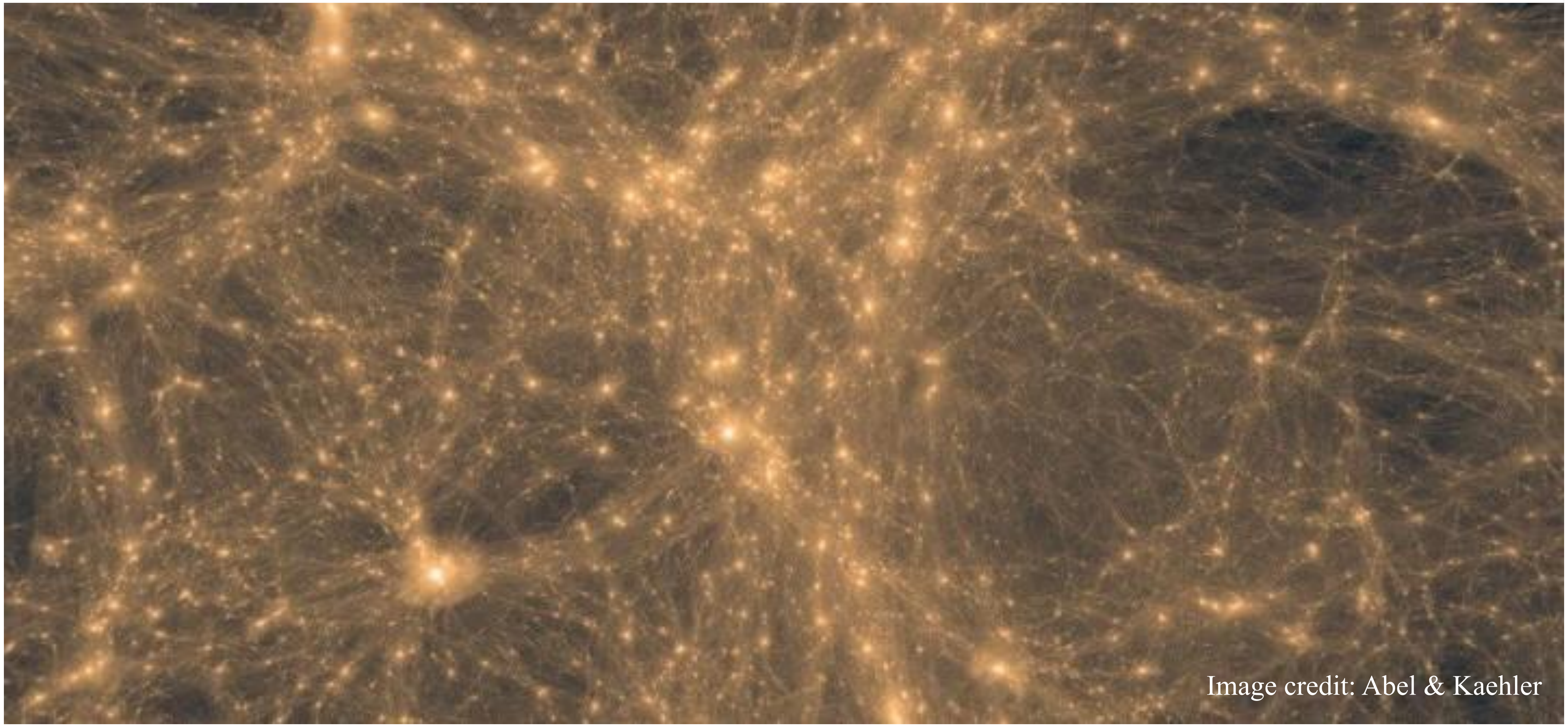
# The Intergalactic Medium

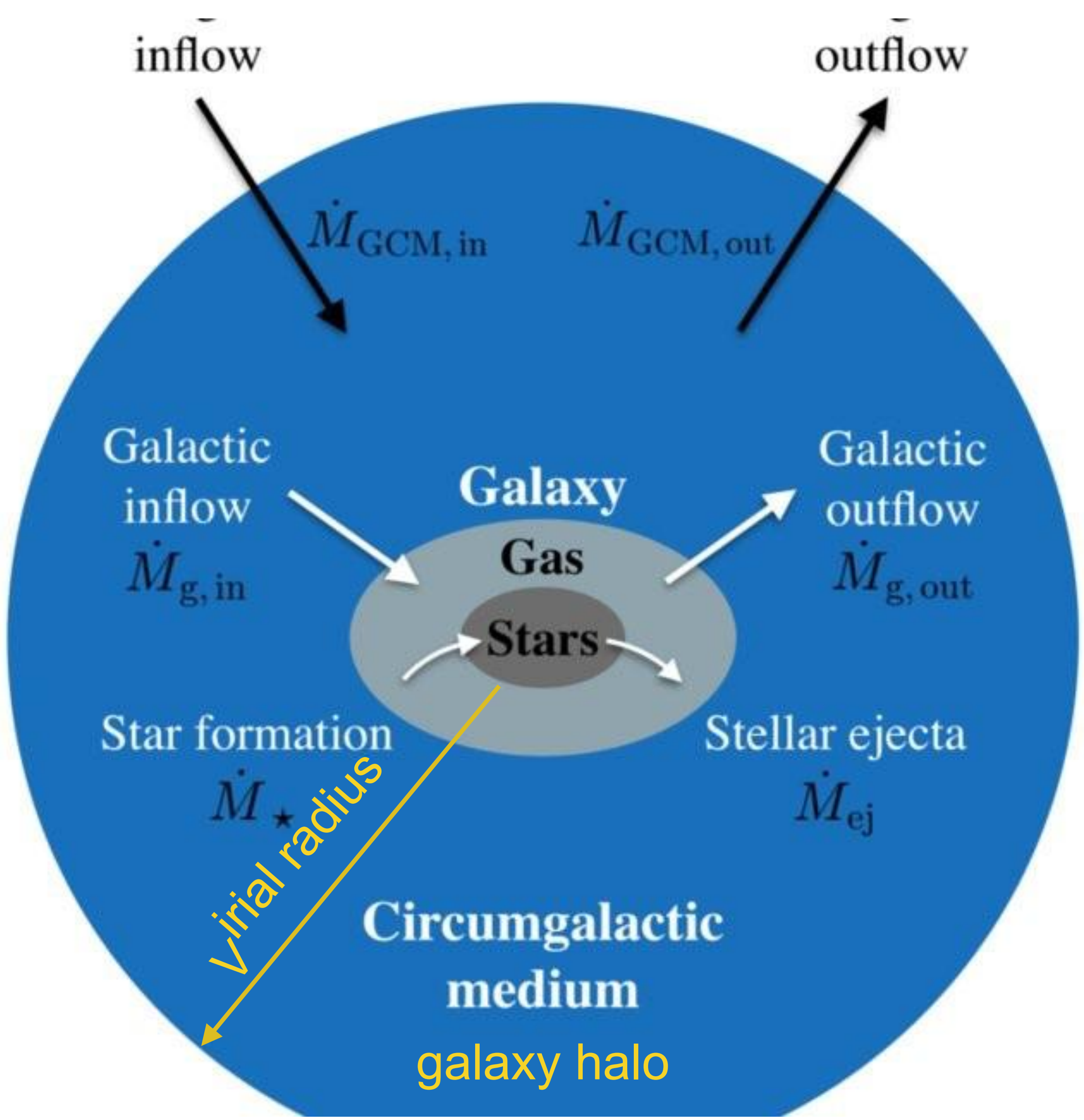
*Formation and Evolution of Galaxies 2023-2024 Q1*

*Rijksuniversiteit Groningen*

# Intergalactic Medium (IGM)

- Essentially, baryons between galaxies
- Its density evolution follows the LSS formation, and the potential wells defined by the DM, forming a web of filaments, the so-called **″Cosmic Web″**






**Intergalactic Medium**

↓

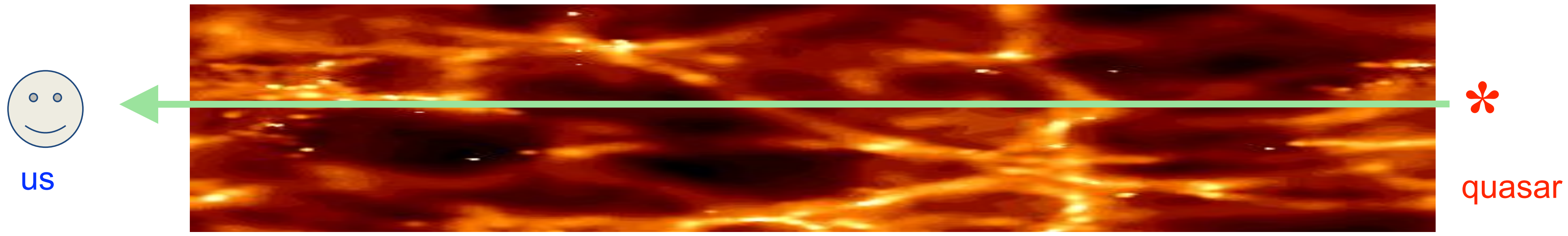
**low density gas making baryonic cosmic web**

Picture based on Coté et al.

# Some general considerations

- Essentially, baryons between galaxies
- Its density evolution follows the LSS formation, and the potential wells defined by the DM, forming a web of filaments, the so - called ″**Cosmic Web**″
- An important distinction is that this gas unaffiliated with galaxies samples the low-density regions, which are still in a linear regime
- Gas falls into galaxies, where it serves as a replenishment fuel for star formation
- Likewise, enriched gas is driven from galaxies through the radiatively and SN powered **galactic winds**, which chemically enriches the IGM
- Chemical evolution of galaxies and IGM thus track each other
- Star formation and AGN provide **ionizing flux** for the IGM

How do you think we can study the properties of this low-density gas between galaxies?

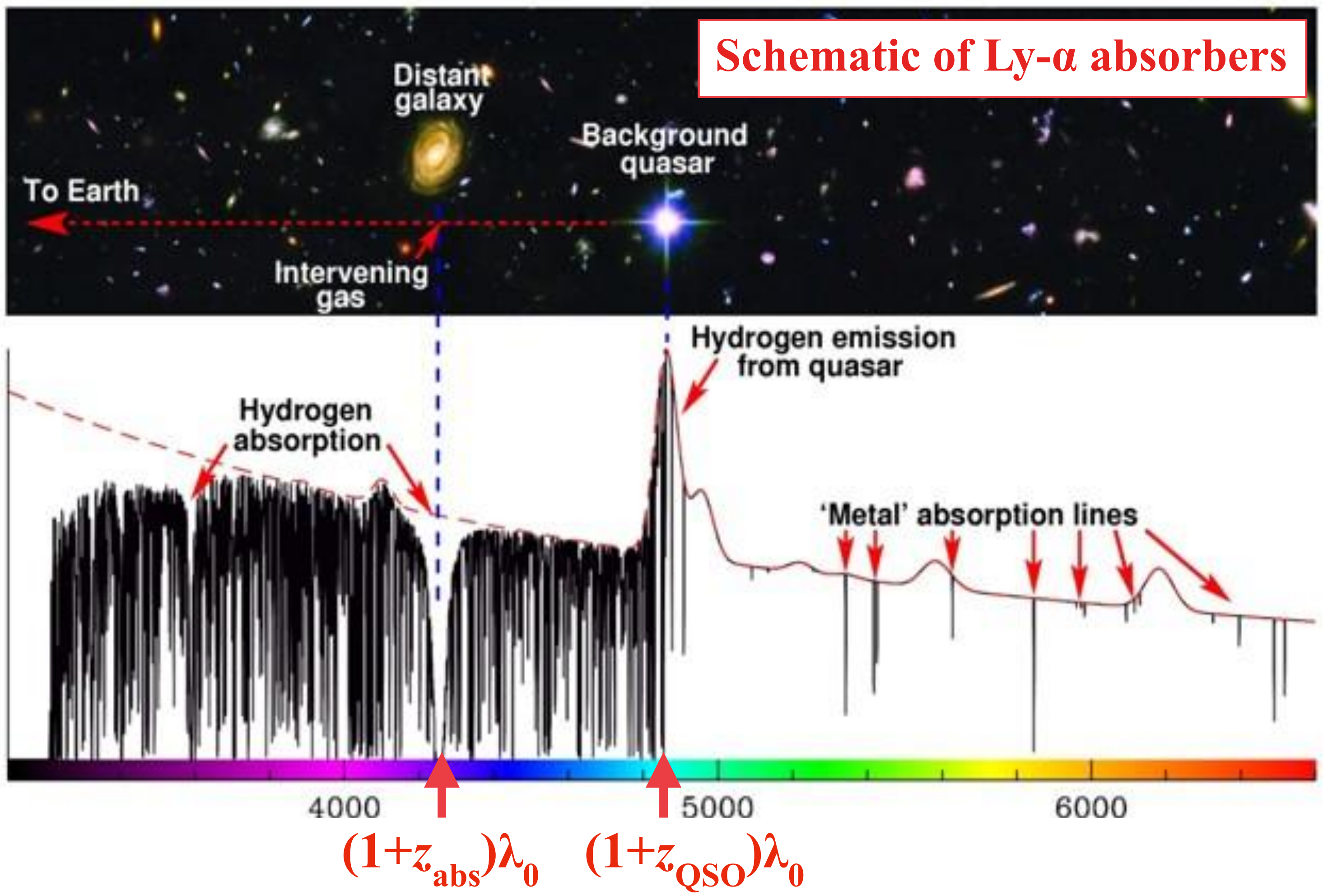



through absorption lines ...

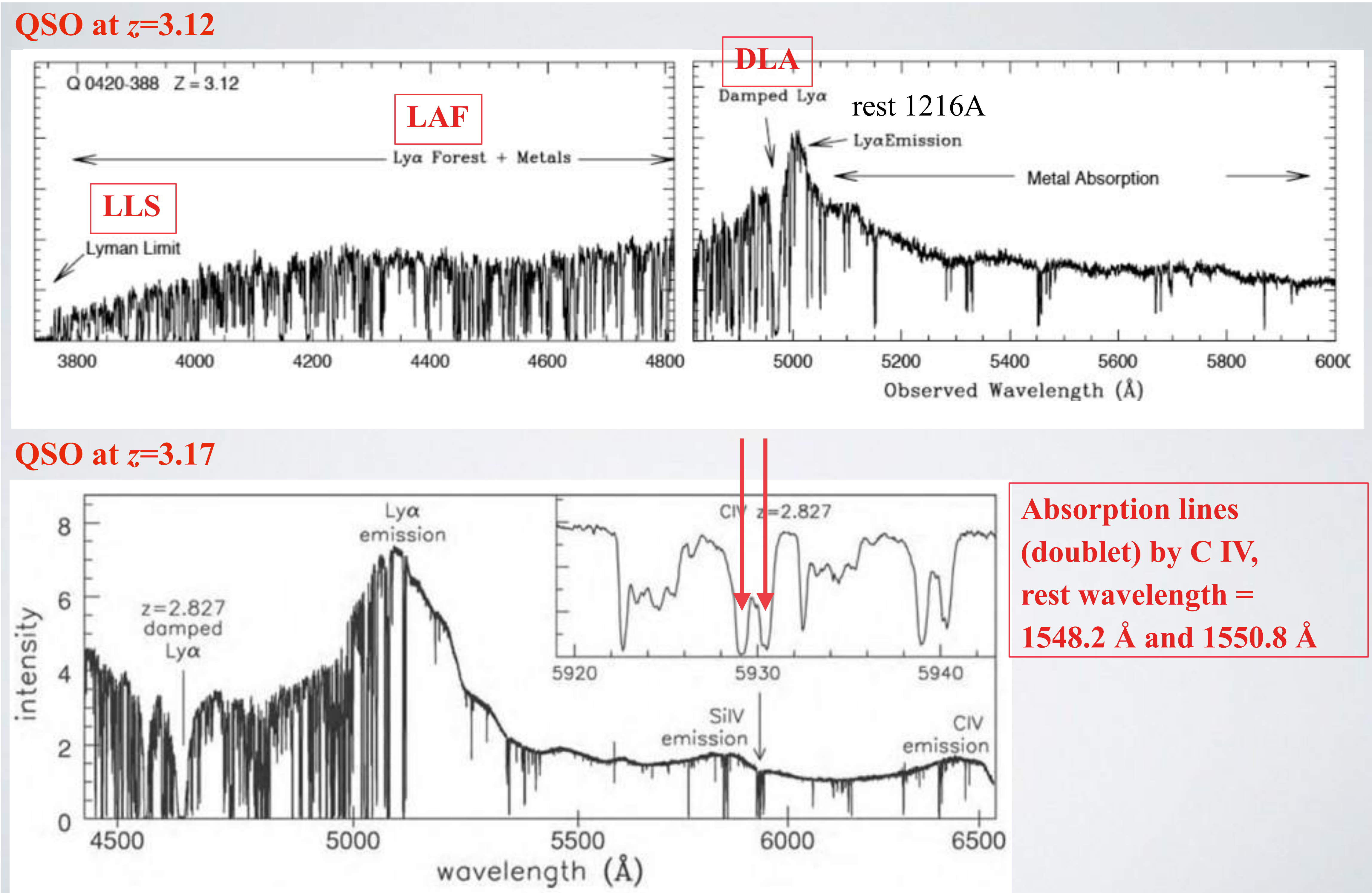
# QSO absorption lines

- An alternative to searching for galaxies by their ***emission*** properties is to search for them by their ***absorption***
- Quasars are very luminous objects and have very blue colours which make them relatively easy to detect at high redshifts

