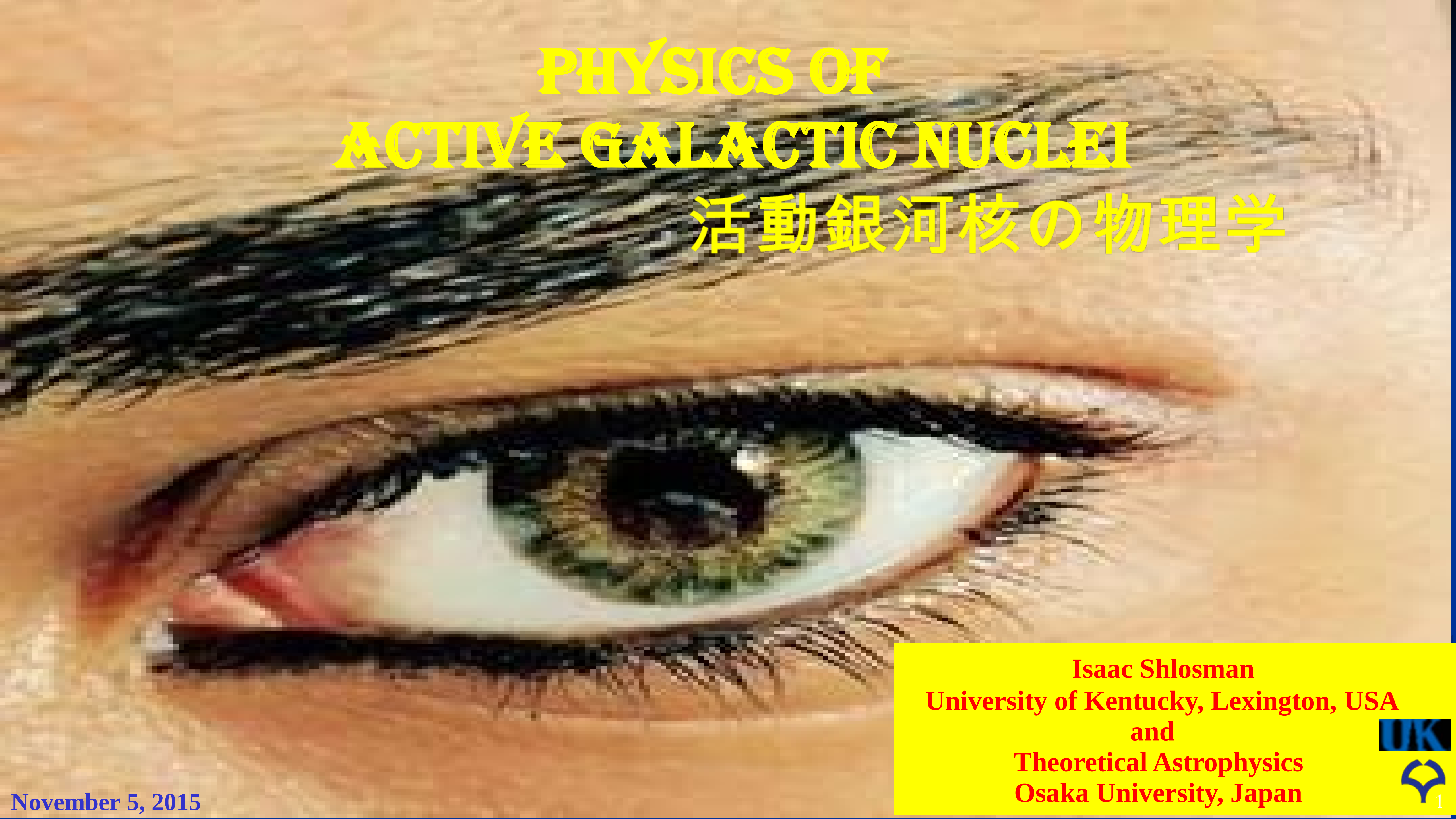


PHYSICS OF ACTIVE GALACTIC NUCLEI

活動銀河核の物理学

Isaac Shlosman
University of Kentucky, Lexington, USA
and
Theoretical Astrophysics
Osaka University, Japan

November 5, 2015

LECTURE 5
FORMATION AND EVOLUTION OF AGN

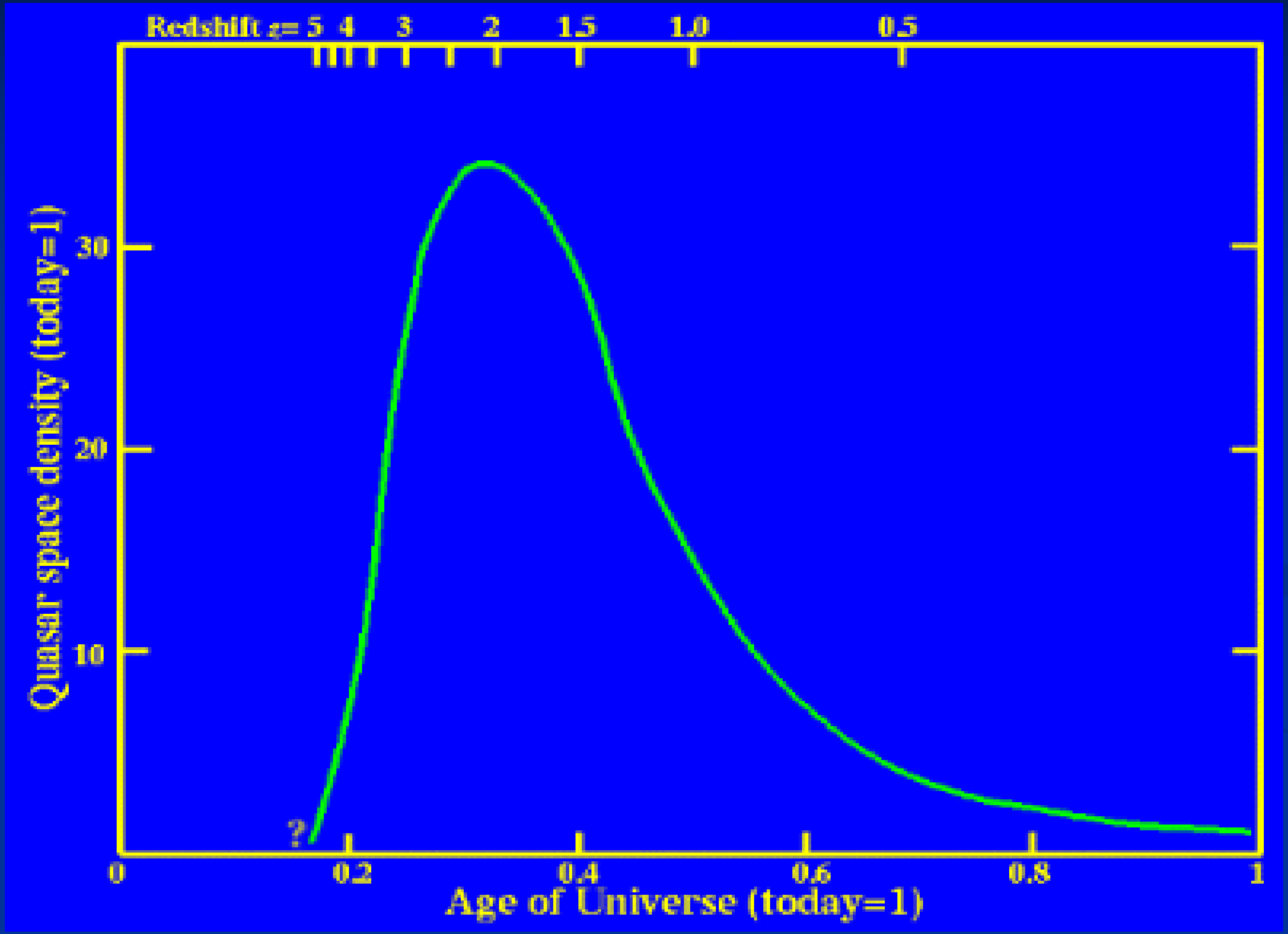
AGN across the Hubble time

Coevolution of SMBHs and galaxies

Population III stars and High-Redshift QSOs

The Making of the Black Hole Seeds: Alternatives

AGN ACROSS THE HUBBLE TIME

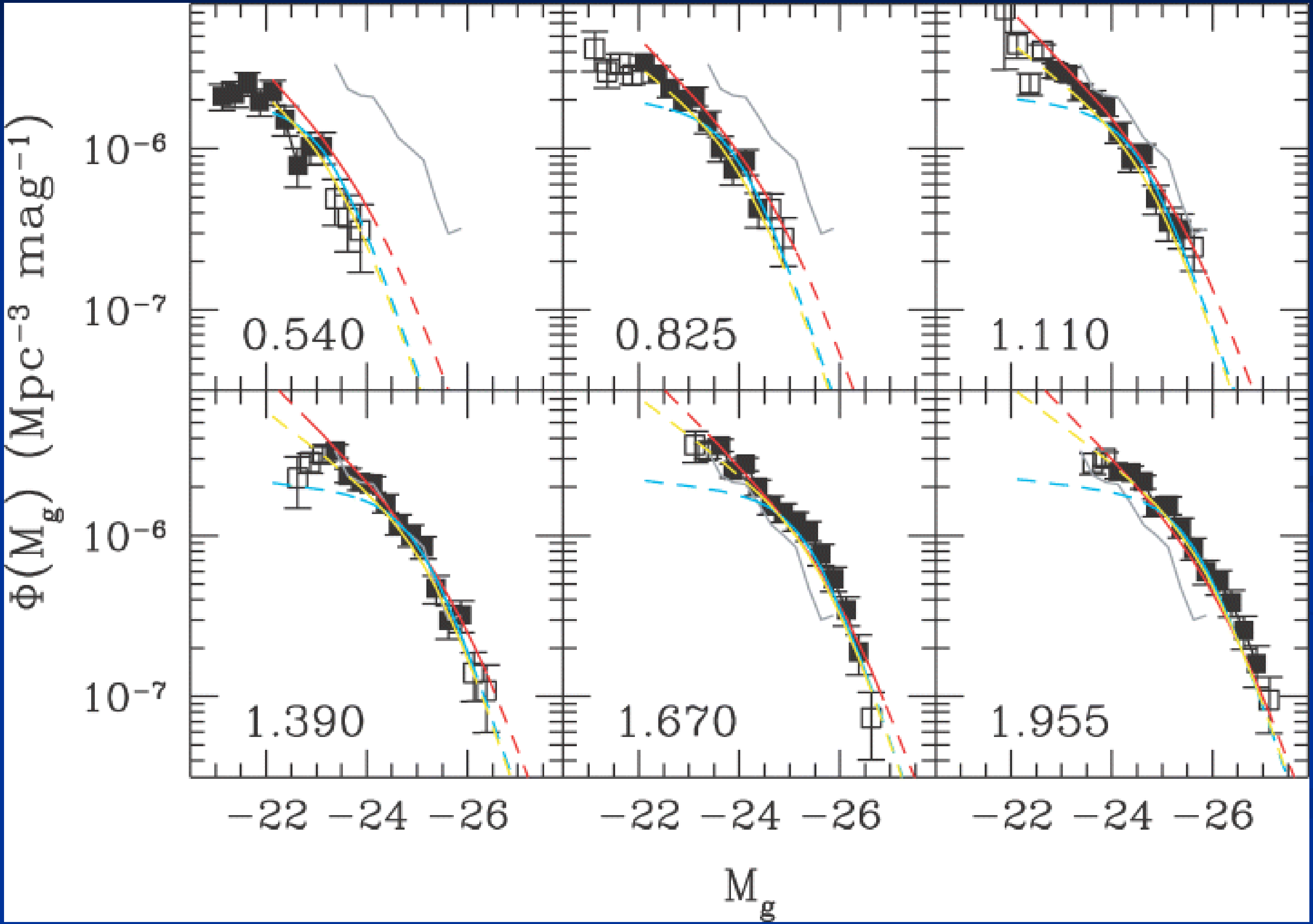


The quasar redshift distribution peaks around z~2

Why around z~2?

This could be related to the formation of galaxies and the star-formation history

AGN ACROSS THE HUBBLE TIME



Richards et al (2005)

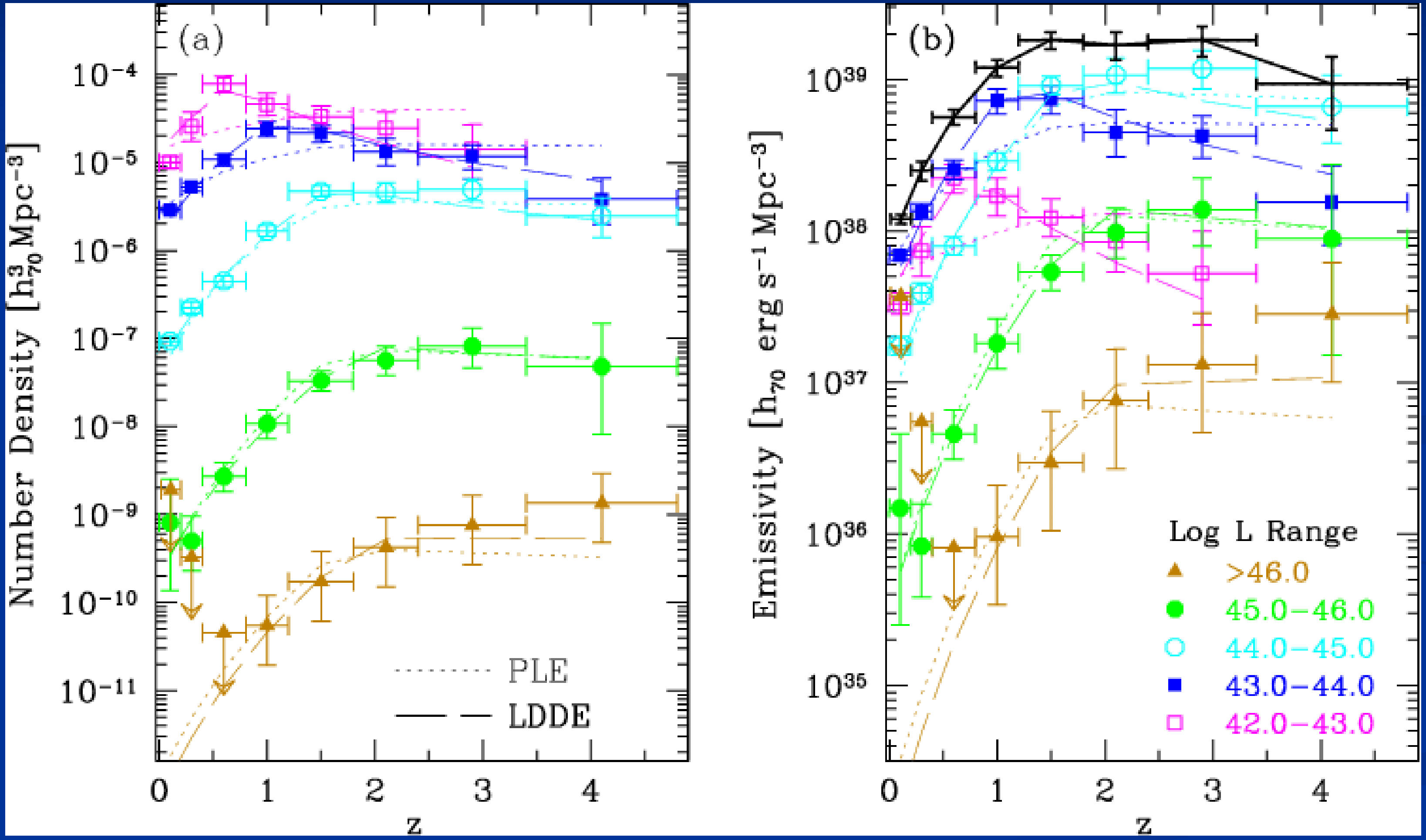
Quasar luminosity function (QSO LF) for various redshifts

