Formation and Cosmic Evolution of Massive Black Holes

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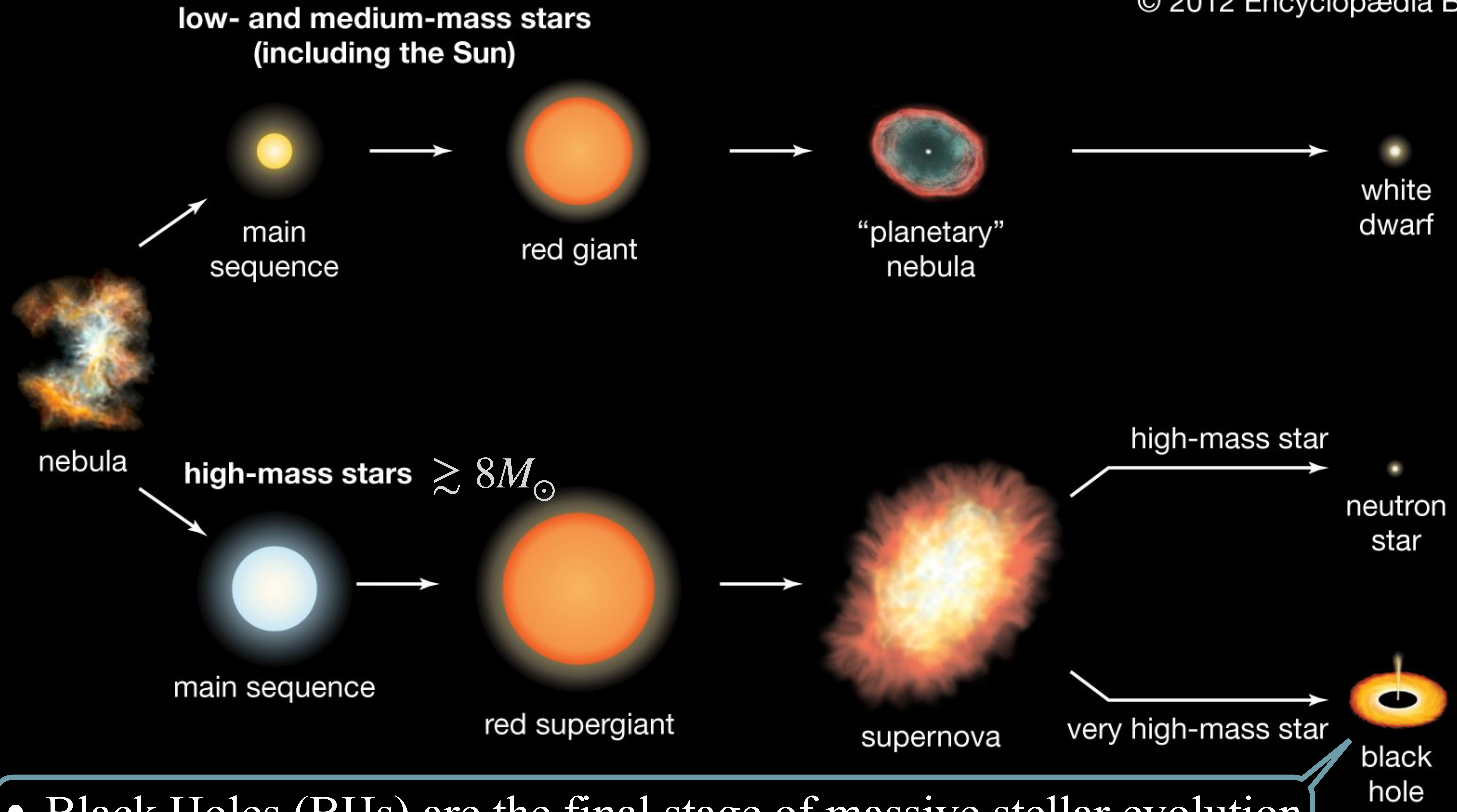
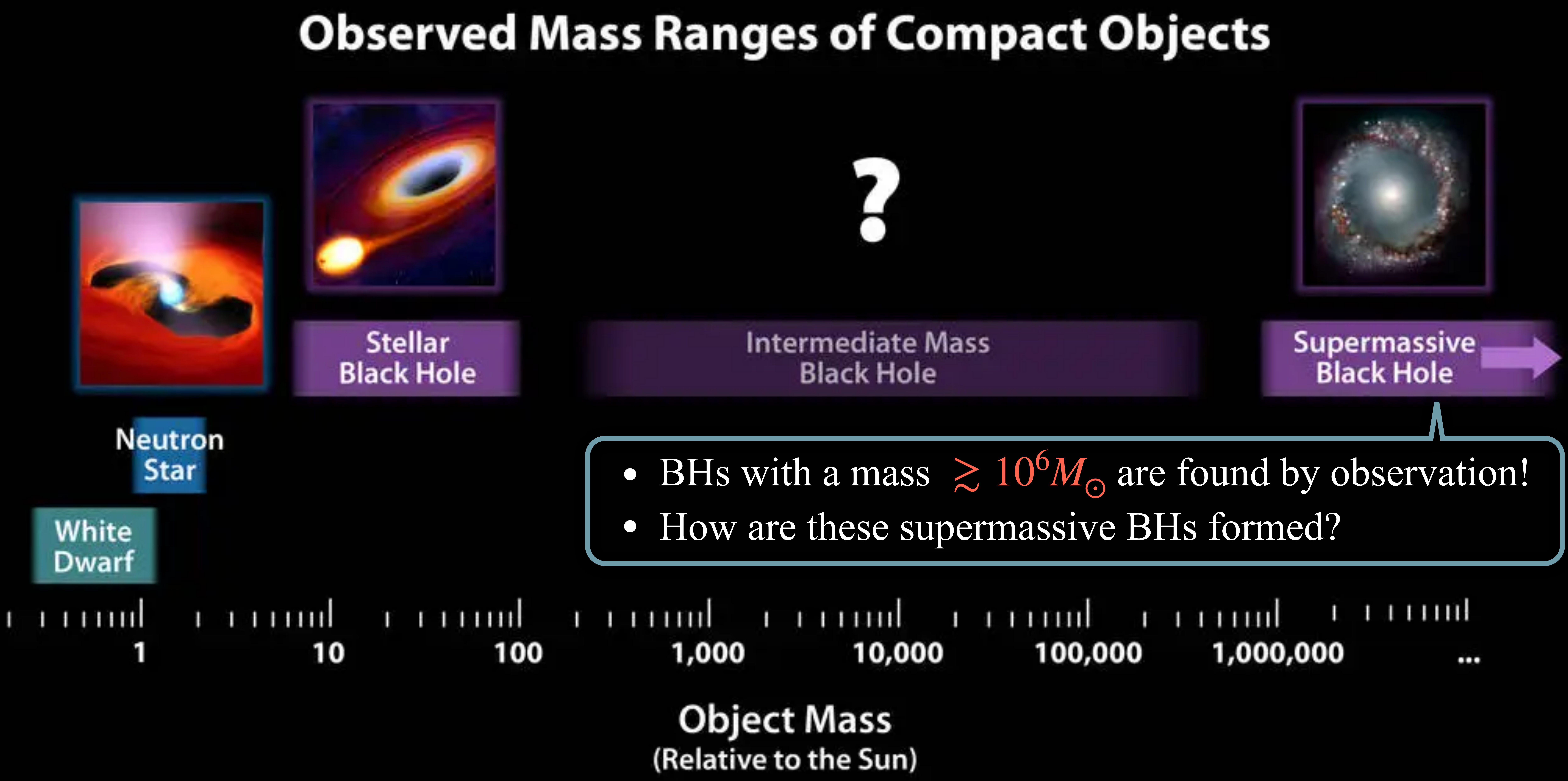
宇宙物理学 2025/06/20



- Black Holes (BHs) are the final stage of massive stellar evolution
- Typical BH mass based on stellar evolution is $\sim$ a few $\times 10M_{\odot}$



- BHs with a mass $\gtrsim 10^6 M_\odot$ are found by observation!
- How are these supermassive BHs formed?

Credit: NASA/JPL-Caltech：https://www.nasa.gov/image-article/mass-chart-dead-stars-black-holes/

History of Supermassive BHs (1784~)

1784 — John Michell
First theoritical idea (classical mechanics)

Optics

1908 — Edward Faith
Observing spectra of Spiral nebula w/ peculiar features
NGC1068

1915-16 — Albert Einstein, Karl Schwarzschild
General theory of relativity

1918 — Heber D. Curtis
First to notice the astrophysical jet
M87

Establishment of galaxy theory

1943 — Carl Seyfert
Seyfert Galaxy

1963 — Maarten Schmidt
Quasar
3C273

Muti-waves observation

2019 — Event Horizon Telescope (EHT)
First BH image

Talk's Outline

■ Observation Properties of Supermassive Black Holes

- How Do We Observe Black Holes (BHs)?
- Accretion onto BHs
- Active Galactic Nucleus (AGNs)
- What Suggests the Existence of Supermassive BHs?
- Supermassive BHs in Our Galaxy
- Supermassive BHs in High-z Universe
- Co-Evolution: Central massive BHs and Host Galaxies

■ Theoritical Model of Formation Process of Supermassive Black Holes

- How to study SMBH formation
- Theoretical Scenario of SMBH Formation
- Seed BH Formation
- Seed BH Evolution
- Simultion of BH Accretion

Observation

How Do We Observe Black Holes?

Accretion onto Black Holes (Theory 1970s~)

Gravitaional Energy

↓

Kinetic (Rotational) Energy

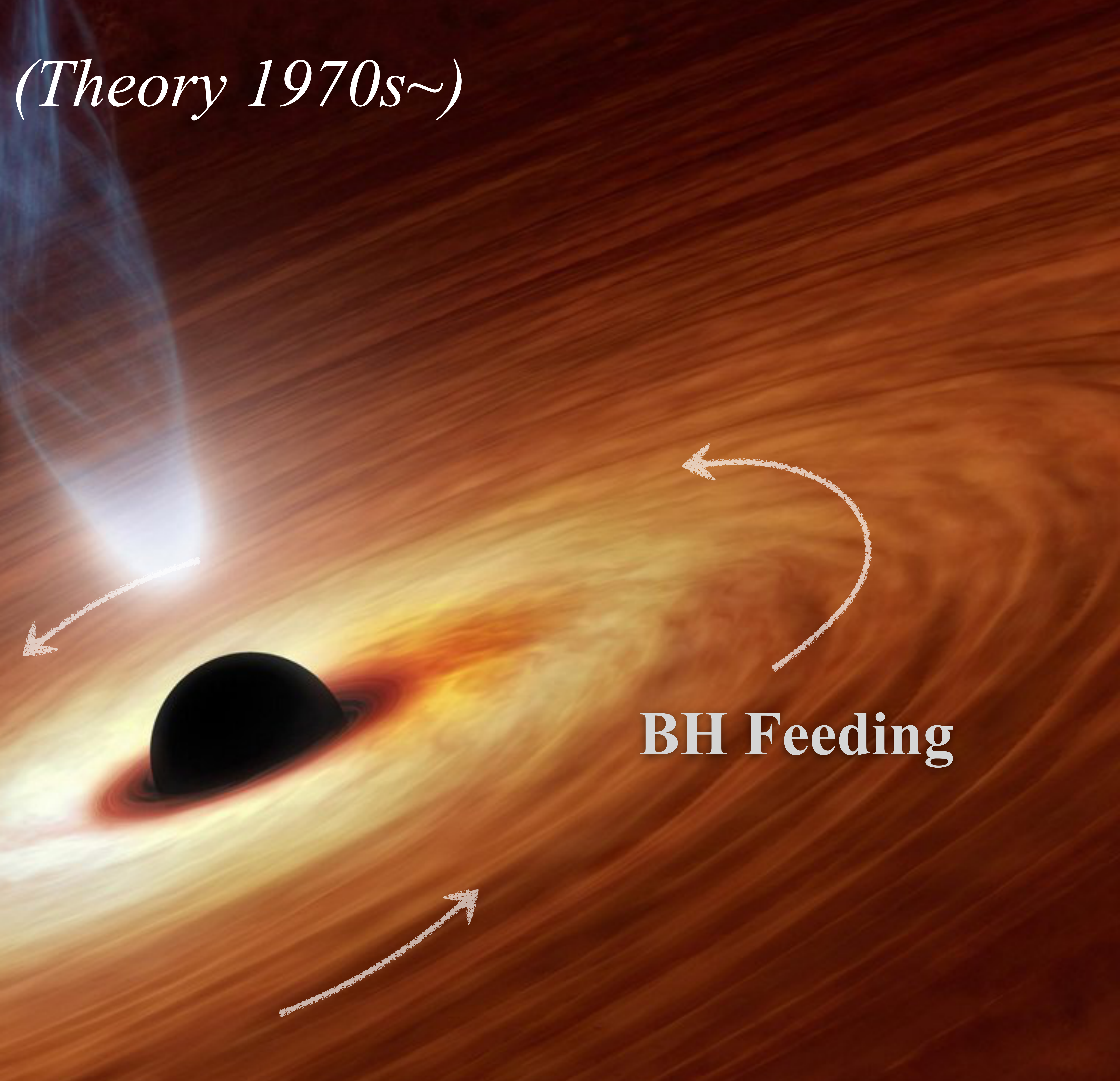
↓

Thermal Energy

↓ **BH**

↓ **Radiation Energy**

↓ **ISM, Observer**



Radiative Efficiency

Assuming Kepler motion : $\dfrac{v_\phi^2}{r} = \dfrac{GM_{\rm BH}}{r^2} \quad \rightarrow \quad 2K = -W$

$\left(\begin{array}{l} K = v_\phi^2/2\text{: Kinetic energy per unit mass} \\ W = -GM_{\rm BH}/r\text{: Gravitationl energy per unit mass} \end{array} \right)$

Total energy per unit mass : $E \equiv K + W = W/2 \ (<0)$

$\left(\text{@Innermost Stable Circular Orbit (ISCO) : } \dfrac{|W|}{2} = \dfrac{GM_{\rm BH}}{r_{\rm ISCO}} \right)$

Radiative Efficiency: $\eta = \dfrac{GM_{\rm BH}}{2 r_{\rm ISCO} c^2} \sim 10\,\%$

$r_{\rm ISCO} \sim \dfrac{6GM_{\rm BH}}{c^2}$

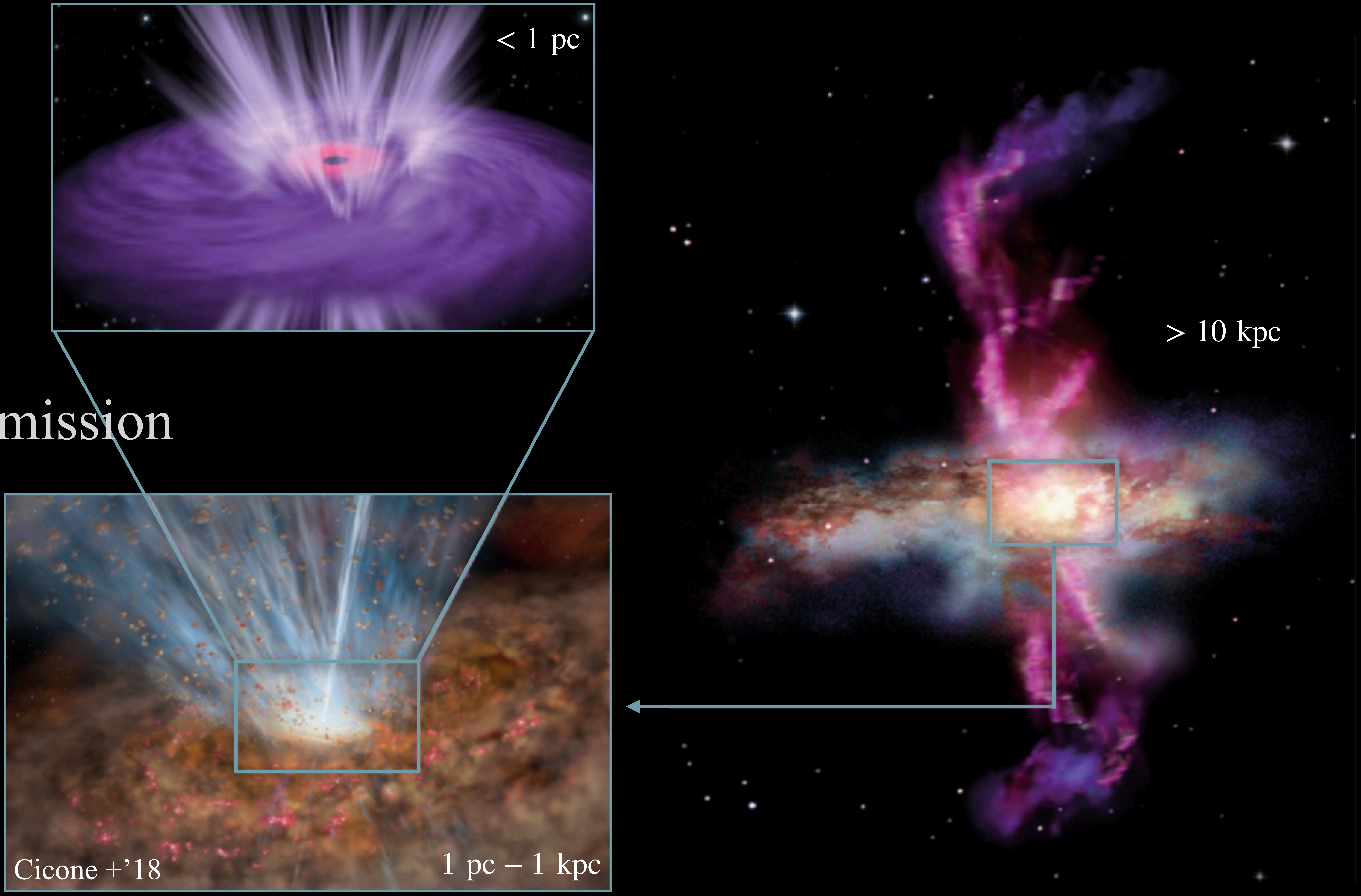
Active Galactic Nucleus (AGNs)

Galaxies
w/ peculiar properties:

- Extremely bright nucleus
- Variability
- High-energy (X-,γ-ray) emission
- Broad emission line
- Polalization
- Relativistic outflow (jet)

↓

Engine:
Supermassive BH



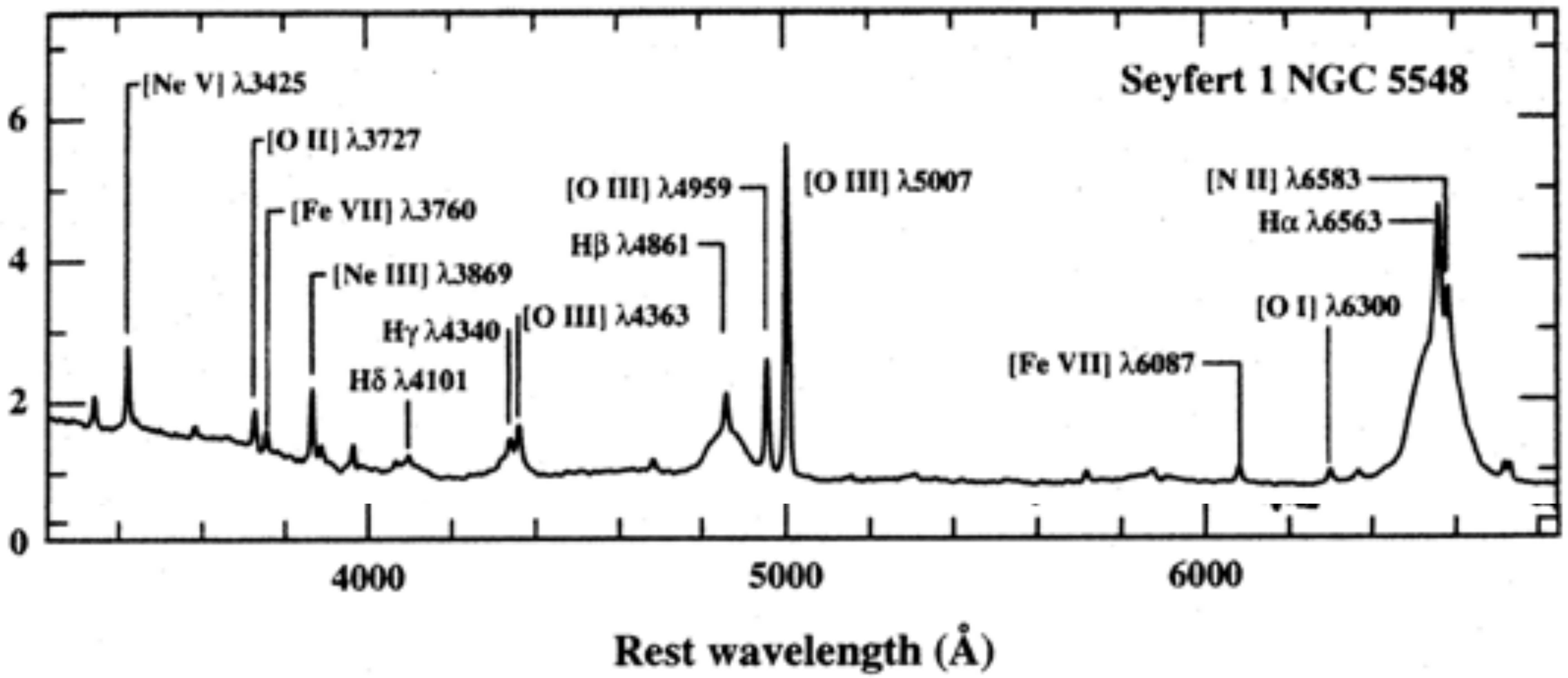
What Suggests the Existence of SMBHs?

“Broad” Line Emission

<u>Assumption</u>: gas is bound to the gravitational potential of the object

$$M_{\rm object} \sim \frac{\sigma^2 R_{\rm BLR}}{2G} \sim 10^8 \left(\frac{\sigma}{10^3\ {\rm km/s}}\right)^2 \left(\frac{R_{\rm BLR}}{0.1\ {\rm pc}}\right) M_\odot$$

※$R_{\rm BLR} \propto L^{0.5}$ ($L \sim 10^{46}$erg/s)

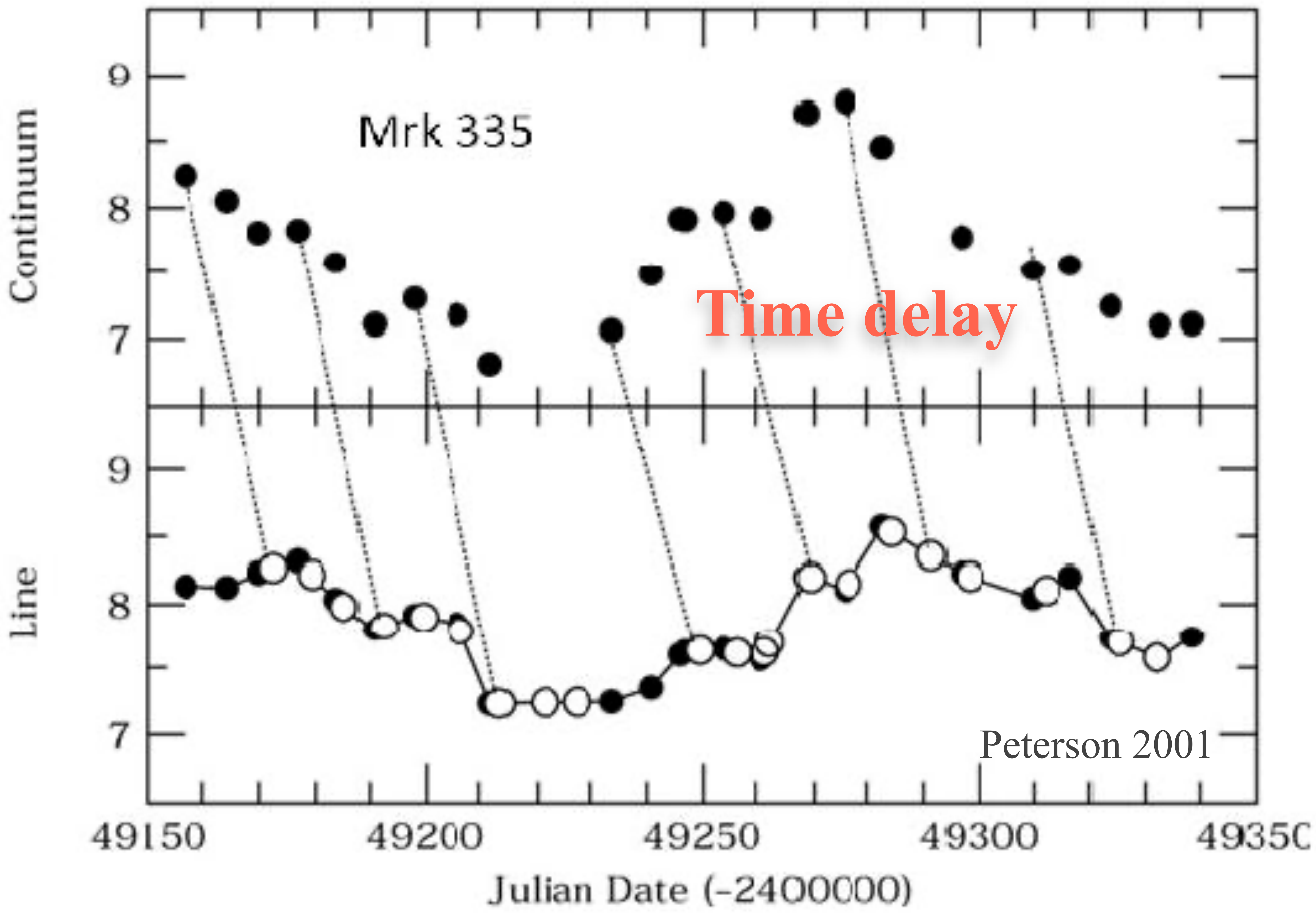


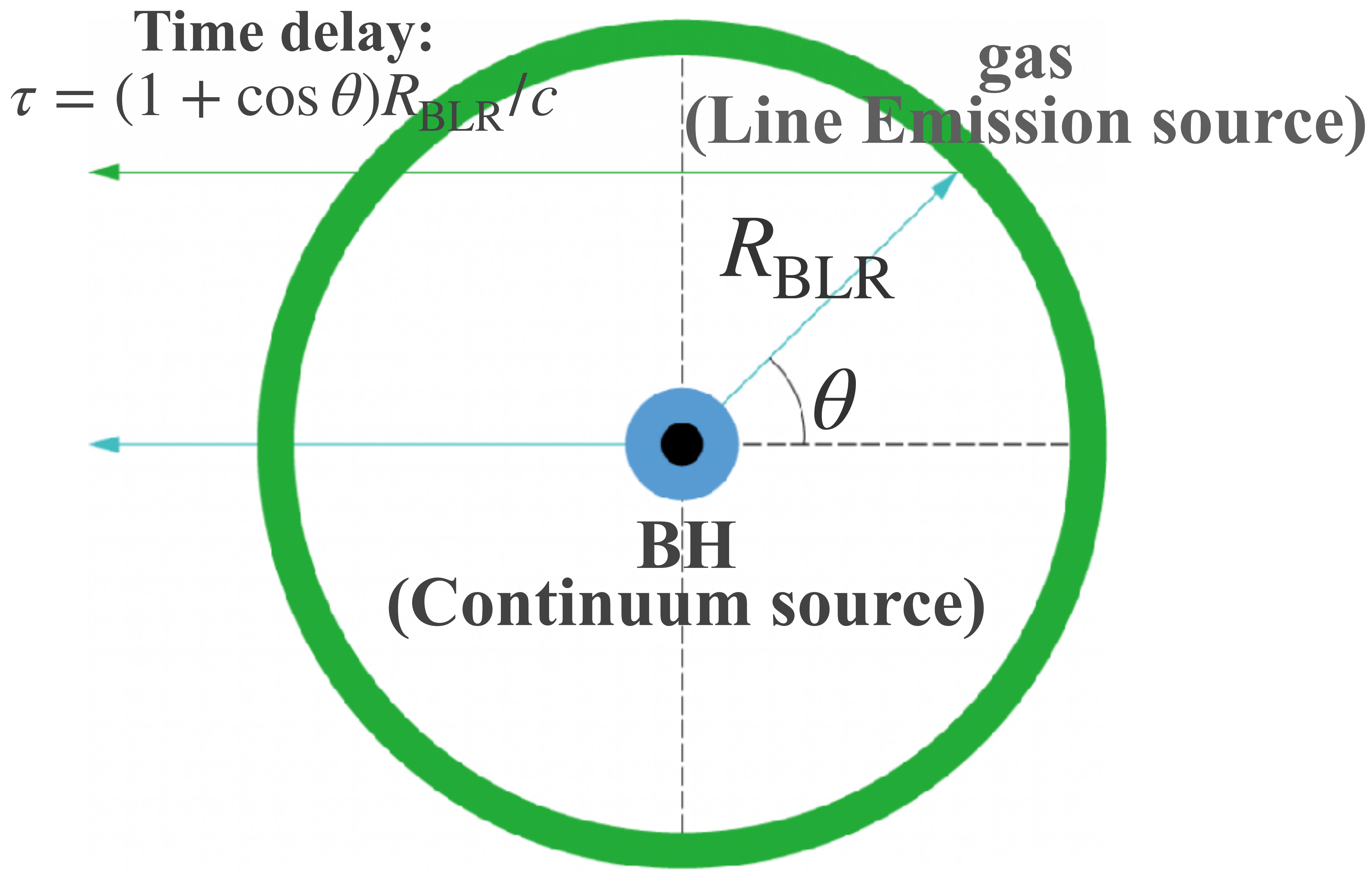
$M_{\rm object}$: Mass of the gravitational object
σ : Velocity dispersion measured by the line broadening
$R_{\rm BLR}$: Distance from the gravitational object ($\propto L^{0.5}$)

What Suggests the Existence of SMBHs?

※How to estimate R_{BLR}: reverberation mapping

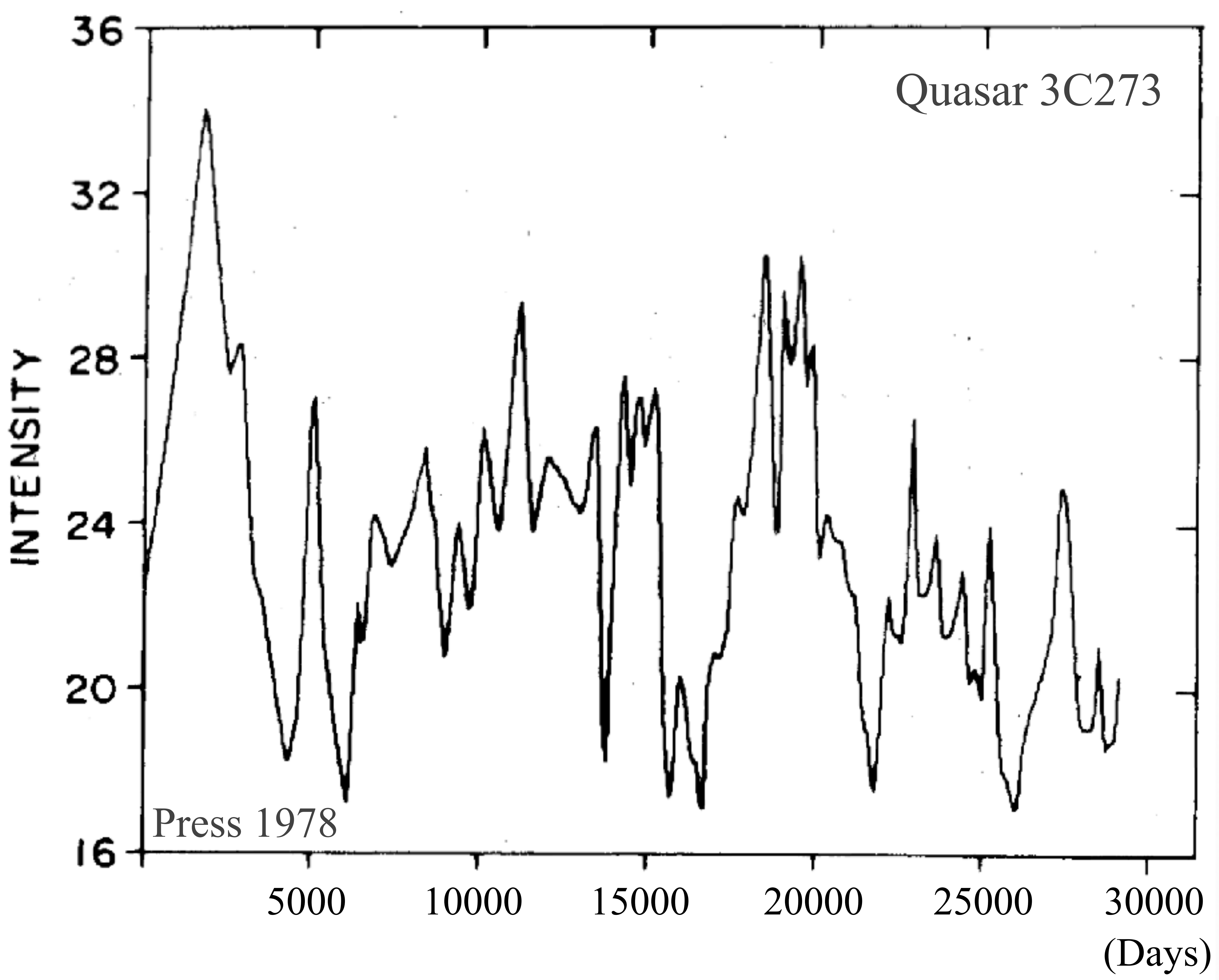
The time delay analysis can tell us the distance between the central BH and the BLR

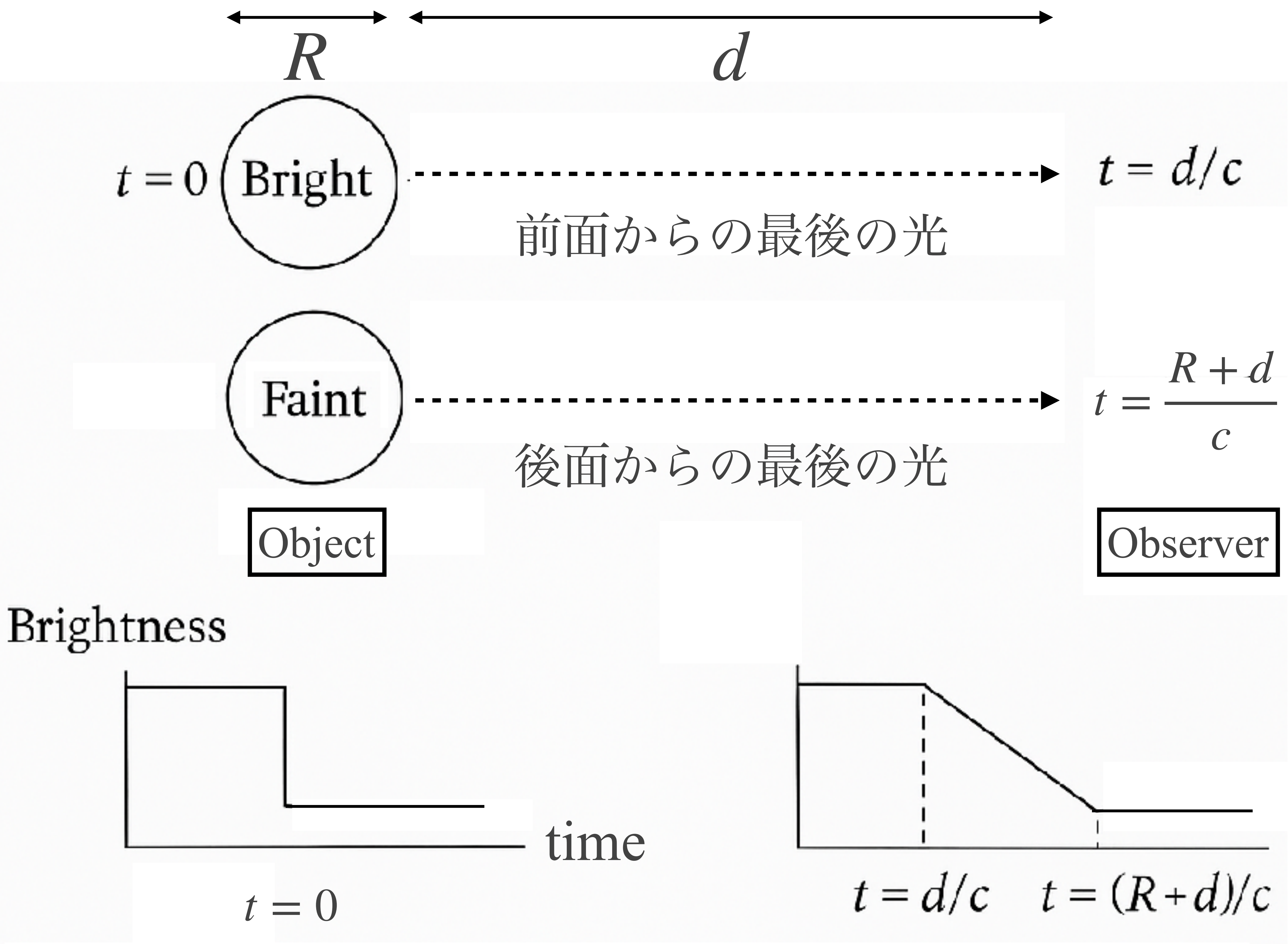




What Suggests the Existence of SMBHs?

