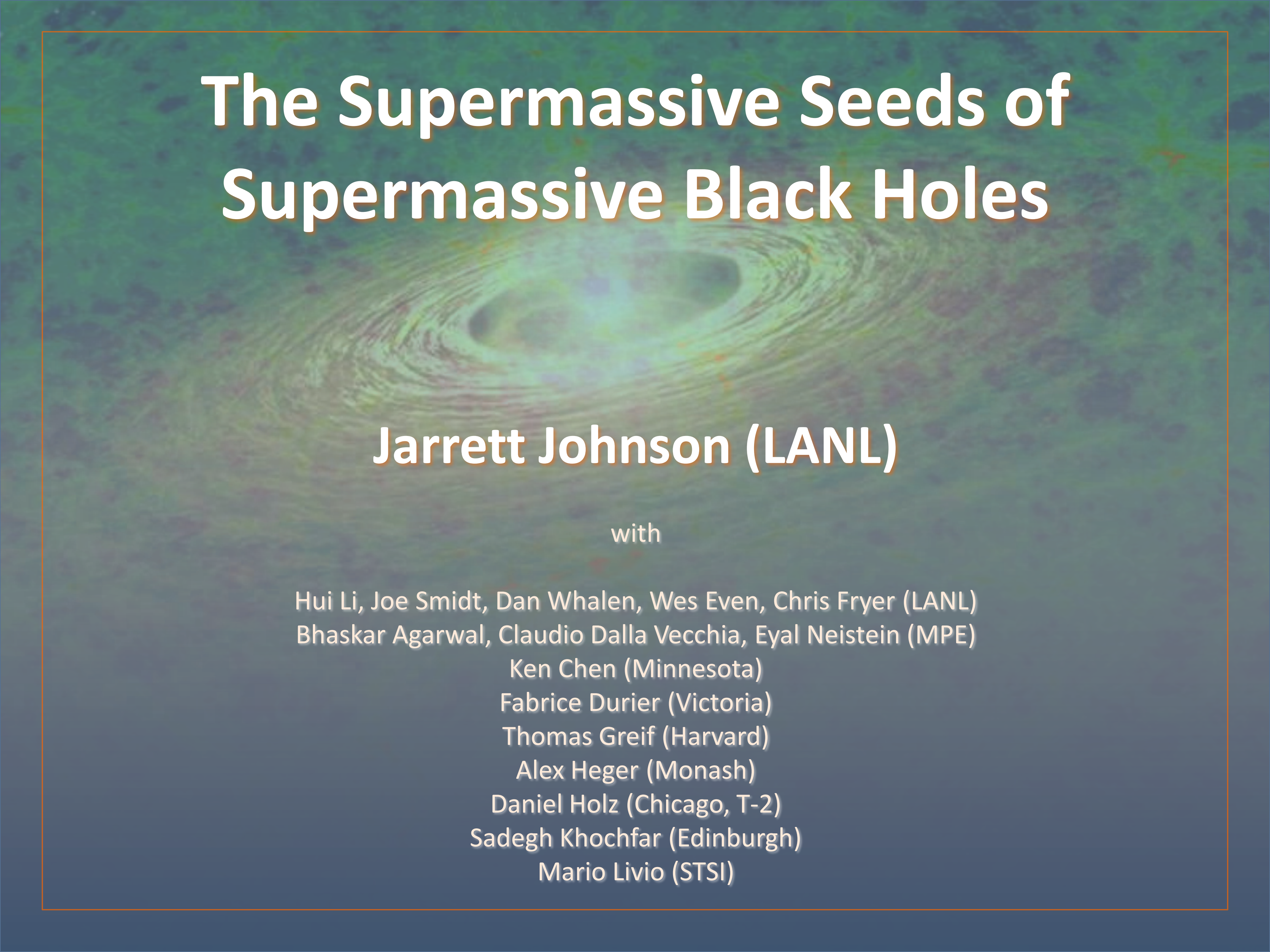

The Supermassive Seeds of Supermassive Black Holes

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with

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Bhaskar Agarwal, Claudio Dalla Vecchia, Eyal Neistein (MPE)
Ken Chen (Minnesota)
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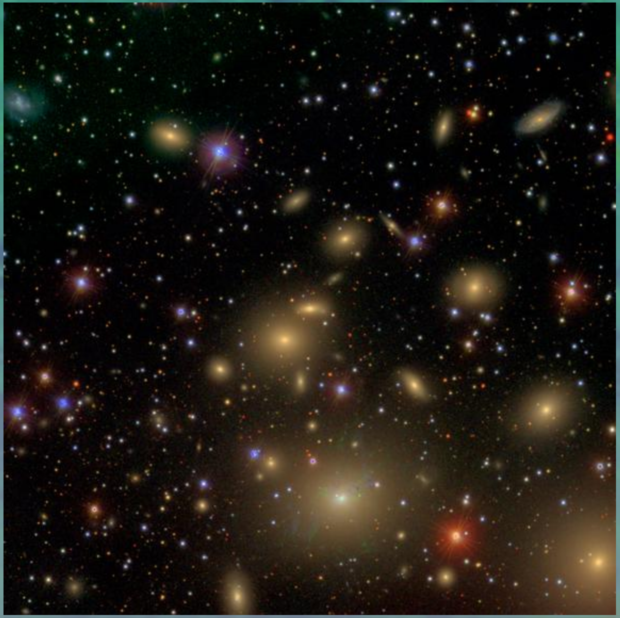
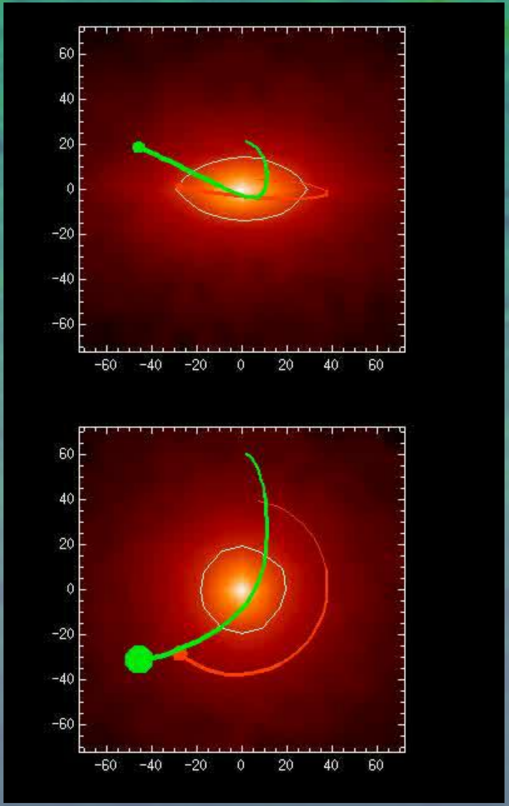
Thomas Greif (Harvard)
Alex Heger (Monash)
Daniel Holz (Chicago, T-2)
Sadegh Khochfar (Edinburgh)
Mario Livio (STSI)

The Ubiquity of Supermassive Black Holes



Every massive galaxy is believed to contain a *supermassive black hole* at its center

What is the origin of supermassive black holes?



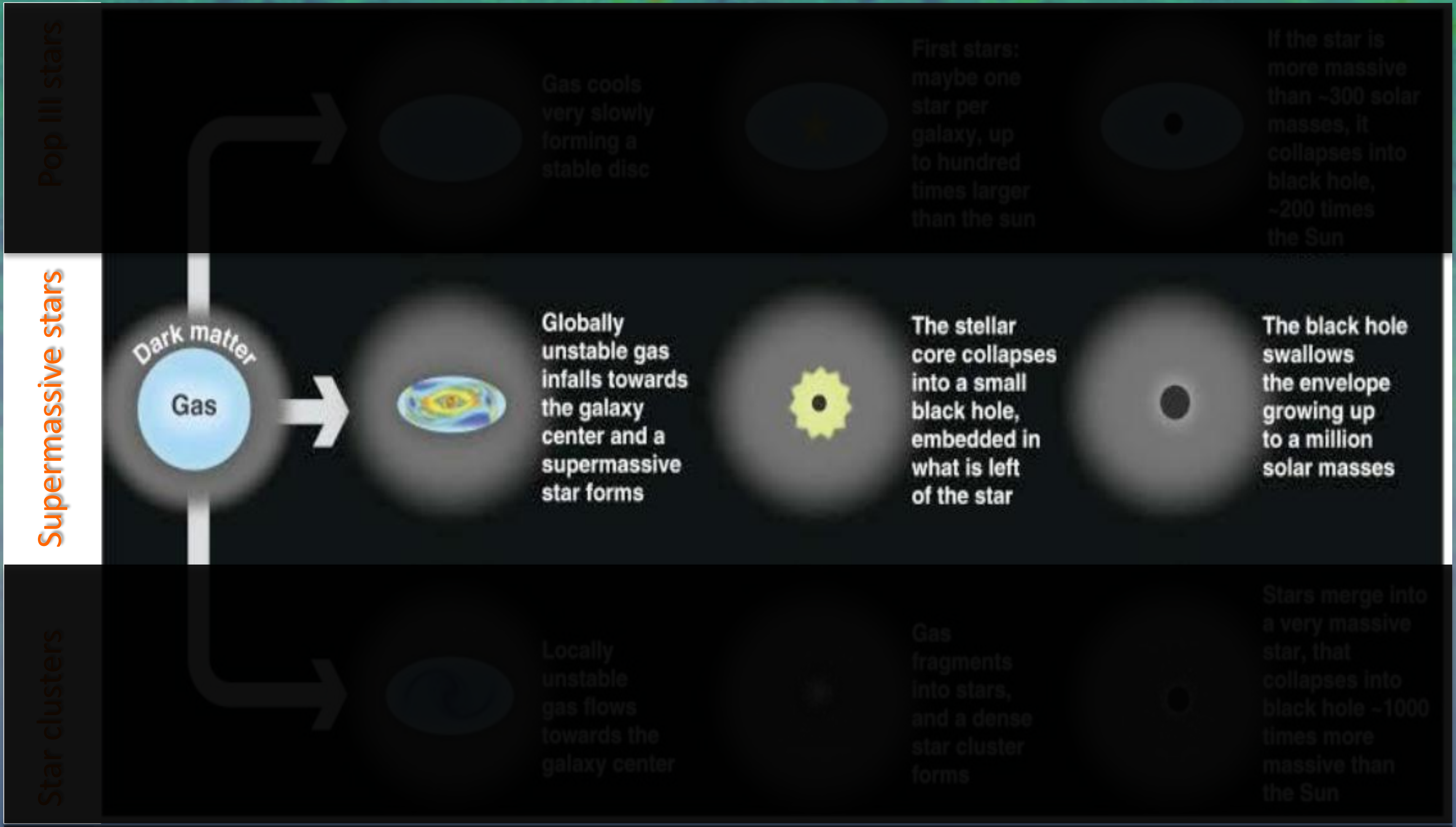
The most massive BH known has a mass of 10 billion M_{sun}