- Note that this has ***different selection effects*** than the traditional imaging surveys: not by luminosity or surface brightness, but by the cross section (size) and column density

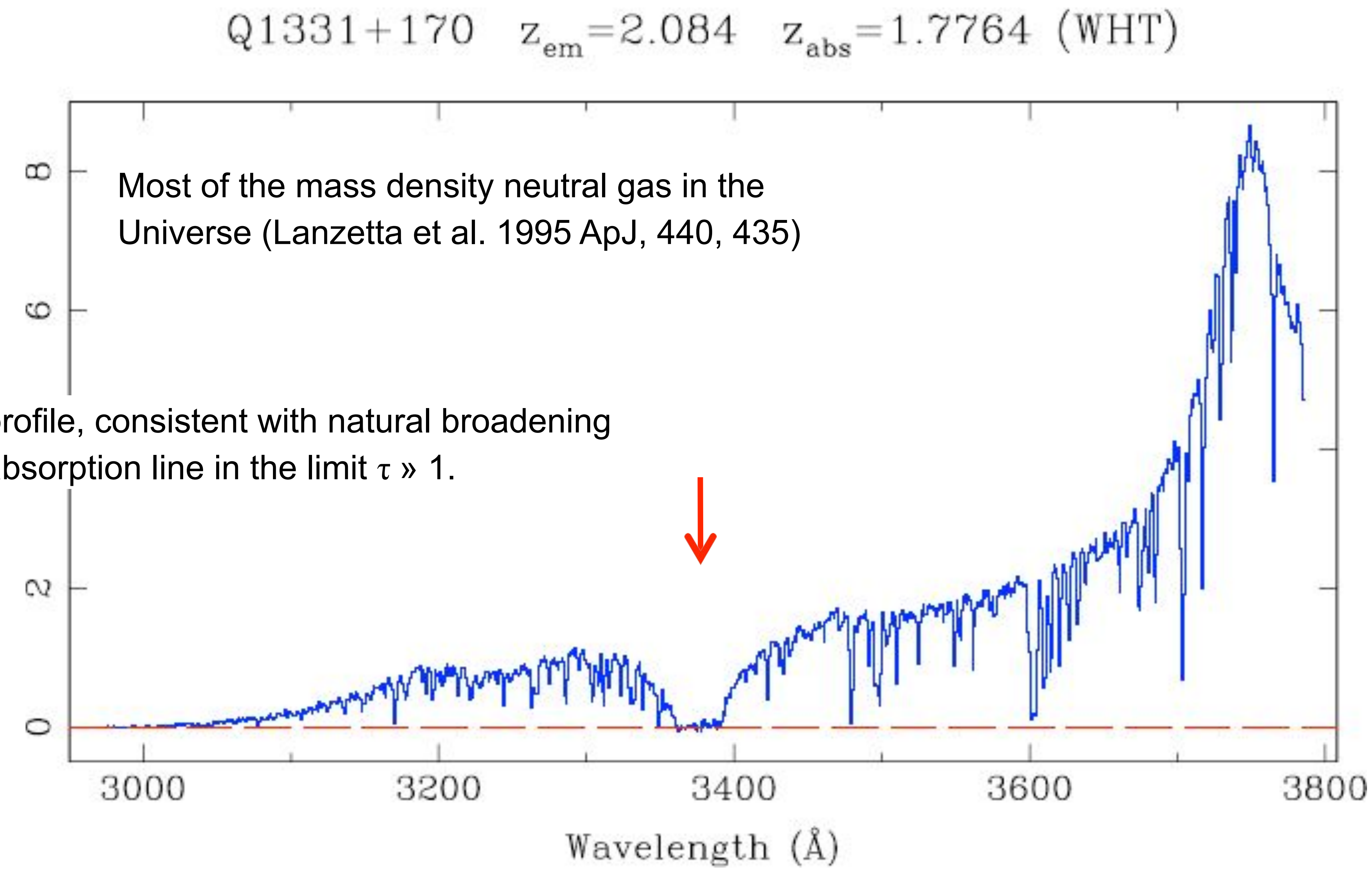


# Lyman-α forest and damped Ly-α absorbers (DLAs)



# Damped Lyman-α absorbers (DLAs)

Most of the mass density neutral gas in the Universe (Lanzetta et al. 1995 ApJ, 440, 435)



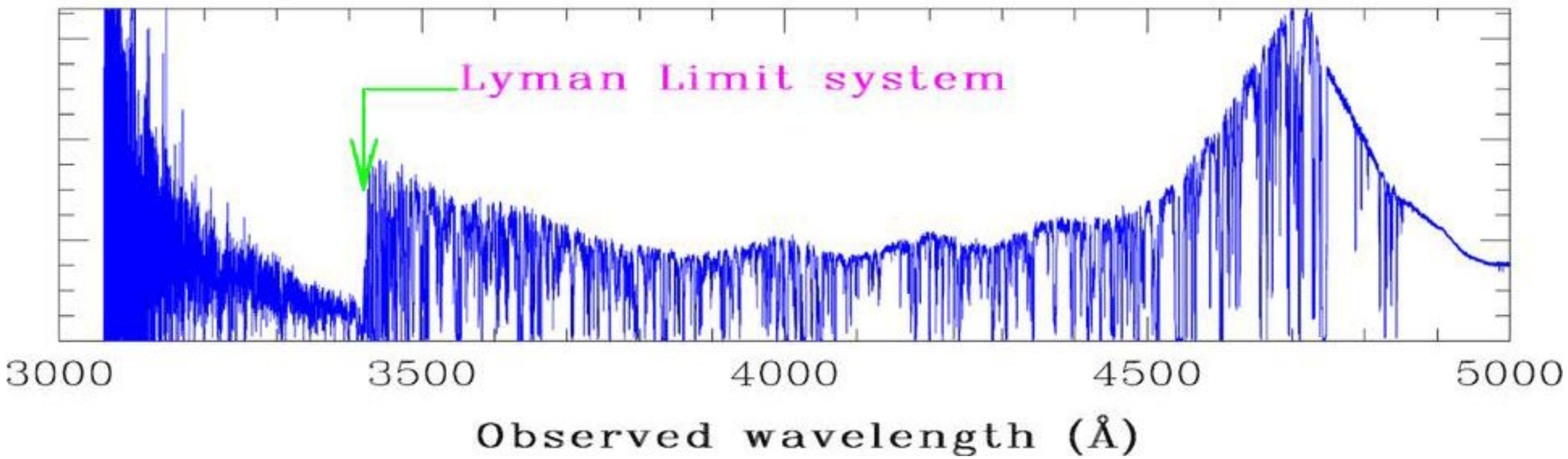

Voigt profile, consistent with natural broadening of an absorption line in the limit $\tau$ » 1.

# Absorption lines in QSO spectra

- Lyman alpha forest:
  - Numerous, weak lines from low-density hydrogen clouds
  - Lyman alpha clouds are proto-galactic clouds, with low density, they are not galaxies (but some may be proto-dwarfs)
- Lyman Limit Systems (LLS) and ″Damped″ Lyman alpha (DLA) absorption lines:
  - Rare, strong hydrogen absorption, high column densities
  - Coming from intervening galaxies
  - An intervening galaxies often produce both metal and damped Lyman alpha absorptions
- Helium equivalents are seen in the far UV part of the spectrum
- ″Metal″ absorption lines
  - Absorption lines from heavy elements, e.g., C, Si, Mg, Al, Fe
  - Most are from intervening galaxies

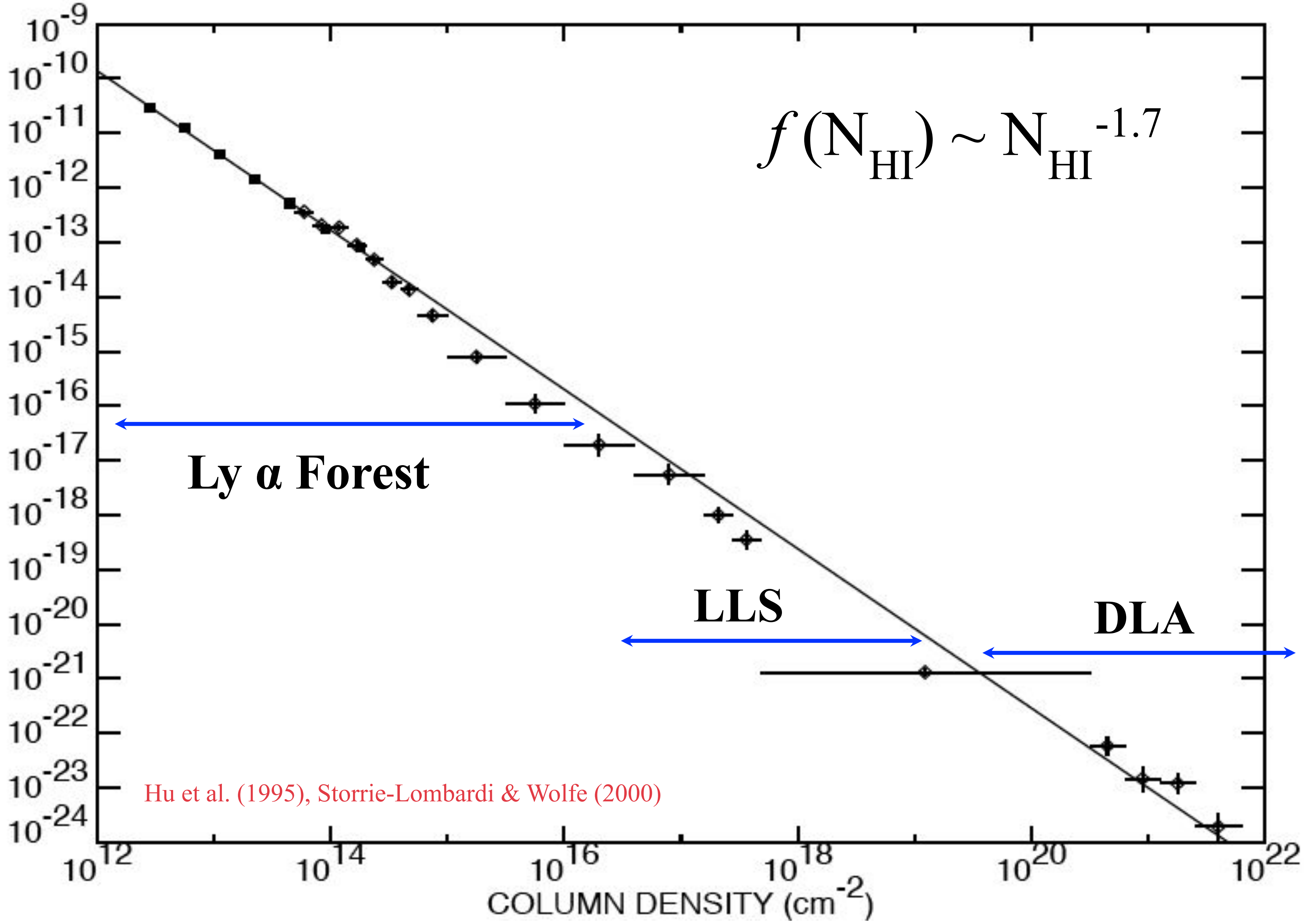
elements heavier than He produced by nuclear burning in stellar cores

# Lyman-limit systems (LLSs)

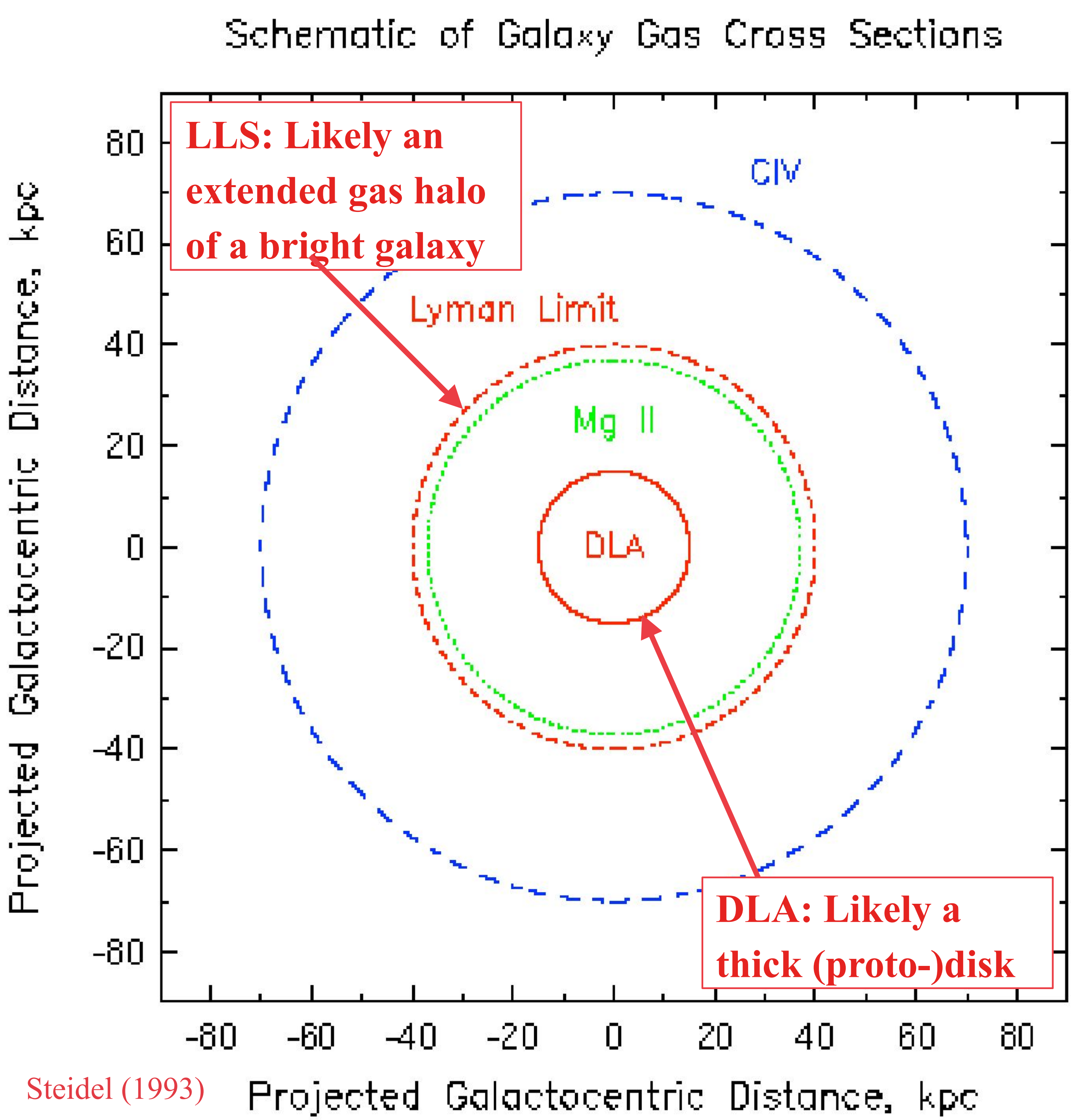



LLS, N(HI) > $10^{17}$ $cm^{-2}$. This is sufficient column density to absorb all ionising photons shortward of the lyman limit (912 Å) in the rest frame (like UV-dropout for Lyman break galaxies). They are associated with strong metal absorption lines and are believed to arise in the halos of galaxies.

