Supermassive black holes

- origins –

Martin Pijnenburg

Picture: EHT Collaboration
https://www.eso.org/public/images/eso1907a/

Supermassive black holes

It is now widely recognized that larges galaxies have supermassive black holes at their centres.

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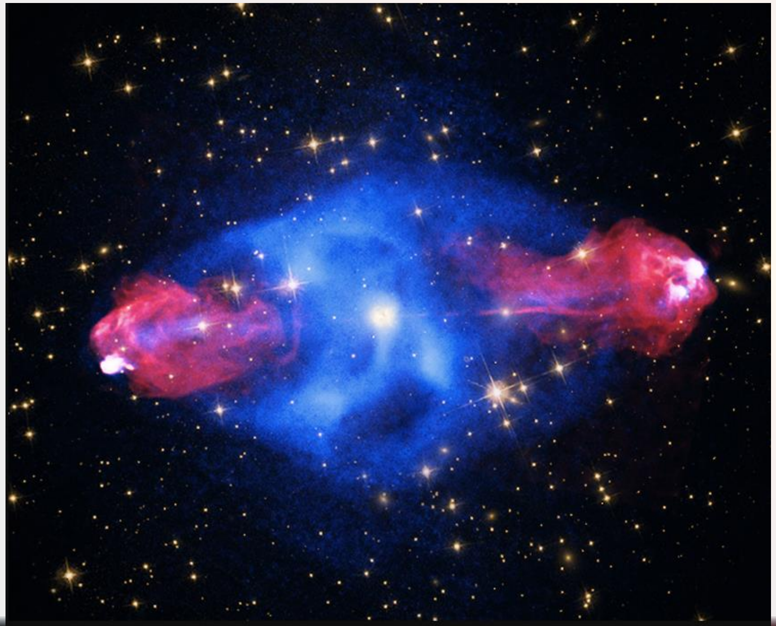

Credits:

Left:
NASA/CXC/SAO

Right:
Eisenhauer, Frank, et al. "SINFONI in the galactic center: young stars and infrared flares in the central light-month." *ApJ* 628.1 (2005): 246.

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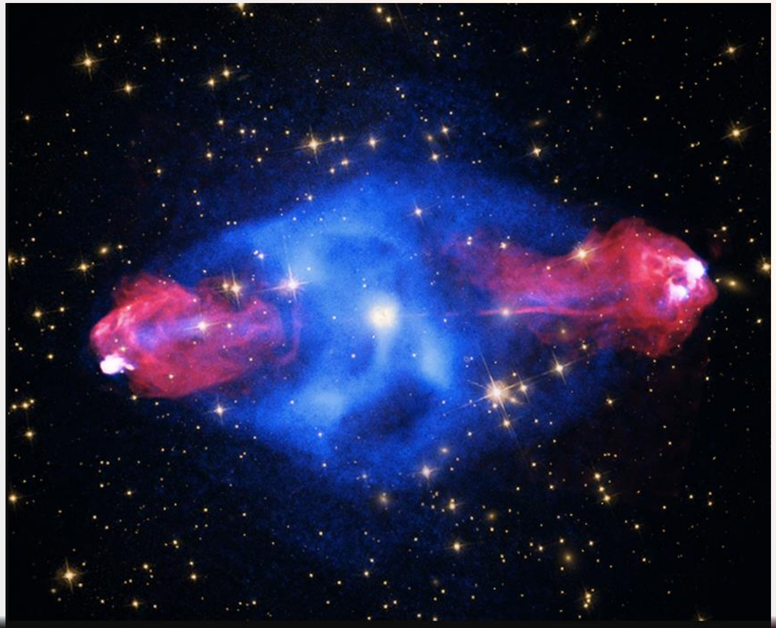

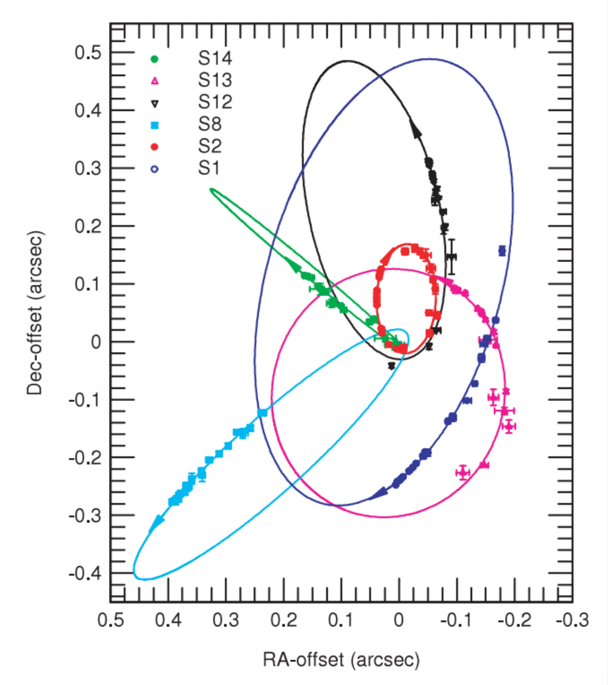

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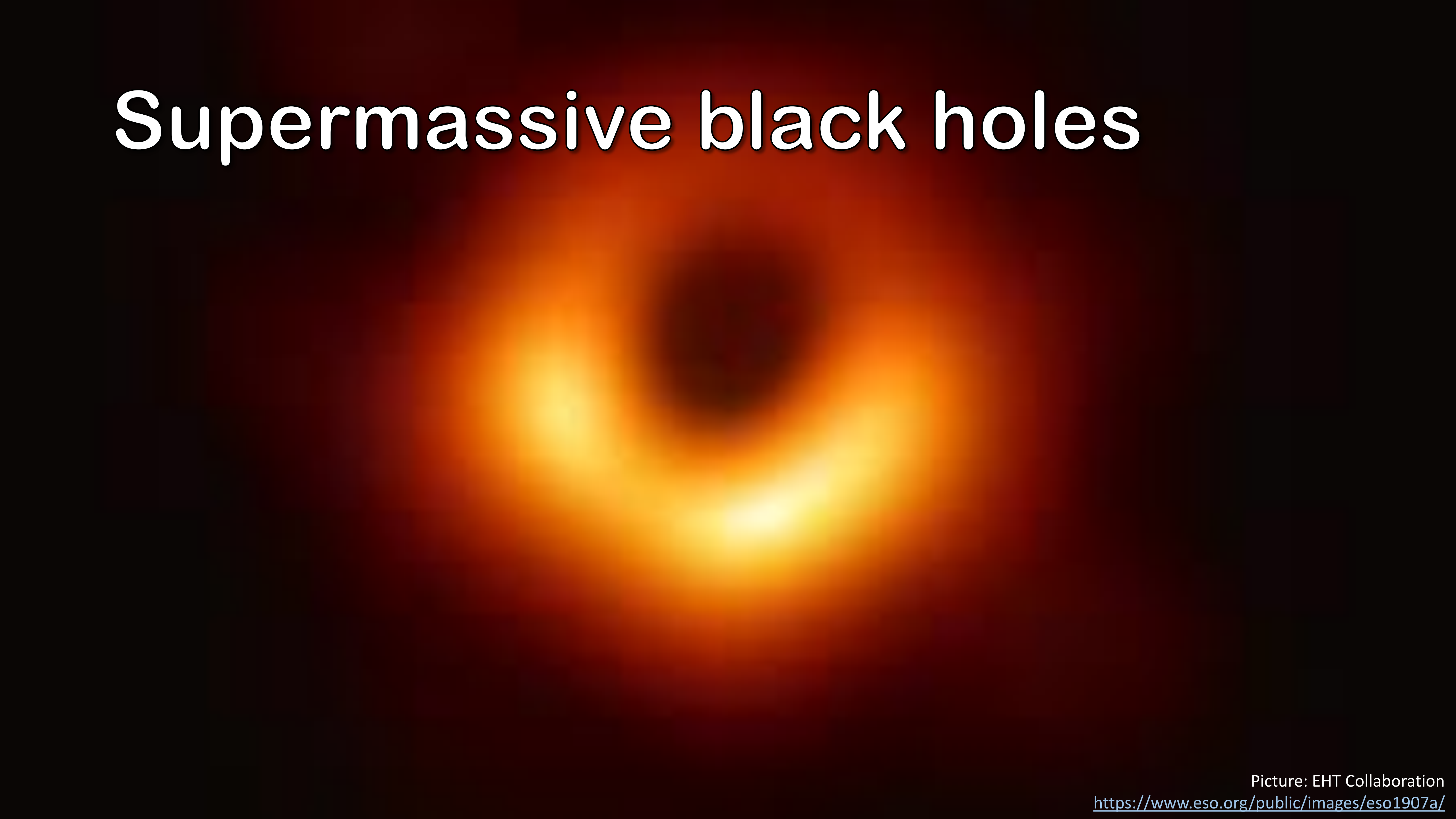
Supermassive black holes



Picture: EHT Collaboration
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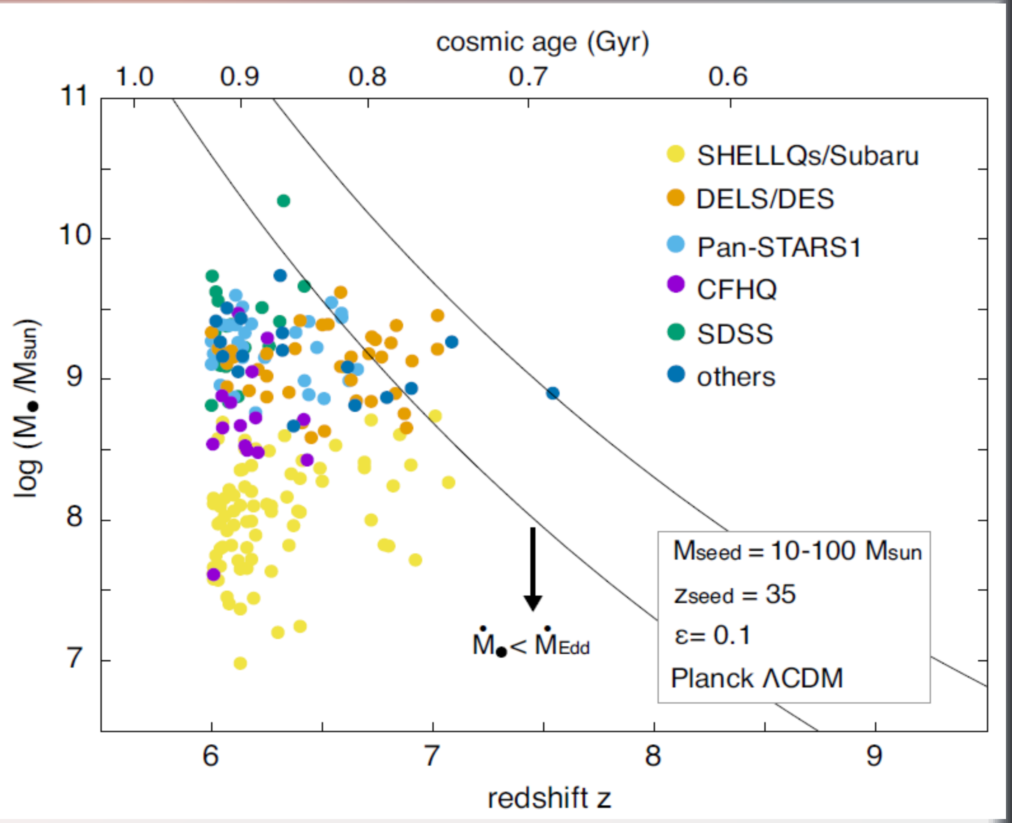
Supermassive black holes

High redshift quasar detections!

Observation at high *z* **biased** towards **most massive** and **luminous** objects (smaller ones should be much more numerous)



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Picture: EHT Collaboration
https://www.eso.org/public/images/eso1907a/

Black holes formation

Stellar mass case:

Once it runs out of nuclear fuel, any star undergoes **gravitational collapse**.

Resulting densities can be so high that the stars can collapse within its **Schwarzschild radius**, leading to a black hole.

