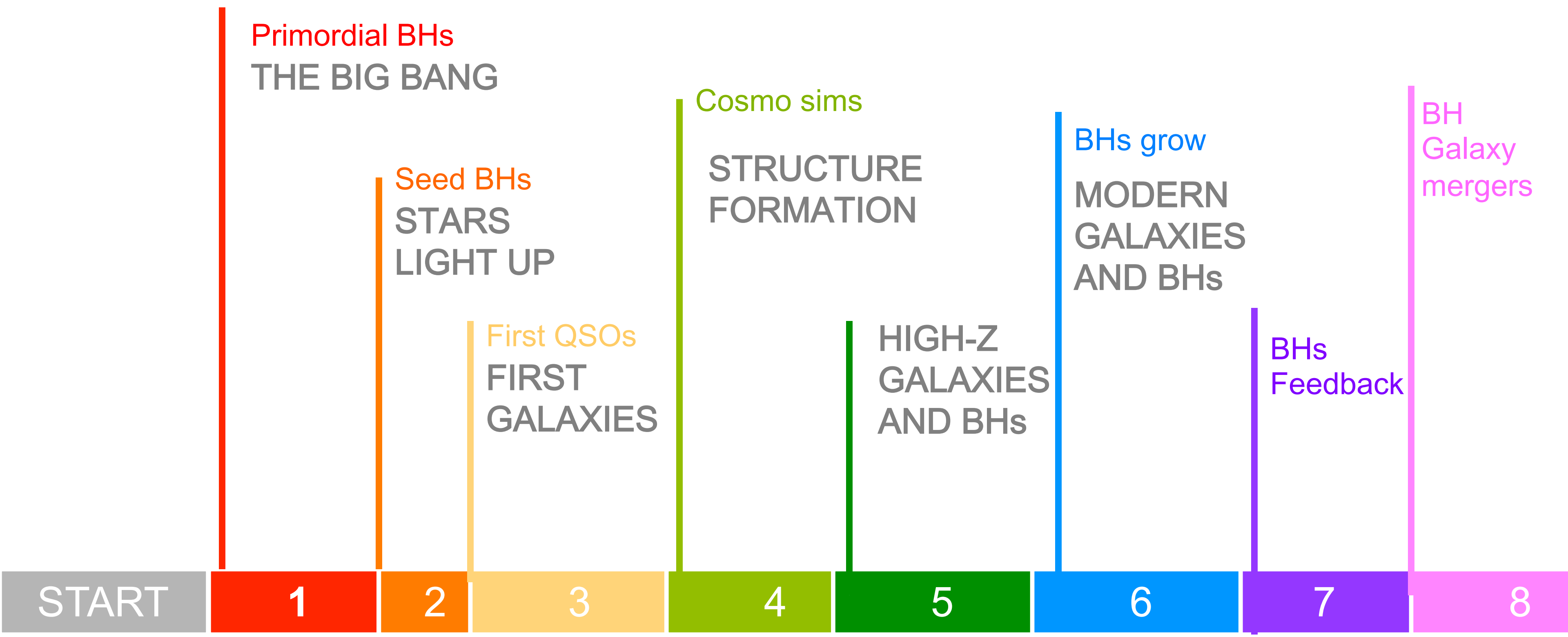
A journey through 13.7 billion years

BHs across cosmic history



Seed Black Holes

STARS LIGHT UP 2

INGREDIENTS + CONDITIONS = $M_{BH, Seed}$ = $100\text{-}10^6 M_\odot$

Rare, high density peaks

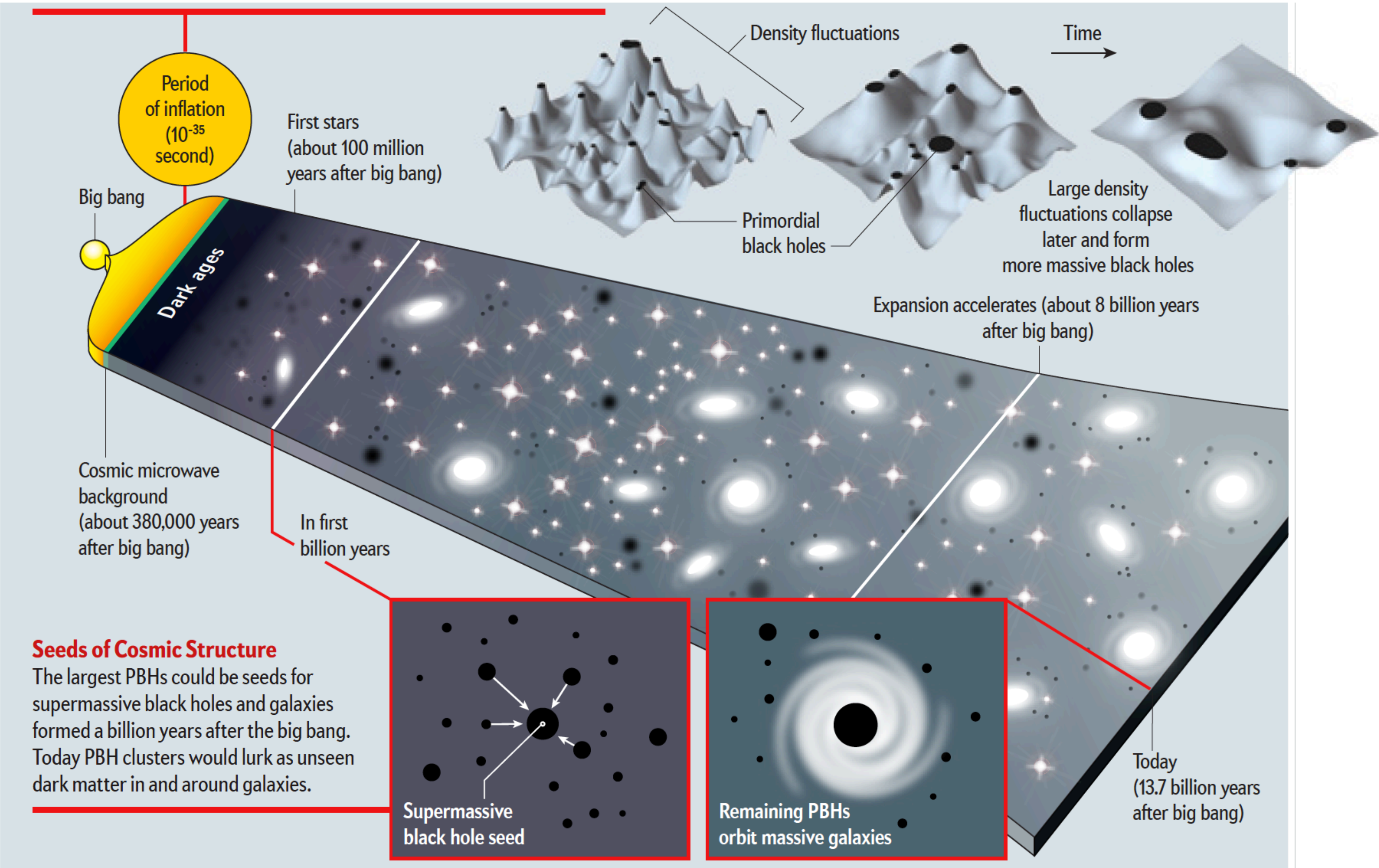
- PopIII formation
- No H2 cooling
- Supermassive star/cluster

