Supermassive black holes: formation, co-evolution with galaxies and growth mechanisms


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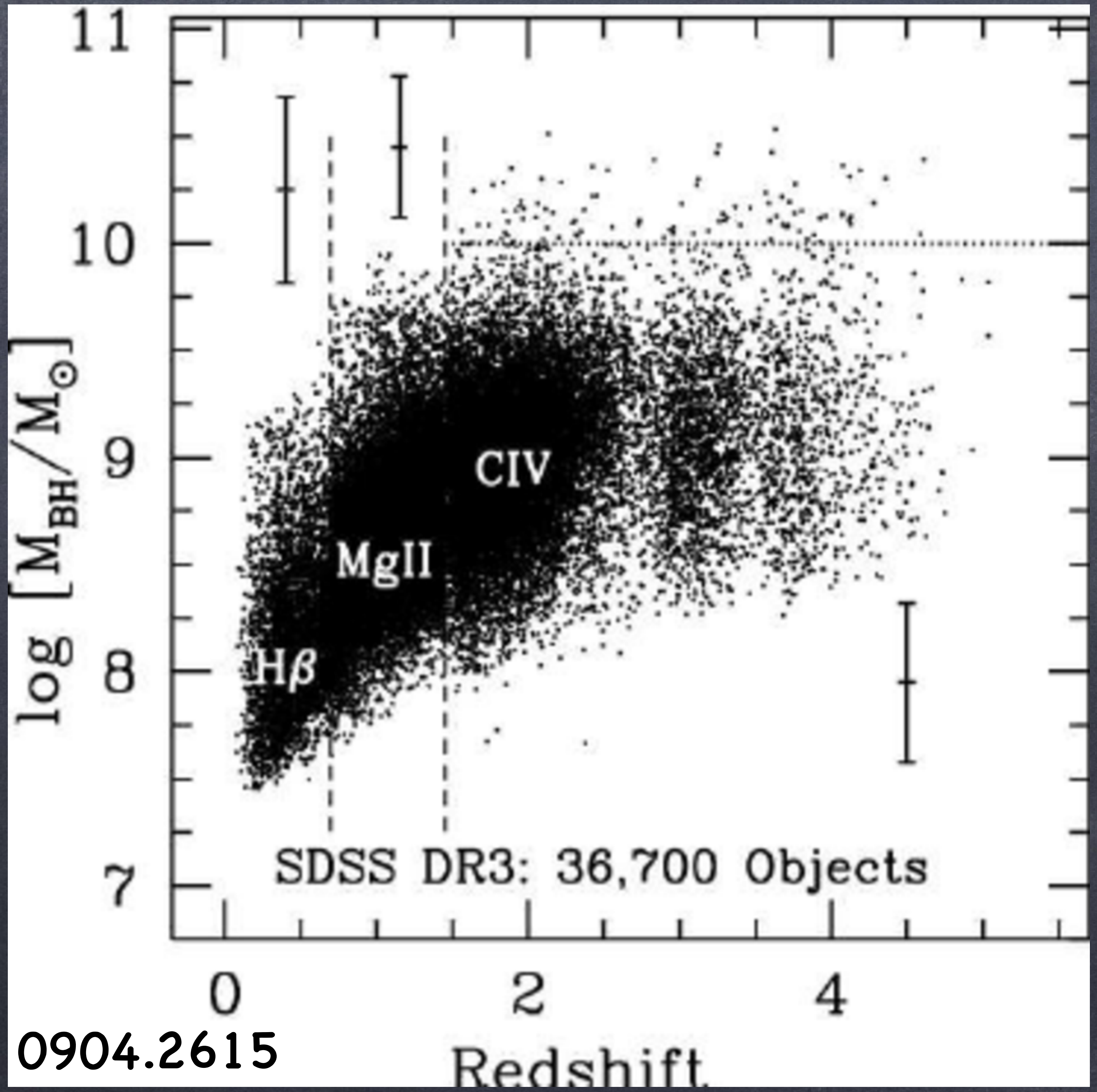
Francesco Iacovelli

SMBHs live in the center of galaxies!

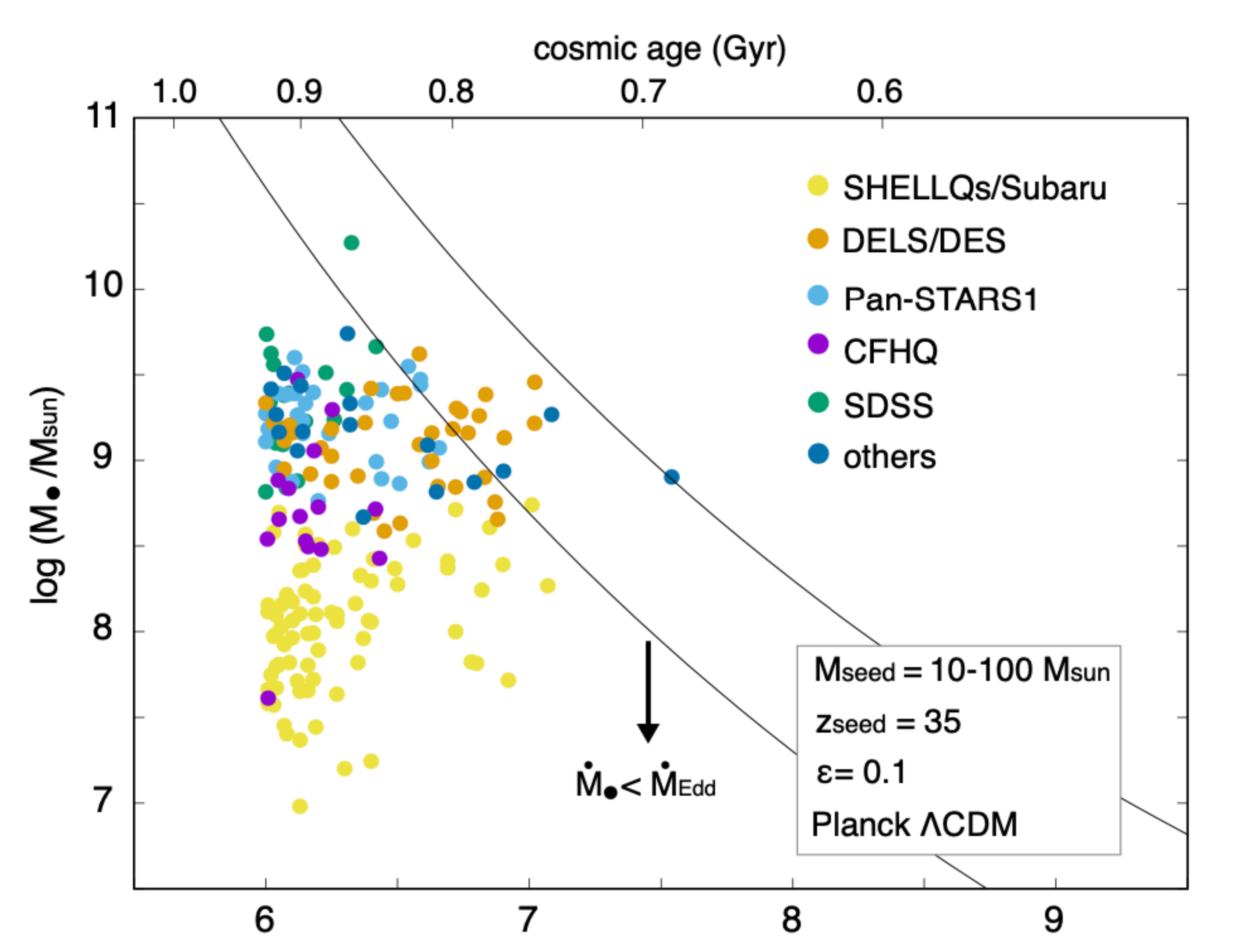
Since several years we discovered that supermassive black holes inhabit the center of (nearly all) galaxies, including ours!



