Early BH Growth with Lynx and LISA

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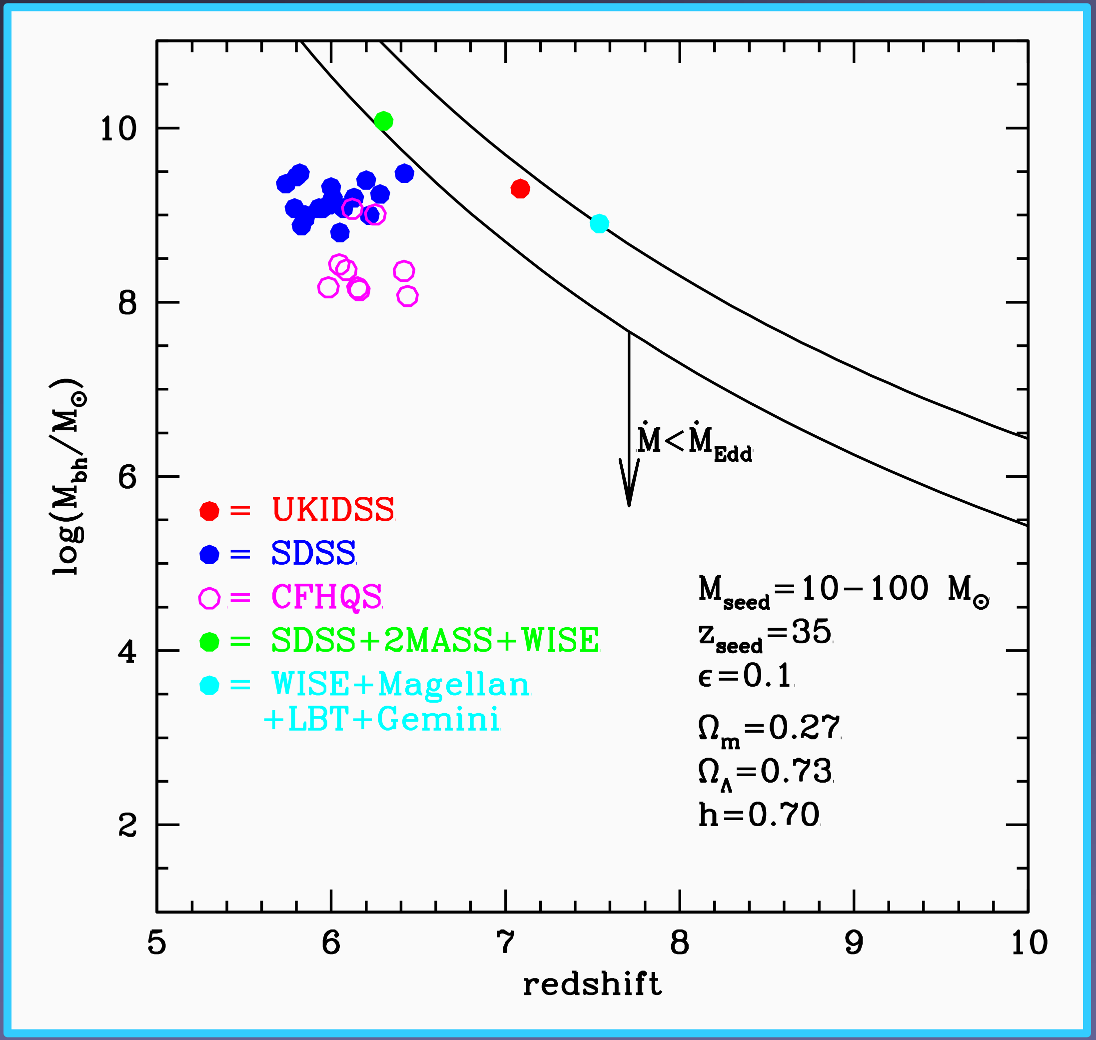
AAS meeting #233 **Seattle, WA** **6-10 January, 2019**

"Maximum" SMBH Masses



e-folding (Edd) time:
$M/(dM/dt) = 4\ (\varepsilon/0.1)\ 10^7$ yr

Age of universe (z=6-7)
(0.8 – 1) x 10^9 yr

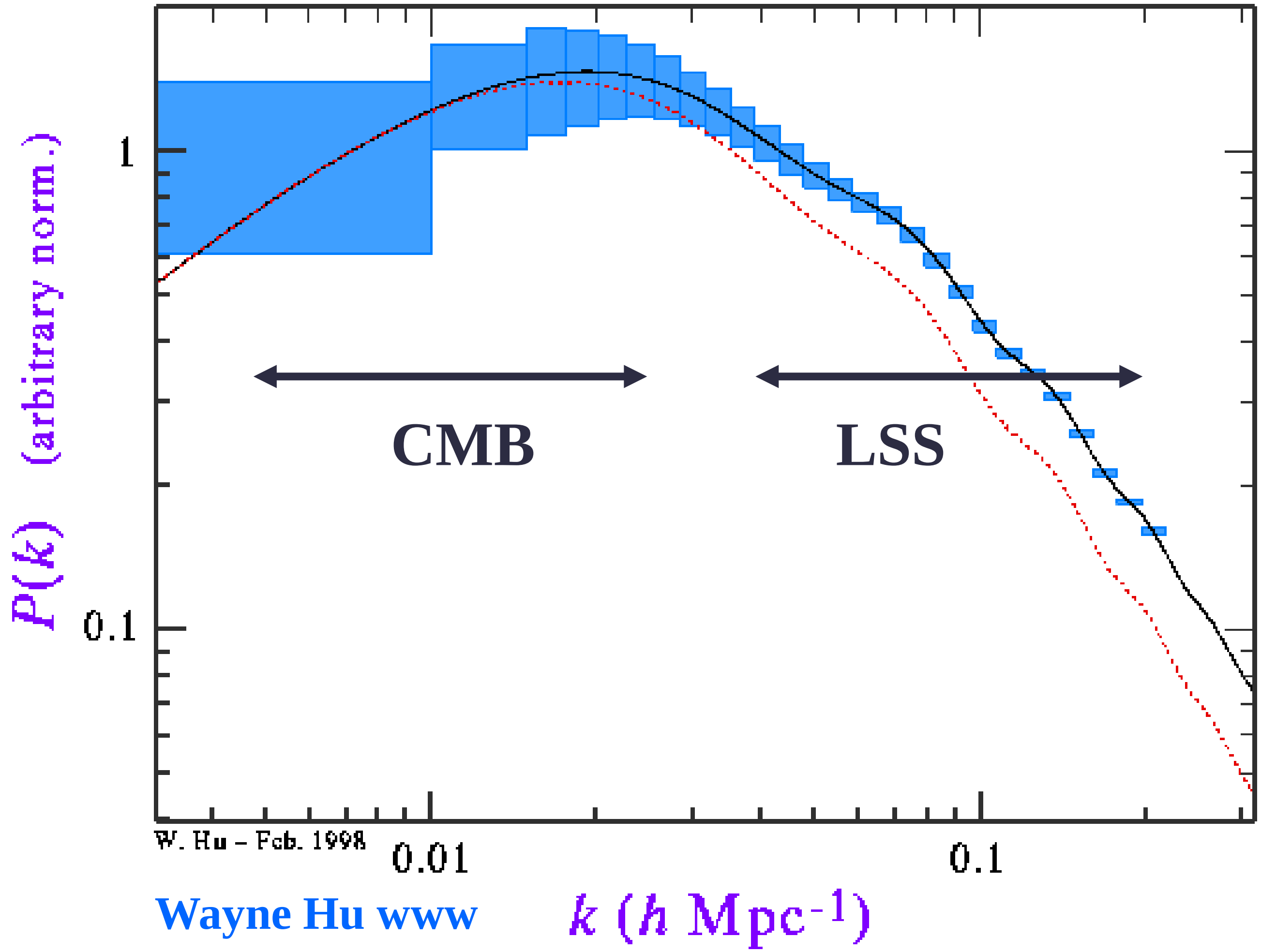
Must start early!

Accretion rate must keep up w/ Eddington most of the time

Obvious alternatives:
(1) merge many BHs
(2) grow faster

Masses estimated from: Fan+ (2006); Willott+ (2010); Mortlock+ (2011); Wu+ (2015)

Seed Fluctuations on Small Scales



extrapolation by a factor of about 100 in linear scale

Dark Age

mass function of DM halos directly tested in simulations at $z=30$; $M=10^6\,M_\odot$

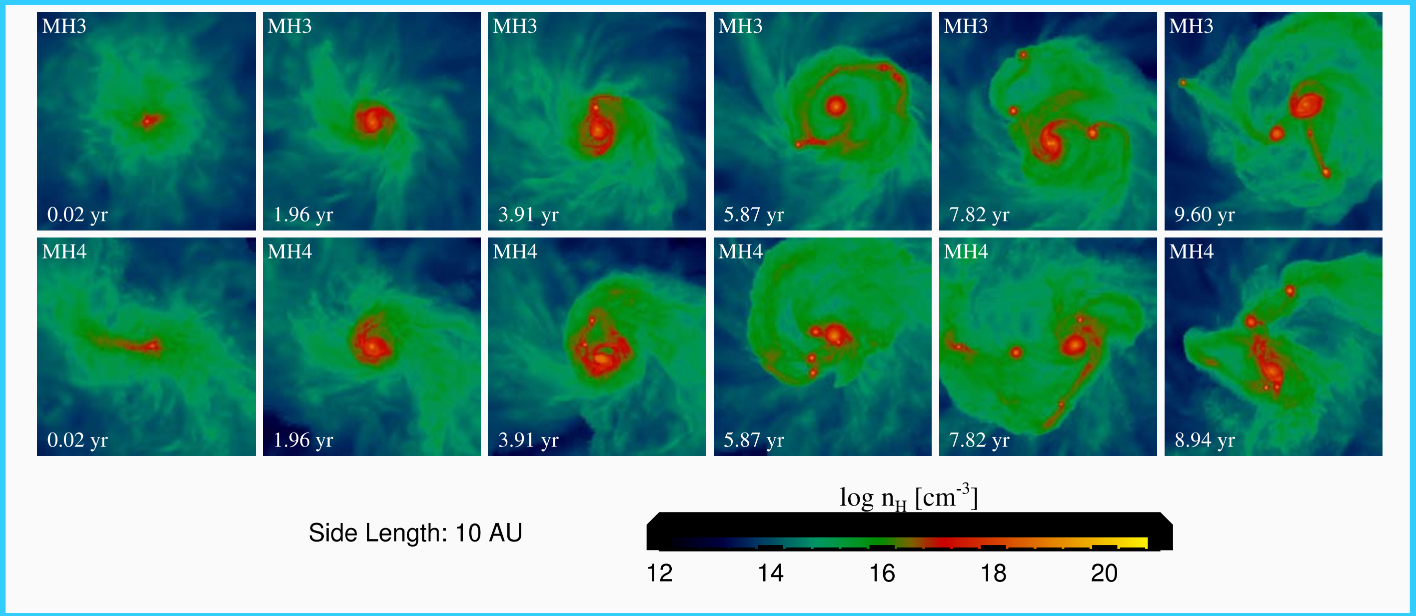
e.g. Lukic et al. (2007)
Reed et al. (2007)

No SMBHs in m_x<keV WDM (Barkana, ZH, Ostriker 2001, Pacucci+2014)

3D Simulation of a Primordial Gas Cloud

Greif et al. (2012, 2014)

Abel et al. (2002), Bromm et al. (2002), Yoshida, Omukai & Hernquist (2008), …



Cosmological mini-halo:
$M_{halo} \approx 3\times10^5\, M_\odot$
$z_{coll} \approx 20$

Protostar(s) in core:
$T \approx$ few $\times$ 100 K
$n \approx 10^{21}$ cm^{-3}
$M_* \approx 0.1$ -1 $M_\odot$

Upper limit on stellar mass

- **Gas infall at sound speed:** $c_s \approx$ 1-2 km/s **dictated by H_2**
- **Mass accretion rate:** $\dot{M}_{acc} \approx c_s^3/G$ = few × $10^{-3}\,M_\odot\,yr^{-1}$
- **Star's mass:** $M \approx \dot{M}_{acc} \times t_{KH} \approx \dot{M}_{acc} \times 10^5$ yr = few × $10^2 M_\odot$
- ***Result: massive stars and stellar-mass BH remnants***

- **Final stellar masses can be reduced by:**
  - **- fragmentation** (O(10) clumps **Greif et al. 2013, Regan et al. 2014)**
  - **- radiation of protostar** (43 $M_\odot$ **Hosokawa et al. 2012, McKee & Tan 2008)**

Very likely that ~100 $M_\odot$ PopIII stars appear early (z~20-30) promptly leaving behind a stellar-mass BH [with no metals]