Van den Bosch, et al., *Nature*, 2012

Our Milky Way harbors a 4 million solar mass (M_{sun}) black hole (BH)

credit: zmescience.com

Models for Black Hole Seed Formation



Gas cools very slowly forming a stable disc

First stars: maybe one star per galaxy, up to hundred times larger than the sun

If the star is more massive than ~300 solar masses, it collapses into black hole, ~200 times the Sun

Globally unstable gas infalls towards the galaxy center and a supermassive star forms

The stellar core collapses into a small black hole, embedded in what is left of the star

The black hole swallows the envelope growing up to a million solar masses

Locally unstable gas flows towards the galaxy center

Gas fragments into stars, and a dense star cluster forms

Stars merge into a very massive star, that collapses into black hole ~1000 times more massive than the Sun

Volonteri, *Science*, 2012

Outline

1. Why supermassive stars may be the seeds of supermassive black holes

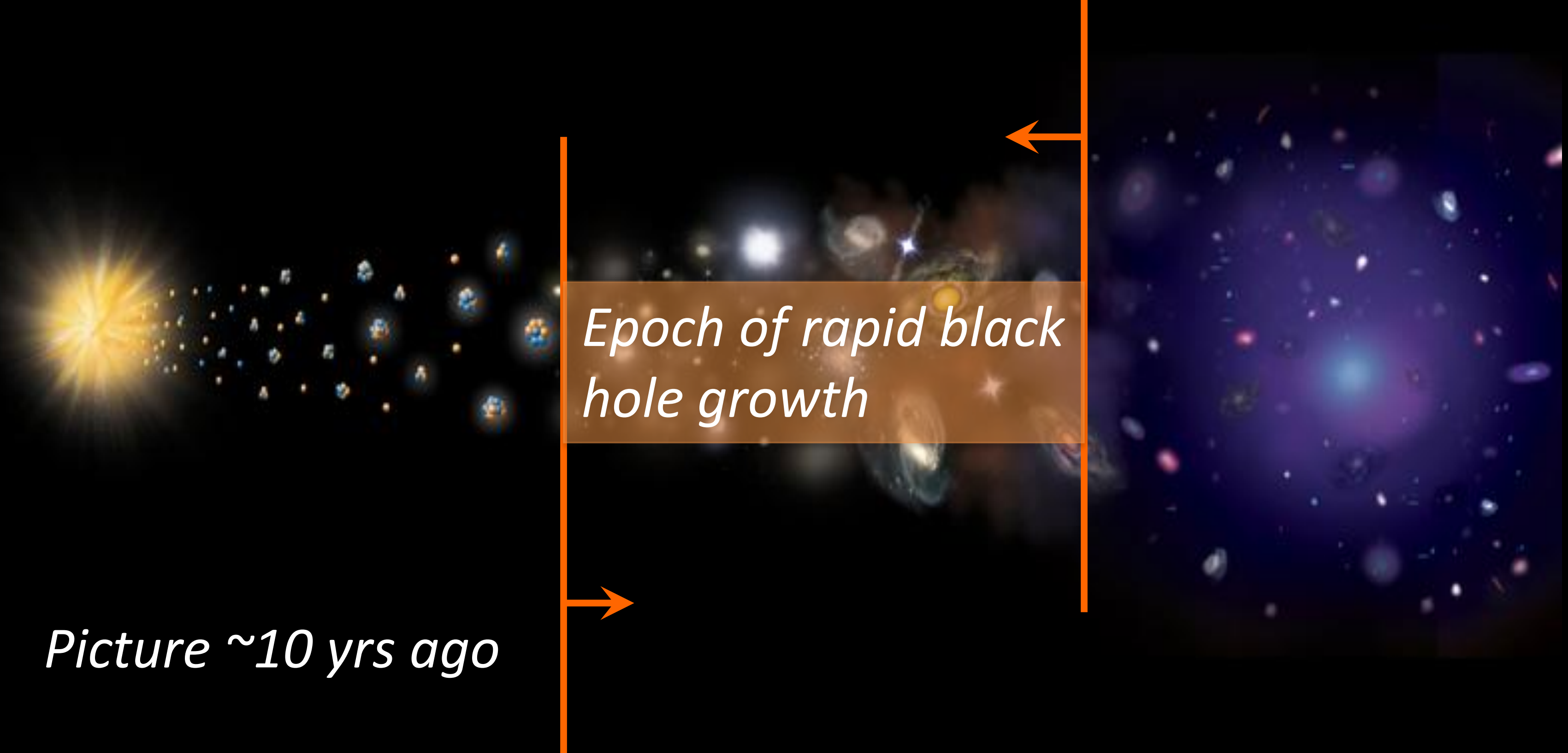
2. The growth of supermassive stars

3. Prospects for detecting them

4. Supermassive supernovae:
   The biggest explosions in the universe

Black Hole Growth in the Early Universe: *Then and Now*

SDSS quasars with 10^9 M_{sun} black holes (BHs) less than a billion years after the Big Bang (at z ~ 6)



Epoch of rapid black hole growth

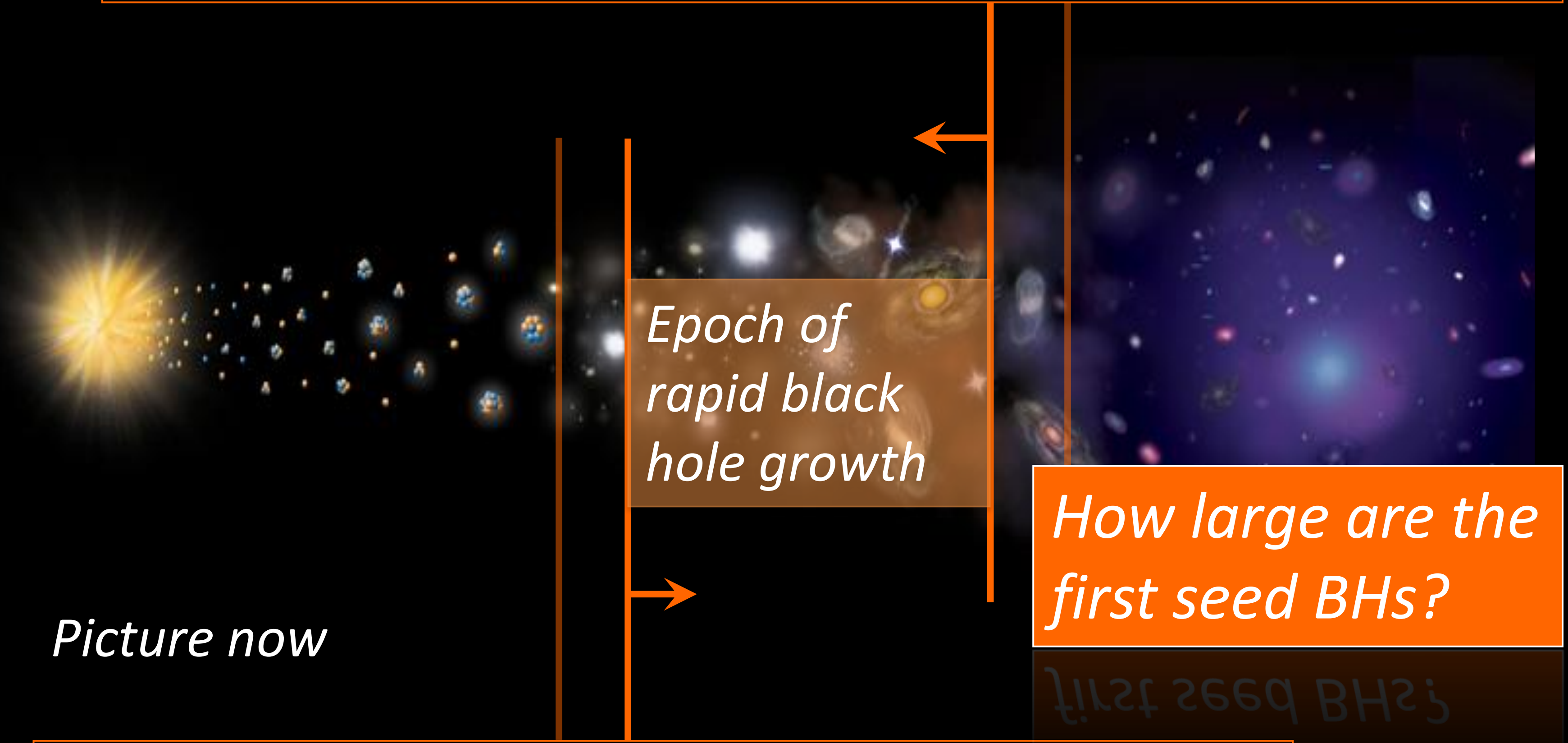
Picture ~10 yrs ago

WMAP1 cosmology: first stars (‘*Population III*’) collapsed to form seed BHs typically ~ 100 million years after Big Bang (at z ~ 30)

credit: chandra.harvard.edu

Black Hole Growth in the Early Universe: *Then and Now*

UKIDSS quasar (Mortlock et al. 2011) with ~2 x 10^9 M_{sun} black hole less than 800 Myrs after the Big Bang (at z ~ 7)



Epoch of rapid black hole growth

How large are the first seed BHs?