SMBHs live in the center of galaxies!

These gargantuan objects have masses ranging from $\sim 10^7 M_\odot$ to $\sim 10^{10} M_\odot$, and appear to be present also in high-redshift galaxies

On the one hand this poses major challenges in trying to understand how SMBH formed and evolved when the universe was so young, but it also opens a window to study the high-z universe



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SMBHs to study the Universe

SMBH can be used to probe the history of our Universe in several ways, e.g.:

- the origin of their seeds (Astrophysical vs. Cosmological) can give insights on the very first instants of the Universe, as well as on the gas cooling mechanisms active at the Cosmic Dawn;

- understanding their growth mechanism(s) can give powerful insights into the gas content of galaxies and…

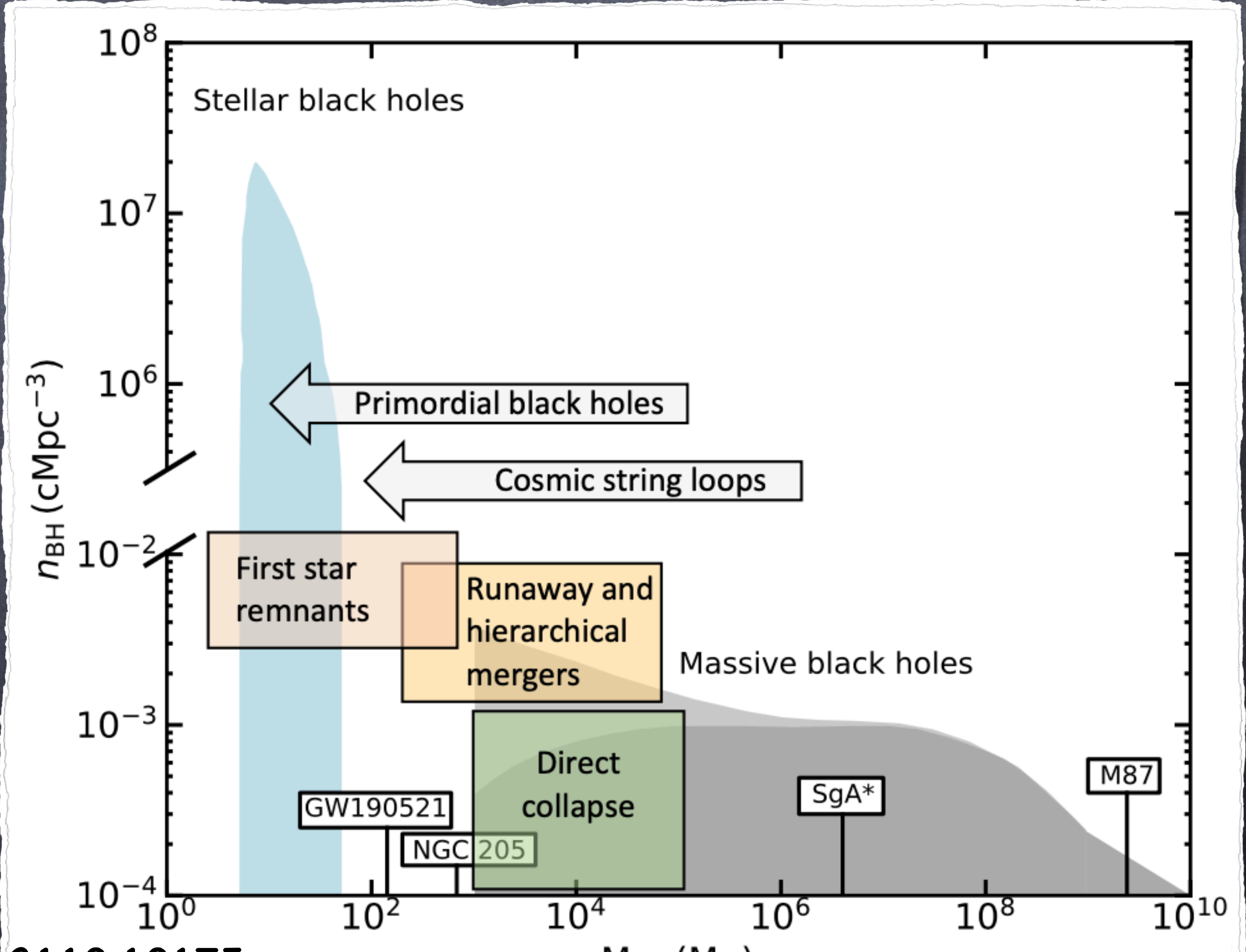
- …the impact of the SMBHs and their host galaxies on the IGM, thus being a complementary tool to study and understand reionisation (QSO are radiatively more efficient than stars in ionising the IGM)

SMBH formation

It is commonly accepted that SMBH must have originated from lighter "seed" black holes, that have grown in mass over time feeding from the environment

Seeds can then be generated in galaxies, from the collapse of massive stars or from mergers of stars or stellar black holes.

