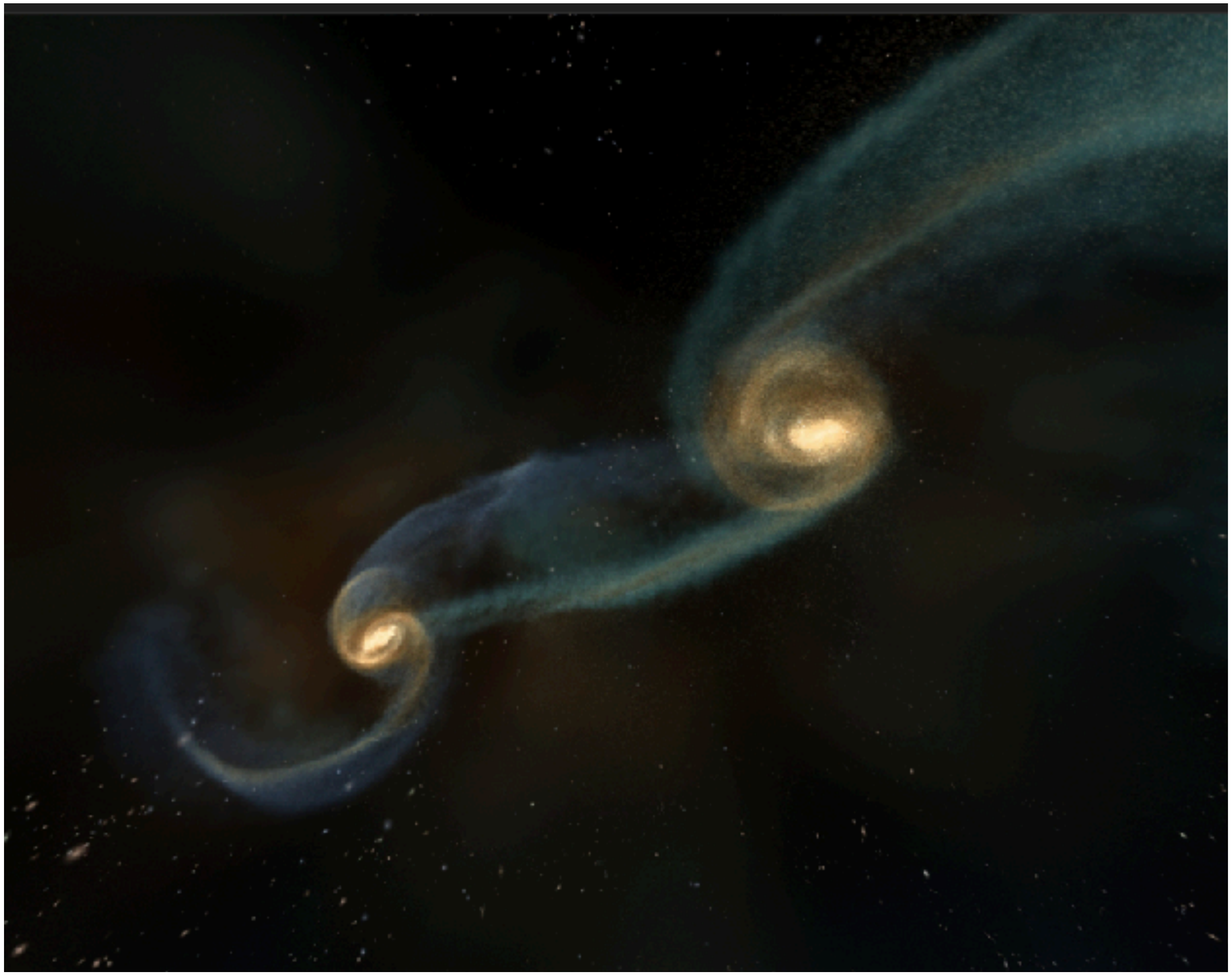
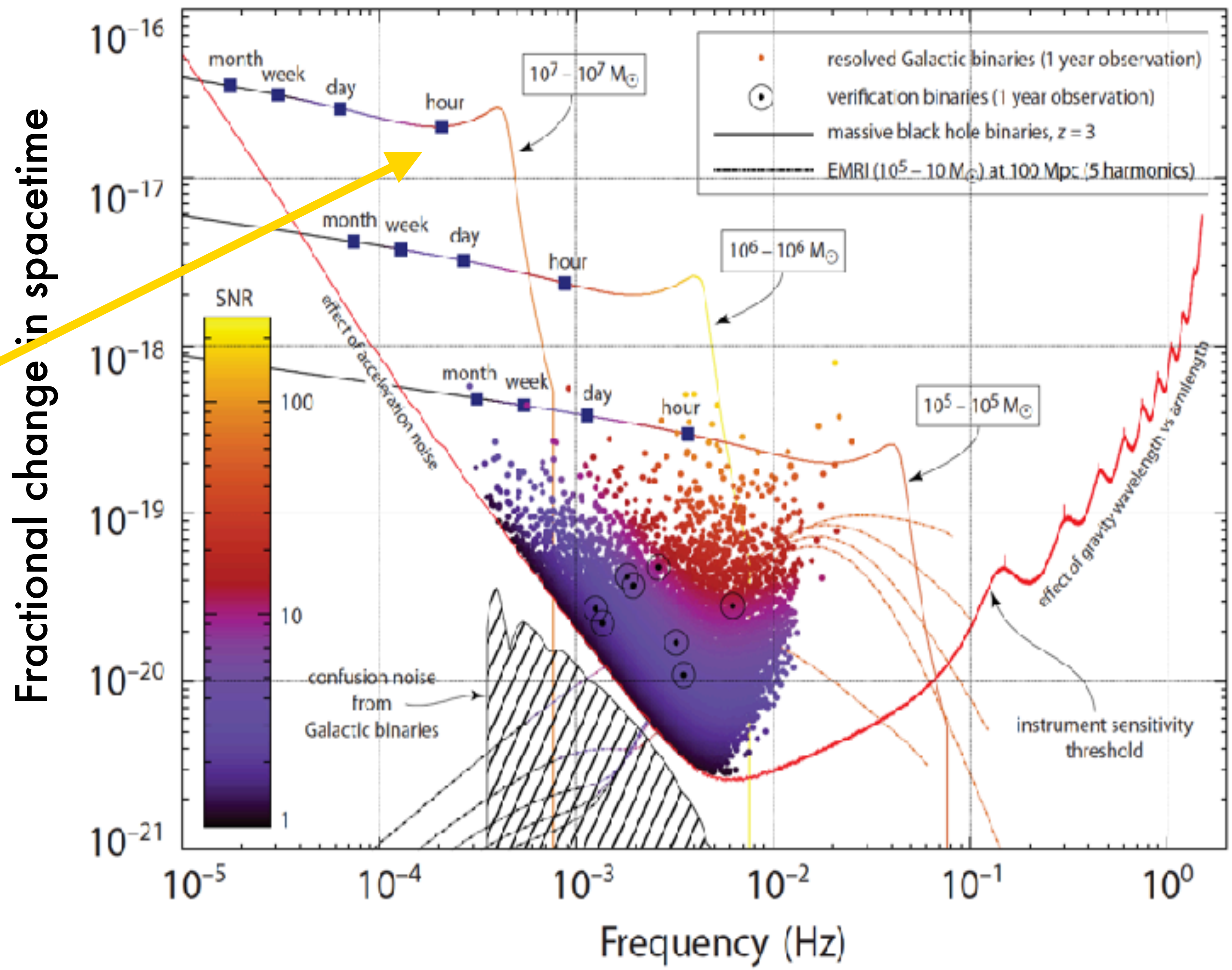
Massive black holes in the wild



Kelly Holley-Bockelmann
k.holley@vanderbilt.edu

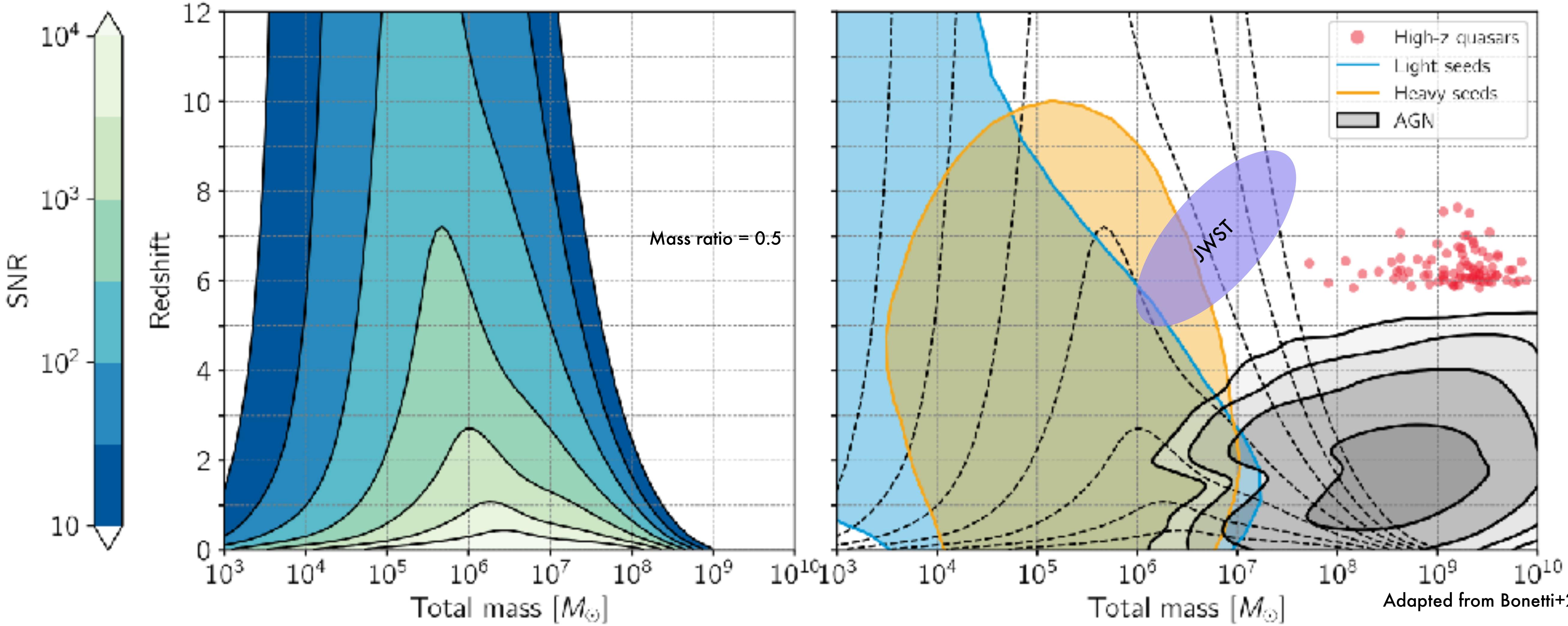
lisa discovery space

Massive Black Hole Mergers



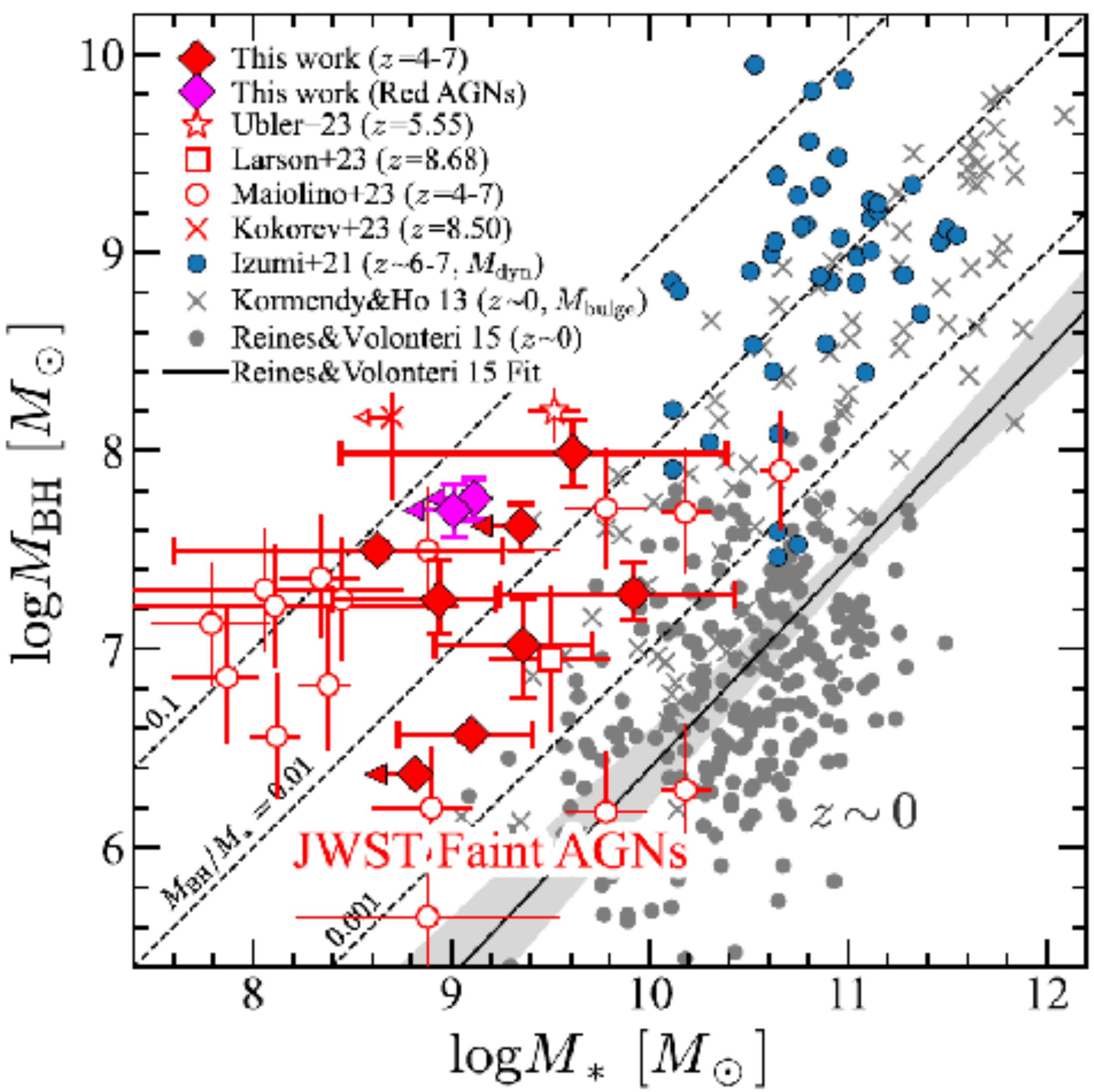
LISA will observe massive black hole mergers out to cosmic dawn and into the dark ages!

LISA Definition Study Report, 2024



Adapted from Bonetti+2019

JWST says...



5x more Massive Black Holes at z>4 than we thought!

Higher merger rate for LISA?

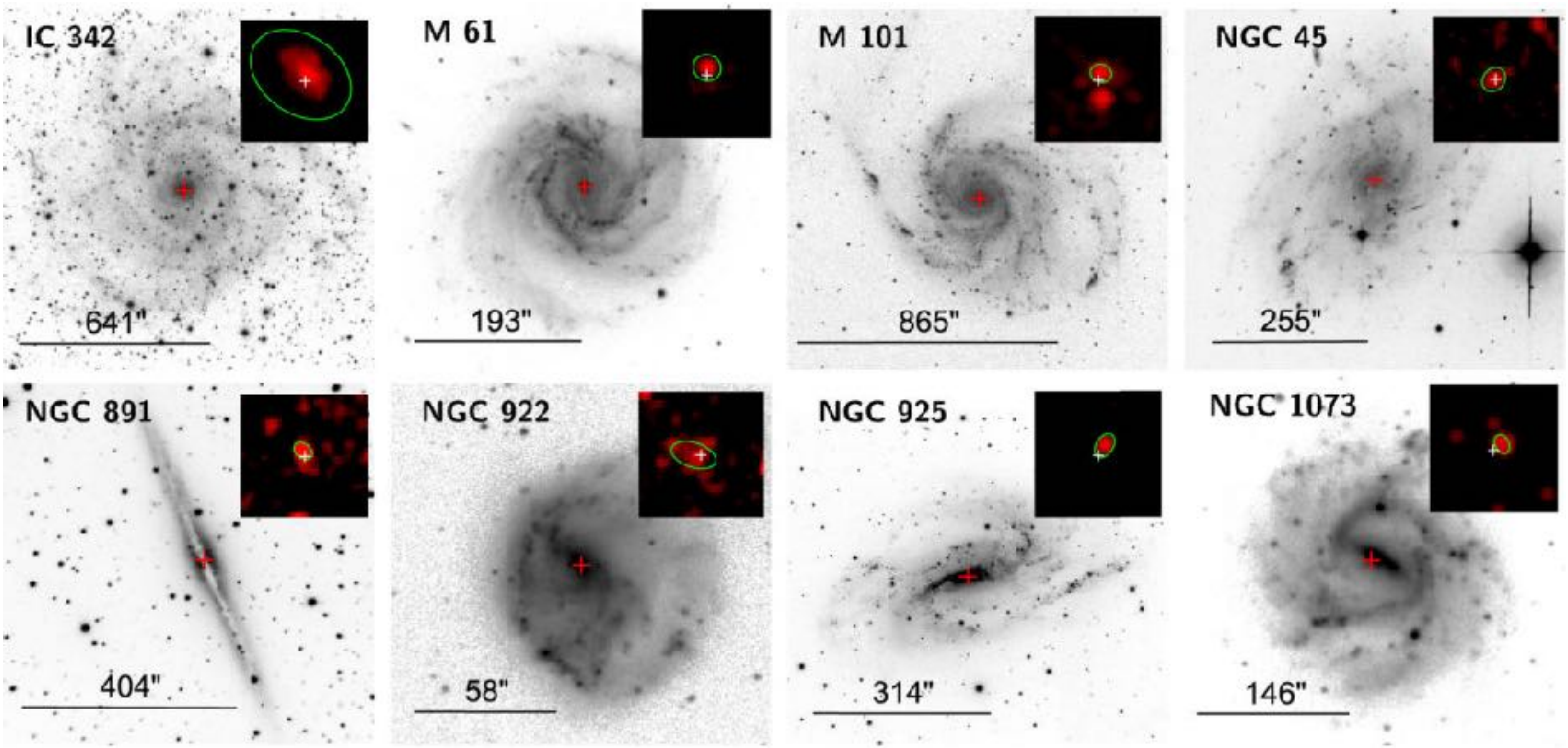
They're (maybe) overmassive compared to their host galaxy!

Higher merger rate for LISA?

Harikane+23b, Kocevski+23, Ubler+23, Larson+23, Maiolino+23ab, Matthee+23, Labbe+23, Kokrev+23,24,Greene+23

LISA massive black holes live in variety of hosts

$10^6\ M_\odot$ MBHs live in disky galaxies



She et al 2017 — 21% of disky galaxies host MBHs like these.

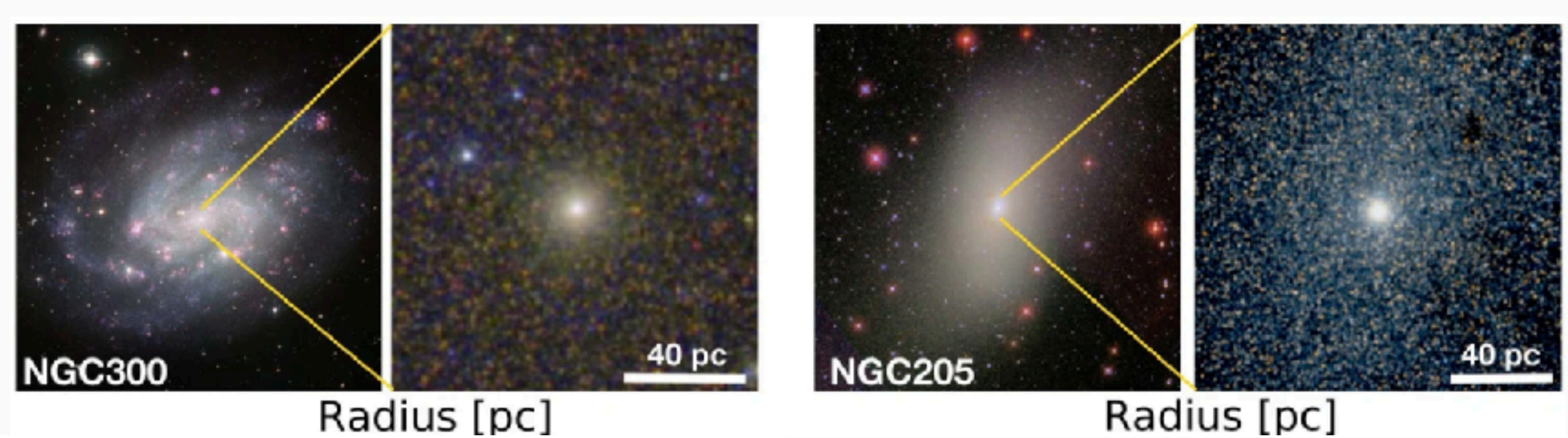
…and in low surface brightness galaxies, like Malin 1…

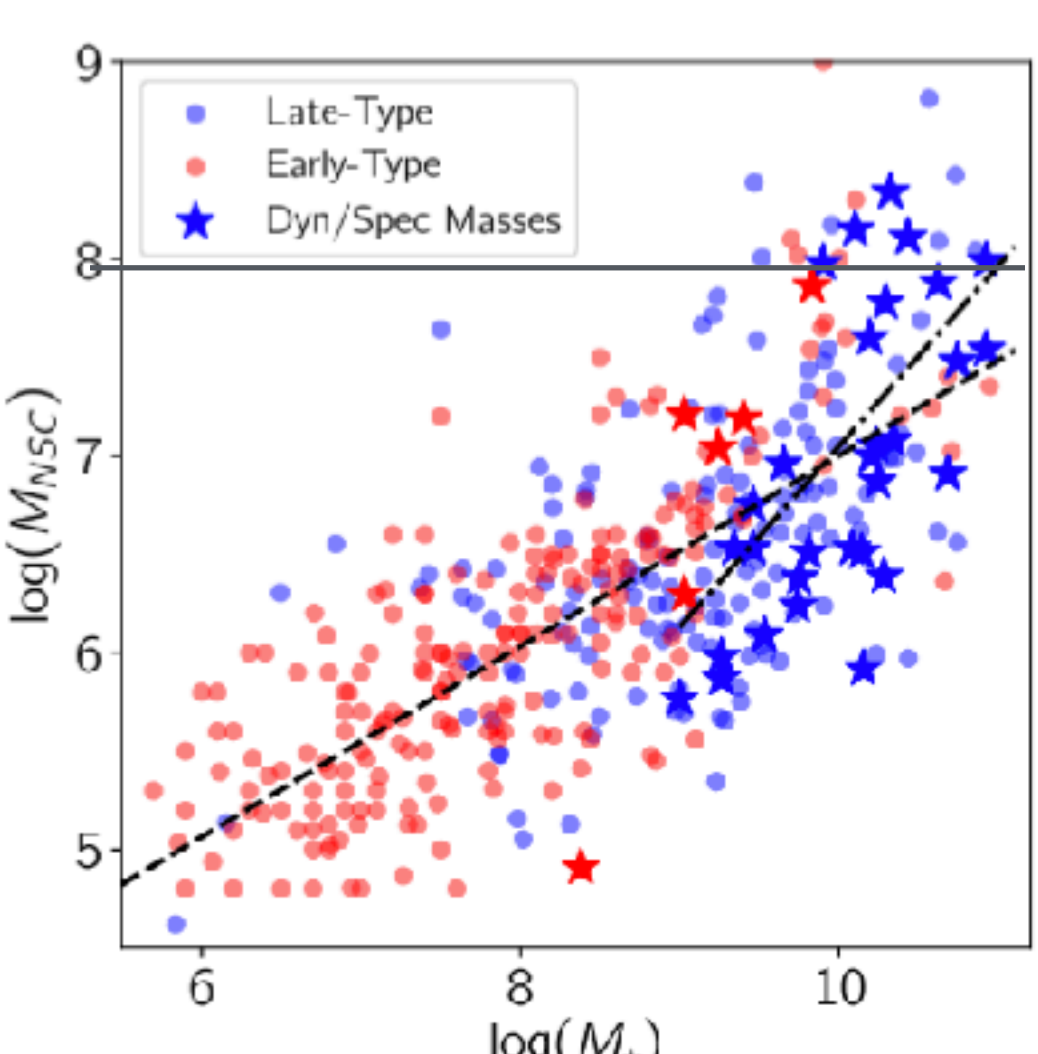
Warning: viral masses – assume line width maps to velocity for Keplerian motion

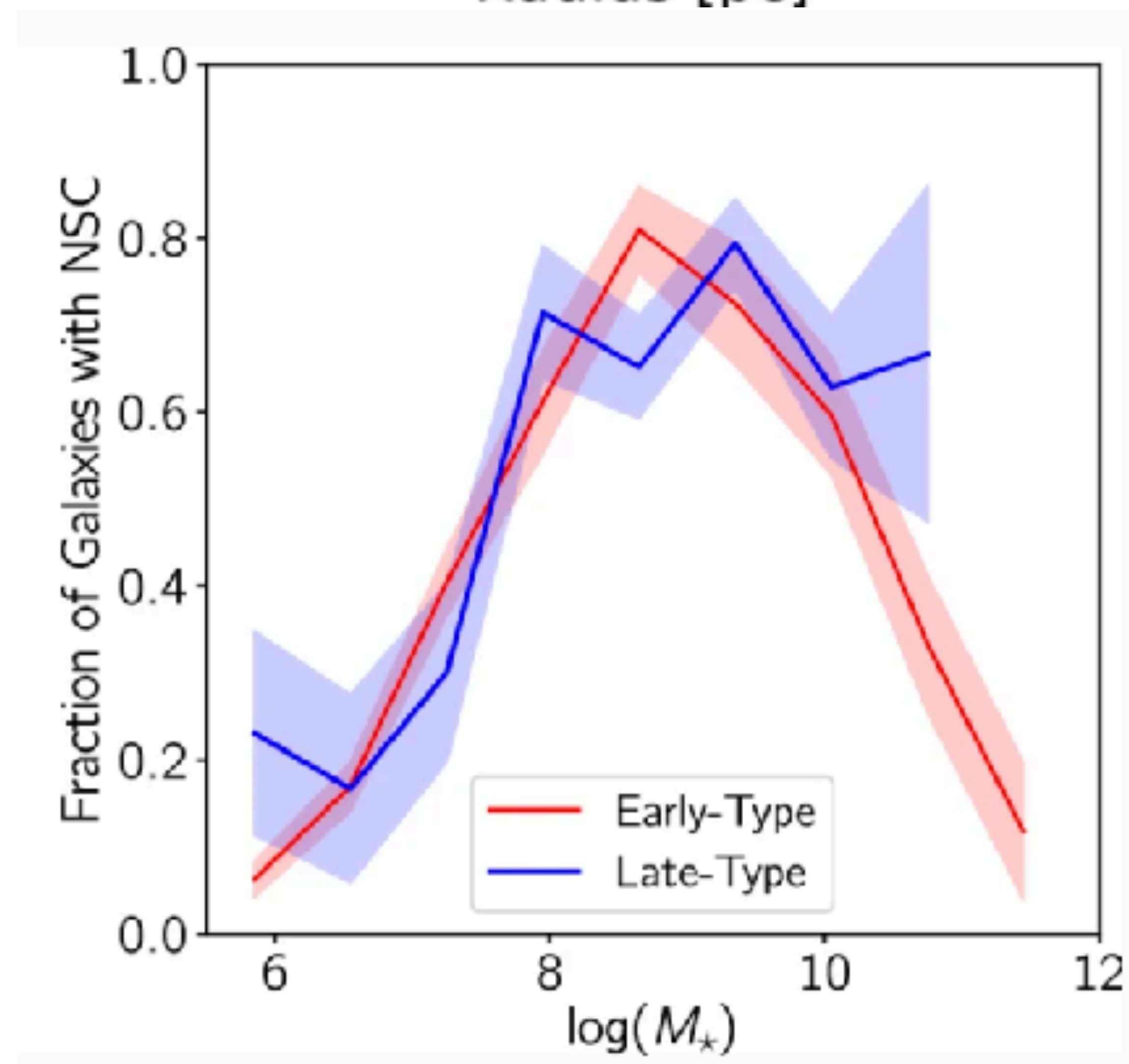
Subramanian et al. 2015

...and in nuclear star clusters...