Only speculate

Only speculate

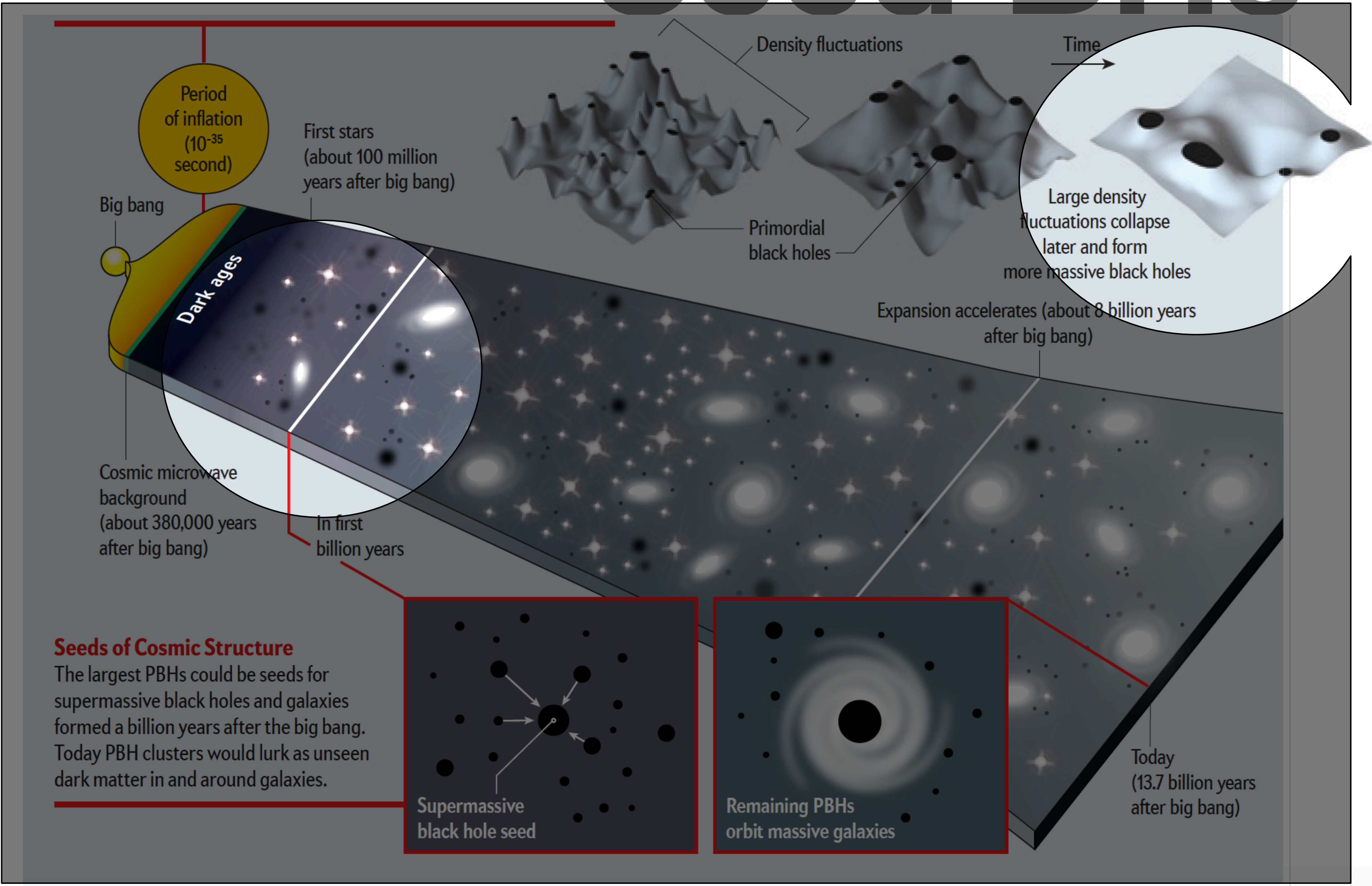
Only speculate

Seed BHs



Period of inflation (10^{-35} second)
First stars (about 100 million years after big bang)
Density fluctuations
Time
Big bang
Dark ages
Primordial black holes
Large density fluctuations collapse later and form more massive black holes
Expansion accelerates (about 8 billion years after big bang)
Cosmic microwave background (about 380,000 years after big bang)
In first billion years
Seeds of Cosmic Structure
The largest PBHs could be seeds for supermassive black holes and galaxies formed a billion years after the big bang. Today PBH clusters would lurk as unseen dark matter in and around galaxies.
Supermassive black hole seed
Remaining PBHs orbit massive galaxies
Today (13.7 billion years after big bang)