The seeds can have primordial origin, generated by the collapse of high density perturbations in the Early Universe



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SMBH formation: Astrophysical channels

Several different pathways can produce both light seeds ($\sim [10^2 - 10^3]\,M_\odot$) and heavy seeds ($\sim [10^4 - 10^6]\,M_\odot$)

Lack of metals is the key:

-> fewer energy exchanges and spectral transitions

-> cooling less efficient

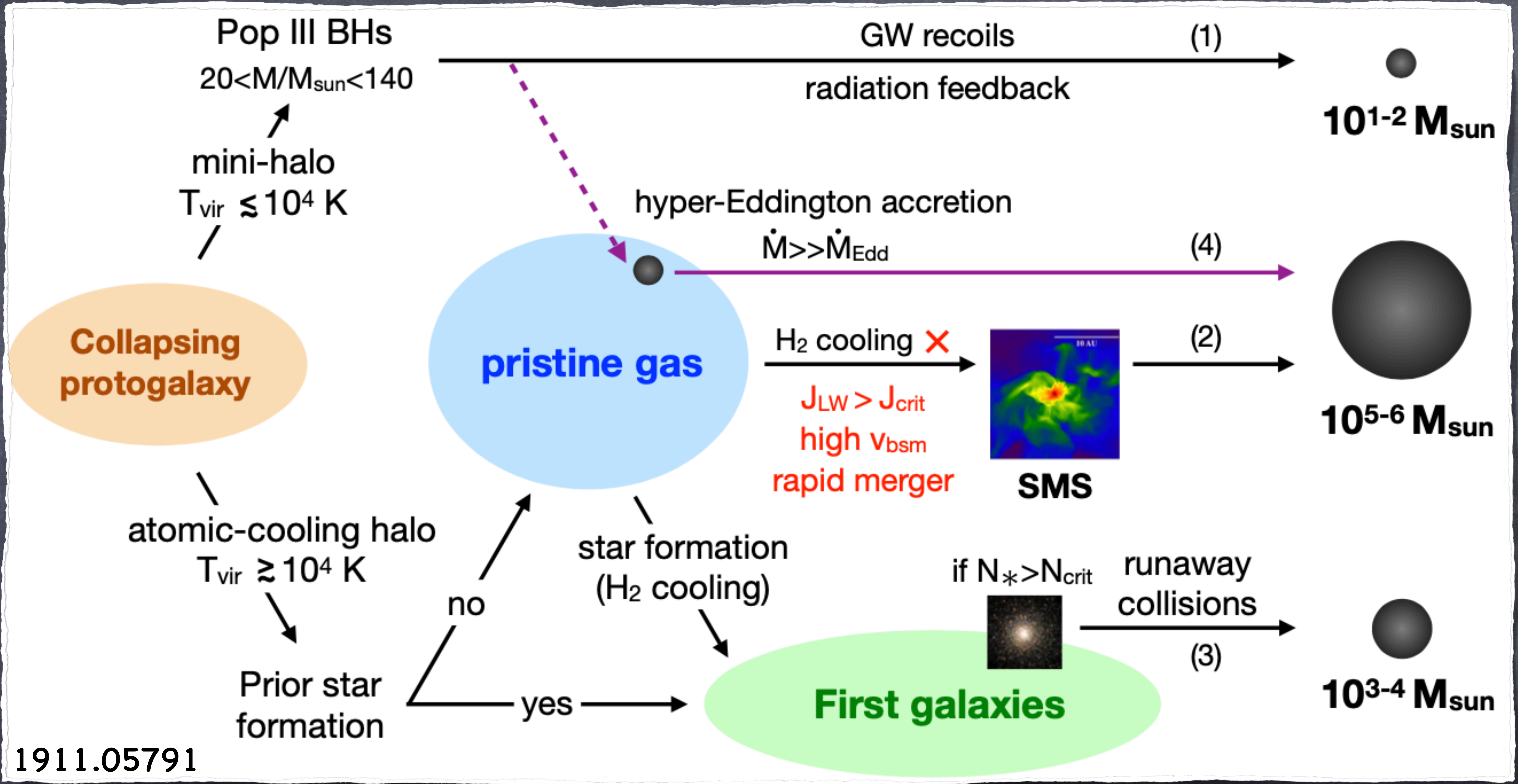
-> hotter Jeans unstable clouds fragment less

-> stars form more massive

-> less effective radiation pressure

-> relic black holes with mass similar to that of the progenitor star

SMBH formation: Astrophysical channels



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Formation pathways of seed BHs in early protogalaxies: (1) Pop III remnant BHs with a mass of M. $\sim 10^{1-2}\,M_\odot$, (2) massive seed BHs with M. $\sim 10^{5-6}\,M_\odot$ in ACHs under peculiar conditions such as strong Lyman-Werner radiation, high baryon-DM streaming velocity, and rapid mergers of DM halos, and (3) relatively massive seeds with M. $\sim 10^{3-4}\,M_\odot$ via runaway collisions in ultra-dense stellar clusters. (4) Hyper-Eddington accretion onto stellar-mass BHs would effectively result in a massive seed at the center of a dense pristine gas cloud

SMBH formation: Astrophysical channels

Single very/super massive stars

The direct collapse scenario in massive halos ($\gtrsim 10^8$ $M_\odot$) can form SMS with masses $\sim [10^4 - 10^6]$ $M_\odot$ that then can collapse in MBH (no molecular hydrogen in the halo)

Runaway stellar mergers

Friction in dense environments can lead massive stars to assemble at the center and give raise to runaway collisions giving birth to a very massive star, then quickly collapsing to a BH

Hierarchical BH mergers

BH relics of massive stars can sink to the center by friction more quickly than stars, then assemble in binaries hardened by encounters and merge (high escape velocities needed)

SMBH formation: Early Universe channels

Seeds can be formed before galaxy formation by collapse of regions in the Early Universe.