Picture: EHT Collaboration
https://www.eso.org/public/images/eso1907a/

Transposing results to high z

At redshift $z \simeq 20 - 30$, in Dark Matter minihalos ($10^5 - 10^6 M_\odot$)

… Collapse of primordial gas clouds → Formation of first stars,

Called **Population III stars**, mass ~$10^2 M_\odot$

Picture: EHT Collaboration
https://www.eso.org/public/images/eso1907a/

Transposing results to high z

SUN

MASS: 1.989×10^{30} kilograms
RADIUS: 696,000 kilometers
LUMINOSITY: 3.85×10^{23} kilowatts
SURFACE TEMPERATURE: 5,780 kelvins
LIFETIME: 10 billion years

FIRST STARS

MASS: 100 to 1,000 solar masses
RADIUS: 4 to 14 solar radii
LUMINOSITY: 1 million to 30 million solar units
SURFACE TEMPERATURE: 100,000 to 110,000 kelvins
LIFETIME: 3 million years

From LARSON, RICHARD B., and VOLKER BROMM. “THE FIRST STARS IN THE UNIVERSE.” *Scientific American*, vol. 285, no. 6, 2001, pp. 64–71. *JSTOR*, www.jstor.org/stable/26059461.

Picture: EHT Collaboration
org/public/images/eso1907a/

Accretion, the (very) basics

Eddington accretion:
assumes spherical symmetry + hydrostatic equilibrium

Ionised (Hydrogen) gas being accreted by BH experiences:

1) Gravitational attraction
2) Repulsive radiation pressure (scattering by BH radiation)

Picture: EHT Collaboration
https://www.eso.org/public/images/eso1907a/

Accretion, the (very) basics

Eddington accretion:

gas opacity κ

Infall if $\dfrac{GMm}{r^2} \geq \dfrac{L\kappa m}{4\pi r^2 c}$, i.e. $L \leq \dfrac{4\pi GMc}{\kappa}$

Picture: EHT Collaboration
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But

$$L \iff \dot{M}$$

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

Radiative efficiency $\epsilon \approx 0.1$

Picture: EHT Collaboration
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$L \iff \dot{M}$

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

$$\boxed{\implies \dot{M} \leq \frac{4\pi G}{c\kappa\epsilon} M =: \dot{M}_{Edd}}$$

Radiative efficiency $\epsilon \approx 0.1$

Picture: EHT Collaboration
https://www.eso.org/public/images/eso1907a/

Accretion, the (very) basics

If κ & $\epsilon = \text{const.}$, at most $M(t) = M_0\, e^{\frac{4\pi G}{c\kappa\epsilon}t}$

Inserting typical values and using $M_0 = 100\, M_\odot$, $M(t) = 10^9 M_\odot$

$$\Longrightarrow\ t = \mathcal{O}(\text{age of the Universe at } z \sim 6)$$

Picture: EHT Collaboration
https://www.eso.org/public/images/eso1907a/

Accretion, the (very) basics

Simple estimates indicate that Pop. III remnants are unlikely to explain massive quasar at redshifts 6 – 7.

Two possible ways out:

1. Accretion happens faster than the Eddington limit
2. Initial seed BH is heavier than a Pop. III remnant

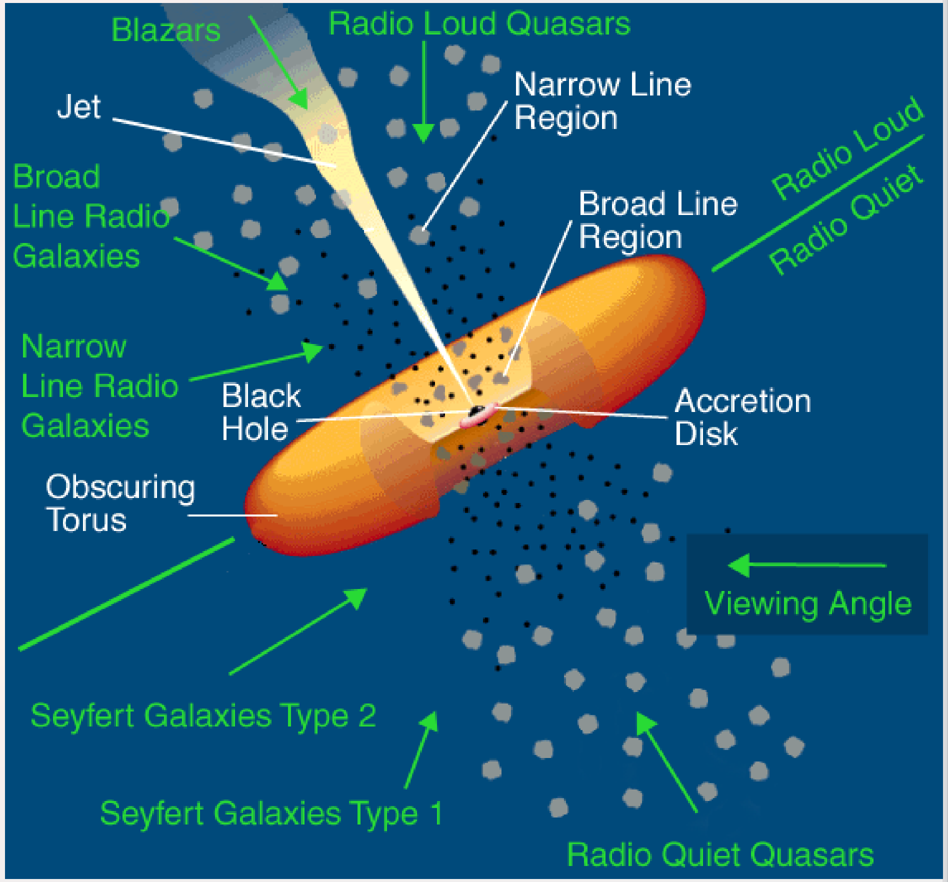
Picture: EHT Collaboration
https://www.eso.org/public/images/eso1907a/

Increasing the growth rate I

Spherical symmetry assumption practically **not valid**…

Geometrical configuration allows to **beat Eddington**!

Picture: Urry, C. M., & Padovani, P. (1995). Unified schemes for radio-loud active galactic nuclei. *Publications of the Astronomical Society of the Pacific*, *107*(715), 803.



Picture: EHT Collaboration
https://www.eso.org/public/images/eso1907a/

Increasing the growth rate II

<u>But:</u> the more active is accretion, the more there is feedback:

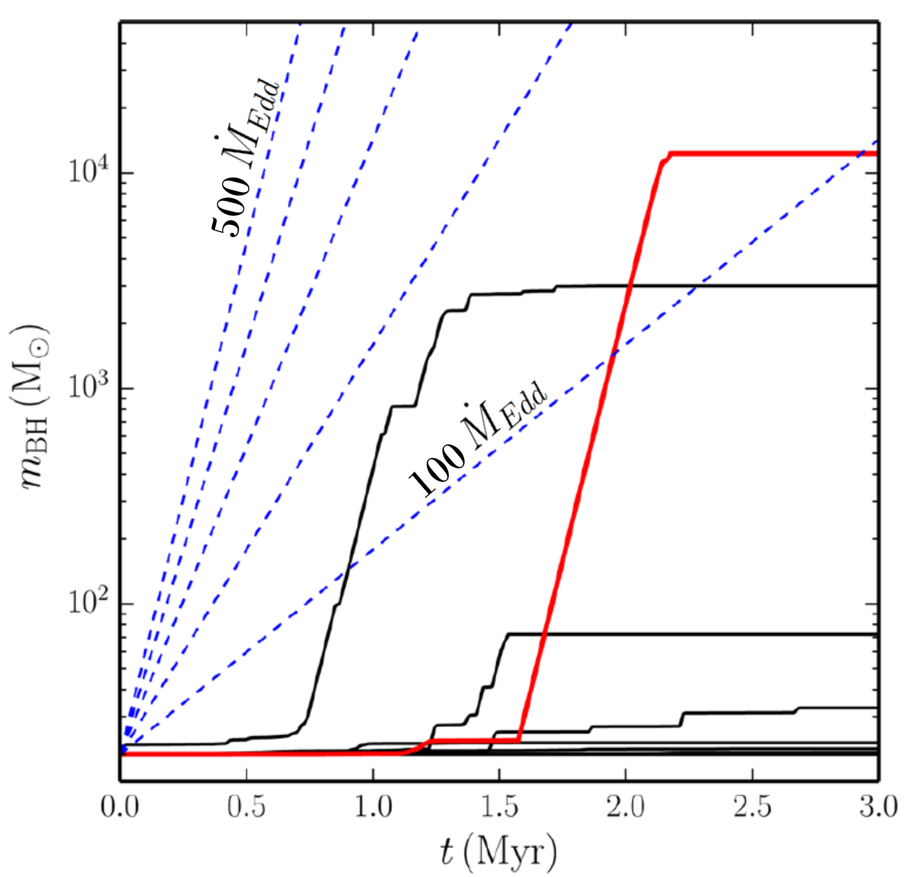
Energy and momentum injection into surroundings via

- Radiation feedback, i.e. photons
- Mechanical feedback, i.e. energetic particles

→ heats up the gas, ionises it, can unbind it … Allows activity bursts

Picture: EHT Collaboration
https://www.eso.org/public/images/eso1907a/

Increasing the growth rate III



E.g.

Lupi, A. , et al. "Growing massive black holes through supercritical accretion of stellar-mass seeds." *Monthly Notices of the Royal Astronomical Society* 456.3 (2016): 2993-3003.

Hydronamical simulation with adaptative mesh refinement.

Includes slim accretion disk, AGN thermal feedback and SN feedback models.

BH environment is that of a well formed nuclear gaseous disk

Picture: EHT Collaboration
https://www.eso.org/public/images/eso1907a/

Increasing the growth rate IV

Remember: Pop. III stars appear **in DM minihalos**, with mass ($10^5 - 10^6 M_\odot$).

Gas escape velocity in such halos is $\sim$ 1km/s

$\sim$ 0.1 sound speed

Pop. III radiation can already **blow gas out**.

Remnant BH is starved, no available material to sustain accretion

Picture: EHT Collaboration
https://www.eso.org/public/images/eso1907a/

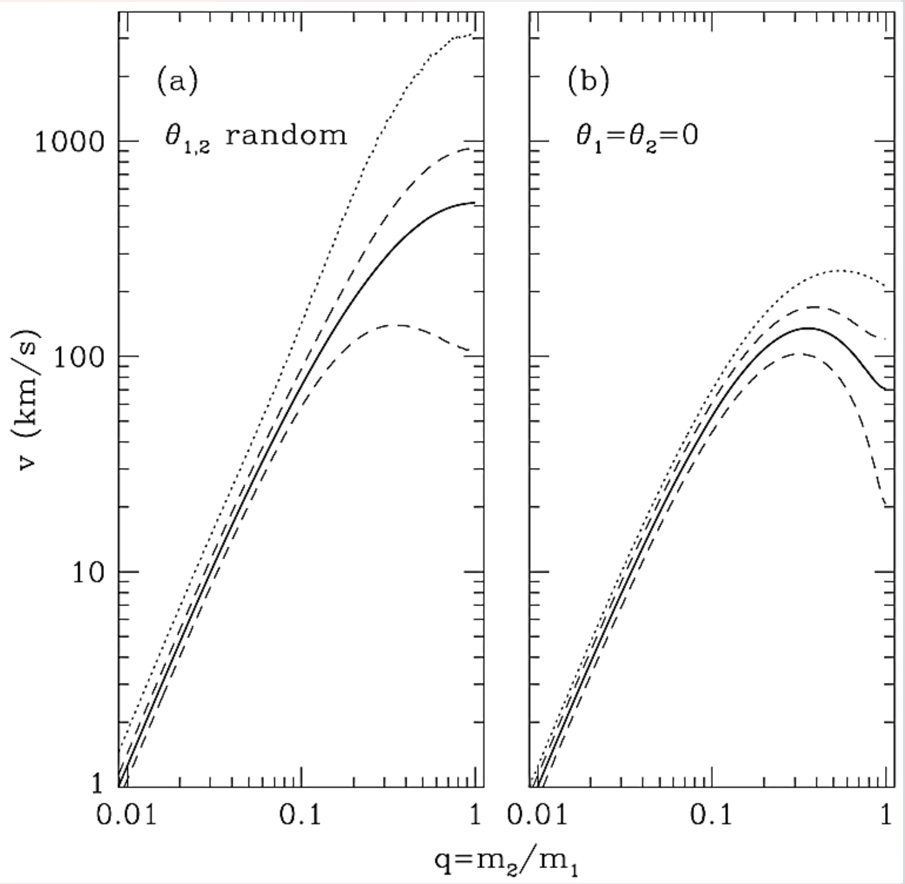
Increasing the growth rate: mergers

Mergers of Pop III remnants BH ?

