The formation of super-massive black holes and on the (probable?) very rapid initial metal & r-process enrichment

2nd lecture

17th Russbach School
14-19 March 2022

Pavel Kroupa
Helmholtz-Institute for Radiation und Nuclear Physics (HISKP)
University of Bonn

Astronomical Institute,
Charles University in Prague

c/o Argelander-Institut für Astronomie
University of Bonn

For recent progress on cosmology
and
the existence of dark matter particles
(for those interested)

"*Dark Matter Kindergarten Stuff*"

https://www.youtube.com/watch?v=O5MbOCgCMDs

Comment

This project was published
prior
to the
black-hole Nobel Prize of 2020.

That is, there is no influence / curruption whatsoever of
this project by that event.

Based on :

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MNRAS **498**, 5652–5683 (2020) doi:10.1093/mnras/staa2276
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Very high redshift quasars and the rapid emergence of supermassive black holes

Pavel Kroupa ,[1,2,3]★ Ladislav Subr,[2] Tereza Jerabkova [1,2,3,4,5,6]† and Long Wang [7]
[1] *Helmholtz-Institut für Strahlen- und Kernphysik, University of Bonn, Nussallee 14-16, D-53115 Bonn, Germany*
[2] *Charles University in Prague, Faculty of Mathematics and Physics, Astronomical Institute, V Holešovičkách 2, CZ-180 00 Praha 8, Czech Republic*
[3] *Astronomical Institute, Czech Academy of Sciences, Fričova 298, CZ-25165 Ondřejov, Czech Republic*
[4] *Instituto de Astrofisica de Canarias, E-38205 La Laguna, Tenerife, Spain*
[5] *GRANTECAN, Cuesta de San Jose s/n, E-38712 Brena Baja, La Palma, Spain*
[6] *European Space Research and Technology Centre (ESA ESTEC), Keplerlaan 1, 2201 AZ Noordwijk, Netherlands*
[7] *Department of Astronomy, School of Science, The University of Tokyo, 7-3-1 Hongo, Bunkyo-ku, Tokyo 113-0033, Japan*

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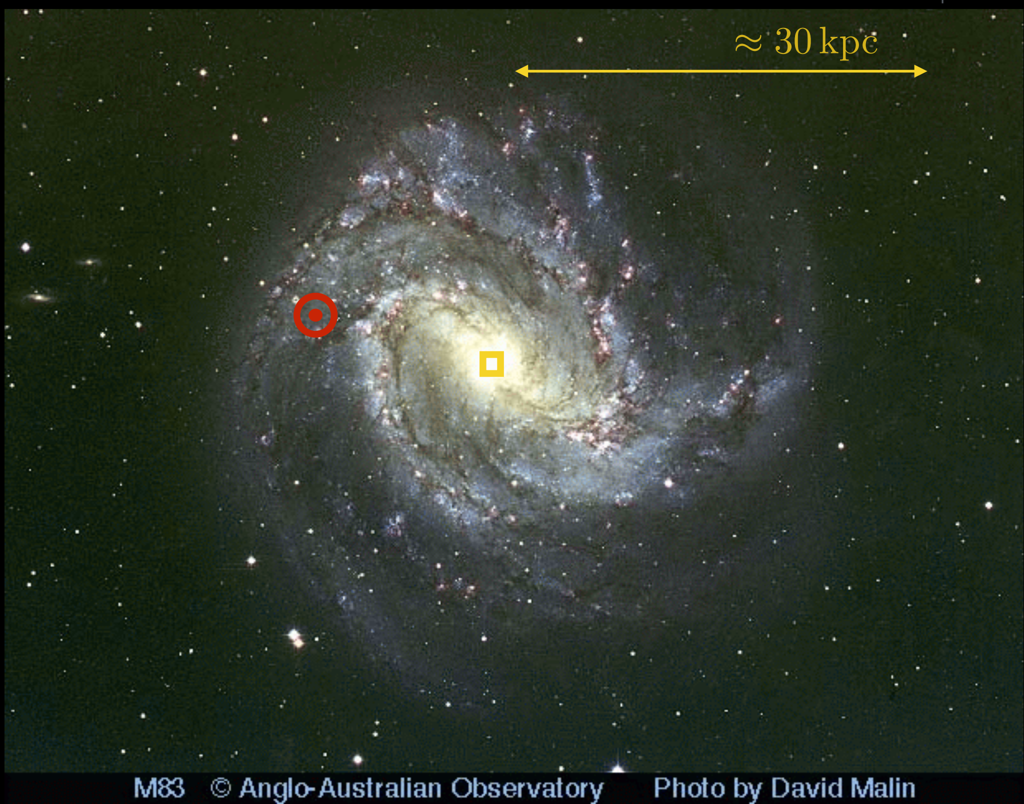
Introduction

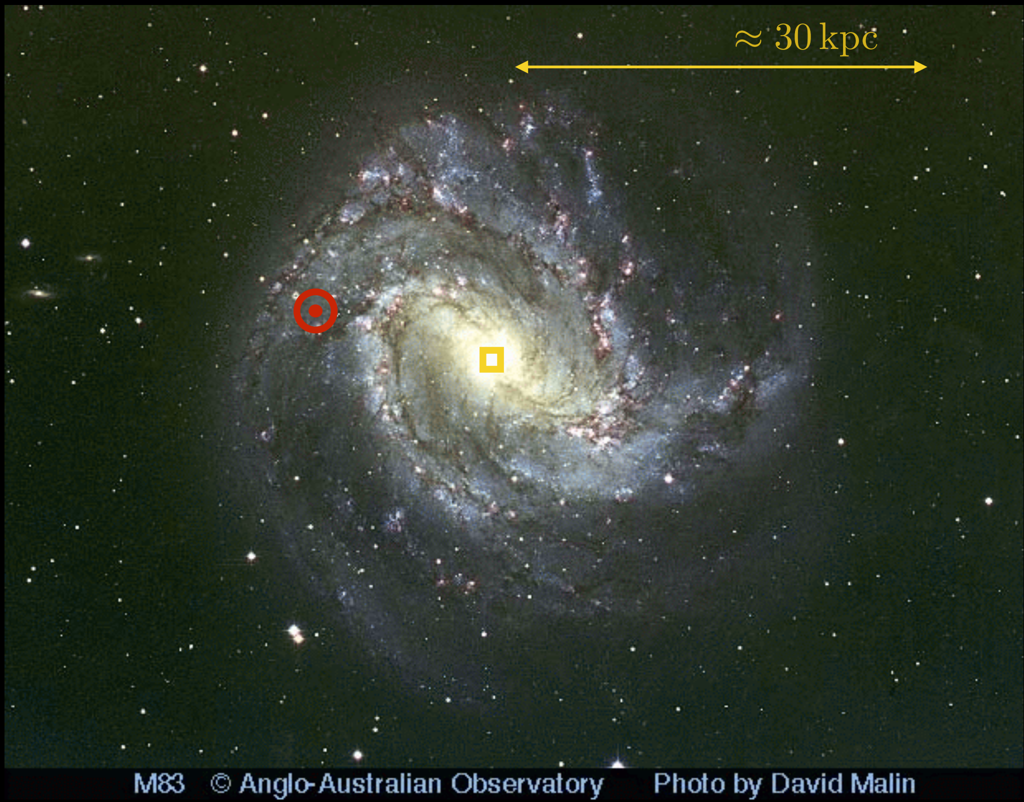
Milky Way

1pc = 3.26 light years



$4.15 \times 10^6\, M_\odot$ SMBH at centre of Milky Way

1pc = 3.26 light years



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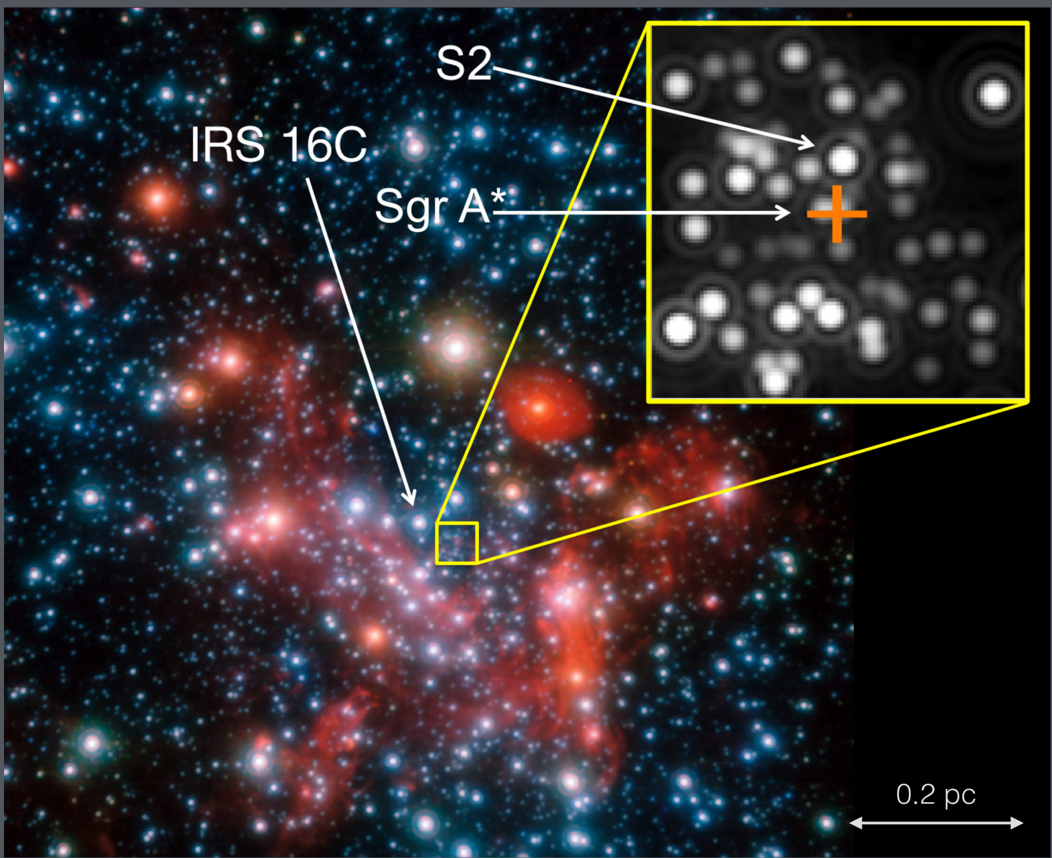

ESO
Credit: ESO/MPE/S. Gilessen et al.

https://www.eso.org/public/images/eso1622b/

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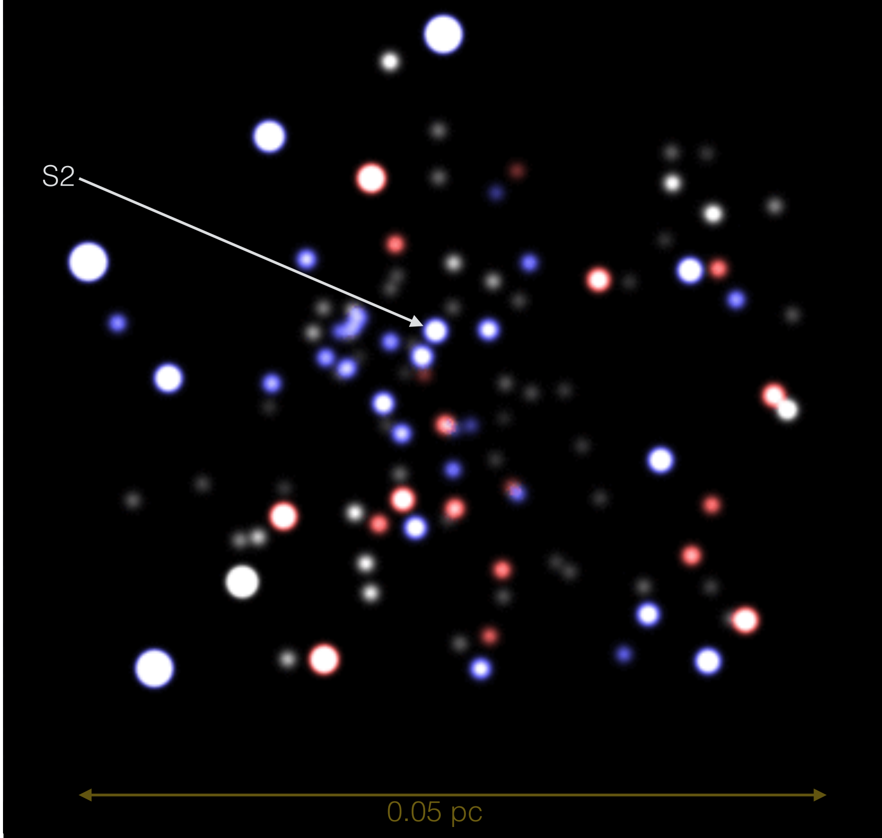
$4.15 \times 10^6\, M_\odot$ SMBH at centre of Milky Way

Max Planck Institute for Extragalactic Physics



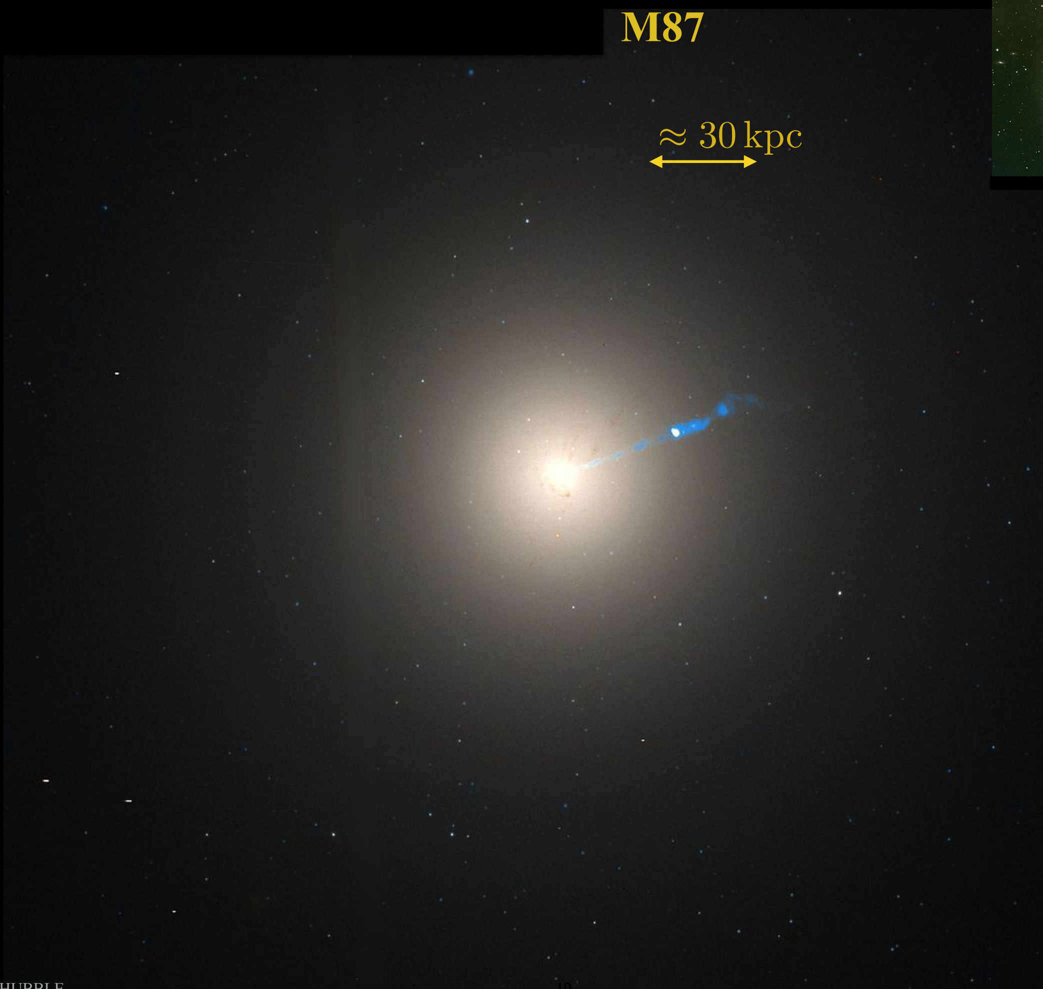
Movement of stars in the central 3arcsec during 1992-2008.