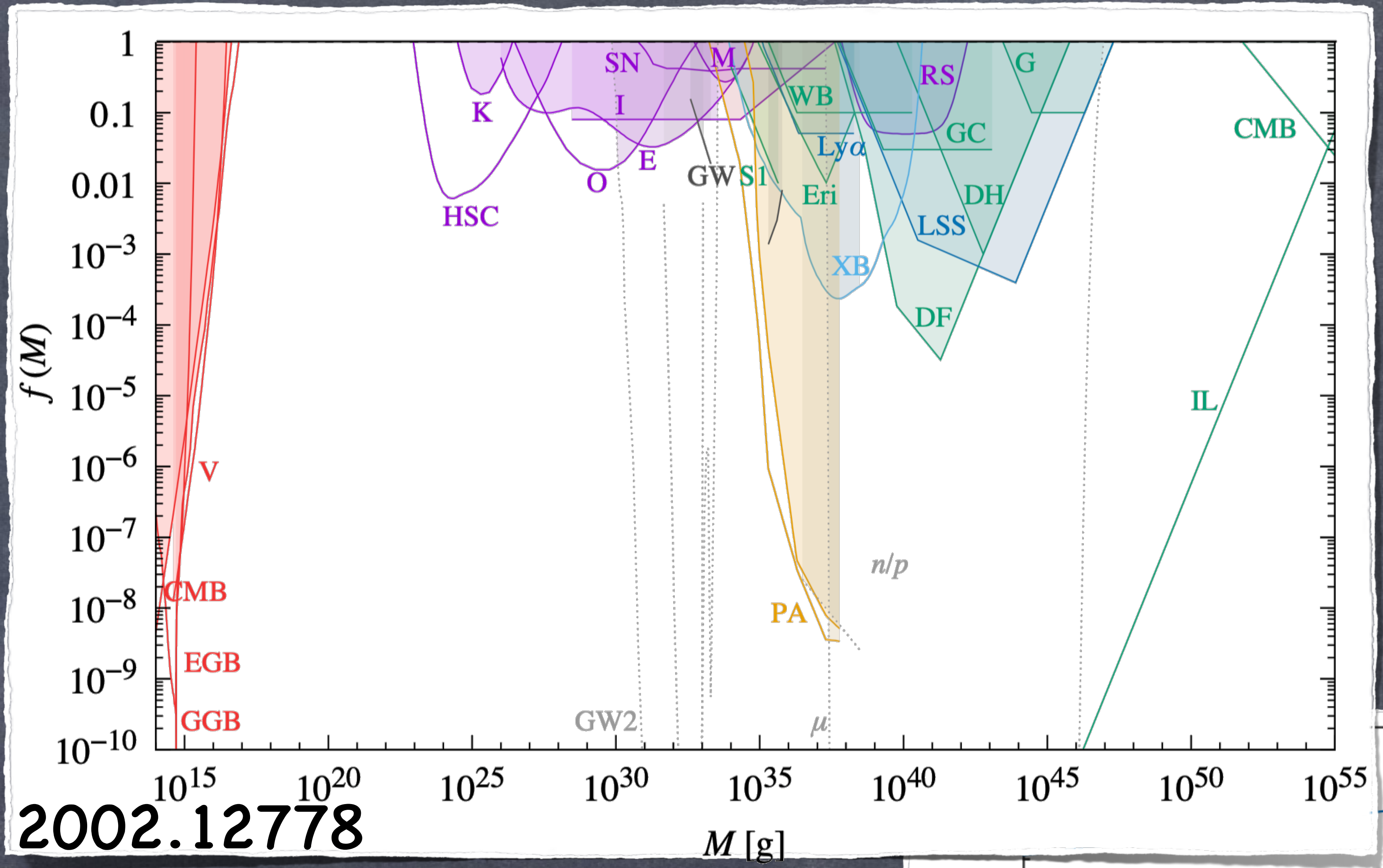
In this case, galaxies form around black holes, and not black holes “in” galaxies

Primordial BH

Can be generated by several inflationary models, and have a broad mass spectrum

Cosmic string loops

Topological defects that can collapse and form 1 seed BH per galaxy, of $\sim 10^5\,M_\odot$



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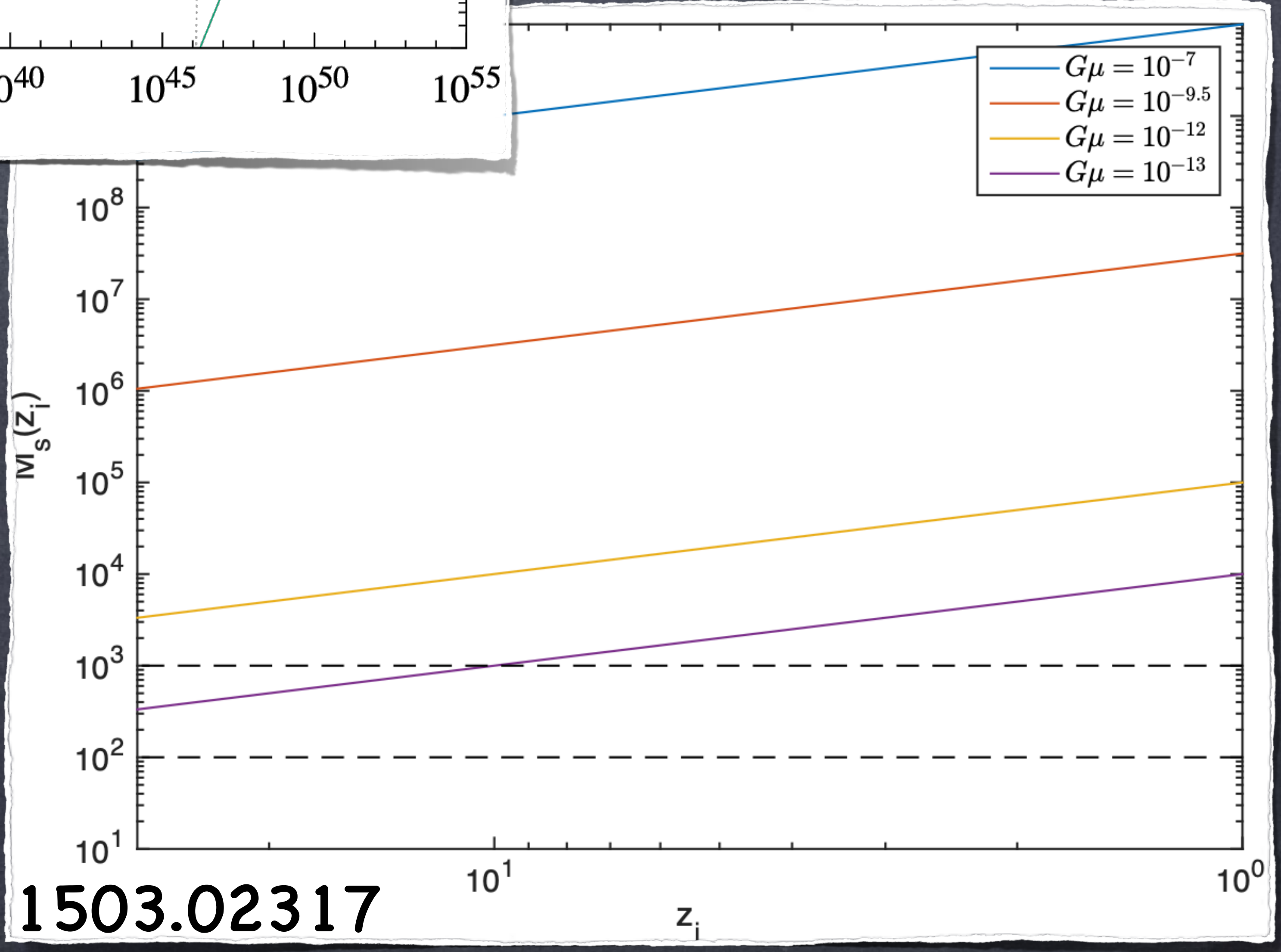

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SMBH growth: accretion

The biggest contribution to MBH growth in the Universe is expected to come from accretion

Even though MBH have a limited sphere of influence as compared to their host galaxies, gas can approach the last stable circular orbit gently spiralling down and forming an accretion disc

SMBH growth: accretion

A key limit can be the Eddington critical accretion rate, i.e. when the outward radiation pressure force on the infalling gas, through electron scattering, matches the inward gravitational force. If this holds, the time-scale for growth to a mass $M_\cdot$ can be as long as

$$t_{grow} \approx \frac{0.45\epsilon}{(1-\epsilon)f_{duty}} \ln\left(\frac{M_\cdot}{M_{seed}}\right) \text{ Gyr} \approx 0.8 \text{ Gyr}$$