Time Variation of Intensity ⟶ Constrain on the size of object $R < c\Delta t_{obs}$





AGN: Accreting massive BHs

Quiz:

光度変動時間スケールから、BH質量の上限を見積もってみよう

ヒント

- 光度変動の時間スケールから、放射領域の空間サイズに制限をつけることができる(前ページ参照)。その空間サイズは、降着円盤の内縁サイズ($r_{\rm ISCO} = 6GM_{\rm BH}/c^2$)より大きいはず
- Quasarの光度変動の時間スケールは、ざっくり1日とする

AGN: Accreting massive BHs

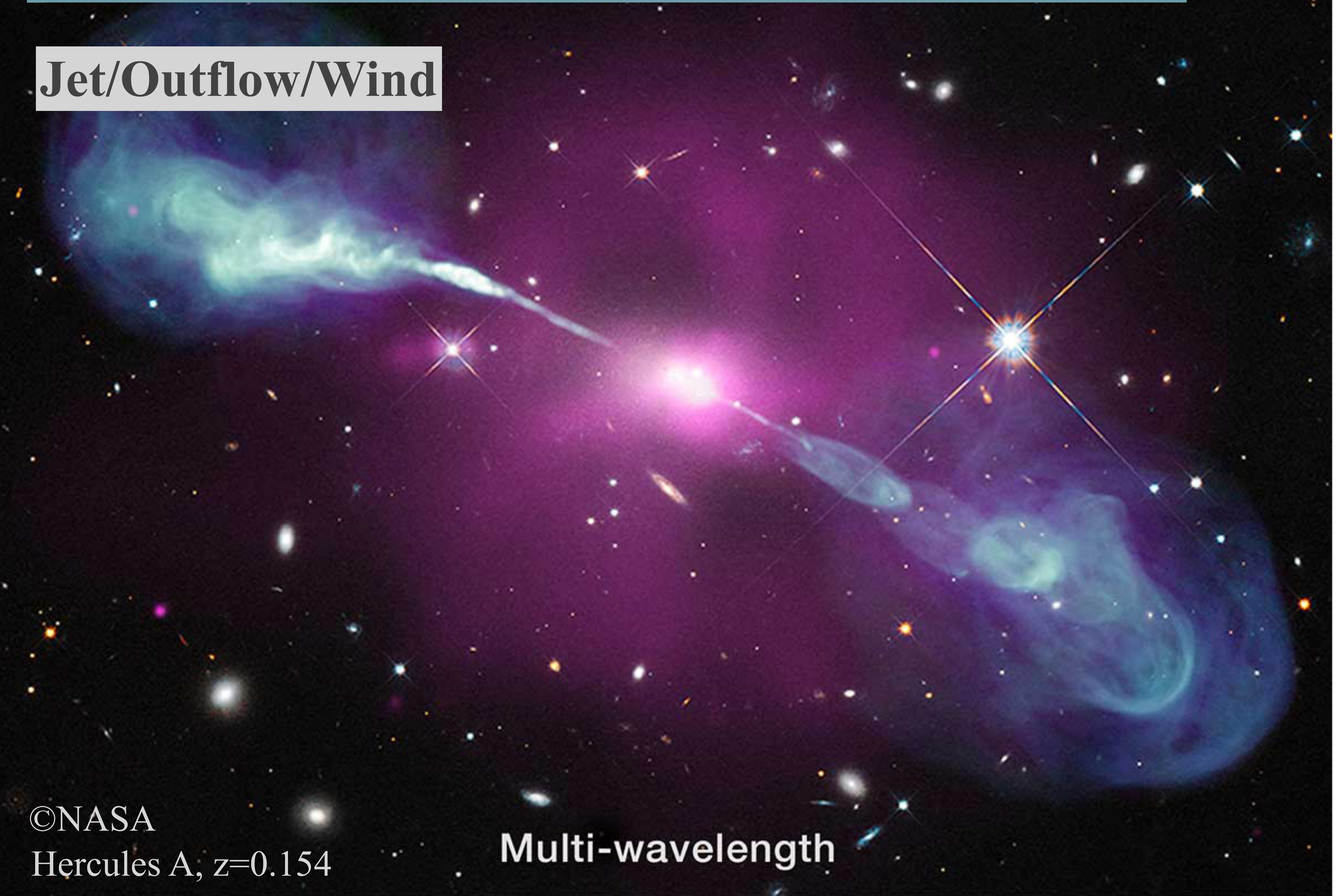
- クエーサーの光度変動の時間スケールが、だいたい1日、つまり約8.6万秒だったとする。この変動スケールから、放射領域の大きさRには次のような上限がつけらるる：$R < c\,\Delta t = (3.0 \times 10^{8}\,\mathrm{m/s}) \times (8.6 \times 10^{4}\,\mathrm{s}) \approx 2.6 \times 10^{13}\,\mathrm{cm}$

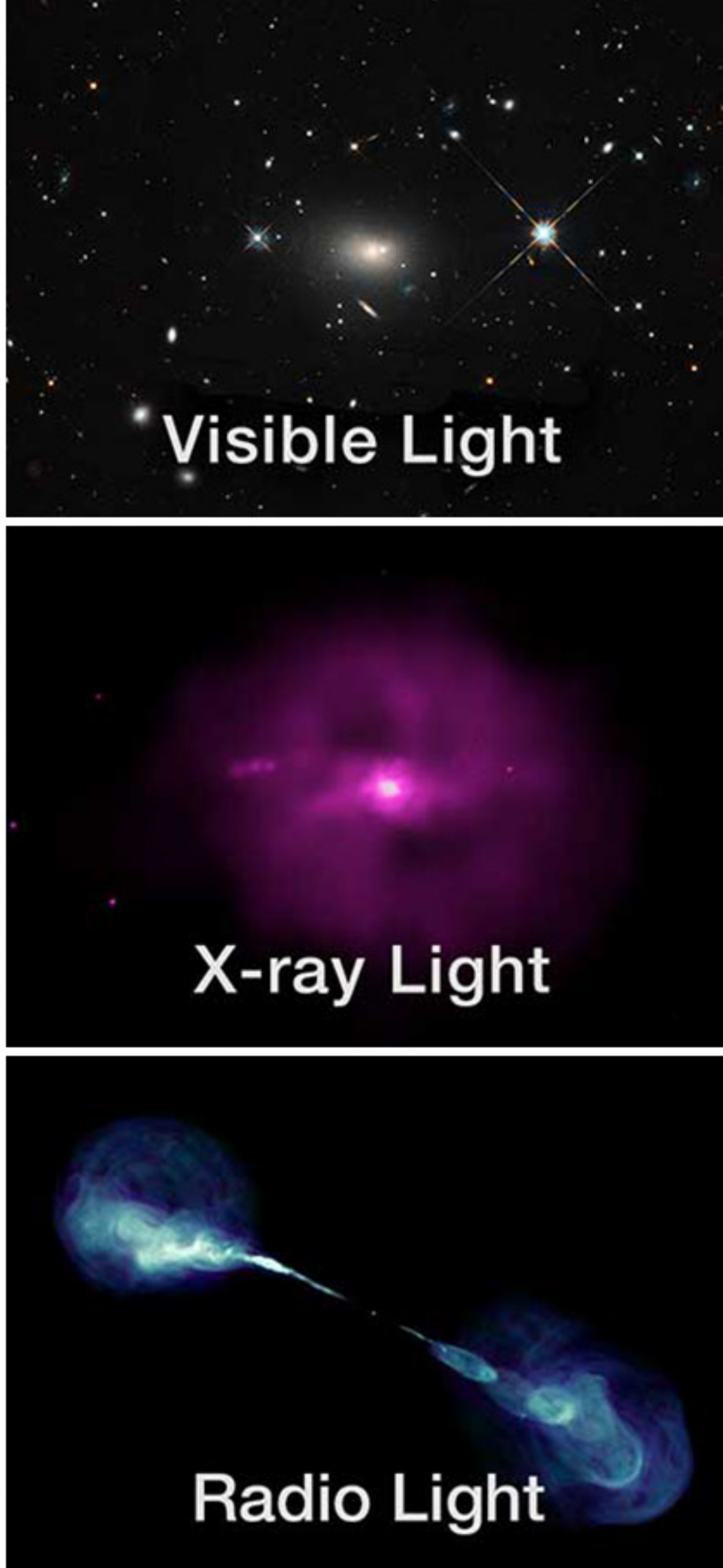
- このRは、降着円盤の内縁、つまり最内安定円軌道r_{ISCO}よりも大きいはず。r_{ISCO}はシュバルツシルトブラックホールの場合、$r_{\mathrm{ISCO}} = \dfrac{6GM}{c^2}$

- 質量Mの上限は、$M < \dfrac{c^2 R}{6G} = \dfrac{(3.0 \times 10^{10})^2 \times 2.6 \times 10^{13}}{6 \times 6.67 \times 10^{-8}} \approx 5 \times 10^{8}\,M_\odot$

What Suggests the Existence of SMBHs?

Jet/Outflow/Wind



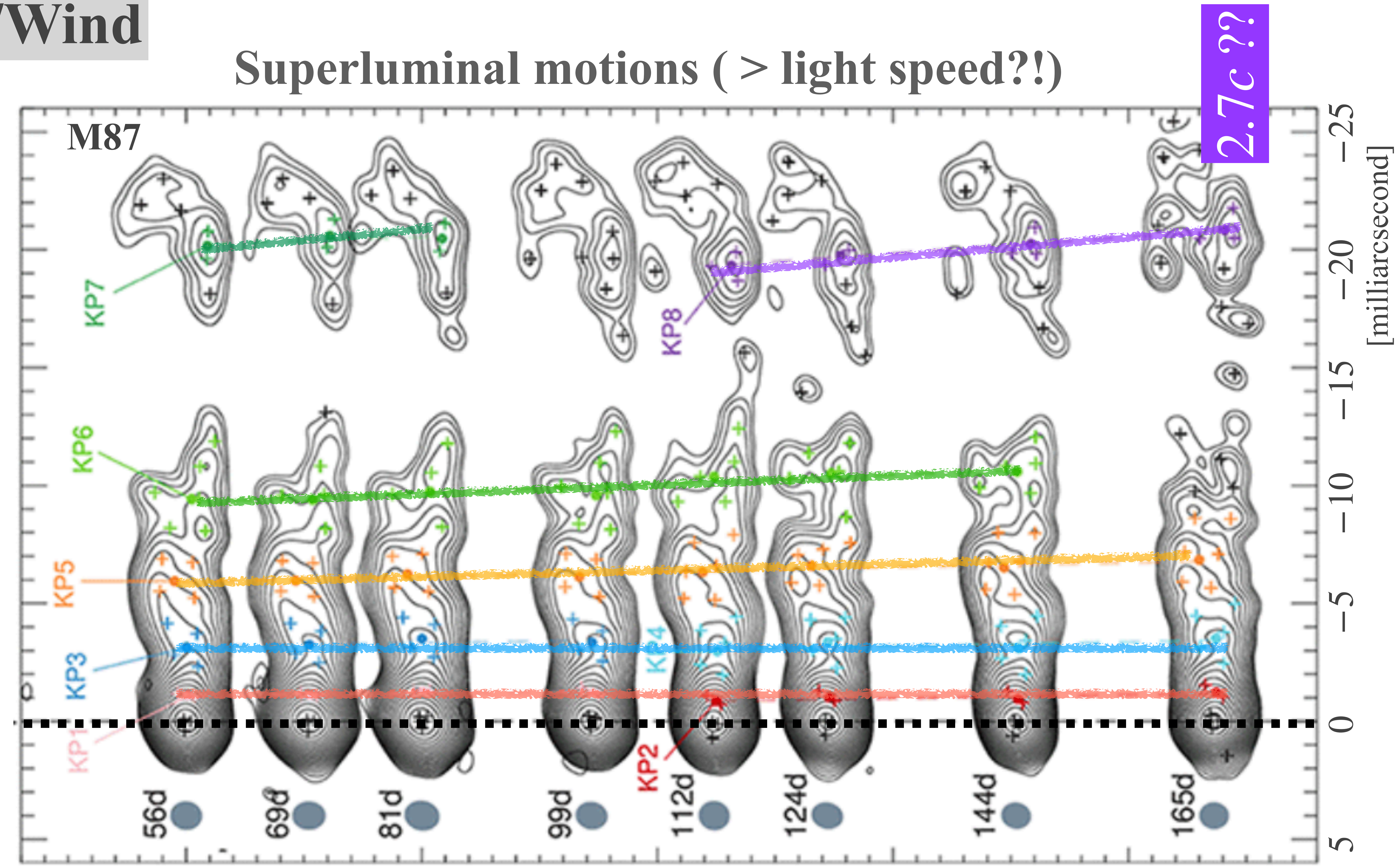


Hercules A, z=0.154

What Suggests the Existence of SMBHs?

Jet/Outflow/Wind

Superluminal motions (> light speed?!)

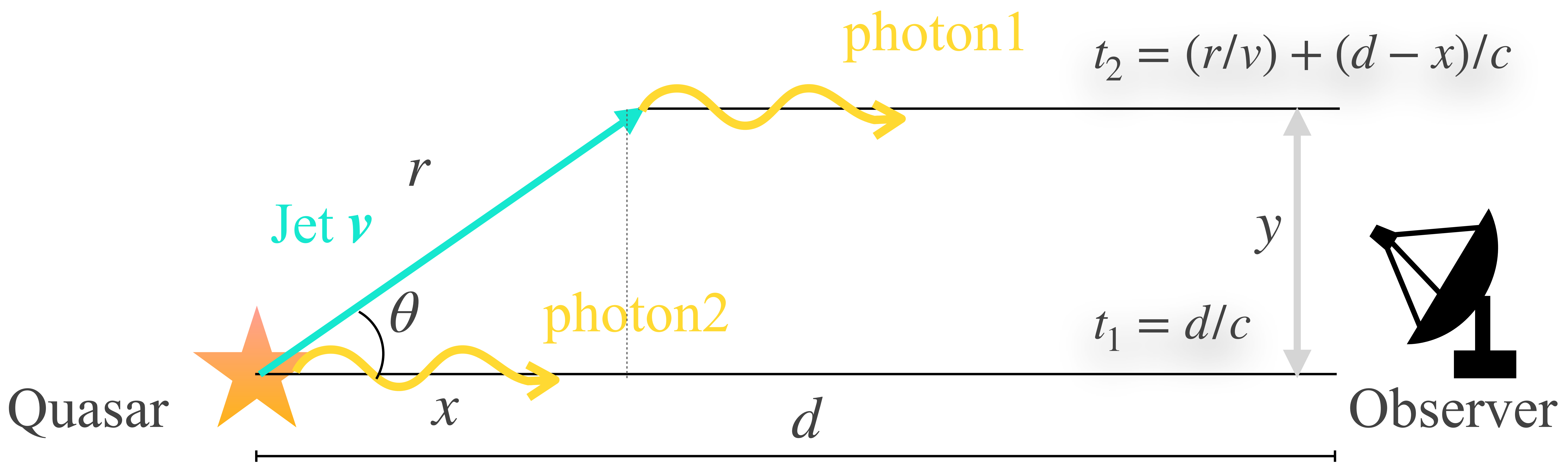


Time evolution

What Suggests the Existence of SMBHs?

Jet/Outflow/Wind

Superluminal motions: **“apparent” velocity > light speed**



$\theta \ll 1$ $\quad v = c(1-\epsilon),\ \epsilon \ll \theta \ll 1$

$$\text{apparent velocity: } v_{\rm app} = \frac{y}{t_2 - t_1} = \frac{v\sin\theta}{1-(v/c)\cos\theta} \sim \frac{v\theta}{1-(v/c)(1-\theta^2/2)} \sim \frac{2c}{(2\epsilon/\theta + \theta)}$$

ざっくりとした計算 $M87 : \theta \sim 15^\circ$ $\rightarrow$ $v/c \sim 0.95$ (ちゃんと計算すると0.99程度)

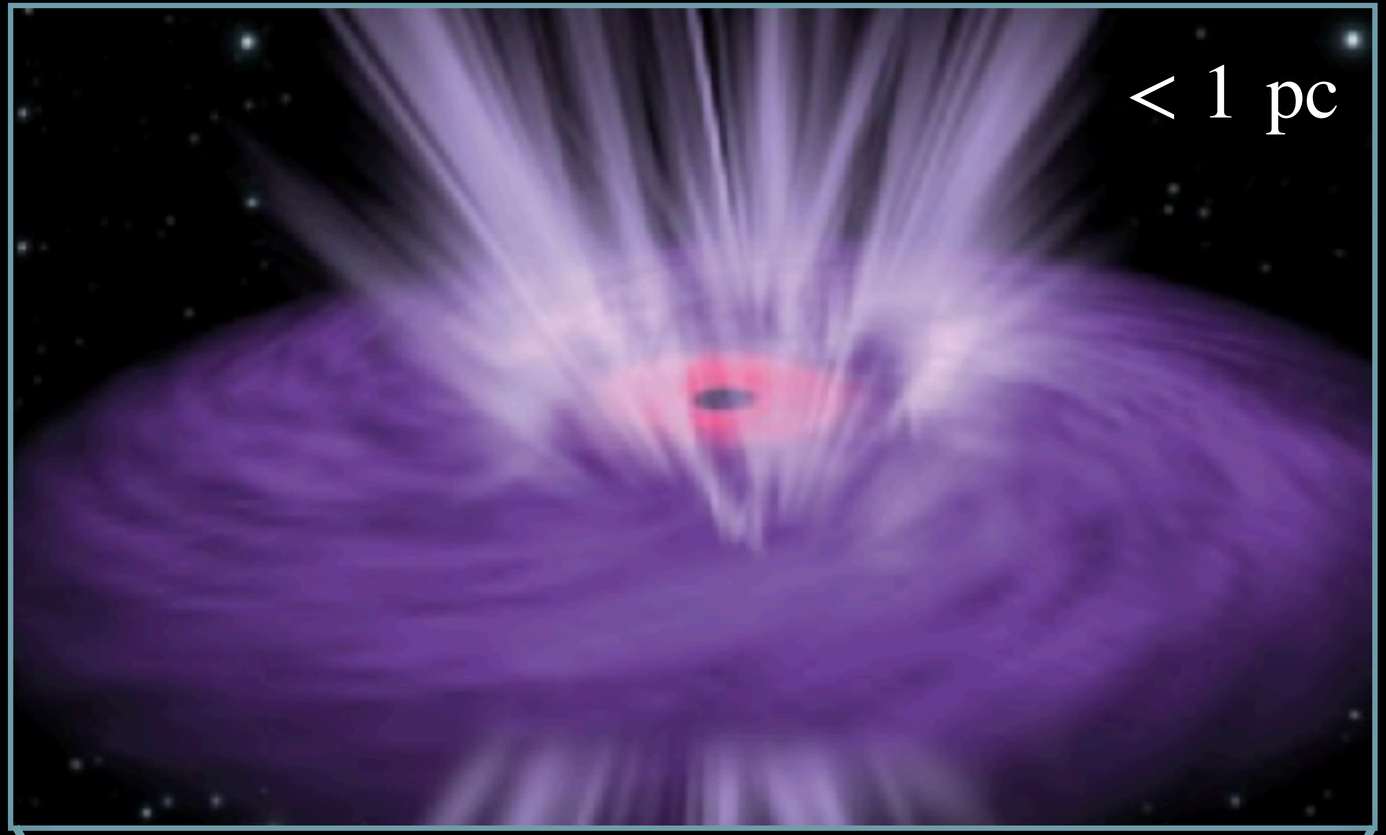
Active Galactic Nucleus (AGNs)

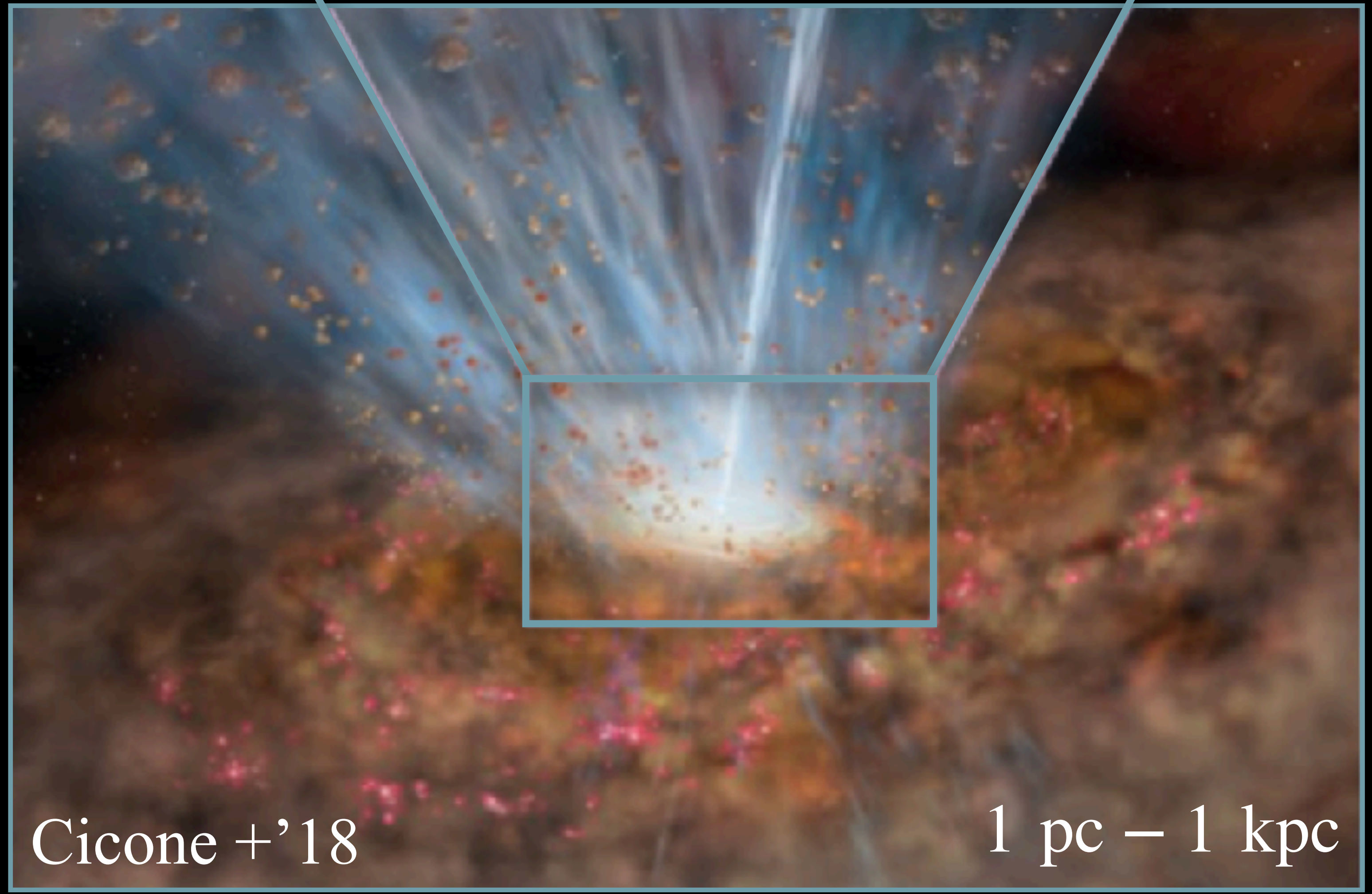
Galaxies
w/ peculiar properties:

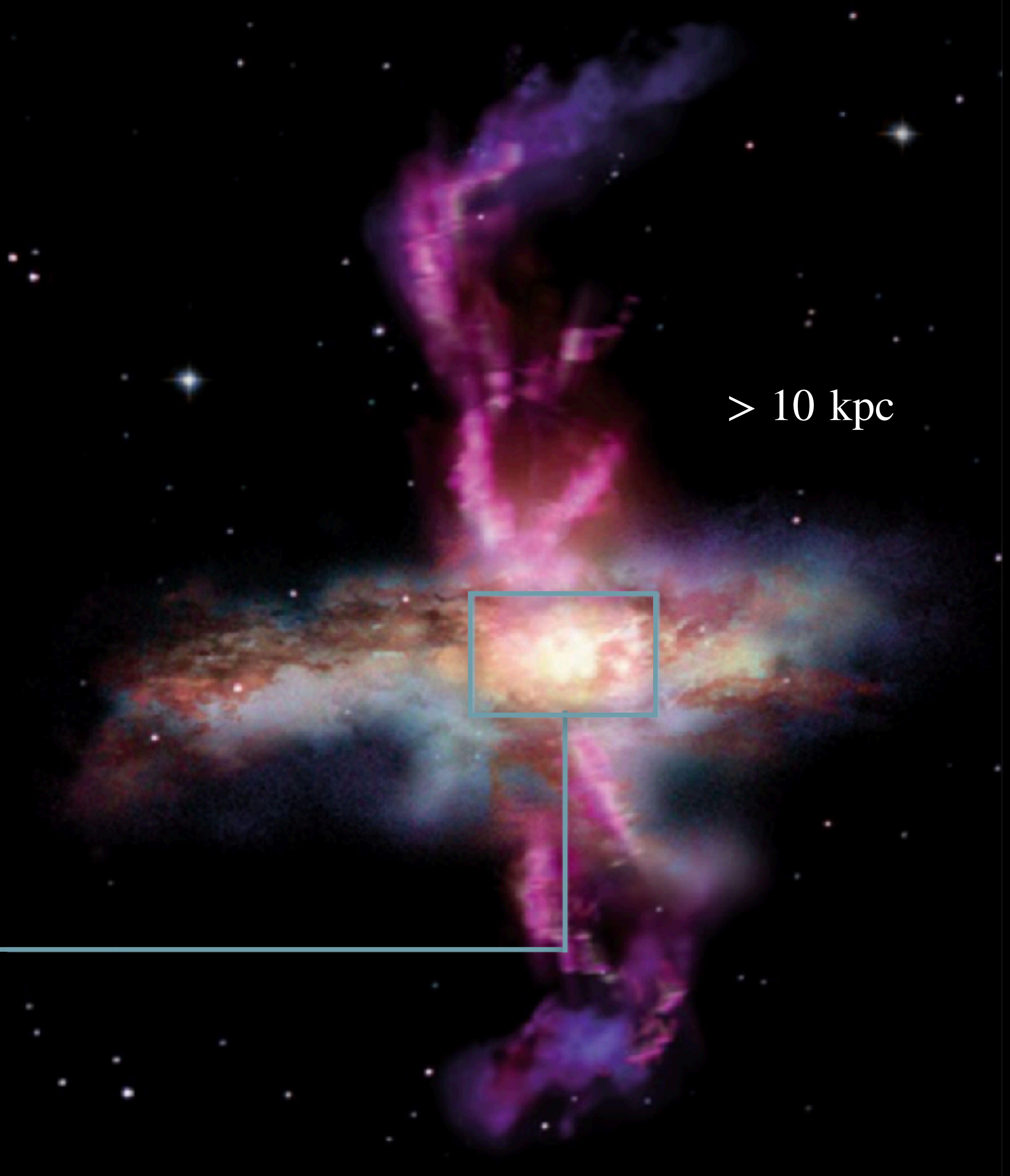
- Extremely bright nucleus
- Variability
- High-energy (X-,γ-ray) emission
- Broad emission line
- Polalization
- Relativistic outflow (jet)