Picture now

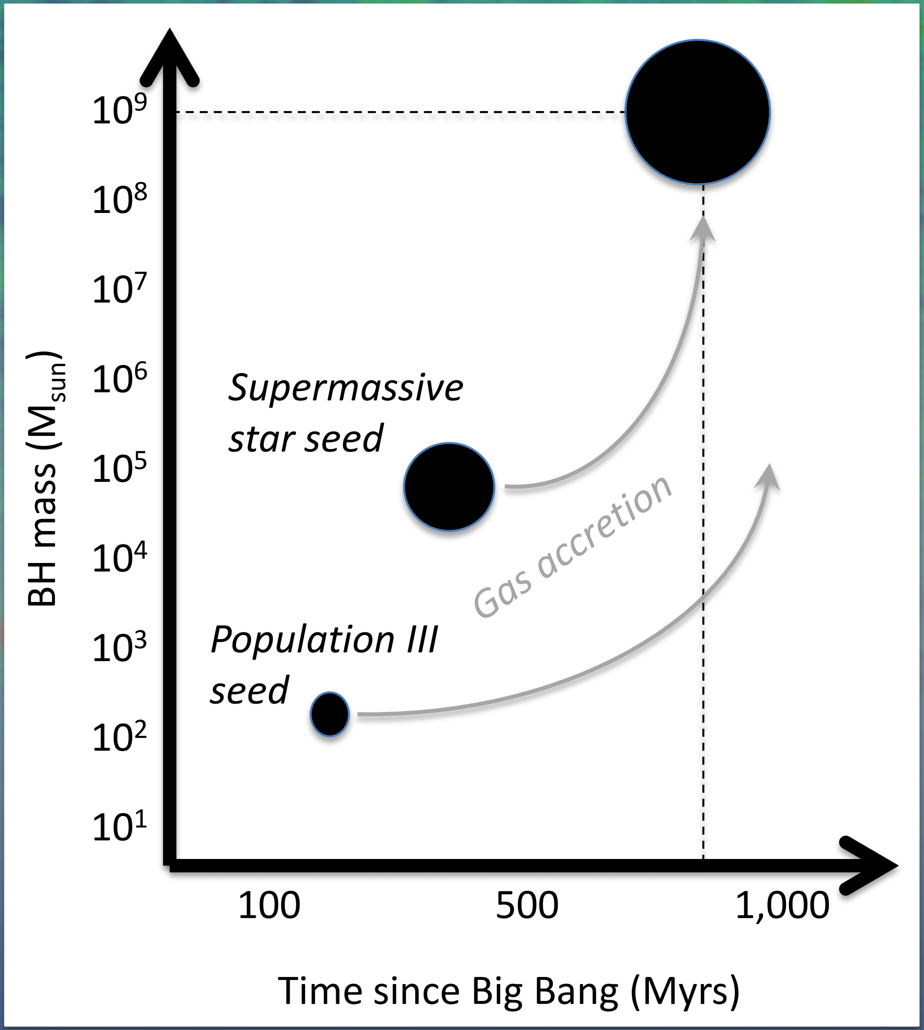
WMAP9/Planck cosmology: *Population III* collapsed to form seed BHs typically ~ 200 million years after Big Bang (at z ~ 20)

credit: chandra.harvard.edu

Supermassive Seeds for Supermassive Black Holes

- Given the limited time for the growth of seed BHs, the existence of the earliest quasars *strongly challenges the Pop III seed model*

- Strongest constraints come from the 2 x 10^9 M_{sun} SMBH at z = 7 (Mortlock et al. 2011) – suggests seeds ~ 10^5 M_{sun}



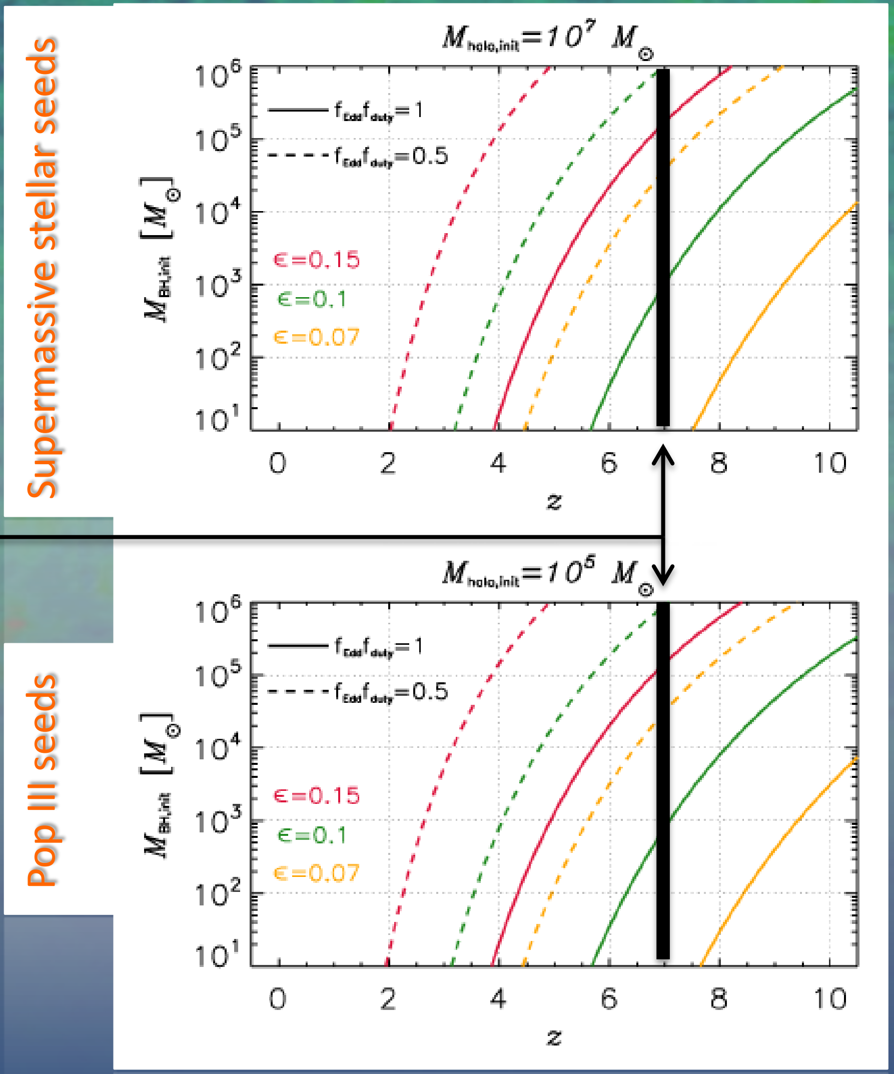
See JLJ, Whalen, Li & Holz 2013

Supermassive Seeds for Supermassive Black Holes

- Given the high radiative efficiency inferred for the highest-z SMBHs ($\varepsilon > 0.1$), the existence of the highest-redshift quasars *strongly challenges the Pop III seed model*

- Strongest constraints come from the 2×10^9 M_{sun} SMBH at $z = 7$ (Mortlock et al. 2011), along with the latest WMAP/Planck cosmological parameters

- This and much theory instead support the *supermassive star* model (e.g. Bromm & Loeb 2003; Wise et al. 2008; Regan & Haehnelt 2009; Shang et al. 2010; Wolcott-Green et al. 2011; Natarajan & Volonteri 2012; Latif et al. 2013)



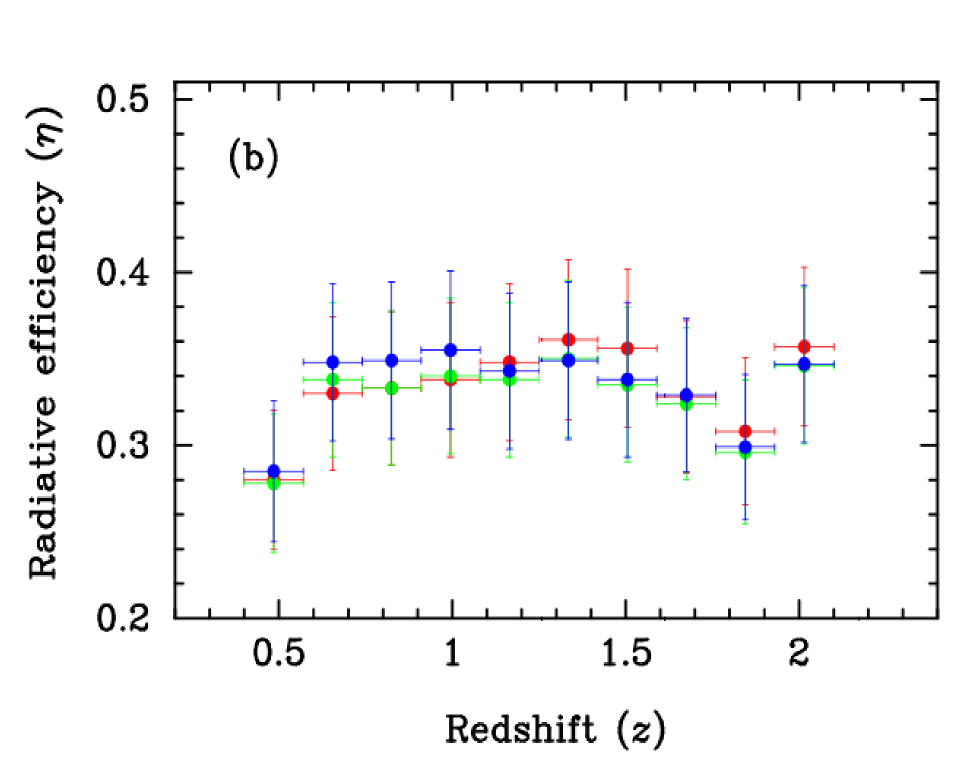
JLJ et al. 2013; see also e.g. Volonteri & Rees 2005, 2006

