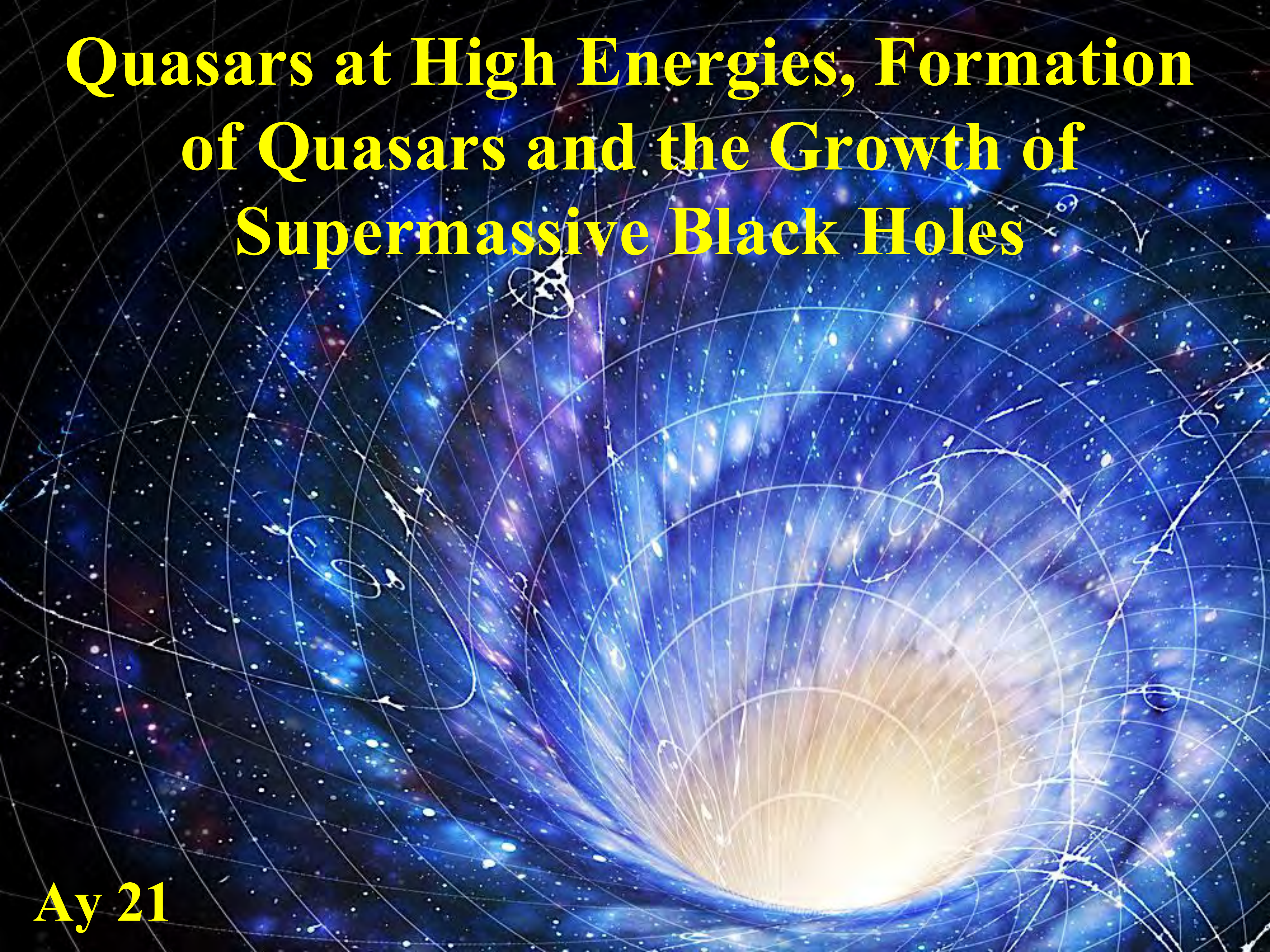
Quasars at High Energies, Formation of Quasars and the Growth of Supermassive Black Holes

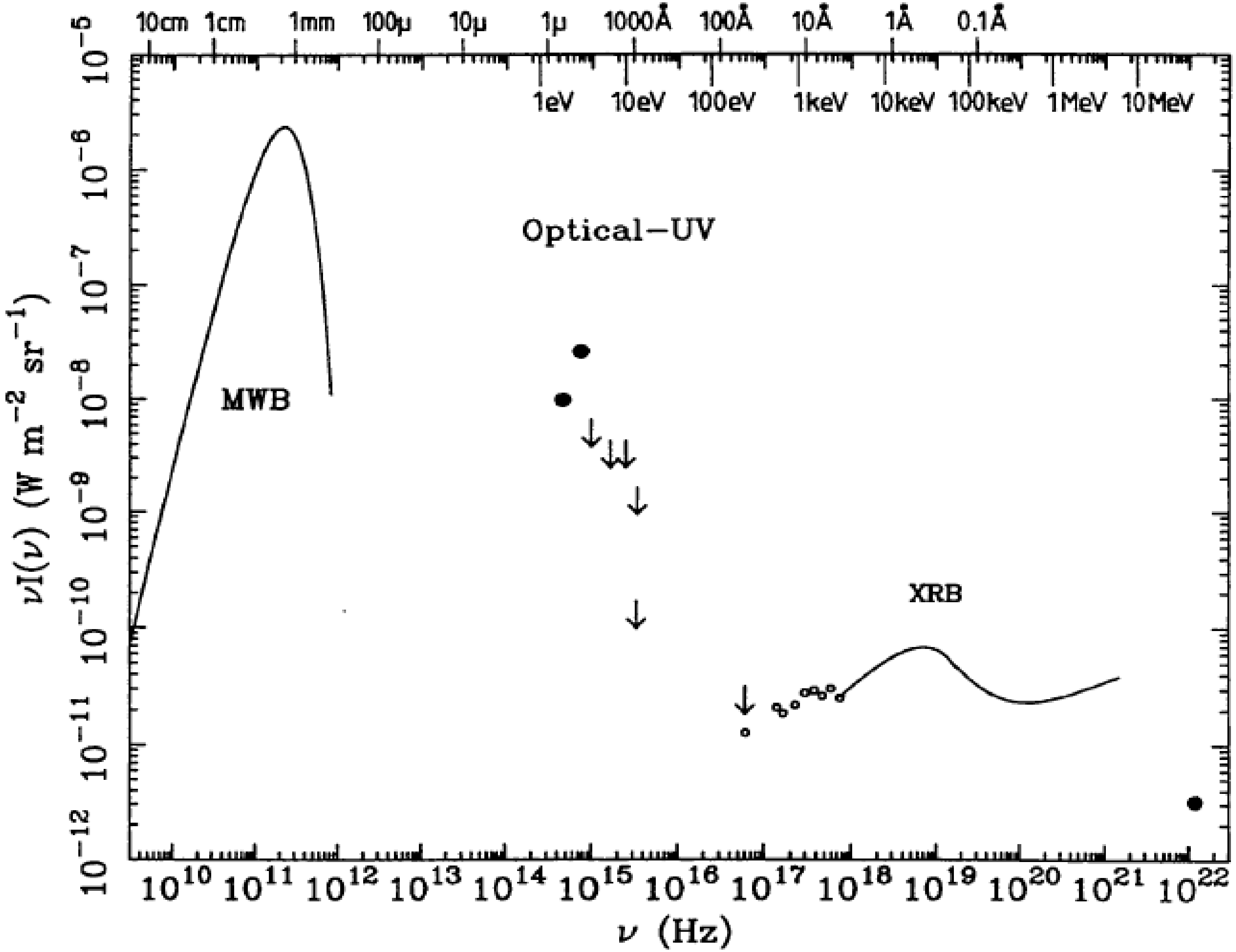


Ay 21

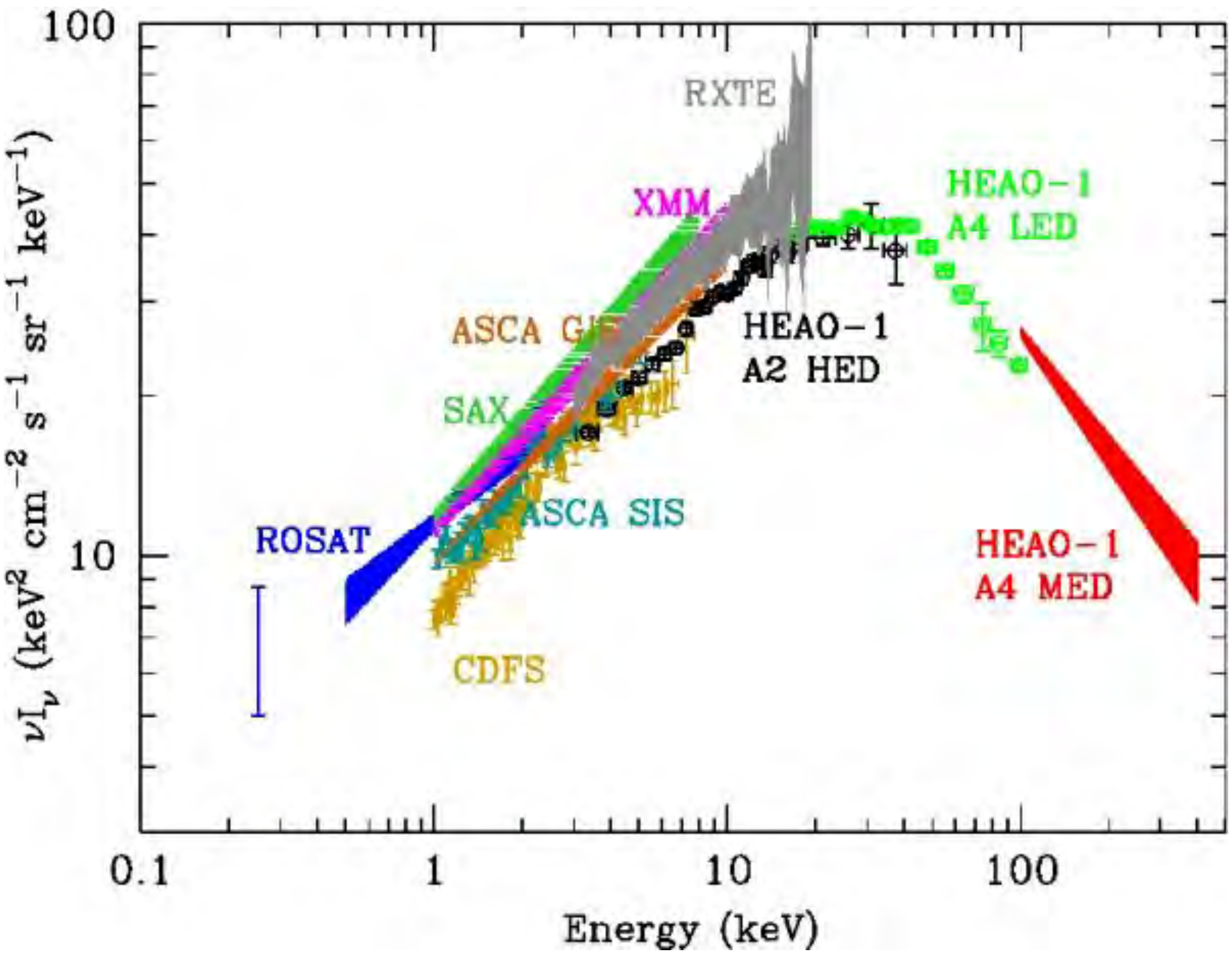
The Cosmic X-Ray Background

- Discovered in 1962 (nearly at the same time as CMBR, in the first X-ray astronomy rocket flight, by R. Giacconi et al. (Nobel Prize in 2002)
- A few percent of the energy density of the diffuse optical/IR backgrounds: $u_{XRB} \sim 10^{-17}$ erg/cm^3, $u_{Opt/FIR} \sim$ a few $\times$ 10^{-15} erg/cm^3, $u_{CMB} \sim$ a few $\times$ 10^{-13} erg/cm^3
- Now believed to be generated almost entirely by AGN, many of them obscured by dust (hard X-rays go through): the bulk of it is resolved by deep X-ray observations
- The puzzle was to explain the energetics and the spectrum shape at the same time; this required the existence of a substantial obscured (Type 2) AGN population, which has now been found
- The cosmic γ-ray background is mainly due to beamed AGN, but some more exotic components are still possible

The Cosmic X-Ray Background (CXRB)



The Spectrum of the CXRB

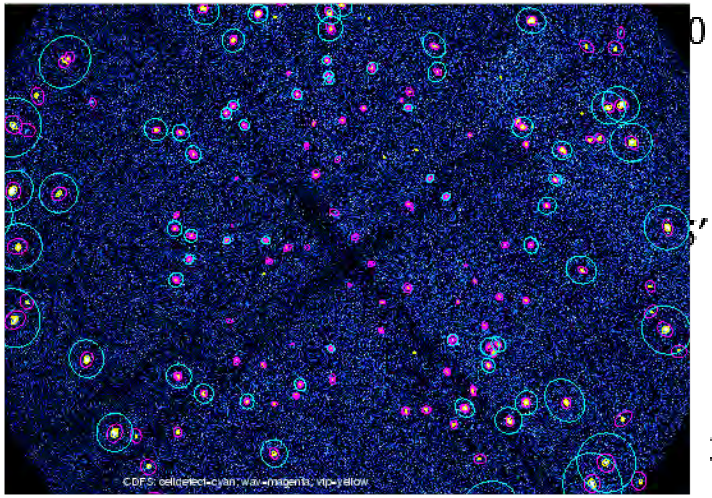


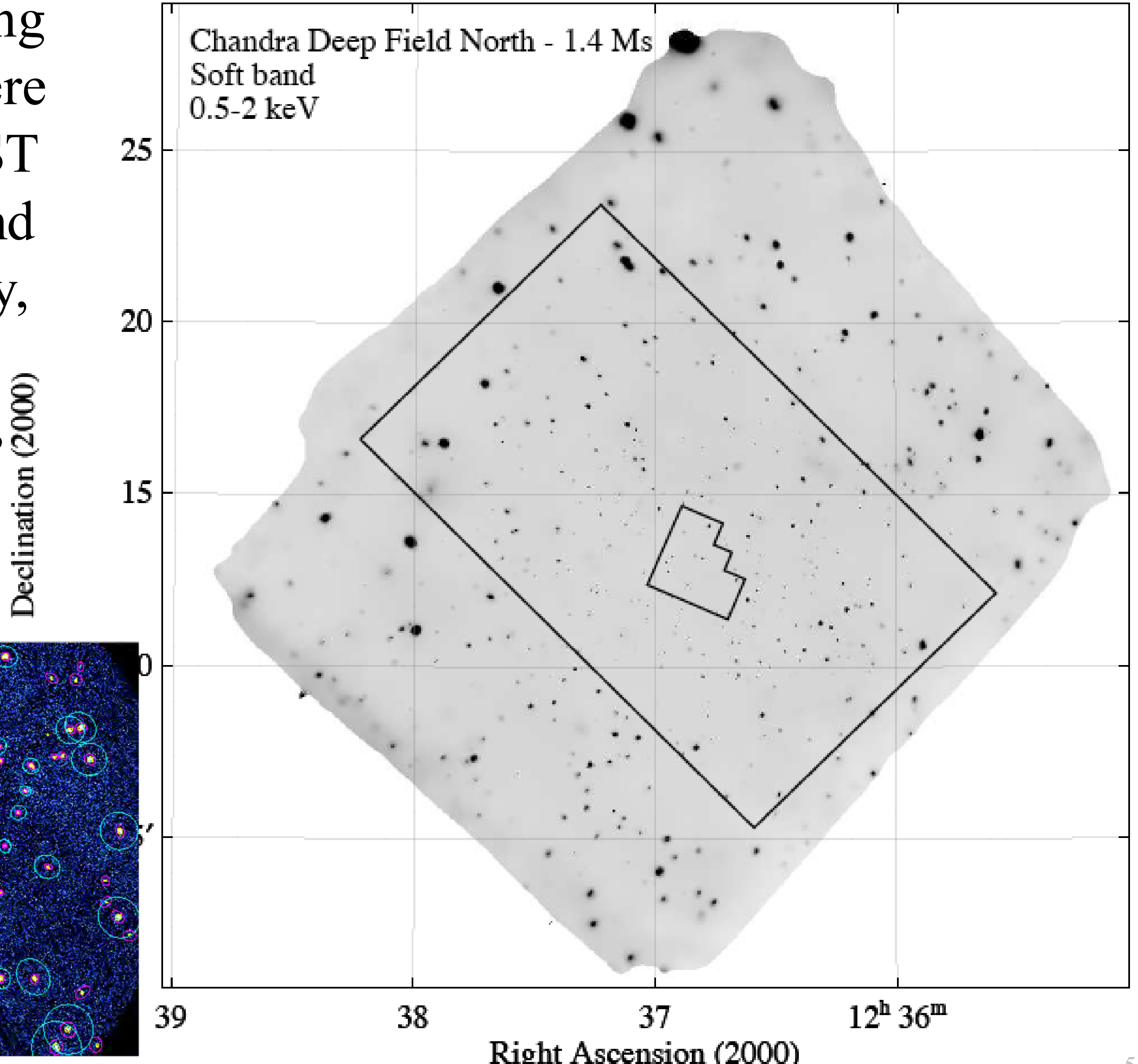
It does not look like an AGN spectrum, but it looks just like the thermal bremsstrahlung of hot plasma (like in a cluster). We now know that is just a coincidence: it is really a sum of the redshiftted AGN spectra, some of which are reflected from the thick dust