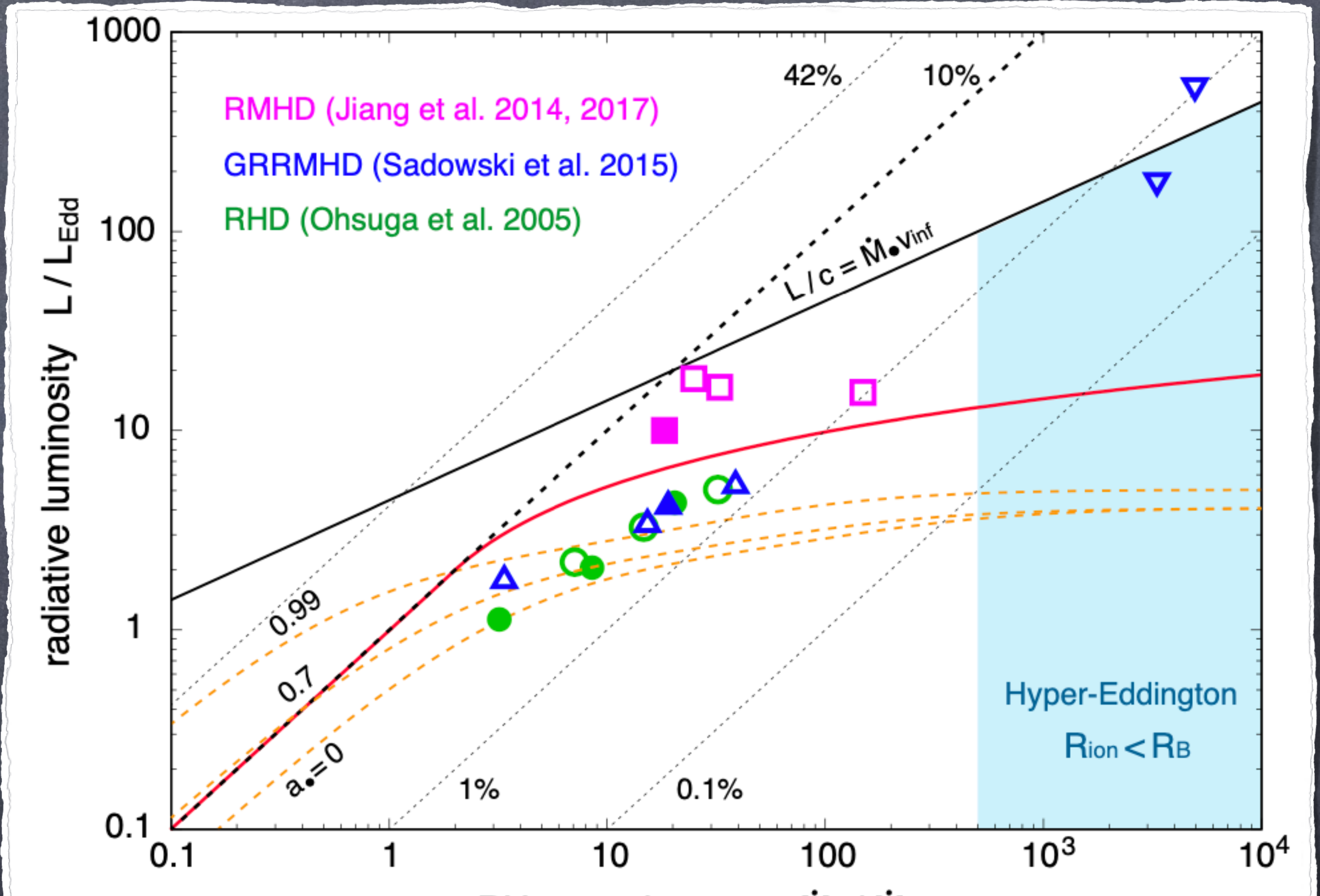
which is comparable to the age of the Universe at $z \sim 6$, so something more must be going on in order to explain the observation of high-z QSOs (even though the density is low, ~ 1 Gpc^{-3})

SMBH growth: accretion rate

Simulation showed that super-Eddington accretion is achievable and can be sustained by accreting MBHs thanks to photon trapping in the optically-thick accreting matter

This mechanism operates when the radial gas inflow speed is faster than the outward photon diffusion speed, at a radius of

$$R_{tr} = 5\frac{\dot{M}_{\cdot}}{\dot{M}_{Edd}}R_{Sch}$$



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SMBH growth: accretion material inflow

Gas inflows from $r \gg R_{Sch}$ can be triggered by several physical processes

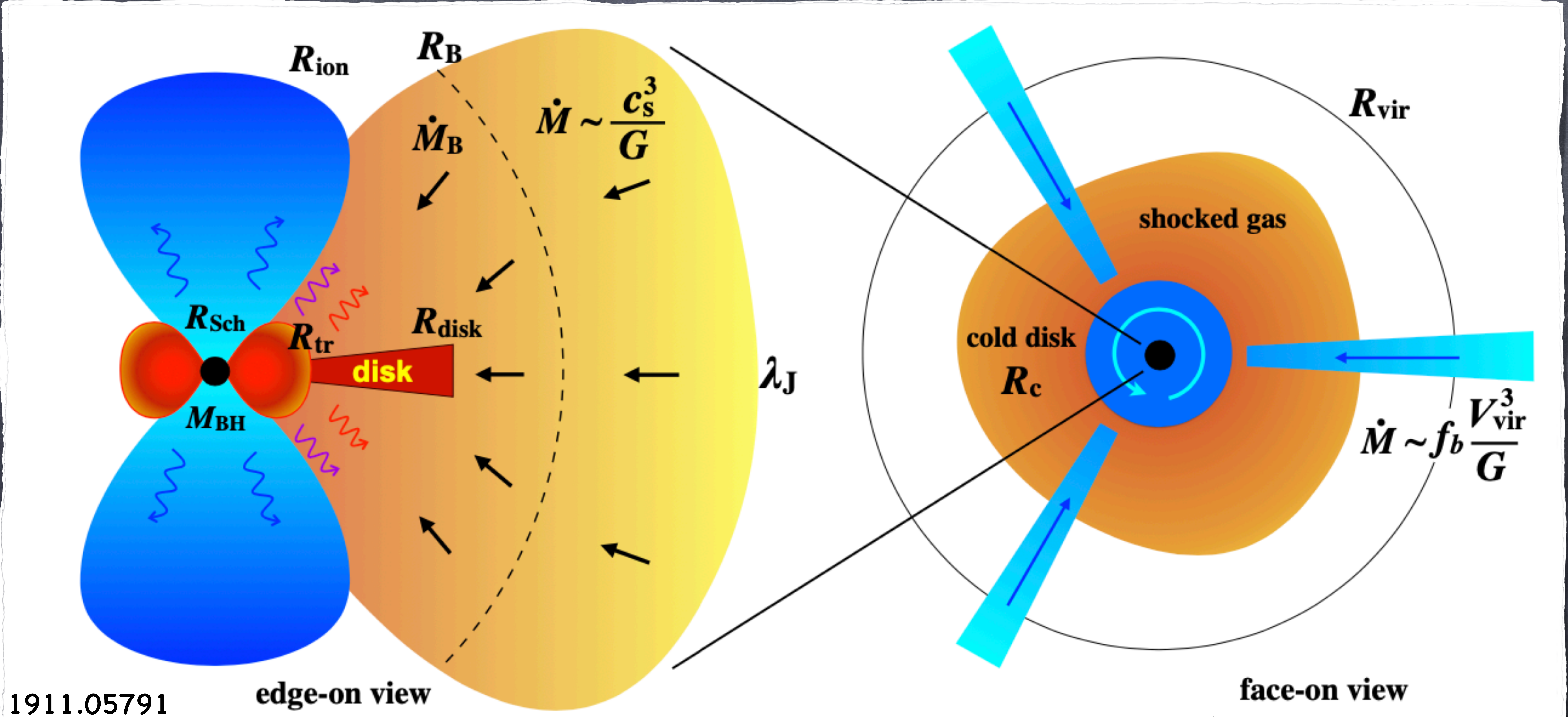
- The mass accretion rate of a DM halo triggered by mergers of galaxies averaged over cosmological timescale is approximately given by