Quasars become brighter at higher redshifts

AGN ACROSS THE HUBBLE TIME

Number density

Luminosity density



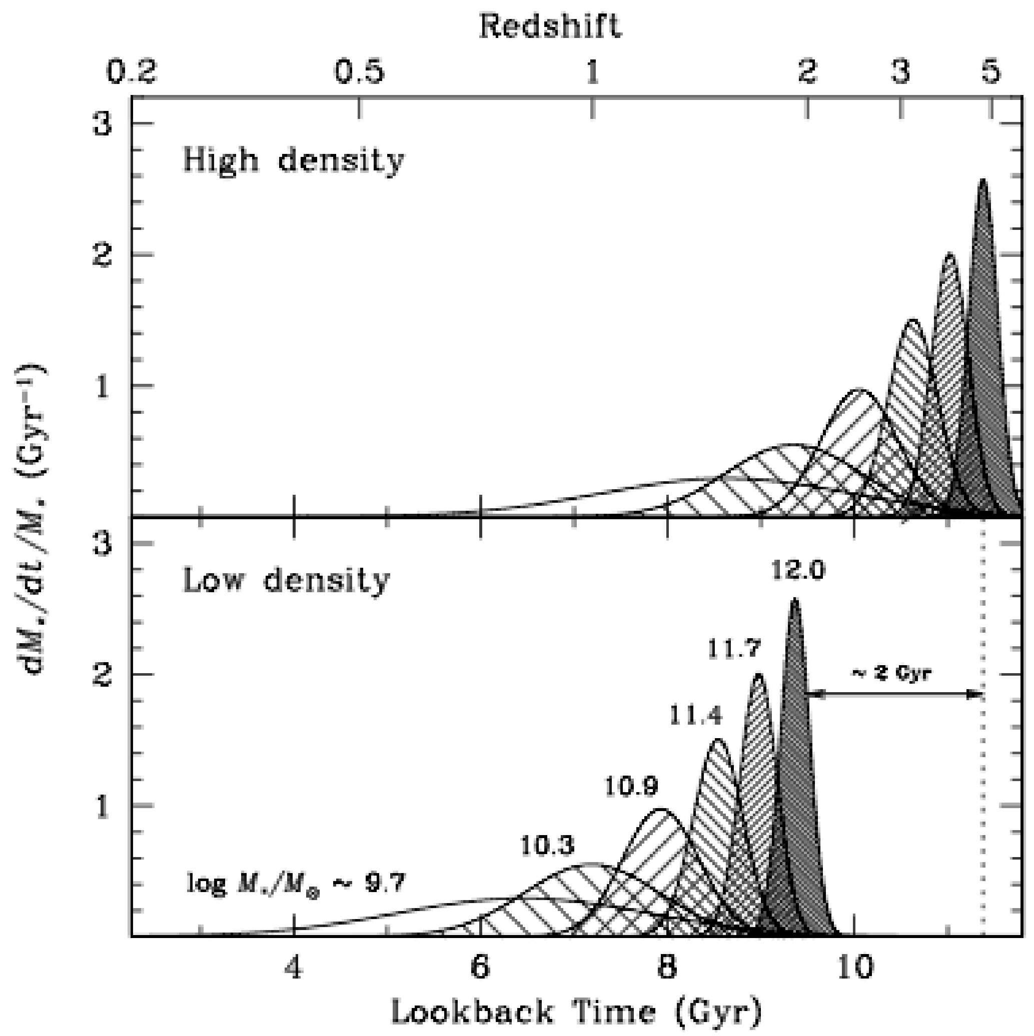
Objects with lower luminosity peak at lower redshift, similar to what is observed for star formation rate (SFR) in galaxies

➔ **cosmic downsizing**

QSOs peak at z≈2-3
Rest of AGN at z≈0.5-1

AGN ACROSS THE HUBBLE TIME

The number density of the most luminous AGN peaks earlier in cosmic time than for less luminous objects → large BHs are formed earlier than their low-mass counterparts?

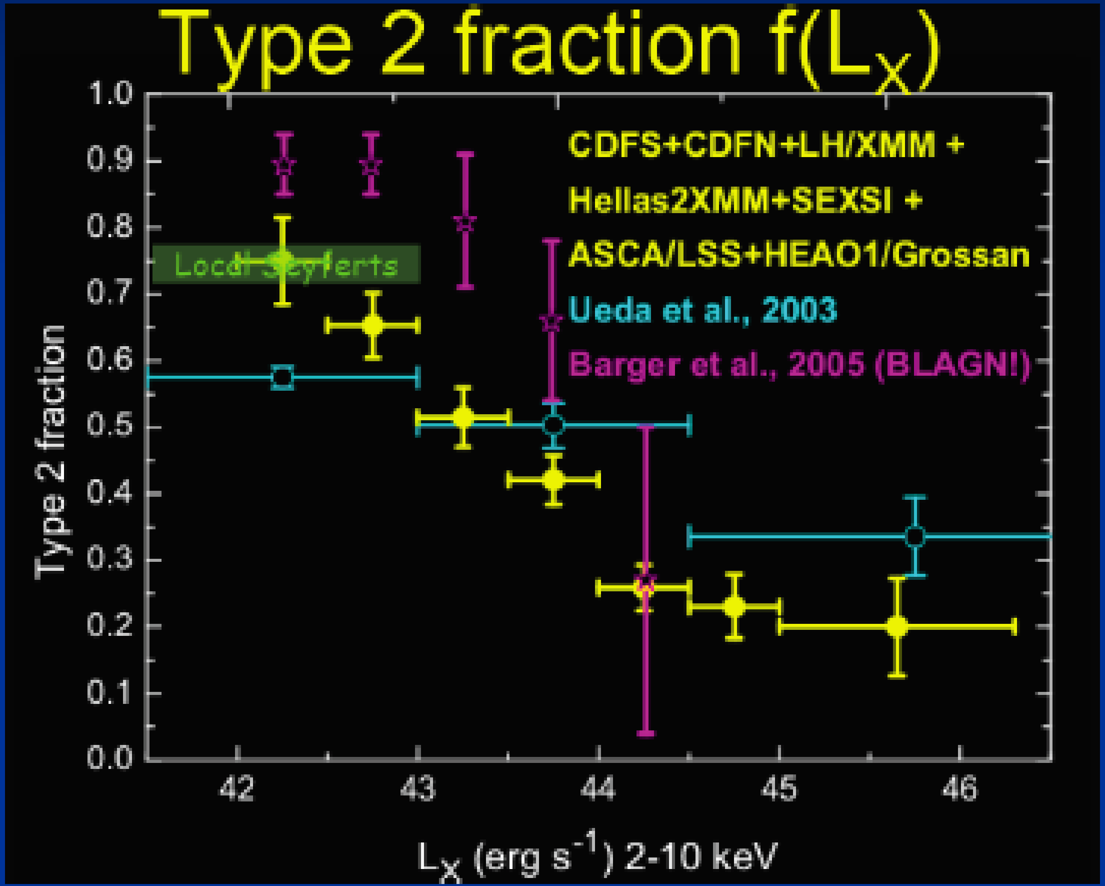


Similar behavior for galaxies:
massive galaxies tend to form stars earlier and faster than less massive galaxies

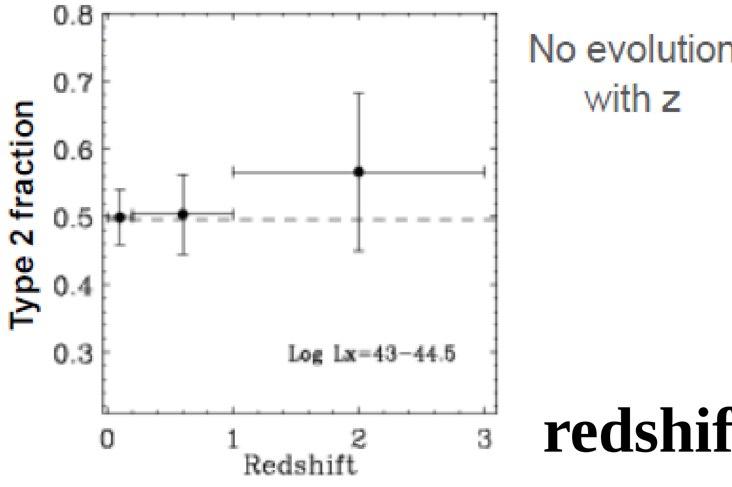
downsizing
(Cowie et al. 1996)

AGN ACROSS THE HUBBLE TIME

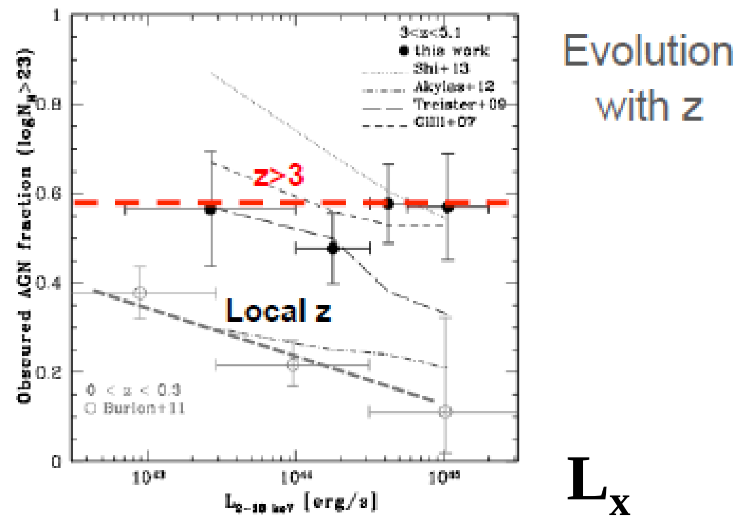
- ❖ Dependence of obscured AGN fraction on X-ray luminosity and redshift



Evolution of type 2 AGN with z: not clear yet



redshift

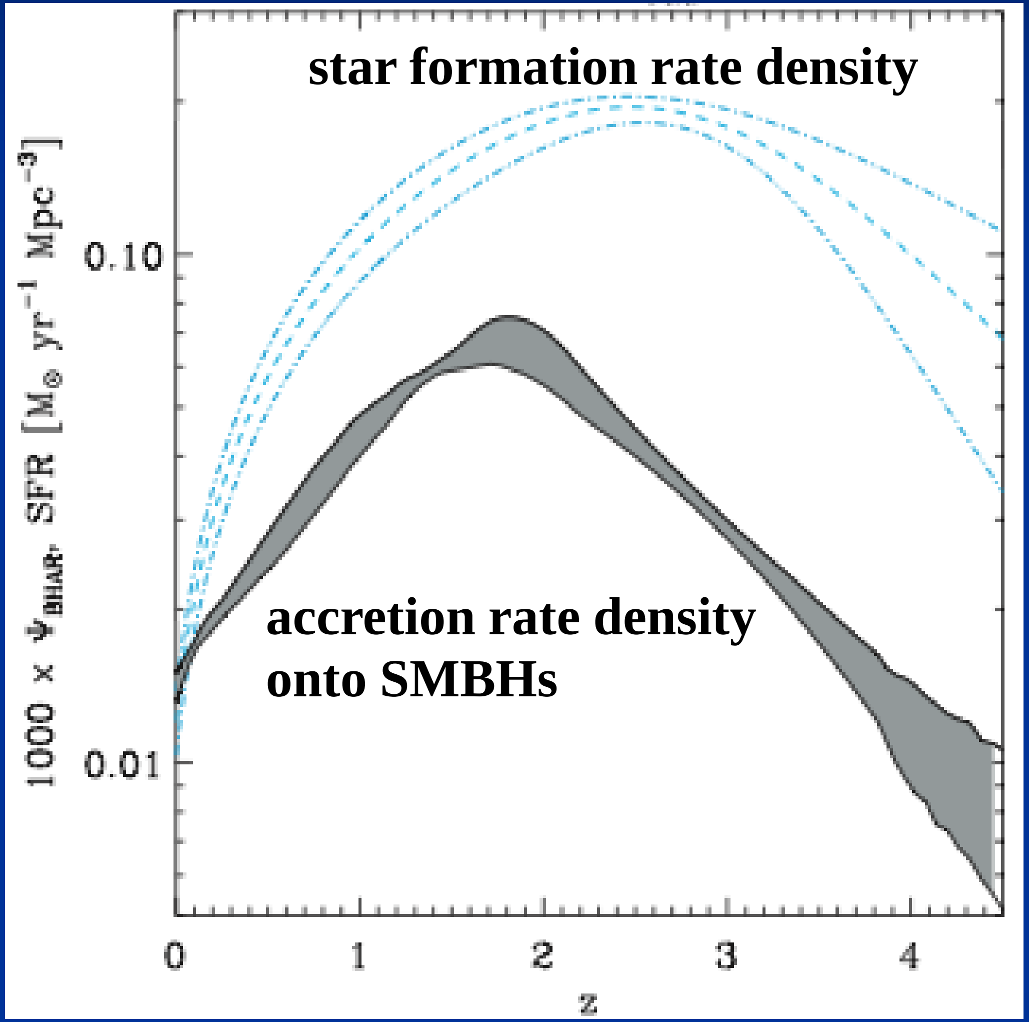


broad consensus: obscured fraction of AGN declines toward high intrinsic luminosities

→ larger opening angle for toroidal obscuration?

AGN ACROSS THE HUBBLE TIME

- Host galaxy and SMBH growth

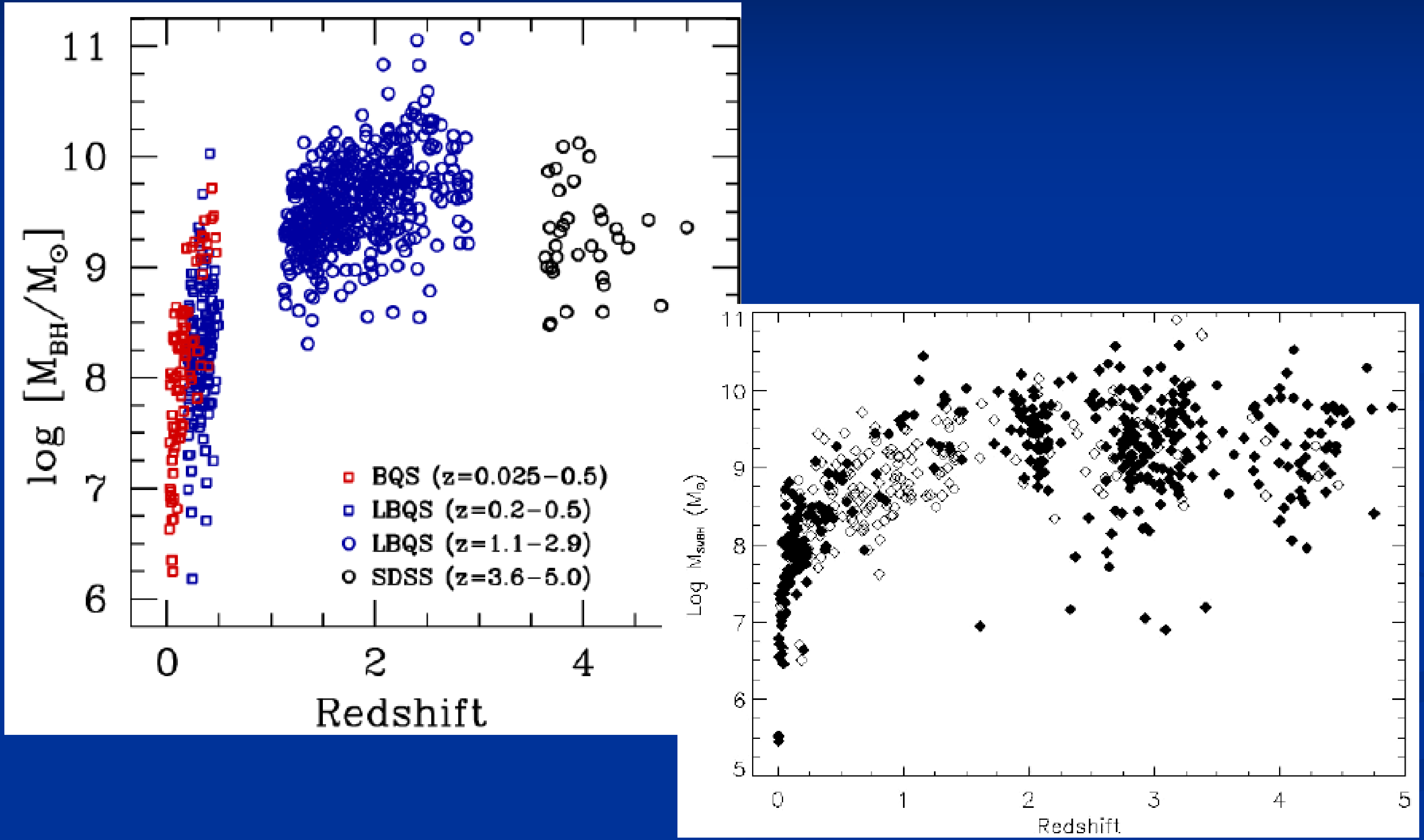


Merloni & Heinz (2008)