Radiative Efficiencies of Observed High-z Quasars

Observations suggest that high-z SMBHs typically have radiative efficiencies of $\varepsilon > 0.1$ -- 0.15 (e.g. Elvis et al. 2002; Yu & Tremaine 2002; Volonteri et al. 2005; Shankar et al. 2010)

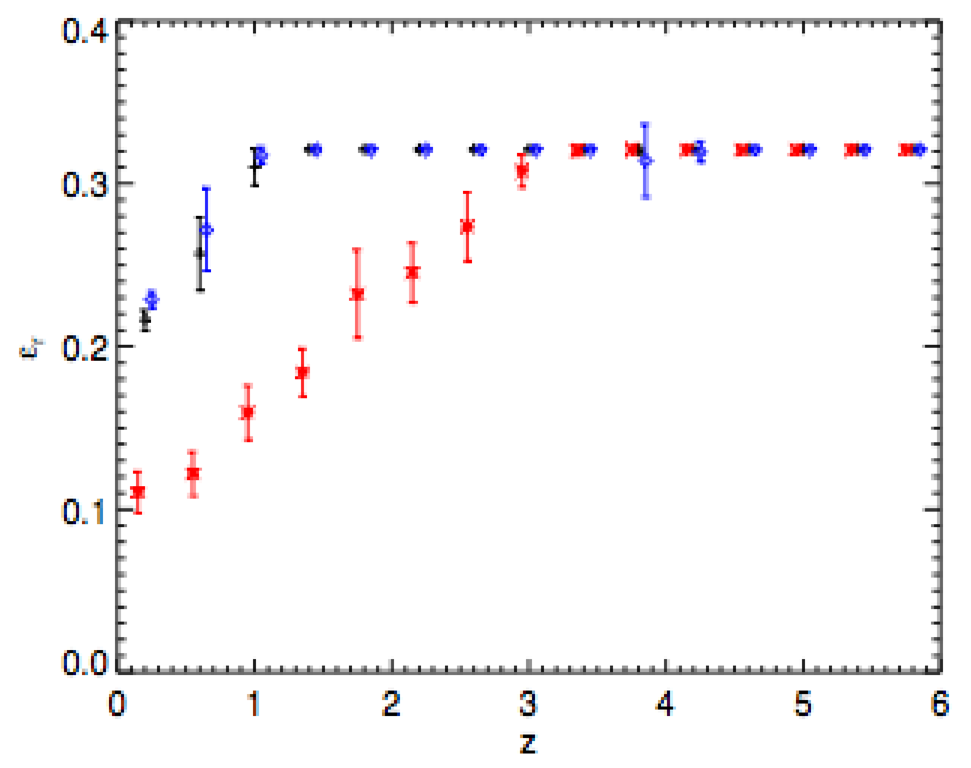
Radiative efficiencies tend to increase with redshift and with BH mass of (e.g. Wang et al. 2006, 2009; Davis & Laor 2011; Shankar et al. 2011; Barausse 2012; Volonteri et al. 2012)

Values as high as $\varepsilon \sim 0.3 - 0.4$ have been estimated for $\sim 10^9$ M_{sun} BHs at high-z (Li et al. 2012)



Wang et al. 2006

Radiative Efficiencies from Cosmological Simulations



Especially at high-z, central BH spins tend to align with angular momentum of the surrounding gas

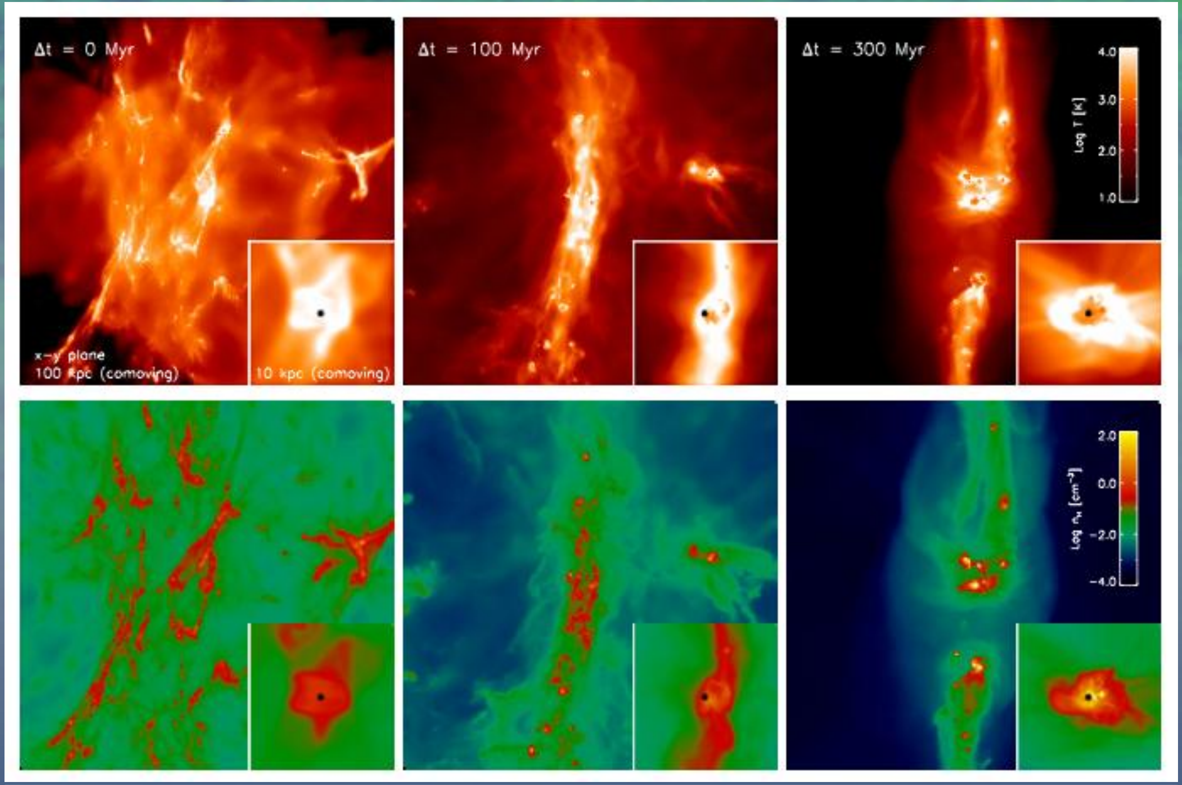
→ High BH spin (a)

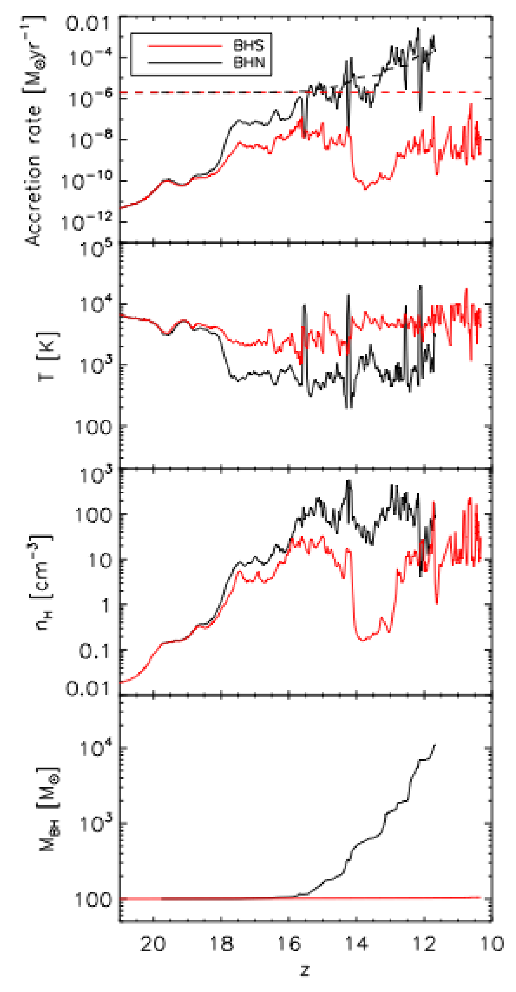
→ High radiative efficiency (ε)

Dubois et al. 2013; see also e.g. Barausse 2012; Dotti et al. 2013

Pop III Seed BH Growth in Cosmological Simulations

Early growth of Pop III BH seeds is found to be slow, due to strong radiative feedback





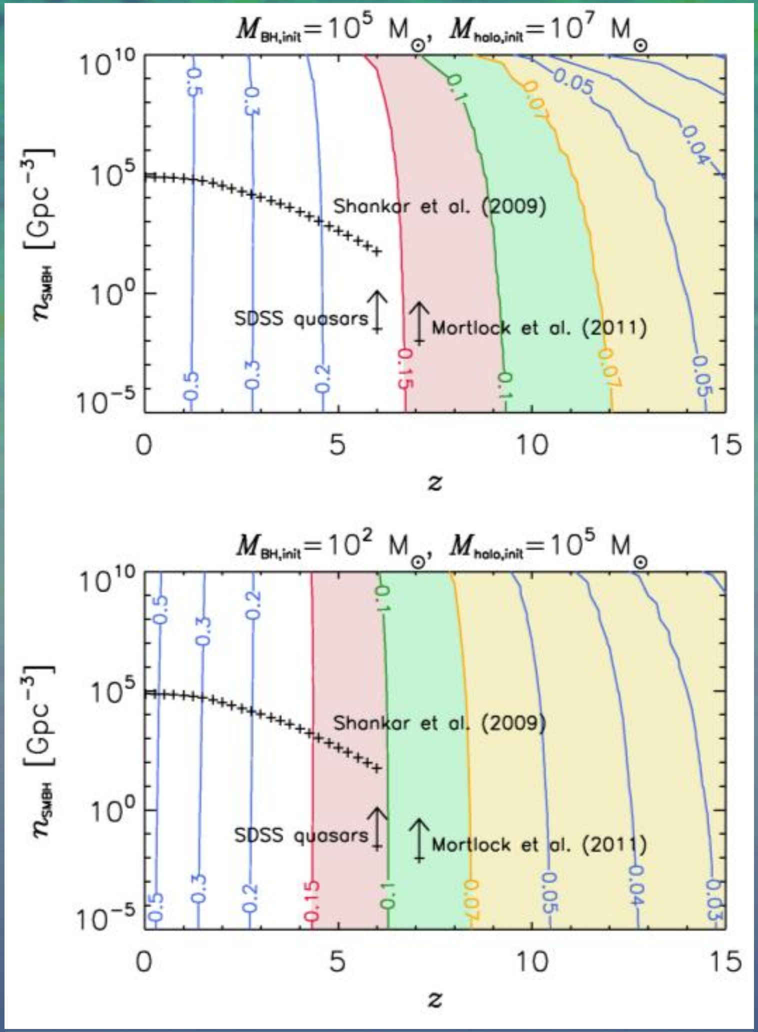
Jeon et al. 2012; also e.g. Alvarez et al. 2009; Park & Ricotti 2013; Milosavljevic et al. 2009