Seed BHs



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Big bang
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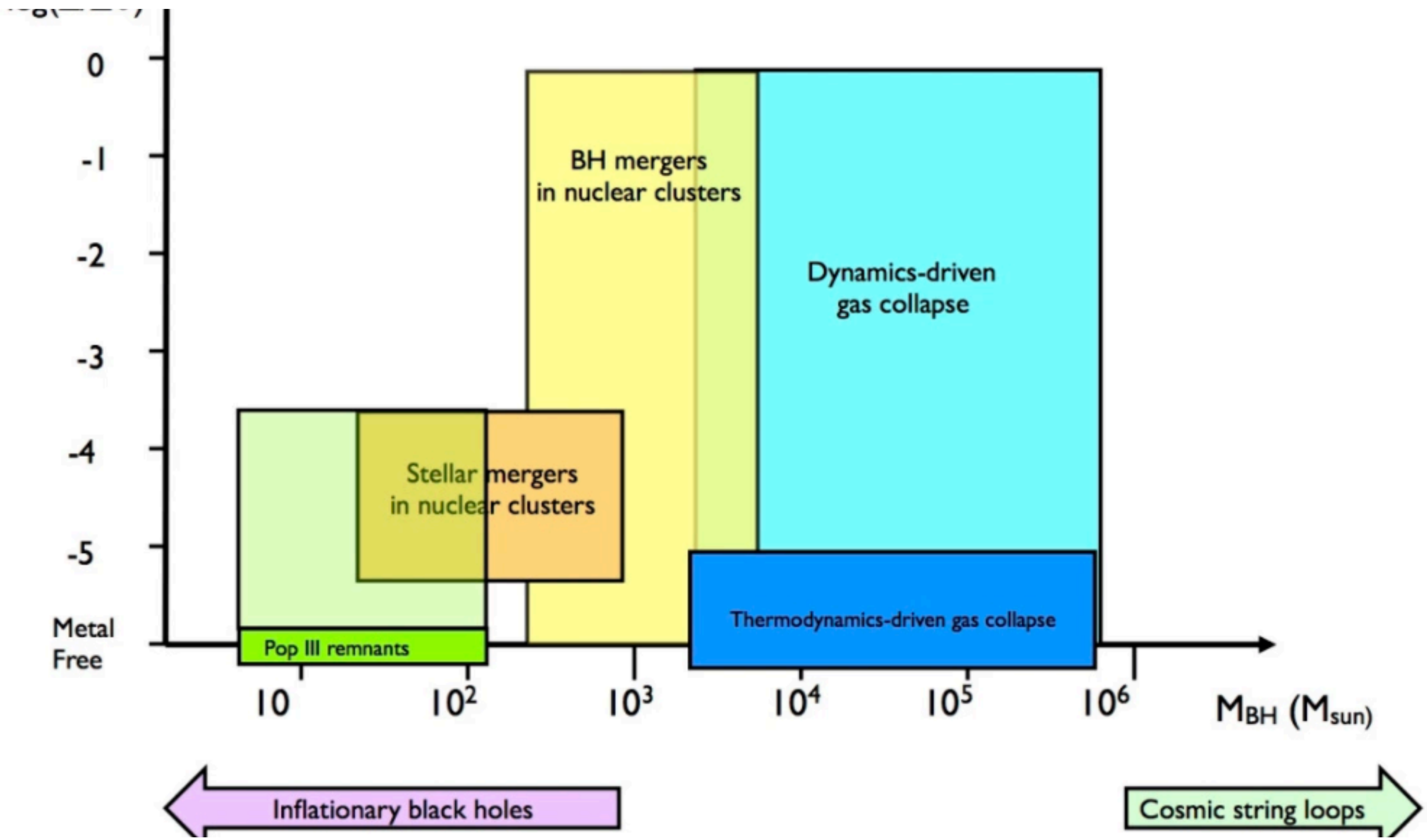
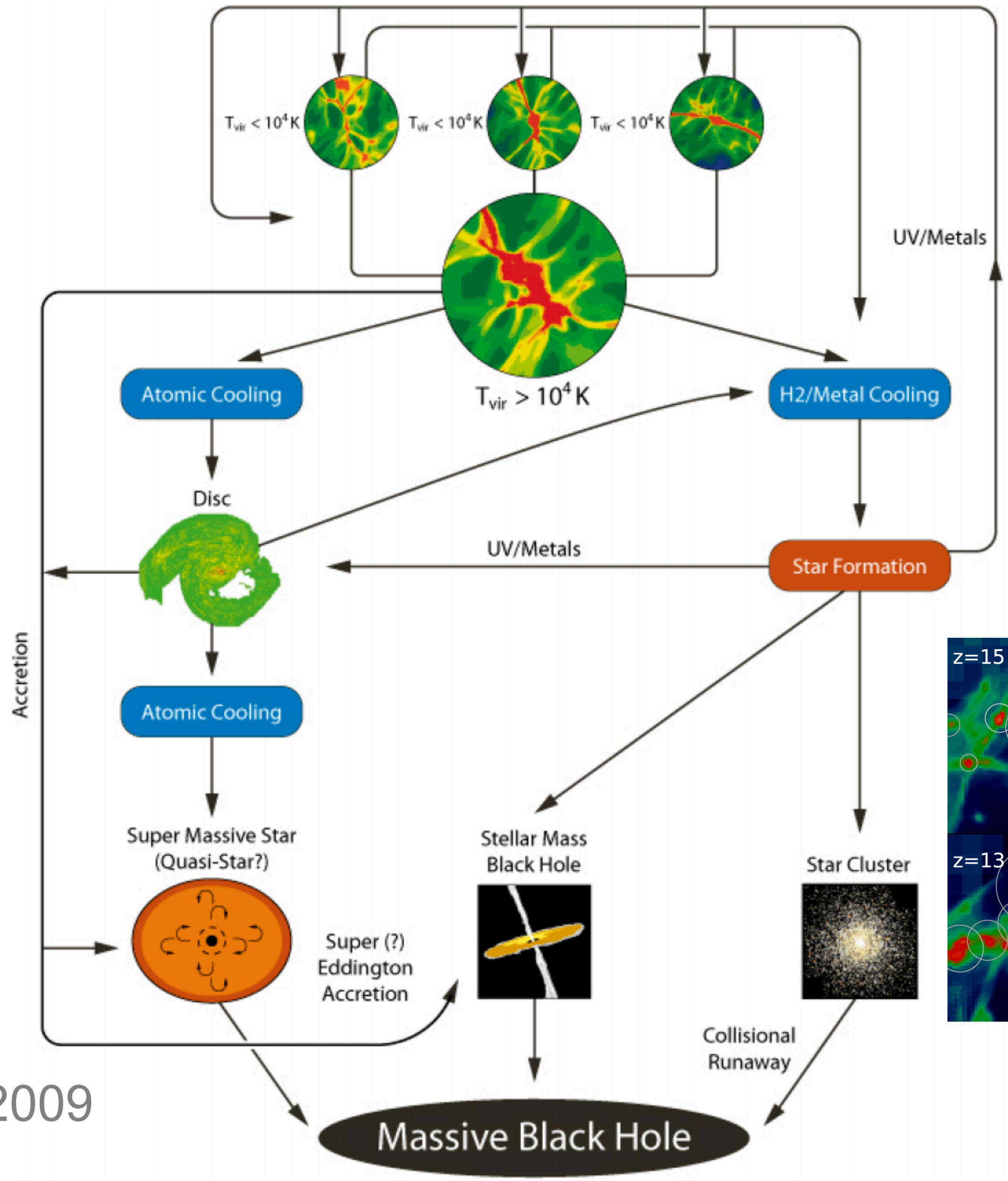
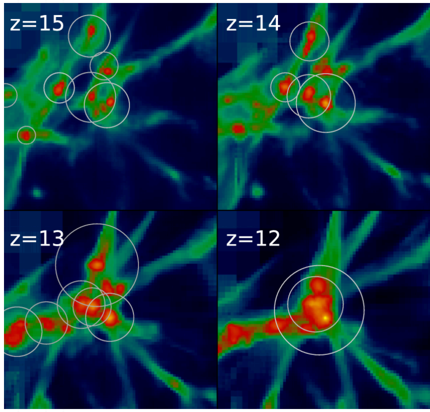
BH Seeds



Courtesy of M. Volonteri





Regan & Haelnet 2009

BH Seeds

Small

Large

Grow

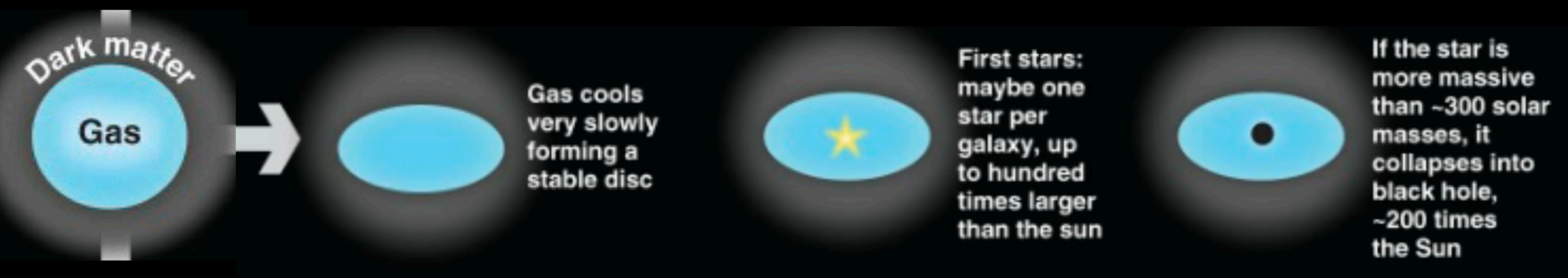
Massiv

Ma

BH Seeds

Small

PopIII stars remnants



Courtesy of Marta Volonteri

BH Seeds

Small

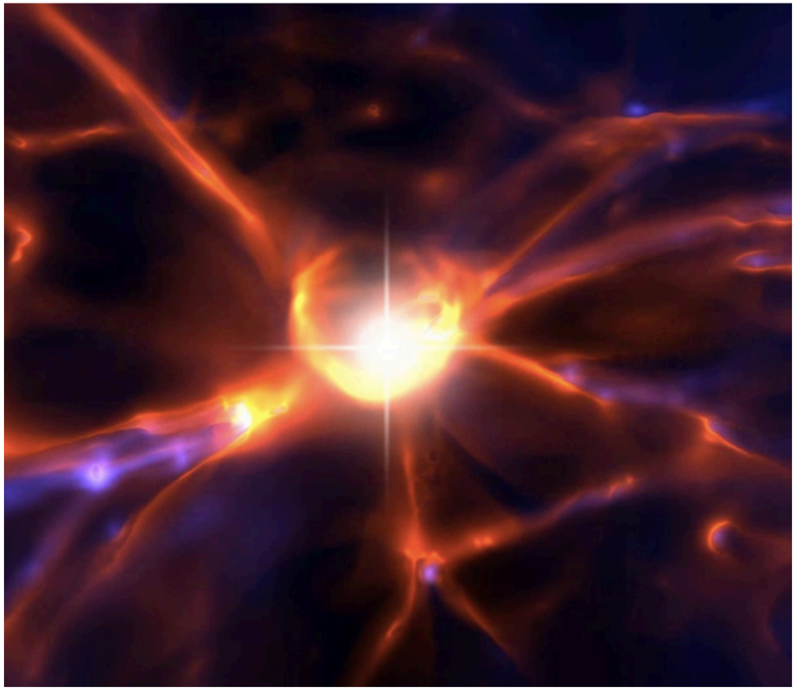
PopIII remnants

Grow

- ✓ First stars (metal free) are massive $M_\star \sim O(100)\ M_\odot$

- ✓ When they die they leave a remnant BHs of $M_{BH,seed} \sim M_\star \sim O(100)\ M_\odot$

