The astrophysics of black hole mergers

1. Pairing massive BHs in galactic nuclei
   from large to small scales, role of gas

2. Electromagnetic signatures of massive BH binaries
   in EM observations or in GW detections

3. Where do massive BHs come from anyway?
   protogalaxy formation after the cosmic dark age

4. ~~[Stellar-mass BH binaries]~~
   ~~in AGN accretion disks with EM signatures~~

Where Do Massive BHs Come From?

Zoltán Haiman
Columbia University

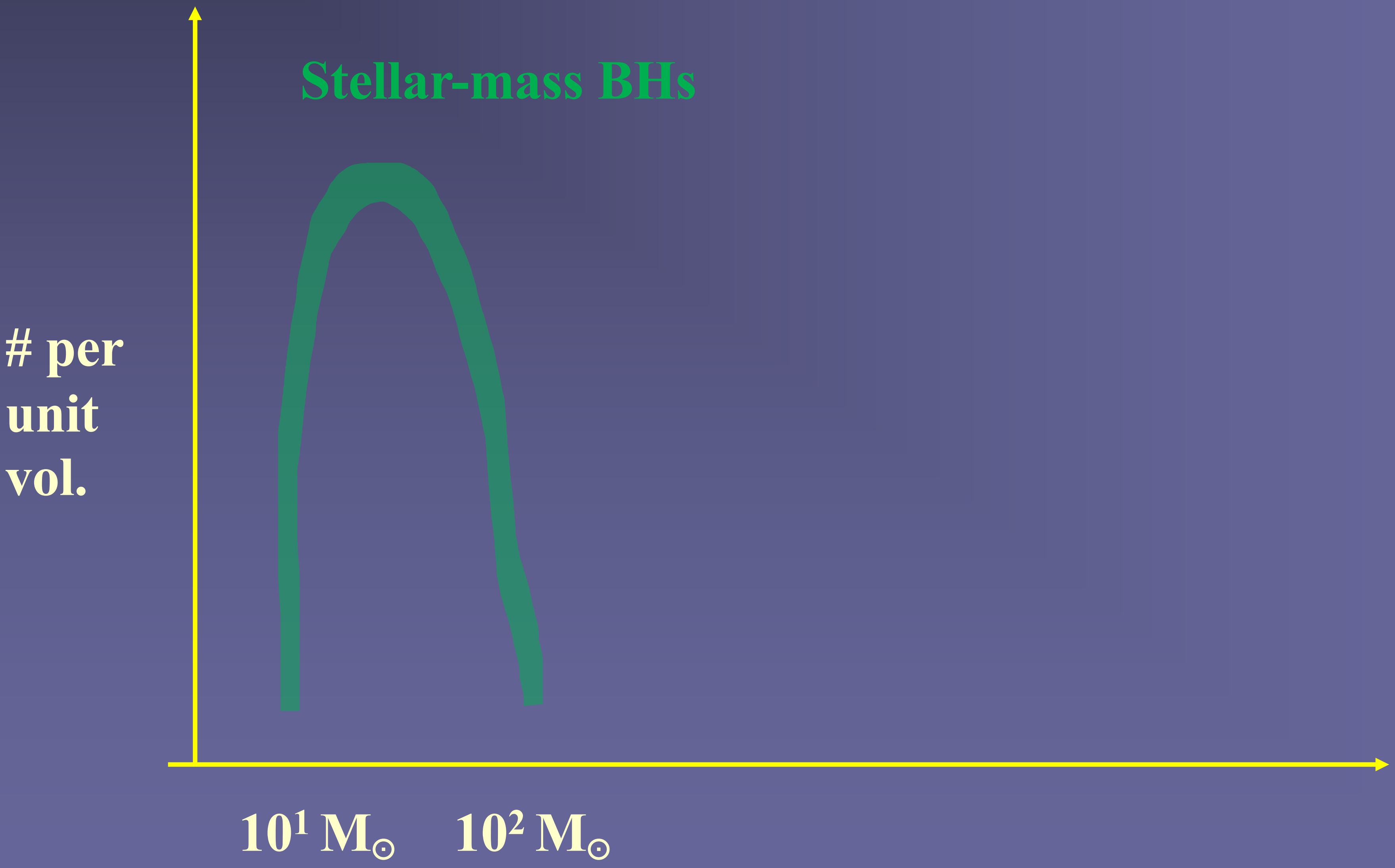
Lecture 3

São Paulo Advanced School on Multi-Messenger Astrophysics *May 29 - June 7, 2023*

Outline

1. Observations: types of black holes in the universe
2. Theory: where do massive black holes come from?
3. The Future: how to distinguish different pathways?

Black Hole Population



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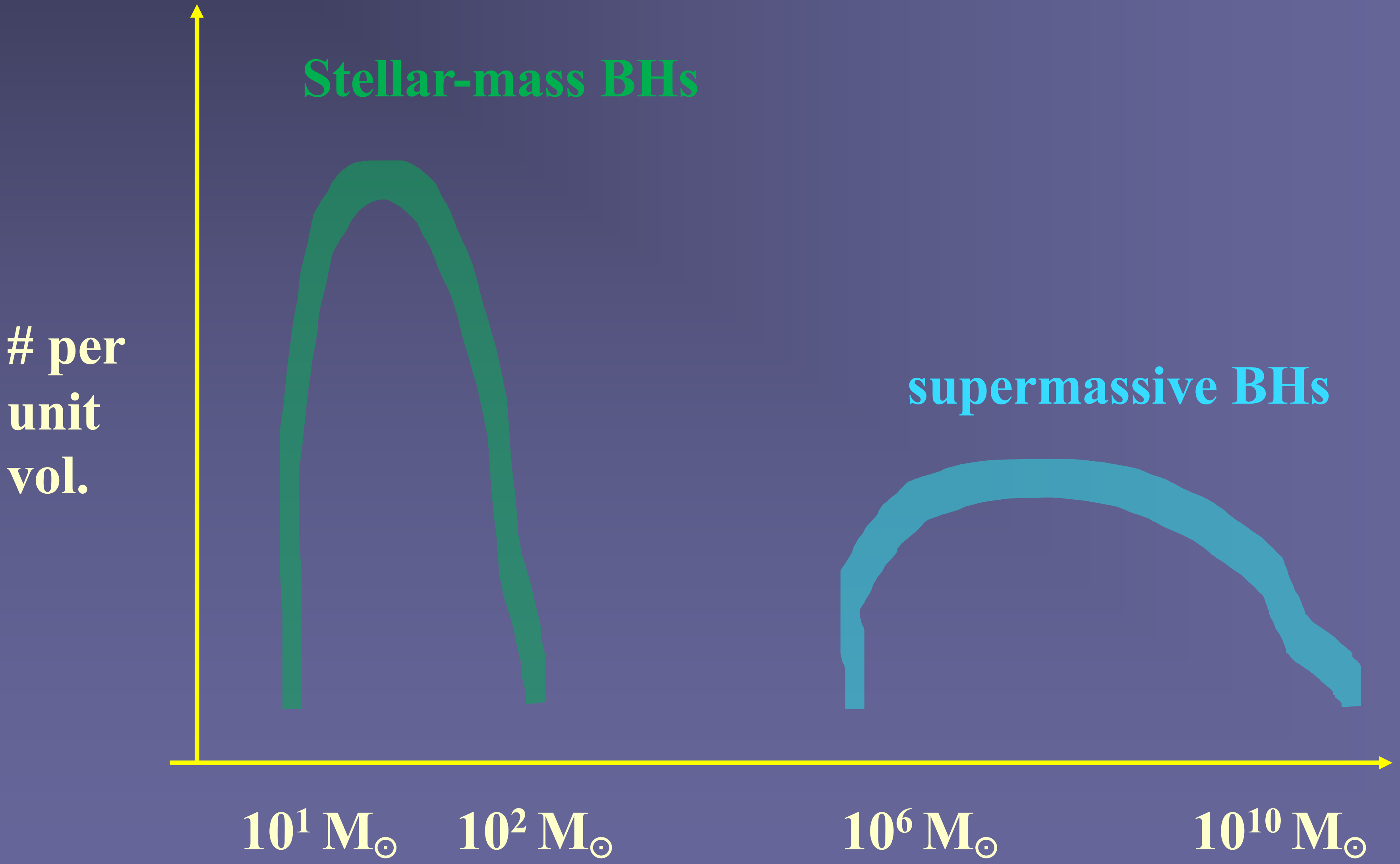

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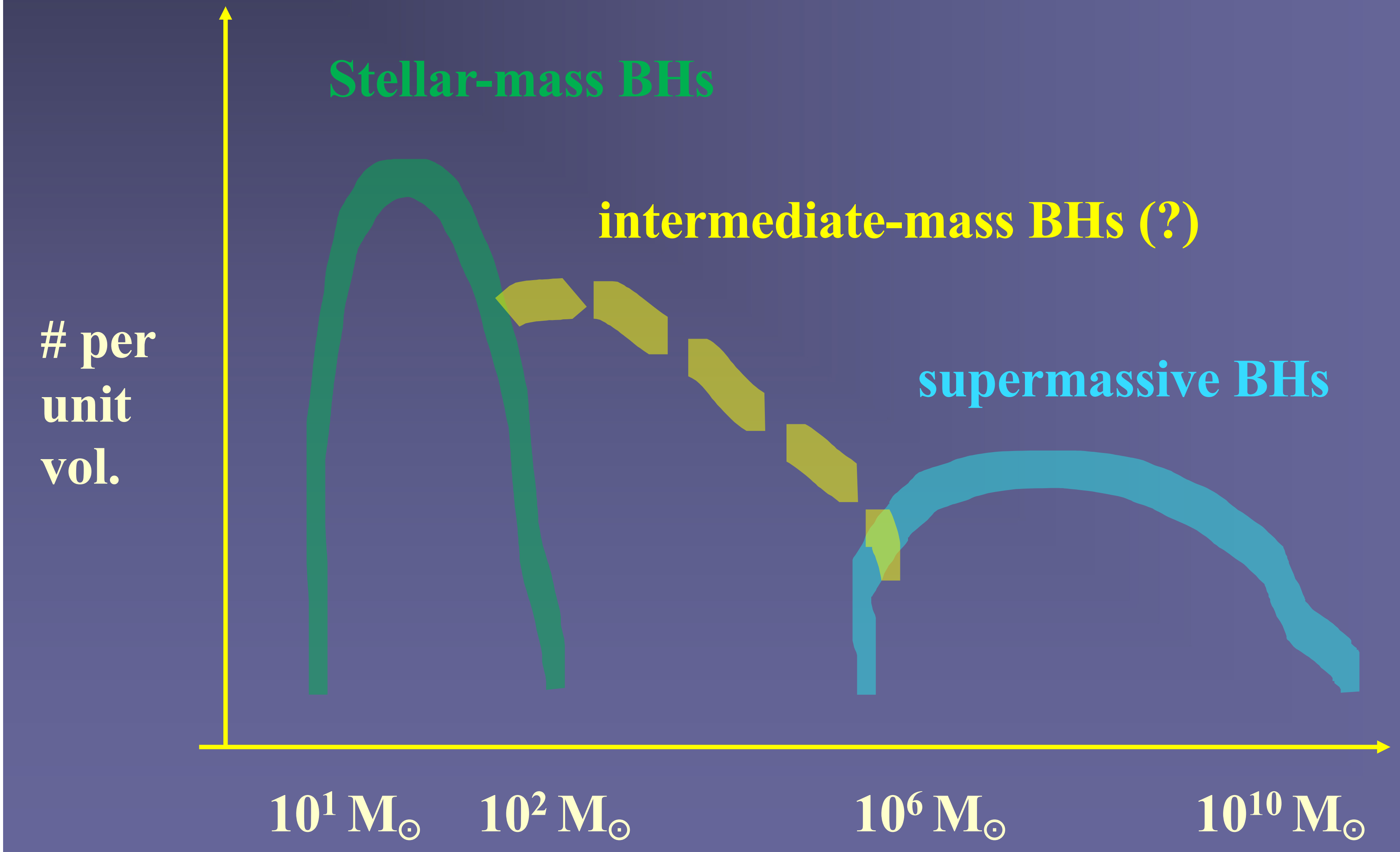
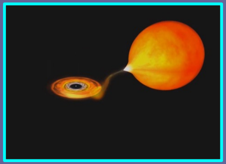
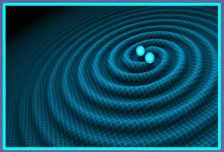


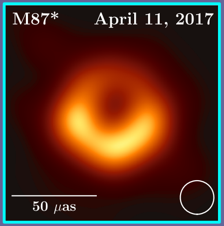
Two types of black holes

- Stellar-mass BHs:
  - End fate of massive stars – well understood
  - Birth masses limited to few $M_\odot \lesssim M \lesssim 60\ M_\odot$
  - 100 million in a typical galaxy like the Milky Way (0.1% of stars)
  - detected only when they have a partner: *X-ray binary* or *GWs*
  - can be seen only in nearby universe (dozens) – too faint otherwise