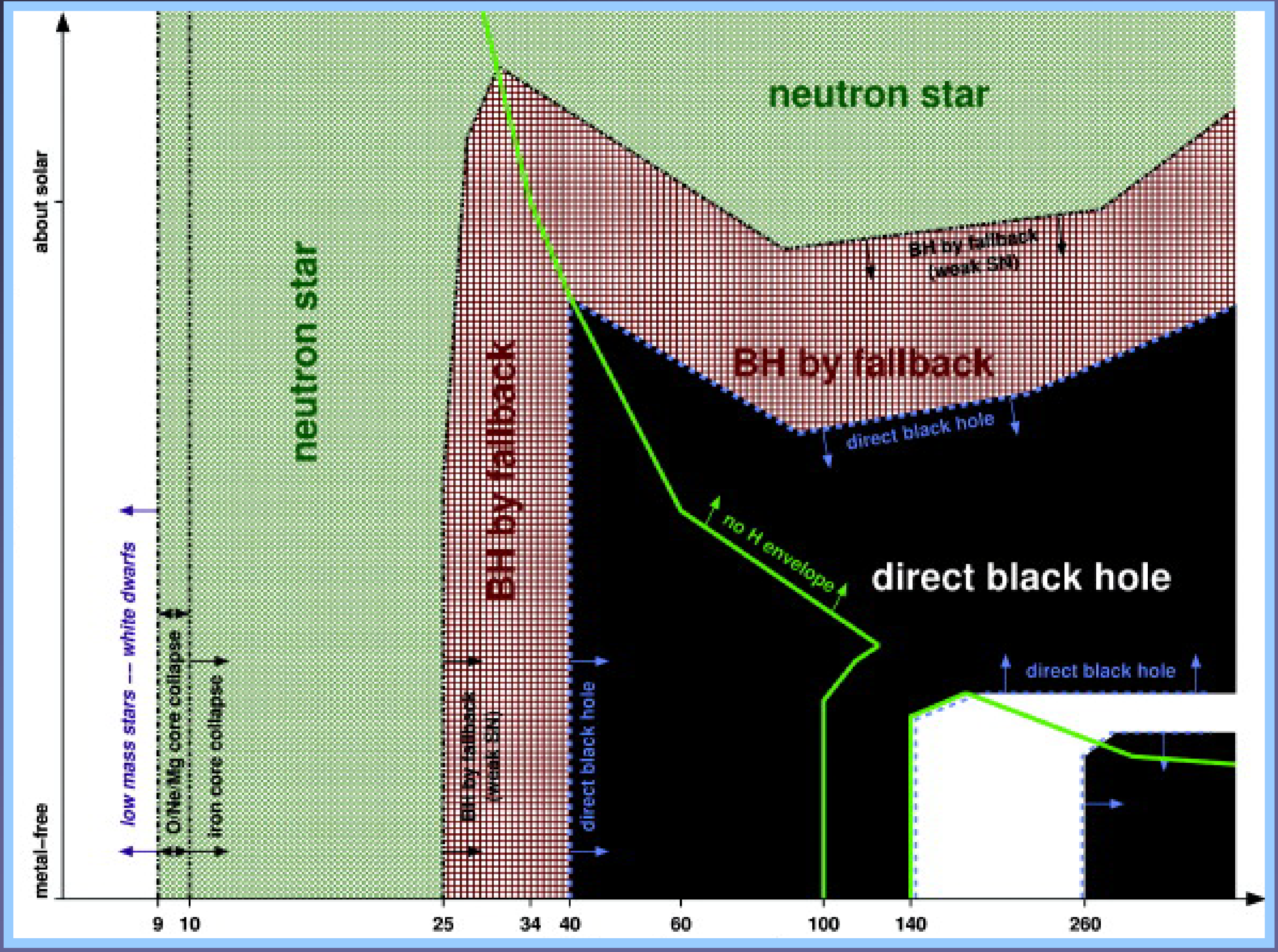
Remnants of Massive Stars

Heger et al. 2003 (for single, non-rotating stars)

$Z=Z_\odot$

metalicity

$Z=0$



$10M_\odot$ $25M_\odot$ $40M_\odot$ $140M_\odot$ $260M_\odot$

Growing Supermassive BHs

- **STELLAR SEEDS**
  uninterrupted near-Eddington accretion onto ~10-100 $M_\odot$ seeds
  - near-continuous gas supply
  - avoid radiative feedback depressing accretion rate
  - avoid ejection from halos and loosing BHs

- **DIRECT COLLAPSE (A.K.A. “HEAVY SEEDS”)**
  rapid formation of 10^5-10^6 $M_\odot$ BHs at z>10 by direct collapse of gas or via intermediary (supermassive star, ultra-dense cluster)
  - gas must be driven in rapidly (deep potential)
  - transfer angular momentum outward
  - must avoid H_2 cooling and fragmentation

- **HYPER-EDDINGTON ACCRETION**
  rapid gas collapse, but onto a pre-existing stellar-mass BH

Growing SMBHs by Accretion + Mergers

z~6

M_{bh} = few × $10^9 M_\odot$

M_{halo} = several × $10^{12} M_\odot$

CDM merger tree

“Mini-halos”

$M_{halo} \sim 10^5 M_\odot$

v_{esc} ~ few km/s

z~30

“Merger trees”: Haiman & Loeb (2001); Haiman (2004); Yoo & Miralda-Escude (2004); Sesana et al. (2004); Bromley et al. (2004); Volonteri & Rees (2006), Shapiro (2005); Tanaka & ZH (2009), Volonteri & Natarajan (2010), Tanaka, Perna & ZH 2012...

Hydro simulations: Li et al. (2007); Pelupessy et al. (2007); Micic et al. (2007, 2011) Sijacki et al. (2009) , Bellovary et al. (2011), di Matteo et al. (2012), …

Growing SMBHs by Accretion + Mergers

Dark matter halo merger trees from z=6 to z>45

Tanaka, Perna & Haiman (2012)

$10^8 M_\odot \leq M_{halo} \leq 10^{13} M_\odot$ ($\mathbf{M_{res} = 3\times10^4\ M_\odot}$; $N \sim 10^5$ trees; $\mathbf{V_{eff} \sim 5\ Gpc^3}$)

Q1: Fraction of minihalos forming stellar BH seeds ?

- "$\mathbf{f_{seed}}$" depends on fragmentation, IMF, feedback
- $\mathbf{f_{seed}} \sim O(1)$ …

Q2: Time-averaged mass accretion rate ?

- **"$\mathbf{f_{duty}}$"** depends on feedback (incl. progenitor star), Eddington/Bondi limits
- $0 \leq \mathbf{f_{duty}} \leq 1.0$ … ? In practice cannot be less than $\sim 10^{-3}$

Q3: What happens to the BHs when the halos merge?

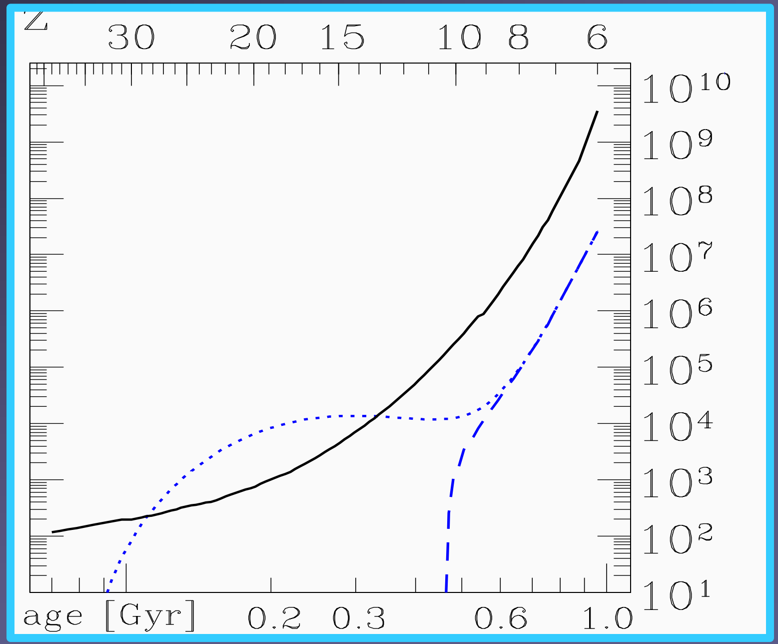
- coalescence of BHs depends on **dynamical friction** and **gas drag**
- BHs can be lot to **gravitational recoil**: v_{kick} depends on spins, orbits
- kicked BH's trajectory: escape, or damped oscillation (gas drag)

Making the ~10^9 $M_\odot$ SMBHs

redshift

M_{BH} [$M_\odot$]

ρ_{BH} [$M_\odot Mpc^{-3}$]



age of universe (Gyr)

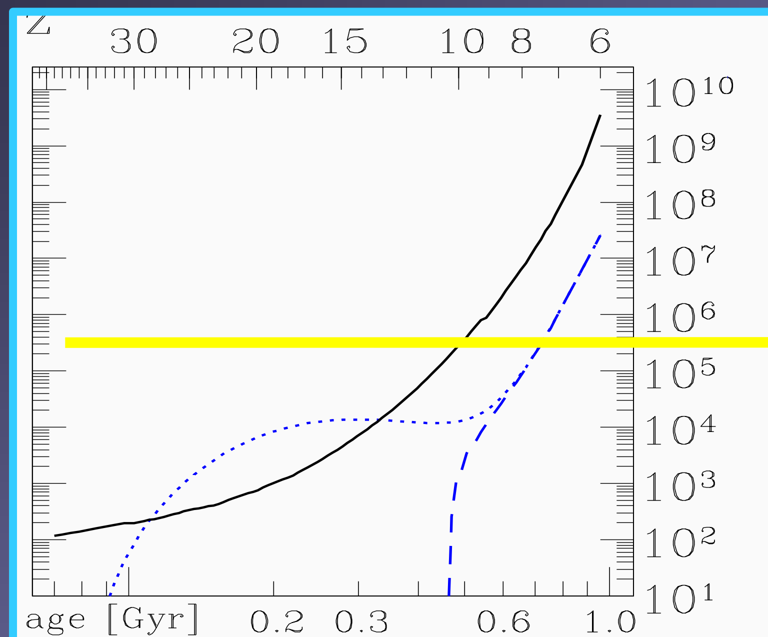
$10^9 M_\odot$ BHs from unusually massive ($10^2 M_\odot$) runaway early seeds (z>20) that avoided ejection at merger: asymmetric mass ratio q<0.01

Making the $\sim 10^9\,M_\odot$ SMBHs

redshift

$M_{BH}\ [M_\odot]$

$\rho_{BH}\ [M_\odot Mpc^{-3}]$



age of universe (Gyr)

Local SMBH Mass density:

$\rho_{tot} \approx 4\times10^5\ M_\odot Mpc^{-3}$

$10^9 M_\odot$ BHs from unusually massive ($10^2 M_\odot$) runaway early seeds (z>20) that avoided ejection at merger: asymmetric mass ratio q<0.01

Eliminating unwanted ~$10^6\ M_\odot$ BHs
(without suppressing most massive ones)

- **Internal feedback:** **(e.g. Ricarte & Natarajan 2018)**

  - M_{BH} limited in each halo by $M_{BH} - \sigma$ relation

- **No BH seeds after PopIII➔PopII ?** **(Tanaka & Haiman 2009)**

  - Requires sharp cut at z~25 and low $f_{seed} \sim 10^{-3}$ (mutually exclusive…)

- **External radiation backgrounds:** **(Tanaka et al. 2012)**

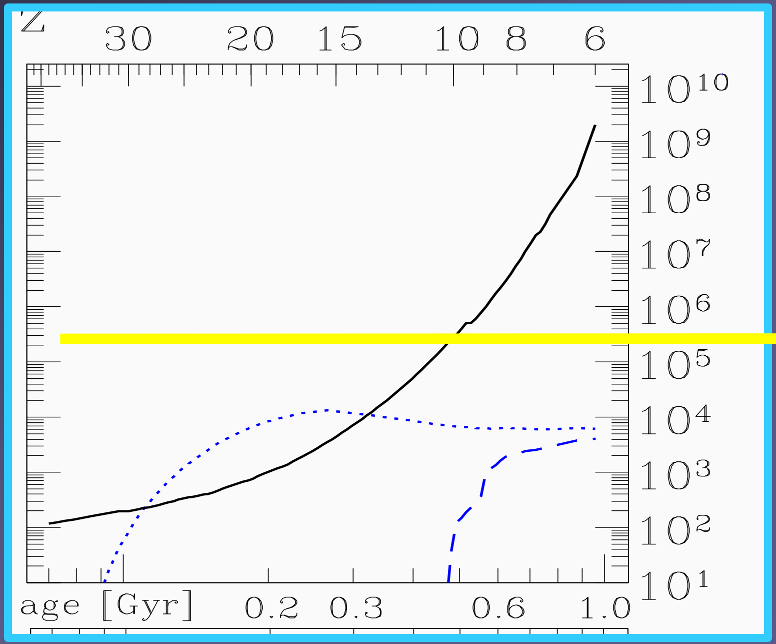
  - stars and their BH remnants build early IR/UV/X-ray

