Massive black holes: their origins and evolution

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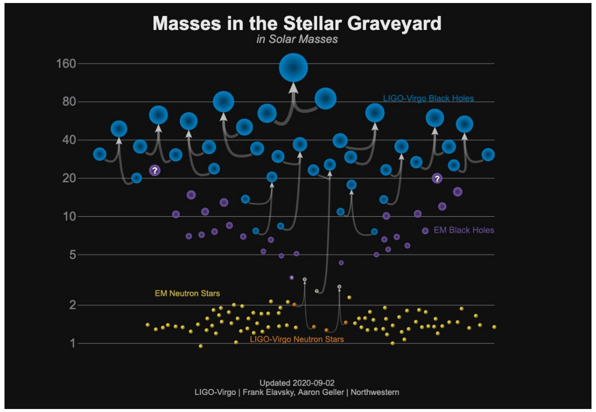
and friends

Black Holes in the Universe

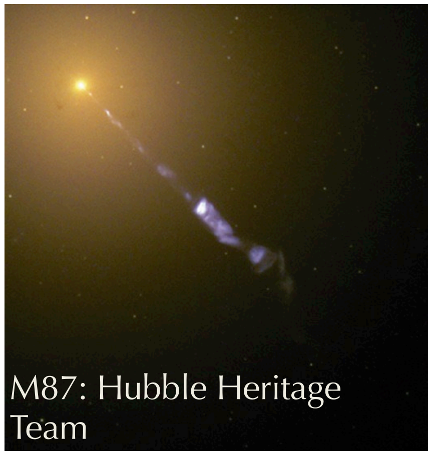
Stellar mass black holes

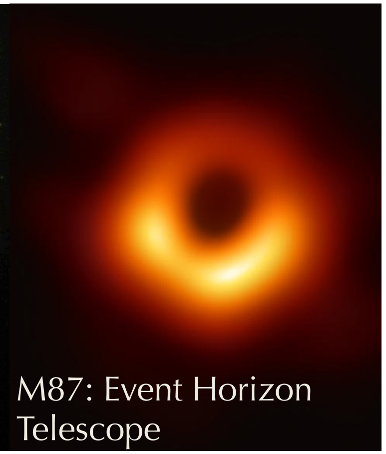
- Endpoint of the lives of massive stars
- Mass from ~2 up to (?) few tens M_{sun}



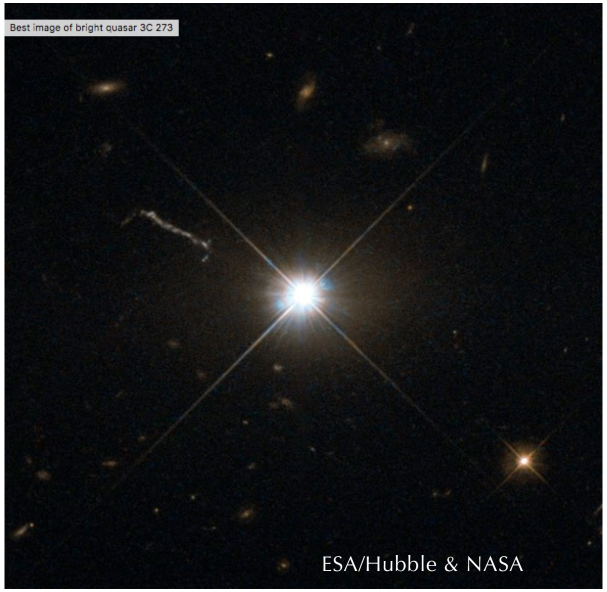
Massive black holes

- Powering active galactic nuclei (AGN) and quasars
- Inhabiting the centers of nearby galaxies, including the Milky Way
- Mass > 10^4 M_{sun} up to (?) ~10^{10} M_{sun}


M87: Hubble Heritage Team


M87: Event Horizon Telescope

Active massive black holes: AGN and quasars

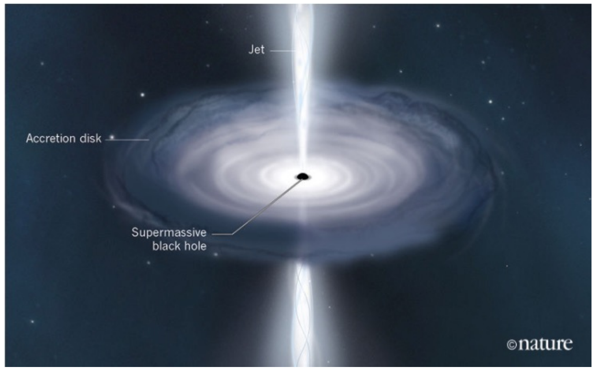


They are as luminous as galaxies: $L \sim 10^{11}$-10^{13} L_{sun}

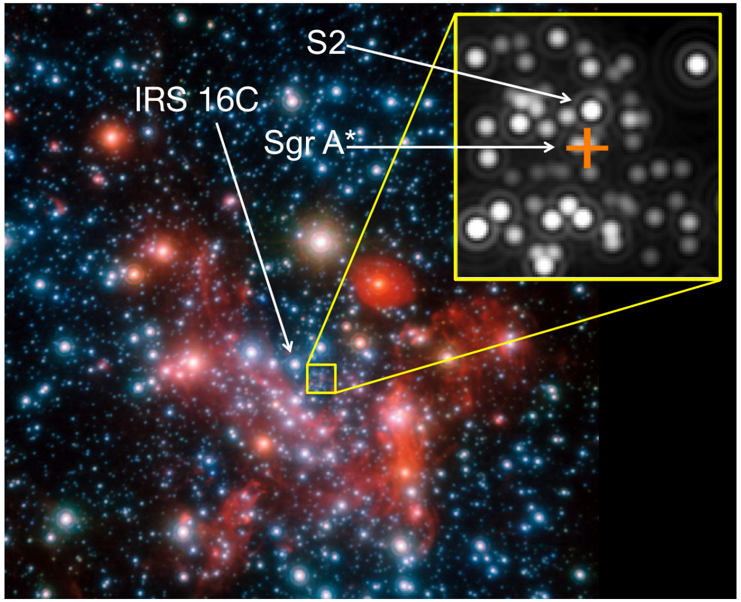
Size of the emitting region is 10^6 times smaller than a galaxy ~ size of solar system

Powered by black holes with masses of millions to billions of Msun that are accreting

Luminosity is produced as gas spirals in from ~10K Schwarzschild radii to the innermost stable circular orbit



Quiescent massive black holes



ESO/MPE/S. Gillessen et al.

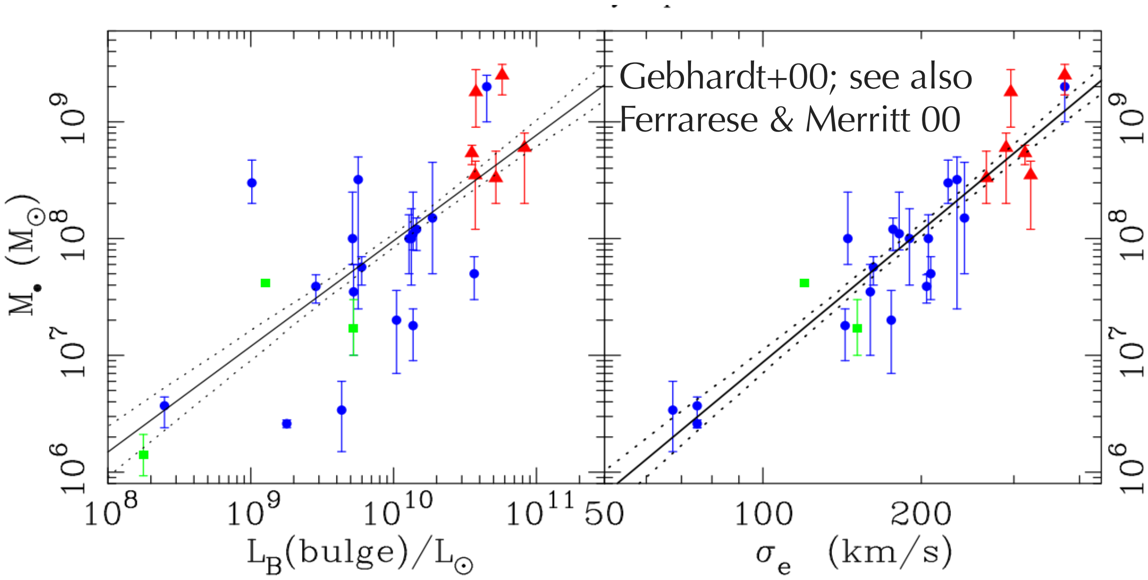
Many massive black holes are quiescent.
We have an example in the center of the Milky Way

The mass of SgrA* is ~4.3×10^6 M_{sun}

The typical luminosity of Sgr A*, is ~10^{34} erg/s

Not much more than the Sun (4×10^{33} erg/s)