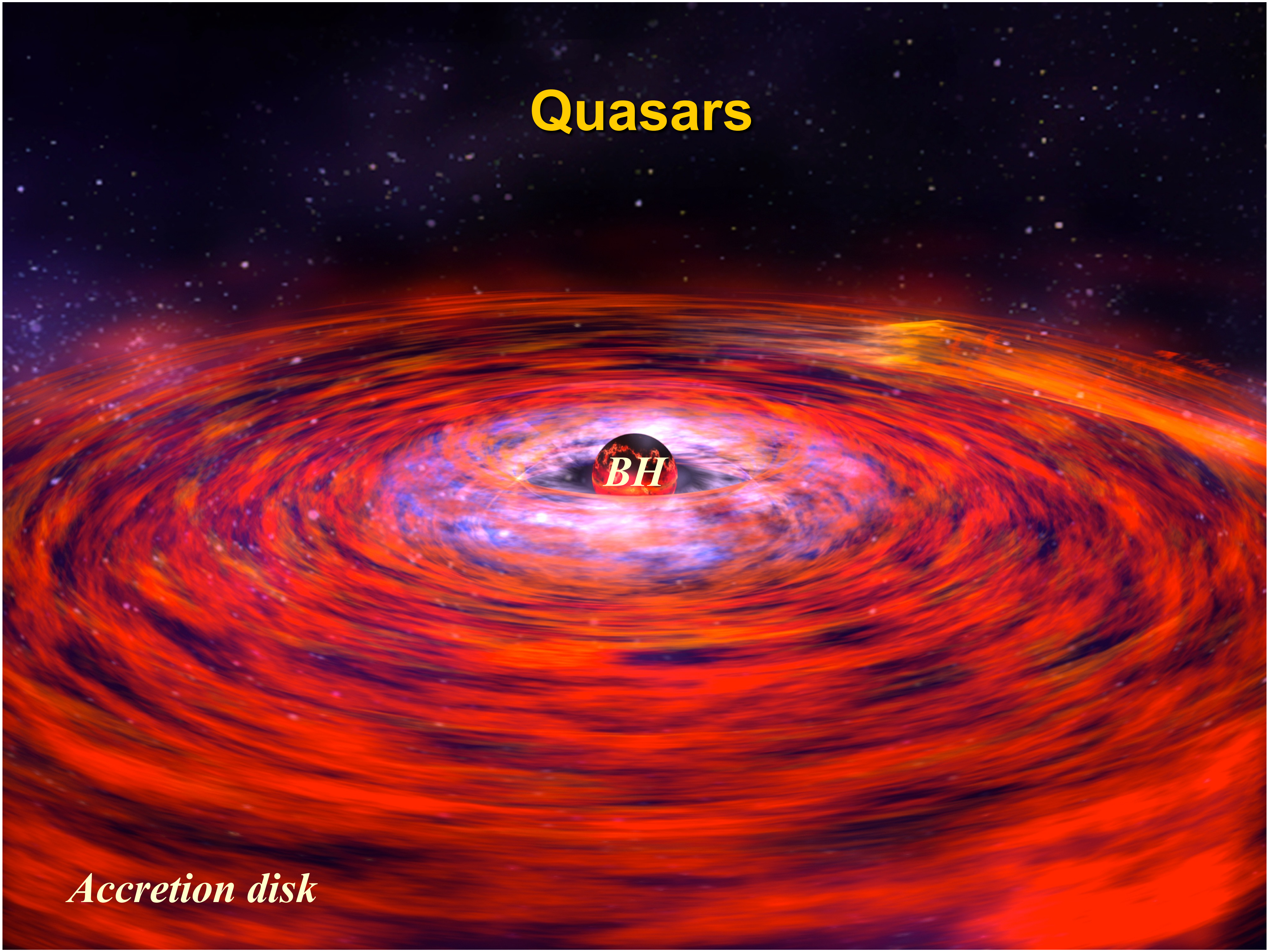


- (Super-) massive BHs:
  - One (or a few?) in center of each galaxy, $M_{BH} = \text{few} \times 10^{-4}\ M_{stars}$
  - Masses limited to $10^6\ M_\odot \lesssim M \lesssim 10^{10}\ M_\odot$
  - 100 detected indirectly (*gas/stars speeds ~0.1c*) or imaged (*M87, SgrA**)
  - 1% are "active", visible to the edge of the universe as quasars (~1 million)
  - origin unknown, but likely formed early on



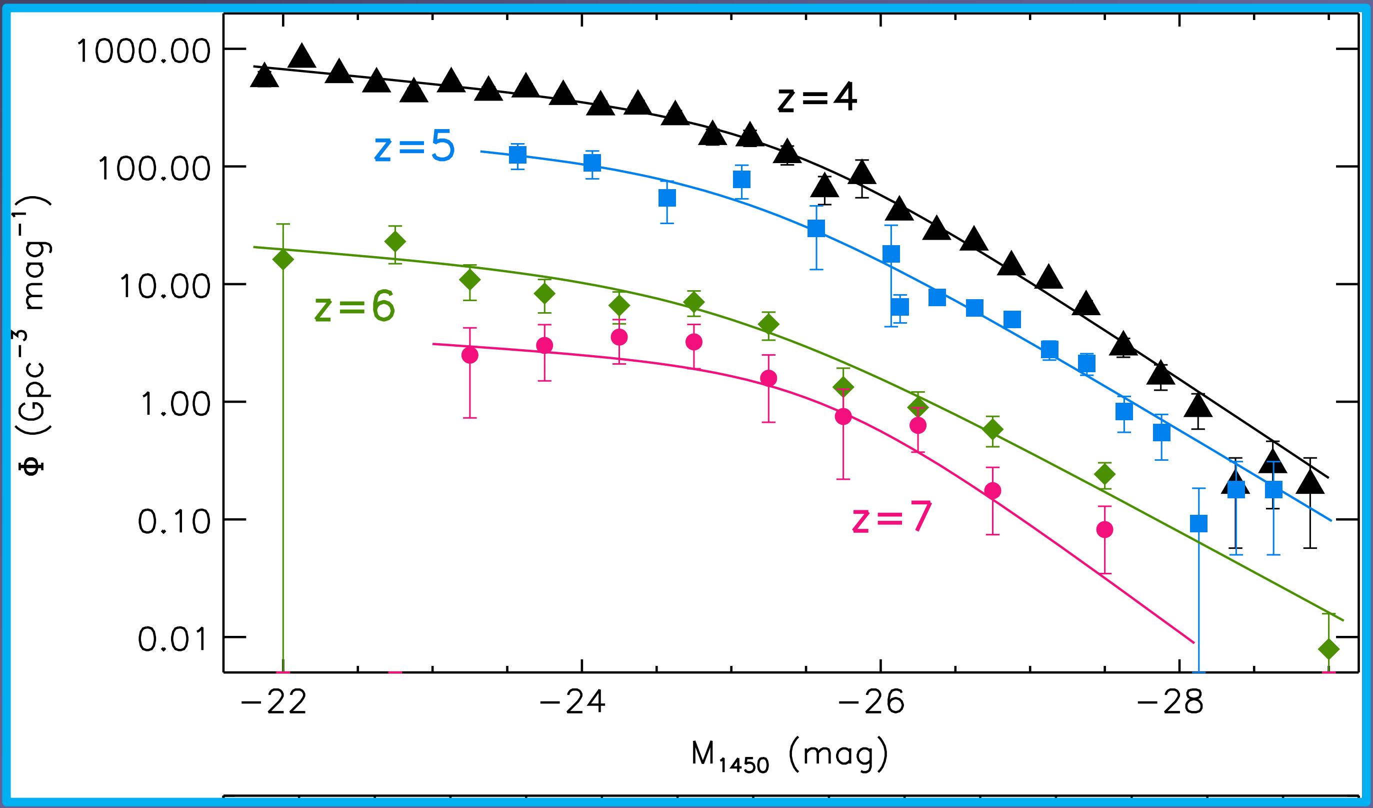
- Intermediate-mass BHs (?):
  - probably not in large numbers, but difficult to detect

Quasars



Evolution of Massive BHs in Nuclei

Quasars with $M_{BH} = 10^{8\text{-}10}\ M_\odot$ seen out to $z=7.54$ (t=700 Myr)



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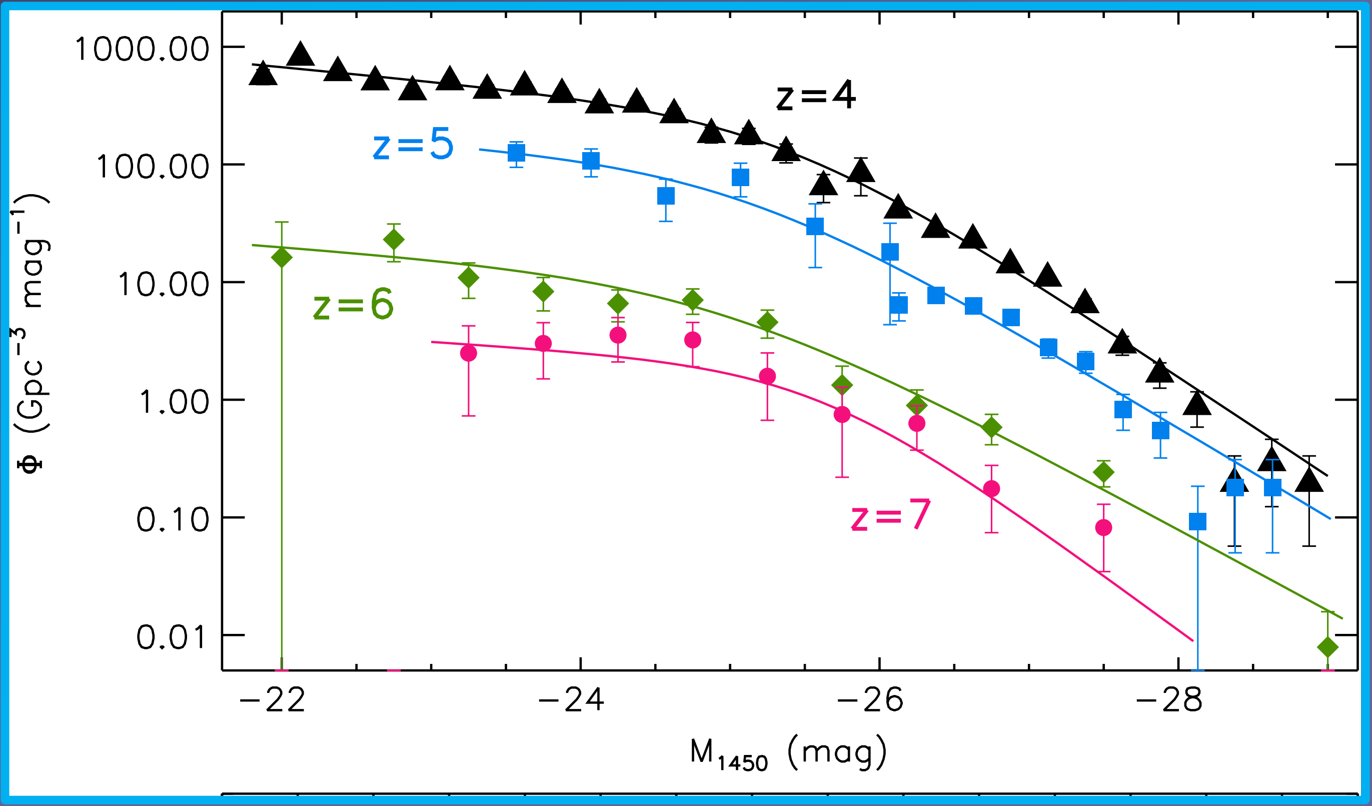


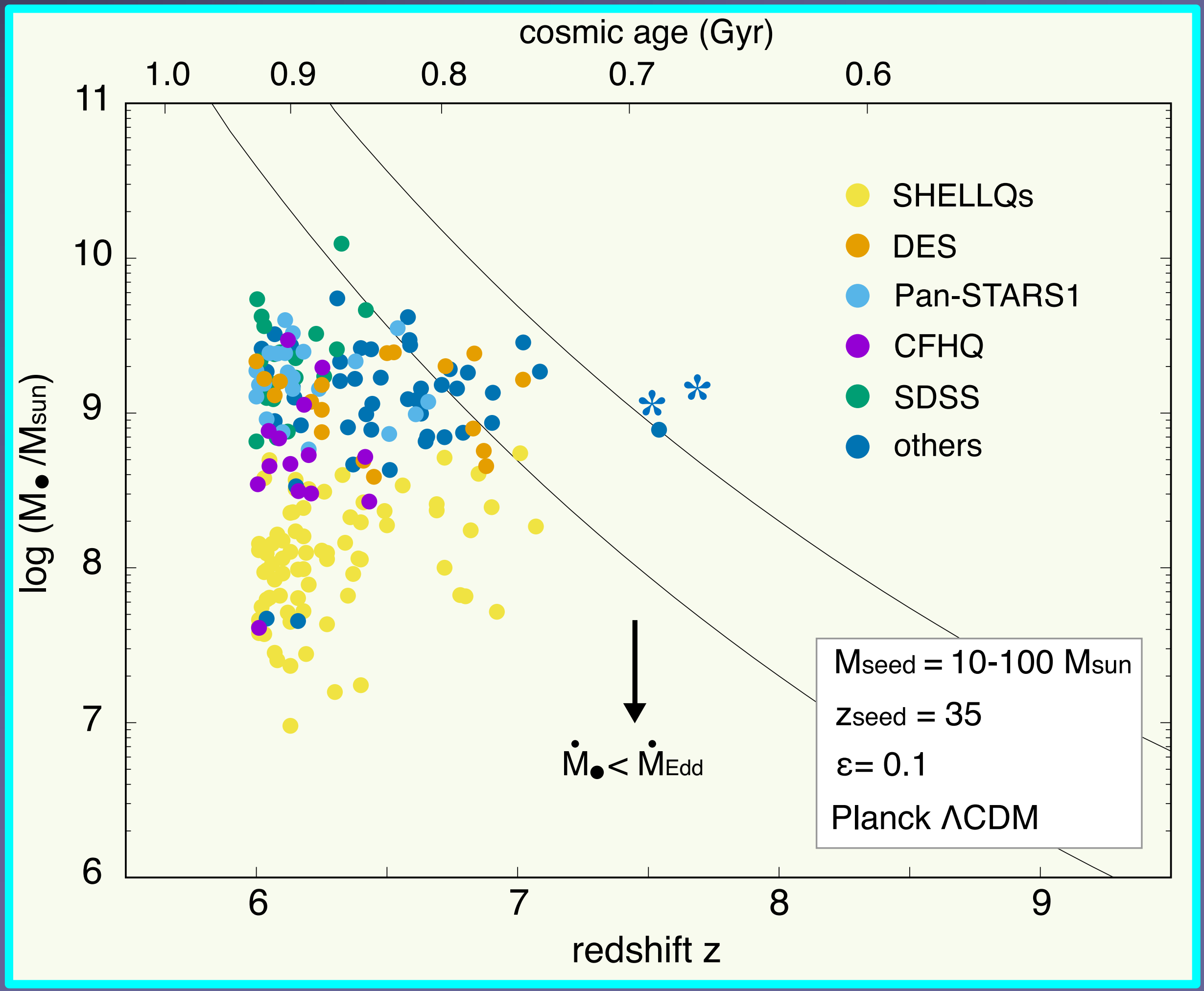
Matsuoka et al.(2023; arXiv:2305.11225)

~$10^6\ M_\odot$ seeds old: evolution at z<6 (t>1 Gyr) understood from quasars: $L_Q = \varepsilon/(1-\varepsilon)\ dM_{BH}/dt$ with ε~10% (Soltan 1991)

The most distant quasars

distance →

mass ↑



Record holder:

$z=7.64$
$t=670$ Myr
$M=1.6\times10^9\ M_\odot$

Wang+2021

Compilation from Inayoshi, Visbal & ZH, Annual Reviews of Astronomy & Astrophysics (2020)

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- Method 1: Collapse gas directly into a massive BH

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  problem: too few mergers

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Solution

Conditions in early universe different from present-day

densities much higher

myriad of small protogalaxies formed very early

gas chemically primitive

First “galaxies”

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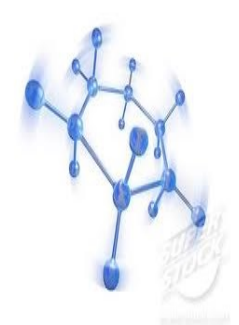