Mergers induce **recoil** !
Could eject BH pairs into the IGM.

At lower z, mergers could be a viable, but secondary growth channel.

Plot: Tanaka, T., & Haiman, Z. (2009). The assembly of supermassive black holes at high redshifts. *ApJ* , *696*(2), 1798.



Picture: EHT Collaboration
https://www.eso.org/public/images/eso1907a/

Heavier black hole seeds

Keeping similar accretion mechanisms ideas, and feedback effects…

Building supermassive black holes at z = 6 would be more likely to succeed if the starting BH has a mass of

$$10^4 - 10^6 \, M_\odot$$

Instead of the $10^2 - 10^3 \, M_\odot$ from Pop. III remnants.

Picture: EHT Collaboration
https://www.eso.org/public/images/eso1907a/

Heavier black hole seeds

Going beyond Pop. III stars as original ingredient…

… and **build supermassive stars**, with $M \sim 10^4 - 10^6 M_\odot$

How ?

Suppress cooling in primordial gas clouds, to prevent fragmentation and collapse

Picture: EHT Collaboration
https://www.eso.org/public/images/eso1907a/

Heavier black hole seeds

Pop. III stars can form thanks to $\mathrm{H_2}$ cooling…

→ Suppressing $\mathrm{H_2}$:

Picture: EHT Collaboration
https://www.eso.org/public/images/eso1907a/

Heavier black hole seeds

Pop. III stars can form thanks to H_2 cooling…

→ Suppressing H_2 :

When exposed to 11 – 15 eV radiation (soft UV):

$$\mathrm{H}_2 + \gamma \longrightarrow \mathrm{H}_2^*$$

Lyman and Werner (LW) lines of H_2

Of which 10% $\mathrm{H}_2^* \longrightarrow 2\ \mathrm{H}$

Picture: EHT Collaboration
https://www.eso.org/public/images/eso1907a/

Heavier black hole seeds

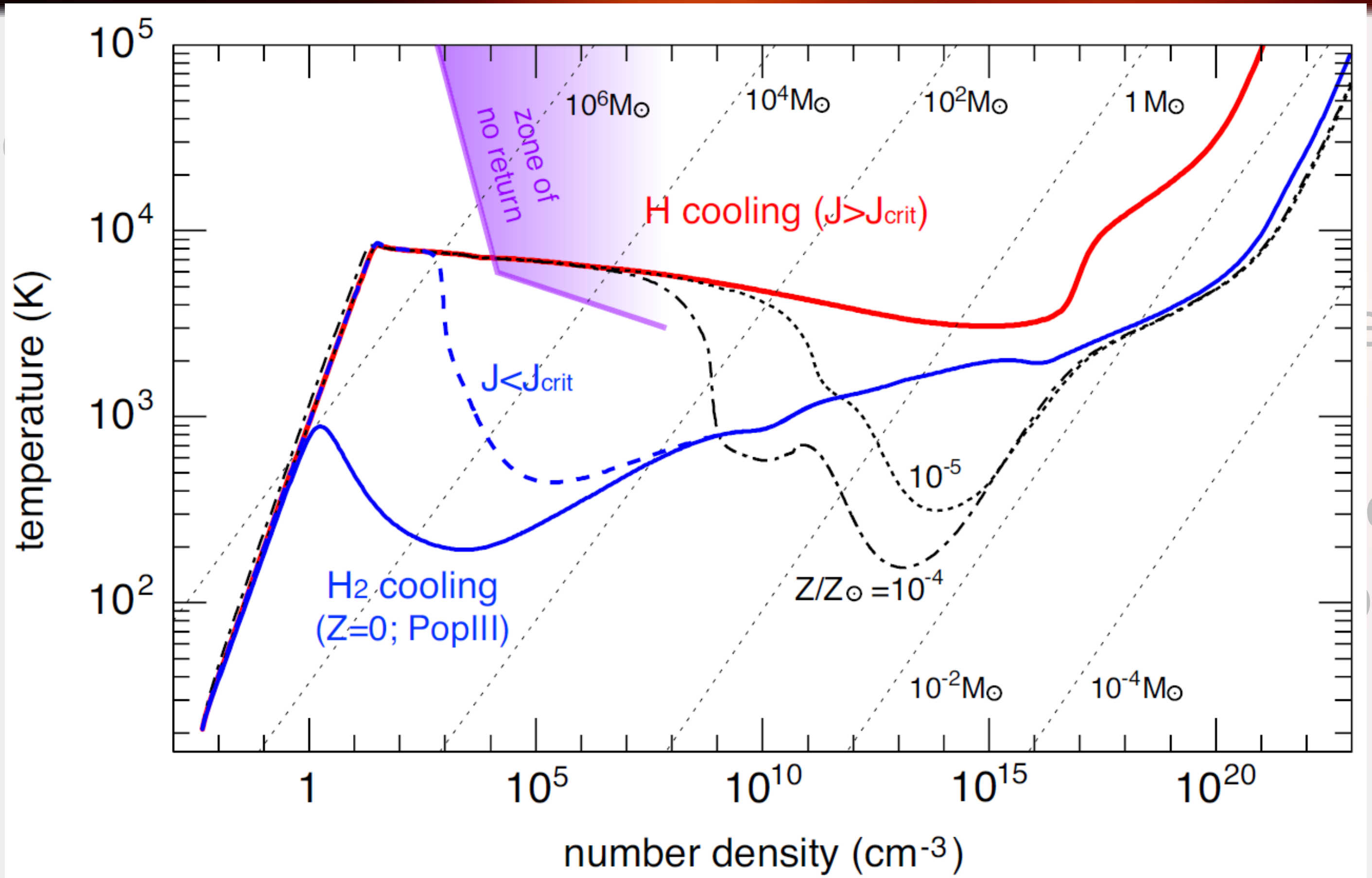
Need an external source of UV radiation:

Stars already formed in a other sufficiently nearby galaxies.

If galaxies **too far**: not enough radiation for process to hold.
If galaxies **too close**: risk of gravitational / tidal pertubations.

Picture: EHT Collaboration
https://www.eso.org/public/images/eso1907a/

Heavier black hole seeds



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Picture: EHT Collaboration
https://www.eso.org/public/images/eso1907a/

Heavier black hole seeds

Then the very massive gas clouds collapses:

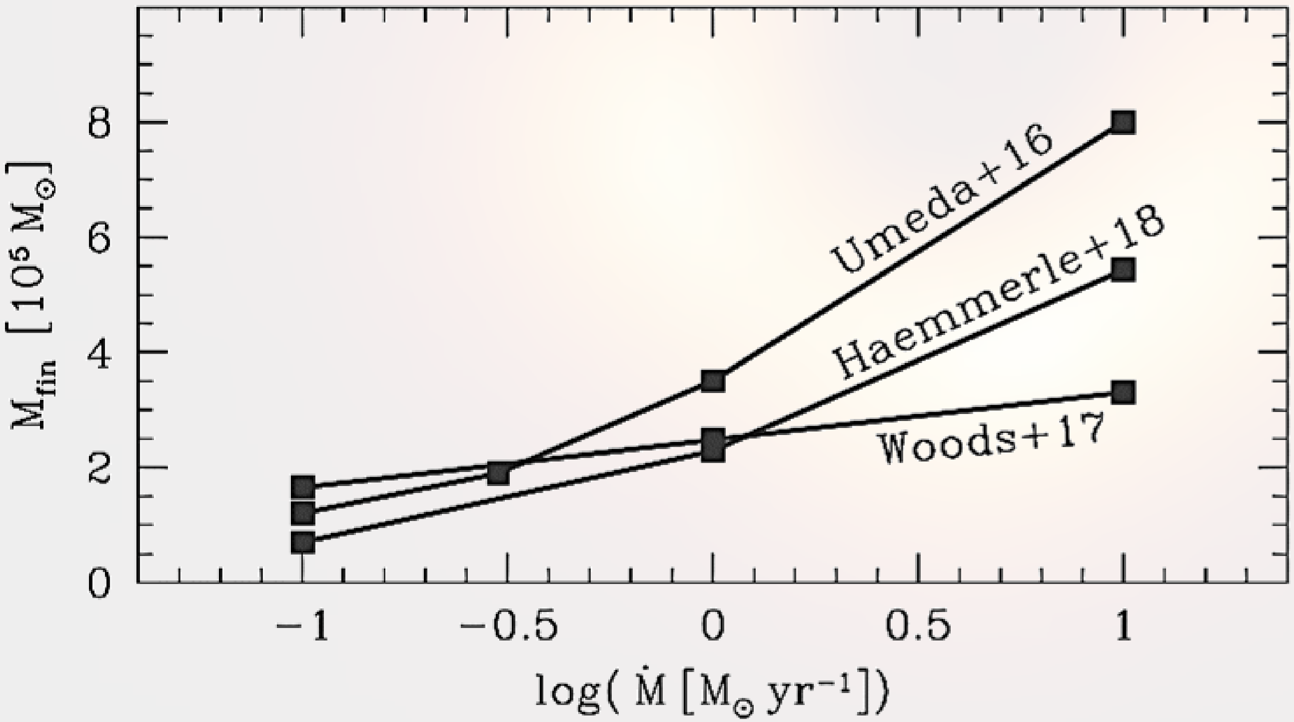
- To a single central protostar, or
- To a quasistar (star with BH at its center), in a more exotic scenario
- …

In any case, objects which then accrete huge amount of gas available from the cloud and grow massively.

Picture: EHT Collaboration
https://www.eso.org/public/images/eso1907a/

Heavier black hole seeds

The final mass of supermassive stars (~ 90 % of which ends in BH)



Plot: Woods, Tyrone E., et al. "Titans of the early Universe: The Prato statement on the origin of the first supermassive black holes." *Publications of the Astronomical Society of Australia* 36 (2019).

Picture: EHT Collaboration
https://www.eso.org/public/images/eso1907a/

Heavier black hole seeds

Conditions for H_2 suppression scenario:

Radiation from stars already formed in a other sufficiently nearby galaxies

If galaxies **too far**: not enough radiation for process to hold.

If galaxies **too close**: risk of gravitational / tidal pertubations.

