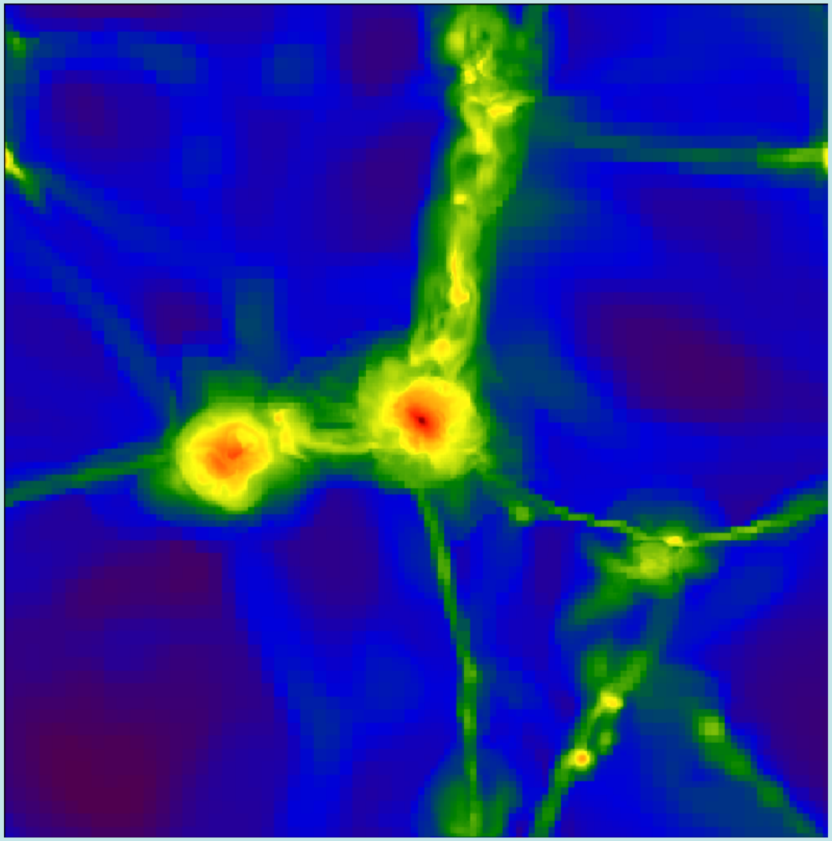
Sowing seeds : assembling the first black holes in the early universe



Priyamvada Natarajan
Yale University

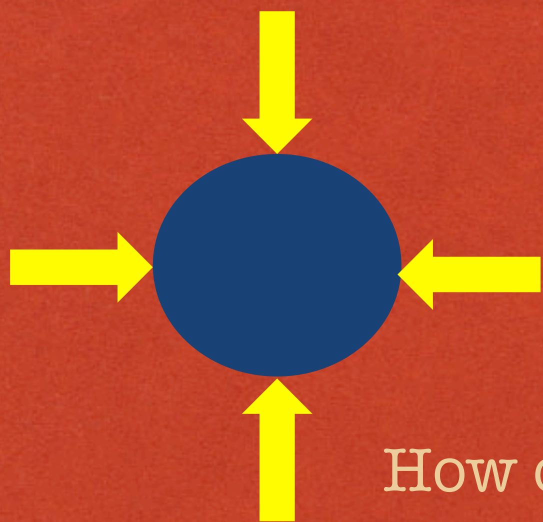
KITP BH CONFERENCE AUGUST 5 – 10, 2013

Talk outline

- What do we know for certain about the growth history of BHs?
- Observational evidence for BHs at high & low z
- Seeding models
- Light vs. massive seeds
- Predictions of seeding models
- Discriminating between seed models at high z and low z
- Open questions and future prospects

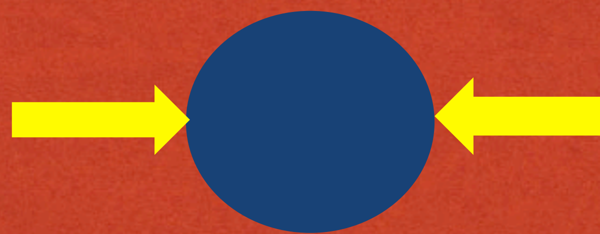
Collaborators: Marta Volonteri, Giuseppe Lodato, Ezequiel Treister,, Britton Smith, Matt Turk, Andrew Davis, Sadegh Khochfar, Bhaskar Agarwal

Challenges in understanding BH accretion



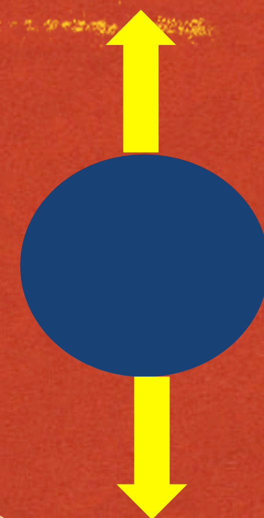
formation

How & where do seeds form?



fueling

How does gas make it to the BH?

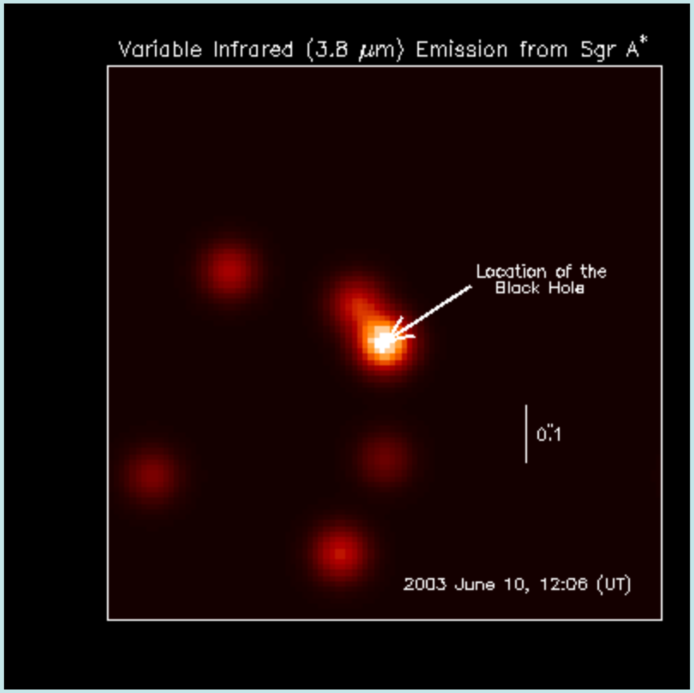


feedback

Impact of the BH

Astrophysical environment of BHs

Empirically, two modes of accretion seen in galactic nuclei, X-ray binaries



UCLA Galactic Center group

- **radiatively inefficient accretion**

e.g. Galactic Center

$$\dot{m} \equiv \dot{M}/\dot{M}_{Edd} \sim 10^{-7}$$

(Shcherbakov et al. 2010; Narayan & Yi)

Ubiquitous: fed by stellar winds, "hot" $T_{ion} \sim T_{vir}$ quasi-spherical flow

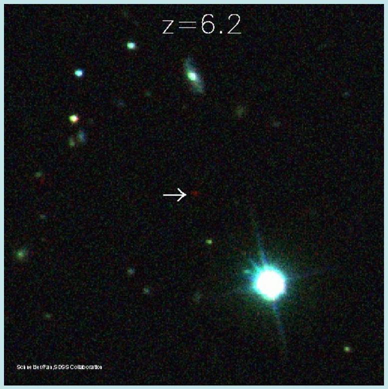
- **thin disk accretion**: radiatively efficient (10%) AGN mode

Feeding mechanism unclear, rare in the local Universe

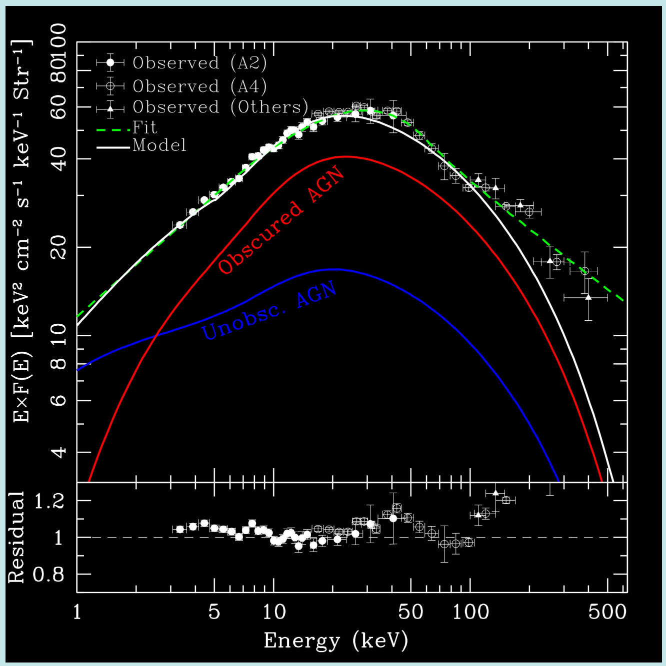
Typical merger environment *only* if thin disks **cause** or are otherwise preferentially correlated with BH coalescences

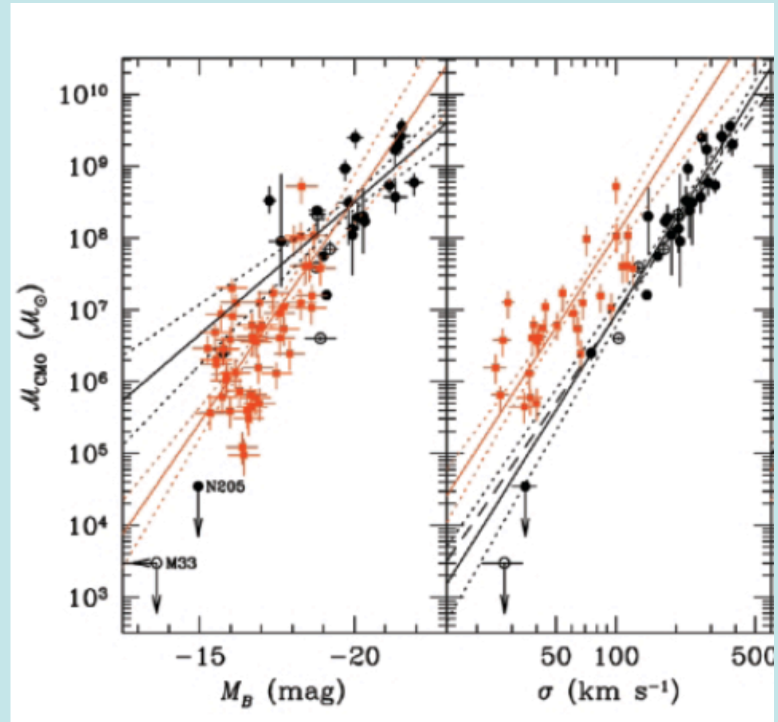
Massive BHs in place @ high z, many in place from low z