Resolving the CXRB

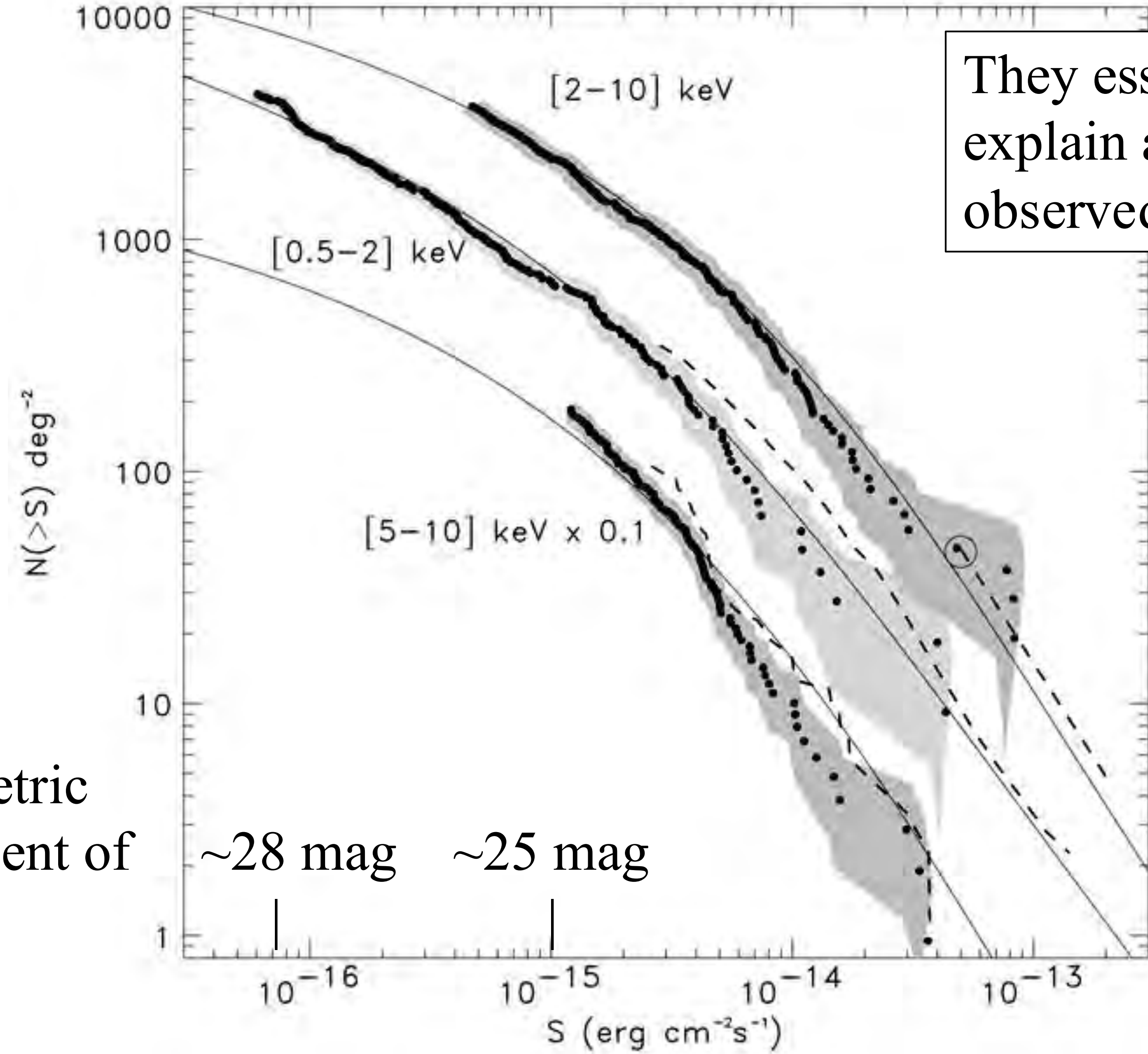
Deep X-ray imaging of fields where there is already deep HST imaging and ground based spectroscopy, also followed in radio, IR (*Spitzer*), etc.

Chandra deep field





The Deep X-Ray Source Counts

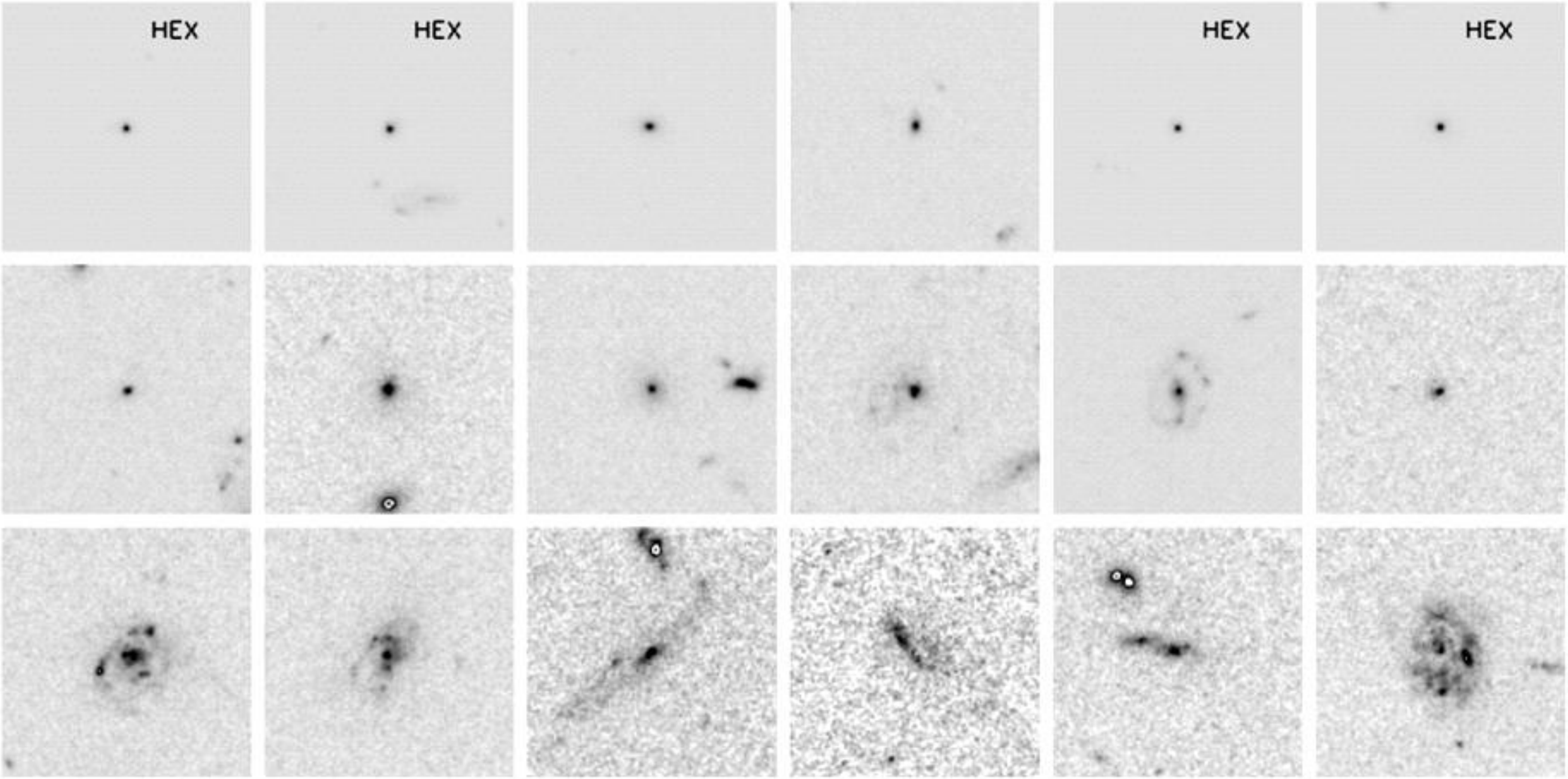


They essentially explain all of the observed CXRB

Bolometric equivalent of

Identifying the Faint X-Ray Sources

Samples of sources:

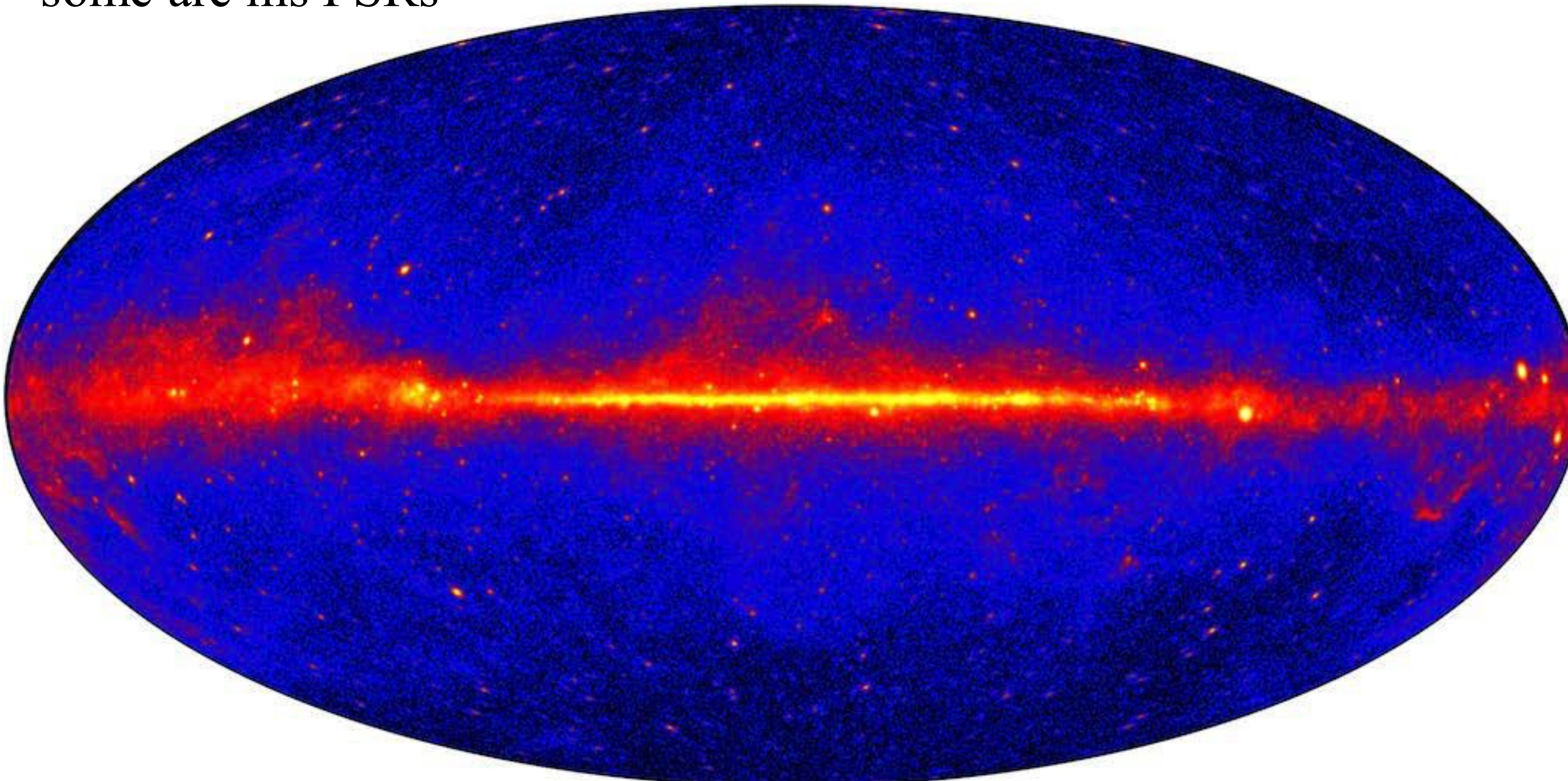


A mixed bag: some QSOs, some galaxies … possibly with hidden AGN

Luminosities reach $L_X \sim 10^{45}$ erg/s $\sim 10^{12}\ L_\odot$

Beamed AGN are the Principal Extragalactic γ-Ray Sources

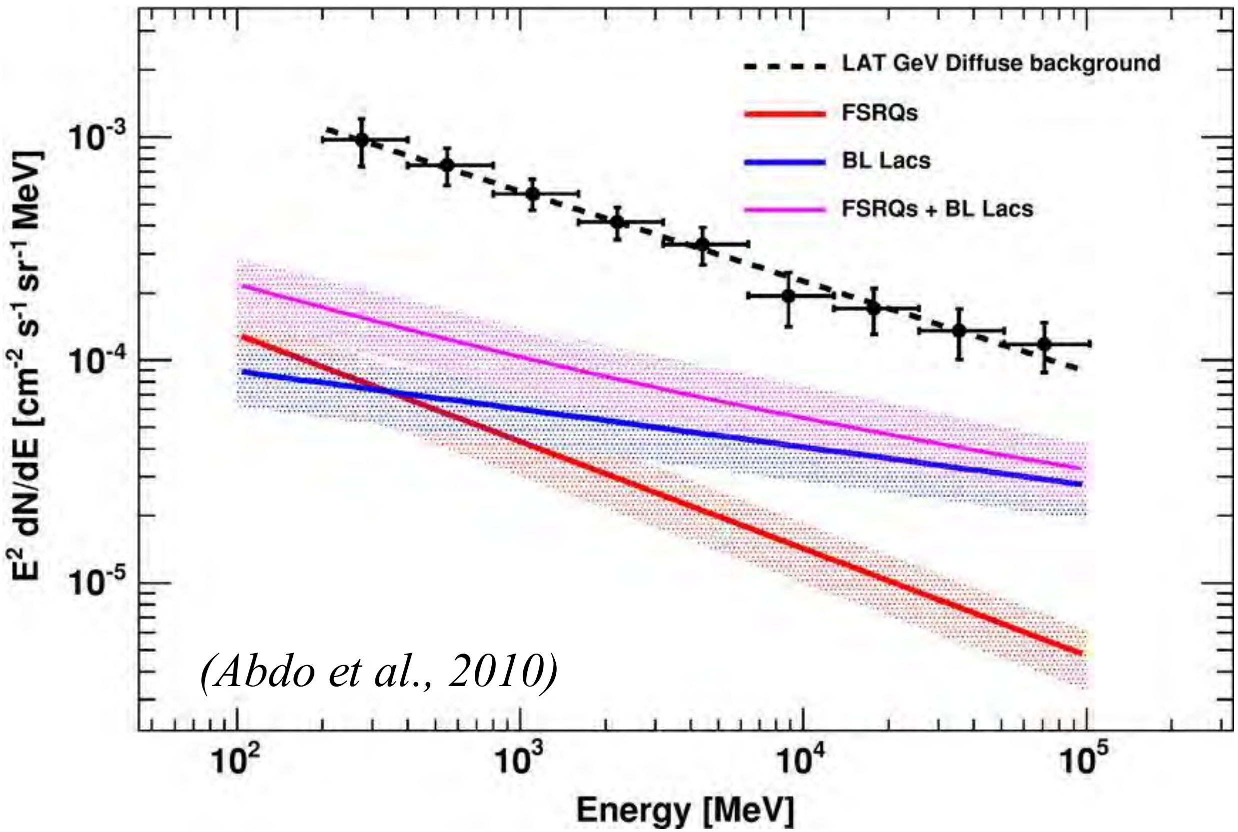
Most of the high Galactic latitude γ-ray sources are beamed AGN, but some are ms PSRs



Fermi LAT 5-year map

The Origins of the Cosmic γ-Ray Bgd

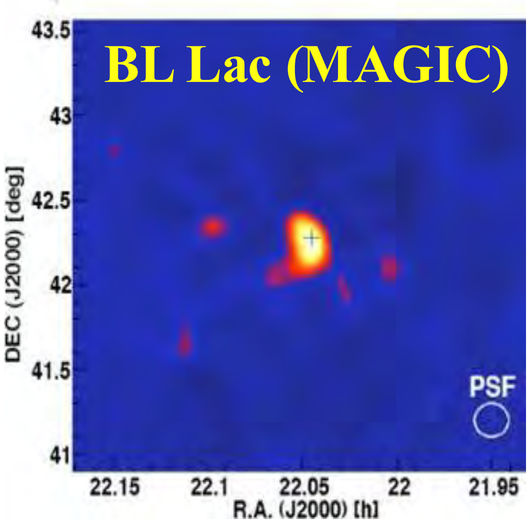
However, new *Fermi* measurements fail to fully account for the observed CGRB by integrating the extrapolated source counts