Constraints on BH Accretion History from High-z Quasars

Pop III seeds with ~100 M_{sun} must grow constantly at Eddington rate with radiative efficiency < 0.09 (or at super-Eddington rates) to explain z ~ 7 quasar

-But such low radiative efficiency and high Eddington factor are not supported by existing observational and theoretical evidence

- Leaves massive seeds as the simplest, most consistent explanation for high-z SMBHs



JLJ et al. 2013; see also e.g. Volonteri & Rees 2005, 2006

Supermassive Stars vs. Standard Pop III Stars

	'Standard Pop III'	**Supermassive Pop III**
Formation site	~ $10^5 - 10^7\ M_{sun}$ halos	~ $10^7 - 10^8\ M_{sun}$ halos
Gas coolant	H_2 molecules	Atomic H
Gas temperature	~ 100 K	~ 10,000 K
Accretion rate	~ $10^{-4} - 10^{-3}\ M_{sun}\ yr^{-1}$	~ $10^{-1} - 1\ M_{sun}\ yr^{-1}$
Typical mass	$10 - 100\ M_{sun}$	$10{,}000 - 10^6\ M_{sun}$
Possible end states	$10^{51} - 10^{53}$ erg SN $10 - 100\ M_{sun}$ BH	~ 10^{55} erg SN $10{,}000 - 10^6\ M_{sun}$ BH

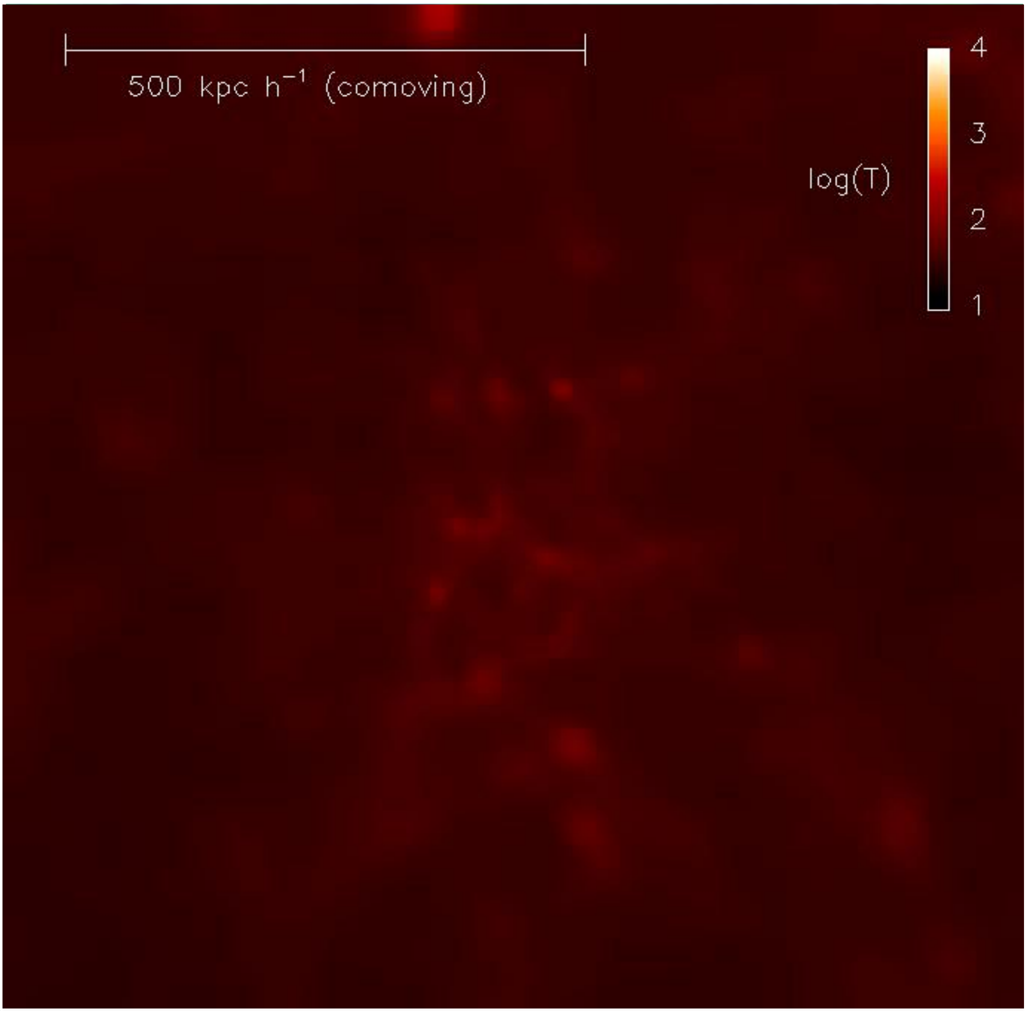
Deciding factor is just the abundance of H_2 molecules*

**See also e.g. Sethi et al. 2010; Inayoshi & Omukai 2012; van Borm & Spaans 2013 on possible additional mechanisms*

Supermassive Star Formation: Hot Primordial Gas

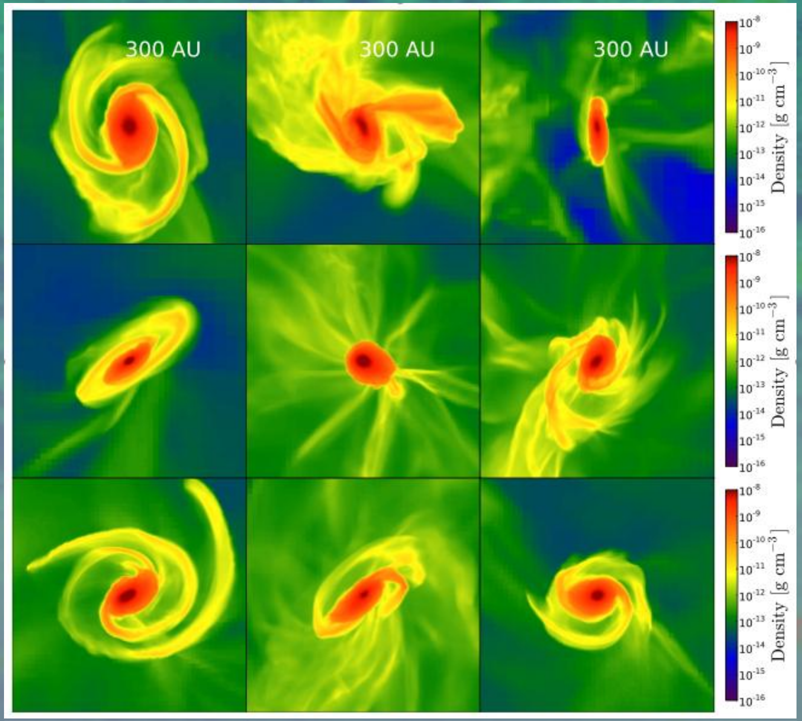
- An elevated H_2-dissociating radiation field suppresses cooling of the primordial gas (e.g. Machacek et al. 2001; Yoshida et al. 2003; O'Shea & Norman 2008; Omukai et al. 2008; but see also e.g. Inayoshi & Omukai 2012)
- Gas cools to only ~ 10^4 K by collisional excitation of hydrogen (e.g. Bromm & Loeb 2003; Spaans & Silk 2006; Begelman et al. 2006; Lodato & Natarajan 2006; Wise et al. 2008; Regan & Haehnelt 2009; Shang et al. 2010; Choi et al. 2013)
- *Gas collapses and accretes onto central supermassive star at ~ $0.1 - 1\ M_{sun}\ yr^{-1}$*