# Column density distribution



# Absorber cross sections

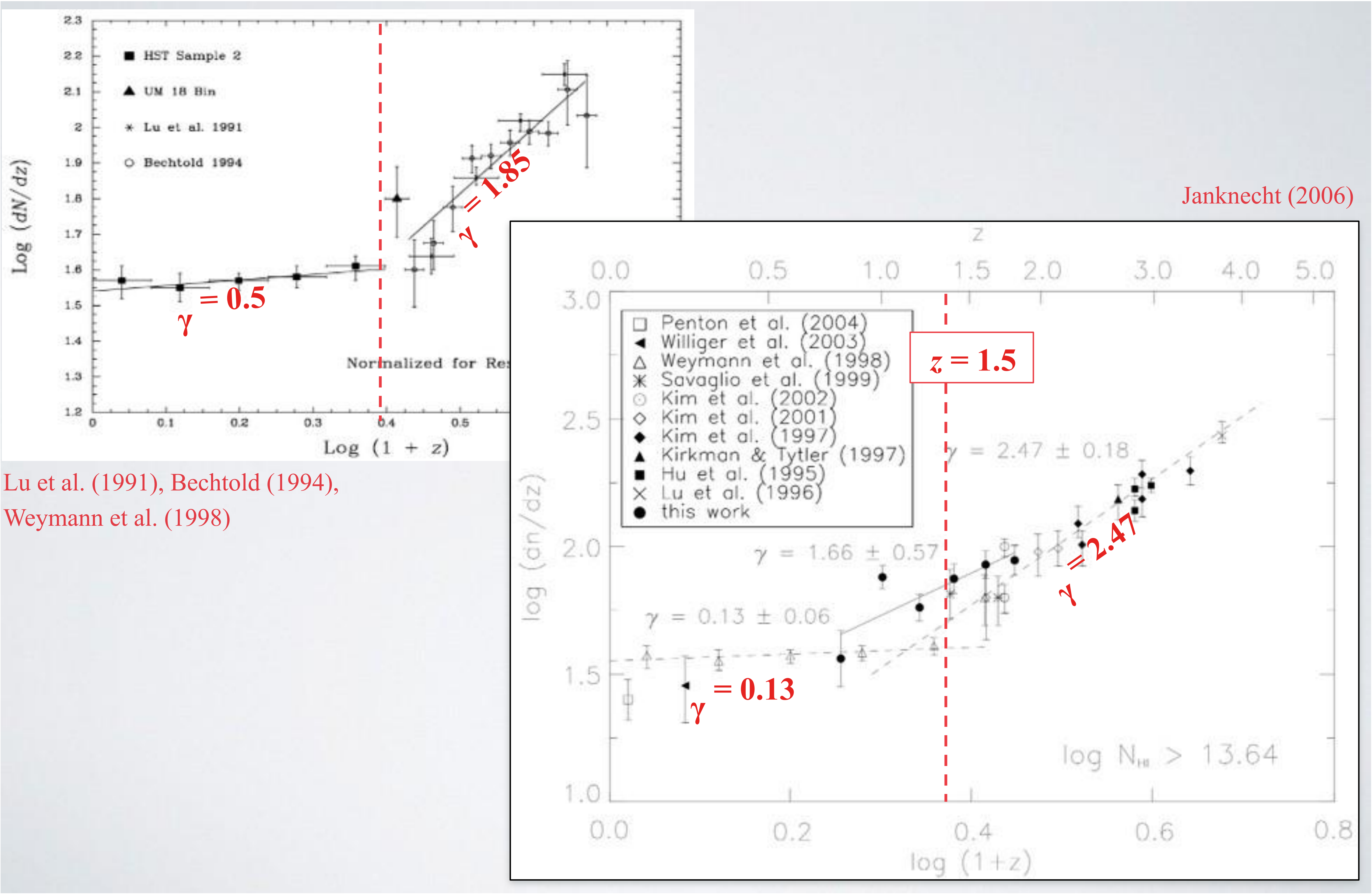



Steidel (1993)

Column density of neutral H is higher at smaller radii, so LLS and DLA absorbers are rare

Metals are ejected out to galactic coronae, and their column densities and ionization states depend on the radius

# Number density evolution of Ly-α absorbers




Lu et al. (1991), Bechtold (1994),
Weymann et al. (1998)

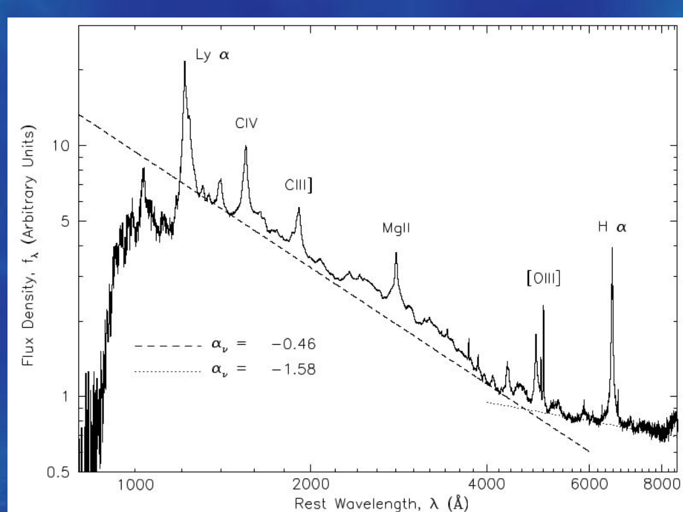
# AGN in Galaxy Evolution

*based on Lecture by Maxime Trebitsch.*

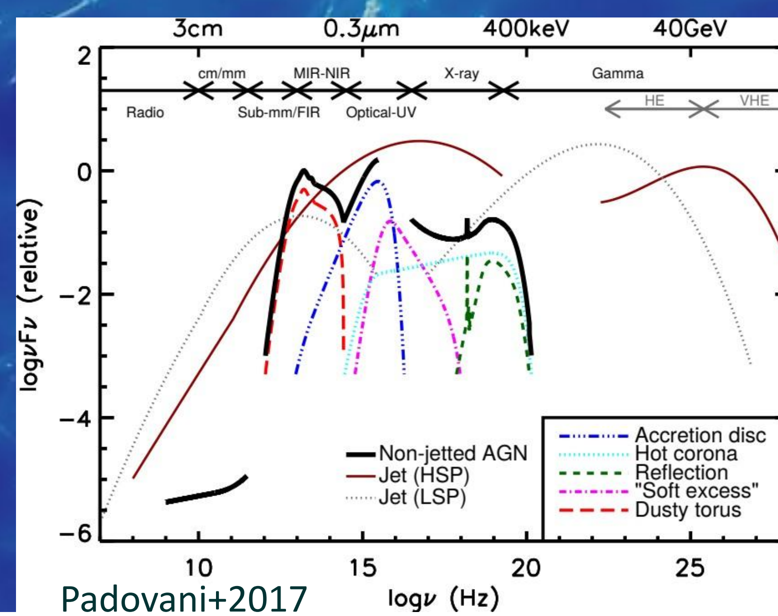
# AGN: Quasars

- Initially detected as "optical counterparts" of radio galaxies (Schmidt 1963)
- Extremely bright: can reach L~$10^{48}$ erg/s, and $M_{AB}$ ~ -30
- Present both broad (type 1) and narrow (type 2) emission lines, can be Radio-Loud or Radio-Quiet
- Emission across the whole EM spectrum
- Found at z ~ 0 ⟶ 7.5 (so far)

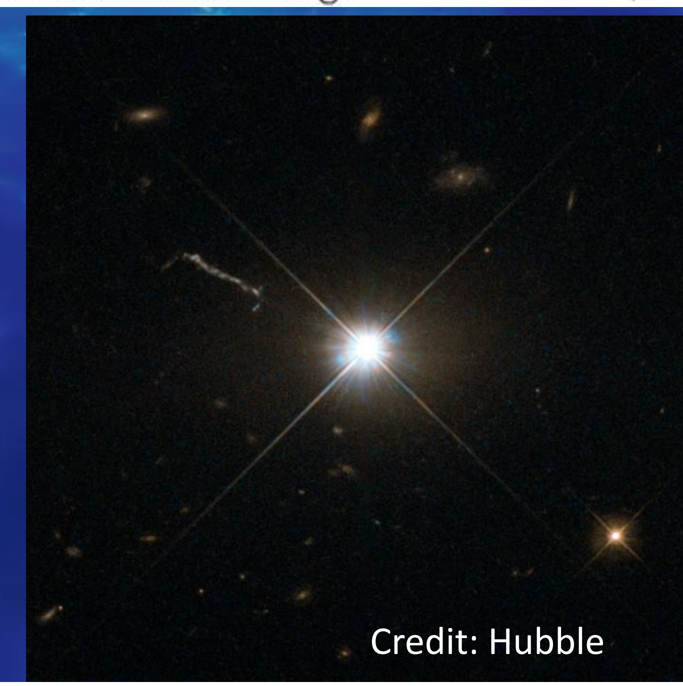
(2) The stellar object is the nuclear region of a galaxy with a cosmological red-shift of 0·158, corresponding to an apparent velocity of 47,400 km/sec. The distance would be around 500 megaparsecs, and the diameter of the nuclear region would have to be less than 1 kiloparsec. This nuclear region would be about 100 times brighter optically than the luminous galaxies which have been identified with radio sources thus far. If the optical jet and component $A$ of the radio source are associated with the galaxy, they would be at a distance of 50 kiloparsecs, implying a time-scale in excess of $10^5$ years. The total energy radiated in the optical range at constant luminosity would be of the order of $10^{59}$ ergs.



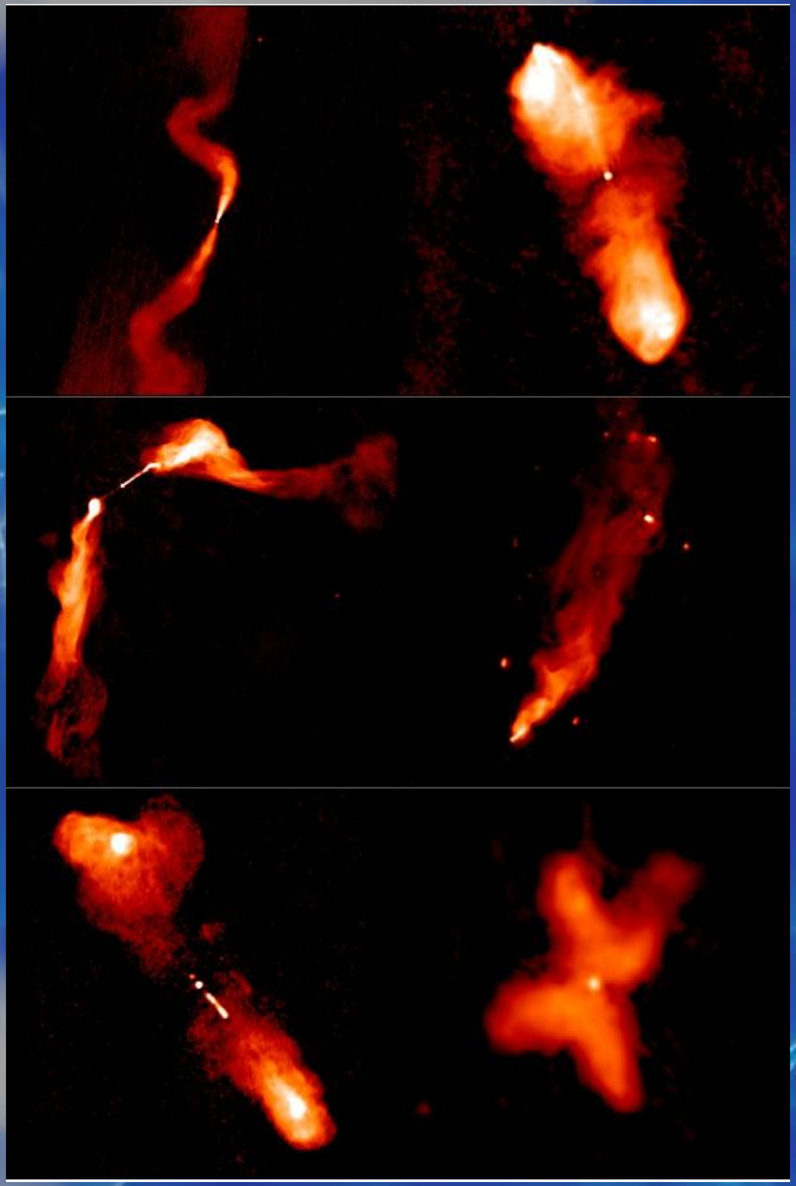
Vanden Berg+2001



Padovani+2017


Credit: Hubble

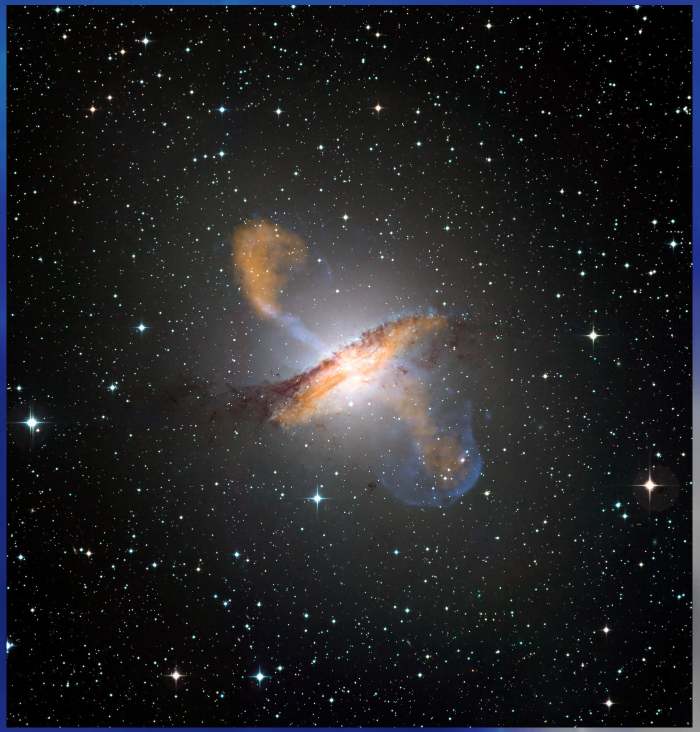
# AGN: Radio galaxies



- Large jets/lobes detected in radio (up to several Mpc)
- Diversity of morphologies
- Usually associated with large elliptical galaxies (in the nearby universe)
- Radiation seen from synchrotron emission:
  - strong B 'eld in the jet
  - electrons are accelerated

    → radiation
- Signatures also in X-rays (later)

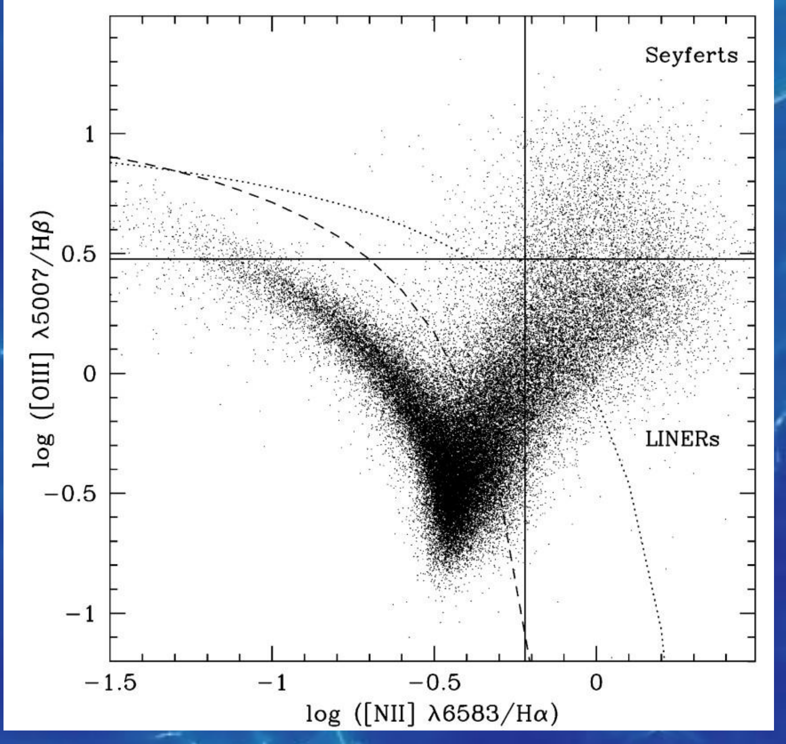
Hardcastle+2020



Centaurus A, credit: ESO

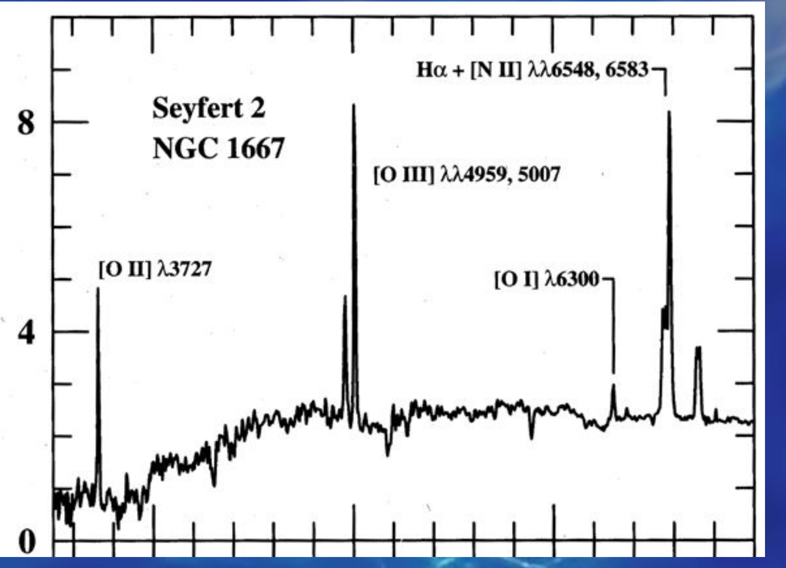
# AGN: Seyfert galaxies

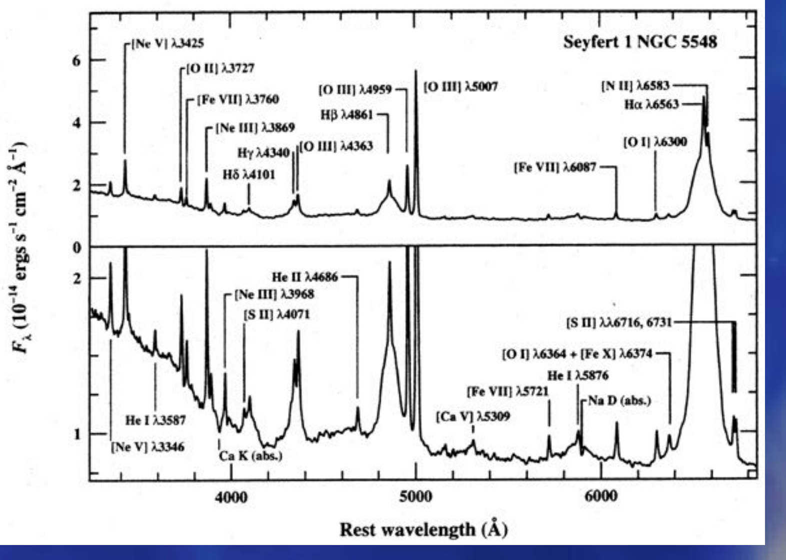
- Emission lines can be
  - Broad: “Type 1”
  - Narrow: “Type 2”
- Line ratios inconsistent with stellar populations