Abundance & LF of High redshift quasars



XRB

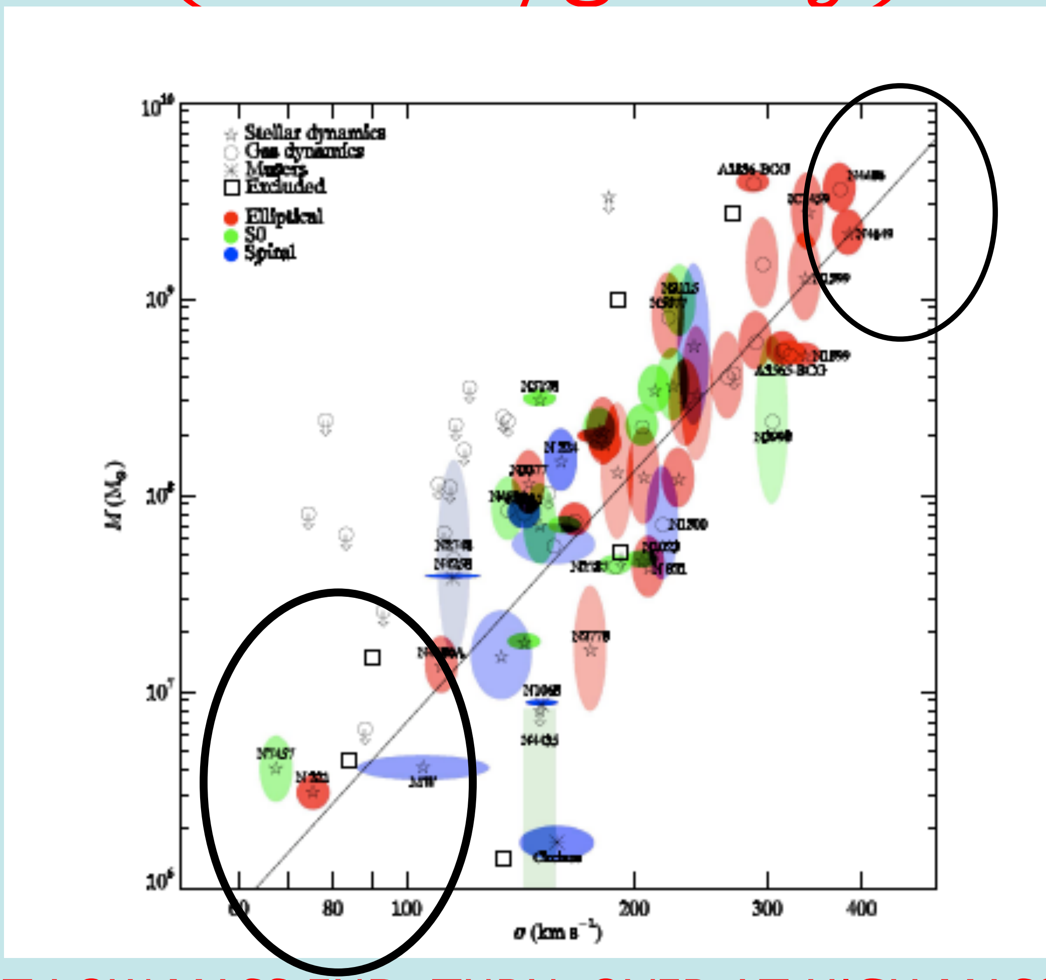




Observational estimates of masses of central massive objects

Ferrarese+ 2006; Ferrarese & Merritt 2002; Tremaine+ 2002; Kaspi+ 2005
Census from SDSS and 2dF Fan+ 2007; Croom+ 2004
Comastri+ 1995; Ueda+ 2003; Treister & Urry 2005; Merloni+ 2004; PN & Treister 2009; Mortlock+ 2010

The Local M_{bh}-sigma relation
(~ 1-BH/galaxy)



<u>SCATTER AT LOW MASS END, TURN-OVER AT HIGH MASS END, OUTLIERS</u>

Gultekin+ 2010; Greene & Ho 2009, Greene+ 2011; Reines+ 2011; Lauer+ 2007; Gebhardt+ 2011; McConnell+ 2011; Bogdan+ 2012; van den Bosch+ 2012

INFERRED MASS FUNCTIONS FOR SDSS BLQSOS 1< z <4.5

10 Kelly et al.

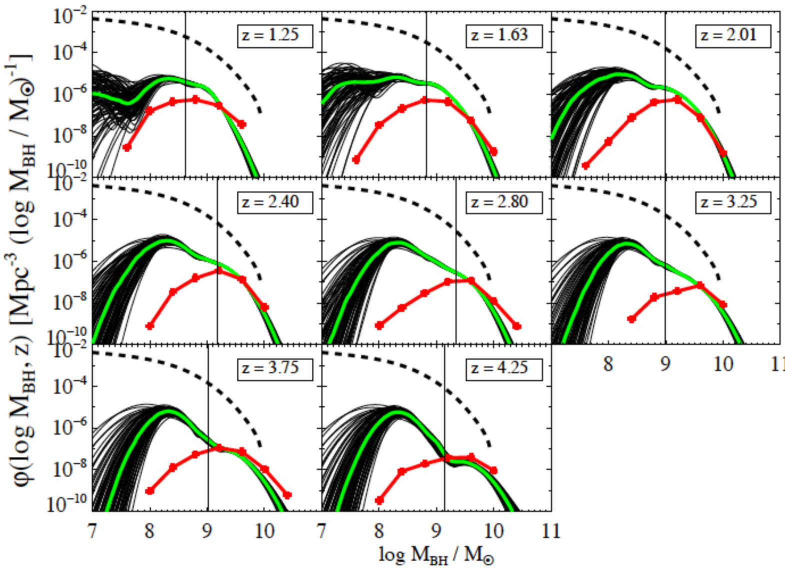
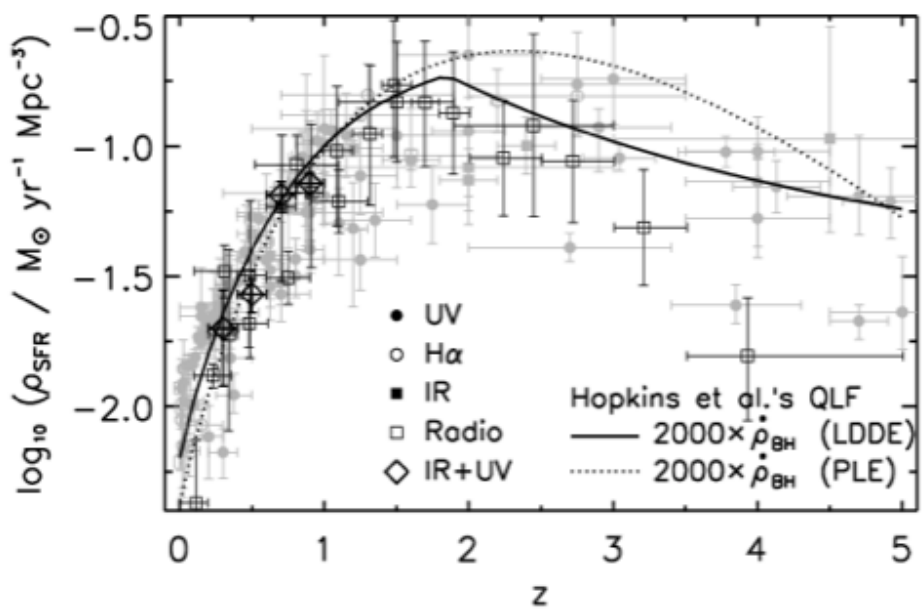


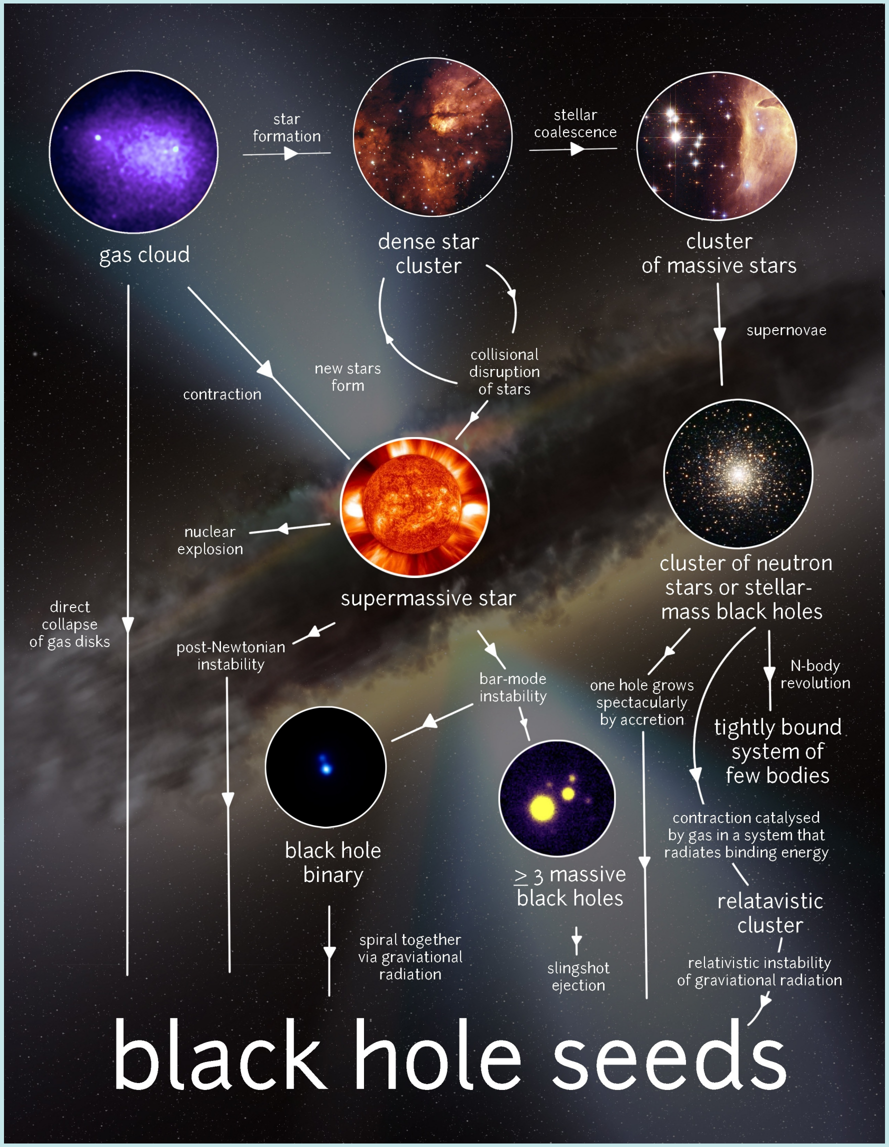
Fig. 3.— BLQSO BHMF (thin solid lines) obtained using our Bayesian approach, compared with the local BHMF line), and the BHMF from Vestergaard et al. (2008, solid red line with points); as in Figure 1, each thin solid line of the BHMF from its probability distribution. The thick green line is the median of the BHMF random draws, our 'best-fit' estimate. The vertical line marks the mass at which the SDSS DR3 sample becomes 10% complete.