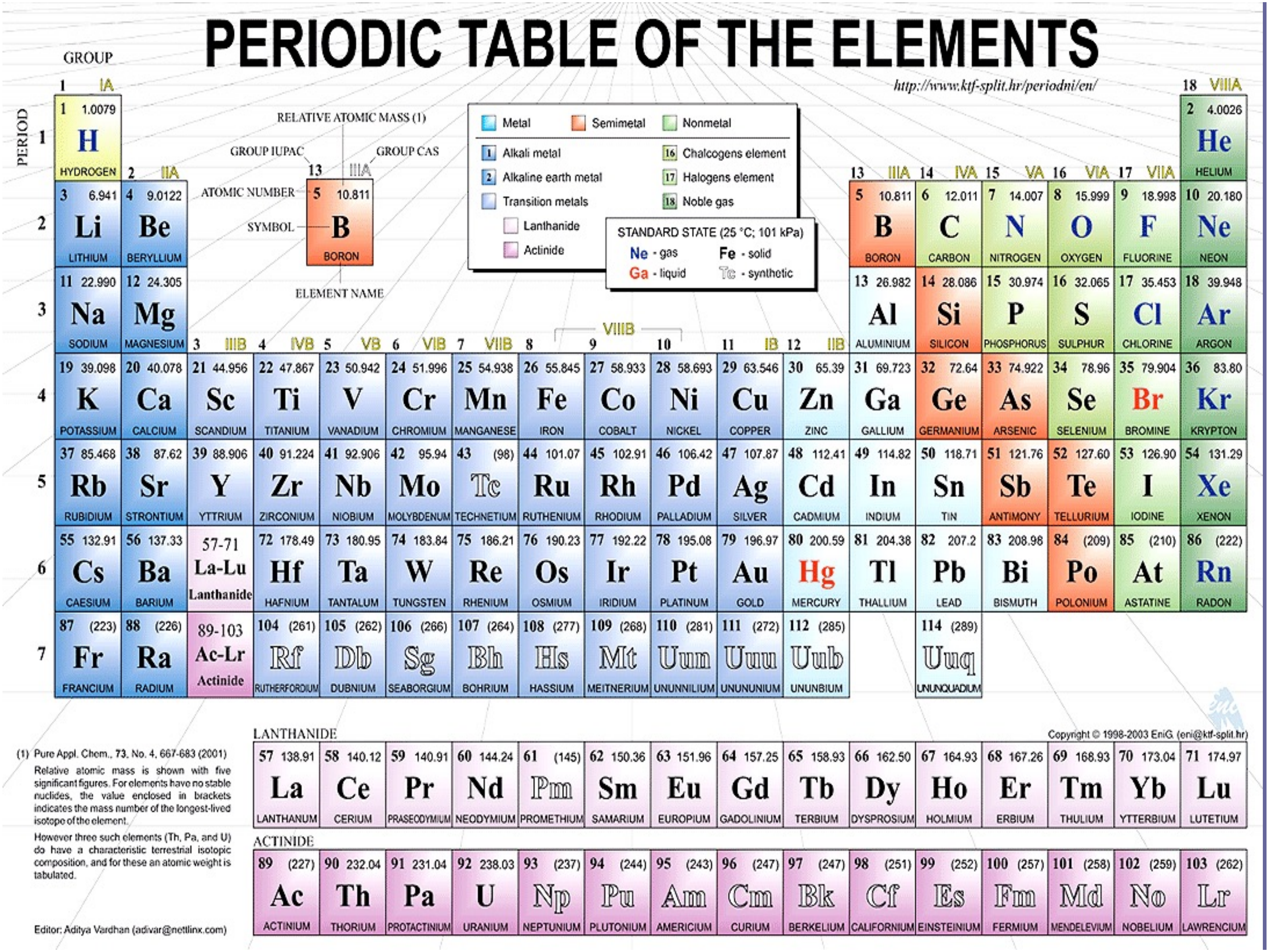

PERIODIC TABLE OF THE ELEMENTS

http://www.ktf-split.hr/periodni/en/

PERIOD \ GROUP	1 IA	2 IIA	3 IIIB	4 IVB	5 VB	6 VIB	7 VIIB	8 VIIIB	9 VIIIB	10 VIIIB	11 IB	12 IIB	13 IIIA	14 IVA	15 VA	16 VIA	17 VIIA	18 VIIIA
1	1 1.0079 **H** HYDROGEN																	2 4.0026 **He** HELIUM
2	3 6.941 **Li** LITHIUM	4 9.0122 **Be** BERYLLIUM											5 10.811 **B** BORON	6 12.011 **C** CARBON	7 14.007 **N** NITROGEN	8 15.999 **O** OXYGEN	9 18.998 **F** FLUORINE	10 20.180 **Ne** NEON
3	11 22.990 **Na** SODIUM	12 24.305 **Mg** MAGNESIUM											13 26.982 **Al** ALUMINIUM	14 28.086 **Si** SILICON	15 30.974 **P** PHOSPHORUS	16 32.065 **S** SULPHUR	17 35.453 **Cl** CHLORINE	18 39.948 **Ar** ARGON
4	19 39.098 **K** POTASSIUM	20 40.078 **Ca** CALCIUM	21 44.956 **Sc** SCANDIUM	22 47.867 **Ti** TITANIUM	23 50.942 **V** VANADIUM	24 51.996 **Cr** CHROMIUM	25 54.938 **Mn** MANGANESE	26 55.845 **Fe** IRON	27 58.933 **Co** COBALT	28 58.693 **Ni** NICKEL	29 63.546 **Cu** COPPER	30 65.39 **Zn** ZINC	31 69.723 **Ga** GALLIUM	32 72.64 **Ge** GERMANIUM	33 74.922 **As** ARSENIC	34 78.96 **Se** SELENIUM	35 79.904 **Br** BROMINE	36 83.80 **Kr** KRYPTON
5	37 85.468 **Rb** RUBIDIUM	38 87.62 **Sr** STRONTIUM	39 88.906 **Y** YTTRIUM	40 91.224 **Zr** ZIRCONIUM	41 92.906 **Nb** NIOBIUM	42 95.94 **Mo** MOLYBDENUM	43 (98) **Tc** TECHNETIUM	44 101.07 **Ru** RUTHENIUM	45 102.91 **Rh** RHODIUM	46 106.42 **Pd** PALLADIUM	47 107.87 **Ag** SILVER	48 112.41 **Cd** CADMIUM	49 114.82 **In** INDIUM	50 118.71 **Sn** TIN	51 121.76 **Sb** ANTIMONY	52 127.60 **Te** TELLURIUM	53 126.90 **I** IODINE	54 131.29 **Xe** XENON
6	55 132.91 **Cs** CAESIUM	56 137.33 **Ba** BARIUM	57-71 **La-Lu** Lanthanide	72 178.49 **Hf** HAFNIUM	73 180.95 **Ta** TANTALUM	74 183.84 **W** TUNGSTEN	75 186.21 **Re** RHENIUM	76 190.23 **Os** OSMIUM	77 192.22 **Ir** IRIDIUM	78 195.08 **Pt** PLATINUM	79 196.97 **Au** GOLD	80 200.59 **Hg** MERCURY	81 204.38 **Tl** THALLIUM	82 207.2 **Pb** LEAD	83 208.98 **Bi** BISMUTH	84 (209) **Po** POLONIUM	85 (210) **At** ASTATINE	86 (222) **Rn** RADON
7	87 (223) **Fr** FRANCIUM	88 (226) **Ra** RADIUM	89-103 **Ac-Lr** Actinide	104 (261) **Rf** RUTHERFORDIUM	105 (262) **Db** DUBNIUM	106 (266) **Sg** SEABORGIUM	107 (264) **Bh** BOHRIUM	108 (277) **Hs** HASSIUM	109 (268) **Mt** MEITNERIUM	110 (281) **Uun** UNUNNILIUM	111 (272) **Uuu** UNUNUNIUM	112 (285) **Uub** UNUNBIUM		114 (289) **Uuq** UNUNQUADIUM				

RELATIVE ATOMIC MASS (1)
GROUP IUPAC
GROUP CAS
13 IIIA
ATOMIC NUMBER
SYMBOL
5 10.811 **B** BORON
ELEMENT NAME

- Metal
- Semimetal
- Nonmetal
- 1 Alkali metal
- 2 Alkaline earth metal
- Transition metals
  - Lanthanide
  - Actinide
- 16 Chalcogens element
- 17 Halogens element
- 18 Noble gas

STANDARD STATE (25 °C; 101 kPa)
Ne - gas
Fe - solid
Ga - liquid
Tc - synthetic

LANTHANIDE

57 138.91 **La** LANTHANUM	58 140.12 **Ce** CERIUM	59 140.91 **Pr** PRASEODYMIUM	60 144.24 **Nd** NEODYMIUM	61 (145) **Pm** PROMETHIUM	62 150.36 **Sm** SAMARIUM	63 151.96 **Eu** EUROPIUM	64 157.25 **Gd** GADOLINIUM	65 158.93 **Tb** TERBIUM	66 162.50 **Dy** DYSPROSIUM	67 164.93 **Ho** HOLMIUM	68 167.26 **Er** ERBIUM	69 168.93 **Tm** THULIUM	70 173.04 **Yb** YTTERBIUM	71 174.97 **Lu** LUTETIUM

ACTINIDE

89 (227) **Ac** ACTINIUM	90 232.04 **Th** THORIUM	91 231.04 **Pa** PROTACTINIUM	92 238.03 **U** URANIUM	93 (237) **Np** NEPTUNIUM	94 (244) **Pu** PLUTONIUM	95 (243) **Am** AMERICIUM	96 (247) **Cm** CURIUM	97 (247) **Bk** BERKELIUM	98 (251) **Cf** CALIFORNIUM	99 (252) **Es** EINSTEINIUM	100 (257) **Fm** FERMIUM	101 (258) **Md** MENDELEVIUM	102 (259) **No** NOBELIUM	103 (262) **Lr** LAWRENCIUM

(1) Pure Appl. Chem., 73, No. 4, 667-683 (2001)

Relative atomic mass is shown with five significant figures. For elements have no stable nuclides, the value enclosed in brackets indicates the mass number of the longest-lived isotope of the element.

However three such elements (Th, Pa, and U) do have a characteristic terrestrial isotopic composition, and for these an atomic weight is tabulated.

Editor: Aditya Vardhan (adivar@netllinx.com)

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GROUP
1 IA
PERIOD 1

1 1.0079
H
HYDROGEN

IN THE EARLY UNIVERSE

18 VIIIA

2 4.0026
He
HELIUM

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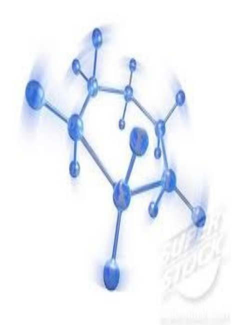

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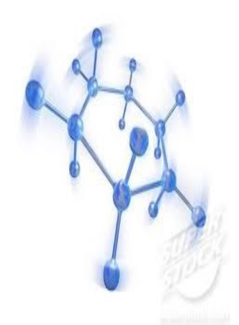

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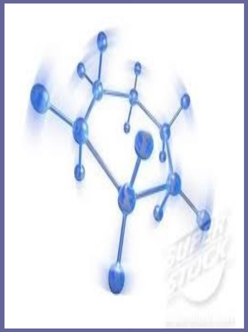


H_2 molecule controls fate of first stars/BHs

H_2 abundance depends on local radiation

🙁

- Formation:

$\mathrm{H} + \mathrm{e}^- \rightarrow \mathrm{H}^- + \gamma(\mathrm{IR})$

$\mathrm{H}^- + \mathrm{H} \rightarrow \mathrm{H}_2 + \mathrm{e}^-$

😀

- Destruction:

$\mathrm{H}_2 + \gamma(\mathrm{UV}) \rightarrow (^*)\mathrm{H}_2$

$(^*)\mathrm{H}_2 \rightarrow \mathrm{H} + \mathrm{H} + \gamma(\mathrm{IR})$

Strong Lyman-Werner radiation (~12eV)
suppresses H2 fraction and cooling
Jemma Wolcott-Green (PhD thesis 2019)

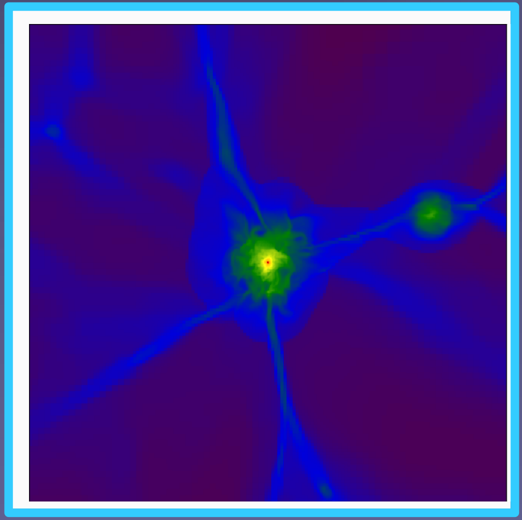
Realized in synchronized formation of a pair of protogalaxies
$\Delta t_{\mathrm{sync}} < 4$ Myr and $d_{\mathrm{sep}} < 1000$ light-yr in ~10^{-4} of protogalaxies

3D simulation of protogalaxy collapse

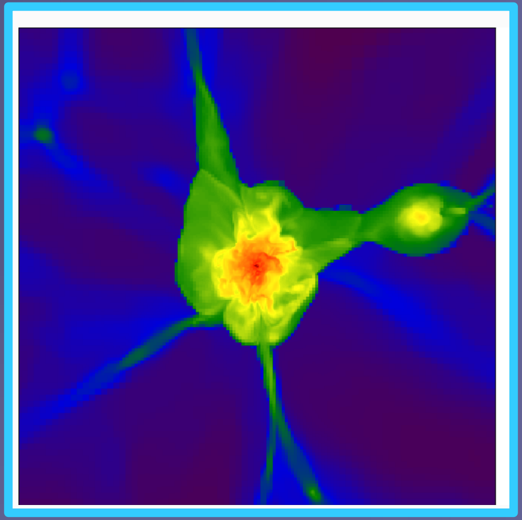
- no free parameters -

$M_{galaxy} \approx 10^{6-8} M_{\odot}$ $t_{coll} \approx 300$ Myr

Fernandez et al. (2014), Regan et al. (2017)



density



temperature

Inflow rate **increases** with temperature

$$dM/dt \sim c_s^3 / G \sim T^{3/2} / G$$

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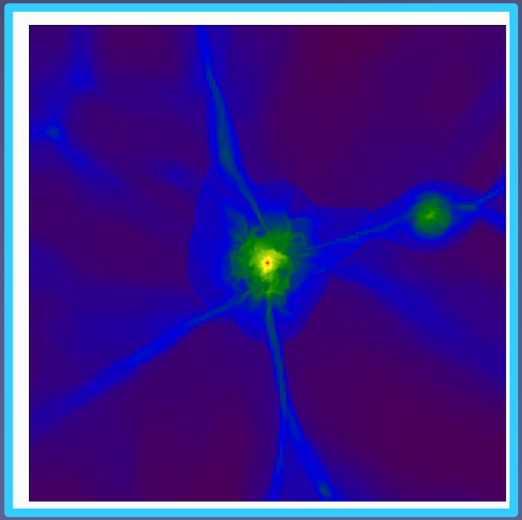