$$\dot{M} \approx 0.3\,\mathrm{M_\odot\,yr^{-1}} \left(\frac{V_c}{20\,\mathrm{km\ s^{-1}}} \right)^3$$

- Clumps of gas form and collapse more easily due to the lack of metal cooling, and if a MBH is embedded into such an unstable environment material is provided at super-Eddington rates

- At smaller scales the gas dynamics is then influenced by the gravity of the MBH (the critical radius is $R_B = GM_{\cdot}/c_s$) which again makes super-Eddington accretion possible

SMBH growth: accretion



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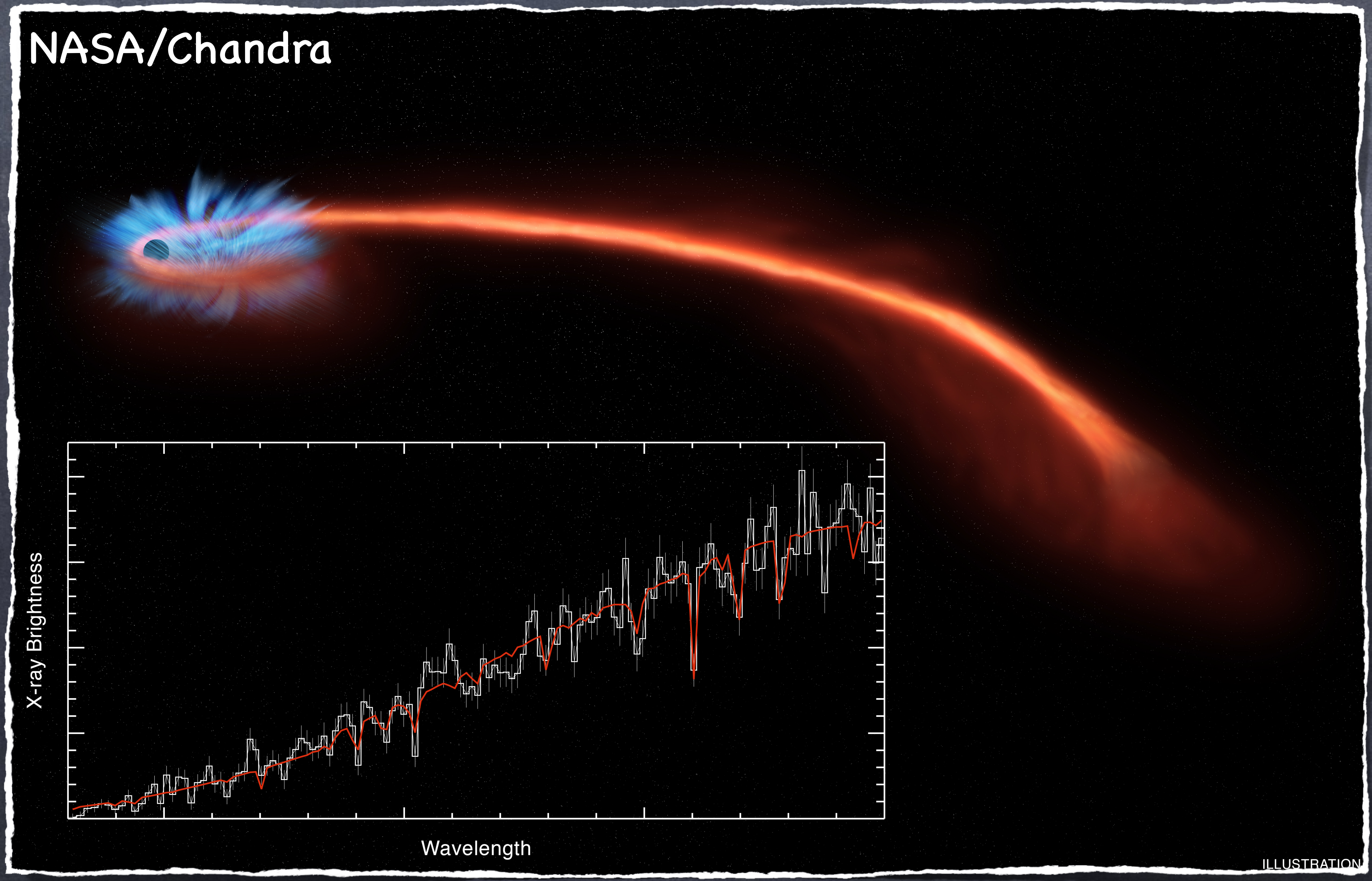
SMBH growth: accretion from TDE

It should also be noted that at least some of the accreted material can come from the so-called tidal disruption events, i.e. when a star passes close enough to the MBH to get stripped of its outer layers.

This transient events can be useful to observe MBHs and attracted a lot of attention in recent years with more conclusive detections



SMBH growth: accretion hurdles

Some physical processes related to MBHs themselves or their host galaxies can anyway hamper or even halt MBH growth. Indeed, MBH feeding is able to release a large amount of energy on scales ranging from sub-pc to tens of kpc, potentially impacting the whole galaxy and beyond.

The released energy or momentum couples to the gas in vicinity of the MBH and can heat it or photoionise it, in particular if the ionisation front expands outside the Bondi radius accretion becomes intermittent with a greatly reduced rate.