Star formation rate density in the universe and accretion rate density onto SMBHs

AGN ACROSS THE HUBBLE TIME

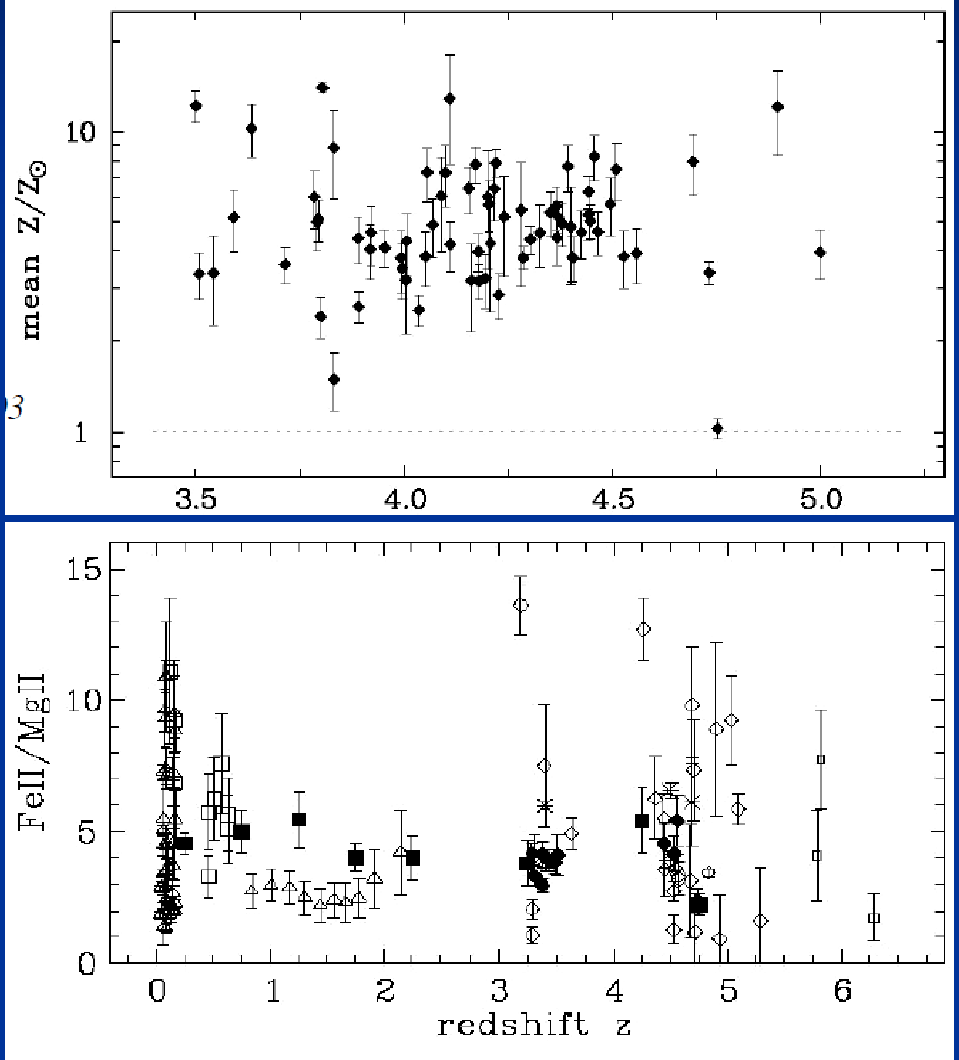
- Masses of SMBHs in distant quasars



SMBHs with masses of up to 10^{10} $M_{\odot}$ built up quickly, already by z~5-6

AGN ACROSS THE HUBBLE TIME

- High-z quasar metallicity



Hamman et al. 2003; Dietrich et al. 2003

Spectra of quasars at all times show very similar metal abundances ← most heavy metals come from SNe

Are all quasars in sites of intense SF and SNe?

Could quasars have triggered this?

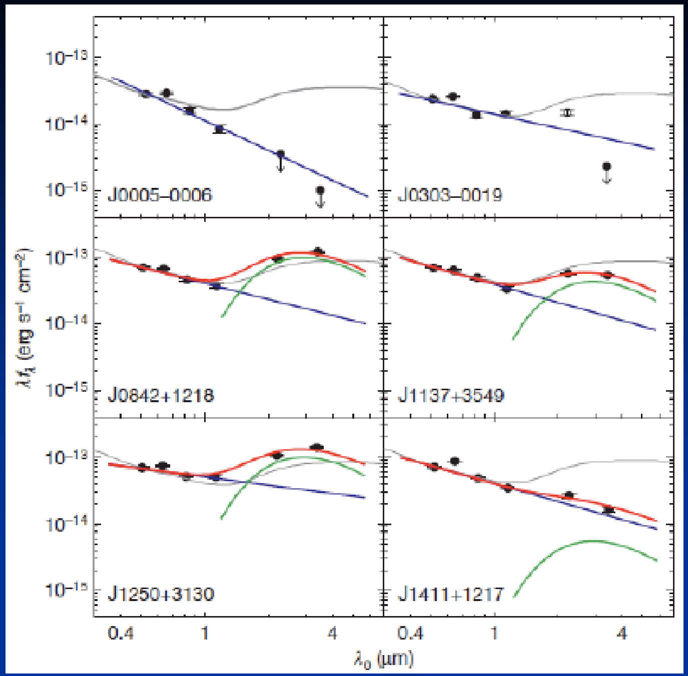
We start to look earlier than the age of Type I SN
→ should see Fe decline!

High-z quasars: abundance patterns (enhanced Fe/α) similar to Ellipticals

→ enrichment by Type 1 SNe for z < 6,
with onset of star formation at z > 10

High-z quasars are very metal rich

AGN ACROSS THE HUBBLE TIME

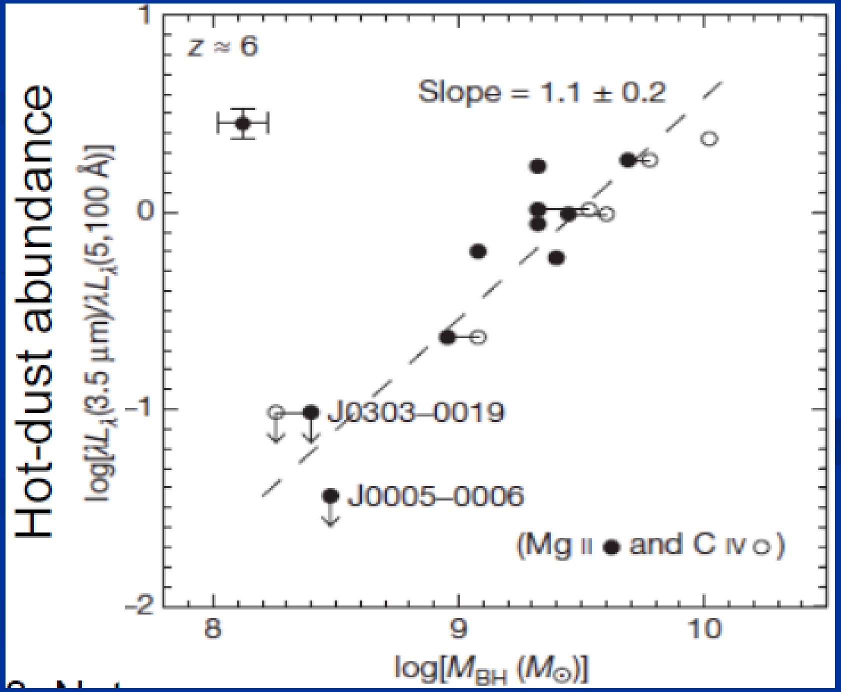


- ❖ High-z (~6) quasar dust

Is dust ubiquitous in z~6 quasars?

2/21 z > 6 quasars w/o hot dust: are quasars born in dust-free environment or not enough time to produce dust?

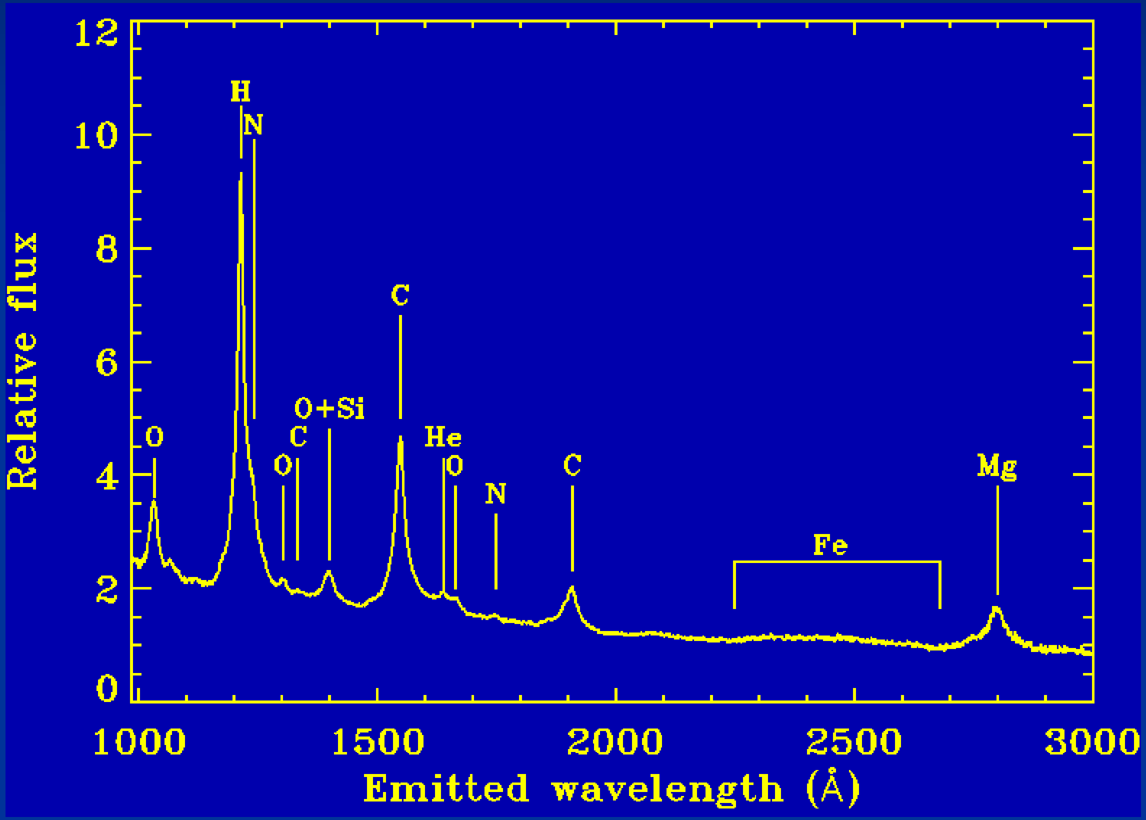
Similar findings for Type 1 AGN in C-COSMOS (Chandra+HST) survey (Hao et al. 2010)
→ from 6% at z < 2 to 20% at z ~ 2-3.5

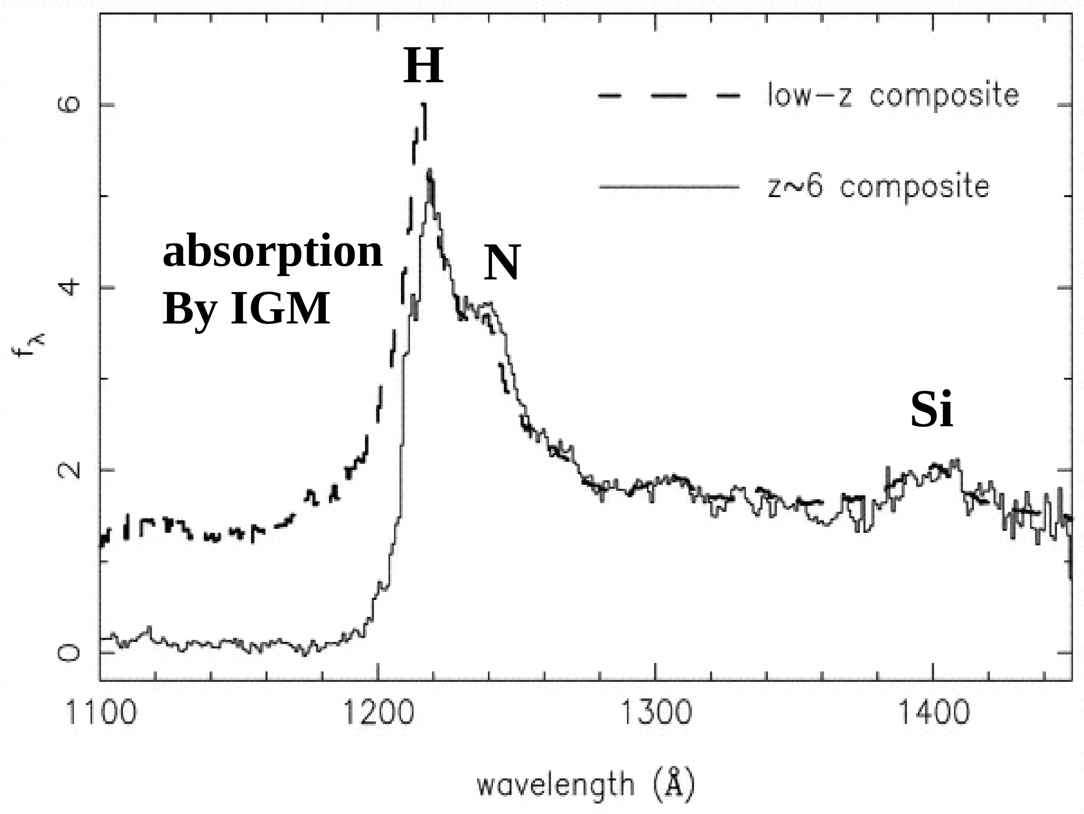


Jiang et al. 2010

AGN ACROSS THE HUBBLE TIME

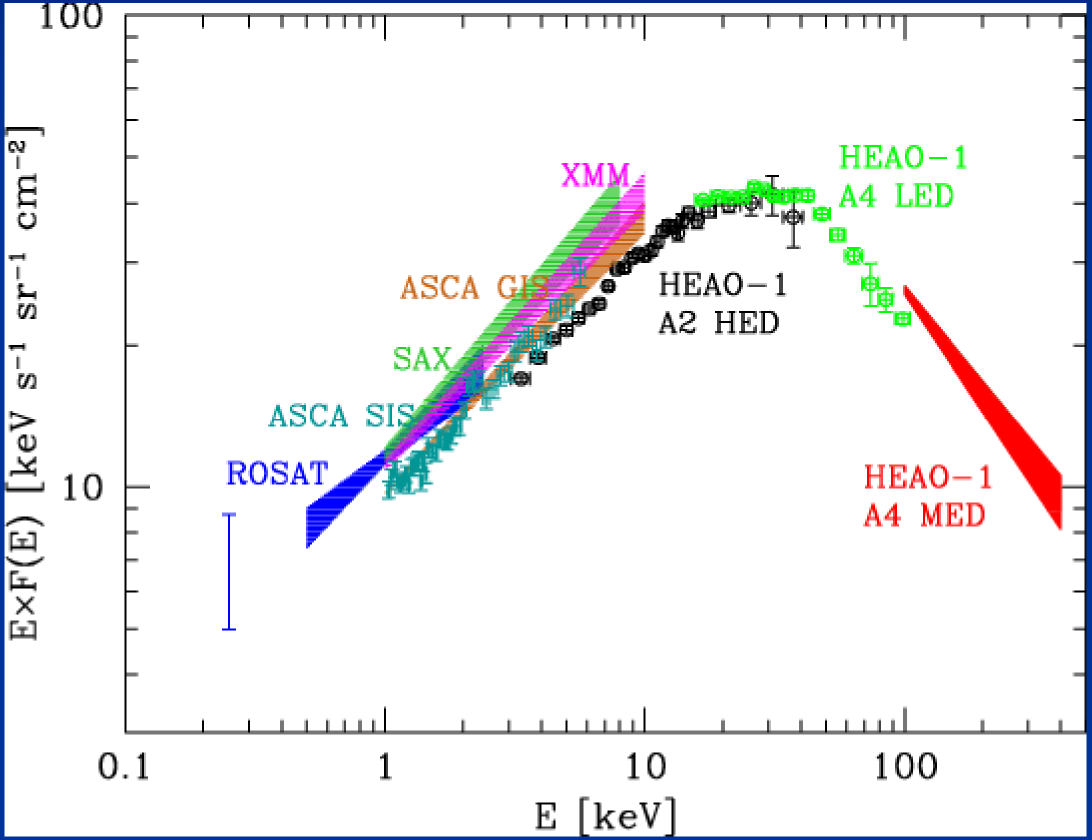
- Composite spectra of high-redshift quasars





AGN ACROSS THE HUBBLE TIME

- AGN contribution to X-Ray background



First spectral data (1980s) in the 3-60 keV band could be reproduced accurately by thermal emission from an optically thin plasma:

$$F(E) \approx E^{-0.29} e^{-E/41\mathrm{keV}} \quad \text{(bremsstrahlung)}$$

So, can a diffuse plasma emission explain the XRB?