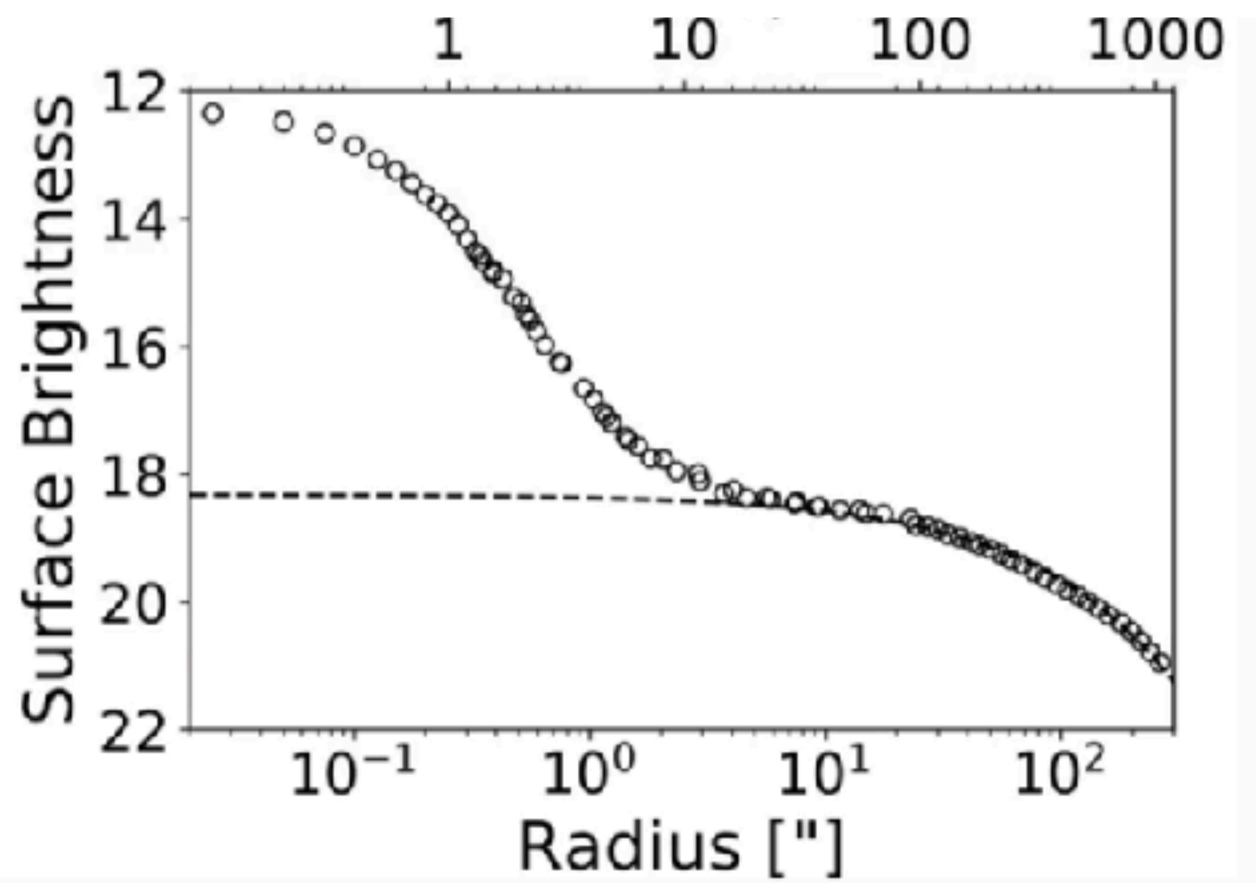
Neumayer et al. 2020



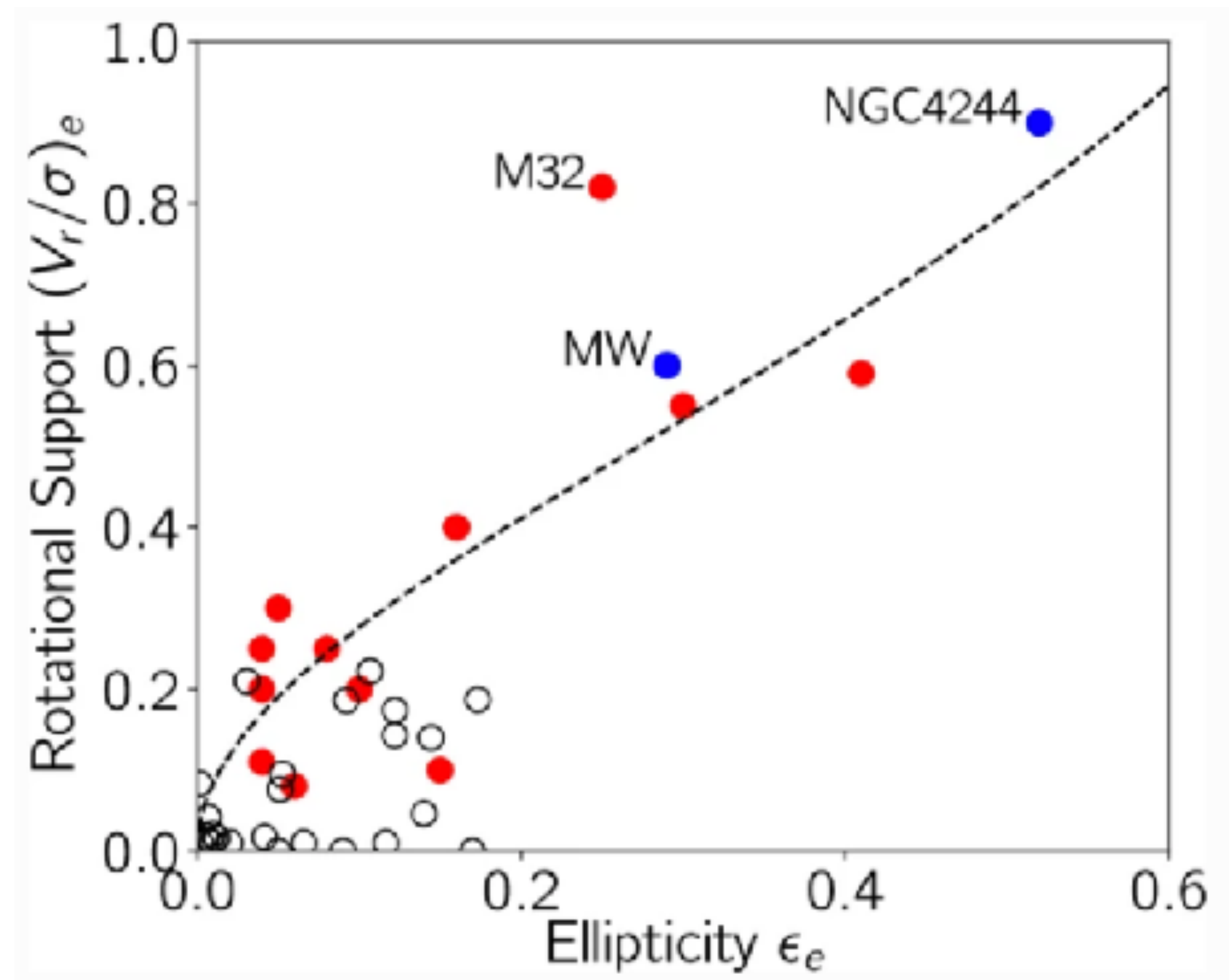




Nuclear star clusters are incredibly dense



They're typically flattened and co- or counter- rotate with the galaxy

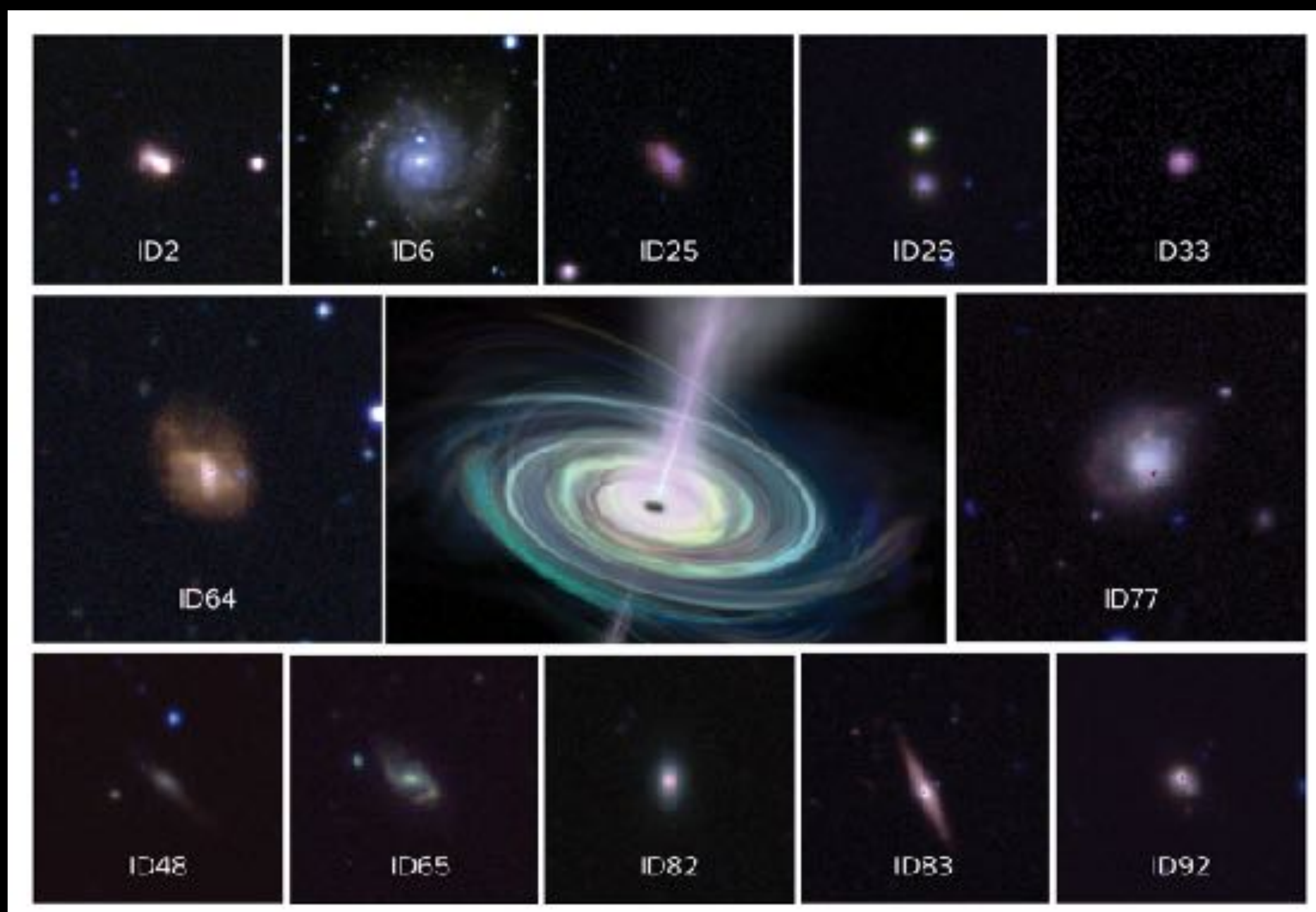


Neumayer et al. 2020

...and in dwarf galaxies...

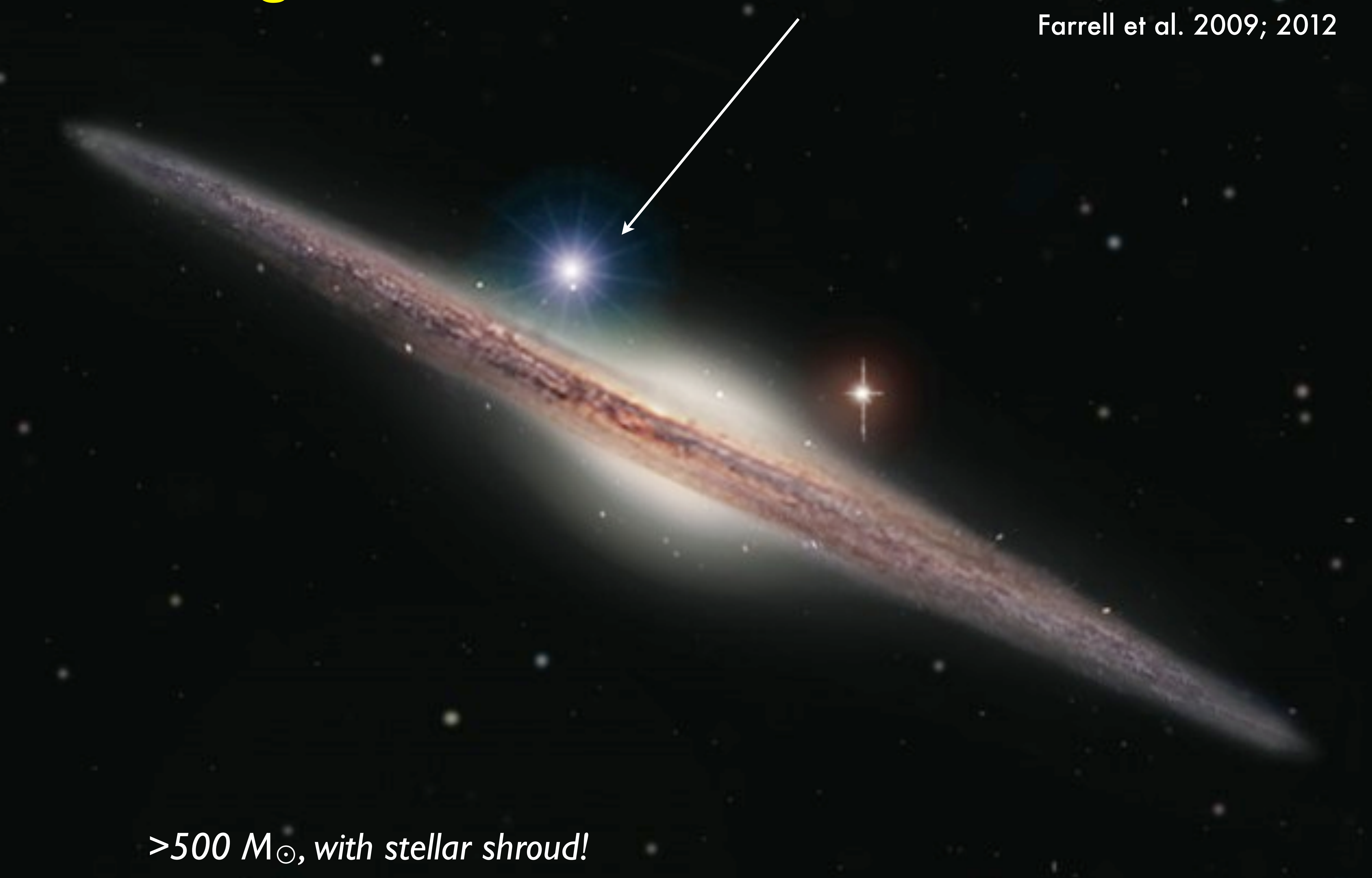

Reines et al. 2011


Bustamante-Rosell et al. 2021

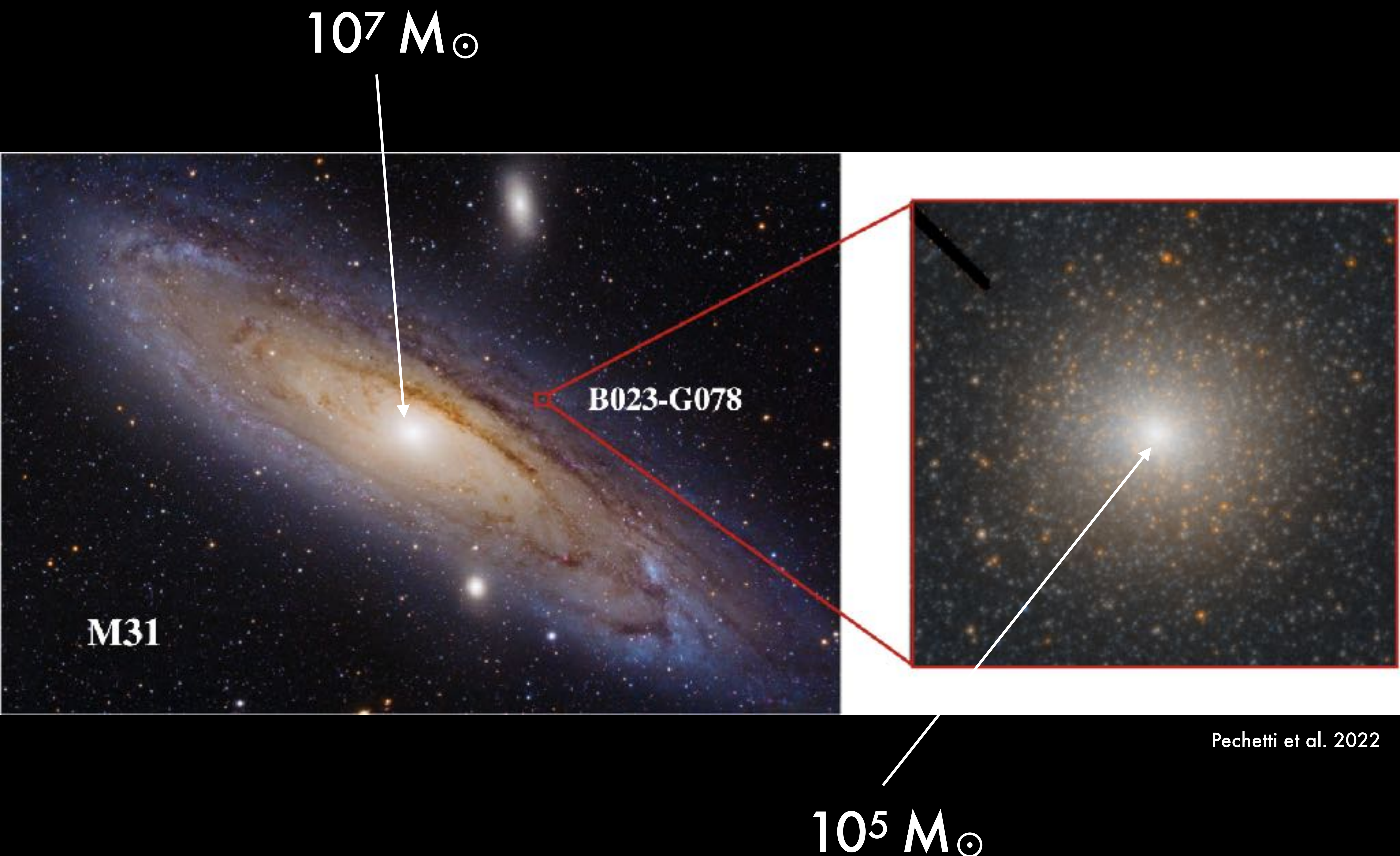


Intermediate mass black holes can live in dwarf galaxies, too

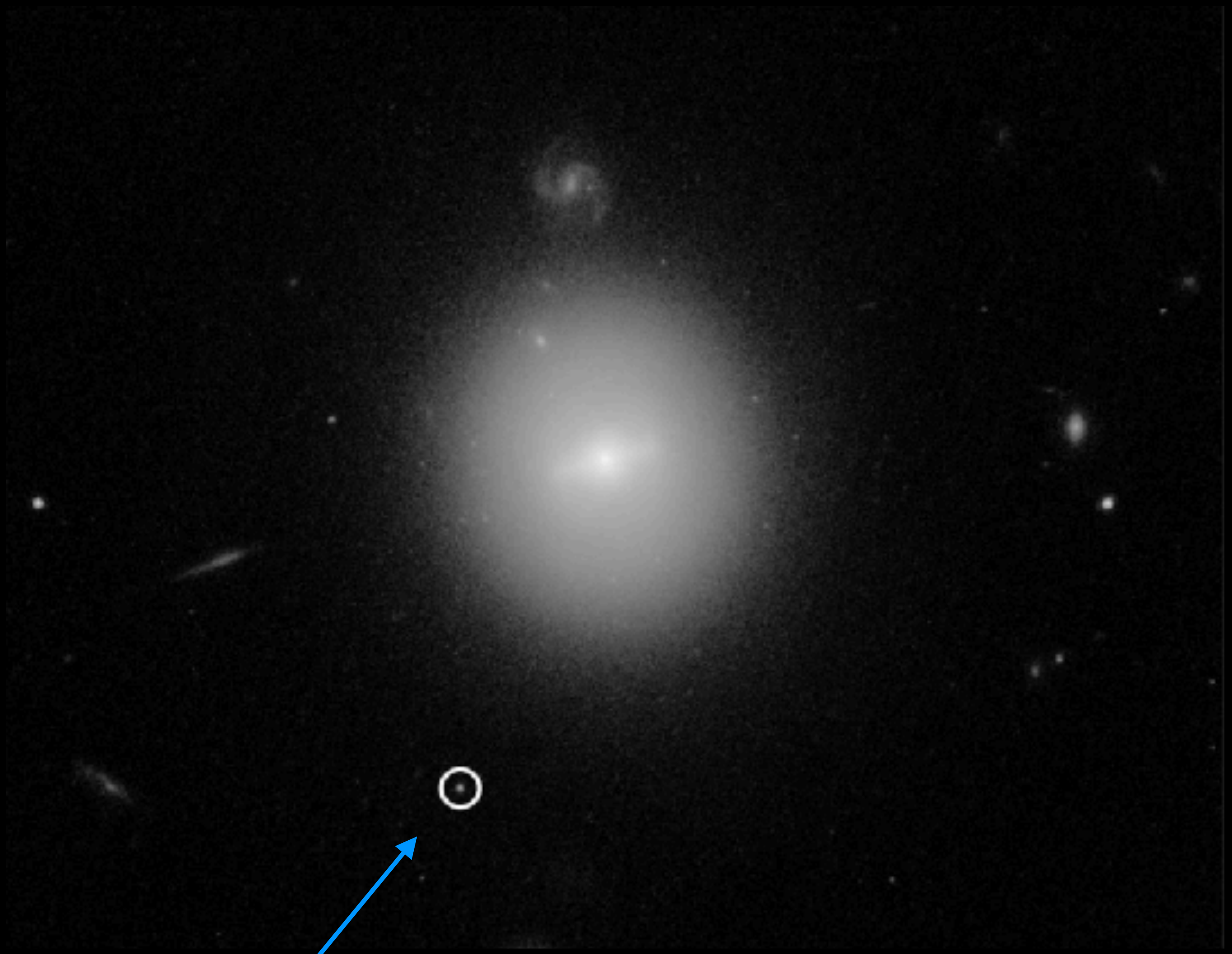
Farrell et al. 2009; 2012



>500 $M_\odot$, with stellar shroud!



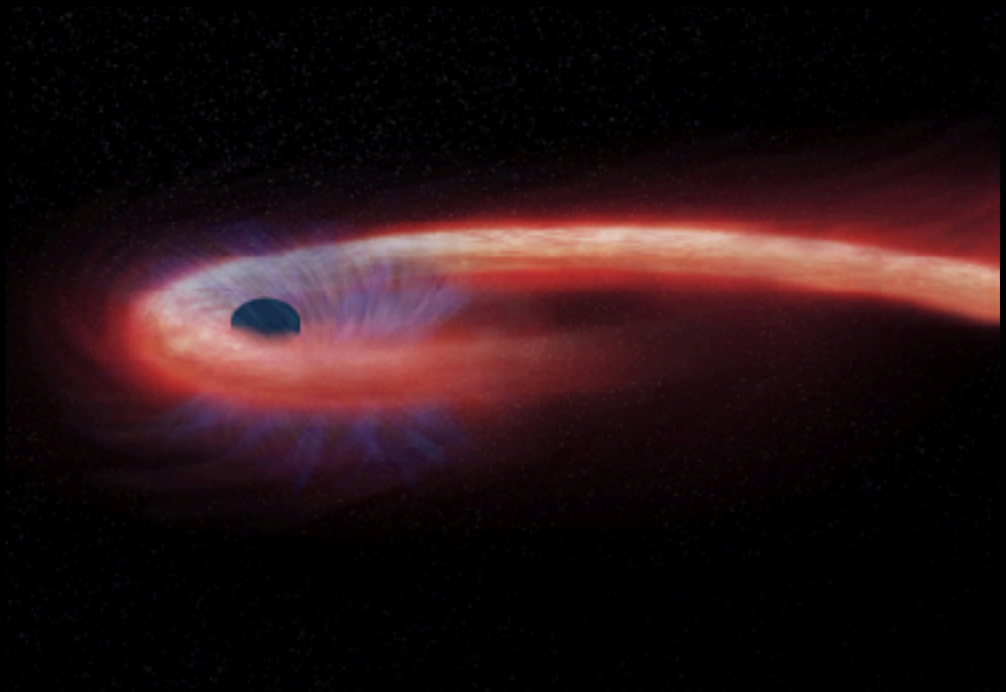
Pechetti et al. 2022



Wen et al. 2021

$10^4\ M_\odot$

(TDE) 3XMM J215022.4−055108

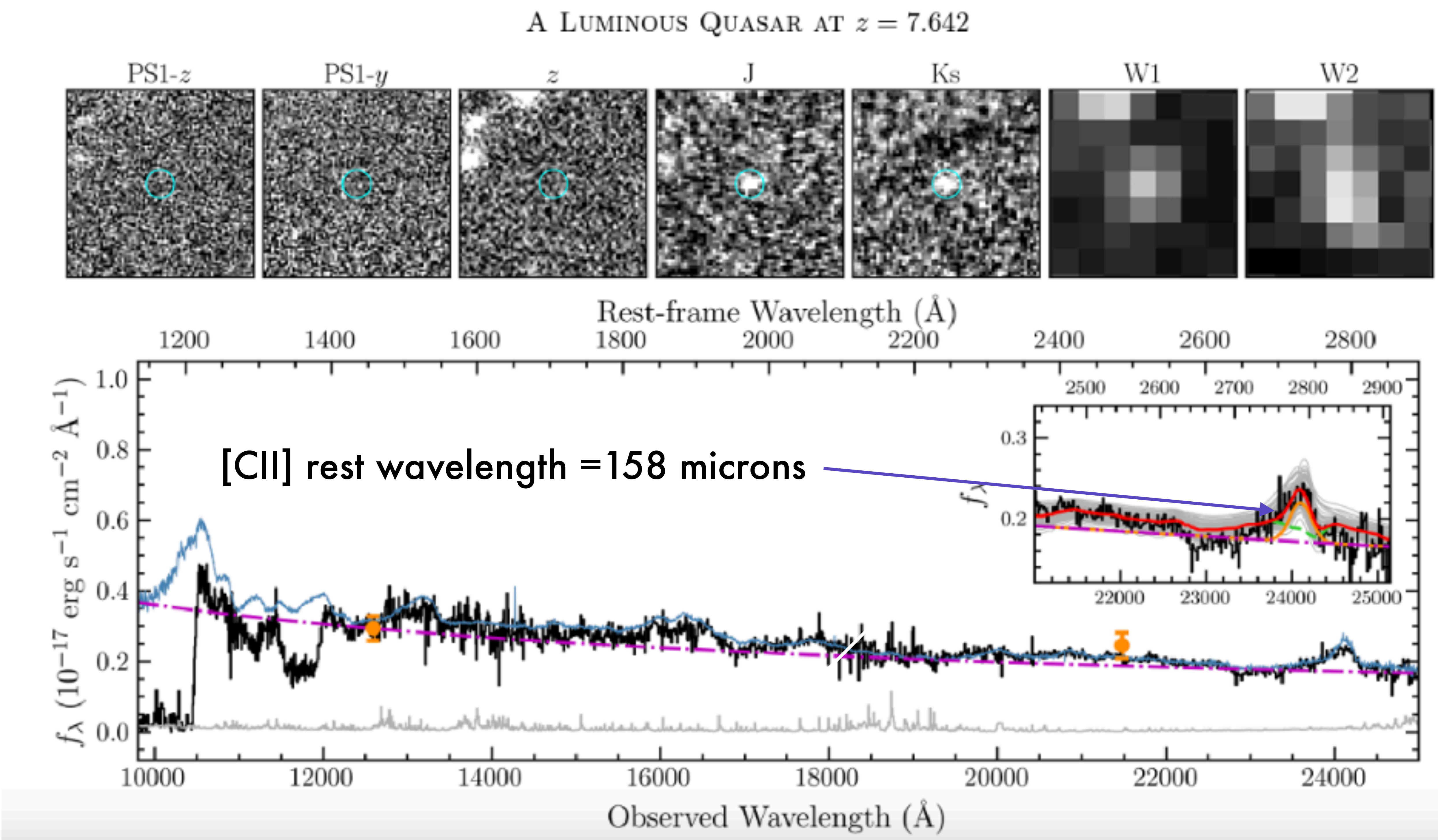


What We Hope to Learn With lisa

10^3-10^7 $M_\odot$ Black Hole Mergers — a new regime!