Picture: EHT Collaboration
https://www.eso.org/public/images/eso1907a/

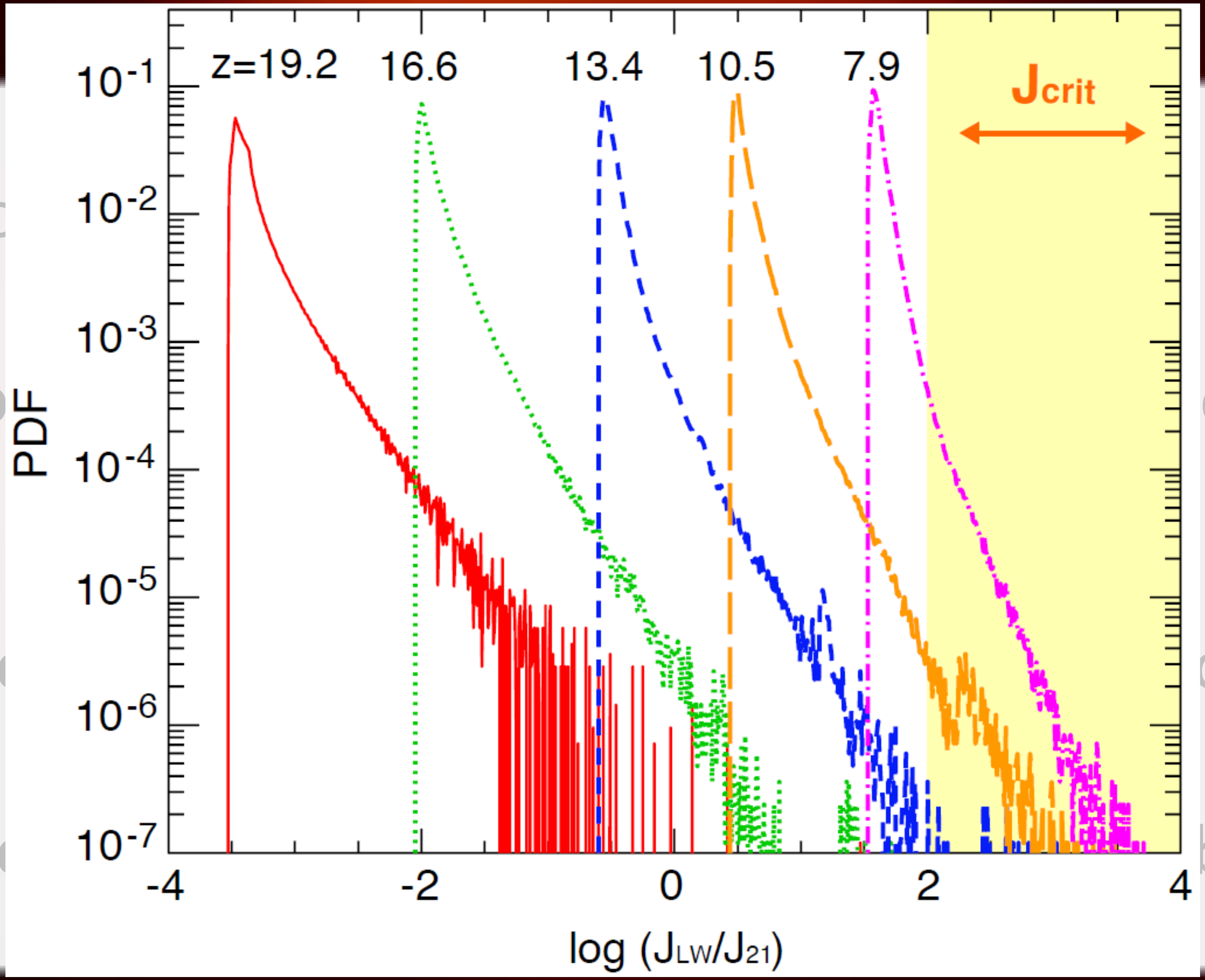
Heavier black hole seeds

Conditions fo

Radiation fro ently nearby galaxies

If galaxies to o hold.

If galaxies to bations.



Plot: Ahn K, Shapiro PR, Iliev IT, Mellema G, Pen UL. 2009. ApJ 695: 1430 - 1445

Picture: EHT Collaboration https://www.eso.org/public/images/eso1907a/

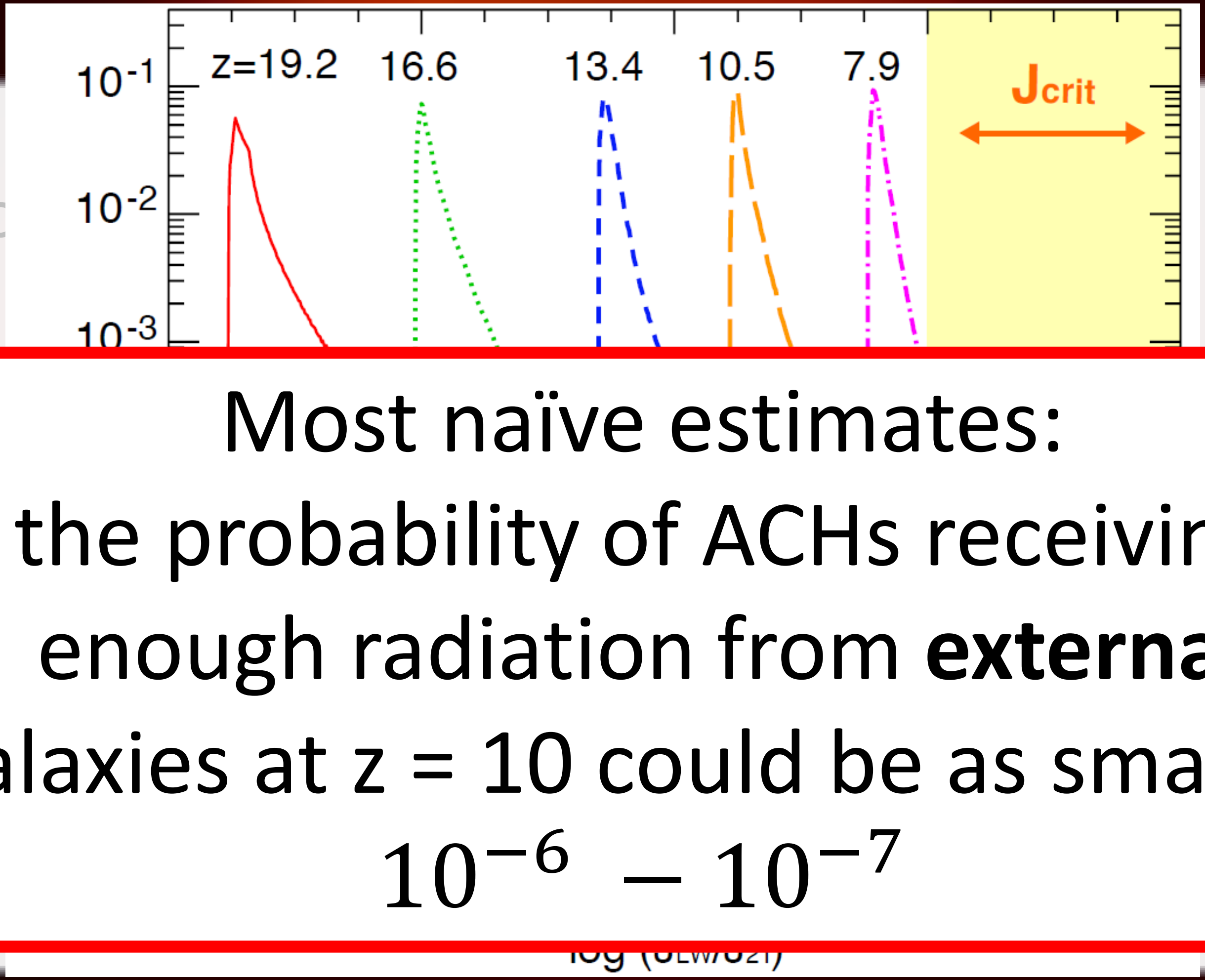
Heavier black hole seeds

Conditions fo

Radiation ... nearby galaxies

If galaxie

If galaxie ... s.



Most naïve estimates:
the probability of ACHs receiving enough radiation from **external** galaxies at z = 10 could be as small as $10^{-6} - 10^{-7}$

Plot: Ahn K, Shapiro PR, Iliev IT, Mellema G, Pen UL. 2009. ApJ 695: 1430 - 1445

Picture: EHT Collaboration
https://www.eso.org/public/images/eso1907a/

Heavier black hole seeds

Rely on additional intra-galactical irradiation from existing stars…

Difficult: causes metal pollution of the gas clouds

→ induces cooling processes
→ induces fragmentation of gas clouds

A priori unwanted!

Picture: EHT Collaboration
https://www.eso.org/public/images/eso1907a/

Heavier black hole seeds

In case of weak metal pollution (~ $10^{-5}\ \mathrm{Z}_\odot$):

No monolithic collapse into single supermassive star

But possible for heavy cloud to have collapse into a **dense cluster of light stars** (density of ~$10^{9-11}\ \mathrm{M}_\odot\ \mathrm{pc}^{-3}$). **Stars merging probable**!

Comparison: densest cluster known in Milky Way $2 \times 10^5\ \mathrm{M}_\odot\ \mathrm{pc}^{-3}$

Picture: EHT Collaboration
https://www.eso.org/public/images/eso1907a/

Heavier black hole seeds

Some simulations outcome: [1]

Star mergers can lead to a massive star with $10^4 \, M_\odot$

[1] Dunn, Glenna, et al. "Sowing Black Hole Seeds: Direct Collapse Black Hole Formation with Realistic Lyman–Werner Radiation in Cosmological Simulations." *The Astrophysical Journal* 861.1 (2018): 39.

Picture: EHT Collaboration
https://www.eso.org/public/images/eso1907a/

Plenty of more exotic channels!

- Primordial black holes
- Cosmic strings
- “Dark matter stars”
- Self-interacting dark matter
- …

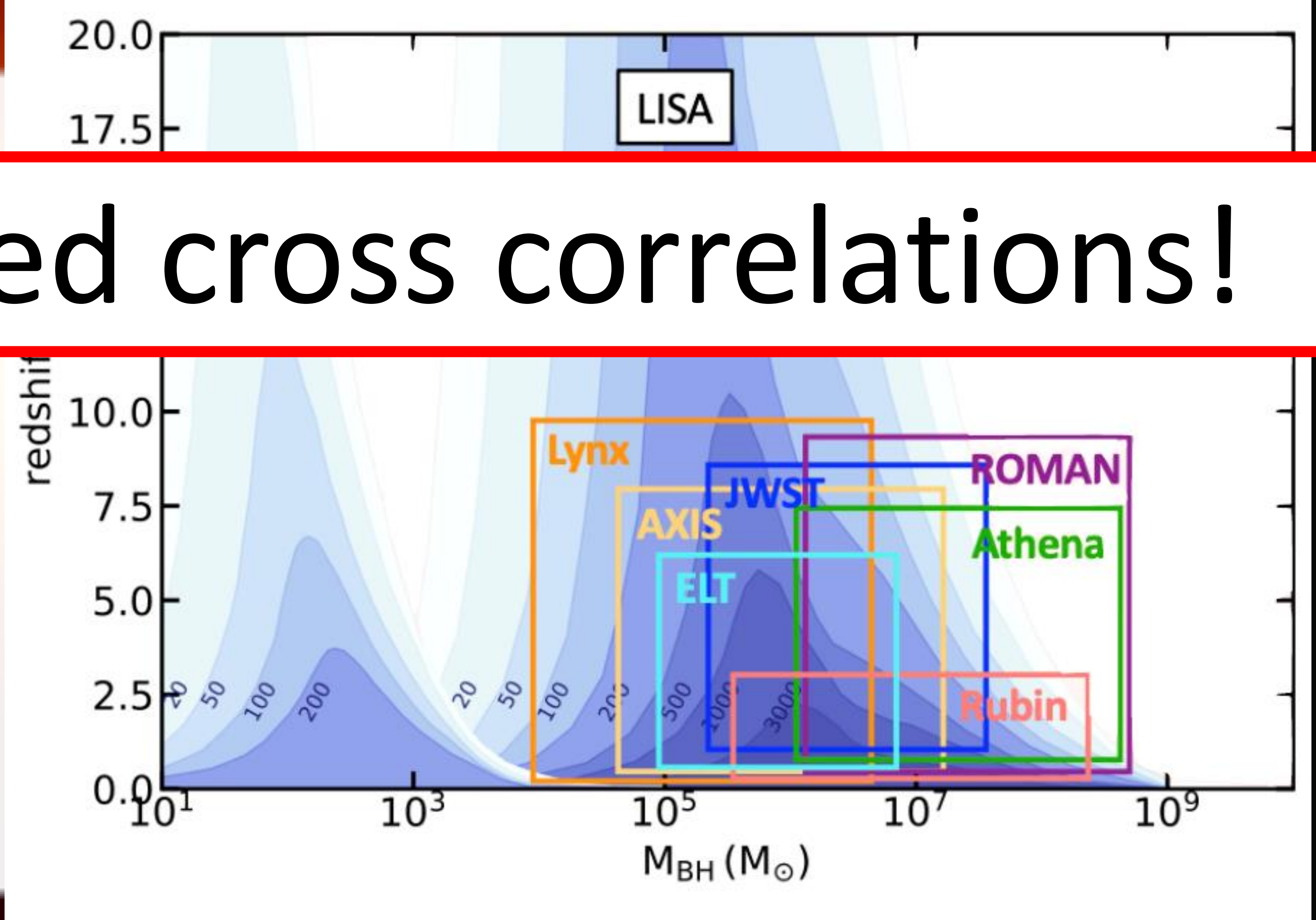
Picture: EHT Collaboration
https://www.eso.org/public/images/eso1907a/

Observation channels

Need cross correlations!

Plot taken from:

Volonteri, M., Habouzit, M., & Colpi, M. (2021). The origins of massive black holes. *Nature Reviews Physics*, *3*(11), 732-743.



