Black hole "seed" formation

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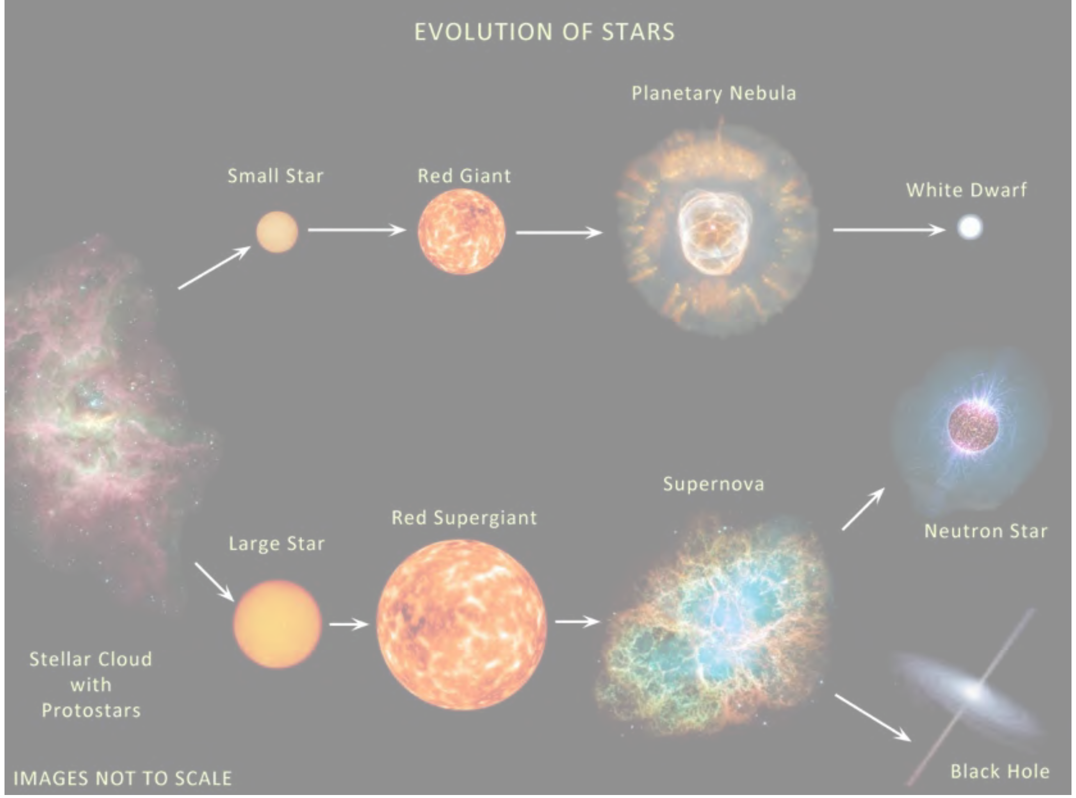
Stellar mass BHs

✔formation through stellar evolution

✔mass < few tens Msun

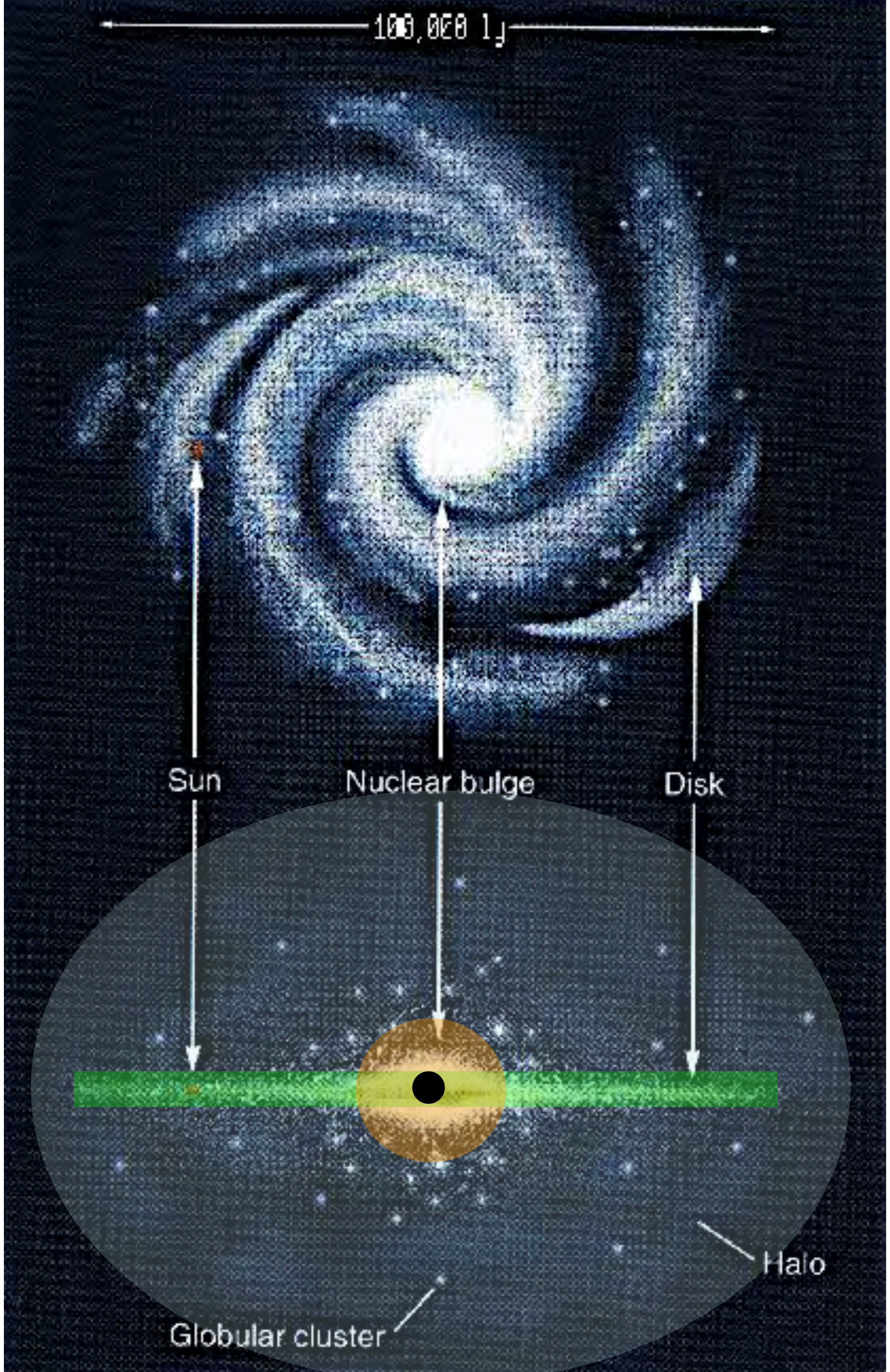


Massive BHs

✔ powering quasars

✔inhabiting the centers of nearby galaxies, including the Milky Way

✔ mass > 10^5 Msun



Galaxies

mass: 10^9-10^{12} solar masses

$R_{halo} \sim GM_{halo}/\sigma^2$ MEGAPARSEC

$R_{bulge} \sim GM_{bulge}/\sigma^2$ KILOPARSEC

1 parsec=3.26 light years=3×10^{18} cm
$\sigma \sim$50-400 km/s for most galaxies

Massive Black Holes

mass: 10^5-10^9 solar masses

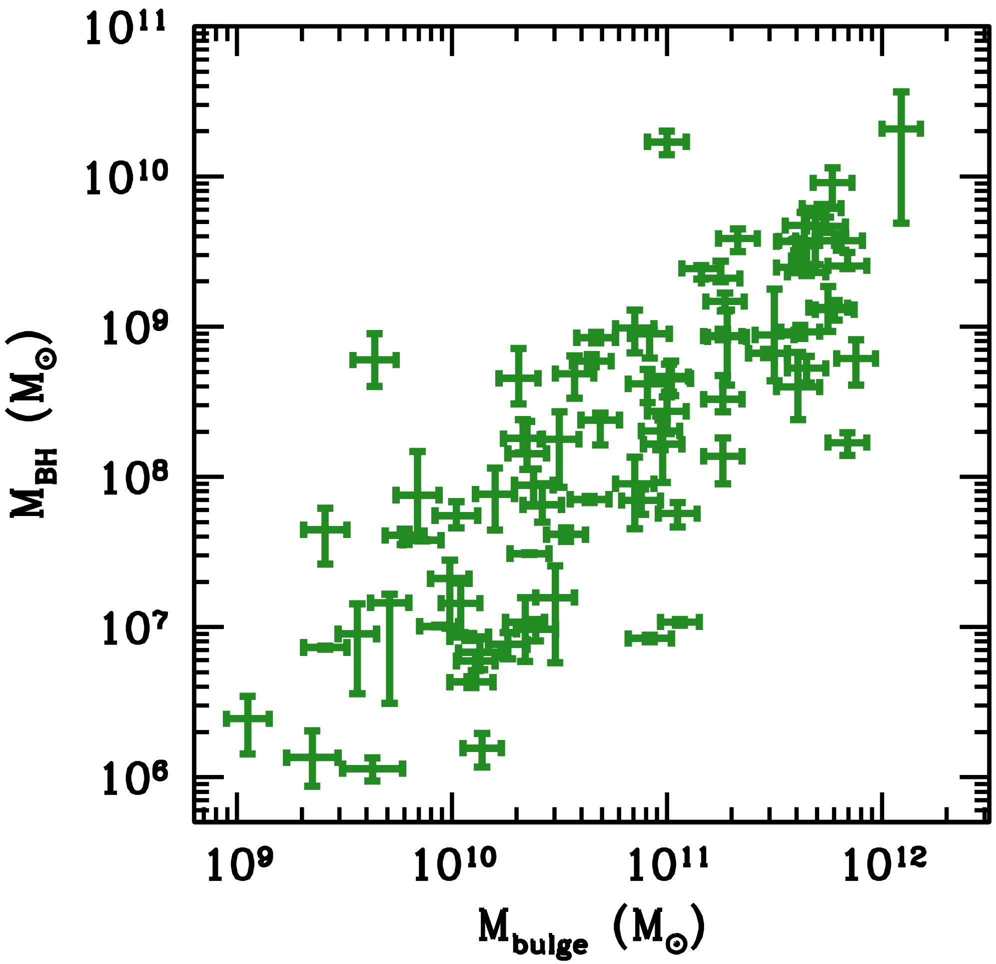
$R_{bondi} \sim GM_{BH}/c_s^2$ PARSEC

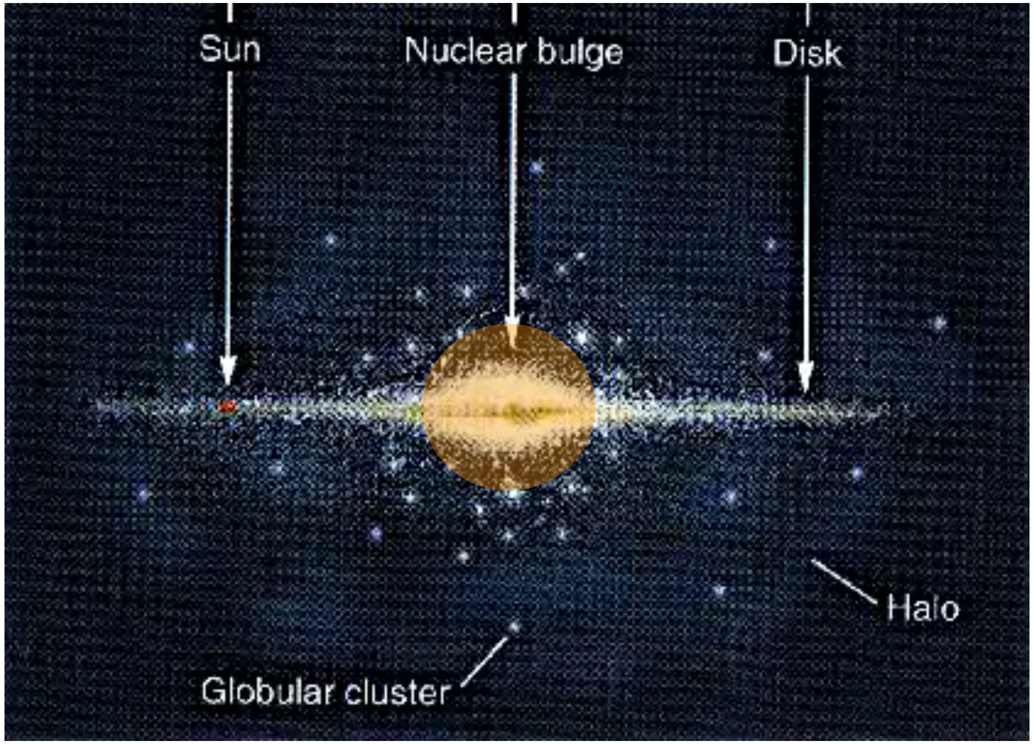
$R_{inf} \sim GM_{BH}/\sigma^2$ PARSEC

$R_{sch}=2GM_{BH}/c^2$ MICROPARSEC

$c_s \sim$10-100 km/s for most galaxies
$c=3\times10^5$ km/s

Local samples





~80 MBHs detected in nearby galaxies to-date

Black hole masses correlate with galaxy properties. This may mean their growth/evolution are intimately connected.

Quasars and Active Galactic Nuclei (AGN)

Hubble Heritage Team

They are as luminous as galaxies: $L \sim 10^{11}$-10^{13} L_{sun}

Size of the emitting region is 10^6 times smaller than a galaxy ~ size of solar system

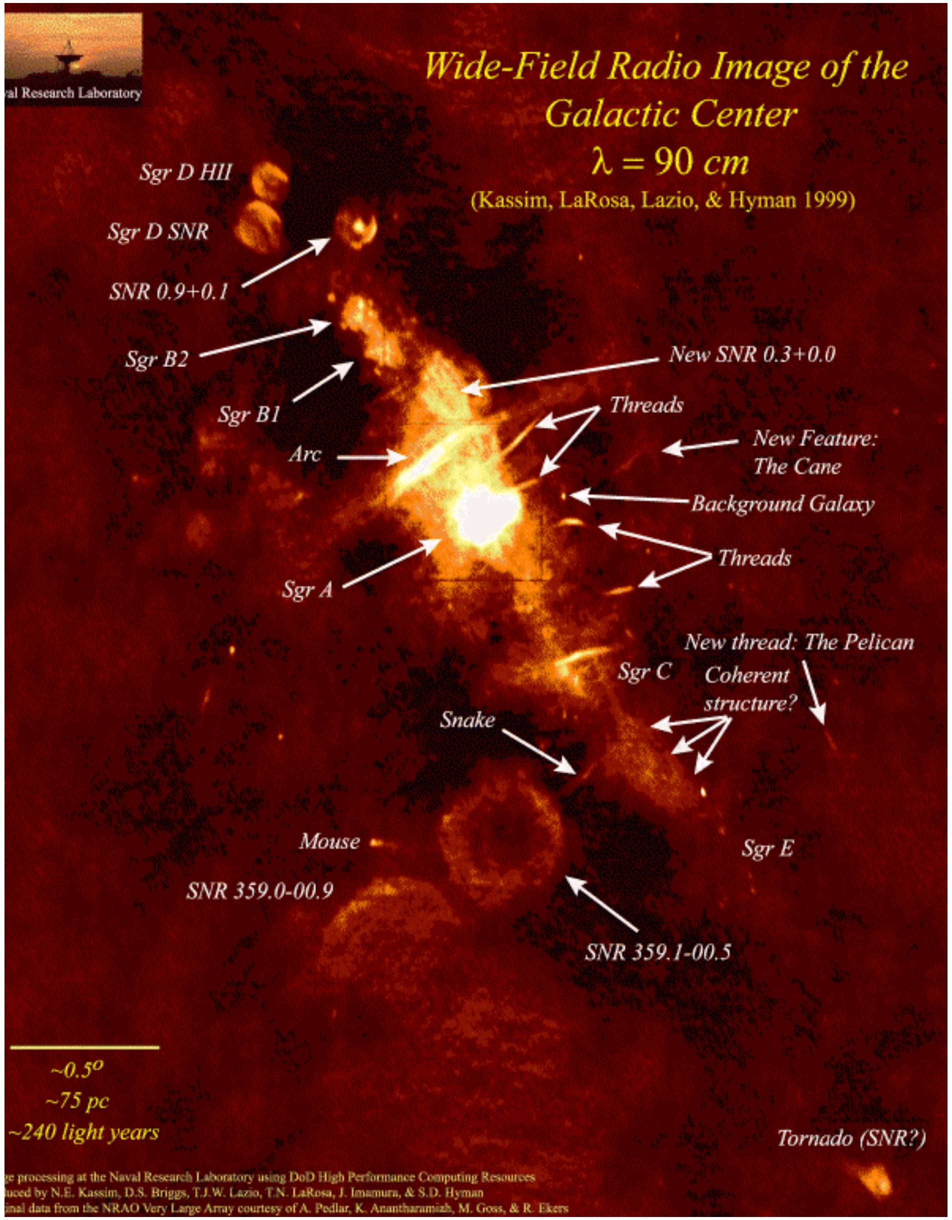
Powered by accreting black holes with masses of millions to billions of M_{sun}

Quiescent MBHs

Many MBHs are quiescent. We have an example in the center of the Milky Way.