BH Seeds



PopIII stars

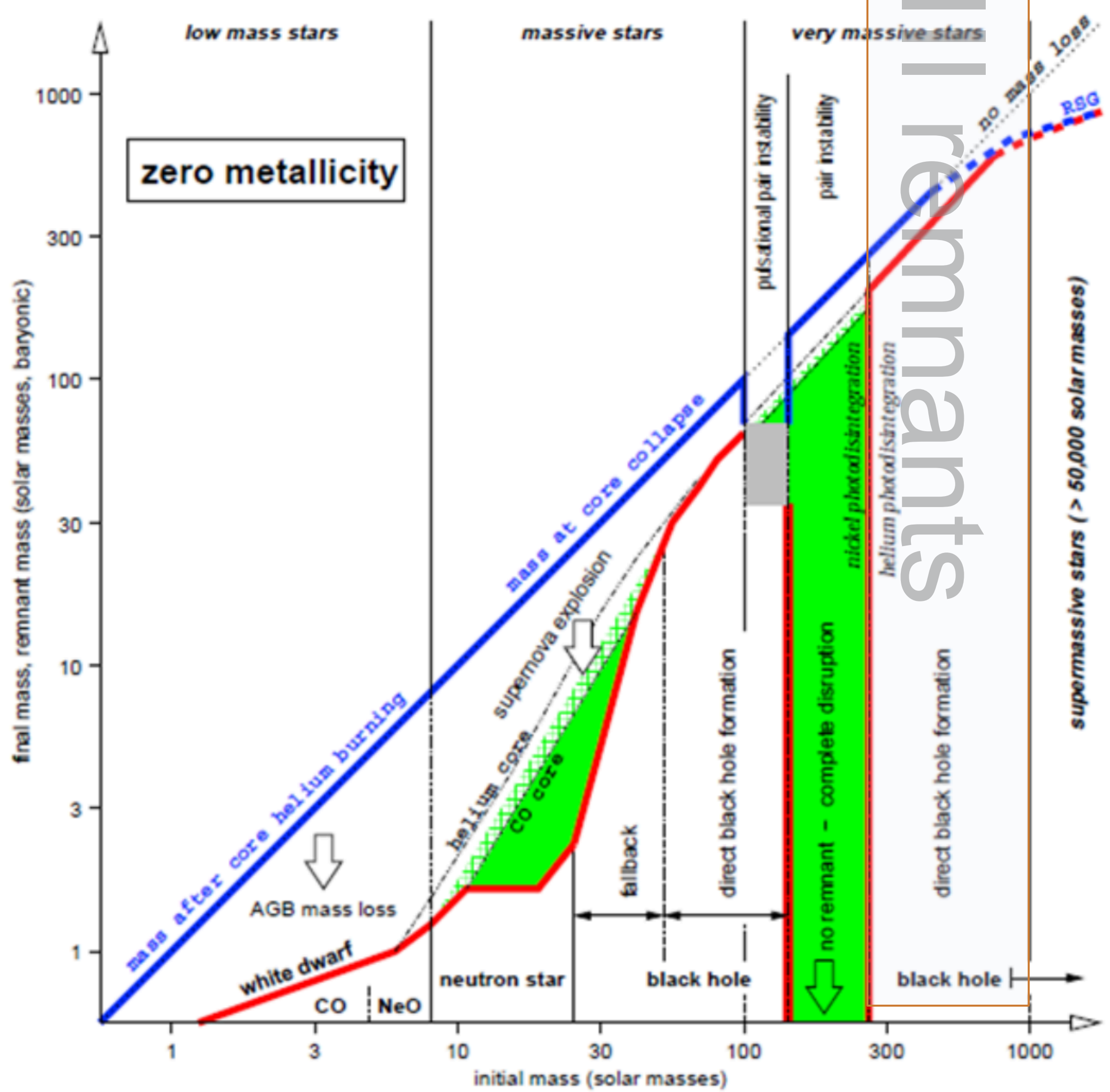
Zero metallicity
z=20-30, halos of $10^6 M_{sun}$ form
H2 cooling

Abel00, Wise+

- ✓ First stars (metal free) are massive
  $M_\star \sim O(100)\ M_\odot$
- ✓ When they die they leave a remnant BHs of
  $M_{BH,seed} \sim M_\star \sim O(100)\ M_\odot$

BH Seeds

Small



$M_{remnant}$

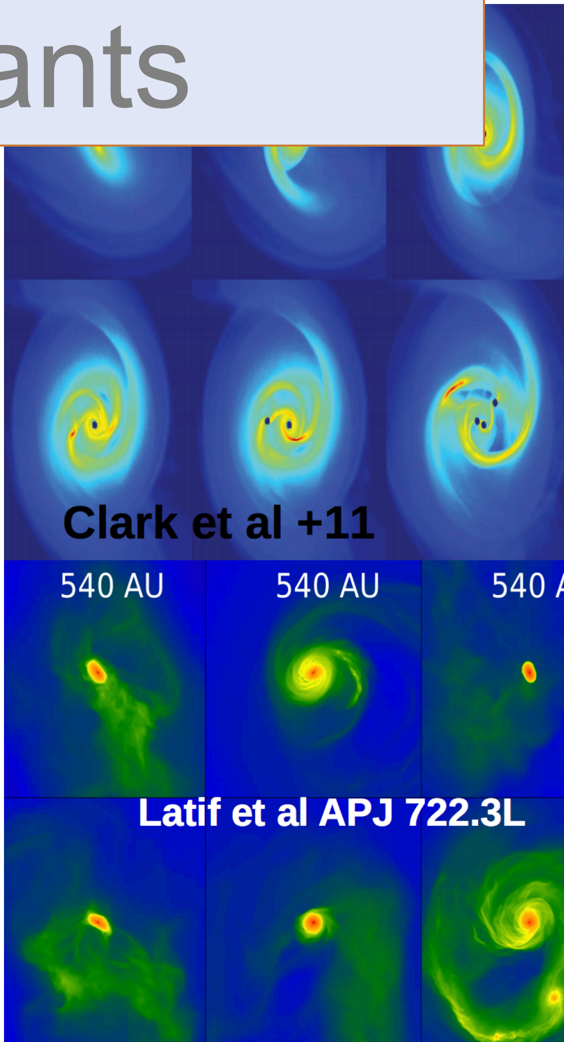
M★

Hager & Woosley 03

BH Seeds

Too Small?

PopIII remnants



- ✓ First stars form in mini-halos of 10^5-10^6 M at z=20-30
- ✓ Current simulations get low mass stars…

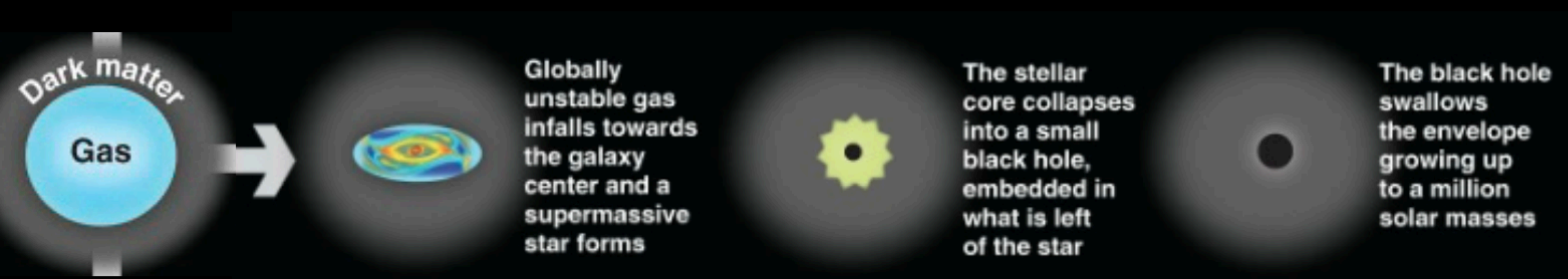
(Clark+11, Greif+12, Latif+12, Hirano+14)

BH Seeds

Large

Gas-dynamical collapse

(e.g. Bromm & Loeb 2003, Begelman, MV & Rees 2006)



Courtesy of Marta Volonteri

BH Seeds

Large

Direct gas collapse

Grow

- ✓ Deep potential well for gas infall and collapse require inflow rete > 0.1$M_{\odot}$