  - affect H_2 chemistry, heat IGM

these backgrounds regulate early star formation history

Self-regulation by X-ray "Global Warming"

redshift



M_{BH} [$M_\odot$]

ρ_{BH} [$M_\odot Mpc^{-3}$]

age of universe (Gyr)

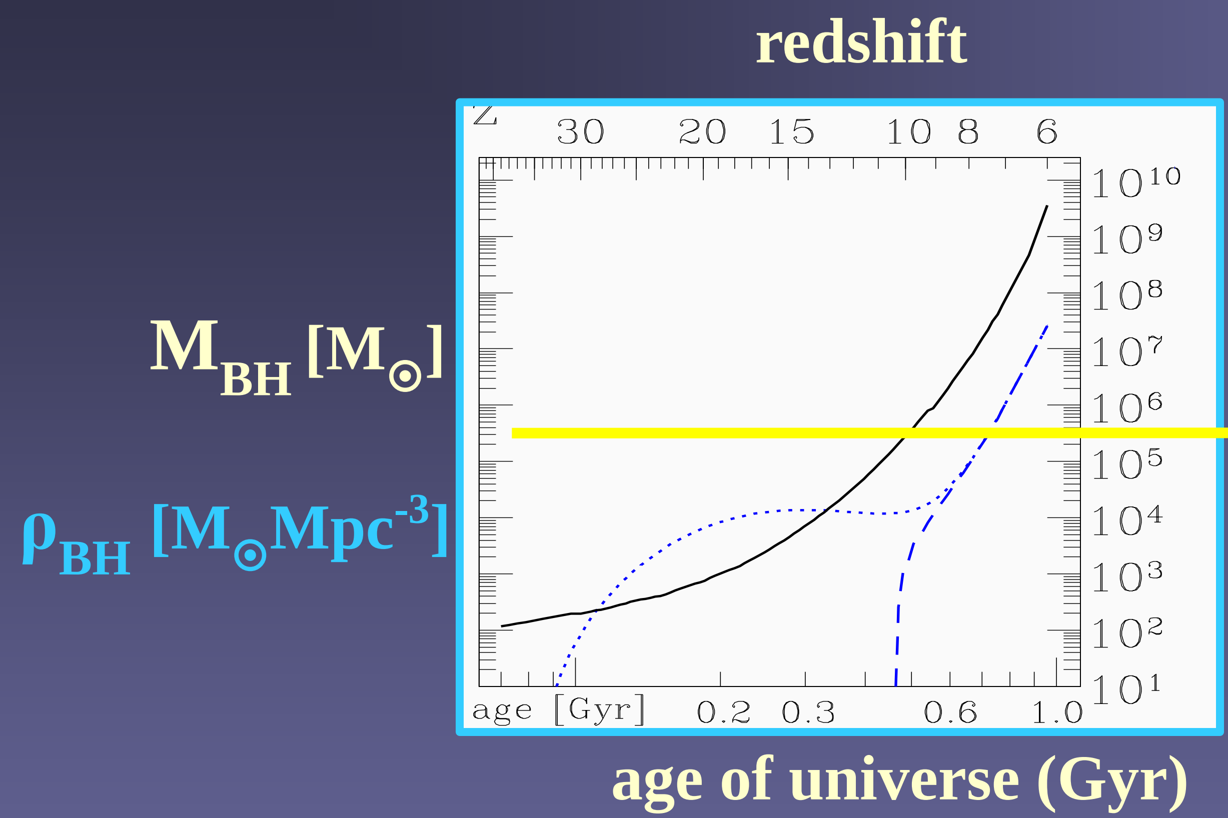
Local SMBH Mass density: $\rho_{tot} \approx 4\times10^5\ M_\odot Mpc^{-3}$

Total BH mass density remains below 10% of its present-day value

NB: recent low Planck τ is independent evidence for suppression

(Visbal, Haiman & Bryan 2016)

Self-regulation by X-ray "Global Warming"



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Alternative: Rapid Gas Collapse

- **$10^{5\text{-}6}\,M_\odot$ BH by z=10-12:** can grow to~$10^9\,M_\odot$ by z=6 at ~Eddington rate

- **REQUIRED MASS ACCRETION RATES**

  - must exceed Eddington rate **$10^{-6}\,(\varepsilon/0.1)^{-1}\,(M_{BH}/40\,M_\odot)\;M_\odot\,yr^{-1}$**
  - but need ~0.1-1 **$M_\odot\,yr^{-1}$** to accrete ~**$10^{4\text{-}5} M_\odot$** in KH time of **10^5 yr**
  - necessarily 'hyper-Eddington'

- **A PROMISING SITE: "ATOMIC COOLING HALOS"**

  - assume no H_2: gas remains hot $T_{gas} \approx T_{vir} \approx 10^4$ K
  - isothermal collapse by Lyα cooling: rapid inflow $M_{acc} \approx c_s^3/G \approx 0.1\text{-}1\,M_\odot\,yr^{-1}$

- **THIS CAN LEAD TO A ~$10^5\,M_\odot$ BLACK HOLE IN MANY WAYS**

  - Hyper-Eddington accretion onto pre-existing stellar BH – radiation trapped
    (Volonteri & Rees 2005; Inayoshi, ZH & Ostriker 2016)
  - Gas collapses directly into a ~$10^5\,M_\odot$ supermassive star or quasistar
    (Begelman et al 2006; Hosokawa et al. 2012, 2015; Haemmerlé et al. 2018)
  - Gas fragments into ultra-dense $10^{4\text{-}5} M_\odot$ star cluster (via trace metals/dust)
    IMBH by core collapse (Omukai, Schneider & ZH 2008; Devecchi & Volonteri 2009, Regan+ 2014)

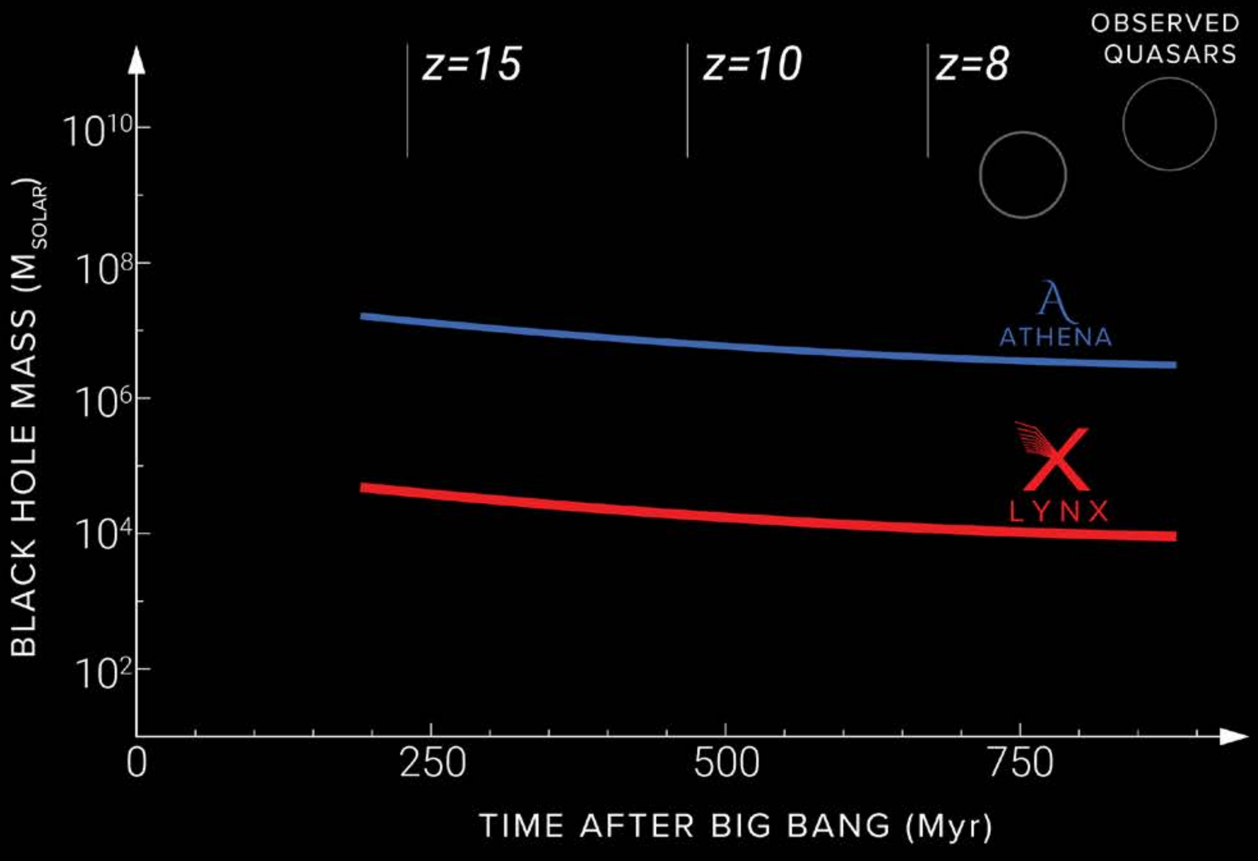
Diagnosing models

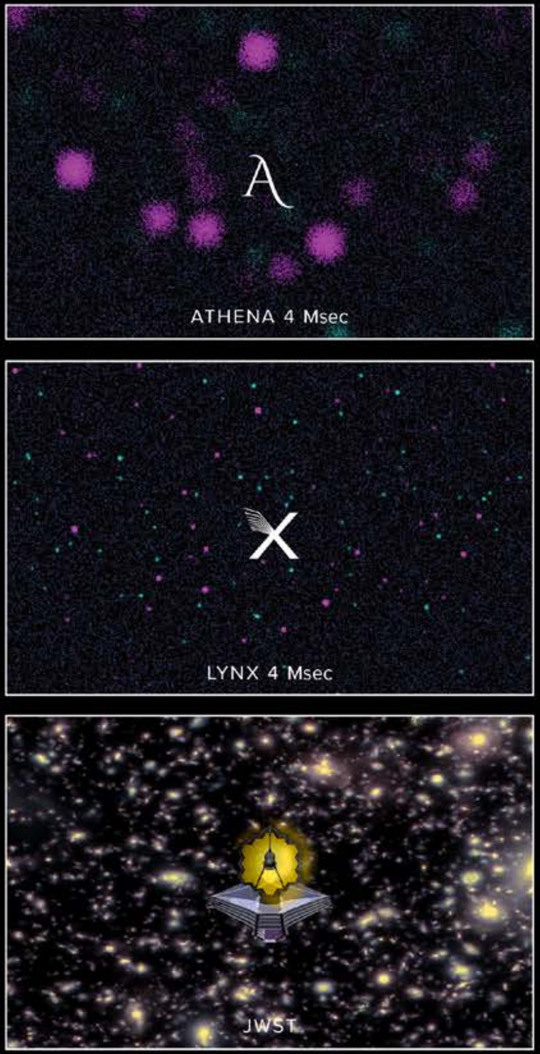
Common feature of 'heavy seeds'
$M \sim 10^5 M_\odot$ at z=10-12

- Needed to grow to $\sim 10^9 M_\odot$ by z=6 at ~Eddington rate

- Maximum mass via a supermassive star
  [via general relativistic instability]
- Maximum mass via hyper-Eddington accretion onto low-mass BH
  [Bondi radius moves to low-density region outside halo core]
- Maximum mass via runaway collisions in ultra-dense star cluster
  [fragmentation must occur at very high density]
- Maximum mass of DM-powered ("dark") stars
  [most of baryons in largest minihalos]