↓

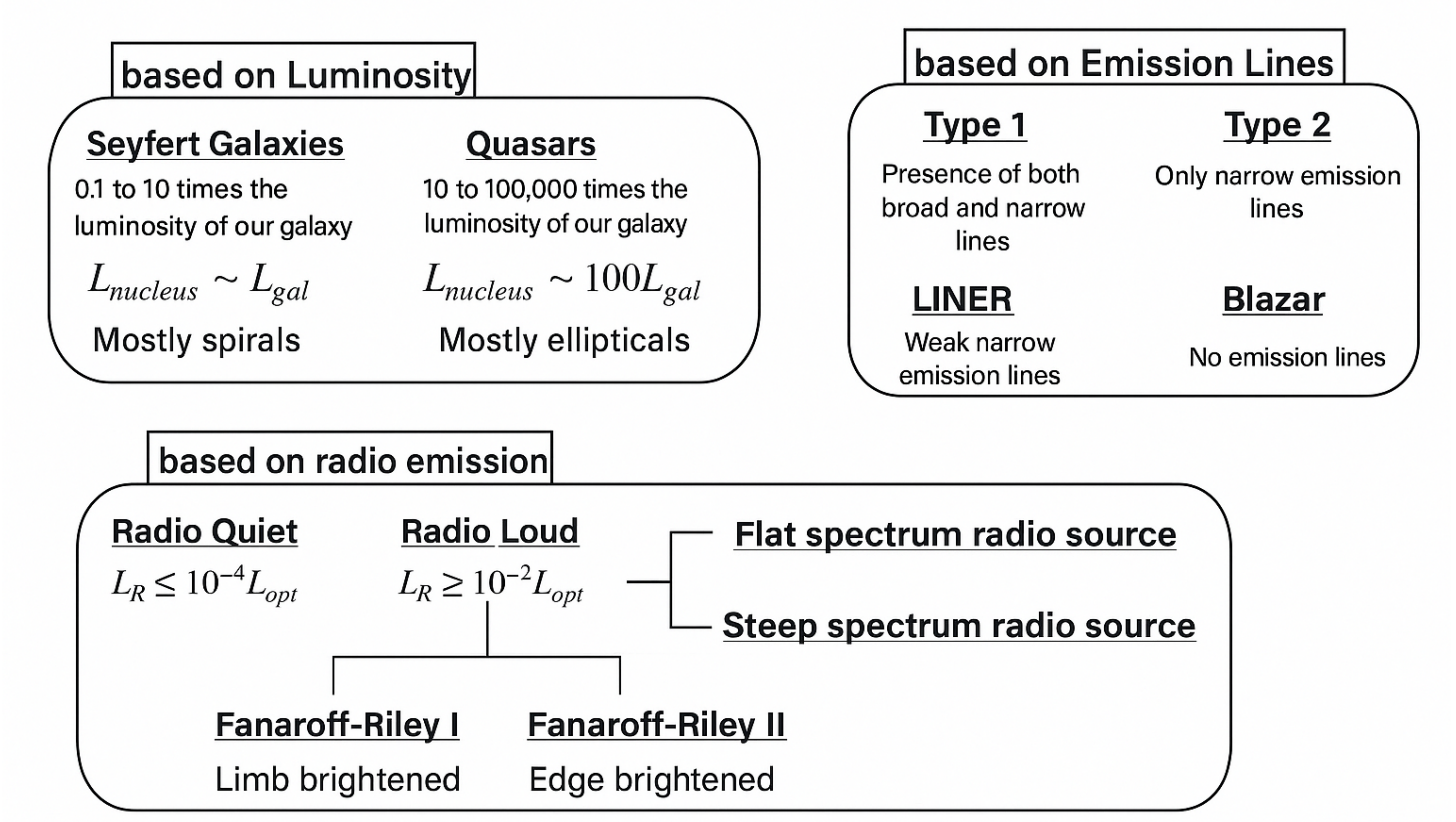
Engine:
Supermassive BH







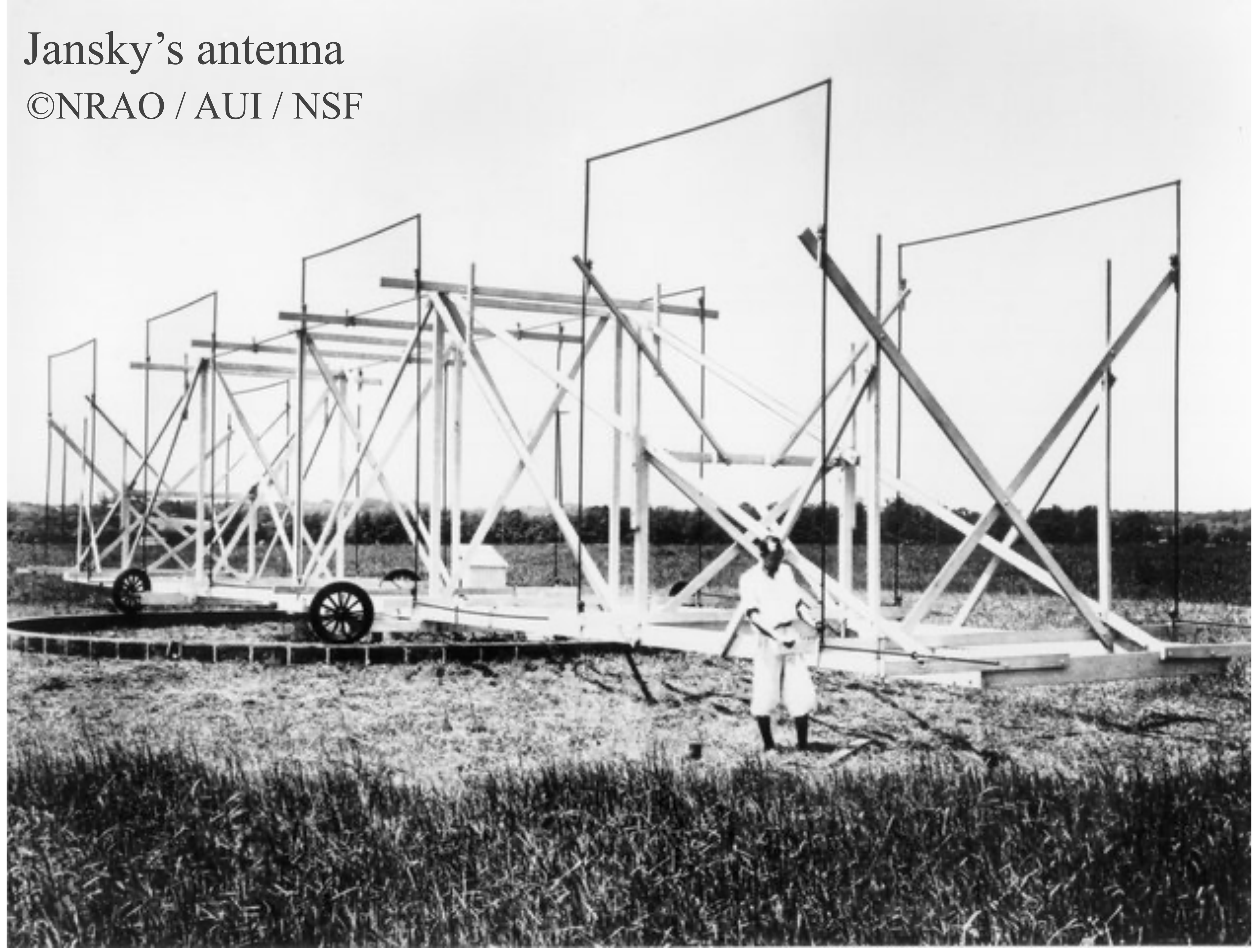
AGN Classification

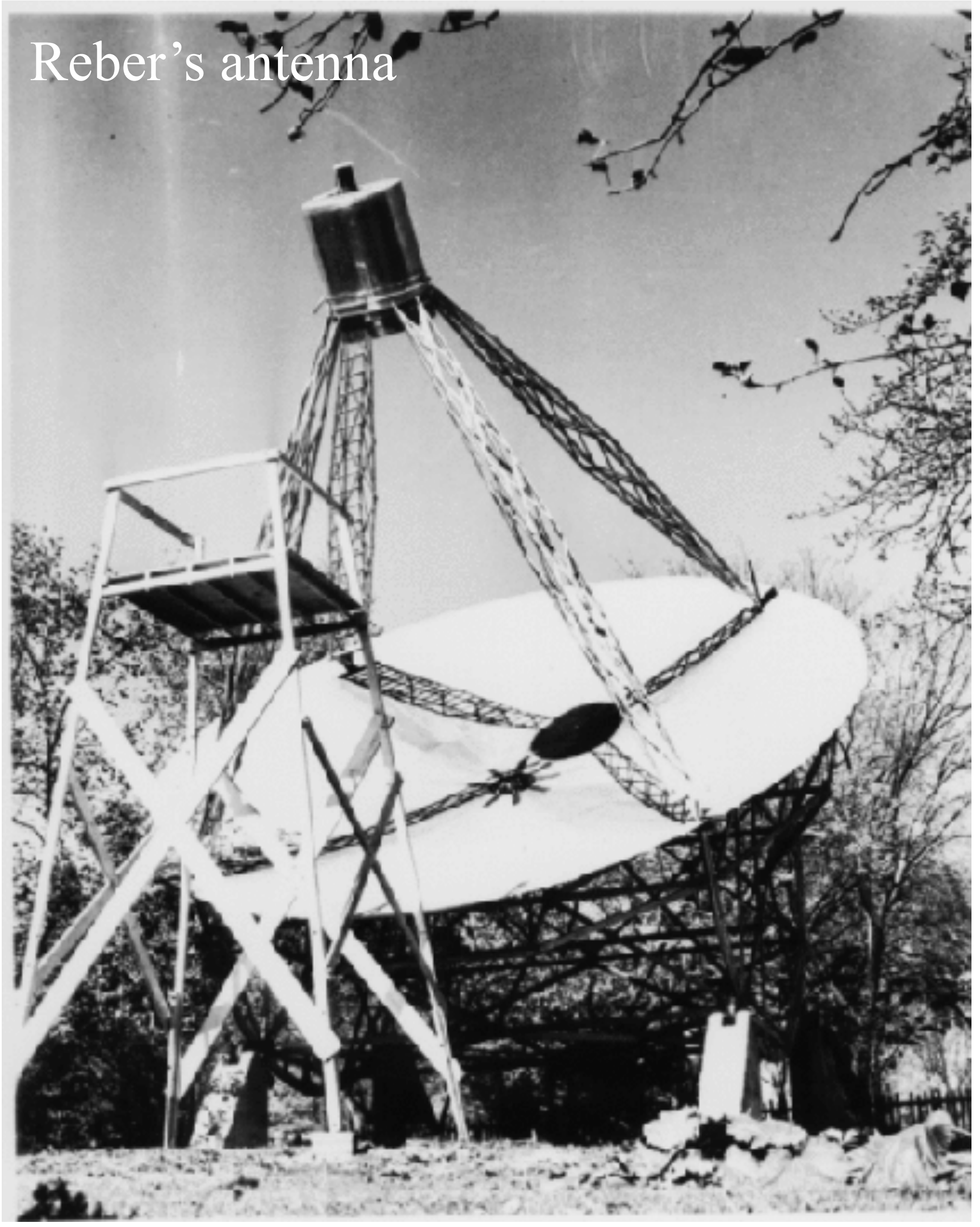


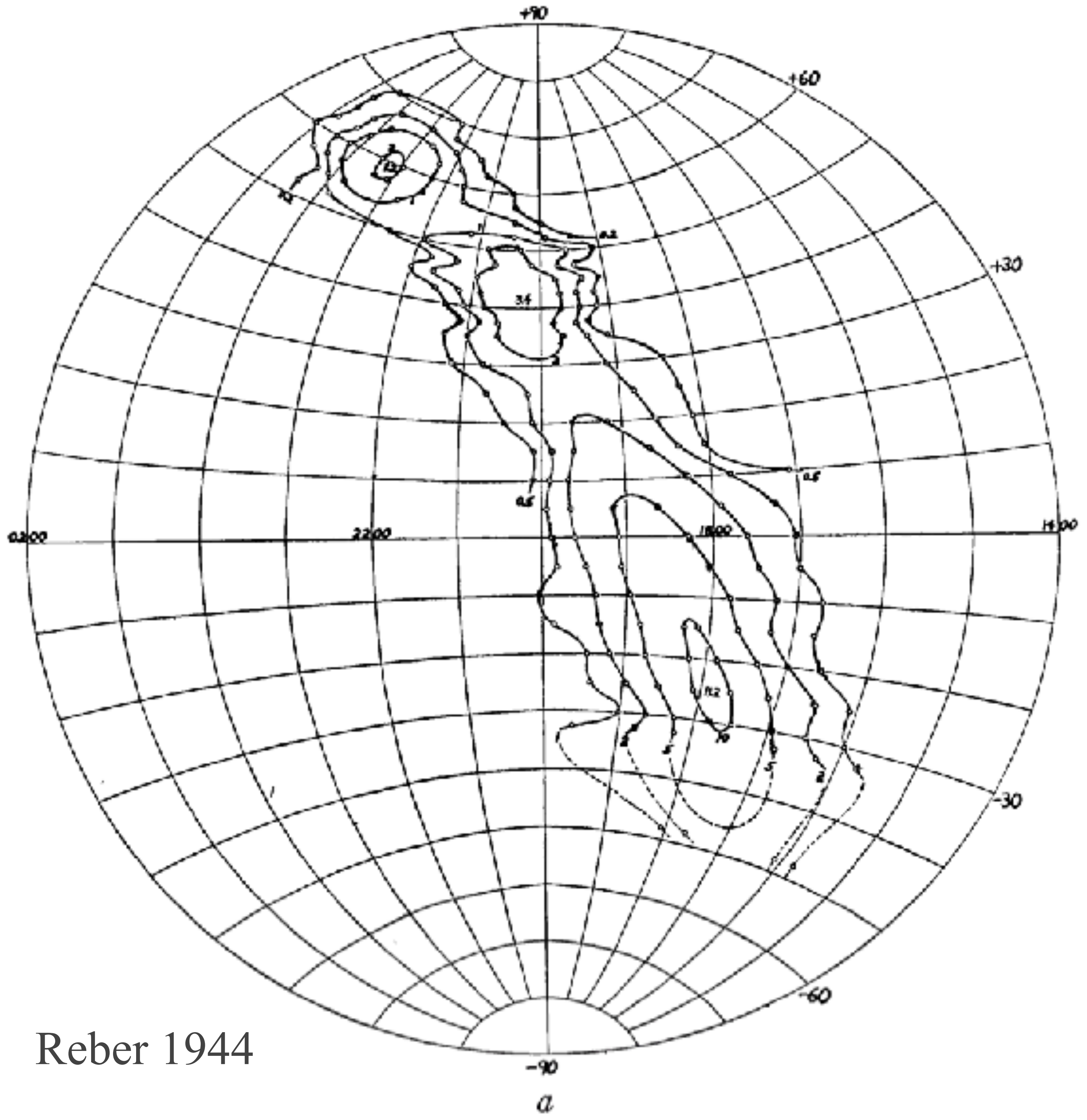
Sivaram '21

Supermassive BHs in Our Galaxy

- Karl Guthe Jansky was the first to detect radio waves from space (1932)
- He discovered that **<u>strong radio signals</u>** were arriving from the direction of **<u>Our Galactic Center</u>**







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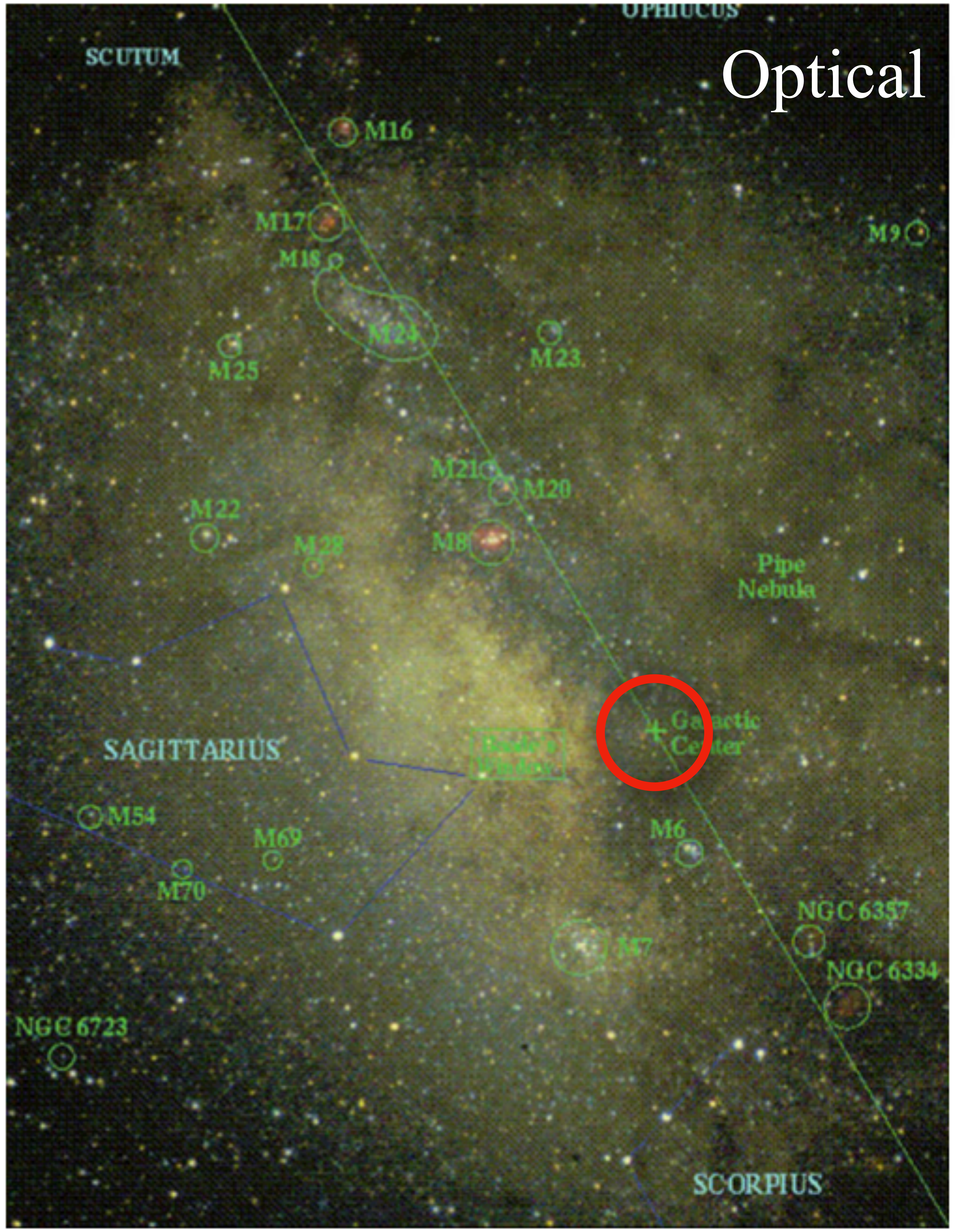
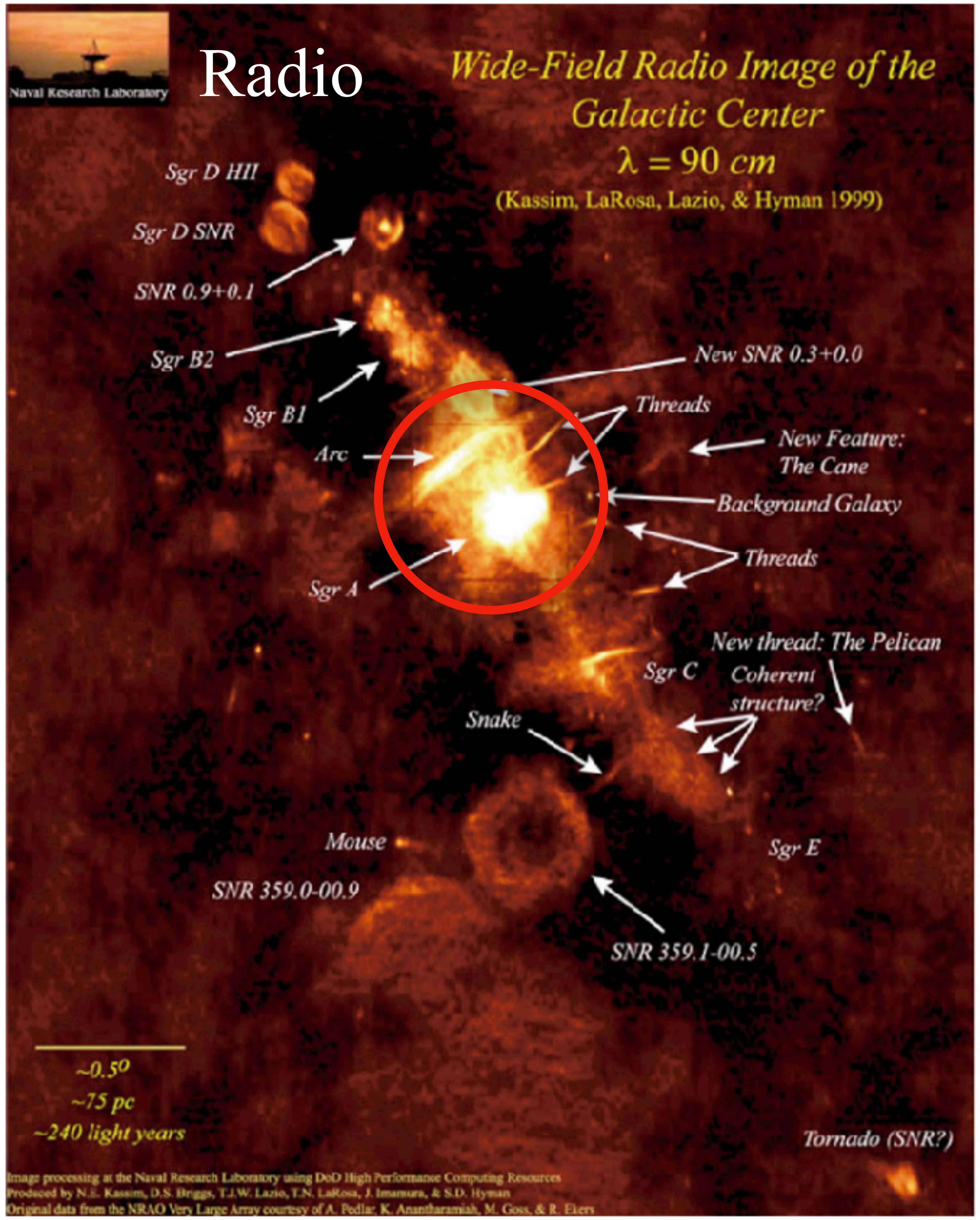
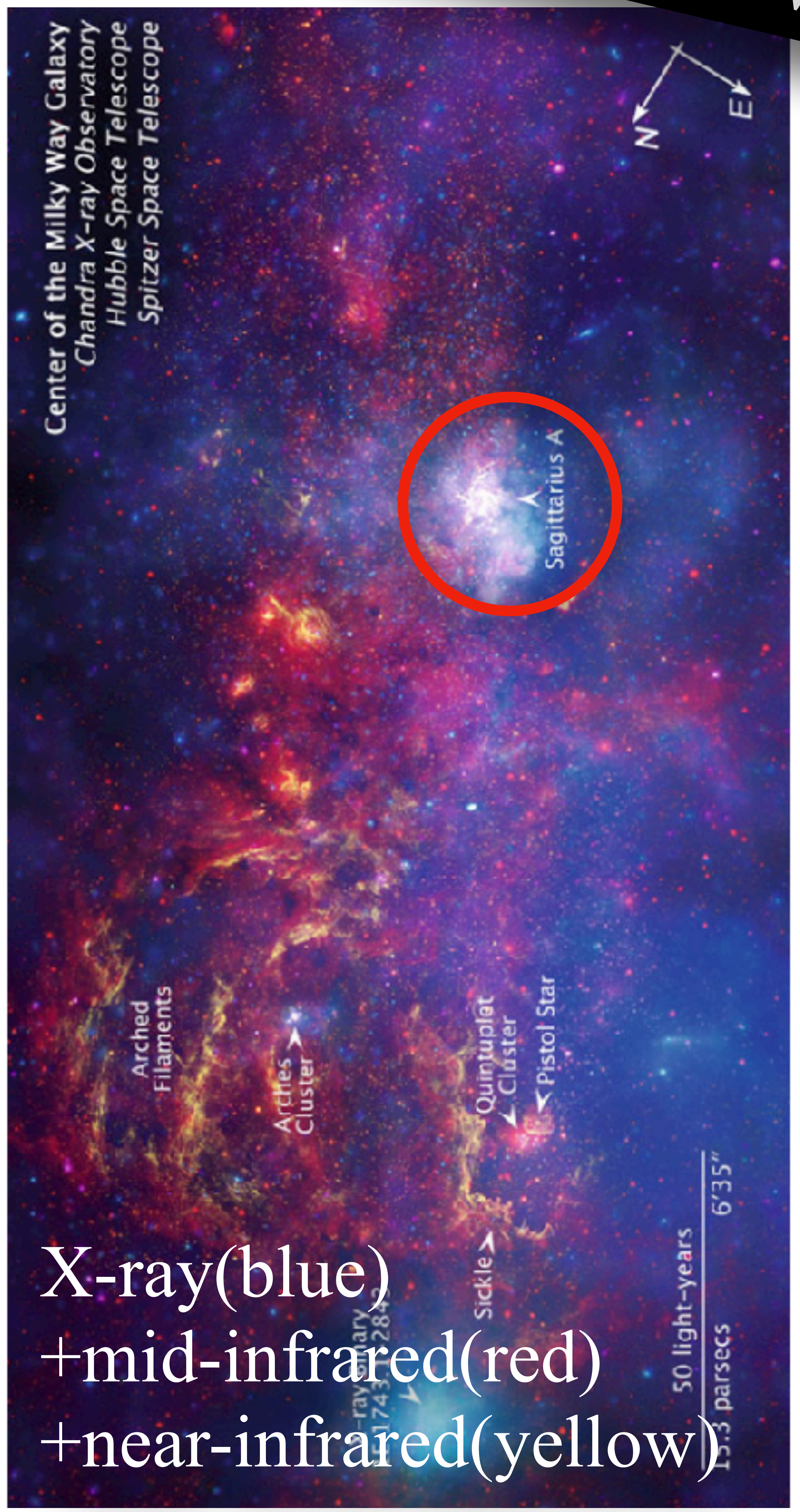
Supermassive BHs in Our Galaxy

Multi-wavelength view



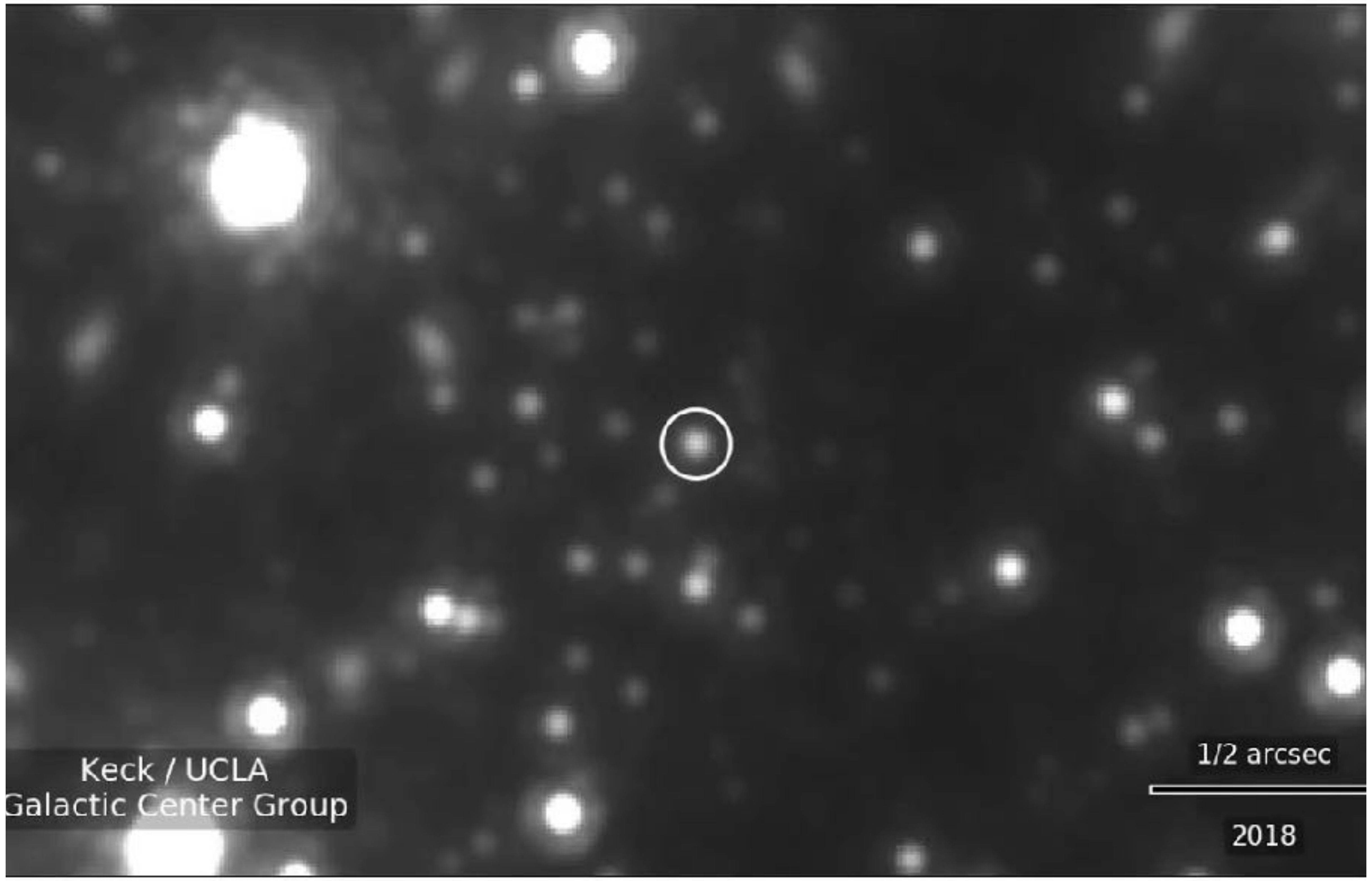


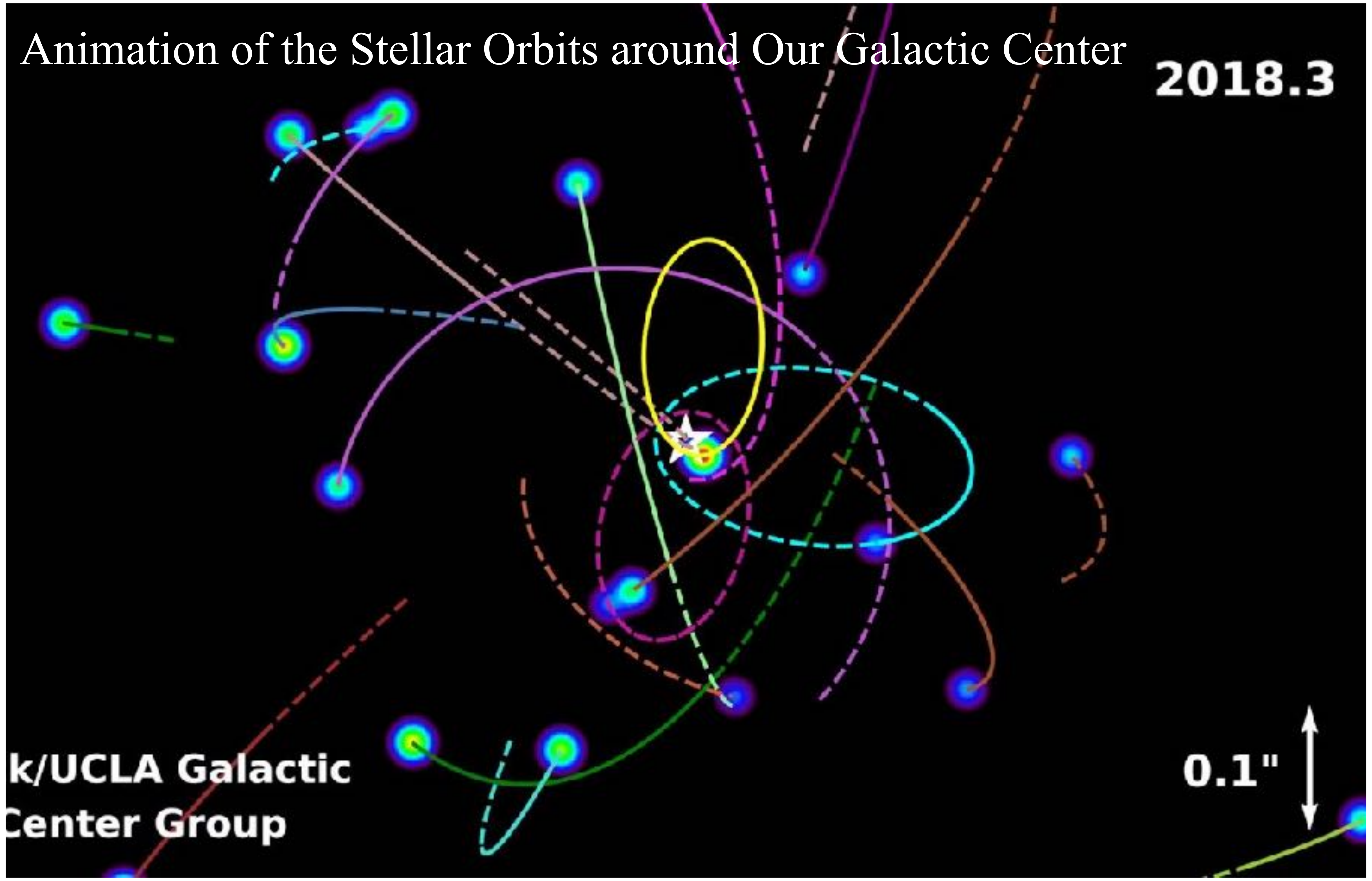


Supermassive BHs in Our Galaxy

- A massive compact object (= Supermassive BH) with $M_{\rm BH} = (4.3 \pm 0.4) \times 10^6 M_\odot$ **inferred from stellar orbits** (1990s~)

Eckart & Genzel, 1996, “Observations of stellar proper motions near the Galactic Centre”
Ghez et al., 1998, “High Proper Motion Stars in the Vicinity of Sgr A*: Evidence for a Supermassive Black Hole at the Center of Our Galaxy”





NOBELPRISET I FYSIK 2020
THE NOBEL PRIZE IN PHYSICS 2020

KUNGL. VETENSKAPS-AKADEMIEN
THE ROYAL SWEDISH ACADEMY OF SCIENCES


Photo: Penrose Institute

Roger Penrose


Photo: Max Planck Institute for Extraterrestrial Physics

Reinhard Genzel


Photo: Christopher Dibble, UCLA

Andrea Ghez

”för upptäckten att bildandet av svarta hål är en robust förutsägelse av den allmänna relativitetsteorin”

“for the discovery that black hole formation is a robust prediction of [illegible]ral theory of relativity”

”för upptäckten av ett supermassivt kompakt objekt i Vintergatans centrum”

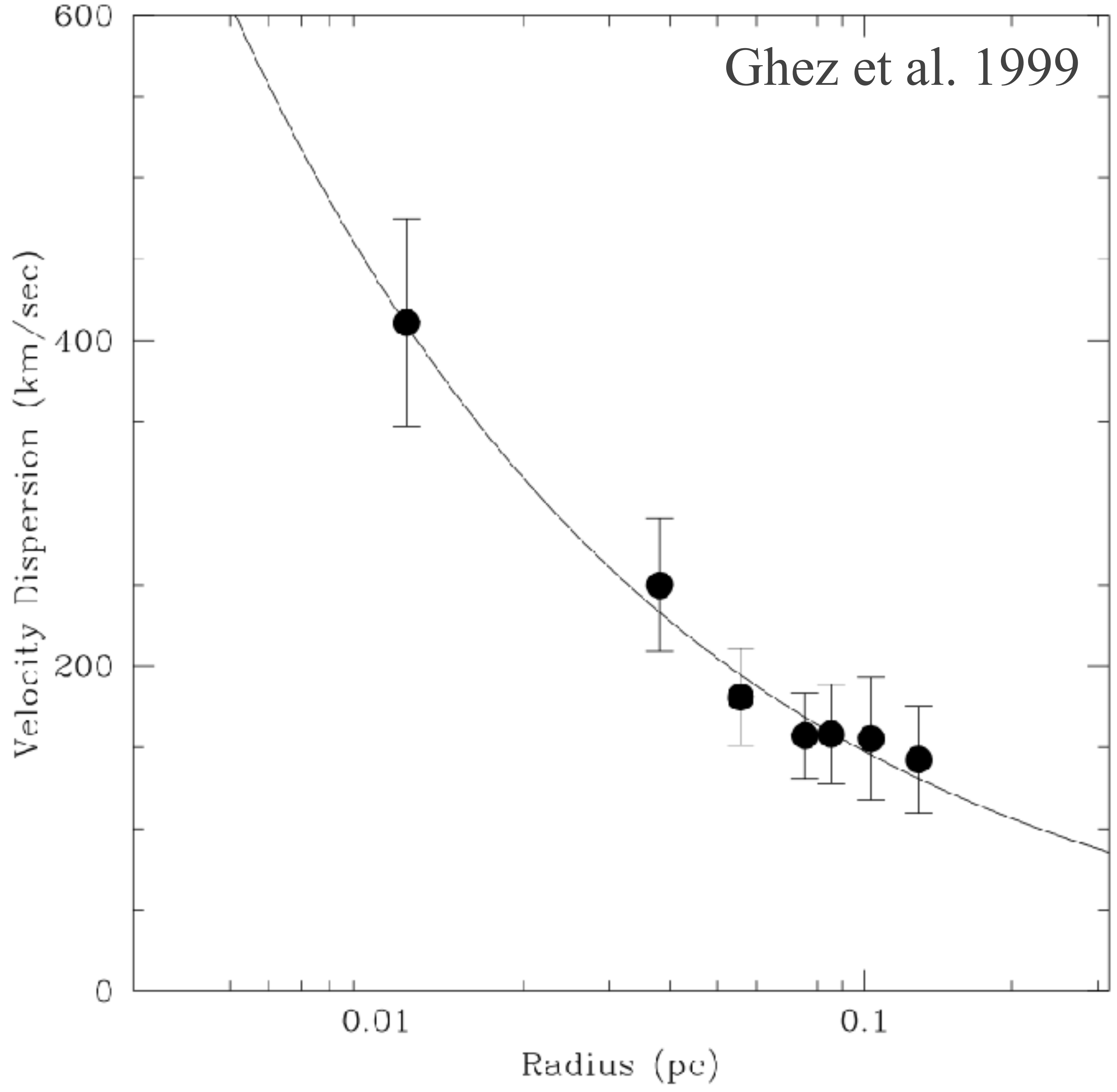
“for the discovery of a supermassive compact object at the centre of our galaxy”