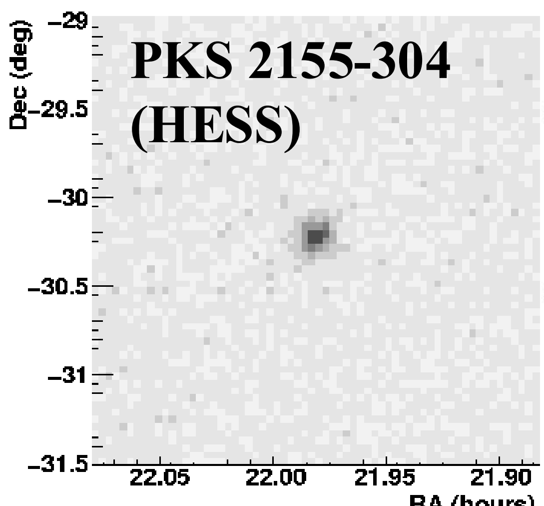


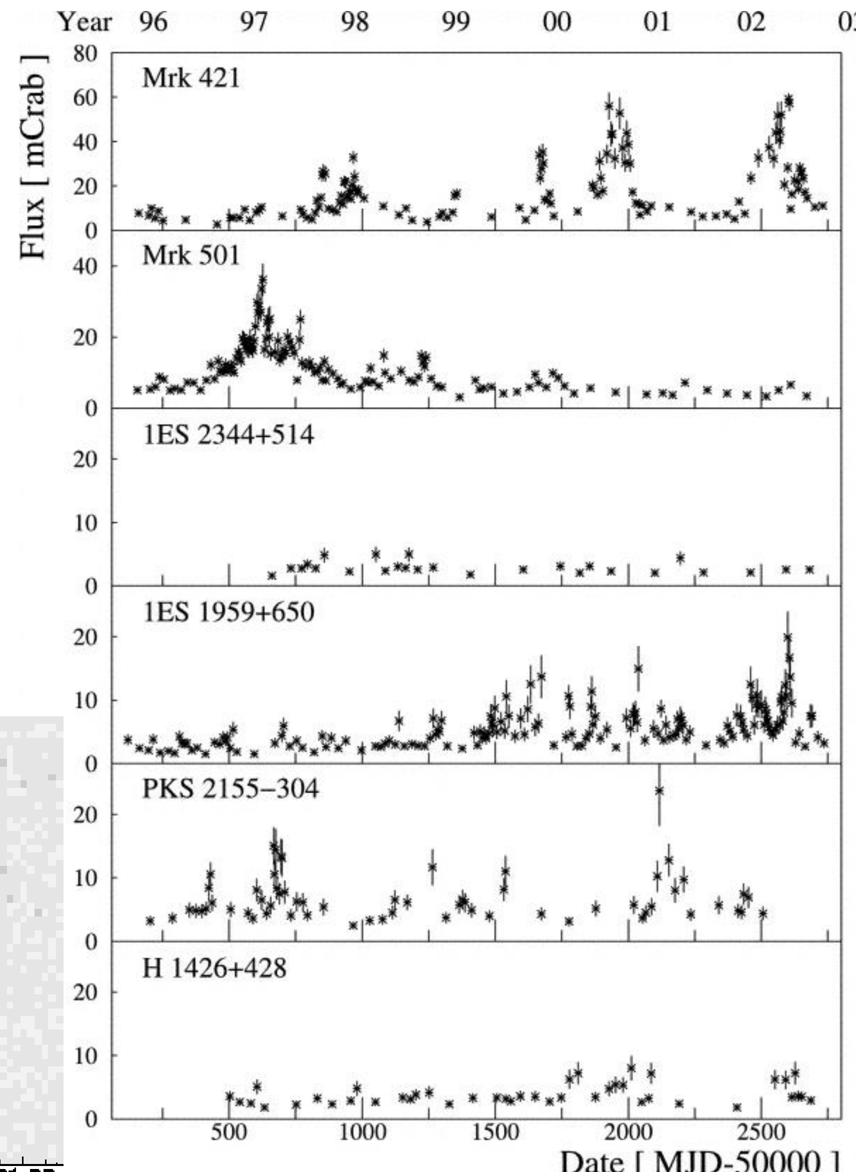
The origin of the "excess" is as yet unclear; it can be some combination of beamed AGN, star-forming galaxies, shocks in clusters, DM annihilation/decay, etc.

The Cosmic Accelerators: TeV γ-ray Detections of Blazars

Variability on time scales of minutes implies origin from very compact regions - possibly internal shocks, and bulk Lorentz $\Gamma > 50$

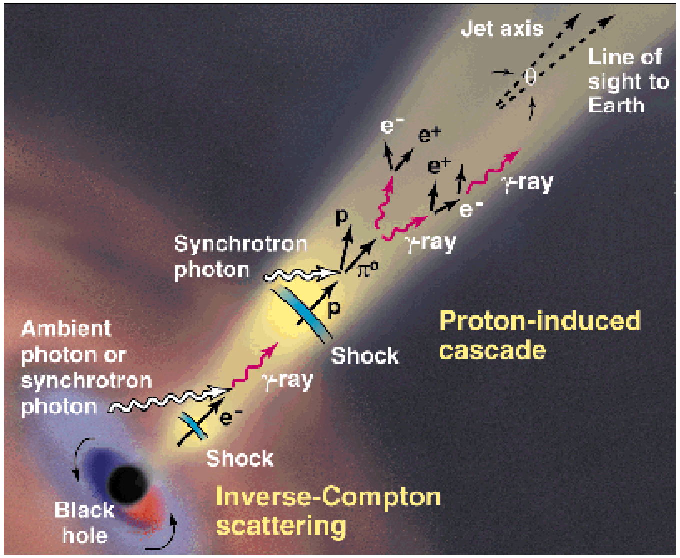




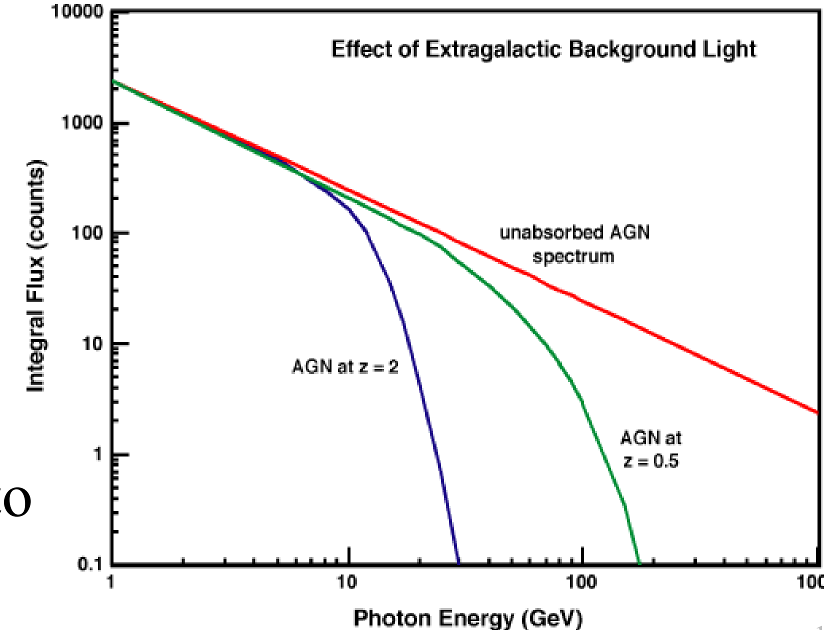


The Many Uses of Blazars

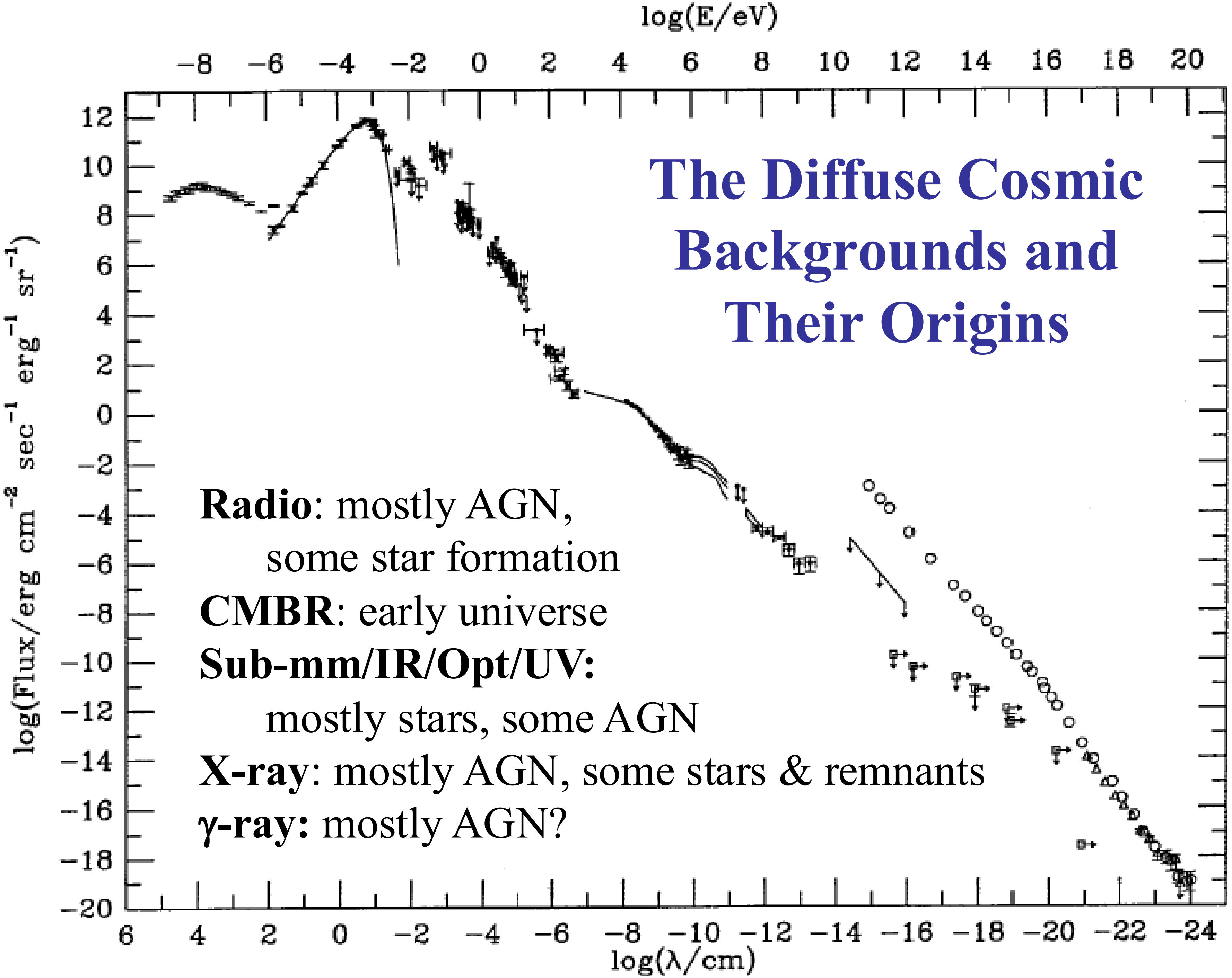
- AGN demographics and evolution
  - Constraints for AGN unification models
  - Origins of the Cosmic γ-Ray Bgd.
  - Possible new AGN sub-populations?
- Understanding the cosmic accelerators
  - AGN jet origins and their physics
  - The UHECR connection? ***Long-term future of particle physics?***



- Astrophysical foregrounds to CMBR fluctuations at high l
- A new probe of the cosmic star formation history, through extragalactic bgd. light as a *f(z)*
  - EBL photon gas is optically thick to high-energy photons



The Diffuse Cosmic Backgrounds and Their Origins



Radio: mostly AGN, some star formation

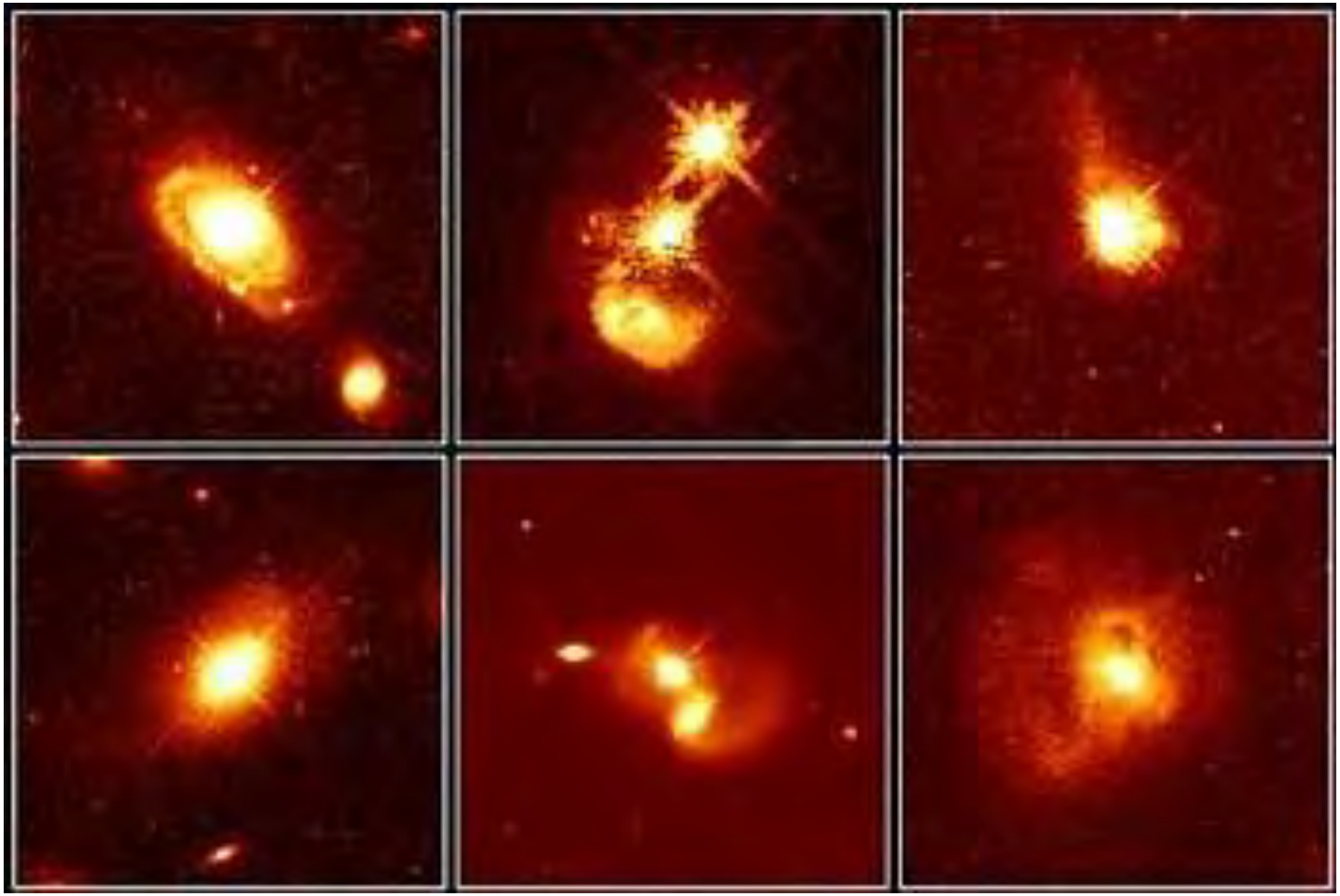
CMBR: early universe

Sub-mm/IR/Opt/UV: mostly stars, some AGN

X-ray: mostly AGN, some stars & remnants

γ-ray: mostly AGN?

What Makes Quasars "Quase" ?