- ✓ Global instabilities to loose angular momentum

- ✓ Form a supermassive star, that accretes envelope forms $M_{BH,seed} \sim O(10^{4-6})\ M_{\odot}$

BH Seeds: Require

Large

Direct gas collapse

✓ Very efficient ang. momentum transport

(or low ang. momentum protohalos)

✓ Gas must avoid fragmentation/star formation

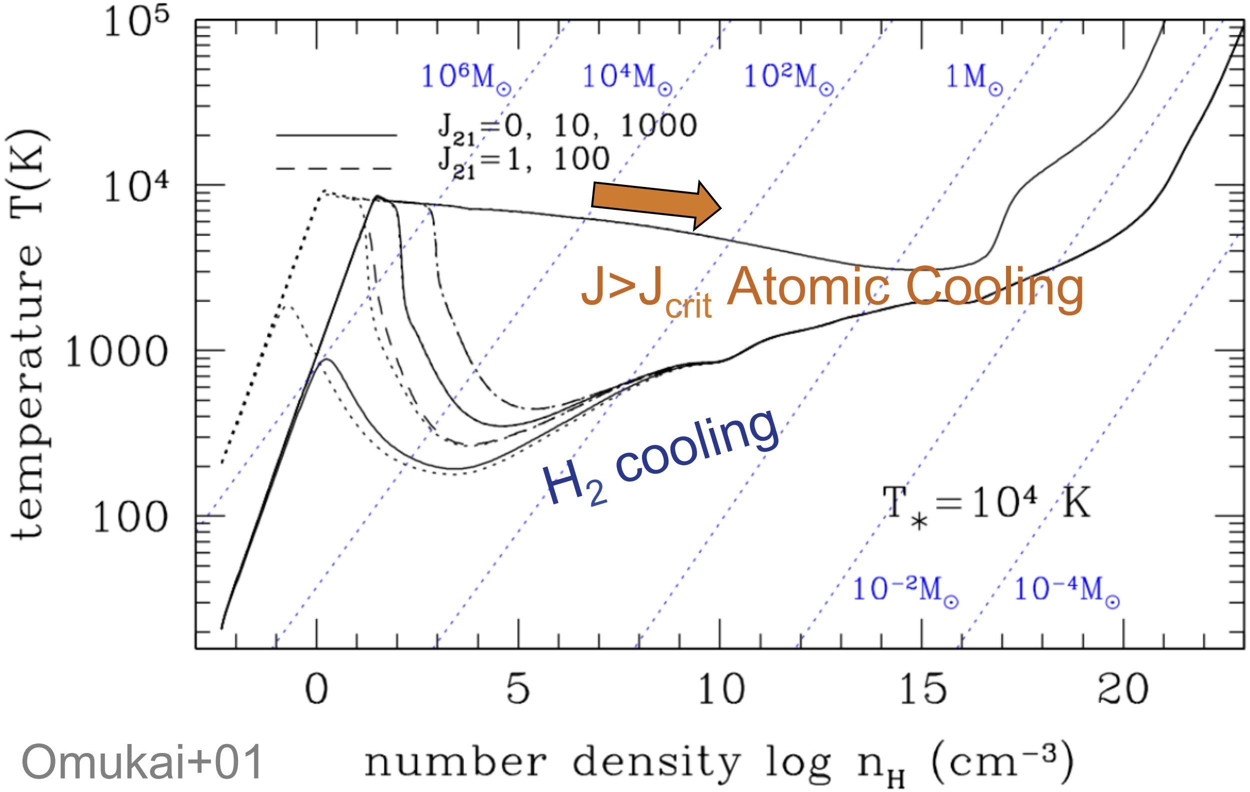
→ zero/ low metallicity +
need intense dissociating UVbackground to quench H_2 formation in proto halo

BH Seeds: Require

Large

Direct gas collapse

$J_{21} > J_{crit}$
in units of
10^{-21} erg/cm^2/s^2/sr



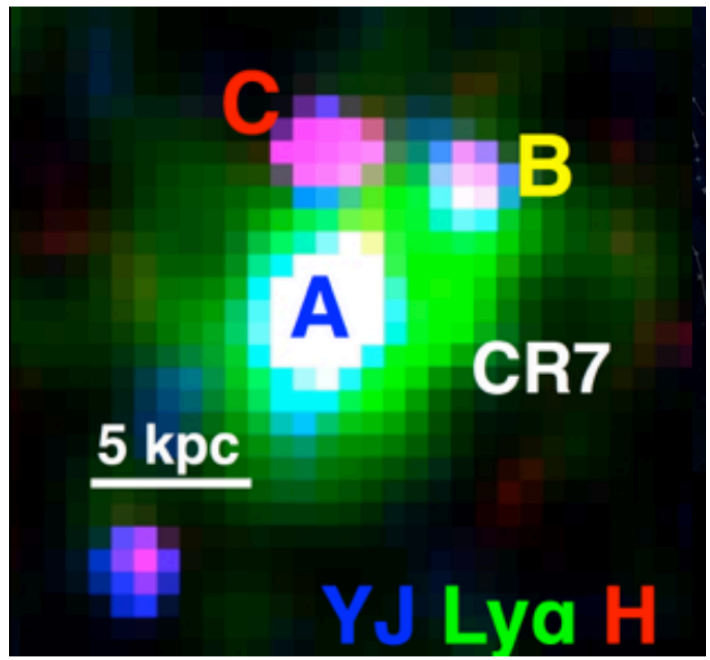
Omukai+01

BH Seeds Evidence??

Direct gas collapse

CR7: Potential host for a DCBH

- The brightest Lyman alpha emitter at z=6.6 (CR7)
- Shows strong Lyman alpha & He1640 emission
- No metal lines detected from UV to infrared
- Such strong line emission can be explained either via 10^7 $M_\odot$ in Pop III stars with top heavy IMF or a massive BH of 10^6 $M_\odot$ residing in metal poor environment