#nobelprize

THE NOBEL PRIZE

Supermassive BHs in Our Galaxy

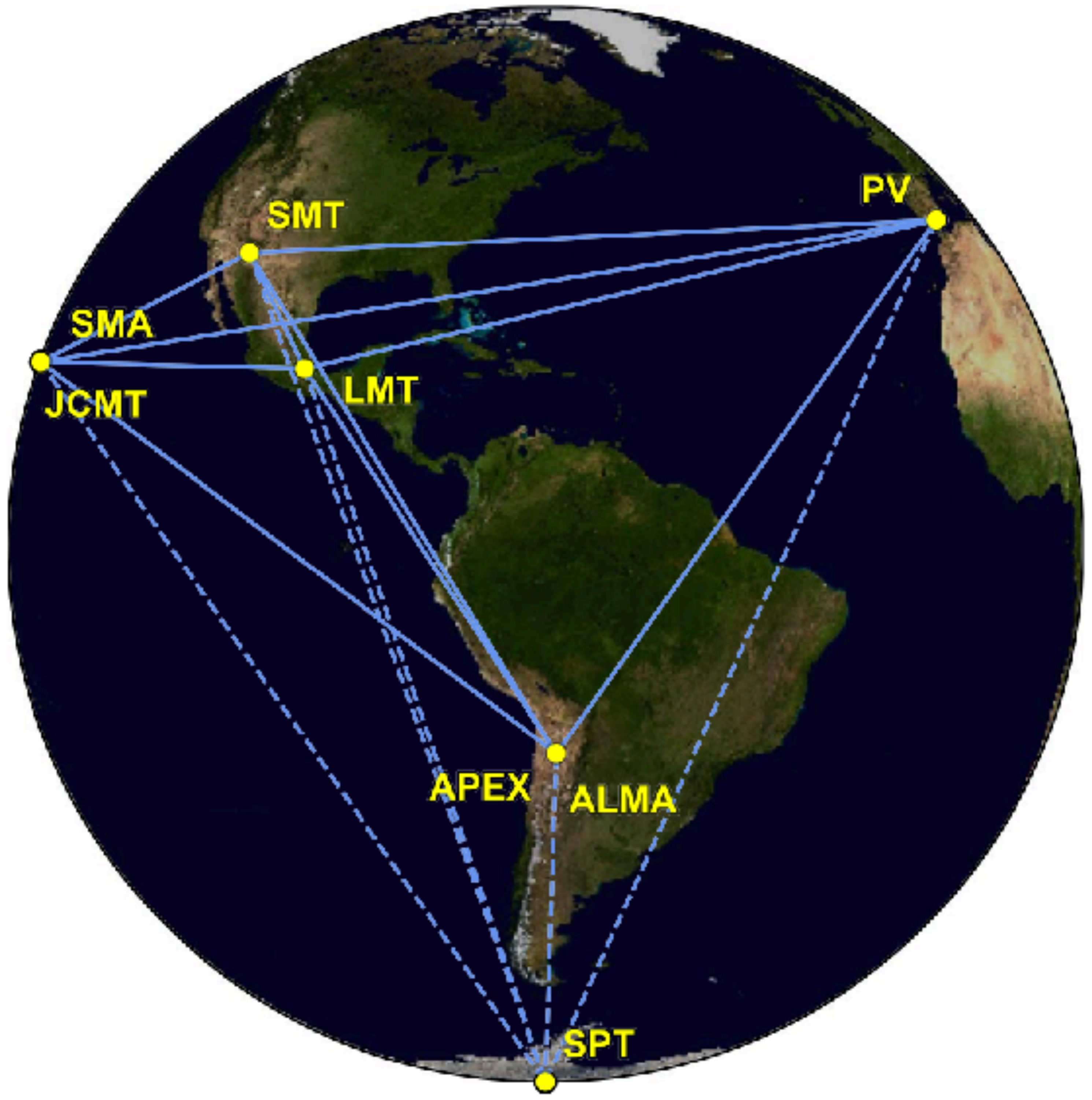
Quiz:
星の速度分散から銀河中心のブラックホールの質量を求めてみよう



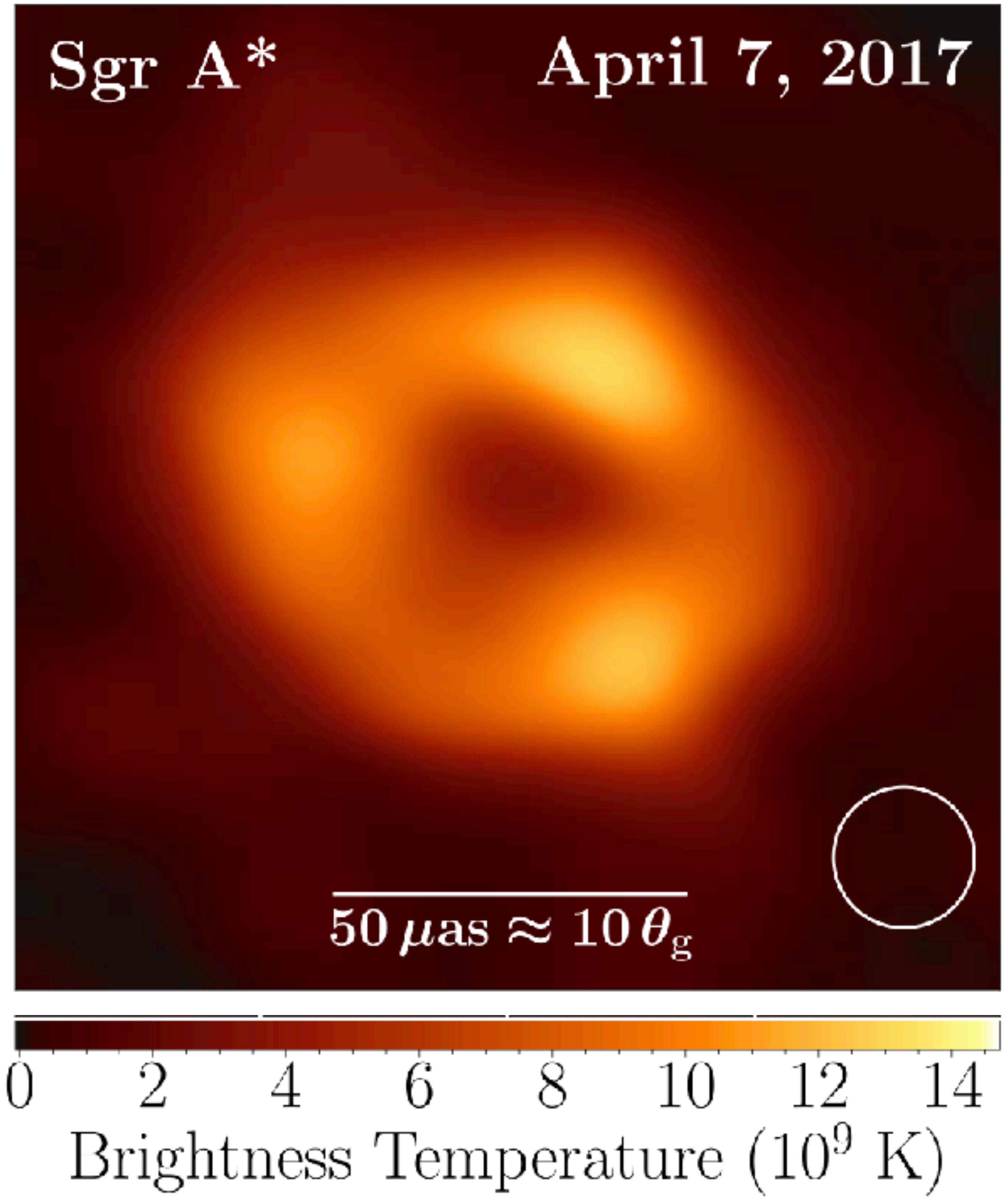
※グラフの観測値から距離と速度のデータを読み取り、ケプラーの法則を当てはめてBH質量を求める

BH shadow

- Direct Evidence of SMBHs : Bright photon ring and central shadow (BH shadow) match predictions from general relativity for light bending around a BH



https://iopscience.iop.org/article/10.3847/2041-8213/ac6674/pdf



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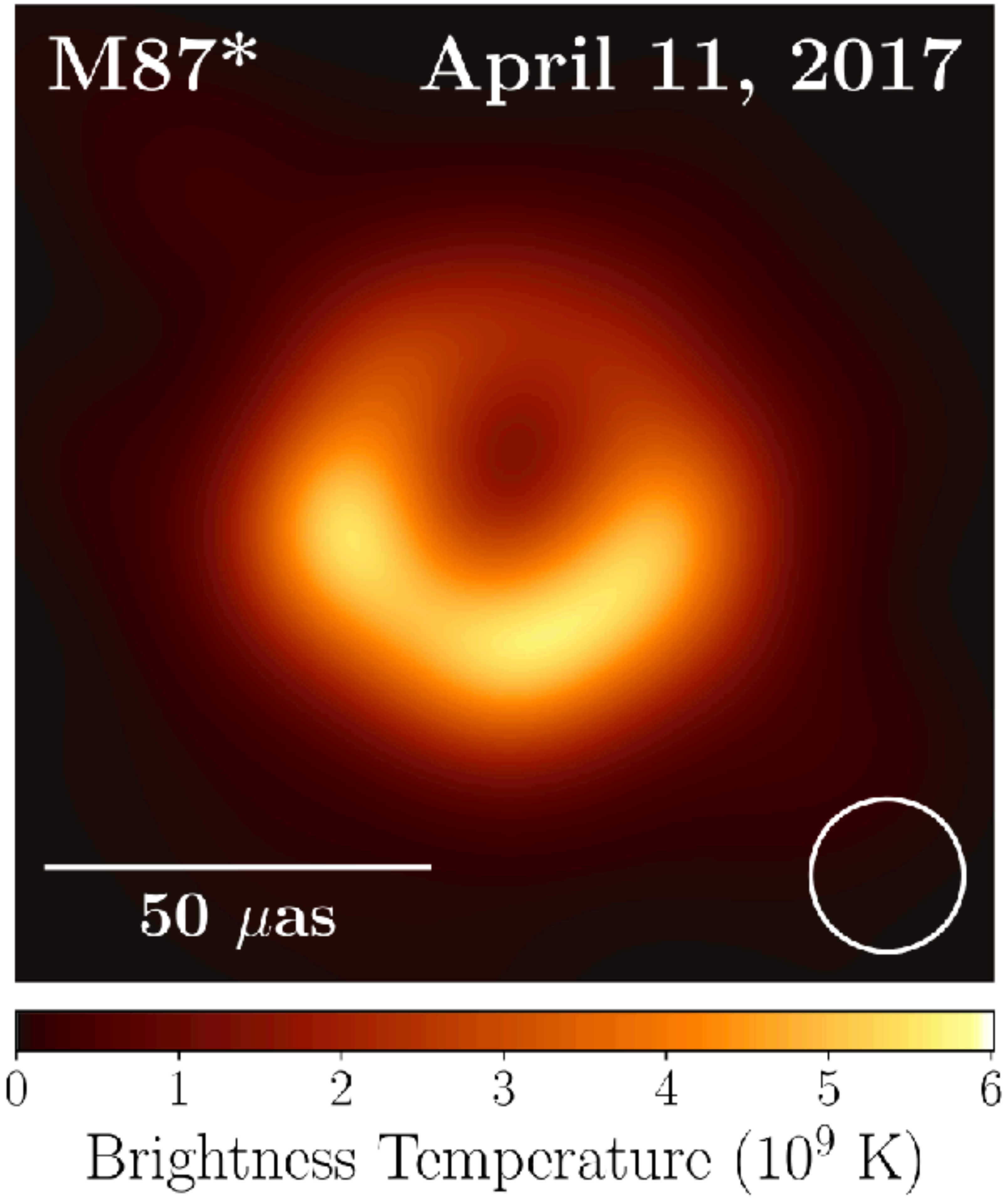
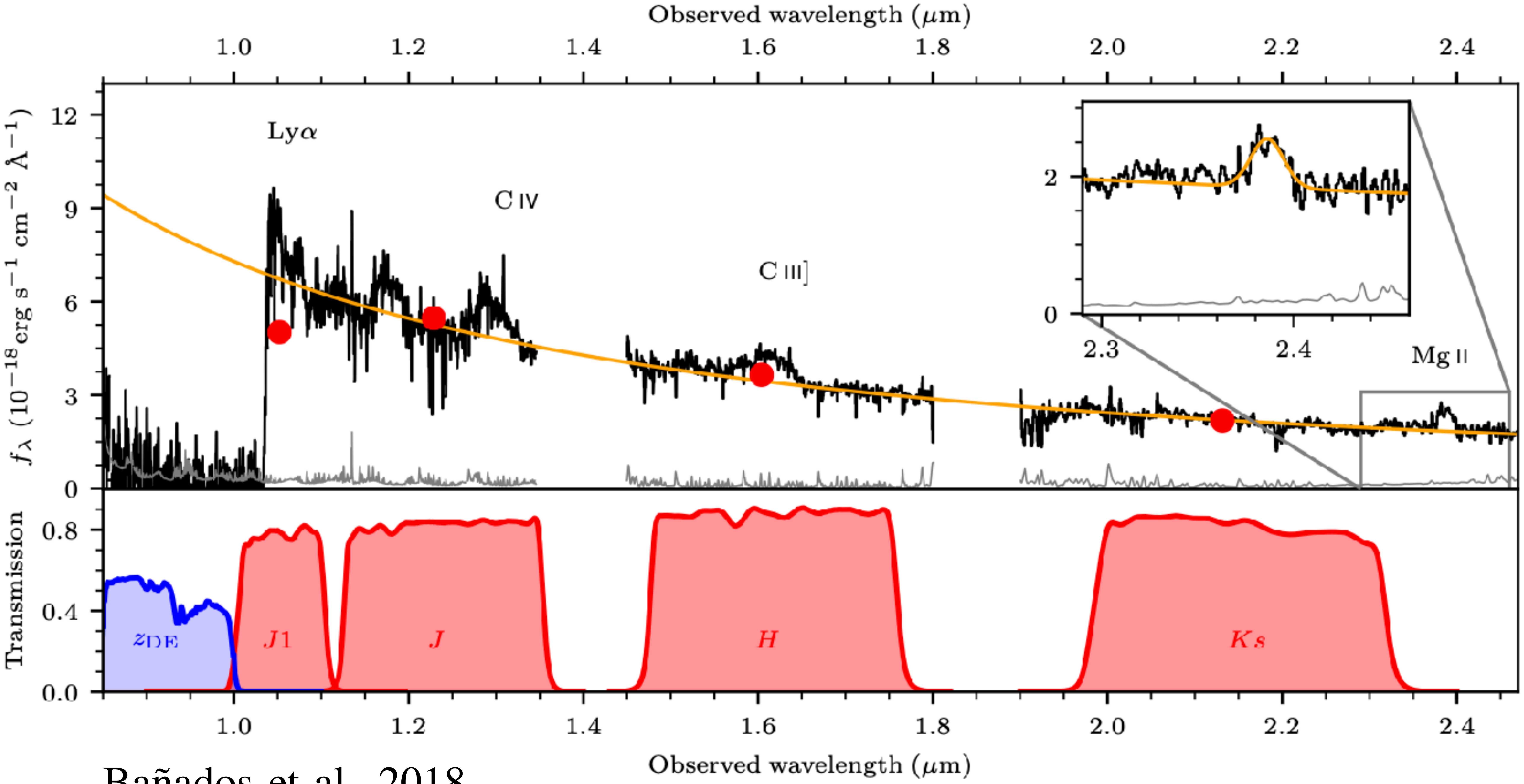


Most Distant SMBH

- Most Distant SMBHs : quasar ULAS J134208.10+092838.61 at resshift $z = 7.54$ (Universe was only 690 million years old—just five percent of its current age)



Bañados et al . 2018

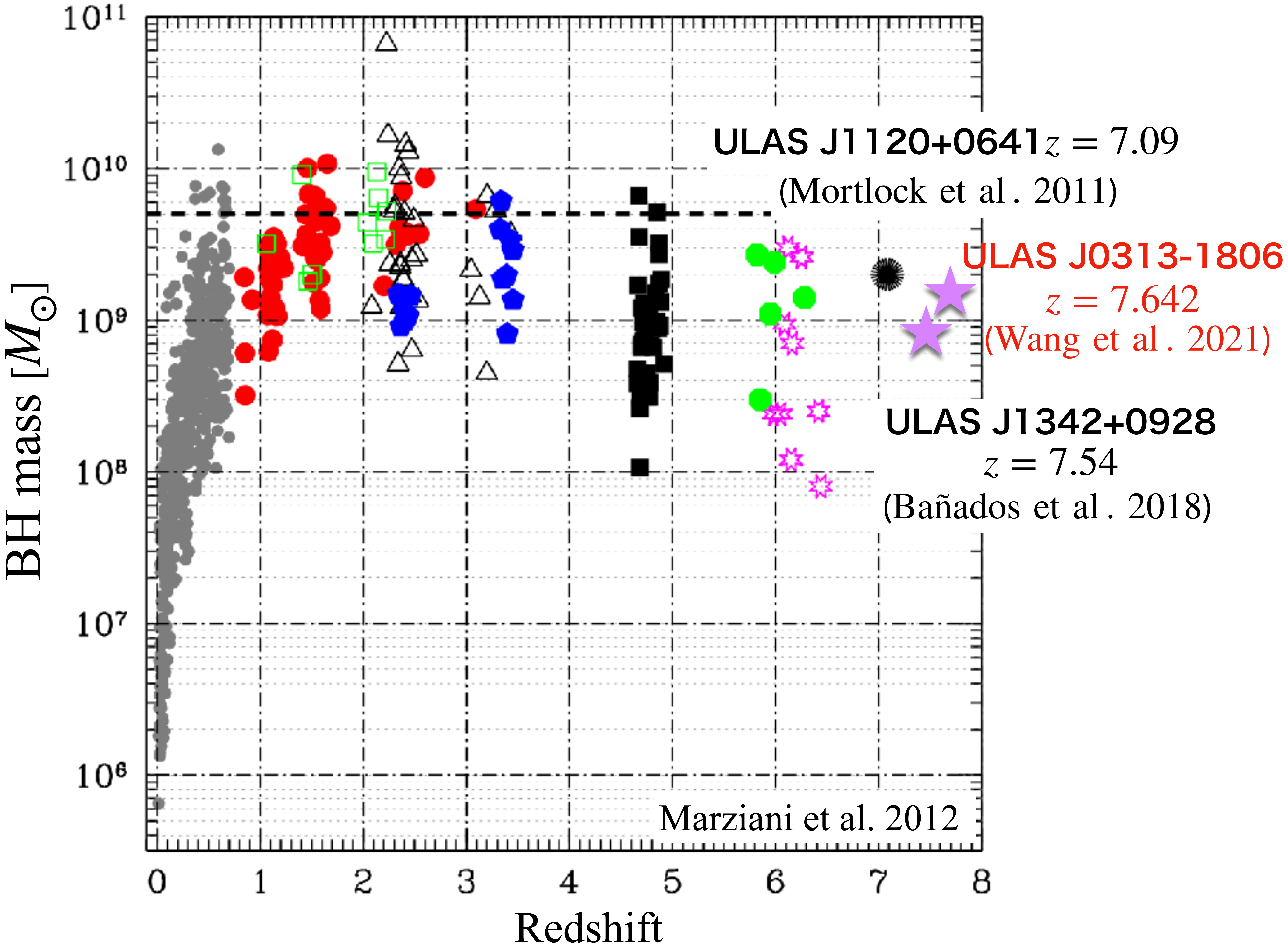
- $L_{bol} = 5.15 \times L_{rest3000Å}$
  $= 4 \times 10^{13} L_\odot$
- FWHM of MgII line:
  2500^{+480}_{-320} km s^{-1}

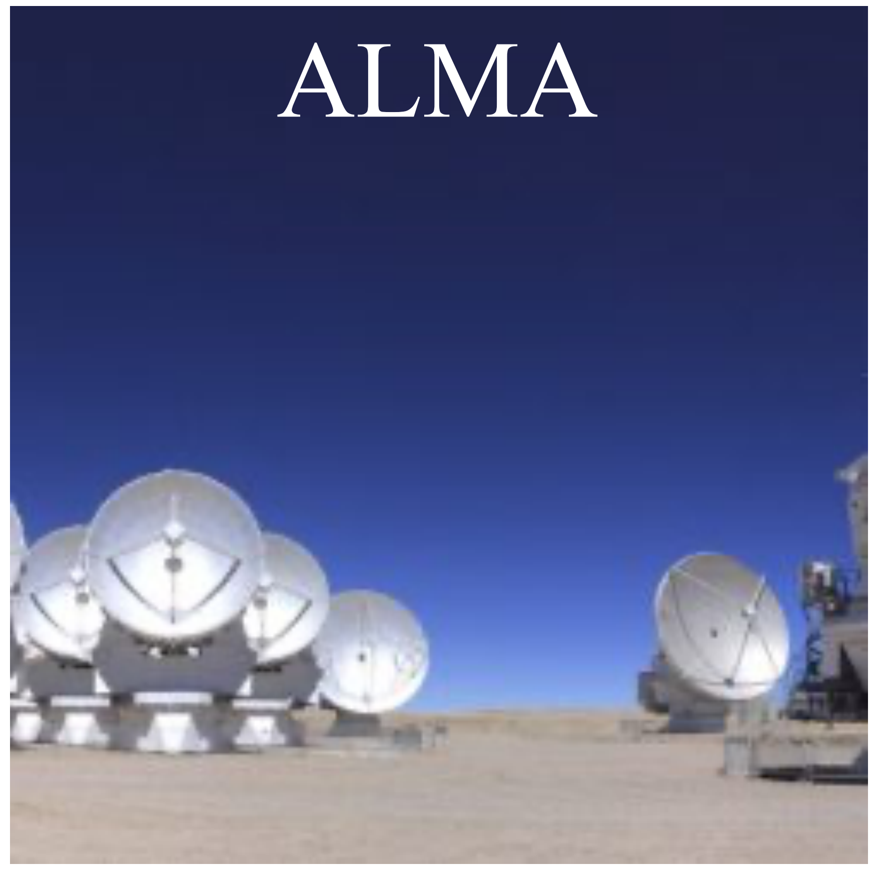
↓

- $M_{BH} = 7.8^{+3.3}_{-1.9} \times 10^8 M_\odot$
- $L_{bol}/L_E = 1.5^{+0.5}_{-0.4}$

SMBHs in High-z Universe

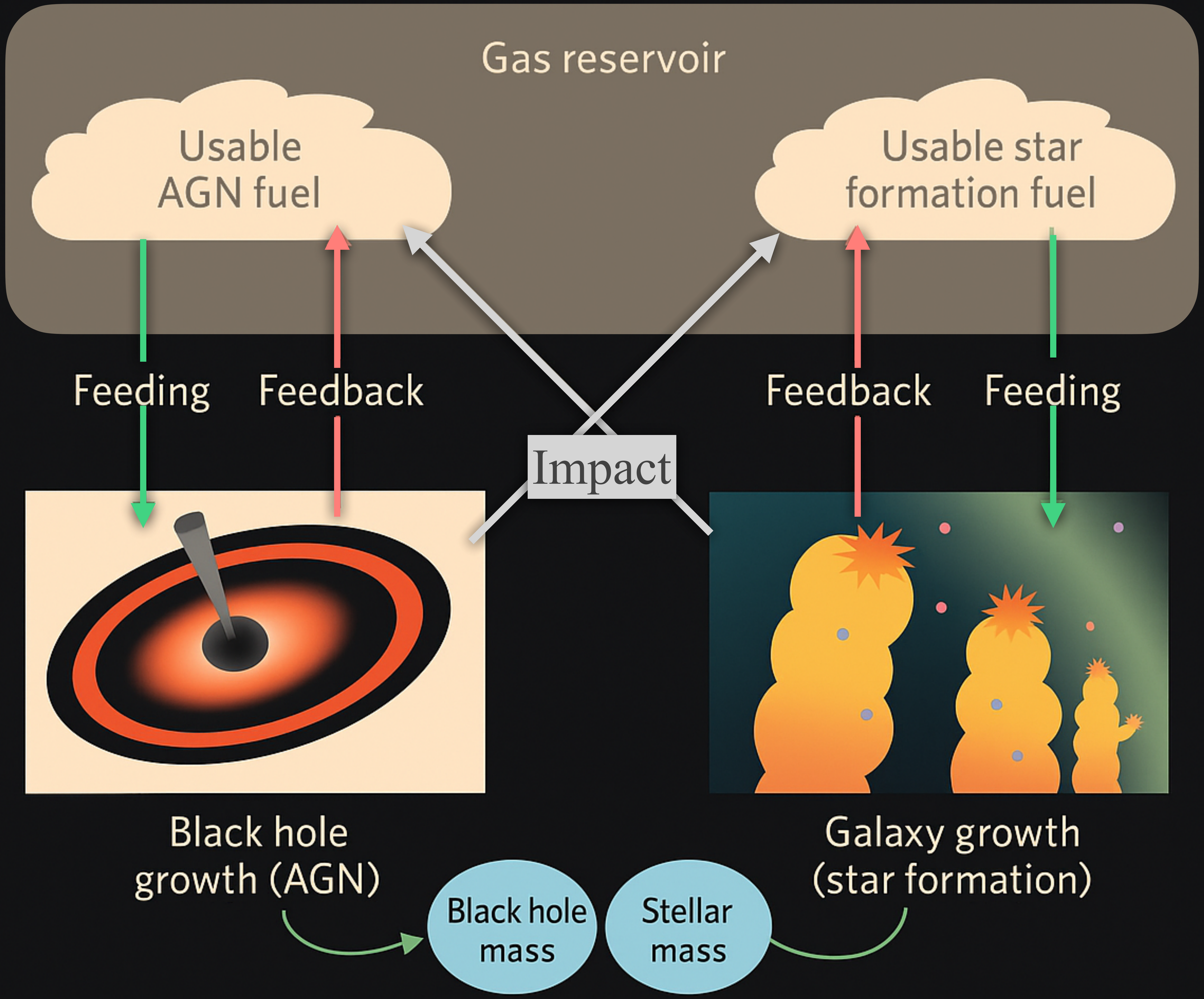
- **The existence of such a massive SMBH just ~670 million years after the Big Bang challenges significantly theoretical models of SMBH growth**





Co-Evolution:
Central massive BHs and Host Galaxies

Supermassive BHs are found at the centres of massive galaxies. During the growth of these BHs they light up to become visible as AGNs and release extraordinary amounts of energy across the electromagnetic spectrum. This energy is widely believed to regulate the rate of star formation in the BH's host galaxies via so-called AGN feedback. However, the details of how and when this occurs remain uncertain from both an observational and theoretical perspective.



Harrison +'17

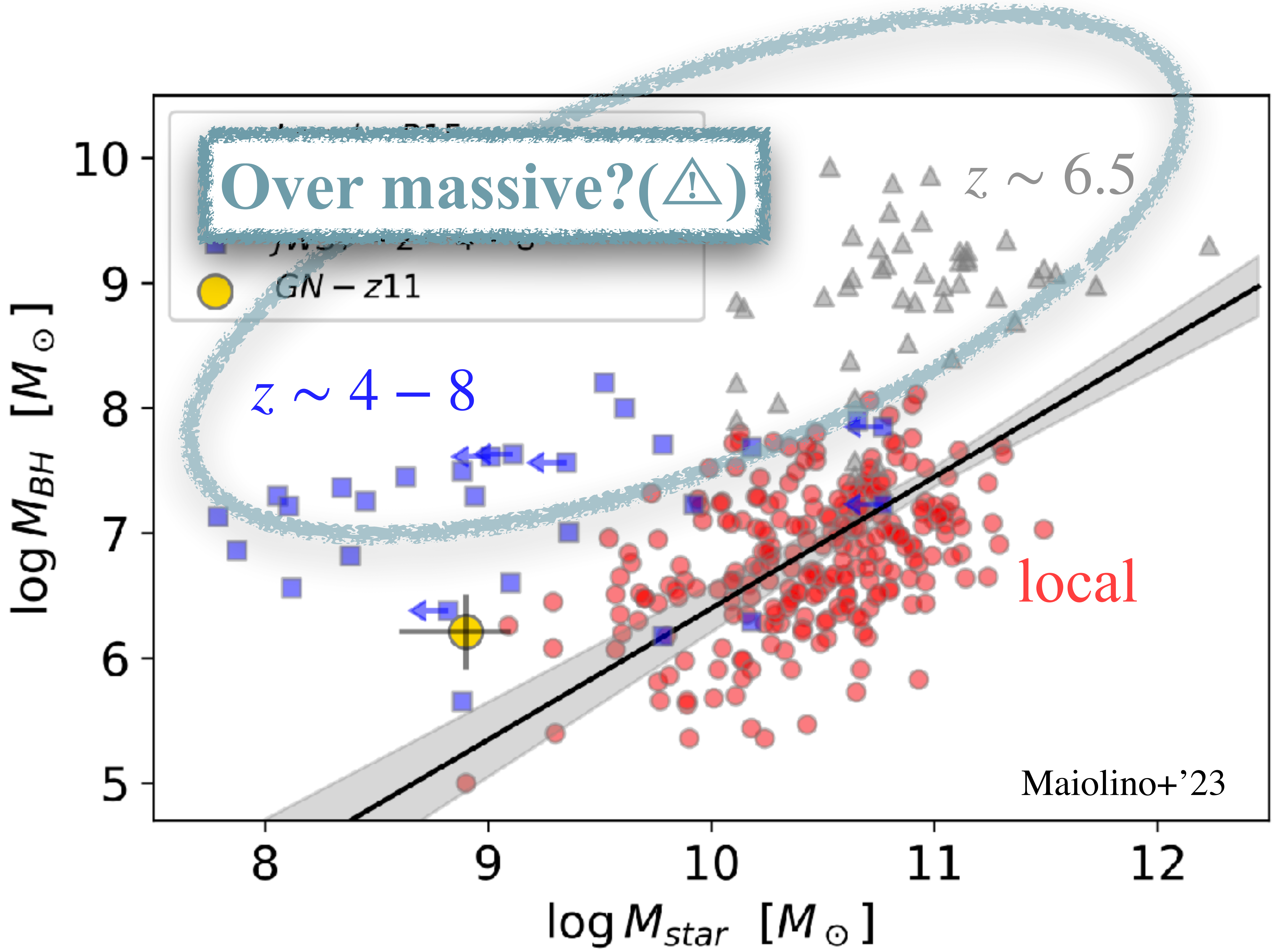
BH-Galaxy Relation：Local Galaxies

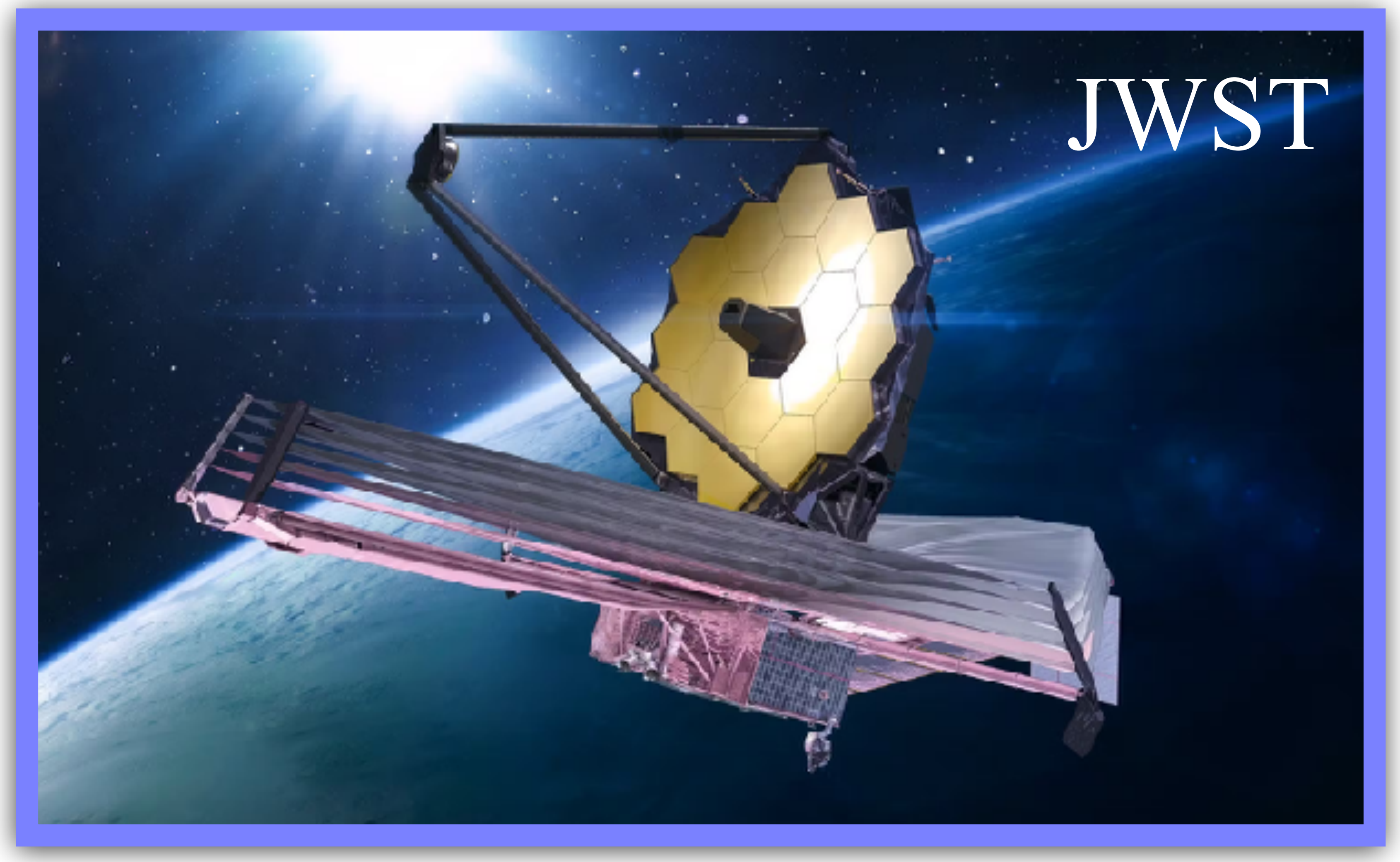
$M_{\rm BH} \sim 0.001 M_{\rm gal}$

→ Observation suggests a strong link between SMBH and galaxy evolution

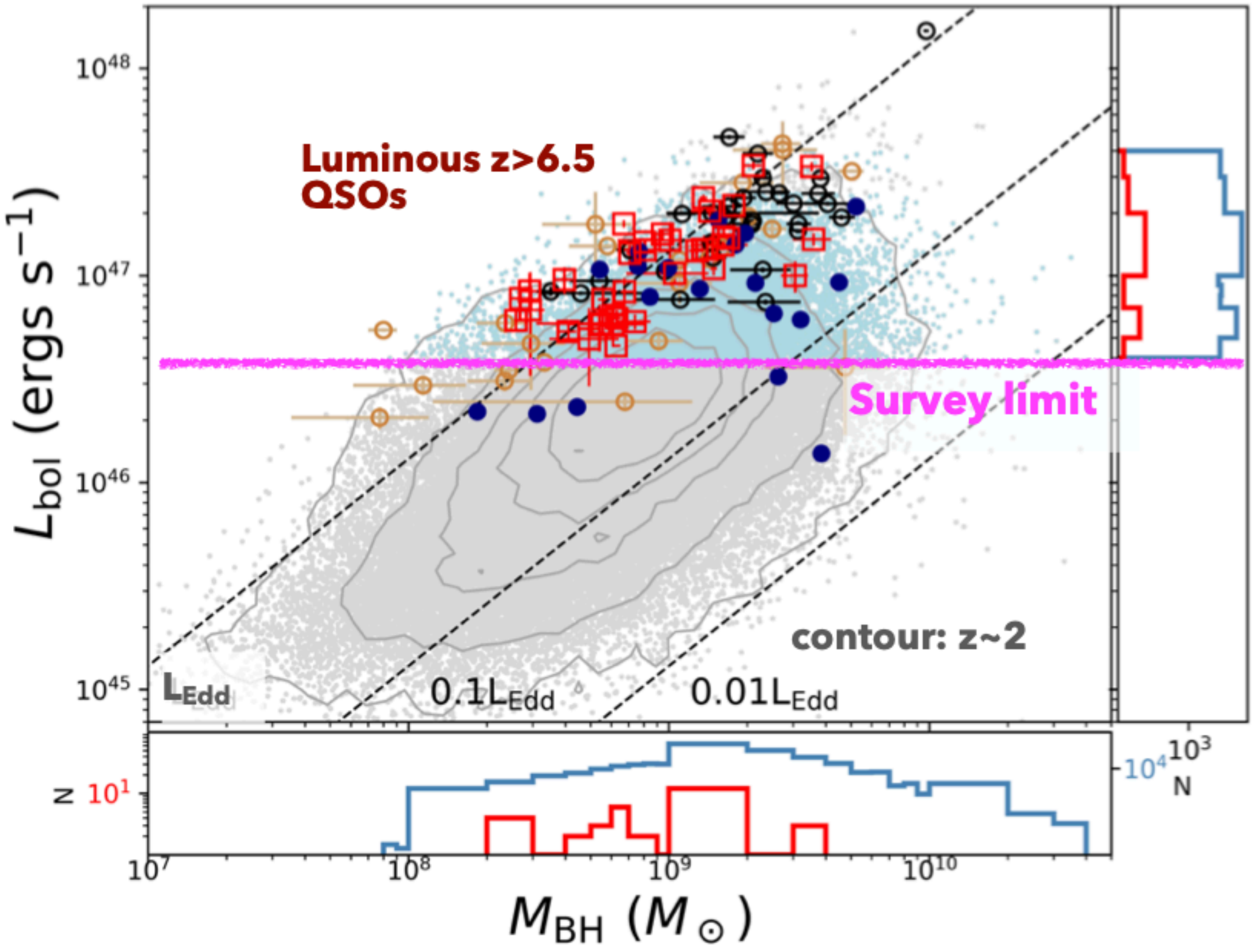
- Stellar vel. dispersion: $M_{\rm BH} = 10^{8.12} M_\odot \left(\sigma / 200\ {\rm km/s}\right)^{4.24}$
- Bulde mass: $\log\left(M_{\rm BH}/M_\odot\right) = (8.8 \pm 0.085) + (1.24 \pm 0.081) \log\left(M_{\rm bulge}/10^{11} M_\odot\right)$
- Total stellar mass: $\log\left(M_{\rm BH}/M_\odot\right) = (7.45 \pm 0.08) + (1.05 \pm 0.11) \log\left(M_{\rm stellar}/10^{11} M_\odot\right)$
- K-band magnitude: $M_{\rm BH}/10^9 M_\odot = -(0.266 \pm 0.052) - (0.484 \pm 0.034)\left(M_{\rm K,bulge} + 24.21\right)$