BH seeds at high redshifts, IMBHs in dwarf galaxies, Milky Way mass black holes

Complement Multimessenger and Multiband data to trace black hole formation, evolution, and connection to host galaxies



Wang et al 2021

Black Hole Mass $1.6 \pm 0.3 \times 10^9\, M_\odot$

Age of the Universe $670\,\mathrm{Myr}$

Growing black holes through gas

$$L_{\rm edd} = \frac{4\pi G M_\bullet c\, m_{\rm p^+}}{\sigma_{\rm T}}$$

Eddington Luminosity = Maximum* energy output of a BH

$$L = \epsilon \dot{M} c^2$$

Infalling matter can generate energy

$$\epsilon \dot{M} c^2 = \frac{4\pi G M_\bullet c\, m_{\rm p^+}}{\sigma_{\rm T}}$$

Equating the two yield maximum* growth rate of a BH

$$M_{\rm Final} = M_{\rm init} e^{t/\tau}$$

$$\boxed{\tau = 45 \times 10^6\, \epsilon_{0.1} \quad \text{years}}$$

Salpeter time – how long it takes an Eddington-limited BH to grow by a factor of e

$\epsilon = 0.08$ Thin disk infall at infinity

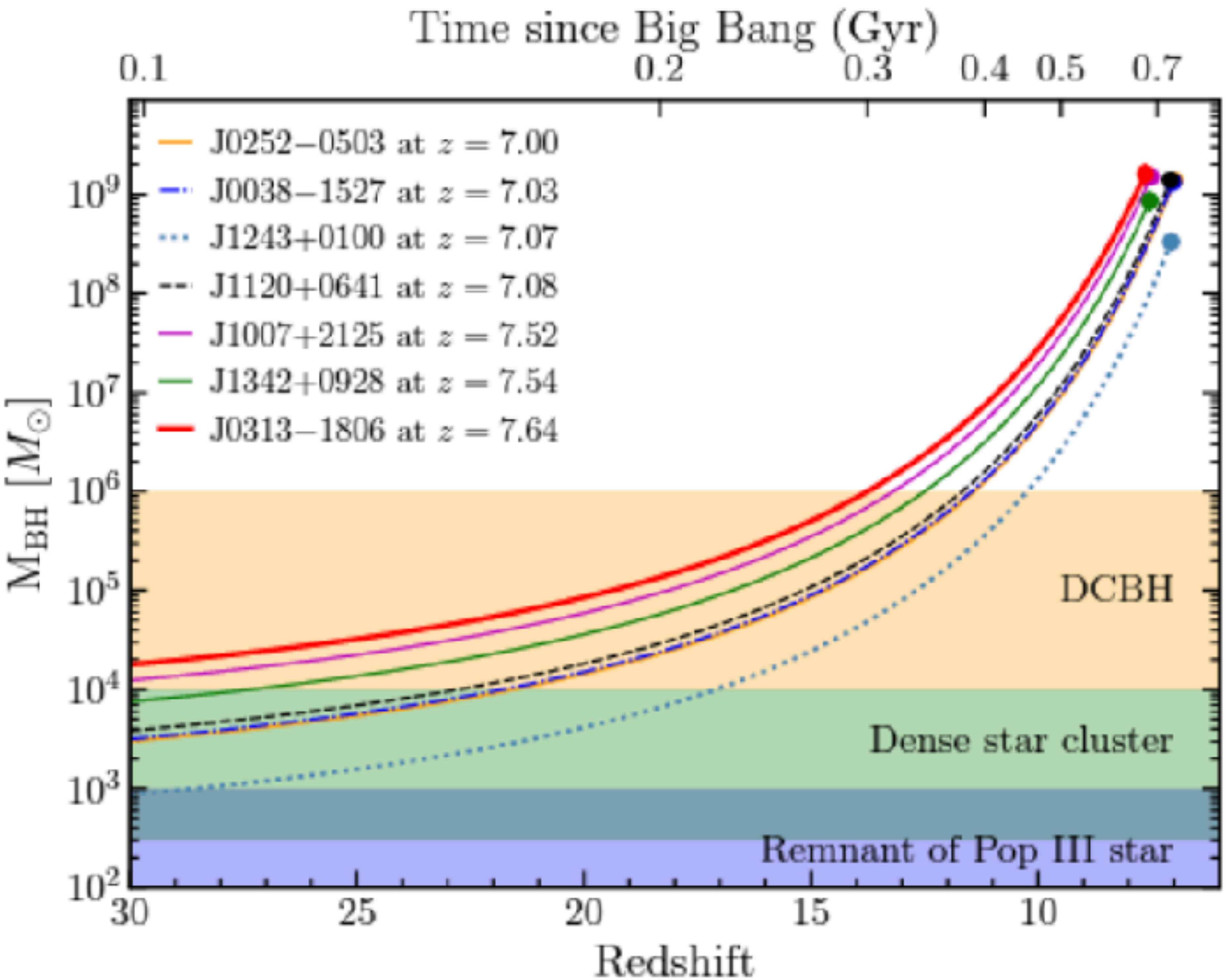
$\epsilon = 0.42$ Infall into Kerr at ISCO

$\epsilon = 0.1$ Because

Frivolous Prize Challenge!

If you start from a LIGO black hole, can you grow this billion solar mass black hole in 700 Myr?

There's barely enough time to grow this SMBH



Pssst….

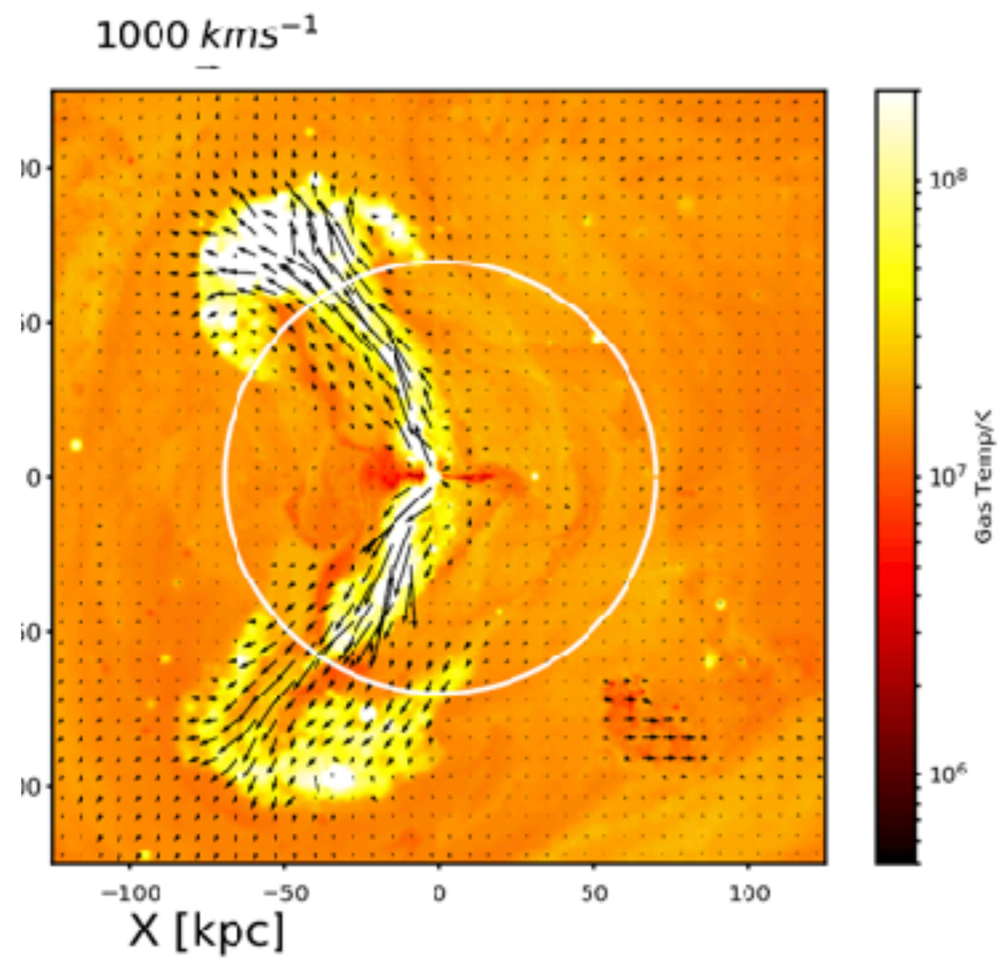
assuming only L_{edd}, growth, eps=0.1, spherical symmetry, hydrogen, Thomson Scattering…

How are MBH important in the context of galactic/extragalactic astro?

Feedback from accreting MBHs have far-reaching effects!

Photons can heat the gas and make it expand
Quenches star formation via radiation pressure

'Thermal' feedback



Jets can push gas out
Shocks quenching/enhance star formation

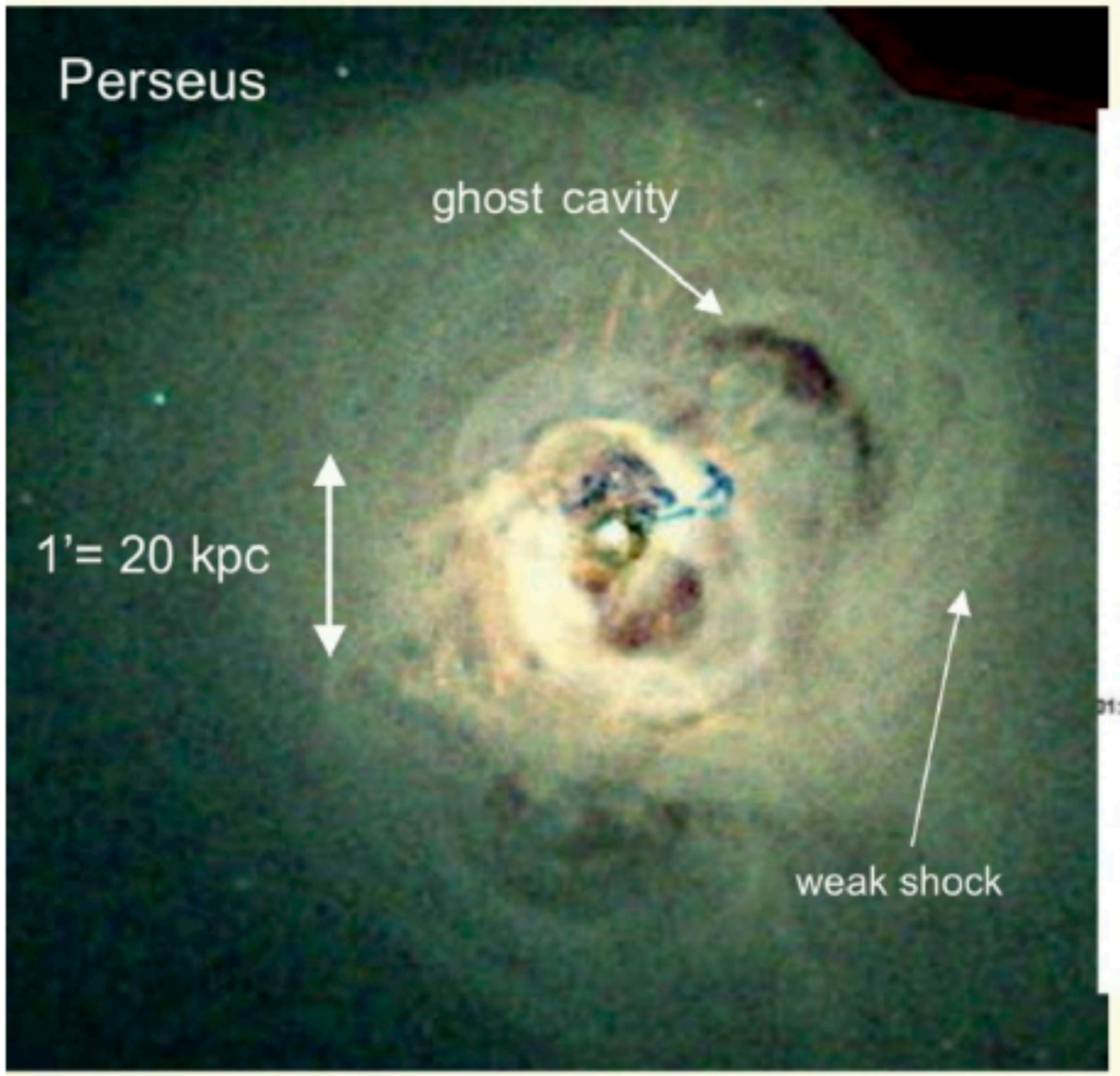
'Mechanical' feedback

Tremmel

Cavities in the IGM from radio plasma

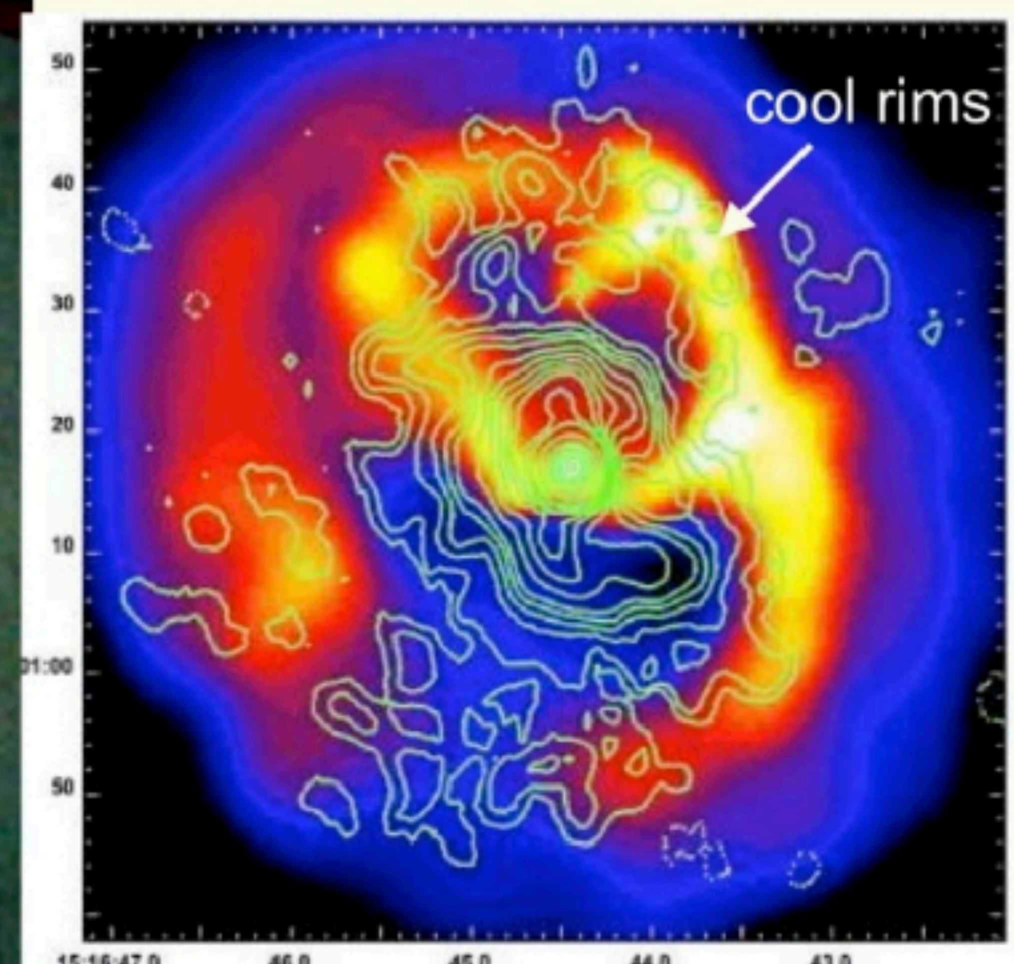
X-ray observations have revealed hot bubbles and cavities in the hot intracluster medium

$E \sim 10^{57\text{-}59}$ erg



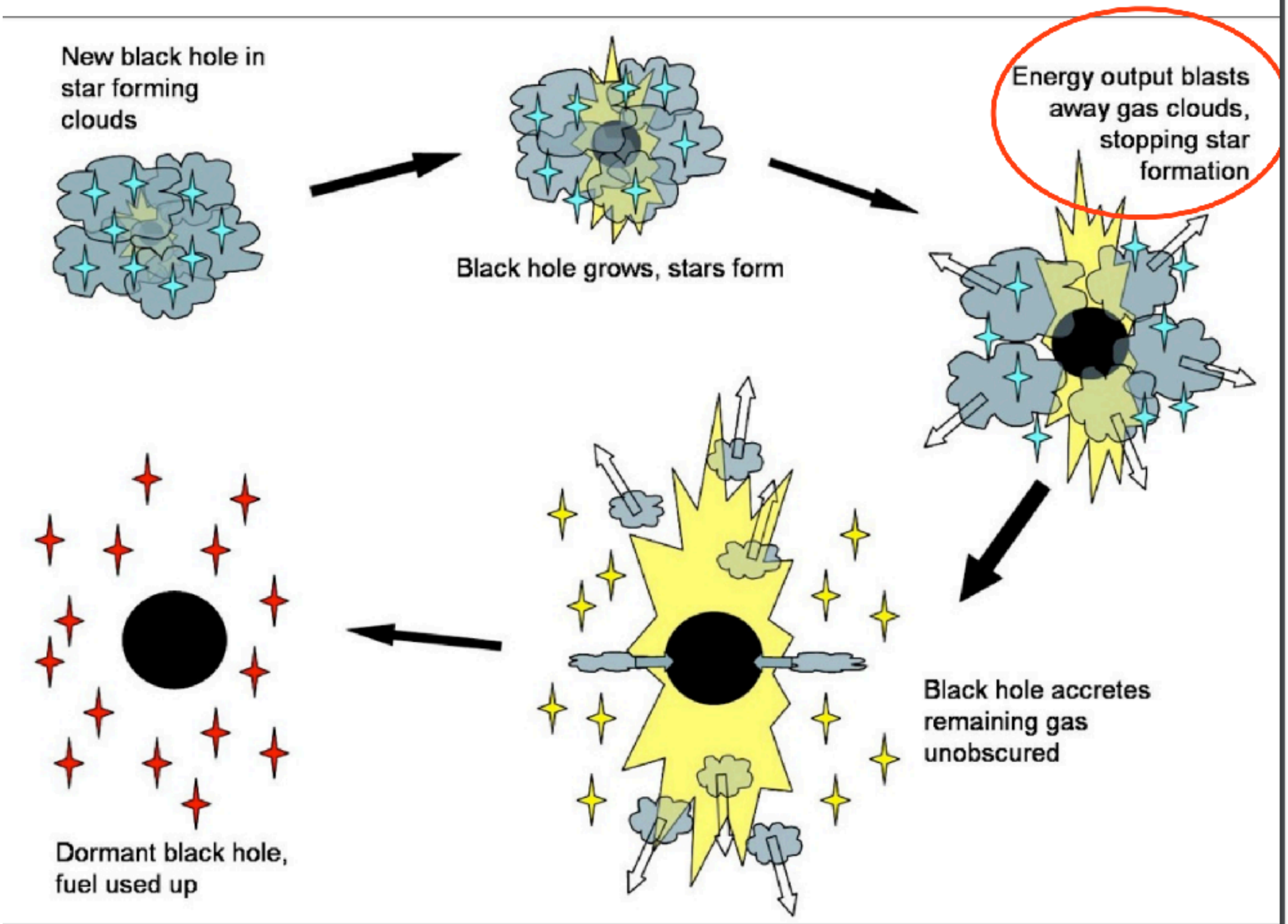
Fabian + 05

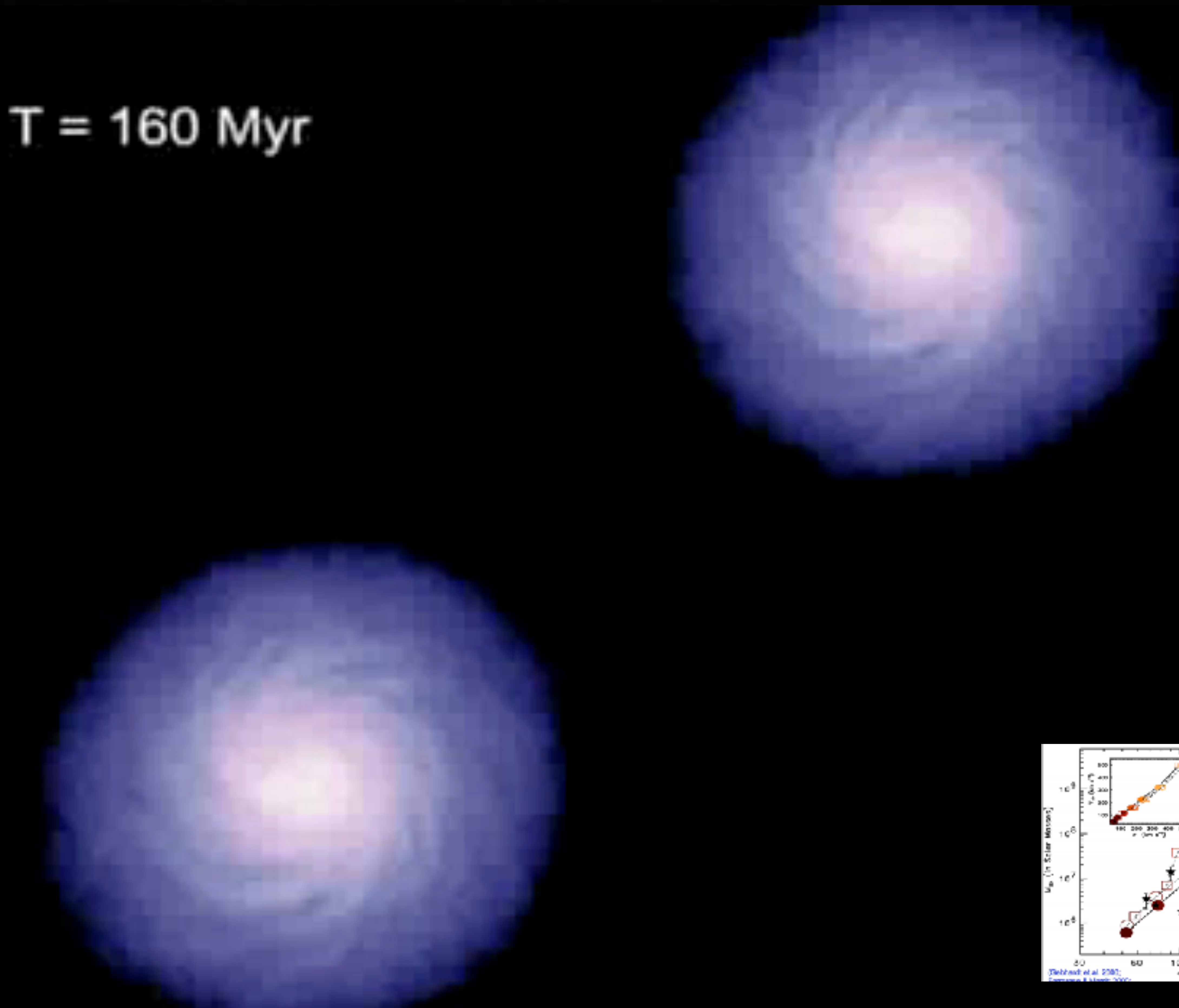
Abell 2052

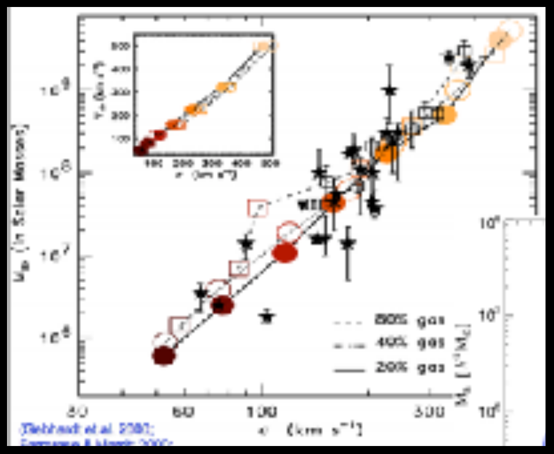


Blanton + 01

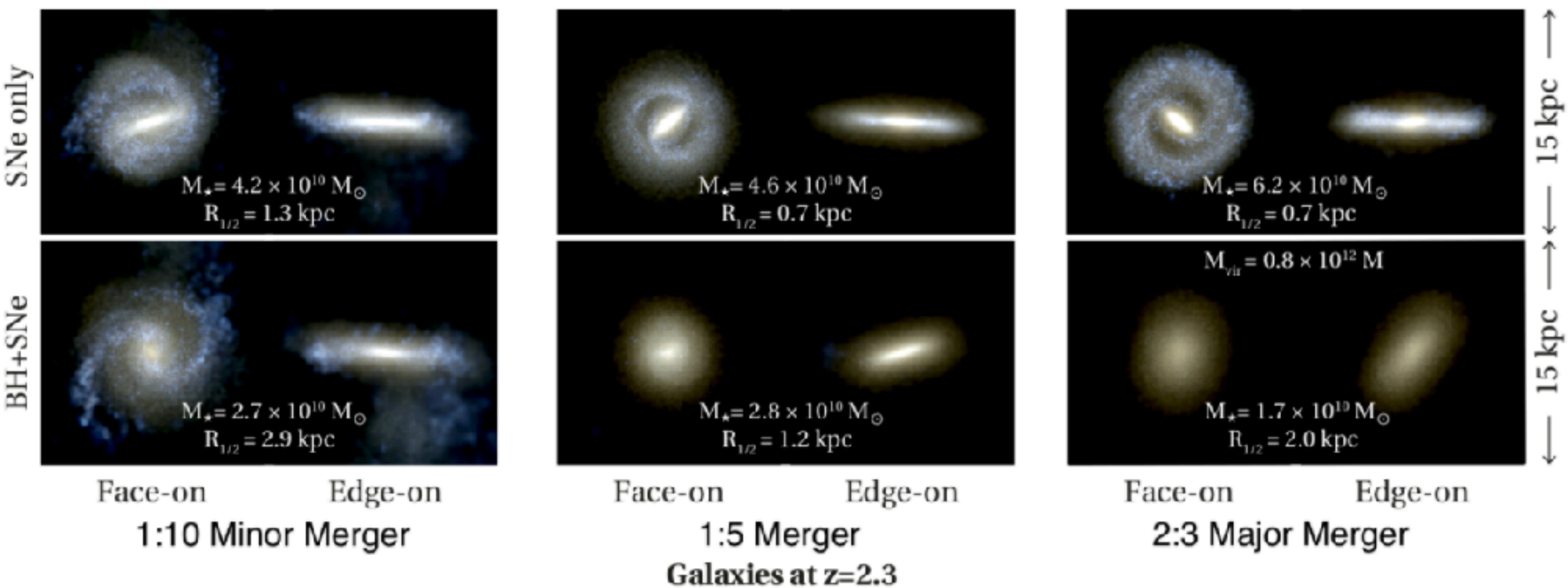

Outflows


New black hole in star forming clouds
Black hole grows, stars form
Energy output blasts away gas clouds, stopping star formation
Black hole accretes remaining gas unobscured
Dormant black hole, fuel used up

