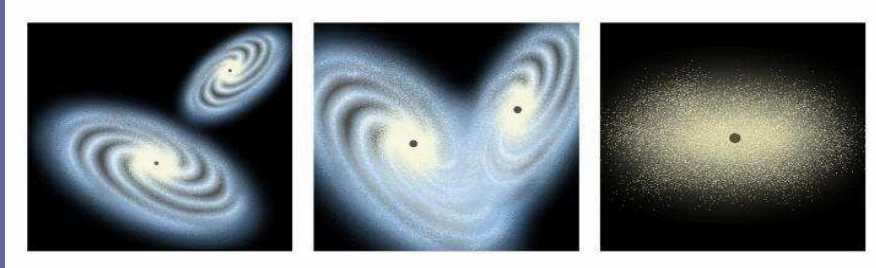


Assembly and merging history of massive black holes



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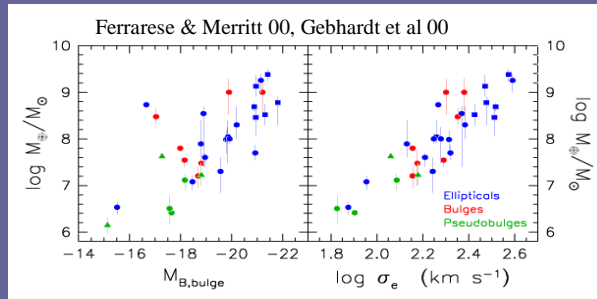
UCSC

Outline

- ✓ *SMBHs in the local Universe: where from?*
- ✓ *SMBHs Mass Growth: Accretion vs Merging*
- ✓ *Dynamical Evolution of BHs:*
 - Formation and Coalescence of BH Binaries*
 - Gravitational Rocket*

1. M_{BH} - σ relation: co-evolution of BHs and galaxies

SMBHs \blacktriangle
 stellar bulges \blacktriangle
 host DM halos (?)



2. A very early assembly epoch for the SDSS QSOs

$M_{BH} = 2 - 3 \times 10^9 M_{\odot}$ time to grow from $M_{in} \sim 150 M_{\odot}$ to M_{BH} is
 $4 \times 10^7 \ln(M_{BH}/M_{in}) = 7 \times 10^8 \text{ yr}$
 —→ comparable to age of the Universe @ $z \sim 6$!!

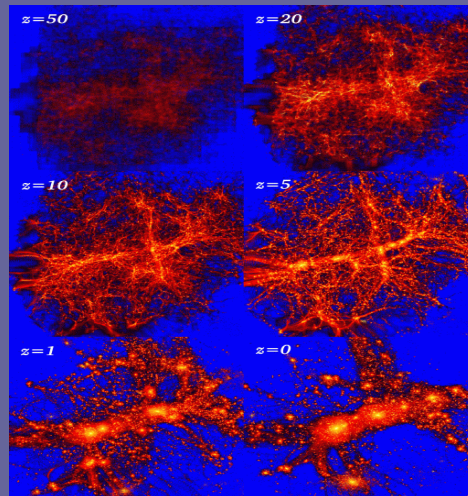
3. First Stars & First black holes

Hierarchical Galaxy Formation:
 small scales collapse first

BARYONS: need to **COOL**
 only the **HIGHEST DENSITY FLUCTUATIONS** at $z \sim 20-30$
 are eligible to host the **FIRST STARS**

The first stars are **MASSIVE:**
 $M \sim 100 - 1000 M_{\odot}$ (Abel et al.,
 Ripamonti et al, Omukai & Nishi)

$Z=0$ dying stars with $M > 260 M_{\odot}$
 leave remnant BHs with $M_{in} \geq 100 M_{\odot}$
 (Fryer, Woosley & Heger)



THE MODEL

SMBHS are grown from *seeds* pregalactic BHs, endproduct of the *first stars*. These seeds are incorporated in larger and larger halos, *accreting gas* and *interacting with each other* after mergers.