Gas temperature

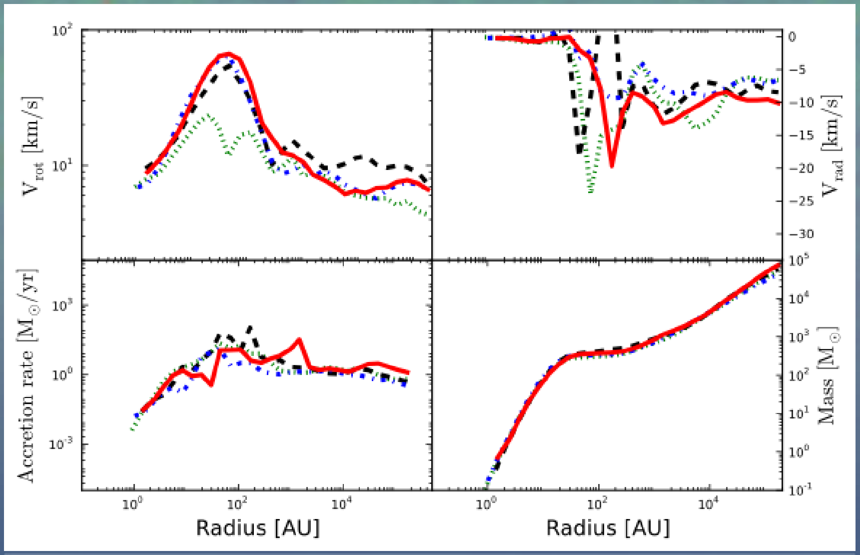


JLJ, Khochfar, Greif & Durier 2011

Resolving Supermassive Star Formation

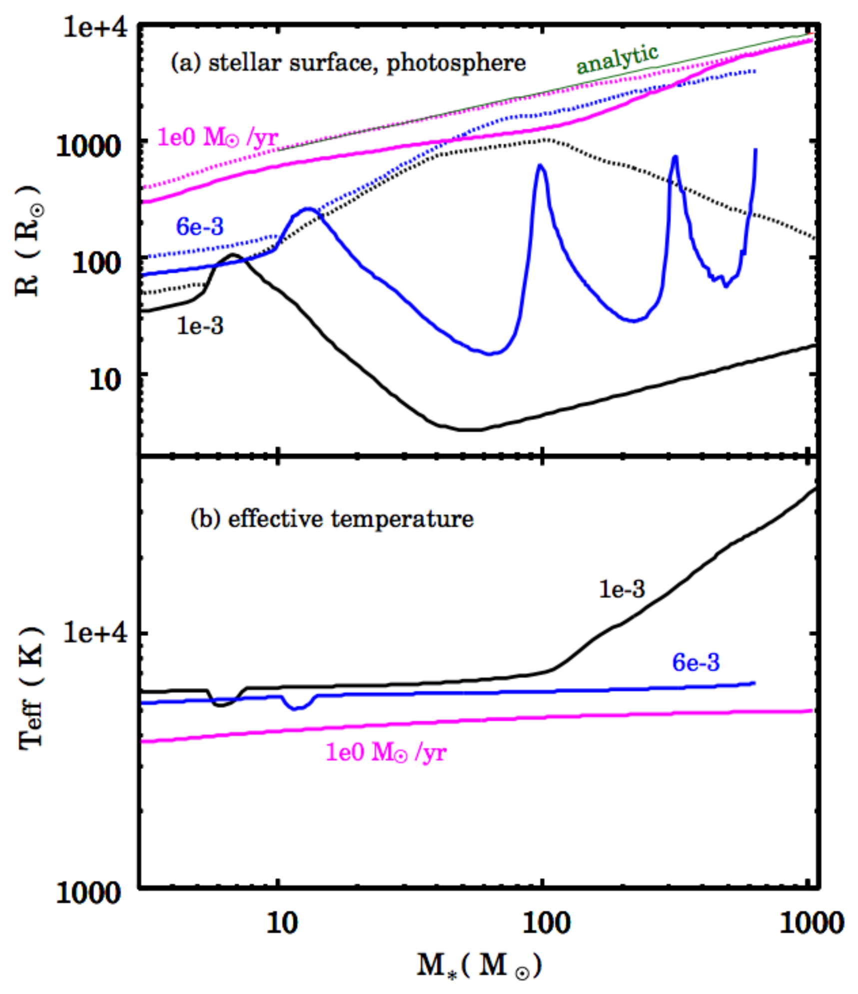


Same high accretion rates (~ *0.1 – 1* M_{sun} yr^{-1}) found even in the highest resolution cosmological simulations of SMS formation



Latif et al. 2013; see also e.g. Wise et al. 2008; Regan & Haehnelt 2009

Weak Radiative Feedback from Supermassive Protostars



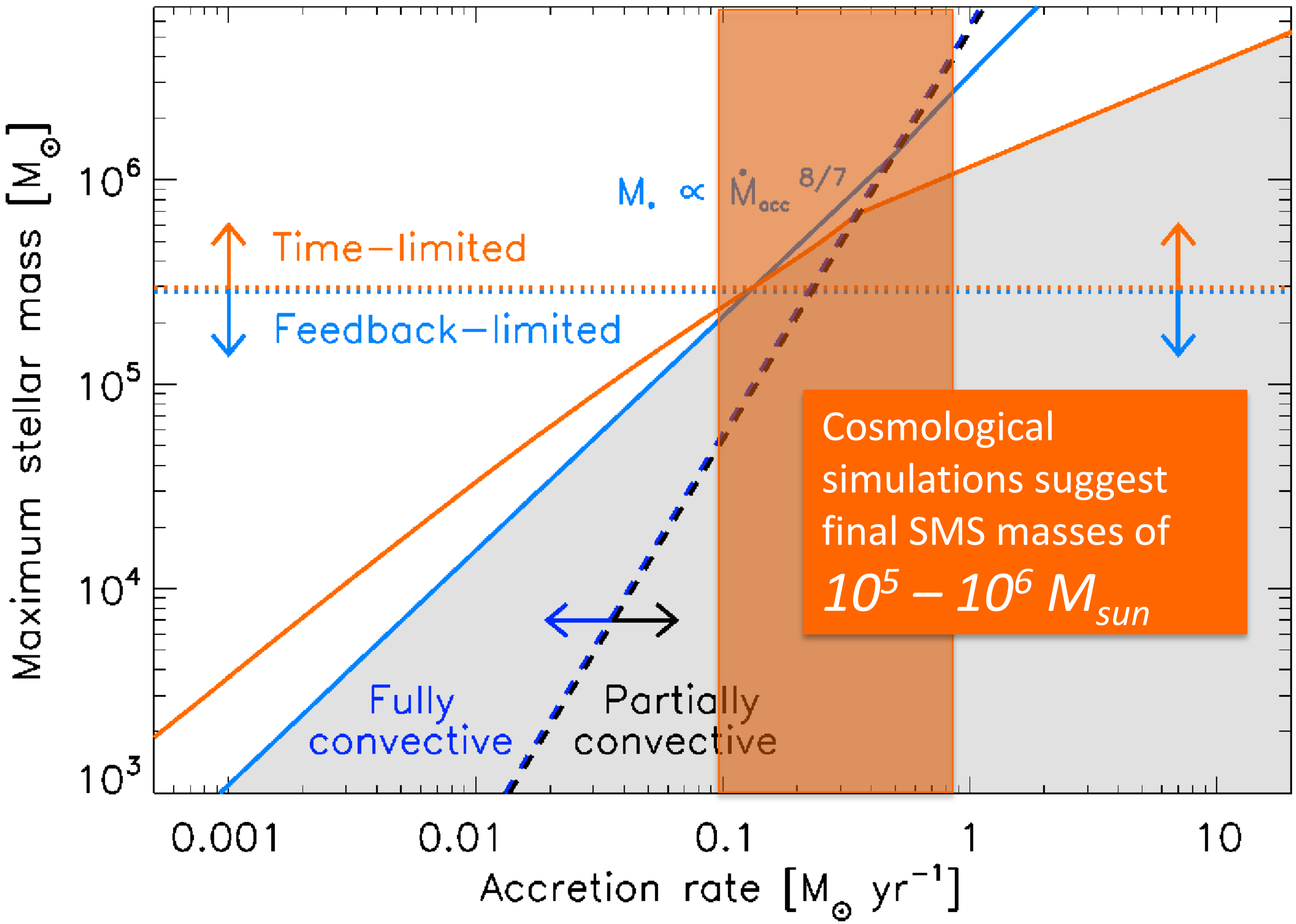
Extended envelopes keep surface temperature low, limit radiative feedback

Growth proceeds easily to $> 10^3\ M_{sun}$

What are the final masses of SMSs under radiative feedback?

Hosokawa et al. 2012

The Maximum Stellar Mass Under Strong Feedback



Cosmological simulations suggest final SMS masses of *$10^5 – 10^6$ M_{sun}*

JLJ, Whalen, Fryer & Li 2012

Identifying the Sites of Supermassive Star Formation

- Requires self-consistently simulating many processes on cosmological scales

- Large-scale (*4+ Mpc comoving*) cosmological simulations with SPH code GADGET:
  - SN feedback and metal enrichment
  - H_2-dissociating radiation from individual (Pop II and III) star clusters

Density

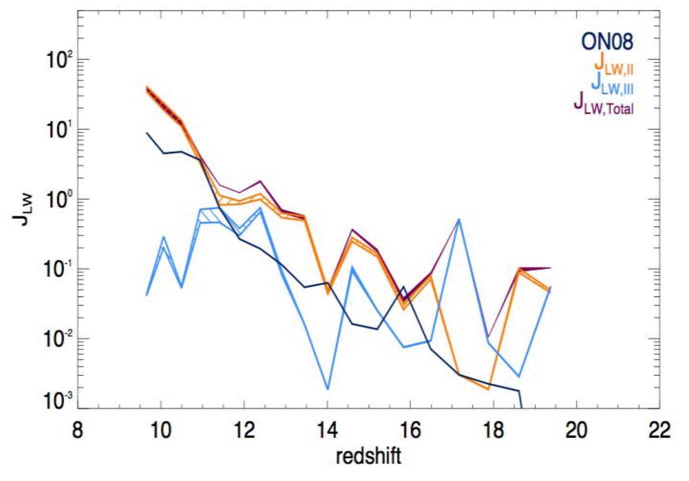
The Milky Way (~100,000 light years across) →

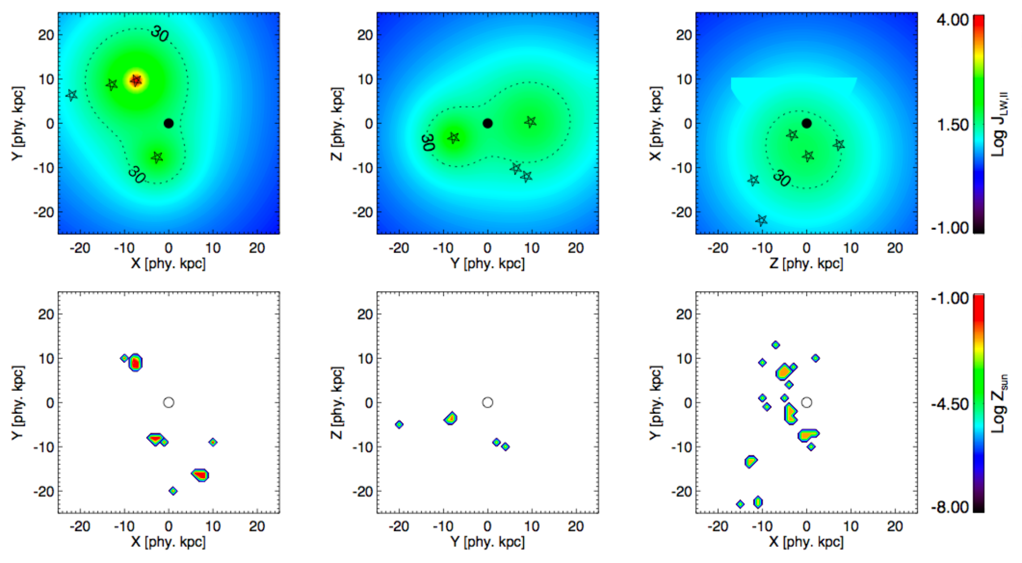
Dalla Vecchia et al. in prep

Supermassive Stars in the FiBY

Surprising result: six candidate SMS host halos found in just a 4 Mpc comoving simulation volume

– Most not expected to grow to billion solar mass scales . . .