Kelly et al. 2010, 2011

BHs AND STARS APPEAR TO GROW IN TANDEM



Pathways to making massive BH seeds



Rees 1978

TWO MAIN CHANNELS

- **Pop III remnants :** Stars form, evolve and collapse
  - $M_* \sim 10^3\, M_\odot$; $M_{BH} \sim 10 - 10^2\, M_\odot$

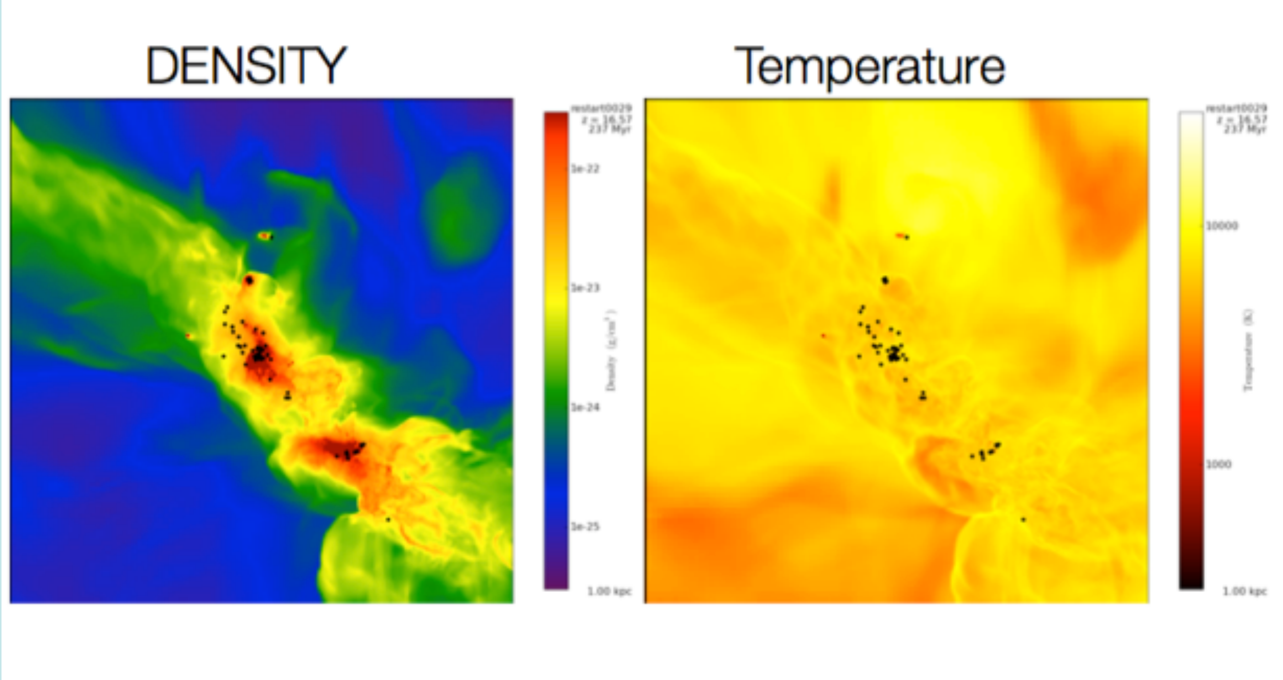
- **Direct collapse:** Massive gas cloud accumulates in nucleus
  - Supermassive star forms but never fully relaxes; keeps growing until collapse
  - $M_* > 10^6\, M_\odot$; $M_{BH} > 10^4\, M_\odot$

First black holes in pre-galactic CDM halos z = 20-30

~~M_{BH} ~ 100 - 500 M_{sun}~~

M_{BH} ~ 10 - 50 M_{sun}

Pop III remnants: Simulations suggested that the first stars were massive (Bromm+ 2002 ; Abel+ 2002; Abel+ 2000; Alvarez+ 2008) & Metal free Pop III stars with M > 260 M_{sun} leave remnant BHs with M_{seed} > 100 M_{sun} (Fryer, Woosley & Heger)



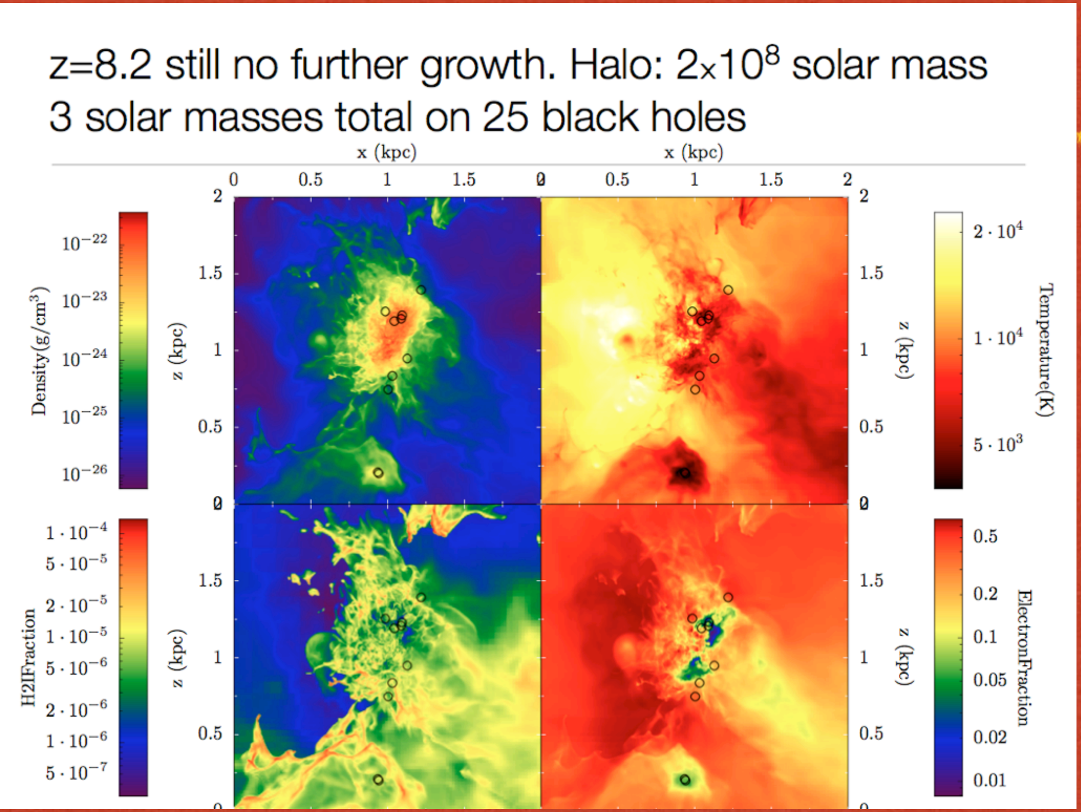
BHs simply not growing much down to z = 8

even when PopIII formation has ceased

BHs spend almost all their time in the wrong place!

WHY DO WE WE NEED MASSIVE SEEDS?

Tracking the fate of Pop III remnant seeds



Pop III now less massive than originally thought as fragmentation is seen in codes
Remnant seeds less massive initially now
BHs simply not growing much down to z = 8
even when PopIII formation has ceased
BHs spend almost all their time in the wrong place!

Abel, Wise, Turk, Alvarez+

MASSIVE SEEDS

$M_{BH} \sim 10^3 - 10^6 M_{sun}$

Viscous transport - efficient angular momentum transfer, suppression of fragmentation – pristine gas

formation of central concentration (Eisenstein & Loeb 1995; Koushiappas+ 2004)+ proper dynamical treatment of disk stability (Lodato & PN 2006, 2007) + Mayer+ 2010 (in mergers)

Supermassive star (Haehnelt & Rees 1993)