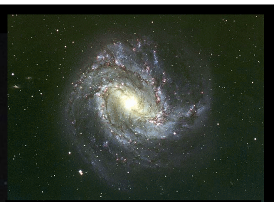
Young stars = blue
old population = red

https://www.mpe.mpg.de/369264/

https://www.mpe.mpg.de/369426/
Publications

M87

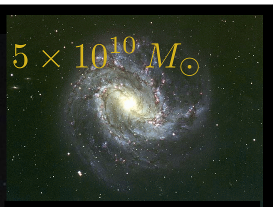


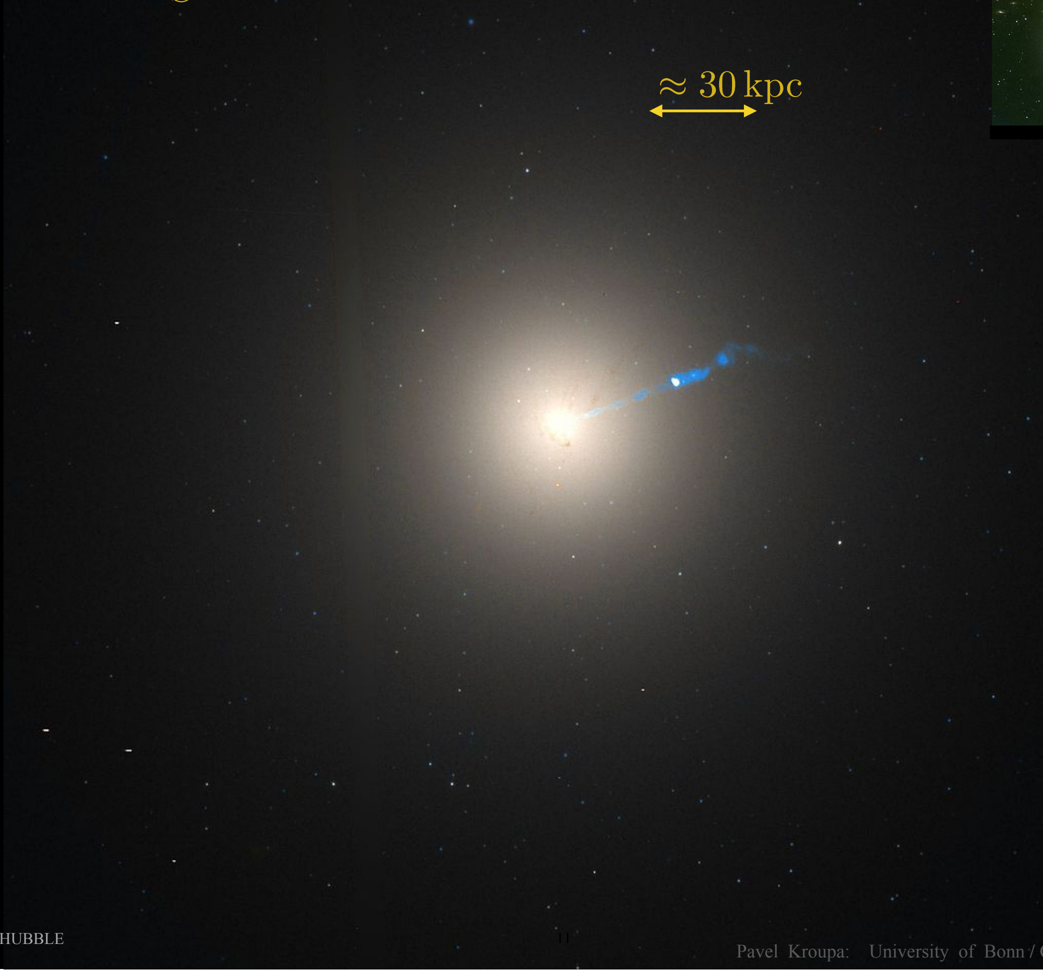


M87 image: PD-HUBBLE

$6.5 \times 10^9\, M_\odot$ **SMBH at centre of M87**

cf $M_{\rm MW} \approx 5 \times 10^{10}\, M_\odot$





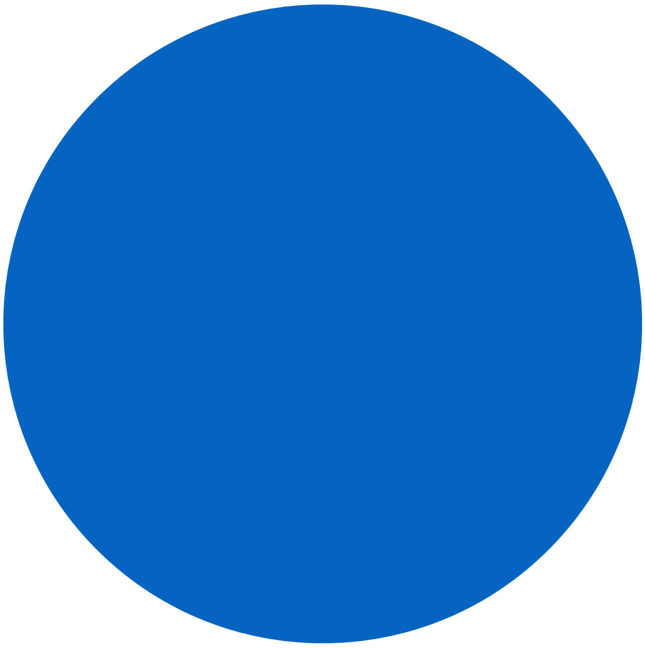
M87 image: PD-HUBBLE

$6.5 \times 10^9\, M_\odot$ **SMBH at centre of M87**

(The Event Horizon Telescope Collaboration, Akiyama et al. 2019, ApJL,)

"the asymmetric ring is consistent with earlier predictions of strong gravitational lensing of synchrotron emission from a hot plasma (10^{10} K) orbiting near the black hole event horizon."
(2019, APJL, 875, L5)

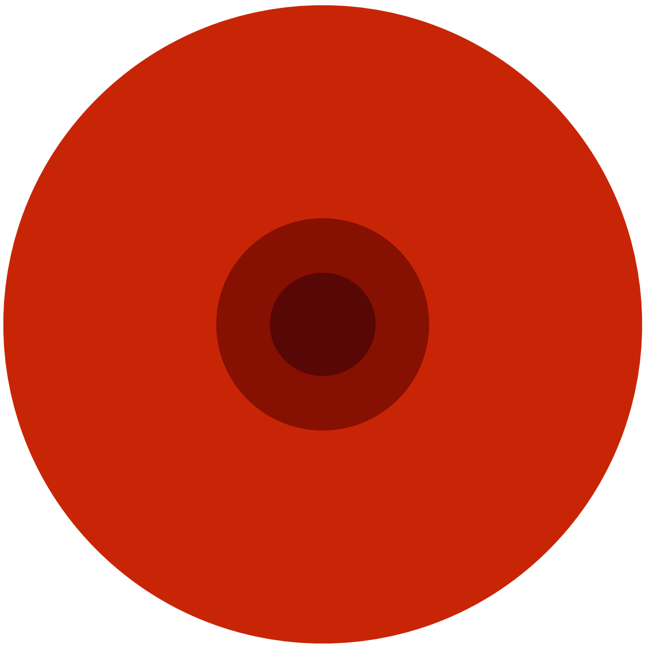
Why "shadow" ?



Extremely hot
(blue emitting)
accretion disk

The SMBH in it
redshifts the light

Why "shadow" ?



Extremely hot
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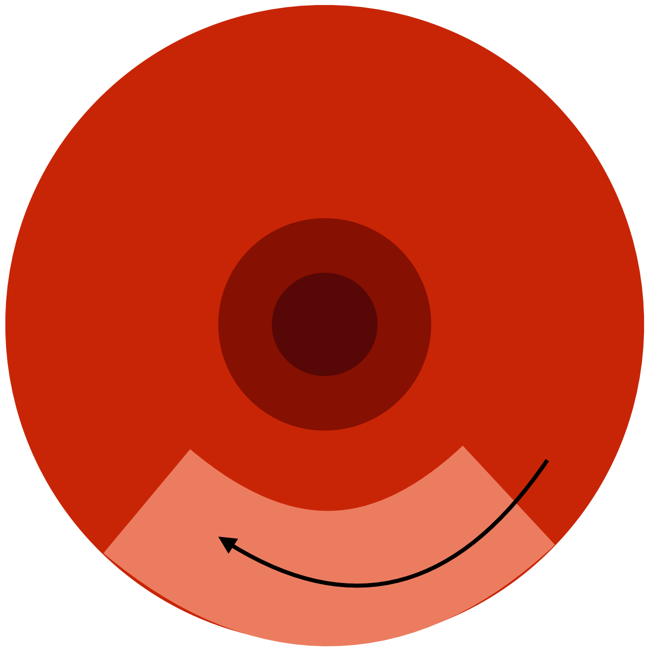
accretion disk

The SMBH in it
redshifts the light

Rotation
doppler boosts
emission
towards observer
(here to the right)

Why "shadow" ?



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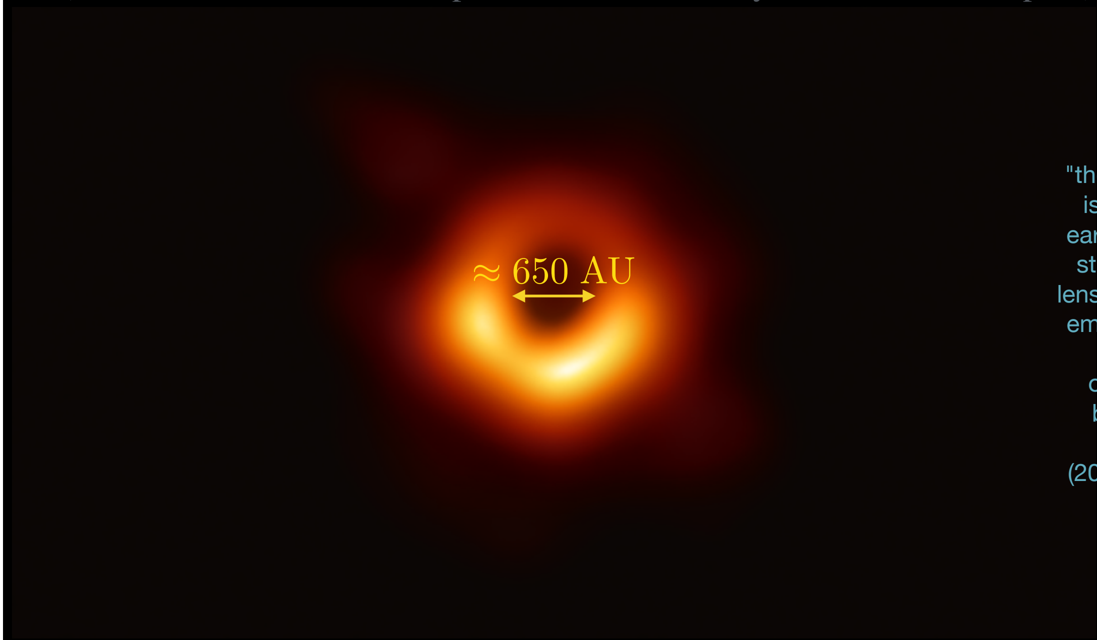
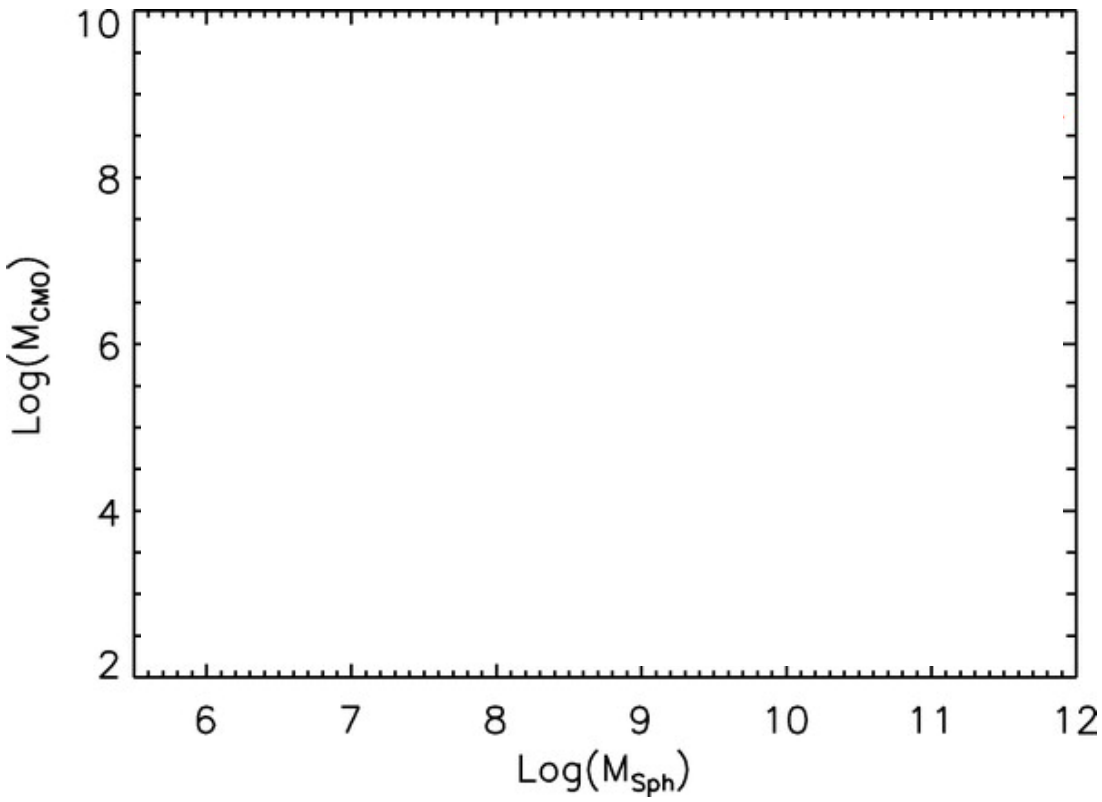


"the asymmetric ring is consistent with earlier predictions of strong gravitational lensing of synchrotron emission from a hot plasma (10^{10} K) orbiting near the black hole event horizon." (2019, APJL, 875, L5)

SMBH mass vs host galaxy mass (spheroid component: elliptical galaxy = classical bulge)

(Gadotti & Kaufmann 2009)



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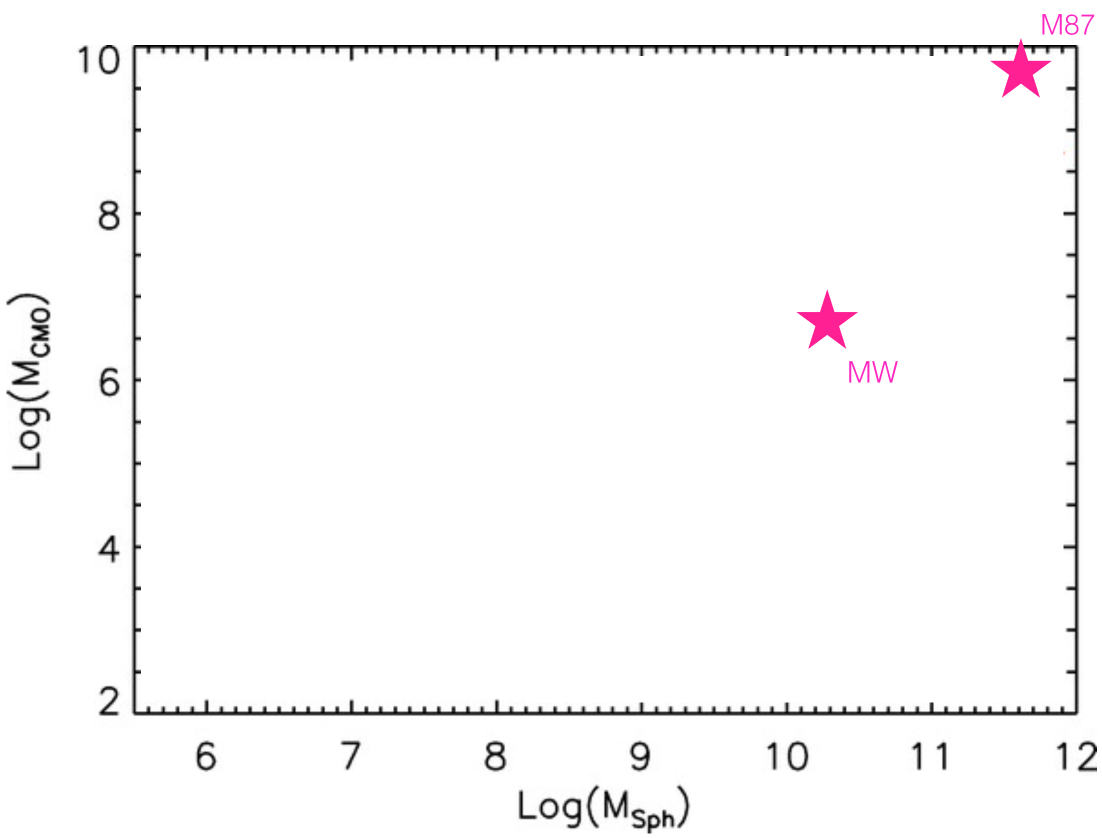
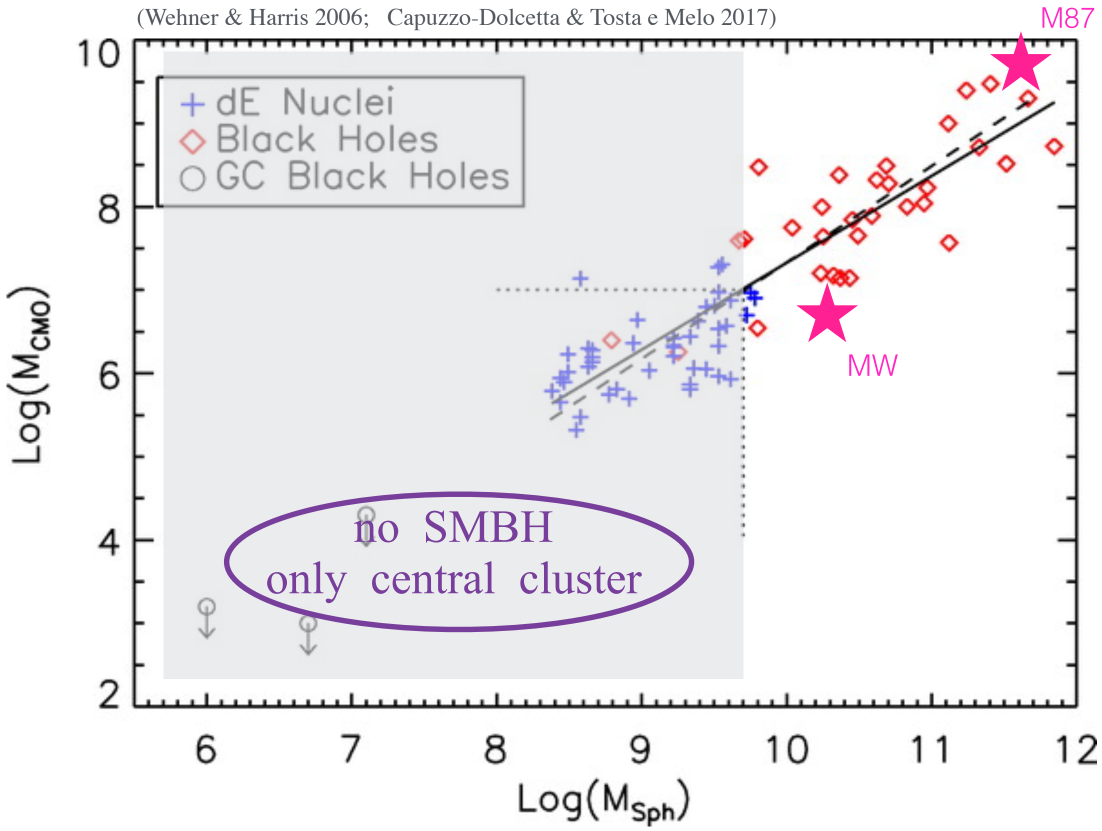