NO!

Subtracting AGN → XRB spectrum no more compatible with bremsstrahlung emission!

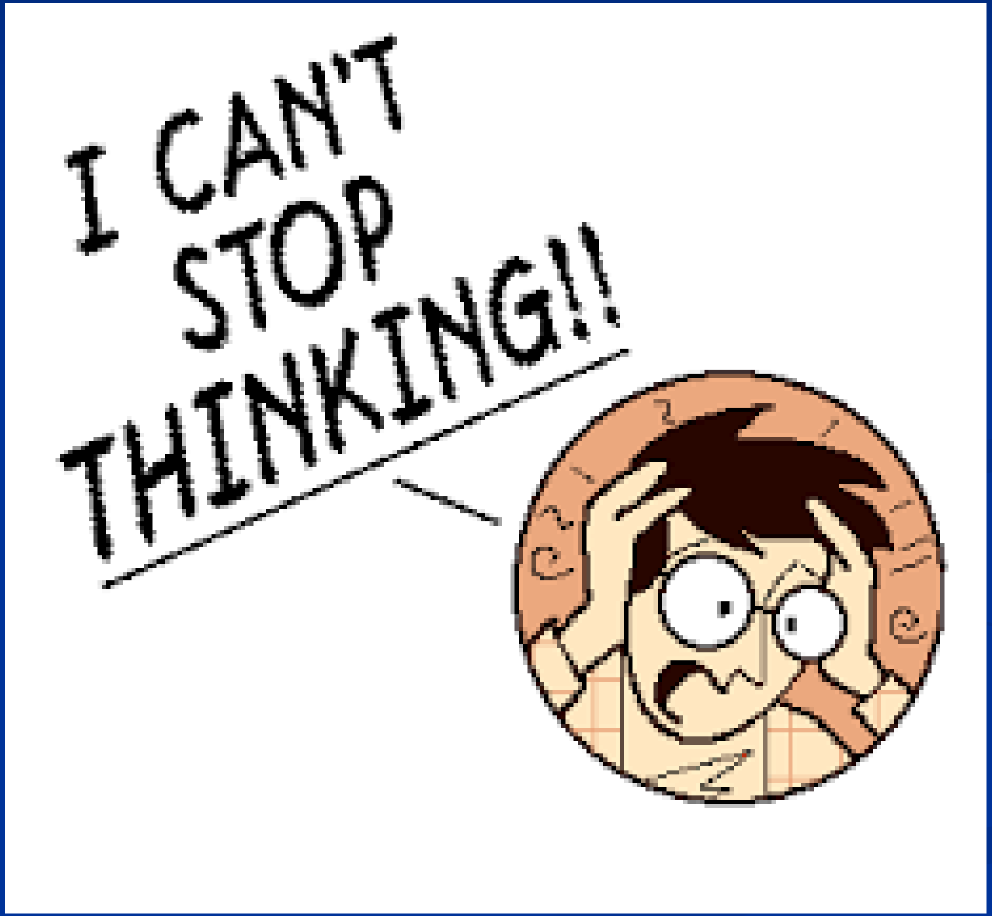
CMB represents a perfect blackbody:

hot gas $T \sim 40$ keV $\approx 4 \times 10^8$ K

would produce distortions by inverse Compton effect

Emission by unresolved, faint individual sources → AGN

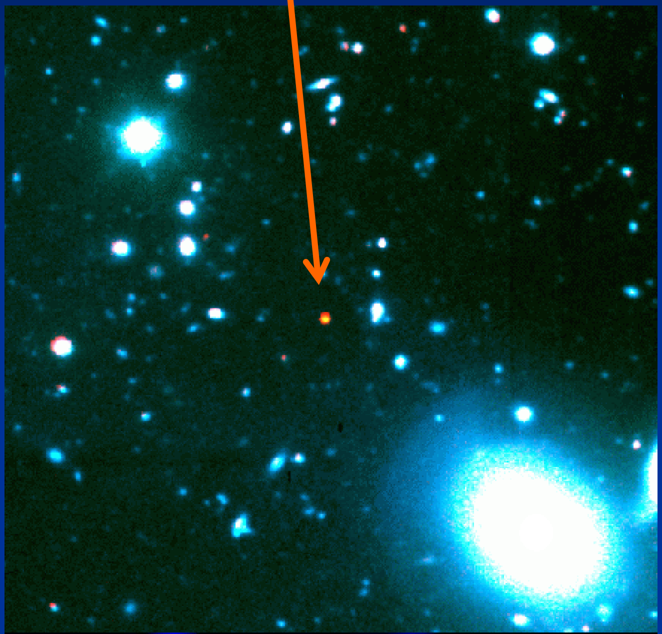
WHAT ABOUT AGN AT HIGH REDSHIFTS?

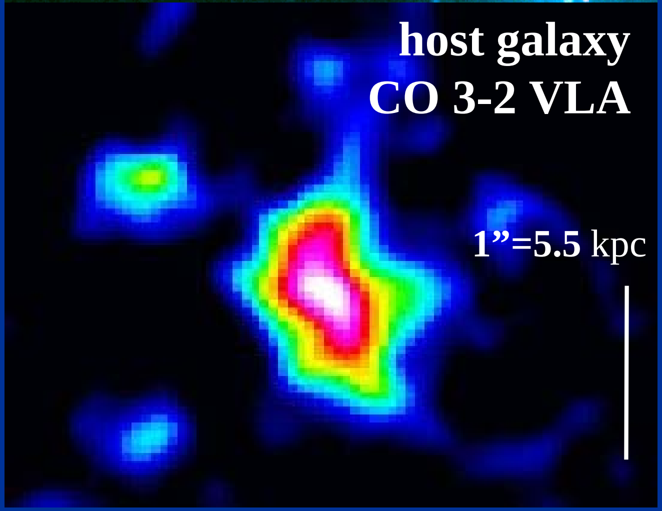


HIGH-REDSHIFT AGN

- High-z QSOs

SDSS J1148+5251





z=6.42 →
age ~ 0.87 Gyr
$L_{bol} \sim 10^{14}\ L_\odot$

$M_\bullet \sim 3\ 10^9\ M_\odot$ (Willott et al. 03)

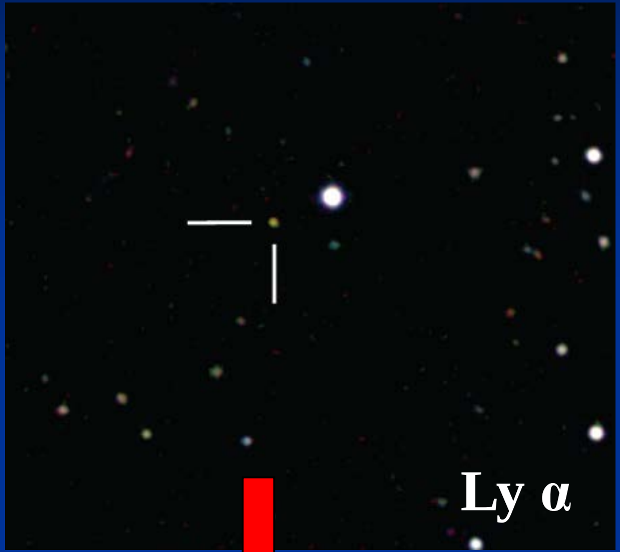
$M_\bullet$ derived from L_E, Mg II width, other

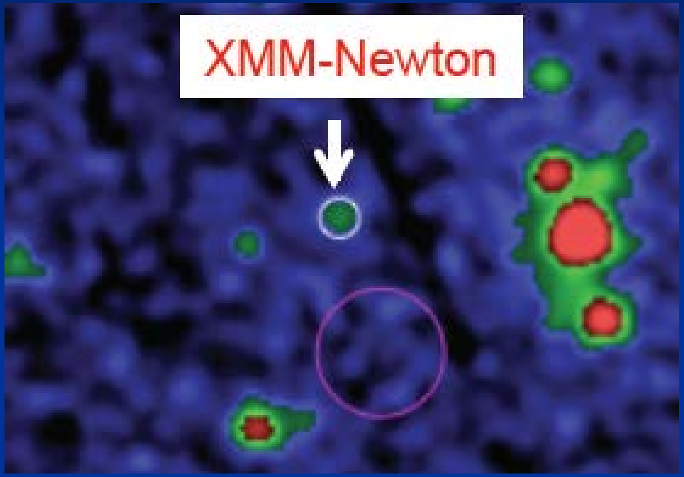
Kurk + 2006-8, Fan + 2003-8
Barth et al.
Bertoldi et al. (2009/10)
Fan et al.

HIGH-Z QSOS

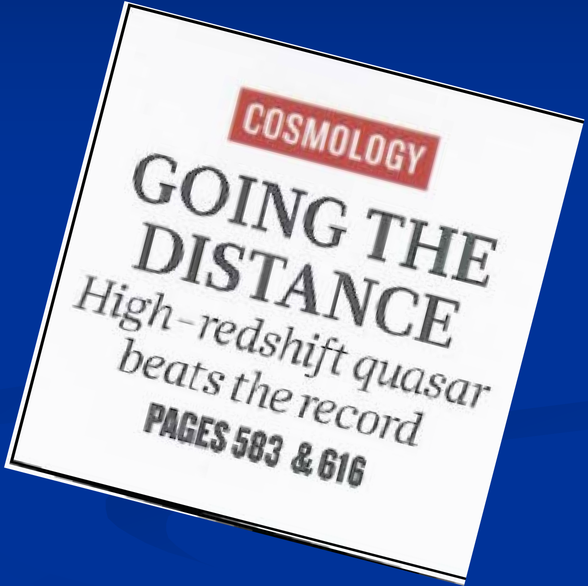
- Mortlock + (2011): **z ~ 7.085**

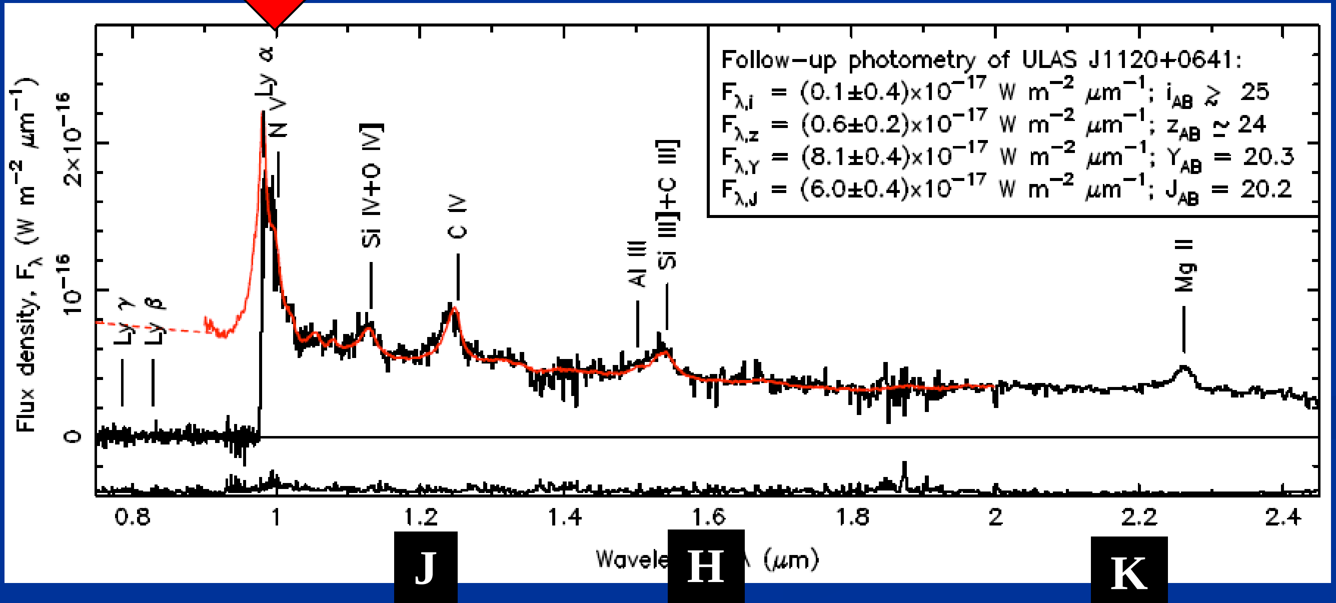
ULAS J1120+0641 $M_\bullet \sim 2 \times 10^9 M_\odot$






nature
THE INTERNATIONAL WEEKLY JOURNAL OF SCIENCE

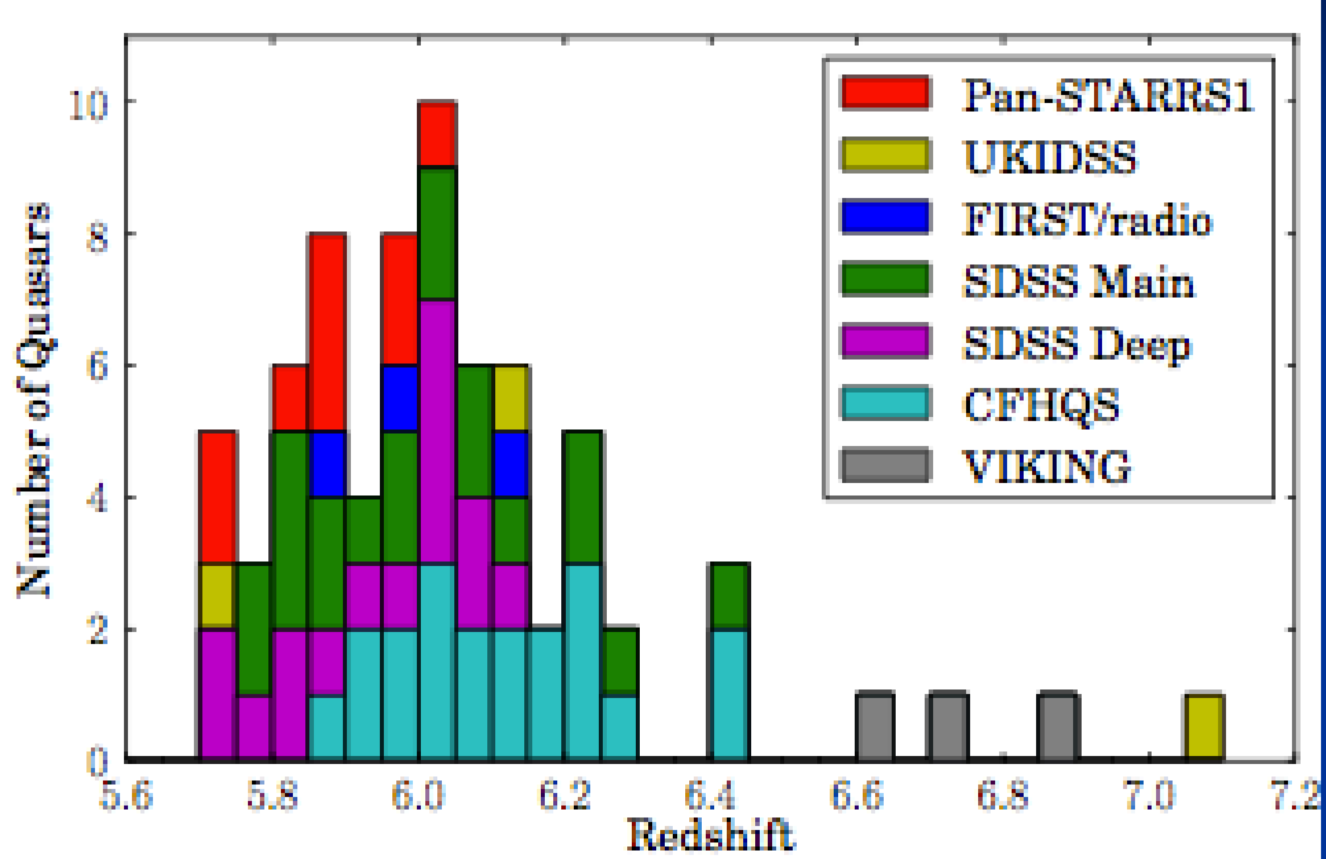

COSMOLOGY
GOING THE DISTANCE
High-redshift quasar beats the record
PAGES 583 & 616



$L_{2\text{-}10keV} \sim 6.7 \times 10^{44}$ erg/s
→ QSO accretes at the Eddington rate

Moretti et al. 2014

WHERE DO WE STAND?



