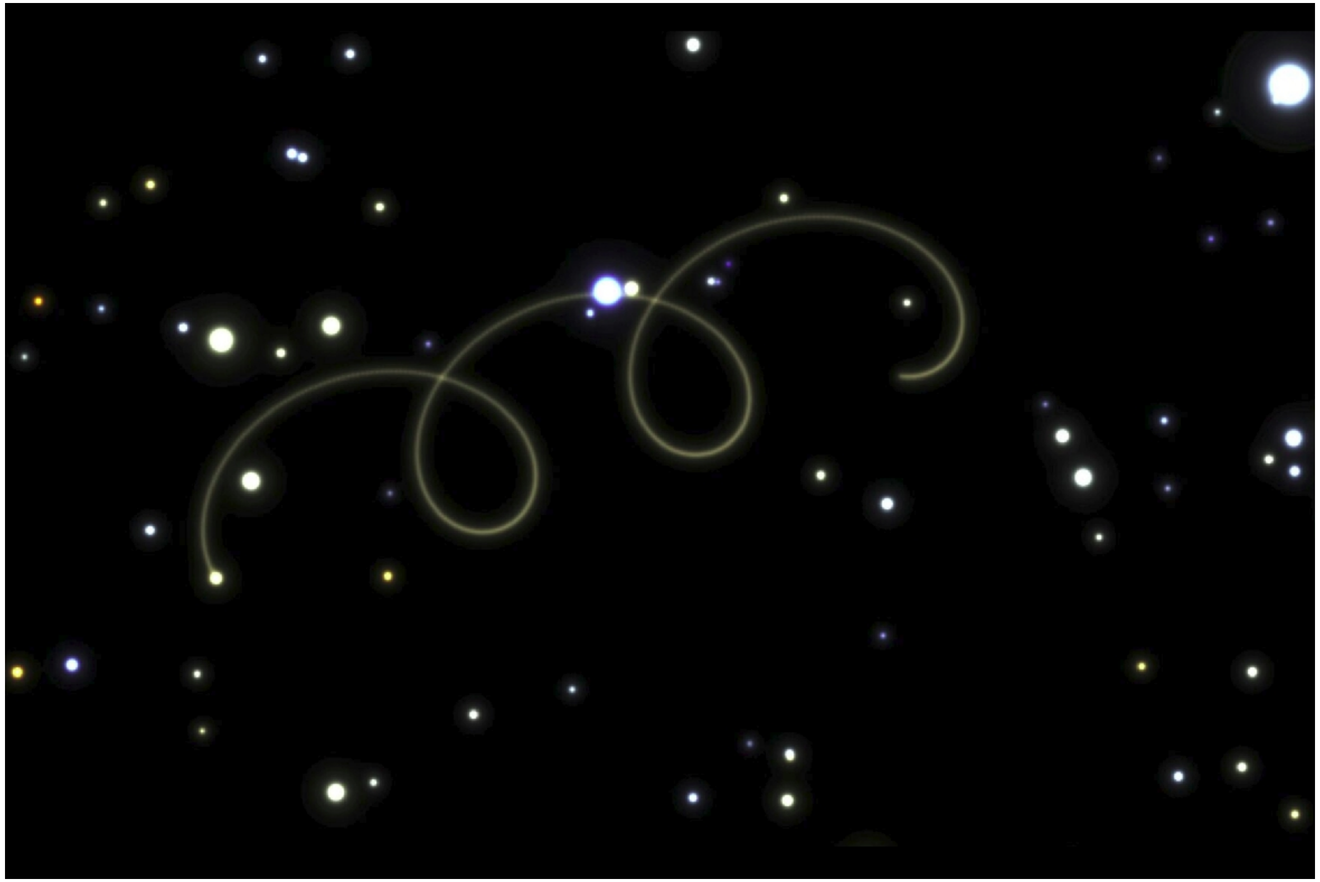
2.3 Fokker Planck models (Dull et al. 1997,2003)



The result of M15: M_{bh}=1.7 (+2.7,-1.7) *10^3 M⊙

二： Stellar and gas dynamical Searches for IMBHs

2.4 Proper Motions & Hypervelocity Stars



Proper Motions : Bound by the gravitational of IMBH

Hypervelocity Stars maybe accelerated by IMBH.

3.1 **Reverberation mapping** （**For NGC 4395** ）

- For objects with **broad emission lines**, reverberation mapping yields information about the **size scale of the broad-line region** (BLR) by measuring the **delay** between the **continuum and line light curve**, emitted from the accretion disk and BLR, respectively (Peterson 2014).