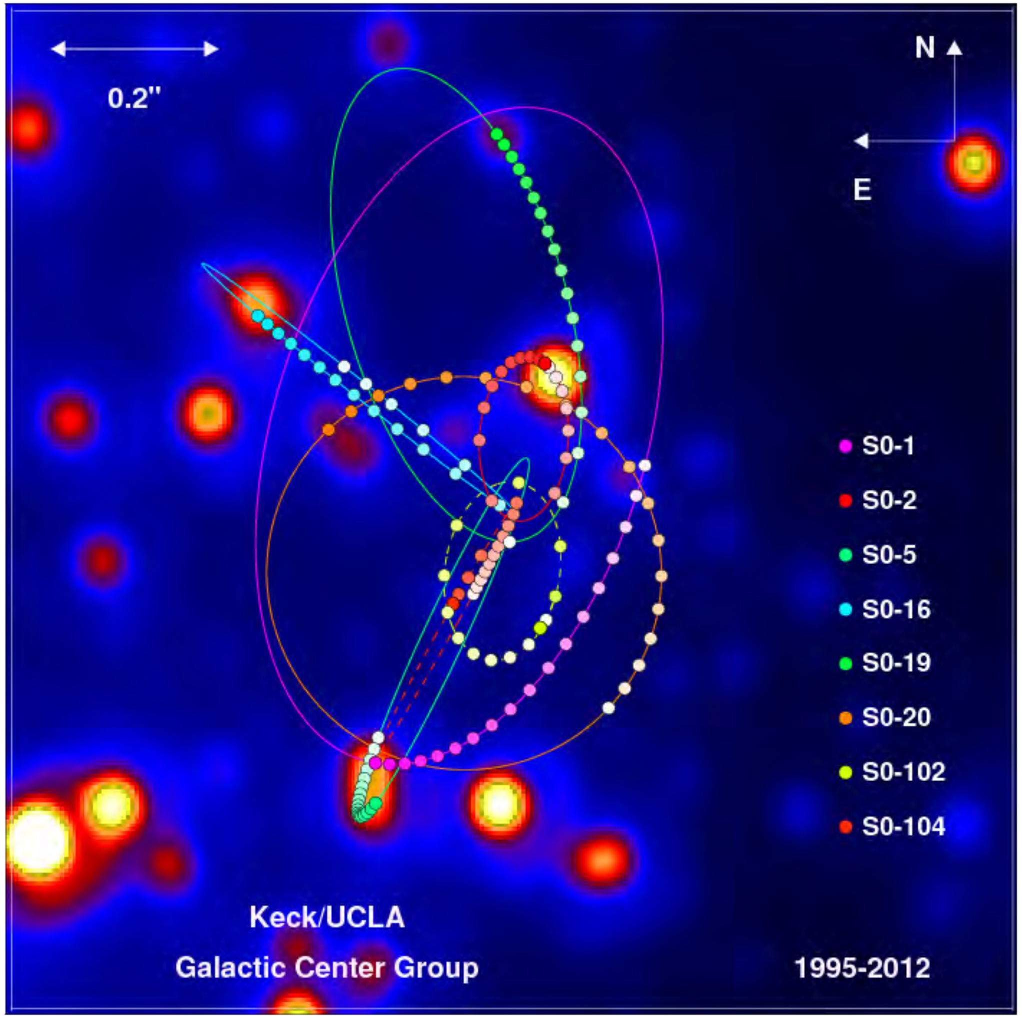
The typical luminosity of Sgr A*, is ~10^{34} erg/s.

Not much more than the Sun (4×10^{33} erg/s).



The closest MBH

The best example of search for a MBH is the MILKY WAY: individual stars can be resolved



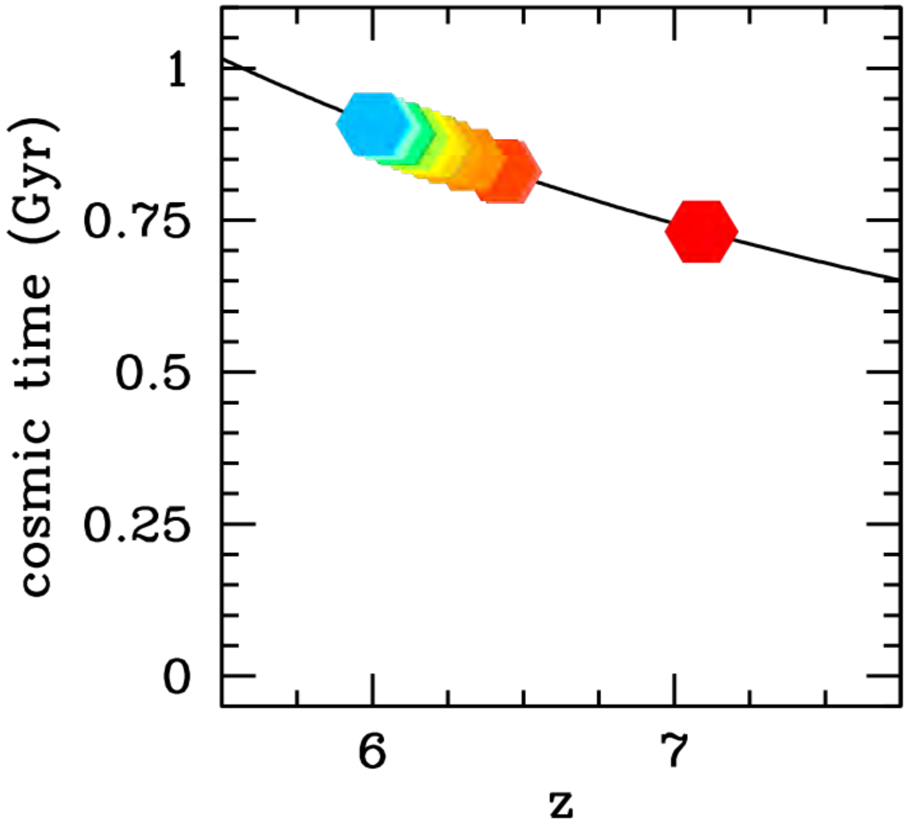
Keplerian motion – the central point mass is $\sim 4\times10^{6}\ M_{sun}$

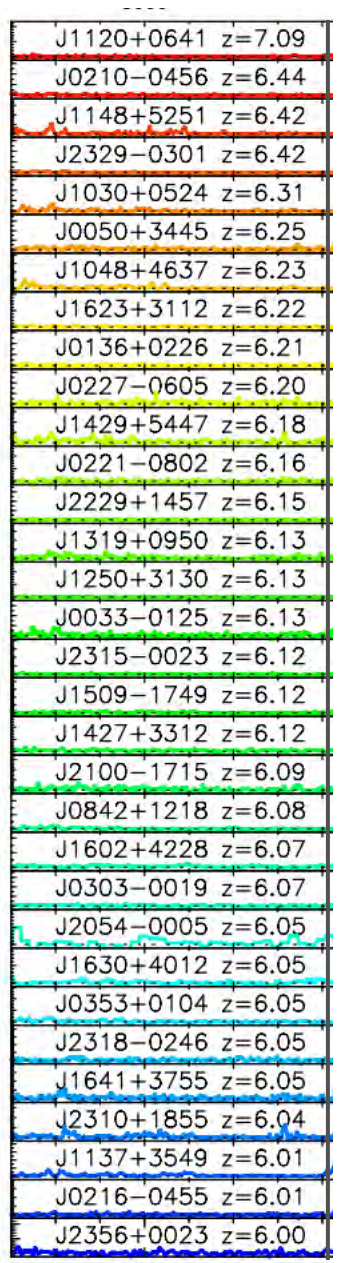
The stellar orbits require density $>10^{13}\ M_{sun}pc^{-3}$

Clusters of stars, neutron stars or stellar mass black holes ruled out

The farthest MBHs

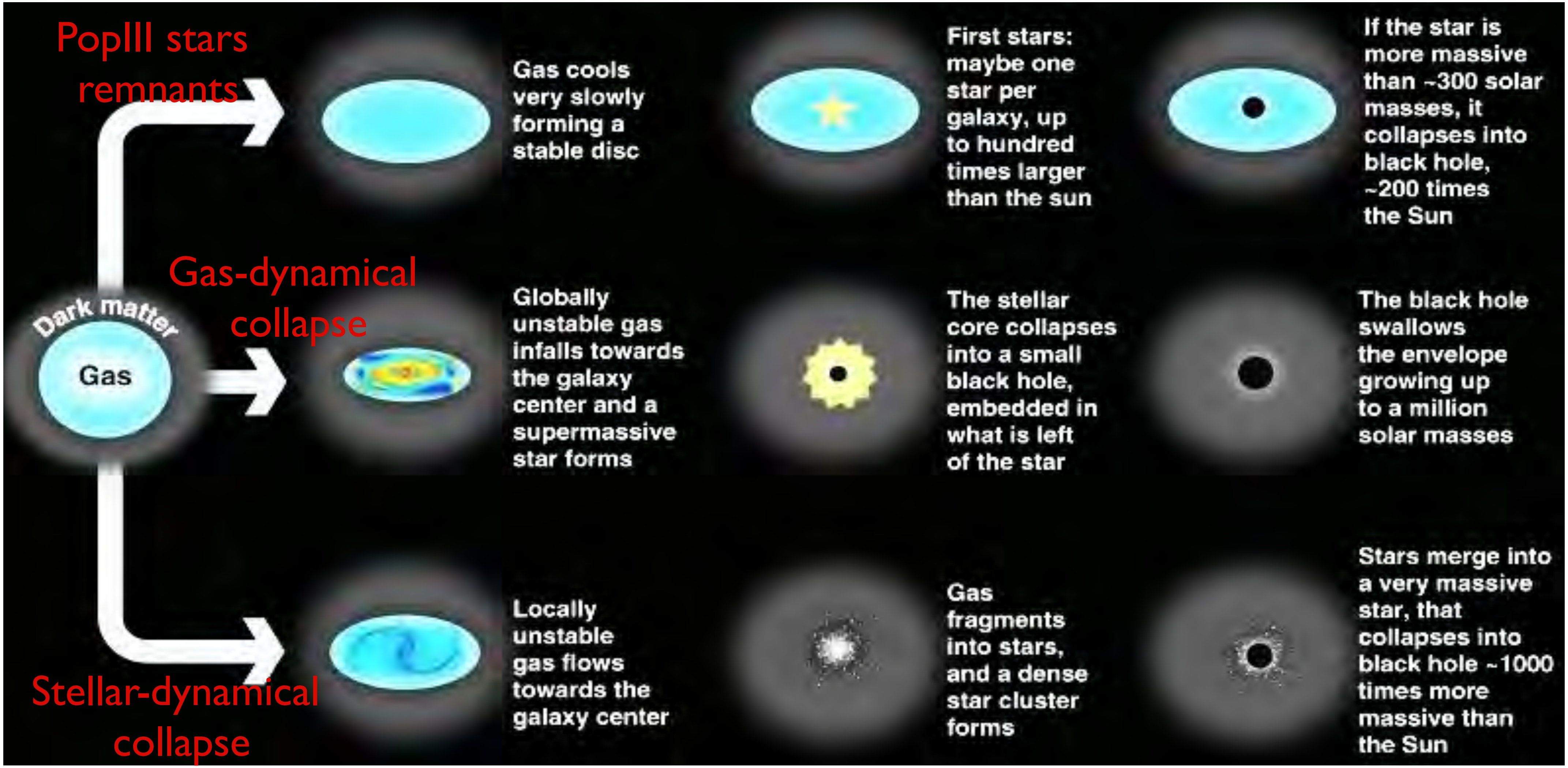
Quasars have been detected at very large distances, corresponding to a very young age of the Universe.





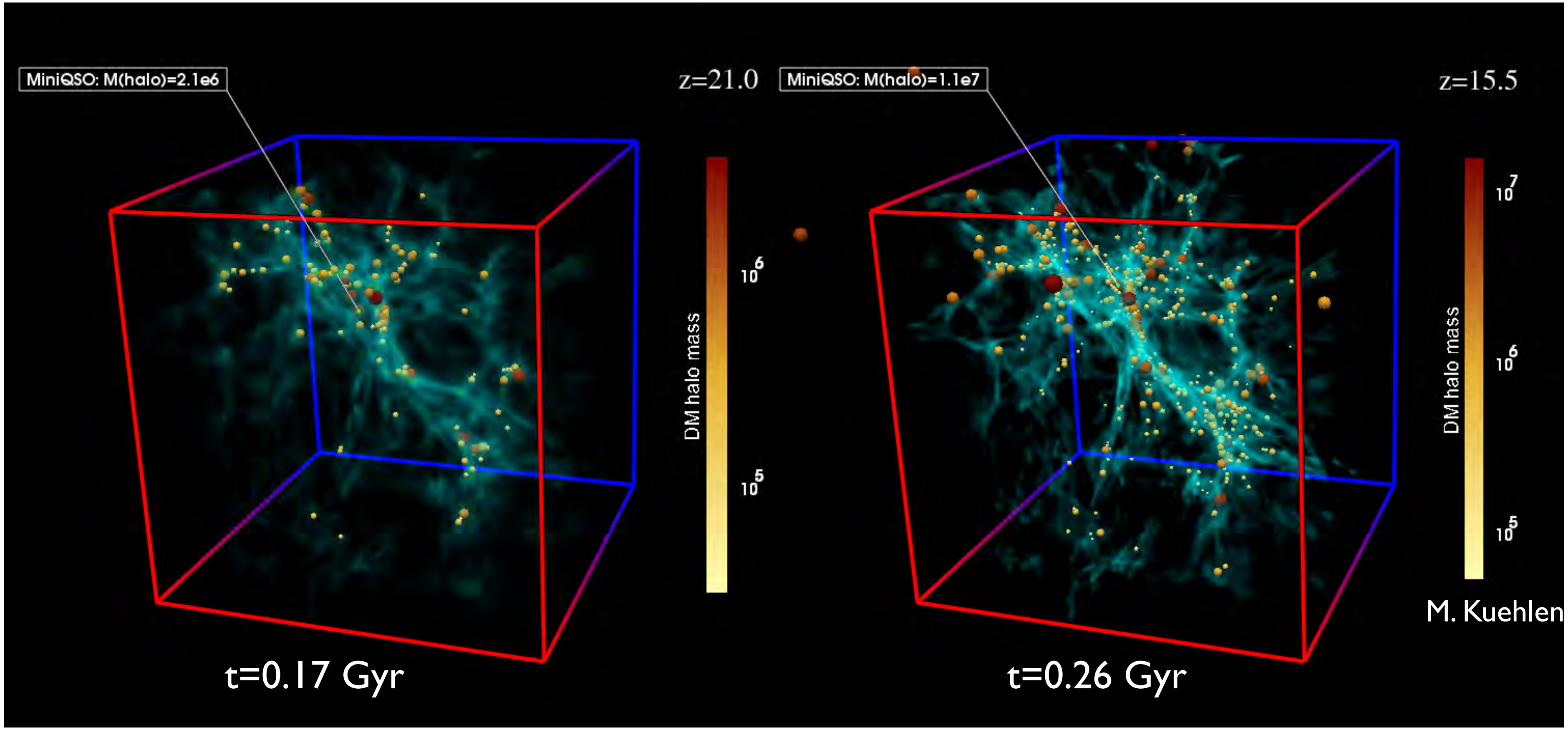
Fan 2012

HOW can you make the first massive black holes?