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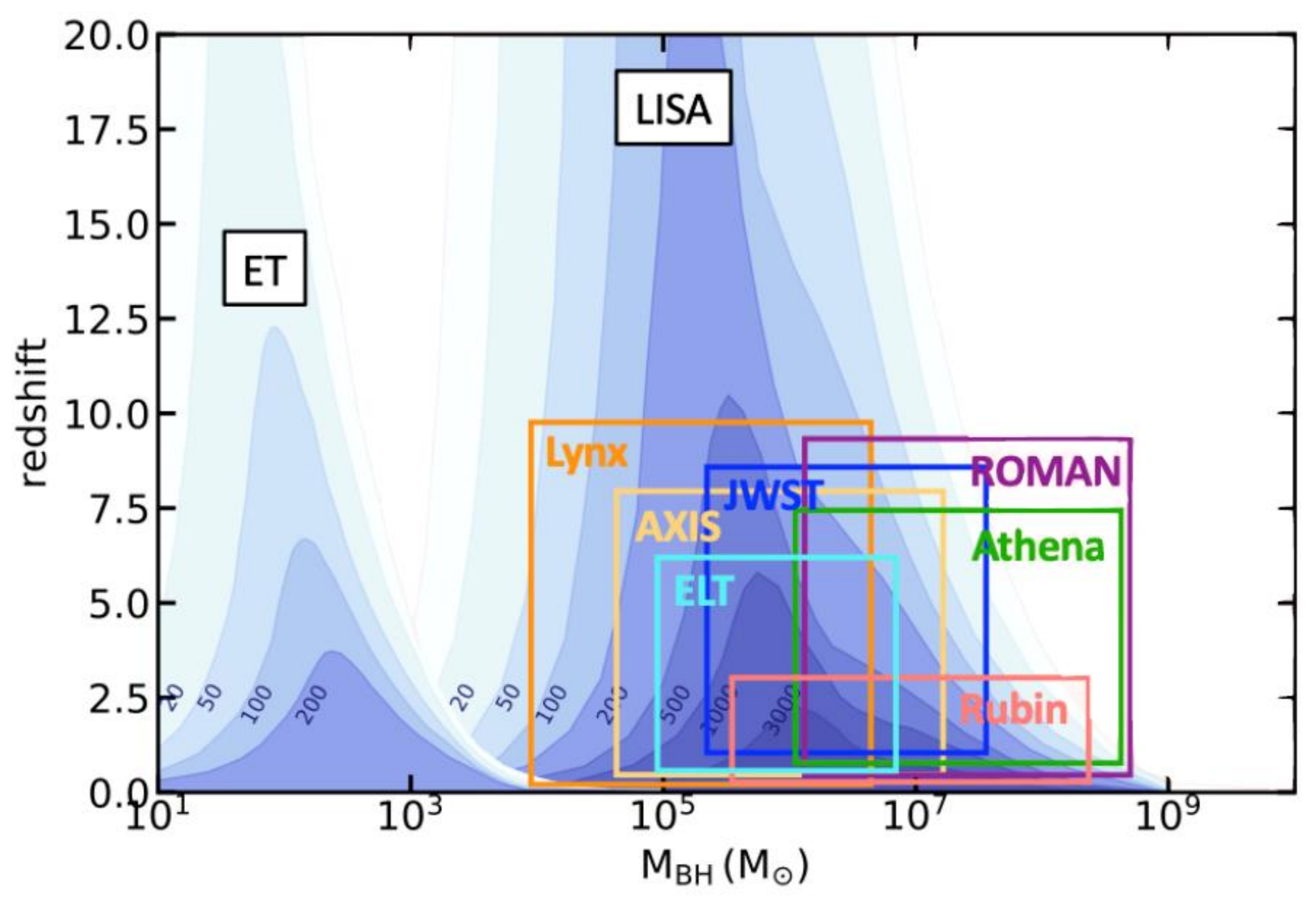


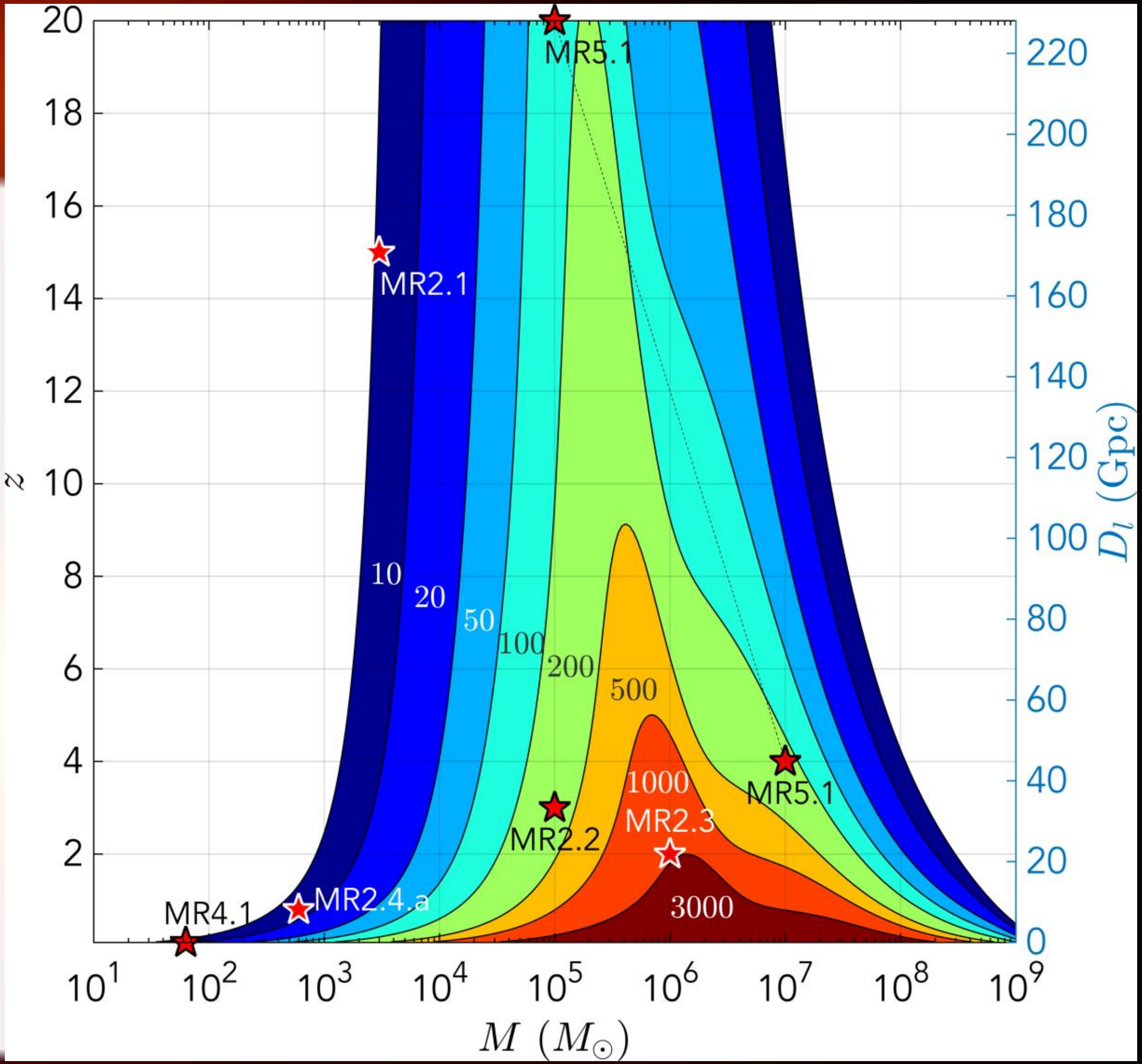
Picture: EHT Collaboration
https://www.eso.org/public/images/eso1907a/

LISA

Signal to noise contours taken from the LISA mission proposal, approved by ESA.

Plot is made for $q = 0.2$

Amaro-Seoane, P., et al. "Laser interferometer space antenna." *arXiv preprint arXiv:1702.00786* (2017).



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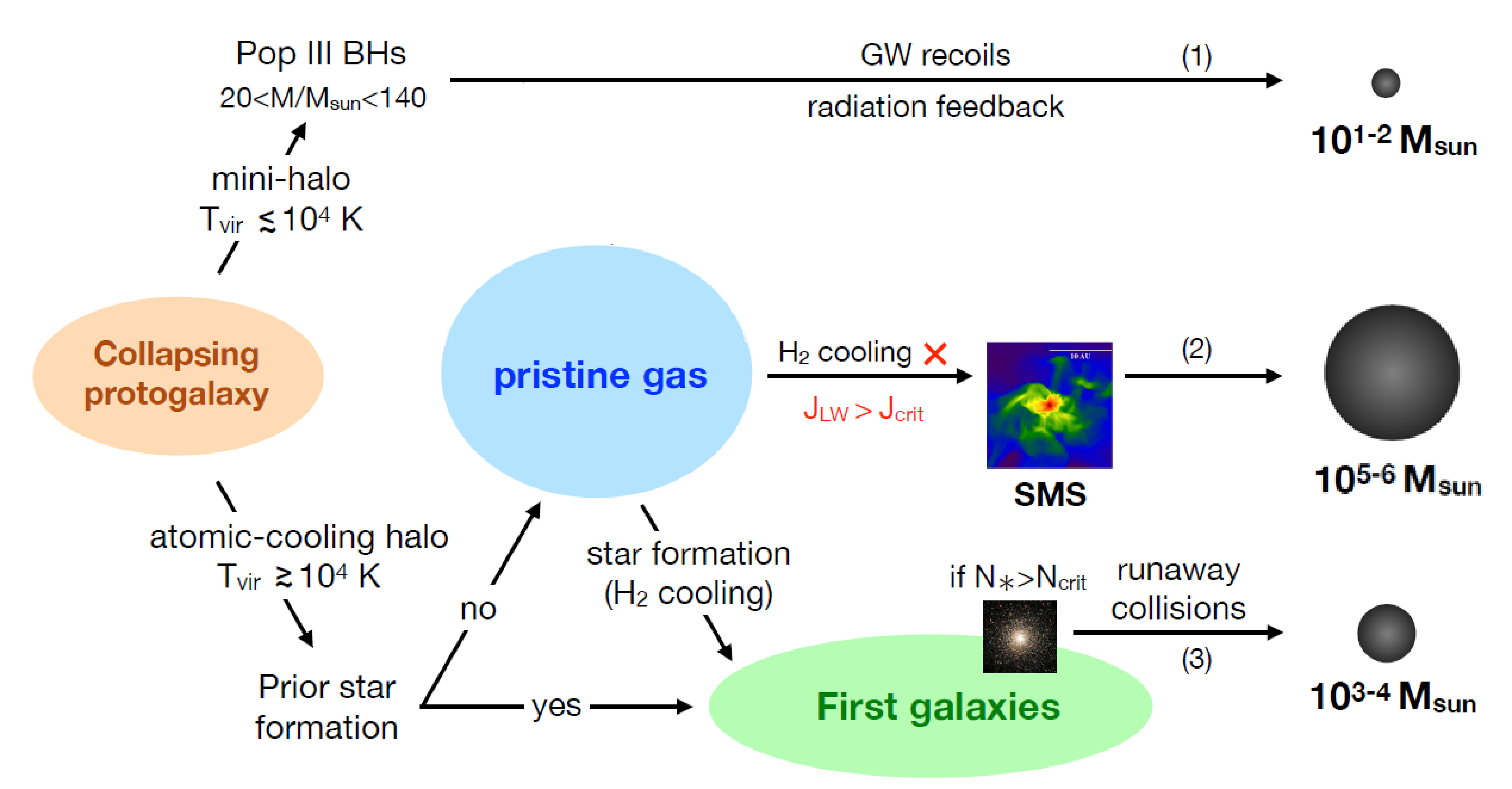
Conclusion



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ollaboration
s/eso1907a/

Thank you !