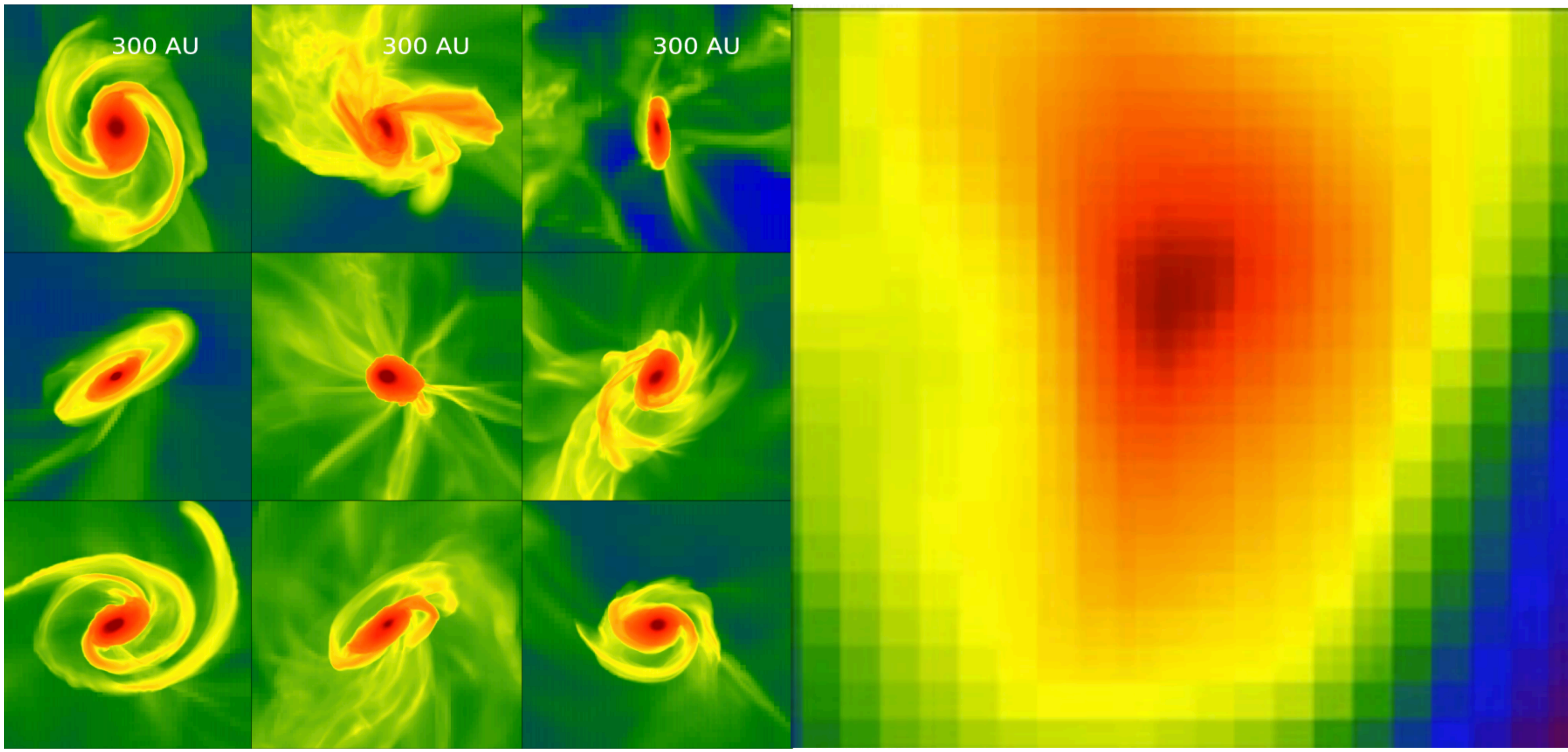


Sobral et al. 2015, Matthee et al 2014

BH Seeds

Direct gas collapse

Cosmological Simulations



★Collapse occurs isothermally with T~ 8000 K

★Provides large inflow rates of ~$1M_\odot$/yr

Latif et al. 2013 MNRAS 433 1607L

BH Seeds

Direct gas collapse

LETTER

Rapid Formation of Massive Black Holes in close proximity to Embryonic Proto-Galaxies

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[astro-ph.GA] 10 Mar 2017

The Direct Collapse Black Hole (DCBH) scenario provides a solution for forming the massive black holes powering bright quasars observed in the early Universe. A prerequisite for forming a DCBH is that the formation of (much less massive) Population III stars be avoided - this can be achieved by destroying H_2 via Lyman-Werner (LW) radiation (E_{LW} = 12.6 eV). We find that two conditions must be met in the proto-galaxy that will host the DCBH. First, prior star formation must be delayed; this can be achieved with a background LW flux of $J_{BG} \gtrsim 100\ J_{21}$†. Second, an intense burst of LW radiation from a neighbouring star-bursting proto-galaxy is required, just before the gas cloud undergoes gravitational collapse, to finally suppress star formation completely. We show here for the first time using high-resolution hydrodynamical simulations, including full radiative transfer, that this low-level background, com-

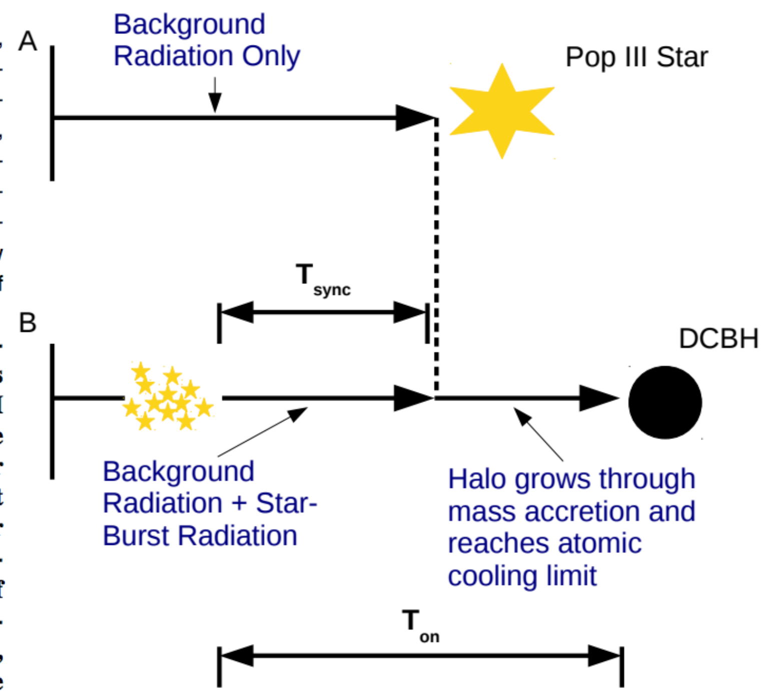


Figure 1 | Modelling Synchronised Haloes. The synchronised proto-galaxy scenario. With only a background field in operation a (delayed) Pop III star forms