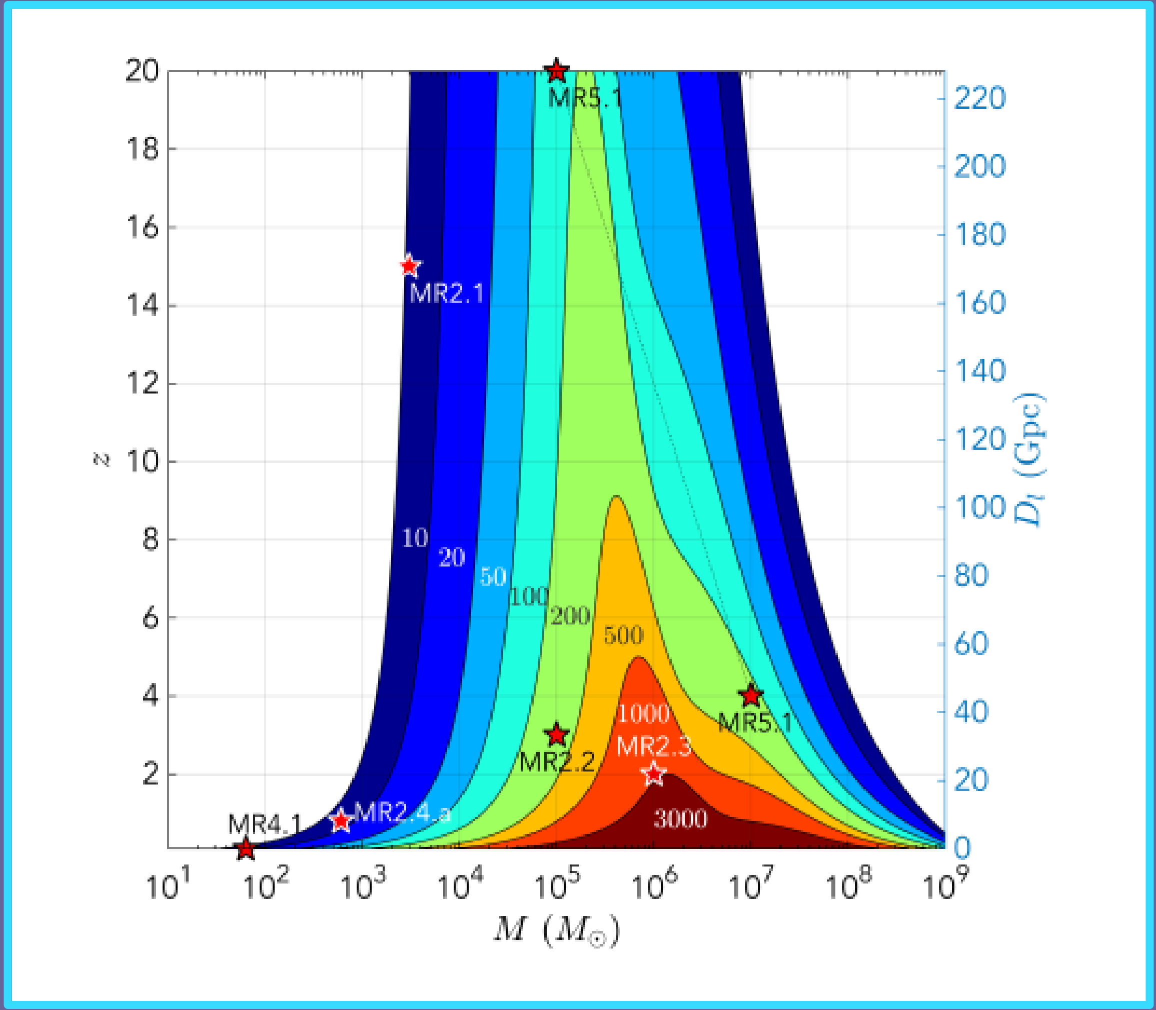
Lynx sensitivity



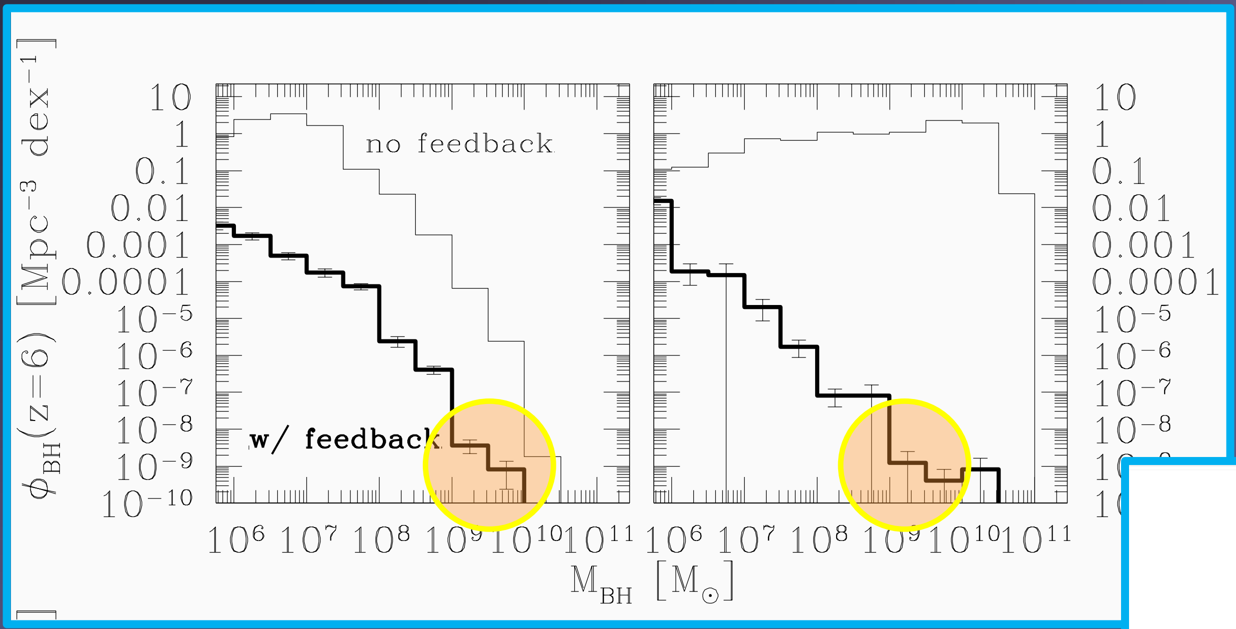


LISA sensitivity

(Accepted LISA proposal)

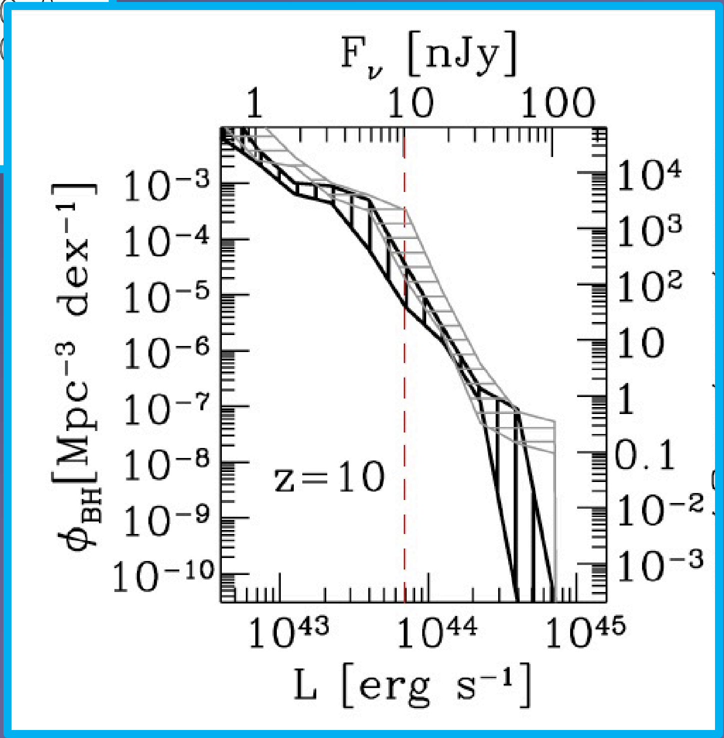


High-z BH mass functions – global feedback



z=6: matches QSO abundance

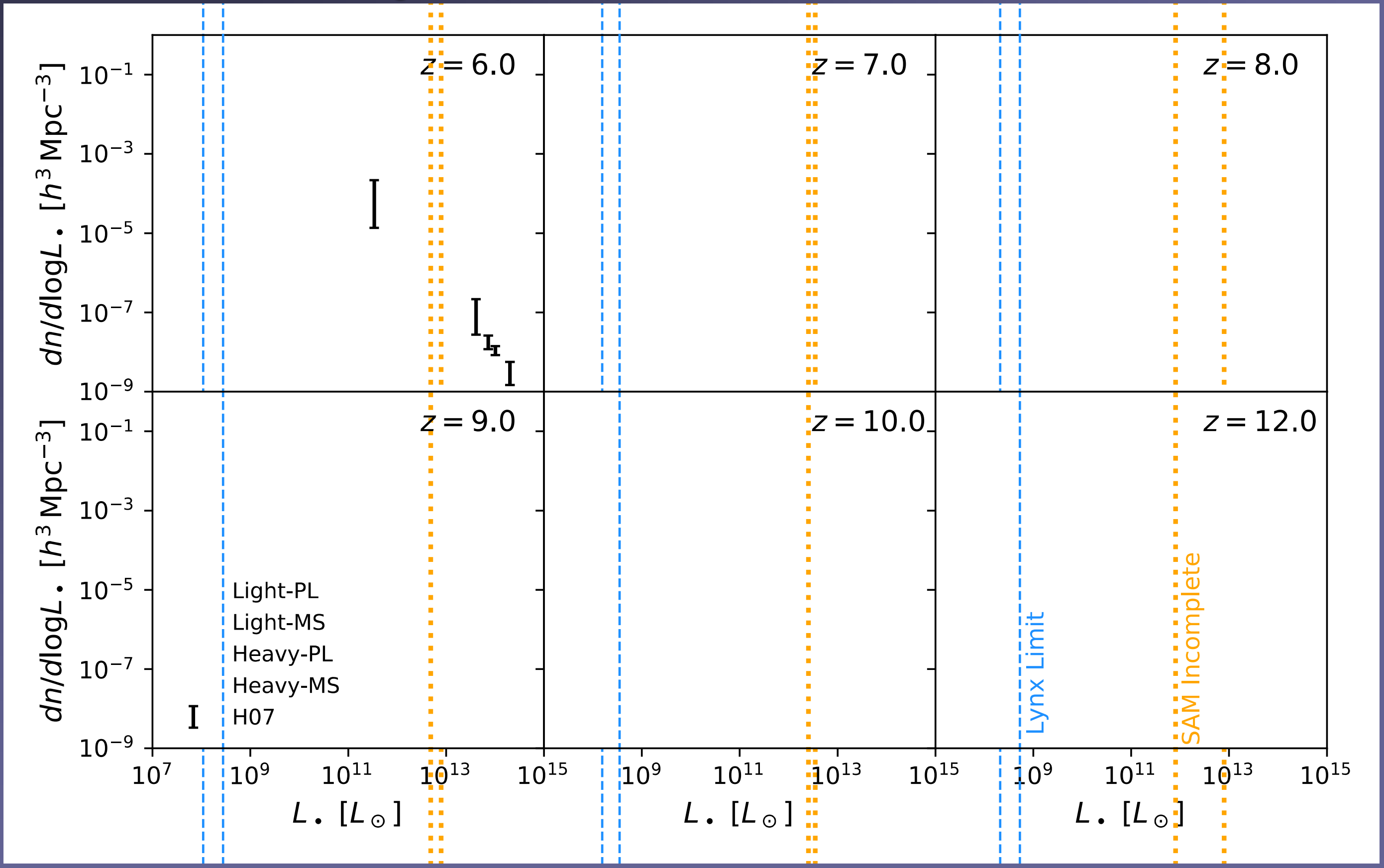
z=10: few × 10^3 quasars in 400 amin^2 Lynx deep field



High-z BH luminosity function – M-σ cap

stellar vs. heavy seeds

Ricarte & Natarajan (2018)



Lynx should detect a ~thousand ~10^5 $M_\odot$ BHs at z~10

Diagnosing models

- **Difficult via the high-z luminosity function alone**

  degeneracies between poorly known parameters

  shape and normalization of high-z LF will constrain a combinations of parameters (e.g. seeding + radiative efficiency + duty cycle).

→ **Combine with LISA data**

two models that have the same LF due to degeneracy should generally produce different LISA rate (**Lippai, Frei, ZH 2009**)

Shown by Bayesian selection between model pairs (**Sesana+2011**)