- Combining the BLR radius r with the line width ΔV yields a virial-like mass

$$M_{BH} = f_{vir} r(\Delta V)^2/G, \text{ with } f_{vir} \text{ the virial constant.}$$

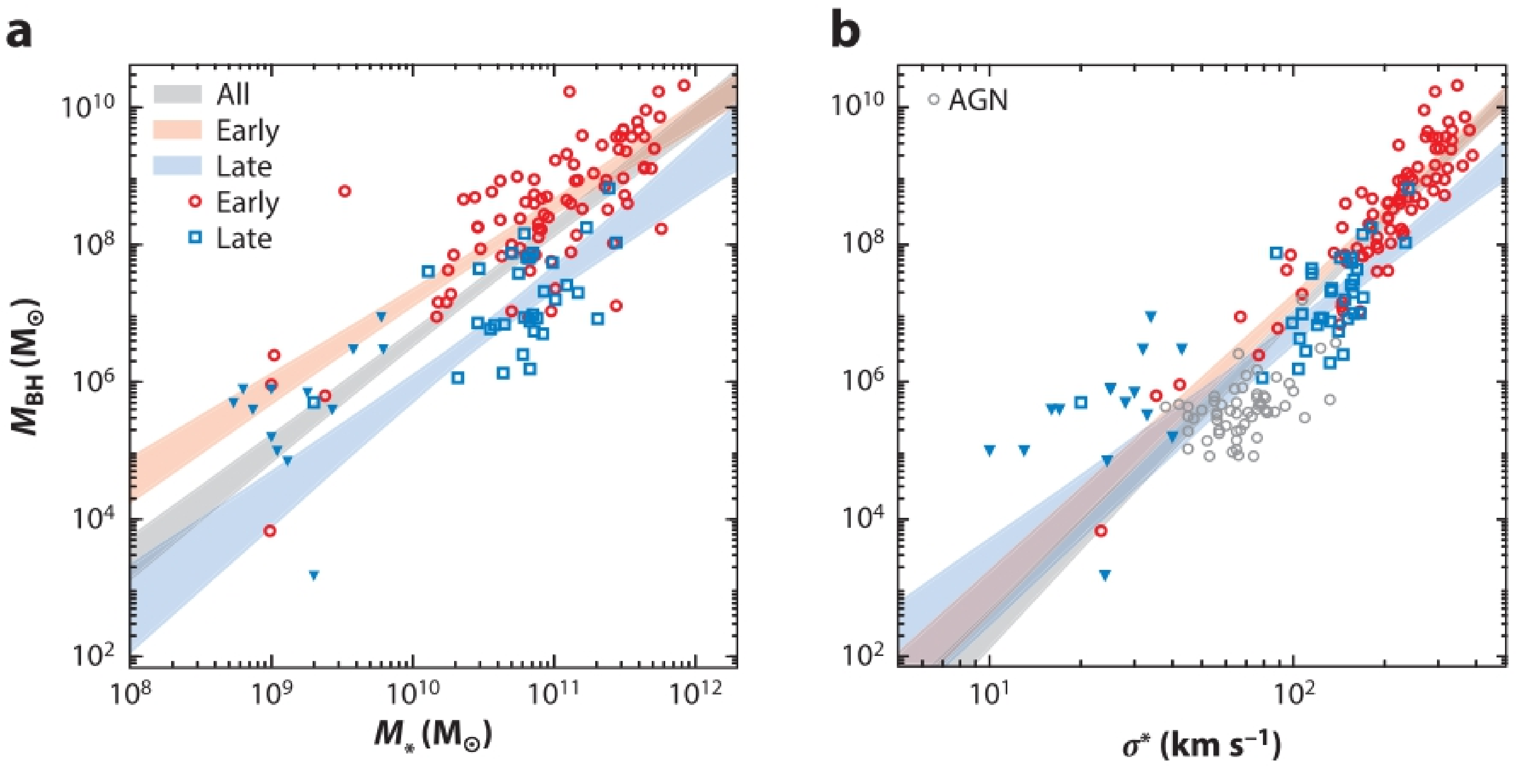
The result of NGC4395: Mbh = (3.6 ± 1.1) × 10^5 M⊙ from Peterson et al. 2005

3.2 Single-epoch

- The single-epoch Verill method has been further calibrated via reverberation mapping (RM) (e.g.,Vestergaard & Peterson 2006; Bentz et al. 2013).
- This method assumes that the BLR gas is following the virial relations, and posits the existence of a radius-luminosity (R-L) relation (Bentz et al. 2013).
- Using the virial constant and the radius–luminosity relation, we can calculate **single-epoch virial masses** for Type I AGNs.