Observational constraints:

1. LF of quasars
2. $M_{\text{BH}} - \sigma$ relation

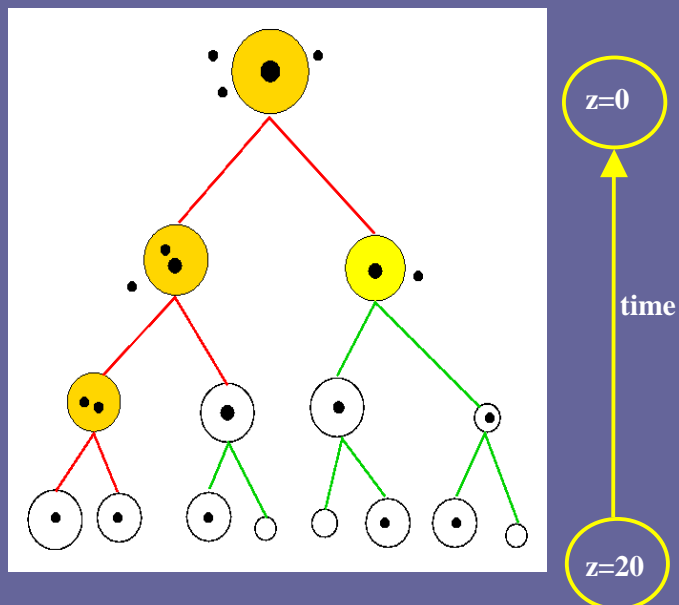
A semi-analytical model for the assembly of BHs

set of binary merger trees starting at $z=20$ in a Λ CDM cosmology

The semi-analytic code follows the *accretion* and *dynamical history* of BHs in every single branch of the tree along cosmic history

seeds $M_{\text{BH}} \sim 150 M_{\odot}$ in

3.5- σ density fluctuations at $z=20$
(Madau & Rees 2001)



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Formation and Coalescence of BH Binaries

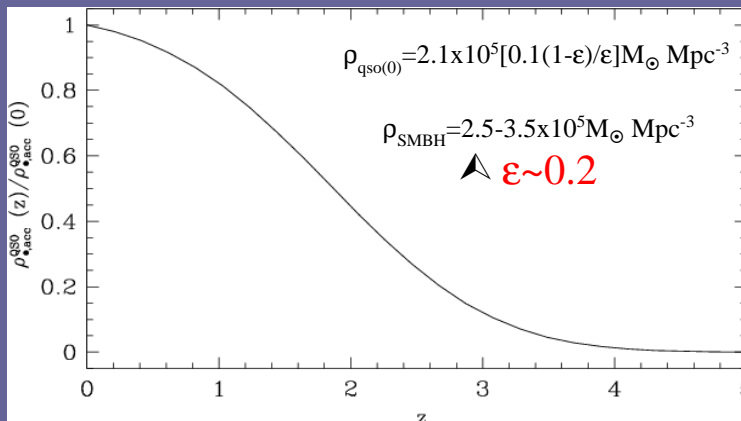
Gravitational Rocket

How does the SMBHs mass grow along the cosmic history?

- Mergers
- Accretion

The final mass of the SMBHs is dominated by accretion, with mergers playing a secondary role

$$M_{BH,acc} \gg M_{BH,merg}$$



from Yu & Tremaine 2002

To recover the local **MBH- σ** & the **quasar LF:**
accretion

✓ *only during major mergers*

✓ *the accreted mass is a fixed fraction of the M_{BH}
 σ relation*
(e.g. self-regulation of accretion due to outflows)