Kauffmann+2003

Adapted from Peterson+1997



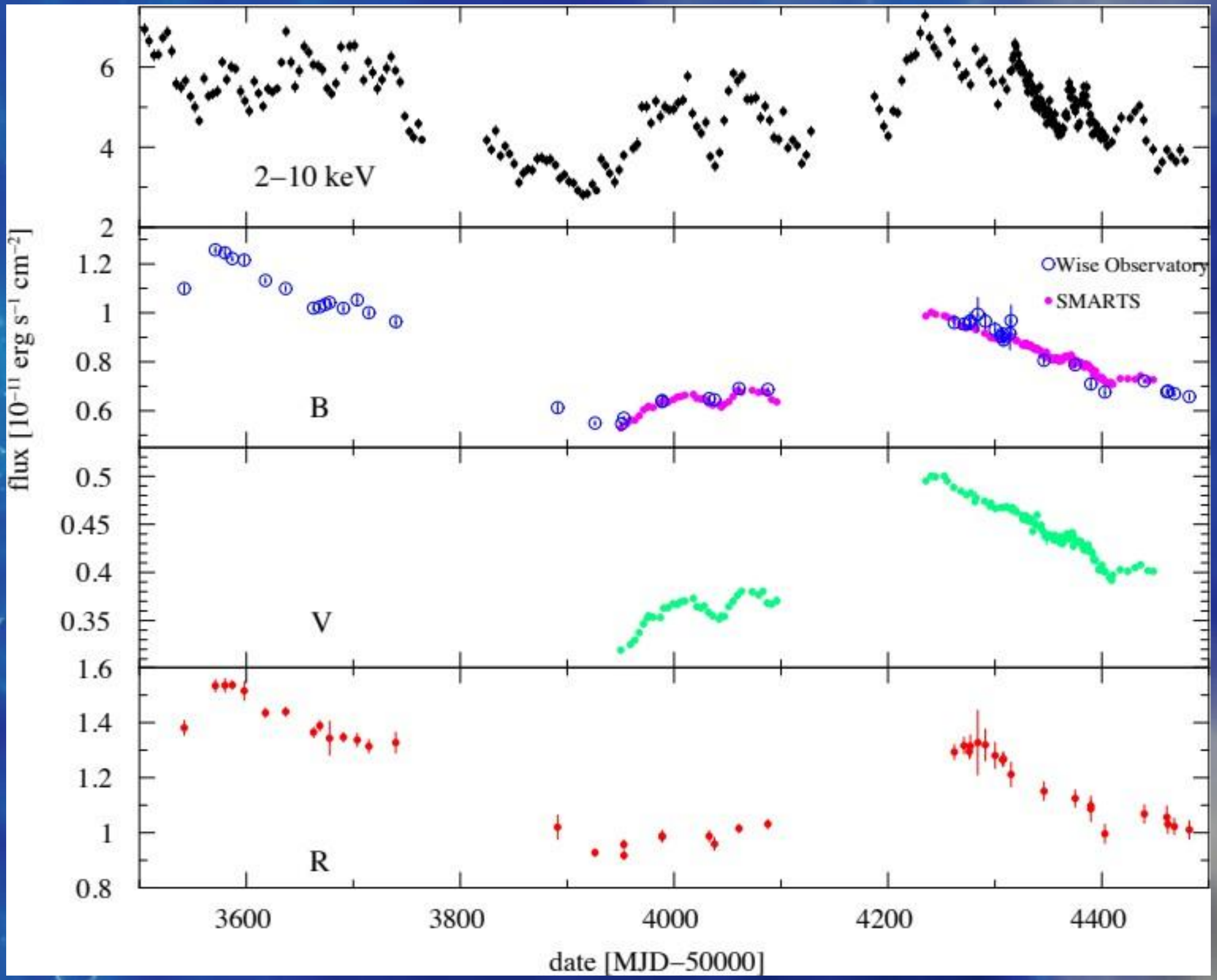
# AGN: Variability

- AGN luminosity varies at all wavelength
- Timescales: hours, days, weeks

  ⟶ related to the size of the emission region!

- Size ~ c $\Delta t_{variability}$
  - $\Delta t_{variability}$ ~ 1h ⟶ size ~ $10^{-5}$ pc
  - $\Delta t_{variability}$ ~ 10 days ⟶ size ~ 0.01 pc

- Very compact emission, but multiple components




Arévalo+2008

# AGN: Zoology and classification

Active galactic nuclei: what's in a name? Page 5 of 91 2

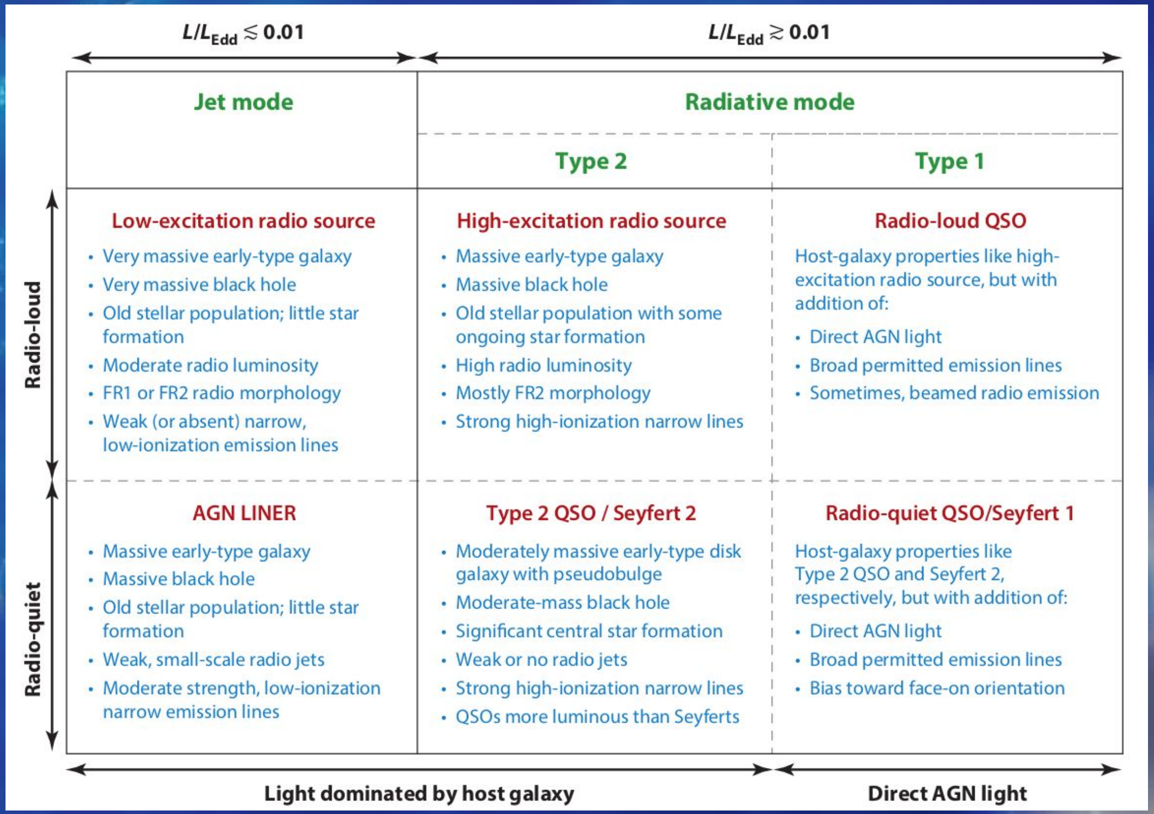
**Table 1** The AGN zoo: list of AGN classes

| Class/Acronym | Meaning | Main properties/reference |
|---|---|---|
| Quasar | Quasi-stellar radio source (originally) | Radio detection no longer required |
| Sey1 | Seyfert 1 | FWHM $\gtrsim 1,000$ km s$^{-1}$ |
| Sey2 | Seyfert 2 | FWHM $\lesssim 1,000$ km s$^{-1}$ |
| QSO | Quasi-stellar object | Quasar-like, non-radio source |
| QSO2 | Quasi-stellar object 2 | High power Sey2 |
| RQ AGN | Radio-quiet AGN | see ref. 1 |
| RL AGN | Radio-loud AGN | see ref. 1 |
| Jetted AGN | | with strong relativistic jets; see ref. 1 |
| Non-jetted AGN | | without strong relativistic jets; see ref. 1 |
| Type 1 | | Sey1 and quasars |
| Type 2 | | Sey2 and QSO2 |
| FR I | Fanaroff-Riley class I radio source | radio core-brightened (ref. 2) |
| FR II | Fanaroff-Riley class II radio source | radio edge-brightened (ref. 2) |
| BL Lac | BL Lacertae object | see ref. 3 |
| Blazar | BL Lac and quasar | BL Lacs and FSRQs |
| BAL | Broad absorption line (quasar) | ref. 4 |
| BLO | Broad-line object | FWHM $\gtrsim 1,000$ km s$^{-1}$ |
| BLAGN | Broad-line AGN | FWHM $\gtrsim 1,000$ km s$^{-1}$ |
| BLRG | Broad-line radio galaxy | RL Sey1 |
| CDQ | Core-dominated quasar | RL AGN, $f_{core} \geq f_{ext}$ (same as FSRQ) |
| CSS | Compact steep spectrum radio source | core dominated, $\alpha_r > 0.5$ |
| CT | Compton-thick | $N_H \geq 1.5 \times 10^{24}$ cm$^{-2}$ |
| FR 0 | Fanaroff-Riley class 0 radio source | ref. 5 |
| FSRQ | Flat-spectrum radio quasar | RL AGN, $\alpha_r \leq 0.5$ |
| GPS | Gigahertz-peaked radio source | see ref. 6 |
| HBL/HSP | High-energy cutoff BL Lac/blazar | $\nu_{synch\ peak} \geq 10^{15}$ Hz (ref. 7) |
| HEG | High-excitation galaxy | ref. 8 |
| HPQ | High polarization quasar | $P_{opt} \geq 3\%$ (same as FSRQ) |
| Jet-mode | | $L_{kin} \gg L_{rad}$ (same as LERG); see ref. 9 |
| IBL/ISP | Intermediate-energy cutoff BL Lac/blazar | $10^{14} \leq \nu_{synch\ peak} \leq 10^{15}$ Hz (ref. 7) |
| LINER | Low-ionization nuclear emission-line regions | see ref. 9 |
| LLAGN | Low-luminosity AGN | see ref. 10 |
| LBL/LSP | Low-energy cutoff BL Lac/blazar | $\nu_{synch\ peak} < 10^{14}$ Hz (ref. 7) |
| LDQ | Lobe-dominated quasar | RL AGN, $f_{core} < f_{ext}$ |
| LEG | Low-excitation galaxy | ref. 8 |
| LPQ | Low polarization quasar | $P_{opt} < 3\%$ |
| NLAGN | Narrow-line AGN | FWHM $\lesssim 1,000$ km s$^{-1}$ |
| NLRG | Narrow-line radio galaxy | RL Sey2 |
| NLS1 | Narrow-line Seyfert 1 | ref. 11 |
| OVV | Optically violently variable (quasar) | (same as FSRQ) |
| Population A | | ref. 12 |
| Population B | | ref. 12 |
| Radiative-mode | | Seyferts and quasars; see ref. 9 |
| RBL | Radio-selected BL Lac | BL Lac selected in the radio band |
| Sey1.5 | Seyfert 1.5 | ref. 13 |
| Sey1.8 | Seyfert 1.8 | ref. 13 |
| Sey1.9 | Seyfert 1.9 | ref. 13 |
| SSRQ | Steep-spectrum radio quasar | RL AGN, $\alpha_r > 0.5$ |
| USS | Ultra-steep spectrum source | RL AGN, $\alpha_r > 1.0$ |
| XBL | X-ray-selected BL Lac | BL Lac selected in the X-ray band |
| XBONG | X-ray bright optically normal galaxy | AGN only in the X-ray band/weak lined AGN |

The top part of the table relates to major/classical classes. The last column describes the main properties. When these are too complex, it gives a reference to the first paper, which defined the relevant class or, when preceded by "see", a recent paper, which gives up-to-date details on it. Reference key: 1. Padovani (2017); 2. Fanaroff and Riley (1974); 3. Giommi et al. (2012); 4. Weymann et al. (1981); 5. Ghisellini (2010); 6. O'Dea et al. (1991); 7. Padovani and Giommi (1995); 8. Laing et al. (1994); 9. Heckman and Best (2014); 10. Ho (2008); 11. Osterbrock and Pogge (1985); 12. Sulentic et al. (2002); 13. Osterbrock (1981)

Padovani+2017

- Very diverse type of sources: how to get some order?
- Broadly, two criteria:
  - How bright is the nucleus?
  - Do we detect radio emission?
- But also:
  - Emission lines?
  - …




Heckman&Best 2014

# AGN: Powered by BH accretion

- We need to produce L $\gtrsim 10^{48}$ erg/s in a very small ($\lesssim$ 1 pc) region The
- source does not seem to match stellar emission

$\longrightarrow$ AGN are powered by accretion onto super-massive black holes (SMBH)