$M_{\mathrm{BH}} = f_{\mathrm{vir}} r (\Delta V)^2 / G$, with f_{vir} the virial constant.

3.3 Scaling relations



The relationship between M_{BH} and $M*$ for dynamical early-type galaxies (red open circles) and late-type galaxies (blue open squares), and dynamical upper limits (blue triangles).We show fits to the early- and late-type galaxies (red and blue shaded regions) and the full sample (gray) (Xiao et al. 2011).

四： Fundamental plane depend on L_X & L_R

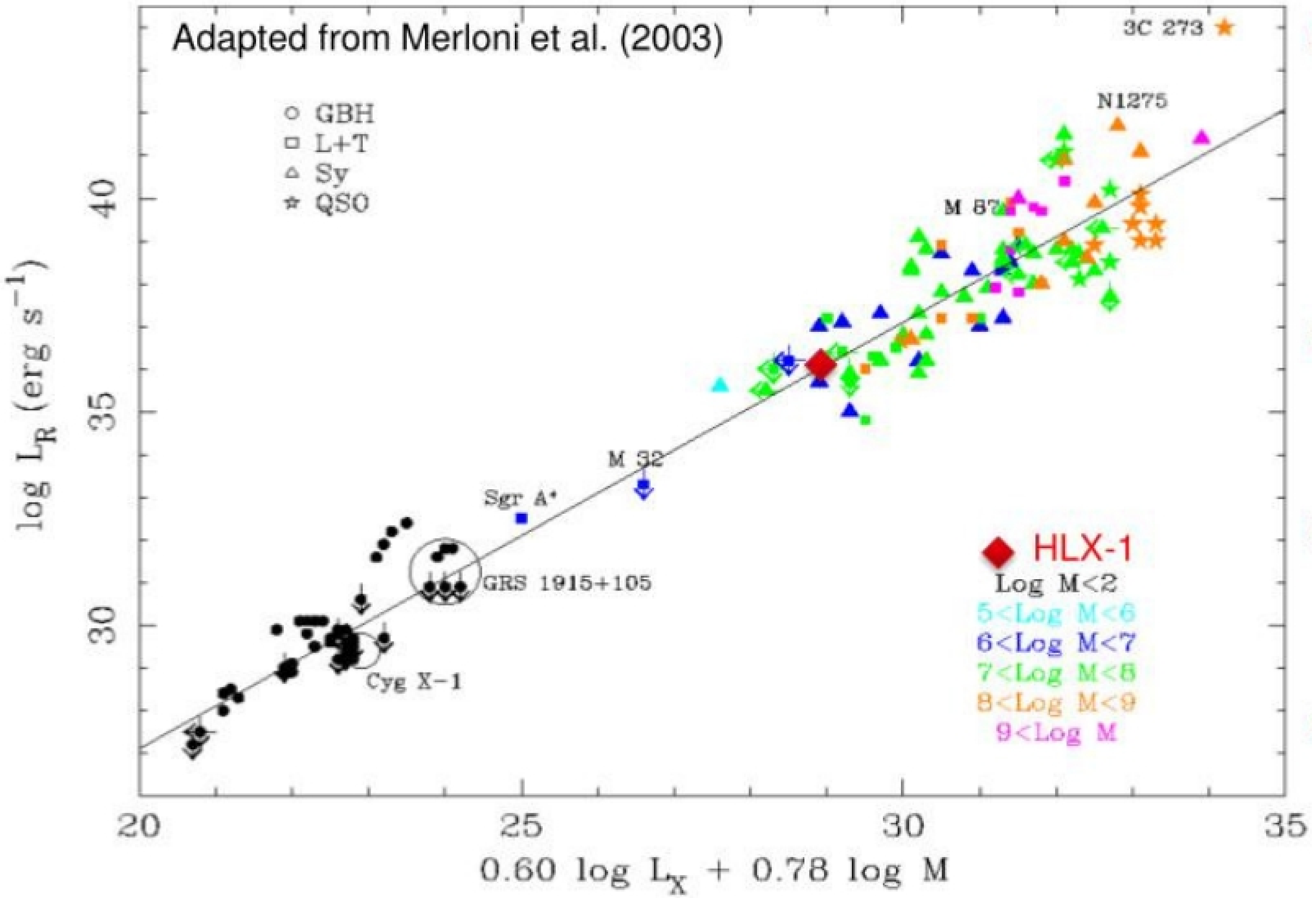
- Combining **radio emission** with **X-rays** could be even more effective at probing AGNs with **very low Eddington ratios**.