SMBH mass vs host galaxy mass (spheroid component: elliptical galaxy = classical bulge)

(Gadotti & Kaufmann 2009)

(Wehner & Harris 2006; Capuzzo-Dolcetta & Tosta e Melo 2017)



Spatial scales

(measurement of SMBH masses see review Peterson, B.M., 2014, Space Science Reviews)

$$R_{\rm horizon} \equiv \frac{2\,G\,M_{\rm SMBH}}{c^2}$$

event horizon = Schwarzschild radius (exact solution of GR for spherical non-rotating mass)

$M_{\rm SMBH} = 5.15 \times 10^6\,M_\odot$ $\quad R_{\rm horizon} = 0.106\,{\rm AU}$

$M_{\rm SMBH} = 5.15 \times 10^9\,M_\odot$ $\quad R_{\rm horizon} = 106\,{\rm AU}$

$$R_{\rm BHinfl} \equiv \frac{G\,M_{\rm SMBH}}{\sigma_*^2}$$

black-hole influence radius (σ_* stellar velocity disp. of stars in bulge)

e.g. globular cluster : $\sigma_* = 10\,{\rm km/s}$, $\quad M_{\rm BH} = 10^4\,M_\odot$

→ $R_{\rm BHinfl} = 0.45\,{\rm pc}$

SMBHs appear at very high redshift

SMBHs appear at very high redshift

THE ASTROPHYSICAL JOURNAL, 833:222 (17pp), 2016 December 20

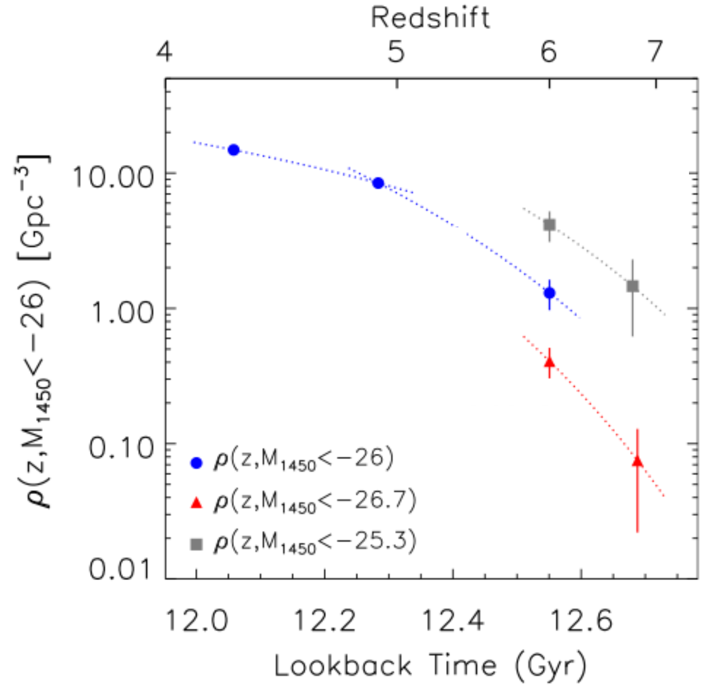


Figure 10. Density evolution of luminous quasars at $z > 4$. The blue circles, red triangles, and gray squares are the cumulative densities down to $M_{1450} = -26.0$, -26.7, and -25.3 mag, respectively. The data points at $z \sim 4$ and 5 are from McGreer et al. (2013), the data points at $z = 6$ are calculated from our new sample. The gray data point at $z \sim 7$ is taken from Venemans et al. (2013), and the red data point at $z \sim 7$ is estimated from two $z > 6.5$ quasars in the UKIDSS area (see details in Section 5.1). The dotted lines are the power-law (Equation (4)) fits to the data points. The figure shows a rapid decline of the quasar spatial density from $z \sim 5$ toward higher redshifts.

(Jiang, McGreer et al. 2016)

13.6 13.8

first stars
thought to form

. . . and at even higher redshift

THE ASTROPHYSICAL JOURNAL LETTERS

≈ 700 Myr $\qquad 1.5 \times 10^9\, M_\odot$

Pōniuā'ena: A Luminous z = 7.5 Quasar Hosting a 1.5 Billion Solar Mass Black Hole

Jinyi Yang[1], Feige Wang[1,13], Xiaohui Fan[1], Joseph F. Hennawi[2,3], Frederick B. Davies[2,4], Minghao Yue[1], Eduardo Banados[3], Xue-Bing Wu[5,6], Bram Venemans[3], Aaron J. Barth[7]
+ Show full author list

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Citation Jinyi Yang *et al* 2020 *ApJL* **897** L14

+ Article information

Need $10^4\ M_\odot$ seed to grow continuously at superEddington rate since z=30 (100Myr after Big Bang).

Abstract

We report the discovery of a luminous quasar, J1007+2115 at z = 7.515 ("Pōniuā'ena"), from our wide-field reionization-era quasar survey. J1007+2115 is the second quasar now known at z > 7.5, deep into the reionization epoch. The quasar is powered by a (1.5 ± 0.2) × $10^9\ M_\odot$ supermassive black hole (SMBH), based on its broad Mg II emission-line profile from Gemini and Keck near-IR spectroscopy. The SMBH in J1007+2115 is twice as massive as that in quasar J1342+0928 at z = 7.54, the current quasar redshift record holder. The existence of such a massive SMBH just 700 million years after the Big Bang

The Problem(s)

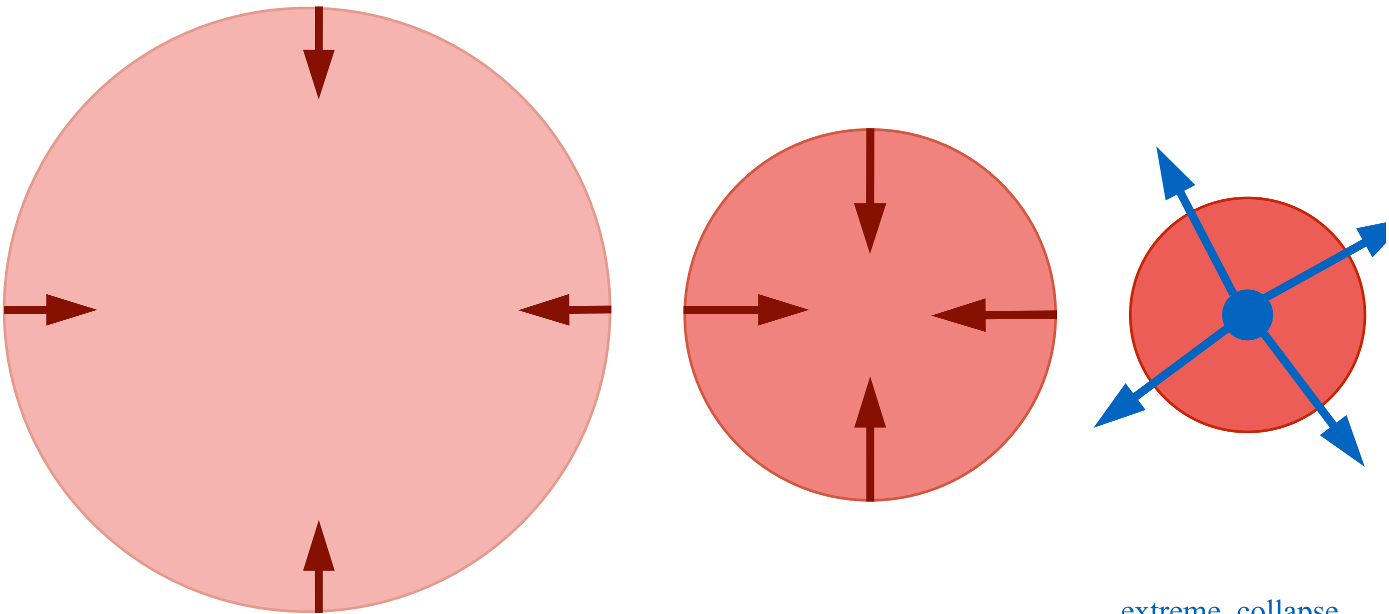
Three problems:

I) How can SMBHs even form ?
(need to squeeze $> 10^6 \, M_\odot$ of matter
into extremely small space)

II) Why do SMBH masses correlate with
the masses of their hosting galaxies ?

III) How can SMBHs form within a few 100 Myr
after the Big Bang ?

Why can a SMBH seed not form
from direct collapse of a post-Big-Bang gas cloud ?



Collapse through self-gravity

opacity increases, temperature increases when radiation trapped

extreme collapse ==> central relativistic gas; radiates and ejects

This leads to self-radiation-limited growth

$$L_{\rm acc} = \epsilon_{\rm r}\, \dot{M}\, c^2$$

$\epsilon_{\rm r} \approx 0.1 - 0.5$
fraction of rest-mass radiated

plus radiation pressure leads to
accretion shutoff → difficult to form BH

$$M_{\rm BH}(t) = M_{\rm BH,0}\; e^{\frac{f_{\rm Edd}\,(t-t_0)}{\tau_{\rm Edd}}}$$

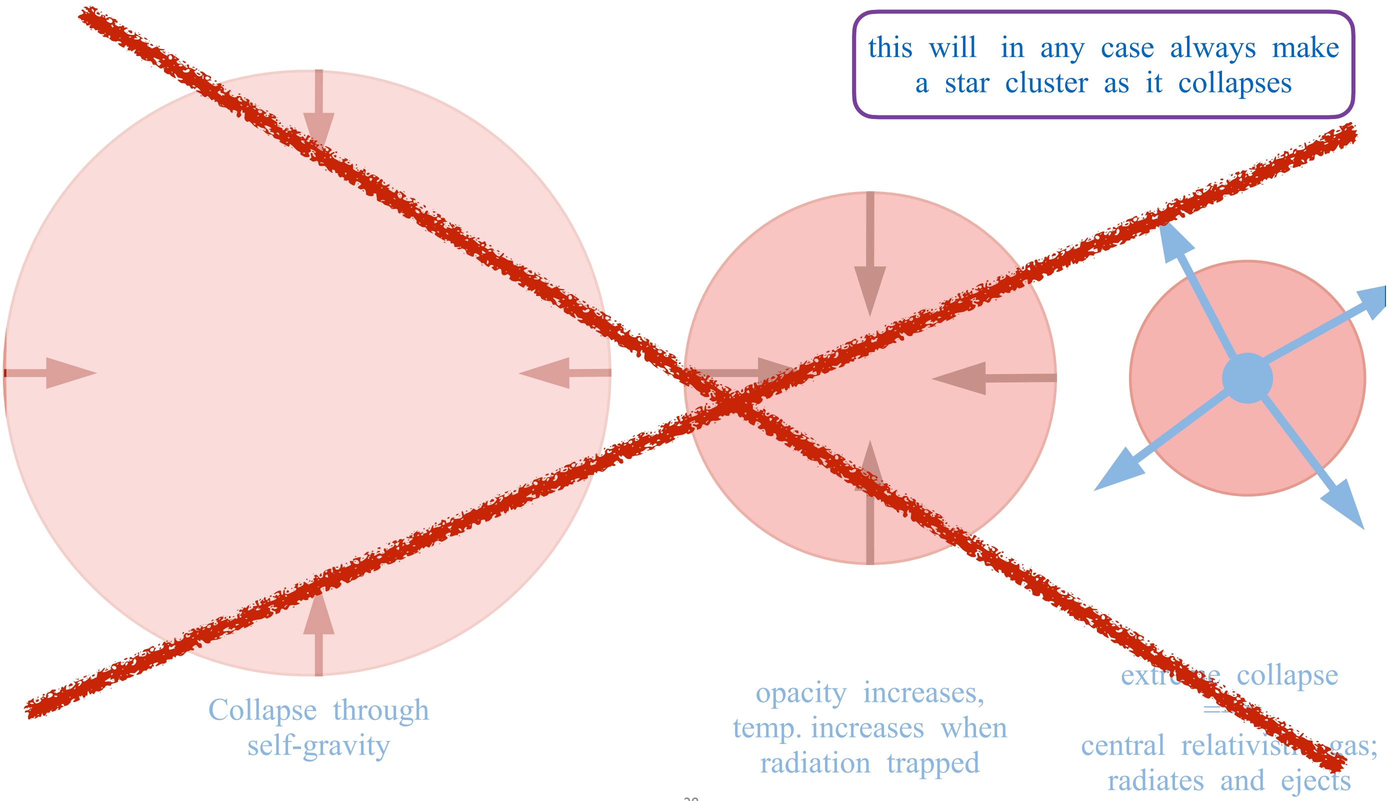
$$f_{\rm Edd} = \frac{1-\epsilon_{\rm r}}{\epsilon_{\rm r}}$$

$$\tau_{\rm Edd} = \frac{c\,\sigma_{\rm T}}{4\pi\, G\, m_{\rm p}} \approx 452\ {\rm Myr}$$

c speed of light
$\sigma_{\rm T}$ Thompson scattering cross section
$m_{\rm P}$ proton mass

Thus, to grow a
$M_{\rm BH,0} = 10\, M_\odot$ seed to
$M_{\rm SMBH} = 10^{10}\, M_\odot$ need sustained continuous accretion for ≈ 1 Gyr
at the superEddington rate $(\epsilon_{\rm r} = 0.1)$.

Why not form an SMBH seed from direct collapse of post-Big-Bang gas cloud ?