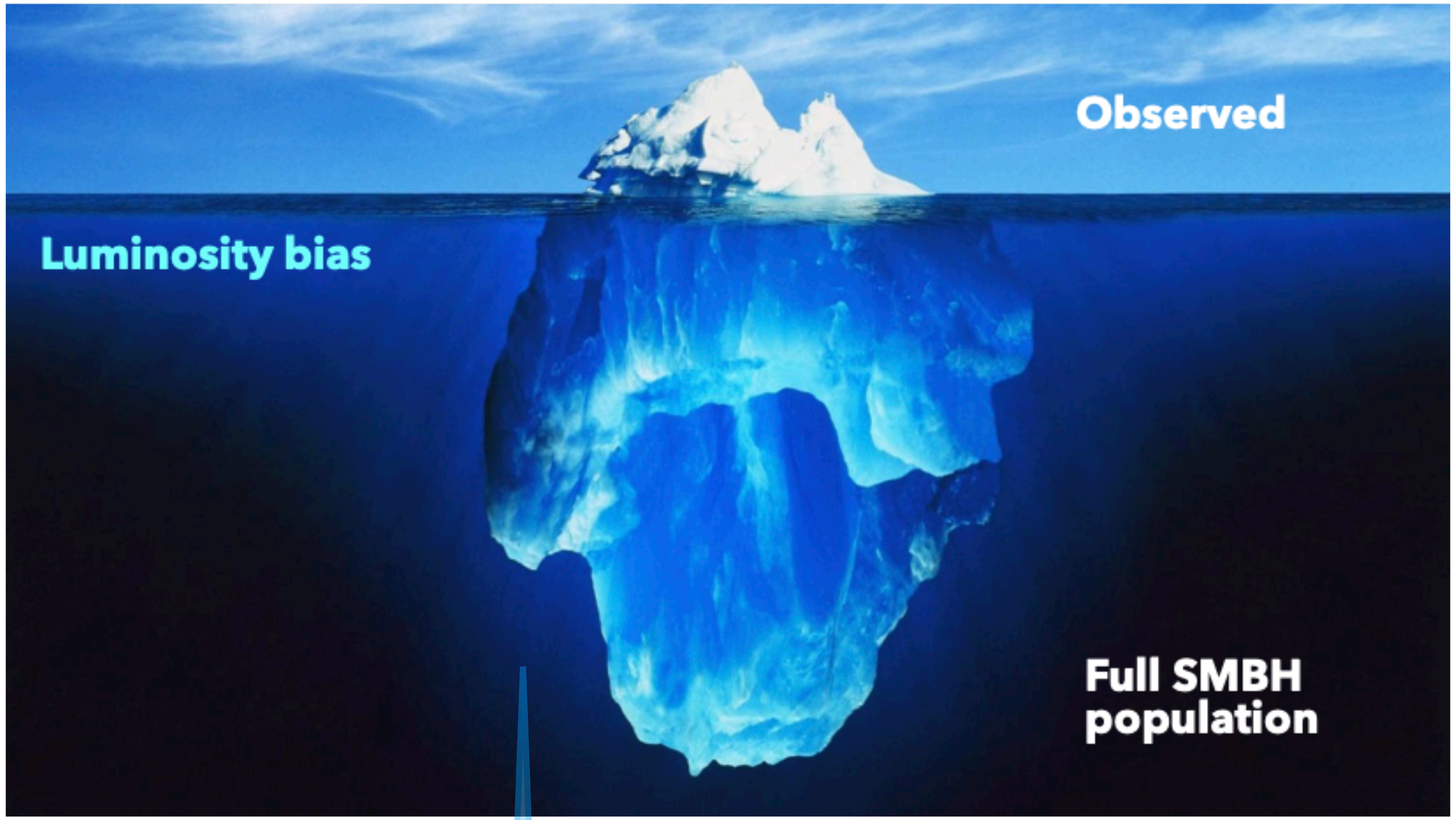
BH-Galaxy Relation：High-z Galaxies





BH-Galaxy Relation：High-z Galaxies





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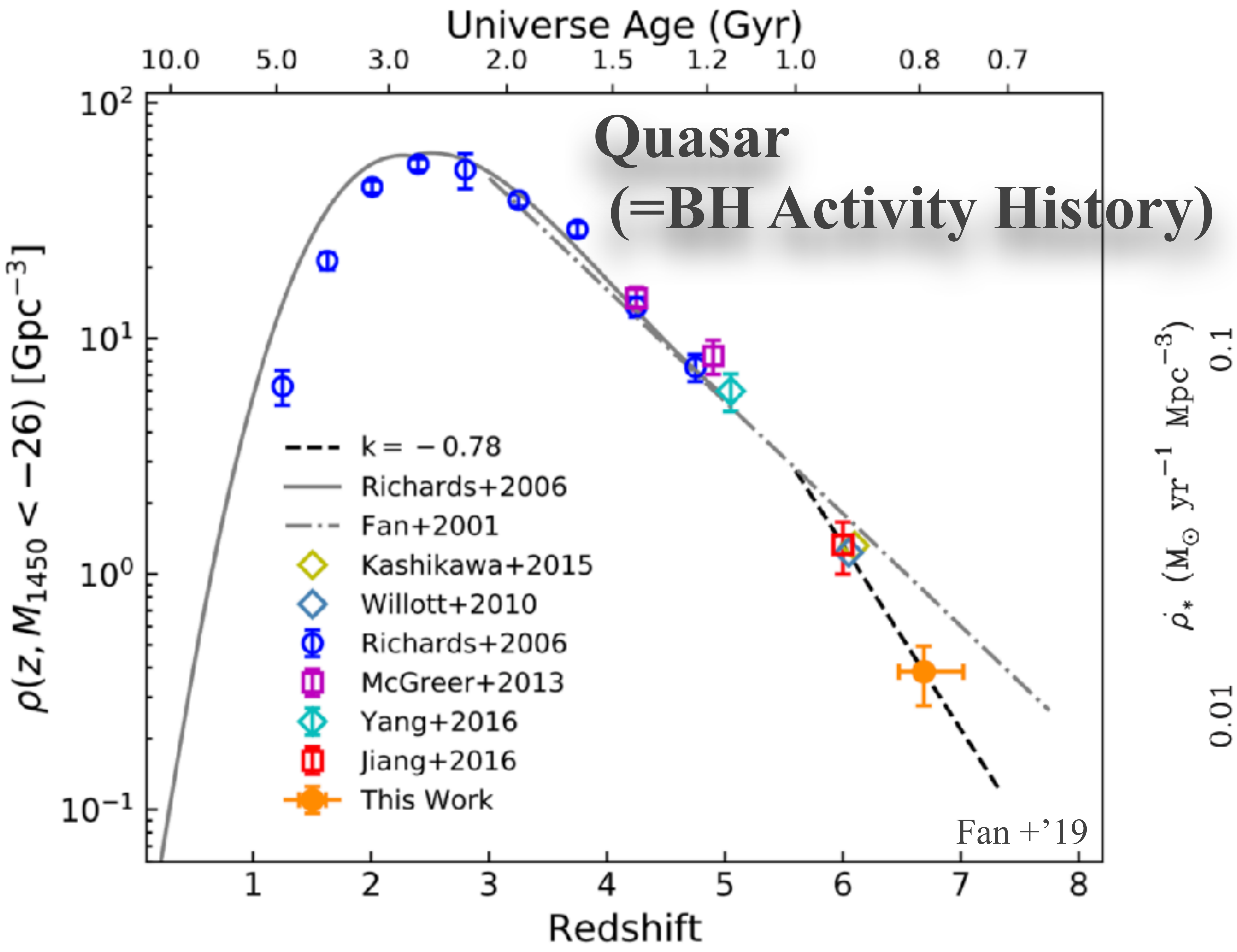
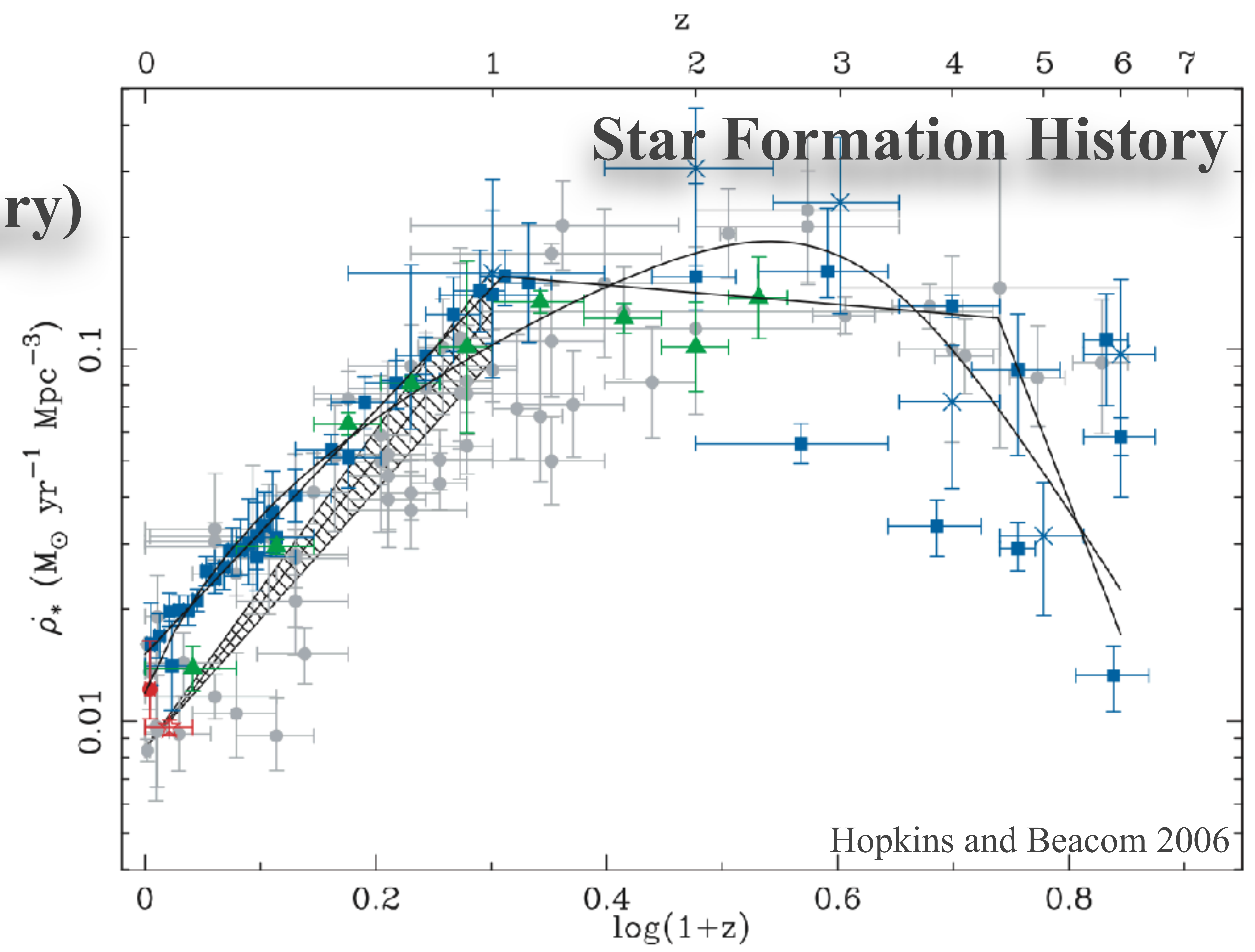
It is essential to probe lower-luminosity quasars to understand the full census of high-z SMBHs (The most luminous QSOs could just be the tip of iceberg)

Cosmic Evolution of Quasars

- Multiwavelength observations have consistently shown that AGN activity peaks around z~2 and declines toward higher and lower redshifts

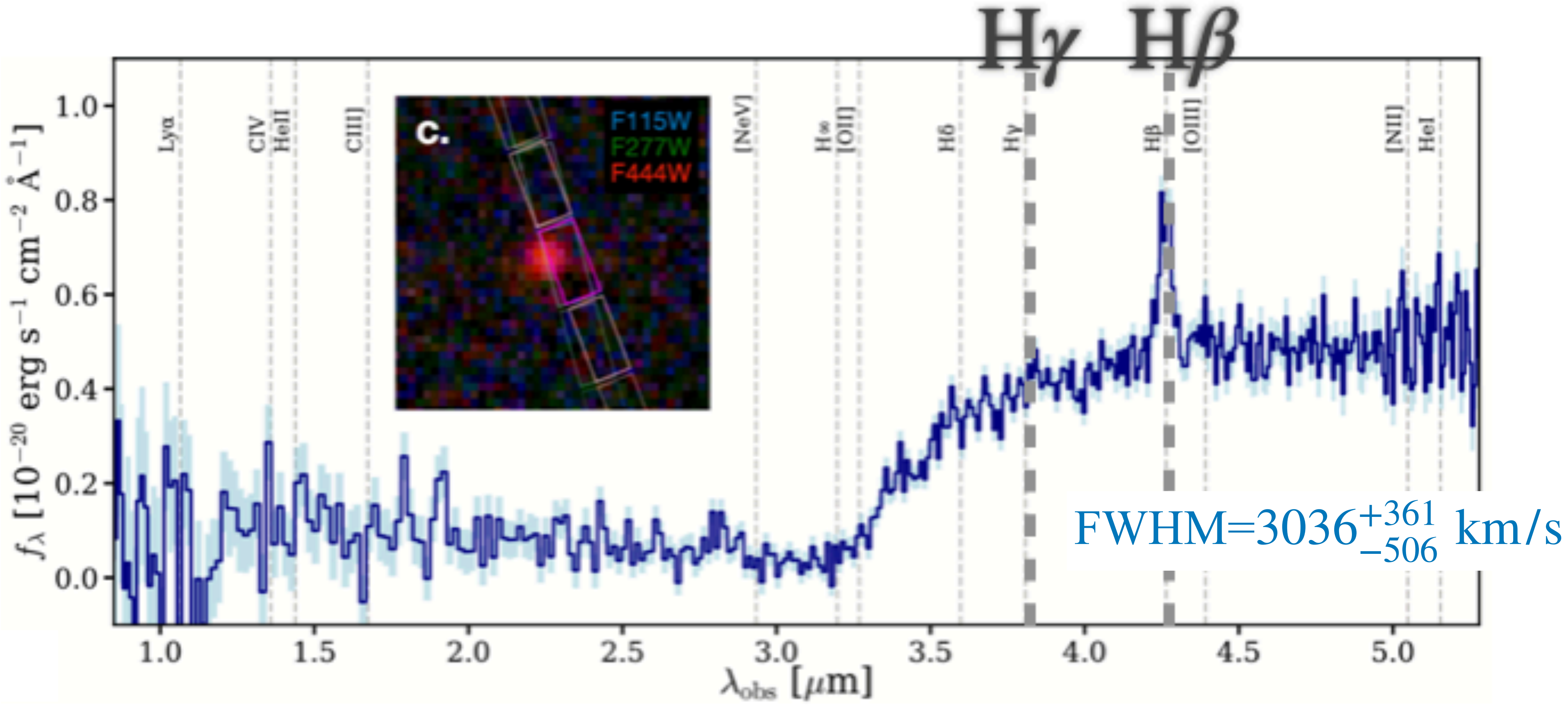




Mysterious Red Objects
Little Red Dots (LRDs)

Little Red Dots (LRDs)

Key Observational Features



General Features

- **Point-like source** (~a few hundred pc)
- **Residing in High-z ($z \gtrsim 3$) galaxies**
- **Broad Balmer emission lines** (FWHM $\gtrsim$ 1000 km/s)
- **V-shaped SEDs** (Brightness rises into the rest-UV as well as in the rest-optical)
- **X-ray and IR weakness** (compared with typical AGN)
- **Lack of UV-variability but hints of optical variability** (compared with typical AGN)

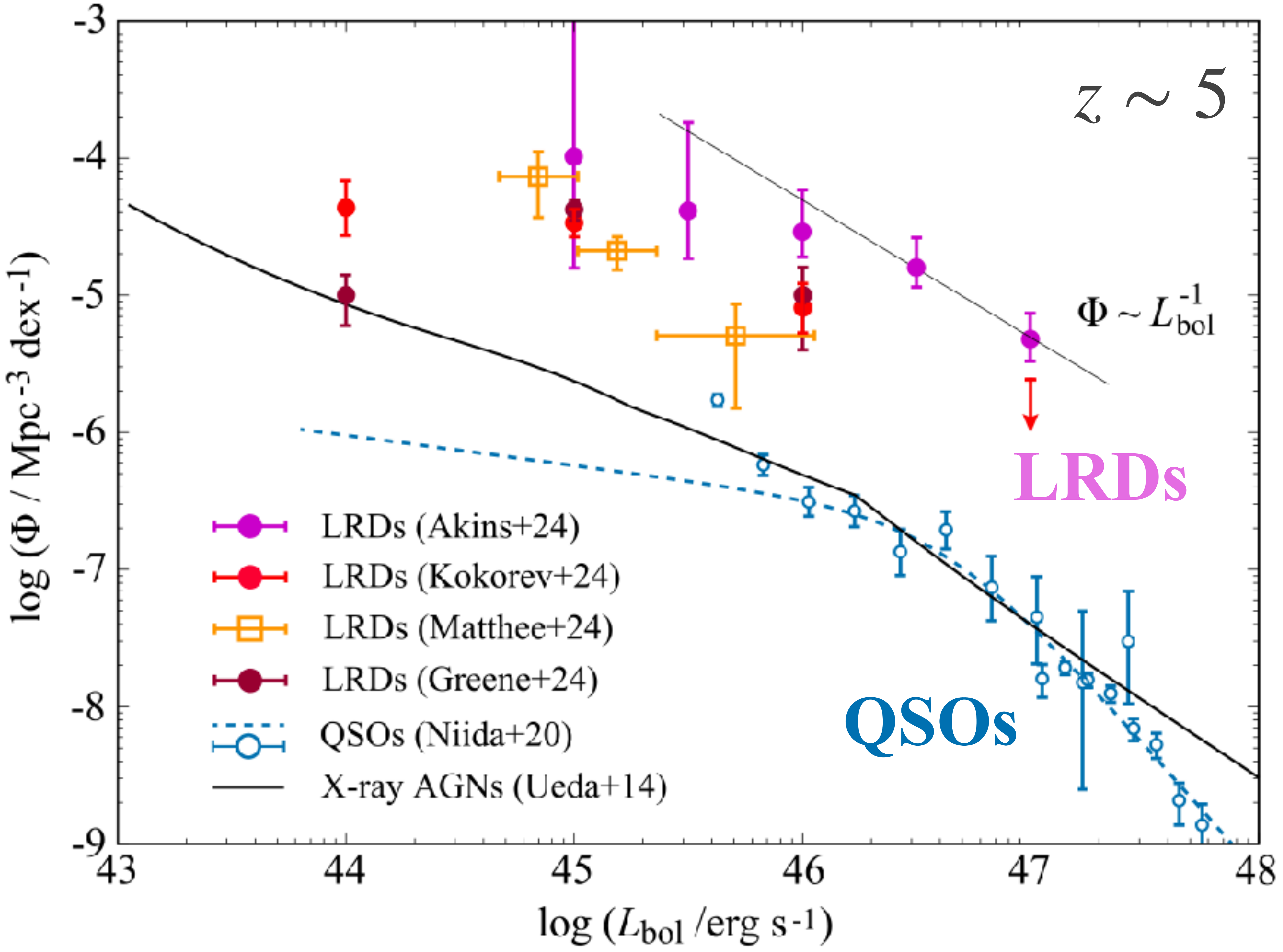
in Some Case

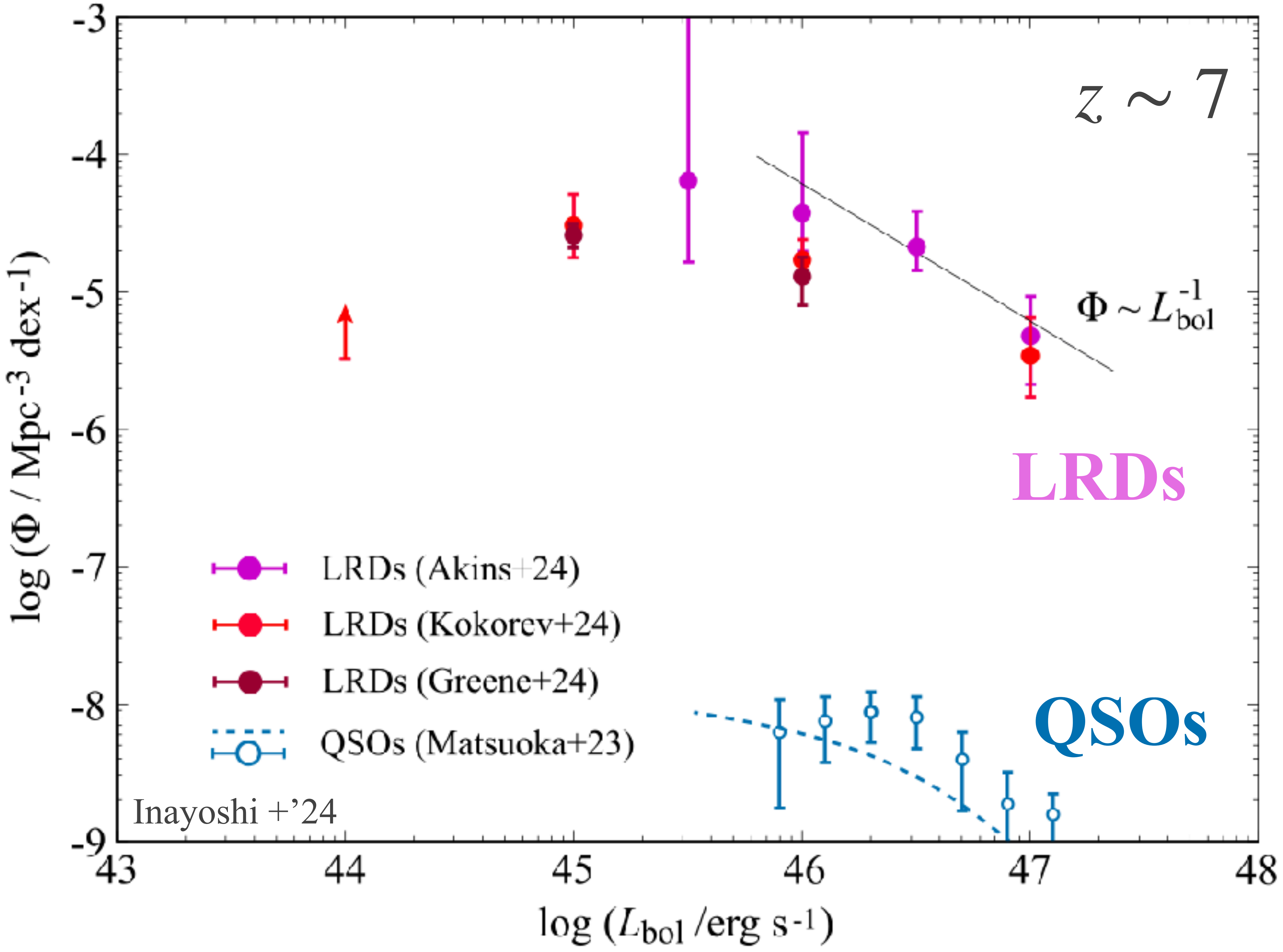
- **Strong Balmer breaks**

LRD = AGN(?)

Cosmic Evolution of Quasars

- JWST observations suggest that in contrast to expectations based on AGN surveys in the pre-JWST era, the cosmic growth rate of BHs within this AGN population does not decline but appears to increase at higher redshifts (z > 6)





AGN as Accreting BHs: The Soltan Argument

- Soltan (1982) first proposed that the mass in BHs today is simply related to the AGN population integrated over luminosity and redshift

$$L_{\rm bol} = \eta \dot{M} c^2$$

$$\mathrm{BHAD(z)} \equiv \Psi_{\rm BH} = \int_0^\infty \frac{(1-\eta)\, L_{\rm bol}}{\eta c^2} \phi\left(L_{\rm bol}, z\right) dL_{\rm bol}$$

Luminosity function

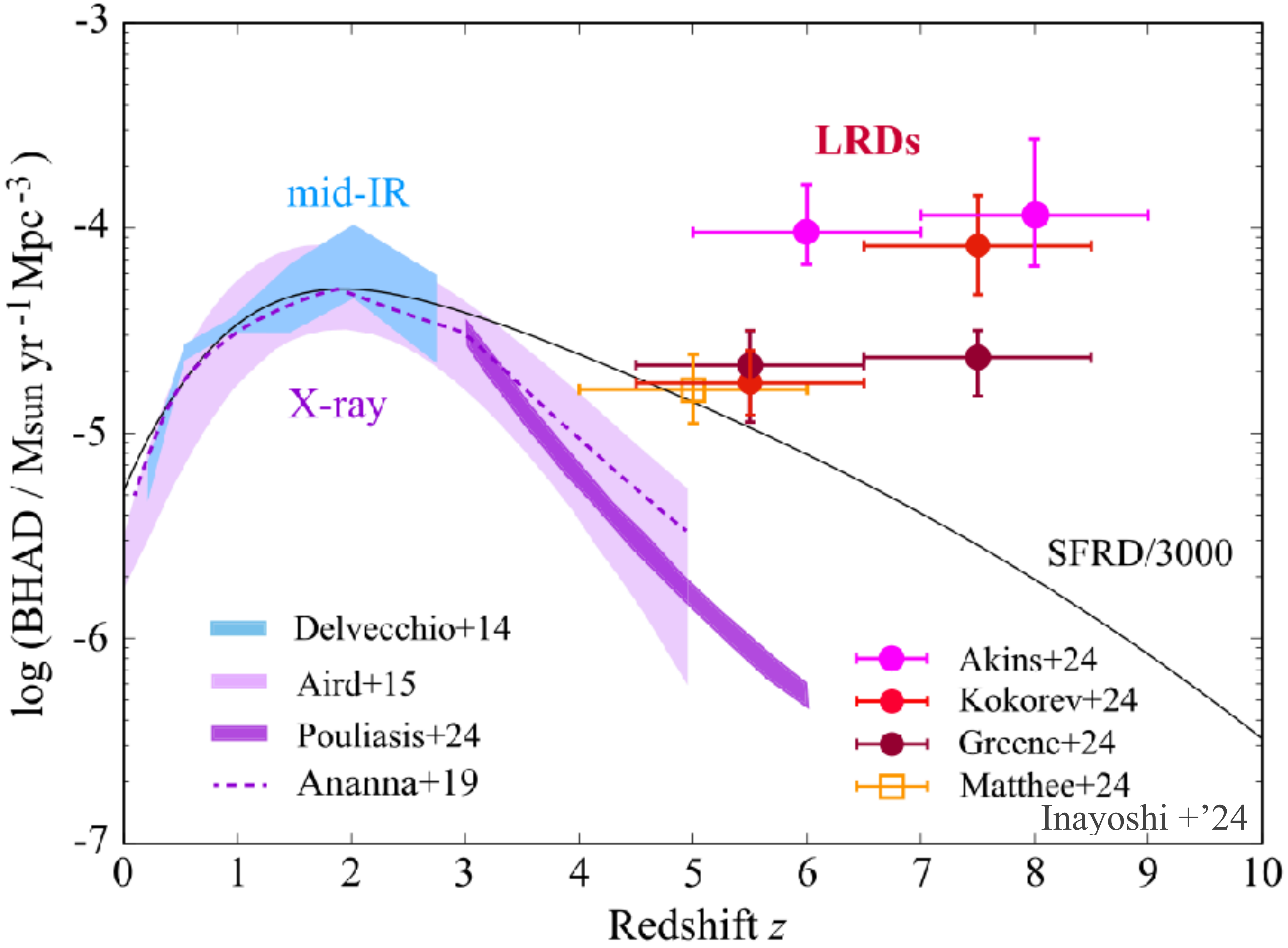
$$\frac{\rho_{\rm BH}(z)}{\rho_{\rm BH,0}} = 1 - \int_0^z \frac{\Psi_{\rm BH}(z')}{\rho_{\rm BH,0}} \frac{dt}{dz'} dz'$$

$L_{\rm bol}$: Bolometric luminosity of AGN, η: Radiative efficiency, $\dot{M}$: Mass accretion rate onto the BH, $\Psi_{\rm BH}(z)$: Black hole accretion rate density, $\phi(L_{\rm bol}, z)$: Luminosity function of AGN, $\rho_{\rm BH}(z)$: BH mass density, $\rho_{\rm BH,0}$: Present-day BH mass density