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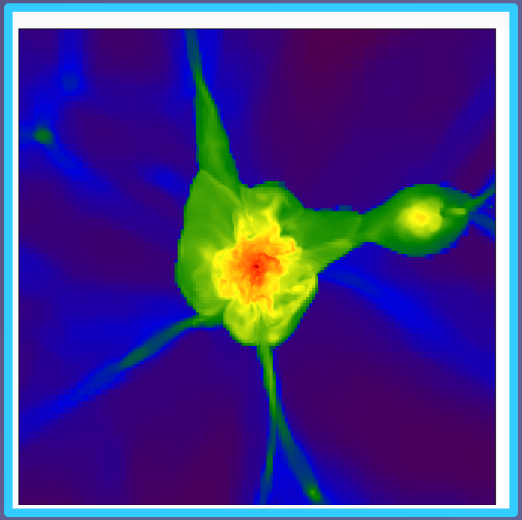

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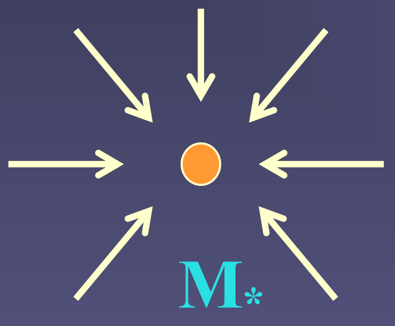
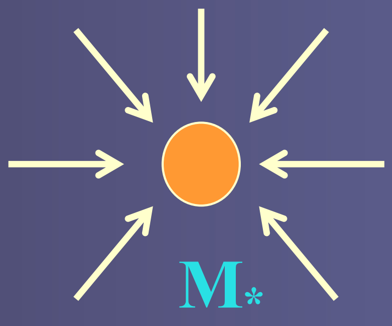
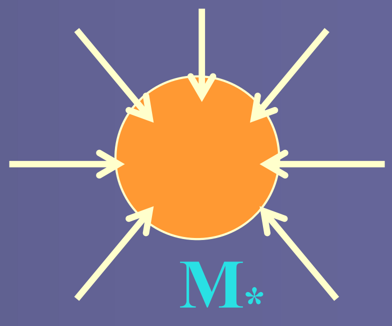
What happens in the (unresolved) core?





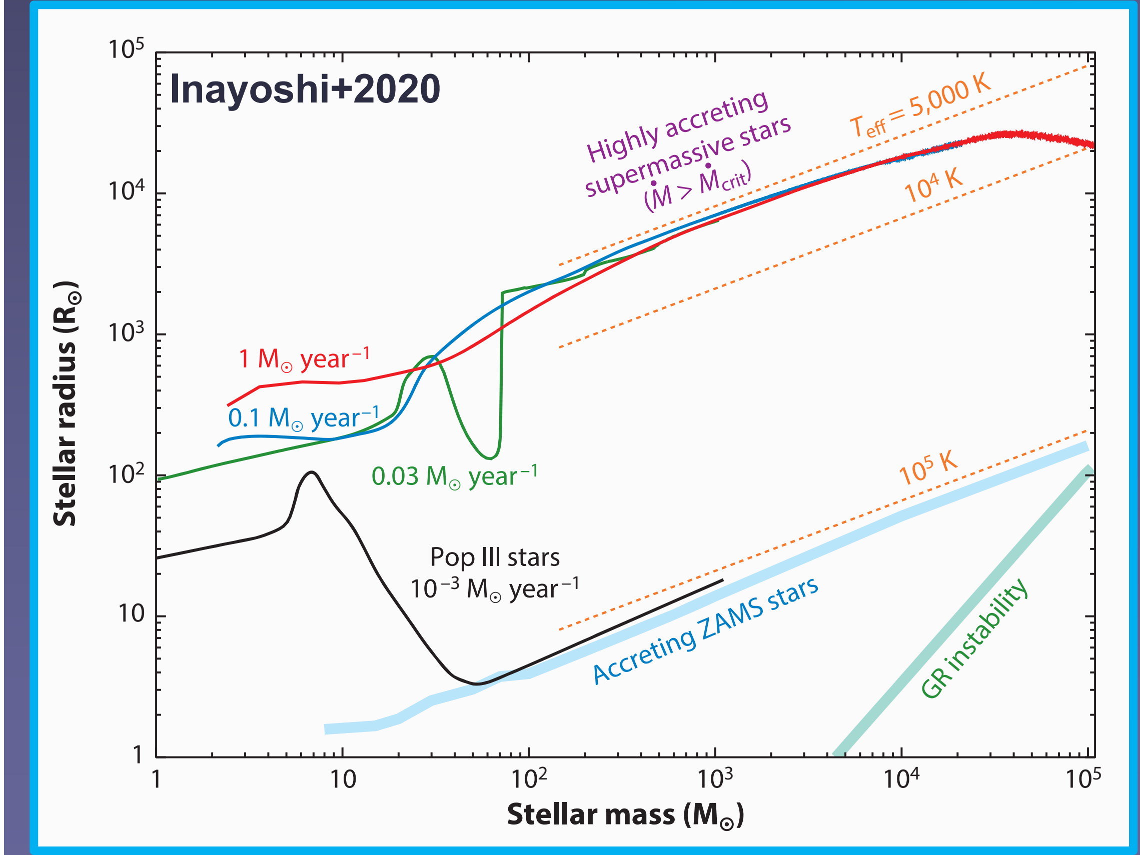


present-day galaxy	$10^6\ M_\odot$ protogalaxy	$10^8\ M_\odot$ protogalaxy
abundant CO, $H_2 0$	abundant H_2	no H_2 - cooling by H
$T \approx 5$ K	$T \approx 200$ K	$T \approx 10{,}000$ K
$\dot{M} \approx 10^{-5}\ M_\odot\ yr^{-1}$	$\dot{M} \approx 10^{-3}\ M_\odot\ yr^{-1}$	$\dot{M} \approx 1\ M_\odot\ yr^{-1}$
result: a star $M_* \approx 1\text{-}10\ M_\odot$	result: massive star $M_* \approx 10\text{-}500\ M_\odot$	supermassive star $M_* \approx 10^{5-6}\ M_\odot$
0.1% chance of BH	**50% chance of BH**	**→ Massive BH**

Direct collapse

→ **Protostar must be building up faster than it can contract (Kelvin-Helmholtz timescale ~ 10^4 years)**

→ **Leave behind massive $10^{5\text{-}6}\,M_\odot$ BHs via GR instability**



Hosokawa et al. 2012, 2015; Haemmerlé et al. 2018

SMS: achieved by rapid gas accretion

Normal star: $M \gtrsim 10^3 M_\odot$ prevented by UV radiation

isothermal collapse via Lyα cooling:

$$\mathbf{M_{acc} \approx c_s^3/G \approx 0.1\text{-}1\ M_\odot\ yr^{-1}}$$

cf. inflow rate with H_2 cooling:

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cf. molecular clouds in ISM:

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~~Direct collapse~~
(rapid inflow → supermassive star → MBH)

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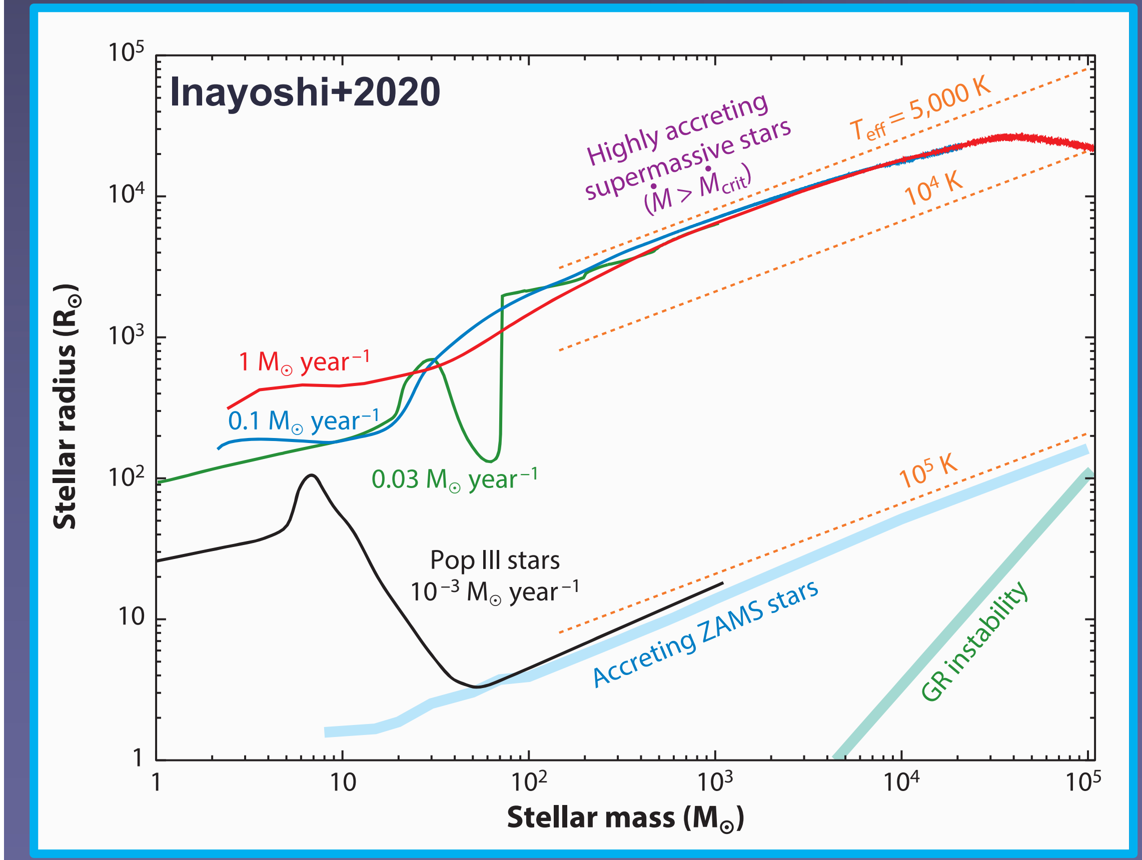

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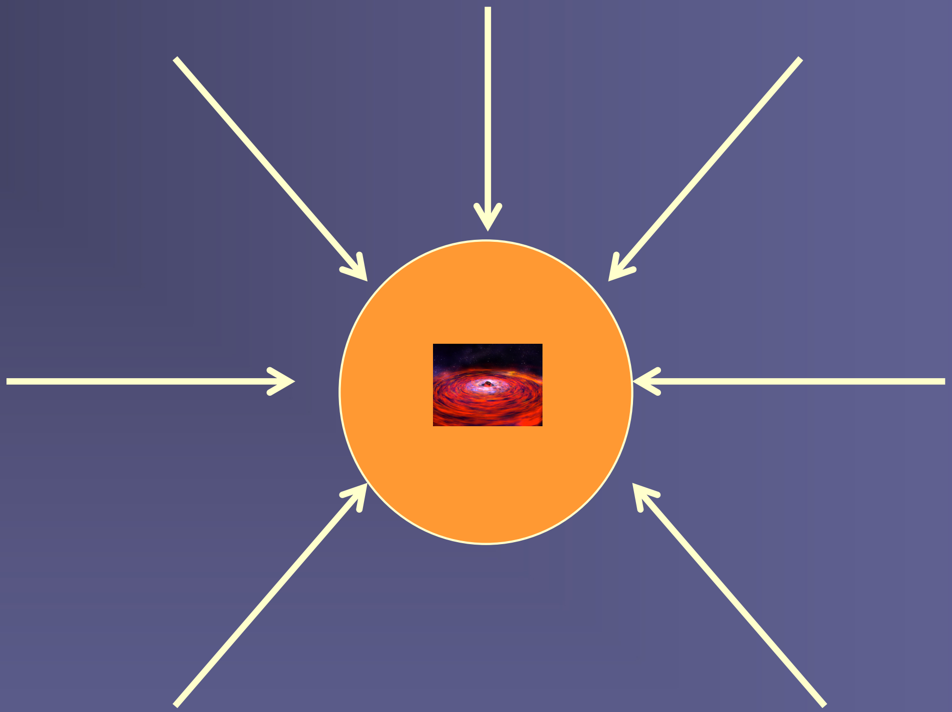

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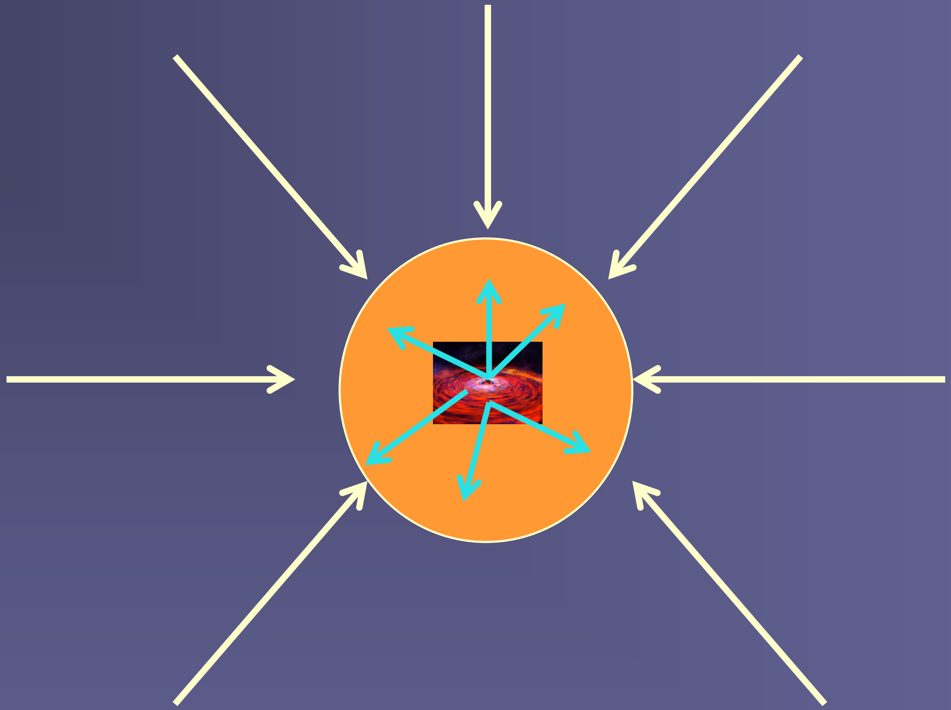