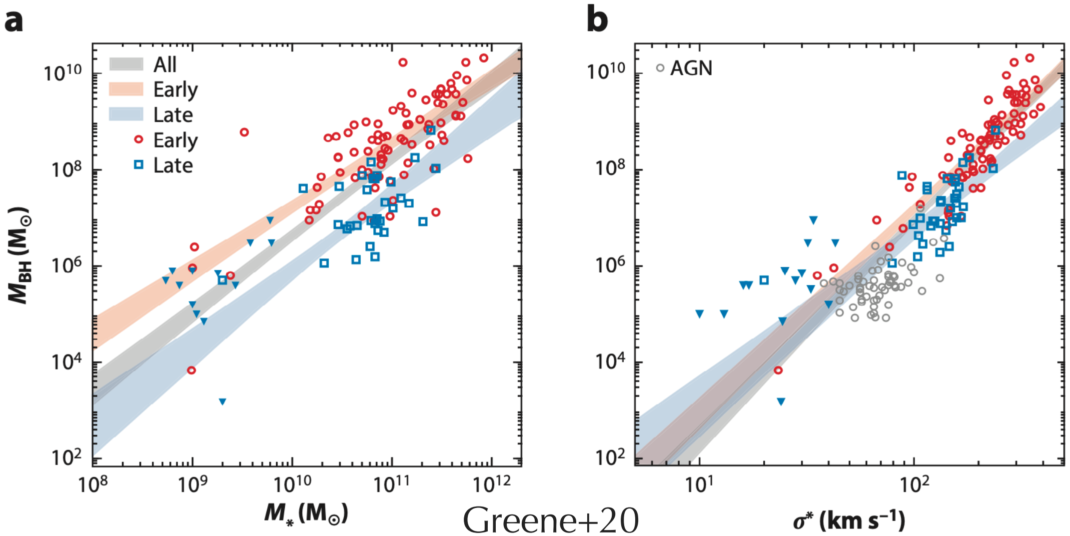
The first revolution: massive black holes in local galaxies



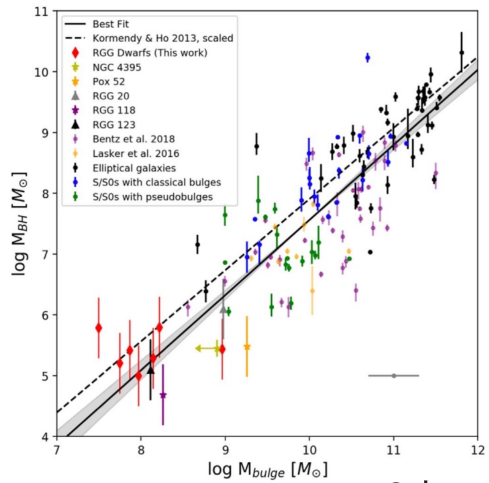
Black hole masses correlate with galaxy properties. This means their growth/evolution are connected: massive black holes are part of galaxy evolution

Magorrian+98; Ferrarese & Merritt 00; Gebhardt+00; Haring & Rix04, Marconi & Hunt03; Kormendy & Ho 14; Greene+20 and references therein

Massive black holes in local galaxies



Greene+20



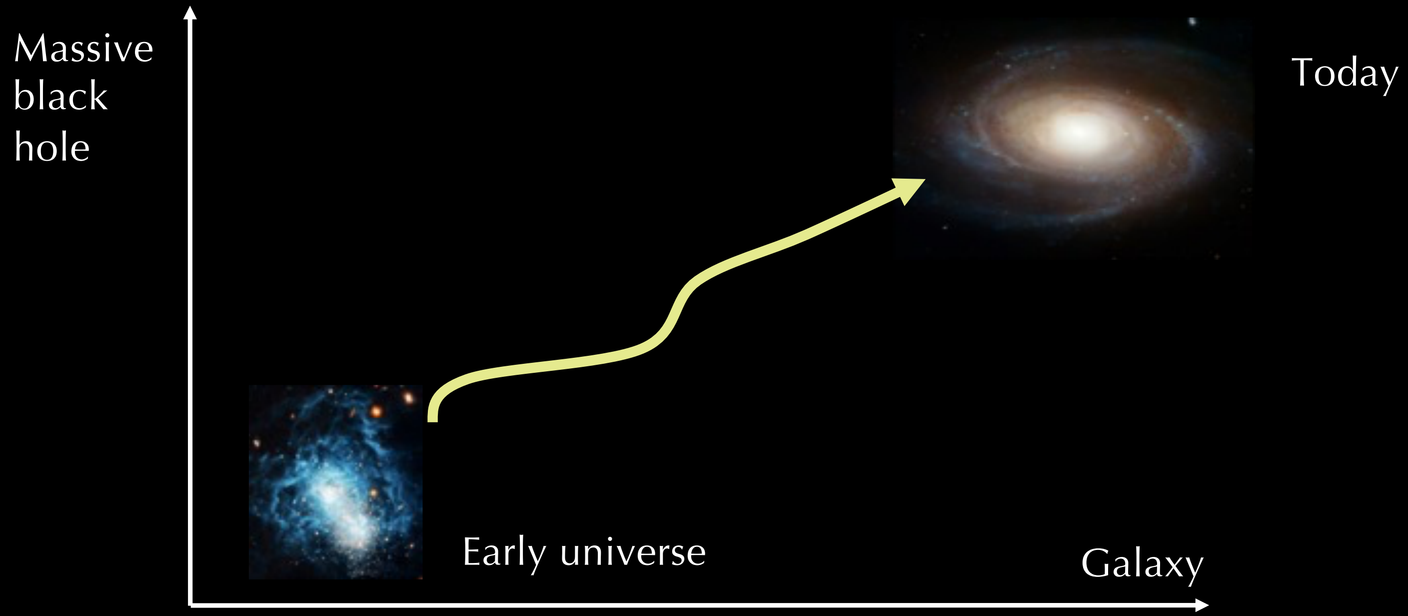
Schutte+19

Twenty years on, relationships are still debated

- low-mass end
- high-mass end
- scatter
- selection/morphology

Magorrian+98; Ferrarese & Merritt 00; Gebhardt+00; Haring & Rix04, Marconi & Hunt03; Kormendy & Ho 14; Greene+20 and references therein

The evolution of massive black holes in galaxies



Massive black hole formation

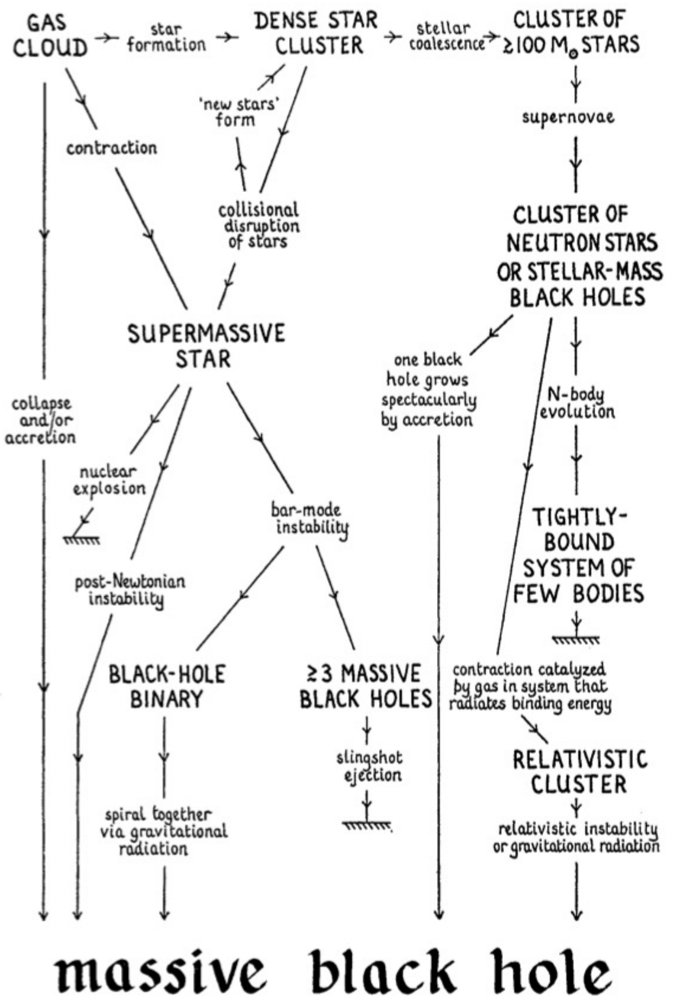
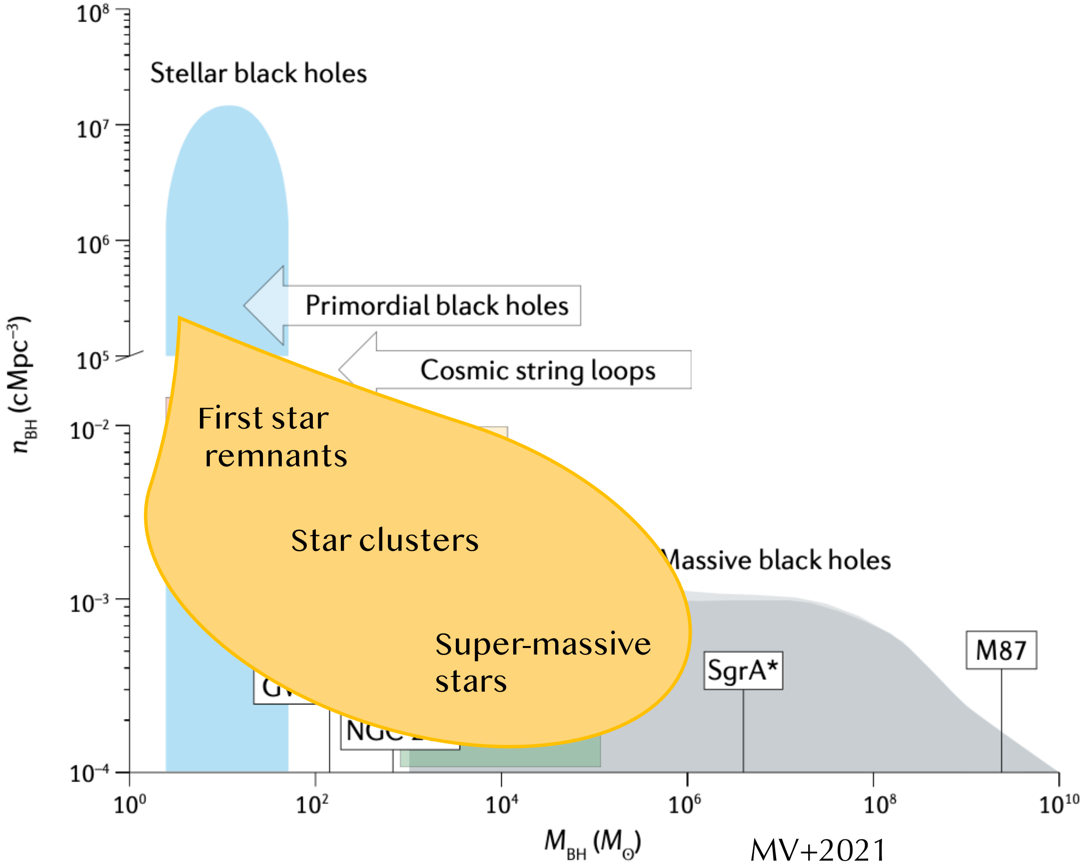