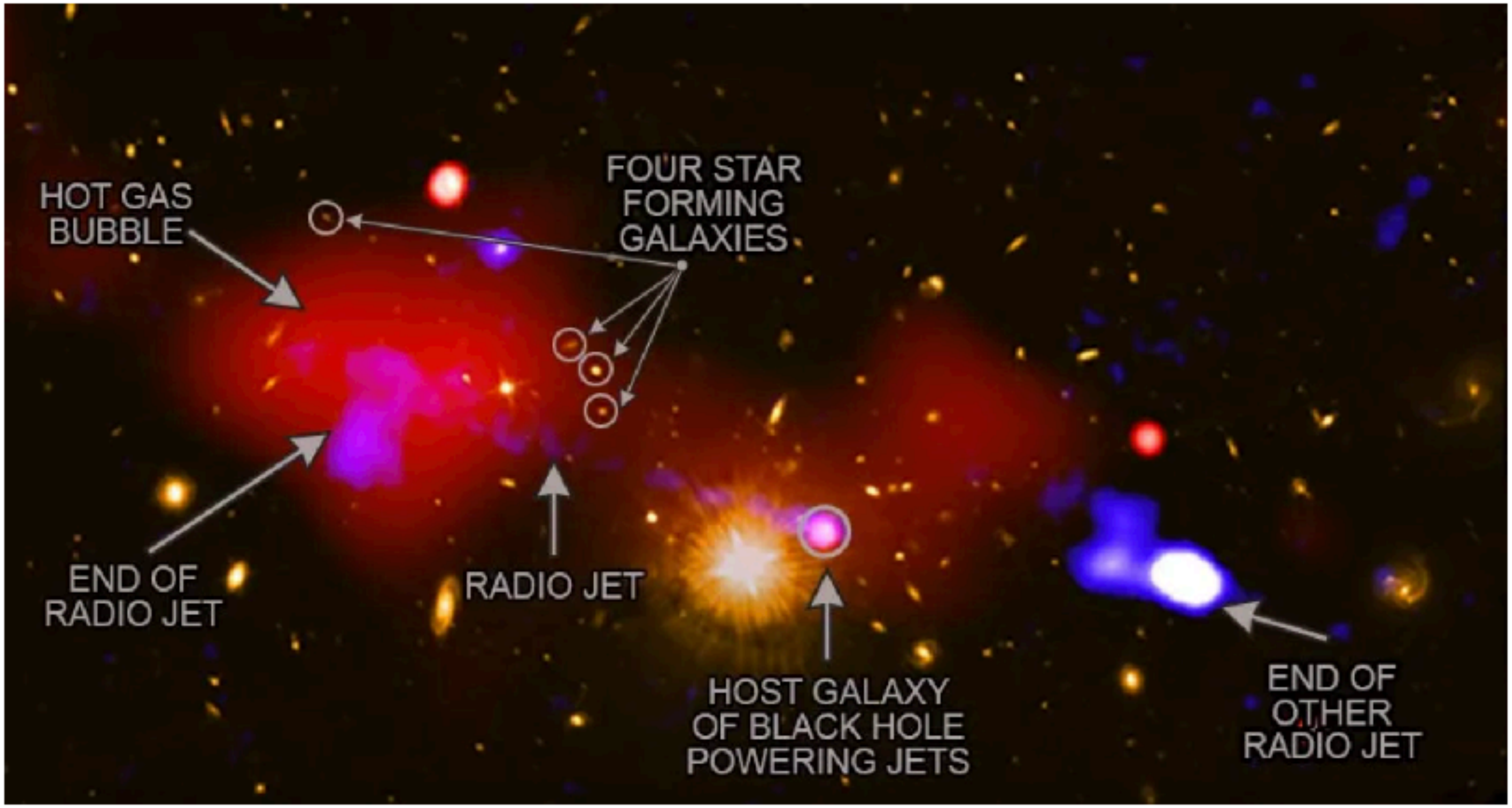

T = 160 Myr



Outflows can quench star formation – and make a red and dead elliptical galaxy



Tremmel

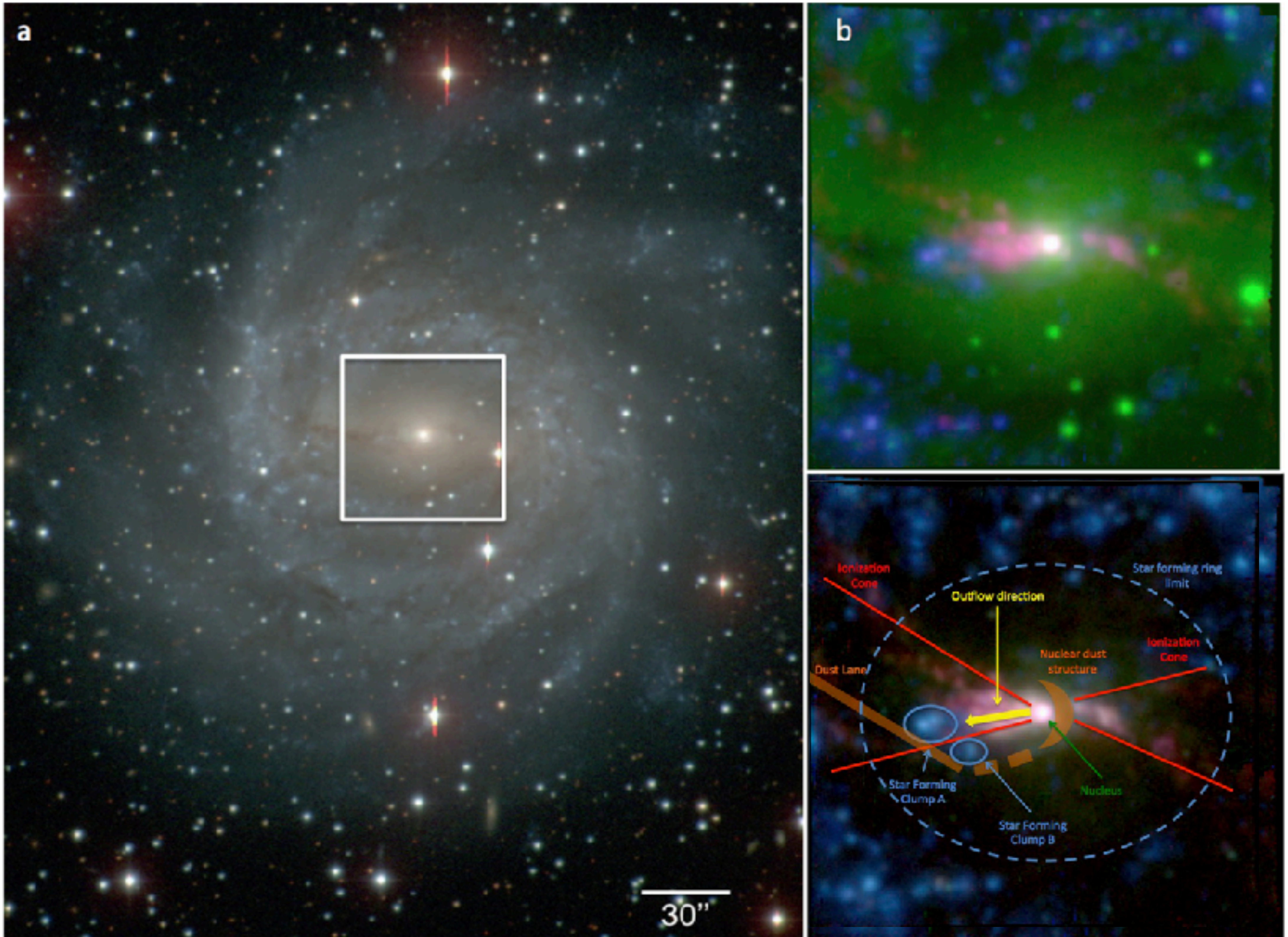


This image contains a black hole that is triggering star formation across the longest distance ever seen. As hot gas swirls around the black hole, it emits large amounts of X-rays that Chandra detects. The black hole is also the source of radio-wave emission from a jet of high-energy particles — previously detected by scientists with the VLA — that stretches about a million light years. Astronomers found that this black hole and jet are responsible for increasing the rates of star formation in newly-discovered nearby galaxies.
(Credit: X-ray: NASA/CXC/INAF/R. Gilli et al.; Radio NRAO/VLA; Optical: NASA/STScI)

Gilli et al. 2019

NGC 5643

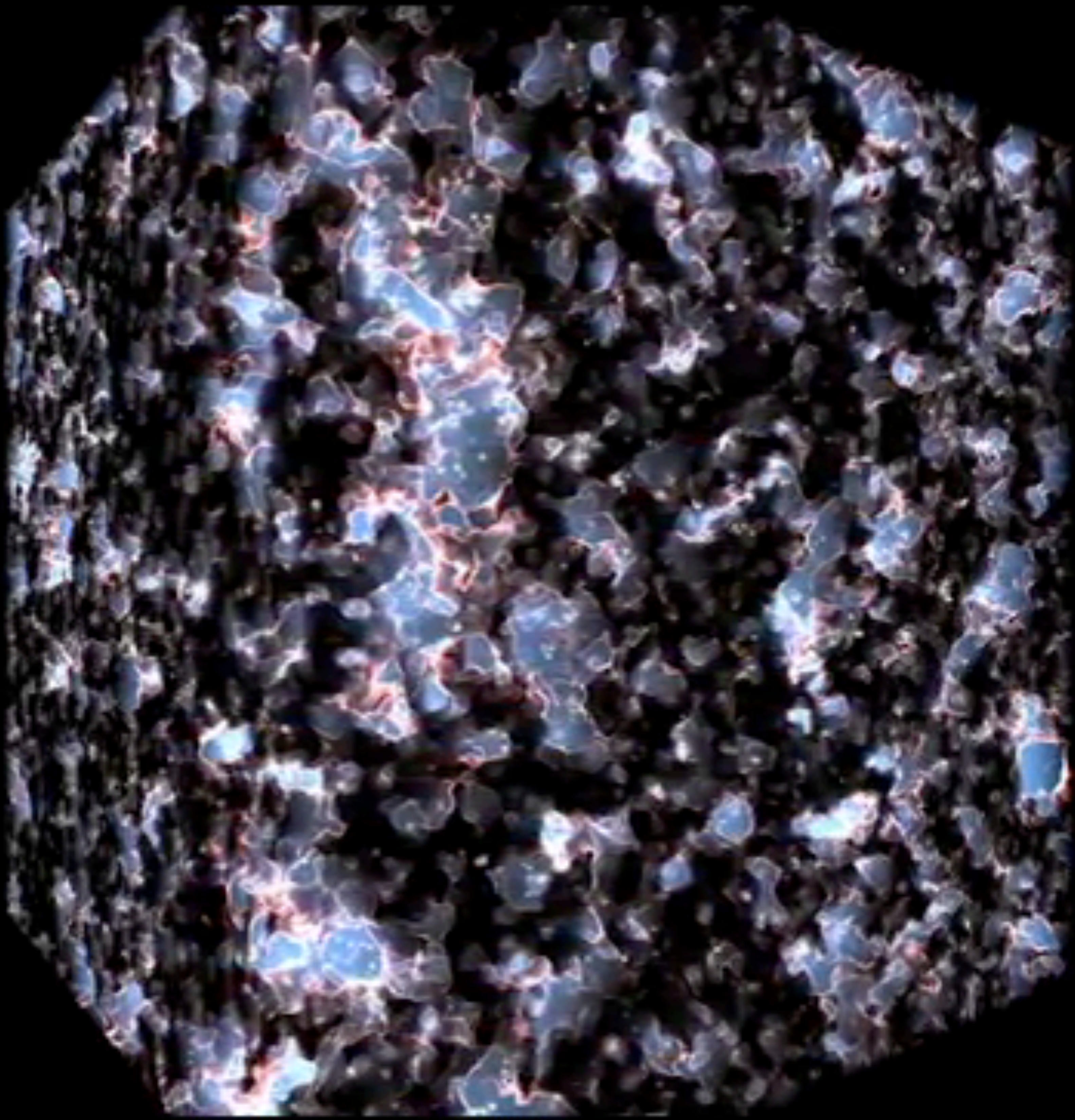
A&A 582, A63 (2015)



Cresci et al 2015

Shin et al 2019

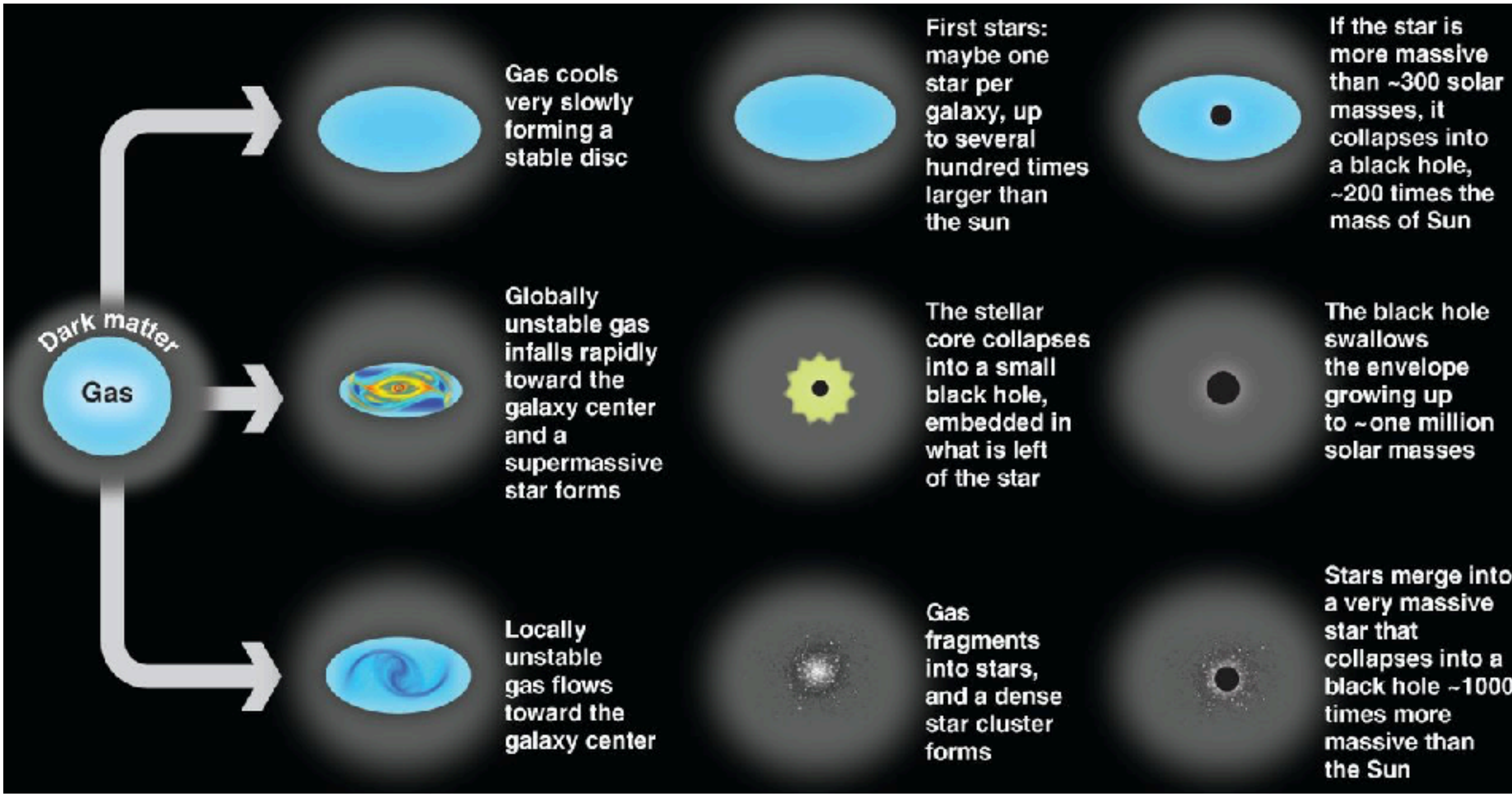
AGN help heat and reionize the universe!



Credits: Simulation: Marcelo Alvarez, Tom Abel; Visualization: Ralf Kaehler

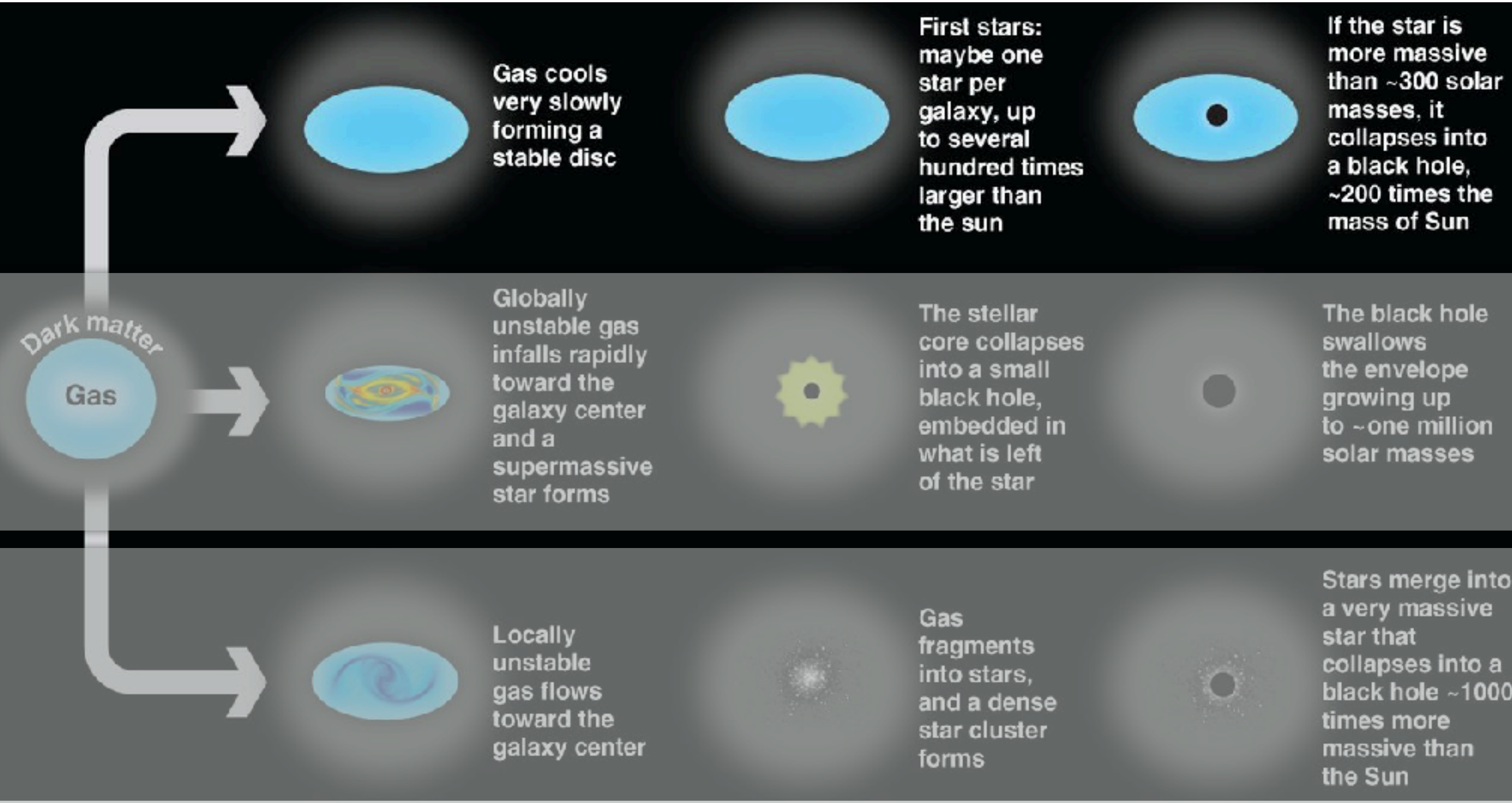
How are supermassive black holes born?