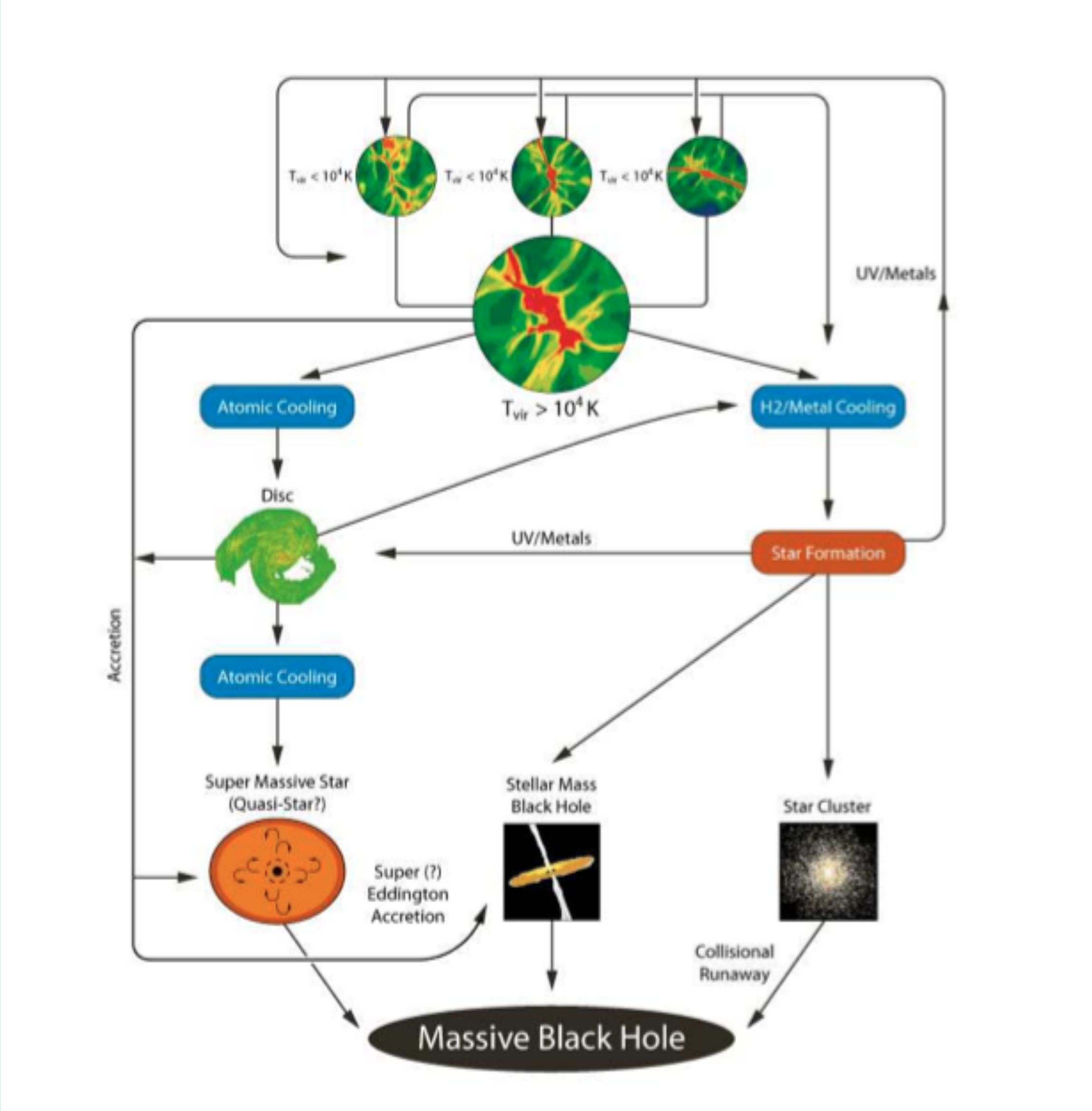
Quasi-star - Bar unstable self-gravitating gas + large quasi-star (Begelman 2008, 2010, 2012)

Direct Collapse Black Holes

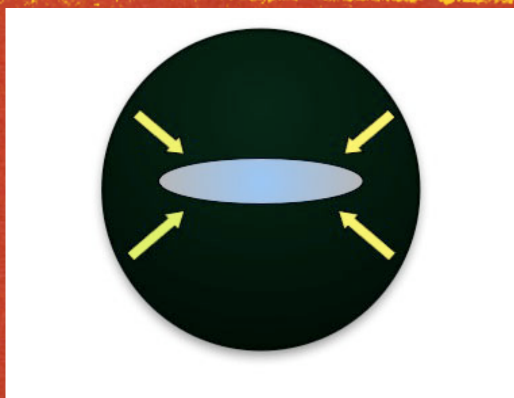
- Metal Free gas in atomic cooling halos ($T_{vir}>10^4$ K): predominantly atomic H
- Avoid fragmentation into stars: high densities
- Prevent H_2 formation (molecular hydrogen) in central region of halo
- High level of LW radiation to dissociate H_2
- SMS followed by black hole of mass ~ 10^5 M_{solar}

Oh & Haiman 2002; Bromm & Loeb 2003; Begelman et al. 2006;
Lodato & Natarajan 2006; 2007, Spaans & Silk 2006; Volonteri+ 2008

Gas collapse to a massive BH seed at high z

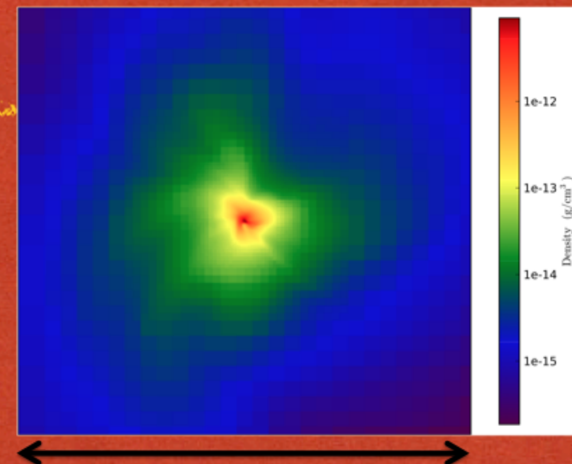


BH seed formation at high z



Baryons inside DM halo collapse and form a rotating pre-galactic disc

Disc becomes gravitationally unstable and accretes to the center



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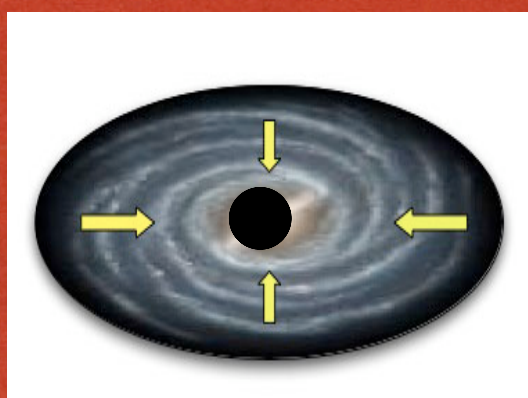
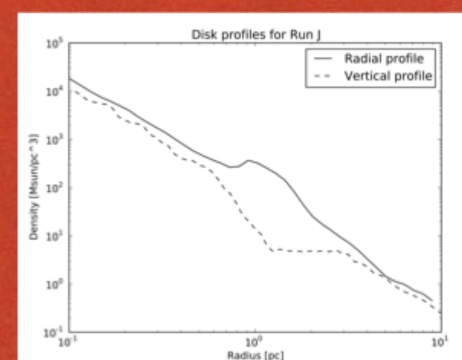
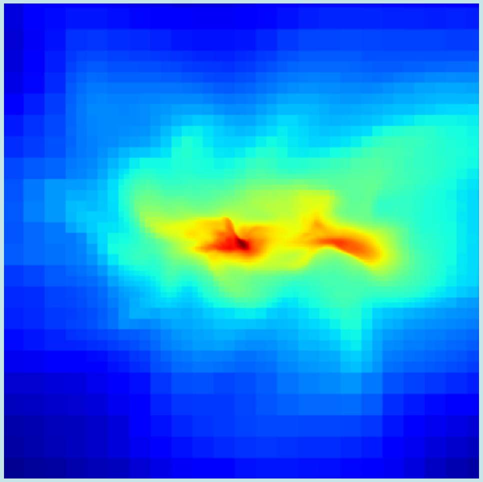


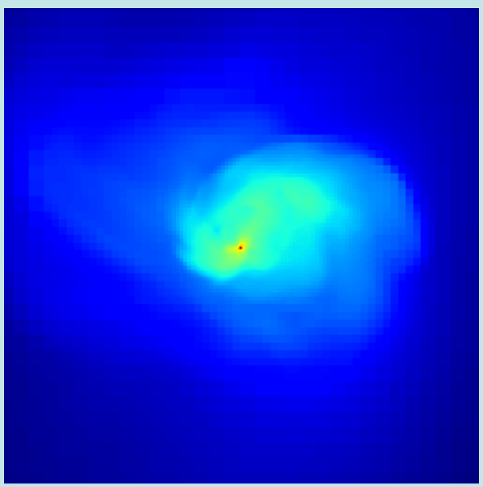
Angular mom of DM halo + Gas reservoir + dynamics (disc stability) + cooling

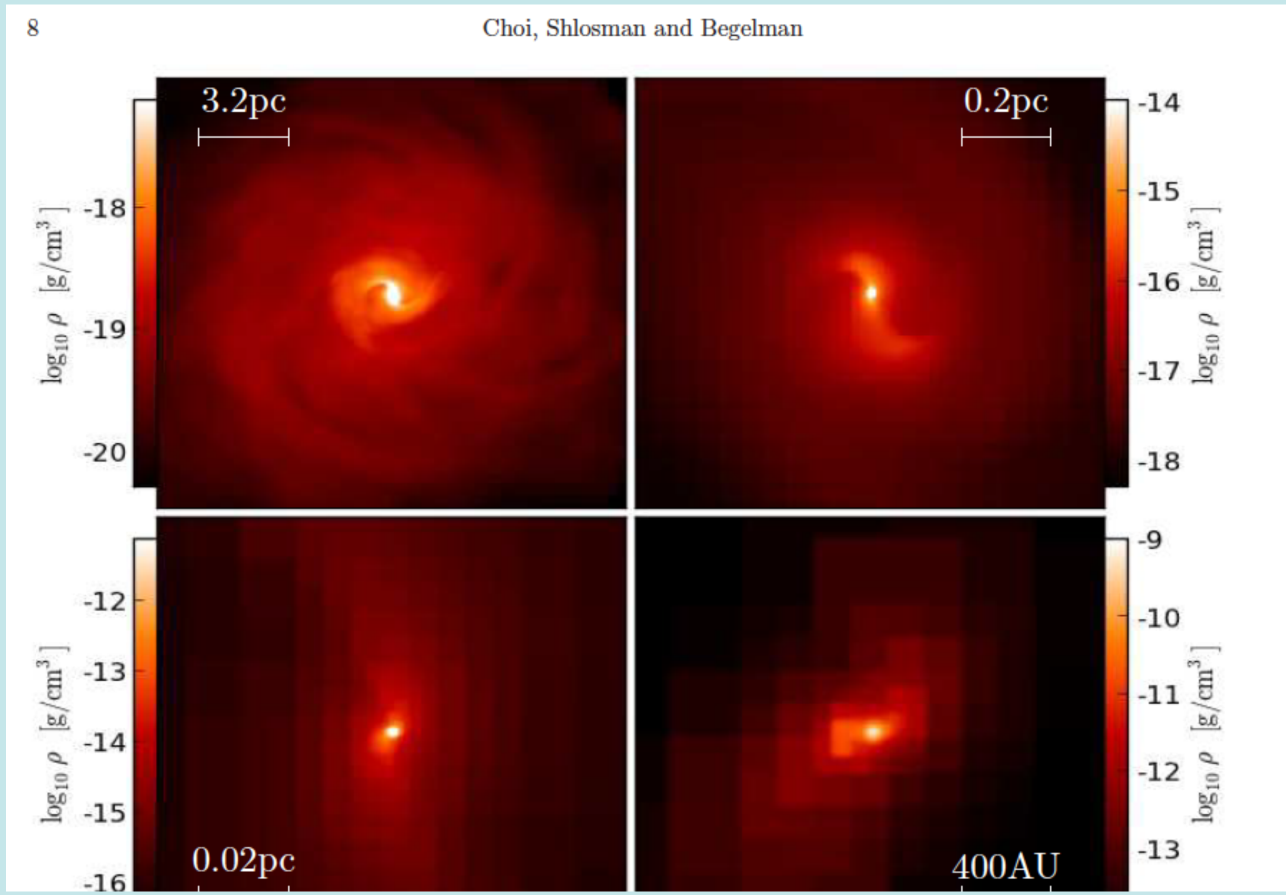


FINAL DCBH MASS

Massive BH seed formation
ENZO







Smith, Davis & PN 2013

see also Regan & Haehnelt 2008 (GADGET)

Sequence of events (bypass formation of the first star!)