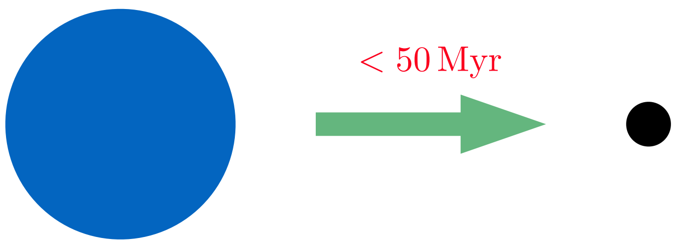
So, how to make SMBHs ? (Kroupa, Subr, Jerabkova, Wang 2020)

Need to *efficiently compactify* matter to a BH seed

Start with first massive stars :

$m > 20\, M_\odot$ $m_{\rm BH} \approx 0.1\, m$ (e.g. Dabringhausen et al. 2009)

$< 50\,$Myr



coalescence of BHs

Star cluster :

(e.g. Martinez, Fragione et al. 2020; Banerjee, S., 2021)

negligible mass loss

coalescence of BHs ===> negligible mass loss :

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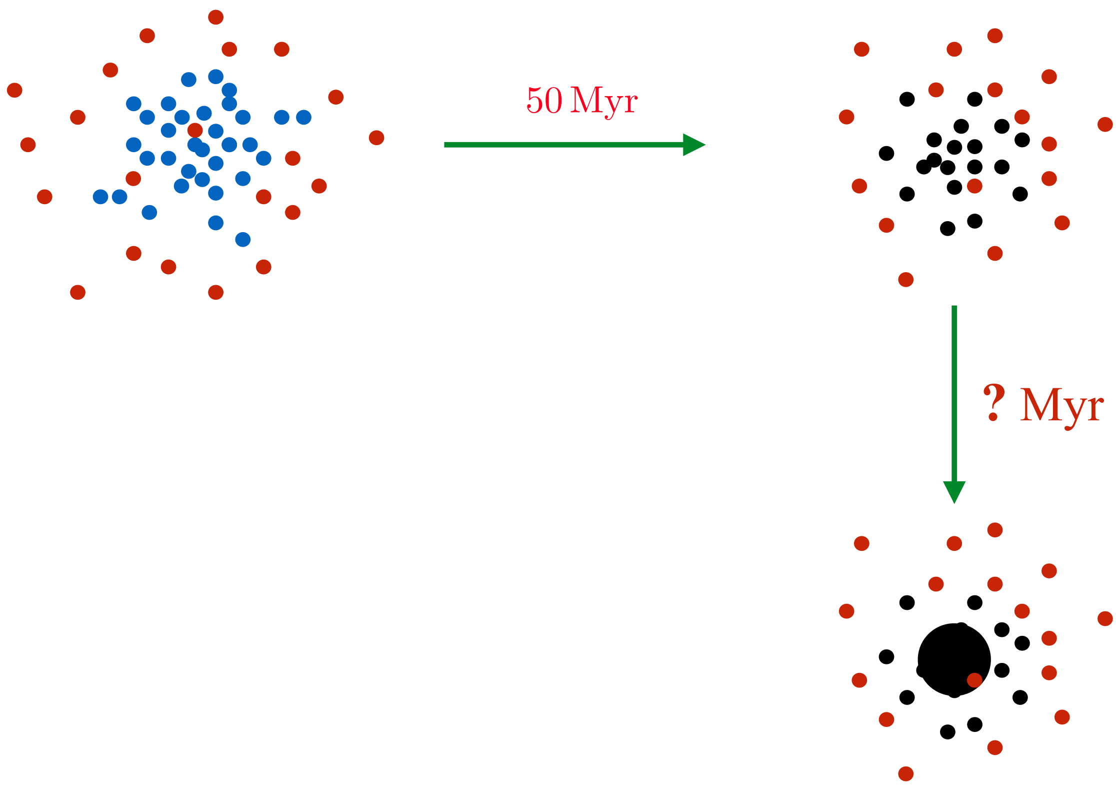
Table III in Abbott et al. 2019; LIGO Scientific Collaboration and Virgo Collaboration)

Event	$m_1/M_\odot$	$m_2/M_\odot$	$\mathcal{M}/M_\odot$	$\chi_{\rm eff}$	$M_f/M_\odot$	a_f	$E_{\rm rad}/(M_\odot c^2)$	$\ell_{\rm p}$
GW150914	$35.6^{+4.7}_{-3.1}$	$30.6^{+3.0}_{-4.4}$	$28.6^{+1.7}_{-1.5}$	$-0.01^{+0.12}_{-0.13}$	$63.1^{+3.4}_{-3.0}$	$0.69^{+0.05}_{-0.04}$	$3.1^{+0.4}_{-0.4}$	3.
GW151012	$23.2^{+14.9}_{-5.5}$	$13.6^{+4.1}_{-4.8}$	$15.2^{+2.1}_{-1.2}$	$0.05^{+0.31}_{-0.20}$	$35.6^{+10.8}_{-3.8}$	$0.67^{+0.13}_{-0.11}$	$1.6^{+0.6}_{-0.5}$	3.
GW151226	$13.7^{+8.8}_{-3.2}$	$7.7^{+2.2}_{-2.5}$	$8.9^{+0.3}_{-0.3}$	$0.18^{+0.20}_{-0.12}$	$20.5^{+6.4}_{-1.5}$	$0.74^{+0.07}_{-0.05}$	$1.0^{+0.1}_{-0.2}$	3.
GW170104	$30.8^{+7.3}_{-5.6}$	$20.0^{+4.9}_{-4.6}$	$21.4^{+2.2}_{-1.8}$	$-0.04^{+0.17}_{-0.21}$	$48.9^{+5.1}_{-4.0}$	$0.66^{+0.08}_{-0.11}$	$2.2^{+0.5}_{-0.5}$	3.
GW170608	$11.0^{+5.5}_{-1.7}$	$7.6^{+1.4}_{-2.2}$	$7.9^{+0.2}_{-0.2}$	$0.03^{+0.19}_{-0.07}$	$17.8^{+3.4}_{-0.7}$	$0.69^{+0.04}_{-0.04}$	$0.9^{+0.0}_{-0.1}$	3.
GW170729	$50.2^{+16.2}_{-10.2}$	$34.0^{+9.1}_{-10.1}$	$35.4^{+6.5}_{-4.8}$	$0.37^{+0.21}_{-0.25}$	$79.5^{+14.7}_{-10.2}$	$0.81^{+0.07}_{-0.13}$	$4.8^{+1.7}_{-1.7}$	4.
GW170809	$35.0^{+8.3}_{-5.9}$	$23.8^{+5.1}_{-5.2}$	$24.9^{+2.1}_{-1.7}$	$0.08^{+0.17}_{-0.17}$	$56.3^{+5.2}_{-3.8}$	$0.70^{+0.08}_{-0.09}$	$2.7^{+0.6}_{-0.6}$	3.
GW170814	$30.6^{+5.6}_{-3.0}$	$25.2^{+2.8}_{-4.0}$	$24.1^{+1.4}_{-1.1}$	$0.07^{+0.12}_{-0.12}$	$53.2^{+3.2}_{-2.4}$	$0.72^{+0.07}_{-0.05}$	$2.7^{+0.4}_{-0.3}$	3.
GW170817	$1.46^{+0.12}_{-0.10}$	$1.27^{+0.09}_{-0.09}$	$1.186^{+0.001}_{-0.001}$	$0.00^{+0.02}_{-0.01}$	≤ 2.8	≤ 0.89	≥ 0.04	$\geq$
GW170818	$35.4^{+7.5}_{-4.7}$	$26.7^{+4.3}_{-5.2}$	$26.5^{+2.1}_{-1.7}$	$-0.09^{+0.18}_{-0.21}$	$59.4^{+4.9}_{-3.8}$	$0.67^{+0.07}_{-0.08}$	$2.7^{+0.5}_{-0.5}$	3.
GW170823	$39.5^{+11.2}_{-6.7}$	$29.0^{+6.7}_{-7.8}$	$29.2^{+4.6}_{-3.6}$	$0.09^{+0.22}_{-0.26}$	$65.4^{+10.1}_{-7.4}$	$0.72^{+0.09}_{-0.12}$	$3.3^{+1.0}_{-0.9}$	3.

This is promising, but how to merge $> 10^4$ BHs sufficiently quickly ?

Star cluster :



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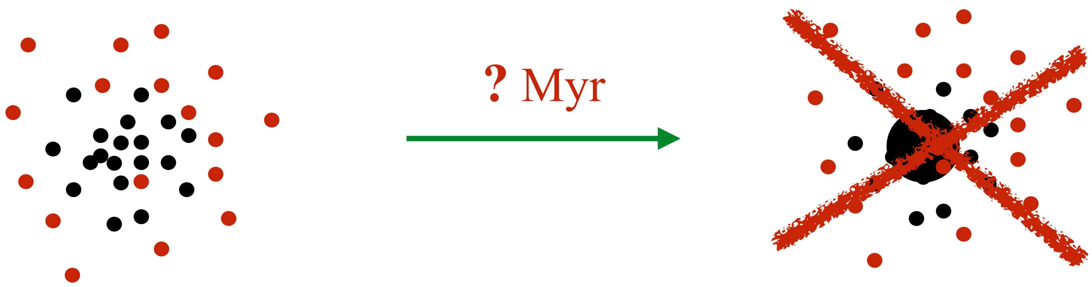
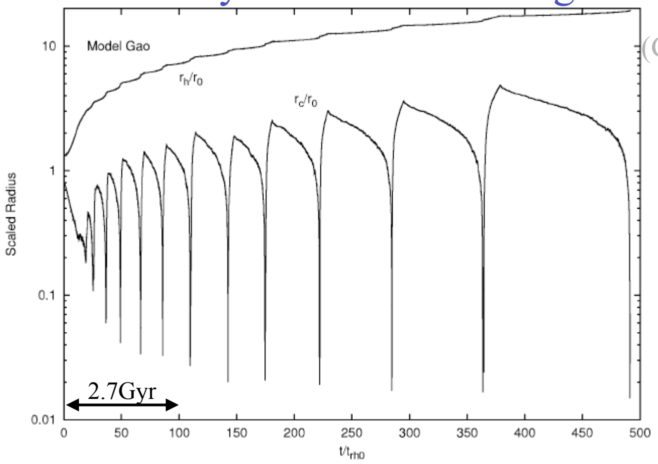


Stellar dynamical modelling shows such a cluster to be stable :



(Giersz & Spurzem 2003)

Figure 4. Evolution of the core and half-mass radii (scaled by the scale-length of the Plummer model) as a function of time (scaled by the initial half-mass relaxation time).

Correlations (binaries) form through 3-body encounters.
The binaries heat the rest of the cluster (like the nuclear reactions in stellar interiors).

"balanced evolution"

(Breen & Heggie 2013; Rodriguez et al. 2016)

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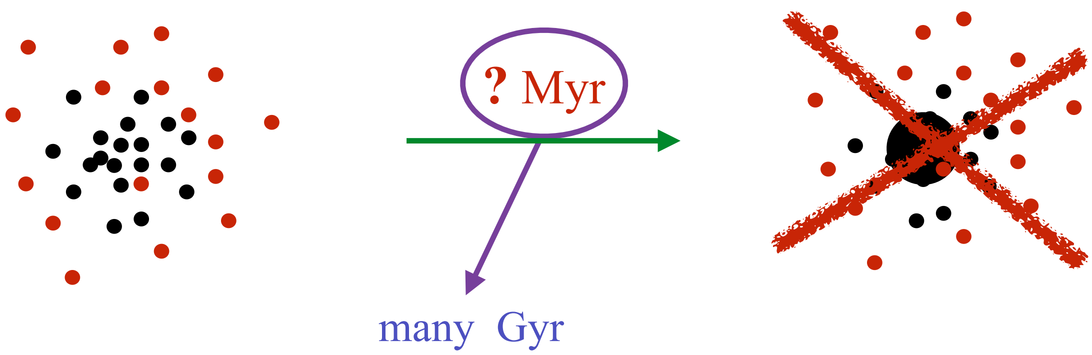


Clusters of BHs cannot evolve to a SMBH seed within ≈ 200 Myr

The Solution

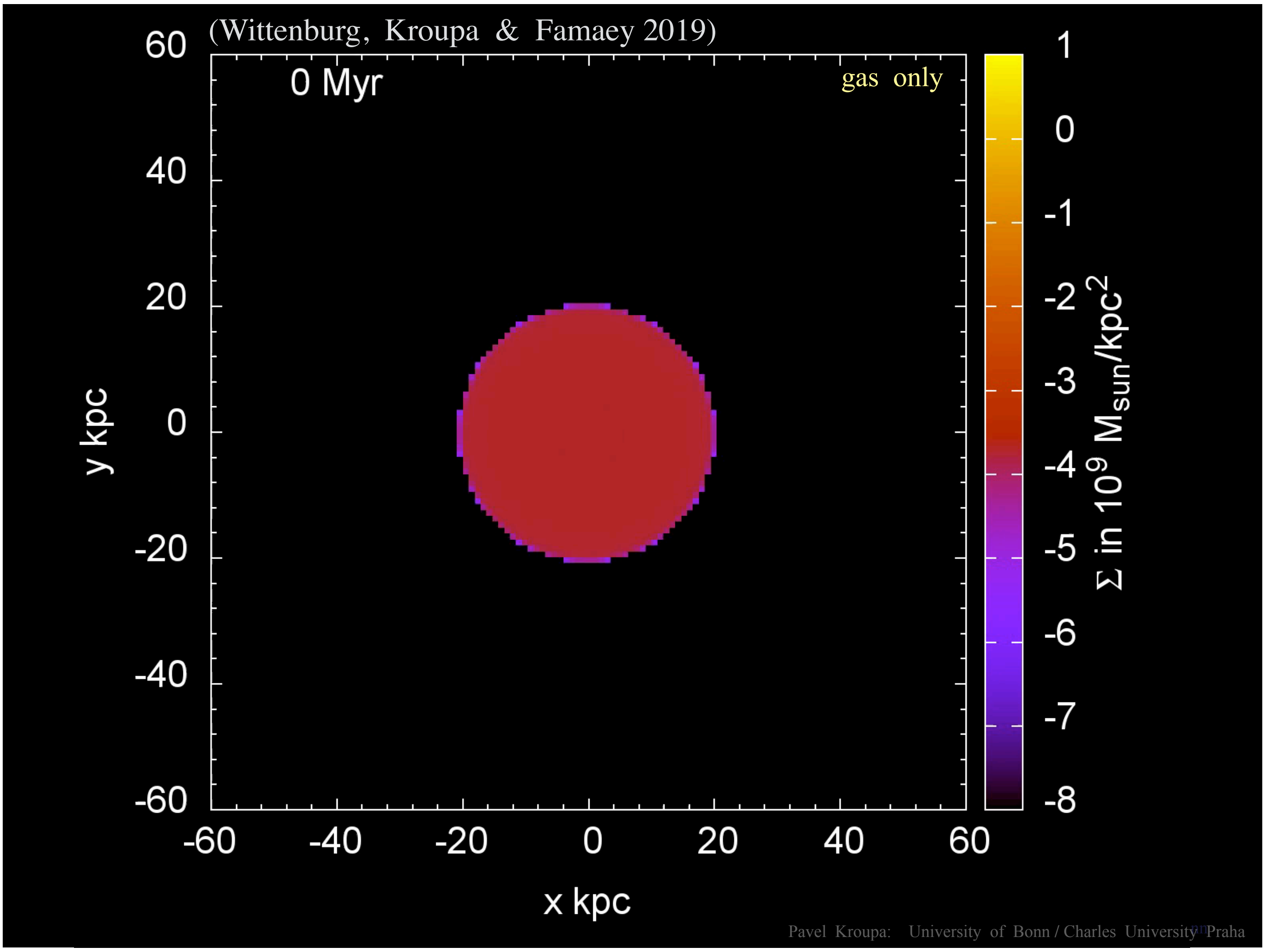
Put this into the context of *galaxy formation and evolution*:
(Kroupa, Subr, Jerabkova, Wang 2020)

First-formed very metal-poor extremely massive star-burst star cluster forms at centre of *future* spheroid : (confirmed by Martin-Navarro et al. 2018 = Vazdekis IACanary team)

Galaxy formation and evolution: (Wittenburg, Kroupa & Famaey 2019)

The evolution over 10 Gyr of a spherical gas cloud of mass $M_{gas} = 6.4\times10^9\, M_\odot$ and $r_{sph} = 20$ kpc and with an initial cylindrical rotational law with $\eta = 0.025\, Myr^{-1}$

Actual E galaxy-formation simulations are underway
(Eappen, Kroupa, Wittenburg & Famaey, in prep.)