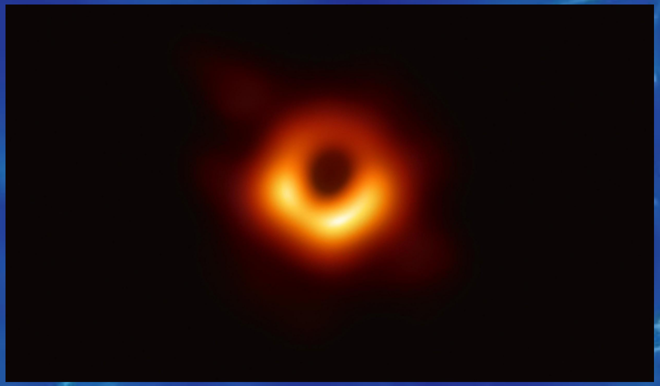
- If we can convert efficiently gravitational energy in radiation:

$$L \simeq \eta \dot{M} c^2 \simeq 0.1 \dot{M} c^2$$

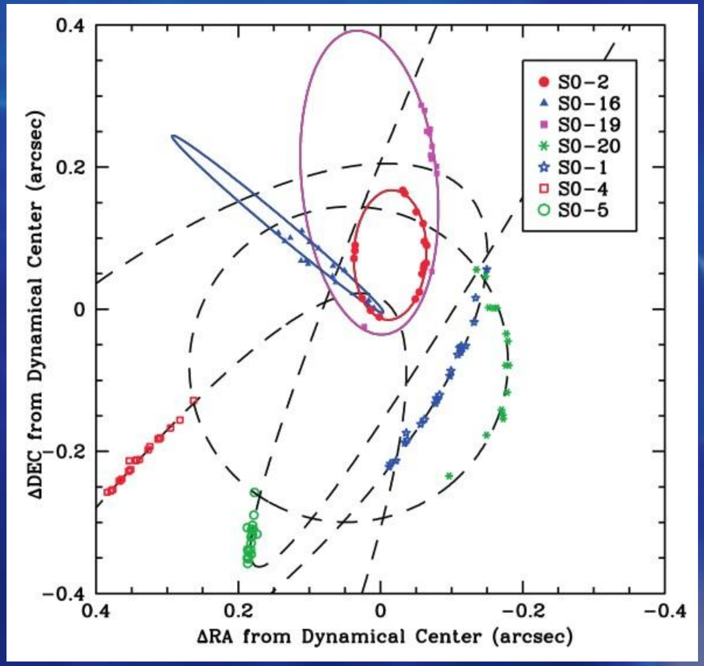
$\longrightarrow$ compared to nuclear burning:

$$L \simeq 0.007 \dot{M} c^2$$

- We have evidence for the presence of SMBH at the centre of galaxies



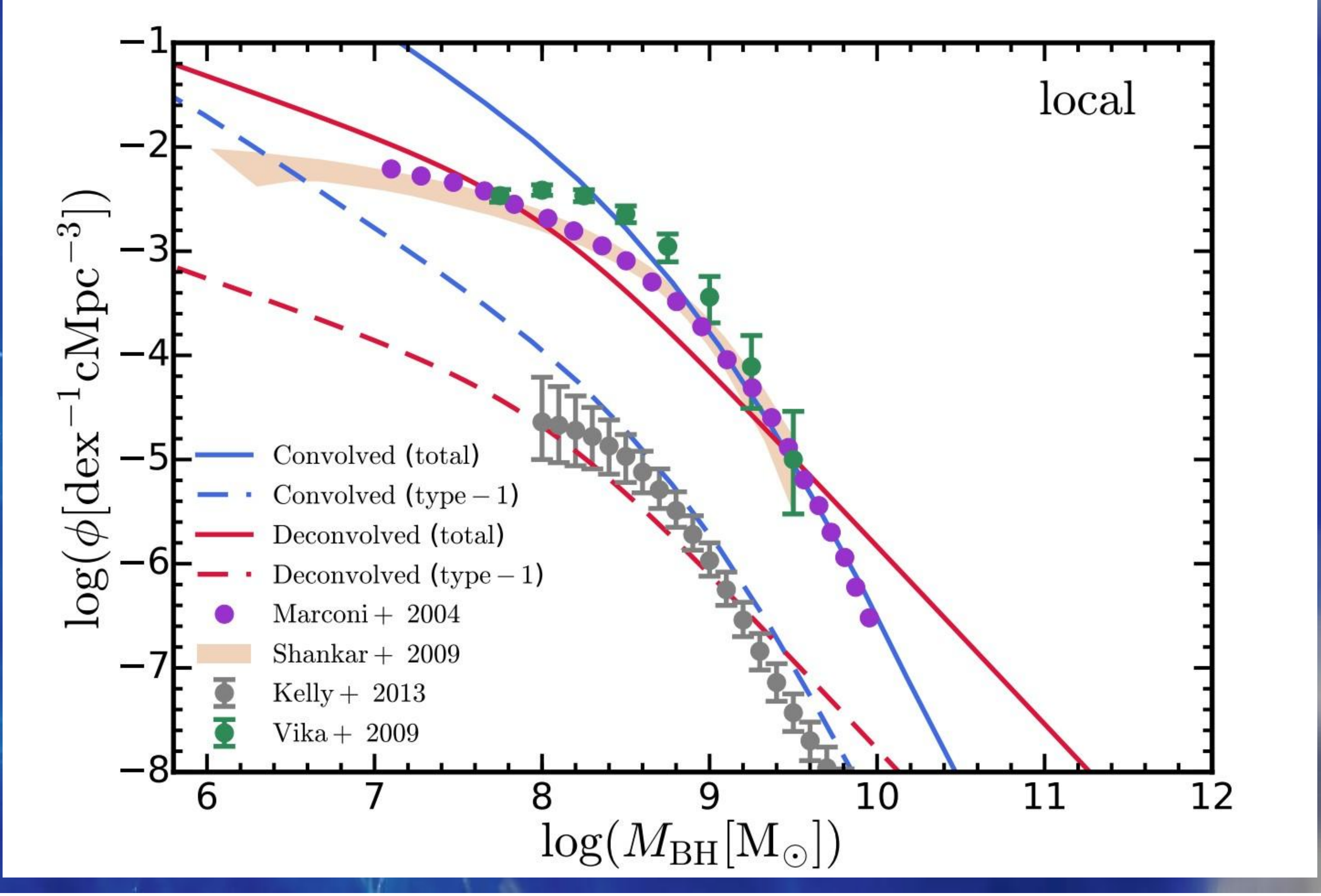
Credit: EHT




Ghez+2005

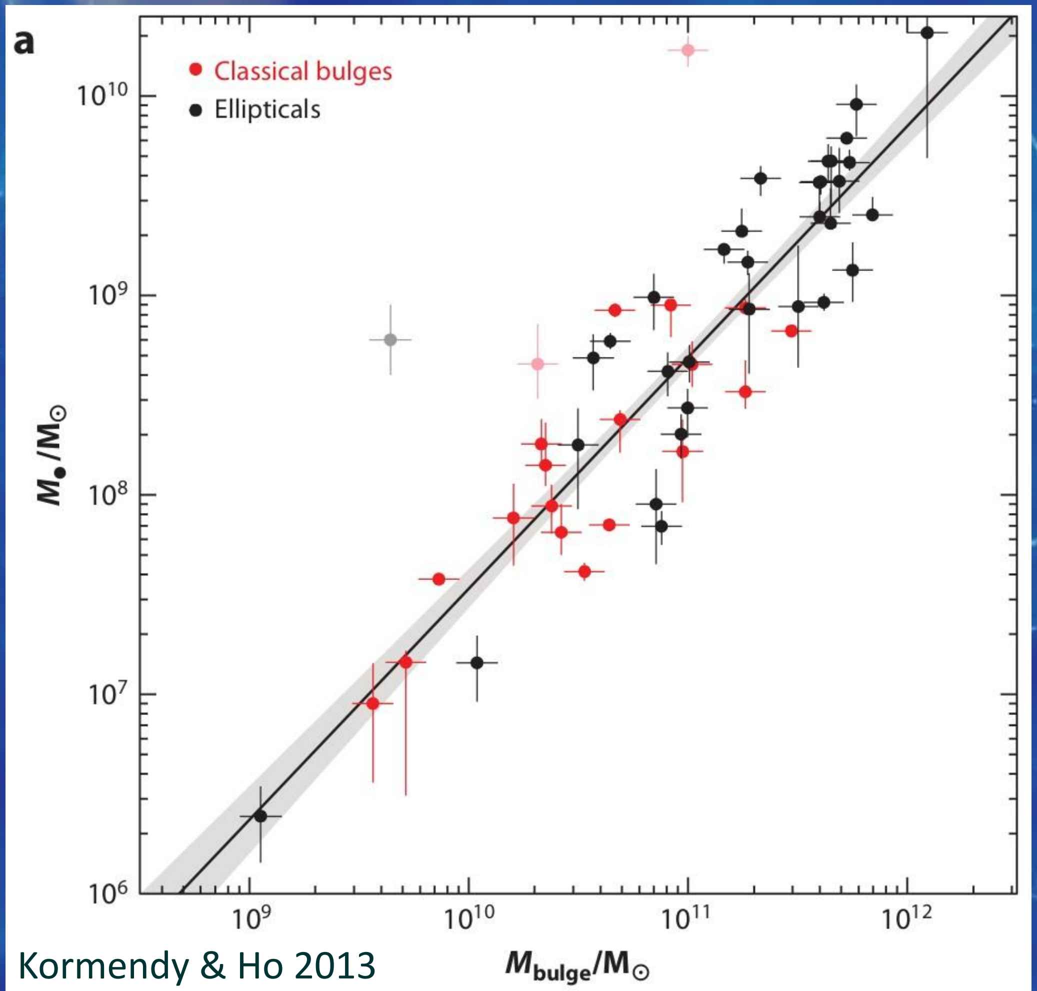
# Distribution of BH masses: the BH mass function

- Just like for galaxies, we can measure the "BH mass function"
- Careful: this really is an *active* BH mass function, since we only see the active BH (as AGN)
- The low-mass end is not well constrained (yet?)

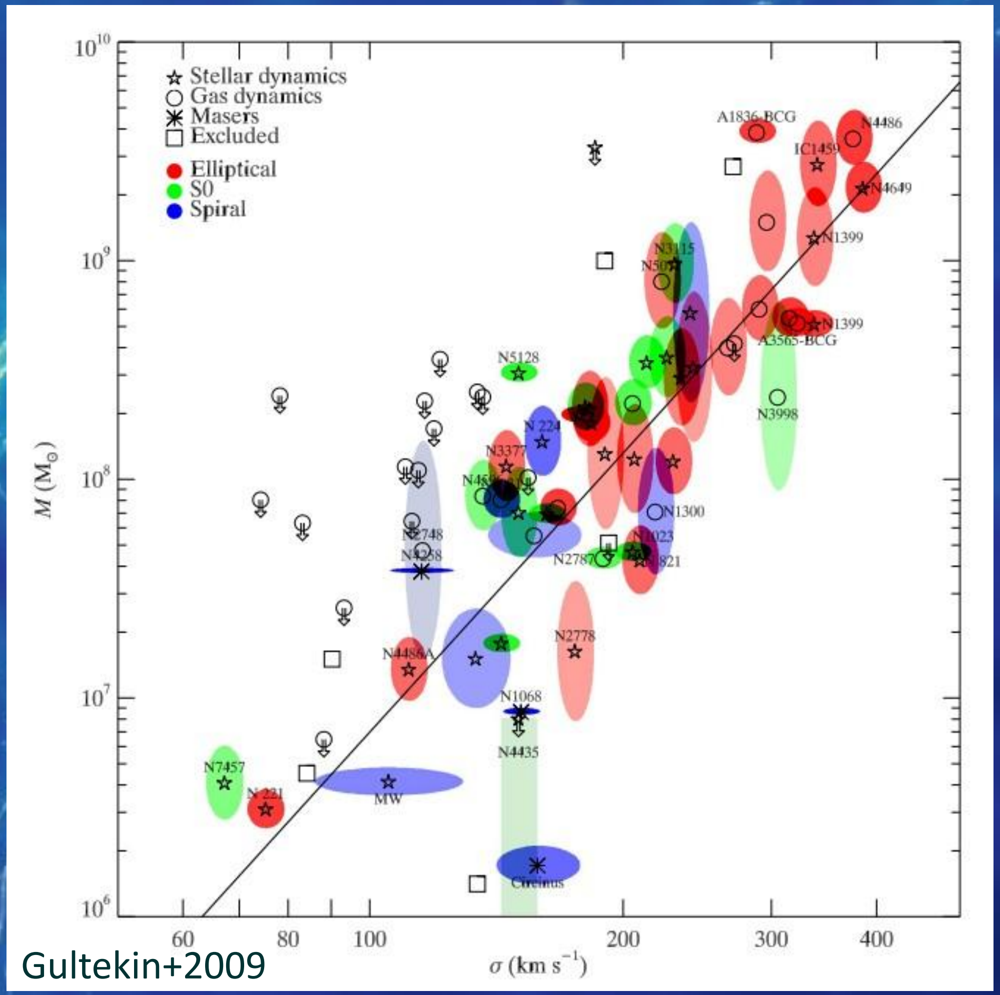


# BH in galaxies at z~0: scaling relations

- The observed masses of SMBH correlate well with the bulge mass of galaxies of all types
- The scatter is reduced if we instead consider the velocity dispersion **σ**




Kormendy & Ho 2013




Gultekin+2009

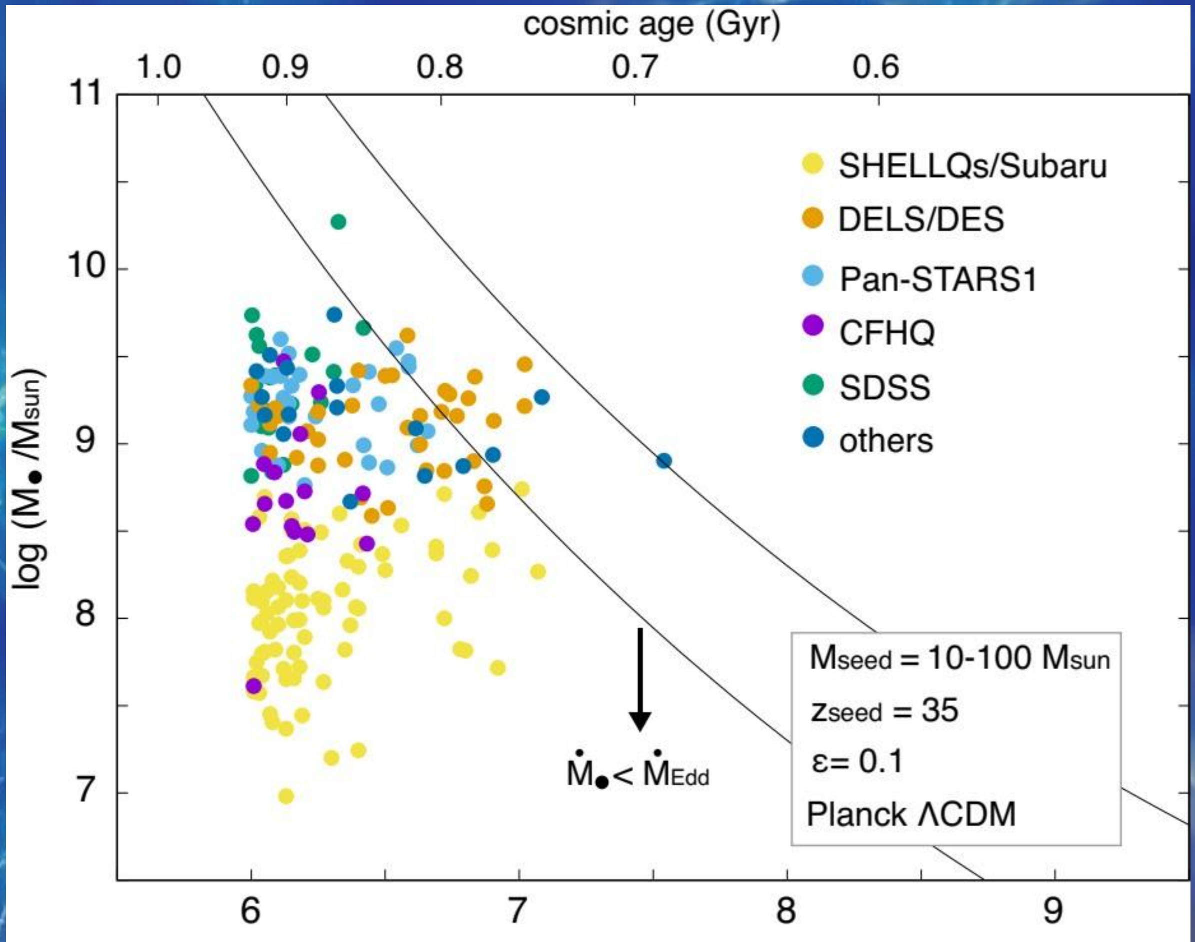
How can we explain this connection?
When is it established in cosmic history?