MV 2012, cf. Rees 1978

Hierarchical Galaxy Formation



Milky Way's dark matter halo mass ~10^{12} solar masses

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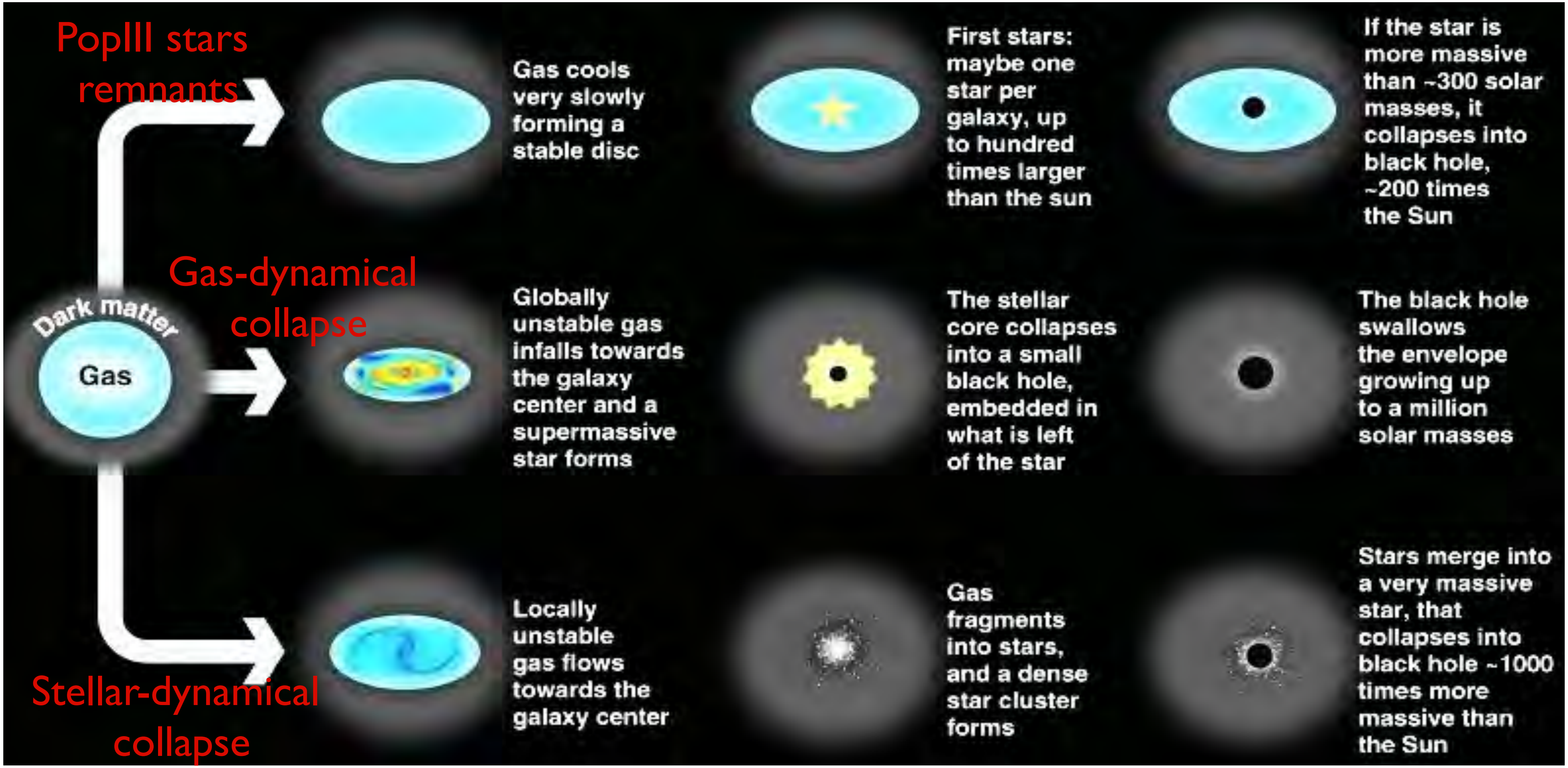
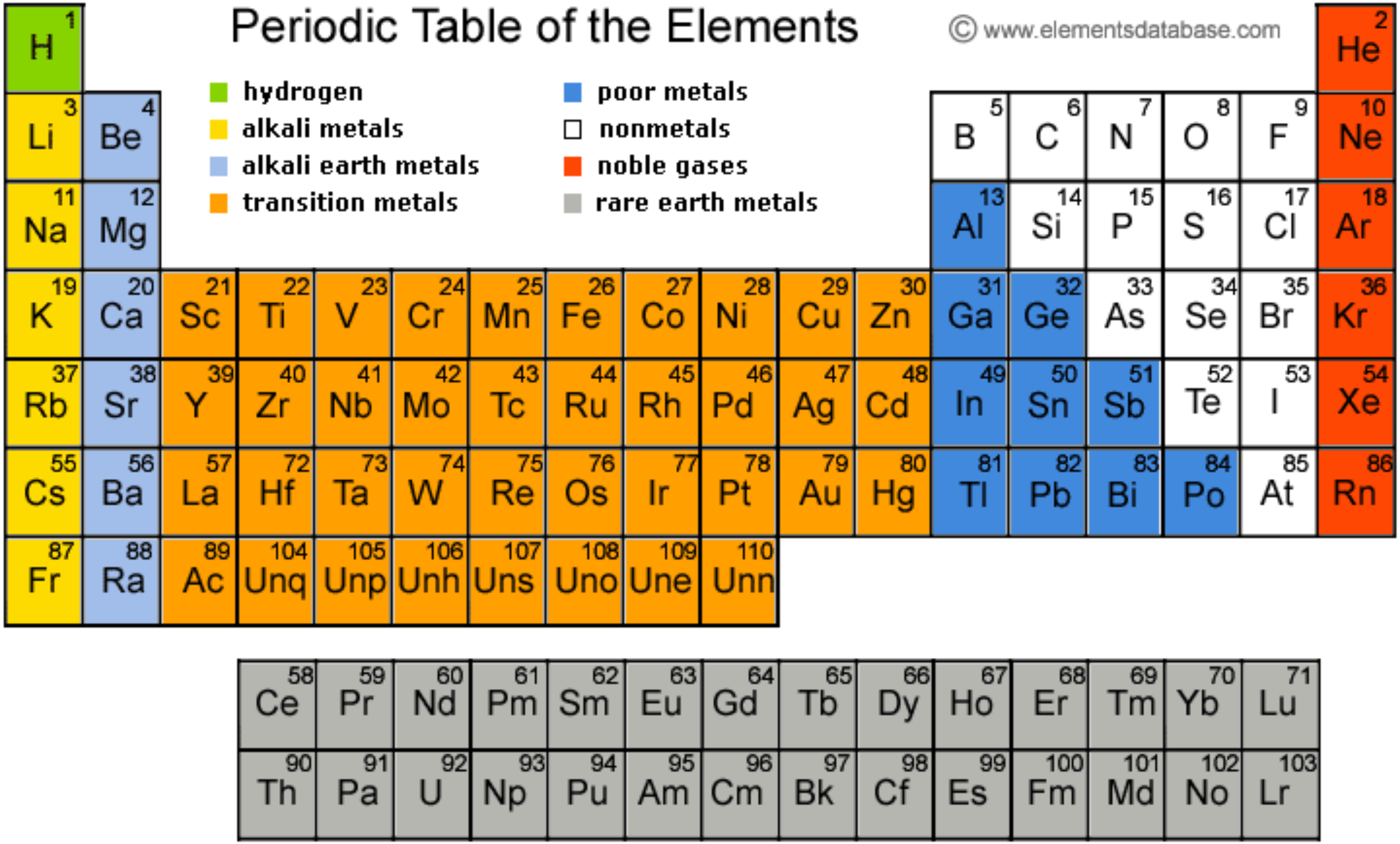


MV 2012, cf. Rees 1978

PopIII stars remnants

(e.g., Madau & Rees 2001; MV, Haardt & Madau 2003)

- ✔ PopIII stars are the very first generation of stars
- ✔ They formed out of primordial gas (=no heavy elements)


Periodic Table of the Elements
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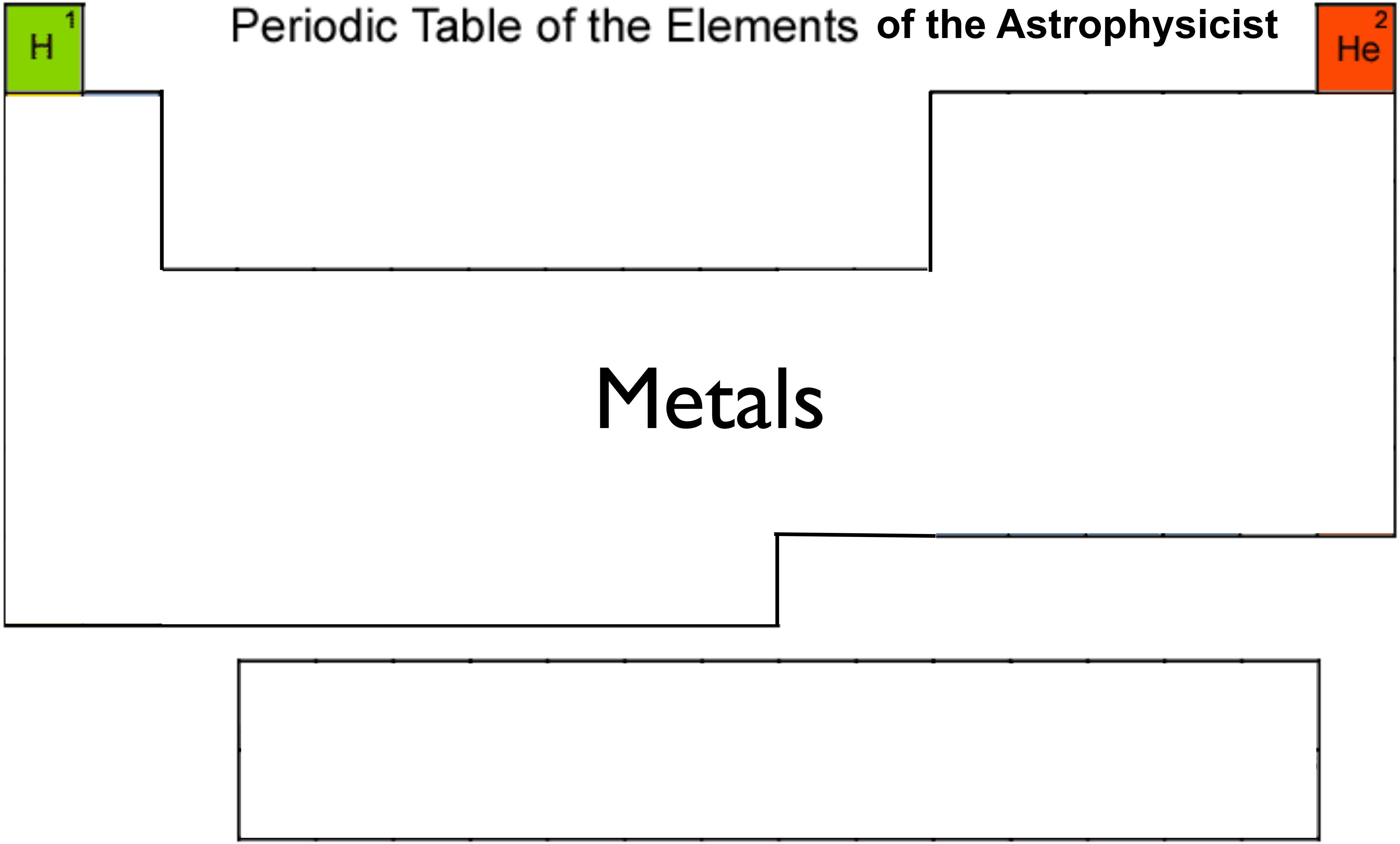
hydrogen
alkali metals
alkali earth metals
transition metals
poor metals
nonmetals
noble gases
rare earth metals
1 H
2 He
3 Li
4 Be
5 B
6 C
7 N
8 O
9 F
10 Ne
11 Na
12 Mg
13 Al
14 Si
15 P
16 S
17 Cl
18 Ar
19 K
20 Ca
21 Sc
22 Ti
23 V
24 Cr
25 Mn
26 Fe
27 Co
28 Ni
29 Cu
30 Zn
31 Ga
32 Ge
33 As
34 Se
35 Br
36 Kr
37 Rb
38 Sr
39 Y
40 Zr
41 Nb
42 Mo
43 Tc
44 Ru
45 Rh
46 Pd
47 Ag
48 Cd
49 In
50 Sn
51 Sb
52 Te
53 I
54 Xe
55 Cs
56 Ba
57 La
72 Hf
73 Ta
74 W
75 Re
76 Os
77 Ir
78 Pt
79 Au
80 Hg
81 Tl
82 Pb
83 Bi
84 Po
85 At
86 Rn
87 Fr
88 Ra
89 Ac
104 Unq
105 Unp
106 Unh
107 Uns
108 Uno
109 Une
110 Unn
58 Ce
59 Pr
60 Nd
61 Pm
62 Sm
63 Eu
64 Gd
65 Tb
66 Dy
67 Ho
68 Er
69 Tm
70 Yb
71 Lu
90 Th
91 Pa
92 U
93 Np
94 Pu
95 Am
96 Cm
97 Bk
98 Cf
99 Es
100 Fm
101 Md
102 No
103 Lr

Periodic Table of the Elements **of the Astrophysicist**



PopIII stars remnants

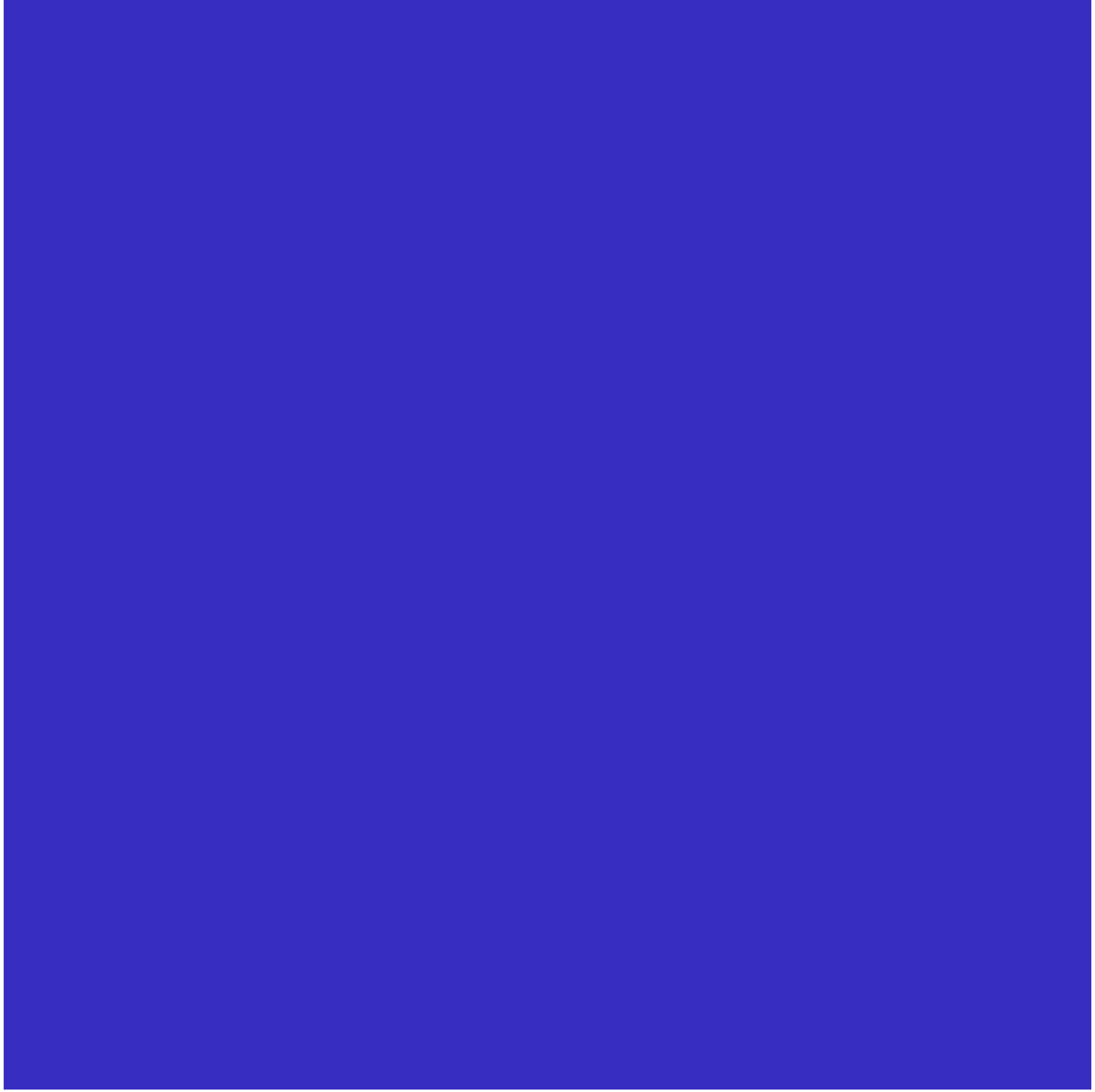
(e.g., Madau & Rees 2001; MV, Haardt & Madau 2003)