DM halo mass M, T_{vir}, no metals, gas mass $f_b M$
hot disc ~4000 K, cold disc ~ 400 K

↓

$T_{vir} > T_{gas}$ gas collapses and forms rotationally supported disc, disc subject to grav. instabilities, onset when Toomre Q_{crit} ~ 1 - 3

Disc evolution tussle between accretion and fragmentation

↓

Bars lead to redistribution of J, feed matter to center continues till central mass stabilizes the disc

Accumulated central mass depends on spin, halo mass, T_{gas}/T_{vir}, max. spin for which the disc is grav. Unstable, provides upper limit to M_{BH}

Initial correlation between BH and host halo properties

Evolution of self-gravitating discs

- Controlled mainly by two parameters:

$$Q = \frac{c_s \kappa}{\pi G \Sigma}$$

- *Q>1* non-self-gravitating
- *Q ~1* subject to grav. instabilities

$$t_{cool}\Omega = \frac{t_{cool}}{t_{dyn}}$$

- $t_{cool}/t_{dyn} < 1$ fragmentation
- $t_{cool}/t_{dyn} > 1$ self-regulation

Zero-metallicity: long t_{cool} => fragmentation can be avoided

When disc self-regulated, steady ang. mom. transport, Max. mass accretion rate

$$\dot{M}_{max} = 2\alpha_{crit}\frac{c_s^3}{G}$$

$\alpha_{crit} \sim 0.06$

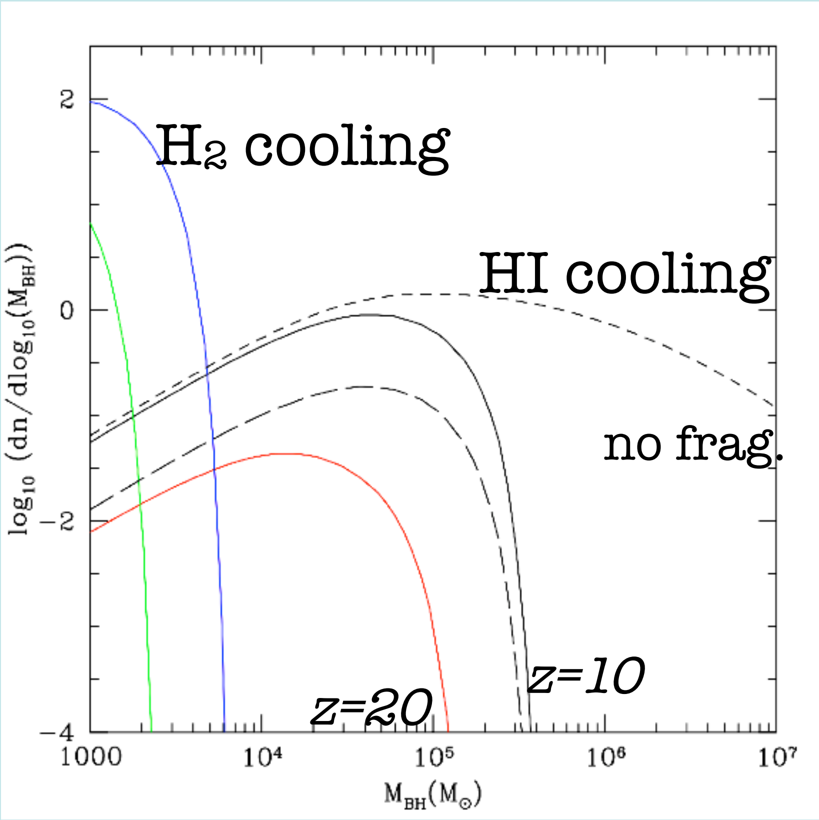
$$\dot{M}_{max} \approx 10^{-2} M_\odot/\mathrm{yr}$$ No H_2

$$\dot{M}_{max} \approx 3\ 10^{-4} M_\odot/\mathrm{yr}$$ H_2 present

Rice, Lodato & Armitage 2005; Gammie 2001; Lodato & Rice 2004, 2006; Mayer+; Durisen +

Black holes at high redshifts

- Given the properties of DM haloes we can deduce the properties of the BH seed population:
  - Mass function of seed black holes

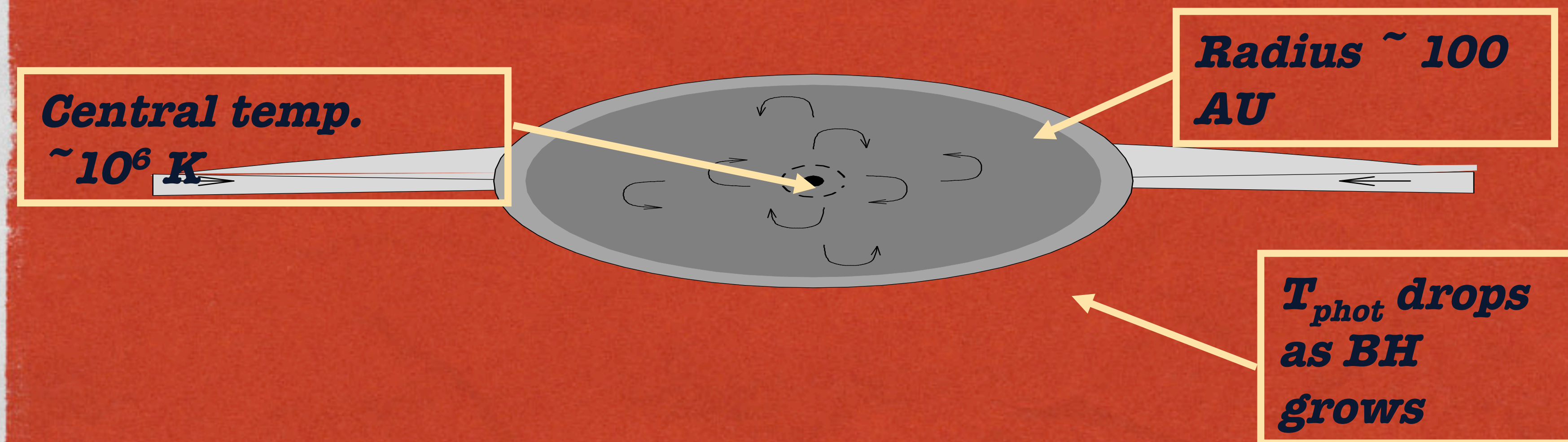


Sharp cut-off above 10^5-$10^6 M_{sun}$ due to fragmentation

Lodato & PN 2006, 2007

"QUASISTAR"

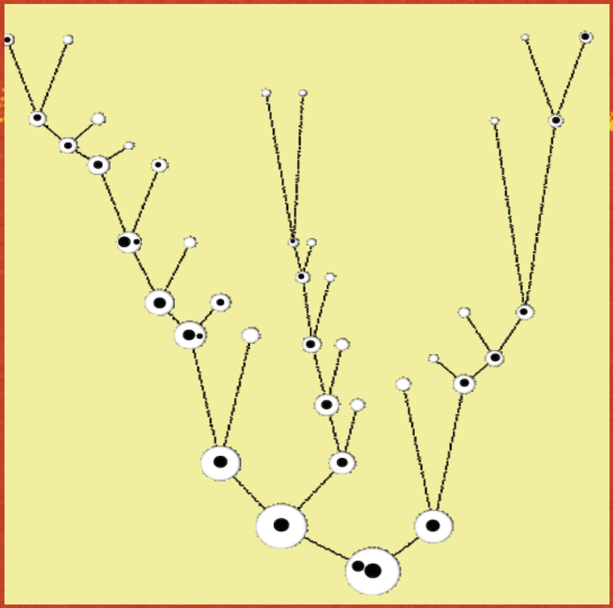
- Resembles a red giant
- Radiation-supported convective envelope
- Photospheric temperature drops as black hole grows

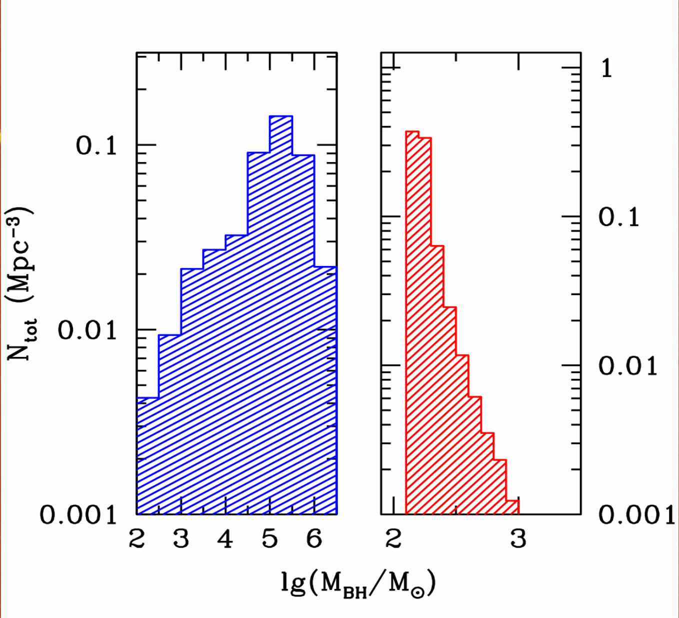


Summary of the massive BH seed formation model

- Models of the dynamics of self-gravitating zero-metallicity discs in high-redshift mini-halos ($T_{vir} \sim 10^4$K)
- If atomic hydrogen cooling dominates, gas kept hot and fragmentation inhibited; mol H cooling curtailed by LW photons
- Spiral structure promotes accretion of large amount of mass ($10^5 M_{sun}$) to the center of the protogalaxy: available for the growth of SMBH seeds
- Properties of such high mass seeds strongly depend on DM halo properties (mass, spin).
- A few percent of $\sim 10^7$-10^8 M_{sun} DM halos at z=15 form such seeds
- MF of seeds peaks at a few times 10^5 M_{sun}