→ **Combine with IR data**

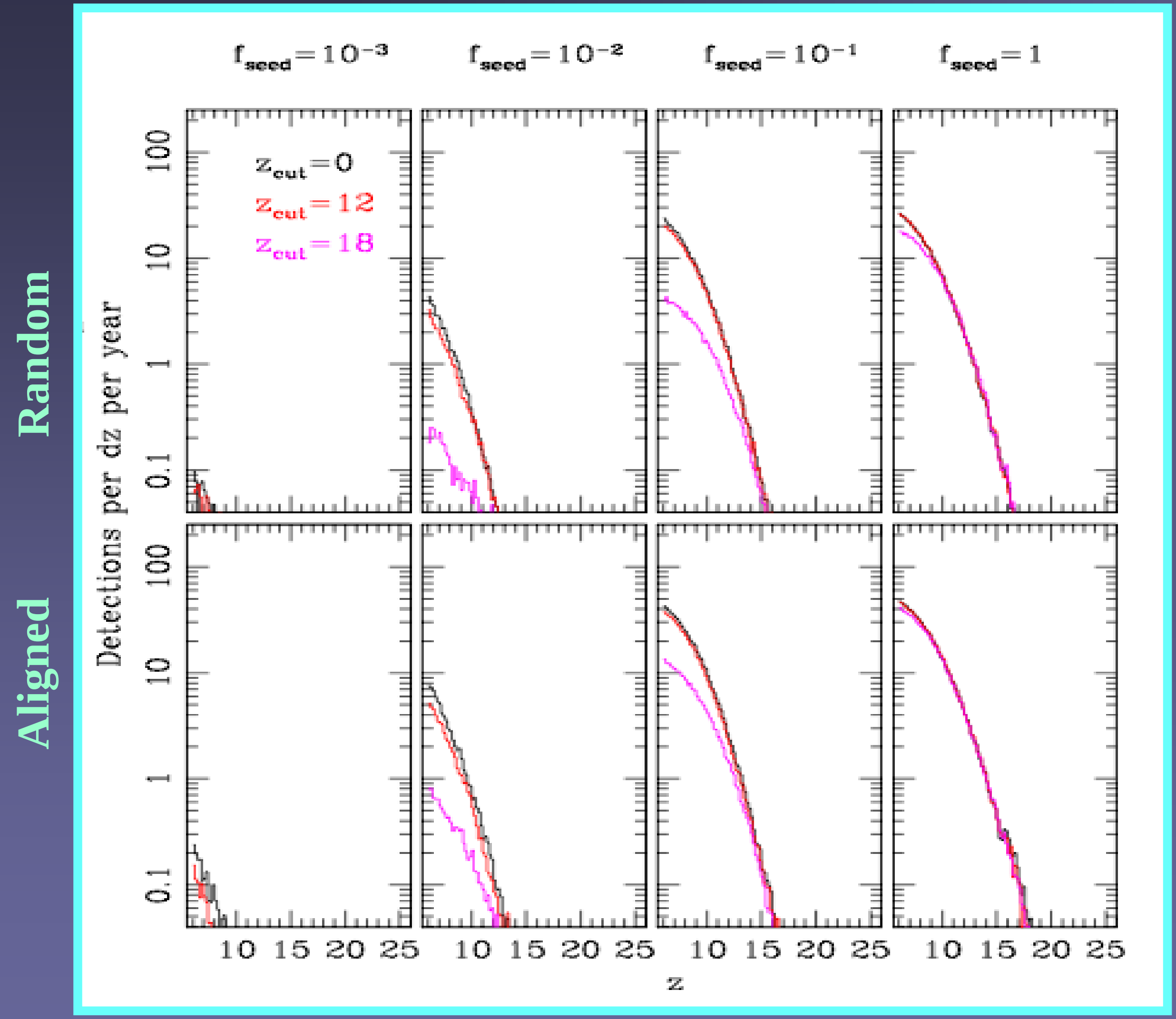
"catch" BHs near threshold, before they grow well above ~10^5 $M_\odot$ and "forget" their origin.

Models differ widely below this mass: "heavy seeds"are born in tiny halos ("obese BHs"; **Natarajan+2018**) and remain outliers for extended periods ($\gtrsim$ 100 Myr **Visbal & ZH 2018**)

LISA event rate: M-σ model

Tanaka & Haiman (2009)

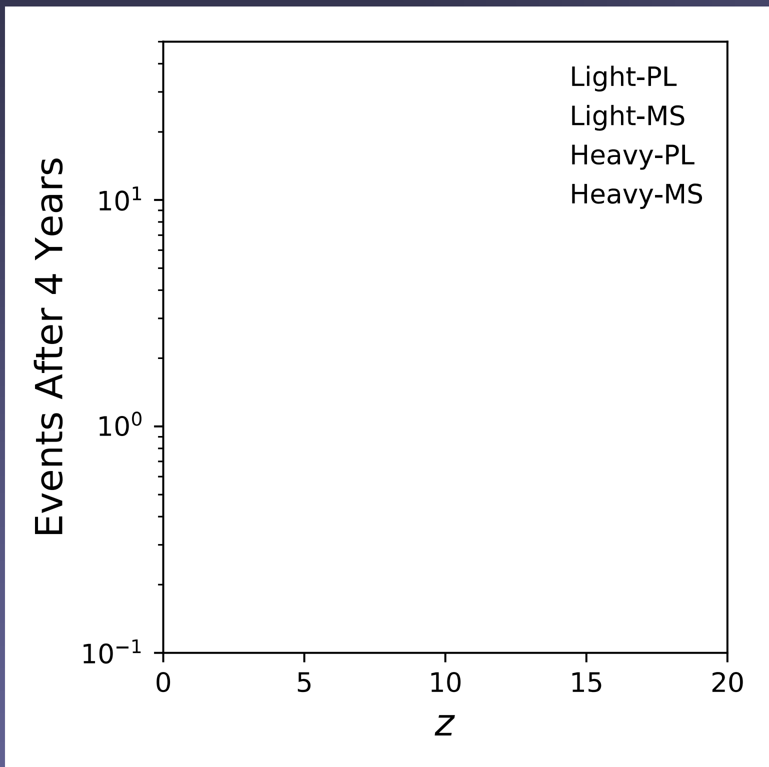
$10^4\ M_\odot < (1+z)M_{bh} < 10^7\ M_\odot$

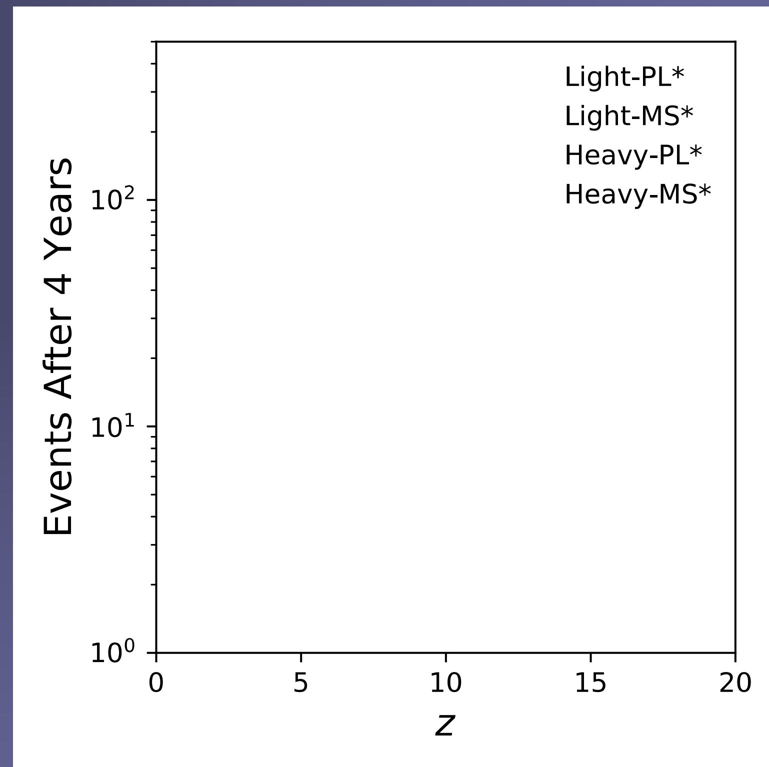


- **Internal feedback regulates BH mass**
  set to maintain extrapolated M-σ relation
- **Growth driven by mergers:**
  slow accretion, tracks halo growth on Hubble time
- **Many ejections**
  can exceed half ρ_{BH}

LISA event rate: stellar vs heavy seeds

Ricarte & Natarajan (2018)





“pessimistic” “optimistic”

LISA should detect a 10-100 $\sim 10^{3\text{-}5}$ $M_\odot$ BHs at z~10

The Astrophysical Journal, 701:360–368, 2009 August 10 doi:10.1088/0004-637X/701/1/360

ON THE OCCUPATION FRACTION OF SEED BLACK HOLES IN HIGH-REDSHIFT DARK MATTER HALOS

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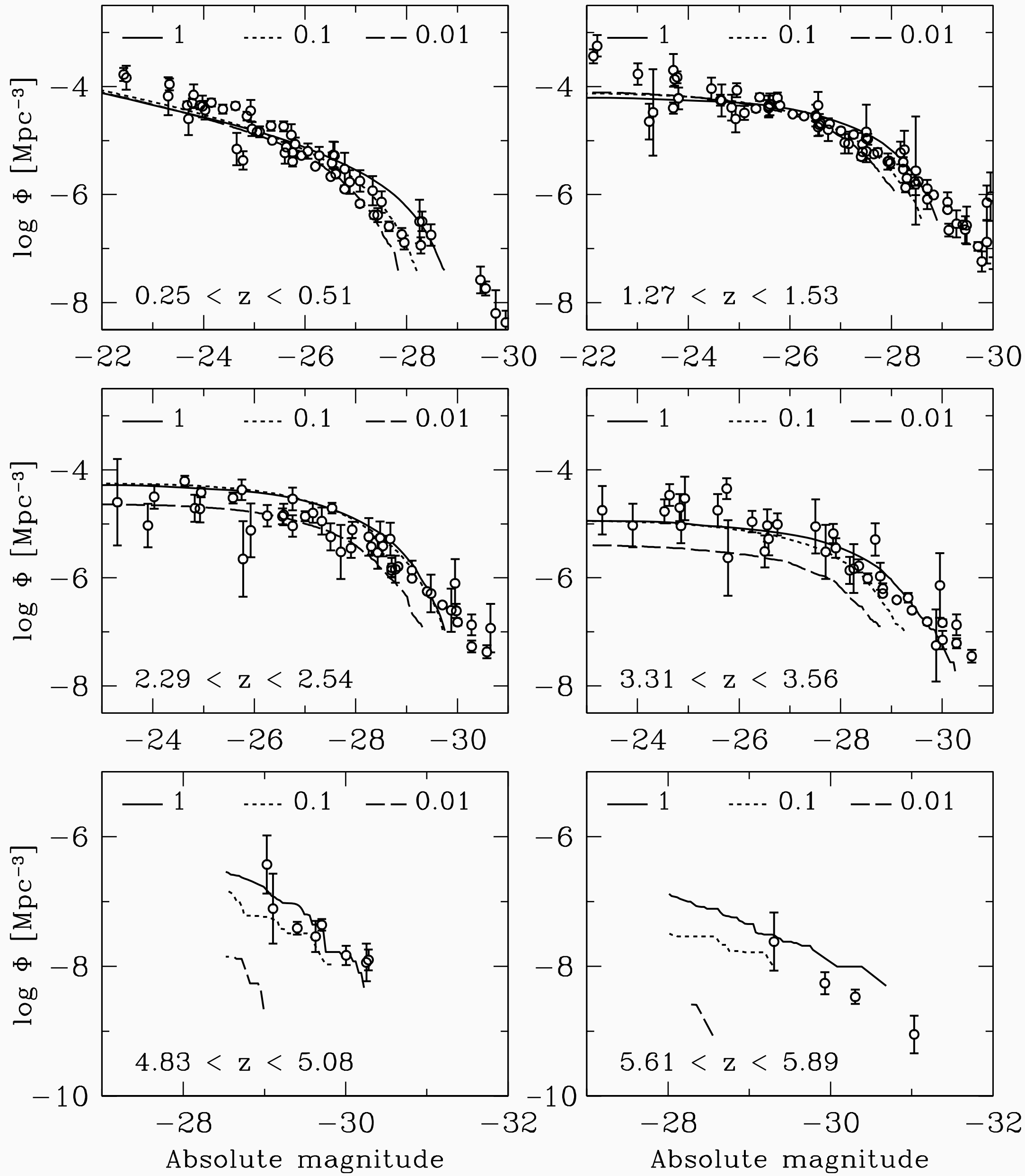
ABSTRACT

It is well known that an initial population of seed black holes (BHs), formed in the nuclei of low-mass galaxies at high redshift, can simultaneously explain, through their subsequent growth by mergers and accretion, both the observed evolution of the quasar luminosity function (LF) and the distribution of remnant supermassive black hole (SMBH) masses measured in local galactic nuclei. Here we consider three very different initial conditions for this scenario: models in which initial seed BHs form in either all, or only a small fraction ($f_{\rm bh} = 0.1$ or 0.01) of high-redshift dark matter halos (with $M_{\rm halo} = 5 \times 10^9 \, M_\odot$ at $z = 6$–10). We show that with a suitable and relatively minor adjustment of two global physical parameters (the radiative efficiency and mass accretion time-scale of quasar episodes), models with $f_{\rm bh} \approx 0.1$ and 1 can accurately reproduce the observed quasar LF at redshifts $0 < z \lesssim 6$, as well as the remnant SMBH mass function at $z = 0$. However, SMBHs remain rare, and the normalization of the high-z quasar LF and the local SMBH mass function are both significantly underpredicted, if $f_{\rm bh} \lesssim 0.01$. We also show that the merger history of SMBHs, in the mass range detectable by the future *Laser Interferometer Space Antenna* (*LISA*) instrument, generically looks different as $f_{\rm bh}$ is varied; this should allow *LISA* to deliver useful constraints on otherwise degenerate models.

Key words: black hole physics – galaxies: nuclei – gravitational waves



1
0.1
0.01
log Φ [Mpc⁻³]
0.25 < z < 0.51
1.27 < z < 1.53
2.29 < z < 2.54
3.31 < z < 3.56
4.83 < z < 5.08
5.61 < z < 5.89
−4
−6
−8
−10
−22
−24
−26
−28
−30
−32
Absolute magnitude

Diagnosing models

- **Will be difficult via luminosity function alone**
  degeneracies between parameters
  trade off lower growth rate with more seeds, etc.