Picture: EHT Collaboration
https://www.eso.org/public/images/eso1907a/

Magnetic fields

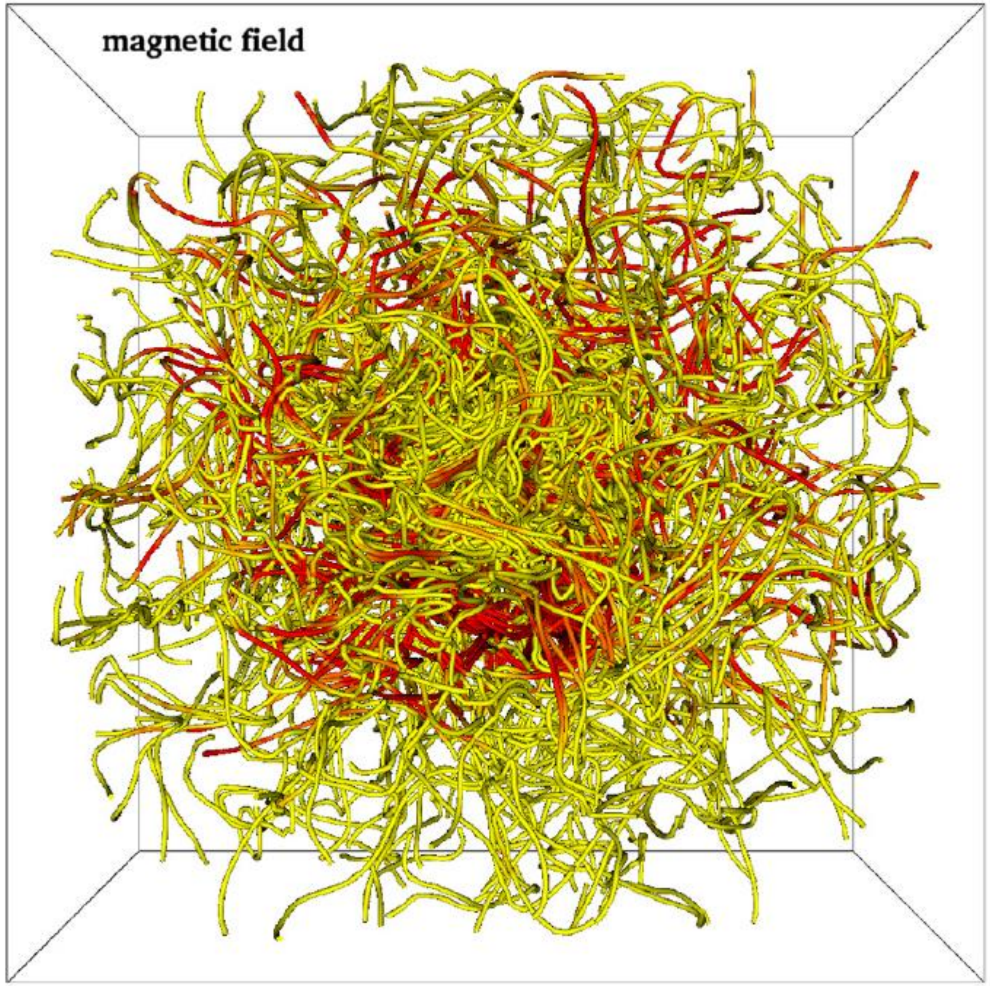


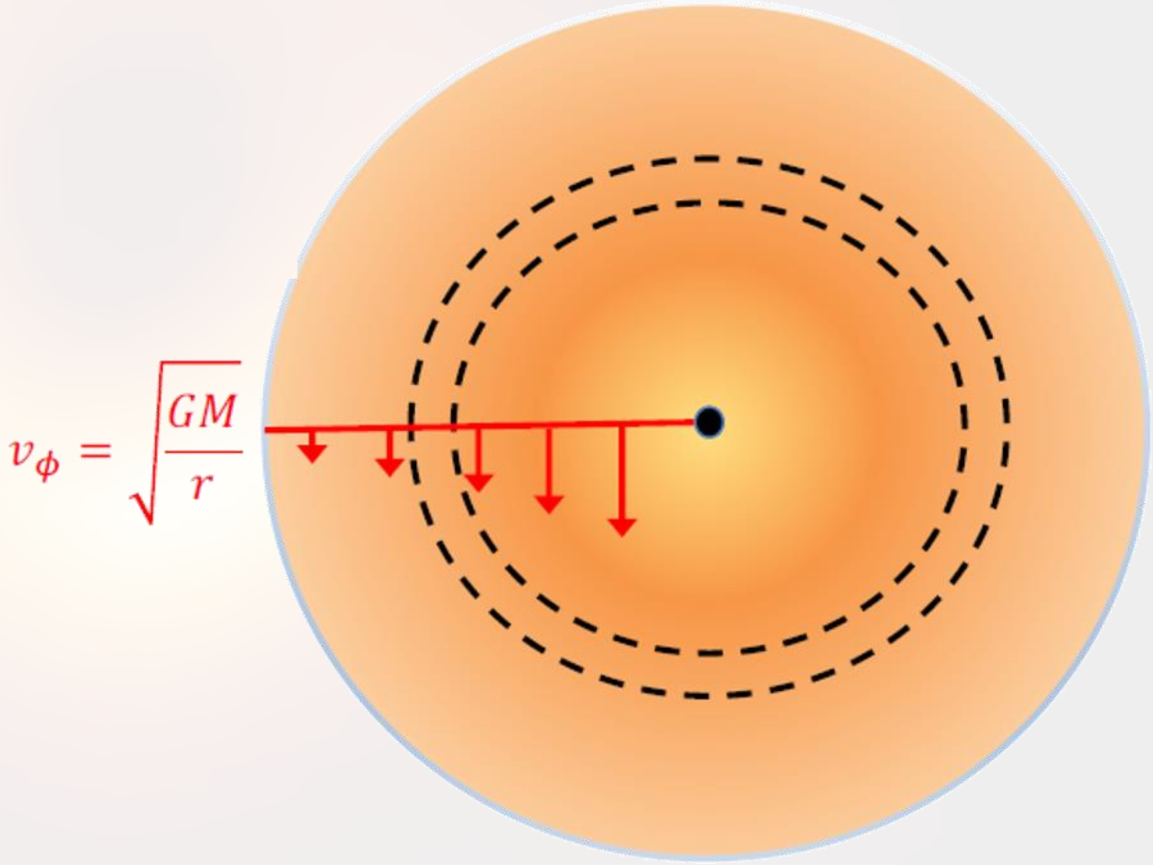
Figure 4. Magnetic field lines (yellow: 0.5 μG, red: 1 μG) illustrating the complex magnetic field structure in the centre of a contracting primordial halo resulting from the small-scale dynamo. The image is adopted from Federrath et al. (2011b).

Picture: EHT Collaboration
https://www.eso.org/public/images/eso1907a/

Angular momentum transport

Once in the accretion disk:

Need viscosity



Picture: EHT Collaboration
https://www.eso.org/public/images/eso1907a/

Angular momentum transport

Fueling the AGN:

transport gas from galactic scales, ie O(kpc), to BH scales, ie O(0.1pc)

Tidal interactions, galaxy mergers can cause unstabilities leading to angular momentum flows (with turbulences, etc.).

Breaks strict disk geometry into bar-like features.

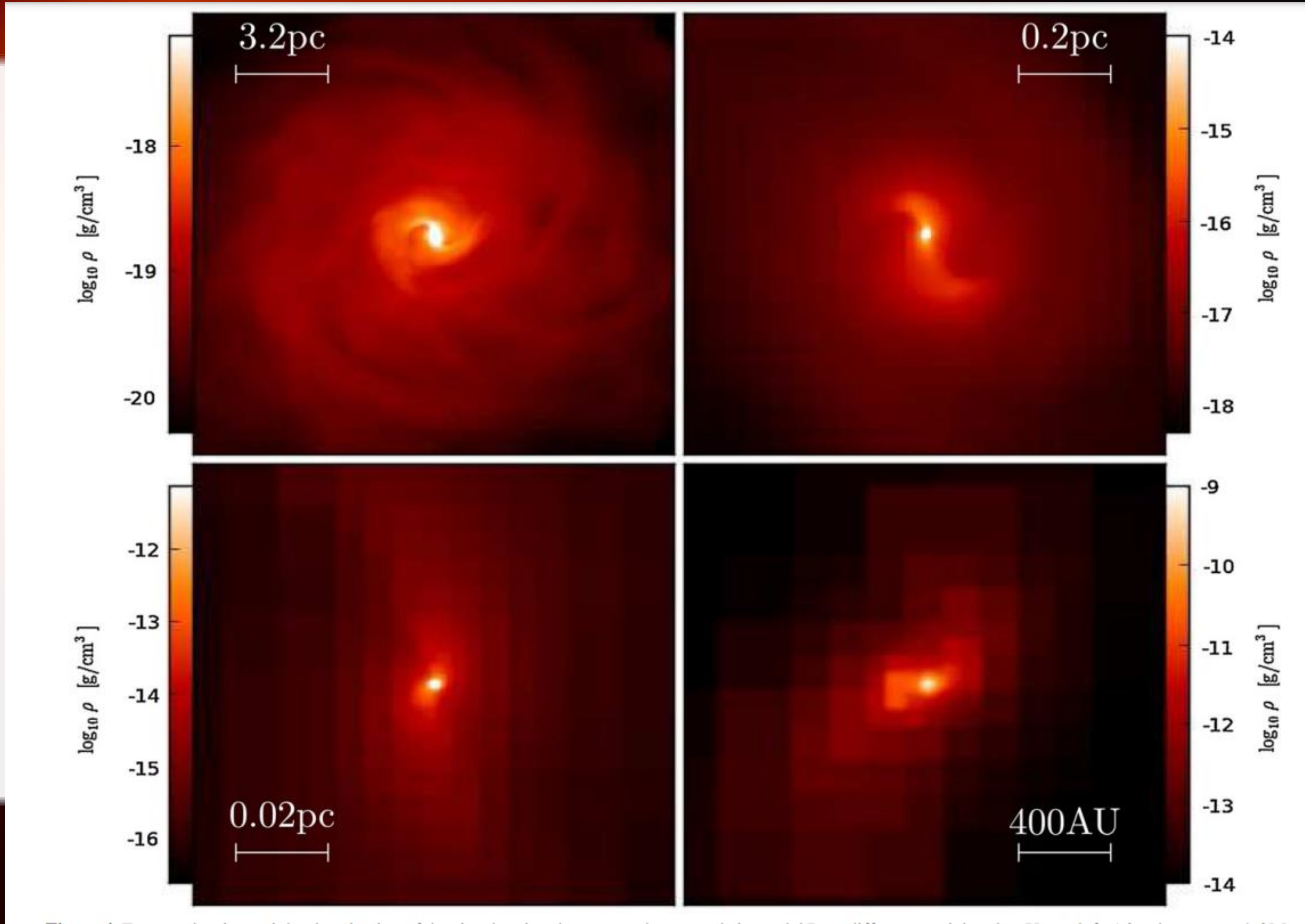
Picture: EHT Collaboration
https://www.eso.org/public/images/eso1907a/

Angular momentum transport

Cascade of bars scenarios

Plot:

Choi, J. H., Shlosman, I., & Begelman, M. C. (2013). Supermassive black hole formation at high redshifts via direct collapse: physical processes in the early stage. *The Astrophysical Journal*, *774*(2), 149.