Merger induced accretion + CDM merger tree + seeds

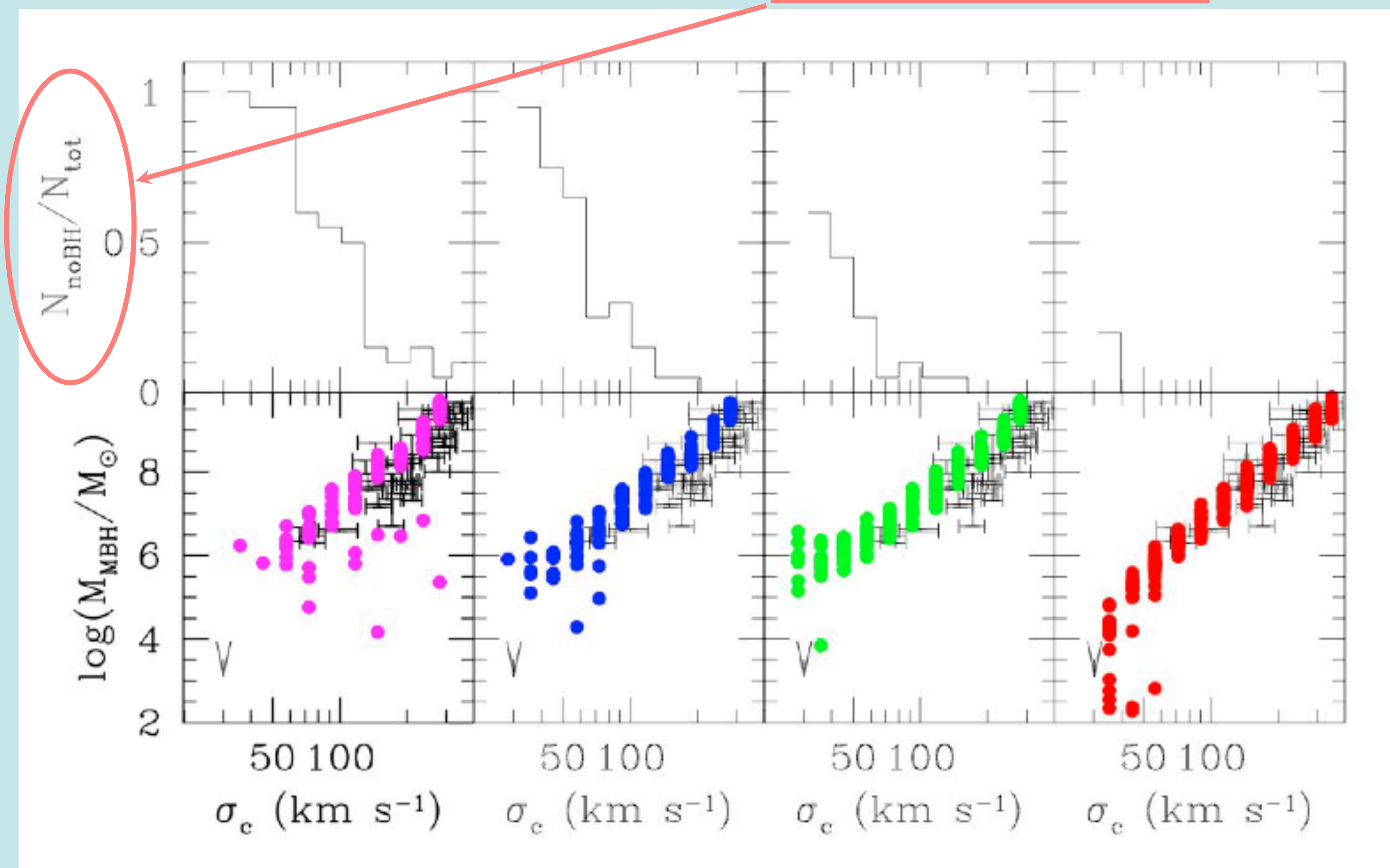




Plant with IMF of seeds
Generate Monte Carlo merger trees
MBH seed formation ceases at z ~ 12
Propagate different BH seed models
Every major merger (mass ratio 1:10 or greater) induces accretion of gas
several models – fixed fraction of gas gets accreted; BH X 2; gas mass accreted scales with v_c

Evolution of massive BH seeds

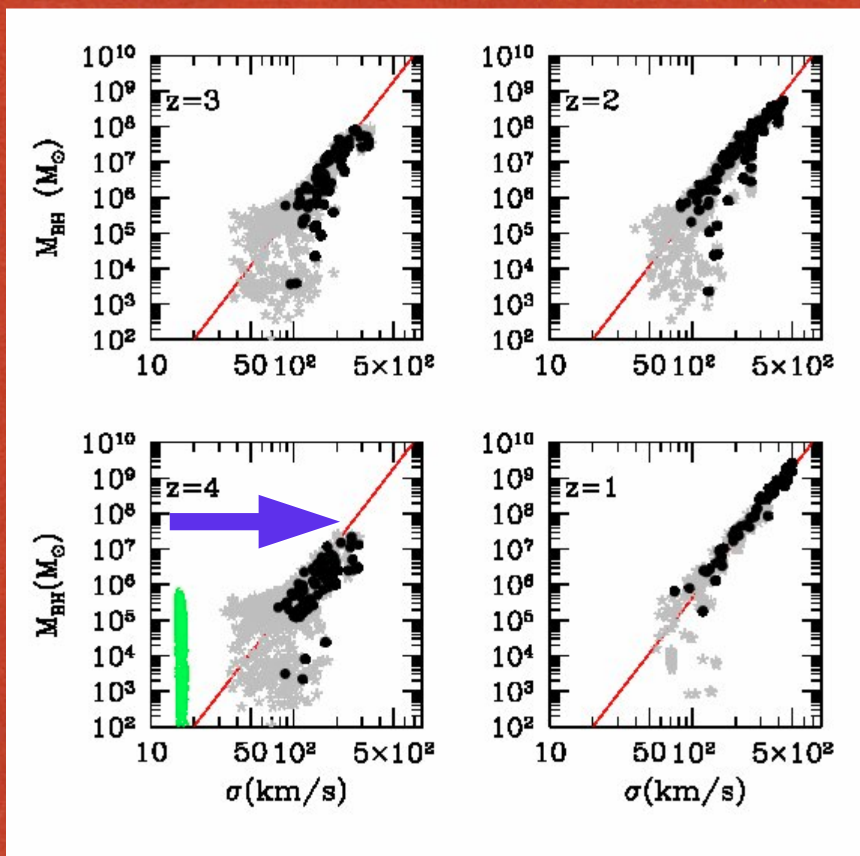
Fraction of galaxies that do NOT host a SMBH



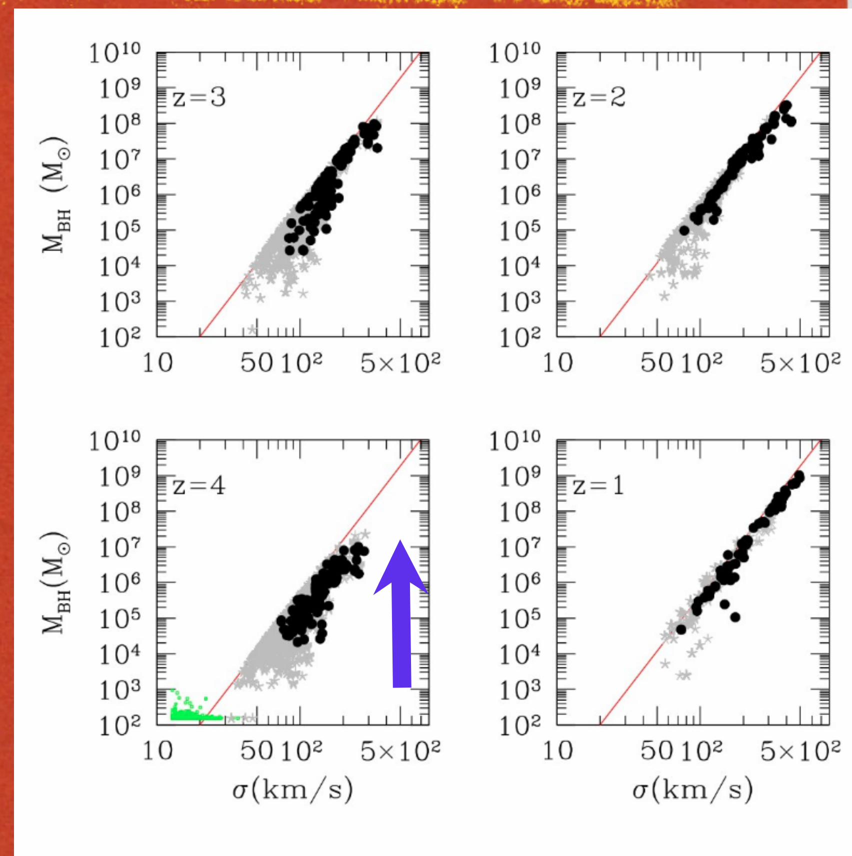
Qc=1 *Qc=2* *Qc=3* Pop III seeds

Journey to the M-sigma relation: differences in the sequence of BH growth vs stellar mass