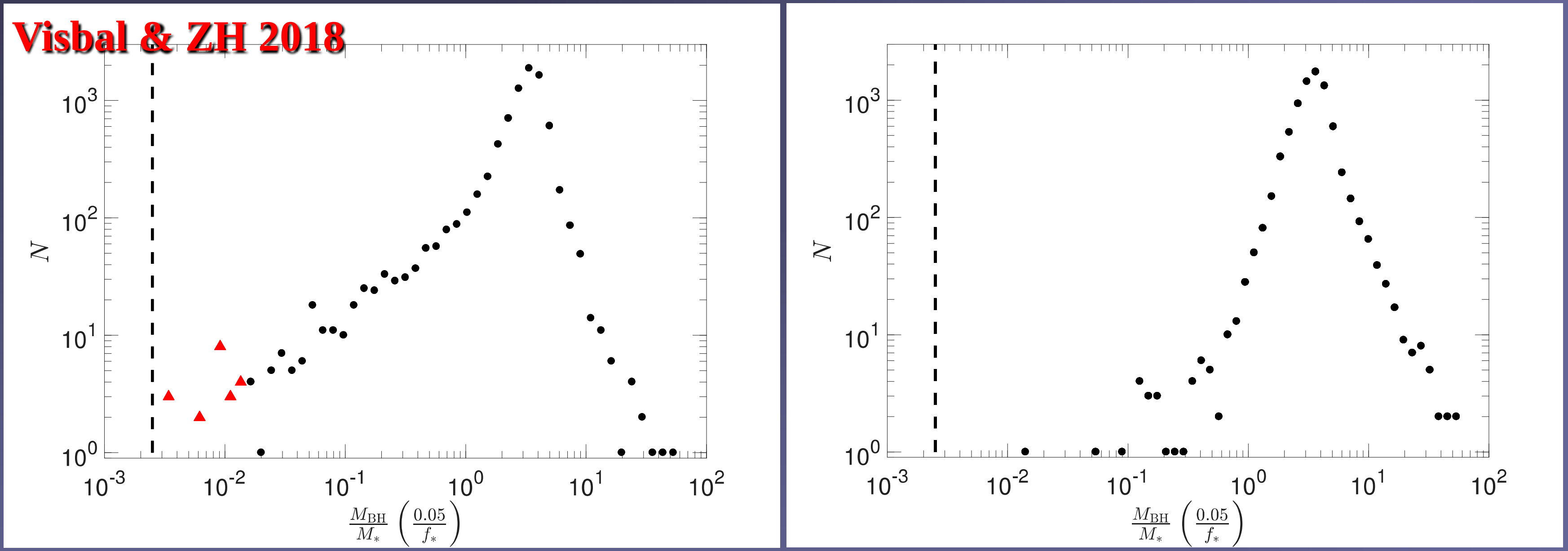
- **Combine with LISA data**
  two models that have the same LF due to degeneracy
  should generally produce different LISA rate

- **Combine with IR data**
  "catch" BHs near threshold, before they grow well above $\sim 10^5\ M_\odot$ and "forget" their origin.

  Models differ widely below this mass: "heavy seeds" are born in tiny halos ("obese BHs"; **Natarajan+2018**) and remain outliers for extended periods ($\gtrsim$ 100 Myr **Visbal & ZH 2018**)

Do heavy seeds remain in "tiny" hosts?

- place heavy seeds in z~10 hosts in N-body sim
- follow merger history of ~8000 hosts for ~100 Myr
- check BH / halo mass ratio at M_{bh} = few $\times$ 10^6 $M_\odot$ (Lynx)



- a few seeds do fall into large halos with $M_{halo} > 10^{10}$ $M_\odot$
- but these remain in resolvable subhalos (few kpc offset)

→ JWST will see faint or no host, or large galaxy offset by ~1"

Proposal

- **Lynx**
  detects X-ray point source ($\sim 10^{5\text{-}6}\ M_\odot$ black holes at z~10-12)

- **JWST**
  looks for host in the IR
  -- ***stellar seed:***
  finds spatially coincident "large" $M_* \sim 10^9\ M_\odot$ galaxy
  similar to local M_{bh} -M_* relation
  -- ***heavy seed:***
  finds nothing, faint $M_* \sim 10^7\ M_\odot$ galaxy, or spatially
  offset (by ~1") $M_* \sim 10^{8\text{-}9}\ M_\odot$ galaxy

Conclusions

1. Growing z>6 SMBHs with $\sim 10^9 M_\odot$ possible in two competing scenarios:

   (i) stellar seeds grow at Eddington rate without interruption, or

   (ii) rapid collapse produces heavier seeds ($\sim 10^{5-6} M_\odot$)

2. Distinguishing modes based on LF alone is hard

   degeneracy between model parameters (occupation fraction, growth rate)

3. Best hope is to study $\sim 10^{5-6} M_\odot$ SMBHs

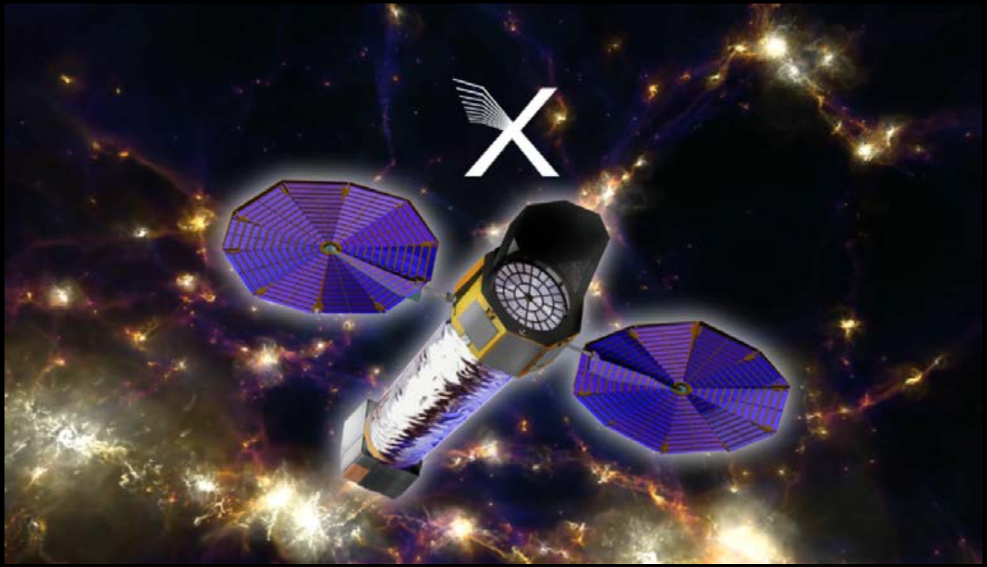
   "direct collapse" BHs are born strong outliers in BH mass vs halo mass

4. Lynx and LISA highly synergistic:

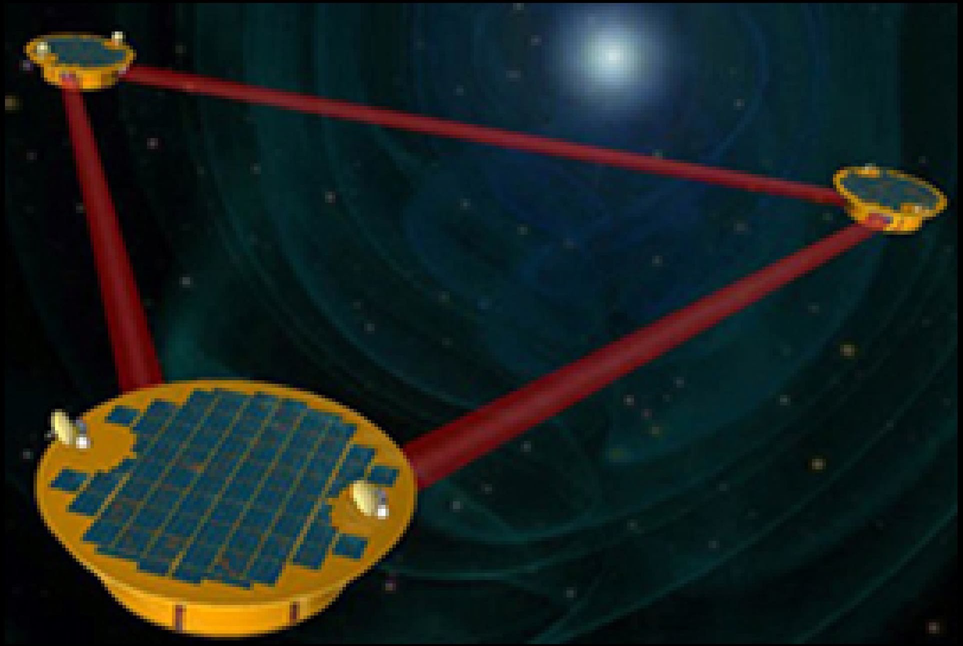
   Lynx probes growth by accretion: ~1000 faint quasars to $\sim 10^5 M_\odot$ at z=10

   LISA probes growth by mergers: up to ~100 merger events from z=6-12

Conclusion



Build both!



Even better:
fly them together!

→ X-ray chirp from
z=1-2 mergers

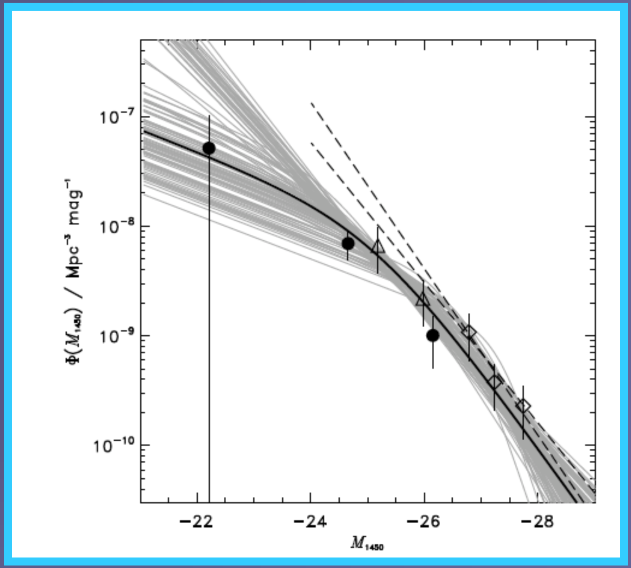
Le Fin

Bright Quasars at z>6

- **Rare ("5σ") objects:**
  10 found in SDSS at z>6
  20 in CFHQS + few others

- **Record: z = 7.08** ***(t=0.77 Gyr, UKIDDS)***
  Mortlock et al. 2011

- **Tip of the iceberg (?):**
  Space density ~1 Gpc^{-3}



Willott et al. 2010

- **Mass estimates**

$$M_{bh} = L_{obs} / L_{Edd} \approx 10^{9-10} M_\odot \quad \text{(Eddington luminosity)}$$

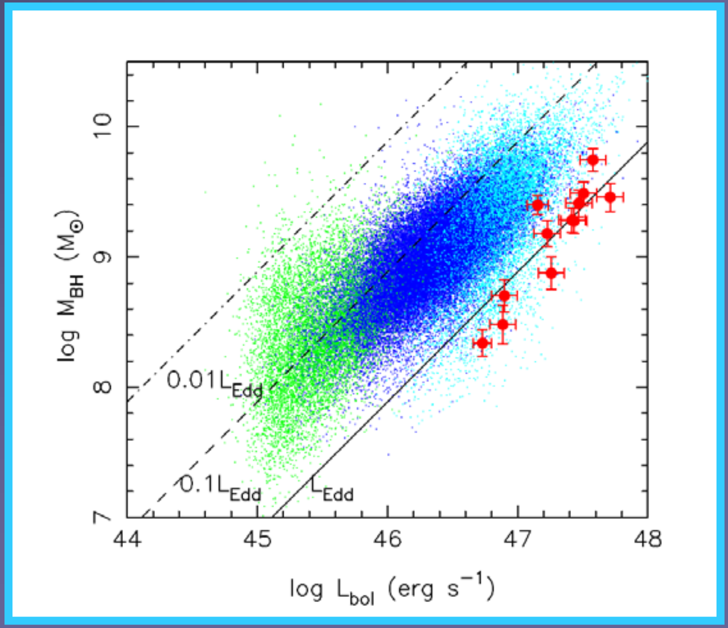
$$M_{halo} \approx 10^{12-13} M_\odot \quad \text{(match space density)}$$

Can we be fooled?