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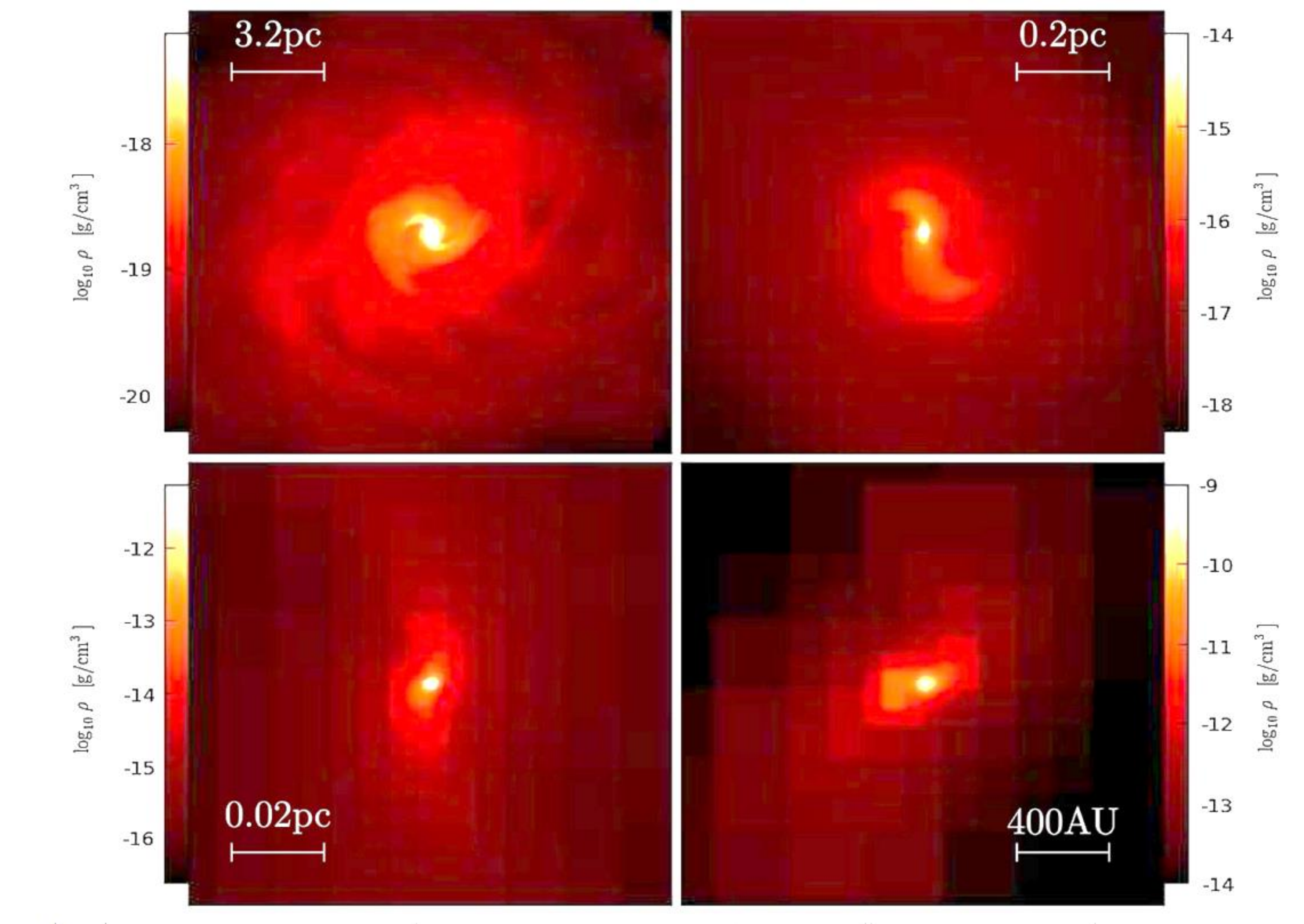

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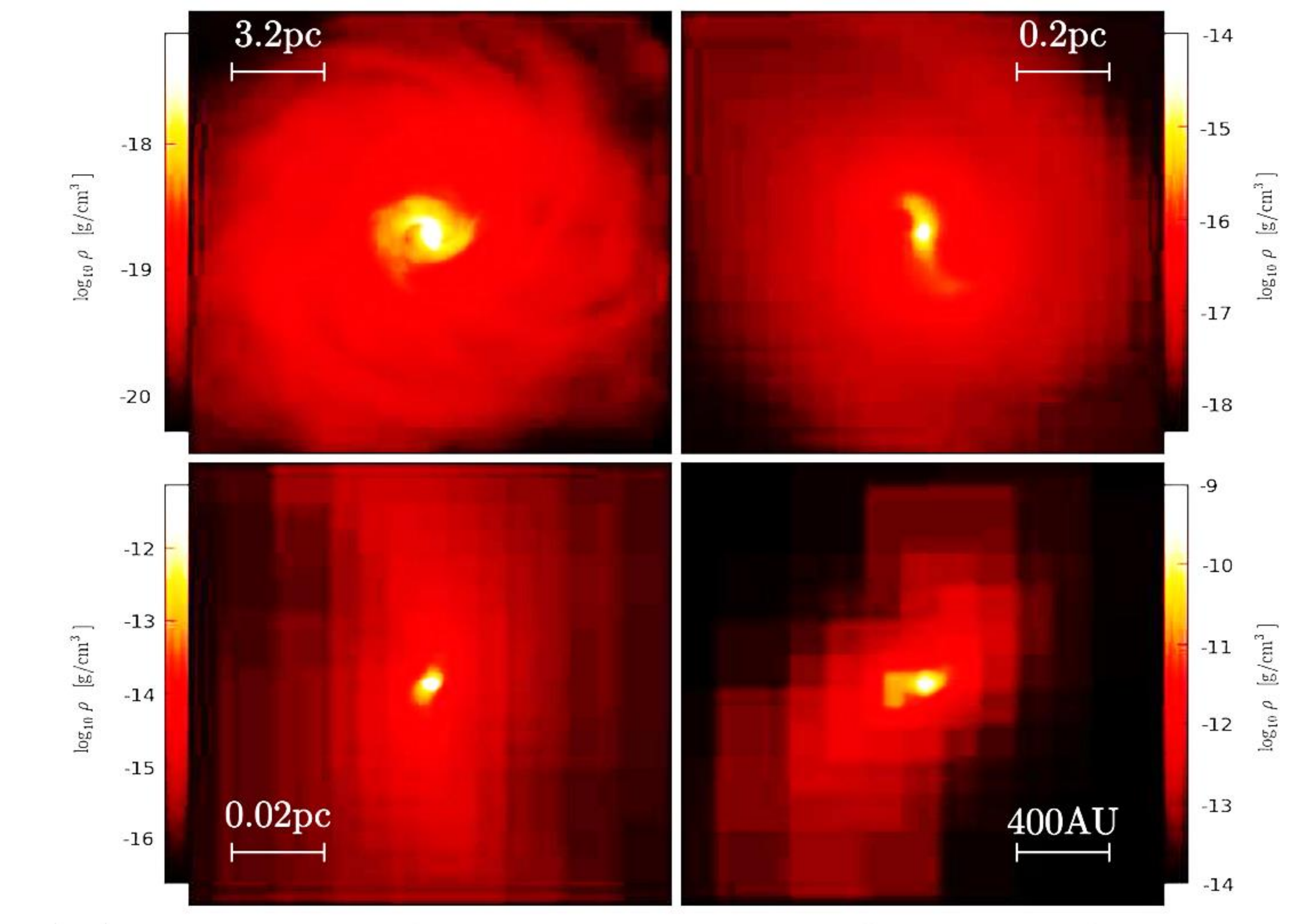

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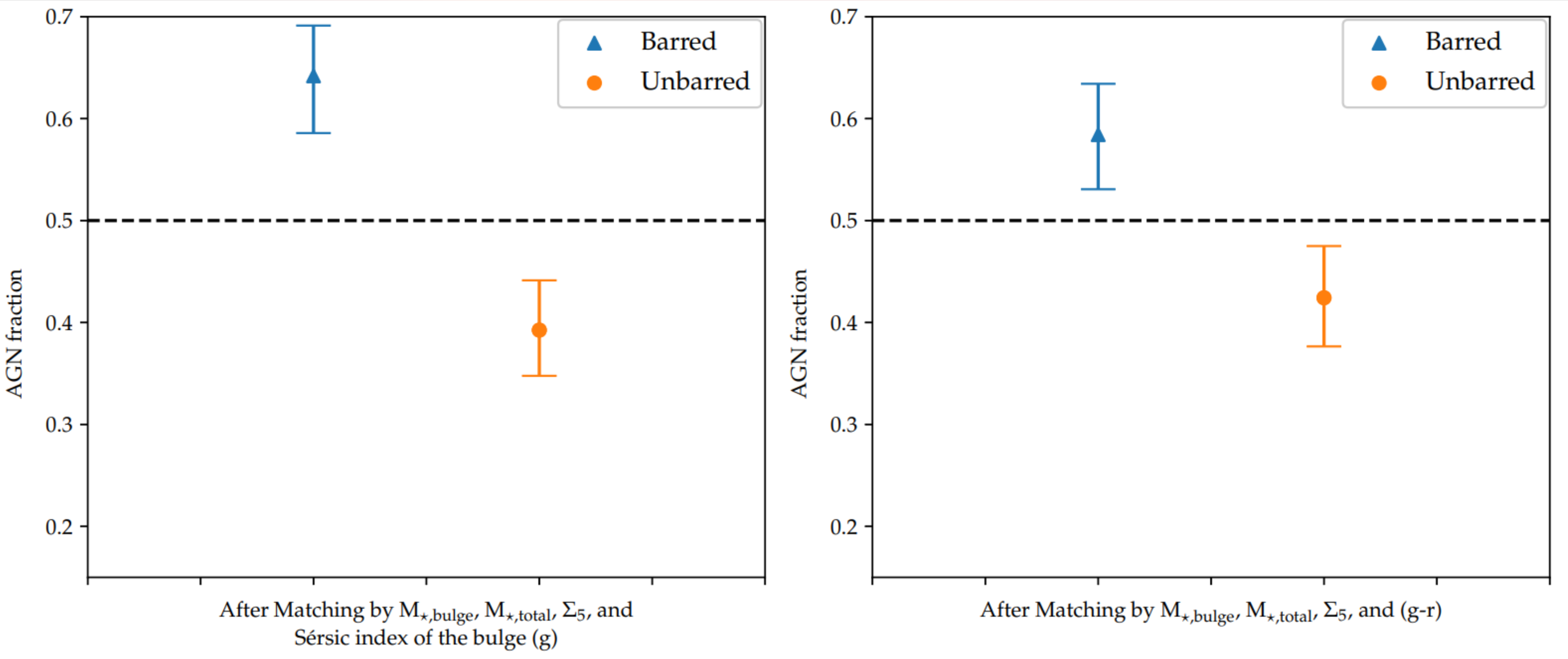

Silva-Lima, Luiz A., et al. "Revisiting the role of bars in AGN fuelling with propensity score sample matching." *Astronomy & Astrophysics* 661 (2022): A105.

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$L \iff \dot{M}$

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

$$\boxed{\implies \dot{M} \leq \frac{4\pi G}{c\kappa\epsilon} M =: \dot{M}_{Edd}}$$

Radiative efficiency $\epsilon \approx 0.1$

Picture: EHT Collaboration
https://www.eso.org/public/images/eso1907a/

Supermassive consequences ?

Consequences of the existence of SMBH, from the point of view of **gravitational attraction**:

Can define a **radius of gravitational influence** r_{infl}
One possibility:

$$M_{stellar,\,encl.}(r) = 2M_{BH} \quad \text{at} \quad r = r_{infl}$$

Picture: EHT Collaboration
https://www.eso.org/public/images/eso1907a/

Supermassive consequences ?