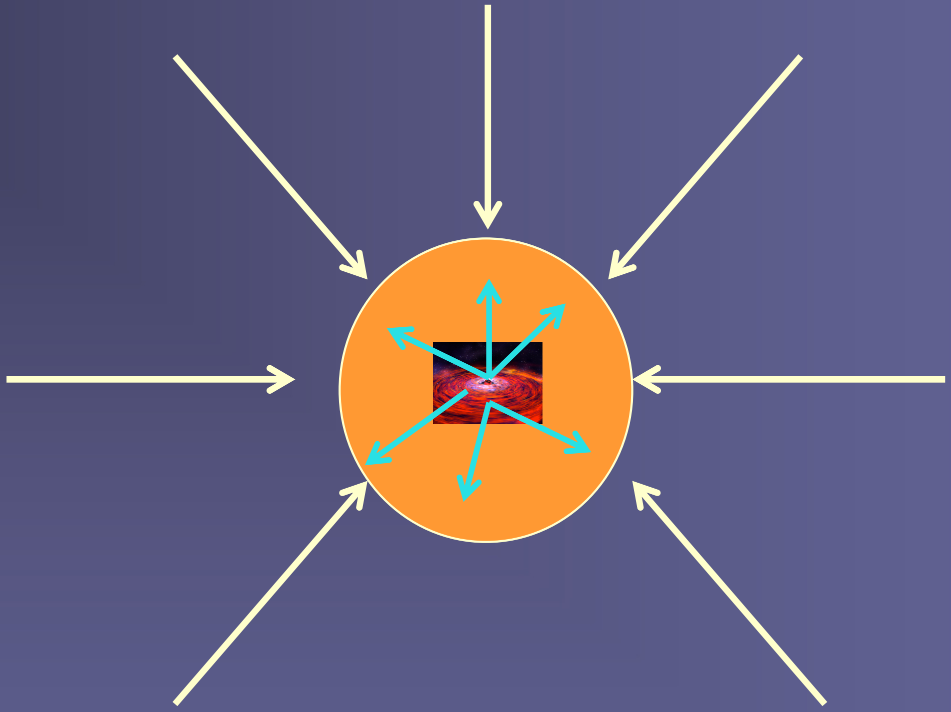
inward
gravity

vs

outward
radiation

$L \sim G\dot{M}_{bh}M_{bh}/R_{bh}$

Feeding Black Holes



inward
gravity
vs
outward
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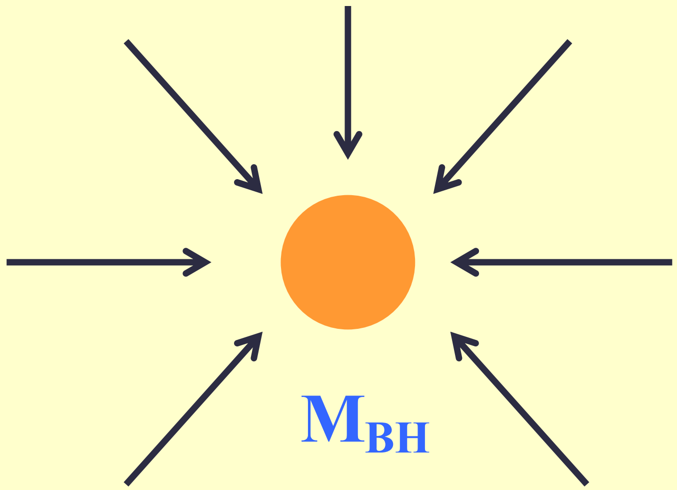
$L \sim G\dot{M}_{bh}M_{bh}/R_{bh}$

there is a
universal
maximum
"Eddington"
feeding rate

Maximum Growth Rate and BH mass



Fueling rate: $$\frac{dM_{gas}}{dt}$$

BH growth rate: $$\frac{dM_{BH}}{dt} = \varepsilon \frac{dM_{gas}}{dt}$$

BH luminosity: $$L_{BH} = (1-\varepsilon)\frac{dM_{gas}c^2}{dt}$$

$$L_{BH} = \frac{(1-\varepsilon)}{\varepsilon}\frac{dM_{BH}c^2}{dt}$$

Outward force:

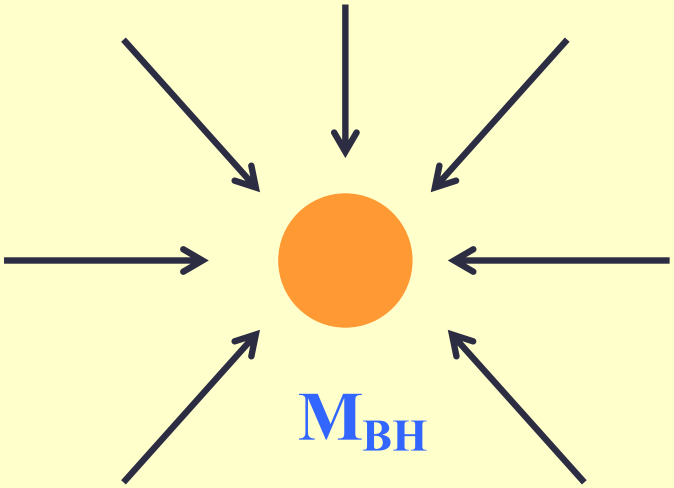
$$F_{rad} = const \times \frac{L_{BH}}{4\pi r^2} = const \times \frac{\dot{M}_{BH}}{r^2}$$

Maximum growth rate:

$$F_{rad} = F_{grav} = \frac{GM_{BH}}{r^2} \rightarrow \dot{M}_{BH,MAX} = const \times M_{BH}$$

$$\boxed{M_{BH}(t) = ???}$$

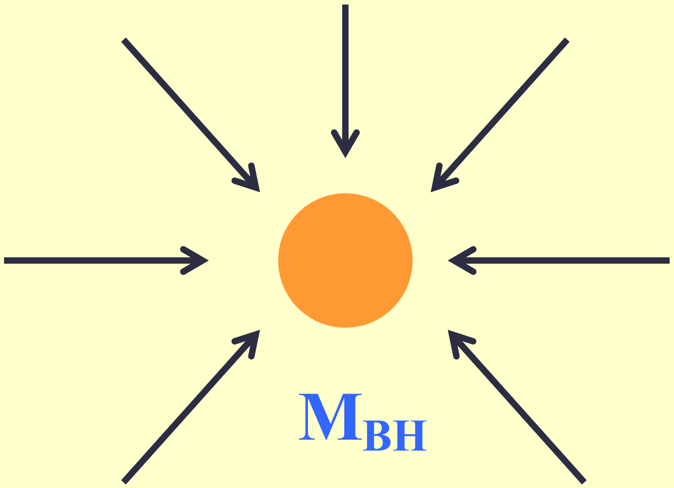
Maximum Growth Rate and BH mass



Maximum growth rate: $\dot{M}_{BH,MAX} = const \times M_{BH}$

→ $\boxed{M_{BH}(t) = ???}$

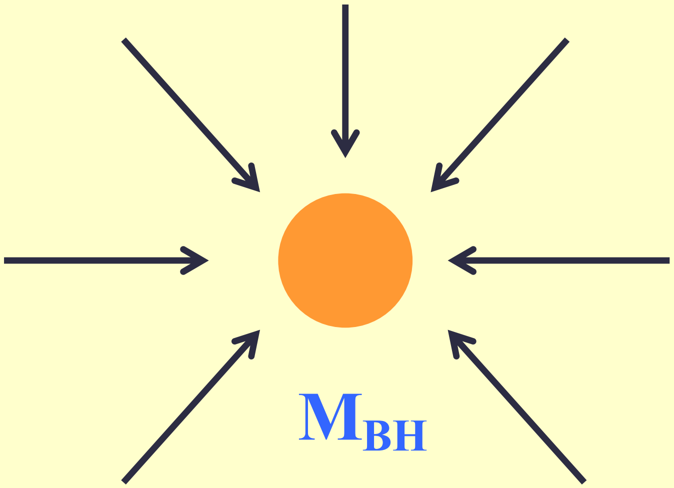
Maximum Growth Rate and BH mass



Maximum growth rate: $\dot{M}_{BH,MAX} = const \times M_{BH}$

→ $$\boxed{M_{BH}(t) = M_{BH}(t=0) \times \exp(\frac{t}{T})}$$

Maximum Growth Rate and BH mass



Maximum growth rate: $\dot{M}_{BH,MAX} = const \times M_{BH}$

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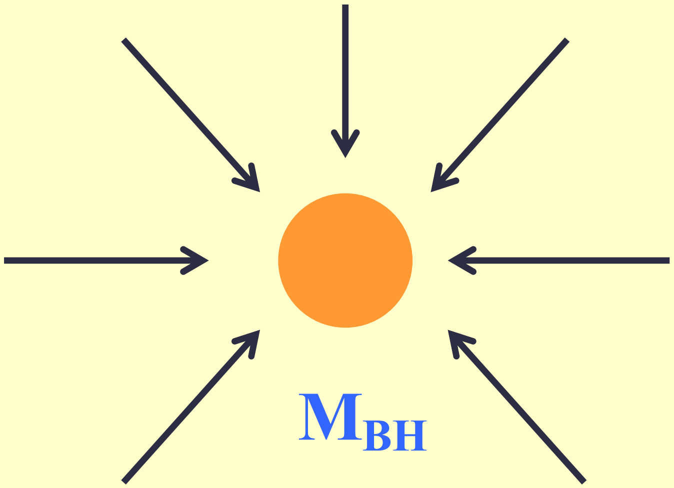
700 million years

Massive star: 100 $M_{\odot}$

~ 40 million years

Maximum Growth Rate and BH mass



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700 million years

Massive star: 100 $M_\odot$

~ 40 million years

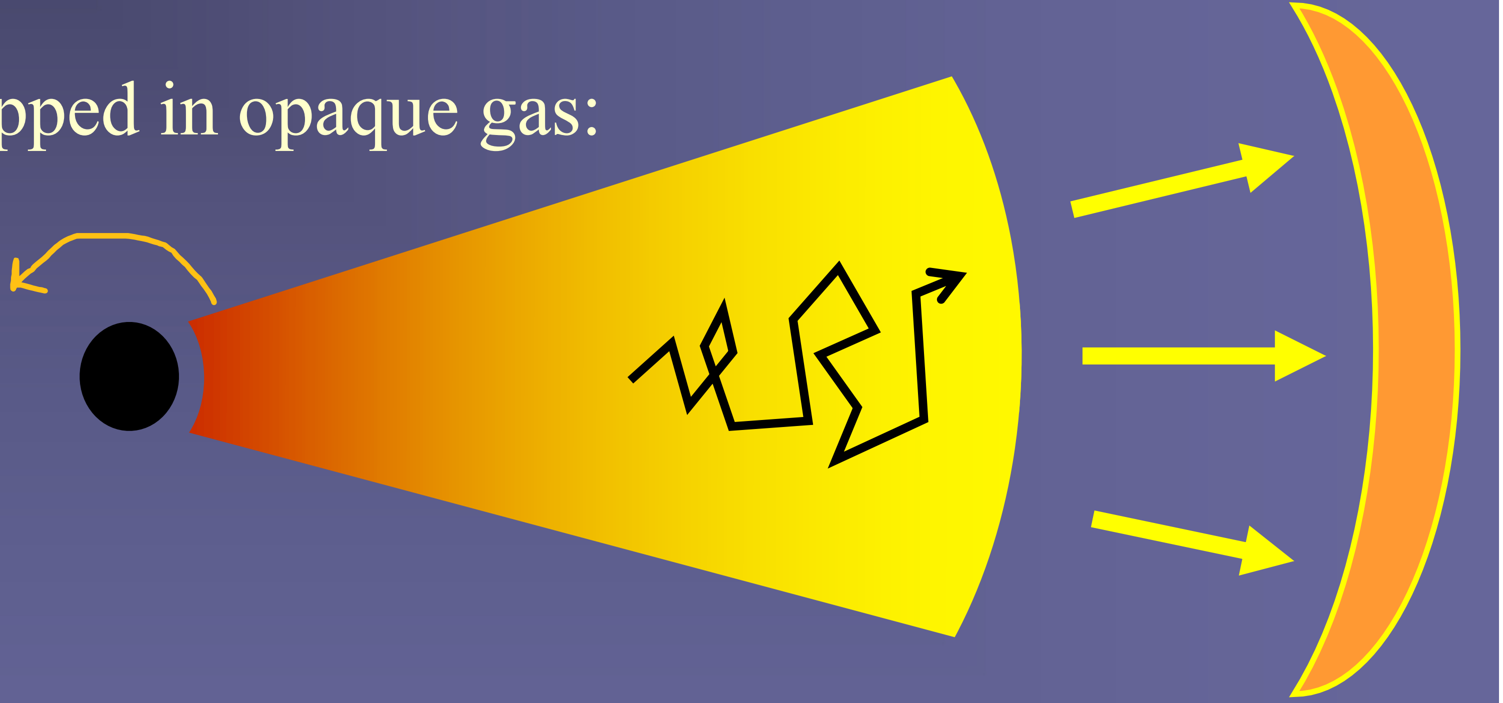
$$\boxed{\rightarrow \quad \text{Maximum } M_{BH} = 10^8 \ M_\odot \quad \text{too small!}}$$

Hyper-accretion onto BH

Spherically symmetric radiation + hydrodynamics simulations

Inayoshi, ZH, Ostriker (2016), Sakurai, Inayoshi, ZH (2017), Hu et al. (2022a,b)