About 80 QSOs at $z > 5.7$
→ SDSS, CFHQS, Pan-STARRS1
(Fan et al. 2000–06; Jiang et al. 2008,09;
Willott et al. 2007,09,10; Banados et al.14)
including UKIDSS/VISTA
(Mortlock et al. 2011; Venemans et al. 2013)

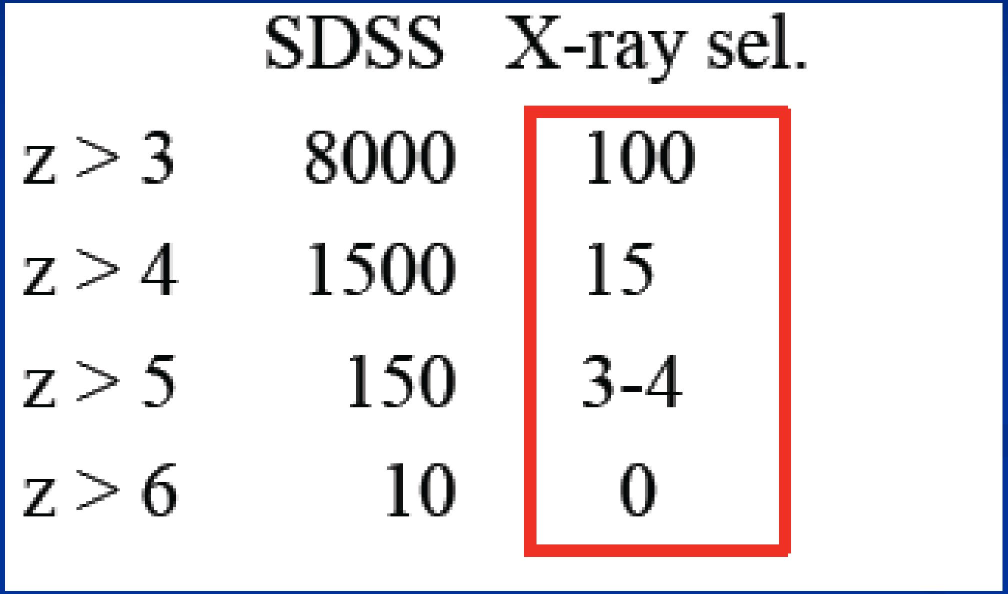
Less than 25% with X-ray detections

SDSS traces the most luminous QSOs
$\log L_X \sim 45$, $\log L_{bol} \sim 46.5$, $M_{1450} = [-24,-28]$

Faint end of the LF still to be achieved!

WHERE DO WE STAND?

- Number of high-z AGN detected so far:

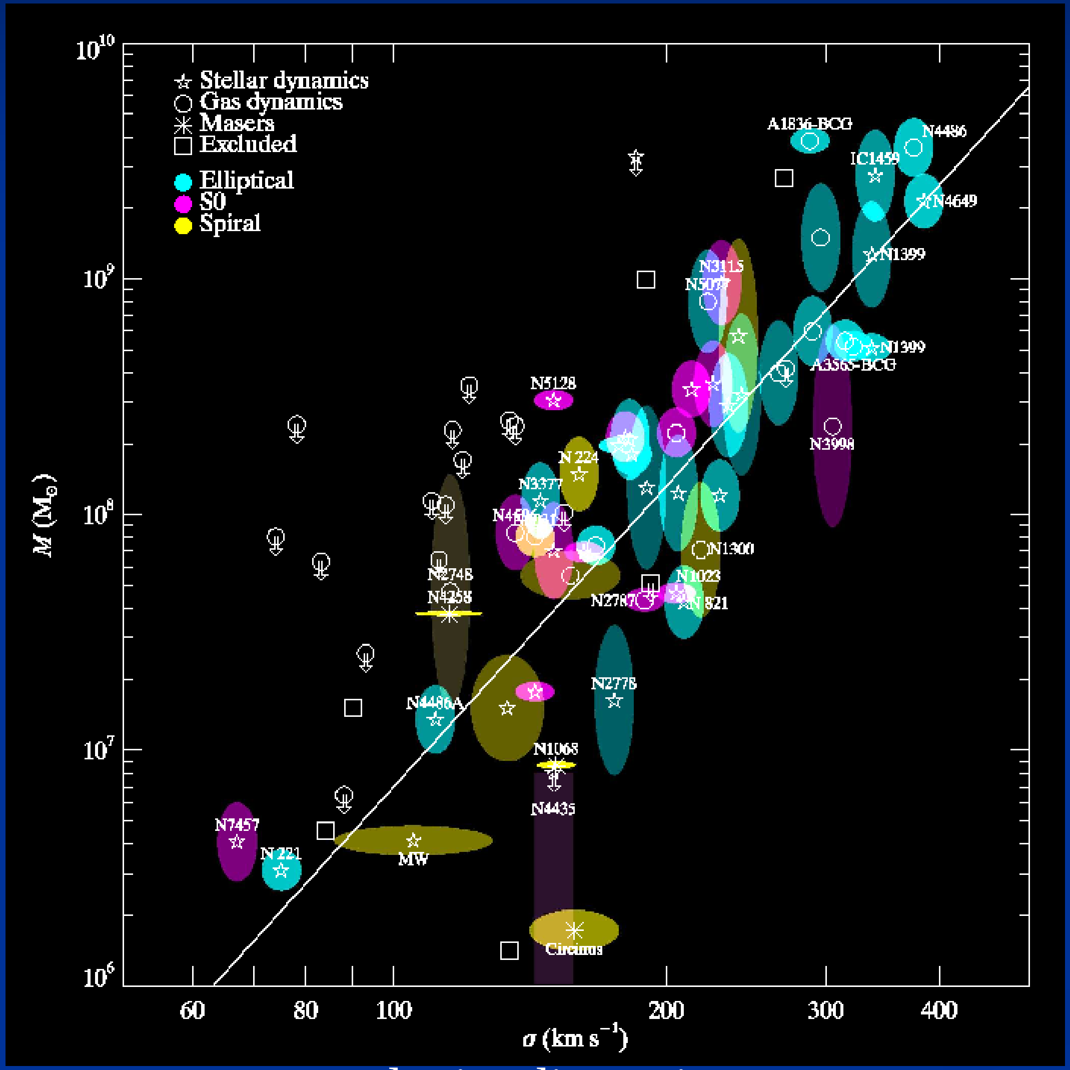


	SDSS	X-ray sel.
z > 3	8000	100
z > 4	1500	15
z > 5	150	3-4
z > 6	10	0

From: Silverman et al. 2008; Hasinger 2008; Brusa et al. 2009;
Civano et al. 2010; Fiore et al. 2012; Vito et al. 2013

DO SMBHs KNOW ABOUT HOST GALAXIES?

- SMBHs and host galaxies: scaling relations



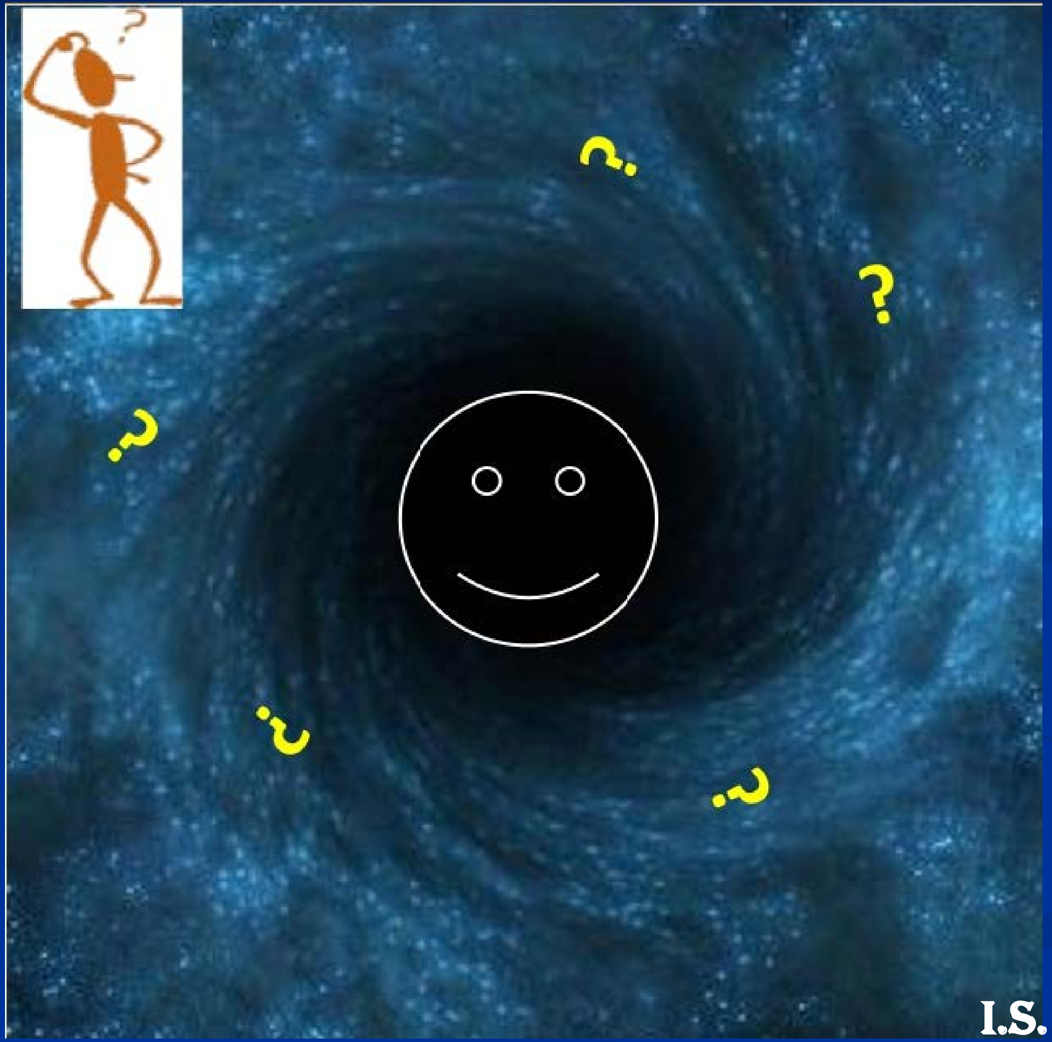
SMBH mass

velocity dispersion

Scaling relations between SMBH masses and host galaxy properties (stellar bulge mass, luminosity, velocity dispersion)

Are AGN and galaxies closely tied in their evolution?

PATHWAYS TO BLACK HOLE SEEDS



PATHWAYS TO BLACK HOLE SEEDS

- ❖ How do SMBHs form?

AGN are the most luminous long-lived objects in the universe

SMBHs power AGN

What are the seeds of SMBHs in the early universe or anywhere?

When did they form? What type of seeds: light, intermediate or heavy?

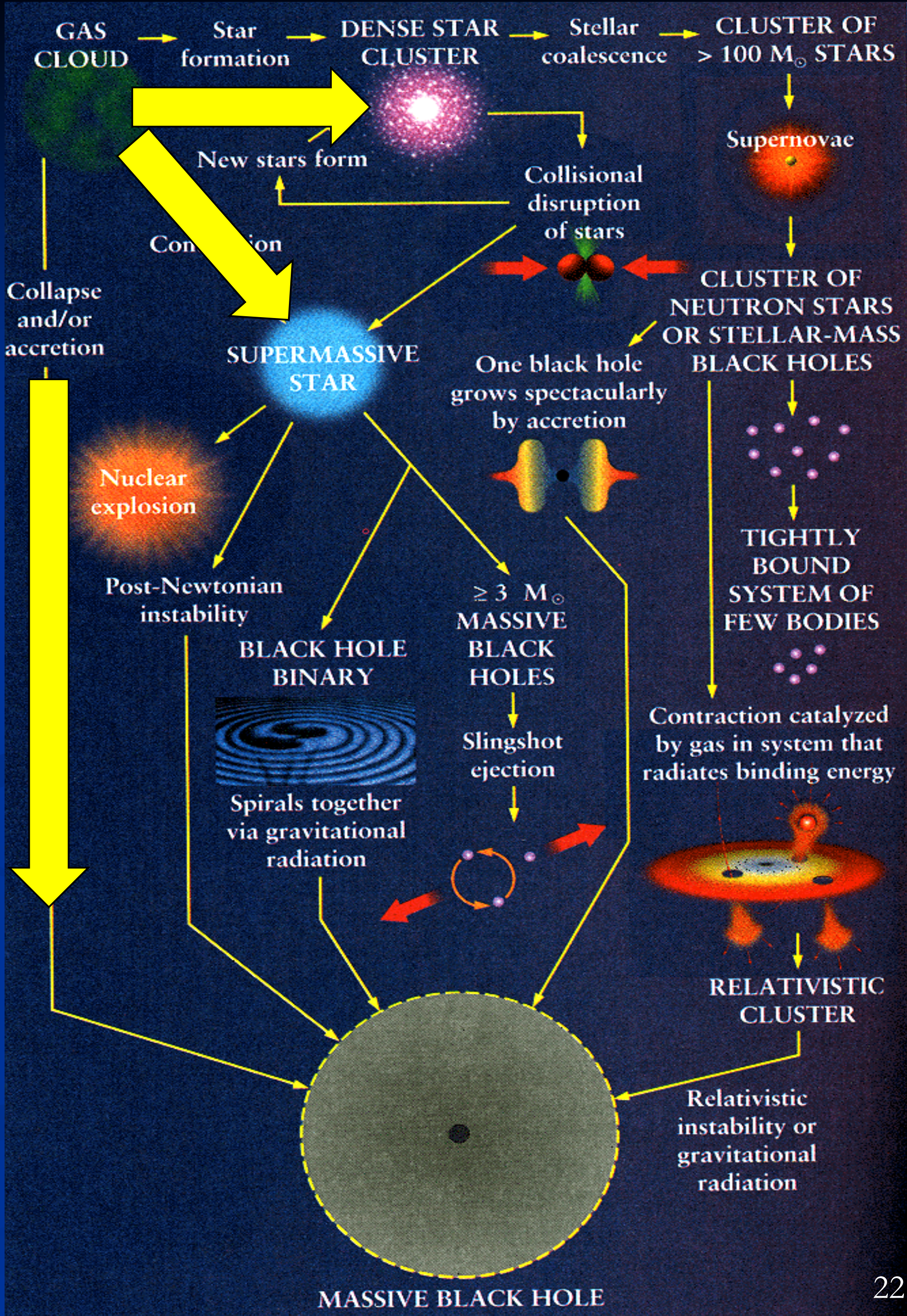
Are SMBH seeds related to the bulge growth?

Impact of first quasars on ISM/IGM structure formation?