Fig. 2
Possible modes of formation of a massive black hole in a galactic nucleus.

In a 1978 seminal paper Martin Rees outlines the “possible models of formation of a massive black hole in a galactic nucleus”

Massive black hole seeds



MV+2021

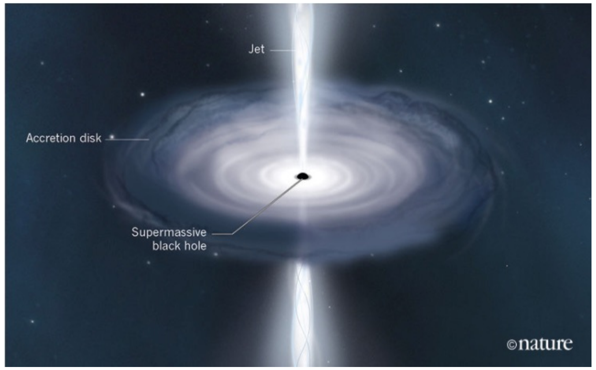
Lighter seeds are predicted to be more ubiquitous and heavier seeds less and less abundant

The most recent models suggest that rather *than a bimodality between light and heavy seeds instead a continuum exists*

Primordial black holes and cosmic string loops are set at arbitrary number densities

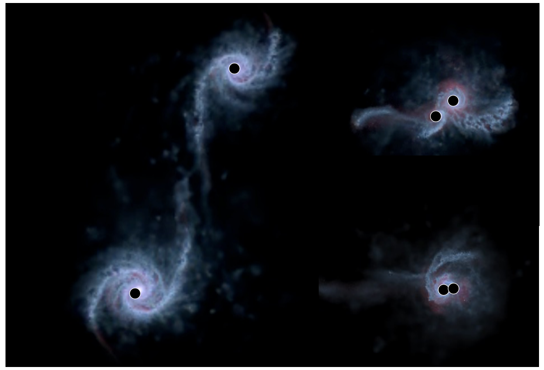
The growth of massive black holes

gas accretion



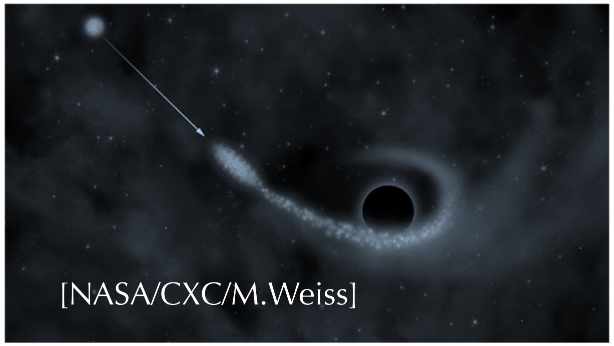
AGN/quasars

MBH-MBH mergers



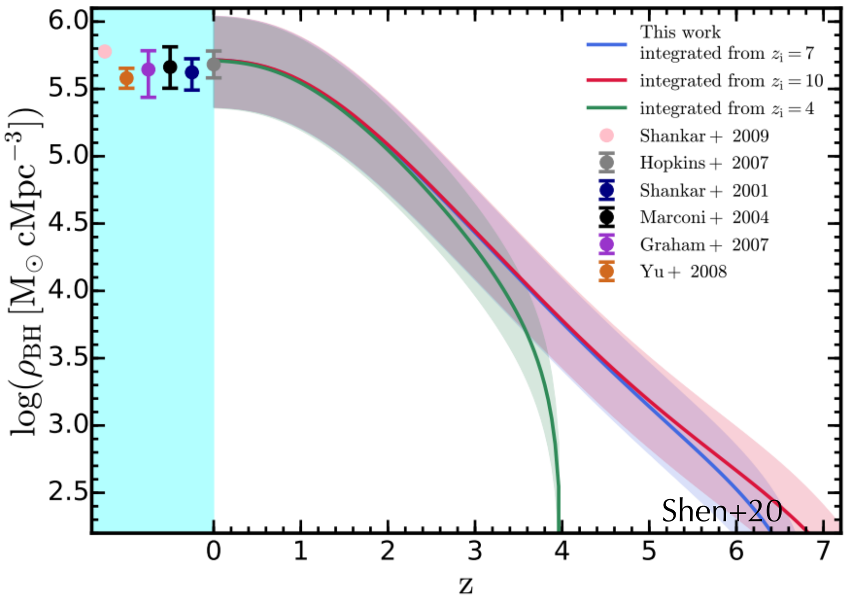
Gravitational waves

accretion of stars



Tidal Disruption Events

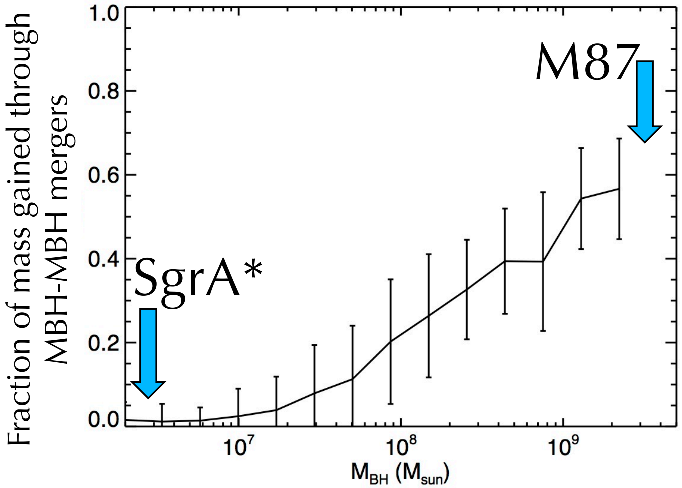
The growth of massive black holes



Soltan's argument: mass density increases by ~ 3 orders of magnitude in the last ~10 Gyr: accretion has a strong (dominant) contribution

(see Inayoshi+25 and Umeda+26 for a discussion on high-z results)

The growth of massive black holes



Dubois, Volonteri & Silk 2014

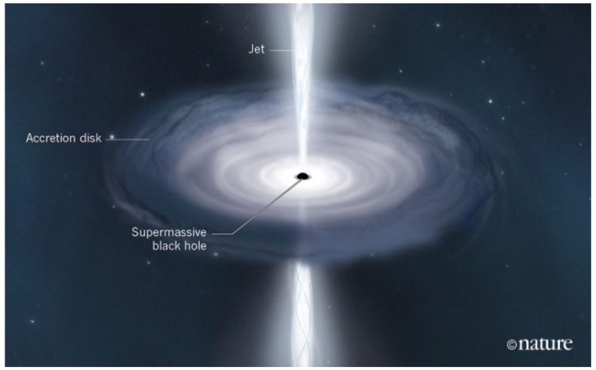
Accretion leads the overall mass density (Yu & Tremaine 2002)