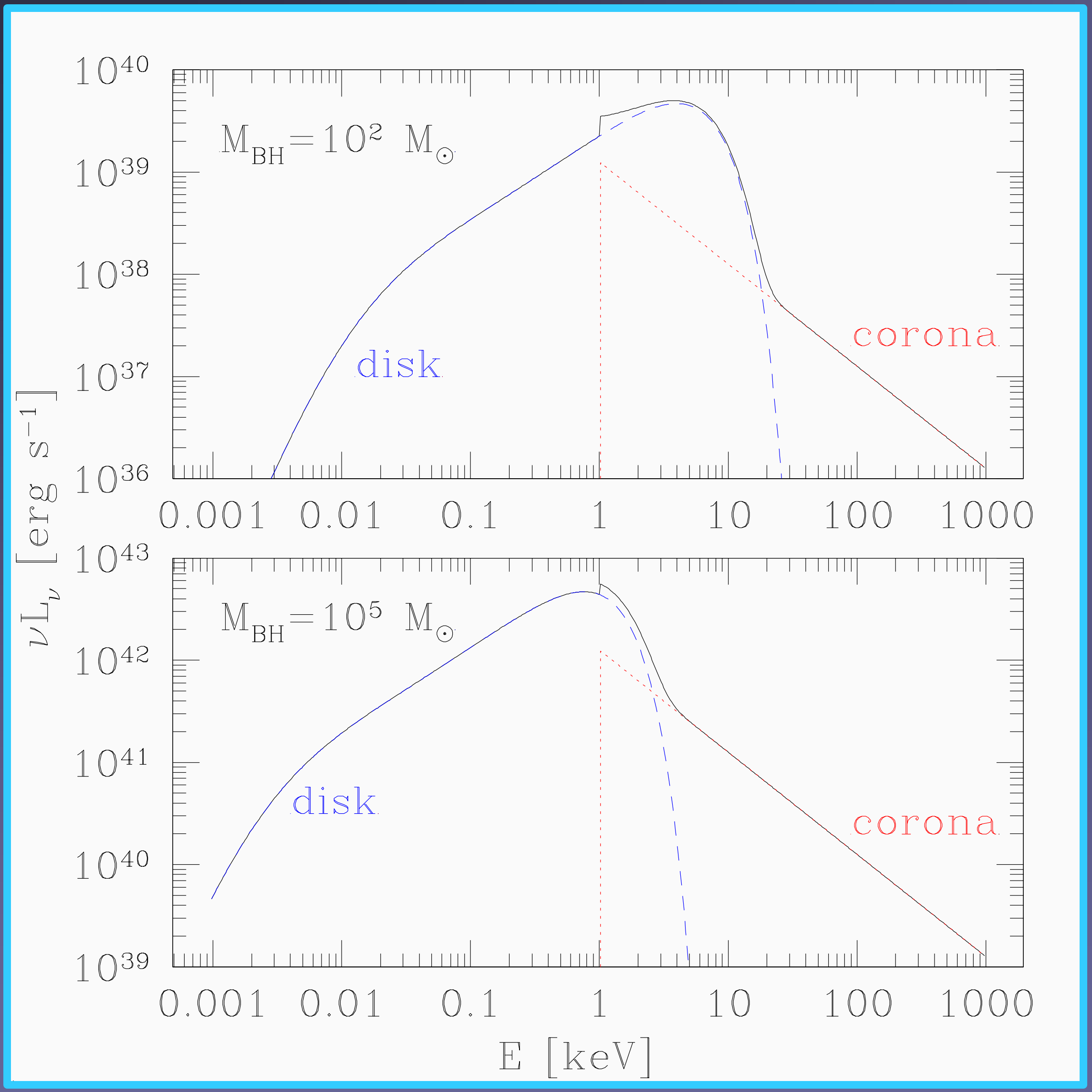
- Short answer: NO. Several × 10^9 $M_\odot$ masses are here to stay.

- Gravitational lensing? No. (Keeton, Kuhlen & Haiman 2004)
- Strong beaming? No. (Haiman & Cen 2002; Willott et al. 2003)

- Empirical measurement of L/L_{edd}
  from CIV and MgII line widths,
  calibrated by reverberation mapping
  (Vestergaard 2004; Kurk et al. 2007
  Jiang et al. 2009)



X-rays from Mini-Quasars



- **Multi-color disk + corona**
- **Emission peaks at 1-5 keV**
- **No significant IR or UV**

- **X-rays heat IGM (by fast photo electrons):**

  1. increase Jeans mass in IGM

  2. decrease central density in halos

Ricotti & Ostriker (2004)
Madau et al. (2004)

A global controversy

Watts Up With That?

The world's most viewed site on global warming and climate change

Quote of the Week: 'global warming stunts black holes'

Posted on June 10, 2012 by Anthony Watts

It appears "global warming" is now the most potent force in the universe, according to a scientist from the Max Planck Institute for Astrophysics. An actual scientific paper preprint published in the Cornell University science archive makes the connection to black holes in the title, and includes "climate change" in the abstract.

Sigh. It isn't even past coffee on Sunday morning and already we have our winner. This one… is weapons grade stupidity. I would not believe that a scientist from a prominent re search institute could utter such a statement had I not read it in a prominent science magazine. It's another "Vinerism" in the making: *Children just aren't going to know what black holes are.*

It immediately reminded me of the famous line uttered by Tom Cruise in the movie a *A Few Good Men*:

> ***"Should we or should we not follow the advice of the galactically stupid!***

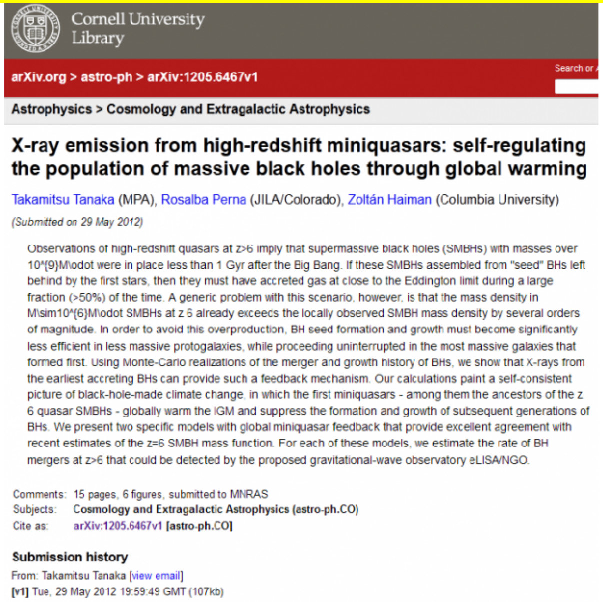
But then again, this is *The New Scientist*. Read on, emphasis mine.

> …
>
> *Something must have limited the growth of these black holes. Now Takamitsu Tanaka at the Max Planck Institute for Astrophysics in Garching, Germany, and colleagues* ***have a climate-based explanation.***
>
> …
>
> *Black holes need cool gas to grow so this would have slowed down the growth of other black holes in smaller protogalaxies, even as the growth of black holes in the most massive protogalaxies continued apace (arxiv.org/abs/1205.6467v1).*

first miniquasars – among them the ancestors of the z 6 quasar SMBHs – globally warm the IGM and suppress the formation and growth of subsequent generations of BHs.

Either way, it shows how global warming on the brain tends to create an environment for such ridiculou s comparisons to make it to press.

I decided I should make a screencap of the paper abstract, becuase I have a feeling it will disappear:



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arXiv.org > astro-ph > arXiv:1205.6467v1

Astrophysics > Cosmology and Extragalactic Astrophysics

X-ray emission from high-redshift miniquasars: self-regulating the population of massive black holes through global warming

Takamitsu Tanaka (MPA), Rosalba Perna (JILA/Colorado), Zoltán Haiman (Columbia University)

(Submitted on 29 May 2012)

Observations of high-redshift quasars at z>6 imply that supermassive black holes (SMBHs) with masses over 10^{9}M\odot were in place less than 1 Gyr after the Big Bang. If these SMBHs assembled from "seed" BHs left behind by the first stars, then they must have accreted gas at close to the Eddington limit during a large fraction (>50%) of the time. A generic problem with this scenario, however, is that the mass density in M\sim10^{6}M\odot SMBHs at z 6 already exceeds the locally observed SMBH mass density by several orders of magnitude. In order to avoid this overproduction, BH seed formation and growth must become significantly less efficient in less massive protogalaxies, while proceeding uninterrupted in the most massive galaxies that formed first. Using Monte-Carlo realizations of the merger and growth history of BHs, we show that X-rays from the earliest accreting BHs can provide such a feedback mechanism. Our calculations paint a self-consistent picture of black-hole-made climate change, in which the first miniquasars - among them the ancestors of the z 6 quasar SMBHs - globally warm the IGM and suppress the formation and growth of subsequent generations of BHs. We present two specific models with global miniquasar feedback that provide excellent agreement with recent estimates of the z=6 SMBH mass function. For each of these models, we estimate the rate of BH mergers at z>6 that could be detected by the proposed gravitational-wave observatory eLISA/NGO.

Comments: 15 pages, 6 figures, submitted to MNRAS
Subjects: **Cosmology and Extragalactic Astrophysics (astro-ph.CO)**
Cite as: **arXiv:1205.6467v1 [astro-ph.CO]**

Submission history

From: Takamitsu Tanaka [view email]
[v1] Tue, 29 May 2012 19:59:49 GMT (107kb)

Next I suppose we'll be reading comparisons of the "global warming process" to problems at the atomic interaction level, such as maybe the sun is now producing fewer neutrinos or some such rot. Don't laug h, it could happen.

Read *The New Scientist* article here.

Unfortunately, comments are only allowed from subscribers, so if there are any subscribers out there, please leave a comment pointing out this idiotic comparison. Better yet, write a letter to the editor of the magazi ne.

In the meantime, feel free to use this motivational poster:

201 responses in a week!

Prompt formation of a ~10^5 $M_\odot$ SMBH ?

- Potential Obstacles -

• **H_2 or metal cooling**

- if H_2 forms in atomic cooling halo, gas cools to several 100 K
- gas infall rate drops back close to **~10^{-3} $M_\odot$ yr^{-1}** (e.g. Shang, Haiman, Bryan 2010)
- worse if there are metals

• **Radiation feedback**

- when radiation of accreting BH is included, accretion episodic
- low duty cycle, average rate becomes sub-Eddington
(e.g. Milosavljevic et al. 2009, Park & Ricotti 2011-2013)

• **Fragmentation**

- gas may form self-gravitating disk, fragment on 100AU scales
- dense star cluster, rather than single supermassive star (Regan et al. 2014)

• **Angular momentum barrier**

- form a disk instead of a massive central BH
- transfer angular momentum via global instability (e.g. Schlosman & Begelman)
- cancel due to erratic BH wobble (Alexander & Natarajan 2015)

3D proto-galaxy simulation with $J_{UV}=10^3$

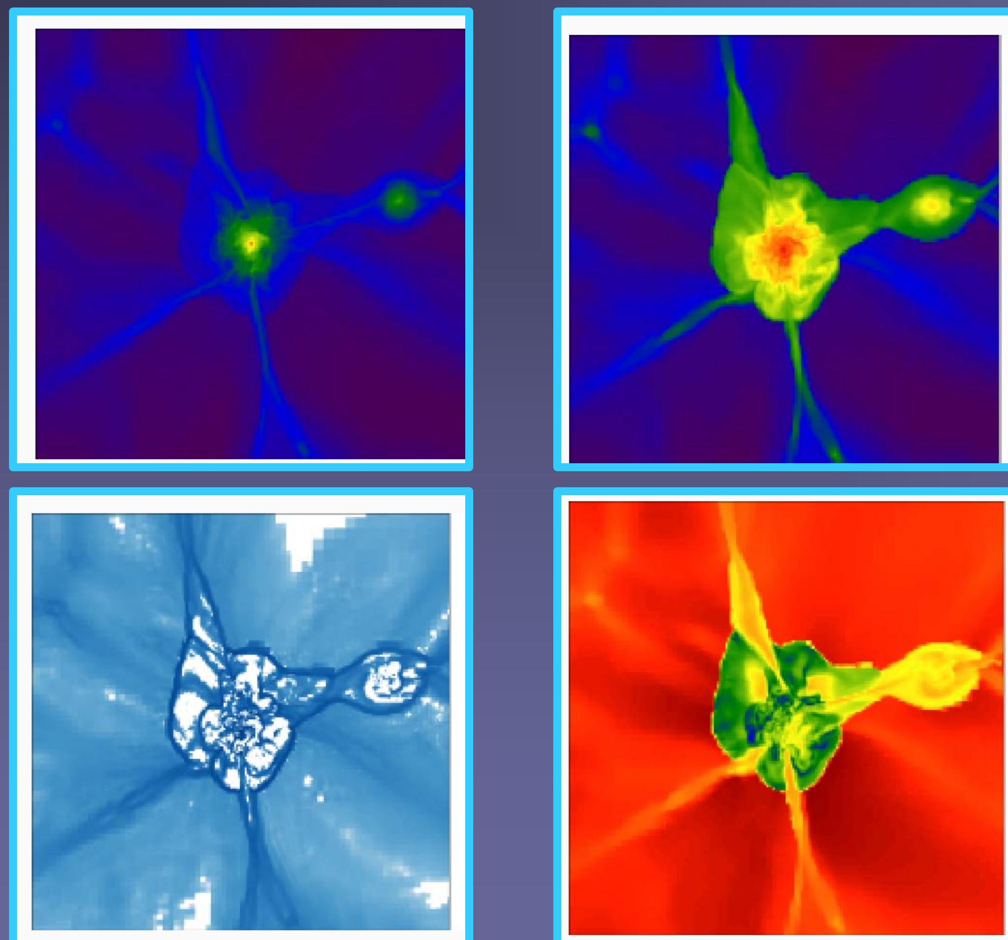
Enzo - atomic cooling halos with $M_{halo} \approx 10^8\,M_\odot$ $z_{coll} \approx 14$