Massive seeds

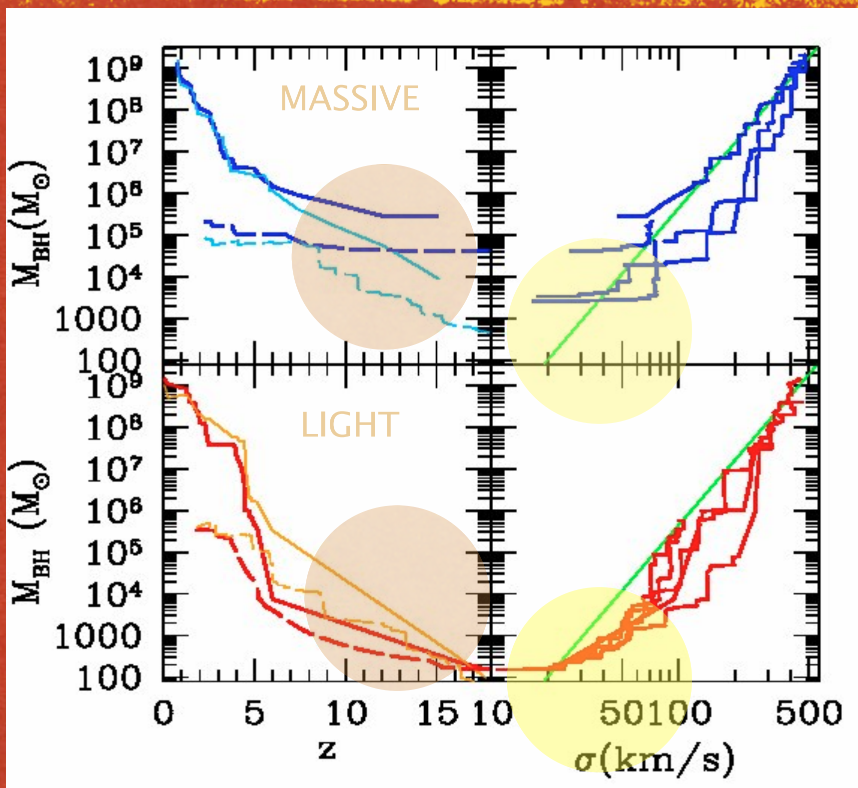


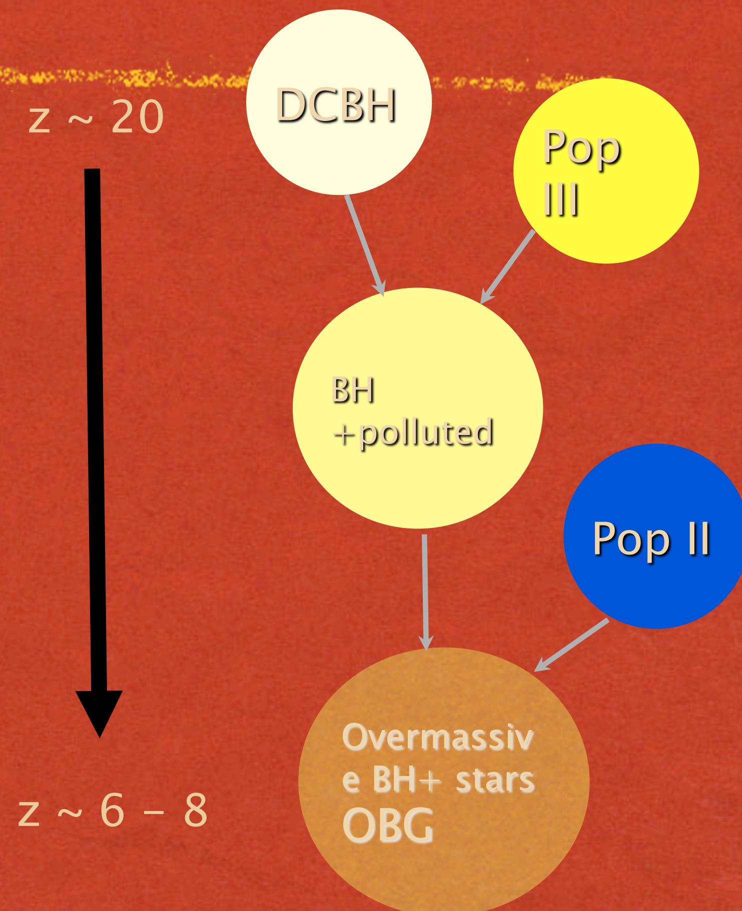
Light seeds



NOTE in this realization the accreted mass was capped to not exceed local M-sigma

CONSEQUENCES OF MASSIVE SEEDS: OVER-MASSIVE BHs at HIGH z





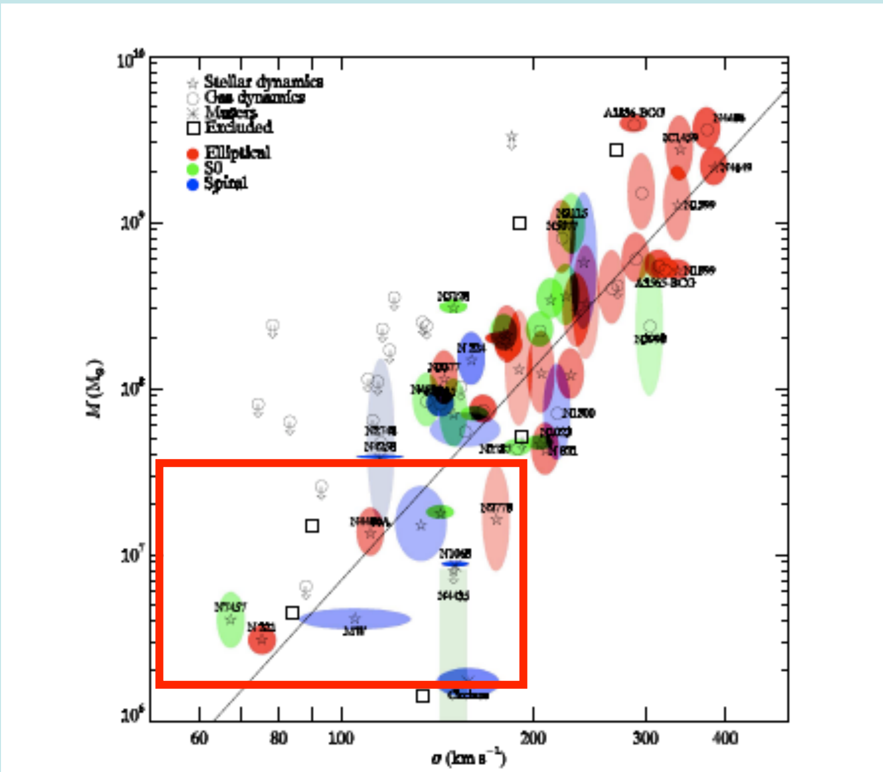
SHOULD BE OBSERVABLE AT HIGH z WITH JWST, ACCRETING BH WITH UNDERMASSIVE STELLAR POPN. Agarwal, Davis+ 2013

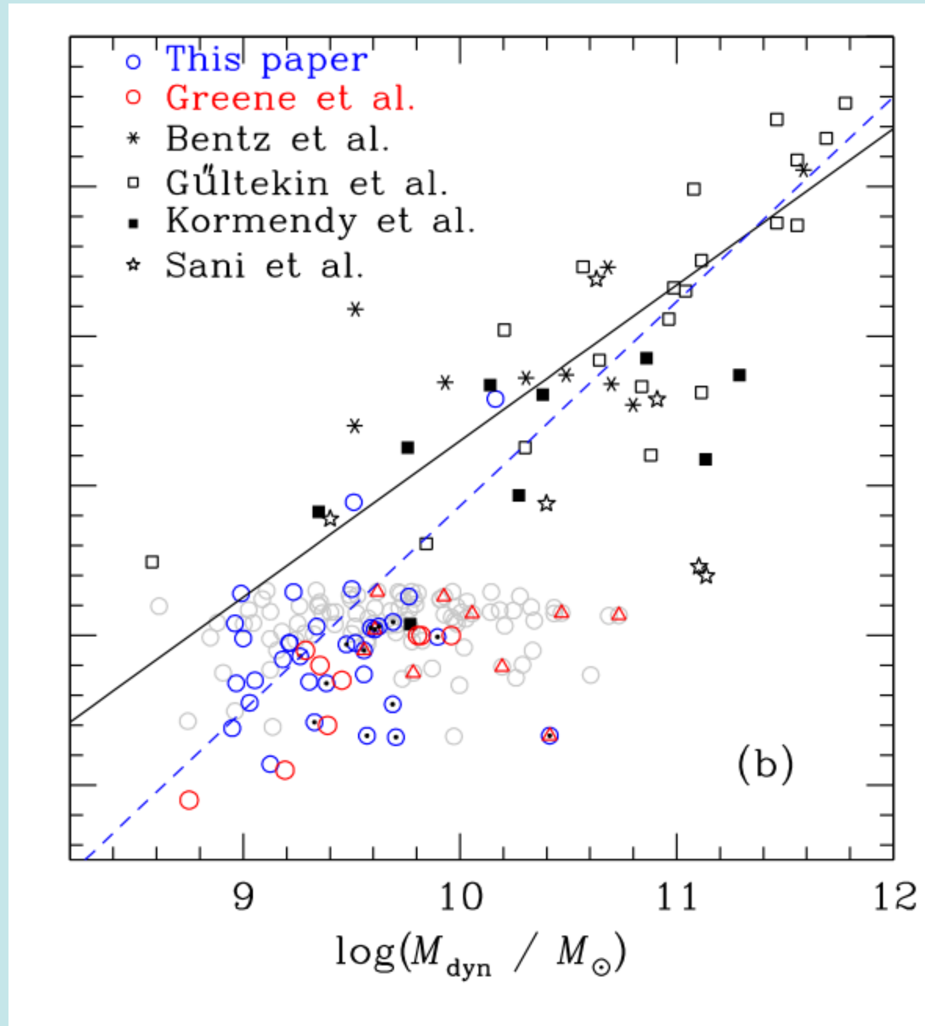
Predictions from evolving massive BH seeds

- BH occupation fraction at z=0
- Massive seed models predict low occupation fraction for small galaxies (below $\sigma \sim$ 50-100 km/sec)
- Progenitors of dwarf galaxies were not massive enough to seed a BH at high redshift
- Predict deviation from M-sigma at z=0 both at high and low BH mass ends
- At higher redshifts bulge growth lags behind BH growth
- Deviation at high mass end encodes more than just the merger history (PN & Treister 2009)
- Predict active, SMBHs in place at z > 8 (Treister+ 2013)