I. Radiation trapped in opaque gas:



$$L \sim G\dot{M}_{bh}M_{bh}/R_{bh}$$

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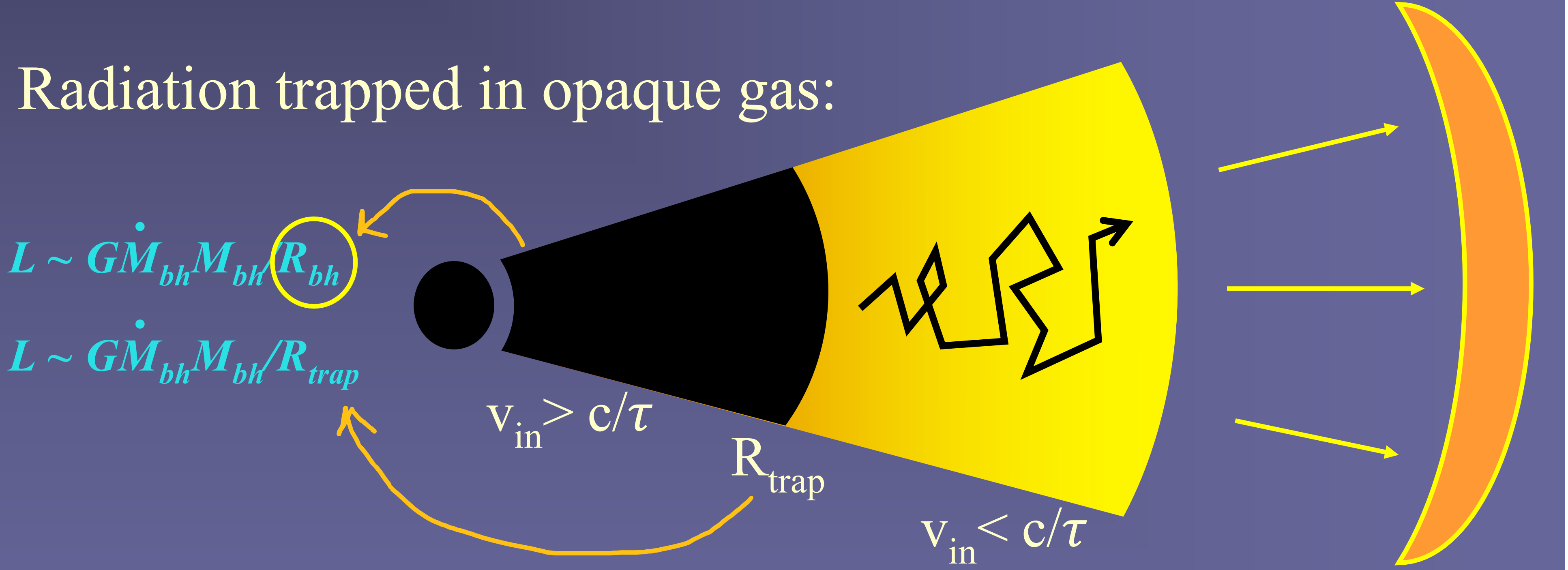

$L \sim G\dot{M}_{bh}M_{bh}/\bigcirc\!\!\!\!R_{bh}$

$L \sim G\dot{M}_{bh}M_{bh}/R_{trap}$

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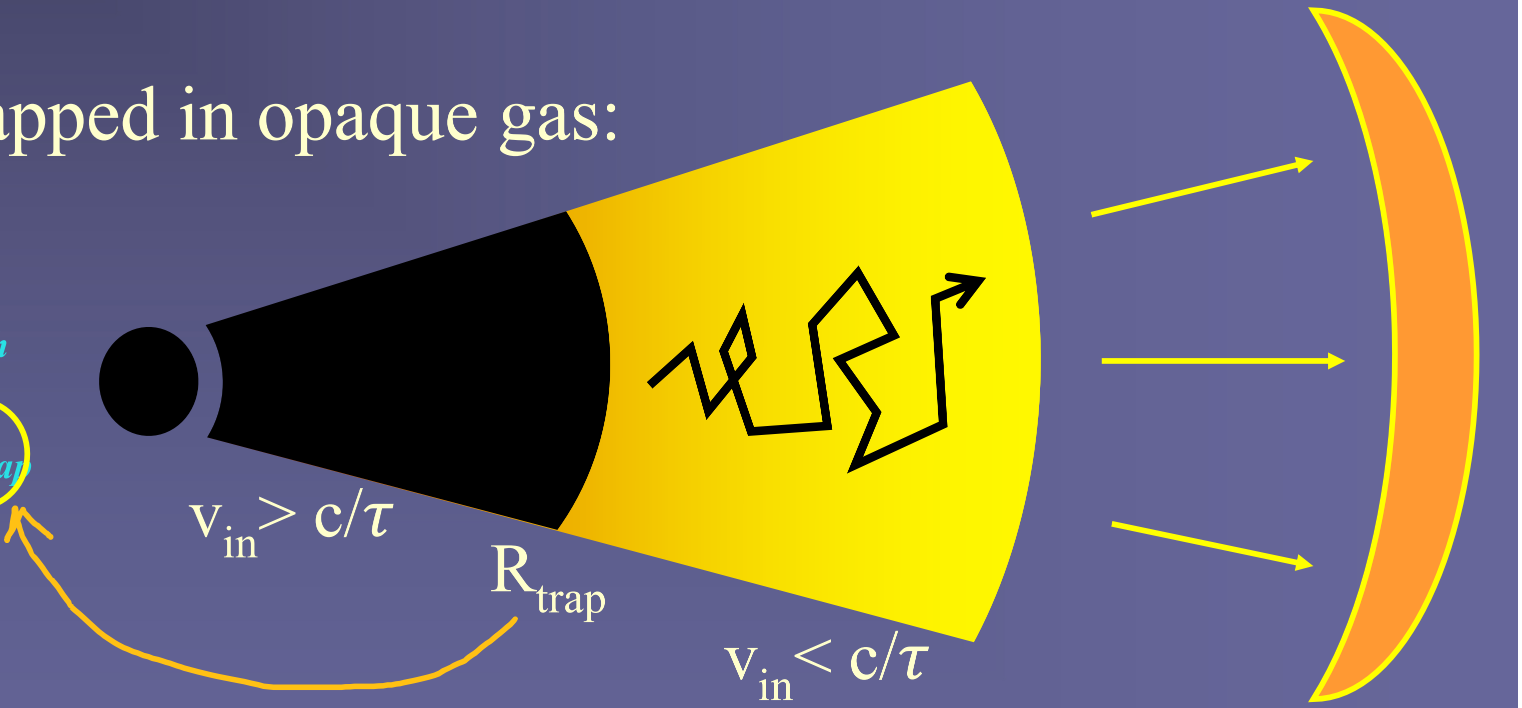

$v_{in} > c/\tau$

R_{trap}

$v_{in} < c/\tau$

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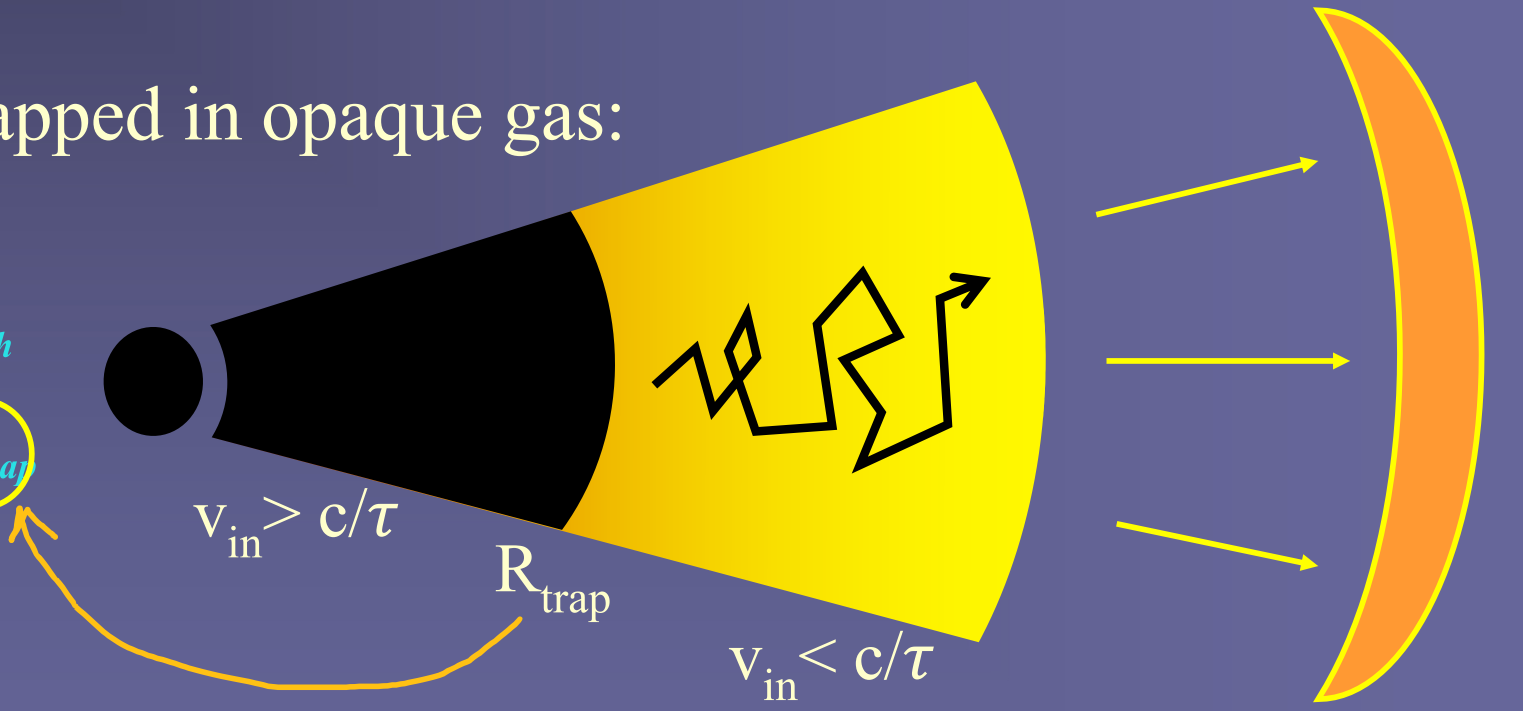
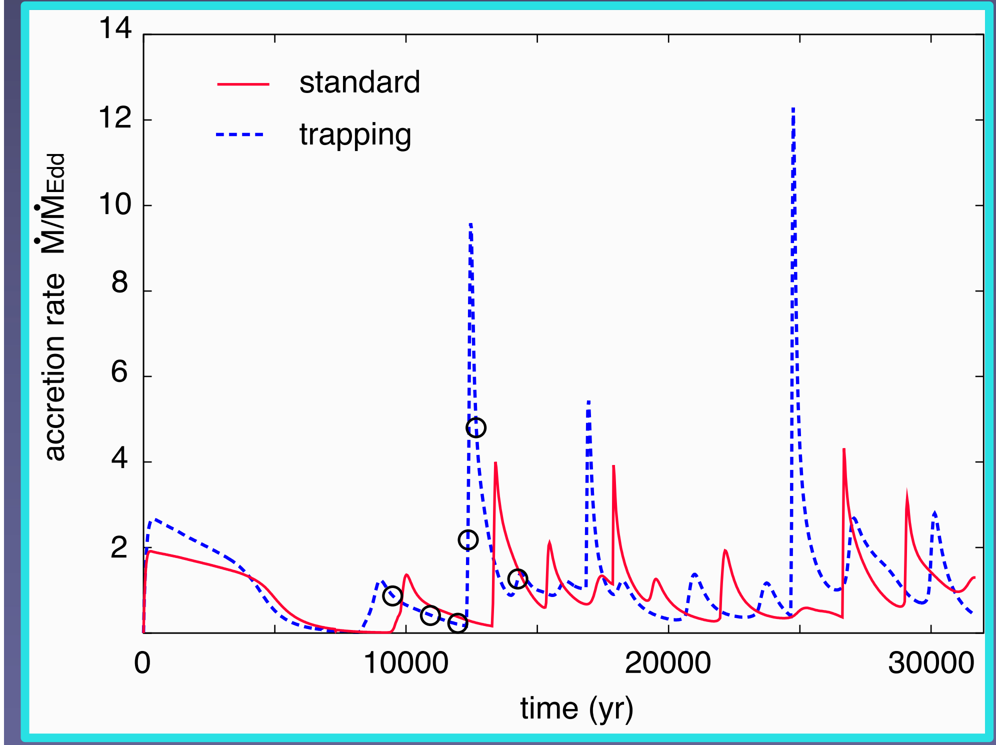


II. If fueling is extremely rapid ($\gtrsim 500 \times$ Eddington rate)
then emerging radiation cannot stop inflow:
the BH swallows everything (otherwise, episodic accretion)

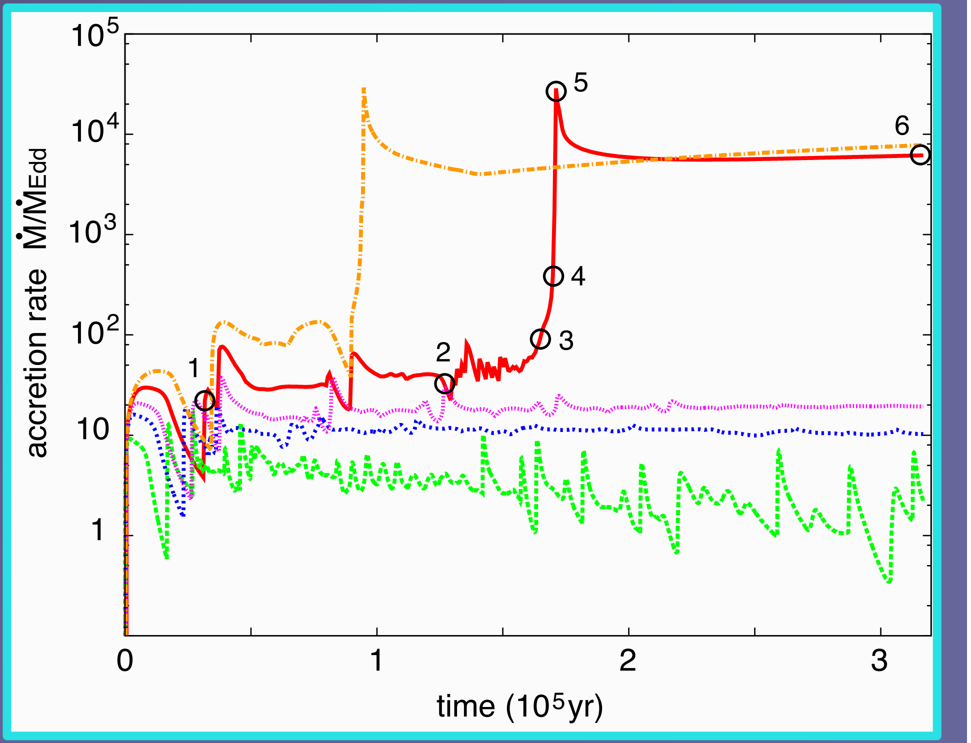
Hyper-accretion onto BH

1D and 2D radiation + hydrodynamics simulations

$\dot{M} = 100\ \dot{M}_{Edd}$



$\dot{M} = 10^4\ \dot{M}_{Edd}$



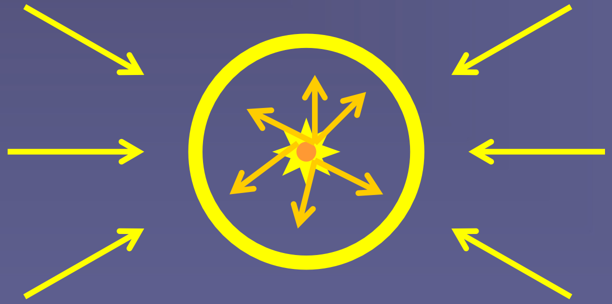
Accretion episodic due to heating
average rate is very low
(sub-Eddington)

Accretion is steady
matches feeding rate
(gas free-falls onto BH)

Toy model for steady hyper-accretion

Sakurai, Inayoshi & ZH (2017)

- Infalling gas neutral → Eddington luminosity irrelevant
- Consider a toy model: geometrically thin, optically thick spherical shell around a point source, driven by radiation force into a rapidly collapsing medium



$$\frac{\mathrm{d}}{\mathrm{d}t}(M_{\rm sh}\dot{R}_{\rm sh}) = \frac{L}{c} - \dot{M}(|v| + \dot{R}_{\rm sh}) - \frac{GM_{\rm BH}M_{\rm sh}}{R_{\rm sh}^2}$$

$$\frac{\mathrm{d}M_{\rm sh}}{\mathrm{d}t} = \dot{M}\left(1 + \frac{\dot{R}_{\rm sh}}{|v|}\right),$$

How to make massive BHs (fast)?