SMBH-galaxy co-evolution is unconstrained at $z > 6$

Heavily obscured accretion mostly unconstrained beyond the local universe

Rees (1978)
Begelman & Rees



PATHWAYS TO BLACK HOLE SEEDS

primordial BH seeds

gas ± dark matter

relativistic star clusters

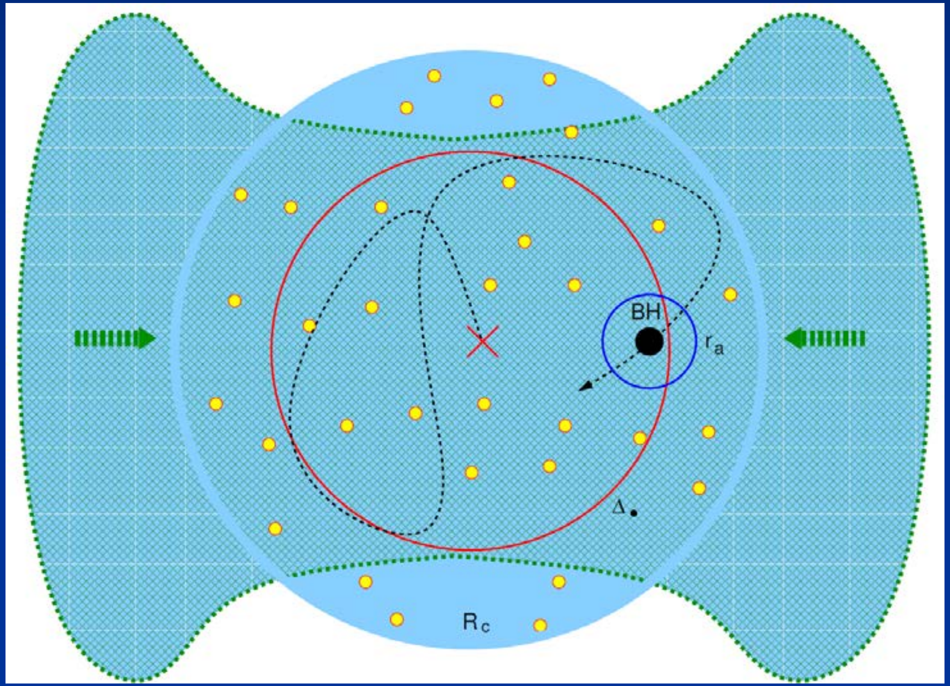
Pop III stars

COLLAPSE

direct collapse

PATHWAYS TO BLACK HOLE SEEDS

- SMBHs from stellar clusters



Alexander & Natarajan (2014)

Supra-exponential growth of a small BH
to SMBH…. in stellar/gaseous cluster…

where do you find
such clusters at high z?

PATHWAYS TO BLACK HOLE SEEDS

- SMBHs from relativistic stellar clusters

Gravitational instability: when stellar cluster is compact enough
→ gravitational redshift from its center > 0.5
→ runaway collapse

How can such a cluster form at high z?

PATHWAYS TO BLACK HOLE SEEDS

- SMBHs from Population III remnants

Population III stars forming in minihalos

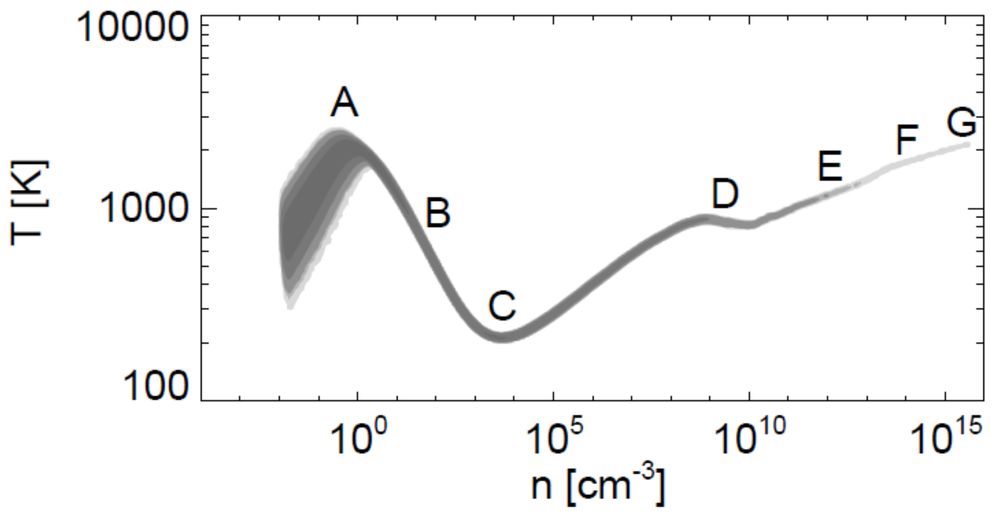
$M_* \sim 10^{2-3}\, M_\odot$?

(Bromm & Loeb 2003…)

radiation feedback!

$M_* \sim 40\, M_\odot$

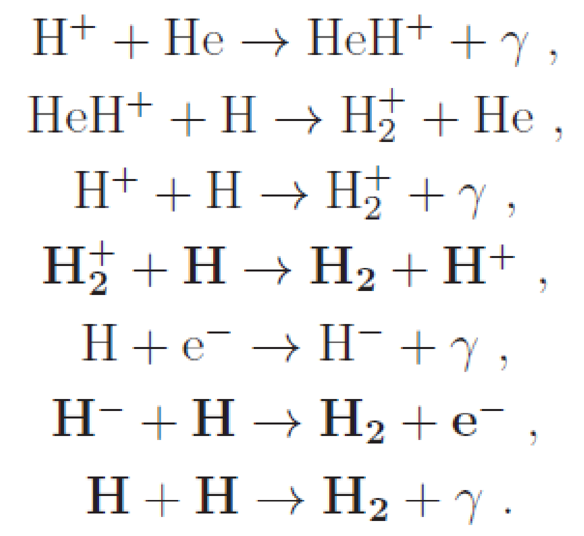
Hosokawa+11,14; Wise + 12



Omukai (2001)
Yoshida (2006)

A: virial shock in mini-halos
B: gas/H_2 cool down to 200 K
C: LTE
D: 3-body reactions → all H_2
E: H_2 cooling inefficient
F: collisional cooling → radiation
G: H_2 dissociates at 2,000 K

important role of H_2



$$
\begin{aligned}
&H^+ + He \rightarrow HeH^+ + \gamma\,,\\
&HeH^+ + H \rightarrow H_2^+ + He\,,\\
&H^+ + H \rightarrow H_2^+ + \gamma\,,\\
&H_2^+ + H \rightarrow H_2 + H^+\,,\\
&H + e^- \rightarrow H^- + \gamma\,,\\
&H^- + H \rightarrow H_2 + e^-\,,\\
&H + H \rightarrow H_2 + \gamma\,.
\end{aligned}
$$

BH seeds: $M_\bullet \sim 10^2\, M_\odot$

$M_\bullet \sim 10\, M_\odot$

BH seeds at z > 20

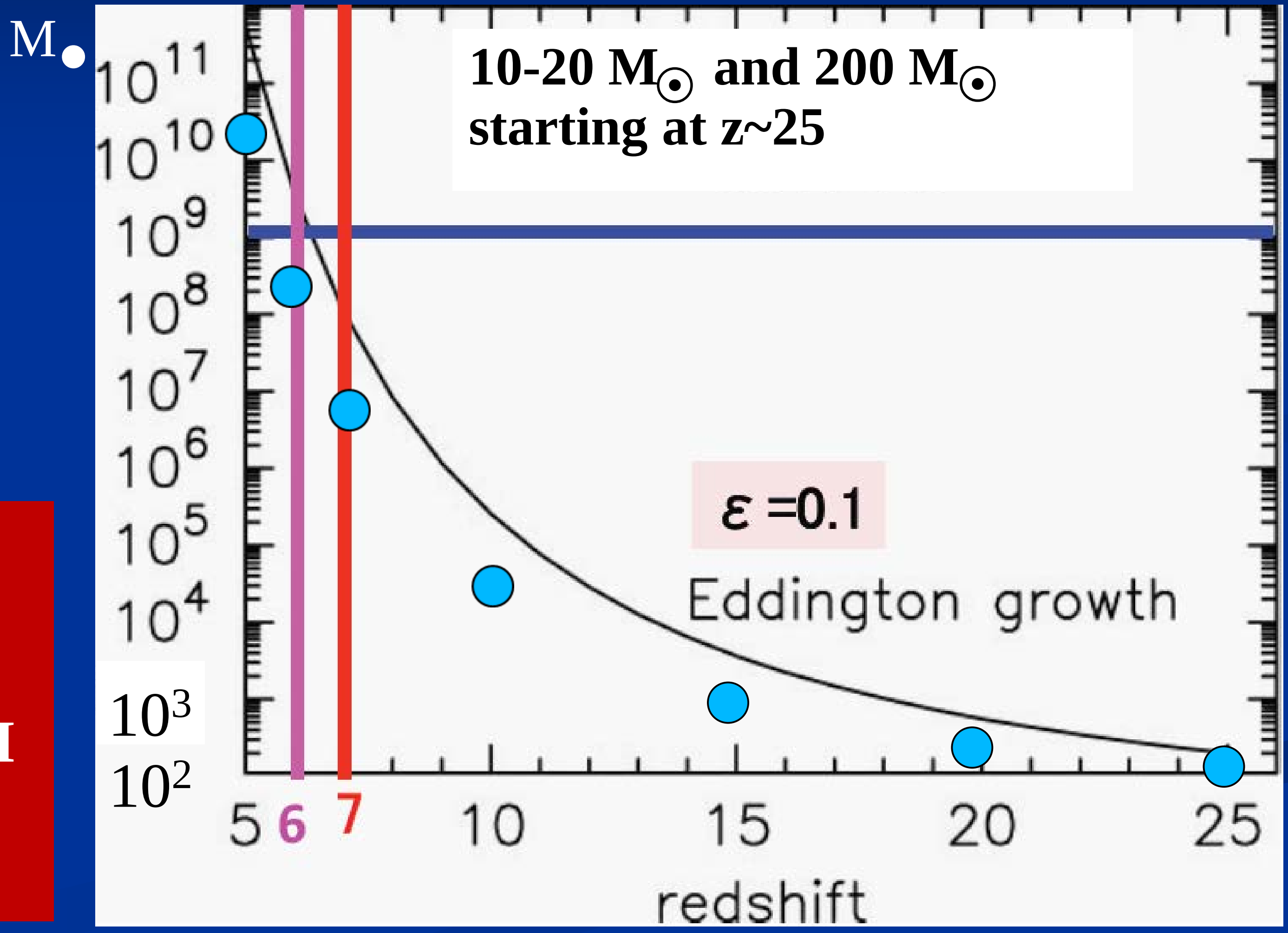
PITFALLS WITH POP III BLACK HOLE SEEDS

If start with ~10-20 $M_\odot$ → we are ~1.5-2 decades off for the SMBH masses at z~7

Needs about

ln (2 10^9 $M_\odot$/10 $M_\odot$)

~19 e-foldings



10-20 $M_\odot$ and 200 $M_\odot$ starting at z~25

too frequent mergers: BH slingshot and ejection from minihalos

BH accretion growth: limited by PopIII + feedback + accretion cutoff

Maybe Pop III remnants grow to smaller SMBH, e.g., 10^{6-7} $M_\odot$?

PATHWAYS TO BLACK HOLE SEEDS

❖ SMBHs from Direct Collapse in dark matter halos

Direct (‘monolithic’) collapse

If primordial gas:
cooling floor $T_{gas} \sim 10^4$ K

collapse into DM halos of
$T_{vir} \geq T_{gas} \sim 10^4$ K
(Haiman & Loeb 2001;
Begelman, Volonteri & Rees 2006)

$M_{vir} \sim 10^8\,M_\odot$

Planck CDM Universe: 16% baryons

$M_\bullet \sim 10^{5-7}\,M_\odot$

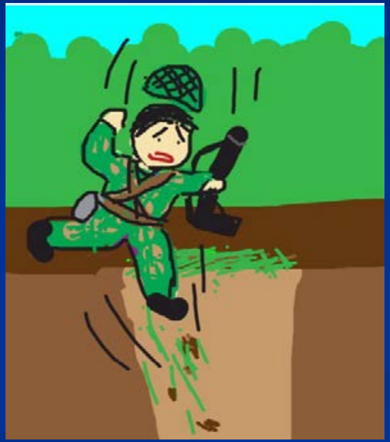
If gas enriched by Pop III
→ BH seeds
$M_\bullet \sim 10^{4-5}\,M_\odot$?
(because gas collapses earlier into smaller halos)

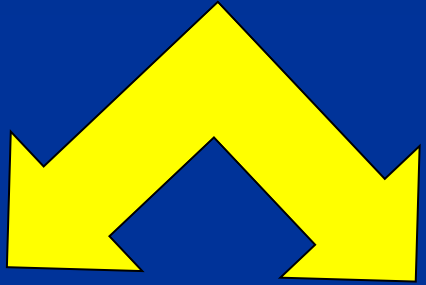
BH seeds at z ~ 10-15

DIRECT COLLAPSE TO SMBH SEEDS: PITFALLS

Growth by accretion/mergers from $z \sim 20$ to $z \sim 7$ → to $10^9\ M_\odot$

less mergers! BUT…





angular momentum barrier
→ fragmentation
star formation
because $\lambda > 0$

gas collapse → fragmentation
star formation

because $M_{gas}/M_J > 1$

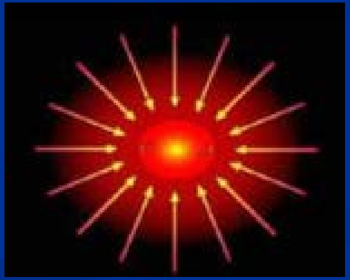
many stars, small black holes(s)?

WHAT IS THE NATURE OF THE CENTRAL OBJECT?

SPECIFICS OF GRAVITATIONAL COLLAPSE

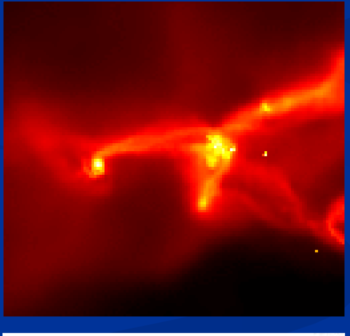
Generic accretion rate (with and w/o central BH):

$$\dot{M} \sim \frac{v^3}{G} \sim 2\,x\,10^{-4}\,T_{100}^{3/2}\ M_\odot\ yr^{-1}$$



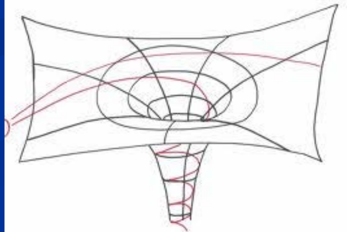
Stellar collapse: T ~ 10 K – 100 K

$$\dot{M} \sim 10^{-5} - 10^{-4}\ M_\odot\ yr^{-1}$$



Pop III stellar collapse: T ~ 10^2 K – 10^3 K

$$\dot{M} \sim 10^{-4} - 10^{-3}\ M_\odot\ yr^{-1}$$



Direct collapse: T ≥ 10^4 K

$$\dot{M} \geq 0.1\ M_\odot\ yr^{-1}$$

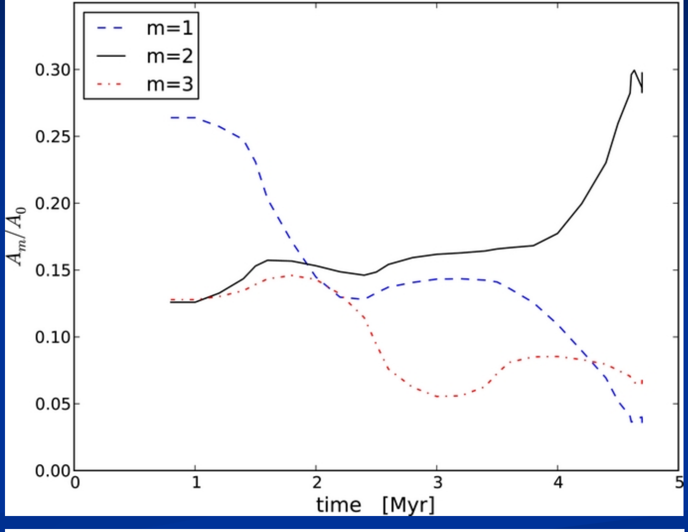
HOW TO COLLAPSE

- Spherical collapse: forget about this → angular momentum barrier

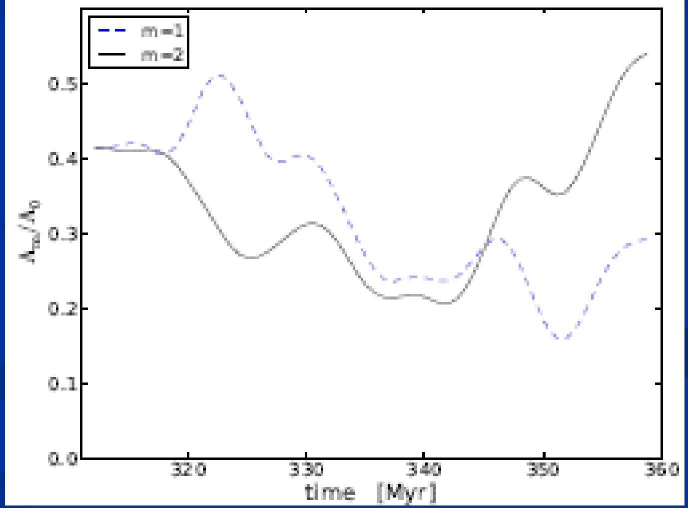
even if the original configuration has only ~ 1% Keplerian support!