- Observationally, the **X-ray luminosity (LX**; a product of the accretion rate and radiative efficiency) and the **radio continuum luminosity (LR**; a measure of the jet power) scale with **the mass of the black hole** in a simple manner, such that a combination of these three quantities forms a tolerably clean two-dimensional sequence (**the fundamental plane**) in three-dimensional space.

- The best-fit: **Gültekin et al. (2019)** is log (M/10^8 $M_\odot$) = (1.09 ± 0.10) log(**LR**/10^38 erg s−1)(−0.59 ± 0.16) log (L**X**/10^40 erg s−1) + (0.55 ± 0.22).

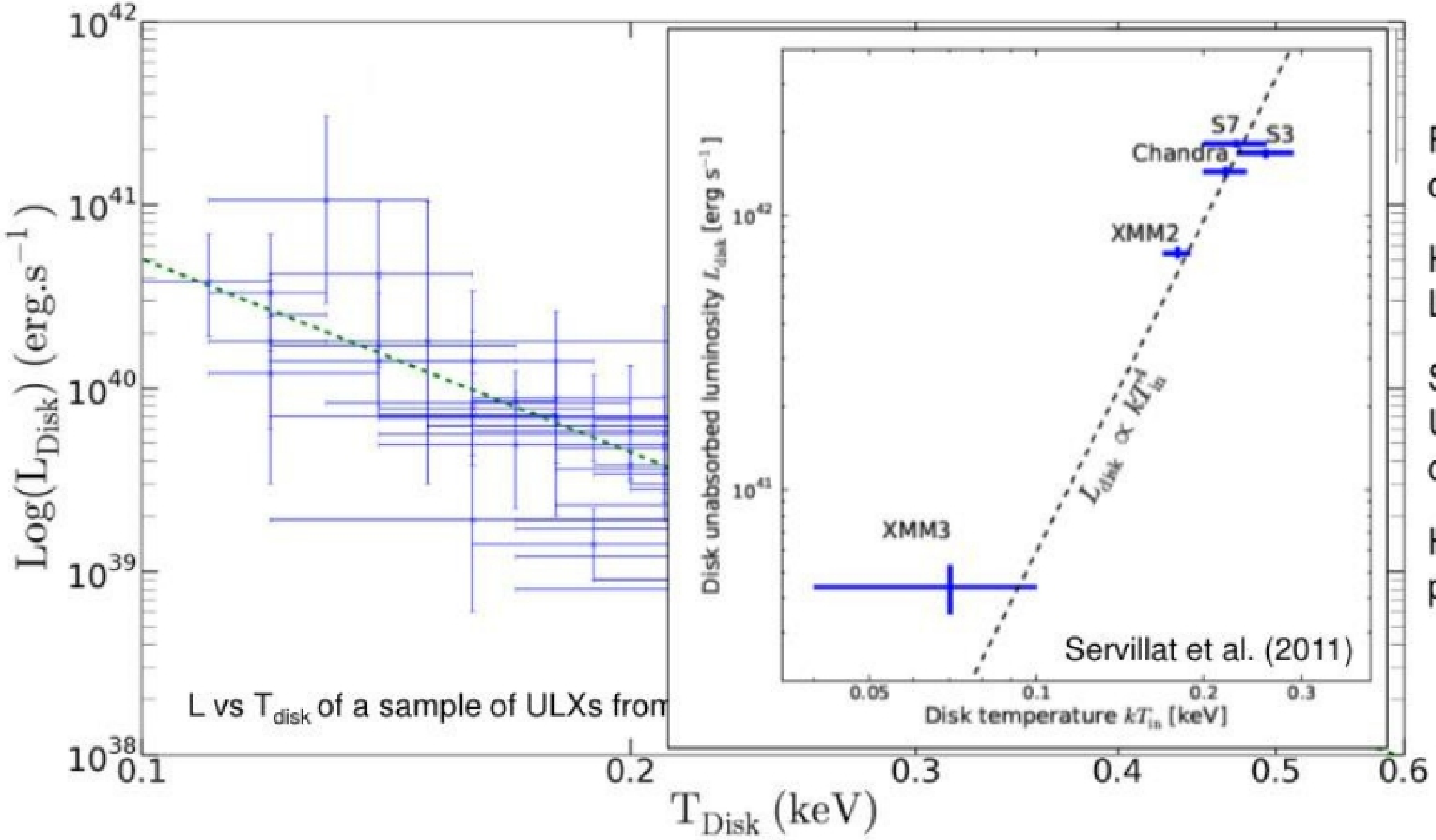
- One is that among **X-ray binaries**, LR/LX can vary by a factor of at least a few at fixed LX (e.g., Jonker et al. 2012).