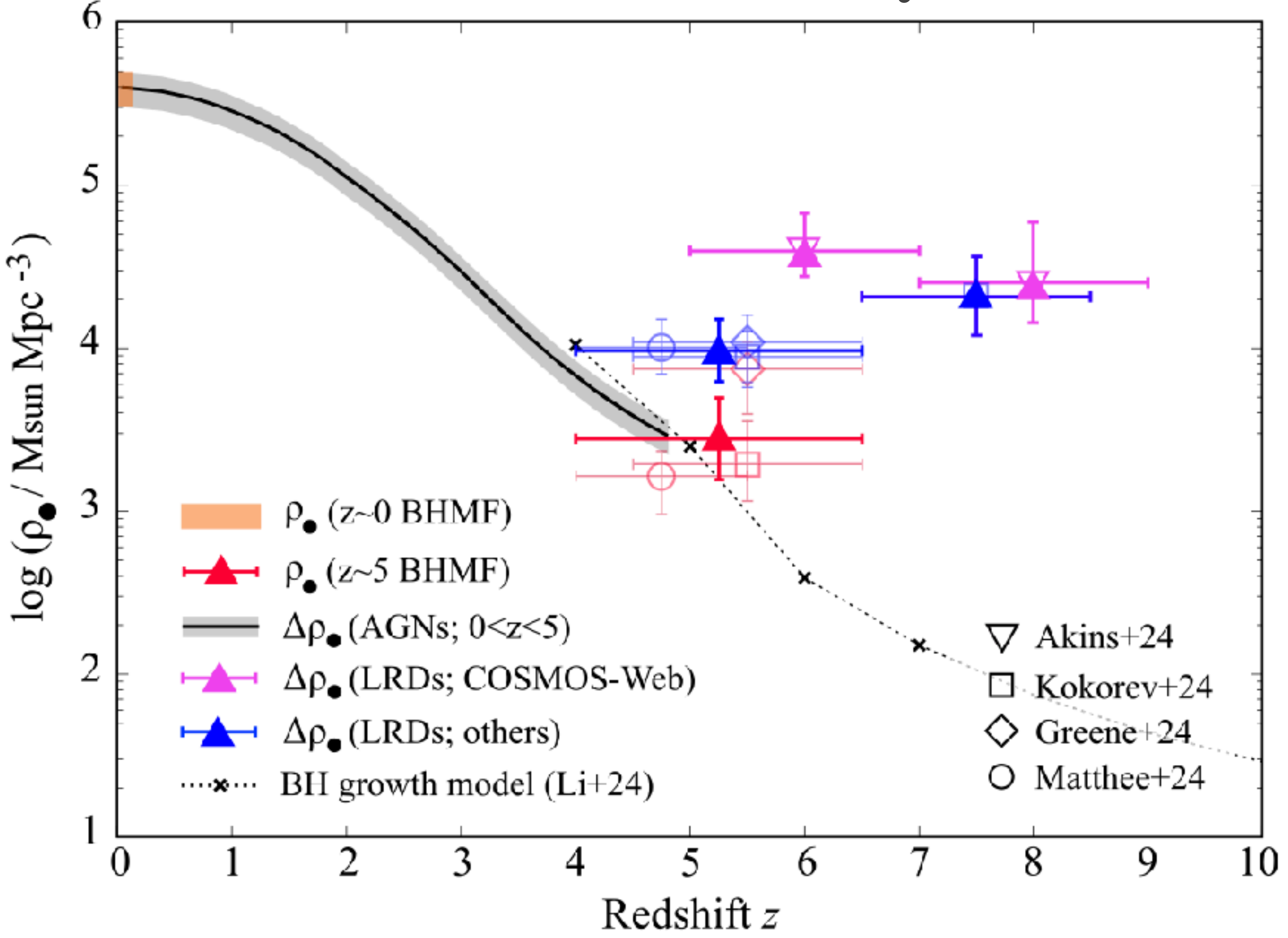
AGN as Accreting BHs: The Soltan Argument

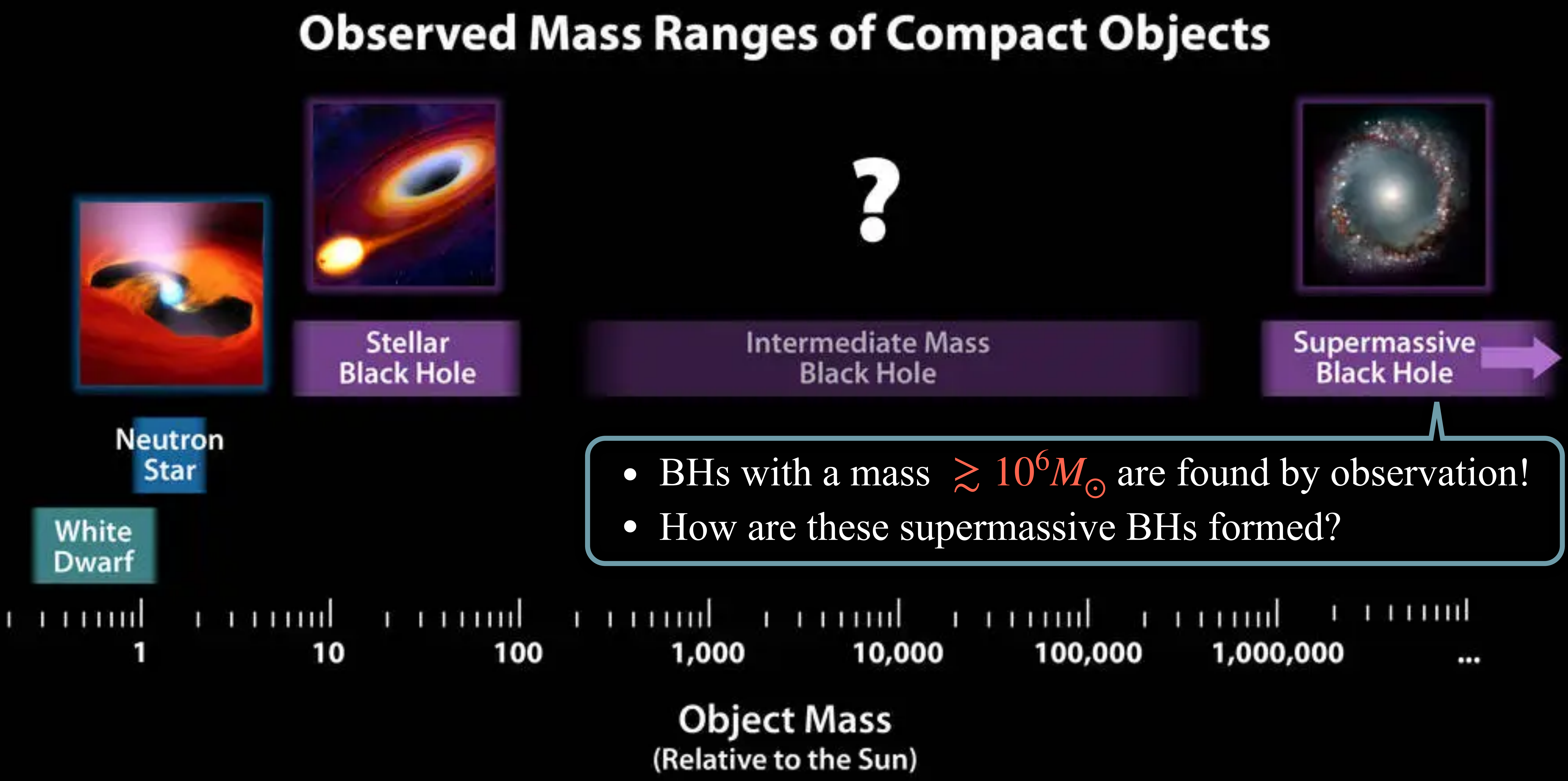
- BHAD inferred from the bolometric luminosity function of LRDs indicates a persistent or even increasing trend toward higher redshifts (4 < z < 8.5), opposite to the declining trend of X-ray-selected AGNs

BH accretion rate density (BHAD)



BH mass density





- BHs with a mass $\gtrsim 10^6 M_\odot$ are found by observation!
- How are these supermassive BHs formed?

Credit: NASA/JPL-Caltech：https://www.nasa.gov/image-article/mass-chart-dead-stars-black-holes/

Theoretical Studies

How to study SMBH formation

- The spatial and time scales of the astrophysical phenomena are so large that laboratory verification is not possible
- Simulation is essential for studying how supermassive BHs are formed

Size of Supermassive Black Hole

(※ Based on classical mechanics)

$$-\frac{GM_{\rm BH}m}{R} + \frac{1}{2}mv^2 > 0 \rightarrow v > v_{\rm esc} \equiv \sqrt{\frac{2GM_{\rm BH}}{R}}$$

$v_{\rm esc} > c$ (light speed)

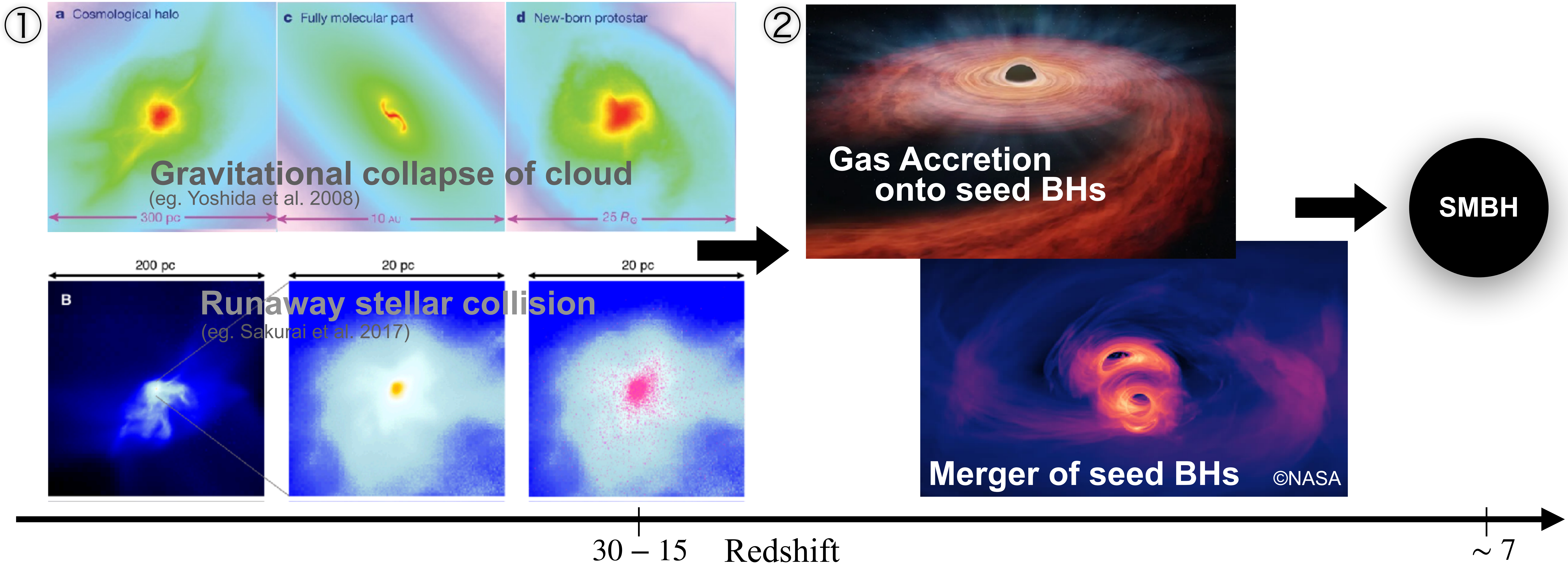
$M_{\rm BH} \gtrsim 10^6\ \mathrm{M}_\odot$

$$R < r_{\rm s} \equiv \frac{2GM_{\rm BH}}{c^2} \sim 3\left(\frac{M_{\rm BH}}{M_\odot}\right)\ \mathrm{km}$$

Theoretical Scenario of SMBH Formation

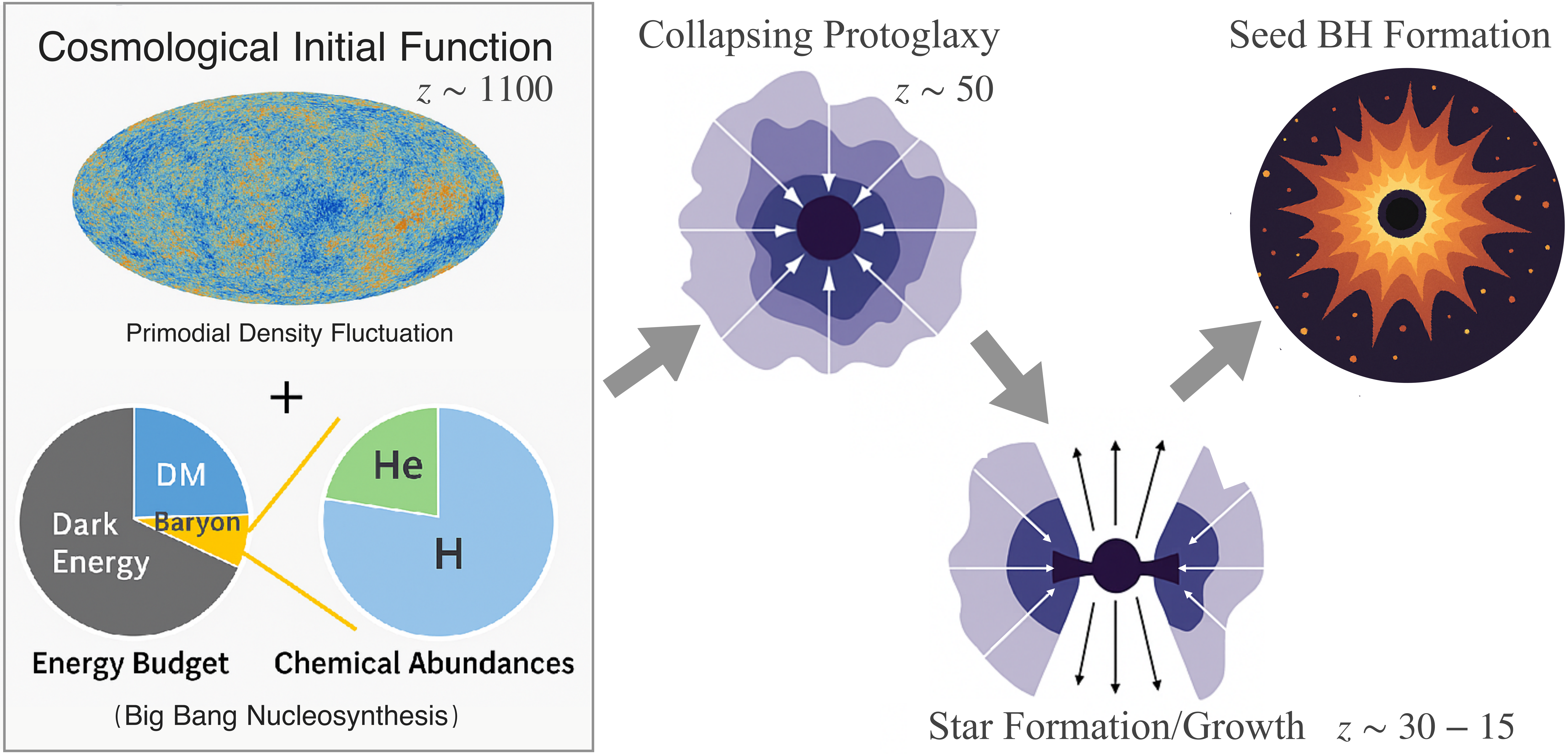
① Birth of low-mass BHs with a mass of $10^{2-5}M_{\odot}$ (seed BHs)

② Growth of the seed BHs to supermassive BHs via gas accretion, merger with other BHs/stars

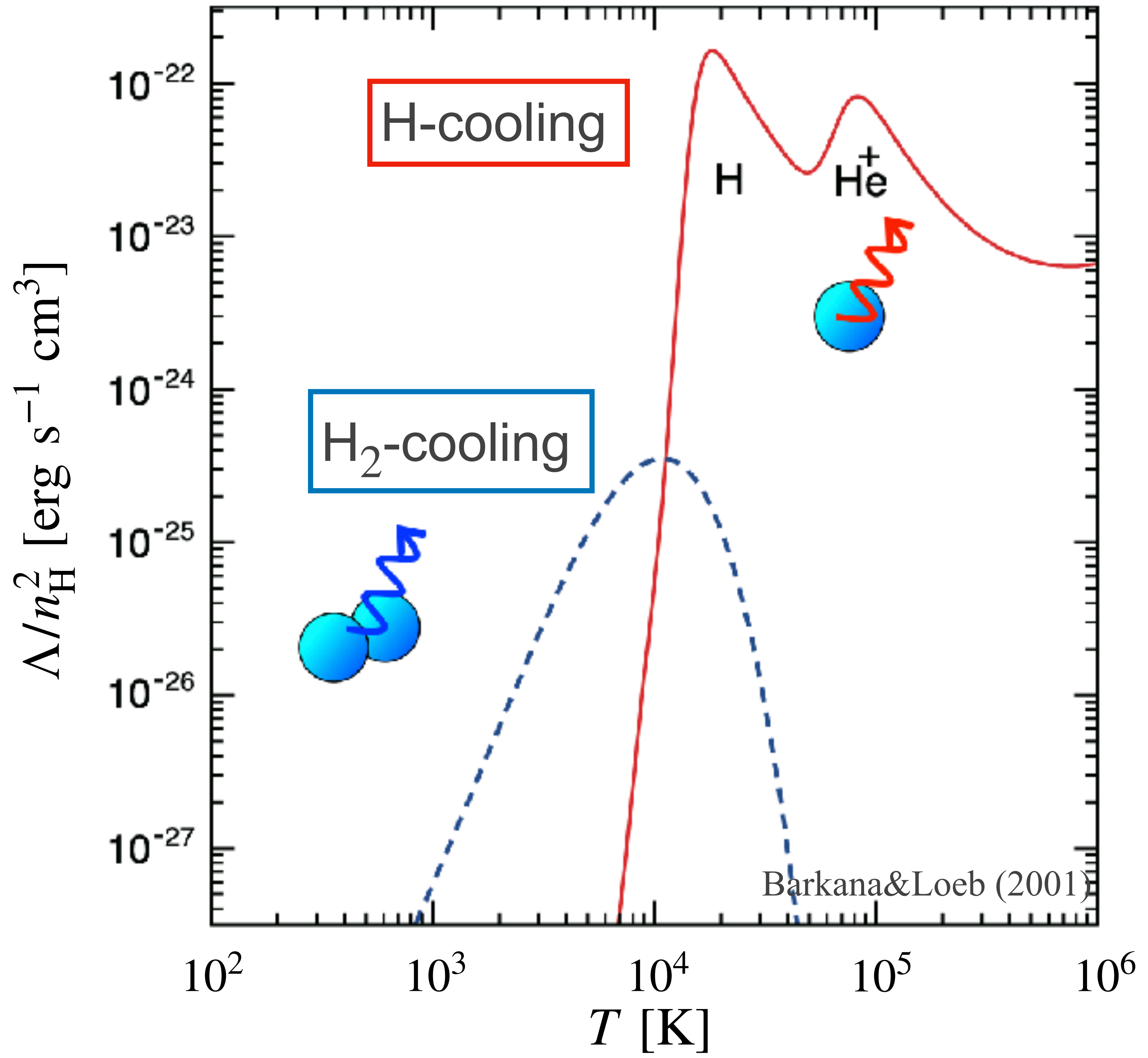


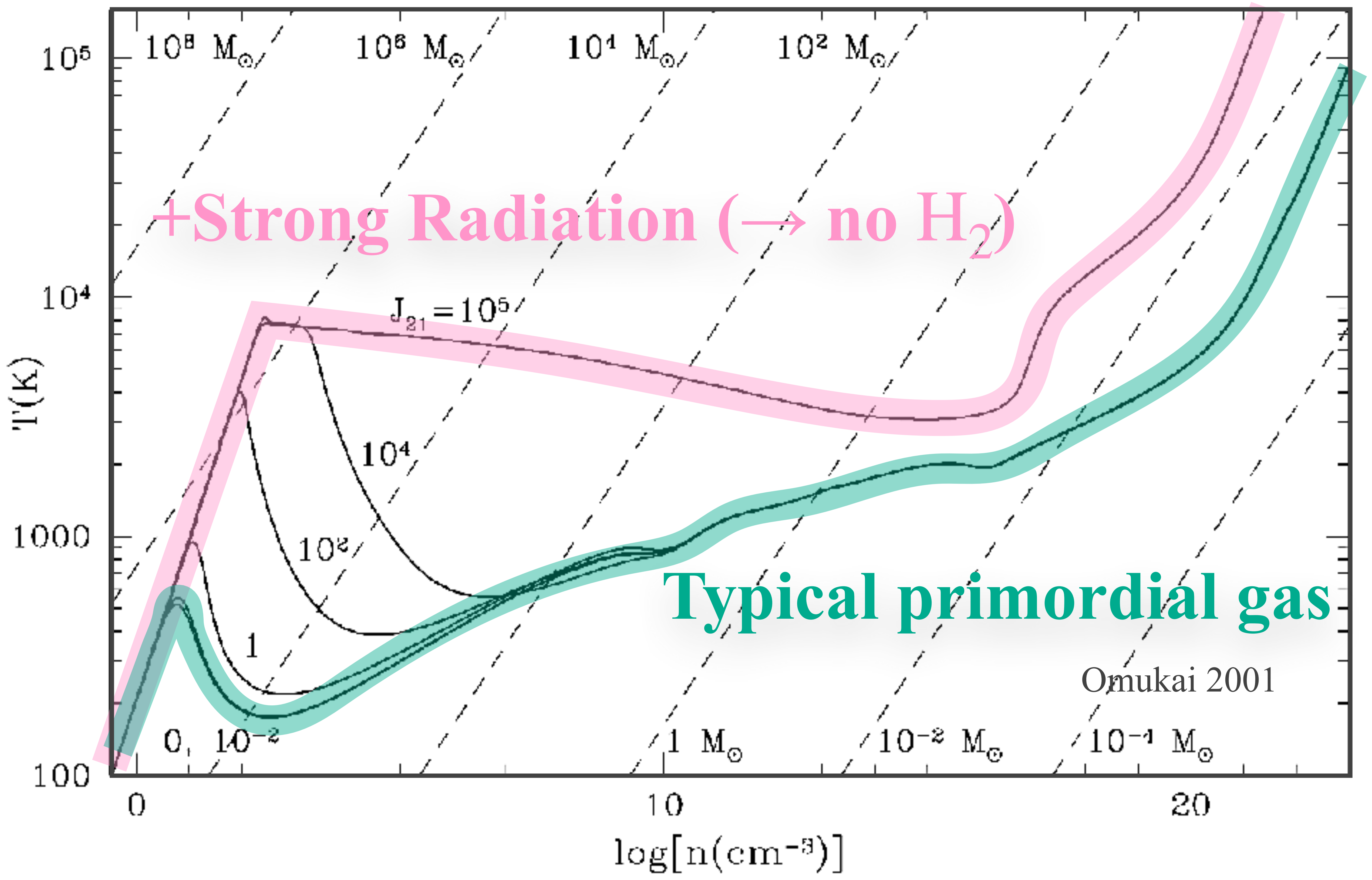
—Seed BH Formation—

Seed BH Formation



Evolution of Primordial Gas



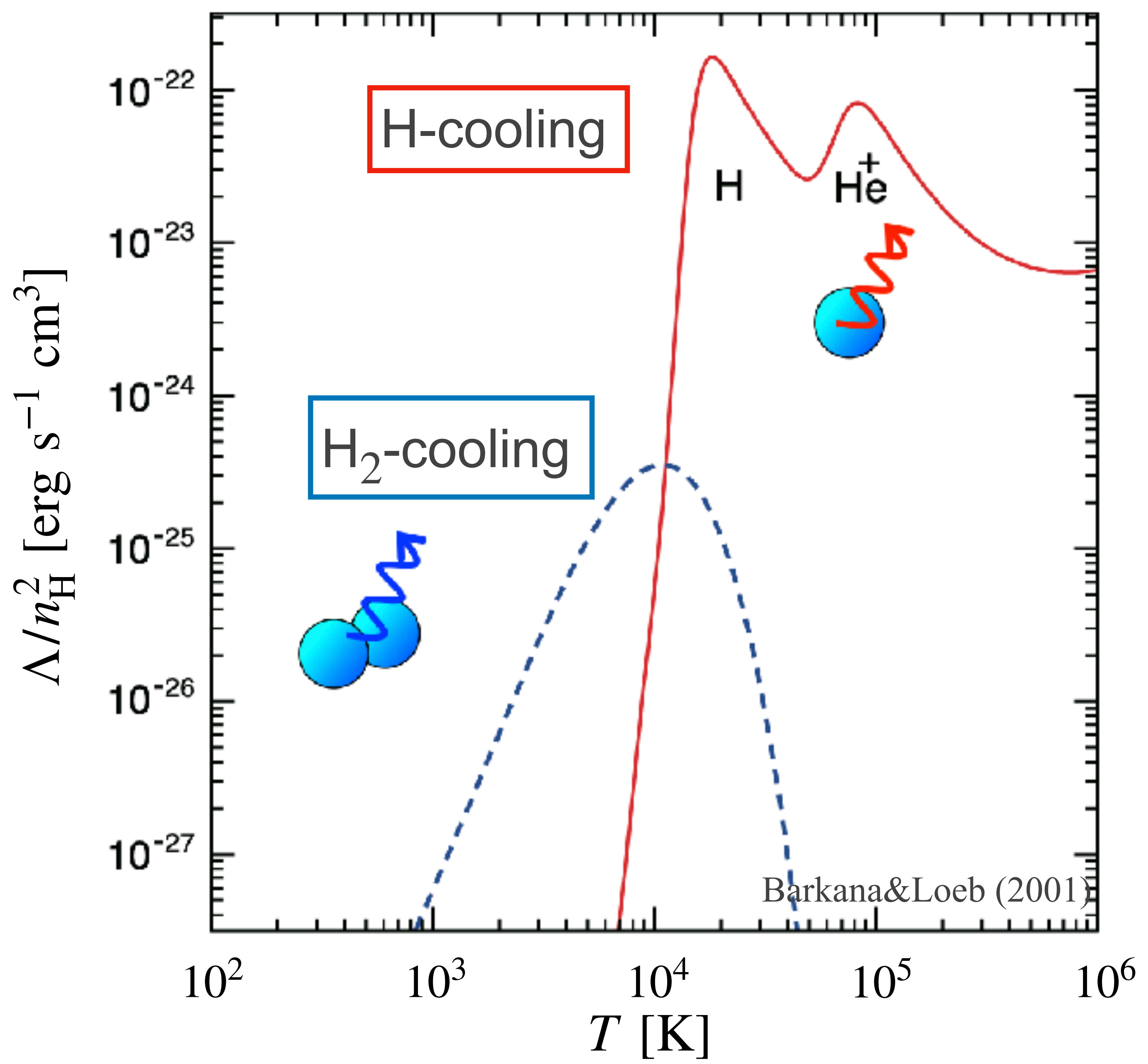


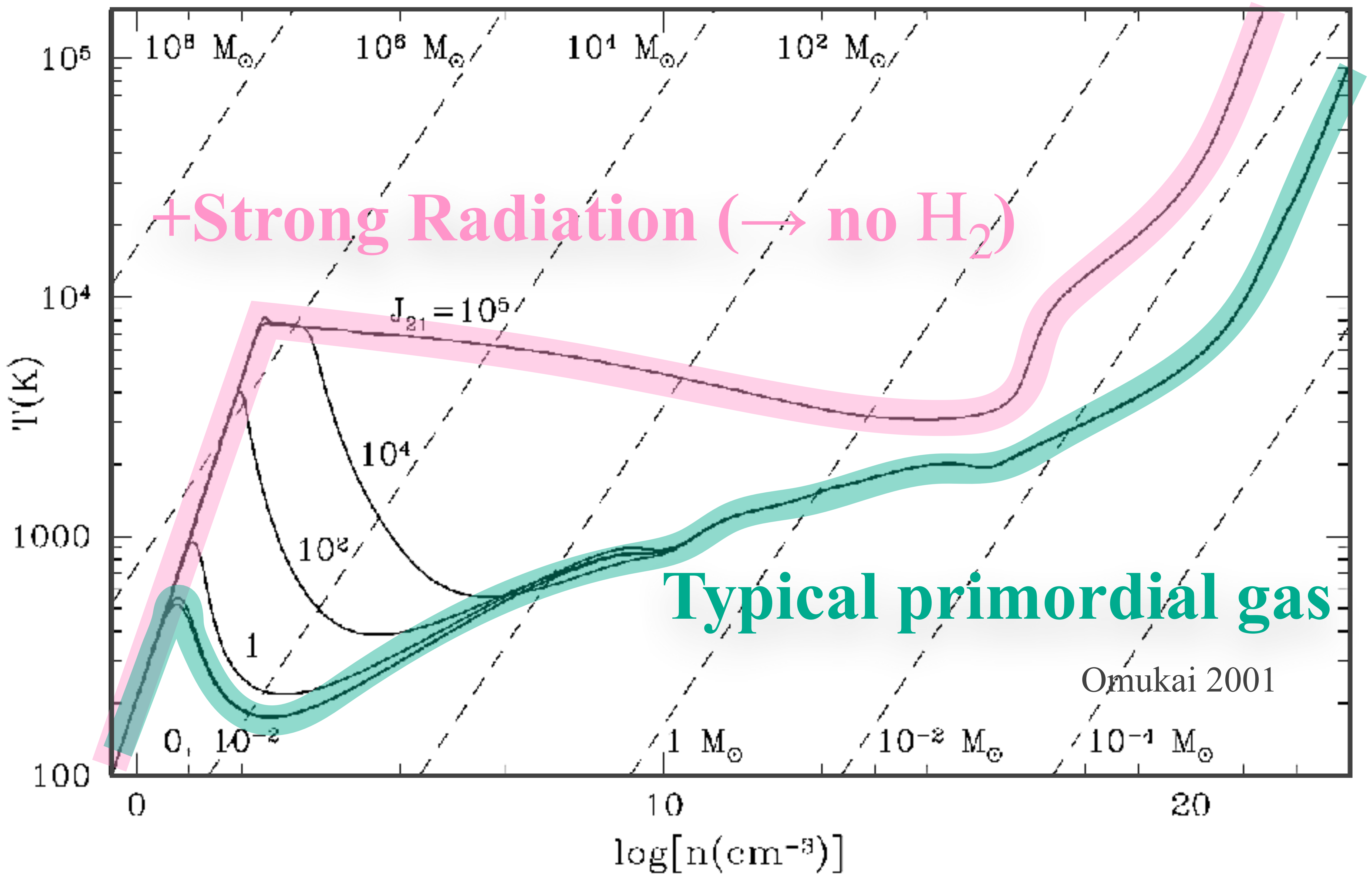
Mass accretion rate onto a star

massive!

$$\dot{M}_{\rm star} \sim \frac{M_{\rm Jeans}}{t_{\rm freefal}} \sim 4\times10^{-4}\ M_\odot {\rm yr}^{-1}\left(\frac{\rm T}{\boxed{200\ \rm K}}\right)^{3/2} \longrightarrow M_{\rm star} \sim \dot{M}_{\rm star} t_{\rm lifetime} \sim 400 M_\odot$$

Evolution of Primordial Gas





Mass accretion rate onto a star

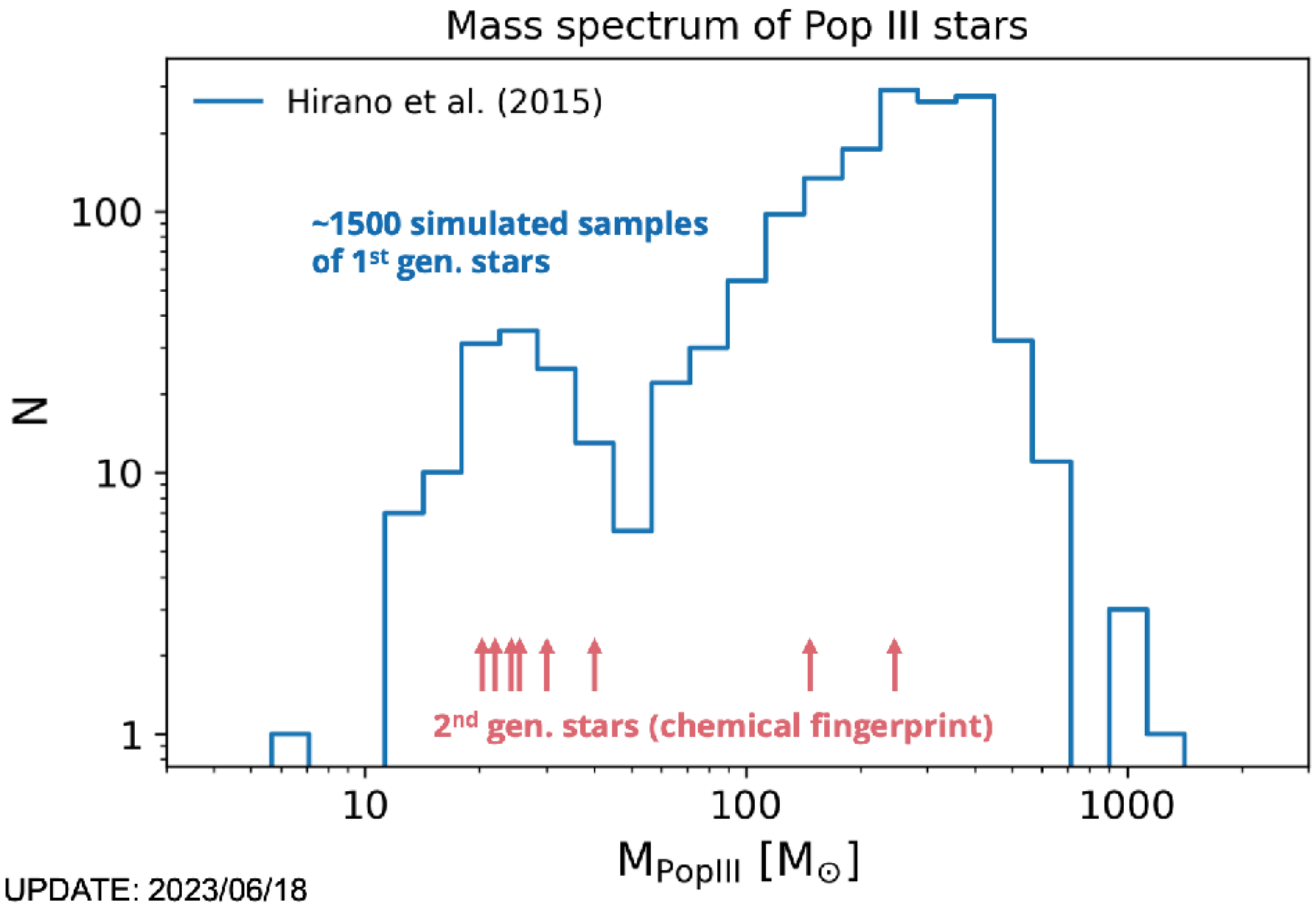
Super massive!

$$\dot{M}_{\rm star} \sim \frac{M_{\rm Jeans}}{t_{\rm freefal}} \sim 0.1\ M_\odot {\rm yr}^{-1} \left(\frac{\rm T}{\boxed{8000\ {\rm K}}}\right)^{3/2} \longrightarrow M_{\rm star} \sim \dot{M}_{\rm star} t_{\rm lifetime} \sim 10^5 M_\odot$$

Mass Function of Seed BHs

Typical primordial gas (First Star, PopIII)