Forming a black hole: let me count (some of) the ways



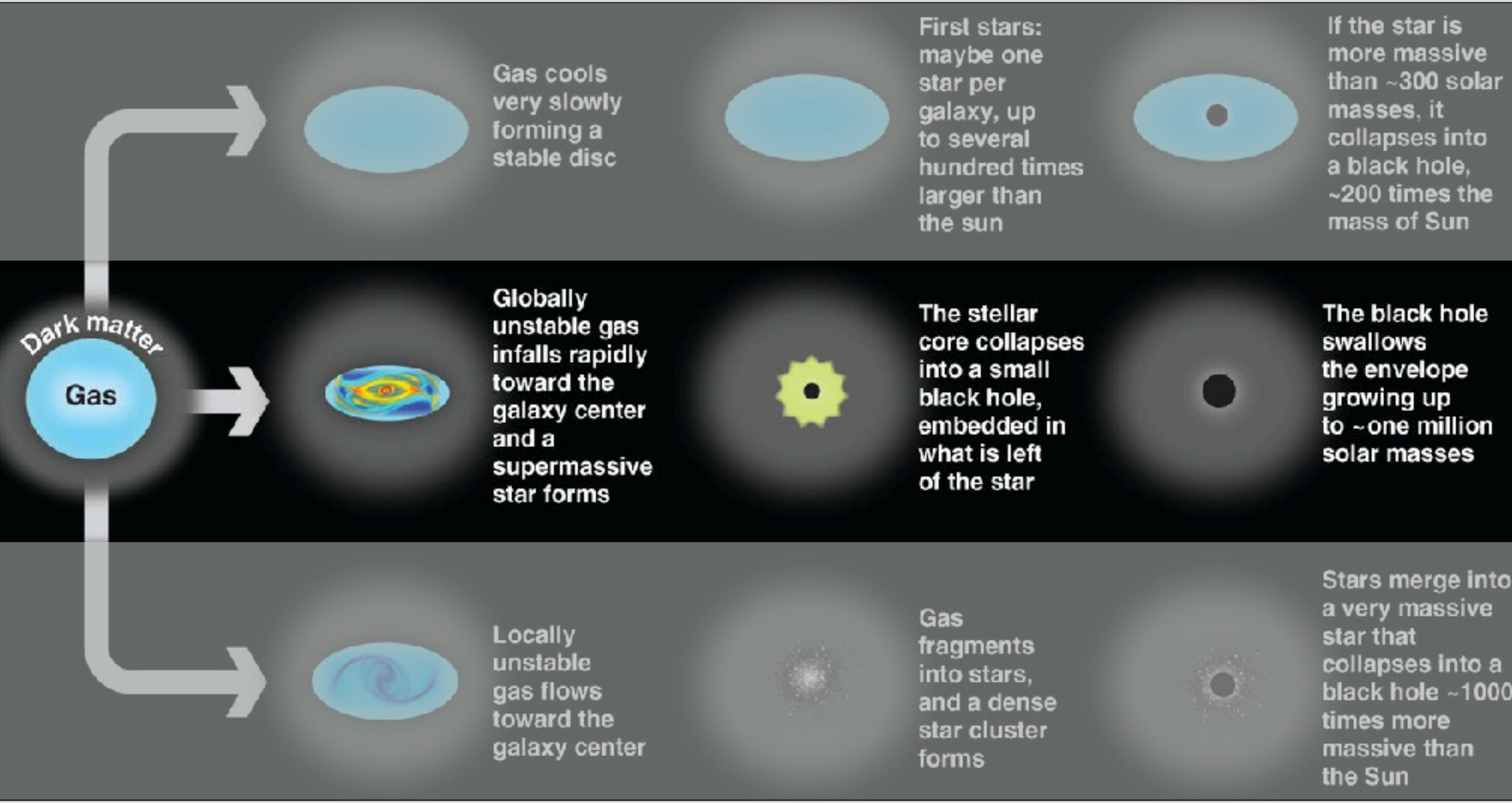
From excellent Volonteri review

One channel: Light seeds from the first generation of stars



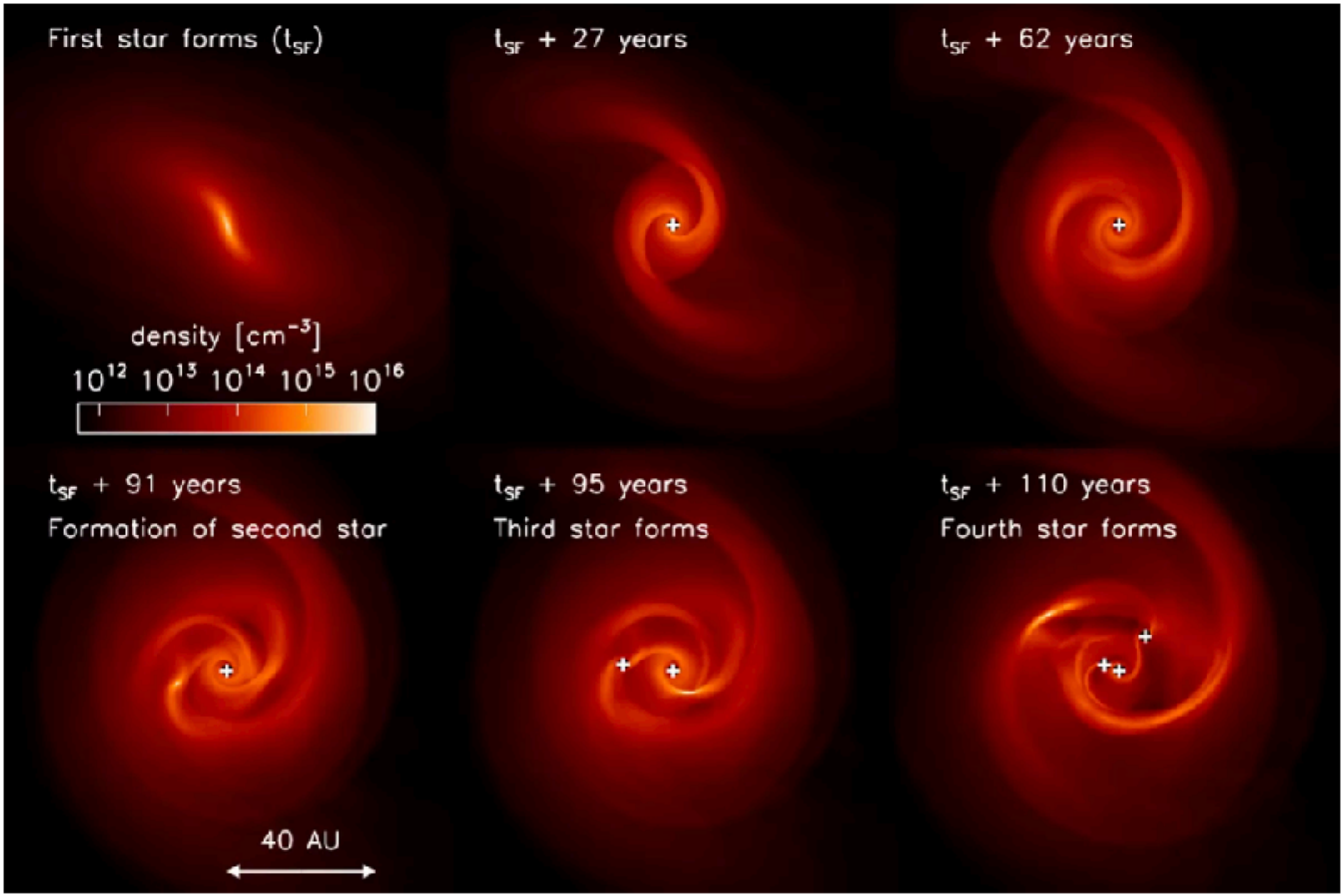
From excellent Volonteri review

One channel: Heavy seeds from directly collapsing black holes

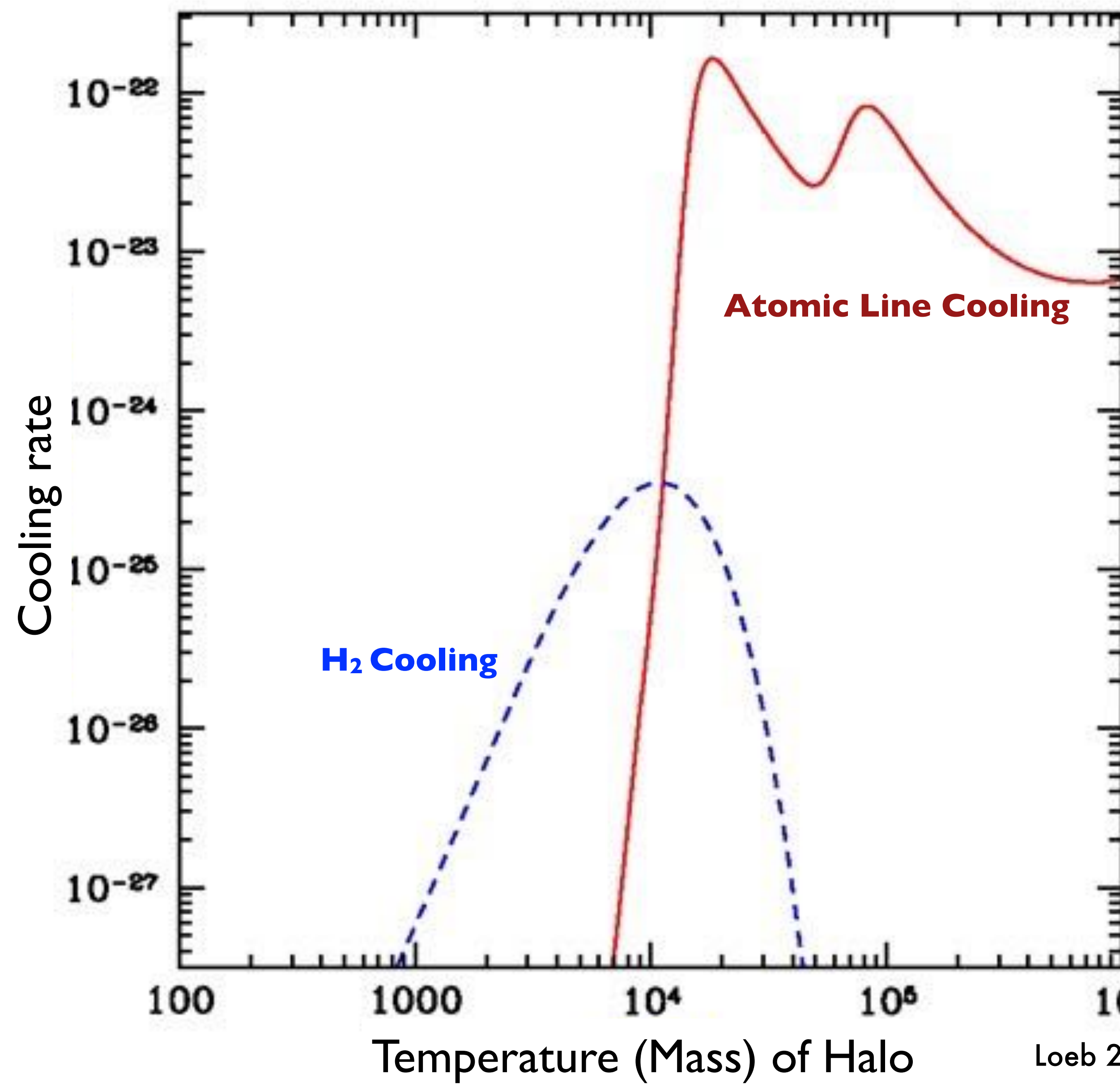


From excellent Volonteri review

If gas cools quickly during collapse, overdensities can fragment into stars

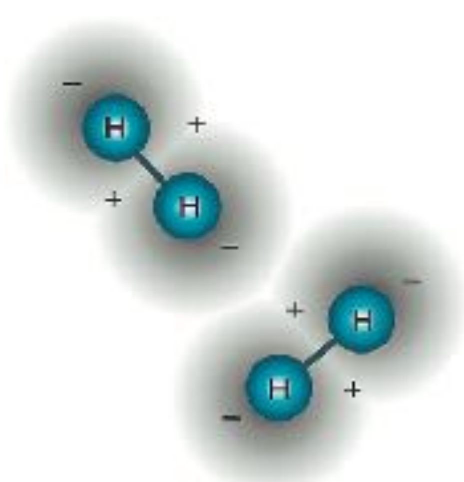


A problem:
To build a heavy BH seed, gas must battle fragmentation

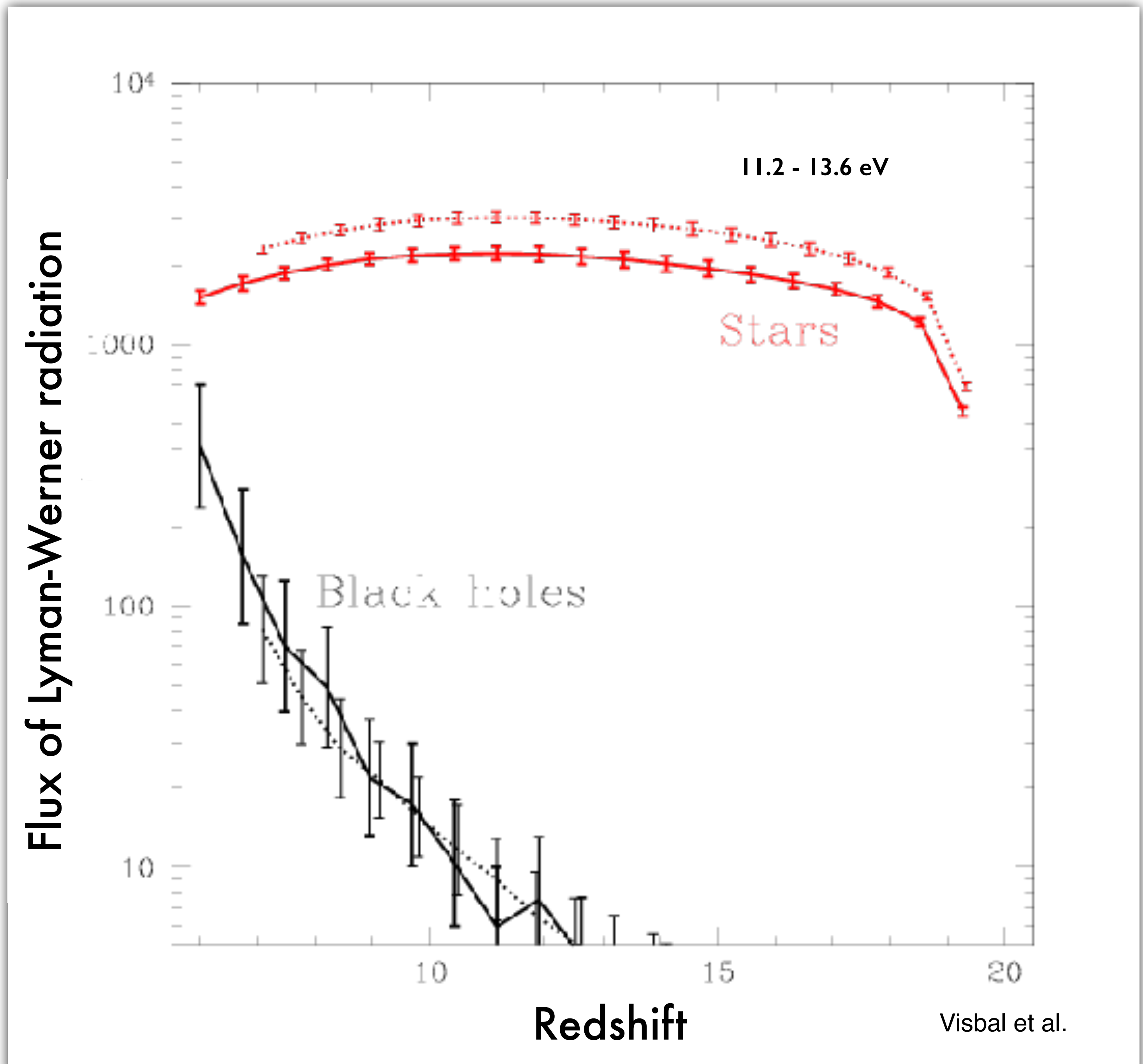


Loeb 2006

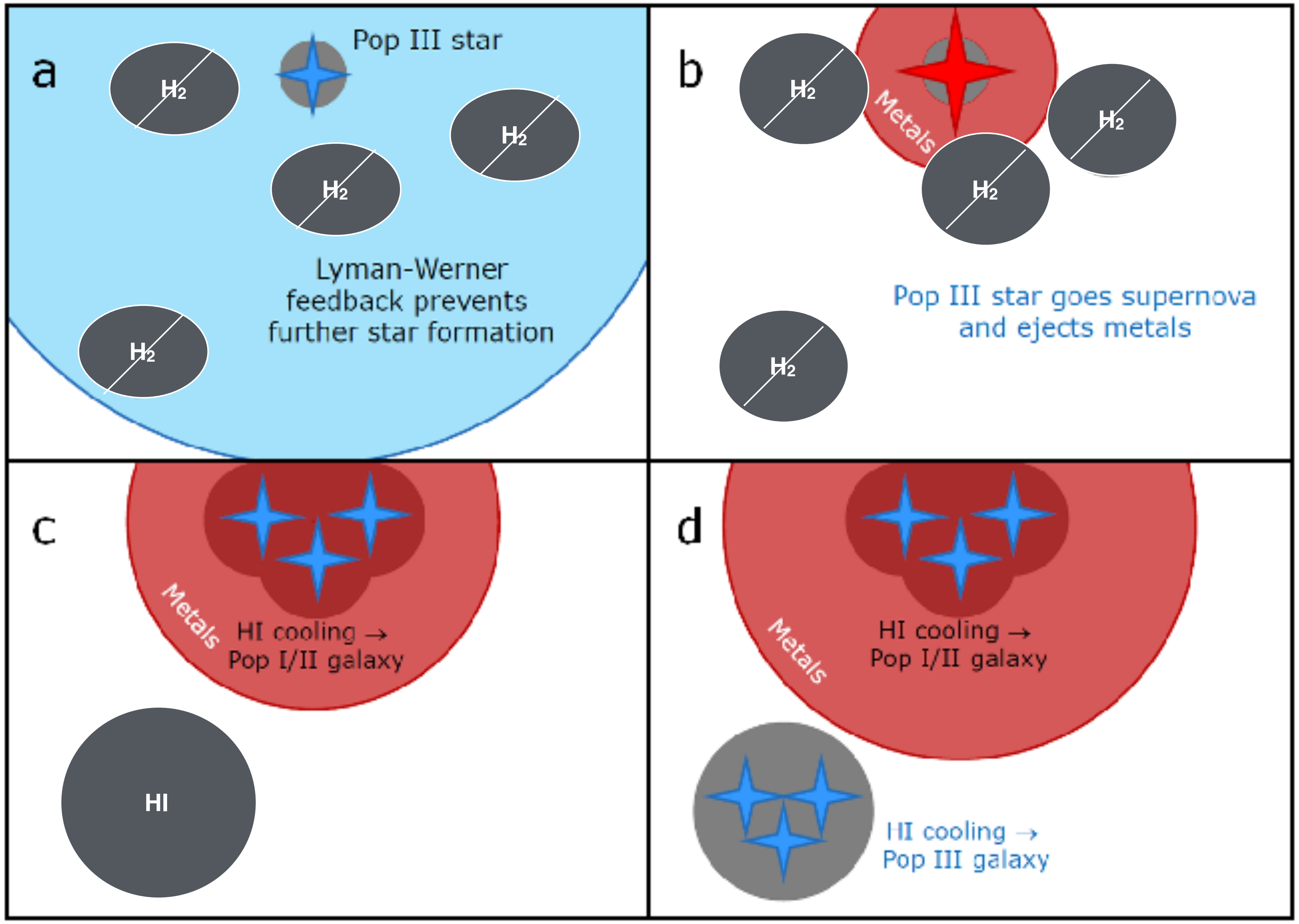
Once halo is polluted with metals, they *really* dominate cooling!



Lyman-Werner radiation from the first stars and black holes can dissociate H_2 – stops cooling in low mass halos

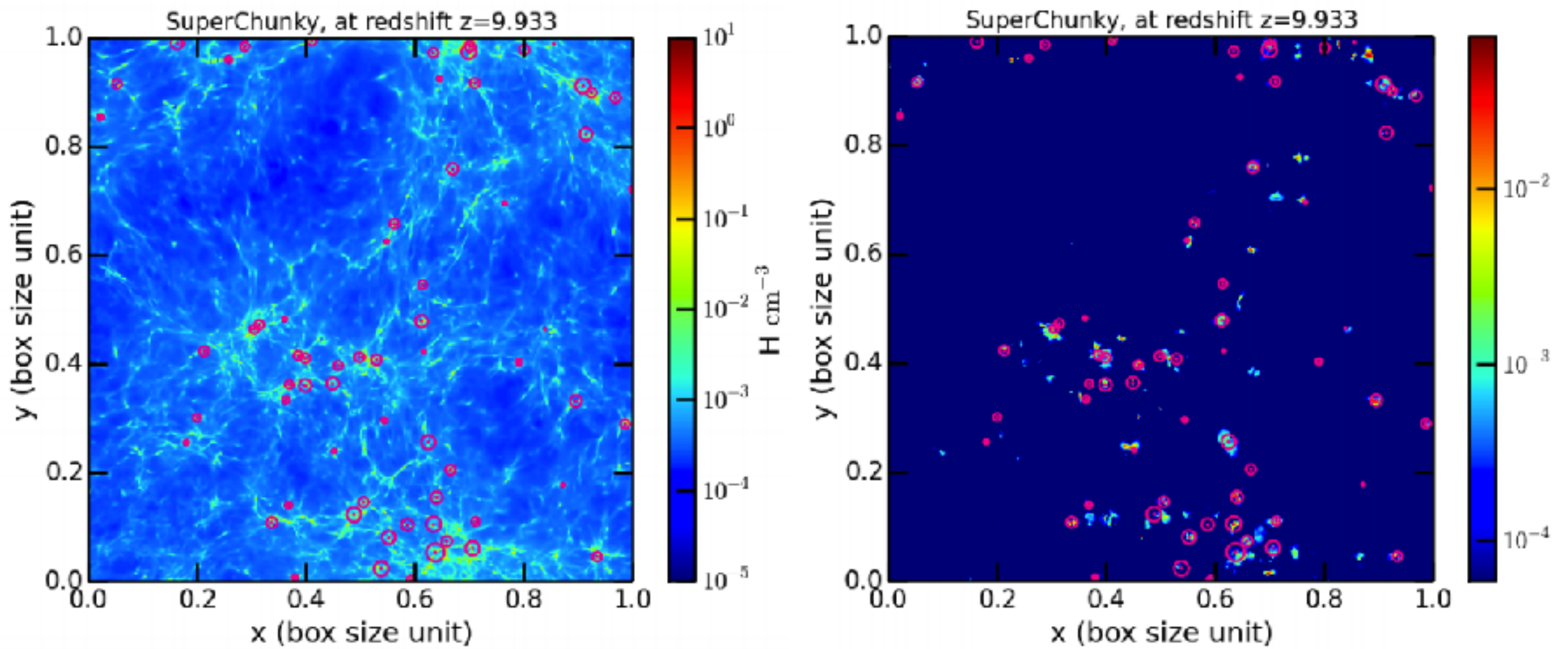


Low mass halos bathed in Lyman-Werner Flux can form Direct Collapse BHs



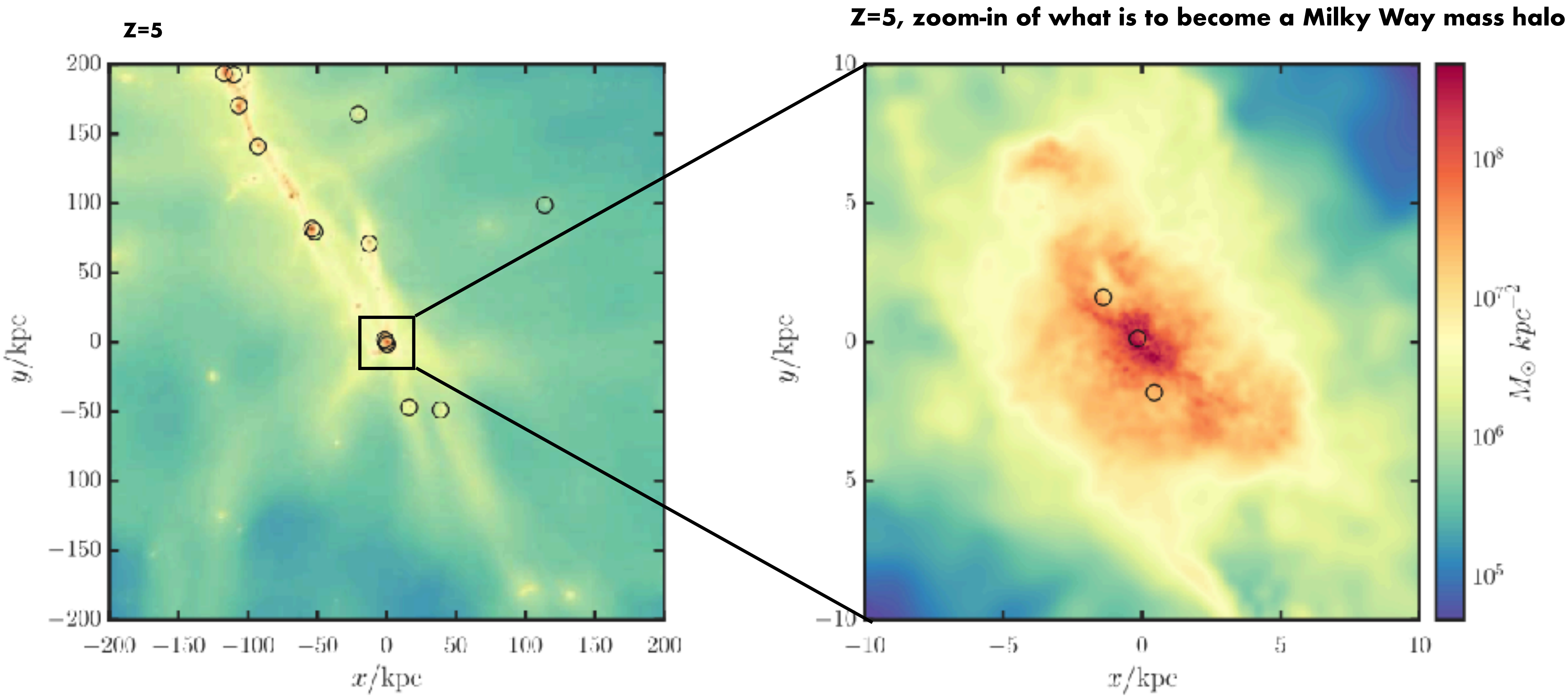
adapted from Zackrisson et al. 2012; see Visbal, Haiman, Bryan 2018

Rare SMBH birthplaces in a uniform UV background



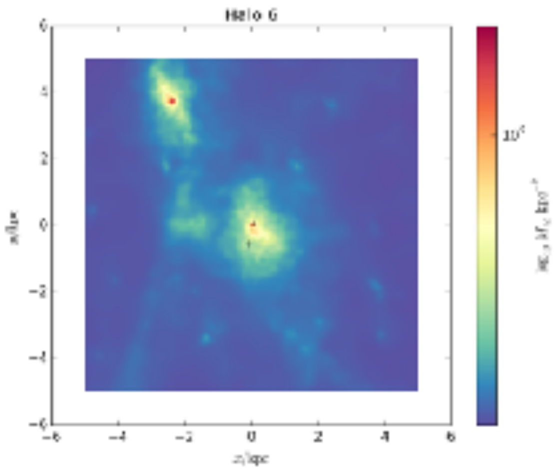
Habouzit et al 2016

See also Agarwal et al. 2013; Akutalp et al. 2014

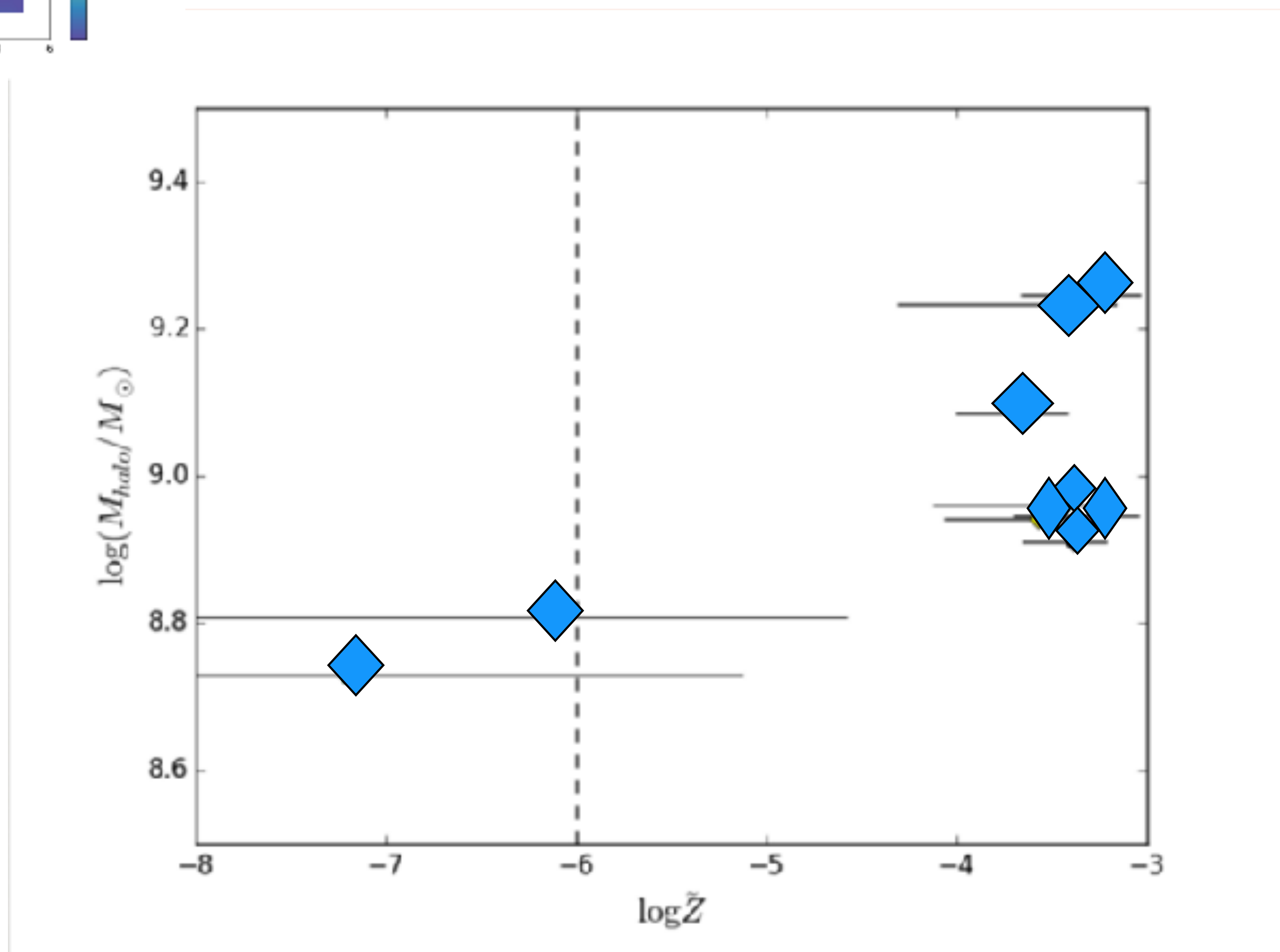


Cosmological Hydrodynamical Simulations of Direct Collapse Black Hole Formation

Dunn, Bellovary, KHB, Christensen, Quinn 2020

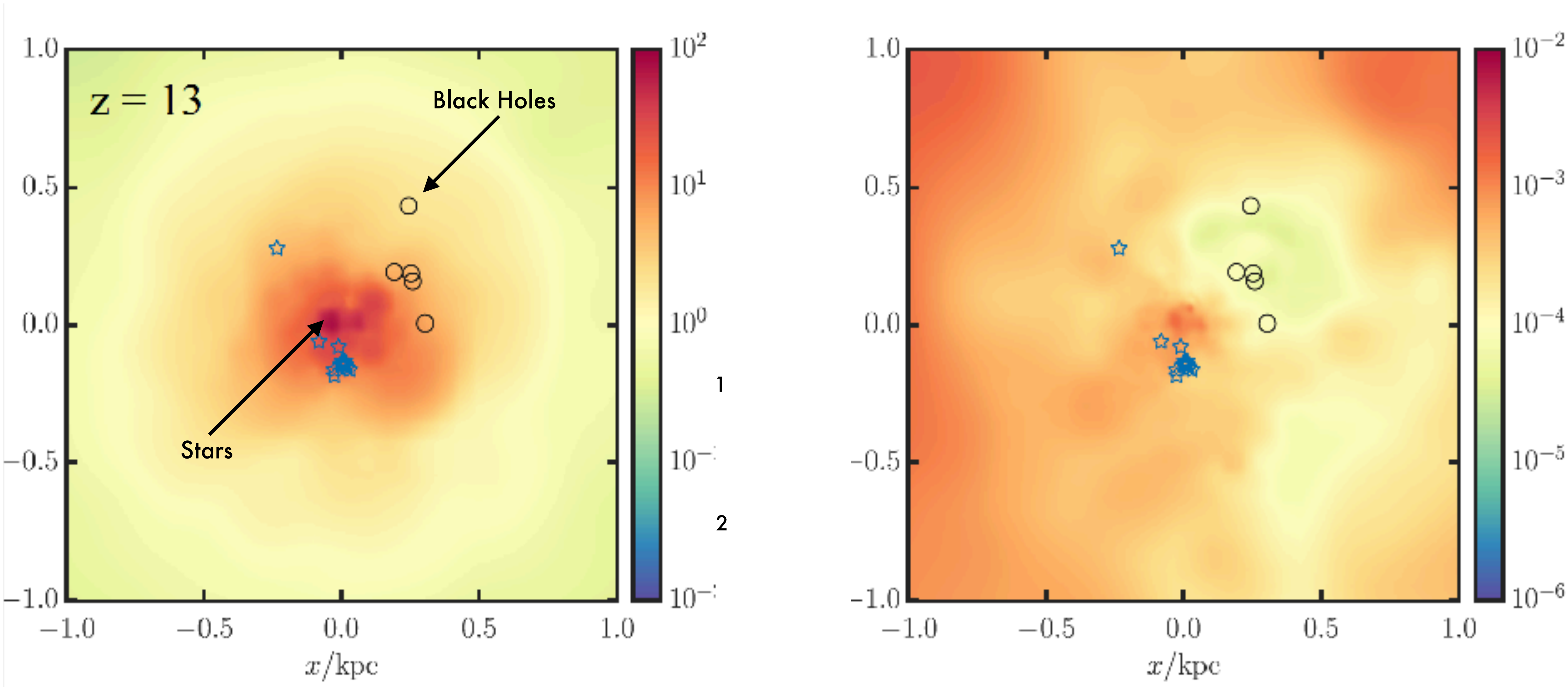


Surprises – several Direct Collapse Black Holes can form in a single halo



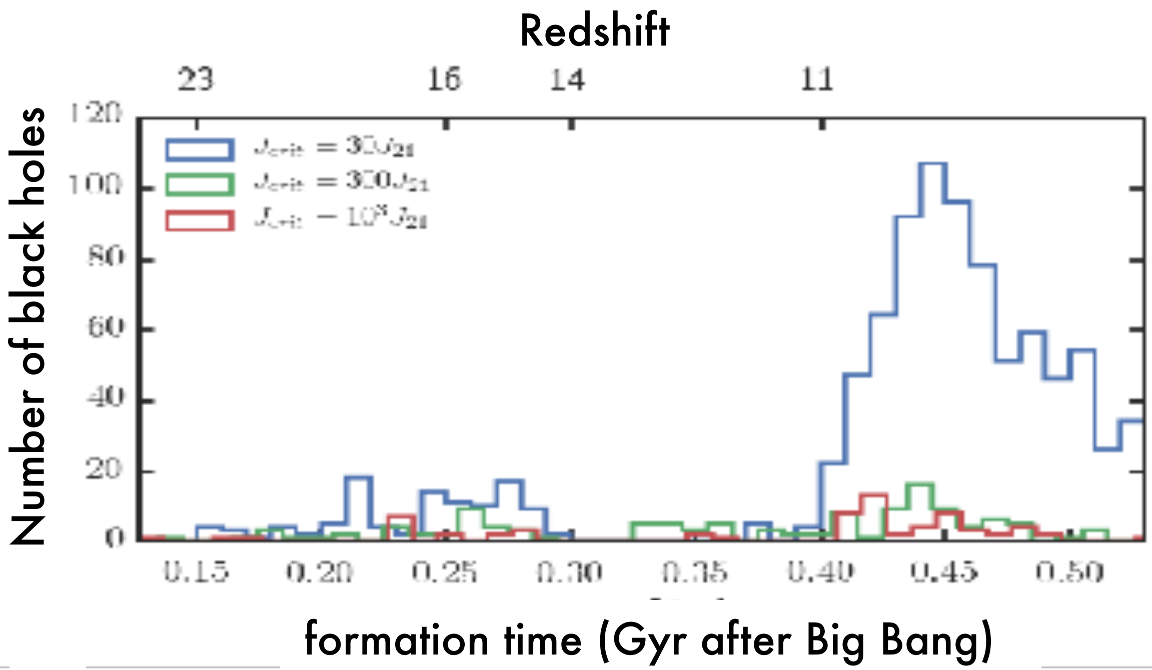
…and seeds can form in 'high' metallicity halos, too!

Seed BHs can form in an irradiated, but pristine pocket of gas in a halo polluted with metals.