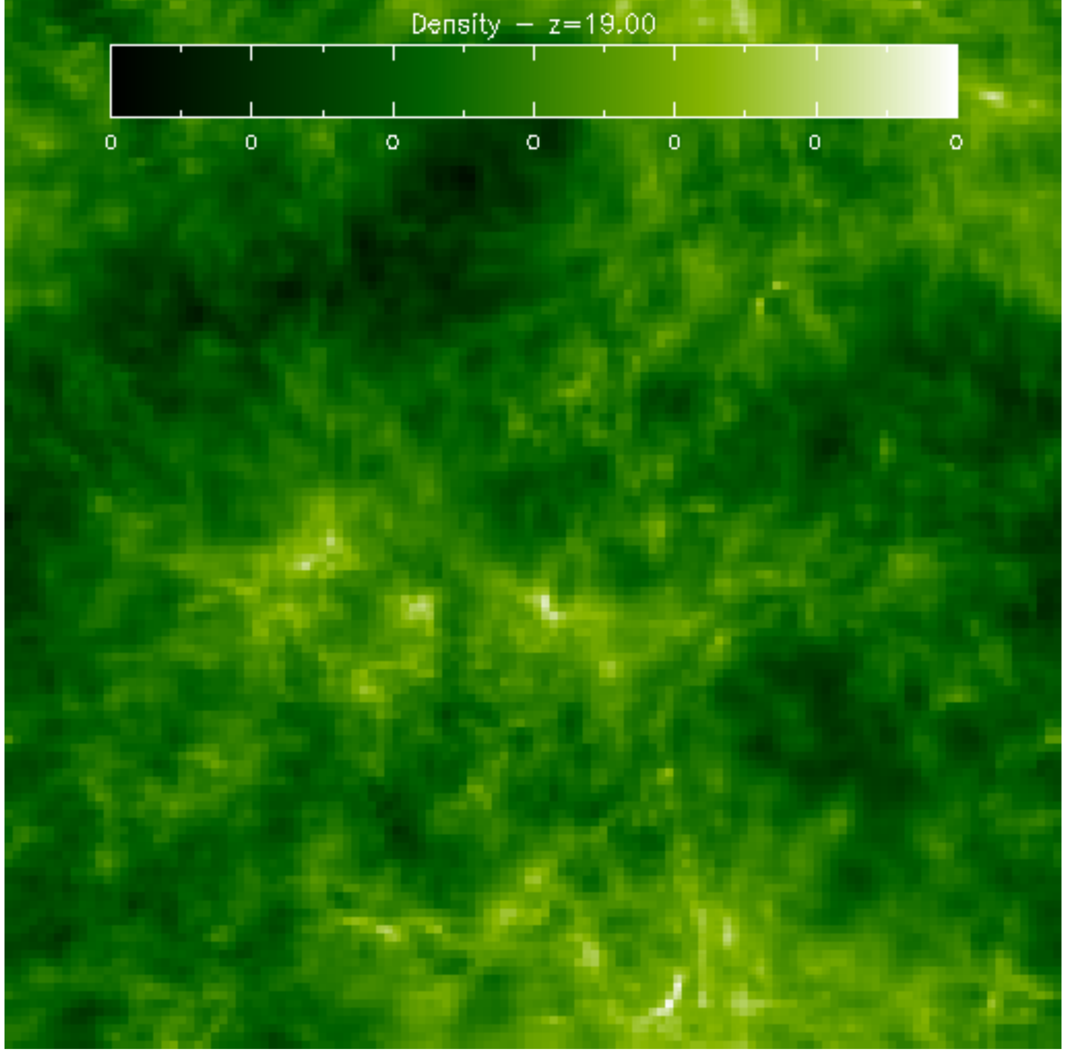
✔Some simulations suggest that the first stars are massive M~100-600 Msun (e.g., Abel et al. 2002; Bromm et al. 2003)

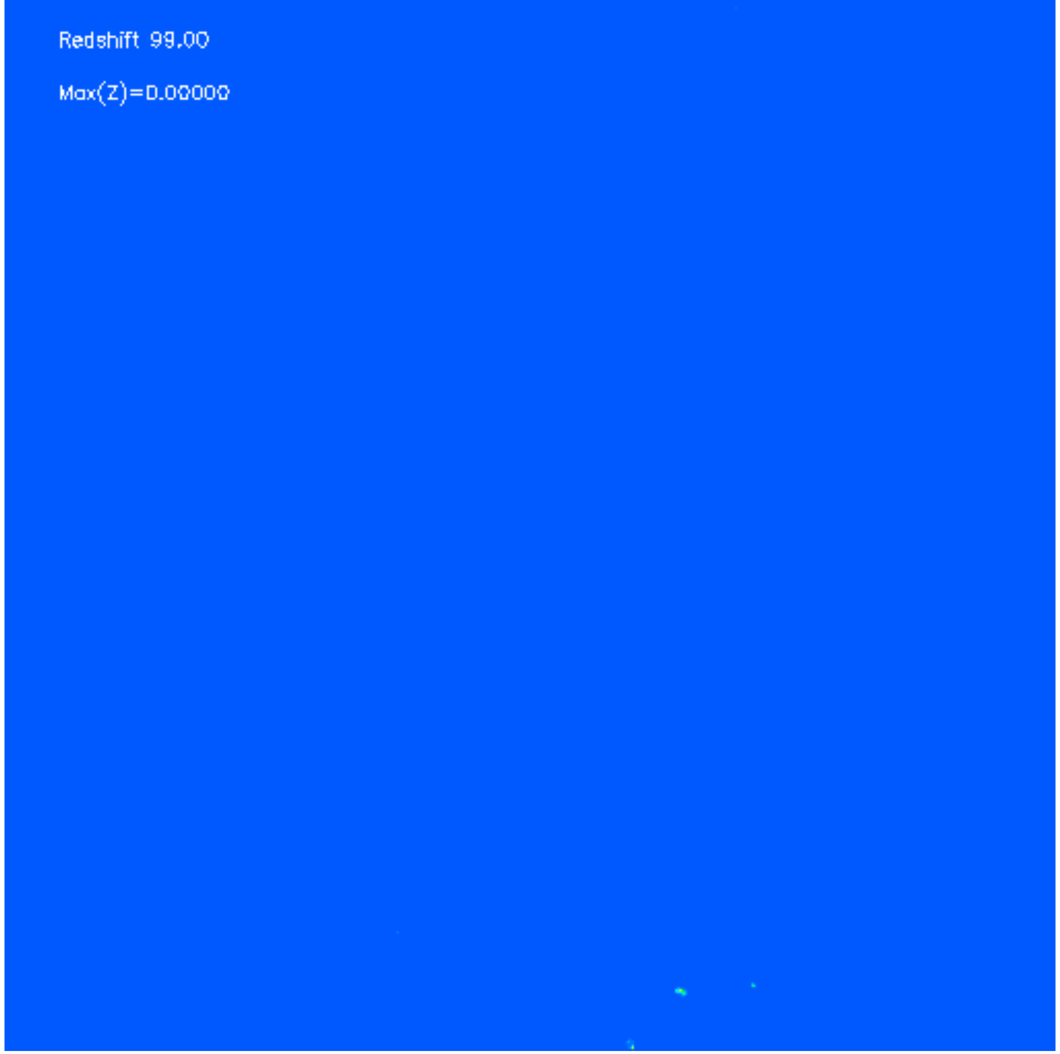
✔ Metal free dying stars with M>260Msun leave remnant BHs with Mseed≥100Msun (Fryer, Woosley & Heger 2003)

✔Recent estimates suggest lower star masses. If BH mass too small may be difficult to grow (but see Alexander & Natarajan 2014)

Heavy elements produced by stars “pollute” the intergalactic medium and eventually most of the universe is “metal-enriched”







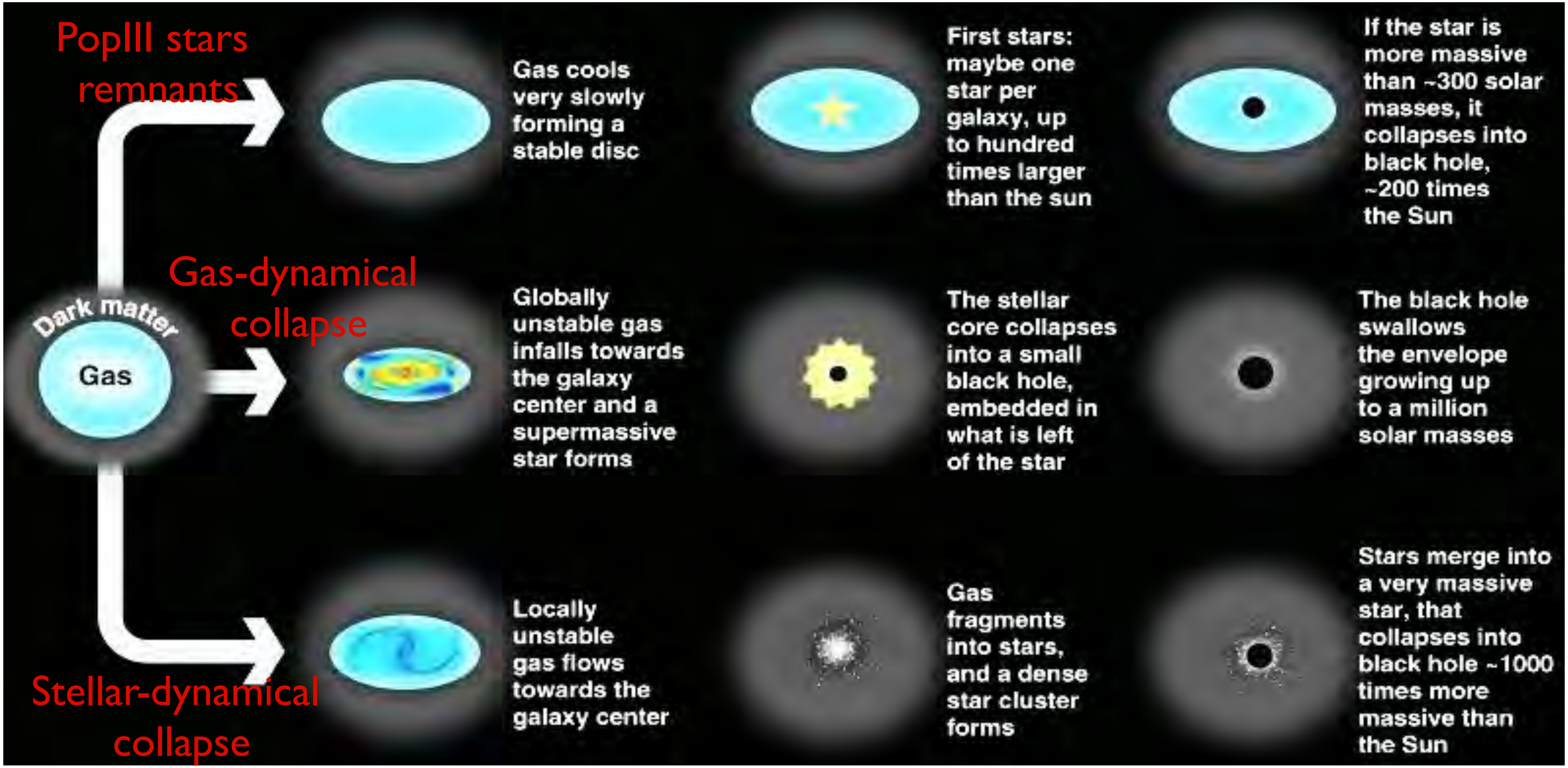
Density map
BHs form only in high gas-density regions

Metallicity map
BHs form in low-metallicity regions

Circles: galaxies with BHs

Mélanie Habouzit

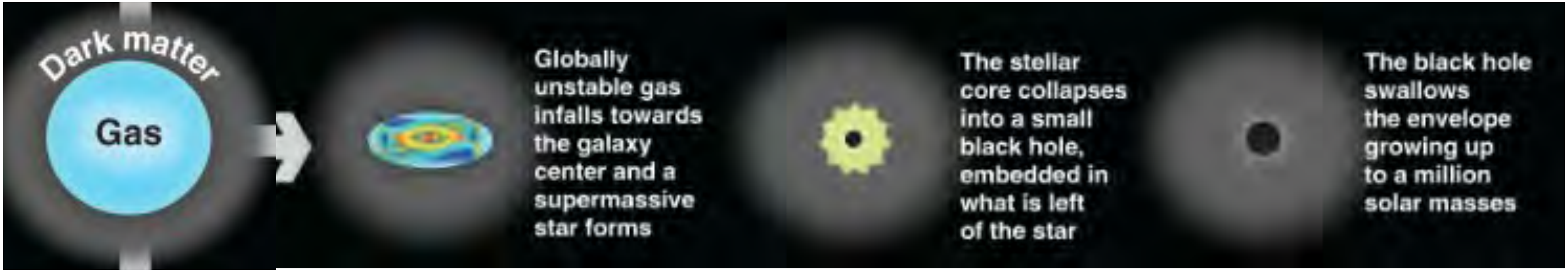
HOW can you make the first massive black holes?



MV 2012, cf. Rees 1978

Gas-dynamical collapse

(e.g. Bromm & Loeb 2003, Begelman, MV & Rees 2006, Lodato & Natarajan 2006, Latif et al. 2013)



✔Formation of supermassive star collapsing into a MBH of $\sim 10^4$-10^6 M_{sun}

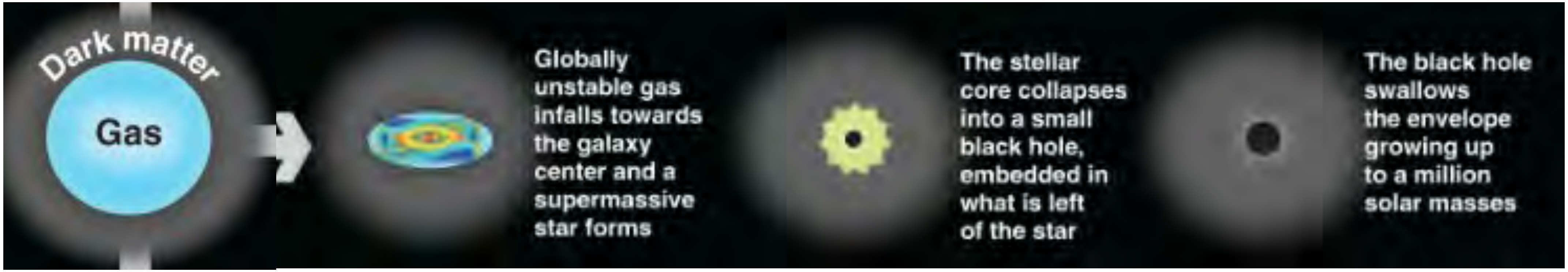
✔ Feasible if star formation is suppressed, and most of the gas is accreted onto the central protostar

✔Key parameter: inflow rate on the central object. If Mdot>0.1 Msun/yr => supermassive star or quasi star*

*powered by accretion on an embedded BH created by core collapse

Gas-dynamical collapse: dynamics

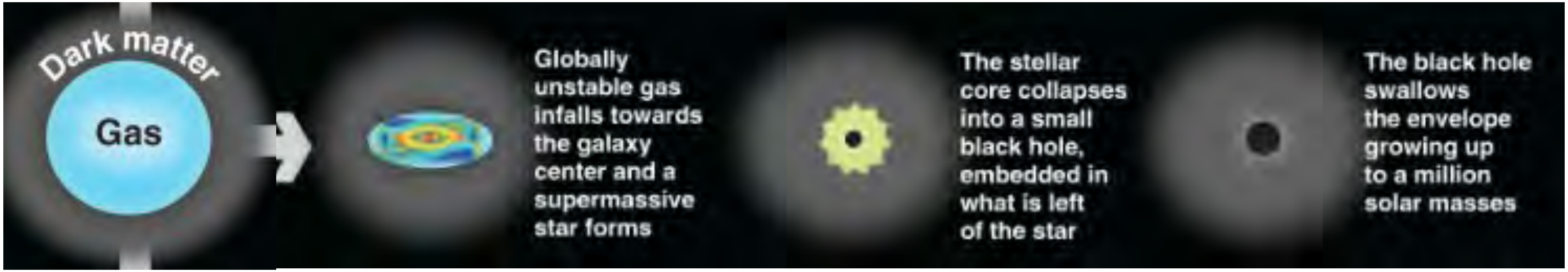
(e.g. Begelman, MV & Rees 2006, Lodato & Natarajan 2006, Choi et al. 2015)