- Consistent with recent surveys of the Virgo cluster in the optical (Decarli et al 2007) and X-ray (Gallo et al. 2008)
- Evidence gathering support from high and low z

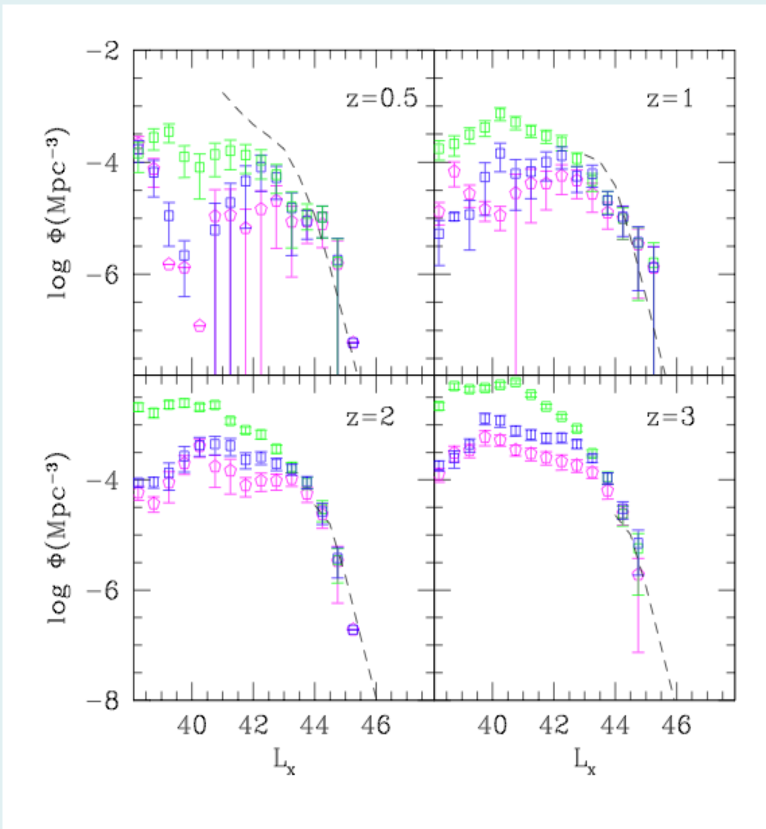
The low mass end of the local M_{bh}-sigma relation

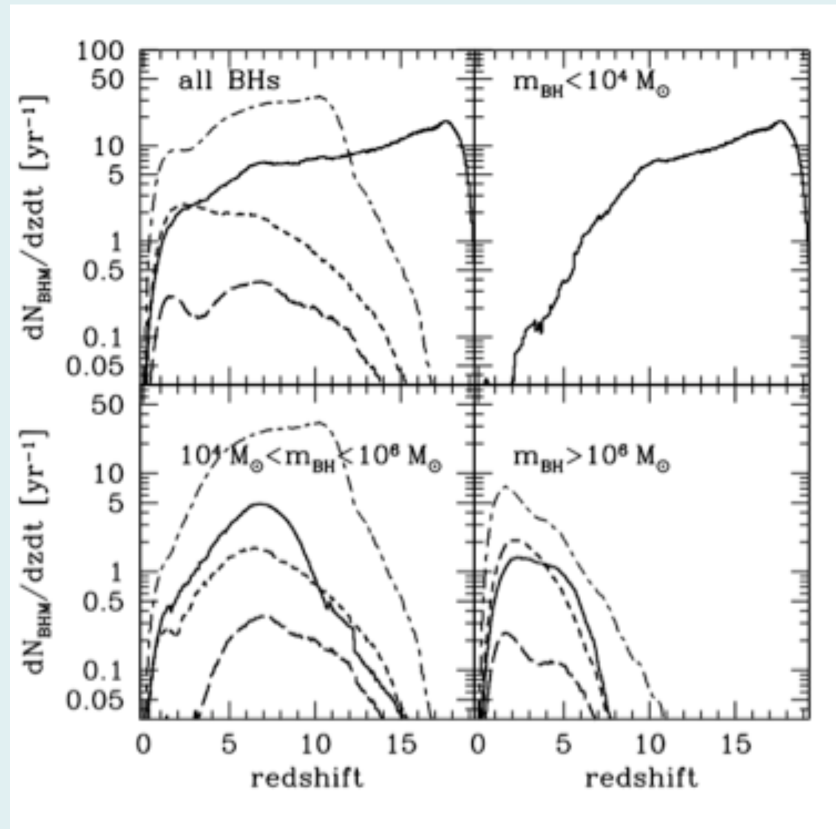




Greene & Ho 2009; Greene+ 2011; Jiang+ 2011

Predictions to test massive seed models: XLF faint end of quasars & merger rates of MBHBs





Volonteri & PN 2010; 2011; Sesana+ 2010

CONDITIONS REQUIRED FOR THE GROWTH OF THE MOST MASSIVE BLACK HOLES

- Average Eddington rate to grow a light seed (~100 Msun) so that at t= 2.1 Gyr z = 3, it needs to accrete continously at <fEdd> ~ 0.38 and by t = 1.5 Gyr z = 4 <fEdd> ~ 0.54

- For massive seeds less stringent <fEdd> ~ 0.27 (z = 3) and 0.3 (z = 4)

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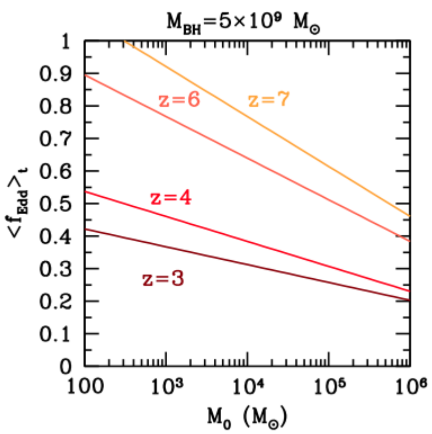


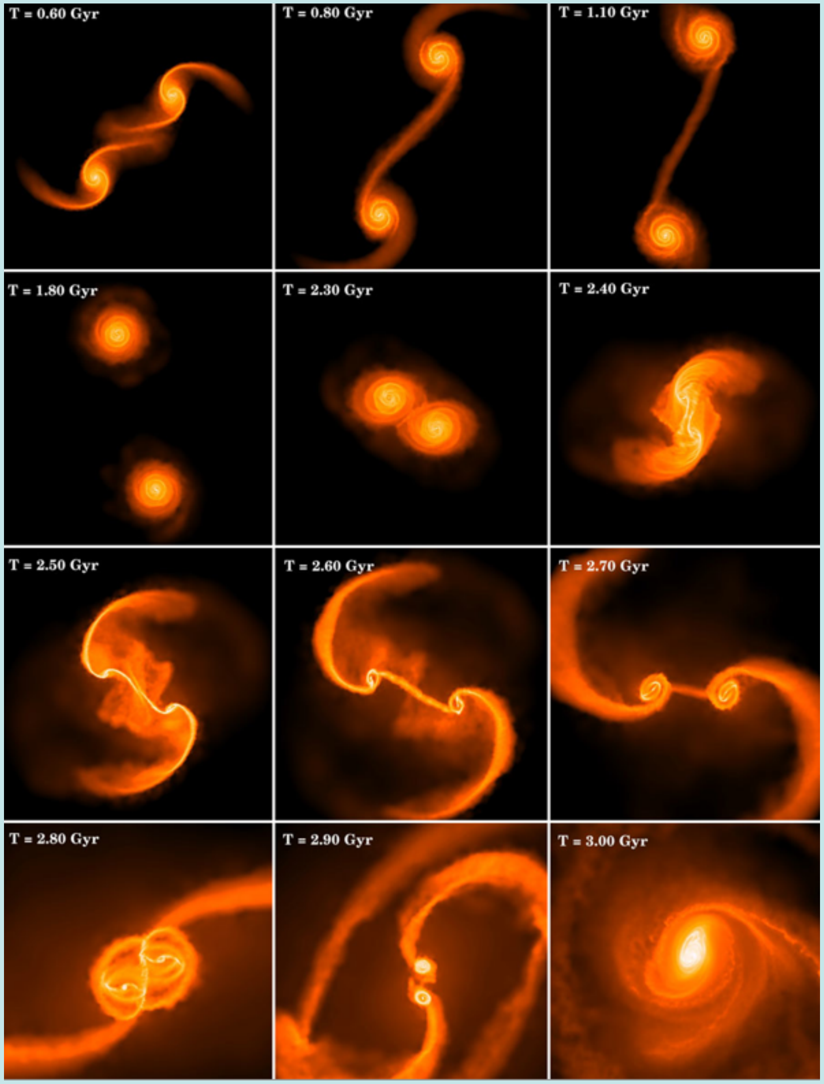
Fig. 1.— Time-averaged Eddington ratio that an MBH with initial mass M_0 requires to grow to a final mass $M_{BH} = 5 \times 10^9 M_\odot$ within the Hubble time at a given redshift $z = 3; 4; 6; 7$ (bottom to top).

- Not for the whole population though.....

$$\dot{\rho} = \frac{\langle f_{\rm Edd} \rangle_{t,all}}{t_{\rm Edd}} \frac{1-\epsilon}{\epsilon} \rho + \dot{\rho}_{form},$$

PN & Volonteri 2013; Johnson+ 2013

MAKING MASSIVE SEEDS AT LATE TIMES



Simulation of gas-rich galaxy mergers with efficient and high inflow rates, results in the formation of a gravito-turbulent disk in the nuclear regions that is stable against fragmentation

Mayer+ 2010
Dolan+ 2011

Implementation in the CDM context with a semi-analytic model

Bonoli+ 2013

Conditions required to ASSEMBLE THE MOST MASSIVE BLACK HOLES AT ALL EPOCHS

- Massive initial BH seeds heavier than Pop III remnants at high z (trade-off between obscured growth vs. massive initial seeds)
- Brief periods of super-Eddington accretion early on
- Periods of obscured growth during merger triggered phases
- very inefficient feedback from these BHs as it stunts their growth prematurely (i.e. AGN feedback cannot be the sole mechanism of suppressing SF in massive halos)
- Long lived steady accretion mode that necessitates natural solution to the last parsec problem (steady trickle through age of universe)