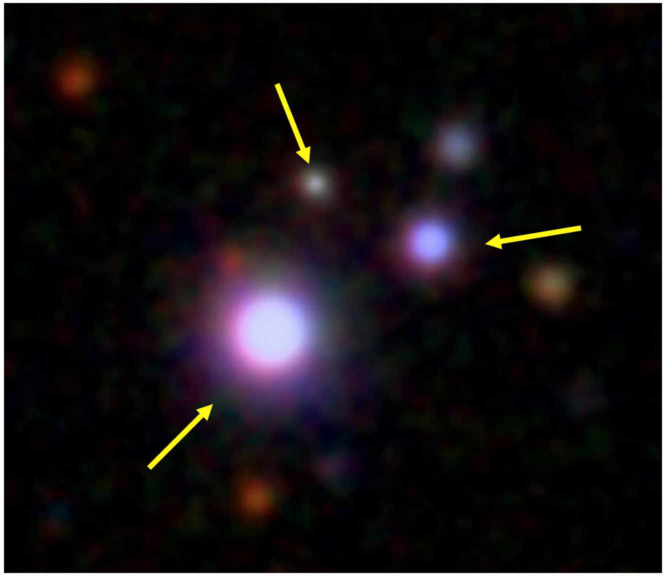
HST Images of QSO hosts, indicative of interacting systems

The same astrophysical processes, **dissipative mergers and infall,** can fuel both bursts of star formation and AGN

Small-Scale Clustering of Quasars

Much stronger than expected from the galaxy clustering, implying that interactions are responsible for the origins of QSO activity

⇧ Examples of binary QSOs ⇧

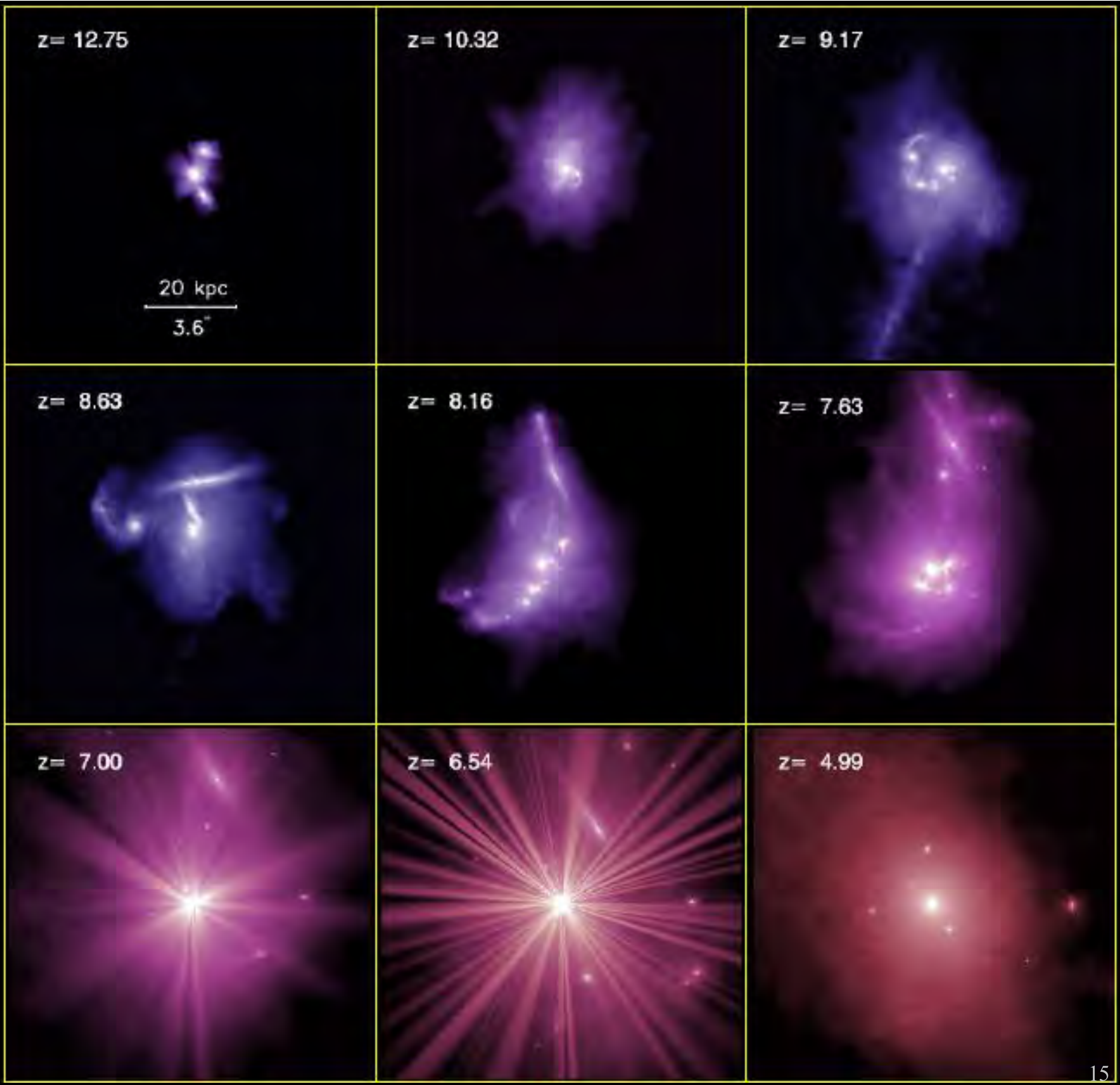


← The first physical triple QSO known, QQQ 1432–0106 at $z = 2.076$. Extremely unlikely, unless interactions are involved.

Typical separations tens to hundreds of kpc, typical for the initial stages of galaxy interactions

Hydro-simulation of the hierarchical build-up of an early Sloan quasar

TIME EVOLUTION OF THE PROJECTED STELLAR MASS



(slide from V. Springel)

Li et al. (2006)

AGN Feedback

Radiative energy input:

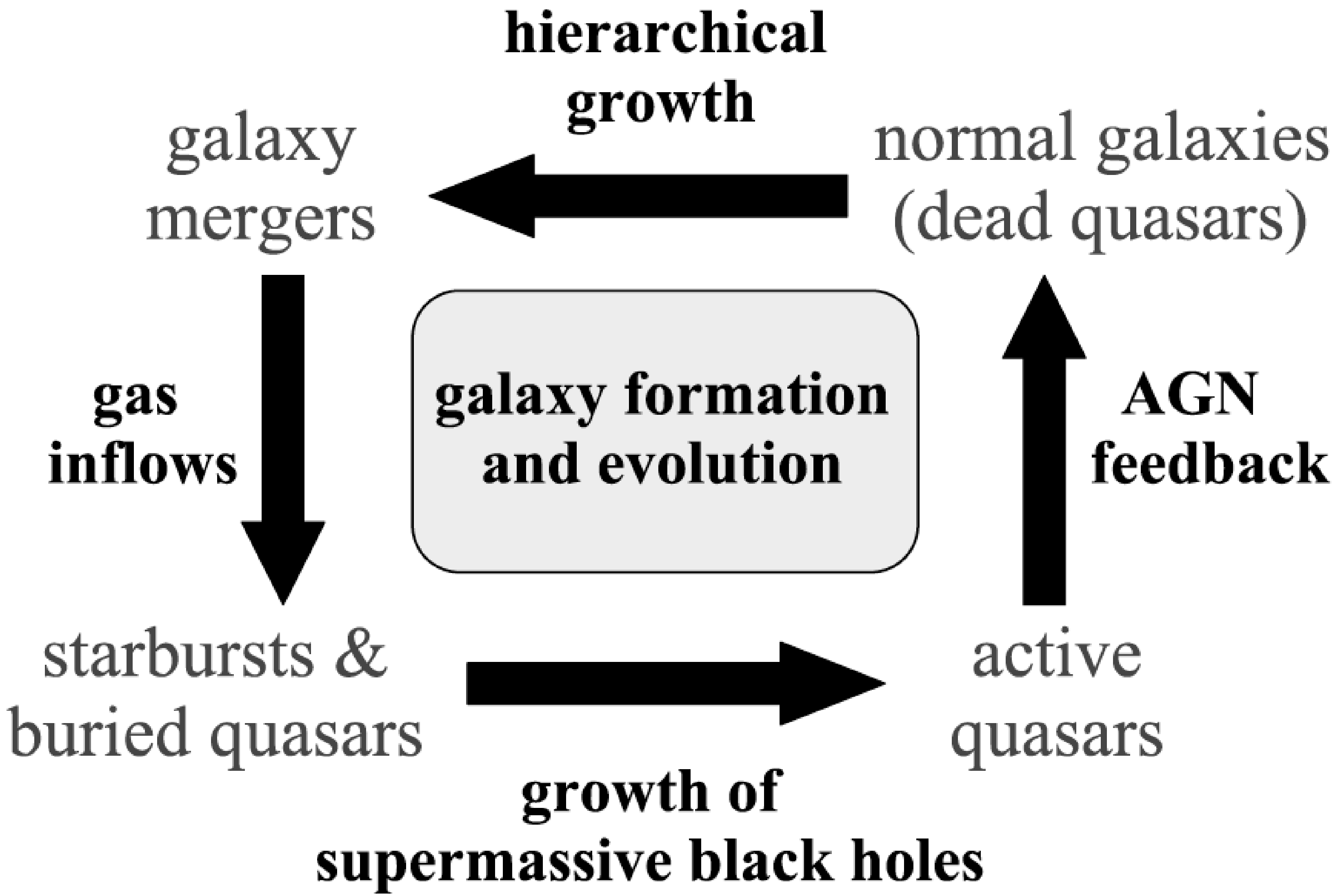
- Ionizes the host ISM and cluster IGM, curtailing star formation
- Negative feedback -> LF cutoff?
- Drives a galactic wind due to coupling with the gas, expels the chemically processed material into the IGM
- Comparable mechanical energy input from the jets (mainly important in clusters?)

- Note:

$$E_{AGN} \sim L_{AGN}\, t_{AGN} \sim 10^{12}\, L_\odot\, 10^{7}\, \mathrm{yr} \sim 10^{60}\, \mathrm{erg}$$

$$E_{bind.gal.} \sim M_{gal}\, V_{gal}^{2} \sim 10^{12}\, M_\odot\, (200\, \mathrm{km/s})^2 \sim 10^{60}\, \mathrm{erg}$$

Co-Evolution of Galaxies and SMBHs

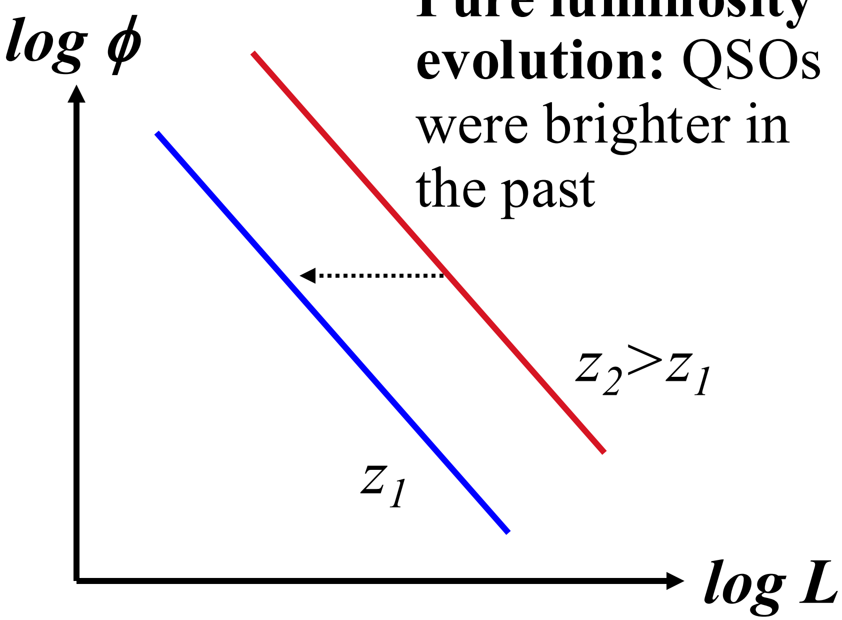


(from P. Hopkins)

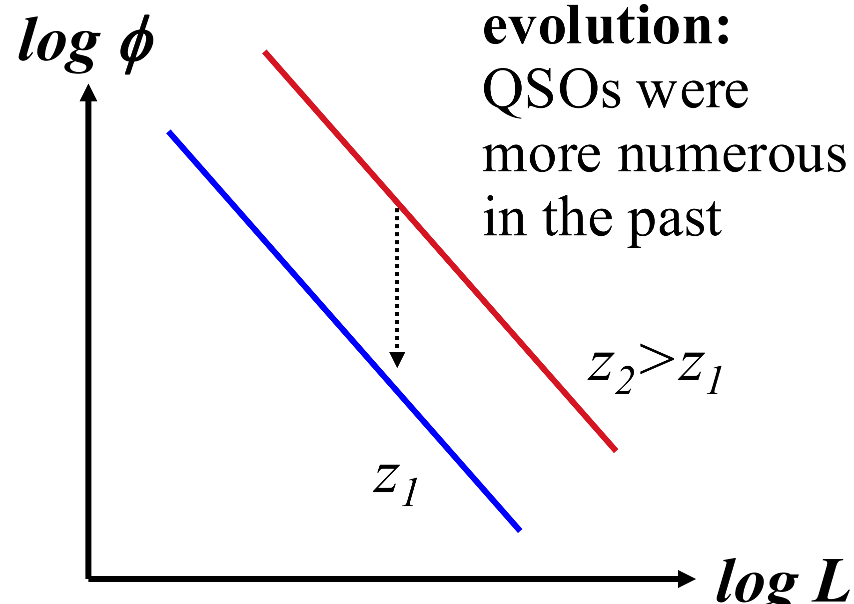
Quasar Evolution

- How is the luminosity function of QSOs, and their total comoving density changing in redshift?
- This may help us understand better the origins of the AGN activity and their relation to galaxy evolution
- QSO numbers increase rapidly with redshift, but are luminosities or densities changing? For a pure power-law luminosity function, the answer is ambiguous:

Pure luminosity evolution: QSOs were brighter in the past



Pure density evolution: QSOs were more numerous in the past

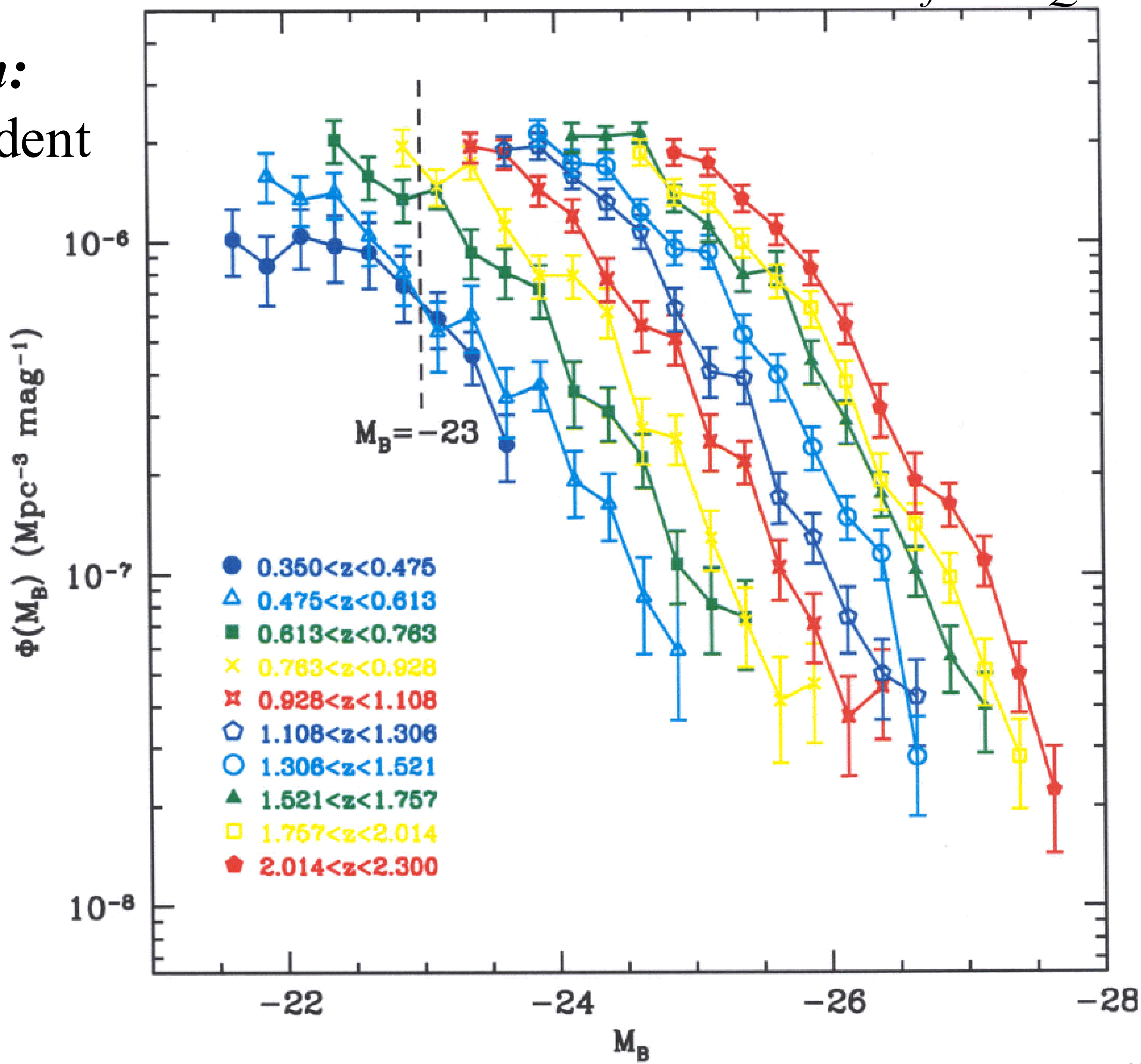


Quasar Evolution

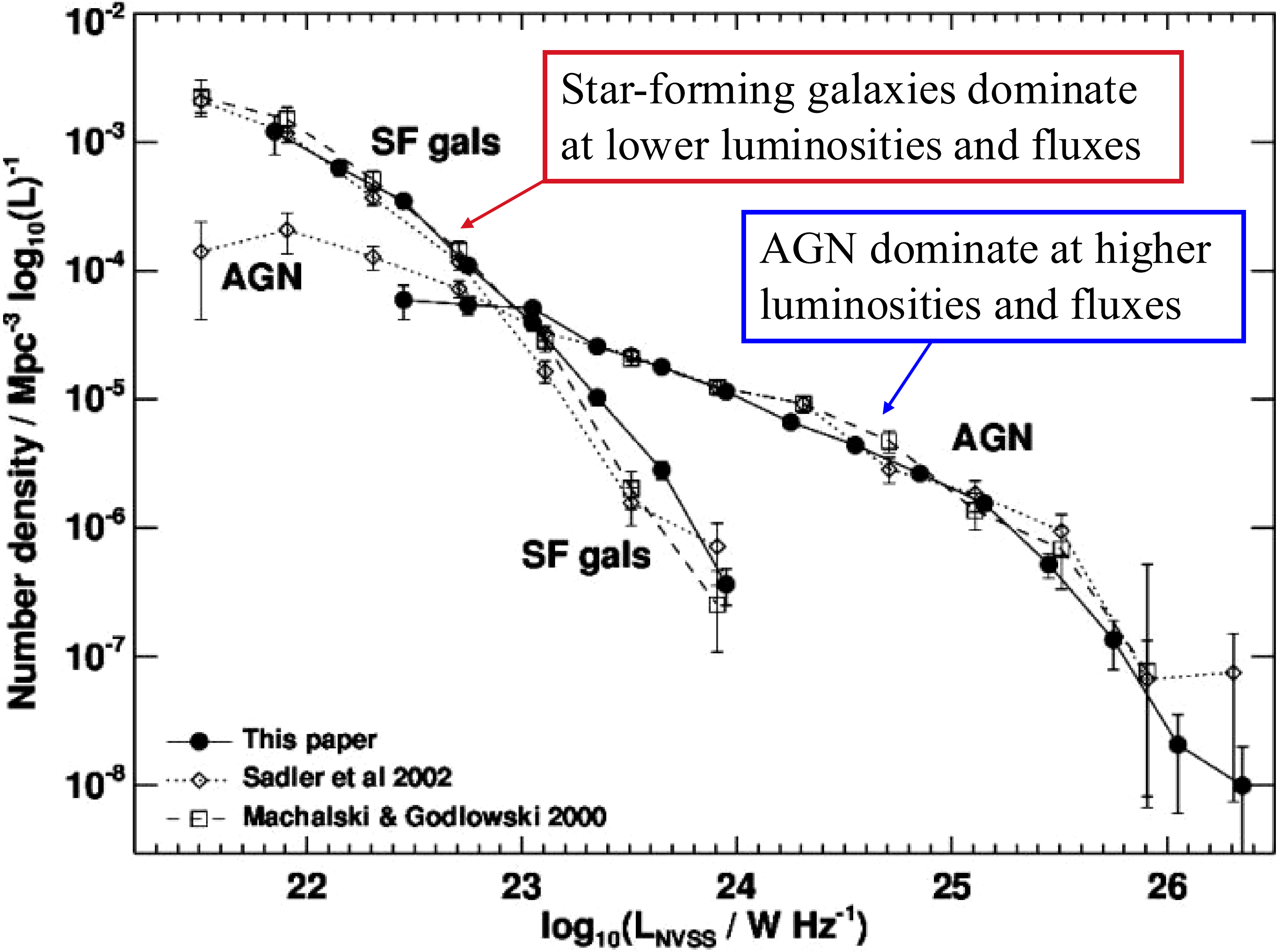
Results from 2QZ

The answer is ***both:*** Luminosity-dependent density evolution

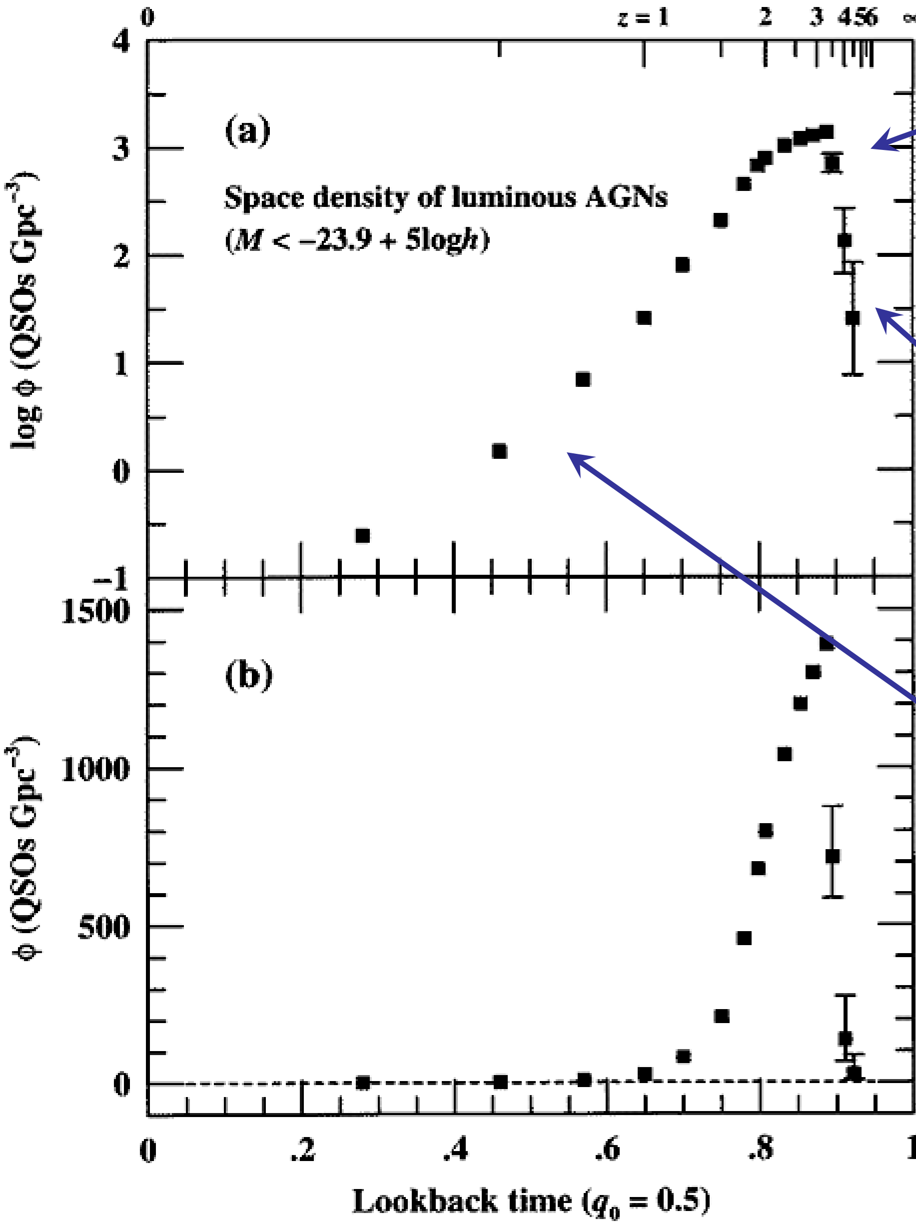
Luminous QSOs evolve faster at higher redshifts, and the shape of the QSO LF changes: there is a break, with a flatter slope at lower luminosities



Local Radio Luminosity Function



The History of the Comoving Number Density of Quasars

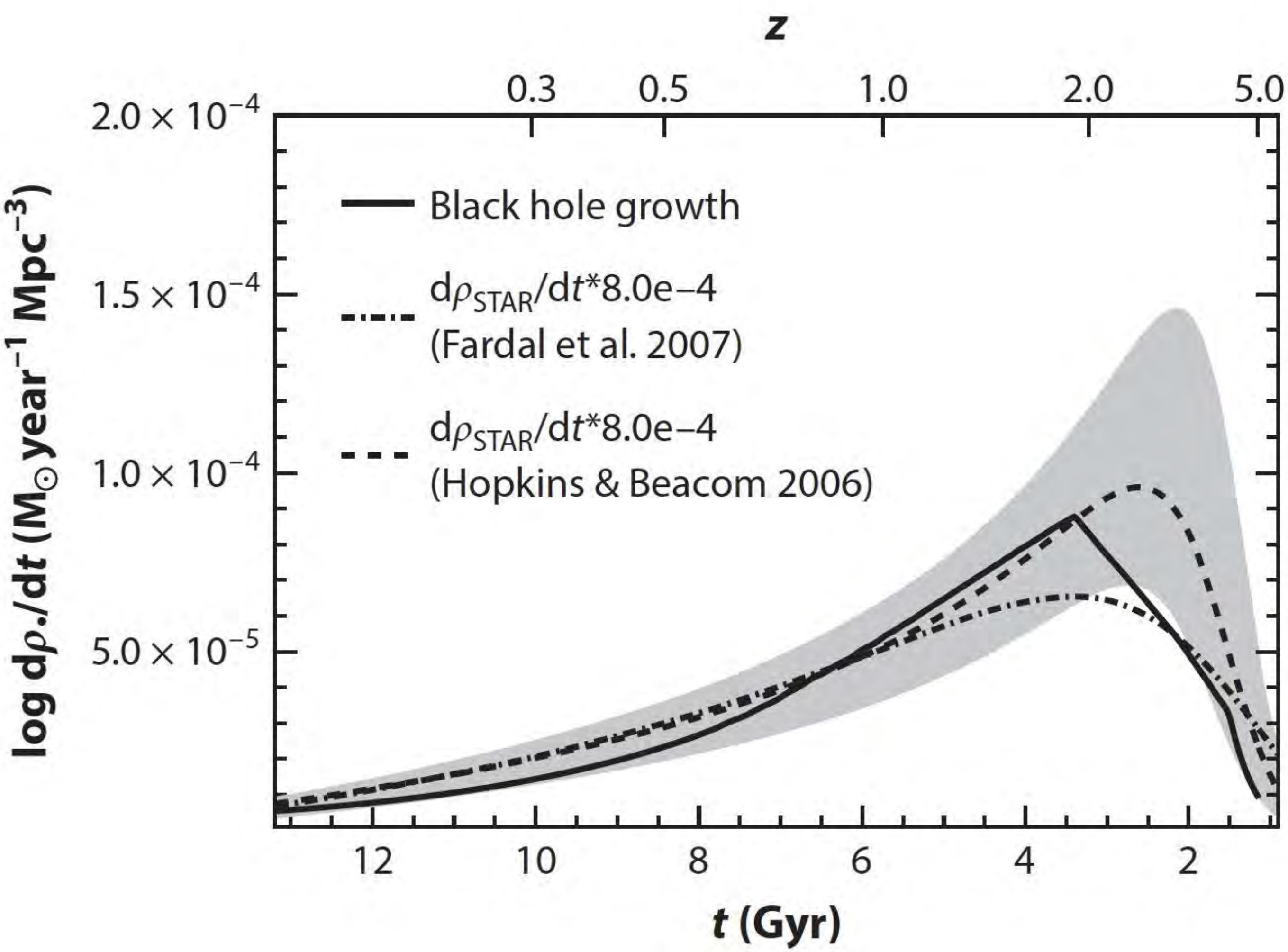


The Peak of the Quasar Era at z ~ 2 - 3: The Maximum Merging Epoch?

The Rise of Quasars: Initial Assembly of the Host Galaxies, Growth of the SMBHs

The Decline at Low *z*' s: Diminishing Fueling Events

SMBH Accretion Growth Tracks the Star Formation History



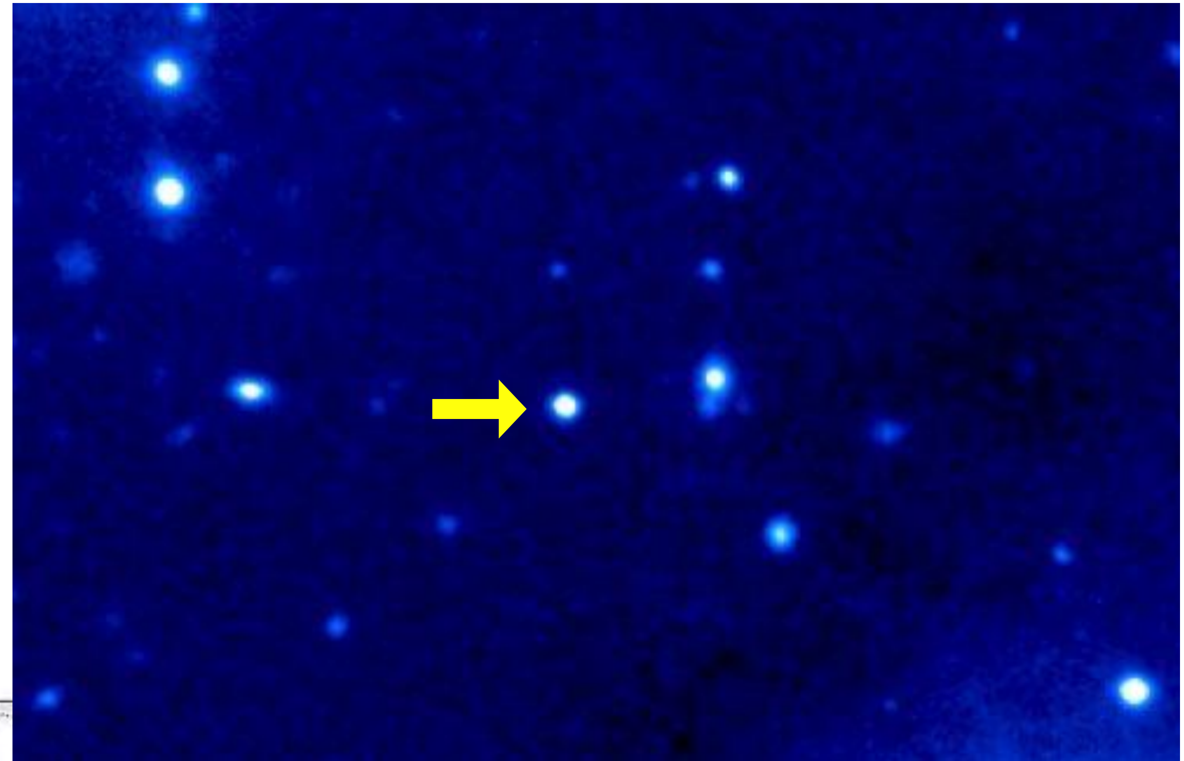
Note: the SF history has been scaled down by a factor of 1250, to account for the ratio of the comoving mass densities of stars and SMBHs today

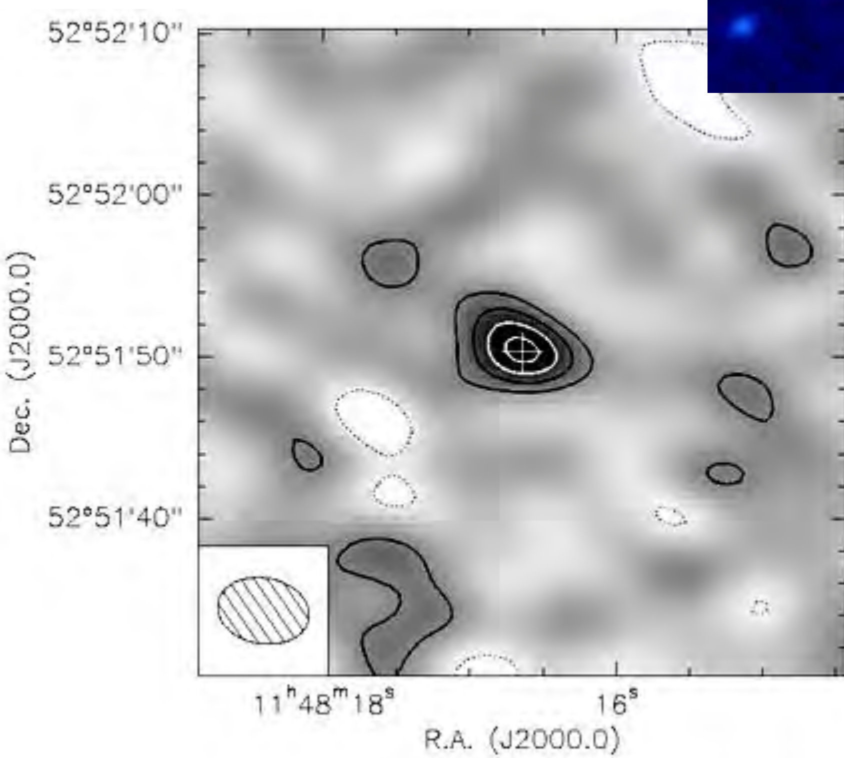
(Heckman & Best 2014)

The distant quasar SDSS 1148+5251

z = 6.41

(Fan et al. 2003)