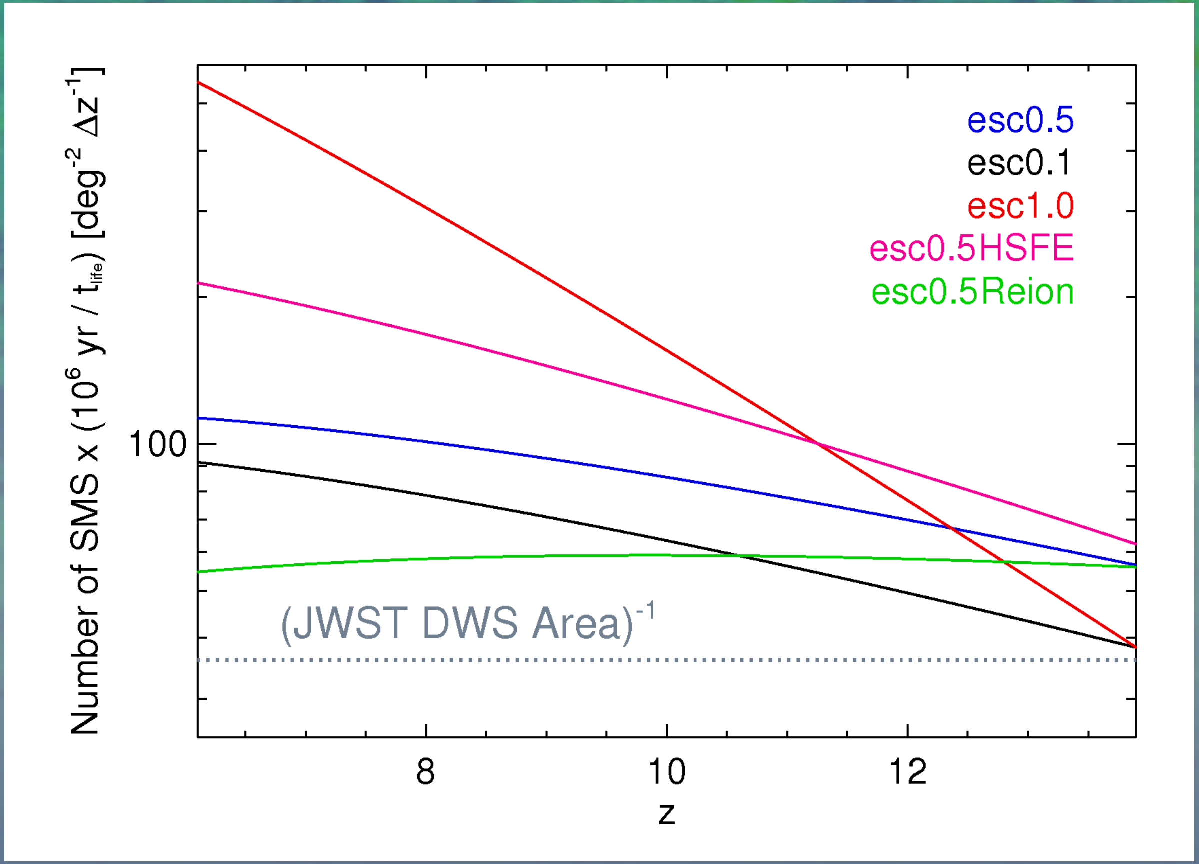




See poster by Bhaskar Agarwal for more!

Agarwal et al. 2013 in prep

Supermassive Star Formation is Common!



Model H_2-dissociating radiation from both Pop II and III stars:

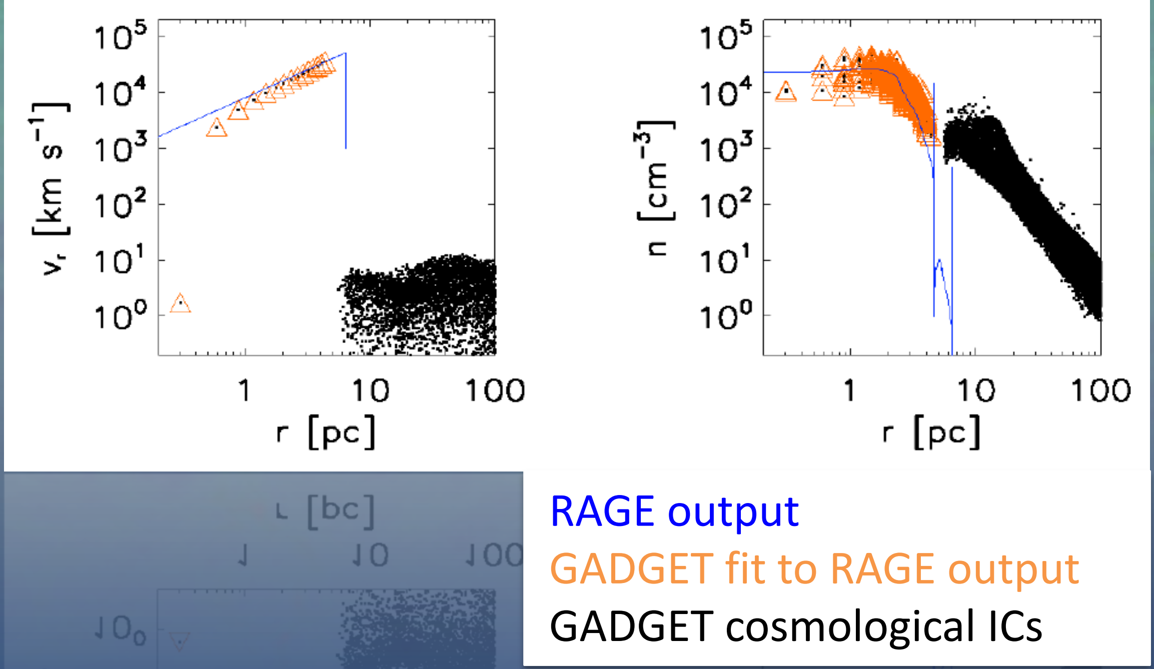
- Vary the photon escape fraction (e.g. Ricotti et al. 2001; Kitayama et al. 2004)
- Vary the star formation efficiency
- Account for photoheating during reionization

Many supermassive stars may be found in deep surveys by the *JWST*!

Agarwal, Khochfar, JLJ, et al. 2012; see also Begelman & Volonteri 2010

Supermassive Stellar Explosions

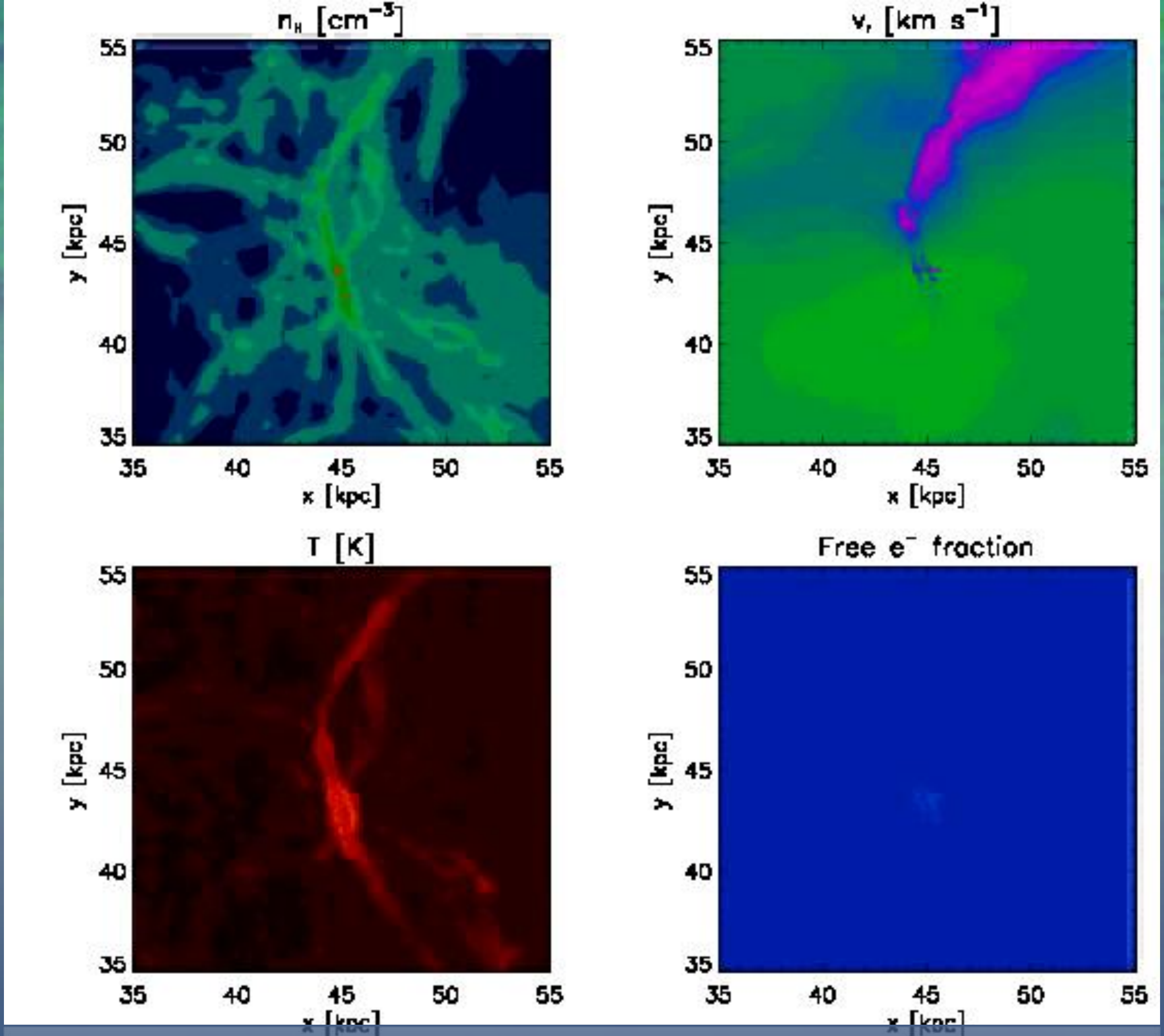
- Stellar evolution calculations by Heger suggest that ~50,000 M_{sun} supermassive stars are completely disrupted
  - *Results in destruction of star in a 10^{55} erg supernova (SN)*
  - *The most energetic thermonuclear events in the universe!*