# SMBH and galaxies at high redshifts: quasars at z≳7

- We observe quasars out to z~7.5
- From their luminosity and spectra, we estimate the mass of their SMBH

  ⟶ up to > $10^9 M_\odot$ at z~7!
- This is comparable to the mass of the most massive SMBH at z~0

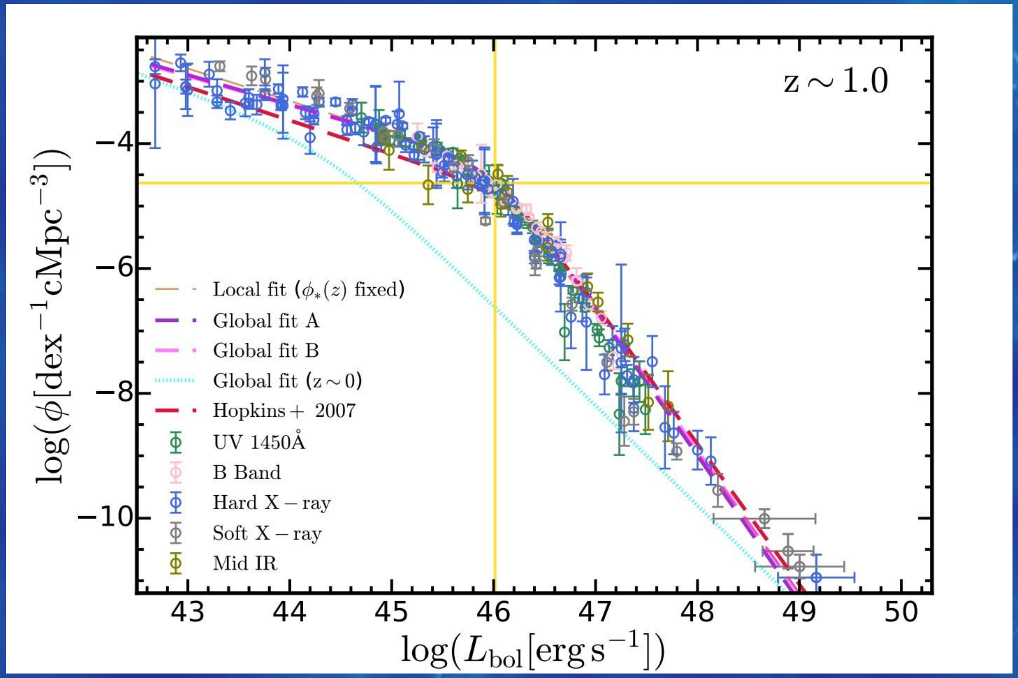
  ⟶ suggests a very efficient, very early growth

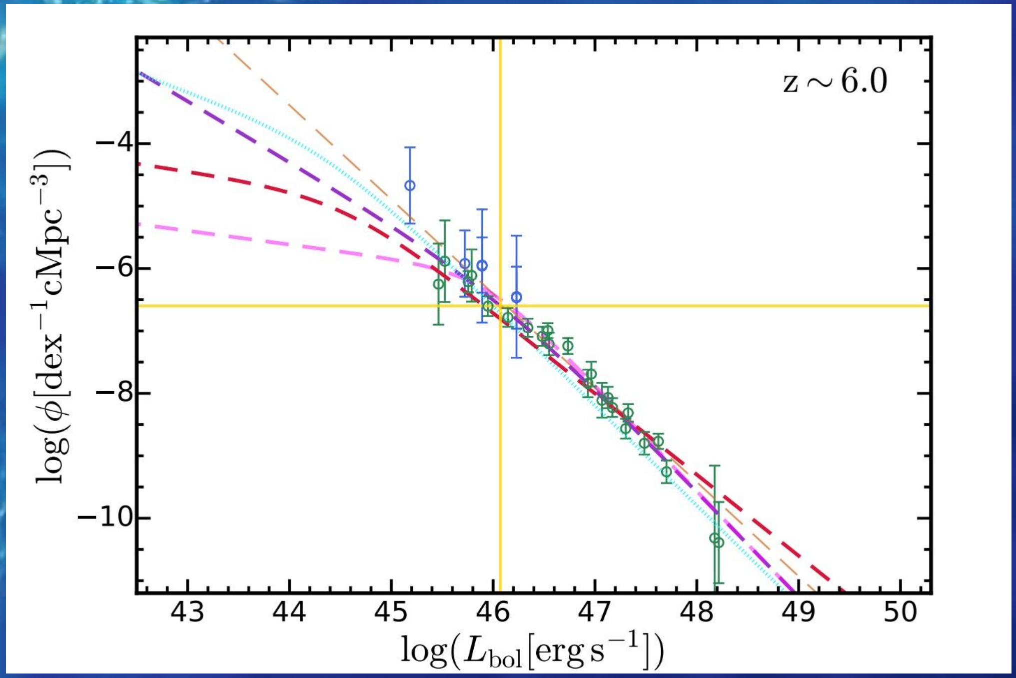


Inayoshi+2020

# SMBH and galaxies at high redshift: evolution of the AGN luminosity function

- We can count the number density of AGN at a given total luminosity → bolometric LF
- Strong evolution of the bolometric LF: AGN activity changes over time
- Already very bright quasars at z ≳ 6

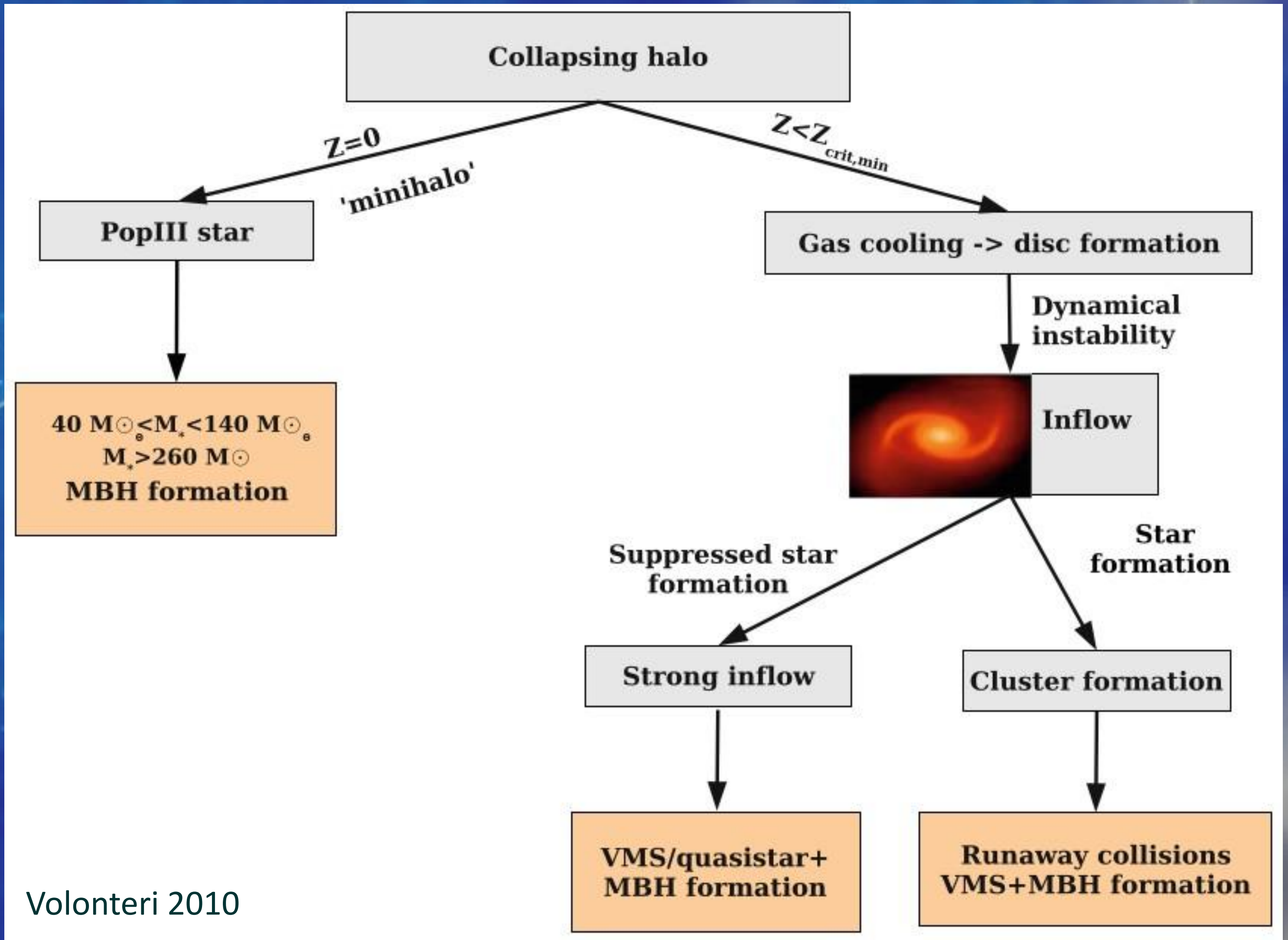



Shen+2020

# Many pathways to SMBH formation

- General scenario: very early universe, in a metal-free or very metal poor halo
- BH can form through 3 main channels
- Details depend on local gas properties (density, metallicity, radiation field, etc…)

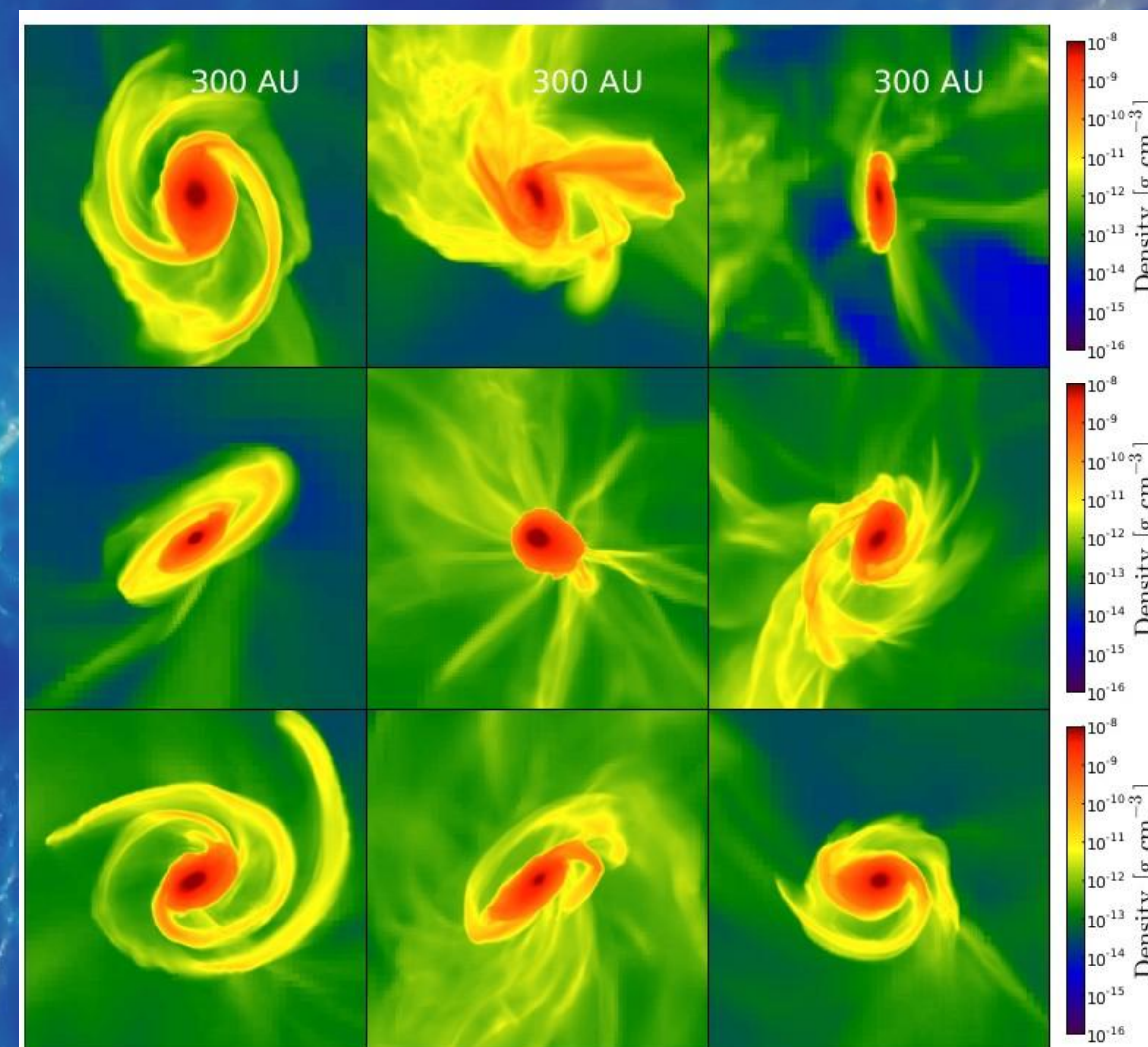



Volonteri 2010

# Gas dynamical processes

- Collapse of gas in a primordial halo
- Something* prevents $H_2$ formation
- No fragmentation ⟶ no star formation
- Formation of a SuperMassive Star
- GR instability ⟶ collapse into a BH
- Rapid growth fuelled by high accretion rate
- Formation of a massive seed $10^{4\text{-}6}\,M_\odot$

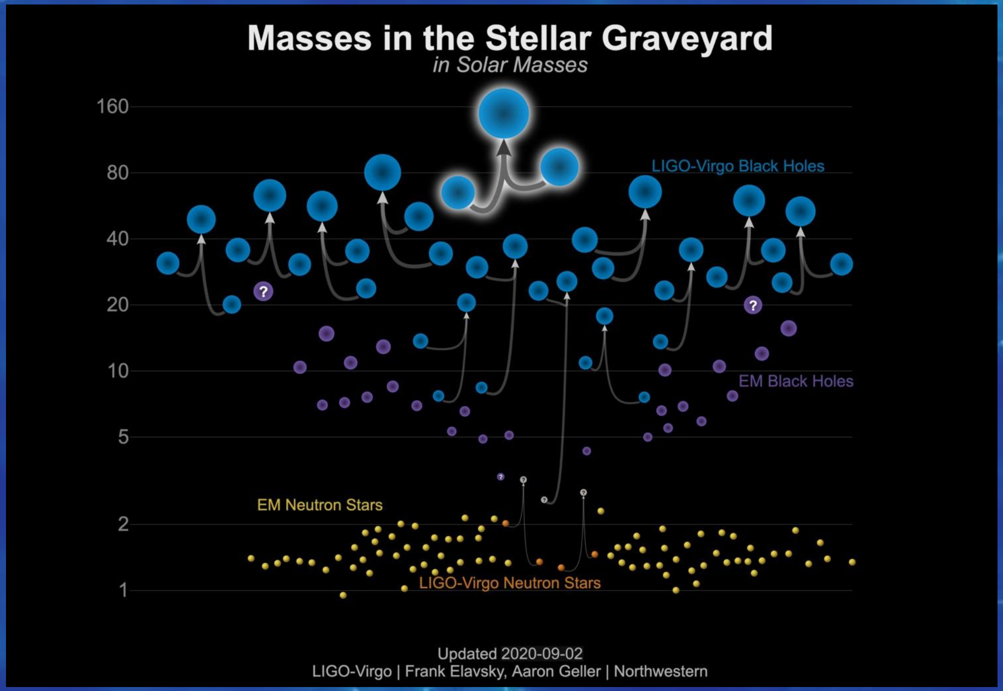
(* usually, strong radiative background, but other mechanisms are viable)