With nonzero spin → angular momentum is not conserved!
→ gravitational torques

isolated halo



cosmological halo

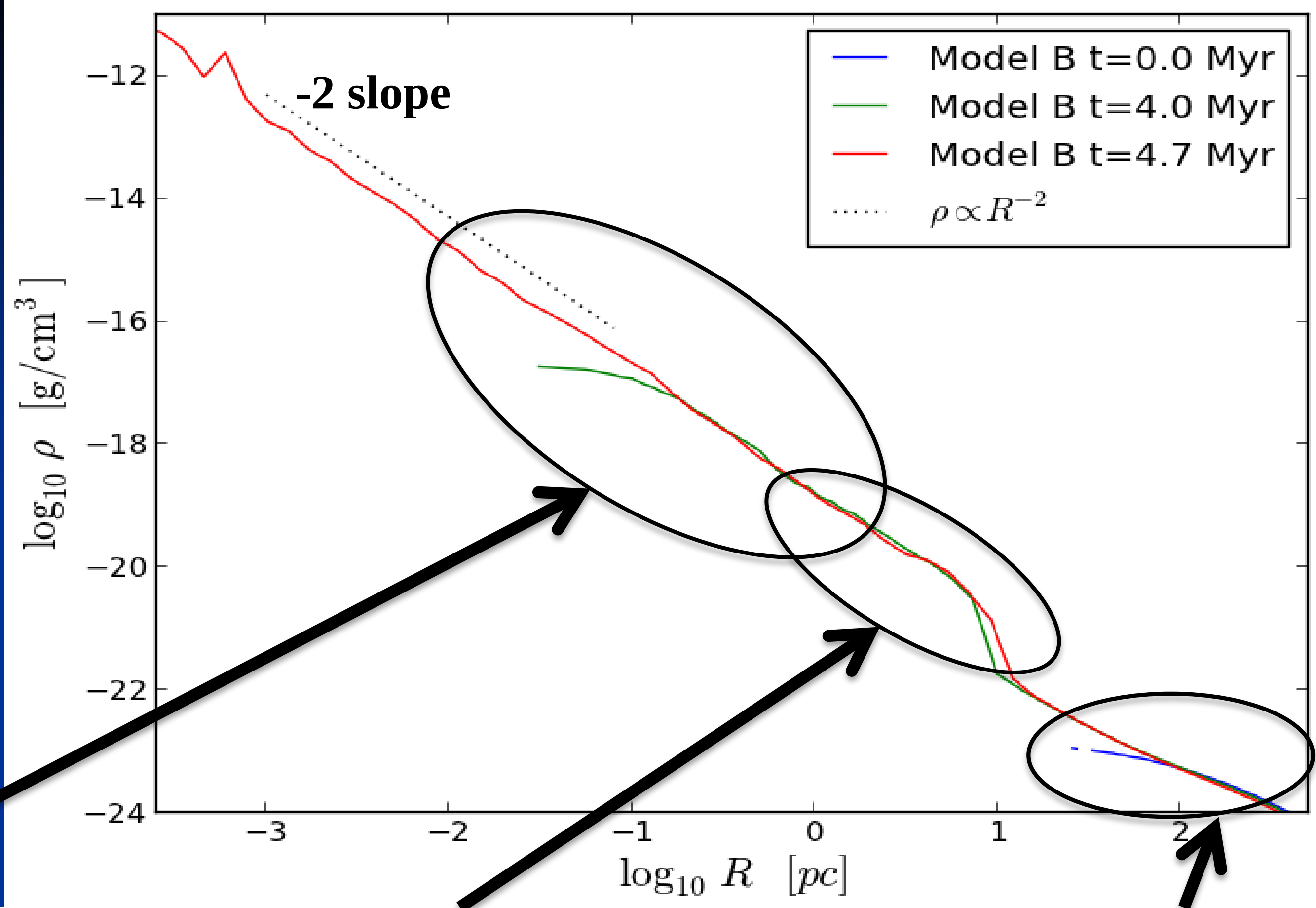


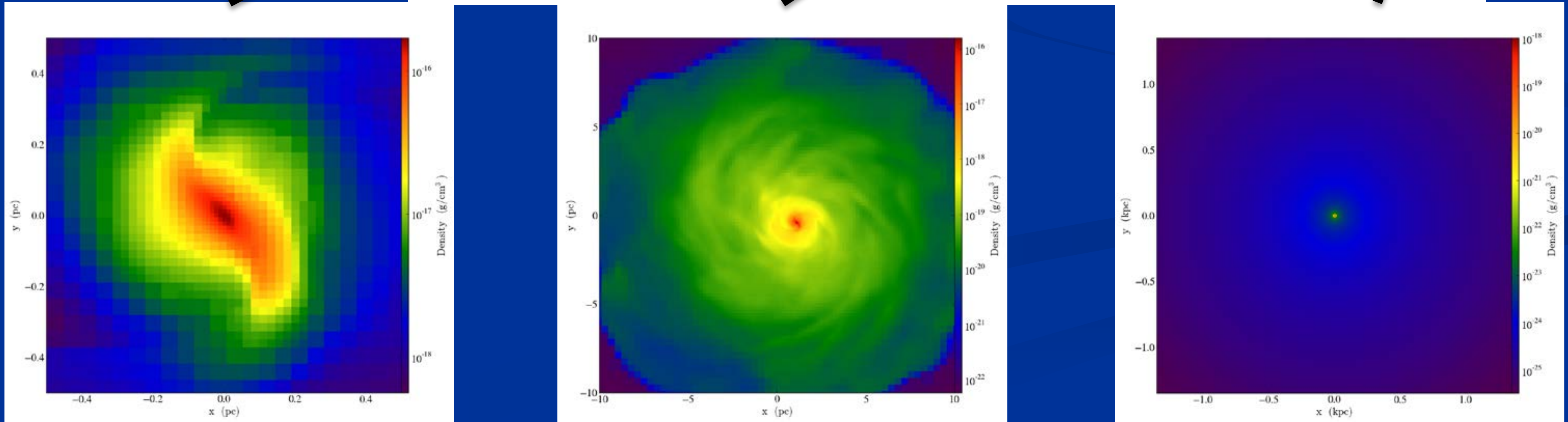
Angular momentum transfer is dominated by the low Fourier modes

Choi et al. 2013, 2015

Overcoming the J-barrier

gas density profile





Self-similar collapse

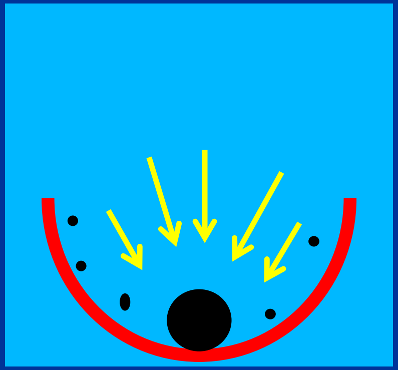
how to break this symmetry?

COSMOLOGICAL SMBH SEEDS: BREAK SYMMETRY OF GRAVITATIONAL COLLAPSE

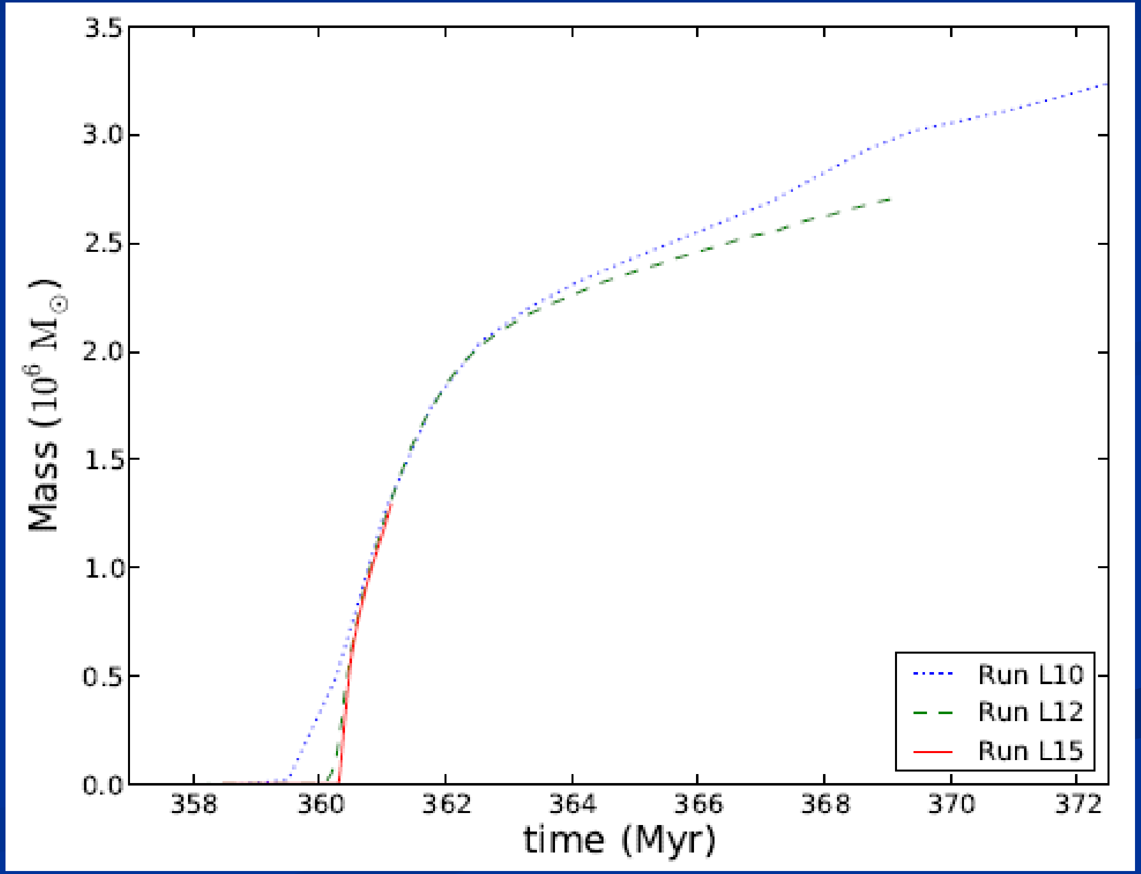
Using sink particles to follow up the collapse

Initial masses ~ 10 $M_\odot$

In all models: one sink particle grows by merging and accreting gas and other sink particles