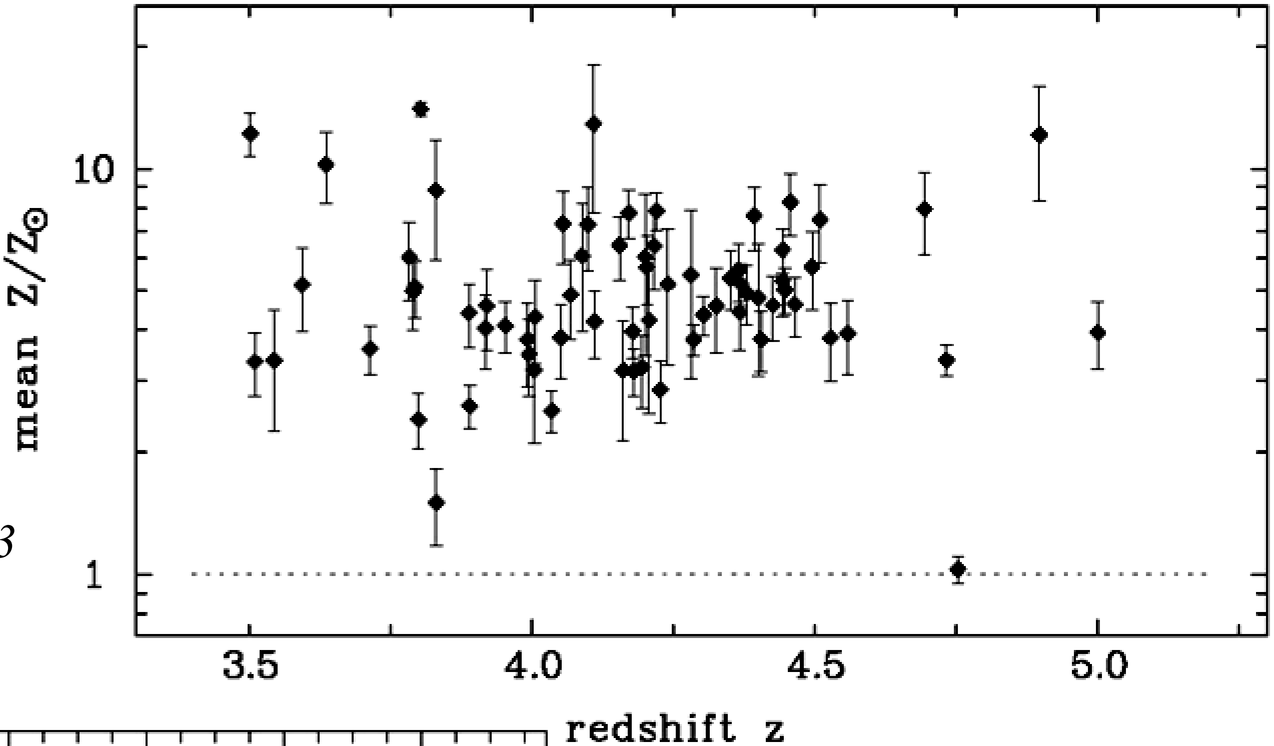
⬅ CO Detection *(Bertoldi et al. 2003)*

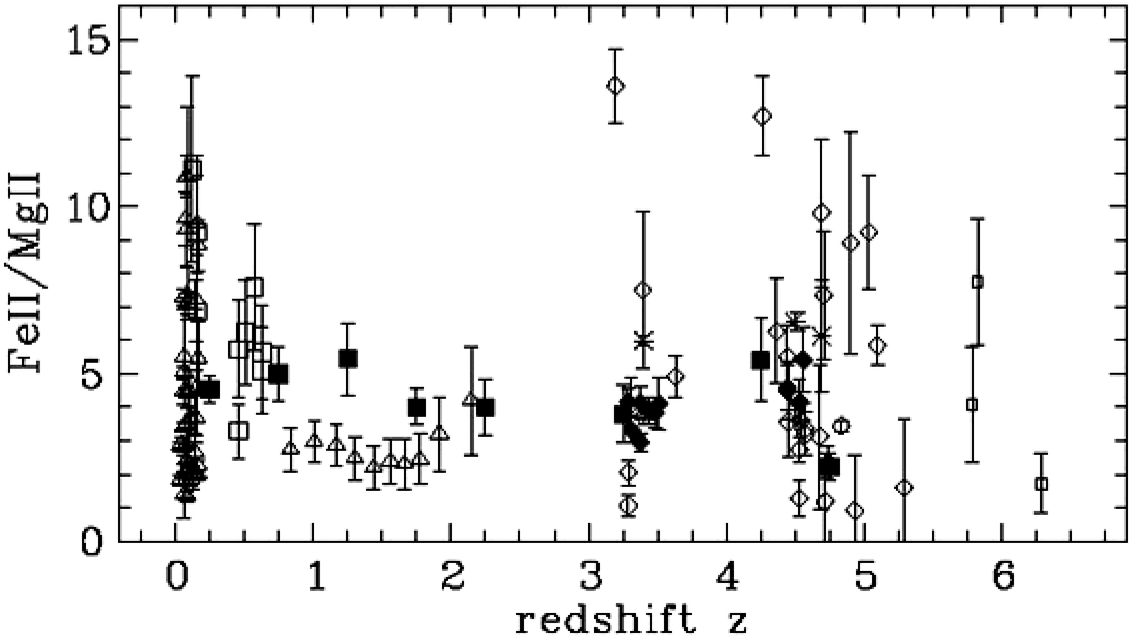
è Substantial chemical evolution already at this epoch

Also: $M_{BH} \sim 3 \times 10^9 M_\odot$

High-z QSOs Are Very Metal Rich!

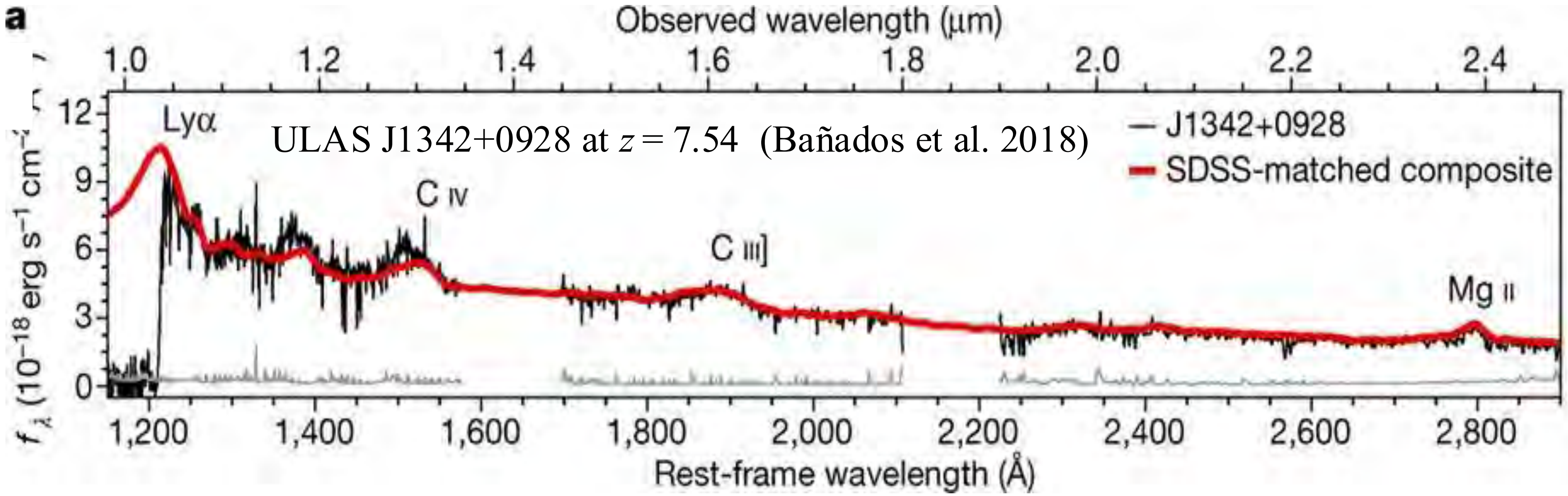
Hamman, Dietrich, et al. 2003

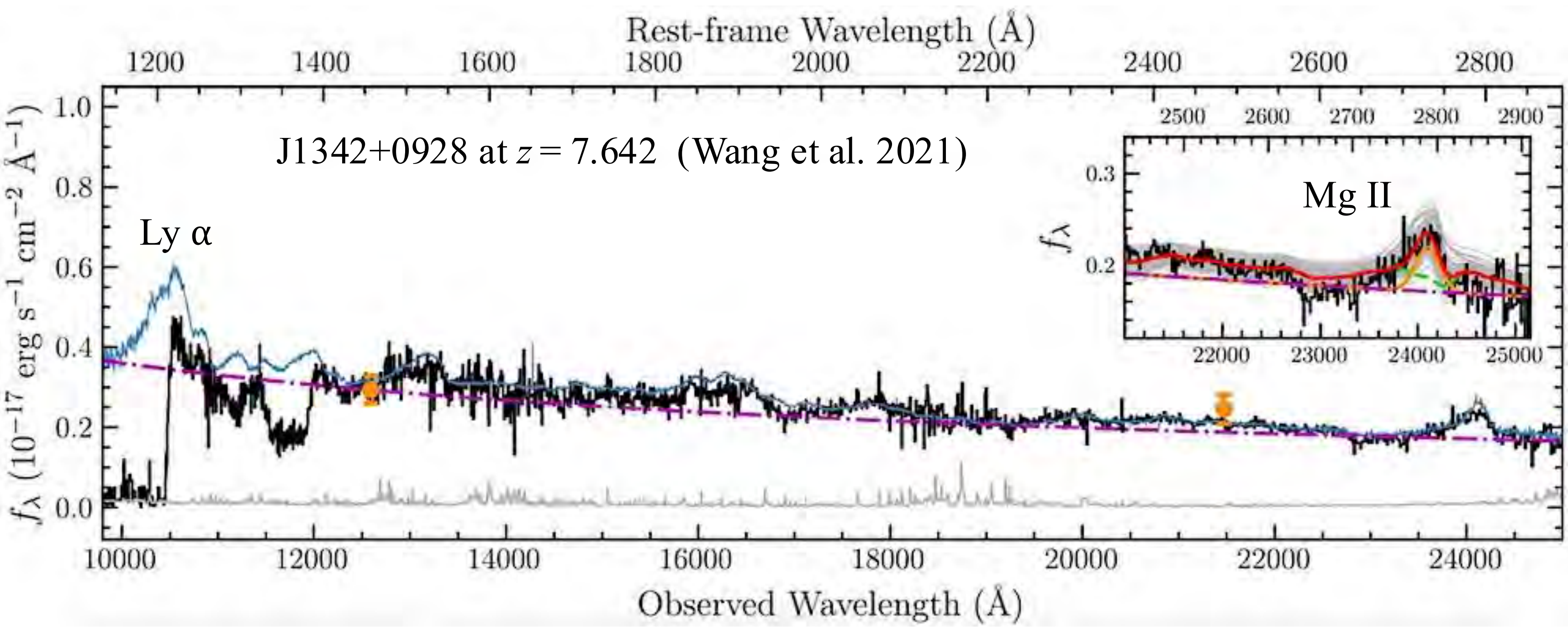




… and their abundance patterns (enhanced Fe/α) are similar to those of ellipticals, suggesting enrichment by type I SNe, with an onset of star formation at $z > 10$

The Most Distant Quasars Known





The Most Distant SMBHs Known

JWST + *Chandra* detection of a posible SMBH (UHZ1) at $z \approx 10.3^{+0.6}_{-1.3}$

(Bogdan et al. 2023)

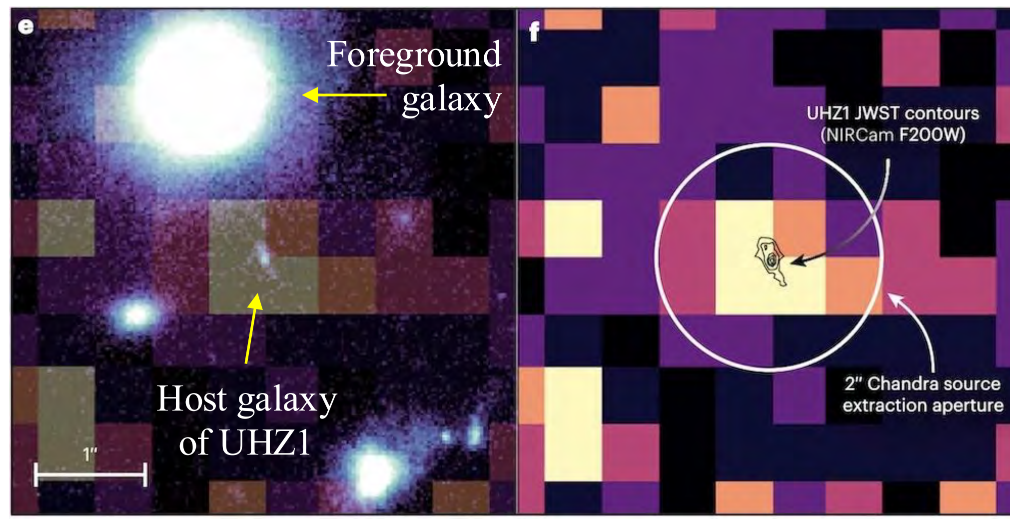
JWST NIRCam UHZ1 images

Presence of an X-ray source with

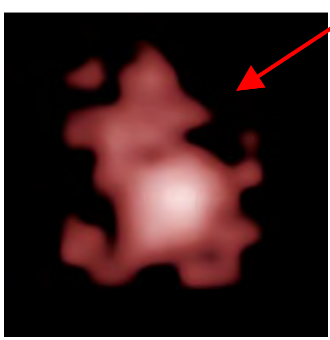
$L_X \approx 1.9 \times 10^{44}\ \mathrm{erg\ s^{-1}}$

implies the existence of a SMBH with $M_{BH} \approx 4 \times 10^{7}\, M_{\odot}$

JWST/Chandra overlays of UHZ1



JWST spectroscopy of the galaxy GNz-11



at z = 10.6 shows emission lines typical of AGN implying the existence of a $M_{\bullet} \sim 1.6 \times 10^{6 \pm 0.3}\, M_{\odot}$ SMBH accreting at ~ 5 times the Eddington rate

(Maiolino et al. 2024)

From Quasar Light to SMBH Demographics

Using the evolving QSO luminosity function and integrating their comoving radiated energy density leads to an estimate of the comoving mass density of their SMBH remnants today

- At any redshift z, the integrated QSO luminosity function gives the averaged QSO radiation density ρ_{rad}
- That leads to the averaged BH density produced by the accretion, $\rho_{\mathrm{BH}} = \rho_{\mathrm{rad}} / c^2\varepsilon$, where $\varepsilon \sim 0.1$ is the accretion efficiency
- Integrate over all redshifts to get the total BH density today

The result: **$\rho_{\mathrm{BH}}(\mathrm{QSO}) \sim 3 - 4 \times 10^5\ M_\odot\ \mathrm{Mpc}^{-3}$**

Accounting for the sources of the XRB, increases this estimate:

$$\rho_{BH} = (8 - 20) \times 10^5\, \varepsilon_{0.1}^{-1} \quad M_\odot\ \mathrm{Mpc}^{-3}$$

But the mass density in MBHs in ***local*** AGNs is ~ 100 times lower ⇒ *MBH remnants of past AGN activity must be present in a large number of normal, quiescent galaxies*

Local SMBH Demographics and Their Comoving Mass Density

Merritt & Ferrarese 2001

$M_\bullet$ from the $M_\bullet$-σ relation
M_{bulge} from Magorrian et al. (1998)

Mass density in local SMBH:

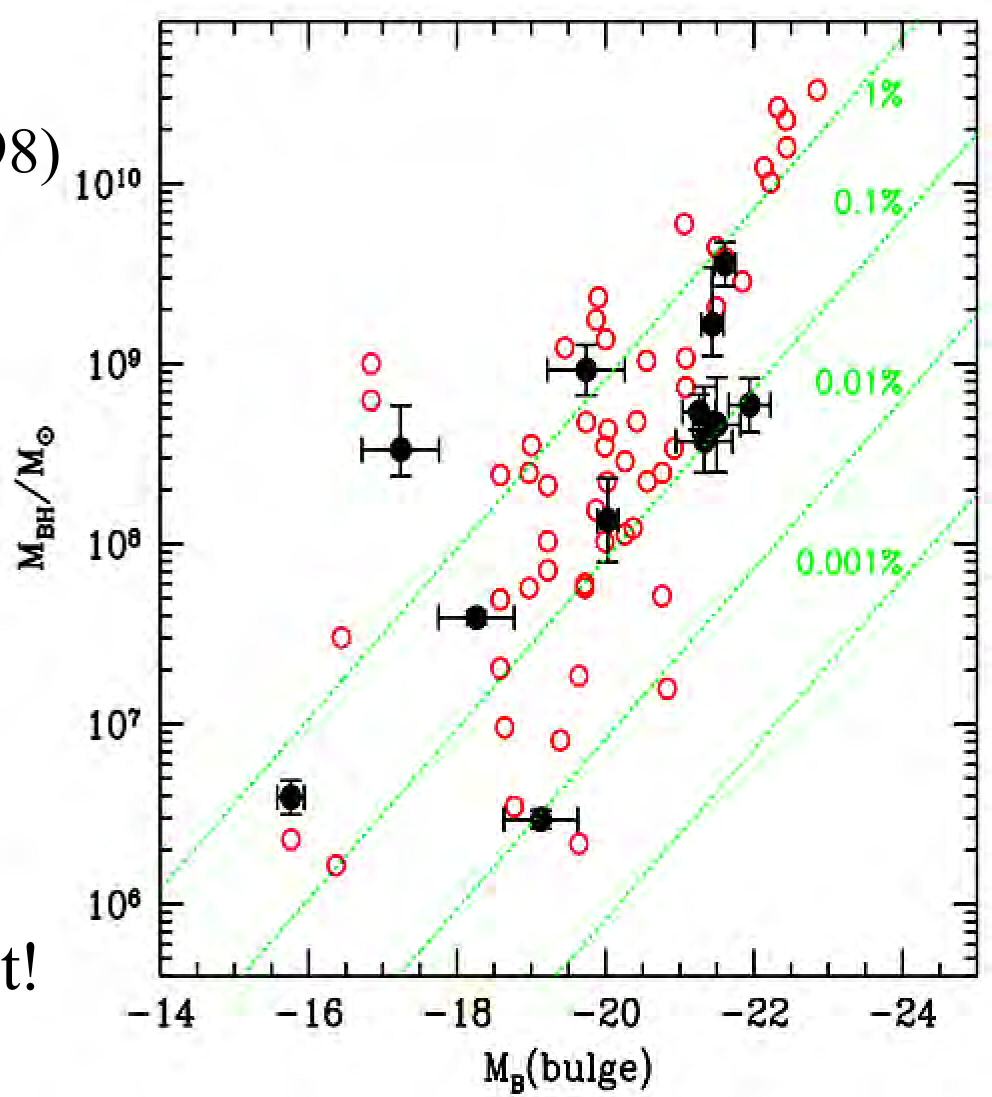
$\mathbf{x = M_\bullet / M_{bulge} \sim 0.13\%}$