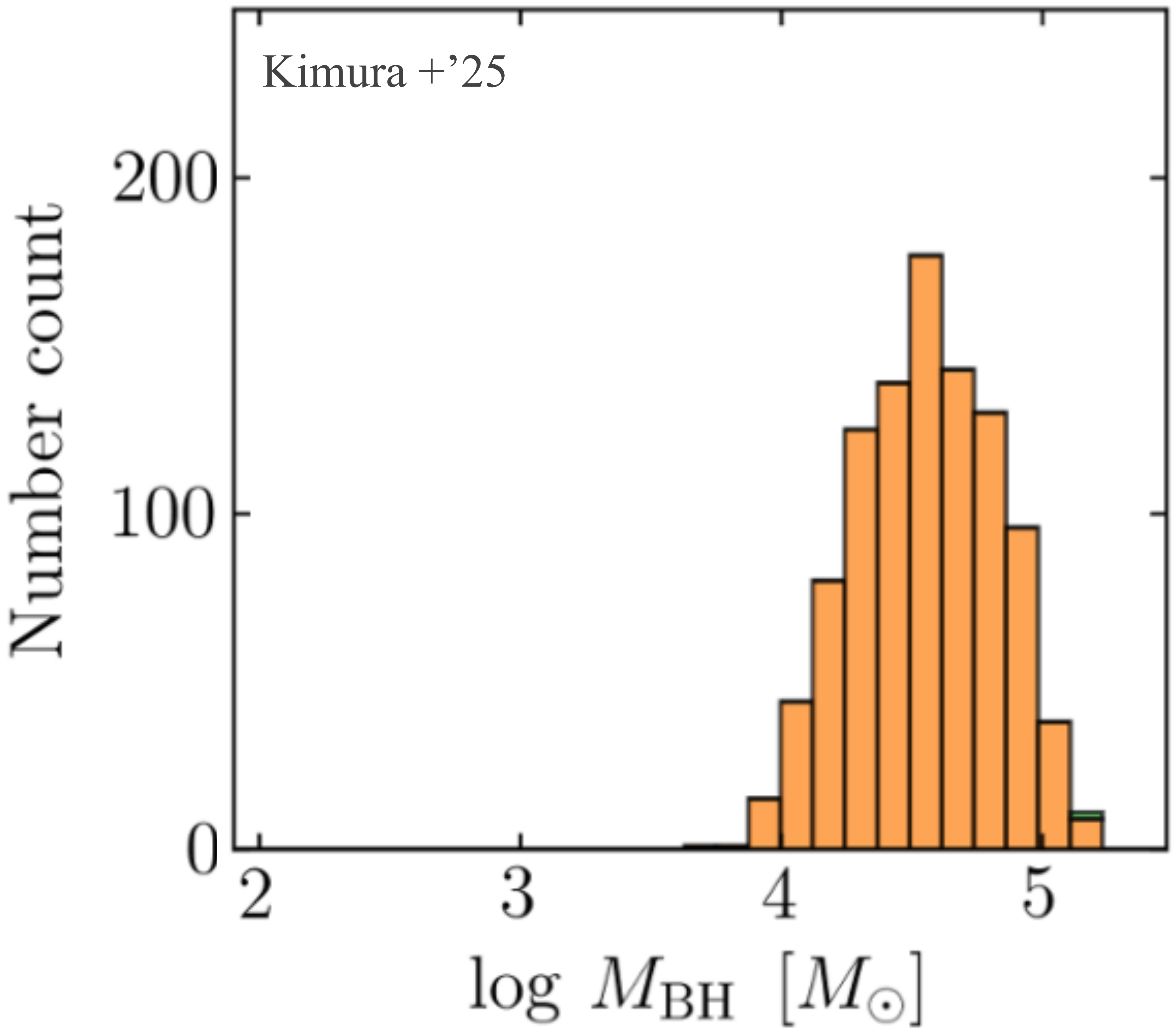
$$10 \lesssim M_{seed}/M_{\odot} \lesssim 10^3$$



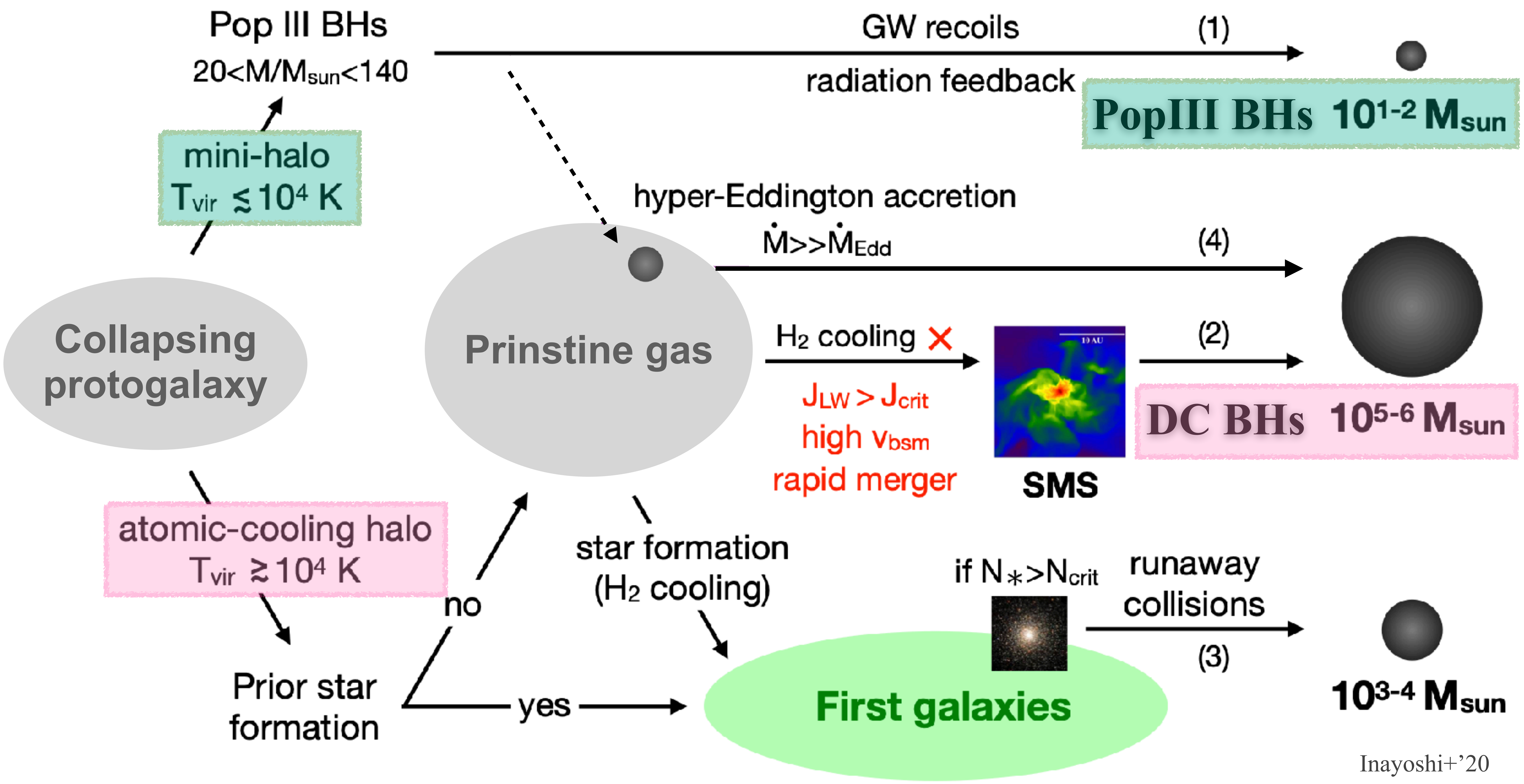
UPDATE: 2023/06/18

High-temp. gas (Direct collapse)

$$10^4 \lesssim M_{seed}/M_{\odot} \lesssim 10^5$$



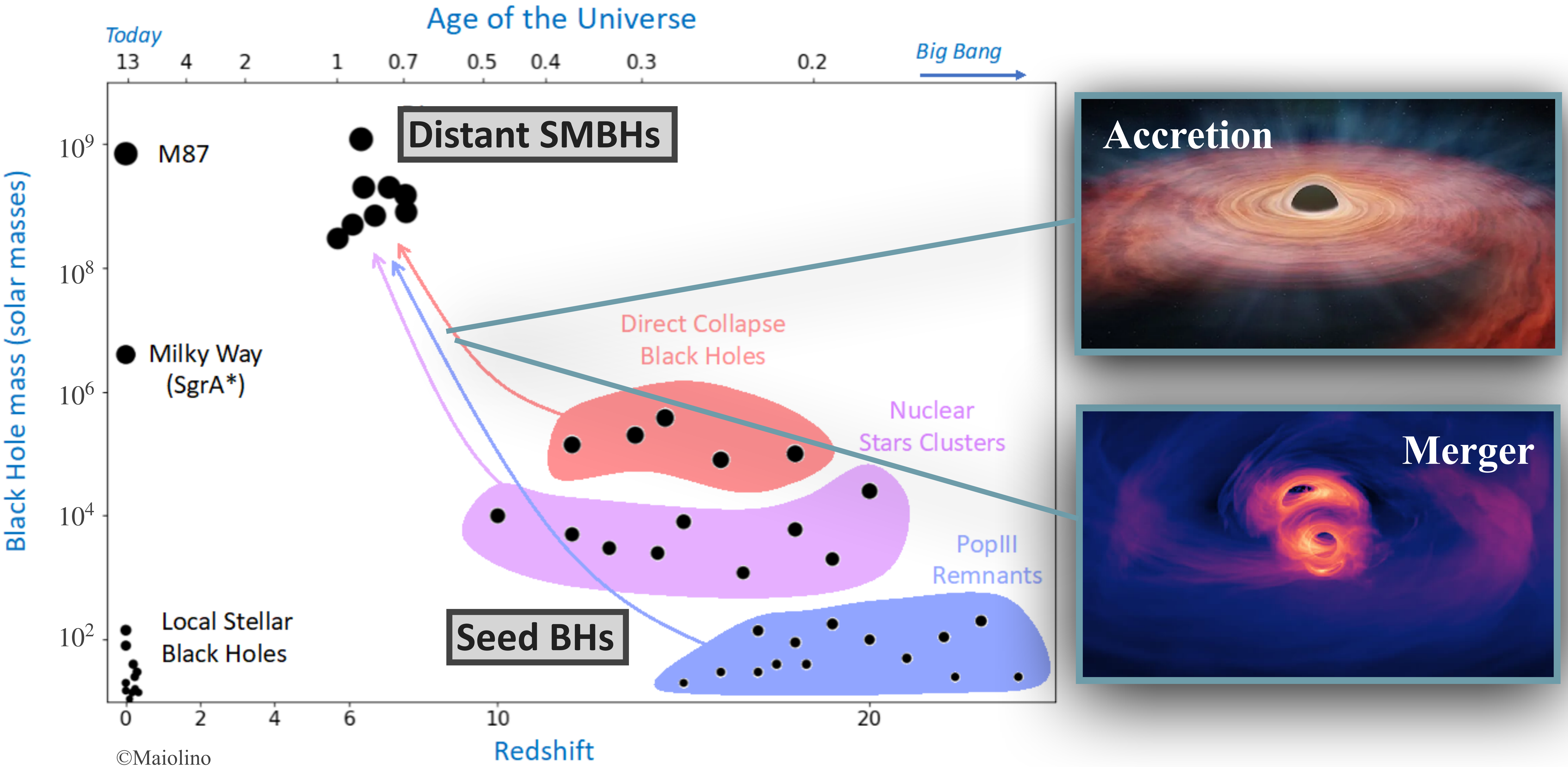
Various Models of Seed BH Formation



Inayoshi+'20

Evolution of Seed BHs

Seed BH Evolution



©Maiolino

Bondi Accretion

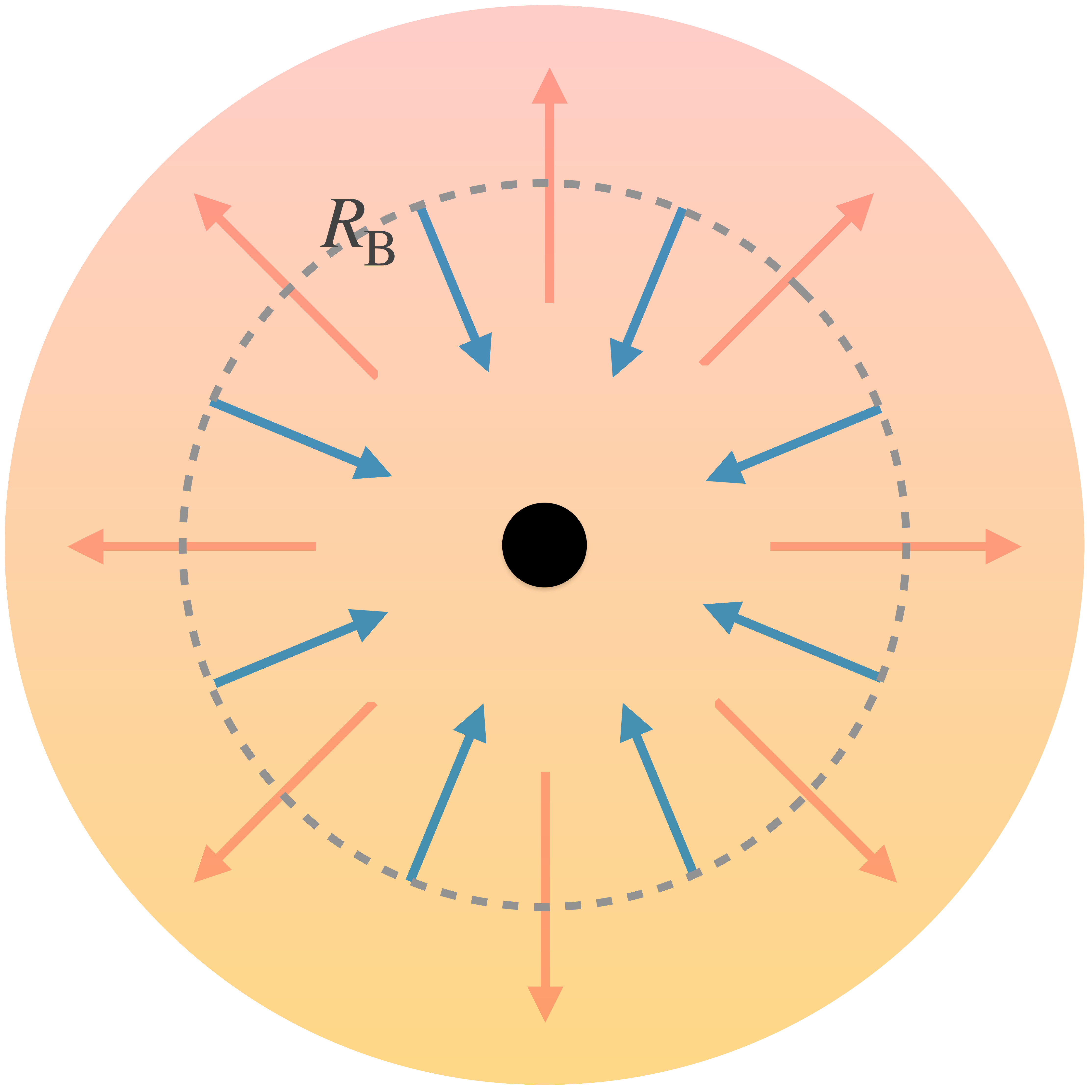
Assumption: spherically symmetric system

BH gravitational force: $f_{\mathrm{grav}} = \dfrac{GM_{\mathrm{BH}}}{R^2}$

Pressure gradient force: $f_{\mathrm{gas}} = \dfrac{1}{\rho}\dfrac{dp}{dR} \sim \dfrac{c_{\mathrm{s}}^2}{R}$

Gas collapse condition：$\boxed{f_{\mathrm{grav}}} \geqq \boxed{f_{\mathrm{gas}}}$

$$R \leqq \frac{GM_{\mathrm{BH}}}{c_{\mathrm{s}}^2} \equiv R_{\mathrm{B}}$$ **(Bondi Radius)**



Bondi Accretion

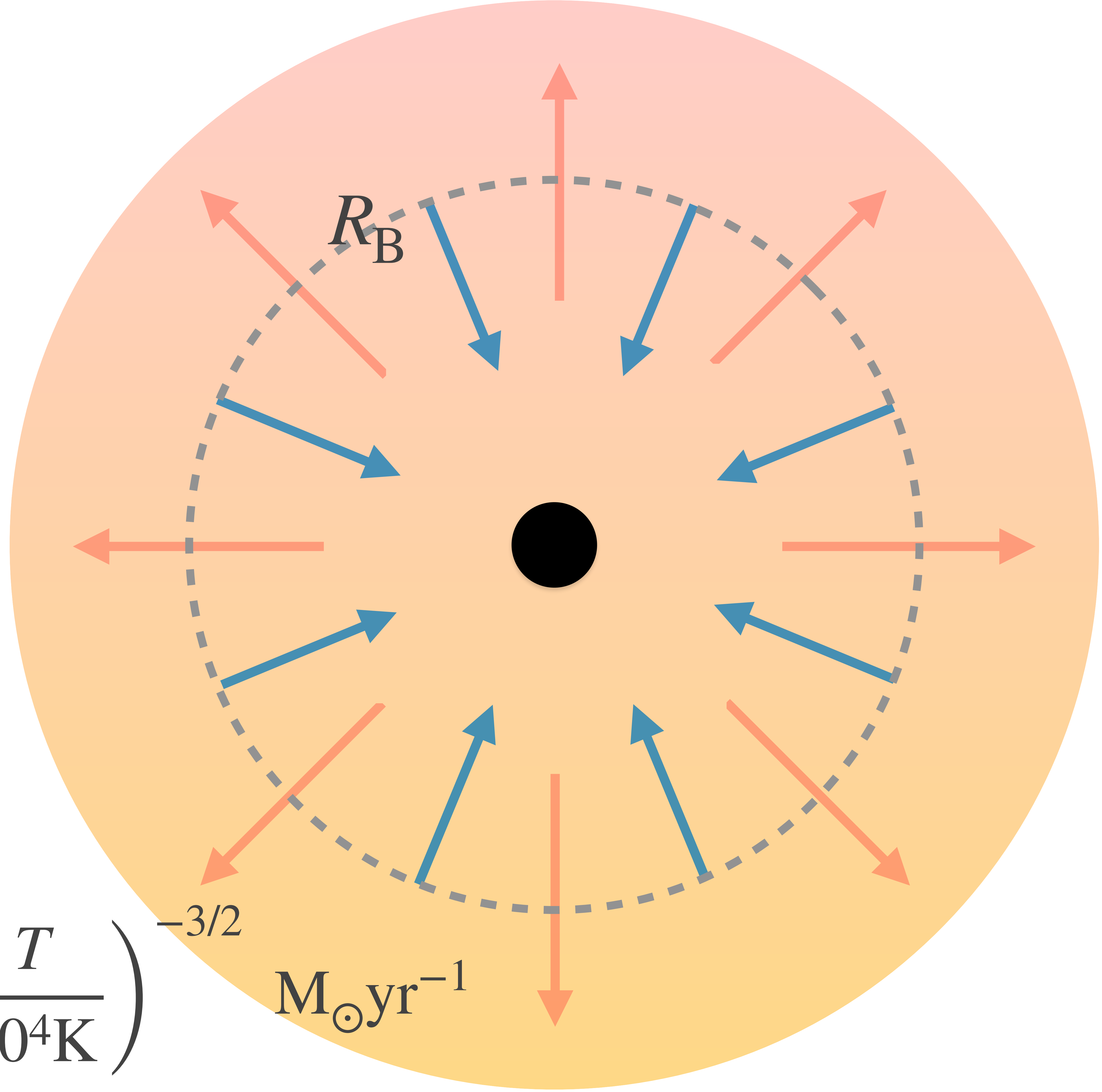
Assumption: spherically symmetric system

$$R \leqq \frac{GM_{\mathrm{BH}}}{c_{\mathrm{s}}^2} \equiv R_{\mathrm{B}} \ \textbf{(Bondi Radius)}$$

<u>Mass growth rate:</u>

$$\dot{M}_{\mathrm{B}} = 4\pi R_{\mathrm{B}}^2 \rho c_{\mathrm{s}} = \frac{4\pi G^2 M_{\mathrm{BH}}^2 \rho}{c_{\mathrm{s}}^3}$$

$$\approx 1.7 \times 10^{-3} \left(\frac{n_{\mathrm{H}}}{10^3\ \mathrm{cm}^{-3}}\right) \left(\frac{M_{\mathrm{BH}}}{10^4 M_{\odot}}\right)^2 \left(\frac{T}{10^4 \mathrm{K}}\right)^{-3/2} \mathrm{M_{\odot} yr^{-1}}$$



Accretion onto Black Holes (Theory 1970s~)

Eddington Limit

Assumption: spherically symmetric system

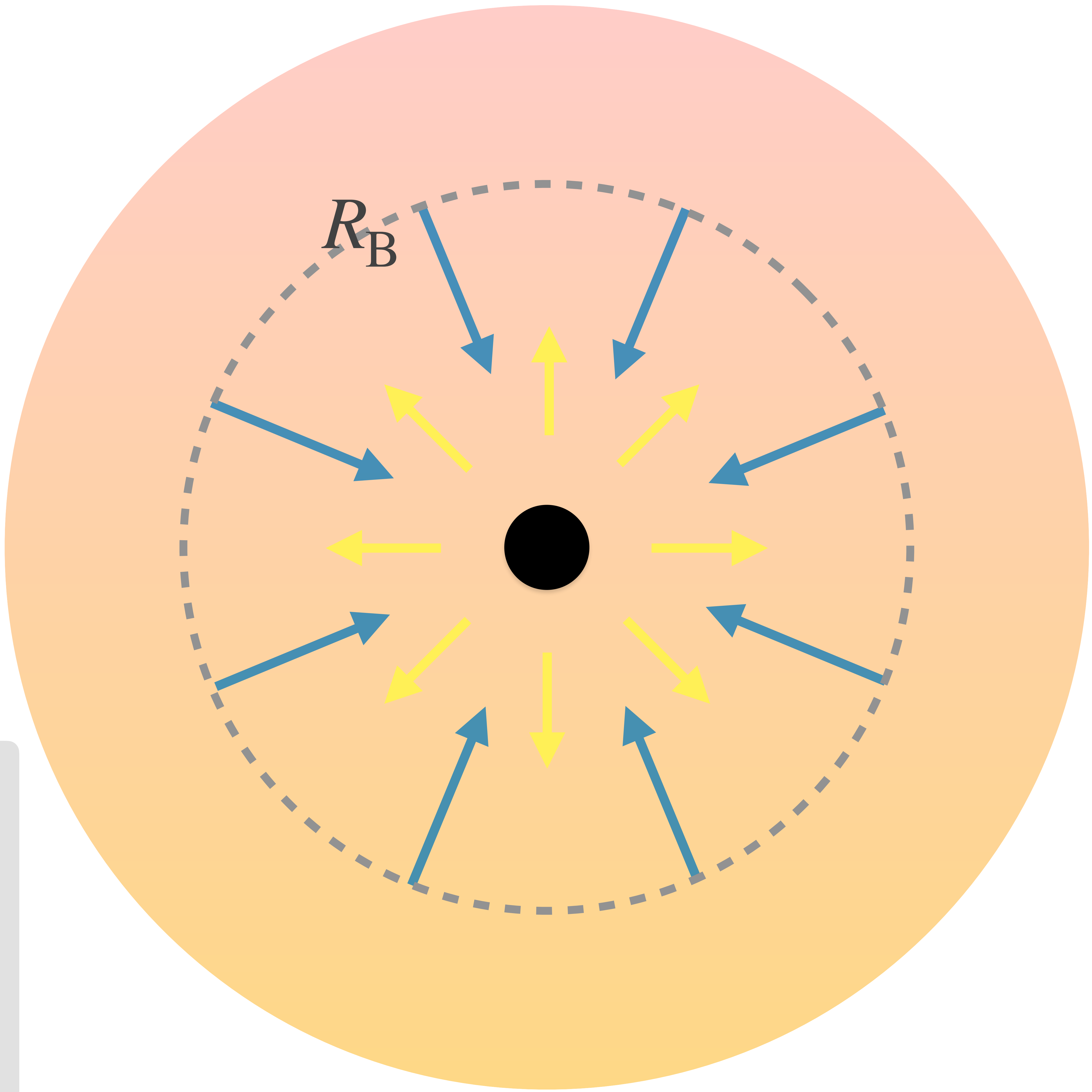
BH gravitational force: $f_{\mathrm{grav}} = \dfrac{GM_{\mathrm{BH}}}{R^2}$

Radiation force $f_{\mathrm{rad}} = \dfrac{\kappa_{\mathrm{es}}}{c}\dfrac{L}{4\pi R^2}$

Gas collapse condition : $\boxed{f_{\mathrm{grav}}} \geqq \boxed{f_{\mathrm{rad}}}$

$$L \leqq \frac{4\pi c G M_{\mathrm{BH}}}{\kappa_{\mathrm{es}}} \equiv L_{\mathrm{E}}\ \textbf{(Eddington Luminosity)}$$

$$\approx 1.3 \times 10^{42} \left(\frac{M_{\mathrm{BH}}}{10^4 M_{\odot}} \right) \ \mathrm{erg/s}$$



Eddington Limit

$$\dot{M} = \frac{L}{\eta c^2} \lesssim \frac{L_{\rm E}}{\eta c^2} \equiv \dot{M}_{\rm E} \quad \textbf{(Eddington accretion rate)}$$

$$\approx 2.3 \times 10^{-4} \left(\frac{M_{\rm BH}}{10^4 M_\odot} \right) M_\odot {\rm yr}^{-1}$$

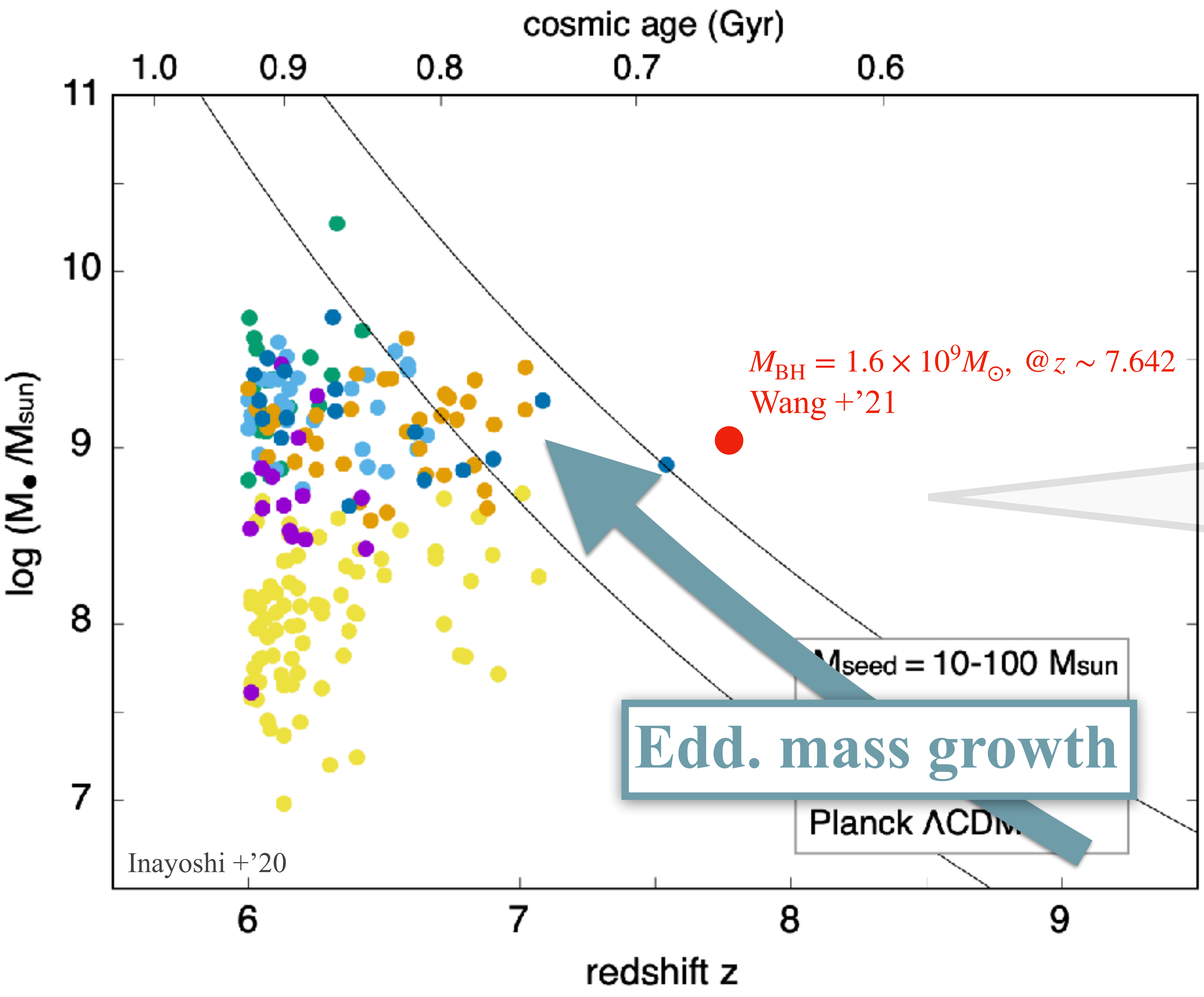
課題:

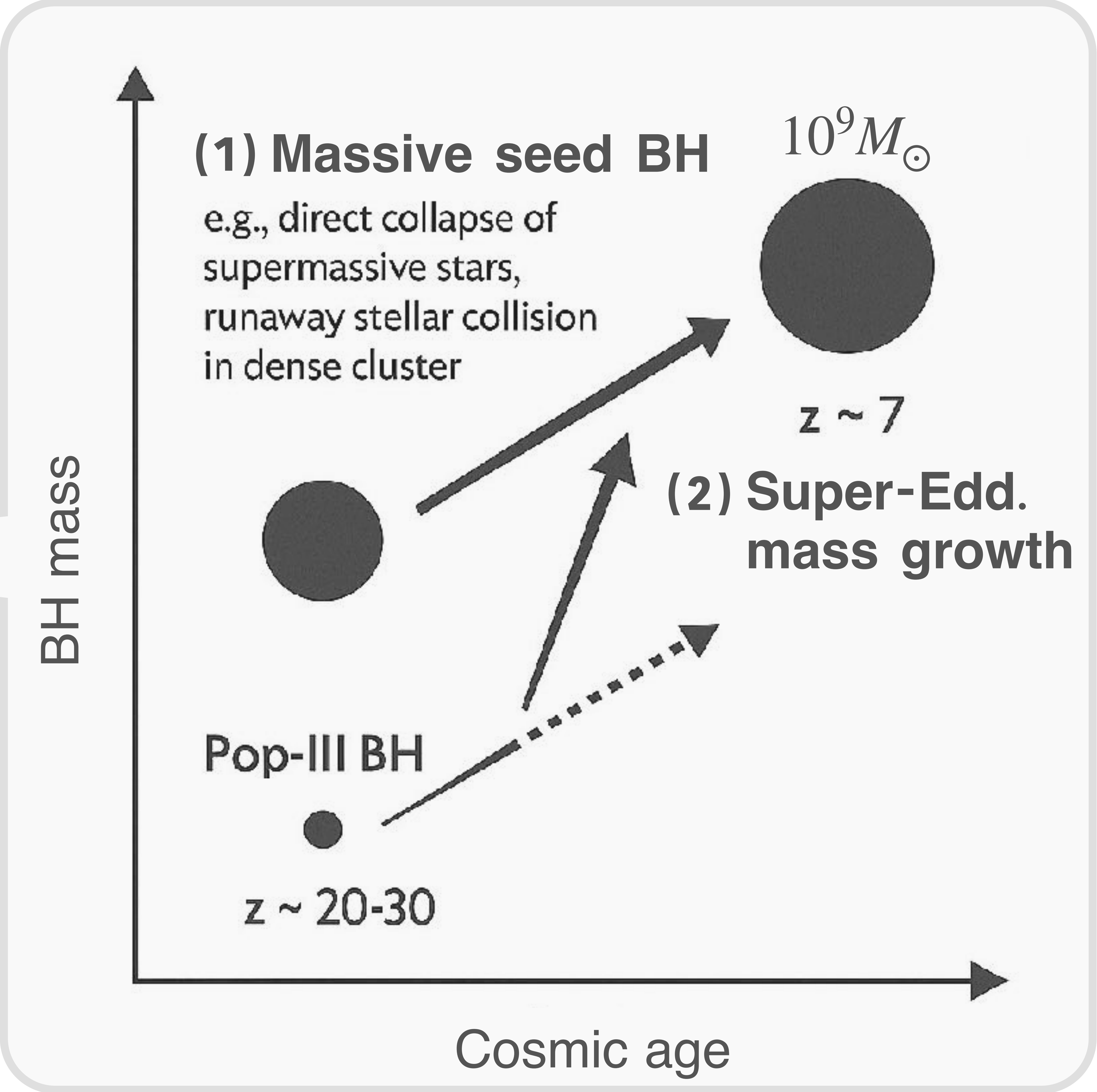
Eddington降着率を仮定して、BH成長のタイムスケール

（Eddington timescale, Salpeter timescale, e-folding timescale）

を求めてみよう。なお、輻射変換効率は10%とする。

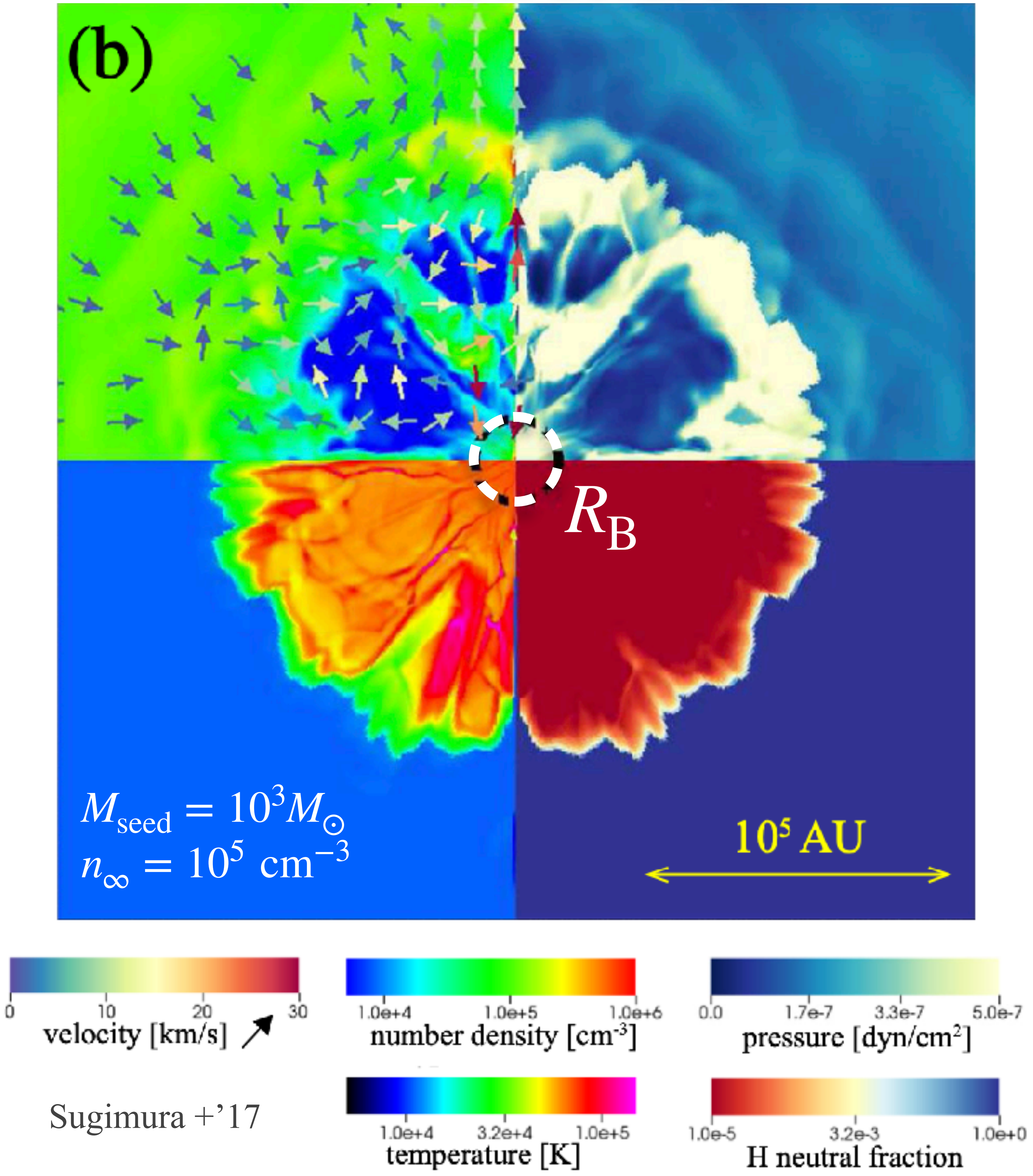
Seed BH Growth: Eddginton Limit





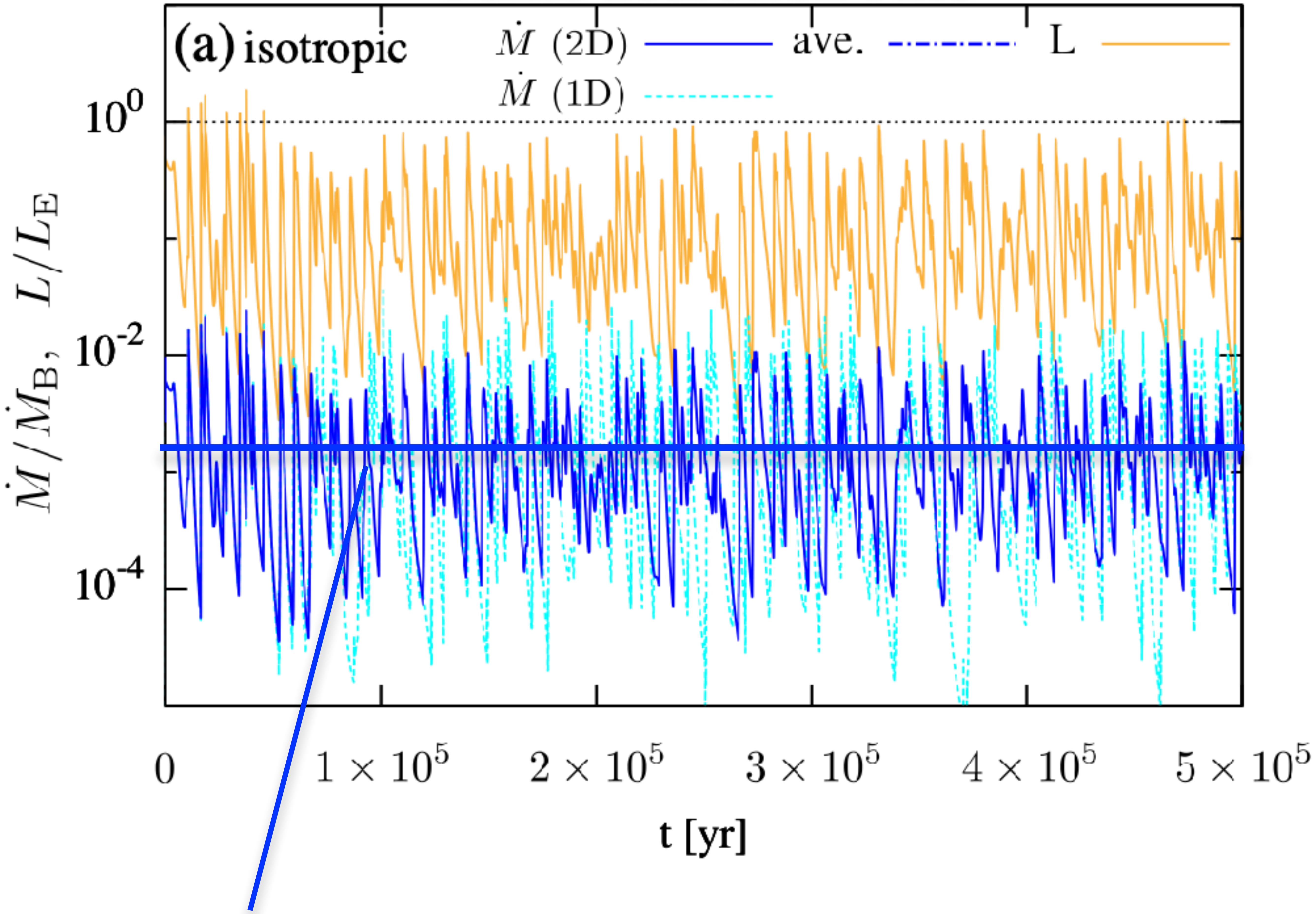
Simulation of BH Accretion

Flow Structure



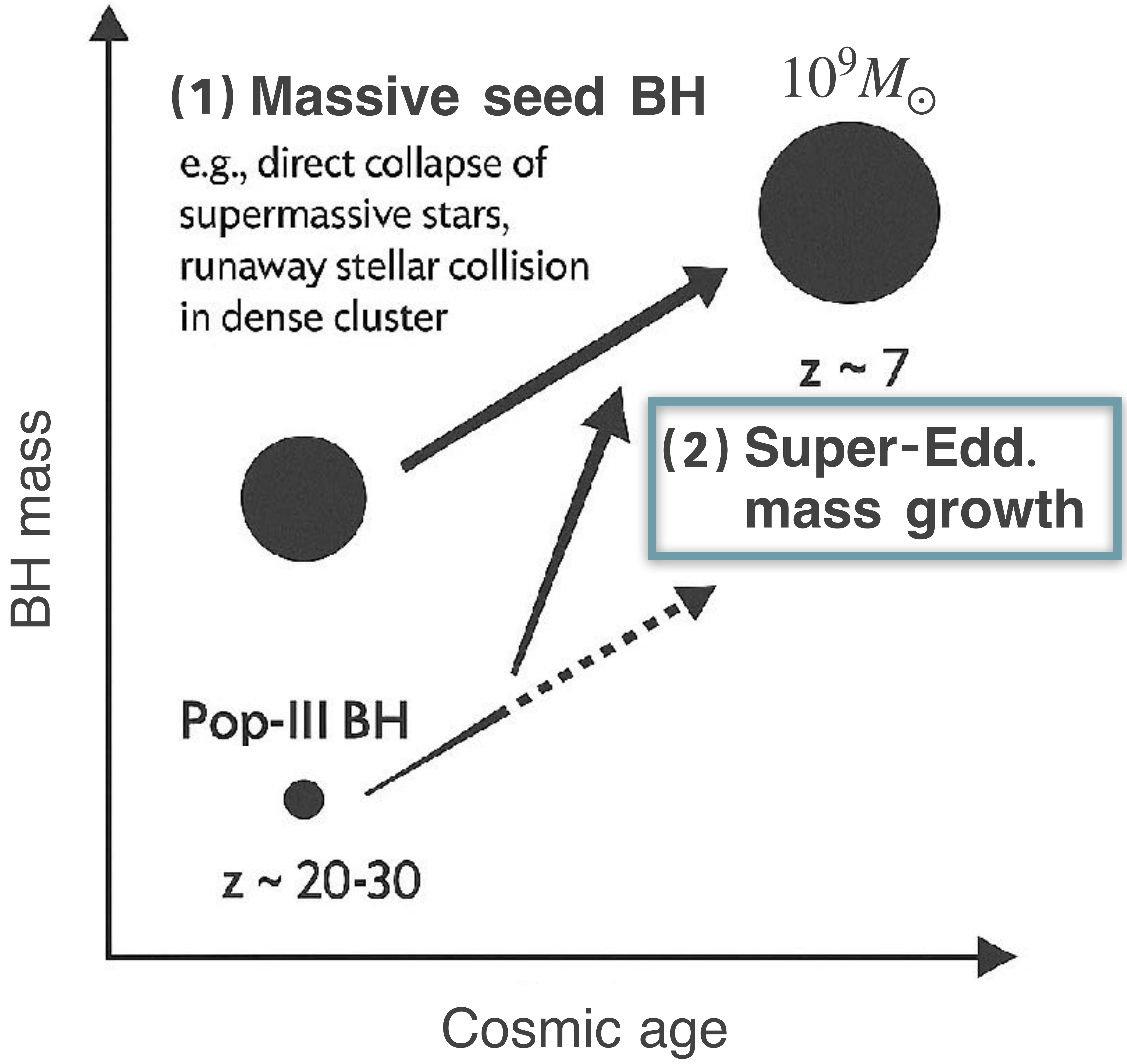
Sugimura +'17

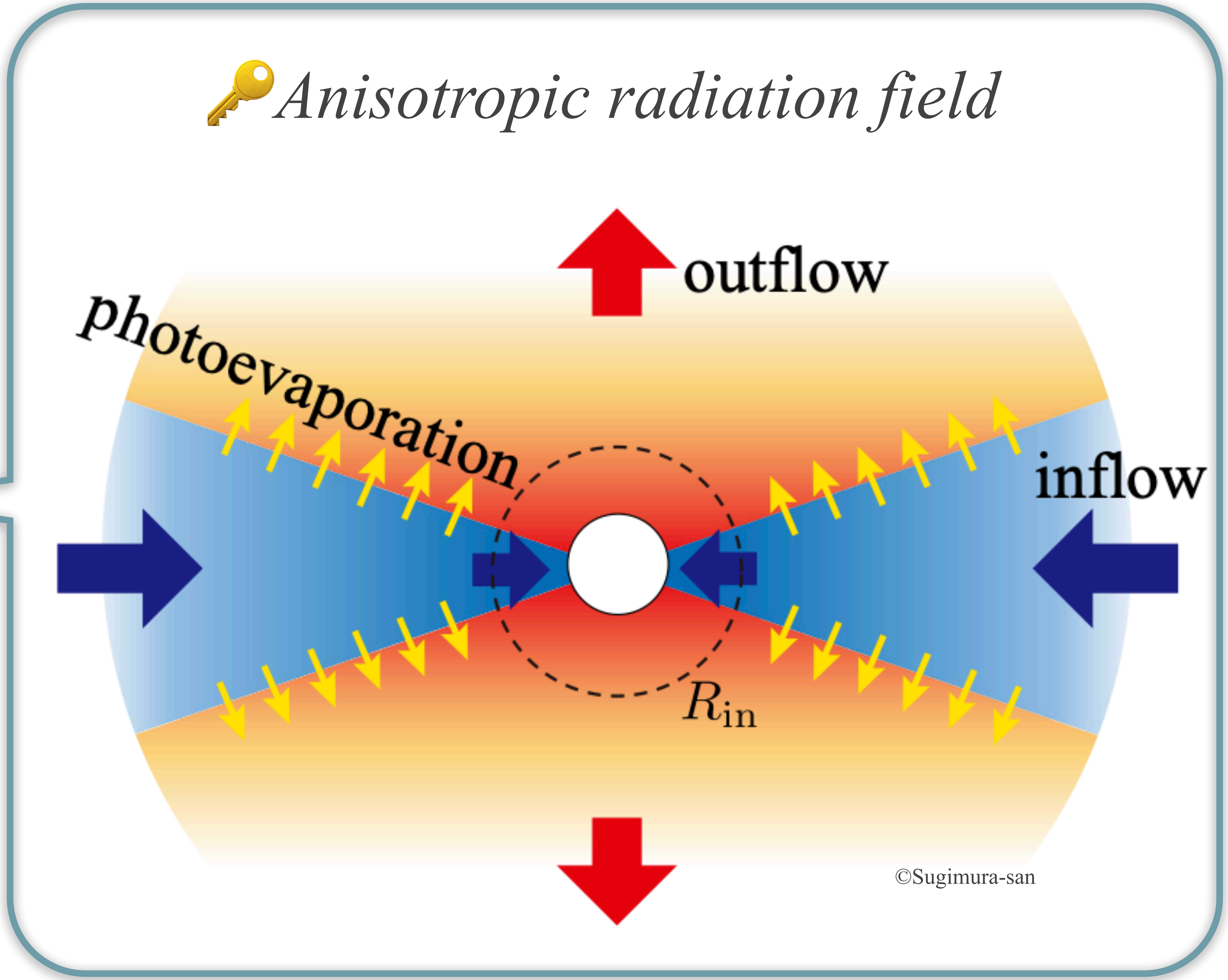
Mass accretion rate



$\overline{\dot{M}} \sim 0.8\dot{M}_E$ ※$\dot{M}_E \equiv L_E/(\eta c^2)$

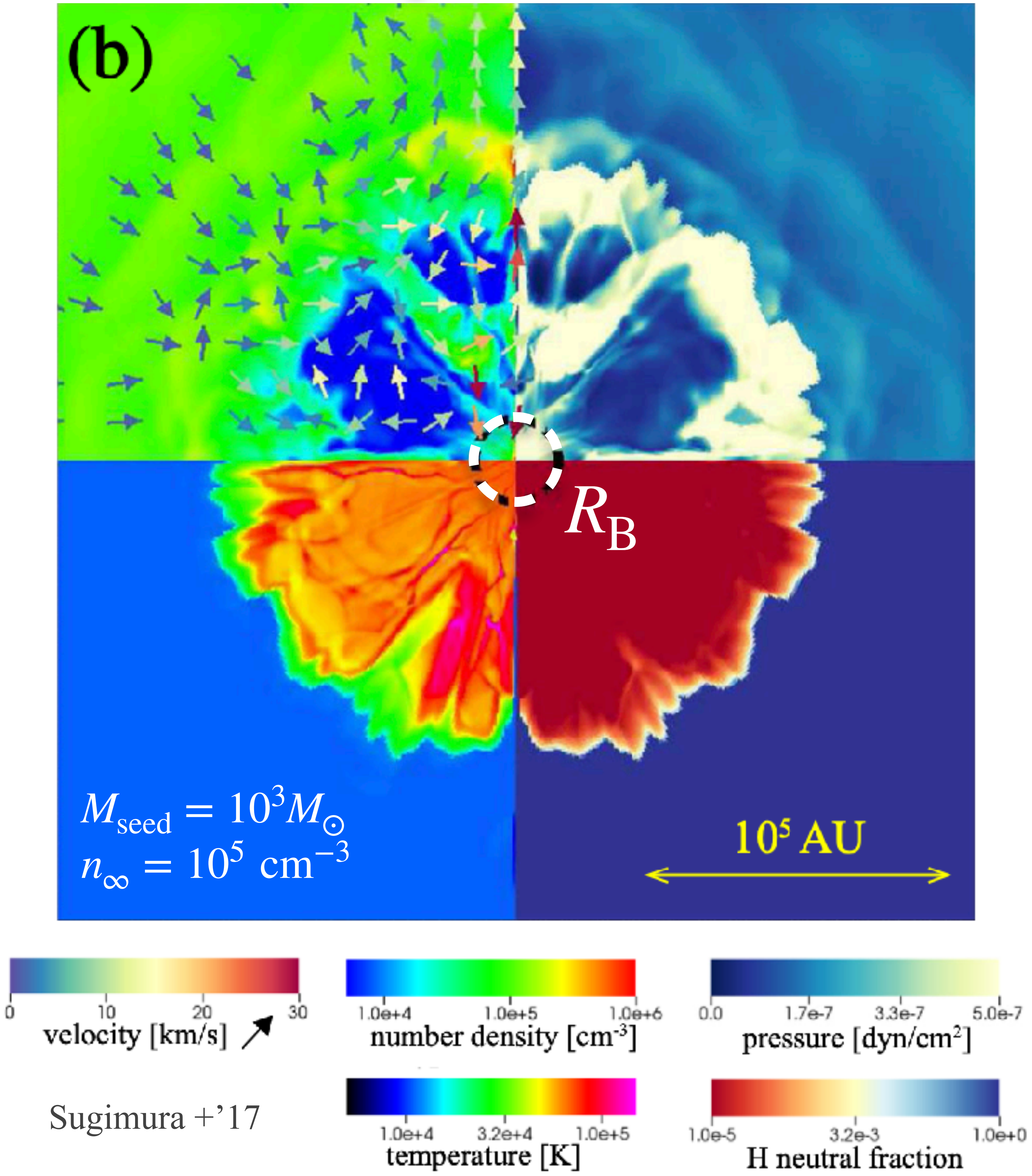
Simulation of BH Accretion





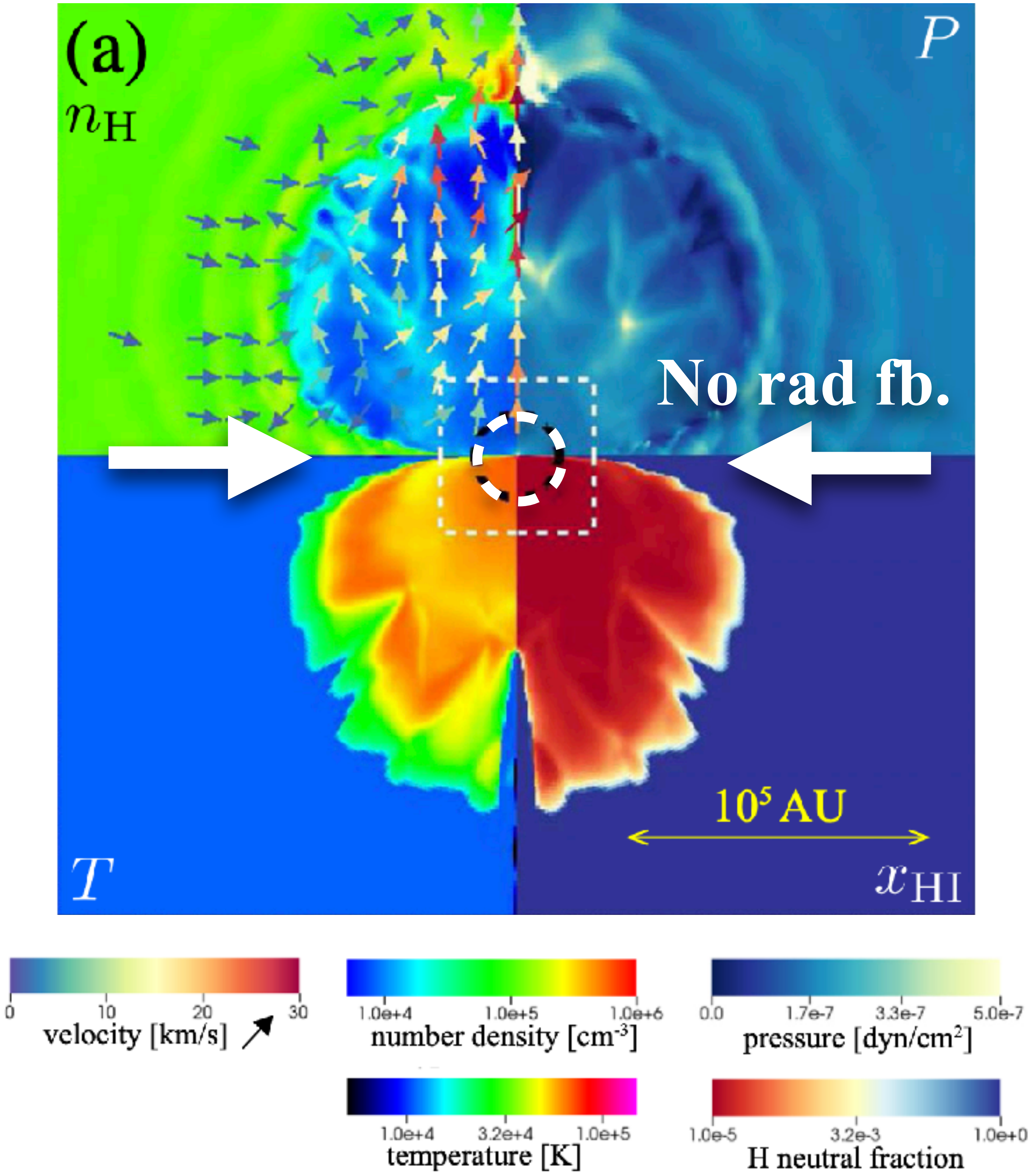
Simulation of BH Accretion

Isotropic Radiation



Sugimura +’17

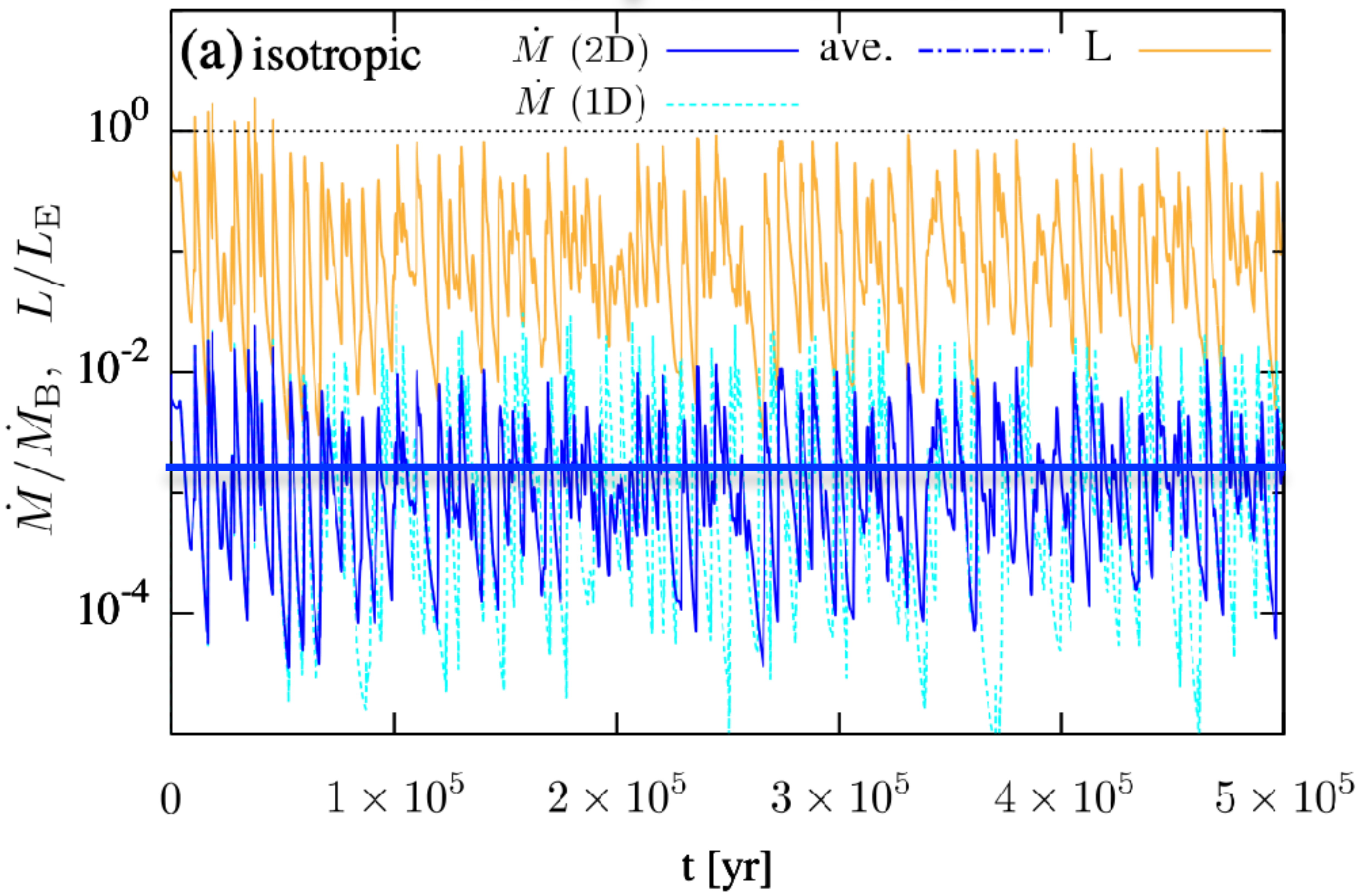
Disk-like Radiation



Simulation of BH Accretion

※$\dot{M}_{\rm E} \equiv L_{\rm E}/(\eta c^2)$

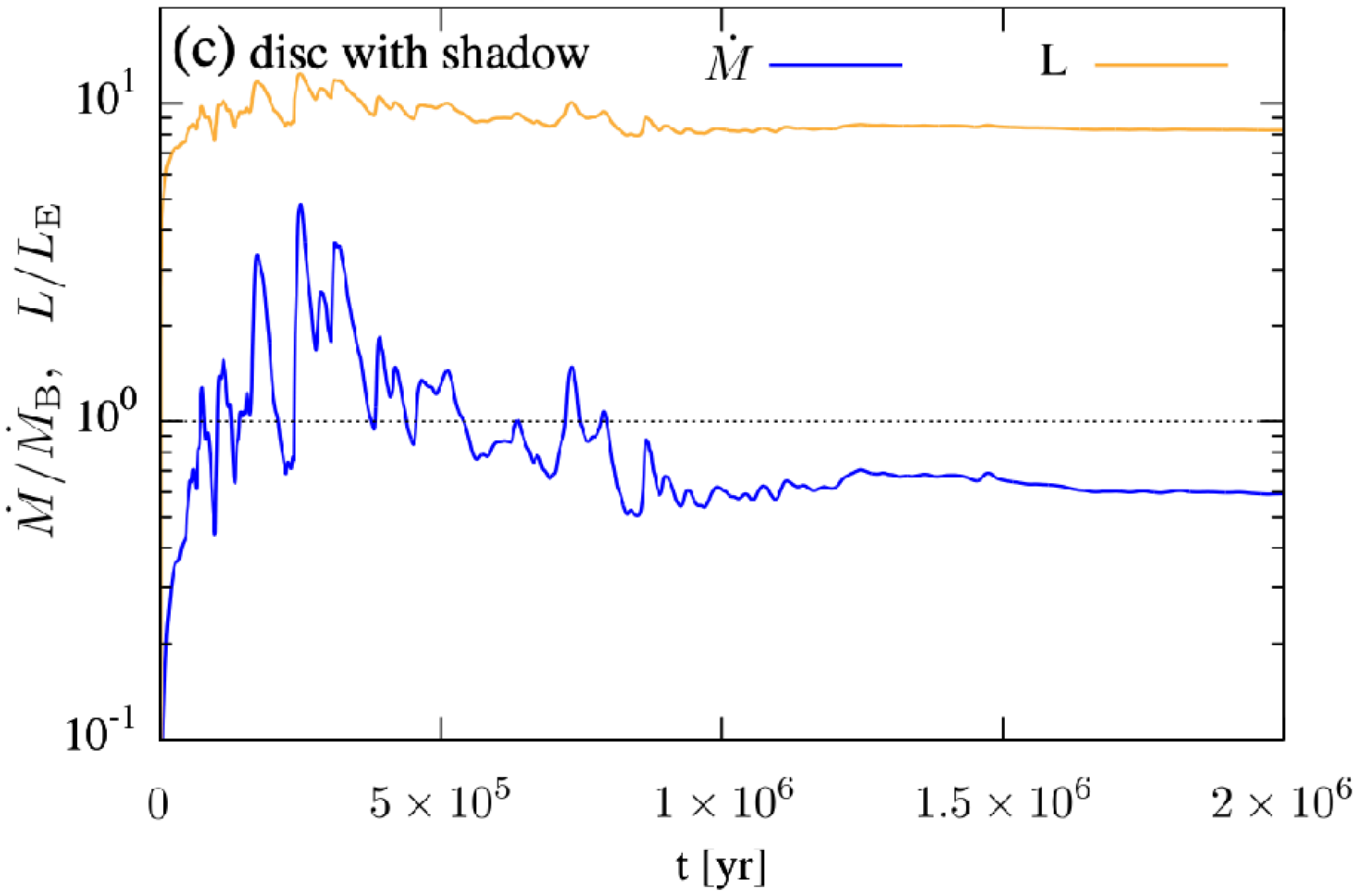
Isotorpic radiation



$$\overline{\dot{M}} \sim 0.8\dot{M}_{\rm E}$$

Sub-Eddington Accretion

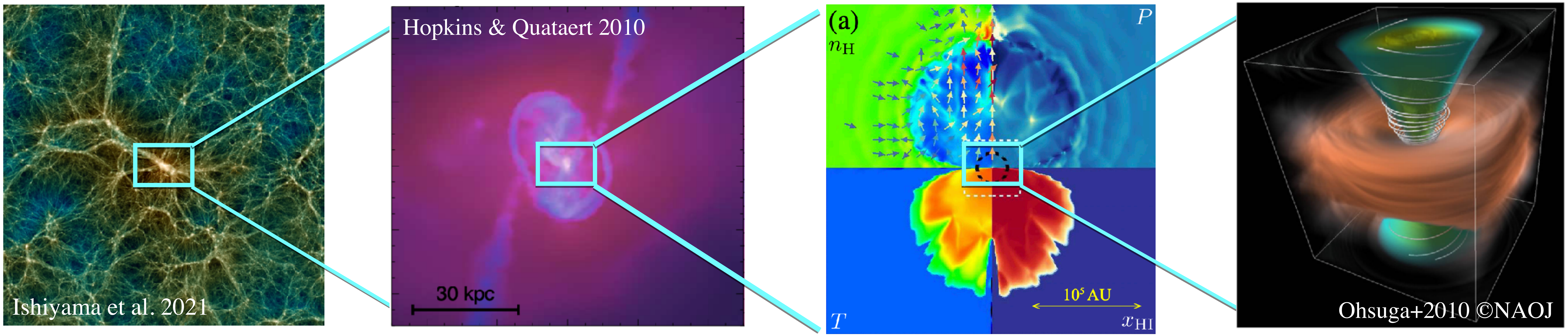
Disk-like radiation



$$\overline{\dot{M}} \sim 400\dot{M}_{\rm E}$$

Super Eddington Accretion!!

Multi-Scale Problem



Mpc scale | kpc scale | pc scale | ≪ pc scale

Cosmological zoom-in simlations

$\dot{M} = \dot{M}_{\rm BHL}$ w/ Eddington limit

Simulations on BH's gravitational scale

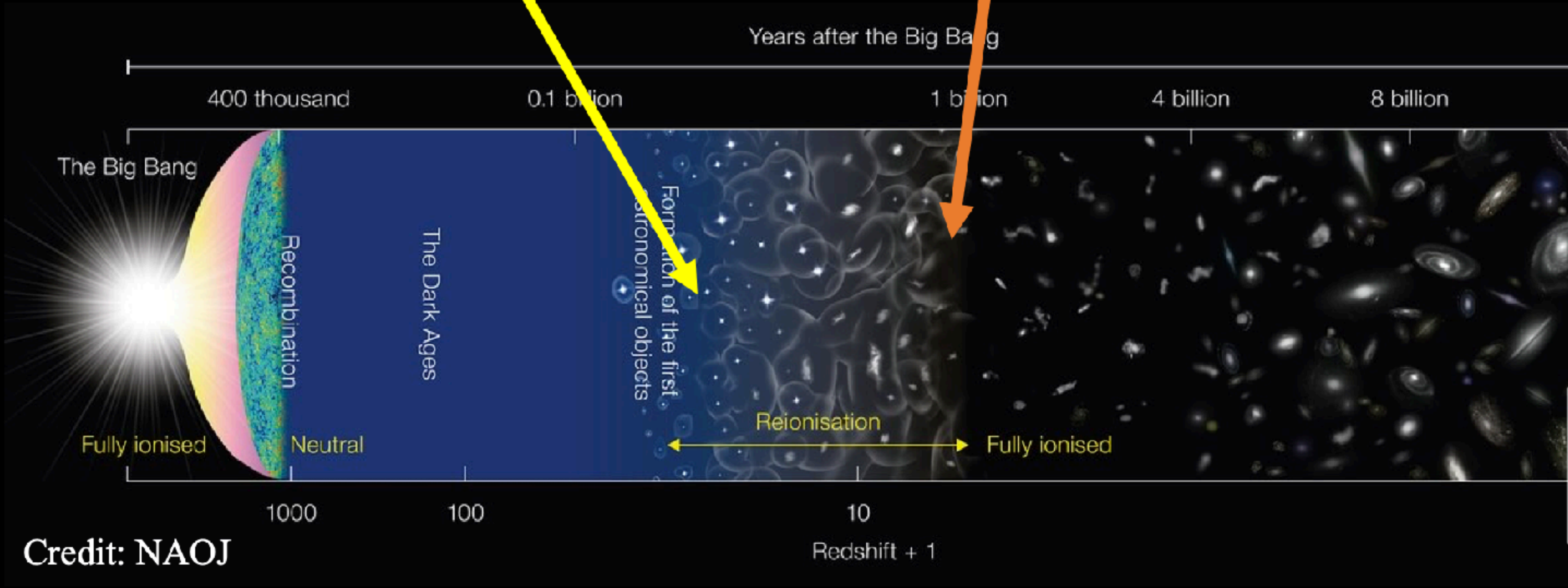
$\dot{M} \neq \dot{M}_{\rm BHL}$ w/ Eddington limit; w/o Eddington limit

More accurately track the BH growth **across cosmic time**

Super massive black holes in the universe

z ~ 20-30
Formation of the first stars

Bright quasars (QSOs) beyond z ~ 6



SMBHs
(> 10^6 $M_\odot$)

Homework

$$L \leqq \frac{4\pi c G M_{\rm BH}}{\kappa_{\rm es}} \equiv L_{\rm E} \text{ (Eddington Luminosity)}$$

$$\dot{M} = \frac{L}{\eta c^2} \lesssim \frac{L_{\rm E}}{\eta c^2} \equiv \dot{M}_{\rm E} \text{ (Eddington accretion rate)}$$

課題:

Eddington降着率を仮定して、BH成長のタイムスケール
（Eddington timescale, Salpeter timescale, e-folding timescale）
を求めてみよう。なお、輻射変換効率は10%とする。

※興味のある人は、高赤方偏移 ($z \sim 8$)で発見されている巨大ブラックホールの成長について、このタイムスケールを使って何か議論してみよう