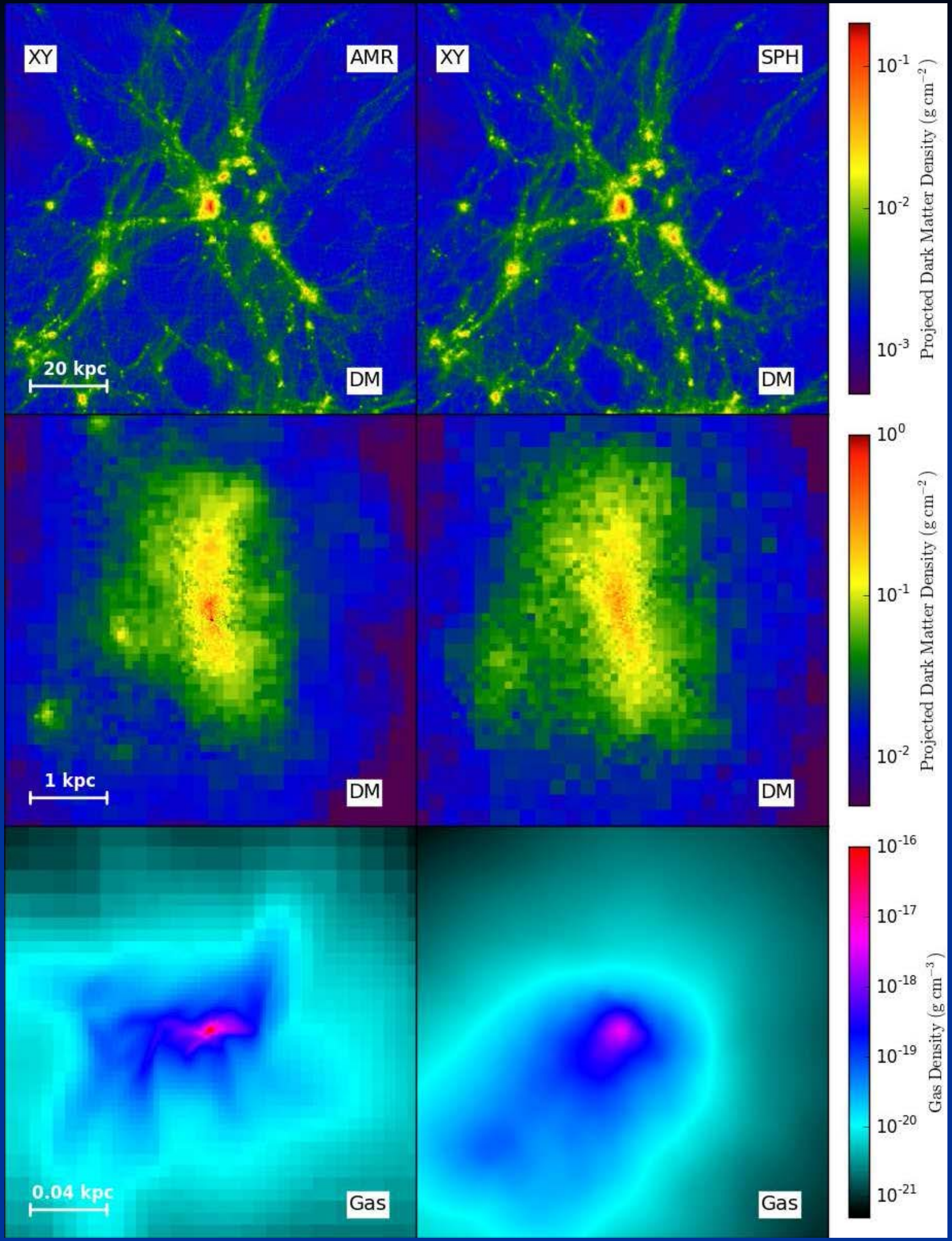


evolution of the central seed



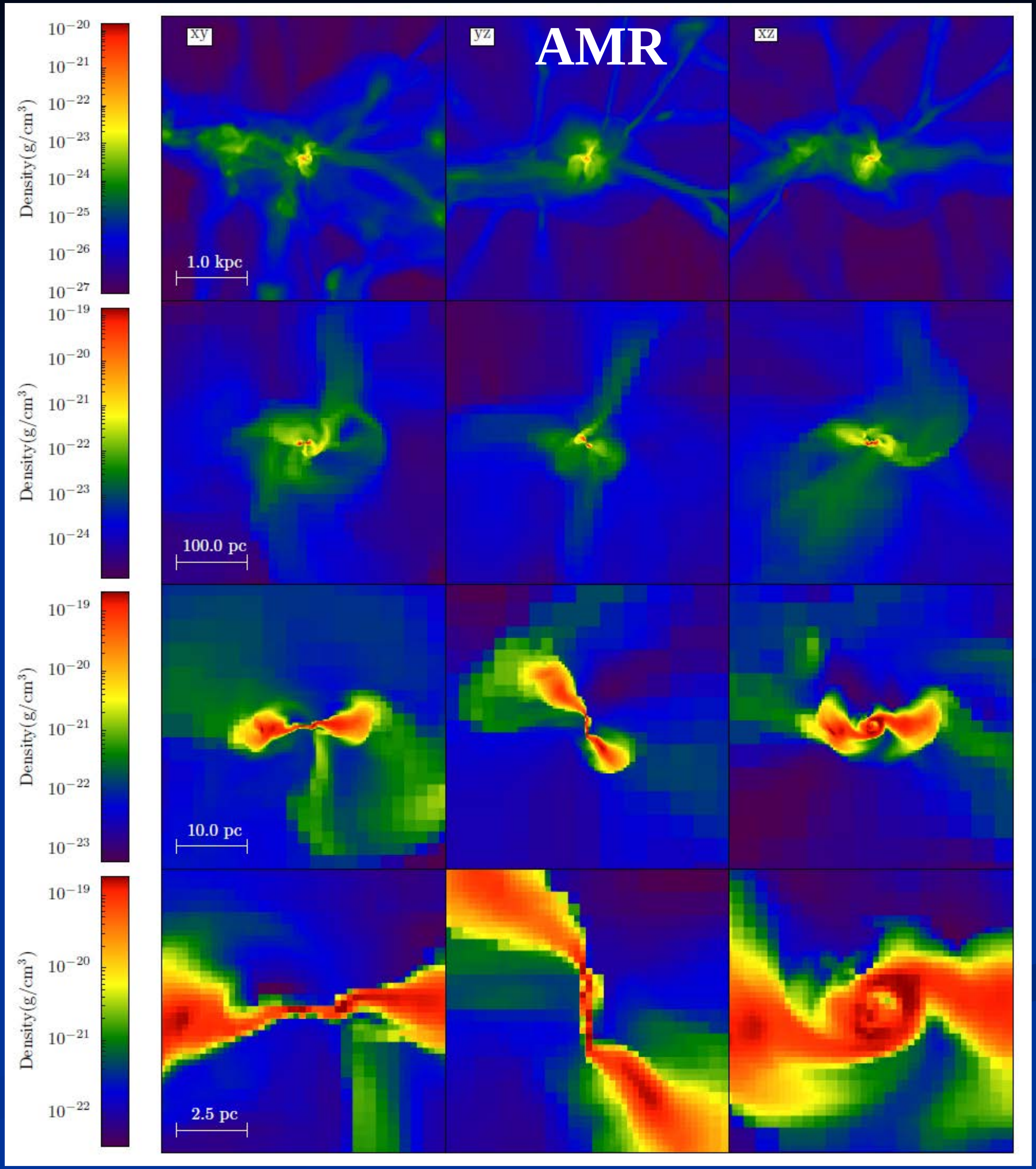
IS, Choi, Begelman & Nagamine 2015

No seeds



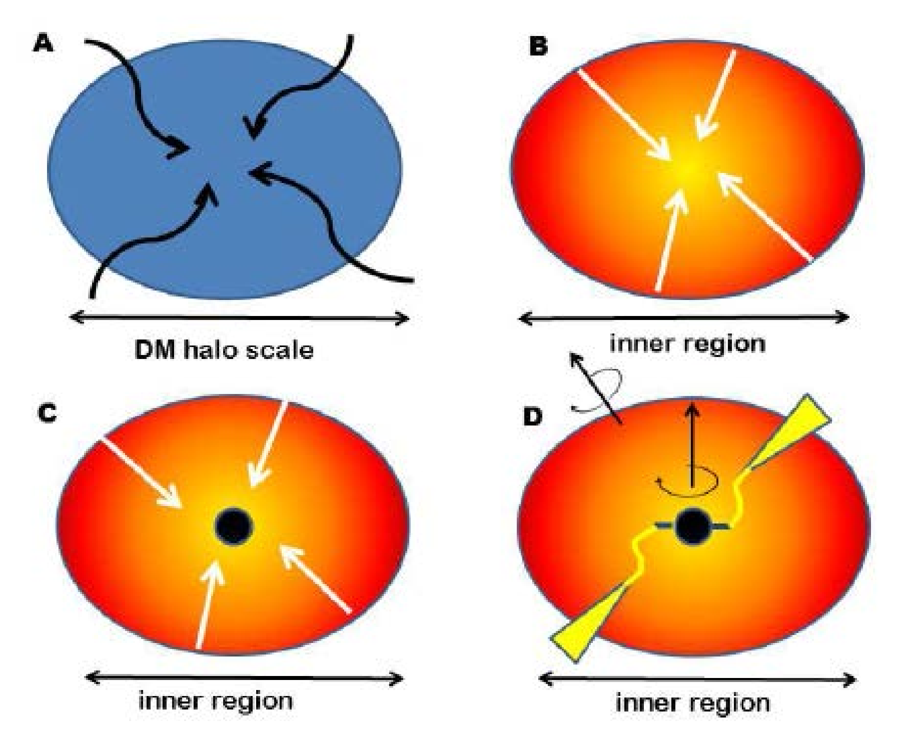
Yang, Nagamine & Shlosman 2015

With seeds

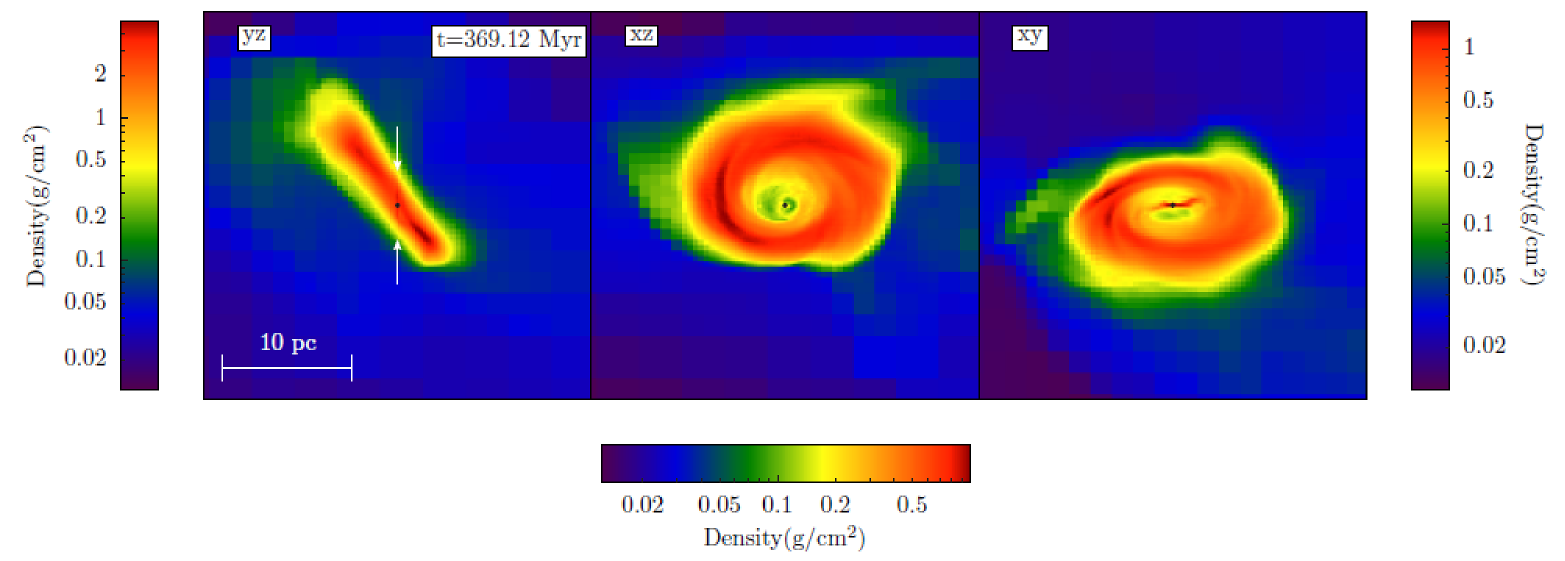


IS, Choi, Begelman & Nagamine 2015

COSMOLOGICAL SMBH SEEDS: BREAK SYMMETRY OF GRAVITATIONAL COLLAPSE



misaligned disks



Breaking collapse symmetry → disk formation
Variability of angular momentum in accreting gas → misaligned disks

DEEP INTERIOR FLOW: OPTICALLY-THICK COLLAPSE

Under what conditions will accretion flow continue to smaller R?

What type of flow(s) for $R < R_{trap}$?

Quite a bizarre flow!

Waterfall by: M.C. Escher

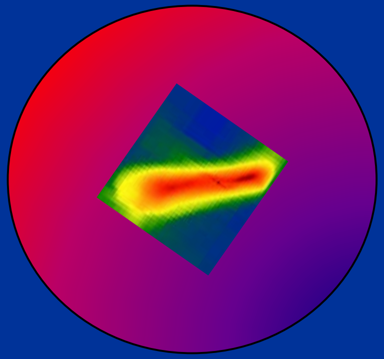
DEEP INTERIOR FLOW: OPTICALLY-THICK COLLAPSE

Two options here (Begelman & Shlosman 2009)

$j(R) \sim \beta\, j_K$

The flow can stay being rotationally supported (+ ∇P_{rad}) (Choi et al. 2013,2015)

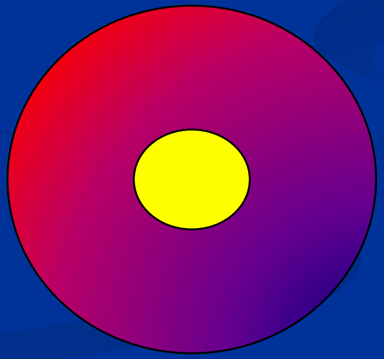
where $\beta < 1$



Disklike flow → *A*DAF/CDAF/ADIOS flow?

The flow can lose *j* in a few rotations by some unspecified way (Begelman 2012)

where $\beta \ll 1$

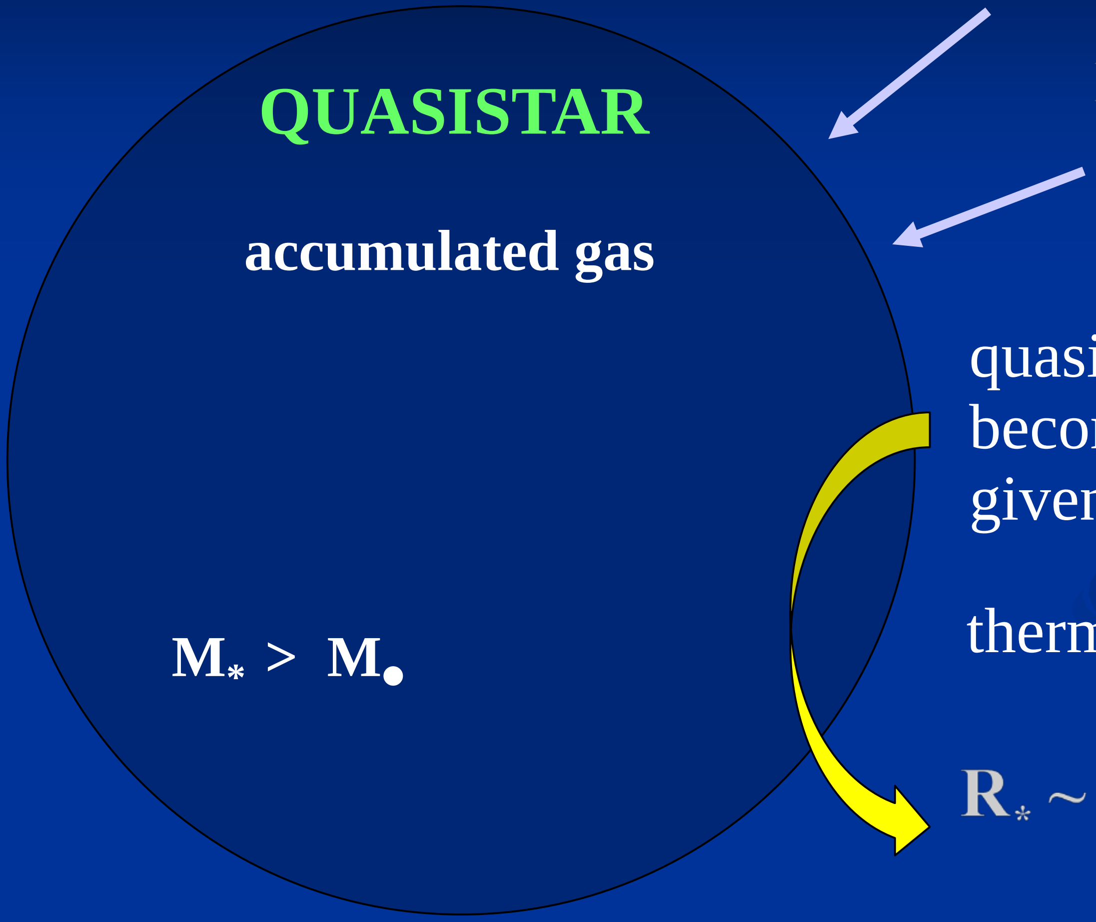


Starlike accretion flow

What does this difference mean?

A QUASISTAR FORMATION? (Begelman, Volonteri & Rees 2006)

Rapid growth of the BH seed in DM minihalos with $\sigma \sim 10\sigma_{10}\ \mathrm{km\ s^{-1}}$



$$\dot{M}_* \sim \frac{\alpha\sigma^3}{G}$$

QUASISTAR

accumulated gas

$\mathbf{M_* > M_\bullet}$

quasistar radius: where accretion becomes super-Eddington for a given opacity → radiation trapping:

thermonuclear reactions: **t ~ $\mathbf{10^6}$** yrs

$$R_* \sim 10^{13}\, \alpha\, \sigma_{10}^3 \left(\frac{\kappa}{\kappa_{es}}\right) \mathrm{cm}$$

Seed BH → from neutrini cooled core of ~10 $\mathbf{M_\odot}$ → grows at the rate of

$$\dot{M} >> \dot{M}_E$$

TWO ALTERNATIVES IN DIRECT COLLAPSE

Starlike accretion flow: **J goes in smoke**

angular momentum is **un**important
→ no preferential channel of
energy release (Begelman et al. 2006-14)

photon trapping
→formation of a single accreting
massive object in pressure
equilibrium
→ quasistar

thermonuclear reactions

neutrini-cooled
core collapse

supermassive black hole
~ 10 $M_\odot$ → 10^4 $M_\odot$

Disklike accretion flow: **J important**

angular momentum dominates
→ defines preferential channel
of energy release
(Begelman & IS 2009; Choi etal. 2013
IS & Begelman, in prep)

no early photon trapping
→formation of a single accreting
massive object supported by
rotation in **R** and pressure in **z**
→ quasi `torus/disk'

dynamical instabilities
no thermonuclear reactions

collapse, photons/neutrini
partially trapped/escape

supermassive black hole
~ 10^{5-7} $M_\odot$

CONCLUSIONS TO TALK 5

- ❖ AGN in general, and quasars in particular, have formed early, and probably compete with Pop III stars in illuminating the universe and ending the Dark Ages

- ❖ There are real problems to grow BH seeds from Population III remnants to ~10^{8-9} $M_\odot$ in less than 1 Gyr, and intermediate-mass BHs have not been found (so far)

- ❖ Direct (monolithic) collapse of gas within ~10^8 $M_\odot$ DM halos to BH appears to be feasible and (at least) two alternatives exist
  → collapse via a supermassive star →**quasi-star,** or via **disklike→SMBH flow → proto-AGN.** Open issues remain with both approaches. The primary role of angular momentum makes the latter approach a realistic one.

- ❖ Probably the crucial point is whether it is possible to avoid the thermonuclear phase → it slows down the collapse by ~10^6 yr
  → angular momentum transfer by magnetic and gravitational torques