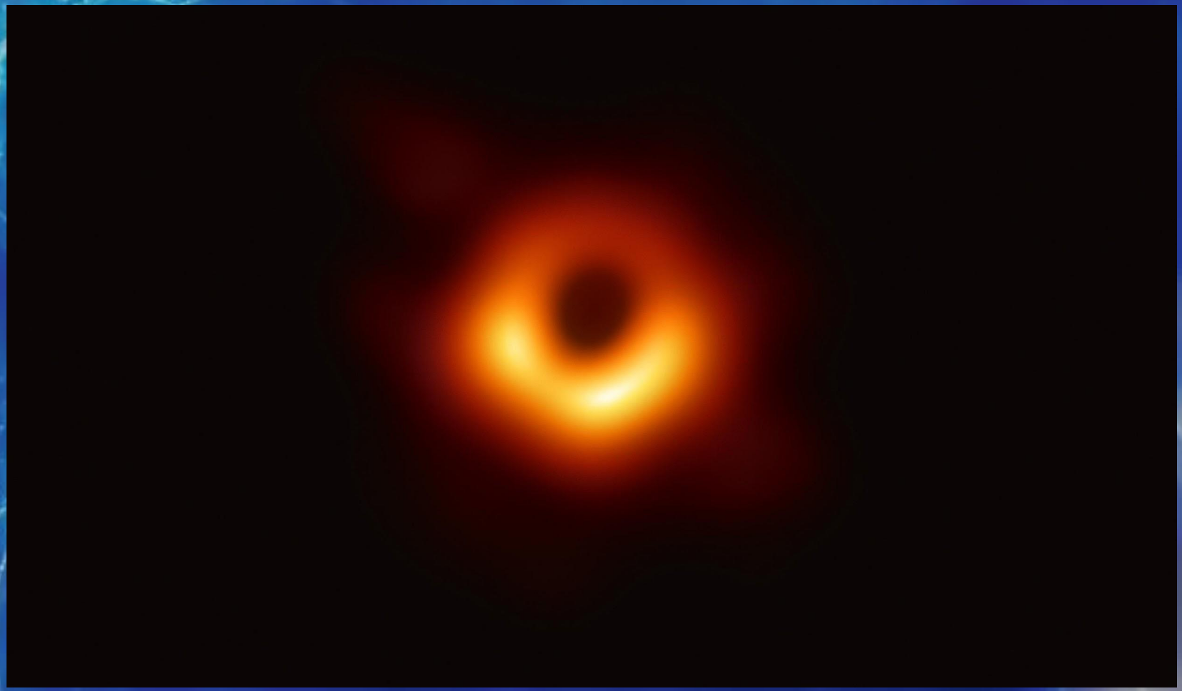



Latif+2013

# Growing BH in growing galaxies: gas accretion or BH-BH merger?

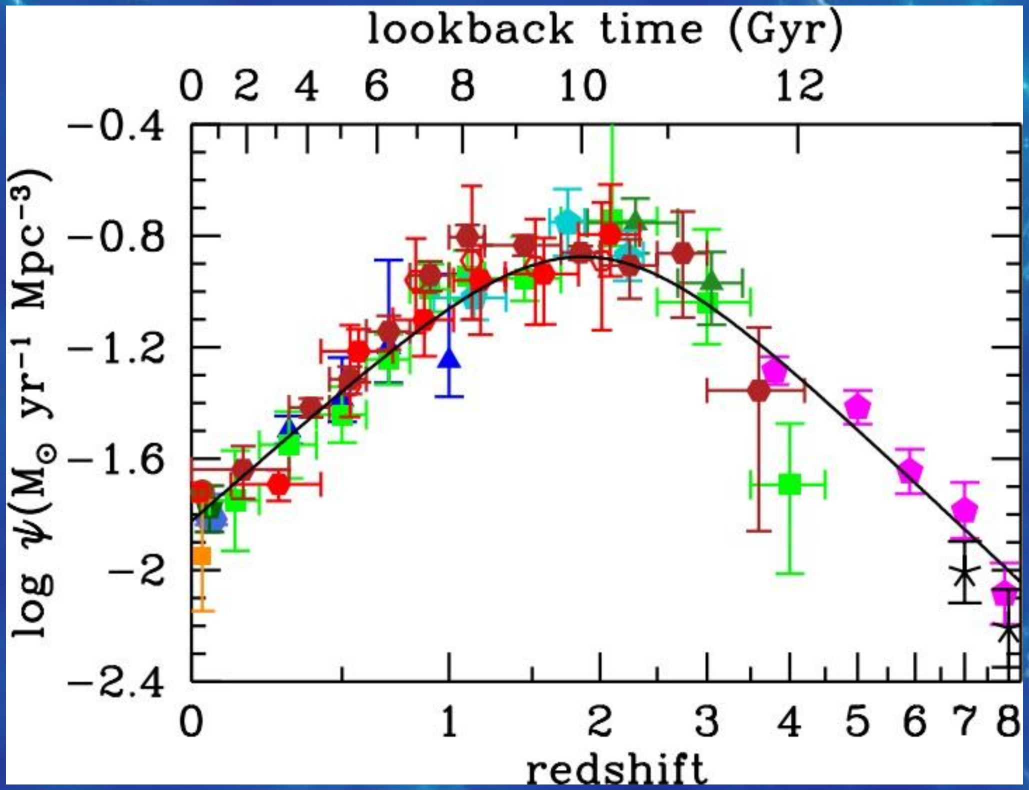
- We need to grow BH to reach the very high masses
- Two possibilities: BH mergers, or gas accretion
- BH grow via mergers → BH mass density constant
- BH grow via accretion → BH mass density increases

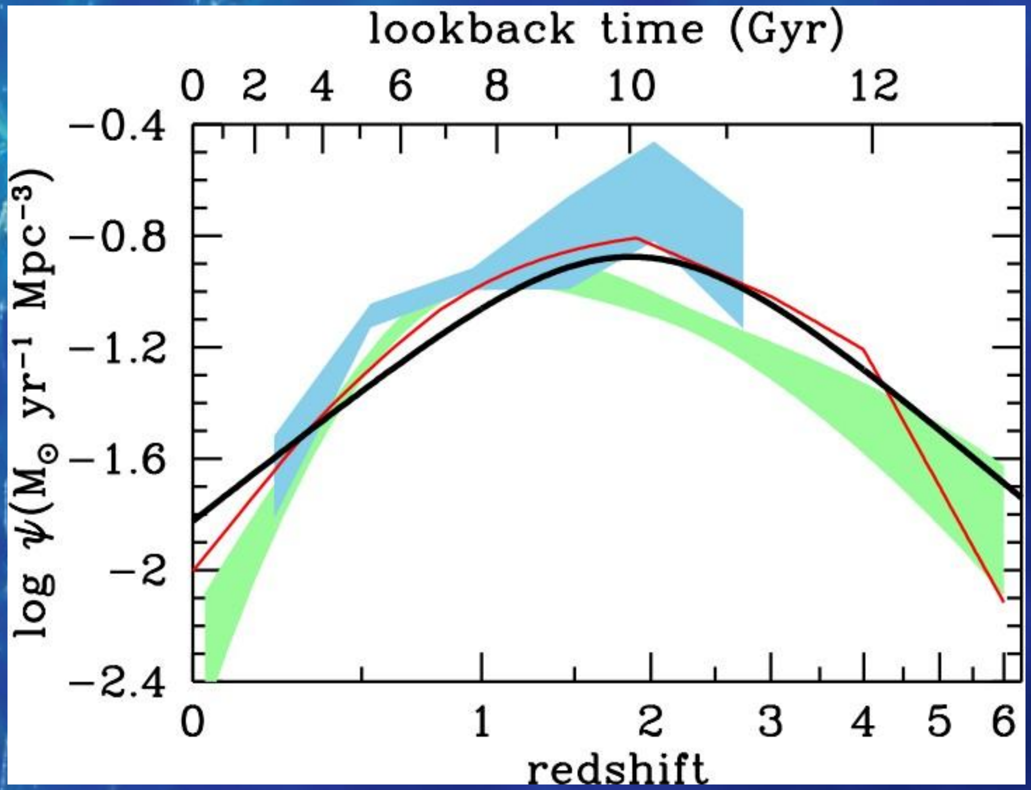


# Cosmic densities: first clue to co-evolution

- Cosmic SFR density (left) and BH Accretion Rate density (right, x3300)
- Similar evolution, peak around the same time…

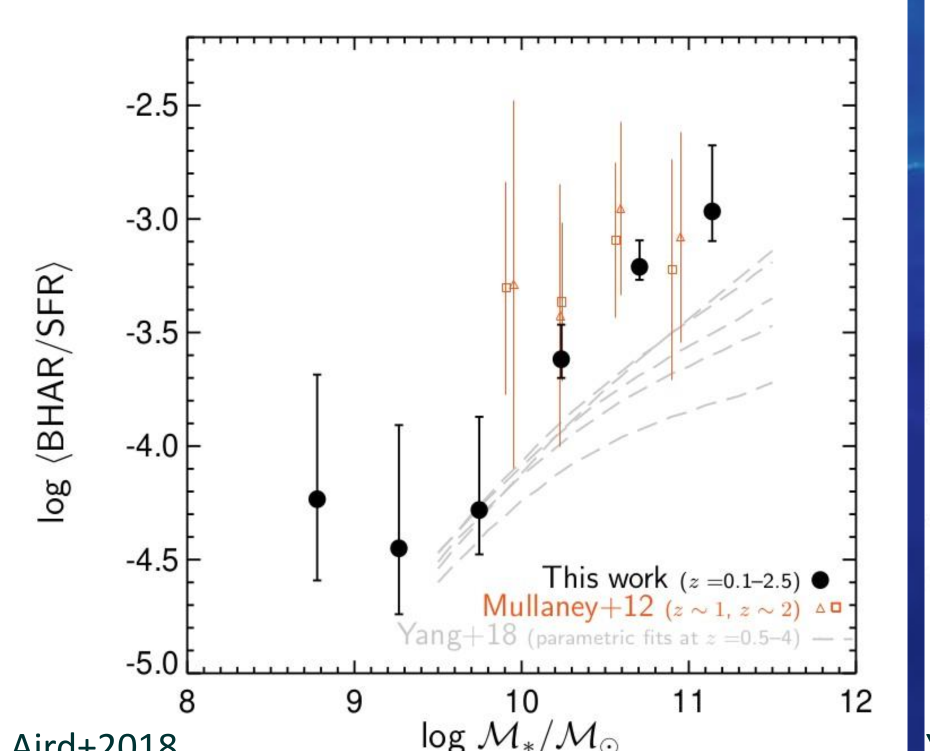


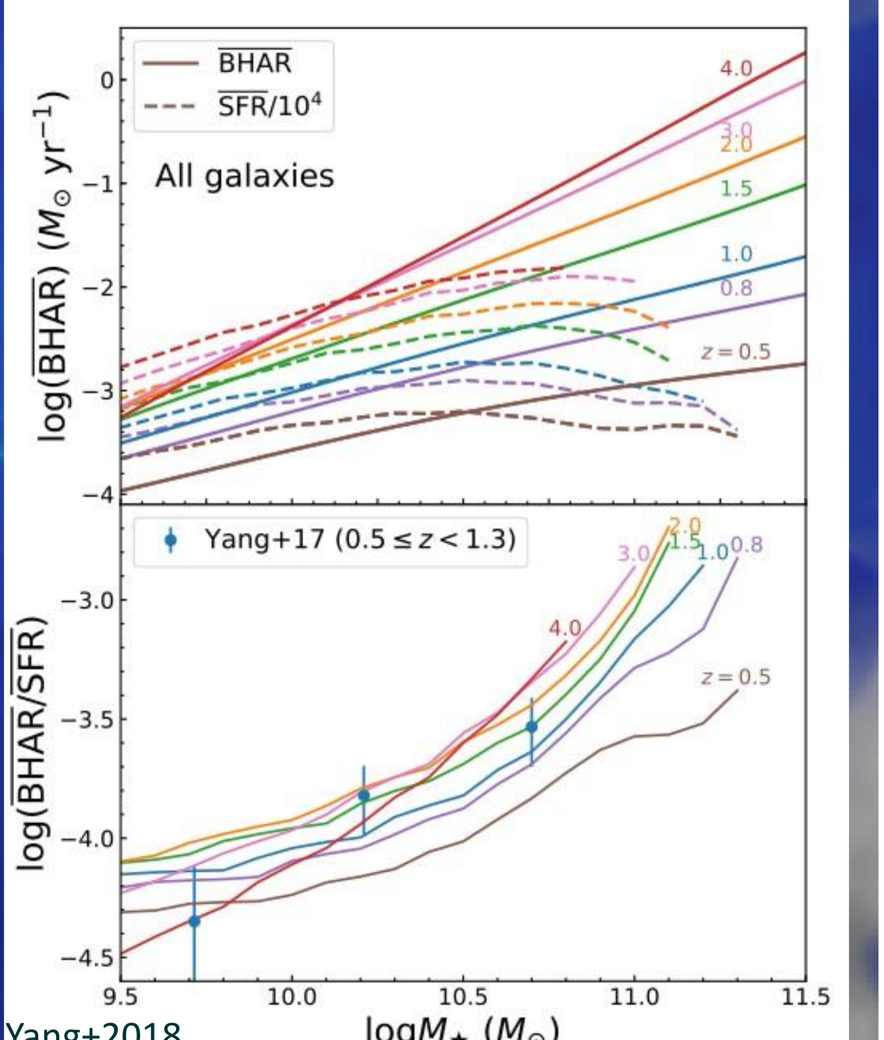

Madau & Dickinson 2014

# Growing BH in growing galaxies: second clue to co-evolution?

- The picture is much more complicated on a galaxy-per-galaxy basis
- Accretion rate / SFR increases a bit with stellar mass
- Some redshift evolution… but not very clear




Aird+2018




Yang+2018

# Maximum accretion rate: the Eddington limit

- Under the assumptions of Bondi accretion, radiation pressure from the AGN will balance the gravitational pull of the BH
- There is a critical luminosity at which the accretion is stalled: this is the Eddington luminosity

$$L_{\mathrm{Edd}} = \frac{4\pi G M_{\mathrm{BH}} m_p c}{\sigma_T}$$

- At a fixed radiative efficiency **η**, this can be converted to a critical accretion rate

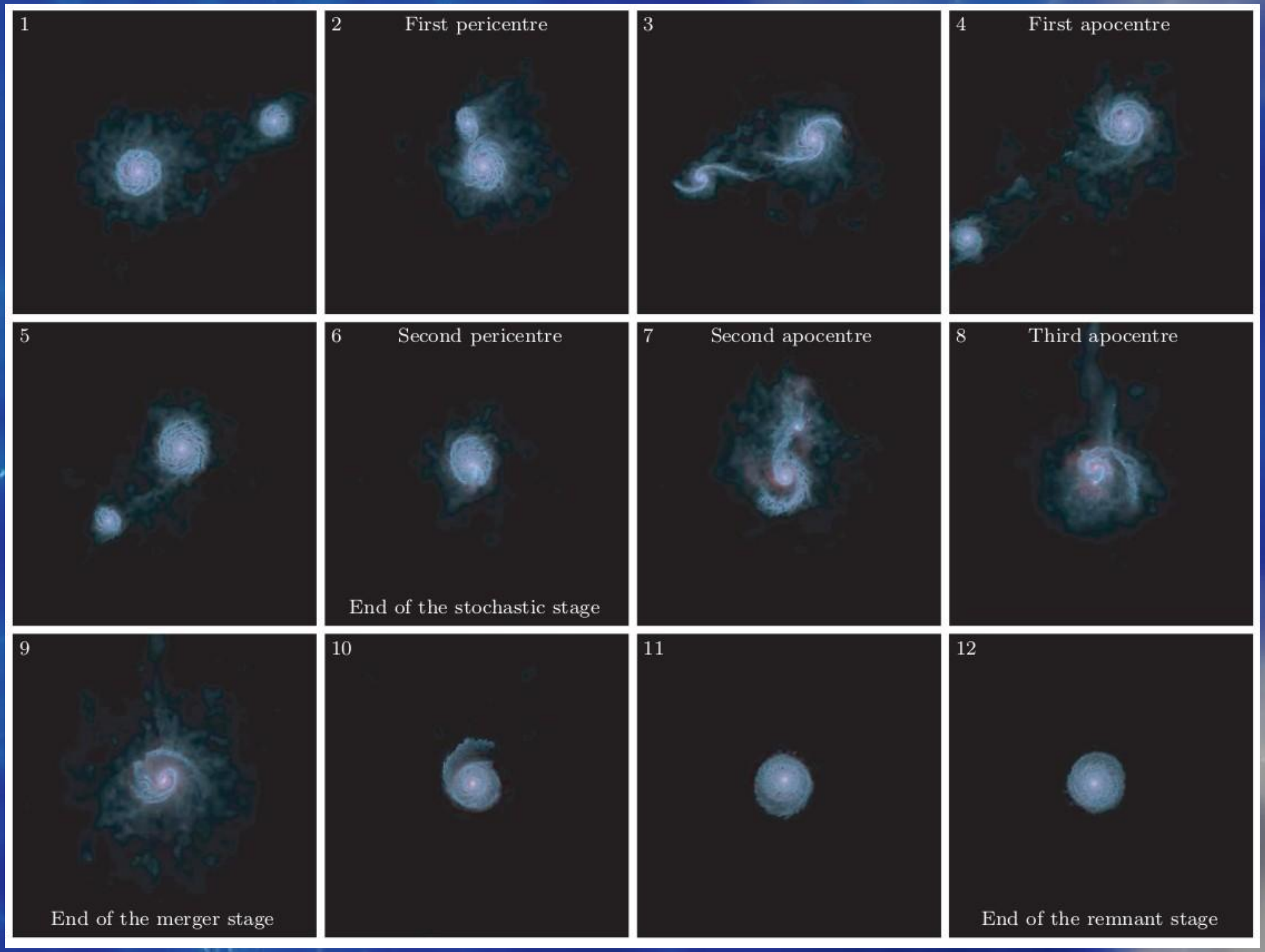
$$\dot{M}_{\mathrm{Edd}} = \frac{4\pi G M_{\mathrm{BH}} m_p}{\eta \sigma_T c} = \frac{M_{\mathrm{BH}}}{\eta t_{\mathrm{Salp}}}$$

- Where $t_{Salp}$ is the "Salpeter time" of the order of 450 Myr

# Galaxy mergers?

- BH-BH mergers are not the main growth mechanism
- But galaxy mergers will drive gas inflows → enhanced growth