- Method 1: Collapse gas directly into a massive BH

  problem: cloud fragments and forms stars

  solution: rapid inflow in large but pristine H_2 –free protogalaxy

- Method 2: Grow a single stellar-mass BH by accretion

  problem: accretion rate low

- Method 3: Merge together many black holes

  problem: too few mergers

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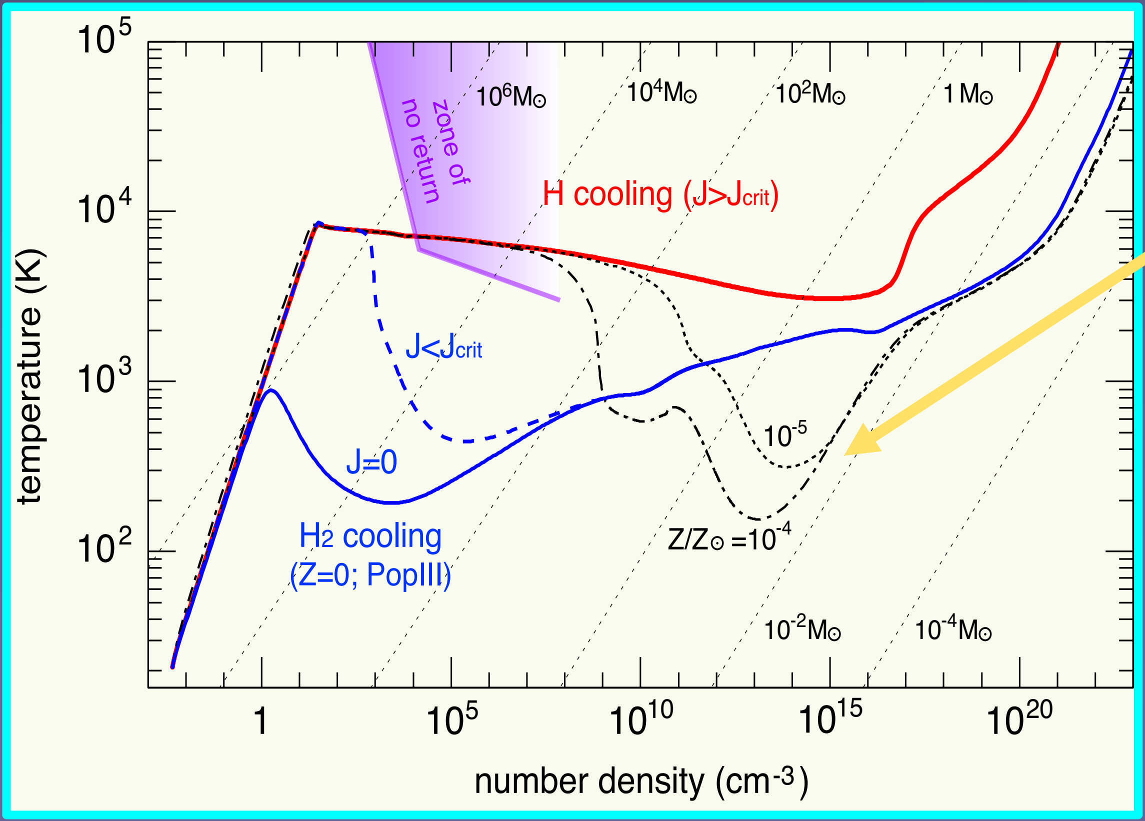
Runaway Collisions

What happens in atomic-cooling halo if there is prior star-formation and corresponding metal-enrichment? (i.e. in more typical case)

Dense stellar cluster forms → core collapse → IMBH with 10^3-10^4 $M_\odot$



key: fragmentation at very high density (~10^{10} $M_\odot$ pc^{-3})

- → **Ultra-dense star cluster**
- → **Runaway core collapse**
- → **VMS**
- → **IMBH**

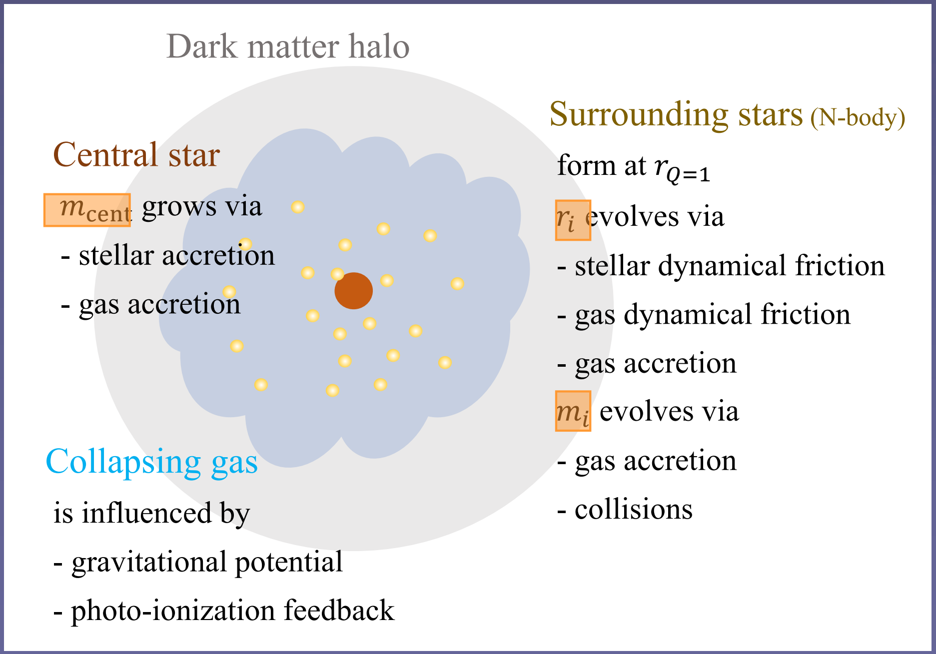
Omukai, ZH, Schneider 2008
Devecchi & Volonteri 2009
Katz+2015, Sakurai+2017
Reinoso+2018, Boekholt+2018
Alister Seguel+2020, Das+2020 ….

Variant: "Stellar Bombardment"

Tagawa, ZH & Kocsis (2020)

atomic-cooling halo with modest $Z\sim10^{-4}\,Z_\odot$

Numerical N-body + gas toy model to follow time-evolution for 3 Myr ("1-dimensional N-body simulation")



Central star

m_{cent} grows via

- stellar accretion
- gas accretion

Collapsing gas

is influenced by

- gravitational potential
- photo-ionization feedback

Surrounding stars (N-body)

form at $r_{Q=1}$

r_i evolves via

- stellar dynamical friction
- gas dynamical friction
- gas accretion

m_i evolves via

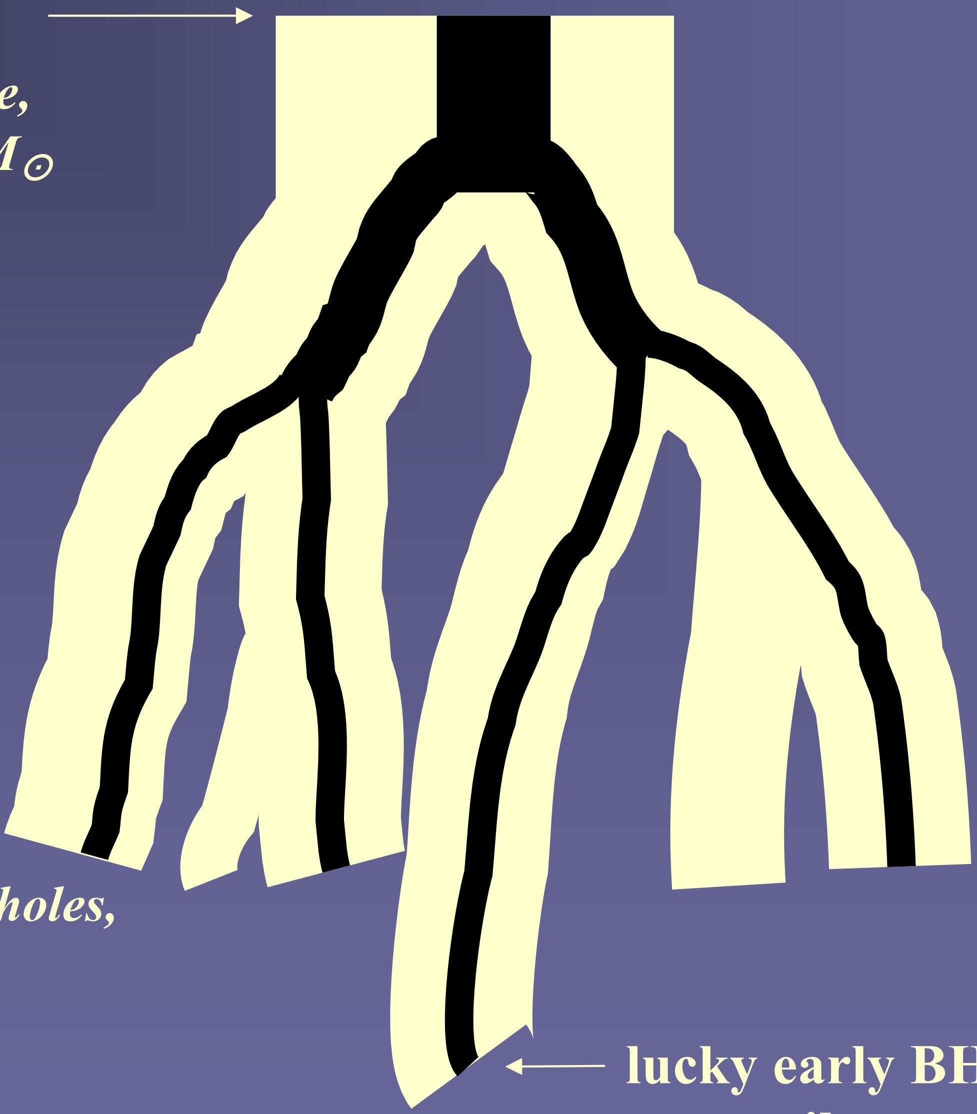
- gas accretion
- collisions

Results:

- Central star grows via **mergers** before it contracts
- **Feedback loop**: increased radius ←→ more rapid mergers
- "Bombardment" different from runaway due to mass segregation
- **Critical density:** $\rho \gtrsim 10^{8\text{-}9}\,M_\odot\,\mathrm{pc}^{-3}$ *(cf.* $\rho\sim10^{7}\,M_\odot\,\mathrm{pc}^{-3}$ *in M32)*

→ SMS with $10^{5\text{-}6}\,M_\odot$

BH growth by cosmological *Mergers and Acquisitions*



1 billion yr:

A single black hole, with mass of $10^9\ M_\odot$

100 million yr:

several hundred stellar-mass black holes, each with $100\ M_\odot$

Galaxy merger tree – follows from cosmological theory

The holes grow by both *accretion* and by many *mergers*

Many holes are ejected into space and lost

lucky early BH at 60-70 Myr
no recoil -- unequal mass at merger

Takamitsu Tanaka PhD thesis

How to make massive BHs fast?

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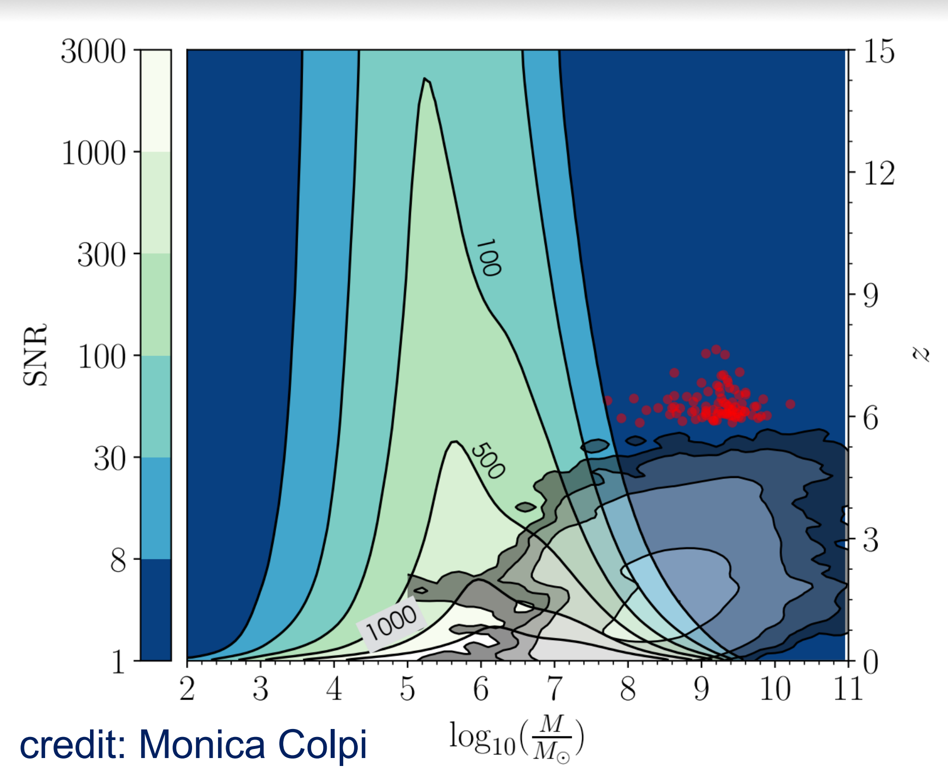
  solution: ultra-dense clusters, and/or lucky ultra-early seed

Outline

1. Observations: types of black holes in the universe
2. Theory: where do massive black holes come from?
3. The Future: how to distinguish different pathways?