Low and high mass massive black holes have statistically different growth histories in terms of mergers vs accretion (Dubois, MV & Silk 2014, Kulier et al. 2015)

Massive black hole mergers contribute a higher mass fraction at the high mass end, where galaxies are gas poor

The growth of massive black holes

gas accretion



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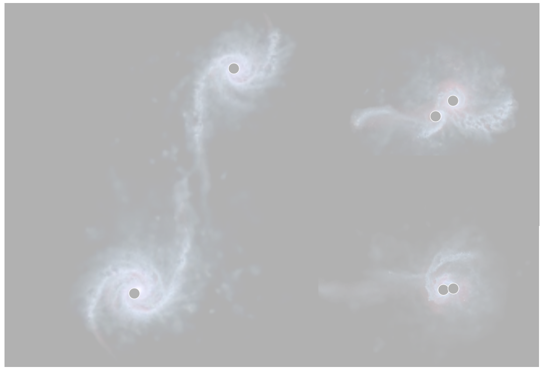
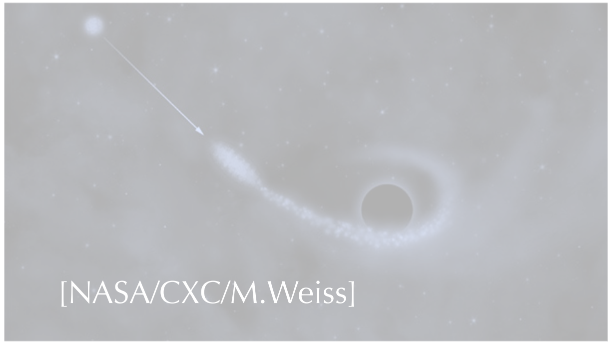


Gravitational waves

stellar accretion



Tidal Disruption Events

Gas accretion: AGN feedback

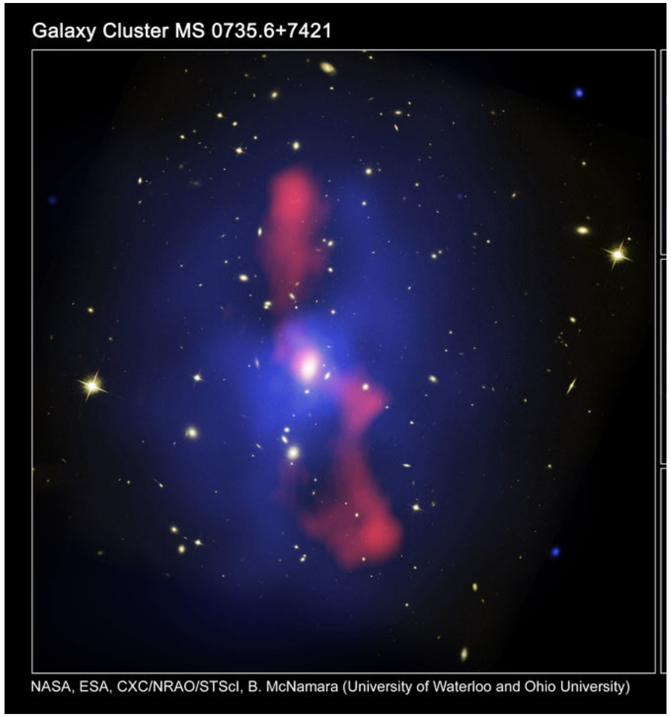
When a massive black hole accretes it injects energy – in various forms – in its surroundings and out to large distances

Gas gets heated and rarefied

Hot and low-density gas cannot form stars or accrete efficiently on massive black holes

AGN feedback is known to regulate star formation in massive galaxies

AGN feedback is also very good at suppressing its own massive black hole growth



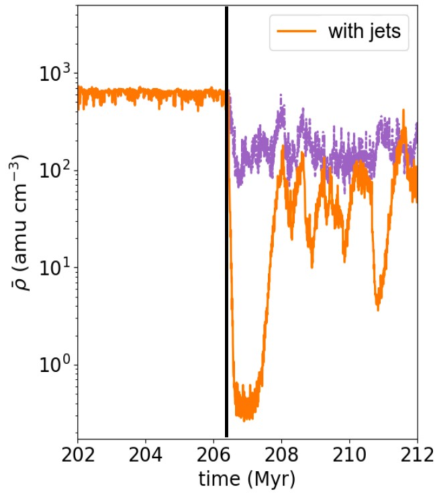
Gas accretion: AGN feedback

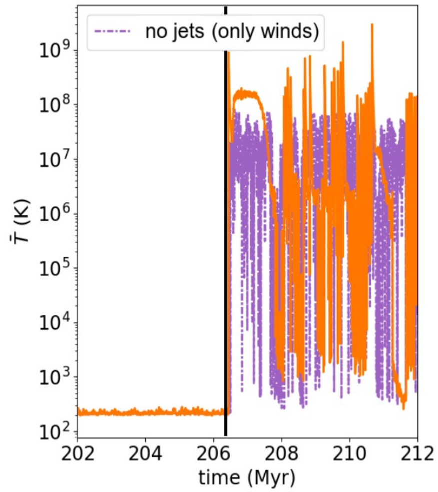
AGN feedback is very good at suppressing its own massive black hole growth

- Density:
  - Strong decrease with jets
  - Mild decrease with winds
- Immediate temperature increase

  ↳ $\dot{M}_{\rm acc}$ ↘

  Reminder: $\dot{M}_{\rm BHL} = \dfrac{4\pi G^2 M_{\rm BH}^2 \bar{\rho}}{(\bar{c}_{\rm s}{}^2 + \bar{v}_{\rm rel}^2)^{3/2}}$
- Sharp drops down to very sub-Eddington regimes



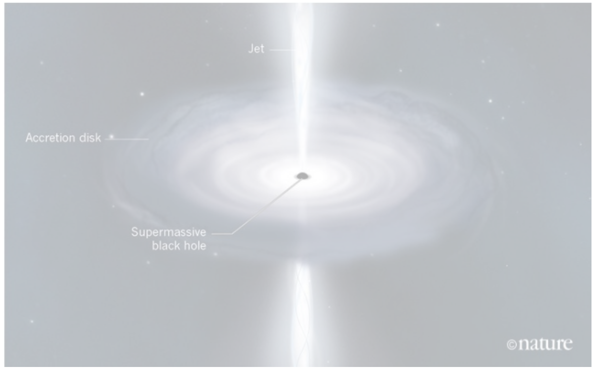


Credit: W. Massonneau

Many (recent) high-resolution simulations use feedback efficiencies calibrated on (old) low-resolution simulations, but *higher resolution* requires *lower feedback efficiencies* to obtain the same massive black hole/AGN/galaxy properties (Negri, MV+17; Lupi, MV+19)