Jets and winds from the central object can exert a negative mechanical feedback on the accreting gas, pushing it away

Other extreme phenomena, such as SN explosions, near the MBH can also suppress accretion

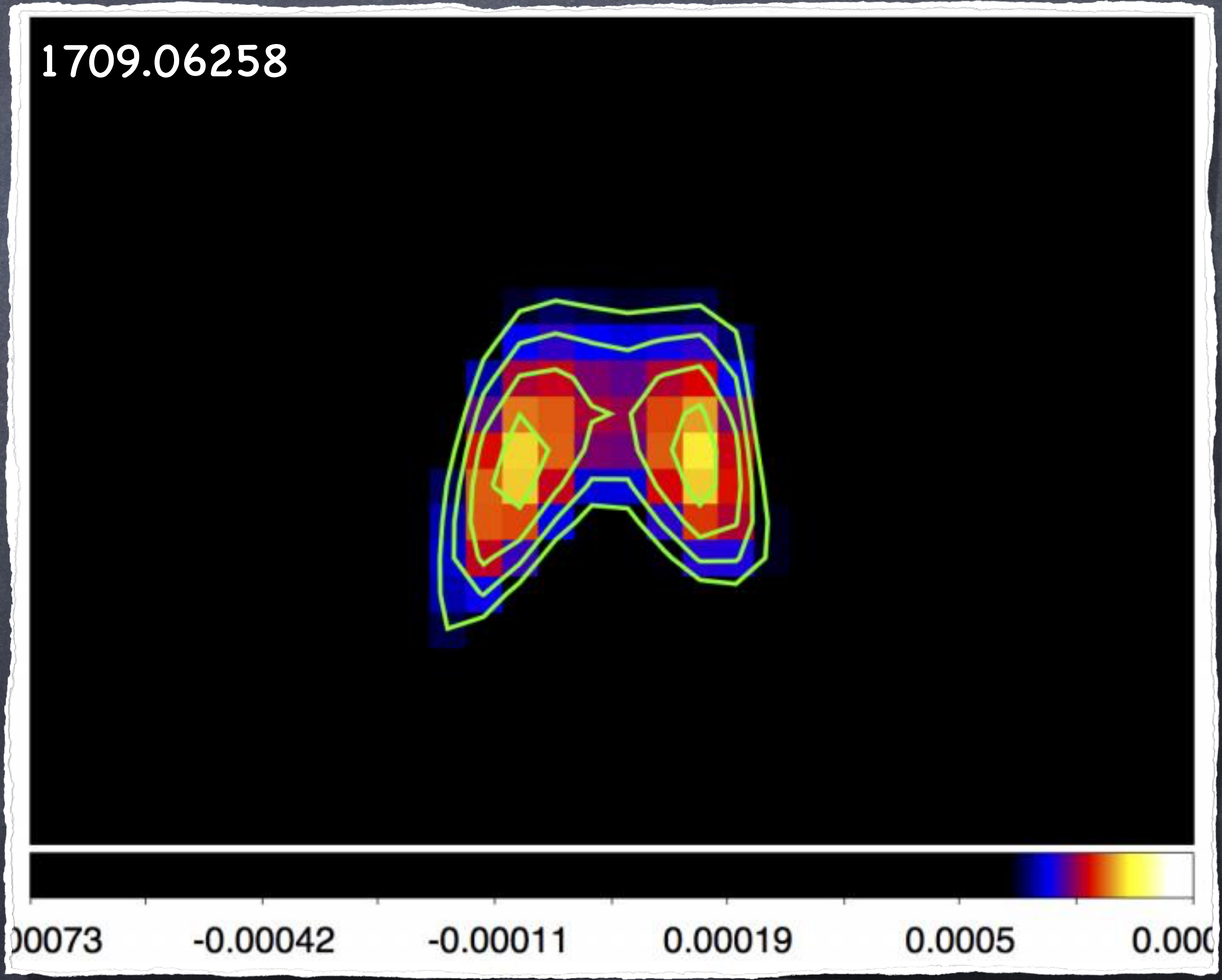
Accretion is suppressed for MBHs not sitting at the center of galaxies

SMBH growth: mergers

MBH mergers play a secondary role in the mass budget of MBHs, but they can be important when gas is not readily available or in galaxies with a rich merger history.

MBH binaries are expected to form in galaxy mergers, and the number of candidates discovered through accretion is raising

PopIII stars are expected from simulations to form in binaries, but nothing guaranties that the binary will merge



SMBH growth: link with host galaxies

There is evidence for a variety of empirical relations between MBH mass and galaxy bulge luminosity, mass, and stellar velocity dispersion.

The circular velocity of the dark matter halo, is found to correlate with the mass of the black hole to that of the halo as $M_{\bullet} \propto V_c^{4-5}$

Also, the SMBH mass is found to be related to the galaxy mass by

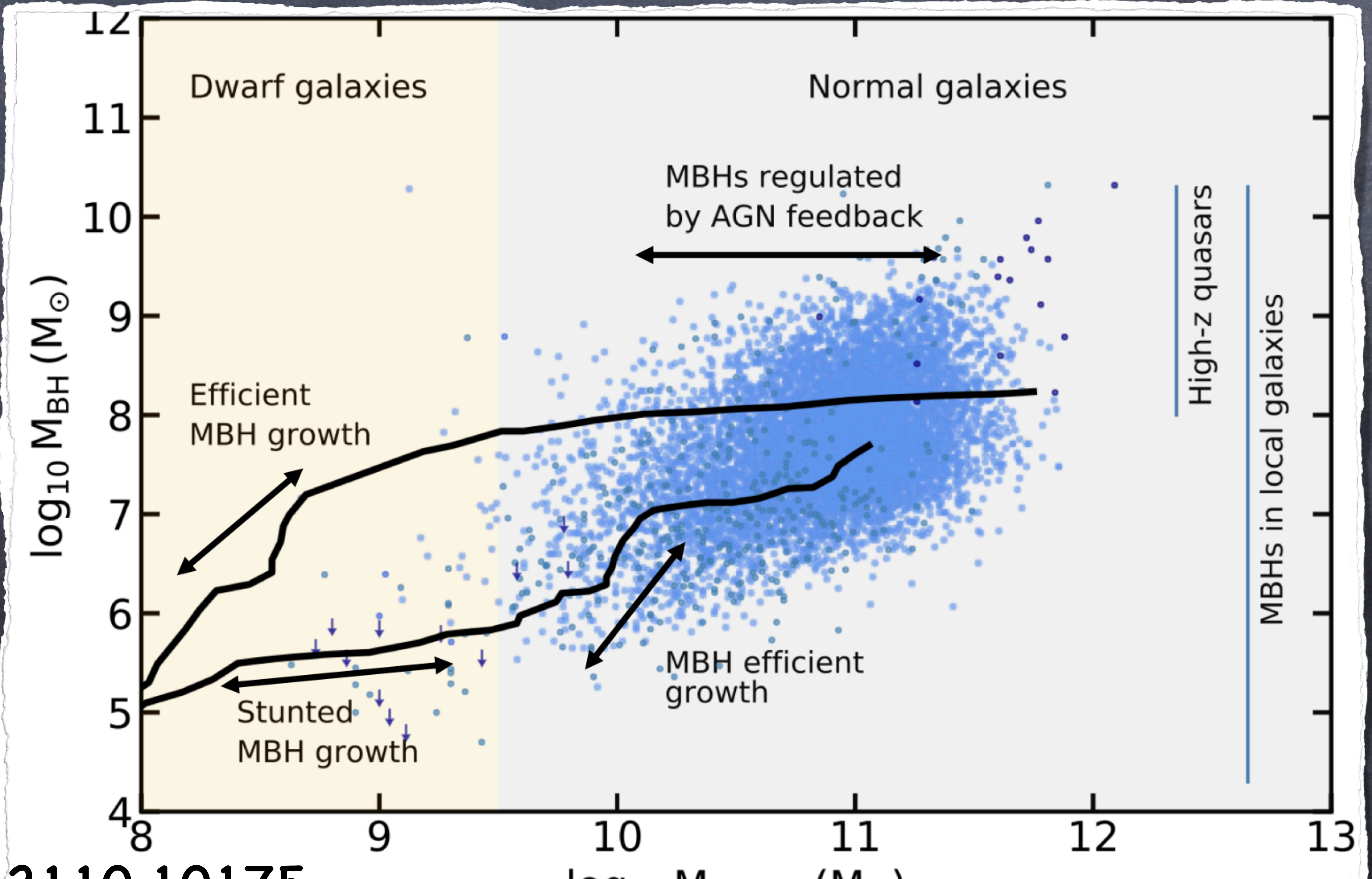
$$M_{\bullet}(M) = M\epsilon_0 \left(\frac{M}{12\,M_{\odot}} \right)^{\frac{\gamma}{3-1}} \left(\frac{\Delta_v \Omega_m h^2}{18\pi^2} \right)^{\frac{\gamma}{6}} (1+z)^{\frac{\gamma}{2}}$$