✔Mdot is high: if <u>*global dynamical instabilities*</u> trigger inflow and dissipate angular momentum on timescales shorter than star formation (Begelman, MV & Rees 2006)

Gas-dynamical collapse: thermodynamics

(e.g. Bromm & Loeb 2003, Begelman, MV & Rees 2006, Shang et al. 2010, Latif et al. 2013)

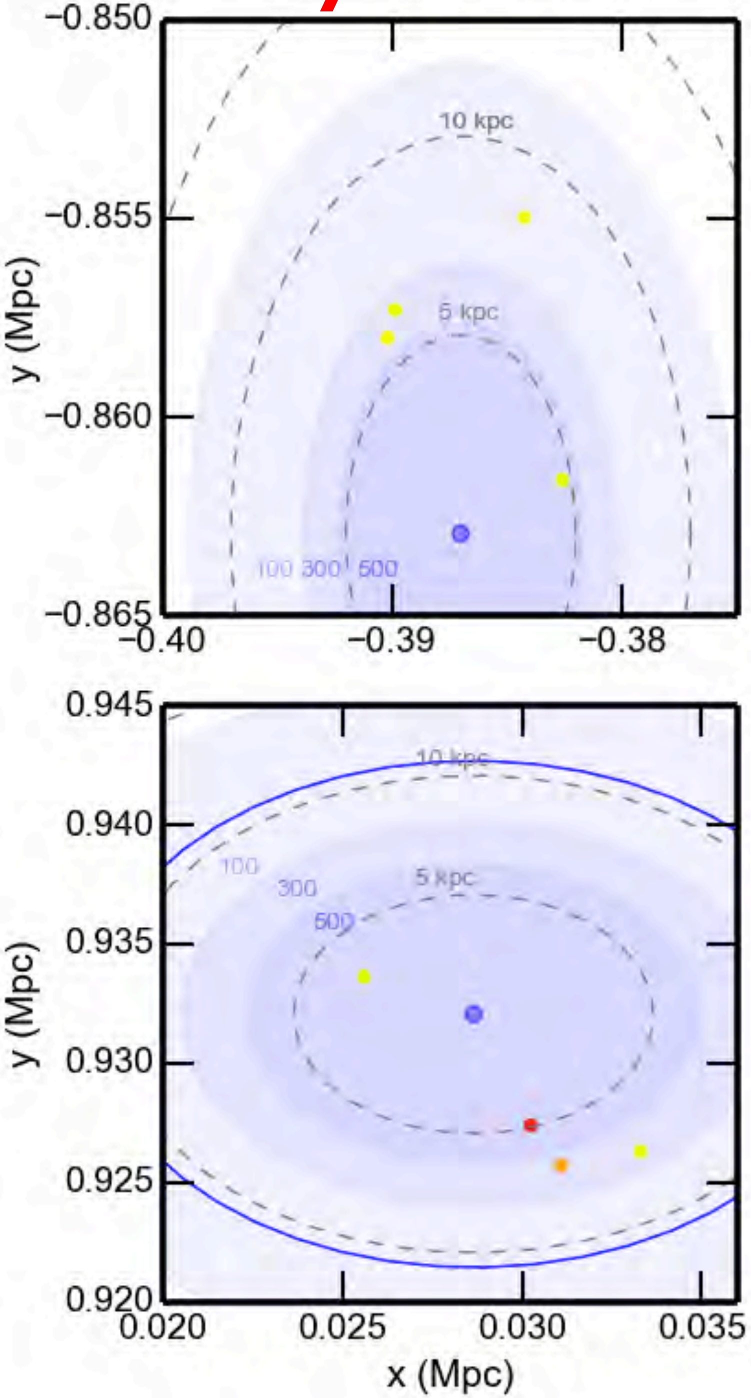


✔Mdot is high: if star formation delayed, e.g.,

-primordial gas composition => radiative cooling inefficient

-H_2 formation suppressed by strong dissociating UV flux => UV background flux (J_{21})

Gas-dynamical collapse: tough conditions



Contours: strength of the dissociating field

yellow J21 ⩾ 100
orange J21 ⩾ 300
red J21 ⩾ 500

Blue ellipse: expansion of the metal bubble

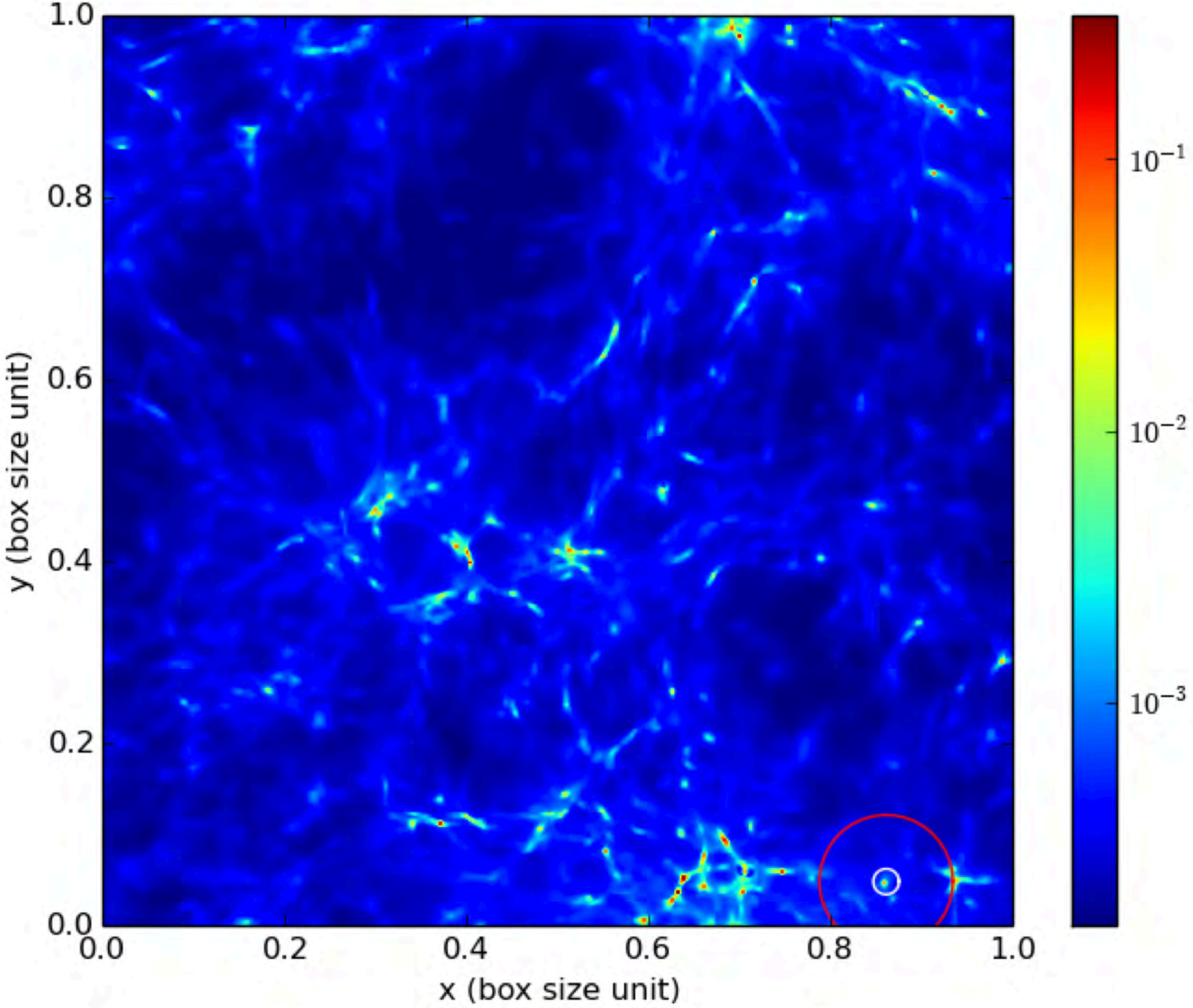
Timesteps: 1 Myr

Within 10 Myr no galaxy meets the metal/ H_2 requirements

Collapse lasts ~80 Myr

Unlikely process?

Mélanie Habouzit



Gas density map (10 cMpc)

White circle: 5 times the halo virial radius of the halo

Red circle: closest old star from which galactic winds can spread metals in the considered halo

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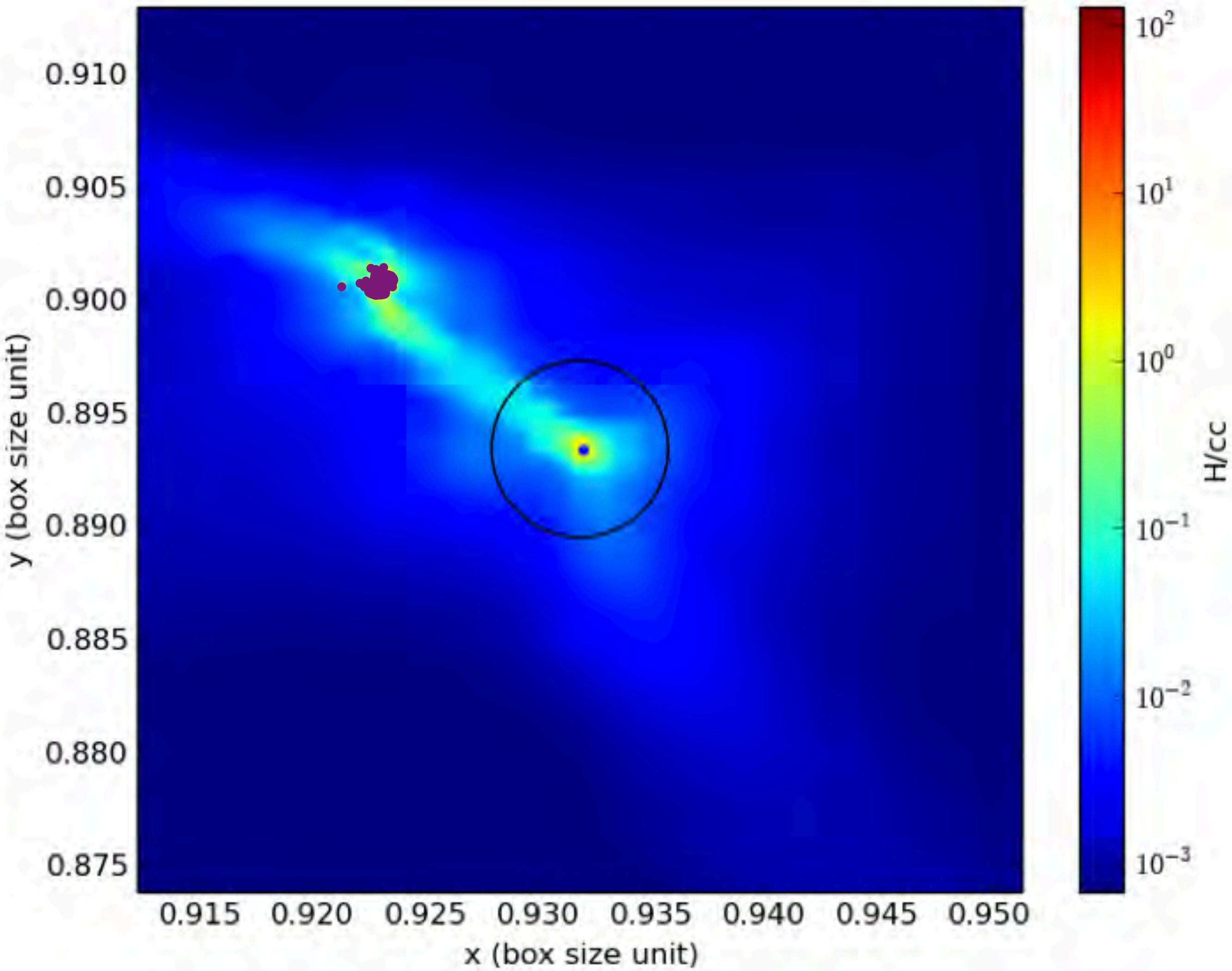

Gas density map: 10 times the halo virial radius of the halo

Black circle: 2xhalo virial radius

Purple: stars

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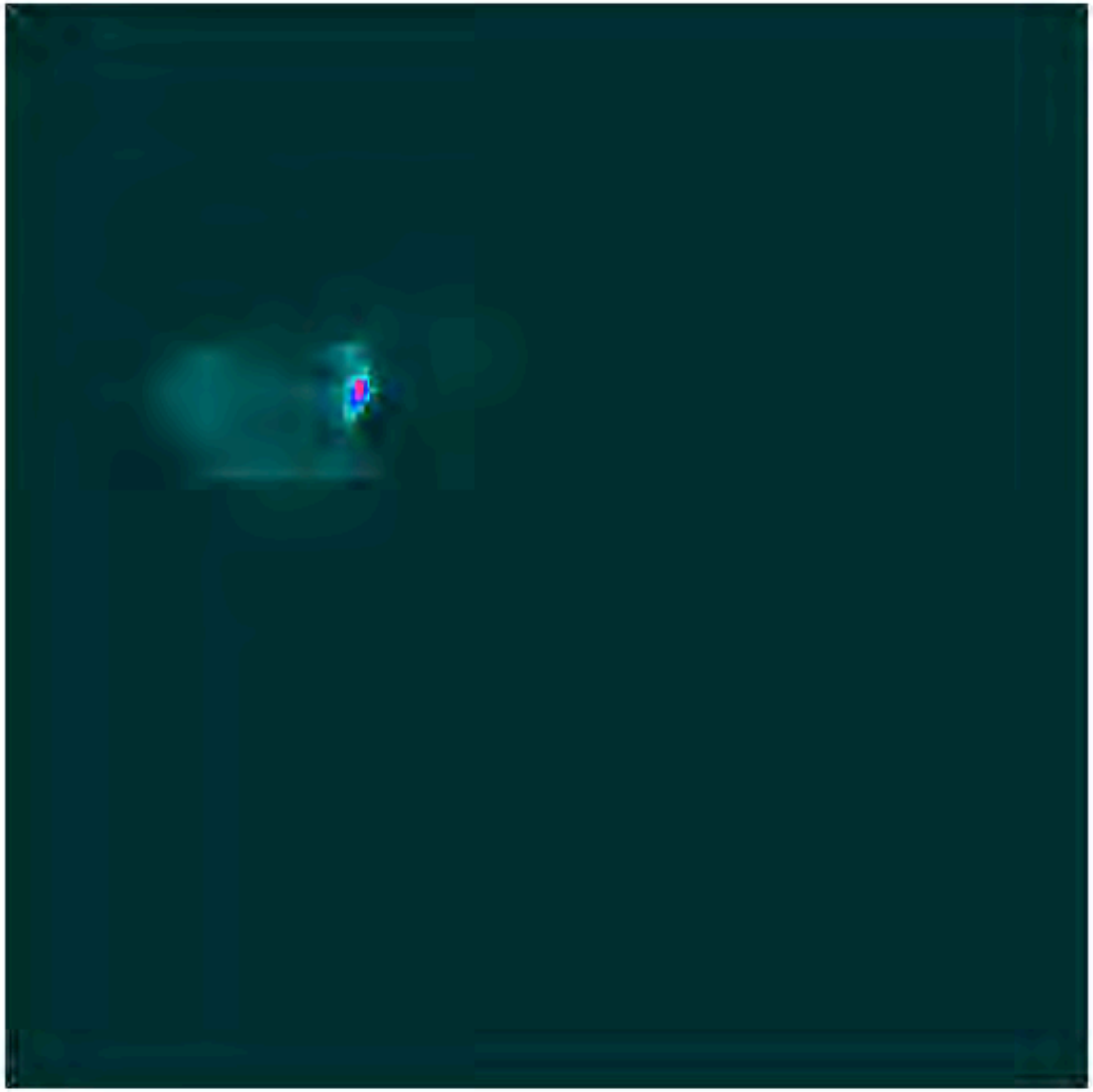