JLJ et al. 2013; Whalen et al. 2013

Supermassive SNe: *The Biggest Explosions in the Universe*

- Explosion results in complete destruction of host protogalaxy
- Shock propagates farthest into the low density intergalactic medium
- Gas remains hot, ionized for up to 100 Myr
- Densest gas eventually begins to recollapse into the host protogalaxy

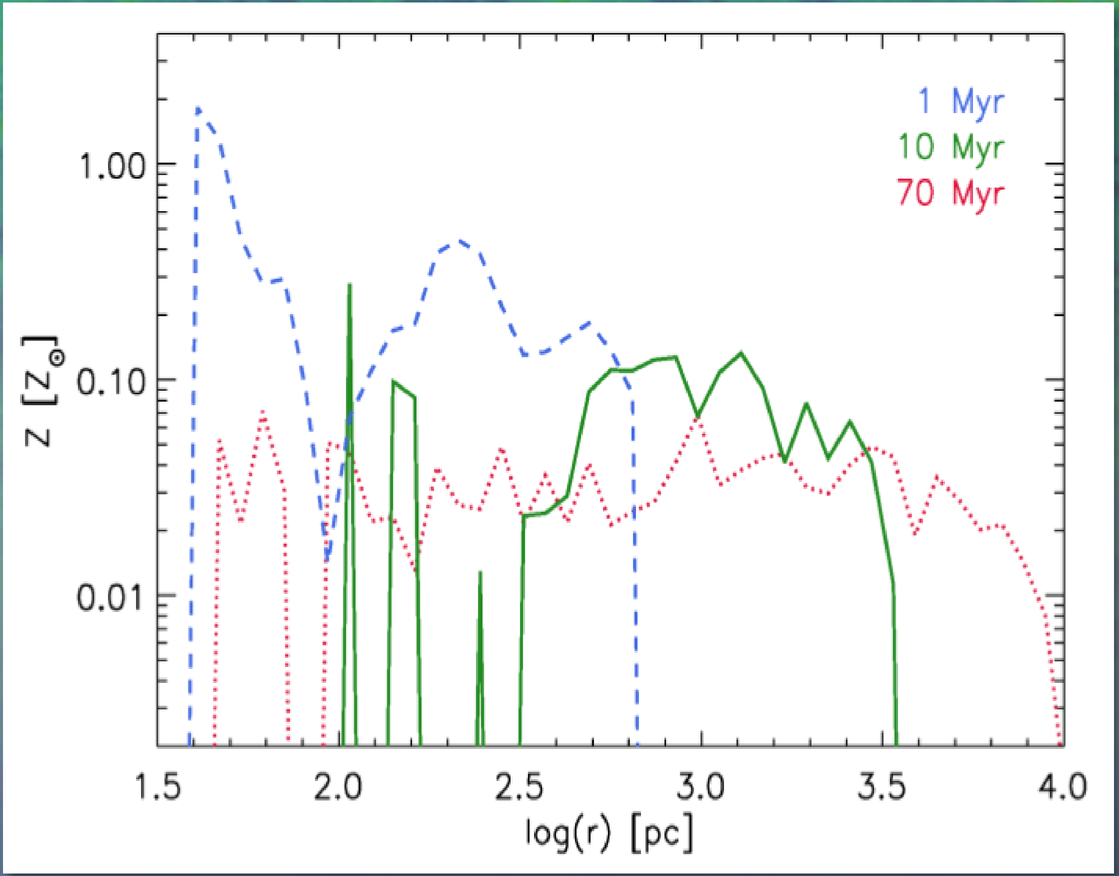


JLJ, Whalen, Even, Fryer, et al. ApJ in press

The Chemical Signature of Supermassive SNe

- ~20,000 M_{sun} in heavy elements mixes with ~10^7 M_{sun} of primordial gas
  - Relatively high metallicity of ~0.05 Z_{sun}!

- The chemical signature of supermassive SNe may be found in relatively high metallicity stars
  - Could have been missed in surveys of low-metallicity (e.g. < 10^{-2} Z_{sun}) stars



JLJ, Whalen, Even, Fryer, et al. ApJ in press

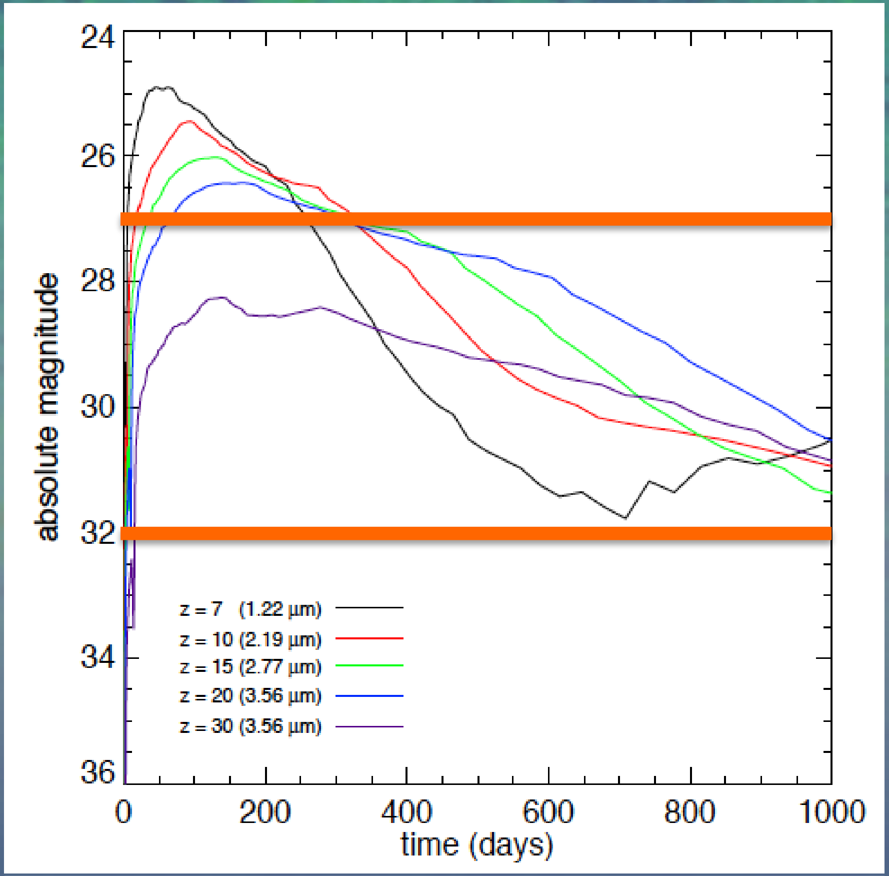
Supermassive Supernovae: Observational Signatures

- Use the SPECTRUM code to calculate the photometric light curve

- Would be bright enough to be detected by:

  - Wide-Field Infrared Survey Telescope (out to z ~ 20)

  - James Webb Space Telescope (out to z > 30)



Whalen et al. 2013

- Overall rate of primordial supernovae may be highest at relatively low redshift (z ~6-10) (e.g. JLJ, Dalla Vecchia & Khochfar 2013)

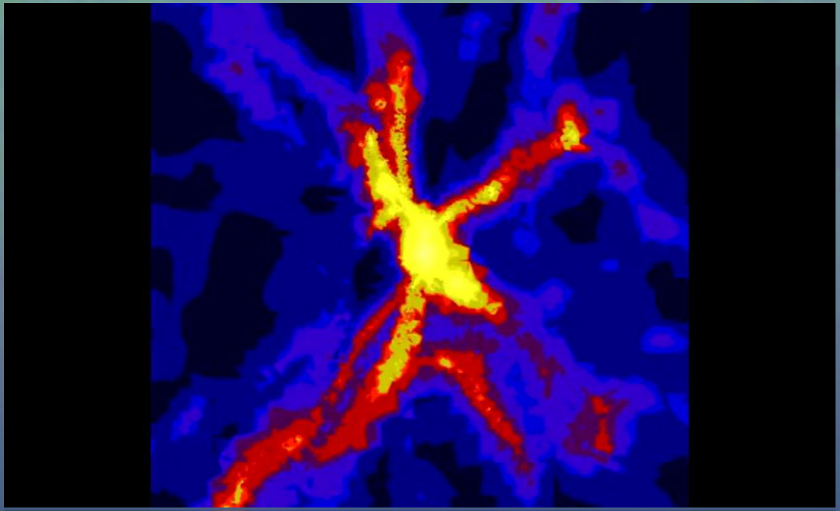
Conclusions

- **Supermassive stars** formed in primordial protogalaxies are the strongest candidates for the seeds of observed supermassive black holes

- The intense ionizing radiation emitted from supermassive primordial stars sets their maximum mass to **~10^5 M_{sun}**

- Supermassive stars may be **common** enough to be detected by the *JWST*

- Supermassive supernovae would have been ***the biggest explosions in the universe***



JLJ, Whalen, Even, Fryer, et al. ApJ in press