Several aspects of galaxy evolution and of MBH assembly can anyway shape such relations (and their scatter)

SMBH growth: link with host galaxies

MBHs could impact the mass growth of their host galaxies and regulate themselves through feedback, while galaxies could instead influence (potentially completely halt) the growth of their MBHs through e.g., supernova feedback.

Scaling relations and their scatter are evidence for the complex co-evolution of MBHs and galaxies, but their extension towards higher redshifts is limited by observation biases



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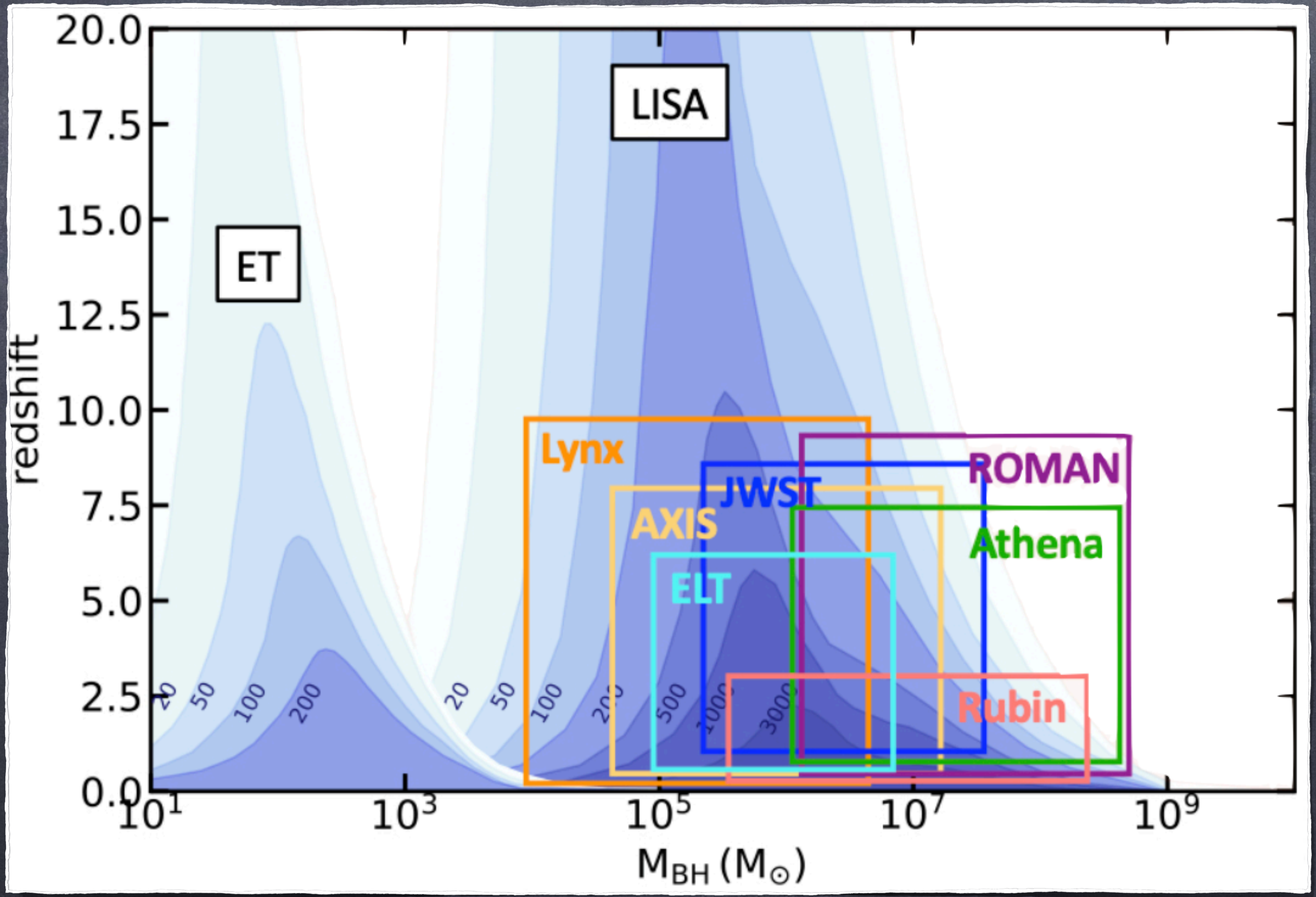
SMBH observational prospects

The quest to constrain the origins of MBHs has already started, and it will intensify in the future with new exciting experiments



Thanks for the attention!

SMBH mergers: final parsec problem

When galaxies merge friction and gravitational slingshot from stars can form a bound binary and further friction can bring it to $\mathcal{O}(\text{pc})$ radius, but at that point gas is depleted.

Before gravitational wave emission is sufficient to efficiently let the binary merge, something has to shrink the radius to $\mathcal{O}(0.1\,\text{pc})$, otherwise the system would not merge within a Hubble time