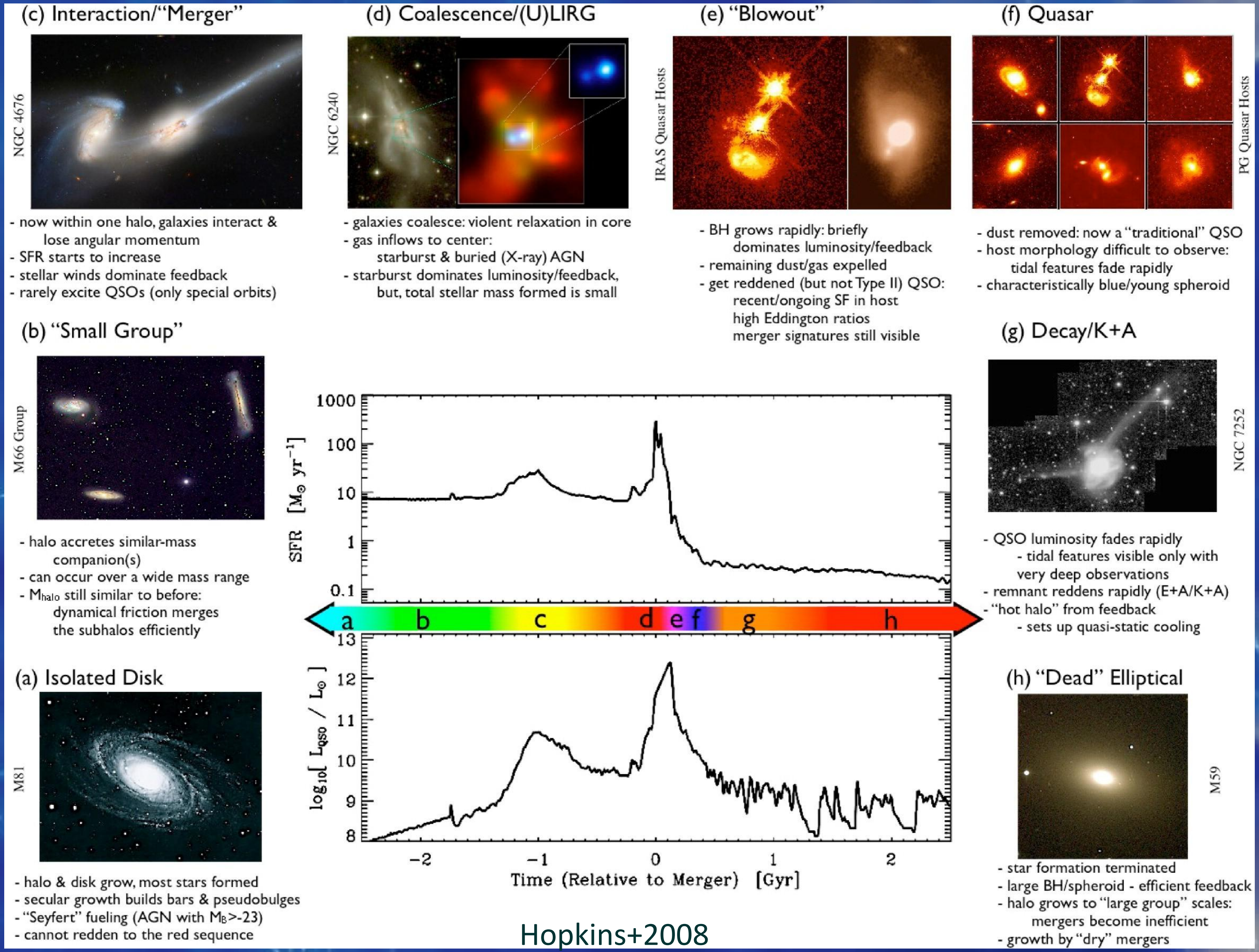
Capelo+2015



# Emerging picture: Galaxy-BH co-evolution

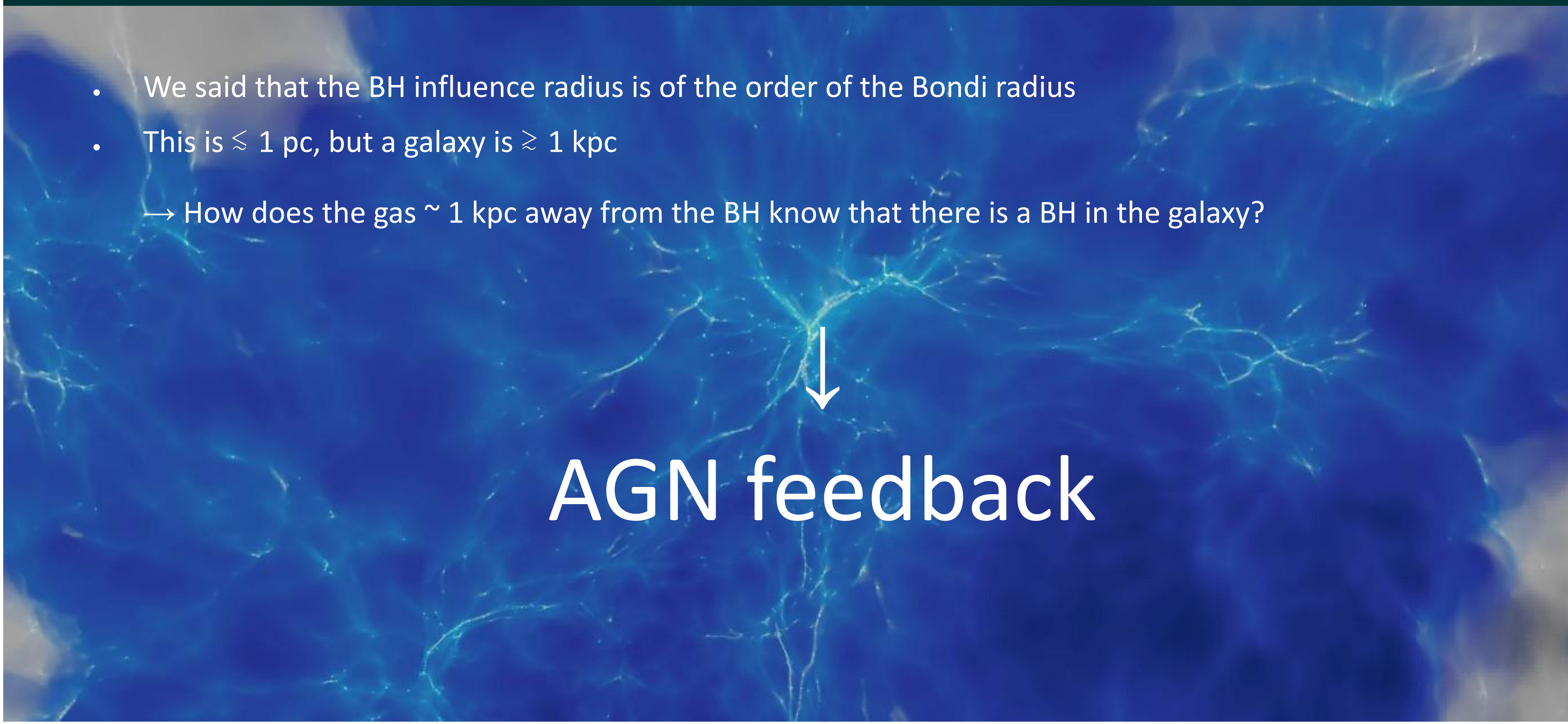
- Picture emerging for the past 15 years:
- AGN as an "evolutionary sequence"

  (also viewing angle)
- Simulations suggest that mergers "trigger" AGN activity
- Observational validation is difficult (samples) and not conclusive yet



Hopkins+2008

## How to explain the co-evolution?



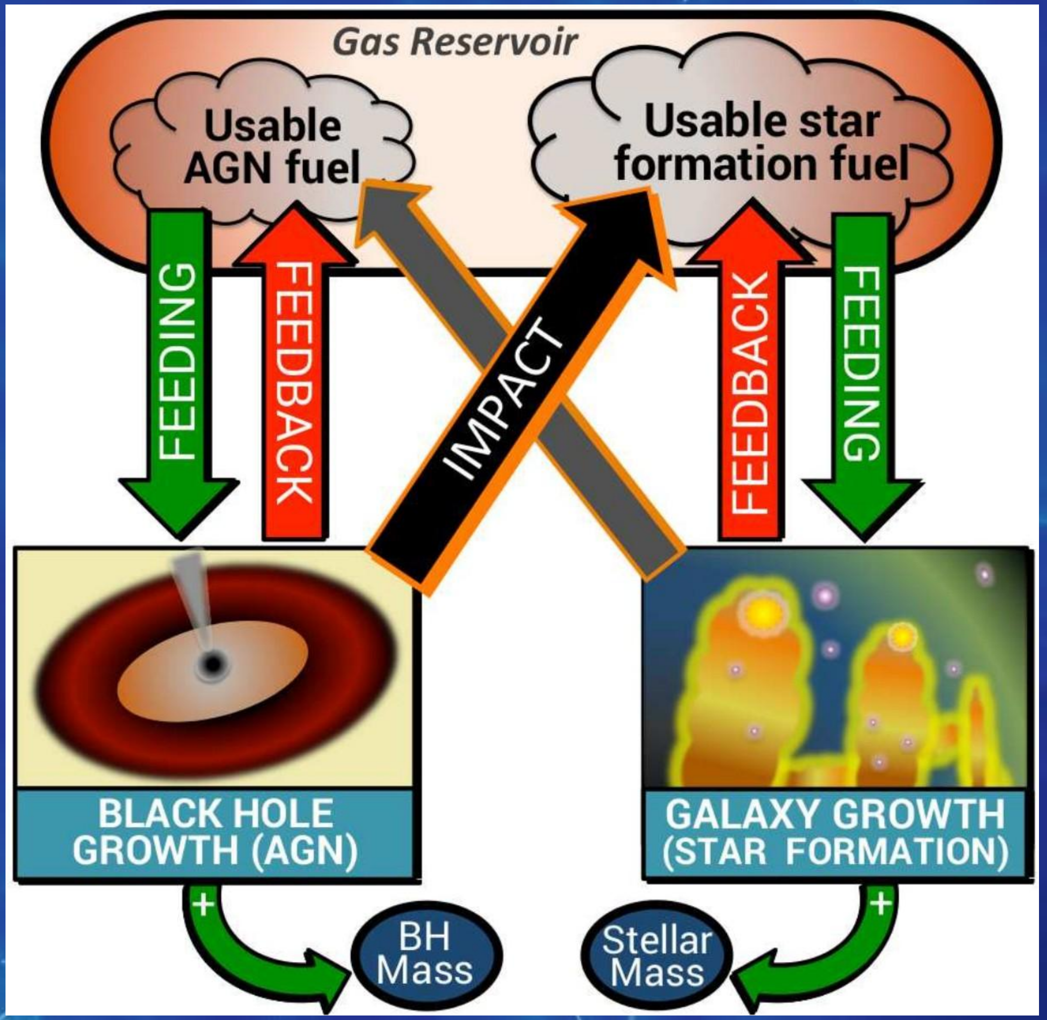
- We said that the BH influence radius is of the order of the Bondi radius
- This is $\lesssim$ 1 pc, but a galaxy is $\gtrsim$ 1 kpc

$\longrightarrow$ How does the gas ~ 1 kpc away from the BH know that there is a BH in the galaxy?

$\downarrow$

# AGN feedback

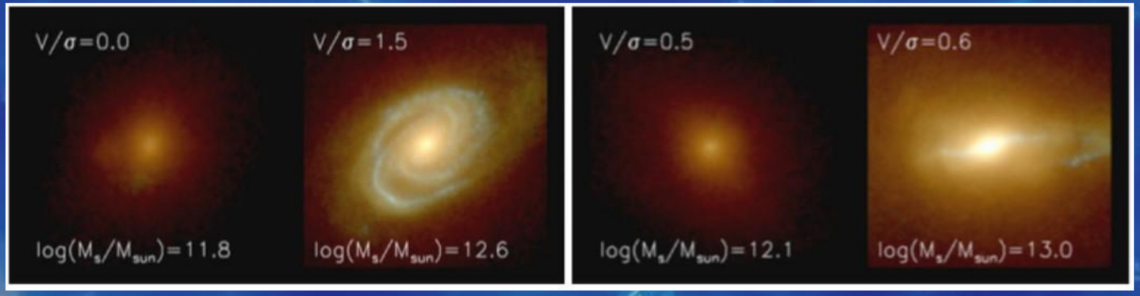
# AGN feedback and galaxy formation: schematic view




Harrison+2017

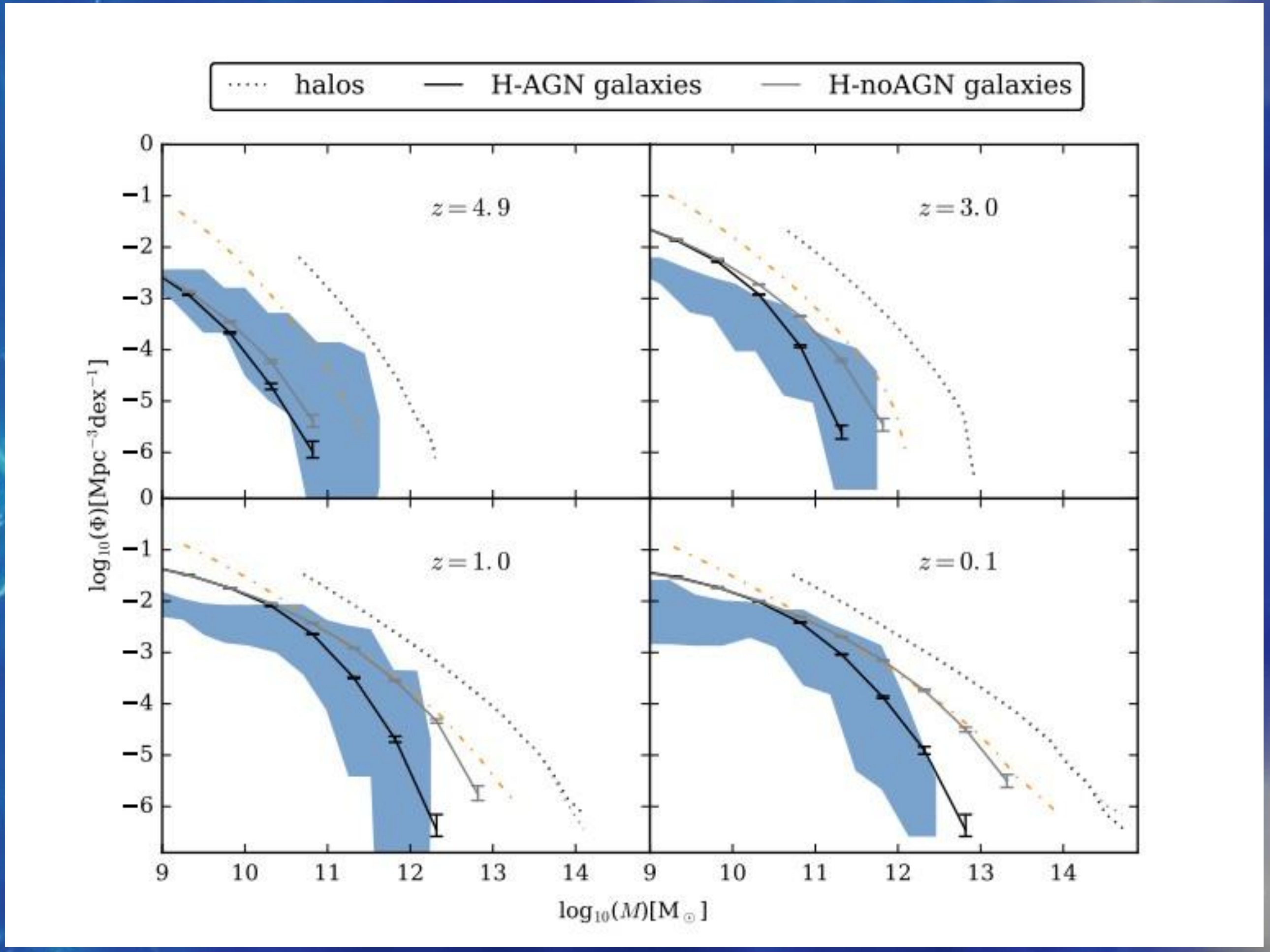
# AGN feedback effect on galaxies

- Very difficult to estimate observationally (we can't "turn it off")
- Simulations can help
- LOTS of detailed numerical issues
- Two main results:
  - Can reduce the stellar mass of the most massive galaxies
  - Helps promoting morphological change Spiral ⟶ Elliptical galaxy




AGN no AGN AGN no AGN

Dubois+2016




Beckmann+2017