$\mathbf{\rho_{bulge} \sim 3.7 \times 10^8\ M_\odot\ Mpc}$

(*Fukugita et al. 1998*)

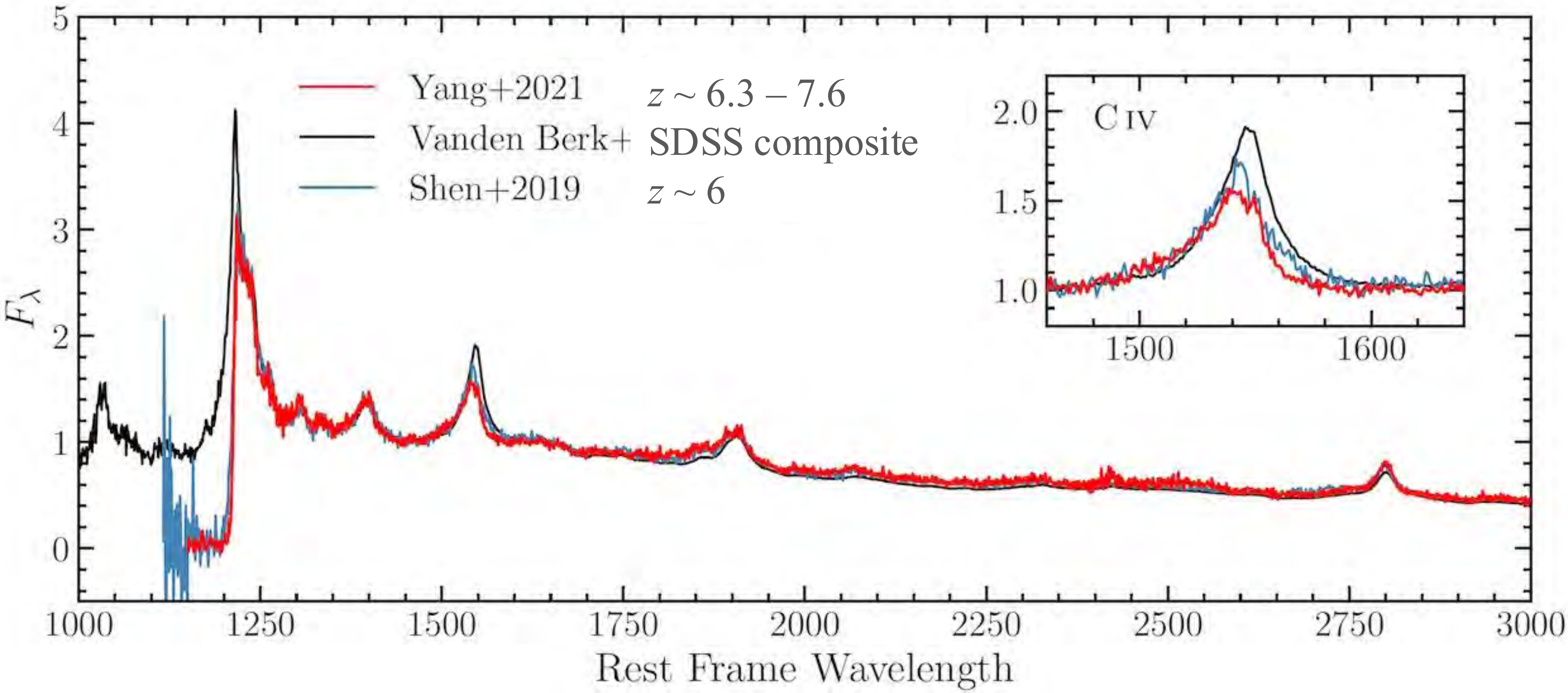
$\Rightarrow\ \mathbf{\rho_\bullet \sim 4.9 \times 10^5\ M_\odot\ Mpc^{-3}}$

i.e., exactly as implied by the integrated AGN light argument!
(a good consistency check)



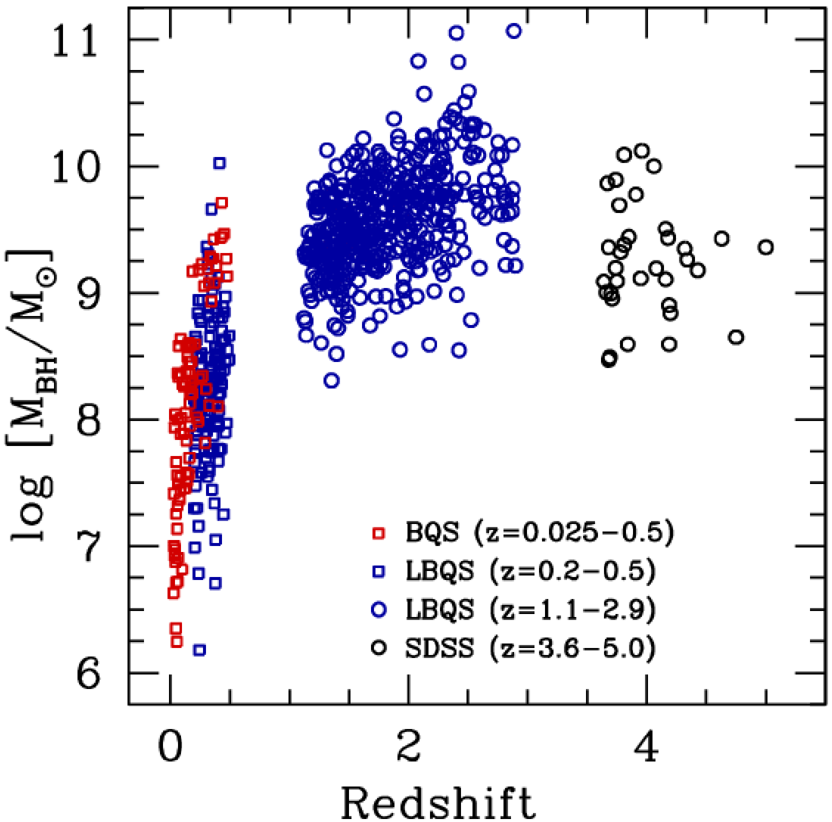
Evolution of Quasar Properties

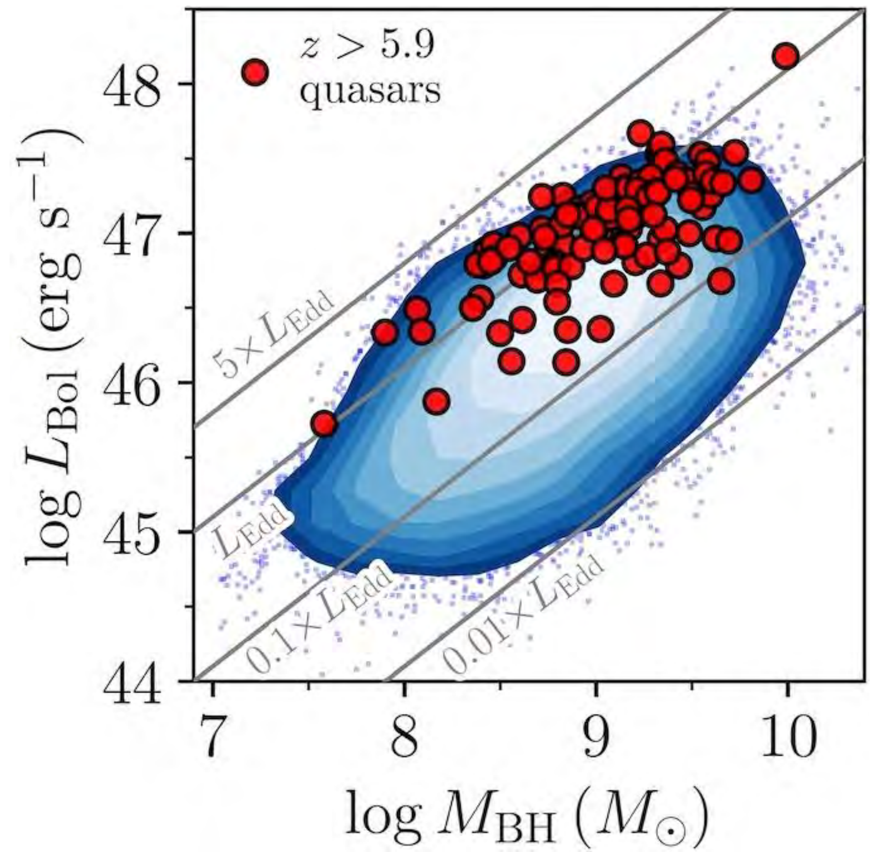
None that we could see, aside from the QLF evolution itself: a rapid formation and chemical enrichment of the hosts. Even the highest redshift quasar spectra look like those of their low redshift counterparts



(Fan et al. 2023)

Masses of SMBHs in Distant Quasars



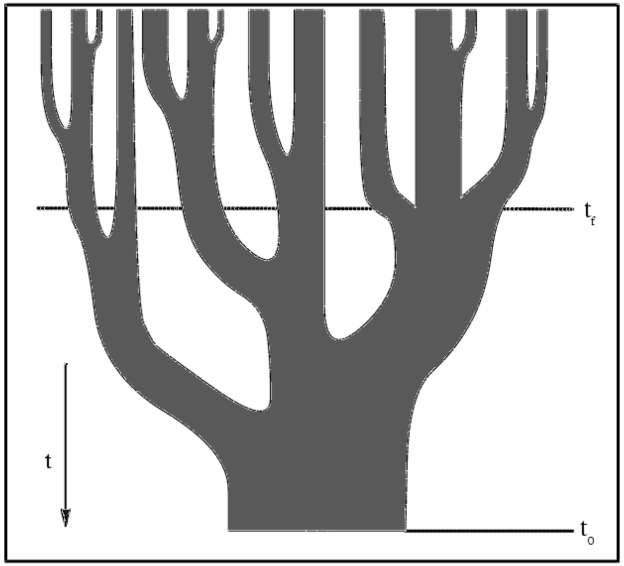


SMBHs with masses of up to ~ 10^{10} $M_\odot$ seem to have been built quickly, already by $z \sim 5-7$, when the universe was < 1 Gyr old

This is not easy to arrange, just like the abundance of luminous galaxies out to $z \sim 12$

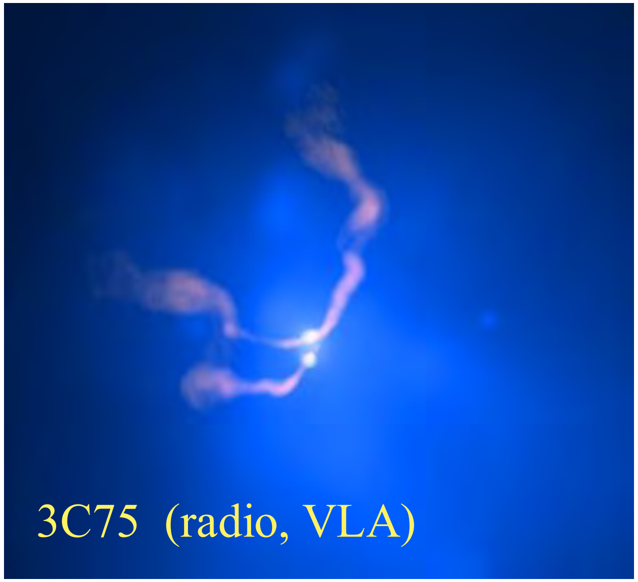
SMBH Growth Mechanisms

- In a hierarchical picture, as galaxies merge so will their BH's
  - Some may get ejected in 3-body interactions; their subsequent fate may be interesting
- This can also naturally account for the establishment of the SMBH - host galaxy correlations, which may be also sharpened by the AGN feedback
- Note that BH merging simply *re-arranges* the distribution of the collapsed mass; *collapsed mass grows by accretion*, following the BH seed collapse



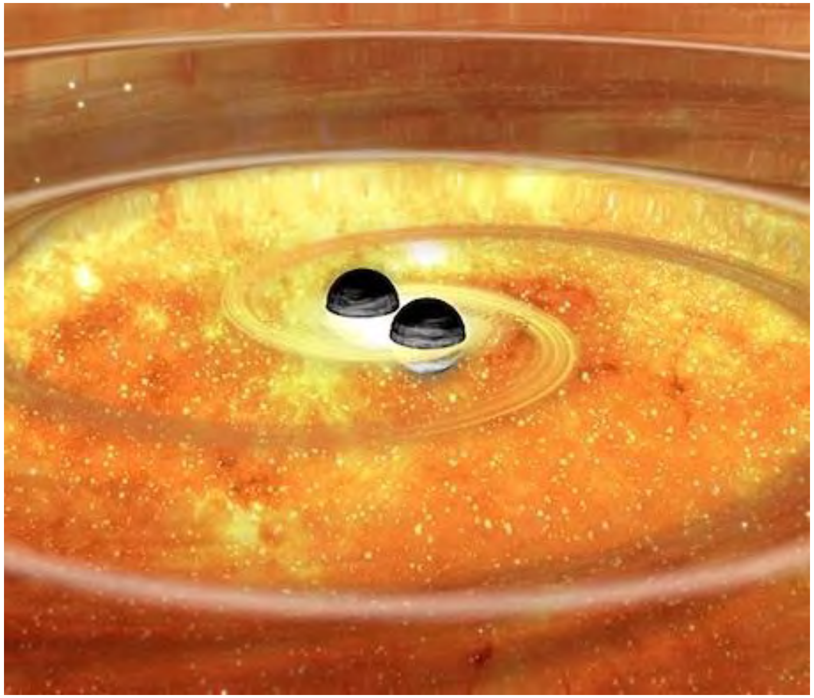
Merger Tree Schematic

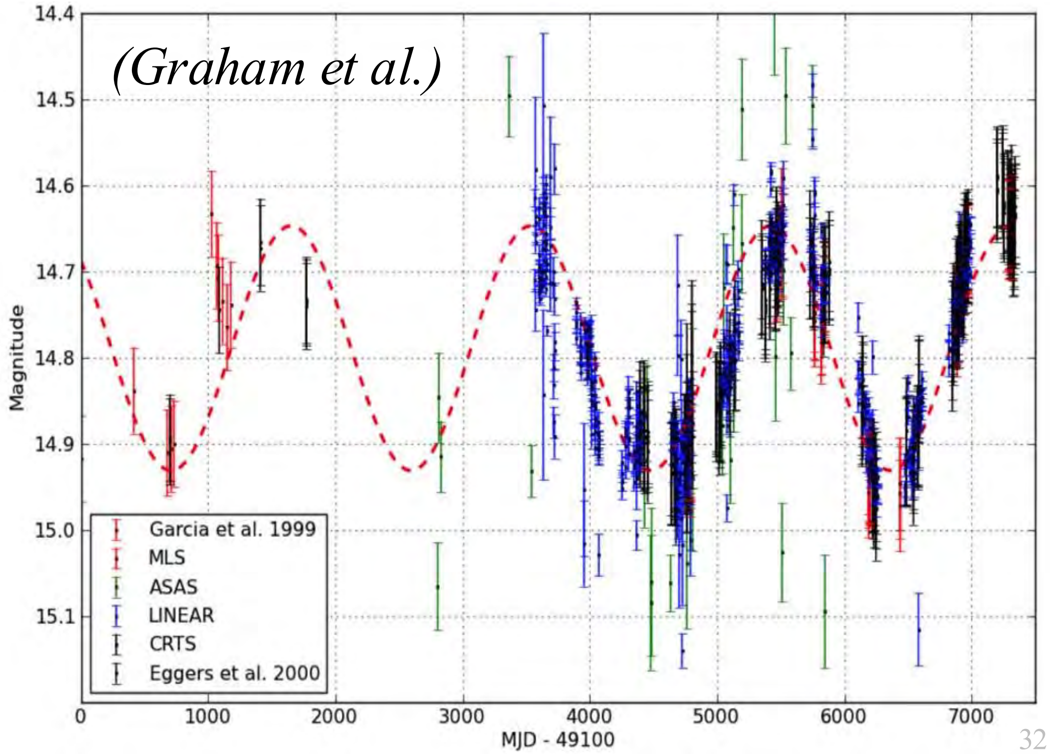
A dual AGN in a galaxy merger →



Supermassive Black Hole Binaries

- Close (sub-pc) SMBH pairs are unresolvable, but a binary can perturb an accretion disk in various ways
- This can manifest as a periodic variability signal superposed on the normal stochastic variability
- About 1 in 4000 quasars show this with the observed periods ~2-5 years, and the estimated separations of tens of *millipc*





Energetics of the Early QSO Growth

Since the baryonic material used to build SMBHs comes from initial radii $R_{init} \sim 10^2$ - 10^4 pc, and ends at $R_{final} \sim R_\bullet \sim 10^{-7}$ - 10^{-4} pc, substantial fraction of the rest mass must be dissipated.

For a Schwarzschild BH, max. efficiency is $\varepsilon_{max} \approx 0.06$; for a Kerr BH, $\varepsilon_{max} \approx 0.42$; typically assumed $\varepsilon \sim 0.1$.