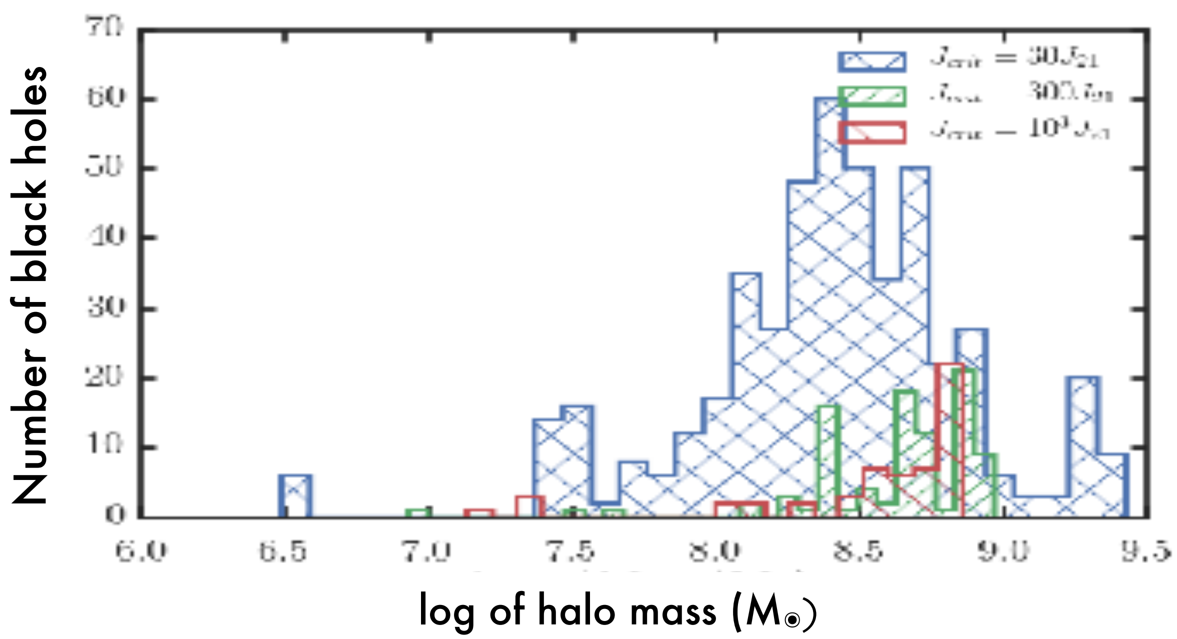


Lyman-Werner Flux

Metallicity

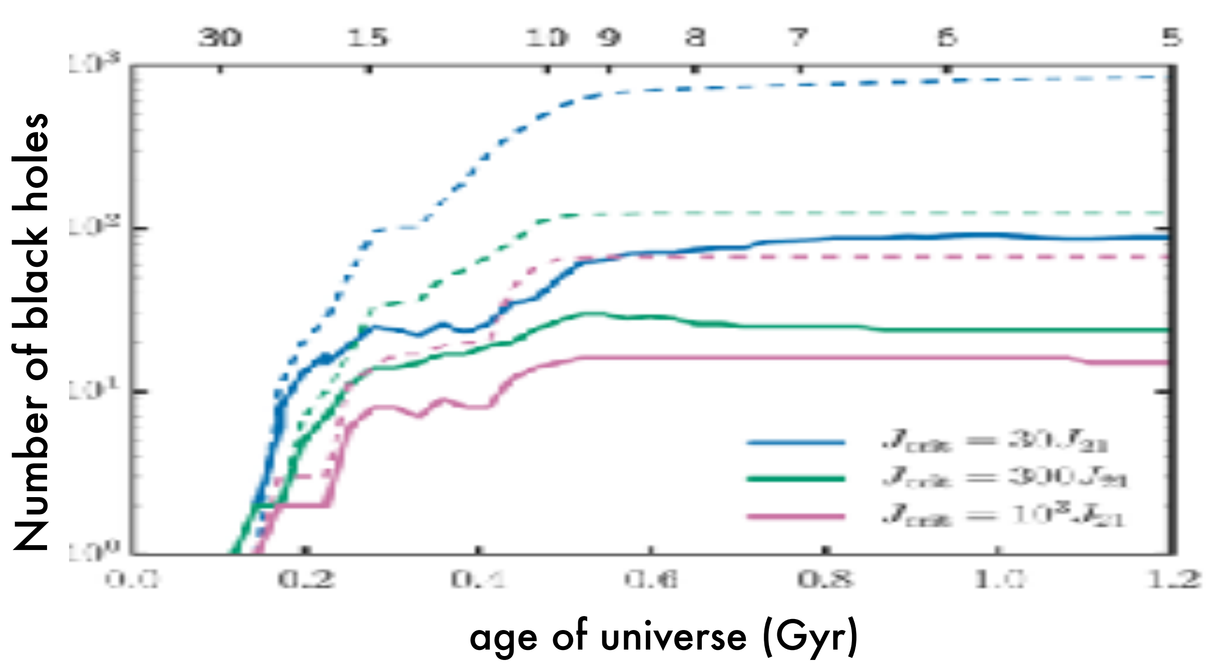


Seeds can form after reionization…



in a wider halo mass spectrum…

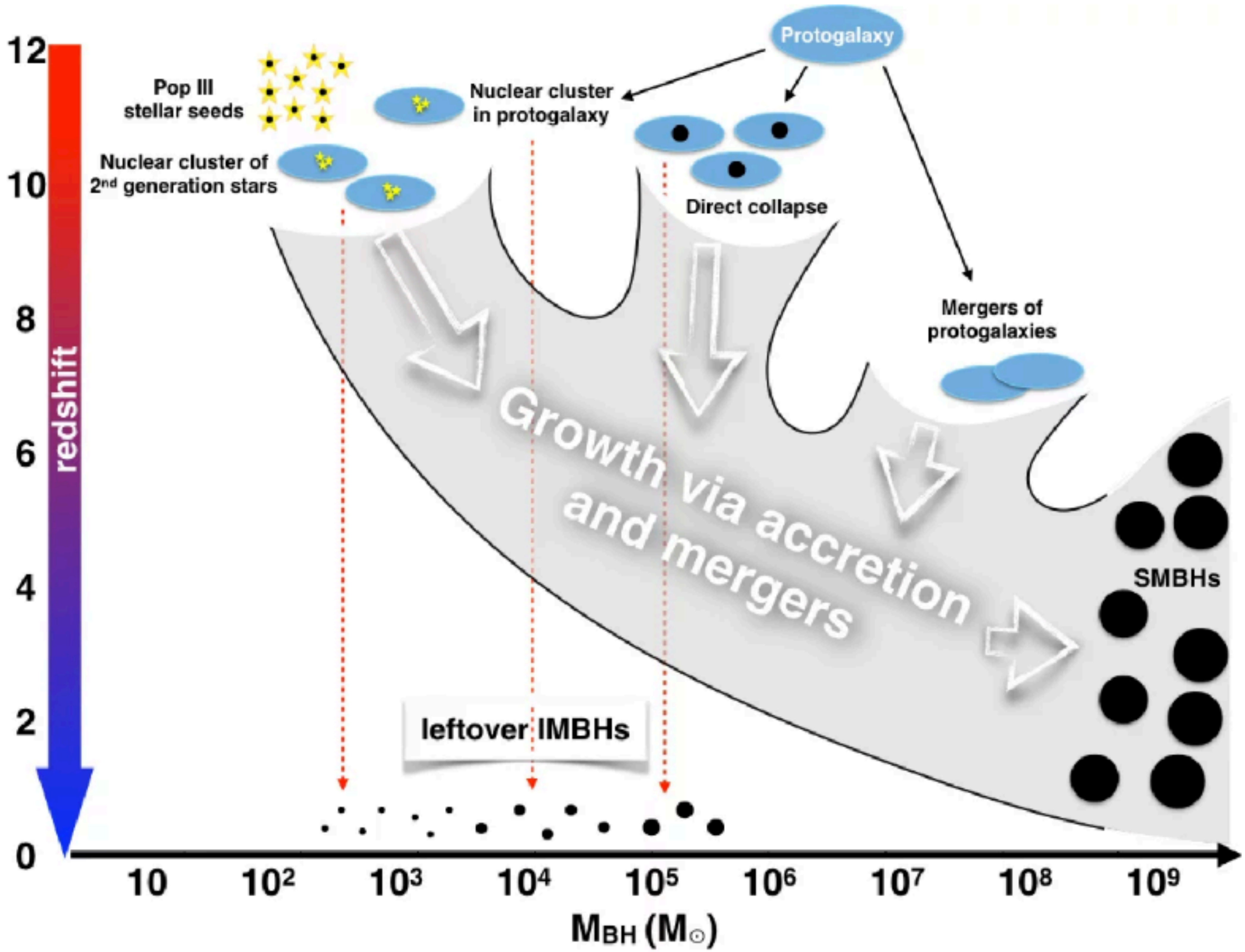
>50% of halos with masses ~10^8 $M_\odot$ host a seed BH by z=4



by the hundreds and off-center!

Dunn et al. 2018

How do supermassive black holes grow?

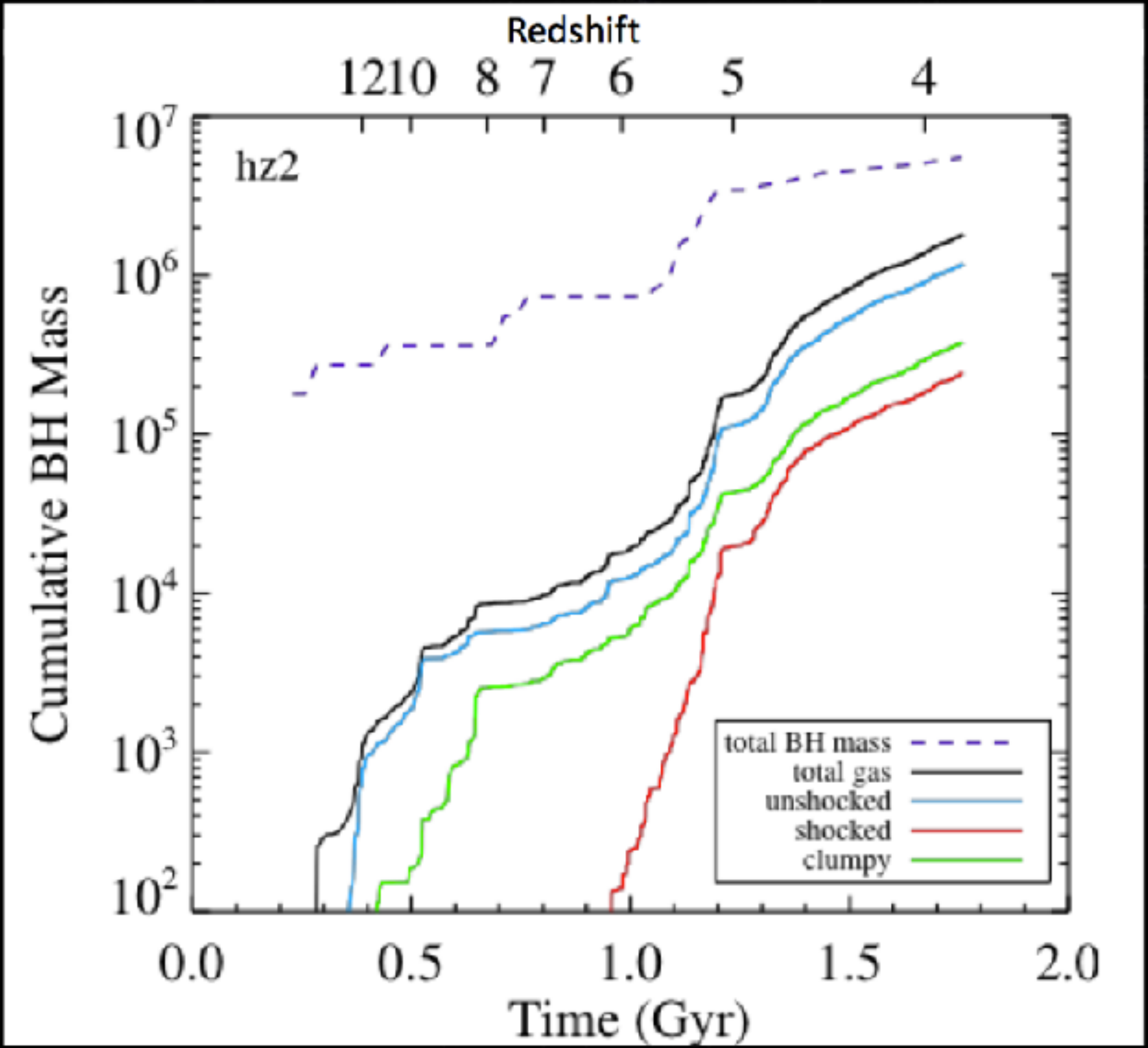


Protogalaxy
Pop III
stellar seeds
Nuclear cluster
in protogalaxy
Nuclear cluster of
2nd generation stars
Direct collapse
Mergers of
protogalaxies
Growth via accretion
and mergers
SMBHs
leftover IMBHs
redshift
12
10
8
6
4
2
0
10
10²
10³
10⁴
10⁵
10⁶
10⁷
10⁸
10⁹
MBH (M☉)

Cosmological Hydrodynamical simulation of early BH growth

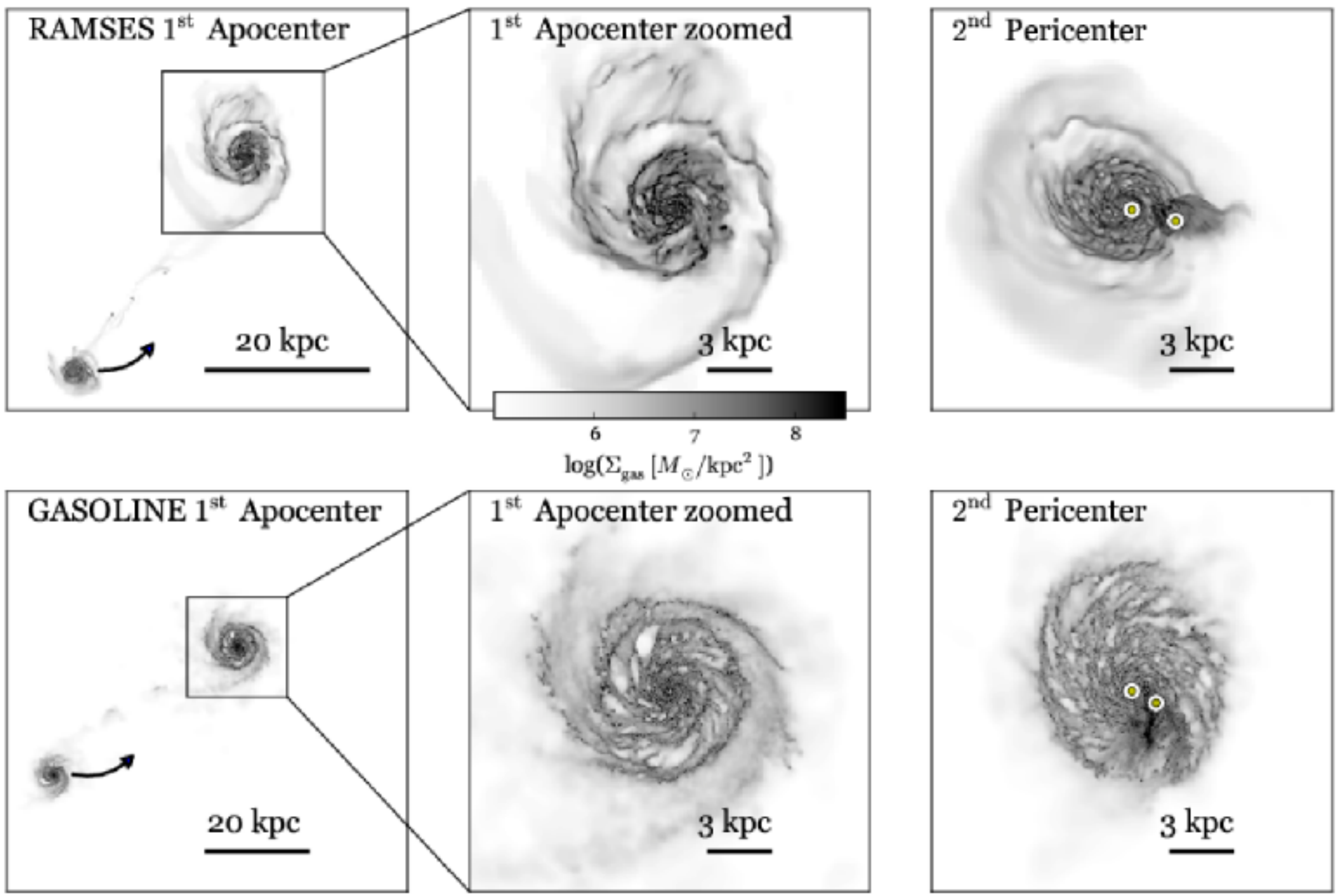
Bellovary et al. 2013

Most of the early SMBH growth is not from gas...
...and the gas that does fuel the SMBH is not from galaxy mergers



Sanchez, Bellovary and KHB 2016

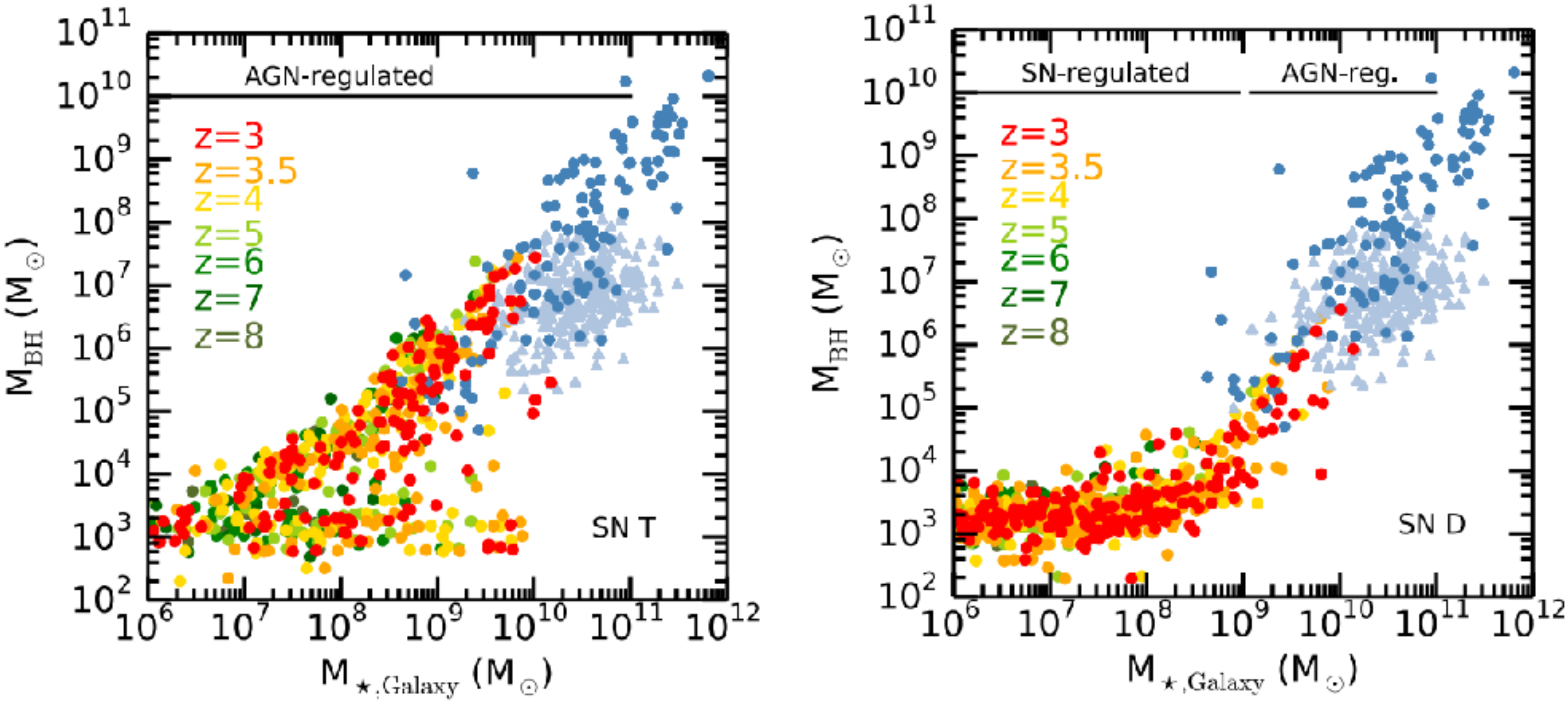
Warning: BH growth depends on the hydrodynamic code



BHs grow less, take longer to merge

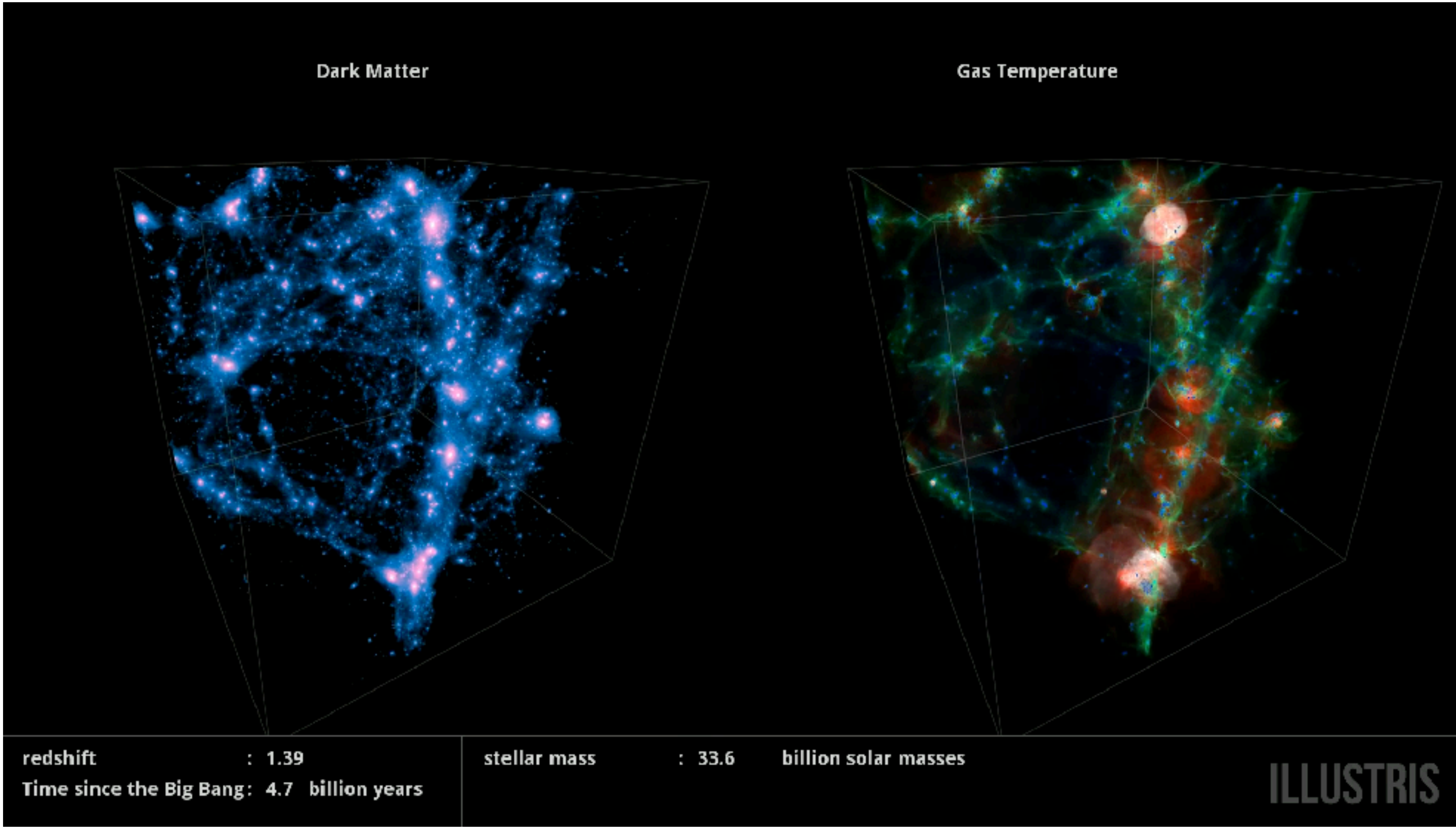
Gabor et al. 2015

Warning: BH growth depends on a feedback recipe



Ramses 10 Mpc (!) box
Habouzit et al 2016
see also Dubois 2015

Warning: Over-zealous AGN feedback stifles BH growth (and star formation, too)



Volgelsburger et al. 2014

Bringing Black Holes Together

Galaxy mergers sink black holes though dynamical friction

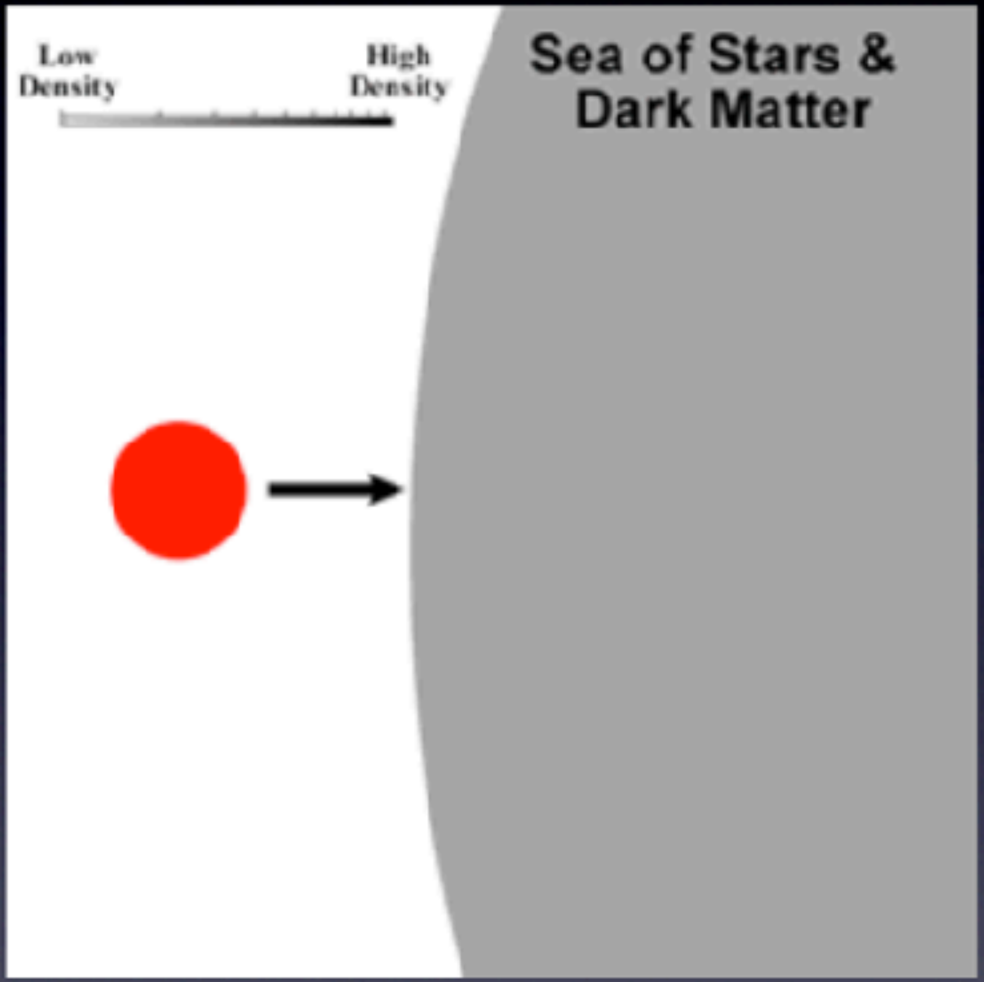
Separation:
$O(10^5)$ pc

Timescale:
$O(10^8)$ yr

when v_M is fast ($v_M >> v_m$):

dynamical friction is low because M moves faster than the wake can react.

M



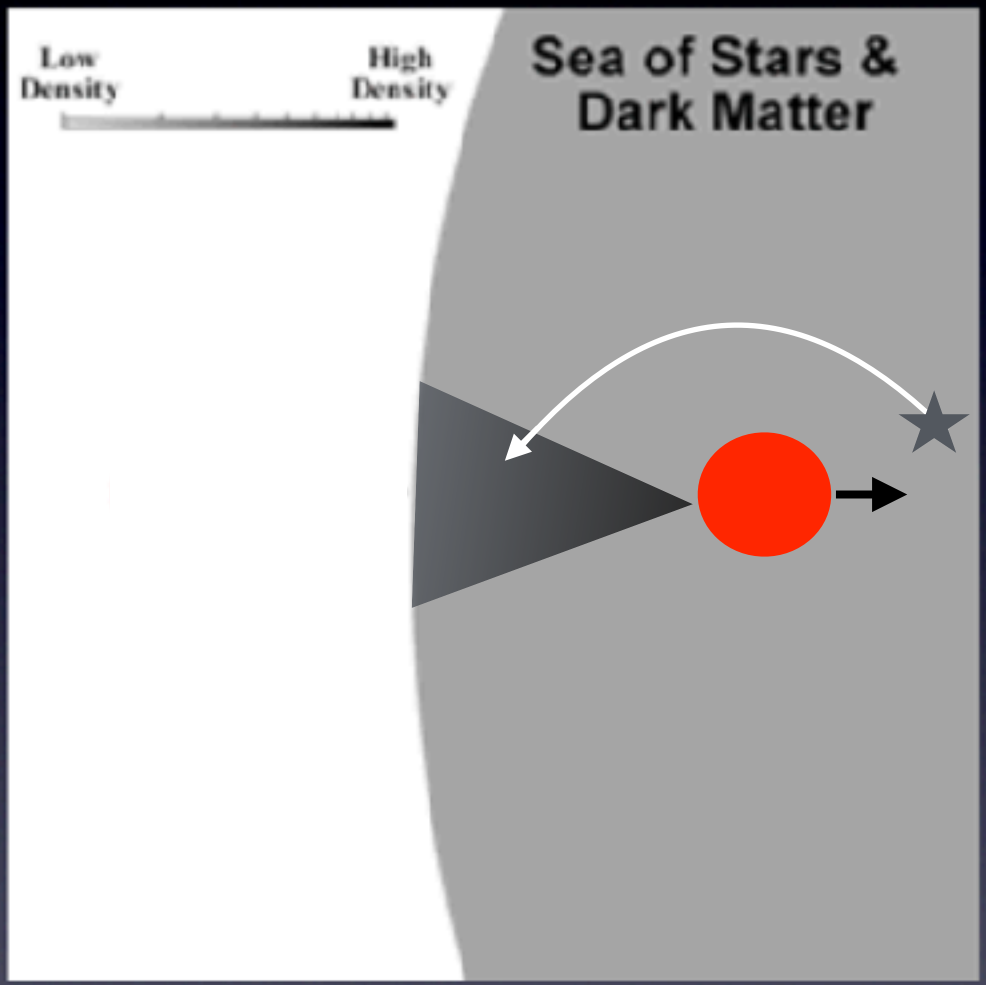
m

when v_M is slow ($v_M << v_m$):

dynamical friction is low because wakes form both in front and behind M when v_M is fast ($v_M >> v_m$):

dynamical friction is low because M moves faster than the wake can react.