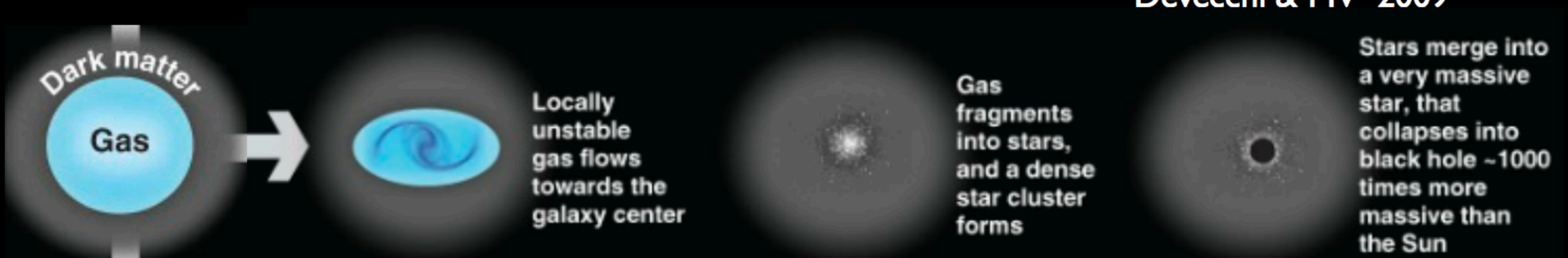
BH Seeds

Large

Direct Collapse
Of Super Massive
Star/ Cluster

Stellar-dynamical processes

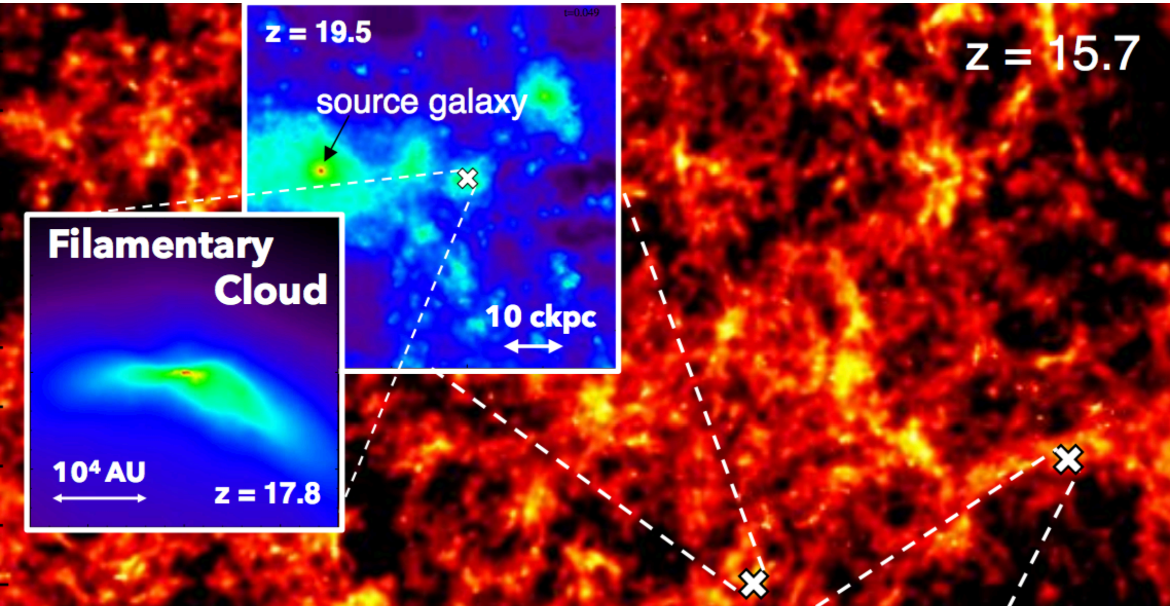
Devecchi & MV 2009



Courtesy of Marta Volonteri

BH Seeds

Direct Collapse Of Super Massive Star



Fully cosmological rad hydro sims

SMS~ 10^4 Msun

Chon, Hokasawa, Yoshida17

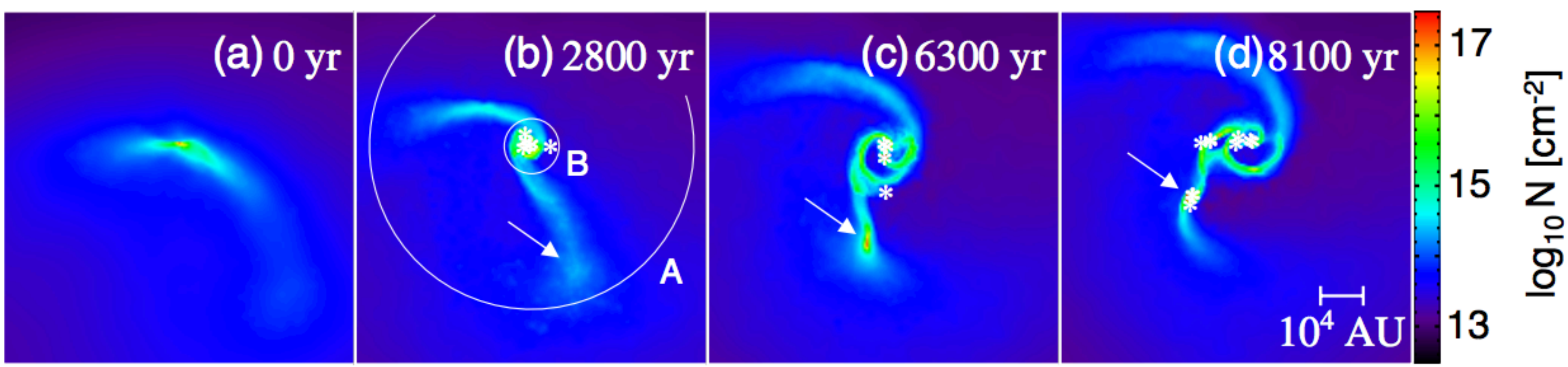
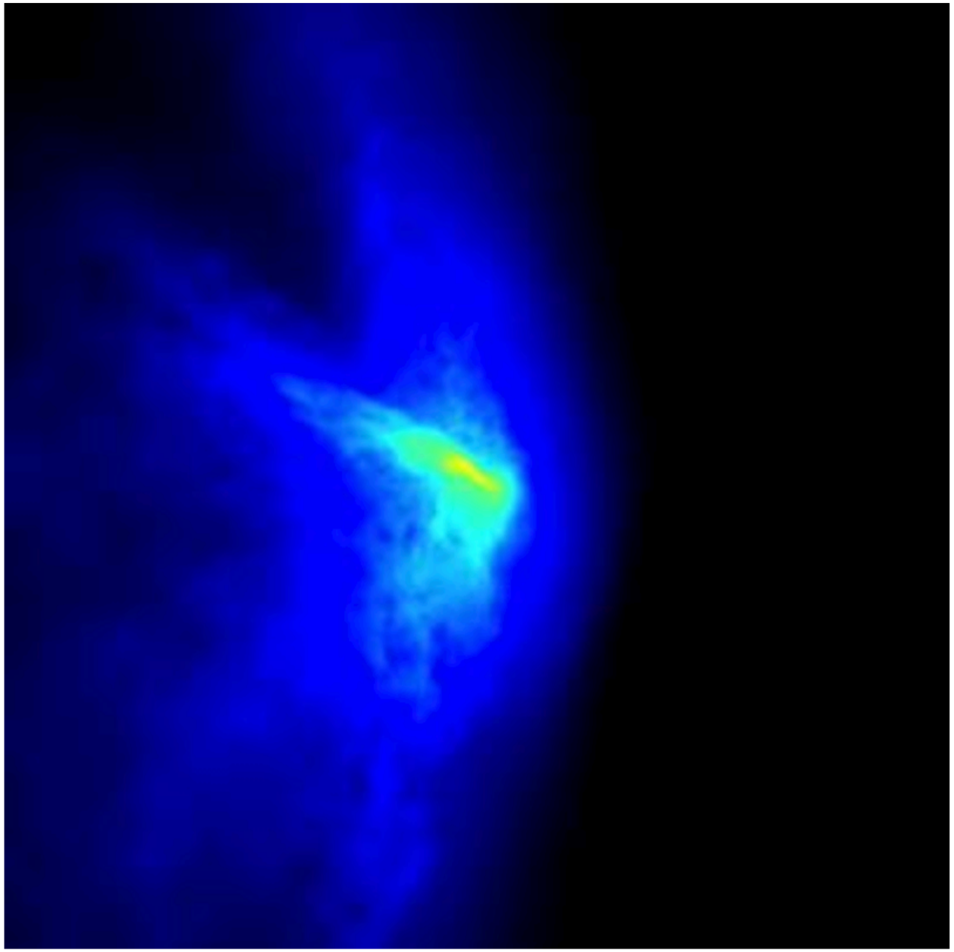


Figure 8. Filament fragmentation occurring in the filamentary cloud. The arrows indicate where a star-disk system forms through such an event. In panel (b), the white circles indicate the different spatial scales A and B appeared in Fig. 3.

BH Seeds

Direct Collapse Of Super Massive Star



The gas density distribution around the new-born protostar. The left-to-right supersonic gas motion results in the non-spherical, compressed density structure. The collapsed inner cloud also shows the turbulated object, which can rapidly accrete onto the central protostar and cause a fast mass growth of it. Credit: Shingo Hirano

Cosmological simulations:

Supersonic gas streams (expected between gas dnd dark matter)

-→gas condensation

SMS~ 34000 Msun

Hirano+17, Science

Cosmological Simulations

How do the first massive black holes grow

1. BH Seed:
-

Pop III stellar Remnant

Gas/stellar Dynamical collapse

THEORY

M_{seed}=100-$10^5 M_{sun}$

High gas density

Cosmological Simulations

Example:

How do the first massive black holes grow

1. BH Seed:

Pop III stellar Remnant

Gas/stellar Dynamical collapse

t < 1 billion yrs

High gas density

2. Gas accretion: Eddington (sustained)

Highest gas inflow rates

Feasible? if so how, where?