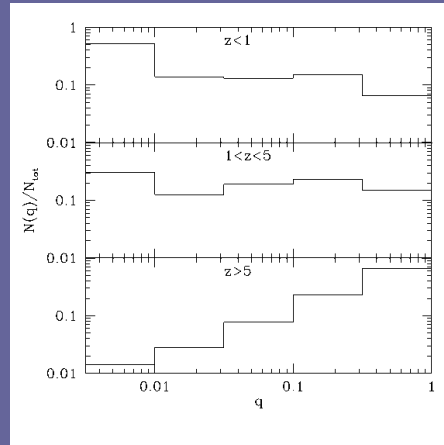
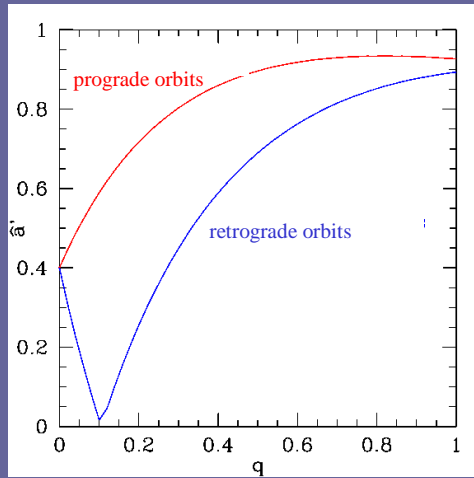
✓ **Eddington** accretion rate

*What is the radiative efficiency?
Are BHs rapidly spinning?*

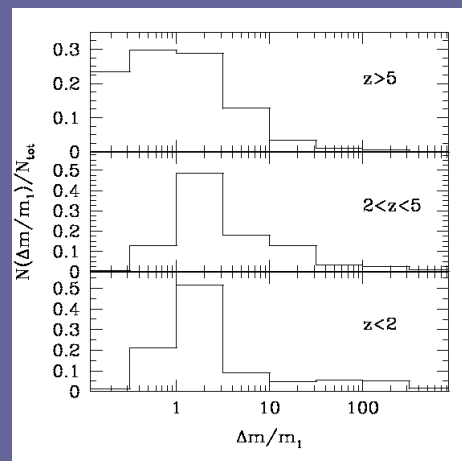
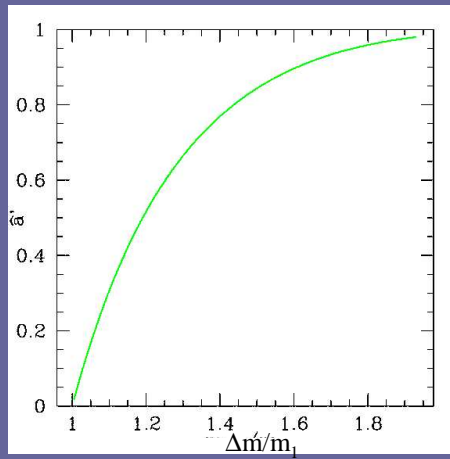
*We have to study the cosmological evolution of BH
spins...*

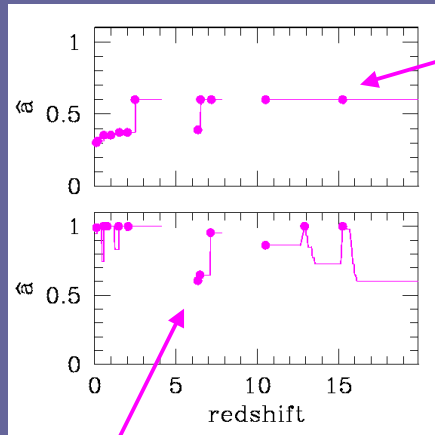
***BHs spin is modified by BH mergers and the
coupling with the accretion disc***

Evolution of BH Spin: MERGERS



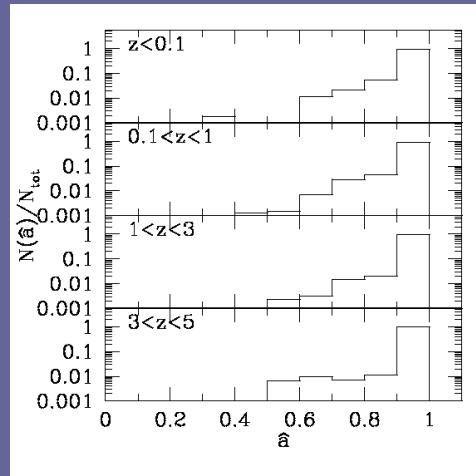
Evolution of BH Spin: ACCRETION





spin evolution by BH mergers only

spin evolution by BH mergers AND accretion



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Formation and Coalescence of BH Binaries