四： Fundamental plane depend on L_X & L_R



五： X-ray spectra

5.1 The ULX spectra of HLX-1（Straub et al. 2014）



For Shakura-Sunyaev α-discs: $L_{disk} \sim T_{in}^4$

However, for most ULXs: $L_{disk} \sim T_{in}^{-3.5}$

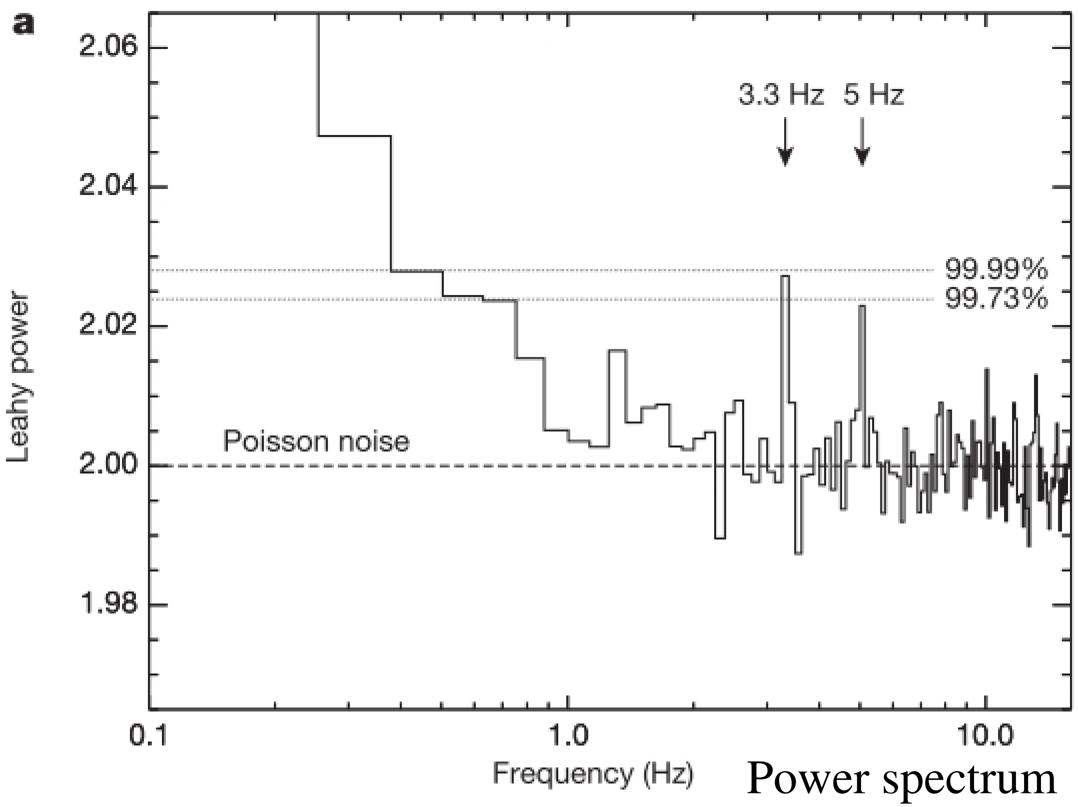
Soft component for bulk of ULXs most likely from outflow such as disc-wind

HLX-1 soft excess varies as predicted for an α-disc

The result of HLX-1: M_{bh} ～ 10^4 – 2 × 10^5 M⊙

五： X-ray QPOs

5.2 The X-ray QPOs of M82 X-1（Pasham et al. 2014）



Power spectrum

Estimate the mass using the **relativistic precession model (Motta et al.2014)**, from which we get a value of 415±63 solar masses.

The result of M82 X-1: M_{bh} = 415 ± 63 M⊙

六： IMBHs searches with transient phenomena

6.1 **Tidal Disruption Events**

- TDEs are the electromagnetic signature that may result if a star passes within its tidal radius of a black hole (e.g., Rees 1988).

- In principle it is **possible** to derive MBH from modeling of the TDE **light curve itself** (Lodato et al. 2009, Guillochon & Ramirez-Ruiz 2013, Mockler et al. 2019), as **the emission** from these events depends on **both the mass and radius of the star** and **the mass of the black hole** (e.g., Law-Smith et al. 2017).

- An **X-ray-detected transient** that is a likely TDE with an M_{BH}–σ_*-based mass estimate of **1.3–6.3 × 10^5 M⊙** (Maksym et al. 2013).

Thank You !