Consequences of the existence of SMBH, from the point of view of **gravitational attraction**:

Milky Way:

$$r_{BH} \approx 4 \cdot 10^{-7} \text{ pc}$$

$$r_{infl} \approx 2 - 3 \text{ pc}$$

$$r_{galaxy\ central\ part} \sim 1'000 \text{ pc}$$

$$r_{galaxy\ disk} > 26'000 \text{ pc}$$

Picture: EHT Collaboration
https://www.eso.org/public/images/eso1907a/

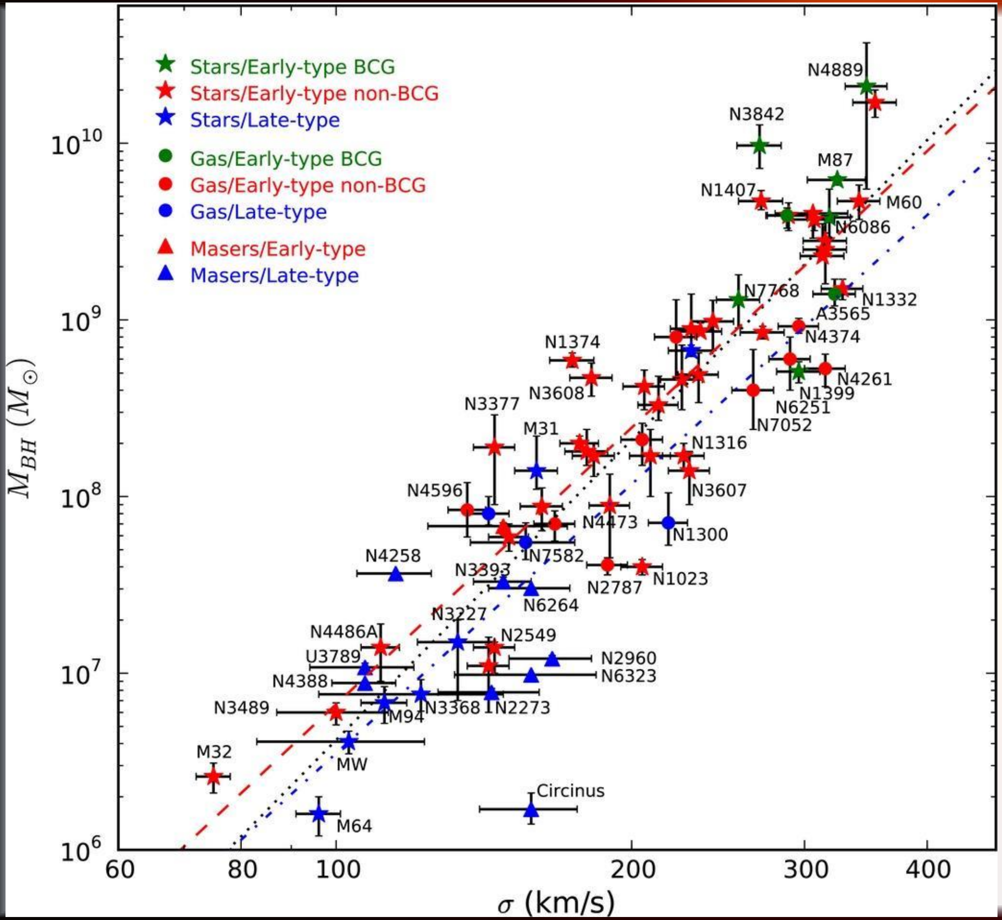
Supermassive consequences ?

The gravitational radius of influence is **completely negligible** at the scale of a galaxy.

Supermassive black holes $\leftrightarrow$ "Superweak" consequences ?

Picture: EHT Collaboration
https://www.eso.org/public/images/eso1907a/

But … The M-σ relation



There is a **strong correlation** between the mass of a supermassive black hole and the stellar velocity in the galaxy center

from *Revisiting the Scaling Relations of Black Hole Masses and Host Galaxy Properties*
McConnell & Ma 2013 ApJ 764 184 doi:10.1088/0004-637X/764/2/184
http://dx.doi.org/10.1088/0004-637X/764/2/184

Picture: EHT Collaboration
https://www.eso.org/public/images/eso1907a/

But … The M-σ relation

This suggests that there is some physics **linking black hole scales and galactic scales.**

We have seen that **gravity cannot play this role**!

Picture: EHT Collaboration
https://www.eso.org/public/images/eso1907a/

Accretion, the (very) basics

$$\text{If } \kappa \;\&\; \epsilon = \text{const., at most } M(t) = M_0 \, e^{\frac{4\pi G}{c\kappa\epsilon} t}$$

Inserting typical values and using $M_0 = 100\, M_\odot$, $M(t) = 10^9 M_\odot$

$$\Longrightarrow \; t = \mathcal{O}(\text{age of the Universe at } z \sim 6)$$

Picture: EHT Collaboration
https://www.eso.org/public/images/eso1907a/

Black holes beyond gravity

If black holes were only about gravity sinks:

- No reason to expect the M-σ relation
- Problems with numerical simulations:
  - Too high star formation rates in high mass galaxies
  - Too many massive galaxies

Picture: EHT Collaboration
https://www.eso.org/public/images/eso1907a/

Black holes beyond gravity

Observational fact:

In active accretion phases, **black holes release energy and momentum.**

This emission can be :

- **radiative**, i.e. energetic photons → “wind” mode
- **mechanical**, i.e. energetic particles → “jet” mode

Picture: EHT Collaboration
https://www.eso.org/public/images/eso1907a/

Active Galactic Nuclei

Energy injections via AGN are appealing because:

- This provides a new track in **building models of the M-σ relation**
- High energy injection could **disable some gas cooling**, and thus lower star formation rates → quenching mechanism
- Possibility for the **gas to be blown away** also limits objects formation

Picture: EHT Collaboration
https://www.eso.org/public/images/eso1907a/

Feedback on star formation

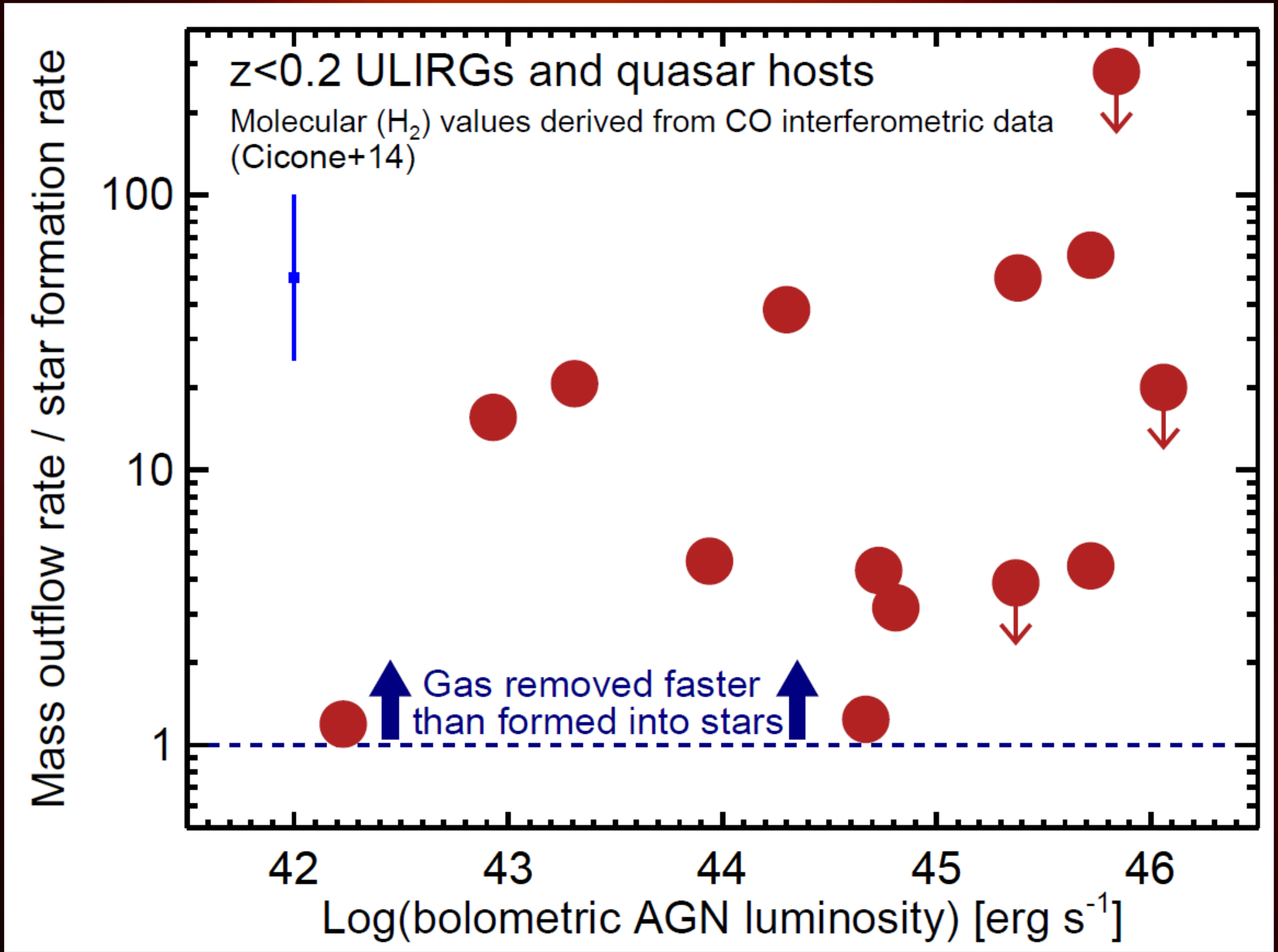
How big can we expect the effect to be?

Accretion physics tells us that **~ 10%** of the the rest-mass energy of accreted material is **released back**.

This is more than gravitational binding energy of a galaxy bulge!
→ **Much more than we need !**
Only a fraction of the released energy will couple to the gas

Picture: EHT Collaboration
https://www.eso.org/public/images/eso1907a/

Feedback on star formation



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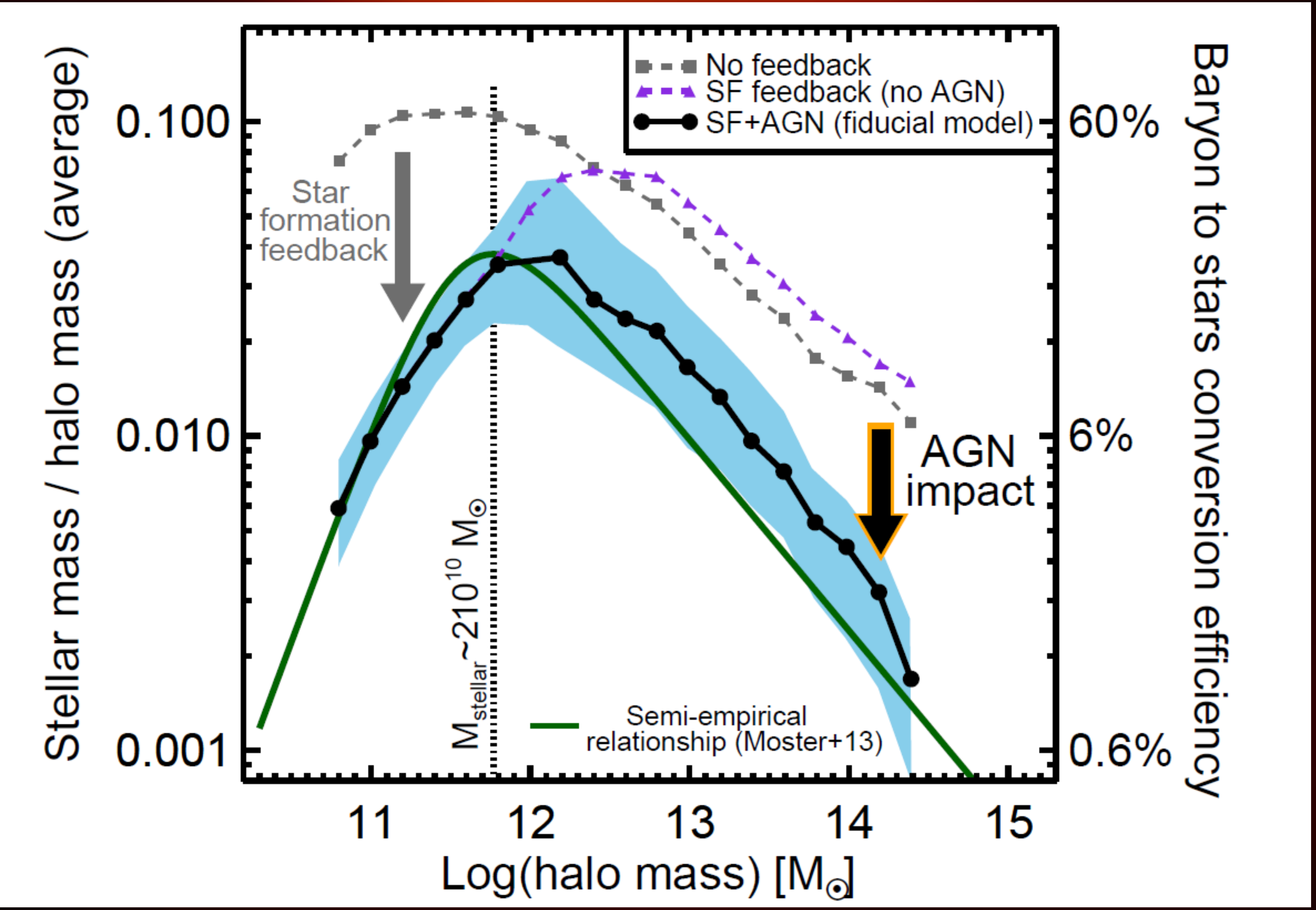
Feedback on star formation



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