Gravitational Rocket

Dynamical Evolution of BH Pairs

The evolution of a SMBH binary roughly follows the following steps:

1. **dynamical friction** (Lacey & Cole 1993, Colpi et al. 2000)

- BHs approach each other, losing angular momentum by dynamical friction, acting on the BHs envelopes

2. **hardening of the binary** (Quinlan 1996, Merritt 1999, Milosavljevic & Merritt 2001)

- **3 bodies interactions** between the binary and the surrounding stars
- the SMBHs create a **stellar density core ejecting the background stars**

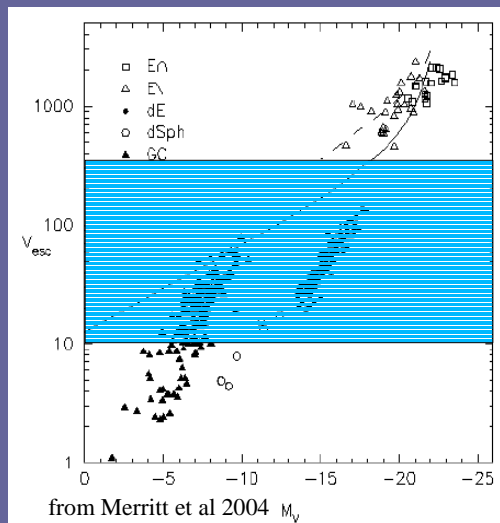
3. **emission of gravitational waves** (Peters 1964)

Takes over at subparsec scales...

Gravitational Rocket

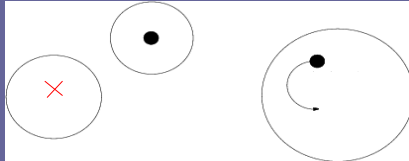
binary center of mass recoil during coalescence due to asymmetric emission of GW (e.g. Fitchett 1983, Favata et al 2004)

*are merging
BHs ejected
from galaxies?*



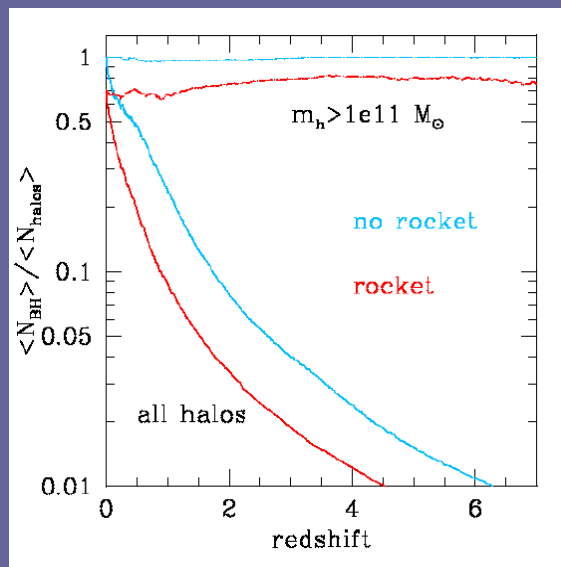
can SMBHs form from mergers of small BHs?

1. *not ALL BHs experience a merger in their lifetime, only ~40-50%*
2. *about 50% of the merging BHs are ejected out of their host halo*
3. *these BHs can be replaced by another BH in a subsequent galactic merger*



4. *SMBHs gain their mass primarily by accretion at "low-ish" redshift ($z < 5$)*

BH Occupation Fraction



for halos with mass larger than $3e12 M_{\odot}$ the occupation fraction is unity, though

Summary

SMBHs can be built up from seeds dating back to the end of cosmological dark ages

- seed BHs from first stars in the highest density fluctuations at high z*
- mass accretion onto BHs triggered by major mergers*
- realistic timescales for binary BHs coalescence \rightarrow harden ejecting stars*
- BHs interactions: slingshots & rockets*



- 1. accretion $\propto M_{\text{BH}} \cdot \sigma$ recovers the LF of quasars*
- 2. ... AND efficiently spins-up black holes*
- 3. dynamical and gravitational interactions can displace BHs*
- 4. ... BUT they don't hinder the assembly of SMBHs*