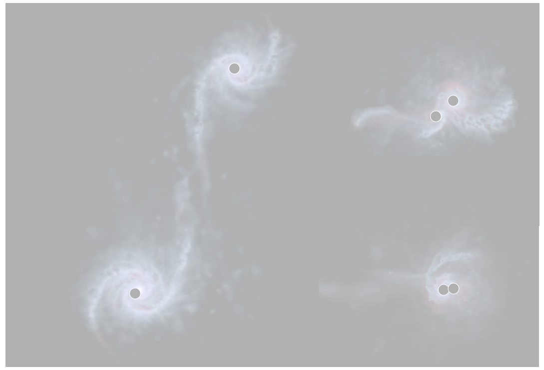
The growth of massive black holes

gas accretion



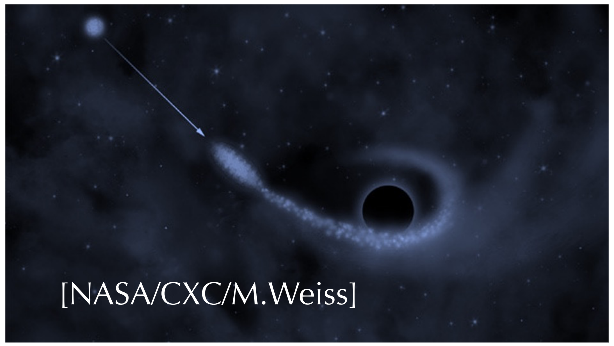
AGN/quasars

MBH-MBH mergers



Gravitational waves

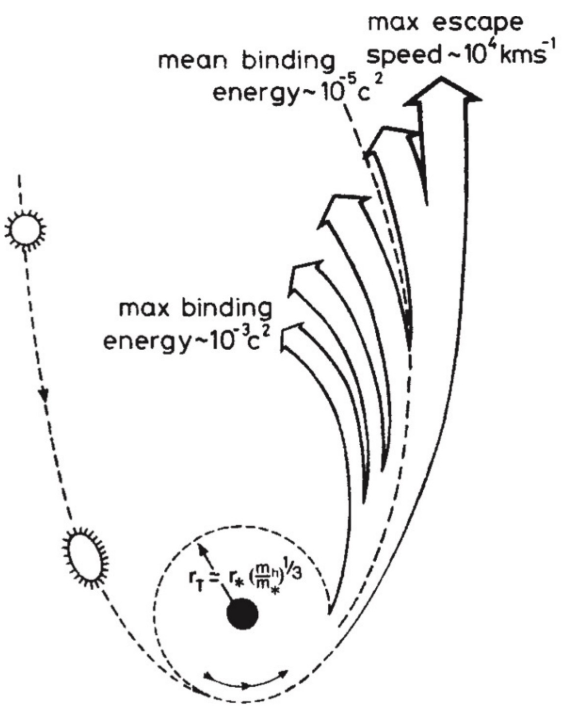
stellar accretion



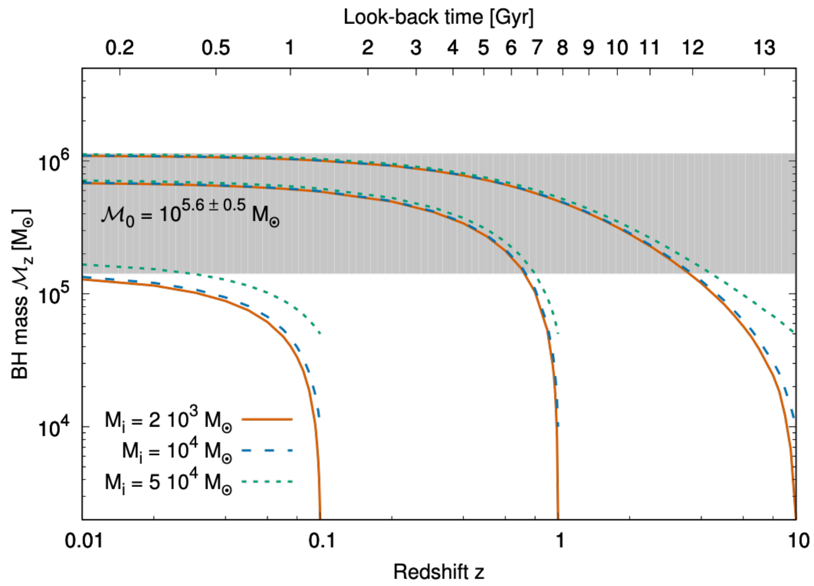
Tidal Disruption Events

Accretion of stars

Stellar disruptions by massive black holes can contribute to massive black hole growth up to ~10^5-10^6 M_{sun} (Alexander & Bar Or 17; Polkas+24)

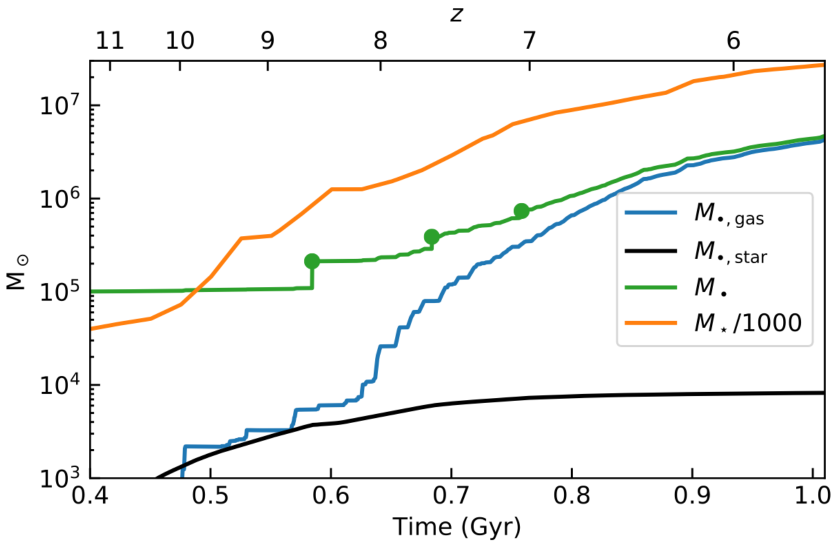


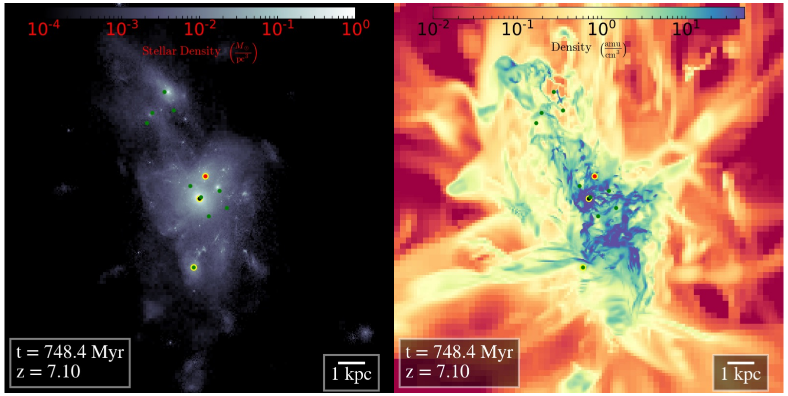
Rees 88



Alexander & Bar Or 17

Accretion of stars





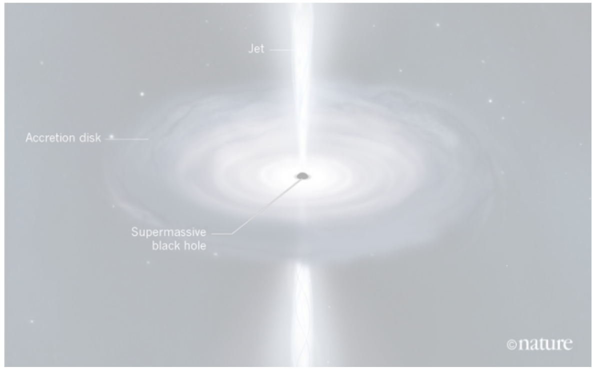
Stellar accretion can be important early on when gas accretion is hampered by feedback in low-mass galaxies

Stellar accretion is less variable than gas accretion: rate ~10^{-5} yr^{-1}

Pfister, Dai, MV+21

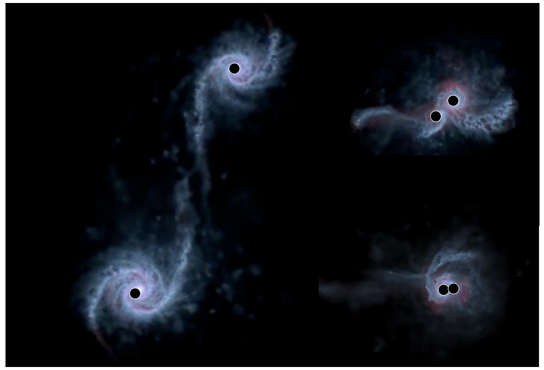
The growth of massive black holes

gas accretion



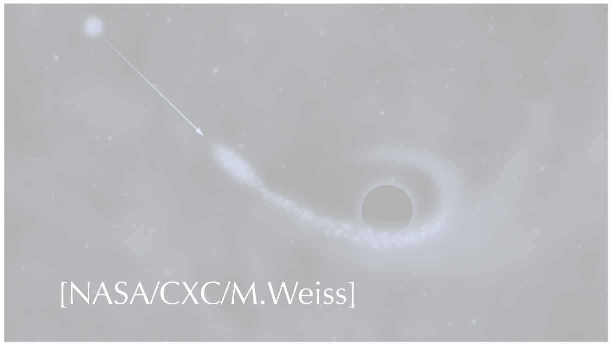
AGN/quasars

MBH-MBH mergers



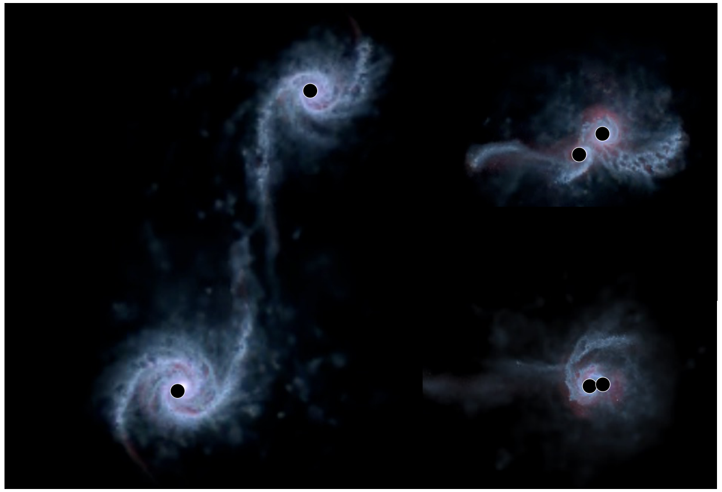
Gravitational waves

stellar accretion



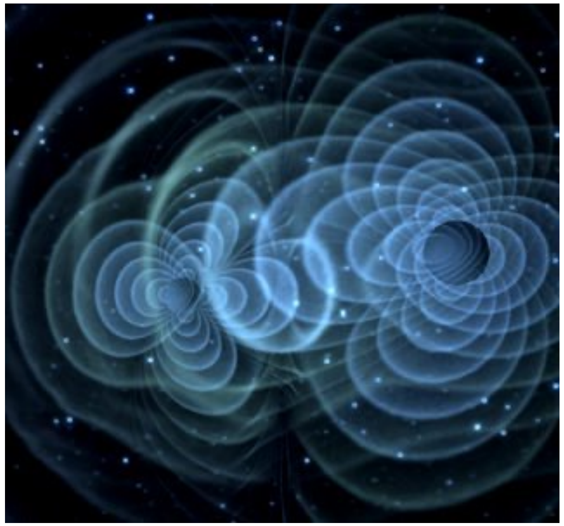
Tidal Disruption Events

Massive black hole mergers



As galaxies merge, the massive black holes they host may merge as well

Massive black hole mergers are powerful sources of low-frequency gravitational waves