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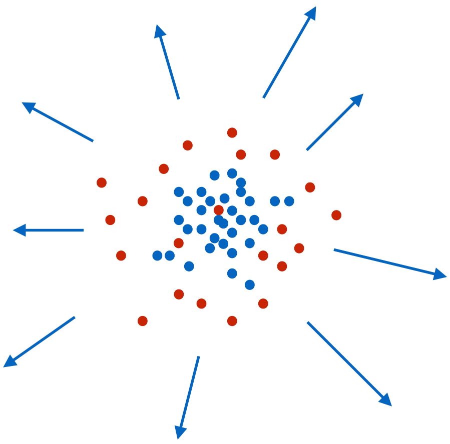

extreme radiation field and outwards wind stops gas infall from surrounding forming spheroid (Ploeckinger et al. 2019)

First-formed hyper-massive star-burst cluster :

(Jerabkova, Kroupa, Dabringhausen, Hilker & Bekki 2017)

T. Jeřábková et al.: The formation of UCDs: Testing for a variable stellar IMF

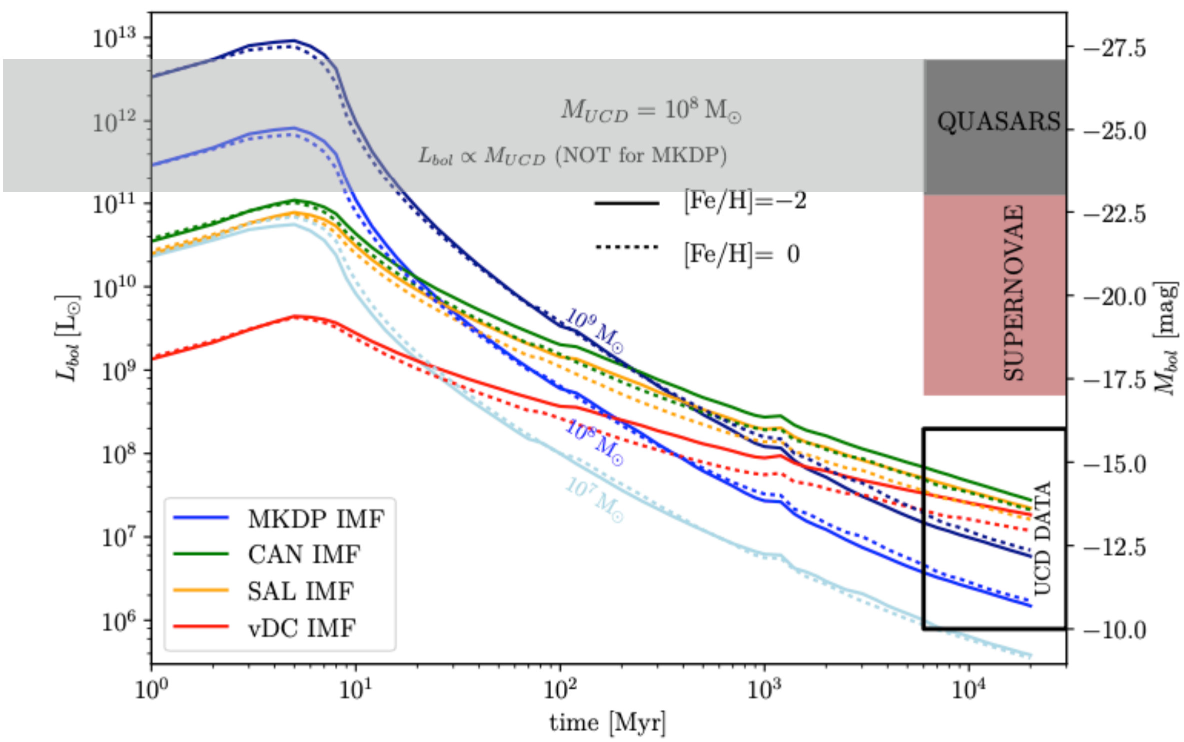

Fig. 3. Time evolution of the bolometric luminosity for different IMFs. The MKDP IMF changes with the initial mass of the UCD and does not scale linearly with its mass. In contrast, the vDC, SAL, and CAN IMFs have UCD-mass-independent slopes and scale proportionally with M_{UCD}. The grey panel shows the typical luminosities of quasars (Dunlop et al. 1993, 2003; Souchay et al. 2015) and the brown panel shows the luminosity span for the peak luminosities supernovae (Gal-Yam 2012; Lyman et al. 2016), which might cause luminosity variations in L_{bol} of UCDs younger than about 50 Myr according to SNe rates.

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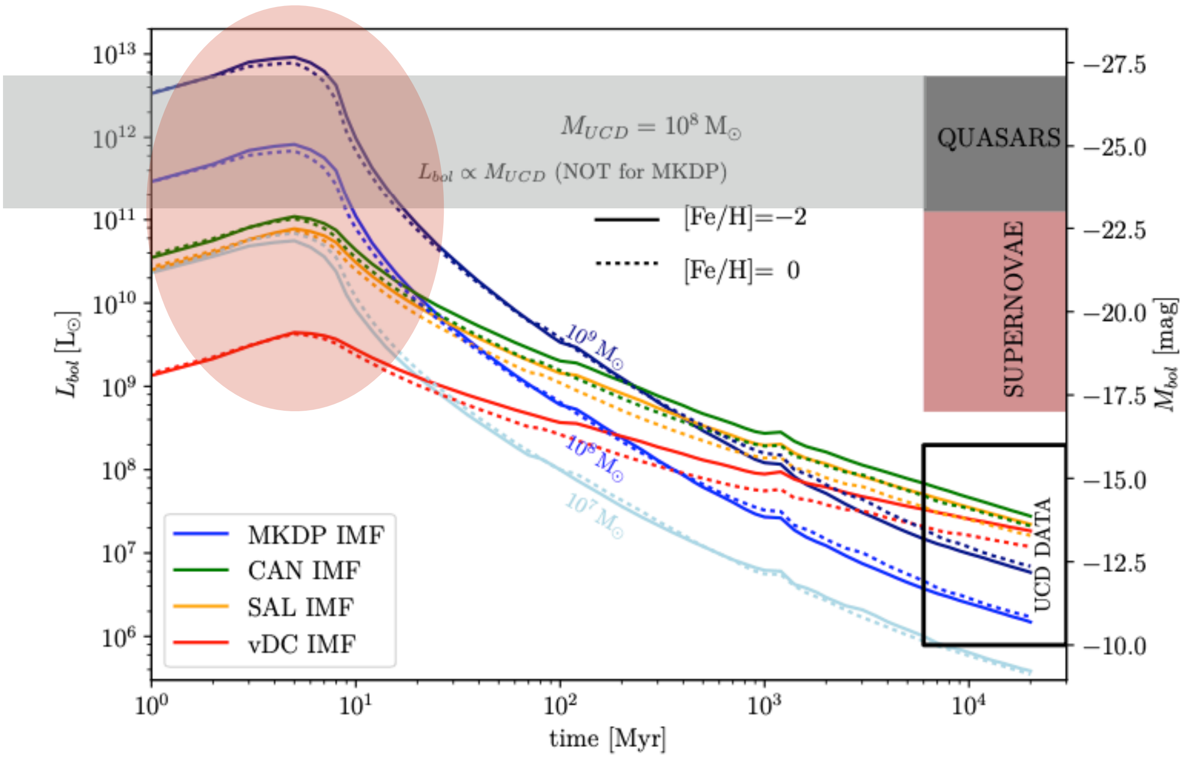

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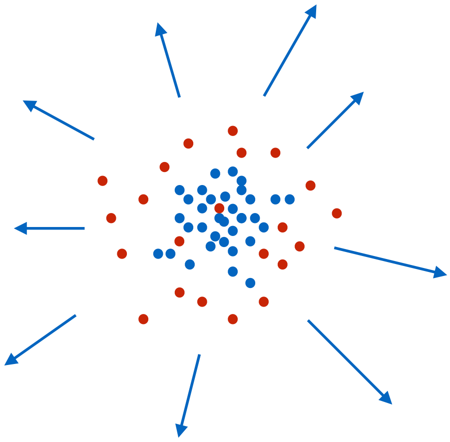

extreme radiation field and outwards wind stops gas infall from surrounding forming spheroid (Ploeckinger et al. 2019)

e.g. for 50 Myr, cluster of $10^8\,M_\odot$ luminosity of $10^{12}\,L_\odot$

drives metal-rich outflow at $2\,M_\odot/\mathrm{yr}$

at few $10^3\,\mathrm{km/s}$

Might well be mistaken for a z>6 quasar.

Put this into the context of *galaxy formation and evolution*:
(Kroupa, Subr, Jerabkova, Wang 2020)

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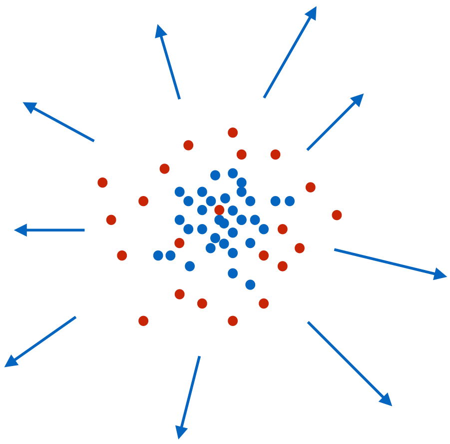

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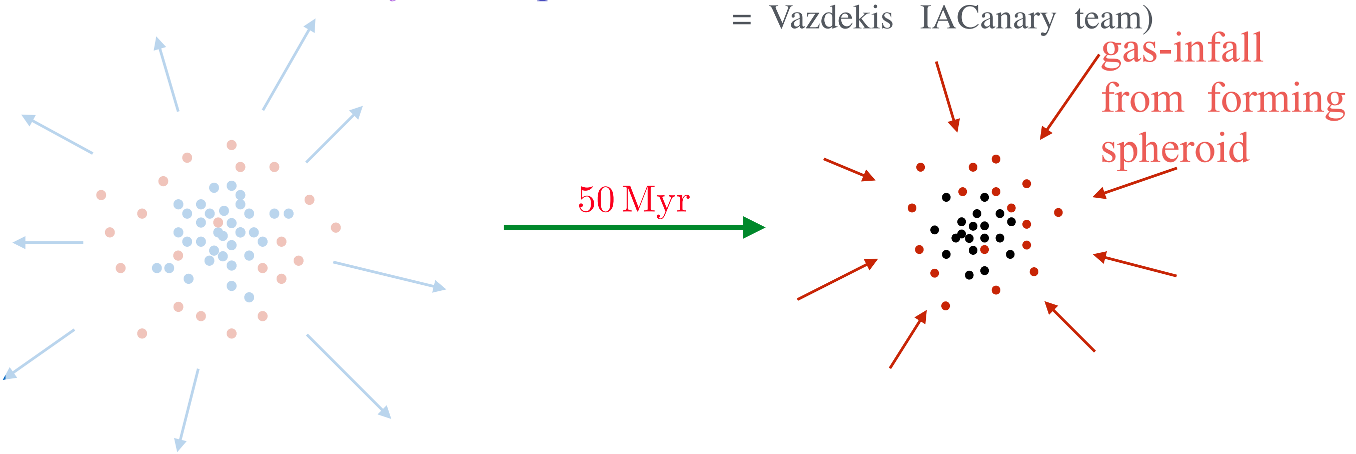

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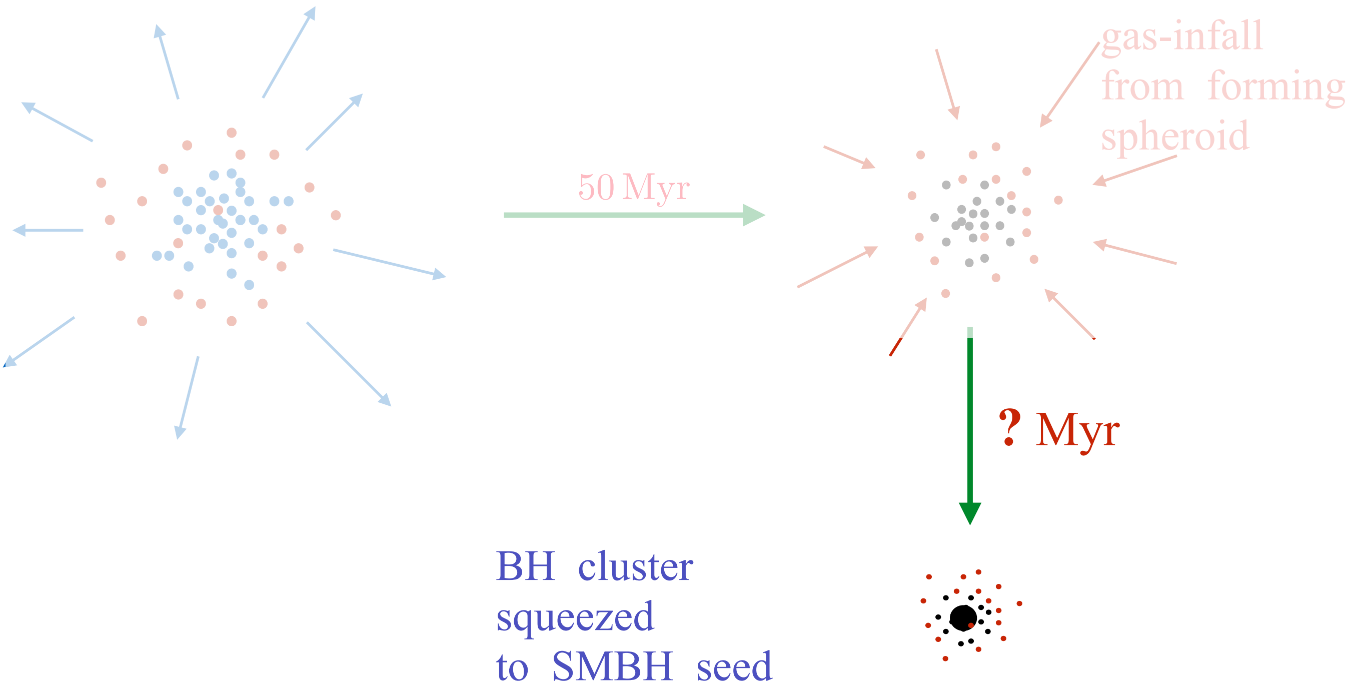

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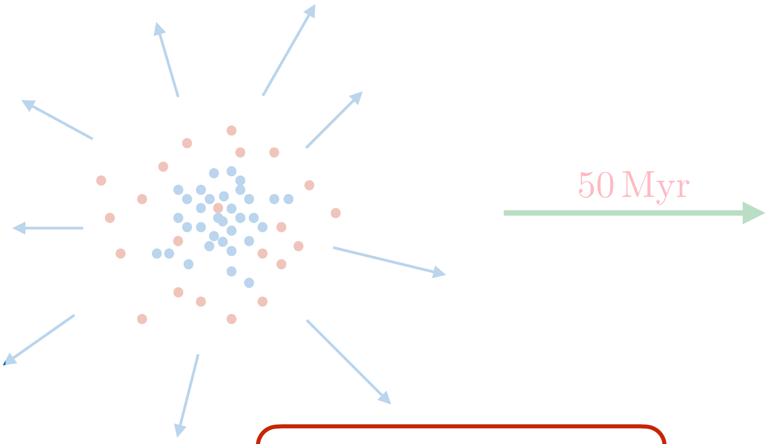

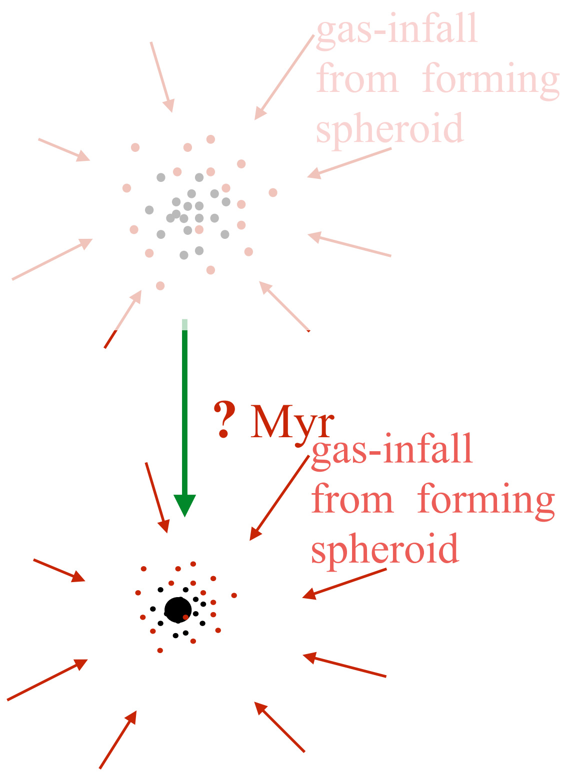

see also
Davies et al. 2011
Lupi et al. 2014
Boco et al. 2020

BH cluster squeezed to SMBH seed which grows by Eddington accretion as long as spheroid keeps forming

Evolution of BH cluster as gas in-falls

(Kroupa, Subr, Jerabkova, Wang 2020)

$$E(t) = \frac{G\,\left(M_{\rm gas}(t) + N\,m_{\rm BH}(t)\right)^2}{R(t)} = N\,m_{\rm BH}(t)\,\sigma(t)^2$$

potential energy; cluster in virial equilibrium at any time.

$$\sigma(t) = \left(\frac{G\,\left(M_{\rm gas}(t) + N\,m_{\rm BH}(t)\right)^2}{R\,N\,m_{\rm BH}(t)}\right)^{\frac{1}{2}}$$

velocity dispersion of BH cluster

$$\dot{R} = \left(\frac{\dot{E}}{G} - \frac{2}{R}(M_{\rm gas} + N\,m_{\rm BH})(\dot{M}_{\rm gas} + N\,\dot{m}_{\rm BH})\right)\frac{R^2}{(M_{\rm gas} + N\,m_{\rm BH})^2}$$

with $\dot{E} = \dot{E}_{\rm diss} + \dot{E}_{\rm bin,heat}$

binding energy change through *gas drag* and *binary heating* through BH-BH binaries.