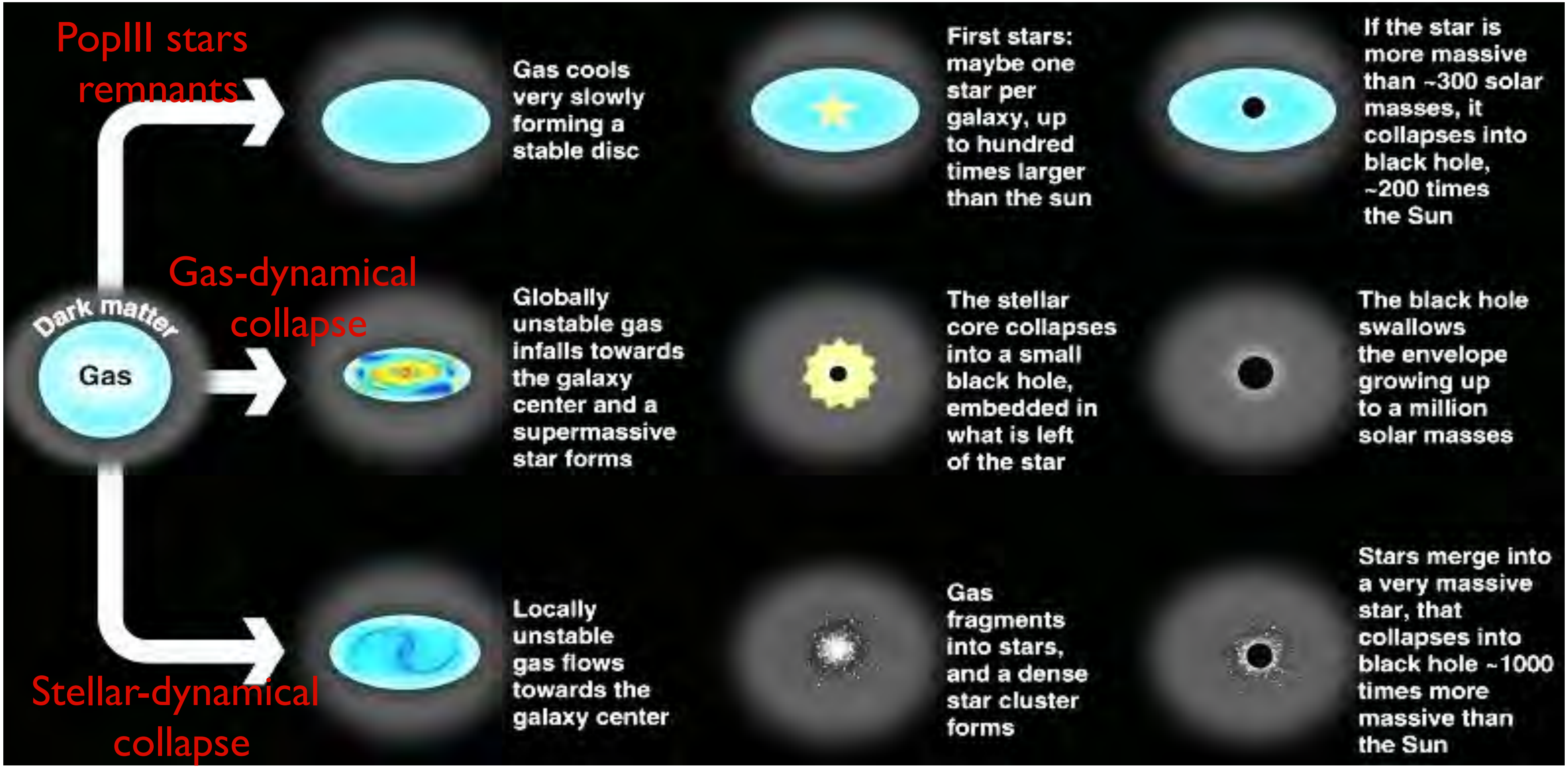
Metallicity map:
10 times the
halo virial radius
of the halo

Black circle: halo
virial radius

Full hydro simulation more optimistic: analytical models overestimate metal pollution?

Mélanie Habouzit

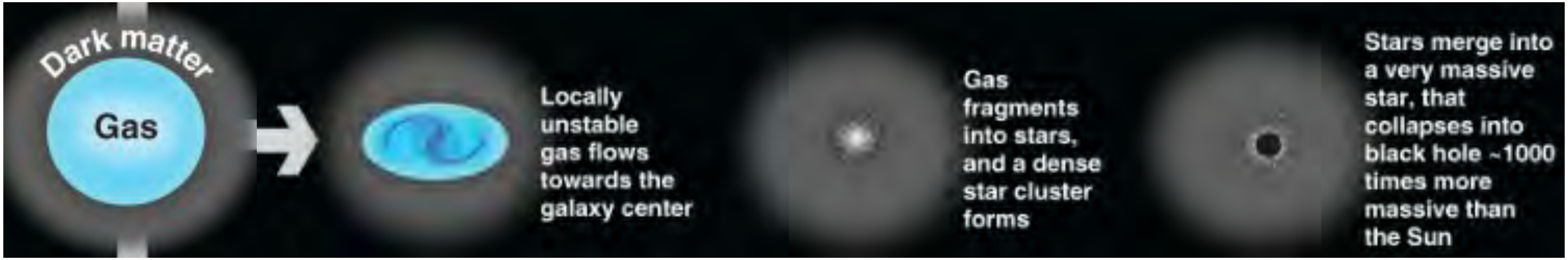
HOW can you make the first massive black holes?



MV 2012, cf. Rees 1978

Stellar-dynamical processes

Omukai et al. 2009; Devecchi & MV 2009



Local dynamical instabilities can lead to mass infall

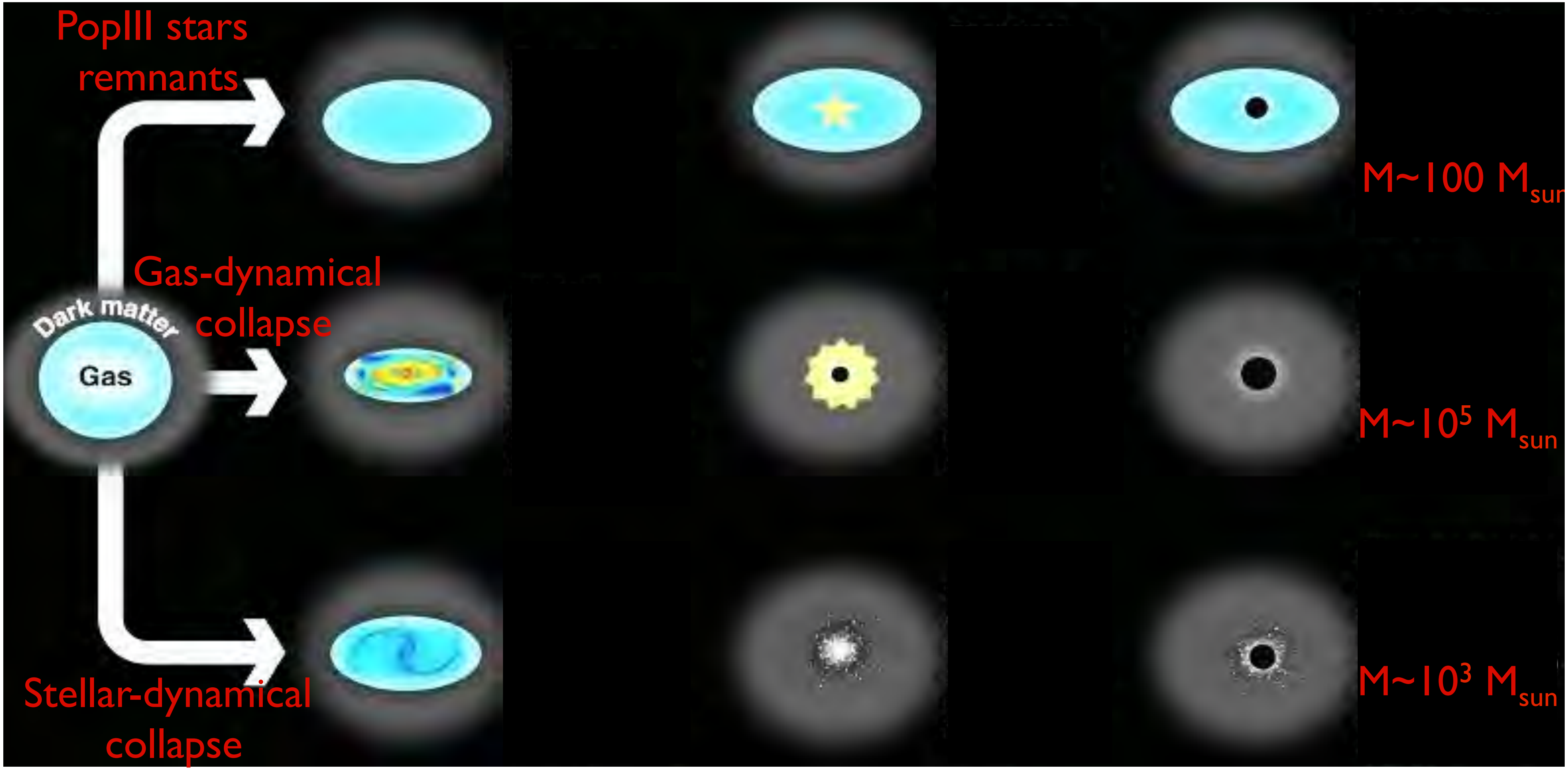
✔ Inflow ⇒ within an inner, compact, region stars form abundantly ⇒ very dense cluster

✔ Mass segregation: massive stars sink to the center

✔ Stellar collisions form a very massive star

✔ At low heavy element enrichment ⇒ massive black hole $\sim 10^3\ M_{sun}$

HOW can you make the first massive black holes?



Can we make some model-independent preditictions?