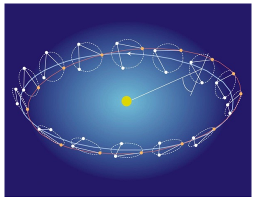
Massive black holes and gravitational waves

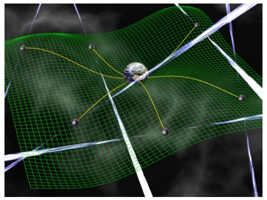
$$f \sim \frac{c}{2\pi R_s} \sim 10^4 \mathrm{Hz} \frac{M_\odot}{M}$$

$10\ M_{sun}$ binary
$f<10^3$ Hz
LIGO/Virgo
inspiral/merger

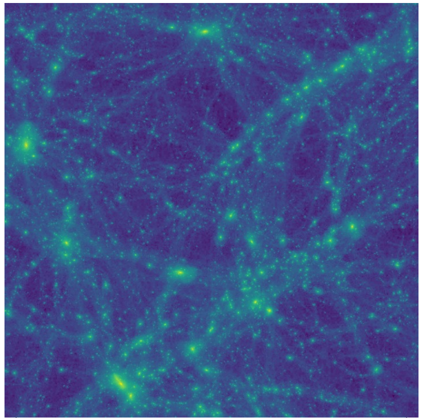
$10^6\ M_{sun}$ binary
$f<10^{-2}$ Hz
LISA
inspiral/merger

$10^9\ M_{sun}$ binary
$f<10^{-6}$ Hz
PTA
inspiral+bk





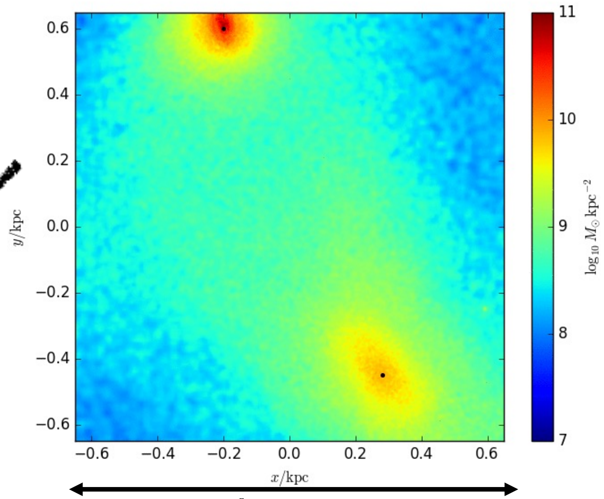
The journey of two black holes



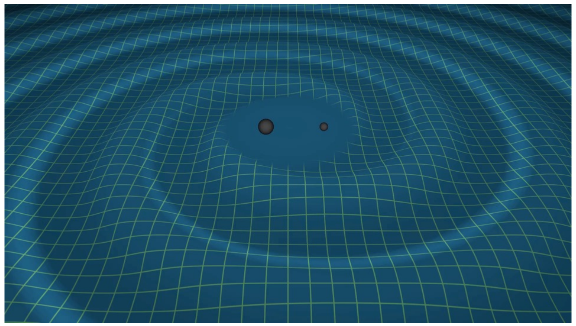
~100 Mpc (cosmology)

~100 kpc -1 kpc (galaxy mergers)

pairing



~1 kpc-1pc

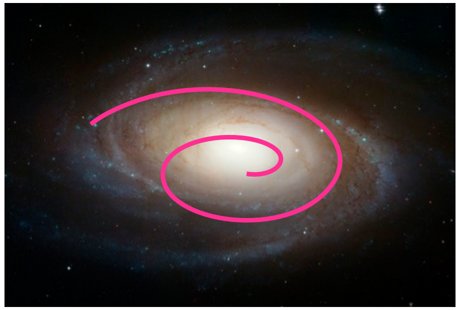


~1 millipc(BH merger)

binary evolution

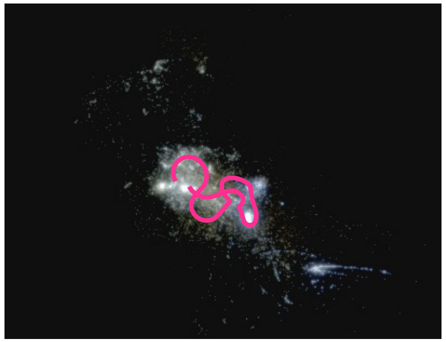
Courtesy of Hugo Pfister

Massive black hole mergers

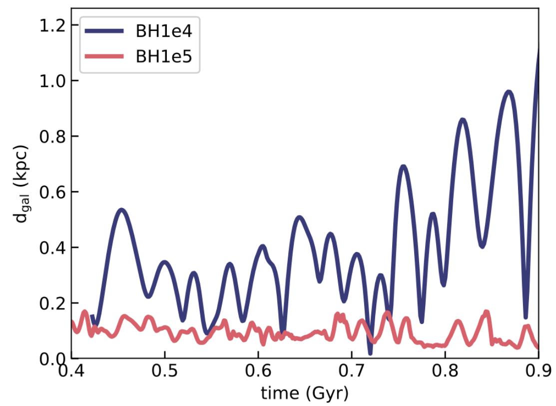


In a smooth potential, e.g., isothermal sphere, dynamical friction causes orbital decay towards the center (Binney & Tremaine) on :

$$t_{\rm df} = 0.67\,{\rm Gyr}\left(\frac{a}{4\,{\rm kpc}}\right)^2\left(\frac{\sigma}{100\,{\rm km\,s^{-1}}}\right)\left(\frac{M_{\rm BH}}{10^8\,M_\odot}\right)^{-1}\frac{1}{\Lambda}$$



High-z dwarf galaxies have messy, non smooth, time-variable potentials, and no real center: erratic dynamics (Pfister, MV+19,Ma+21)



Massive black hole mergers

Massive black holes form a binary when their separation is *a few parsecs*
They merge at separations of the order of *μparsec*

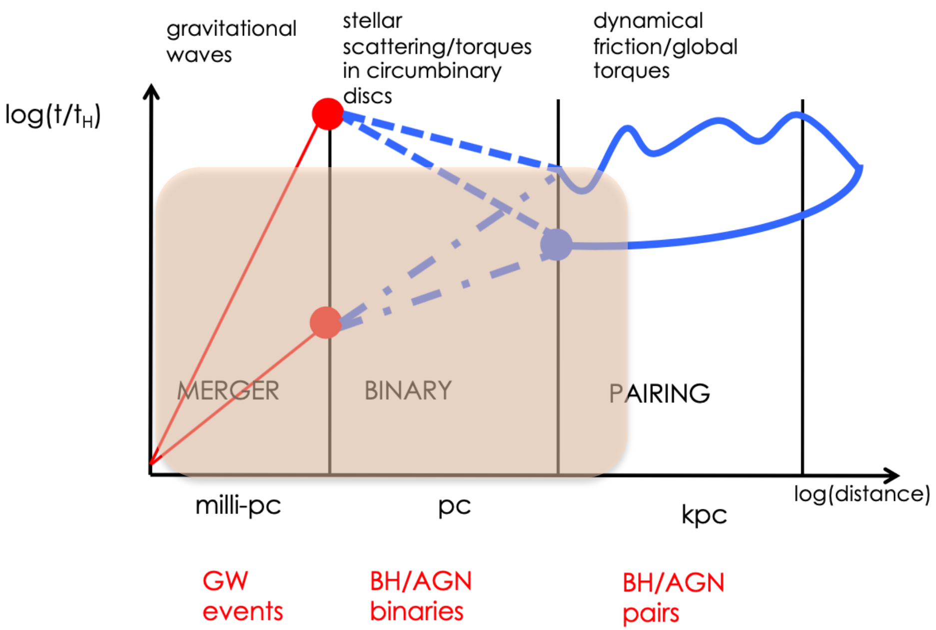


Figure concept: M. Colpi

Most cosmological simulations have a resolution of 0.1-1 kpc

Cannot resolve the late evolution of massive black hole mergers

Key orbital parameters such as mass ratio and eccentricity, cannot be followed

KETJU

(e.g., Mannerkoski+19,20,21,23)