Evolution of BH cluster as gas infalls

(Kroupa, Subr, Jerabkova, Wang 2020)

$$\eta_g \equiv \frac{M_{gas}}{N\, m_{BH}}$$

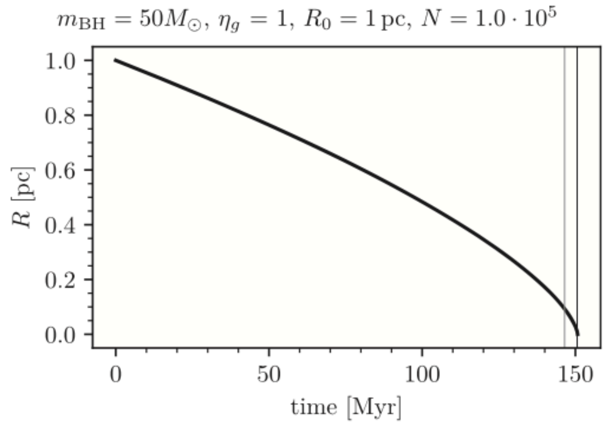

Figure 5. The evolution of the cluster radius, $R(t)$, for $\eta_g = 1.0$, $m_{BH} = 50\,M_\odot$, $M_{BH,0} = 5 \times 10^6\,M_\odot$, and $R_0 = 1$ pc. The cluster of BHs contracts because gas drag outweighs binary heating. See Fig. 6 for the ratio of the rates of energy change due to gas drag and binary heating. The vertical thin grey line represents the time, t_{crit}, when binary heating ceases to be relevant (equation 17) and the vertical thick line shows the time, t_{rel}, when the BH cluster reaches the relativstic state (equation 20).

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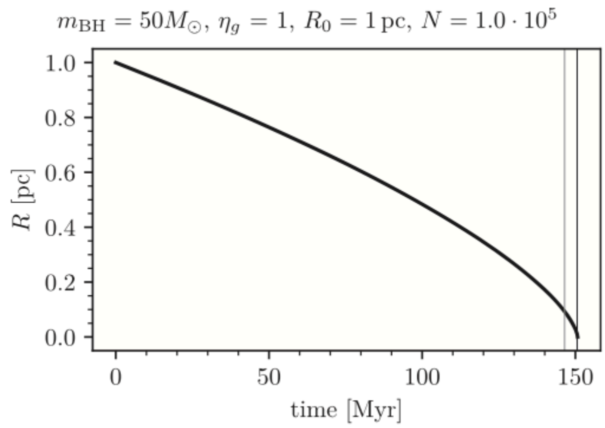

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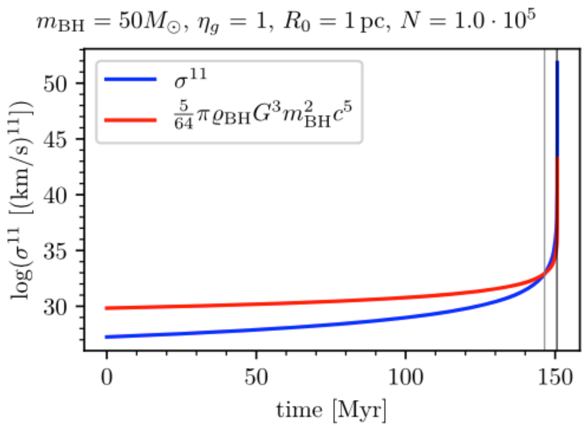

Figure 7. The evolution of the velocity dispersion (equation 24, blue line) and of the condition when binaries cease to be a heating source (equation 17, red line) for the parameters as in Fig. 5. The velocity dispersion increases as the cluster plus gas cloud shrinks. When the two lines intersect (the left vertical line), binary heating ceases to be active. The vertical lines have the same meaning as in Fig. 5. Note that $\log = \log_{10}$.

Evolution of BH cluster as gas infalls

(Kroupa, Subr, Jerabkova, Wang 2020)

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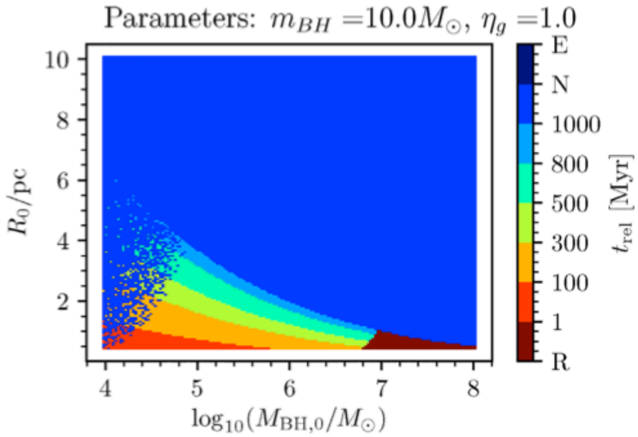

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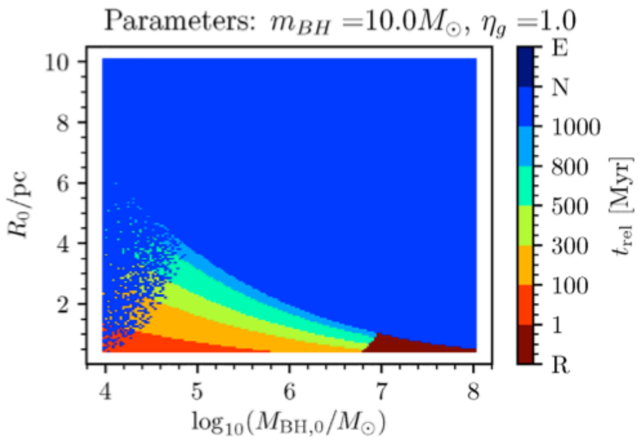

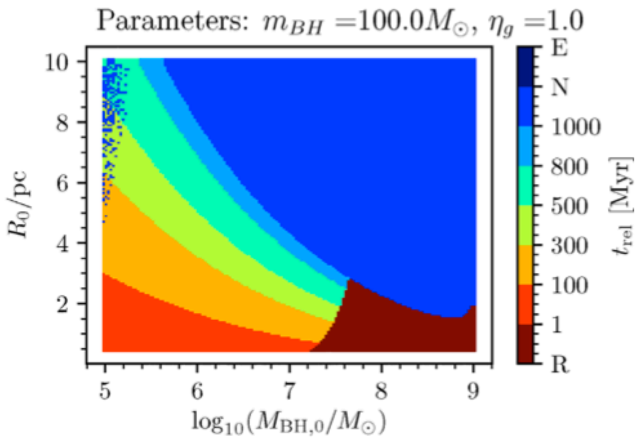

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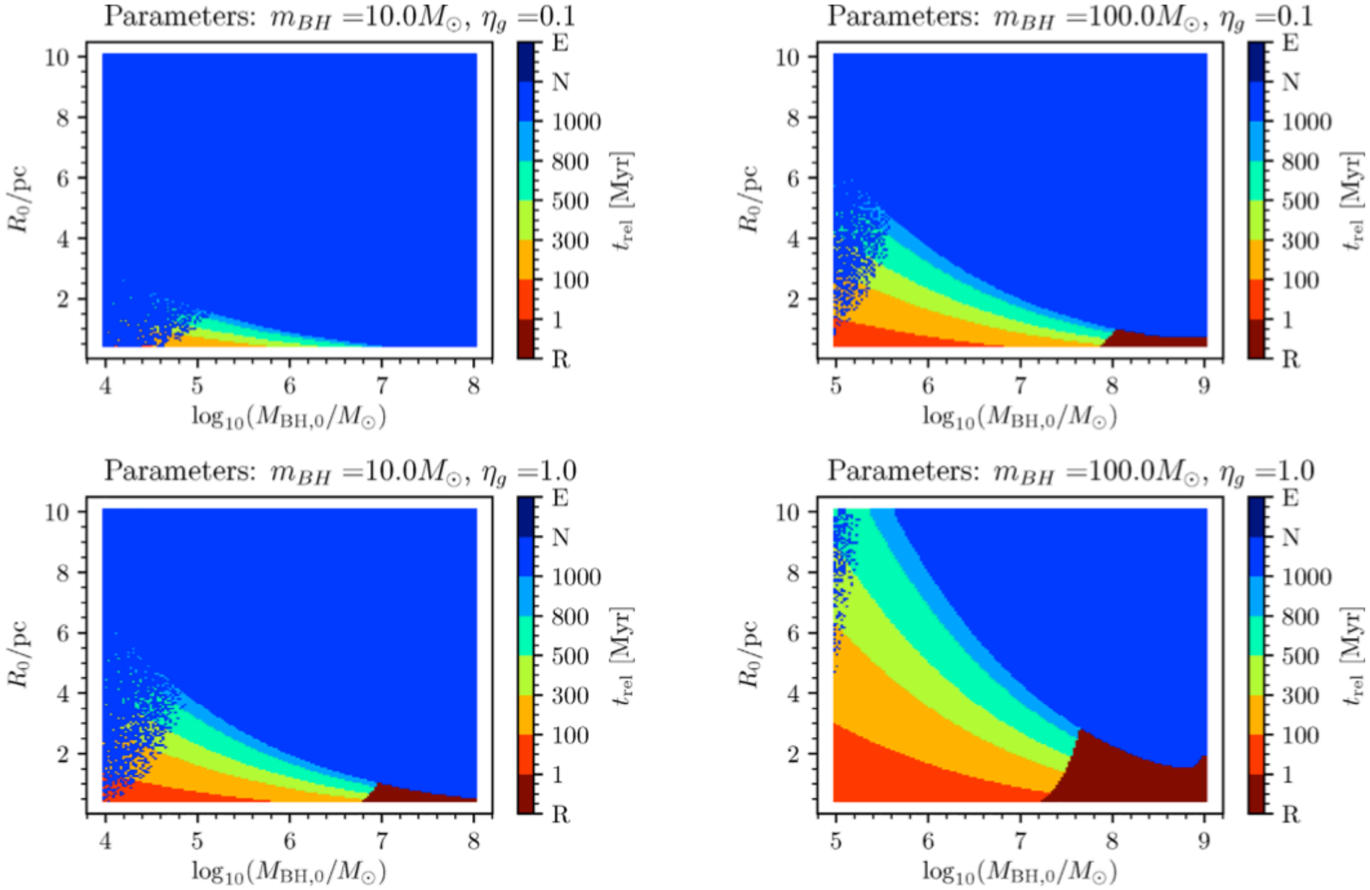


Evolution of BH cluster as gas infalls

(Kroupa, Subr, Jerabkova, Wang 2020)

→ shrinkage to relativistic regime ($\sigma_{rel} \equiv 3000$ km/s) within 200 Myr of BH cluster formation (250 Myr after 1st star forms).

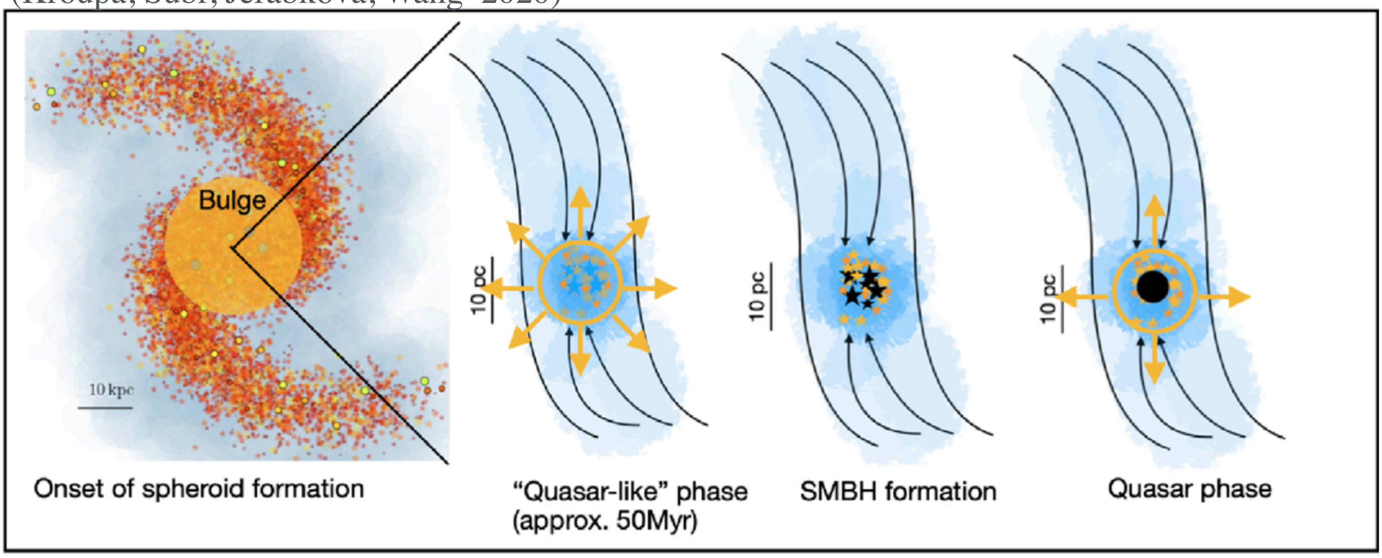
then *collapse of >5%* of BH cluster to SMBH seed through gravitational wave energy loss essentially *instantaneous* (see also Lee 1993; Kupi et al. 2006 for Nbody).

A SMBH seed weighing >5% of the BH cluster is possible within 200-300 Myr of the formation of the first stars.

Implications for early nucleosynthesis

Remember/Summary

(Kroupa, Subr, Jerabkova, Wang 2020)



Evolution of BH cluster as gas infalls

(Kroupa, Subr, Jerabkova, Wang 2020)

During the squeeze millions of neutron stars are squashed together

Strong flux of elements before any CCSN ?

Strong flux of neutrons ?

To intergalactic distances ?

Within 11 Mpc there are about 140 galaxies more massive than 10^9 Msun

i.e.

140 SMBHs

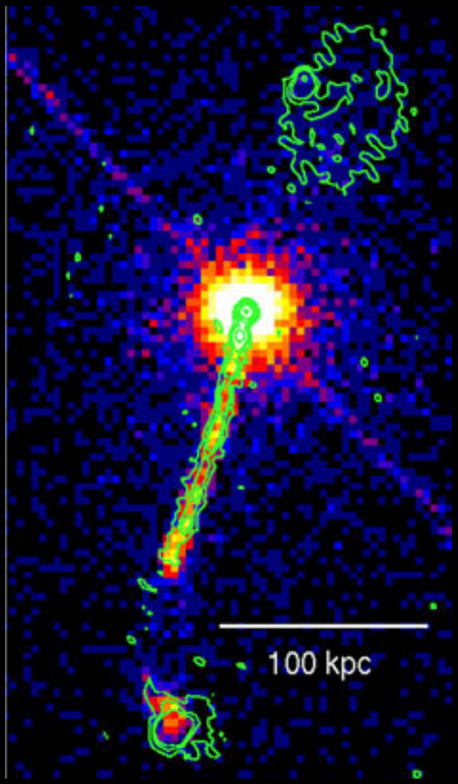
First star formation about 200Myr after Big Bang

i.e. at redshift z=20

the Universe was 1/21 its present size

i.e. there were 140 forming SMBHs within 500kpc of "us"

Jets from quasars can reach lengths of 100s kpc



A Chandra X-ray image of the quasar 3C19.44. The overlayed contours show the radio emission (the dimension 100kpc corresponds to 329,000 light-years; the extremely bright core produces a line of bright pixels as an artifact).
Credit: NASA/Chandra VLA and Harris et al

Enrichment by heavy elements
(even r-process ?)
within a Myr after Big Bang
to distances of 100s of kpc,
i.e.
all of space
?