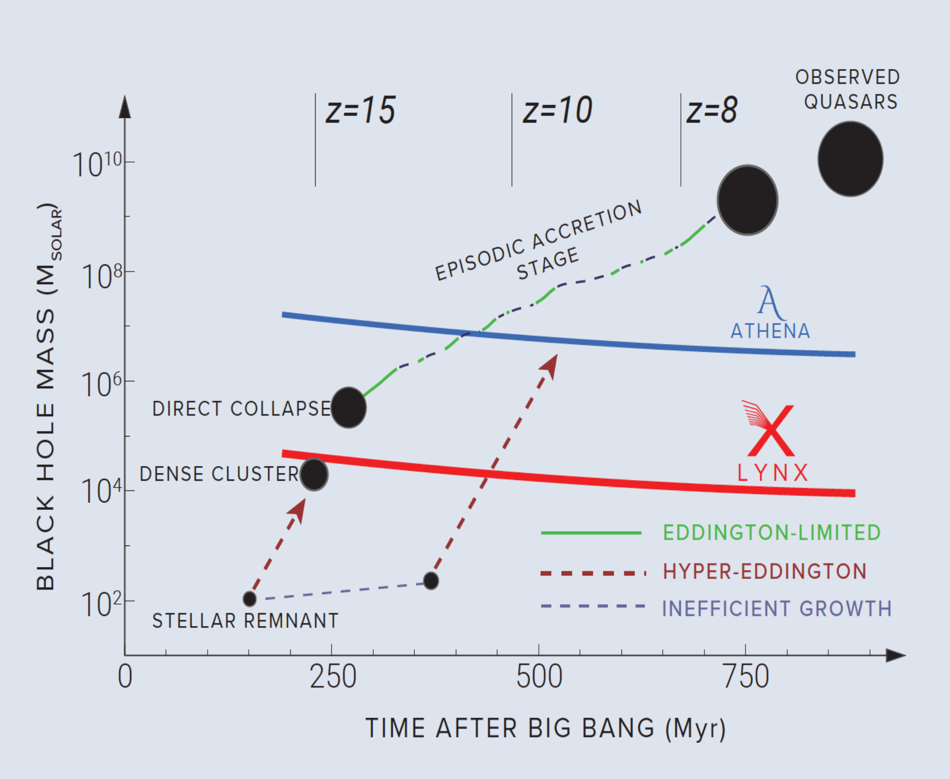
Looking for early black hole growth

Growth by mergers: **LISA**



credit: Monica Colpi

Growth by accretion: **LynX**



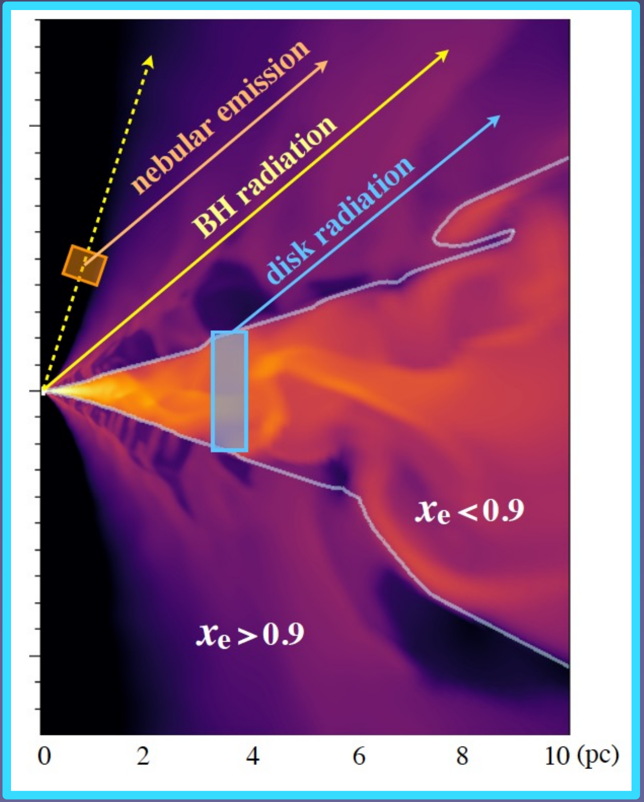
Emerging spectrum

2D radiation-hydro simulations for hyper-accretion

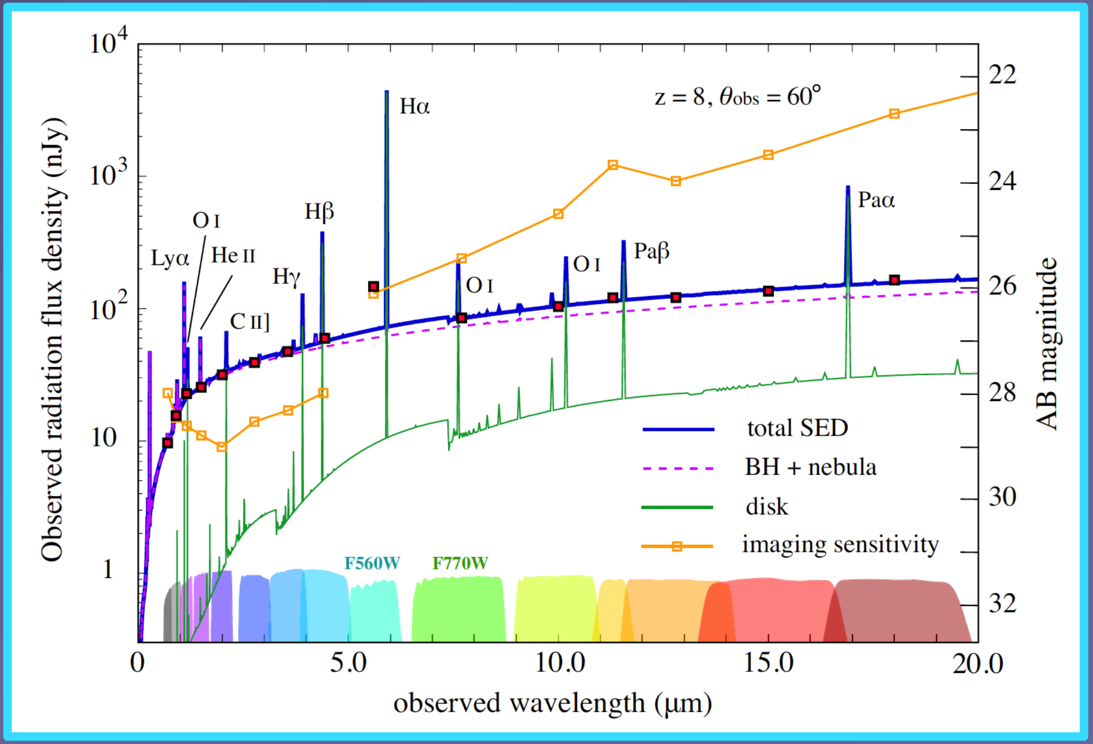
Hu, Inayoshi, ZH, Quataert, Kuiper 2022a; Inayoshi+2022

CLOUDY post-processing of 0.1-100pc around $10^{5\text{-}6}$ $M_\odot$ BH accreting 1 $M_\odot$/yr

$L_{bol} \sim 10^{45}$ erg/s



→



rapidly accreting BHs detectable to z<17 or z<13
expected abundance: 1 per 10 NIRCam fields

Distinguishing signatures

- Strong Balmer lines

  collisional excitations of n≧3 levels from n=2 populated by trapped Lyα

  due to high column density of the dense inner disk (0.1-1 pc)

  Hα rest-frame EW~1300Å (~6-7 times stronger than low-z quasars)

  Hβ rest-frame EW~100Å (~2-3 times stronger than low-z quasars)

- Red colors in broad bands, due to strong Hα

  broad-band selection by multiband photometry with NIRCam & MIRI

  F356W – F560W > 1 $(7 < z < 8)$

  F444W – F770W > 1 $(9 < z < 12)$

- OI lines (1304, 8446, 11287Å) excited by Lyβ fluorescence coinciding with OI 3d

  (Lyβ trapped but OI cascade lines (3d → 3p, 3p → 3s, 2s → 2s) escape

  detectable by NIRSpec

BH mass to host galaxy mass ratio

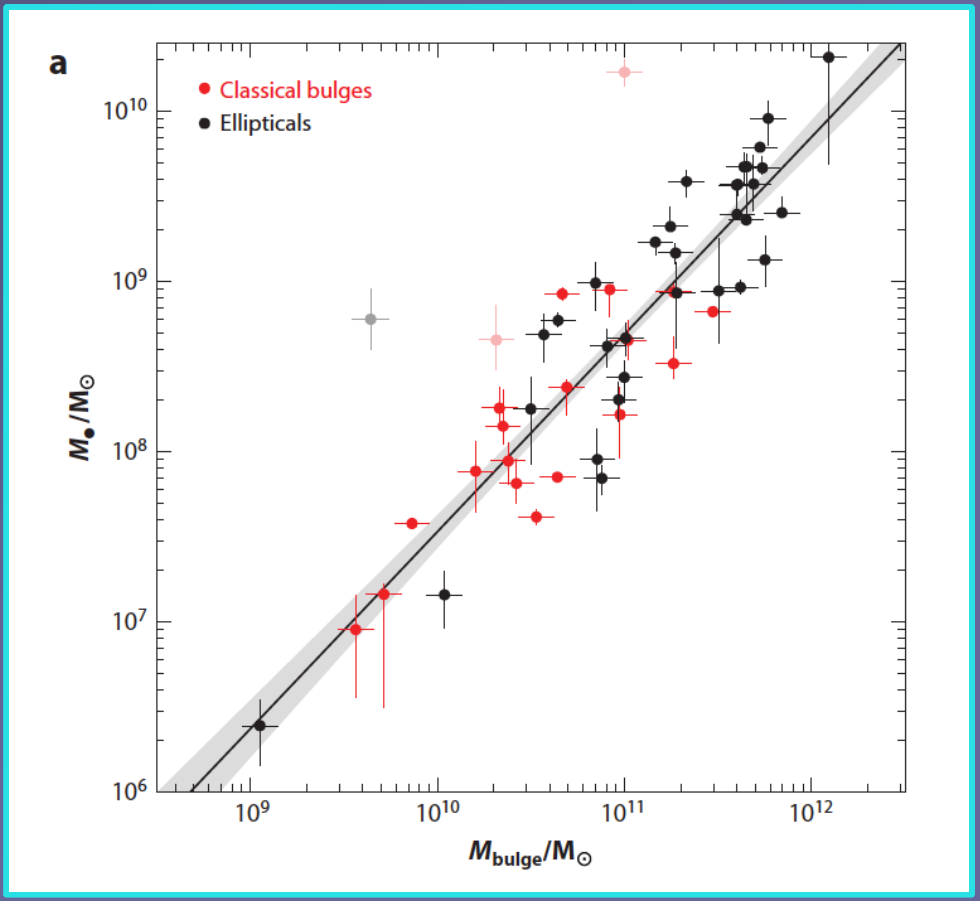
Visbal & ZH 2018; Scoggins, ZH & Wise 2023

In rapid formation/growth models, massive BHs are born as extreme outliers in BH – galaxy mass relation

Nearby galaxies:
$M_{bh}/M_* \sim \text{few} \times 10^{-3}$

Early massive seed BHs:
$M_{bh}/M_* \sim \infty$

stay outliers for few 100 Myr when $M_{bh} \sim 10^7\,M_\odot$ and $M_{bh}/M_* > 1$



Kormendy & Ho (2013)

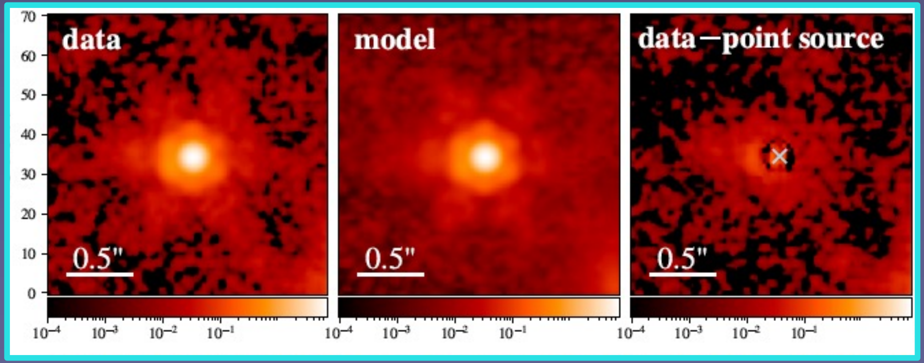
BH mass to host galaxy mass ratio

Ding et al. 2023; arxiv:2211.14329, Nature (submitted)

Extended starlight from host galaxies detected for the first time

JWST images for two z~6.4 quasars

J2255+0251 z=6.34

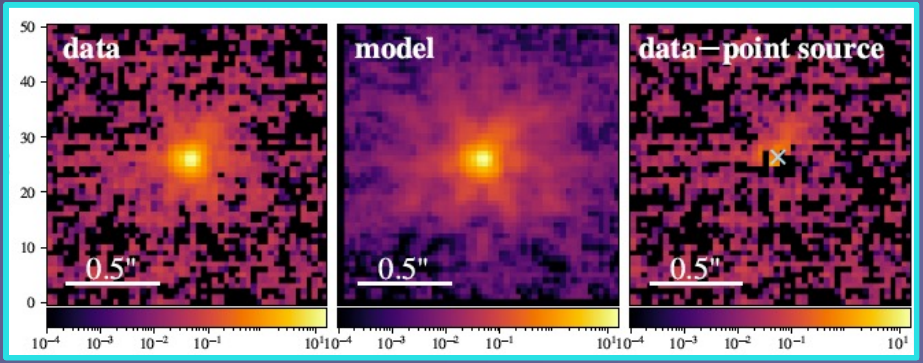


$M_* = 3.4 \times 10^{10}\ M_\odot$

$M_{bh} \sim 1.2 \times 10^{9}\ M_\odot$

$\rightarrow M_{bh}/M_* \sim 0.035$

J2236+0032 z=6.40



$M_* = 9.1 \times 10^{10}\ M_\odot$

$M_{bh} \sim 1.9 \times 10^{8}\ M_\odot$

$\rightarrow M_{bh}/M_* \sim 0.02$

Conclusions

- H_2 molecules control early massive black hole formation. Chemically pristine primordial gas falls into protogalaxies at accretion rates 100-10^5 times higher than in present-day
- Yields massive 10^6 $M_\odot$ BHs via supermassive star or hyper-accretion onto stellar-remnant BH within first few 100 Myr
- In ultra-dense star clusters, and/or with the help of gas disk torques, black holes can also merge efficiently
- Combination of gravitational waves (probing mergers) and optical/X-ray telescopes (probing accretion) offer diagnostics of early black hole assembly

Thanks!