M



m

when v_M is slow ($v_M << v_m$):

dynamical friction is low because wakes form both in front and behind M

Coulomb logarithm. Has to do with range of impact parameters

$v_{\mathrm{M}}/(\sqrt{2}\sigma)$

$$\frac{d\mathbf{v}_M}{dt} = -\frac{4\pi \ln \Lambda G^2 (M+m)\rho}{v_M^3} \left[\mathrm{erf}(X) - \frac{2X}{\sqrt{\pi}} e^{-X^2} \right] \mathbf{v}_M$$

Density of stellar sea

Assumes the stellar 'sea':

Is Infinite, isotropic, and constant density

Has Maxwellian velocity distribution

M>>m (and a constant point mass)

For a point mass particle on a circular orbit with radius r_i and velocity v_c...

2. The orbit remains nearly-circular
3. Galaxy density profile is:

$$\rho(r) = \frac{v_c^2}{4\pi G r^2}$$

where $v_c = \sqrt{2}\sigma$

From Chandrasekhar's formula:

$$F(r) \approx 0.428 \ln \Lambda \frac{GM^2}{r^2}$$

Point mass example, continued...

Angular Momentum loss:

$$\frac{dL_z}{dt} = -Fr \approx -0.428 \ln \Lambda \frac{GM^2}{r}$$

Assuming the effect is weak (and the BH orbits remains circular):

$$r\frac{dr}{dt} = -\alpha \Longrightarrow r(t) = \sqrt{r_i^2 - 2\alpha t}$$

Decay time:

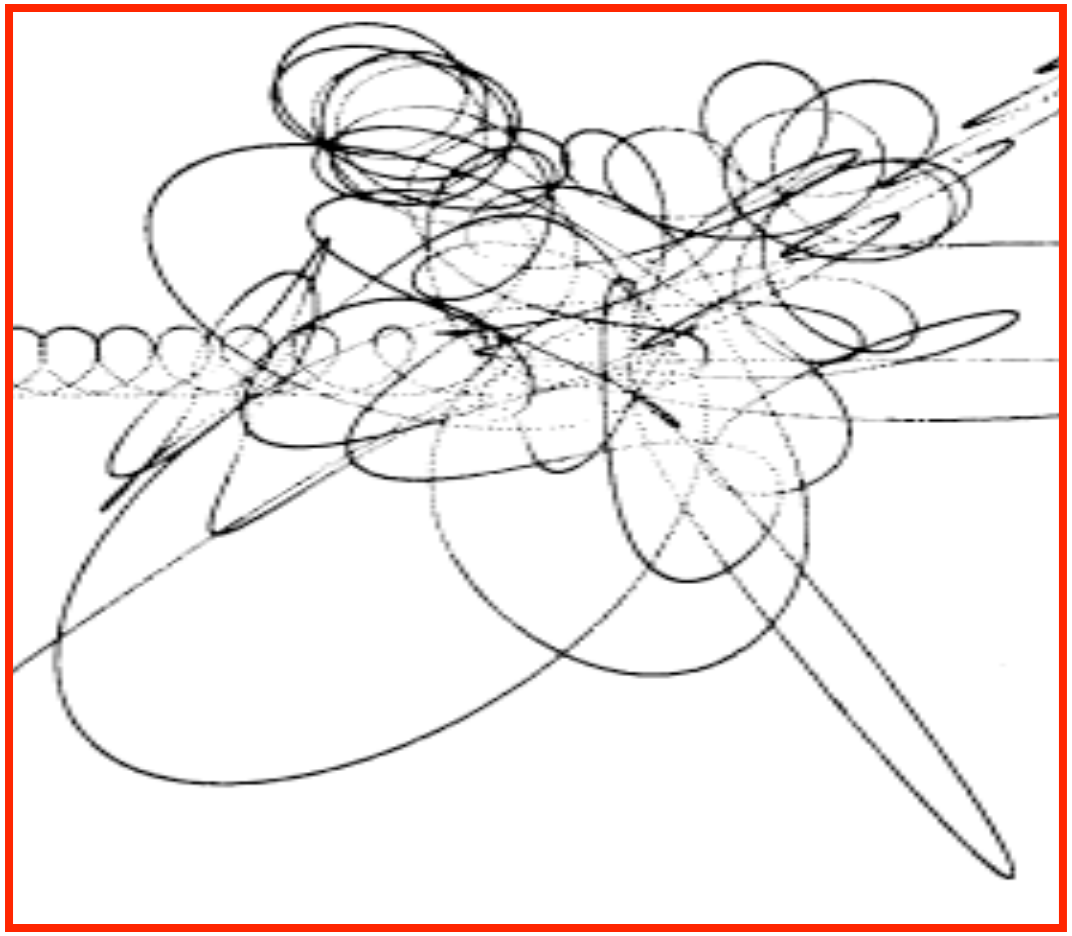
$$r(\tau_{\rm fric}) = 0 \Longrightarrow \tau_{\rm fric} = \frac{r_i^2}{2\alpha} = \frac{1.17}{\ln \Lambda}\frac{r_i^2 v_c}{GM}$$

Taking $b_{\rm max} = 5$ Kpc, $M = 10^8 M_\odot$, $v_{\rm typ} \approx \sigma = 200$ km s^{-1} we have $\ln \Lambda \simeq 6$

$$\tau_{\rm fric} = \frac{1.17}{\ln \Lambda}\frac{r_i^2 v_c}{GM} \approx 3 \text{ Gyr}$$

Next: black holes sink closer via 3-body scattering.

Quinlan 1997; Sesana et al 2006,2007,2008

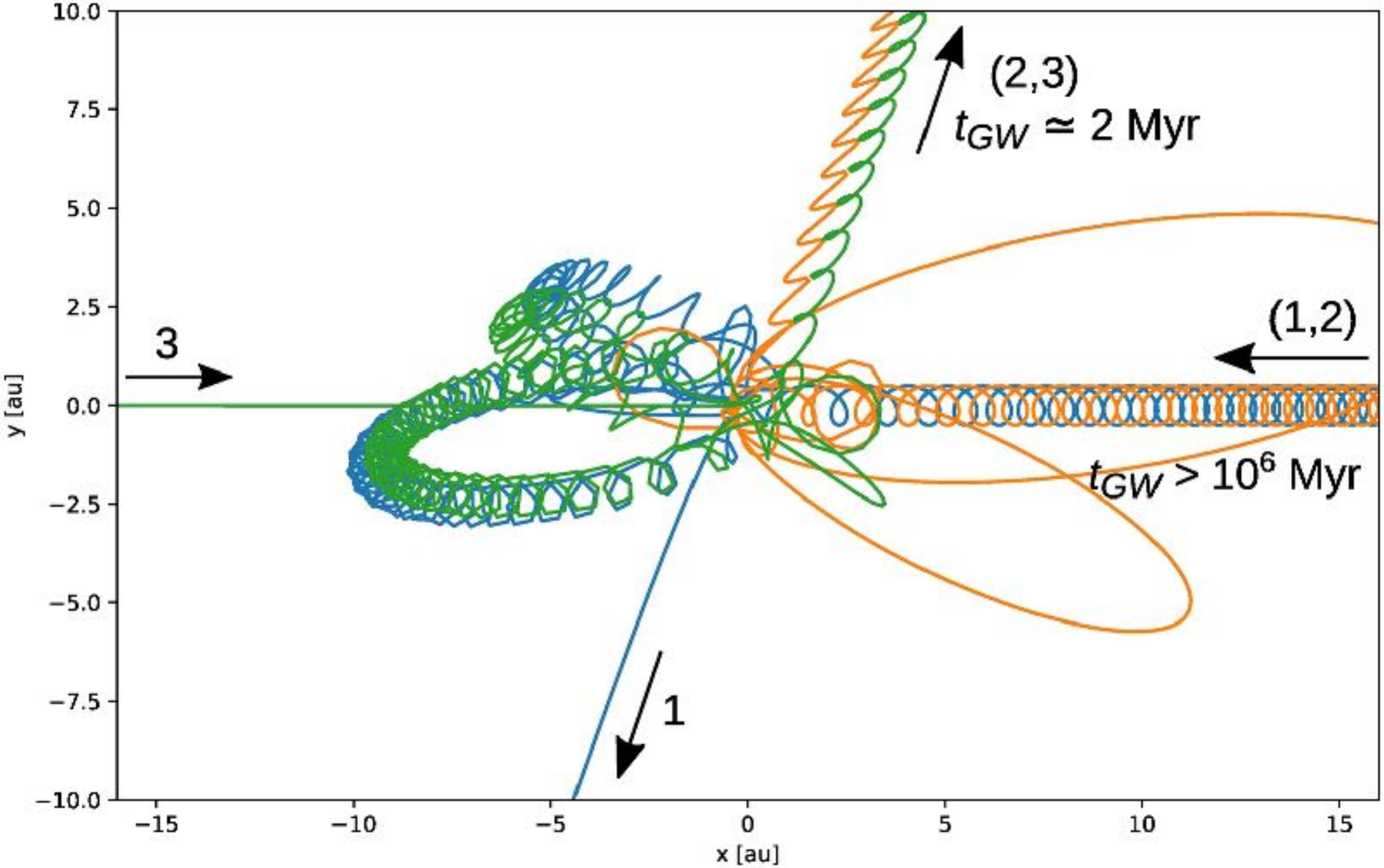


$$a_h := \frac{G\mu_r}{4\sigma^2} \sim \frac{1}{4}\frac{q}{(1+q)^2} r_h,$$

> $O(10^1)$ pc

> $O(10^{10})$ yr!**

**in a static spherical galaxy with permanent ejections and no resonances



(2,3)
$t_{GW} \simeq 2$ Myr
3
(1,2)
$t_{GW} > 10^6$ Myr
1
y [au]
x [au]
10.0
7.5
5.0
2.5
0.0
−2.5
−5.0
−7.5
−10.0
−15
−10
−5
0
5
10
15

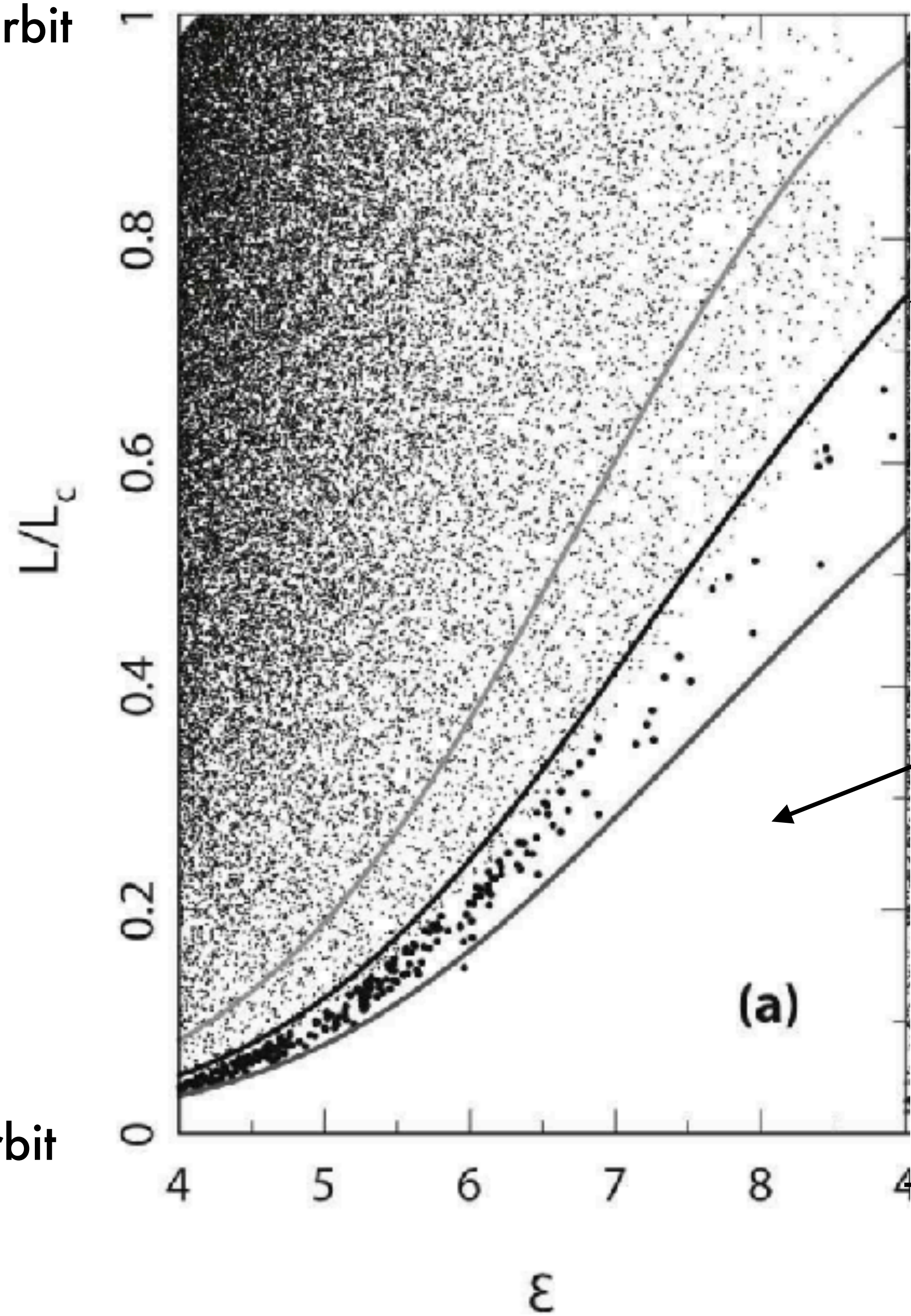
Circular orbit

Hardening radius

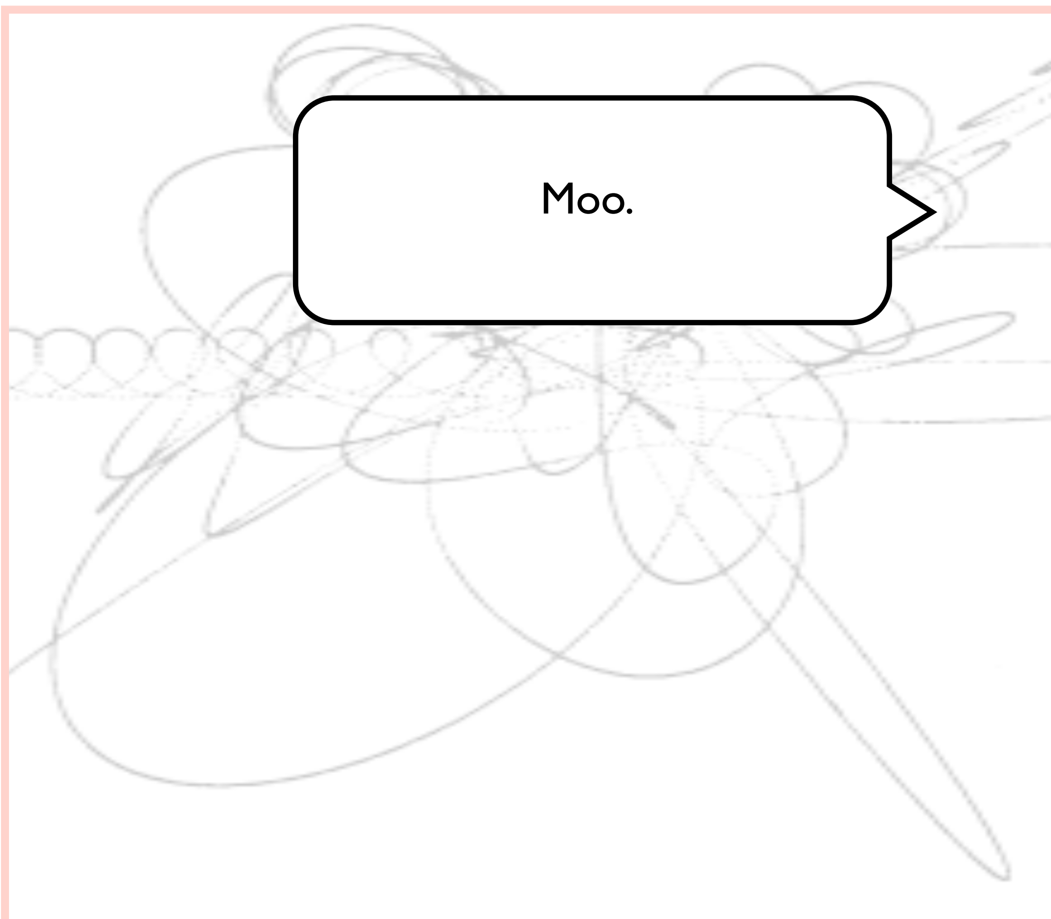
Stars in the loss cone fall into the black hole

Radial orbit

Black hole

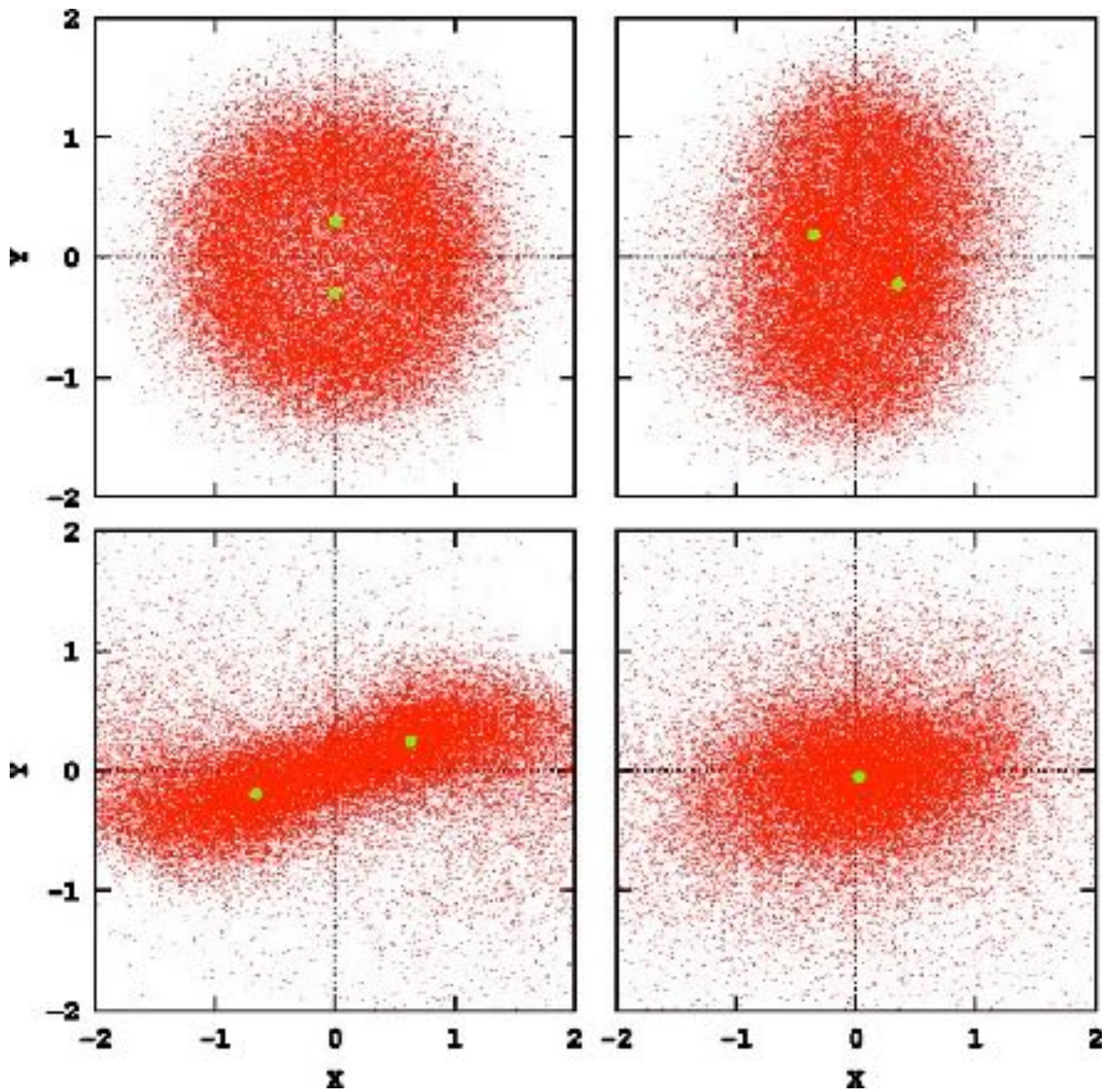


The final parsec problem – refilling a spherical loss cone takes > t_{Hub}

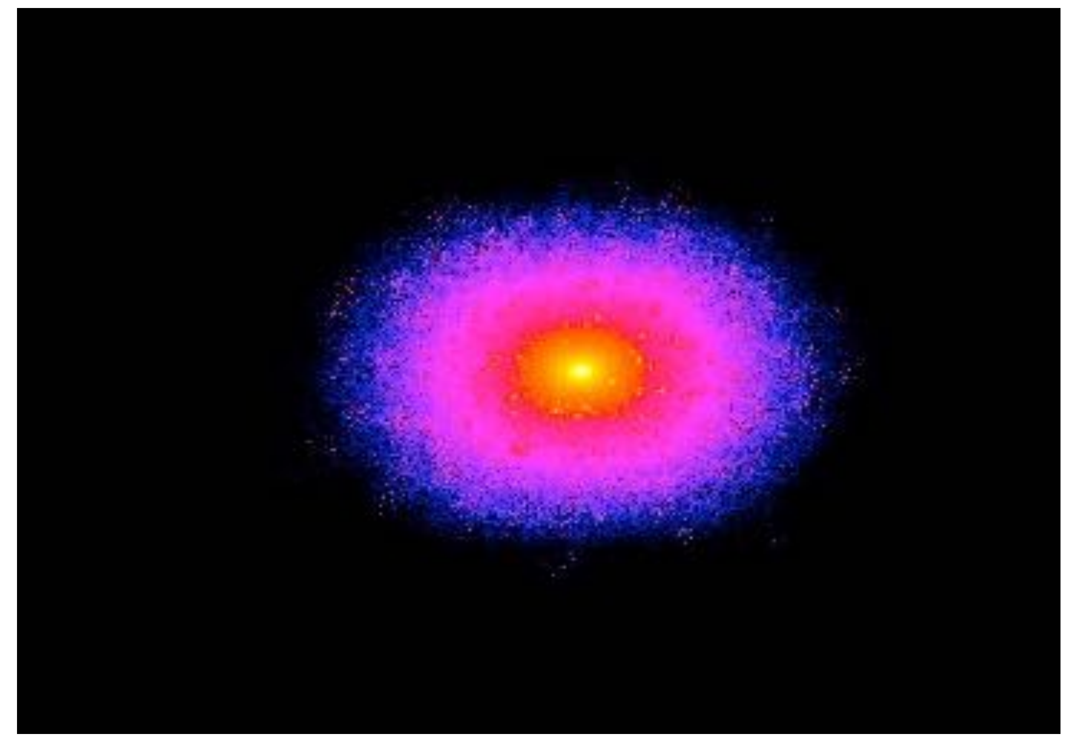


$$a_h := \frac{G\mu_r}{4\sigma^2} \sim \frac{1}{4}\frac{q}{(1+q)^2} r_h,$$

Final Parsec Problem? Not a problem for a non-spherical galaxy!