How/ where do MBH seeds grow at early time?

z=6 quasars imply
$M_{BH}=10^9\ M_{sun}$

First billion years
requires extremely
large accretion rates

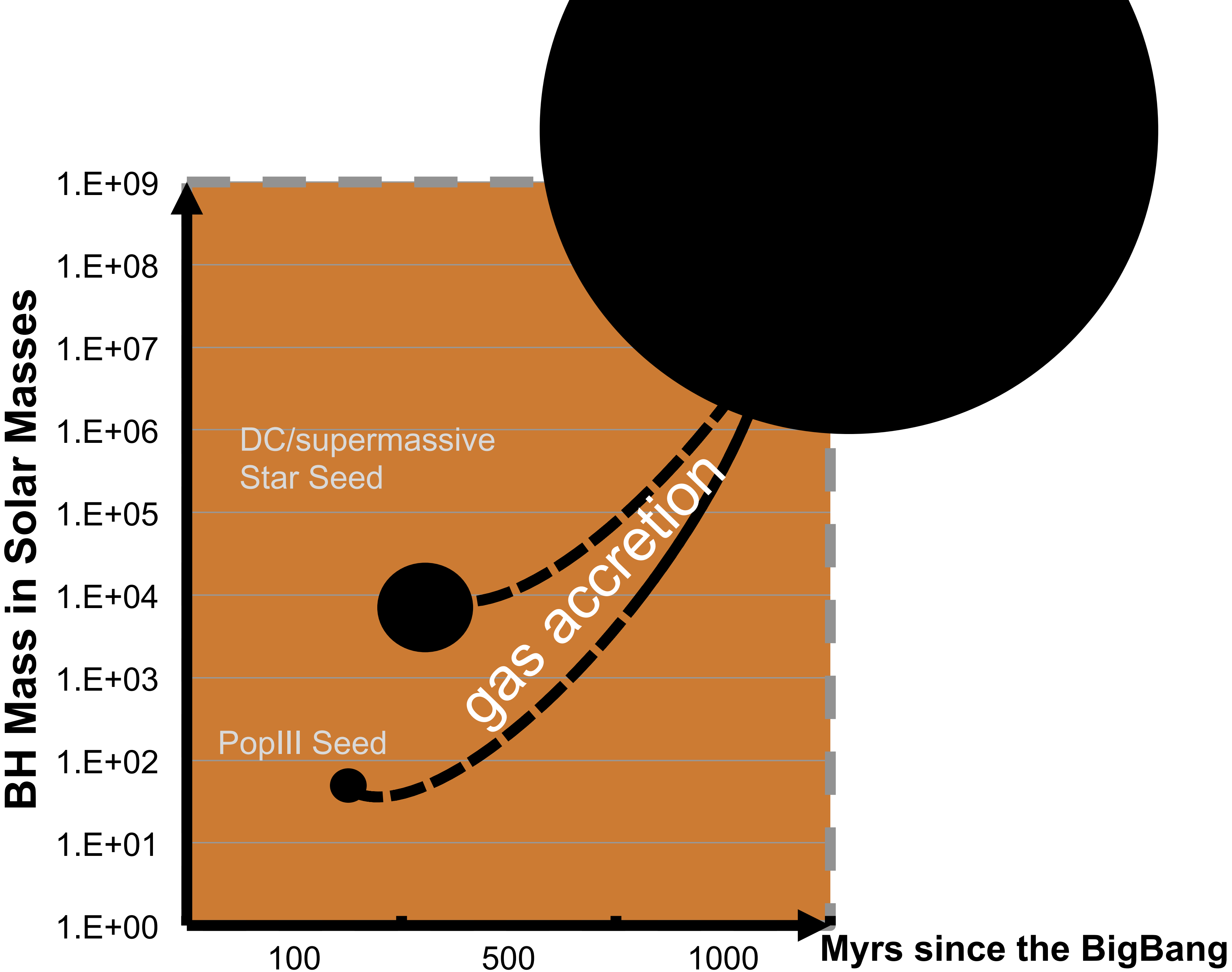
$$L_{Edd} = \frac{4\pi G c m_p}{\sigma_T} M_{BH} = \varepsilon \dot{M} c^2$$

$$M_{BH} = M_{seed}\ e^{\frac{t}{t_{Edd}}}$$

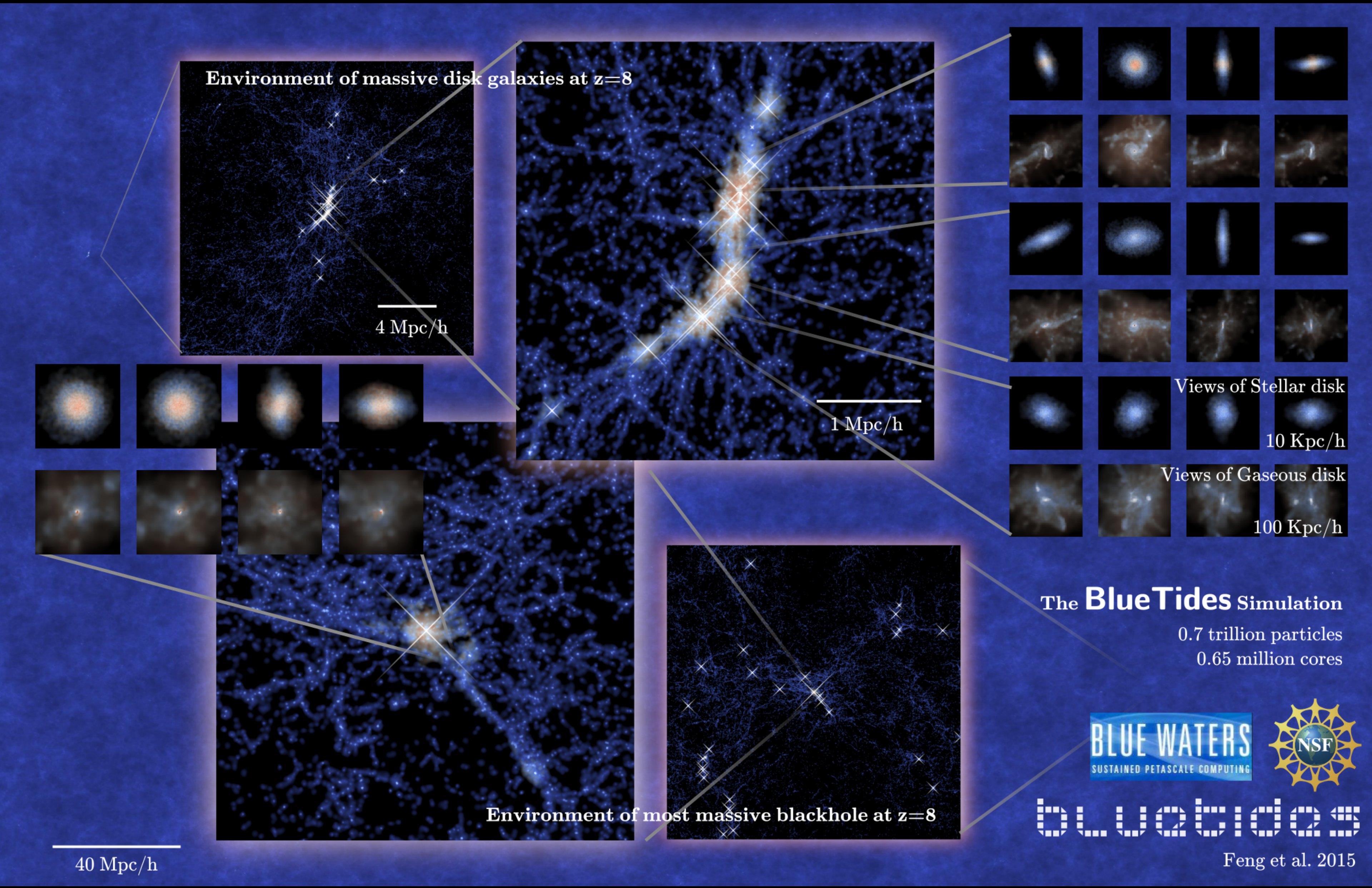
$$t_{Edd} = 450\ Myr \frac{\varepsilon}{1-\varepsilon}$$

$$\ln(M_{BH}/M_{seed}) = \ln[10^9/(100-1e5)]$$
$$= 10-17\ \mathrm{e-foldings}$$

sustained accretion at Eddington rates
in early growth



1.E+09
1.E+08
1.E+07
1.E+06
1.E+05
1.E+04
1.E+03
1.E+02
1.E+01
1.E+00
BH Mass in Solar Masses
DC/supermassive
Star Seed
PopIII Seed
gas accretion
100
500
1000
Myrs since the BigBang


Environment of massive disk galaxies at z=8
4 Mpc/h
1 Mpc/h
Views of Stellar disk
10 Kpc/h
Views of Gaseous disk
100 Kpc/h
Environment of most massive blackhole at z=8
40 Mpc/h
The BlueTides Simulation
0.7 trillion particles
0.65 million cores
BLUE WATERS
SUSTAINED PETASCALE COMPUTING
NSF
bluetides
Feng et al. 2015

SURVEY MONKEY II:

https://www.surveymonkey.com/r/PXBTSMY