Fernandez, Bryan, Haiman & Li (2014)

Gas stays near 10^4K – never forms enough H_2 to cool further

density

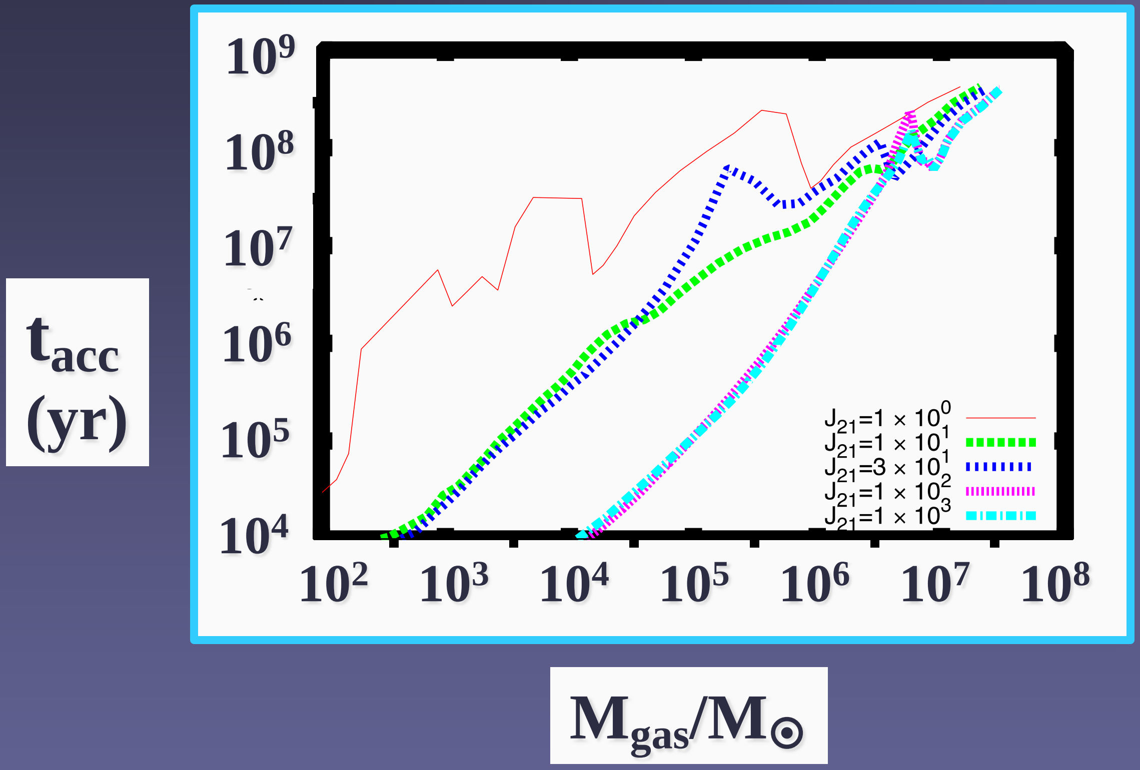
Temperature



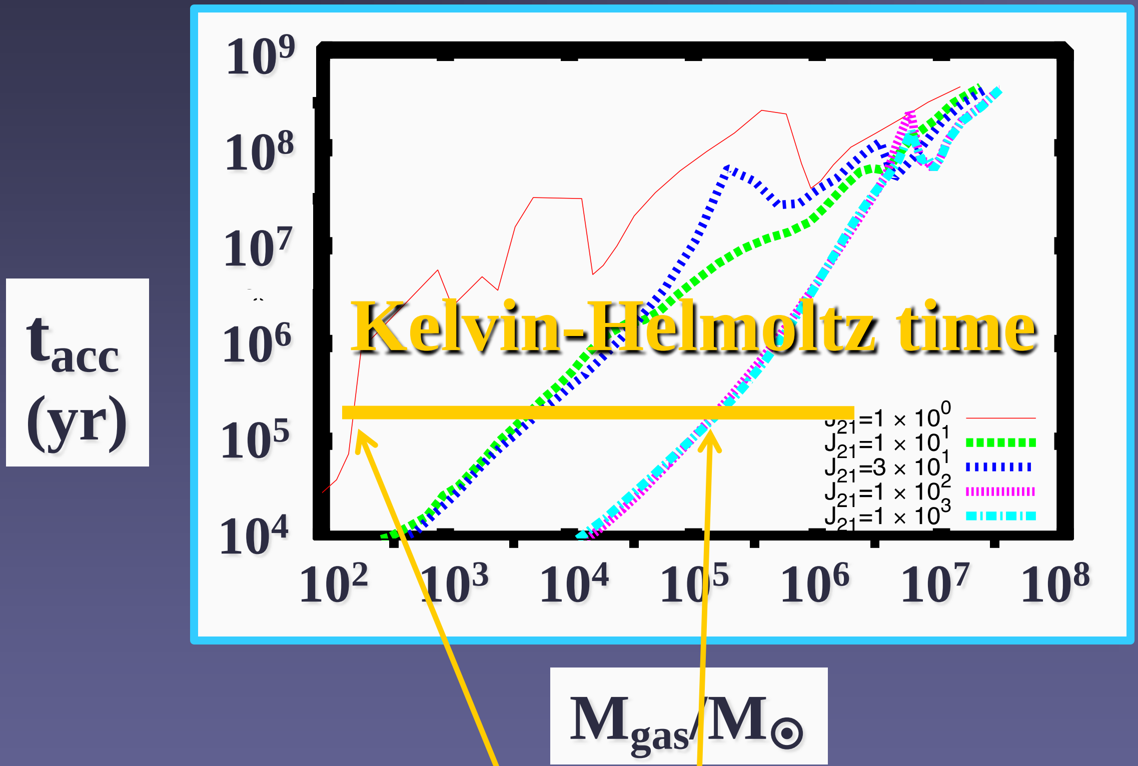
$-\nabla \cdot v$

Mach number

Mass of Central Object



Mass of Central Object



10^2 $M_\odot$ Pop III star   Abel et al.; Bromm et al.; Yoshida et al.

10^5 $M_\odot$ supermassive star/BH ($M_{acc} \sim 1\ M_\odot\ yr^{-1}$)

rapid collapse of warm atomic gas

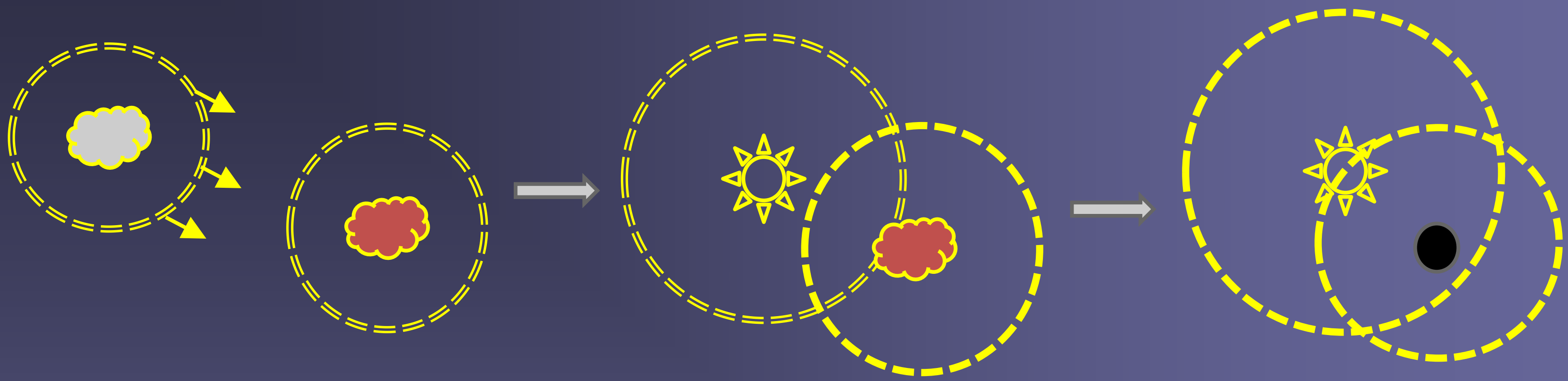
- **In-fall proceeds at sound speed** $c_s \approx 10$ km/s
- **Mass accretion rate** $M_{acc} \propto c_s^{\ 3} \sim 1\ M_{\odot}\ yr^{-1}$
- **Fragmentation is not seen in simulations**
- **Central object has mass** $M \approx 10^5 M_{\odot}$
  (cf. $M \approx 10^2\ M_{\odot}$ **with** H_2**, when** $c_s \approx 1\text{-}2$ km/s**)**

- BUT –

- **Worry 1: is such large UV flux possible ?**
- **Worry 2: metals present and cool the gas?**
- **Worry 3: fragments ultimately ?**
- **Worry 4: radiation suppresses in-fall rate?**

Synchronized pairs of atomic cooling halos

Dijkstra et al. (2008); Visbal, Haiman & Bryan (2014)



- dynamical time in core of atomic cooling halo $t_{dyn} \sim$ 10 Myr
- require that halo is illuminated by $J>J_{crit}$ during this time

- flux can be provided by neighboring halo at a distance d=0.5kpc with $f_* \sim$ 1-20% if stars are 20-5 $M_\odot$

- same neighbor would photoevaporate the target halo's progenitor in ~20 Myr → two halos must be synchronized to $\Delta t_{sync} \sim$ 10 Myr

- orbital separation r>0.2 kpc to avoid ram pressure stripping

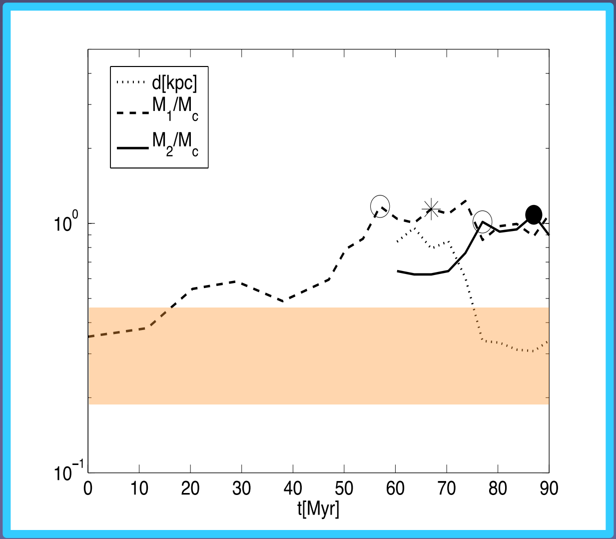
(Sub)halo pairs N-body simulations

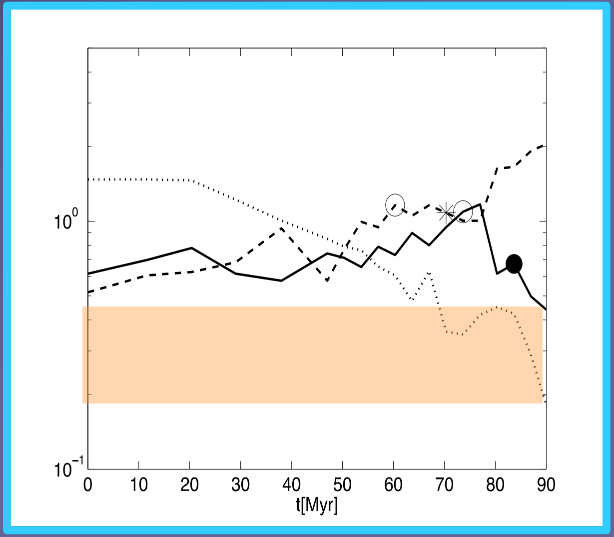
- Five Gadget-2 runs (768^3 particles, L=15 cMpc)
- Halos and subhalos are identified with ROCKSTAR

Behroozi et al. (2013)

2 suitable pairs found

- forming within 10 Myr < Δt_{form} < 20 Myr
- staying within 0.2 kpc < Δr < 0.5 (for 10+ Myr)





Synchronized pairs to z=6 quasar BHs

Visbal, Haiman & Bryan (2014)

- 10^5 $M_\odot$ z=10-12 seed can grow to 10^9 $M_\odot$ at Eddington by z~6
- Abundance of z>6 SMBHs with M_{bh} ~10^9 $M_\odot$ is n ~ 1 $cGpc^{-3}$
- Need only ~1 candidate per 60 N-body boxes (→ "overdid it")
- Extrapolate w/analytic model: enough pairs with much tighter synchronization (Δt_{sync} ~0.2 Myr)
- This can help to avoid external metal pollution: 10^5 $M_\odot$ BH forms (or gets past point of no return) before stars in neighbor produce SNe and metals reach host halo of the seed SMBH