In a small region around the MBHs dynamics is treated using a *fast high-accuracy integrator*

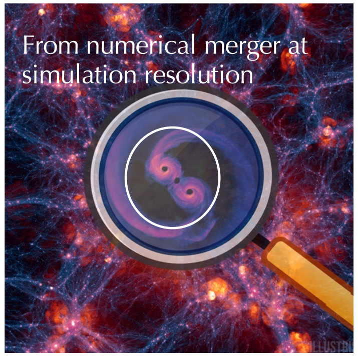
- Dynamical friction and binary hardening from interactions with stellar particles are directly captured
- Post-Newtonian dynamics for GW emission

RAMCOAL

(Li, MV+25, 26)

A *sub-grid model* integrated in adaptive mesh refinement code RAMSES

- Tracks the orbit to coalescence in galaxy simulation on-the-fly with high computational efficiency
- Includes interactions with stars, gas, triples, gas accretion, spin evolution



- Dynamical friction: Gas, star, DM
- Radiation feedback effect on gas dynamical friction
- Loss-cone scattering
- Viscous drag in circumbinary disk
- Gravitational wave emission
- Accretion & AGN feedback
- Spin evolution and recoils
- Triple interactions

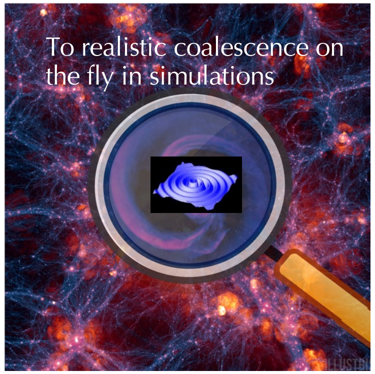
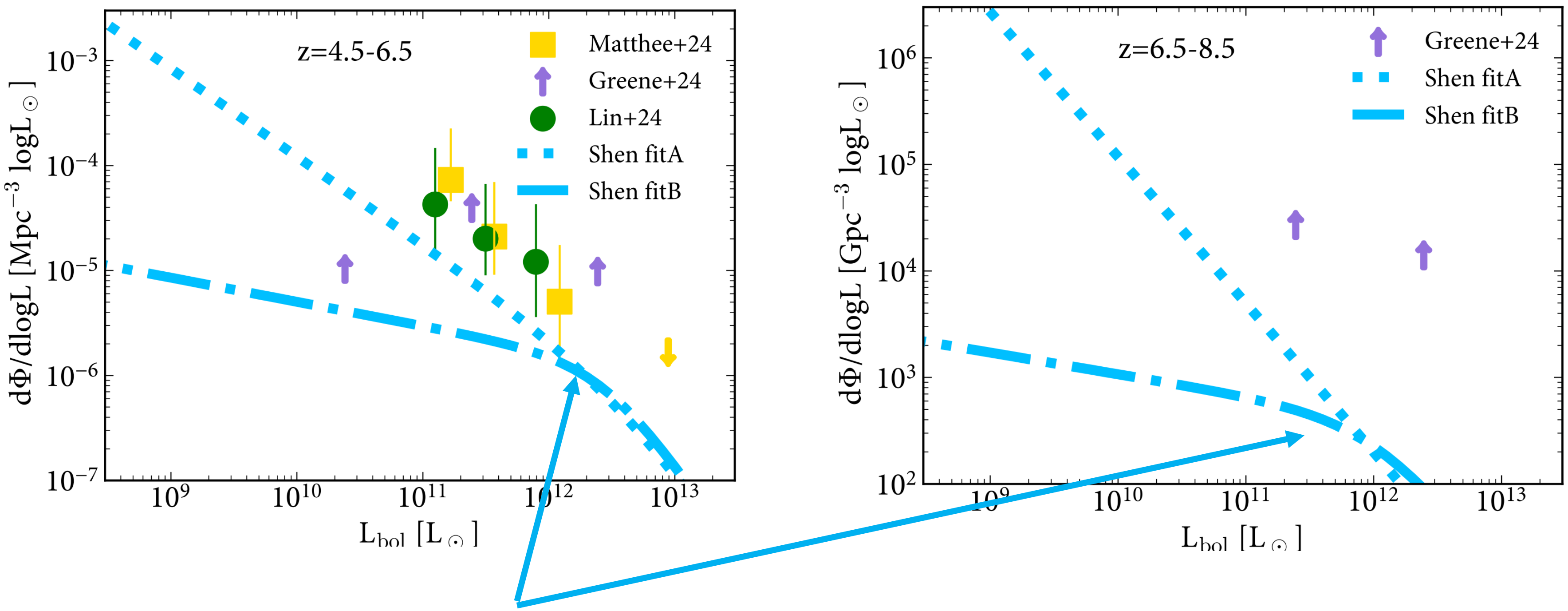


Figure credit: K. Li

The second revolution: JWST has uncovered a large population of high-z AGN



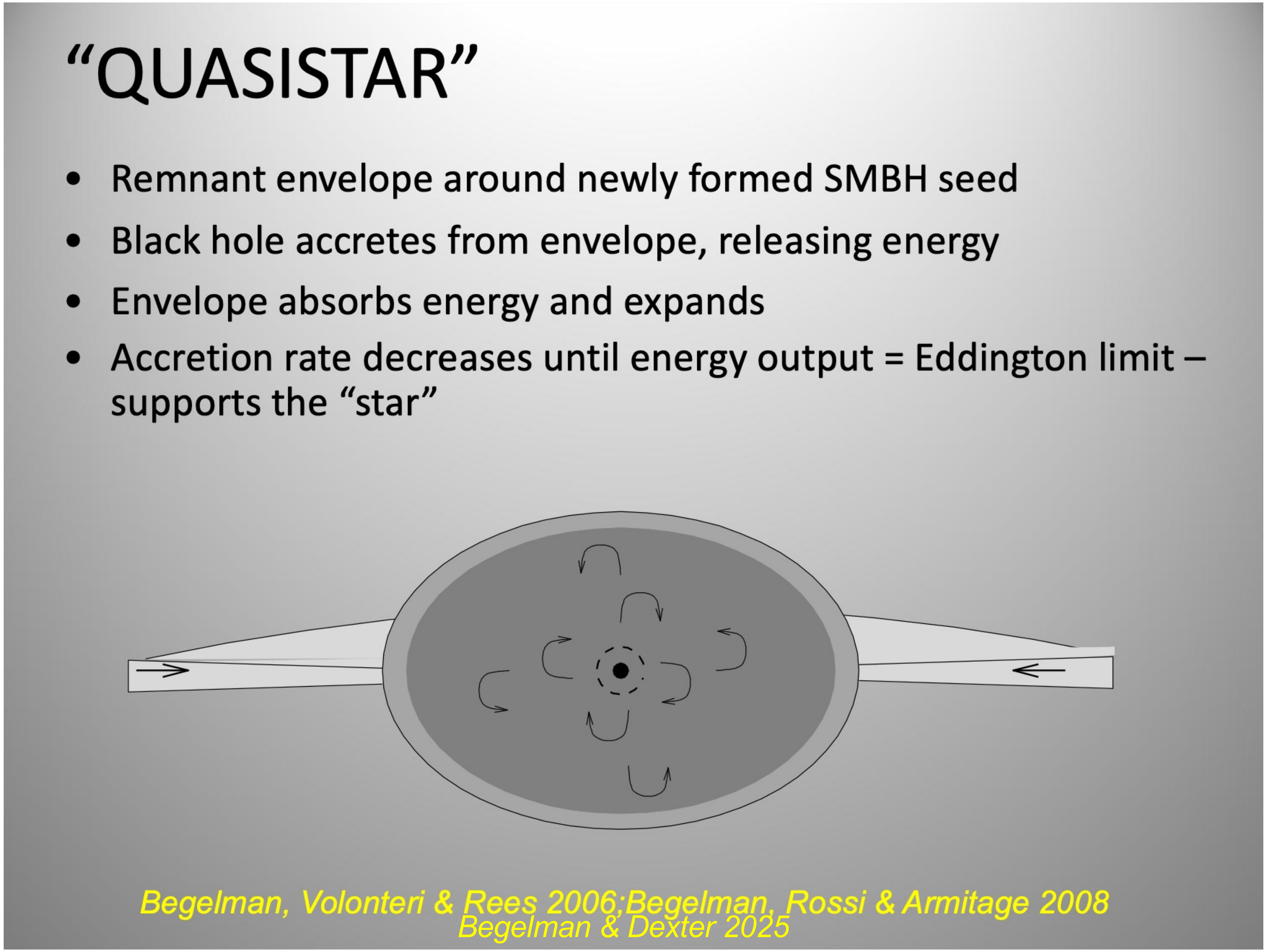
pre-JWST observations were inconsistent with this population