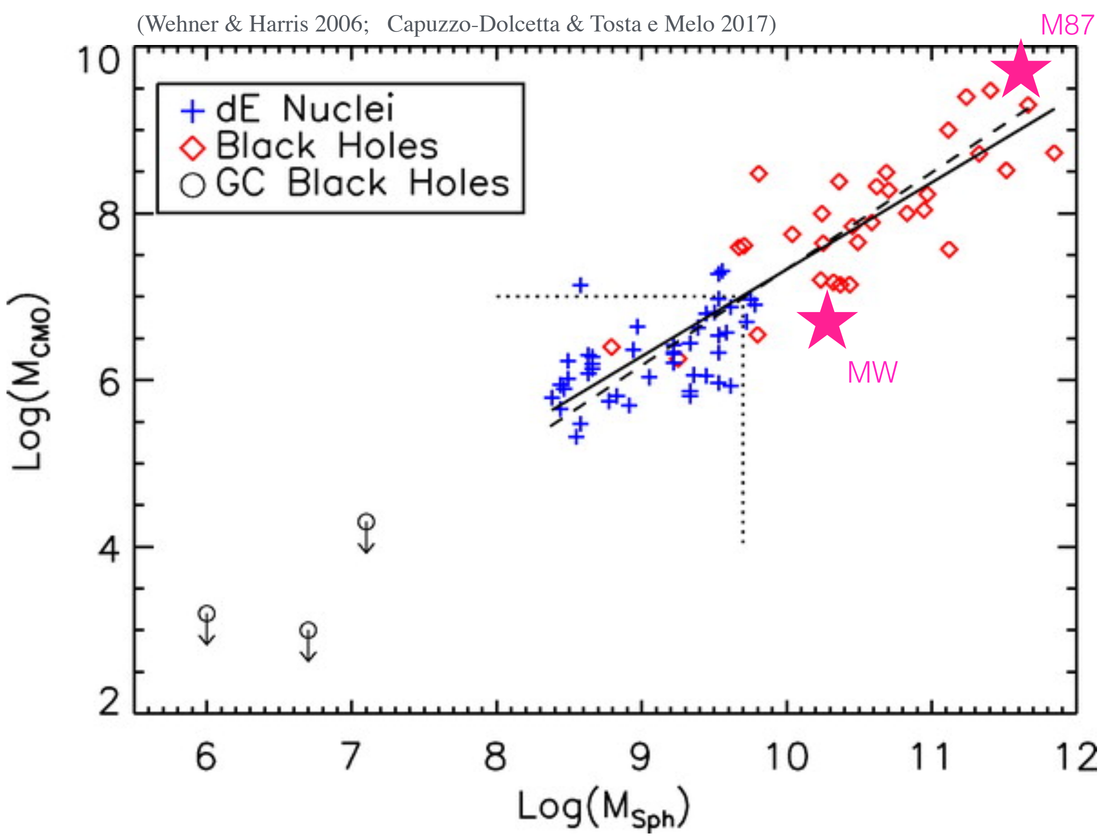
this is likely to be non-homogeneous
i.e. more r-process "here" vs more s-process "there"
etc.

Pavel Kroupa: University of Bonn / Charles University Praha

What about the correlation between the SMBH and host galaxy mass ?

Remember: SMBH mass vs host galaxy mass (spheroid component)

(Wehner & Harris 2006; Capuzzo-Dolcetta & Tosta e Melo 2017)



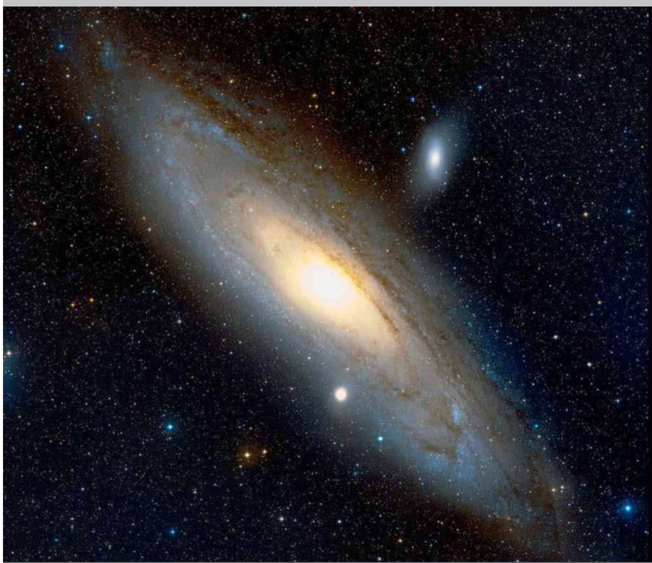
Need to ensure that enough gas
falls into the central region
of a forming galaxy.

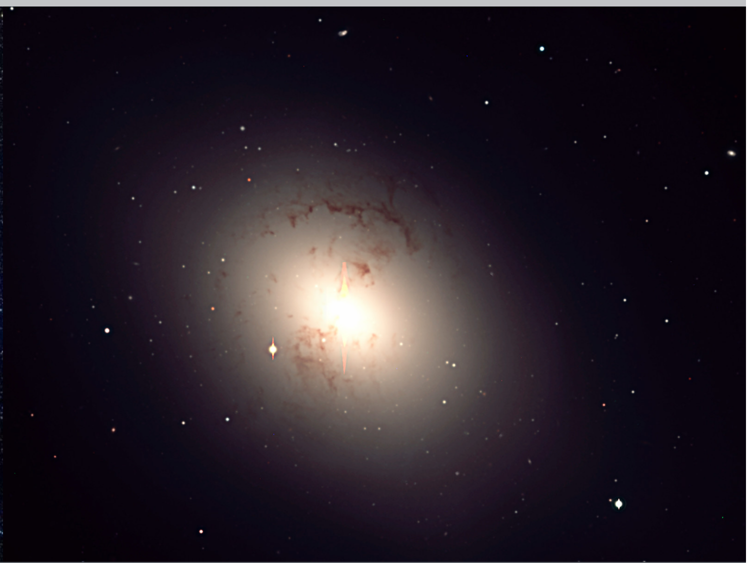
This is not possible in disk galaxies,
they form too slowly.

EWASS 2019

Halve of all disk galaxies have bulges,
and a few percent of all galaxies
are huge bulges = elliptical galaxies

These galaxy spheroids form rapidly after Big Bang,
vast quantities of gas collapsed rapidly.





https://ned.ipac.caltech.edu/level5/Sept14/Kormendy/Kormendy7.html

ESO

Need to calculate the most massive forming star cluster ($M_{\rm ecl,max}$) in a galaxy with a global star-formation rate (SFR)

$$SFR = \frac{\text{mass of galaxy spheroid}}{\text{time to form galaxy}}$$

$$SFR = \frac{M_{\rm i,gal}}{\Delta\tau} \approx \frac{M_{\rm p,gal}}{\Delta\tau}$$

What about the correlation between the SMBH and host galaxy mass ?

Easy : use IGIMF theory (Kroupa & Weidner 2003; Kroupa et al. 2013; Yan, Jerabkova et al. 2017; Jerabkova, Yan et al. 2018)

The total mass in stars formed in a galaxy over time δt is $M_{\rm tot} = SFR \times \delta t$

But $M_{\rm tot} = \int_{M_{\rm ecl,min}}^{M_{\rm ecl,max}} \xi_{\rm ecl}(M_{\rm ecl})\, M_{\rm ecl}\, dM_{\rm ecl}$

For $M_{\rm ecl,min} = 5\, M_\odot$ and with $1 = \int_{M_{\rm ecl,max}}^{M_{\rm ecl,max*}} \xi_{\rm ecl}(M_{\rm ecl})\, dM_{\rm ecl}$

where $M_{\rm ecl,max*} = 10^{10}\, M_\odot$

Thus $\boxed{M_{\rm ecl,max} = {\rm fn}(SFR)}$ as observed (Weidner et al. 2004; Randriamanakoto et al. 2013)

What is δt ?

The time-scale on which the interstellar medium spawns a complete population of new star (Egusa et al. 2004; 2009; Fukui et al. (2010); Meidt et al. 2015; Leisawitz 1989).

→ $\boxed{\delta t \approx 10\ {\rm Myr}}$

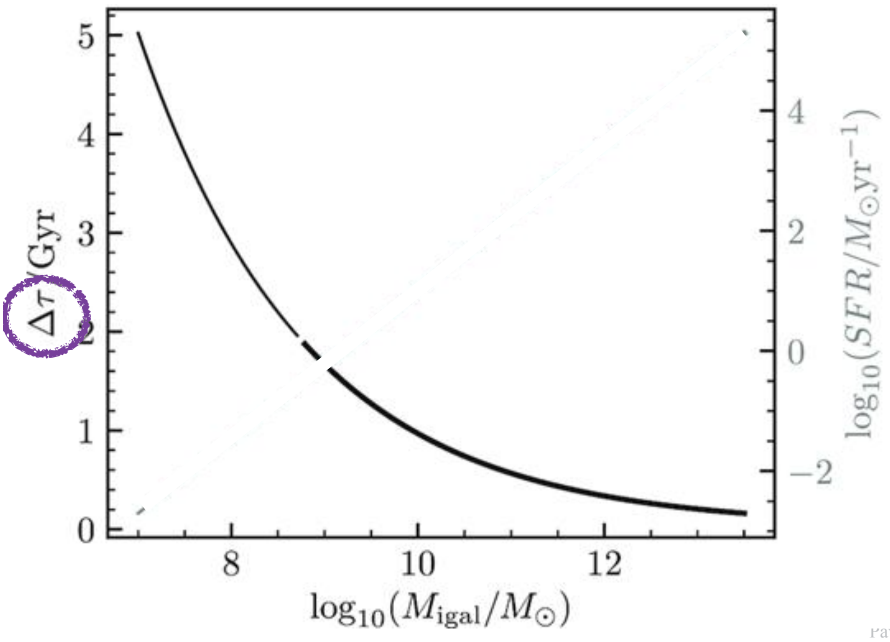
The mass of this cluster, $M_{\rm ecl,max}$, strongly correlates with later host galaxy mass, $M_{\rm p,gal}$, through

$$SFR = \frac{M_{\rm i,gal}}{\Delta\tau} \approx \frac{M_{\rm p,gal}}{\Delta\tau}$$

via $M_{\rm ecl,max} = {\rm fn}(SFR)$ from above

The "downsizing" or "Thomas time" $\Delta\tau$

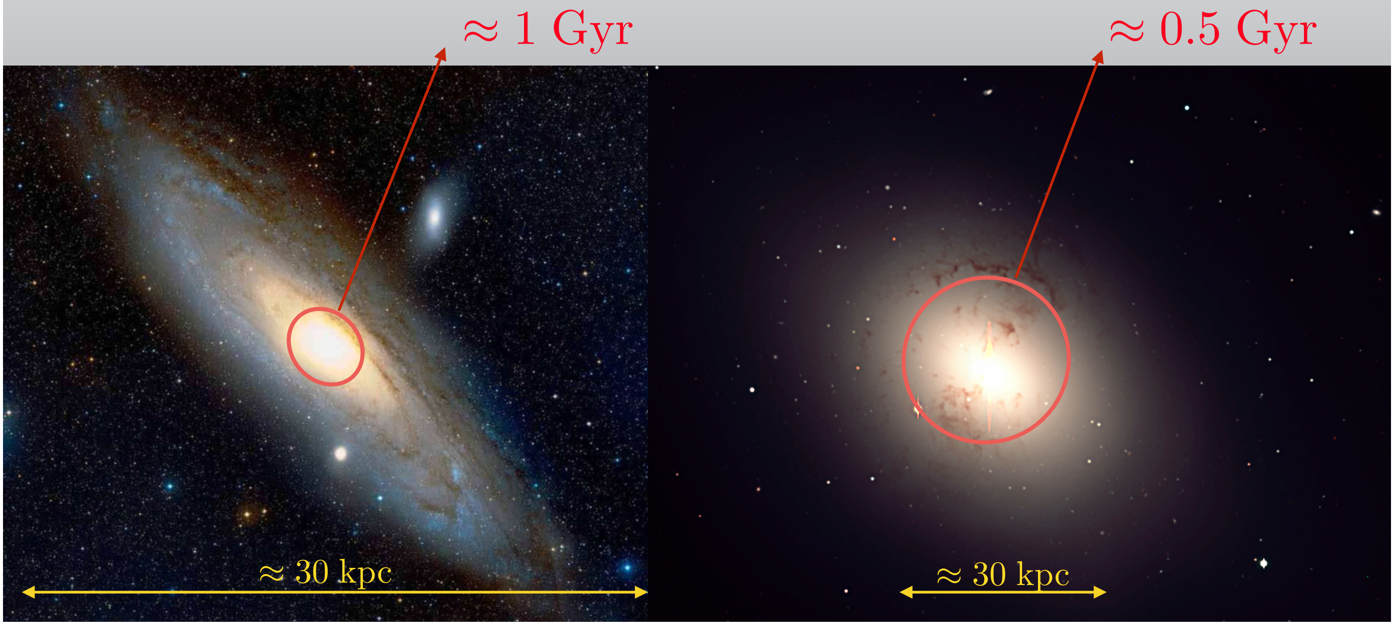
ages, Z, $\left[\frac{\alpha}{\rm Fe}\right]$ values for 124 early-type galaxies
(Thomas et al. 2005; Recchi et al. 2009)



confirmed by
de la Rosa et al. 2011;
McDermid et al. 2015;
Martin-Navarro et al. 2018;
Salvador-Rusinol et al. 2020
Yan, Jerabkova et al. 2021

These galaxy spheroids form rapidly after Big Bang, vast quantities of gas collapsed rapidly.

These more massive, the faster it formed = "downsizing".



https://ned.ipac.caltech.edu/level5/Sept14/Kormendy/Kormendy7.html

ESO

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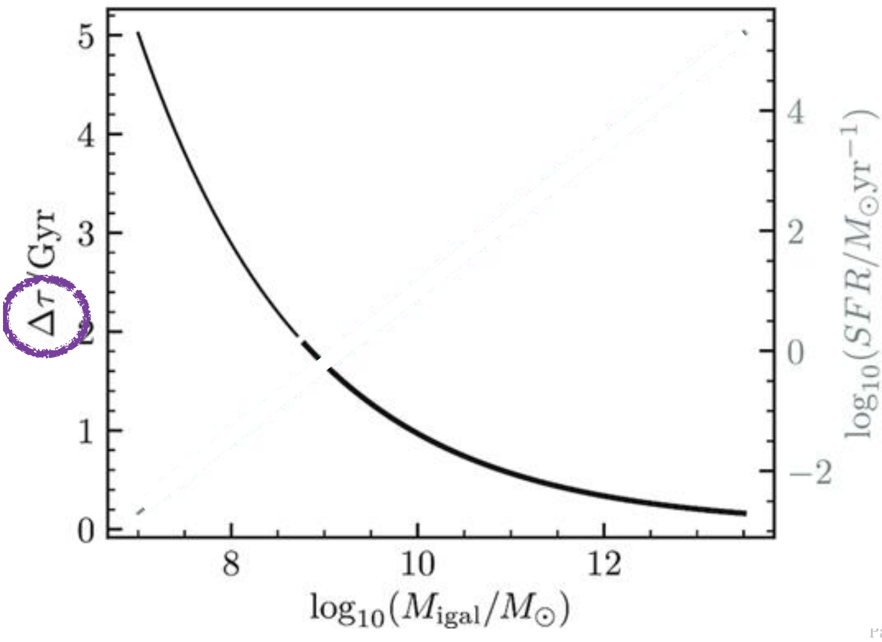

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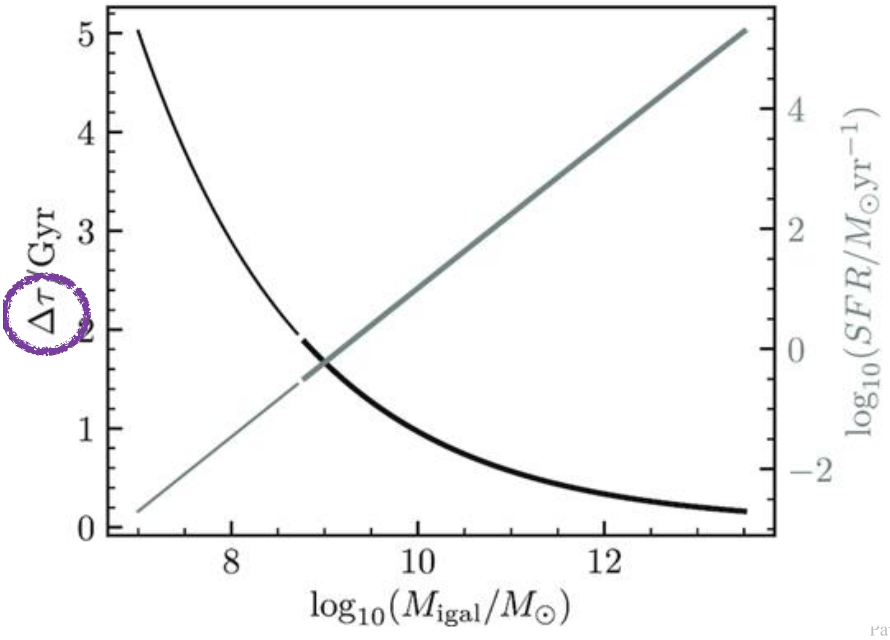