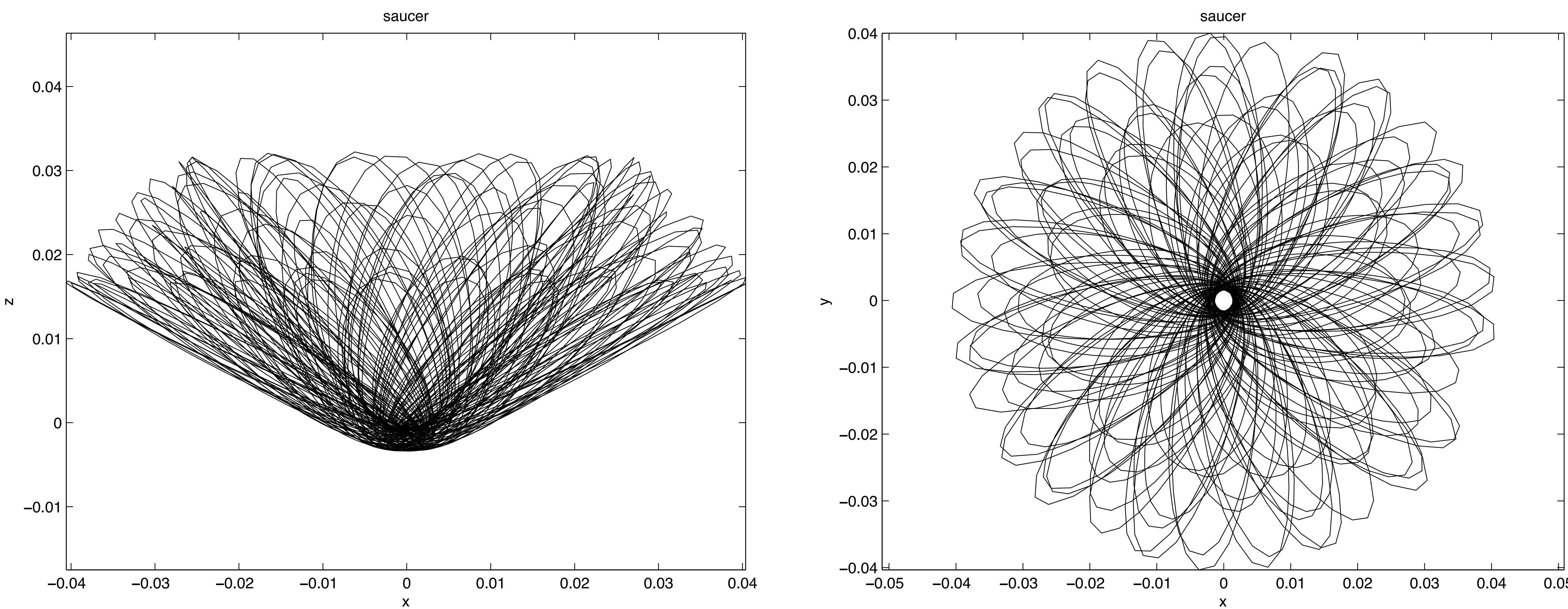
Berczik et al. 2006



KHB+Sigurdsson 2006
Khan+KHB 2013

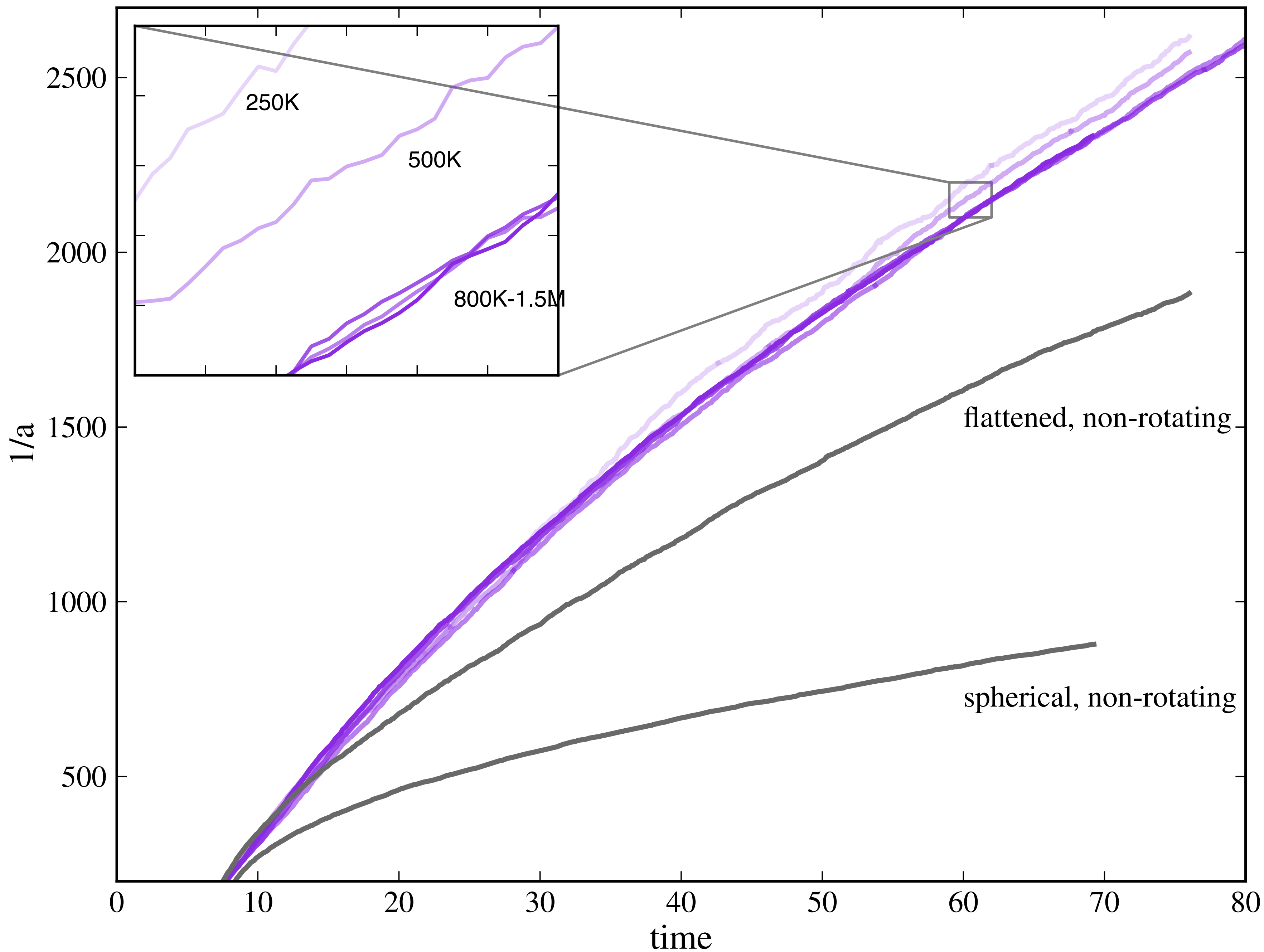
Expect $10^8\ M_\odot$ Binary BHs to take less than 3 Gyr to coalesce in an equilibrium axisymmetric galaxy

Axisymmetric galaxies have low angular momentum orbits that overfill the loss cone



~60% of the stars within the inner 100 pc are saucers

Now, let's add rotation — and the black hole orbit shrinks faster



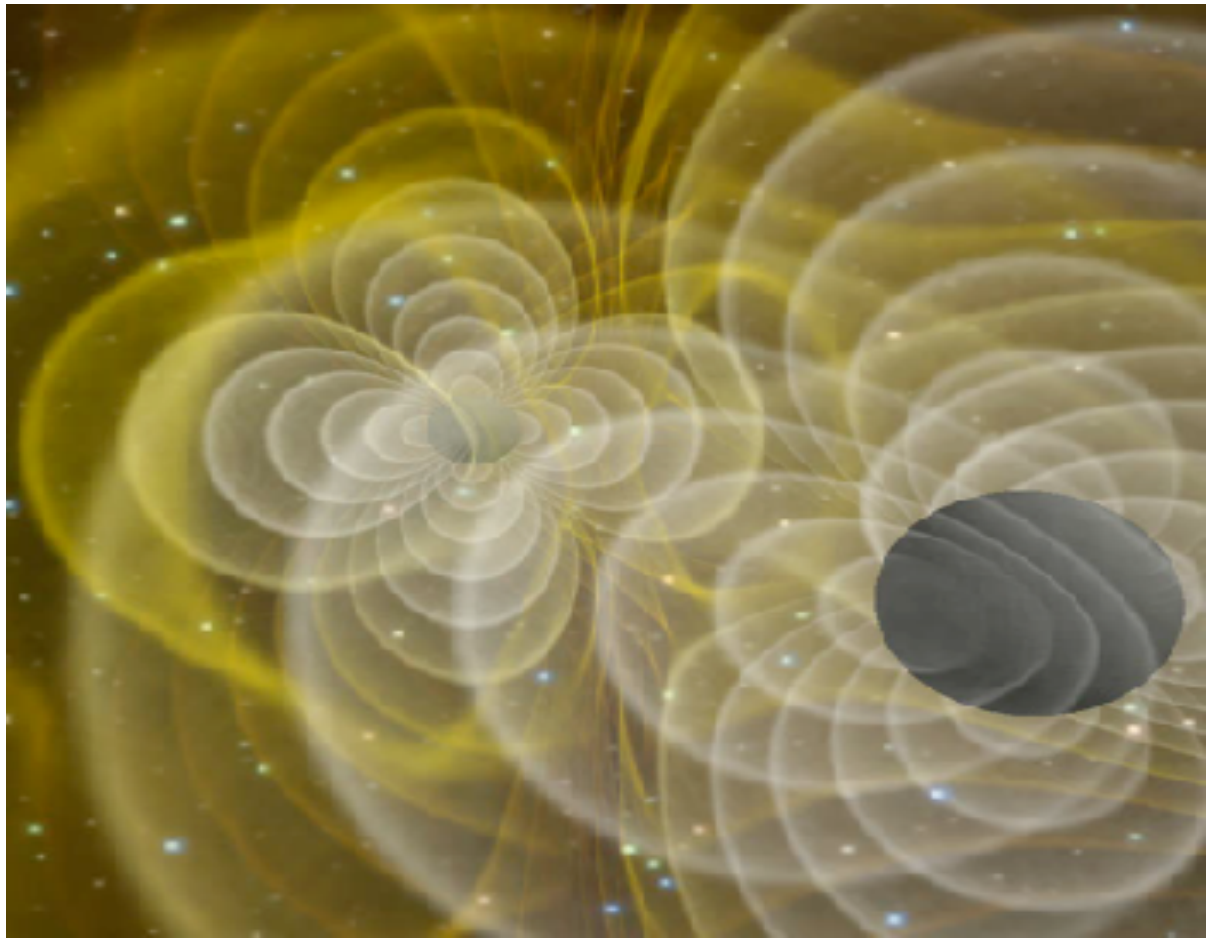
KHB+Khan 2014

Direct N-body code with GPU acceleration and 2.5 PN terms included.

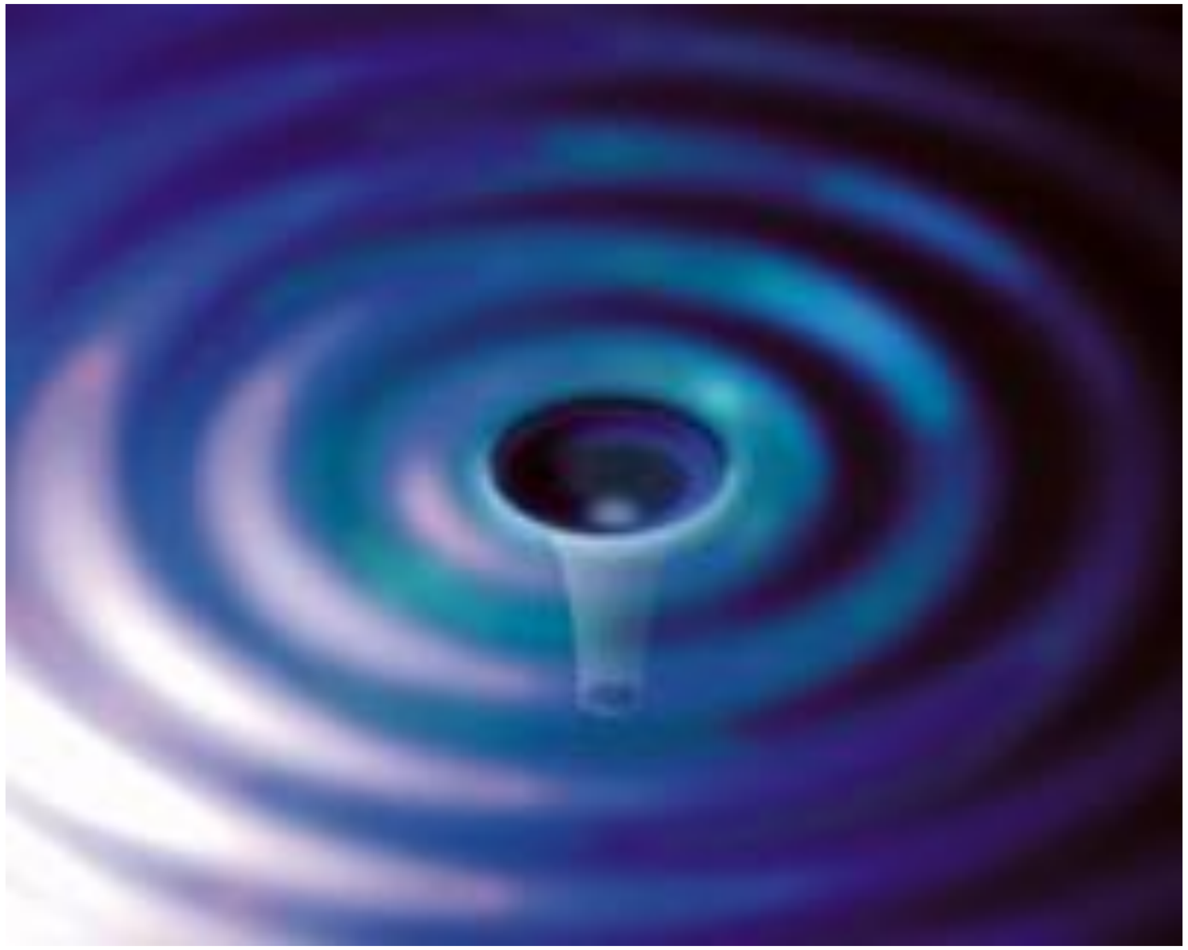
Black holes *can* merge quickly…or not.

galaxy type	black hole merger timescale	eccentricity in the gw regime
spherical	> 15 Gyr	N/A
axisymmetric (c/a=0.75)	3 Gyr (t_{Hub}@z~0.4)	Small
axisymmetric, rotating	1 Gyr	Medium
axisymmetric, counterrotating	100 Myr	~1
triaxial	O(10) Myr	depends
Gas-Rich	10 Myr — 1Gyr	depends

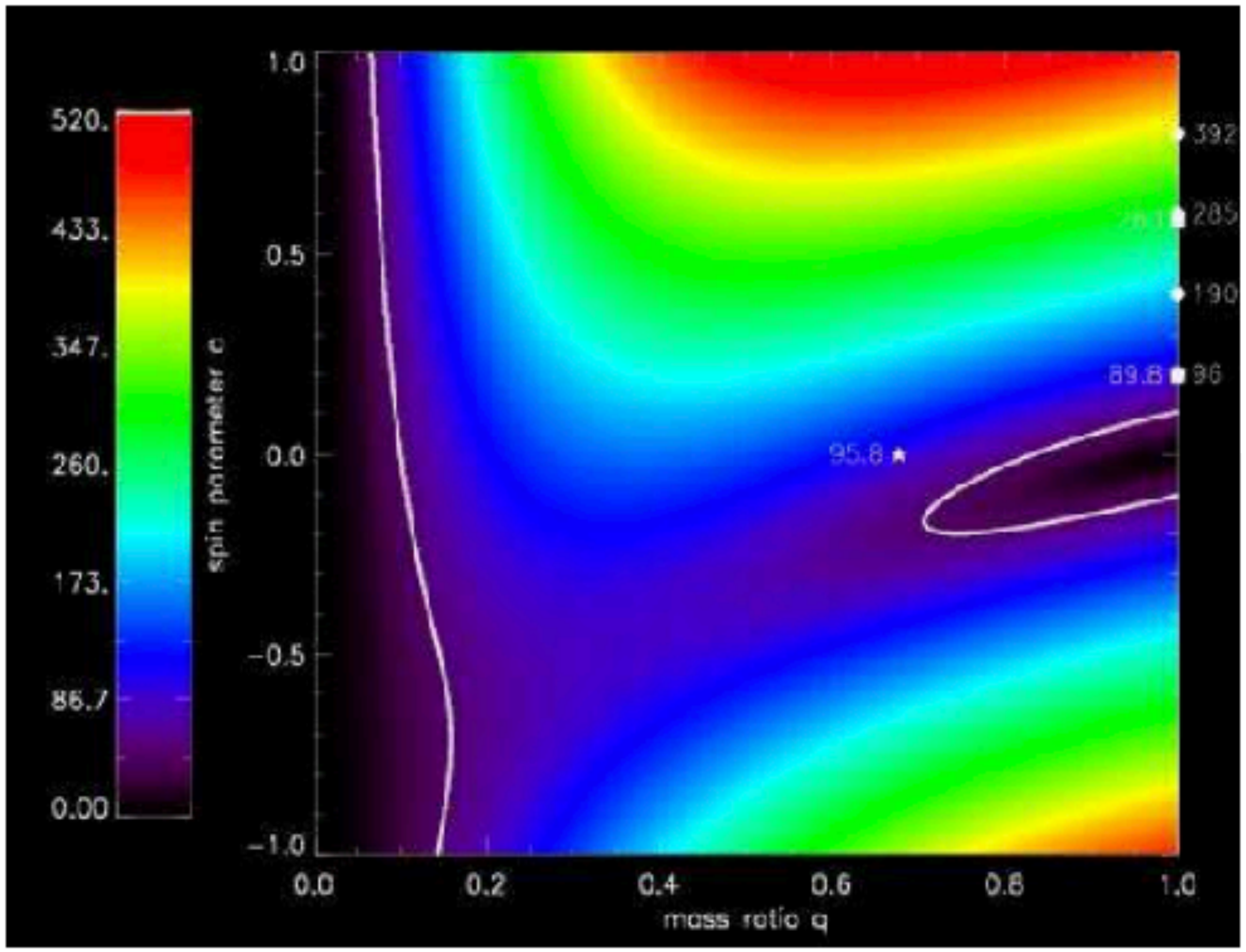
Finally, gravitational waves complete the coalescence



O(10^{-5}) pc



> O(10^{10}) yr!*



$$v_{\mathrm{kick}} = (1+e)\left[\hat{x}\ (v_m + v_\perp \cos\xi) + \hat{y}\ v_\perp \sin\xi + \hat{z}\ v_\parallel\right], \tag{1}$$

where

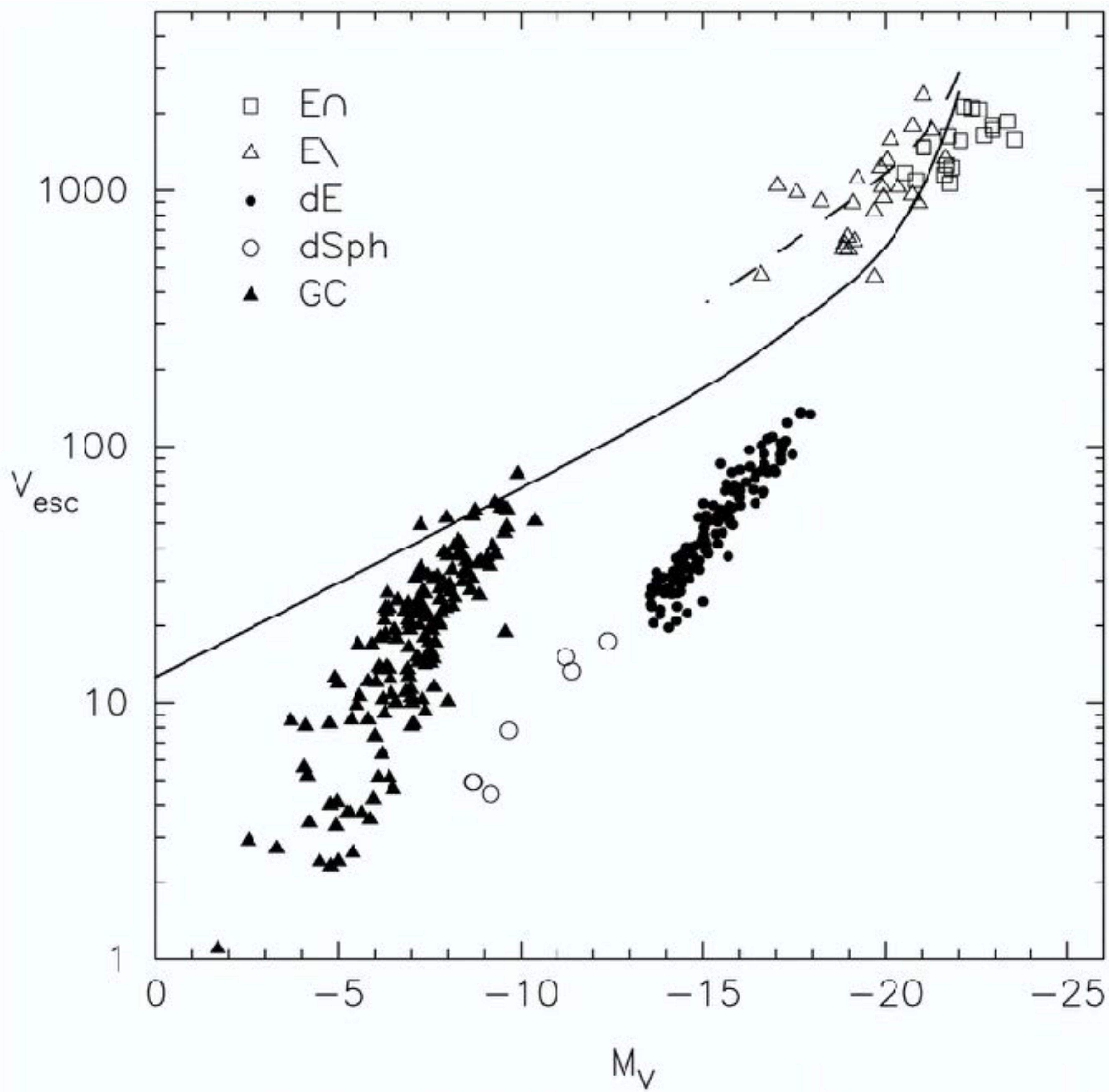
$$v_m = A\frac{q^2\,(1-q)}{(1+q)^5}\left[1 + B\frac{q}{(1+q)^2}\right], \tag{2}$$

$$v_\perp = H\frac{q^2}{(1+q)^5}\left(\alpha_2^\parallel - q\alpha_1^\parallel\right), \tag{3}$$

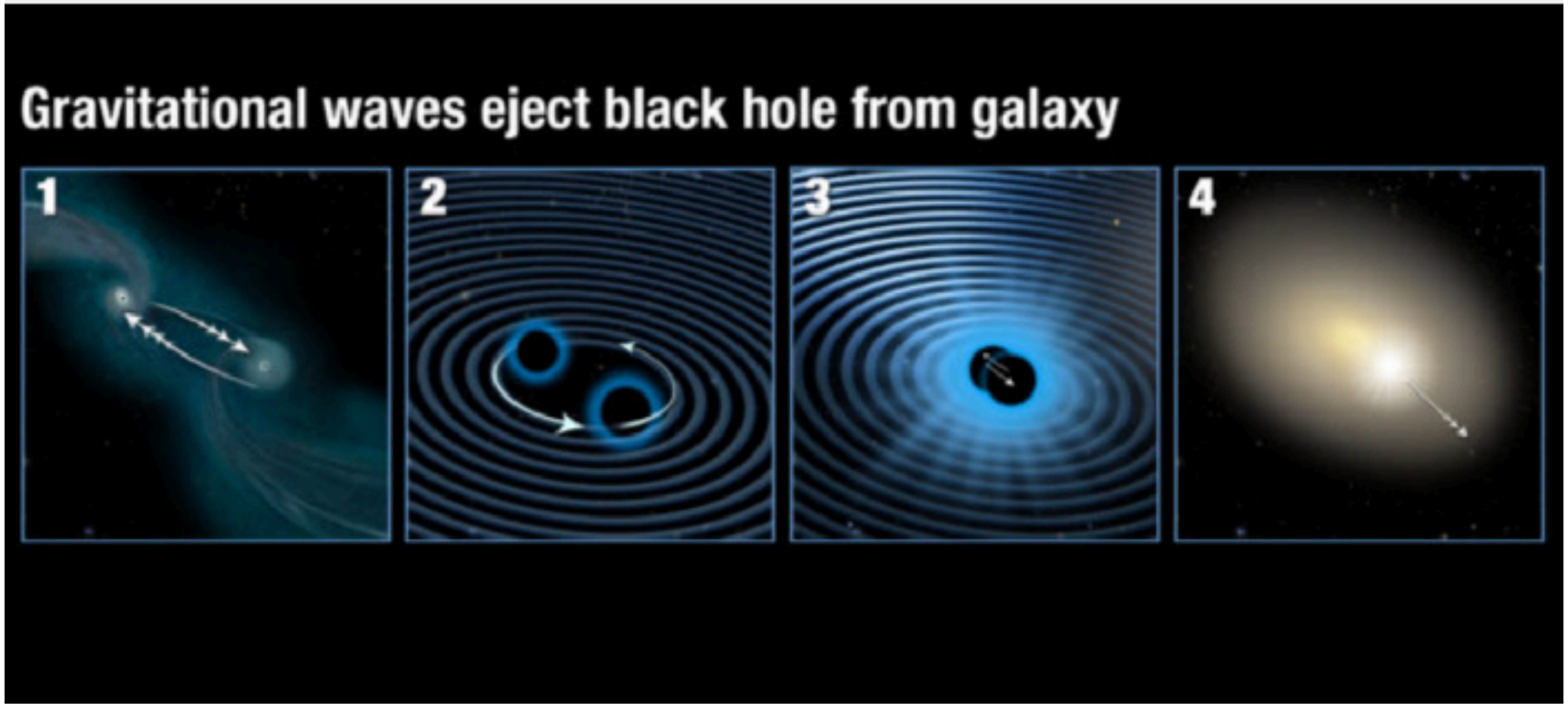
and

$$v_\parallel = K\cos\left(\Theta - \Theta_0\right)\frac{q^2}{(1+q)^5}\left(\alpha_2^\perp - q\alpha_1^\perp\right), \tag{4}$$

where the fitting constants are $A = 1.2 \times 10^4\ \mathrm{km\ s^{-1}}$, $B = -0.93$, $H = (7.3 \pm 0.3) \times 10^3\ \mathrm{km\ s^{-1}}$, and $K = (6.0 \pm 0.1) \times 10^4\ \mathrm{km\ s^{-1}}$, while the subscripts 1 and 2 refer to the first and second BH respectively. The unit



Recoil can eject the MBH from the galaxy – so how do galaxies keep their MBH?



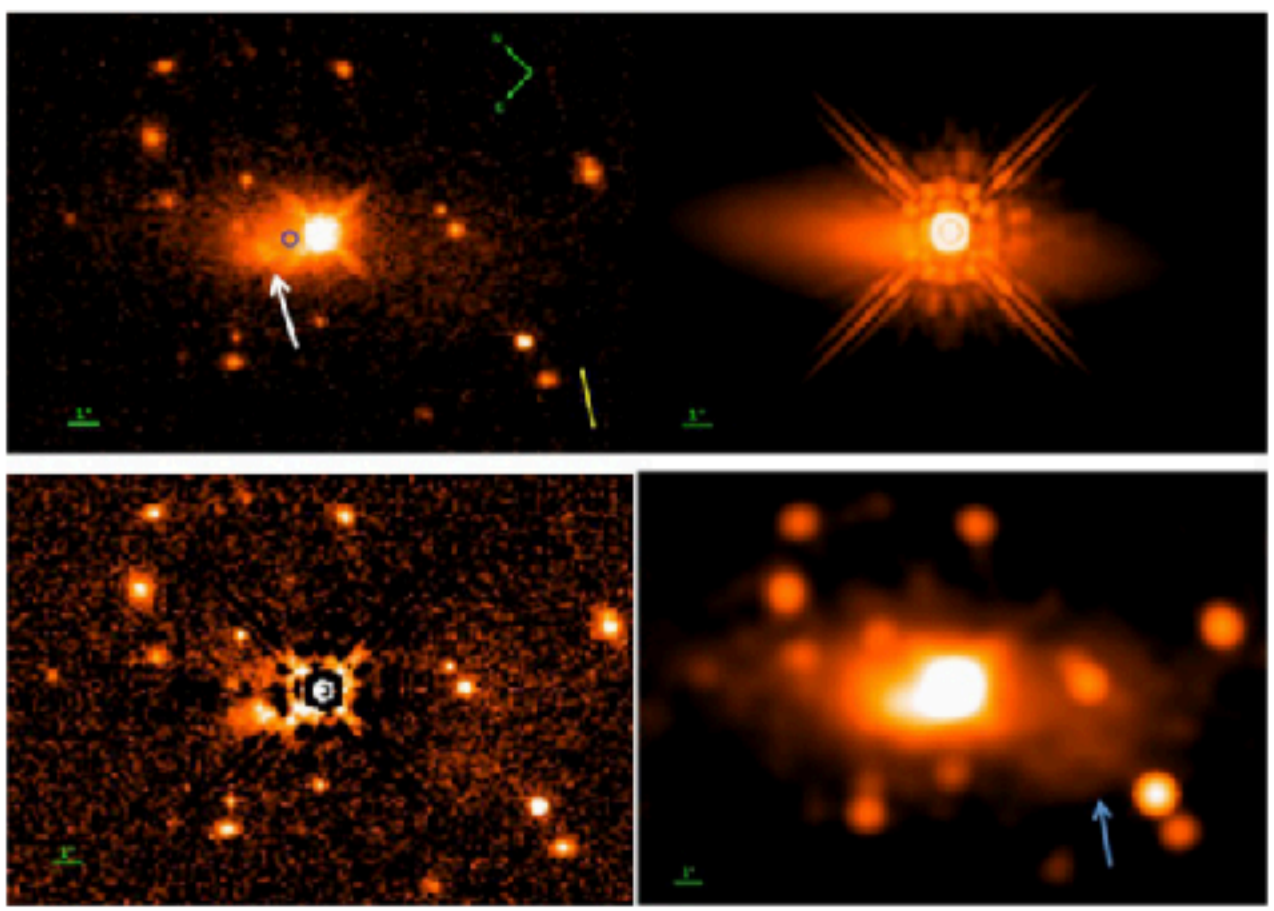


Fig. 1. HST image of 3C 186 (top-left). The host galaxy center is indicated with a blue circle. The orientation of the radio jet is shown as a yellow line. The white arrow indicates the location of the so-called blob of unknown origin, ~ 2 arcsec East-North-East of the quasar point source. Top-right: model of the source, which includes a PSF and a Sérsic model. Bottom-left: residuals after model subtraction. Bottom right: smoothed (4-pixel kernel) version of the HST image showing the presence of low S/N shells or tidal tails in the host galaxy (indicated by the blue arrow).

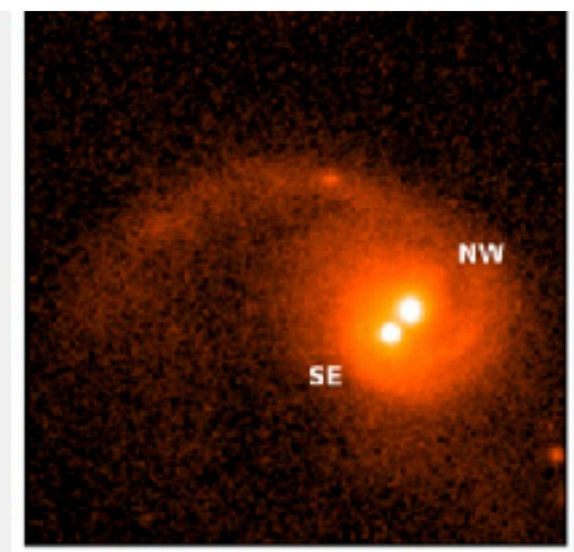


Figure 1: An optical image of CID-42 from the Hubble Space Telescope ACS, with the northwest (slightly extended) and southeast (point-like) components labeled - east is to the left. Image taken from an earlier study by Civano et al. 2010.

Lots of work to do on basic massive black hole theory and simulation to maximize our understanding of LISA observations!

We need you!