JWST's high-z AGN are weird

- Weak X-ray emission
- Little dust-reprocessed far infrared emission in broad line AGN
- Absorption features driven by dense gas

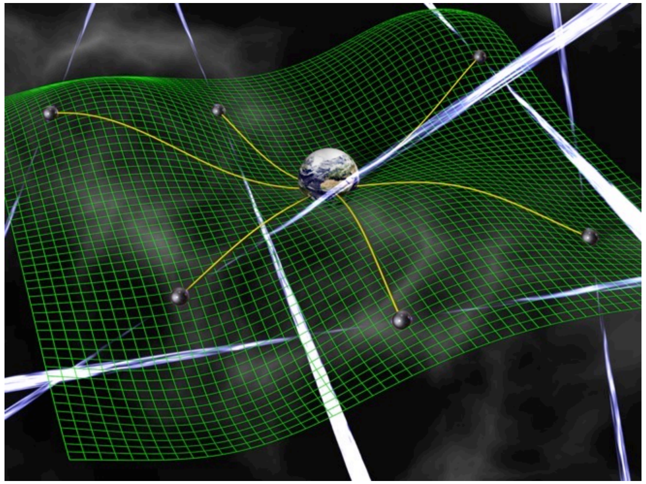
Bolometric luminosity and/or MBH overestimated (?)
Wide-spread super-Eddington (?)
A new class of sources: supermassive/quasi-stars (?)

(Maiolino+24; Inayoshi+24, Ananna+24; Sacchi+25; Greene+25, Lambrides+24; Madau+25; Lupi+24; Naidu+25; De Graaff+25; Setton+25; Rusakov+26, Chen+25; Casey+25, etc etc etc)



Slide credit: Mitch Begelman

Pulsar Timing Arrays

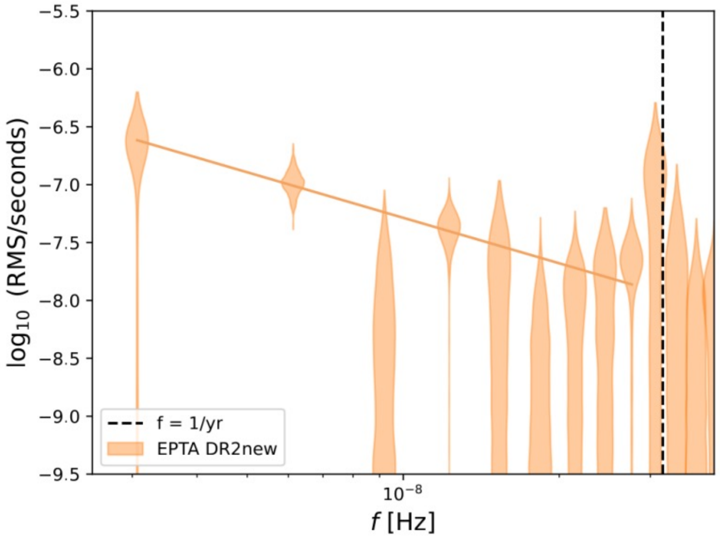


Pulsars are neutron stars that behave like lighthouses – we can detect their light when they point towards us

The passage of a gravitational wave changes the distance between pulsar and earth and therefore the time of arrival of the pulse

Pulsar timing arrays (PTAs) look for coordinated glitches from a population of pulsars

PTA detections in 2023: lots of merging MBHs (?)



In 2023 various groups around the world announced the detection of a gravitational wave background at nano Hz frequencies

The background is characterized by an amplitude and a spectral slope

EPTA+InPTA Collaboration 2024
Similar results from NANOGrav, PPTA, CPTA
(Agazie+23; Reardon et al. 2023; Xu et al. 2023)

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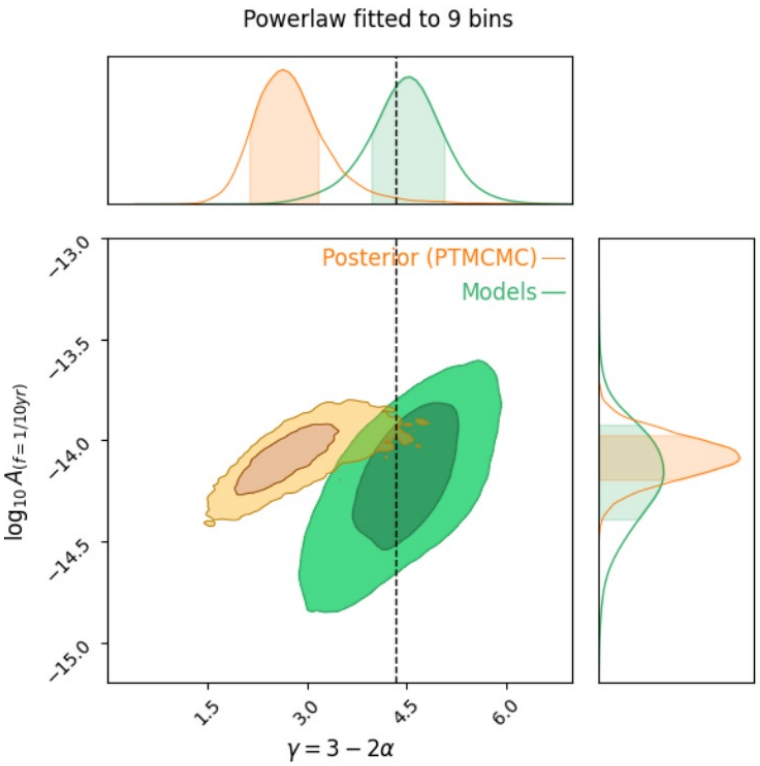


EPTA+InPTA Collaboration 2024
Similar results from NANOGrav, PPTA, CPTA
(Agazie+23; Reardon et al. 2023; Xu et al. 2023)

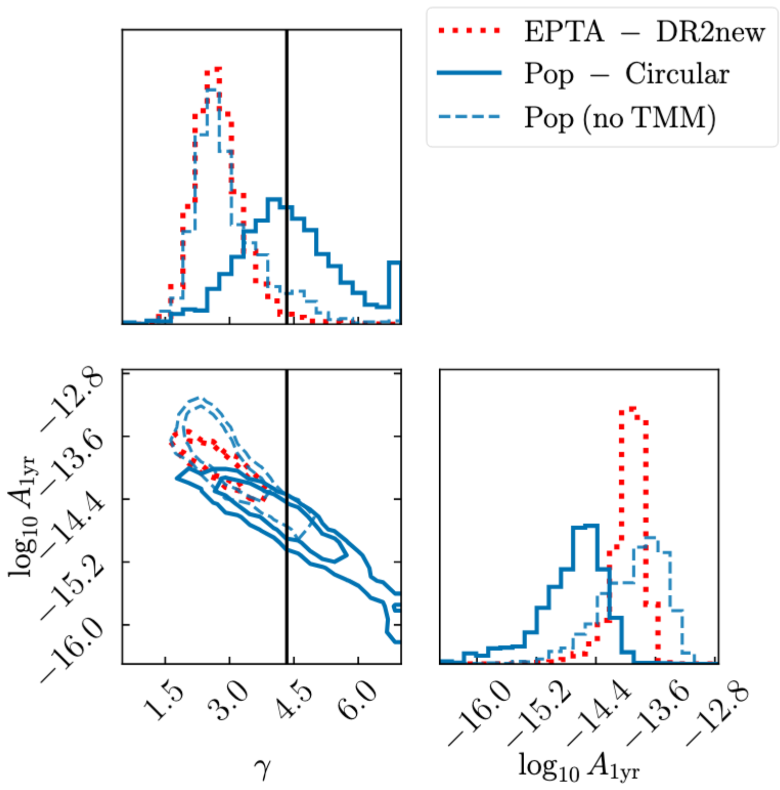
The (current) amplitude of the GW background is somewhat higher than expected from theoretical models, and the slope shallower

Eccentric binaries, or evolution driven by interaction with gas and stars would give a shallower slope

Many more, or more massive, binaries would increase the amplitude

(Sesana+13, Simon & Burke-Spolaor16, Chen+17, Middleton+21 etc)

PTA detections in 2023: lots of merging MBHs (?)



Quelquejay-Leclere, Li, MV+25

The inference on amplitude and slope may be biased (e.g., Goncharov+24; Quelquejay+2025; Crisostomi+25)

Considering the finite duration of the observations, binaries can contribute to multiple frequencies (spectral leakage: not a Dirac function in frequency domain). This increases the measured amplitude and decreases the measured slope (Quelquejay-Leclere+2025; Crisostomi+25)

Massive black holes: their origins and evolution

Massive black hole evolution is embedded in galaxy evolution, but it has its own challenges and specific physics

We have made significant progress in the last ~20 years in both modeling and observing massive black holes

New observations bring new puzzles and questions to address, both by understanding better observations and their systematics, and by including overlooked or undervalued processes in theoretical models