PopIII stars remnants

Gas-dynamical collapse

Stellar-dynamical collapse

✔High gas density

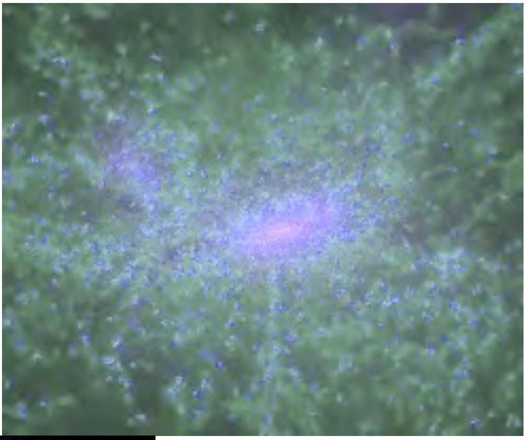
✔Little or no heavy elements

Testing MBH seed formation

hz1

at z = 5: $M = 6 \times 10^{11}\ M_\odot$

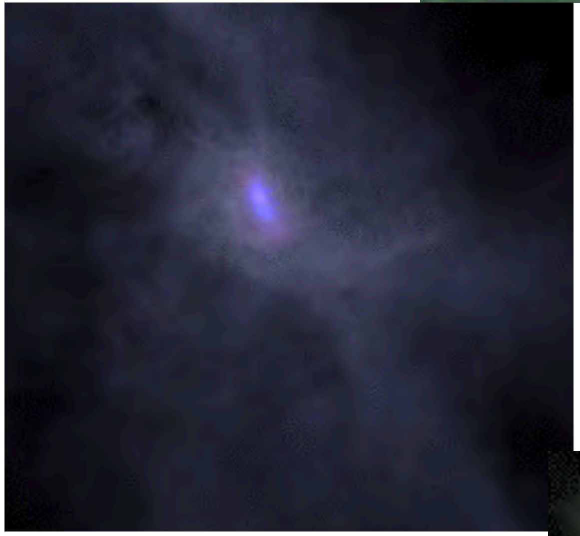
at z = 0: Massive elliptical



h258

at z = 5: $M = 3 \times 10^{10}\ M_\odot$

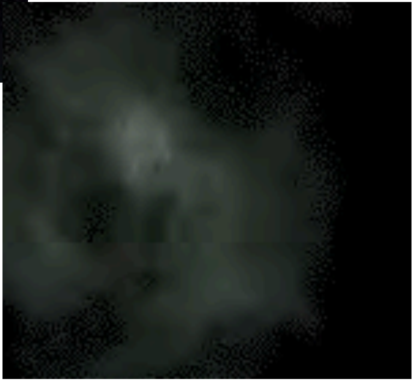
at z = 0: Milky Way mass



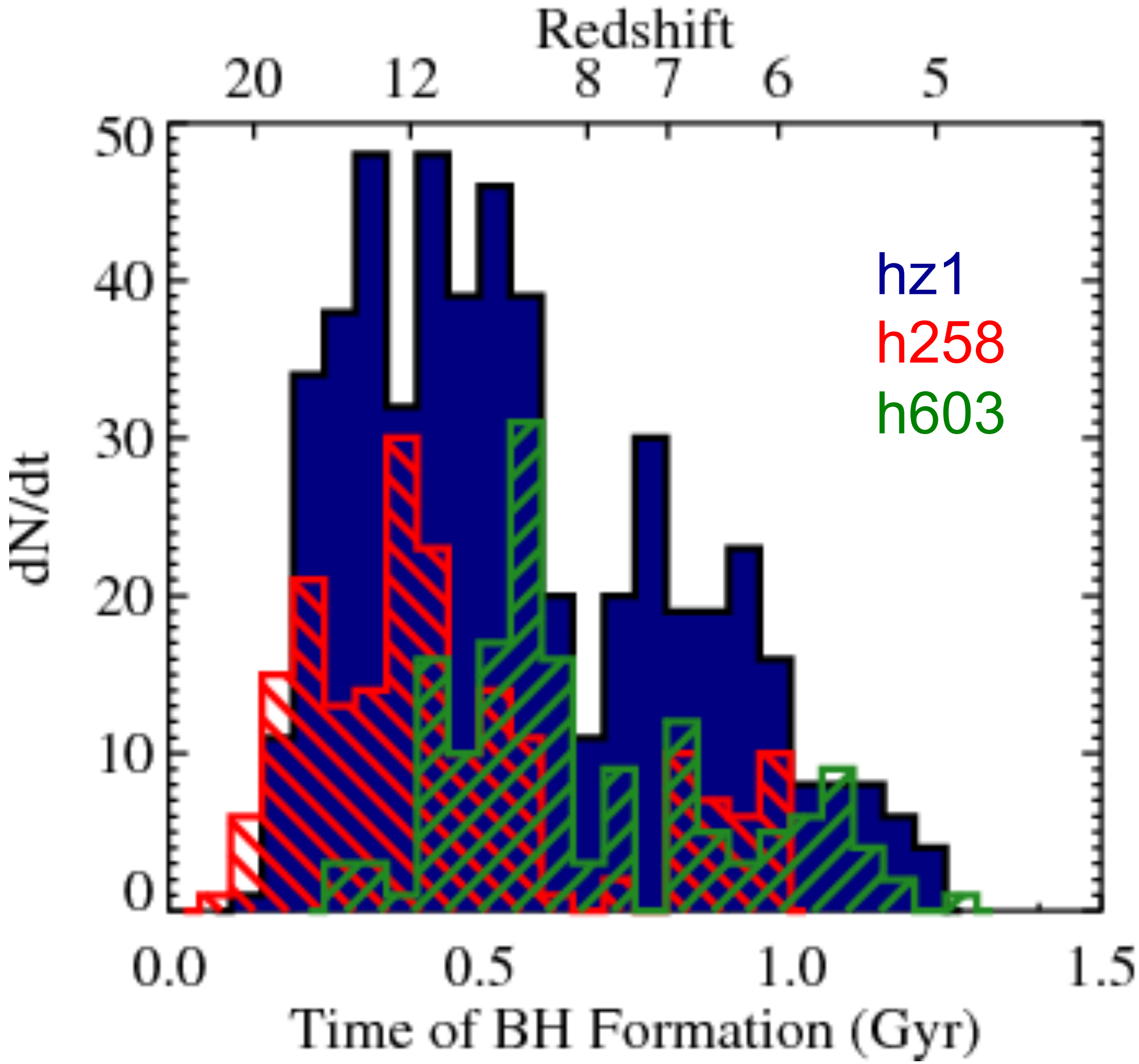
h603

at z = 5: $M = 8 \times 10^{9}\ M_\odot$

at z = 0: Low-mass disk galaxy



MBH seeds form early

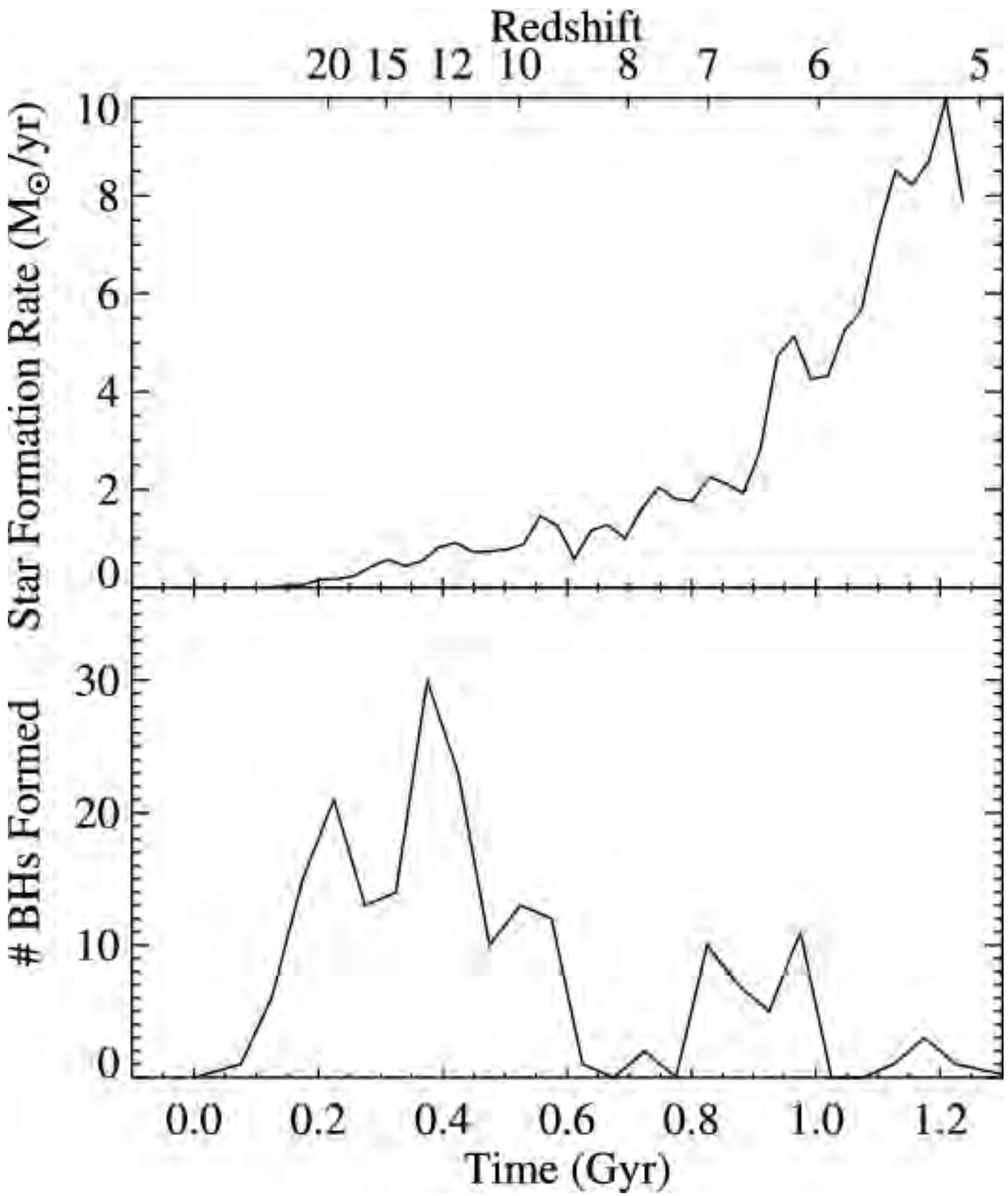


Black holes form earlier in more biased halos

Different efficiencies just change how many MBHs form

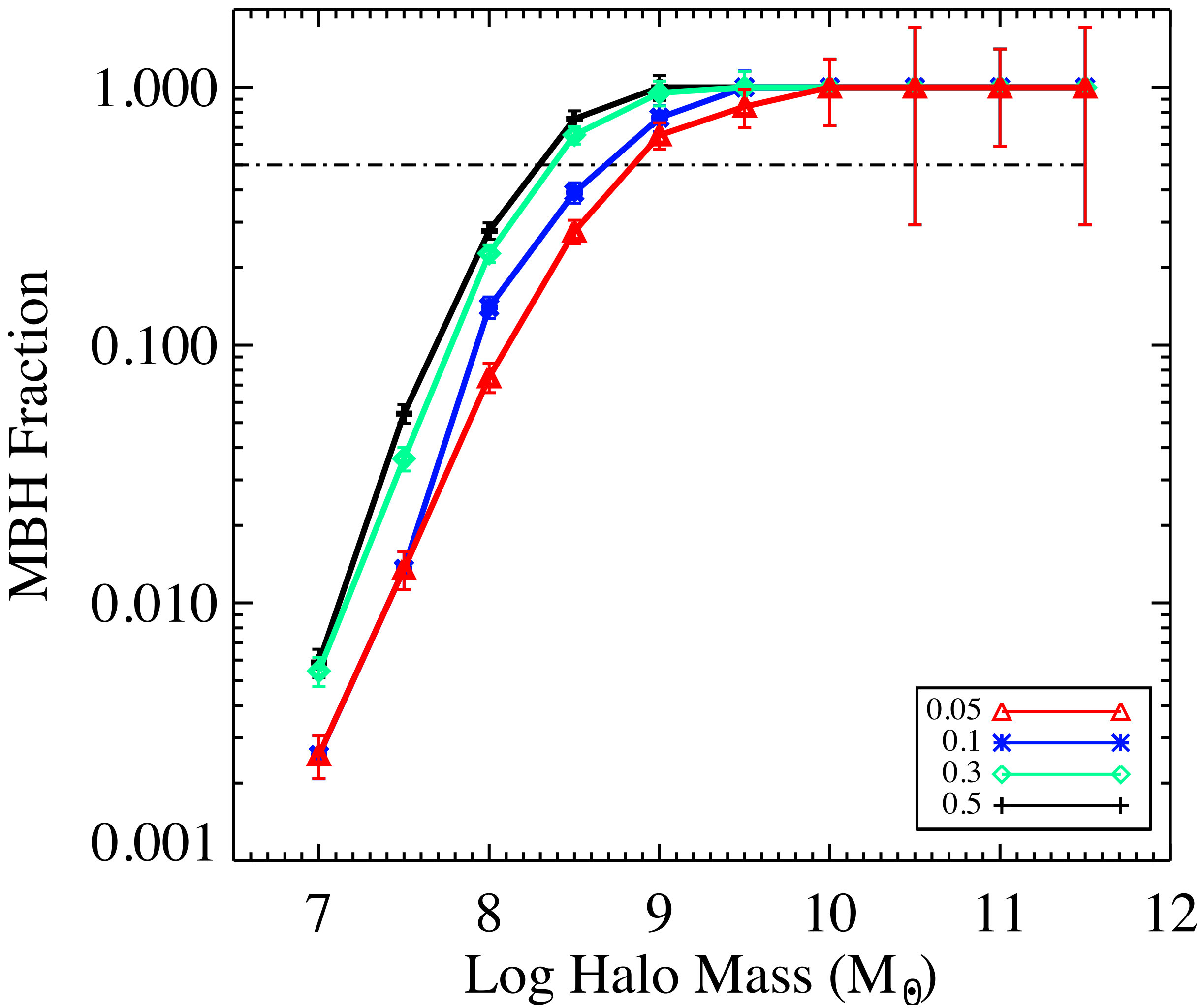
Bellovary, MV et al. 2011

MBH seeds form early



MBH formation is truncated due to contamination by heavy elements, while stars continue forming

Not all galaxies host BHs



While all massive halos are expected to form BHs, the occupation fraction at low halo masses is well below unity

Low-mass MBHs in low mass galaxies

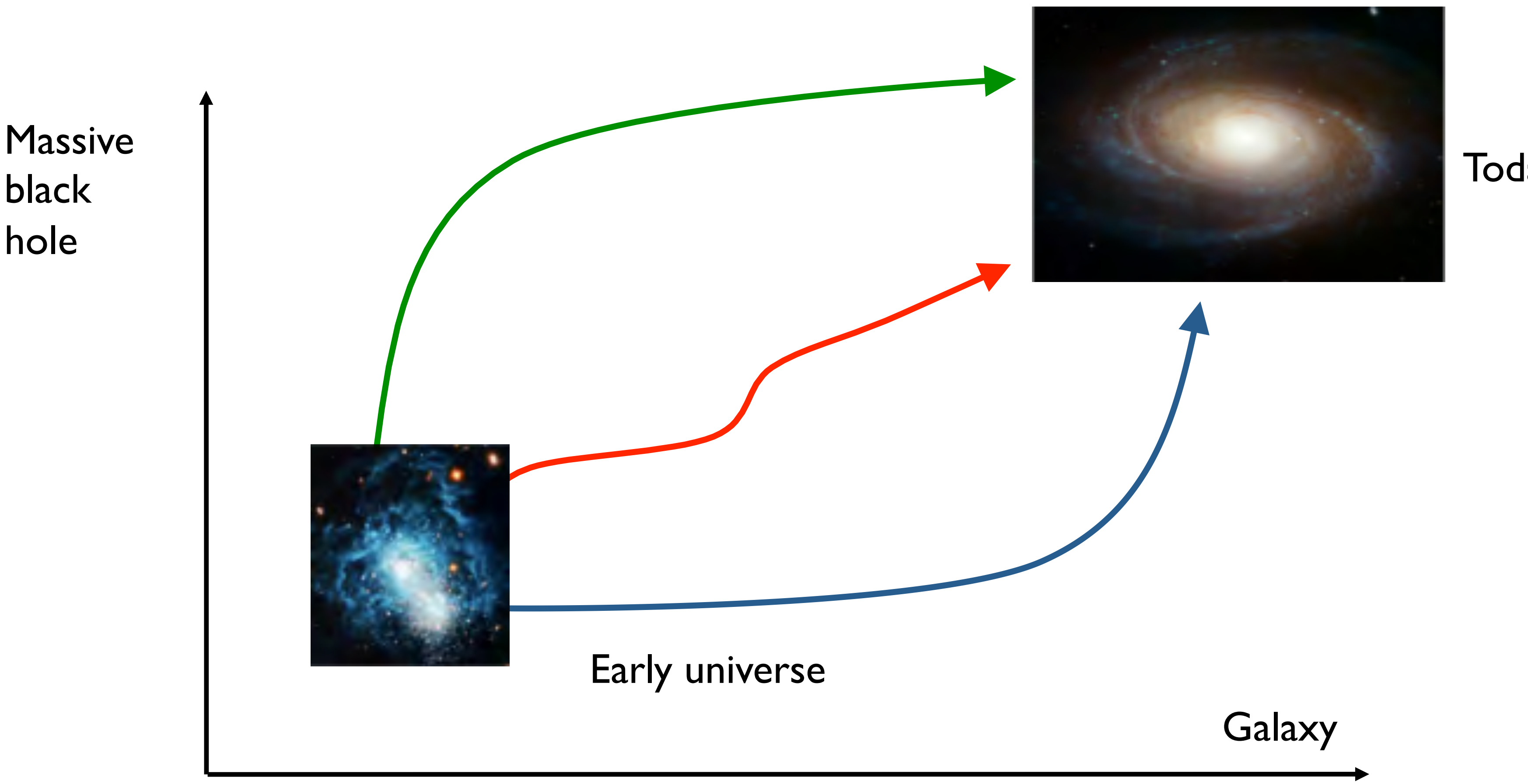
A MBH in a massive galaxy has increased its mass by accretion, or it has experienced mergers and dynamical interactions.

Dwarf galaxies undergo instead a quieter evolution, and their MBHs still retain some "memory" of the initial conditions

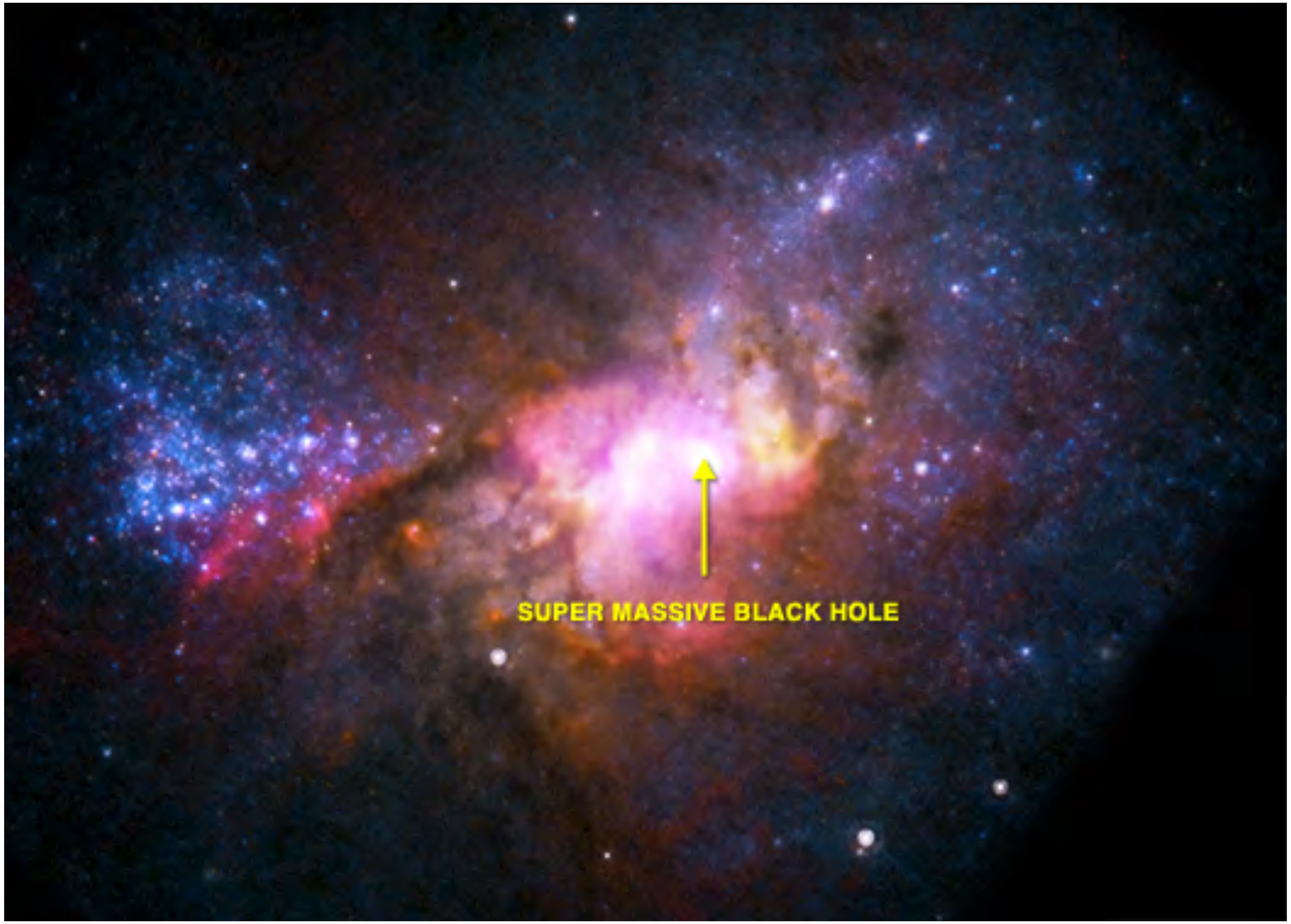
How can we find signatures of ‘seeds’?