Thus, a total dissipated energy is:

$$E_{SMBH} \sim 2 \times 10^{62} (M_\bullet/10^9 M_\odot) (\varepsilon/0.1) \text{ erg}$$

Released over $\Delta t \sim 700$ Myr $\sim 2 \times 10^{16}$ s, it implies

average luminosity $L \sim 10^{46}$ erg/s $\sim 2 \times 10^{12} L_\odot$

(summed over all progenitor pieces)

Depending on the relative rates of BH and star formation, this may provide a significant fraction of the early reionization photons

Accretion-Driven SMBH Growth

BHs grow through accretion, which gives rise to the AGN luminosity, which also limits the accretion rate:

$$L = \varepsilon\,(dM/dt)\,c^2$$

where ε is the mass-to-energy conversion efficiency, typically assumed to be ~ 0.1, and dM/dt is the mass accretion rate

For an Eddington-limited accretion:

$$L_E = 31.5\,(M/M_\odot)\,L_\odot$$

Combine the two: $L \sim M \sim dM/dt$, $dt \sim dM/M$, $t \sim \ln M$

The mass grows **exponentially**: $M(t) = \text{const.} \times \exp\,(t/t_S)$

Where t_S is the *Salpeter time* ~ 45 (ε/0.1) Myr

For a BH accreting steadily over the Hubble time, the mass would increase by ~ 10^{135}, so the accretion must be *sporadic*

The Rapid SMBH Growth Challenge

In $\Omega_m = 0.3$, $\Omega_\Lambda = 0.7$, $h = 0.7$ cosmology:

Redshift	Age/Myr
30	97
20	175
10	464
7	748

➡ **Available time to grow a SMBHs observed at *z* ~ 7–10 is ~ 300 - 700 Myr**

For an Eddington-limited accretion and a final SMBH mass $M_\bullet \sim 10^9\ M_\odot$:

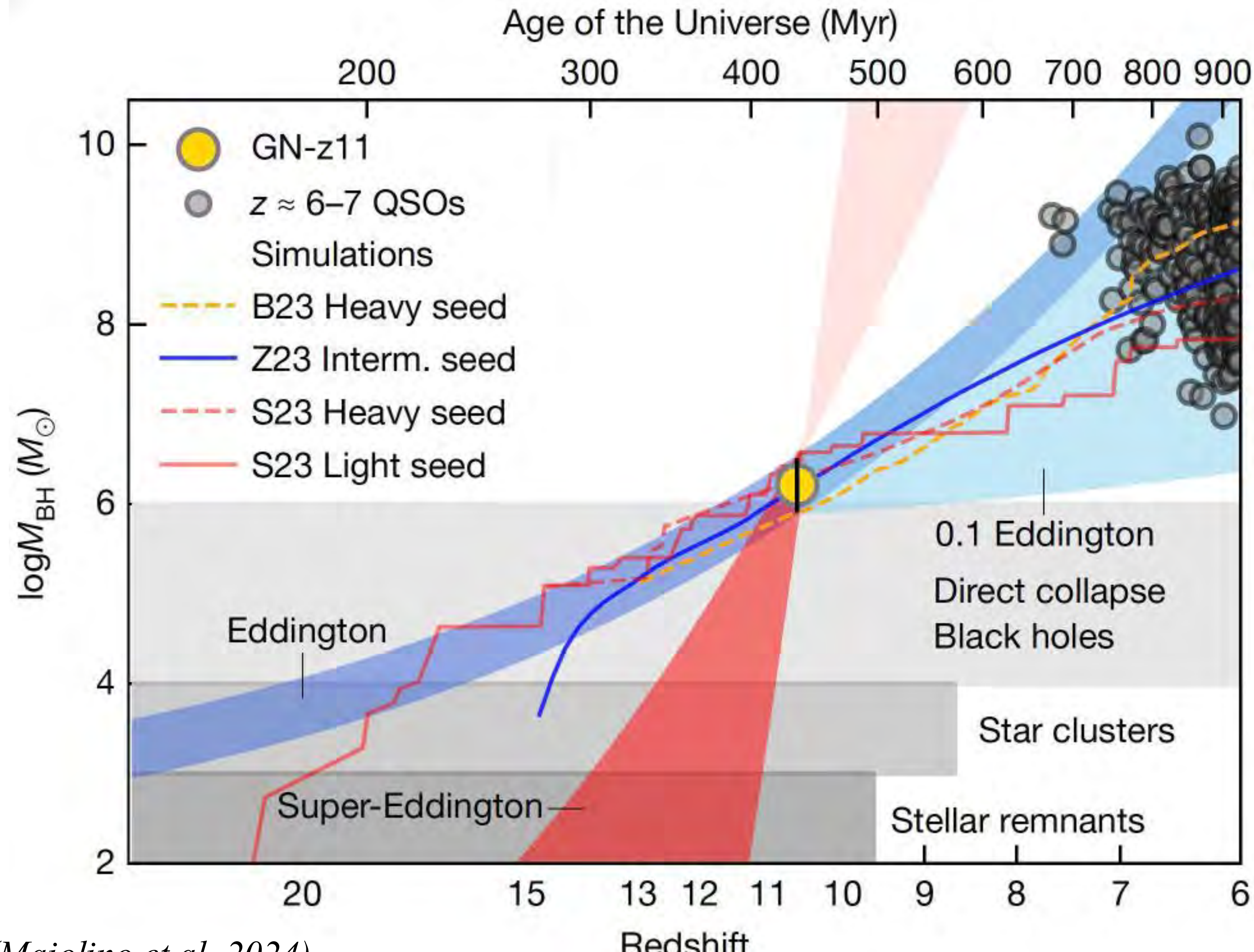
- For the seed BHs mass $M_{seed} \sim 10\ M_\odot$, need ~ 18 *e*-foldings
- For the $M_{seed} \sim 100\ M_\odot$, need ~ 16 *e*-foldings

For a final SMBH mass $M_\bullet \sim 10^{7.5}\ M_\odot$ and the same seed masses, the corresponding times are ~ 15 and ~ 12.5 *e*-foldings

For the Salpeter time ~ 45 (ε/0.1) Myr, 12.5 to 18 *e*-foldings corresponds to ~ 560 to 810 Myr

Thus the accretion either has to be *super-Eddington*, and/or requires *more massive seeds*, e.g., $M_{seed} \sim 1000\ M_\odot$

The Rapid SMBH Growth Challenge



Possible accretion growth mechanisms

(Maiolino et al. 2024)

First black holes in pregalactic halos
$z \approx 10-30$

$M_{BH} \sim 100-600\ M_{sun}$

PopIII stars remnants
(Madau & Rees 2001, Volonteri, Haardt & Madau 2003)

✓ *Simulations suggest that the first stars are massive $M \sim 100-600\ M_{sun}$* *(Abel et al., Bromm et al.)*

✓ *Metal free dying stars with $M > 260 M_{sun}$ leave remnant BHs with $M_{seed} \geq 100 M_{sun}$ (Fryer, Woosley & Heger)*

(from M. Volonteri)

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

Viscous transport + supermassive star (e.g. Haehnelt & Rees 1993, Eisenstein & Loeb 1995, Bromm & Loeb 2003, Koushiappas et al. 2004)

✓ *Efficient viscous angular momentum transport + efficient gas confinement*

Bar-unstable self-gravitating gas + large "quasistar" (Begelman, Volonteri & Rees 2006)

✓ *Transport angular momentum on the dynamical timescale, process cascades*

✓ *Formation of a BH in the core of a low entropy quasistar $\sim 10^4 - 10^6$ Msun*

✓ *The BH can swallow the quasistar*

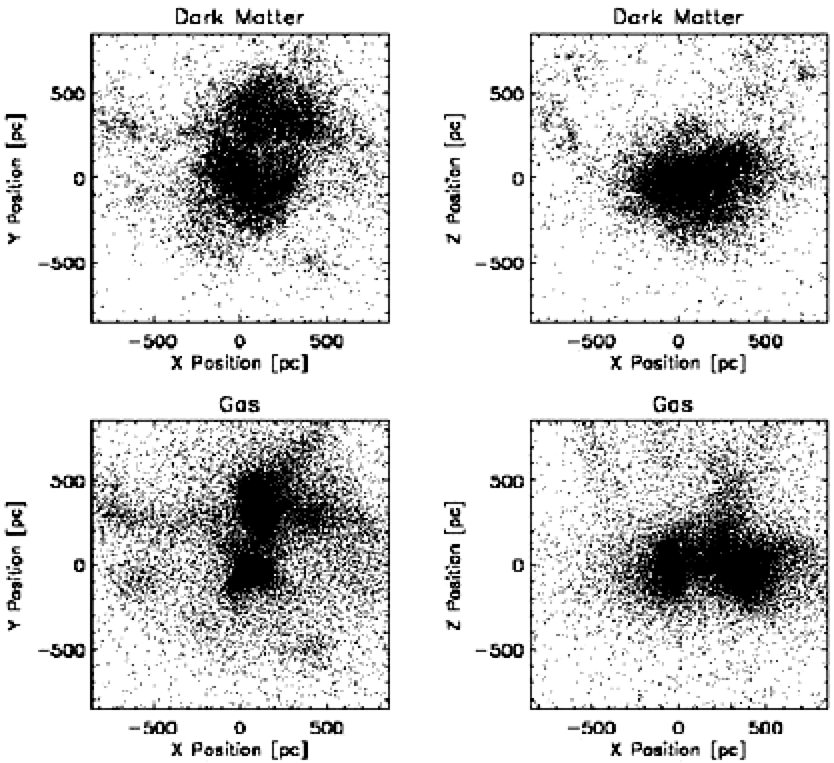
The Nature of the BH "Seeds"

Some plausible choices include:

- Primordial, i.e., created by localized gravitational collapses in the early universe, e.g., during phase transitions
  - No evidence and no compelling reasons for them, but would be very interesting if they did exist; could have "any" mass…
- Remnants of Pop. III massive stars: $M_{seed} \sim 10$ - $100\ M_\odot$
  - Could be detectable as high-*z* GRBs
- Gravitational collapse of dense star clusters, or runaway mergers of stars: $M_{seed} \sim 10^2$ - $10^4\ M_\odot$
- Direct gravitational collapse of dense protogalactic cores: continues directly as a SMBH growth

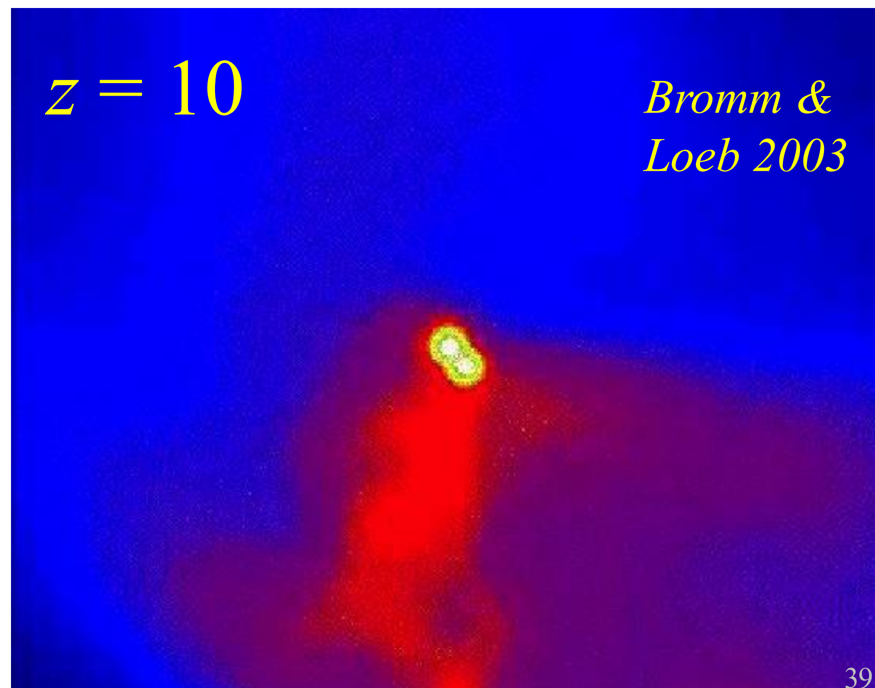
More than one of these processes may be operating …

Pop III Black Holes and the Origin of AGN

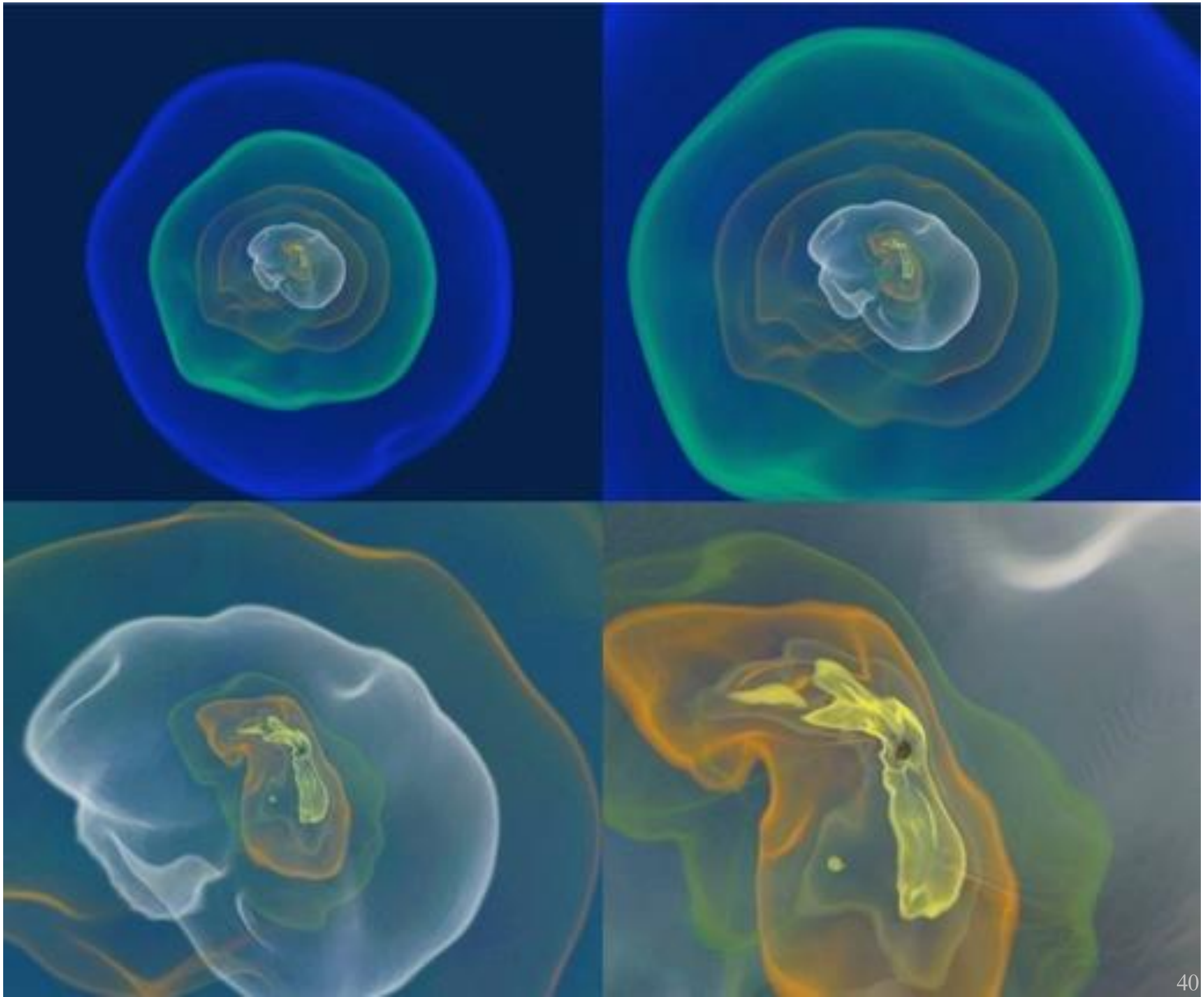


- Explosions of massive Pop III stars can produce relict BHs with $M_{\square} \sim$ few - $10^2\ M_\odot$
- Direct collapse of zero-spin mini-halos may lead to BHs with $M_{\square} \sim 10^4 - 10^6\ M_\odot$

- They can grow through rapid accretion and merging to become central engines of AGN (SMBH)
- Mergers of these early BHs may generate gravitational waves detectable by LISA



Formation of a SMBH by Direct Collapse



Numerical simulation by Wise, Turk, Abel (KIPAC)

Summary of the Key Points

- Quasars and other AGN (including the obscured ones) give raise to the Cosmic X-ray Background
- Beamed AGN (like Blazars) account for most, but perhaps not all of the Cosmic ɣ-ray Background
- The co-moving number density of quasars increases rapidly out to $z \sim 2 - 3$, and then declines towards higher redshifts. It tracks well the history of star formation in galaxies, indicating that the same processes (dissipative mergers, AGN feedback) are involved in both
- Quasars at $z \sim 5 - 7$ have SMBHs with up to $\sim 10^{10}\ M_\odot$, with a strong early chemical enrichment. JWST now detects SMBHs with masses of $\sim 10^{6\text{-}7}\ M_\odot$ at $z > 10$. This poses the same challenges as the early galaxy assembly
- The origin of the SMBH "seeds" is still unclear: stellar BHs from Pop III stars, direct collapse … even primordial BHs?
- Binary QSOs/SMBHs support their hierarchical assembly