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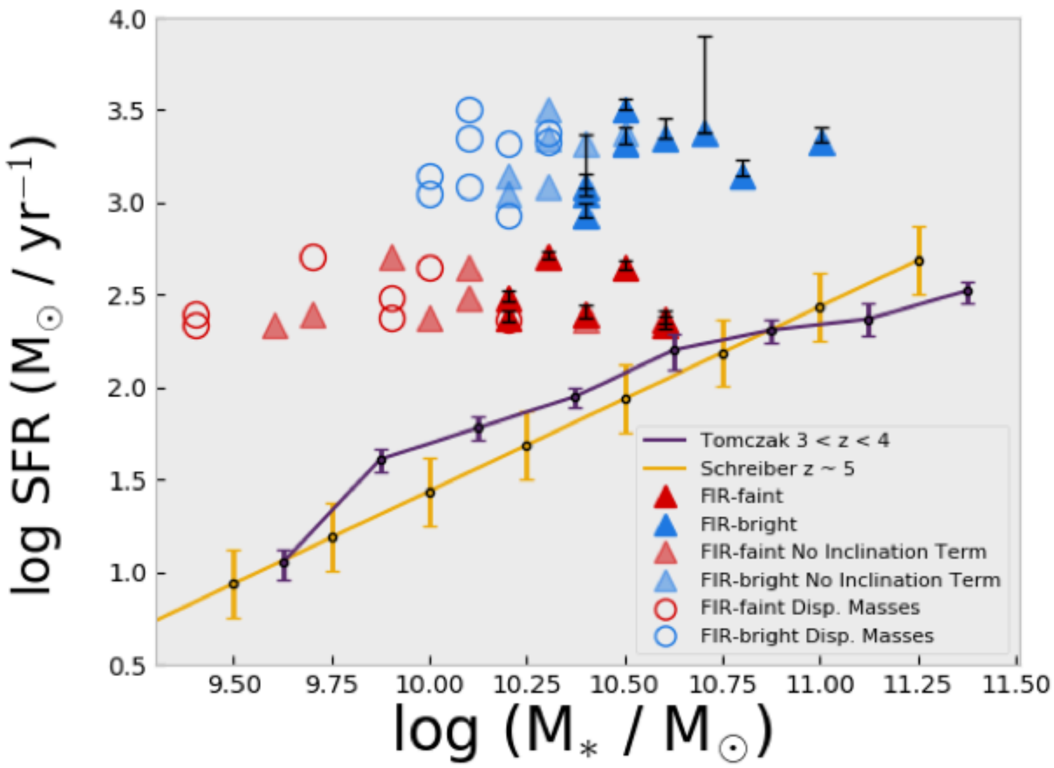
ALMA Observations of Quasar Host Galaxies at $z \simeq 4.8$

Nguyen, Lira, Trakhtenbrot et al. 2020

$t \approx 1.2$ Gyr after Big Bang



Thus we obtain

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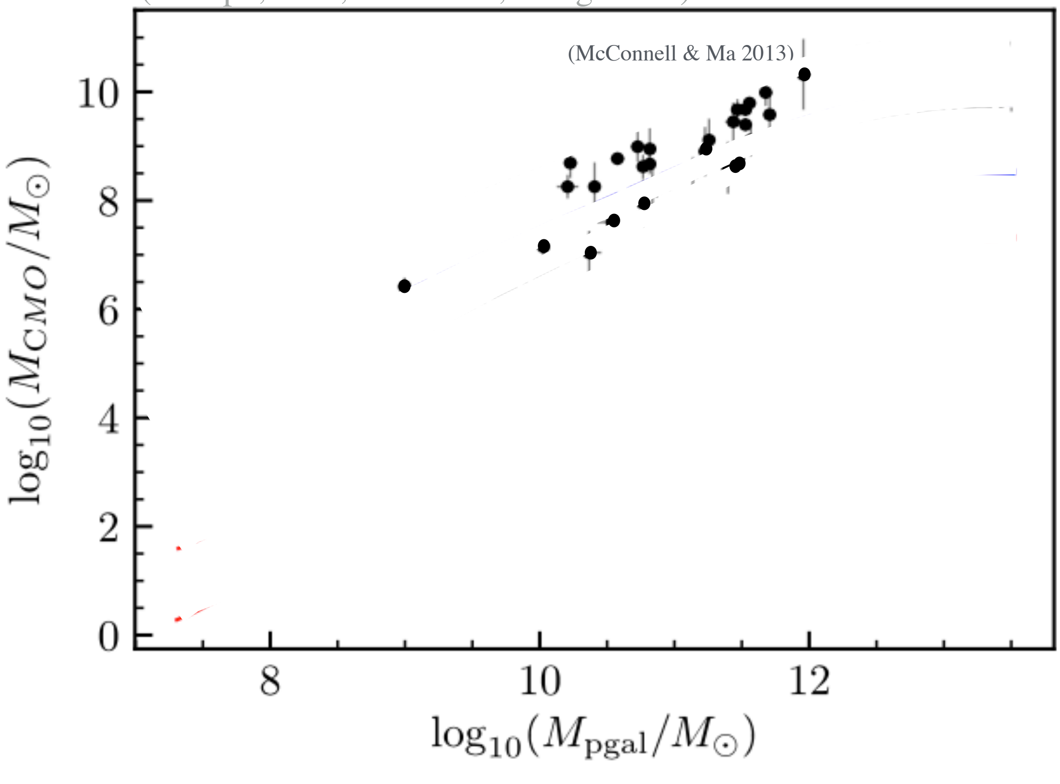
(Kroupa, Subr, Jerabkova, Wang 2020)



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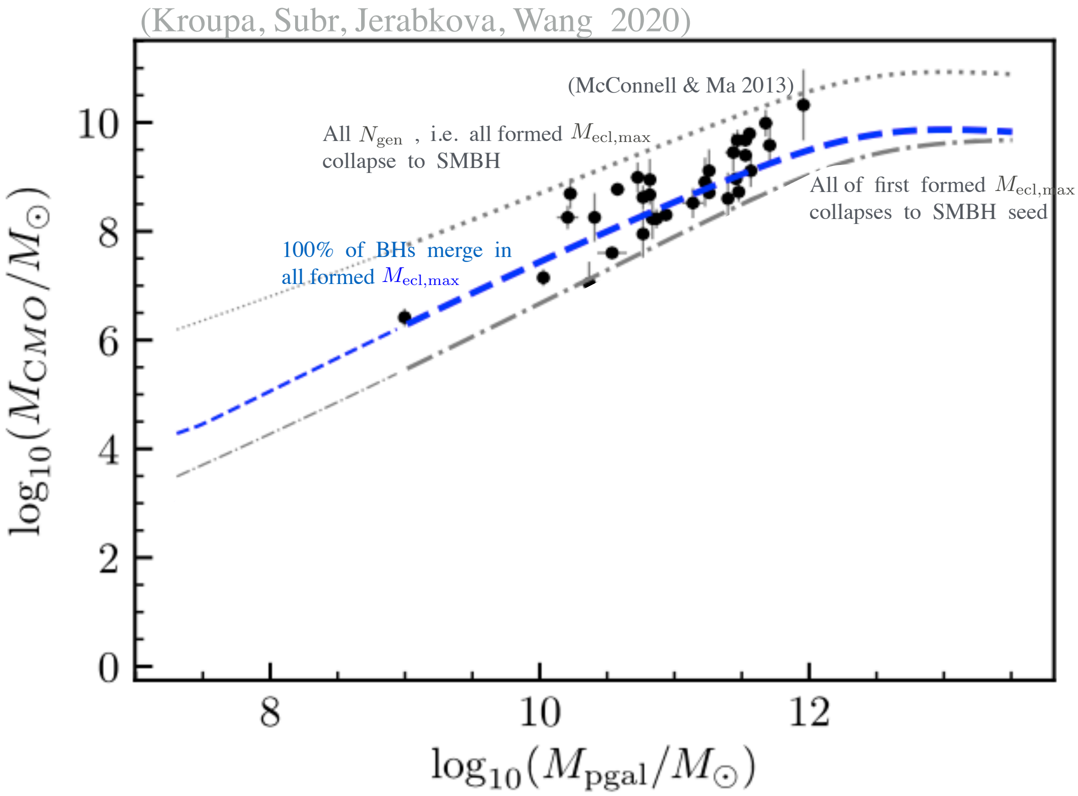

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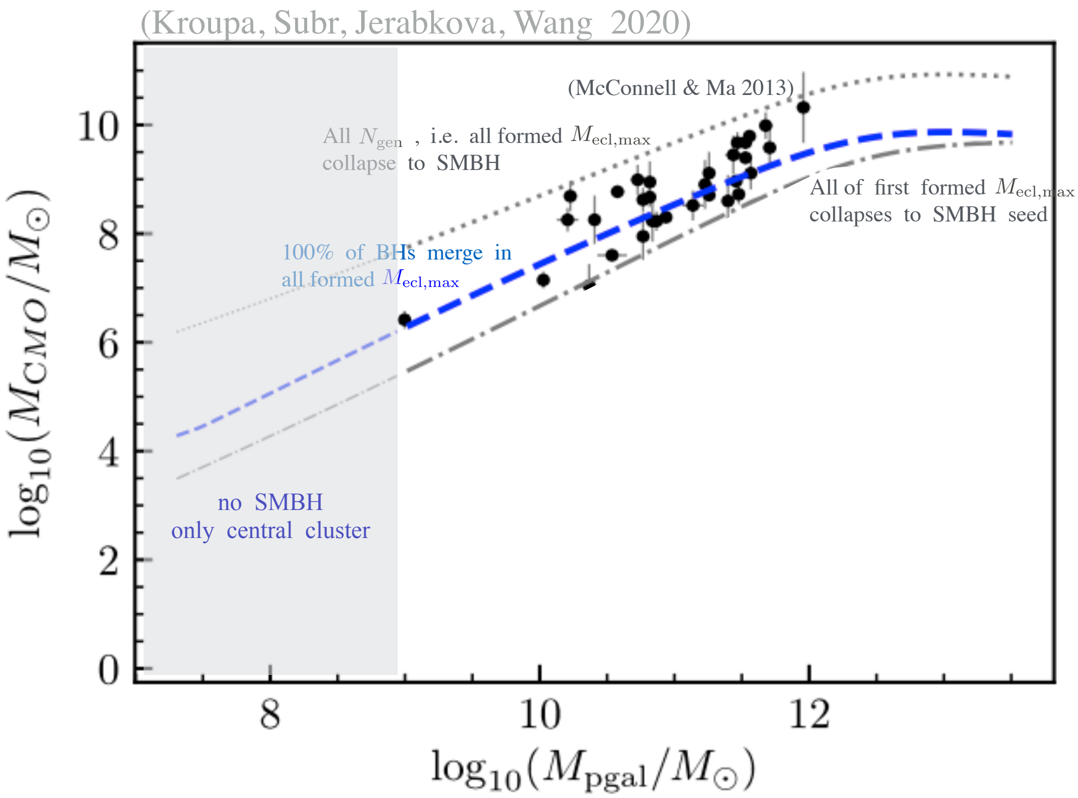
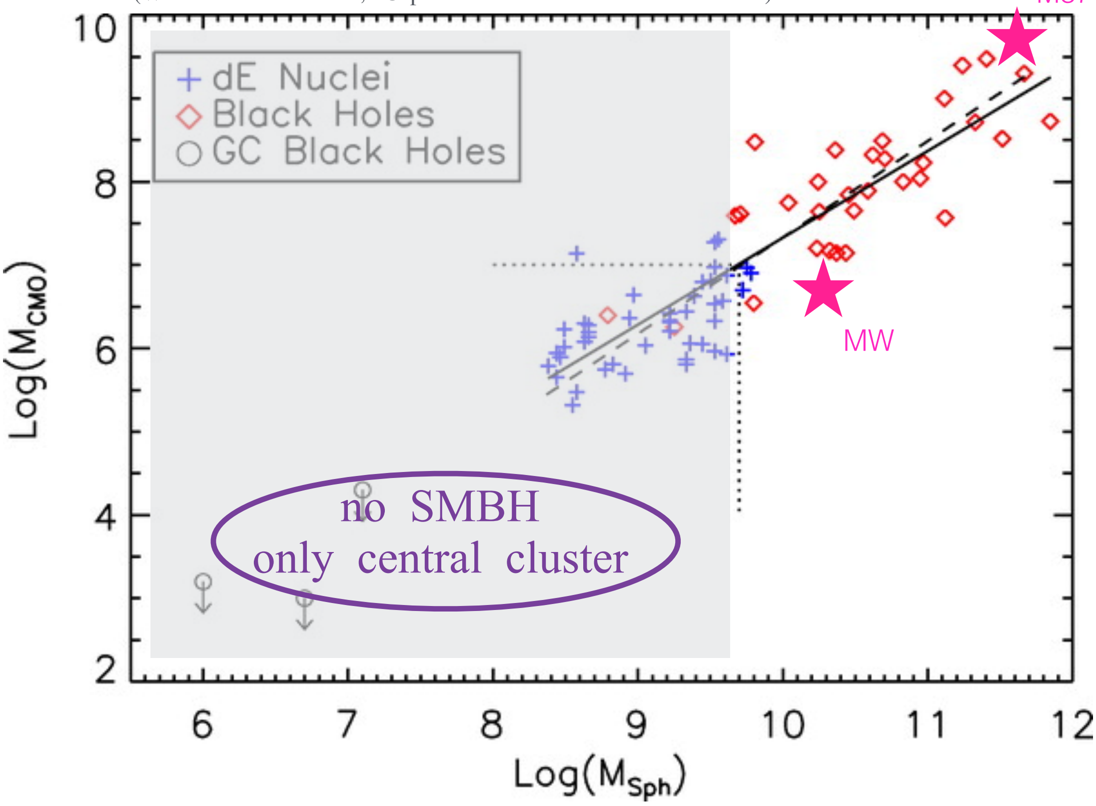


SMBH mass vs host galaxy mass (spheroid component)

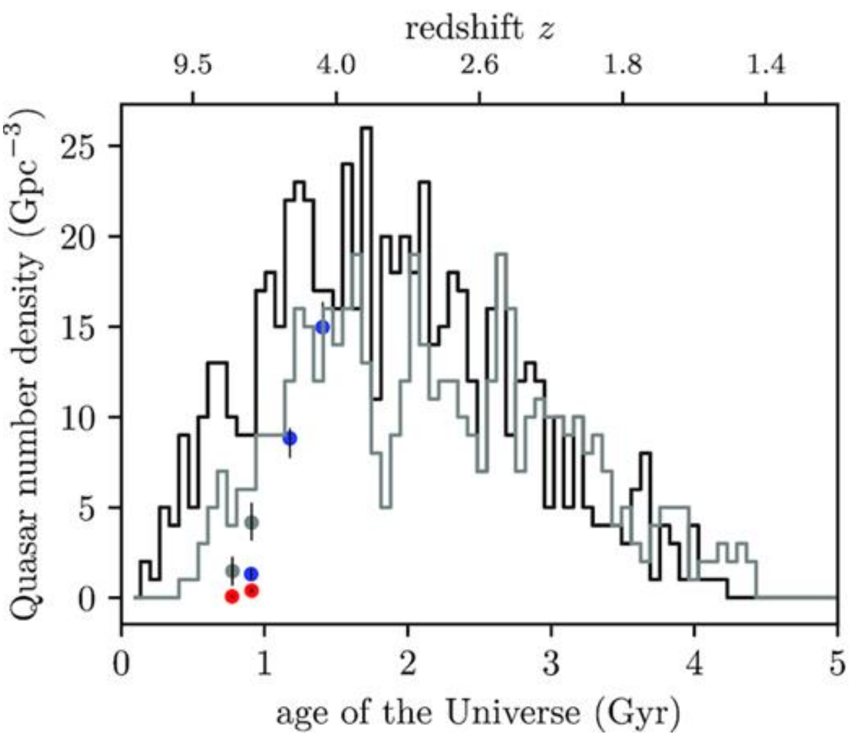
(Wehner & Harris 2006; Capuzzo-Dolcetta & Tosta e Melo 2017)



The appearance of the first quasars

(Kroupa, Subr, Jerabkova, Wang 2020)

Based on the *empirical* galaxy-formation times scales of Thomas et al. (2005)



hypermassive star-burst clusters

accreting SMBH seeds

Data: Jiang et al. (2016)

The Conclusions

Solutions to the three problems:

I) How can SMBHs even form ?

Primarily through coalescence of $> 10^4$ *stellar BHs (driven by gas-infall onto the central BH cluster)*

II) Why do SMBH masses correlate with the mass of the hosting galaxy ?

Essentially through the downsizing (Thomas) time and via the IGIMF theory.

III) How can SMBHs form within a few 100 Myr after the Big Bang ?

The highest-z quasars are hypermassive star-burst clusters with top-heavy IMF (Jerabkova objects).

IV) 10^8 quasars / SMBHs exist per co-moving Gpc^3

V) Thus rapid enrichment everywhere (even if patchy) ?

Essentially :

Given
(i) the standard properties of normal matter
(ii) the observed downsizing (Thomas) time
(iii) the correlations of the stellar population
with the downsizing (Thomas) time

quasars *must* appear about 200Myr after BigBang
as *hypermassive star-burst clusters* (Jerabkova objects)
and SMBHs *must* correlate with host galaxy.

Solutions to the three problems:

I) How can SMBHs even form ?
Primarily through coalescence of $> 10^4$ *stellar BHs*

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END