Since the average MBH grows by several orders of magnitude the initial conditions are washed out

"The night in which all cows are black” (Hegel)



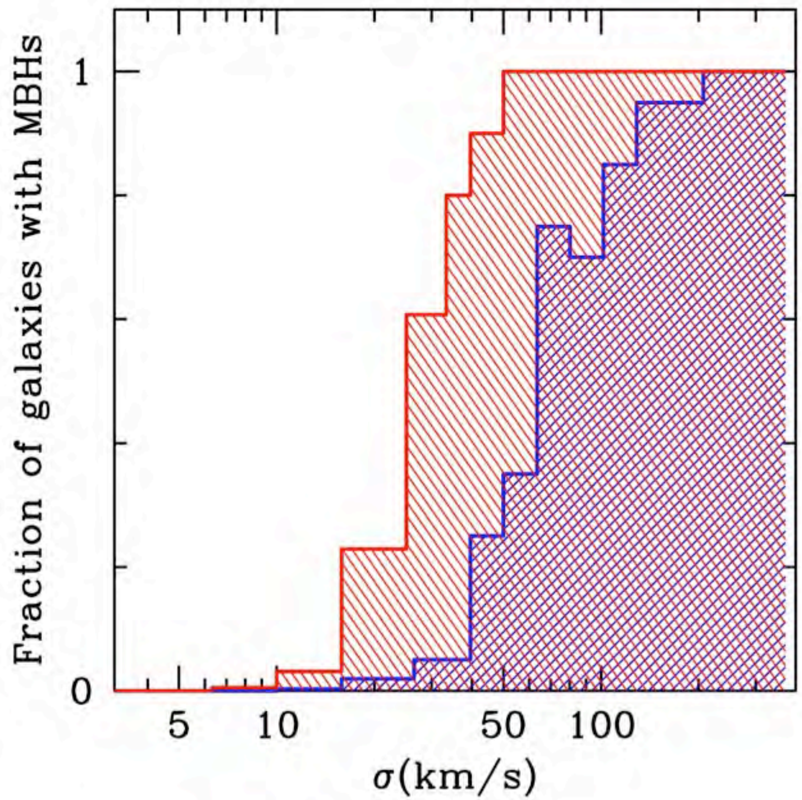
Low-mass MBHs in low mass galaxies



Henize 2-10: ten times smaller than the Milky Way

Occupation fraction @ z=0

Theory

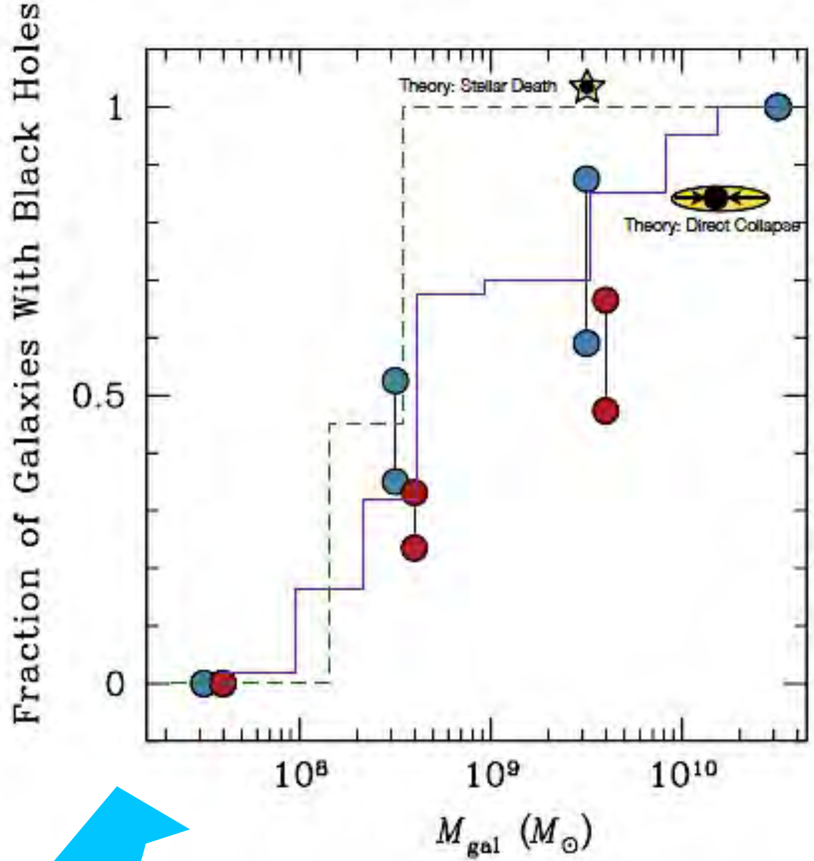


Gas-dynamical collapse: fewer MBHs

PopIII remnants: BHs more common

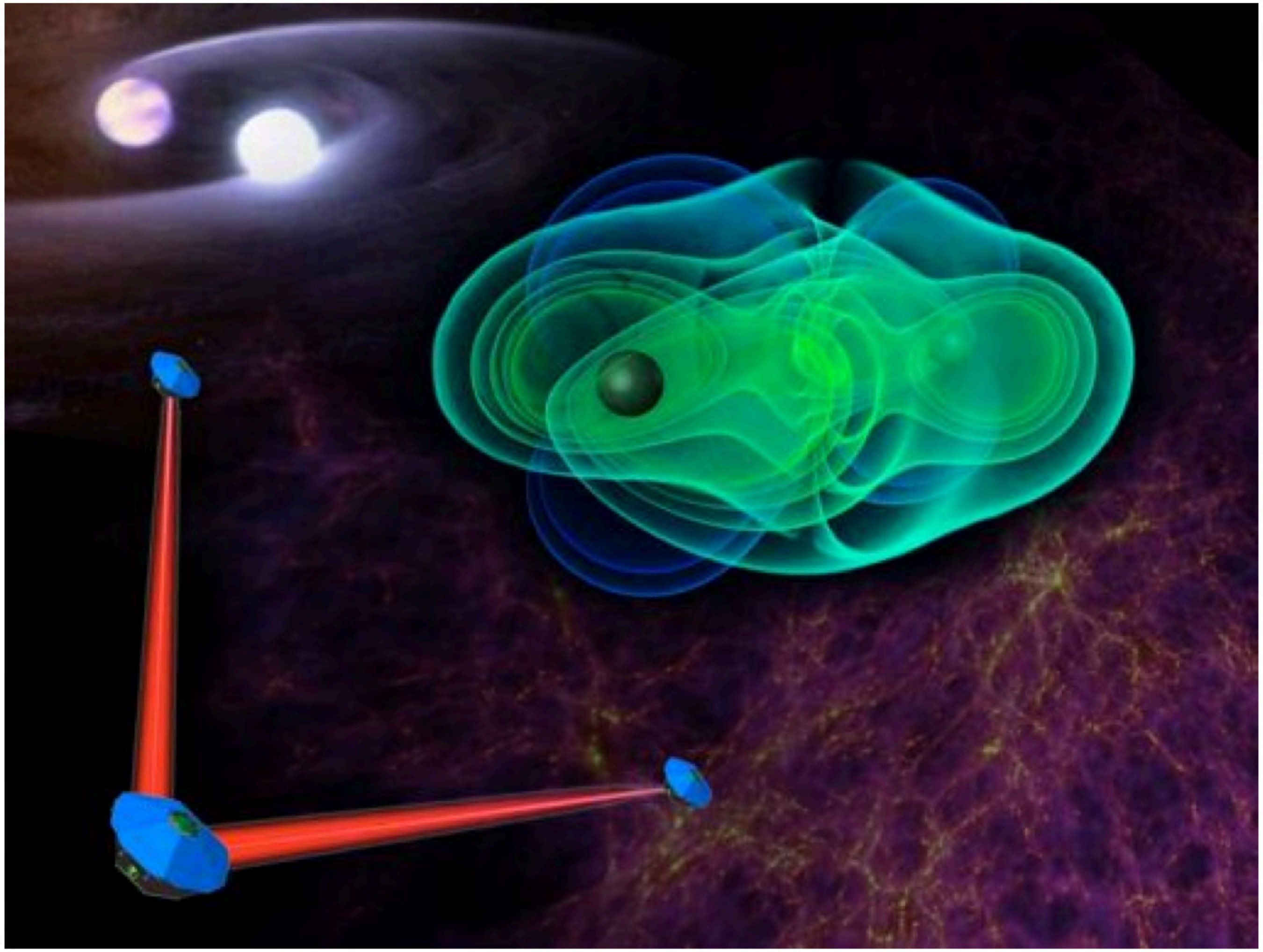
MV, Lodato & Natarajan 2008
+ Van Wassenhove, MV et al. 2010

Observations



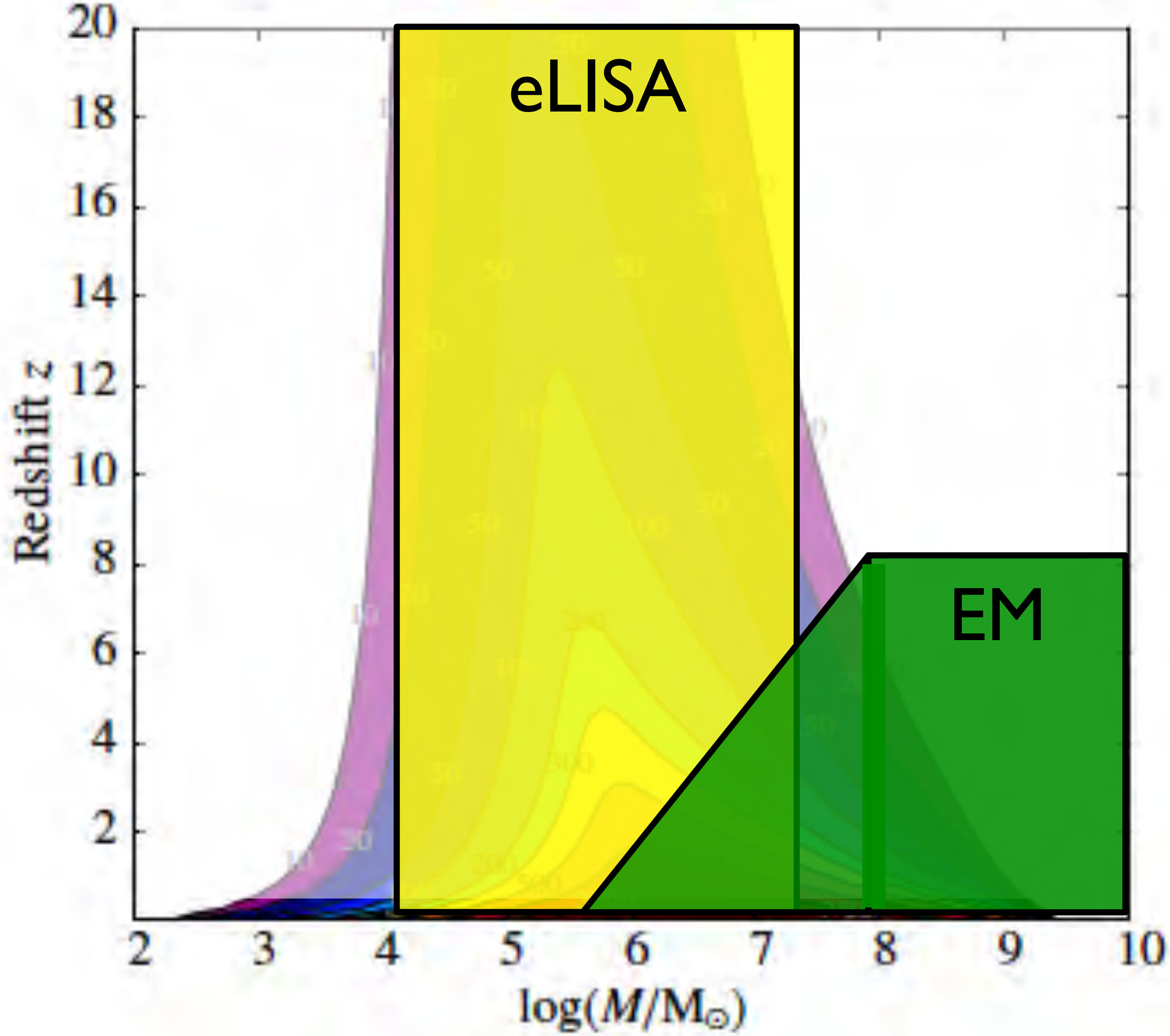
Greene 2012

MBH-MBH mergers: gravitational waves

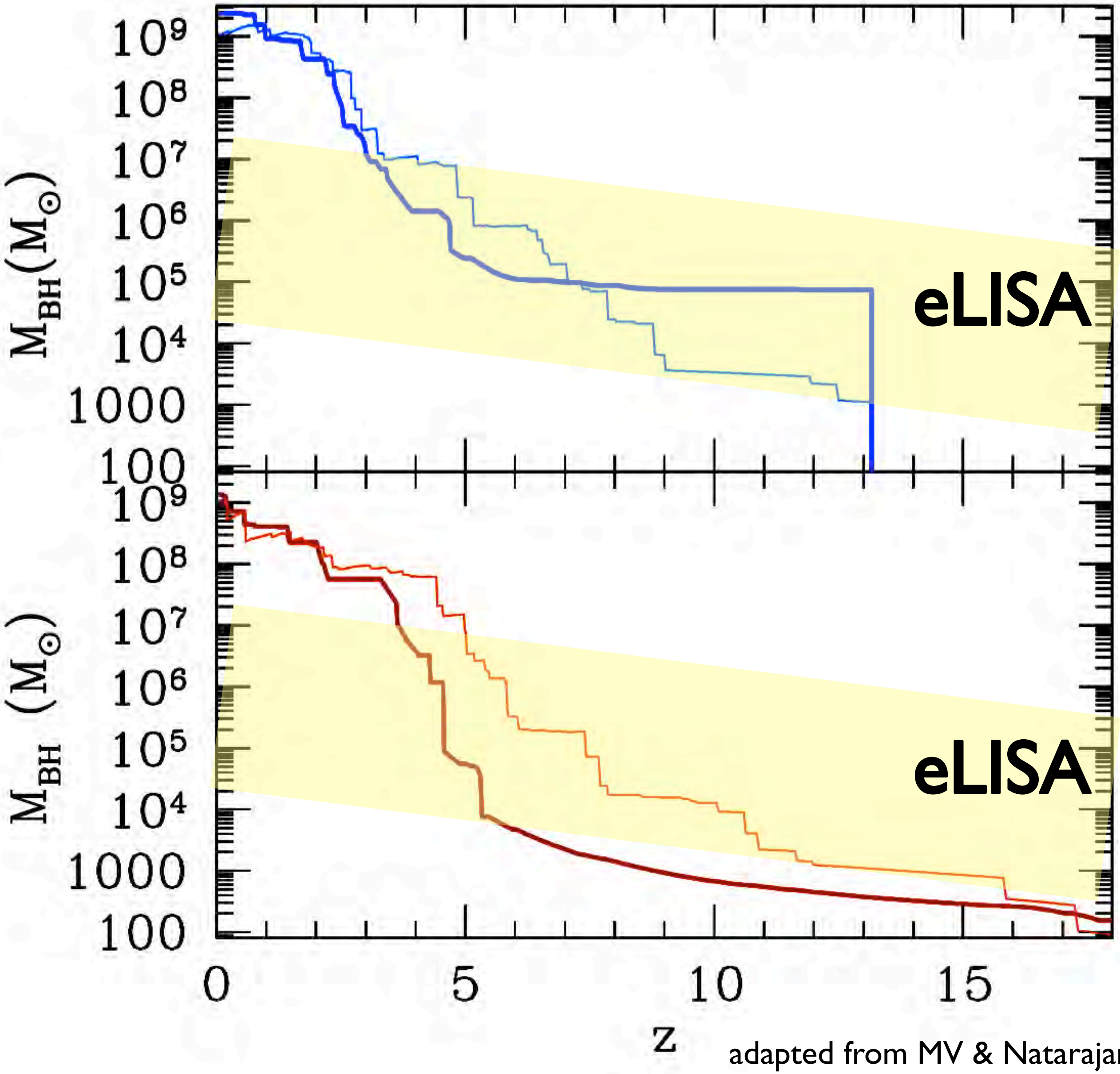


eLISA: detect gravitational waves from merging MBHs

eLISA is *complementary* to electromagnetic observations



Most, if not all, MBHs are in eLISA's band at some point in their cosmic evolution



adapted from MV & Natarajan 2009

eLISA will probe the cosmic evolution of MBHs in a way complementary to electromagnetic observations

- detect MBHs up to the highest redshifts

- probe the mass range inaccessible through electromagnetic observations

Summary – forming MBHs

- Physics of MBH formation determines *masses* and *abundance* of MBHs in galaxies

- MBHs @ low masses tell the story:

  – gas-dynamical collapse: many galaxies are bereft of MBHs, but when they're there, they're large-ish (~10^4-10^6 M_{sun})

  – Pop III remnants: even dwarfs may have MBHs, can be as small as 100 M_{sun}